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Series Lecture on Advanced Fusion Reactors

J.M. Dawson*

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RESEARCH REPORT

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Preface

This set of lecture notes was derived from a series of talks given by Professor Dawson at IPP Nagoya in October 1982.

Professor Dawson was invited to spend the fall of 1982 at IPP Nagoya, as a Visiting Professor by the President of Nagoya University. This invitation was extended as part of activities of JIFT(Joint Institute of Fusion Theory). Professor Dawson has a long history of scientific collaboration with Japan and IPP Nagoya in particular. He first spent a year at IPP in 1964-65 as a Visiting Fulbright Fellow and since then he has returned to Japan frequently. He has also invited many Japanese Plasma and Fusion Scientist to visit his laboratories, first while he was at the Princeton Plasma Physics Laboratory and more recently to the Center for Plasma Physics and Fusion Engineering at UCLA where he is now the Director.

Here we would like to acknowledge his important efforts. These valuable lecture notes serve as to commemorate his long collaboration.

Series lecture on Advanced Fusion Reactors

by Professor J.M.Dawson.

20-22, October, 1982

Thank you, gomennasai. Watakushi wa eigo de hanashi masu, Watakushi no Nihongo warui desu. I'm sorry I have to speak in English.

This talk will be taken from several references. The fundamental one and the one I use most is an article in "Fusion" a book recently published by Academic press and edited by Edward Teller. There is chapter in this book called advanced fusion reactors by myself. This primarily examined some ideas associated with alternate fuels and paticulary, non-Neutron producing reactions, and how one might achieve these. I will also use a reference on the use of polarized nuclei, in a fusion reactor by Kulsrud et al., and this is a Princeton plasma physics report PPL - 1912. I'm not sure but this may already have appeared in Phys. Rev. Letters.

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I will also say a little bit about two other ideas, if there is time, one is current maintenance in Tokamak using synchrotron radiation, and the other is a new idea for heating Tokamak using MeV singly ionized ions of, say, Li or some heavier element like that.

First the motivation for this work. Nearly all fusion research is devoted to the D-T reaction, and that is natural, because it is the easiest reaction to sustain. The reaction D+T goes to $^4He+neutron$. The α particle has 3.5 MeV, the neutron

14 *MeV*. there is a large amount of energy produced by this reaction. The α particles are charged and therefore confined by the magnetic field and can be used to sustain the plasma temperature. On the other hand, because Tritium does not occured in nature in any substantial amount, we need to use the 14 *MeV*. neutron to breed it. *D-T* has the largest of all fusion crosssections at low temperatures, it uses singly charged nuclei, and that gives the minimum amount of bremsstrahlung radiation and the coulomb barrier is also lowest. Being singly charged means also only one electron per nuclei, so you get the fewest number of electron per reacting nuiclei; these electrons must be heated so there is a minimum energy consumption here. *D-T* has the minimum ignition temperature; against bremsstrahlung losses, the ignition temperature is shightly lower then 5 *KeV* and people picture *D-T* reactors operating between 10 and 20 *KeV*. At 10 *KeV* the *D-T* reaction is already generating fifty times is much energy as it is emitting *in* bremsstrahlung.

The Low ignition temperature means that for a given density of fuel, the plasma pressure is the lowest, and therefor the magnetic field required is lowest or a given magnetic field can confined the maximum plasma density. If you combine this with the large crosssection you get a maximum power density per unit volume. Thus in some sense, you are making optimum use of your magnetic volume; you are geting the most power per unit volume from that.

This is one important consideration, but it is not the only consideration when you are thinking of a fusion reactor. Probably, the ultimate consideration is the power per dollar, power per yen or something like that, not power per unit volume. Now, in spite of these very substantial advantages, and I think, these advantages are so strong that undoubtedly D-T reactors will be the first reactors to be built, we should not stop our thinking with them. It is very important that we built such a D-T reactor, because we have to demonstrate that fusion can produce energy or else support for fusion research will go away. On the other hand, the D-T reaction is not the only fusion reaction that can go. Other reactions have some substantial advantages which in the end may be very important. Consequently, we may as we learn more about fusion devices and how to confine burning plasma, we may want to shift to other fuels with these other advantages.

What are the disadvantages. As I already mentioned, Tritium dose not exsist in any subsantial quantities in nature, because of it's 12 years half life, so any generated decays rather quickly. This means you need to surround your fusion reactor with a breeding blanket. That blanket has to be like a meter thick. Thus, there is large amount of volume there, where we are not getting any reactions. This to some extent off sets the advantage of high power density inside the plasma because now you have a big volume outside plasma which you must use for breeding.

The breeding reactions that we would use is $^6Li+n \rightarrow T+^4He+4.7MeV$ or you can use $^7Li+n \rightarrow T+^4He-2.6MeV$ and I should have indicated here that the neutron survives this reaction. That is very important, because the Tritium is decaying, so, we are loosing some of it. Also not every neutron will be captured by ^6Li; there will be some lost. and so you need to produce more than one Tritium per neutron. The second reaction plus secondary ones of the first type allows us to generate more Tritium than one per neutron, and that allows us to have Tritium balance. That is extremly important.

One point here is that. if you did have a D–T power economy. the Tritium that you are holding in your inventory would be decaying into ^3He. One would gradually accumulate some substantial amount of ^3He, and one could burn that; one would want to. Even if you did simply go to a D–T reactor economy you probably would still want to built some ^3He burning reactors.

There is a second possible sourse of Tritium which to my knowledge has not really been investigated to any great extent. although. some people have written about it. This is to used the n– ^{10}B reaction. Normally. ^{10}B interact. with a neutron to give ^7Li and ^4He plus 2.9 MeV. Now. One could use this reation in conjunction with the second reaction above to produce Tritium. This reaction would provide a supply of ^7Li. If B were more easily mined than Li or if the supply is greater one might want to do this. There is another branch to this reaction. That is ^{10}B plus neutron goes to two alpha plus Tritium plus only 367 KeV. However. for energetic neutron. 14 MeV neutron. there is hardly any energy difference between these two reactions. The fraction that under goes this reaction can be considerable but seems to be less than one. It seems to be a small fraction. may be 10 %.

Now, Tritium is, of course, radioactive as already stated so that causes a problem. Tritium. of course. can form water and get into the water supply. In such a case if the quantity were large enough it could pose a serious radioactive environmental hazard. One can not let Tritium escape, that is a problem. Furthermore, you want to burn it as fuel. I think this is one of the problems that people here are now thinking quite hard about.

In addition 14 *MeV* neutrons are so energetic, they can cause a lot of nucler reactions in the reactors structure. For example, one of these neutrons plus a nuclei of the wall can undergo *n*, 2*n* reactions and or *n*-*P* reactions or the neutron can be absorbed or you can produce a proton and the neutron can survive or you can knock out a duteron or you can knock out an alpha particle; there are many other reactions. Some of these products will be radioactive, so 14 *MeV* neutron activate the structure of the device. Now, most of this radioactivity would be relatively short lived, probably less than 100 years. It varies, of couse from element to element and isotope to isotope. Still the fact of the activity of the device means that one has to go to remote handling of the device, at least, for nearly all materials and that complicates the operation of the reactor greatly; it also complicate experiments on such devices greatly. For example, for TFTR in Princeton, they talk about a neutron morages. There is a certain number of shot, *D-T* shots they can make on that machine before it becomes so hot they can not handle it with hand on maintenance. They would have to do it remotely. In that case, you have buy a lot of robots, or something like that. This costs a lot of money. I think, that the number of shots for TFTR is not so great; it is less than 100, *D-T* shots, more like 10 *D-T* shots. If you spend 300 million dollars on a machine for 10 shots with *D-T* that is a lot. Of couse, one does other experiments beside *D-T* experiments, but still you want to make sure that the 10 *D-T* shots that you get are made good use of. From this point of view, I think that the investigations going on here, looking into low activation wall material are very important. If one can double or triple the number of *D-T* shots, one can get, I am certain one would pay quite alot of that.

Some more disadvantages: as I said, when a 14 *MeV* neutron hits a nuclei in the wall, it can knock out a protron or an alpha particle. This forms a little gas; bubbles develope inside the meterial and that causes bristering and swelling, embrittlement and many problems. The material's people have a lot of works.

Also when a nuclius in the wall gets hit by a 14 *MeV* neutron t gets quite a jolt and goes flying off into the lattice. That sort of tears up to the wall material. At present people are thinking in terms of 20 $MW/year/m^2$. This implies that every atom in the wall will be displaced some hundred times during the life times of the device. Of course, one wonders whether the wall really can maintain it's integraty under that kind of treatment.

Now, Engineers are quite ingenious and I am sure, they will find solutions but there are a lot of problems there.

Some people say well, why don't we just make use of the neutron. Since we have to live with them for the *D-T* reaction, why don't we try to make use of them for something besides boiling water. Boiling water seems like an inefficient way to use them. If we can produce something more valuable than just hot water why not do that. This would be a more efficient use of a fusion reactor. One such proposals is to make a hybrid reactor to breed fission fuel. One would then use the fusion reaction plus some $n, 2n$ reaction to get one neutron to breed Tritium and one neutron to breed either plutonium or ^{233}U. You could breed plutonium from uranium or use Thorium and breed ^{233}U. The latter reaction is nice, because, first of all, one can take ^{233}U and mix it with natural uranium to make what is called denatured ^{233}U. Because this is now not useful as a weapon material it is quite safe. This would make a safe fuel for existing light water reactors. It turns out that one fusion reactor can support something like 10 ~ 15 light water reactors of the same power. In effect, one would multiply the energy production of the fusion reactor by some factor like 10 ~ 15 . Because, such a breeder supports so many light water reactors you don't need many of them. This means you can locate them in isolated places, and you can make them very secure so that one can avoide terrorist problems. For all these reasons, H. Bethe has proposed this would be very good use for fusion: perhaps that will be the first economic use of fusion.

There are a lot of people in the world who are a little uneasy about fission for safety reasons and because of the very long life time of the radioactive products. Although one might build breeders one might also look at what else one could do with fusion and in this vein, we look at the advance fuels and see if there are not some possibilities for low neutron producing fuels which would produce little radio activity and also have other advantage.

The physics of advance fuels is more difficult because one need higher temperature and better confinement. We will be trading physics difficulty for engineering simplicity and environmental advantages: whether or not this is possible remains to be seen. One doesn't know at this time because one has not really tried.

Advanced fuel generally run at about 100 *KeV* rather than around 10 *KeV*. People say, oh, a factor of 10, that makes it so much harder; if we have so much trouble getting to 10 *KeV* how do you expect to get to 100. I think that, that is not a good argument. Just as an example, I would refer to our experience: for many years, fusion devices never got above 100 *eV*. All through the 60's, stellarators only got to 100 *eV* or so. Then the Russians showed that with Tokamak they could get *KeV* temperature. Suddenly, temperatures jumped by 10 and that simple discovery did not take new invensions or technology beyond what existed. A second example is what happen with PLT when high powered neutral beam were put on it. Tokamaks ran along at 1 to 2 *KeV* for quite a while. It was expected you might get three or four *KeV* temperature with the neutral beams. However, the temperatures went right on up to almost seven and one half *KeV*: the temperature increased by a factor of 4 or so.

Thus by improving technology, one can make jumps in temperature like those required I think, we should not be detered by the prospect of physics difficulties, because we should keep in mind if those are solved, then we have many more alternatives in fusion. I think, to some extent fusion research has been blinded by aiming totaly toward *D-T* and not thinking about the other possibilities.

Amoung, the possibilities are, of course, *D-D*, and this one has been considered considerably. Some people in considering *D-D* say, well, you haven't reduced the neutron very much. *D-D* produces Tritium. Tritium reacts and you get a energetic neutron.

For *D-D*, 38 % of the energy comes out in neutrons and 32 % in 14 *MeV* neutrons and this gives the same radioactive problems as *D-T*. However, we have reduced their production from 80 % of the energy, to a say 32 % of the energy; that is more than factor of two. Now. You may think that a factor of two is not very much but remember that wall lifetime depends on the total radiation, so wall life might be doubled, and that is quite an economic gain. I think the simplest way to think of this is in terms of your salary, suppose your salary were be doubled or halved; this is rather equivalent to what we would gain here. You can see that there is indeed an advantages.

Now, There is even a further gain because you don't have to breed Tritium in a blanket. One can use the neutrons coming out, and absorb them by some material which produces energy but no long lived radioactivity and by doing this, you can generally gain roughly 9 *MeV* additional per neutron. This means the total energy we get is like 60 *MeV* for 4 deuterons and that further reduces the fraction of the energy coming out as 14 *MeV* neutrons to may-be 25 % of less. So *D-D* is certainly something to keep in mind. Also deuterium is quite plentiful. The amount in the ocean is so great that it could supply all the energy the world recieves from the sun for a million years. You certainly are not going to produce as much energy as the earth gets from the sun. If we did the earth would be too hot to live on. That means that the deuterium will certainly last more than million years. Also one burns up so little of the ocean only one part in six thousand of the hydrogen there, so if you burn all deutrium in the ocean, it would lower the ocean level by something like $2 \sim 3$ feets.

Another possibility is $D\text{-}^3He$. This one, I think, is in some ways really the most atractive of all the advanced fuel reactions. First of all, It is, the next easiest reaction to make go; both $D\text{-}D$ and $D\text{-}^3He$ have ignition temperature of about 30 KeV. This reaction produces an alpha particle and a proton, both charged, so both are contained by the magnetic field. This means more of the energy is retained by the plasma to sustain the reaction. If one use this reaction, of course, there are side reactions, $D\text{-}D$ and secondary $D\text{-}T$ reactions and the $D\text{-}T$ reactions produce 14 MeV neutron. You haven't totaly eliminated neutron although their numbers are greatly reduced. One can further reduce the number of neutron by running rich in ^3He and lean in deuterium. That provides one possibility, and it looks like one can reduce the number of neutron by, at least, two order of magnitude by this kind of scheme.

A second possibility which has just recently been realized is that, of using spin polarized nuclei in fusion reactors. you can probably by this means virtually turn off the $D\text{-}D$ reaction and stop the Tritium production. You also enhance the $D\text{-}^3He$ crosssection by a factor of one and half, and so may be we could reduce neutron production by another factor of 100 or 1000. Thus you can perpaps get a total reduction of 10^4 to 10^5 .

^3He has its problems. The main problem is the supply. ^3He does not exist in large quantities in nature, but it does exist. There is some, in the atmosphere. The total ^3He contained in atmosphere is about enough to supply the U.S., electric power, industry for 10^3 years, something like that. That would means in 10^3 years you have to process the whole atmosphere to get it, if you want to run the power industry on it. Of course, other people on the earth want energy too, so that is really not much.

It occurs also naturally in volcanic gasses. This is, in fact, a recent discovery of about 15 year. In fact volcanic gasses are enriched in it and it's conceivable that one could find on the earth a pocket which has sufficient ^3He to be worth mineing. I think, nobody has looked for it. The principle places where you find it are in hot spring's, and volcanic gasses, something Japan has. Unfortunately, to date these are still too lean. It seems that the geothermal energy given by these hot springs is about 100 times what you can get from the ^3He supply. However, the possibility of a place where ^3He is enriched has not been explored. All people doing oil well drilling, could sample the gas they encounter to see how much ^3He is in it. It wouldn't cost very much and may be, they would hit pay gas.

One can breed ^3He , that is you breed Tritium which you store and periodically you take out the ^3He and burn it. You can do this in isolated breeders and store the Tritium in small packages so that if one of them break open there is no serious escape of Tritium. This has been proposed by Miley.

One could also consider putting such a breeder on the moon. This is not impossible. Now because ^3He is a really valuable commerdity in terms of the energy per unit weight, and we know, you can go to the moon, I am sure, if we can build a fusion reactor, we could build one there. That is a little science fiction but if one thinks back to a hundred years ago and imagine what the situation was and compares it to now, one can quite well imagine such a things could be happen.

The earth is not a typical sample of the universe and actually when the universe was created, at least according to the best present theory, the big bang theory, there was considerable amount of ^3He generated. Roughly some where between the same amount as to one tenth as much as deuterium. Primoidal ^3He is presumably the source of ^3He that is coming out of the earth: it was trapped when the earth was formed. That's why volcanic gasses are enriched in ^3He . The earth has not retain much of its ^3He , but there are place in the solar system which almost certainly have, like Jupiter, Uranus, Saturn, those places. Again if you are willing to do what is today a little science fiction thinking, you can imagine going to those places and mineing them for ^3He . We probably need a robot for this. ^3He is a light gas, and so it would probably tend to be on top of the atmosphere and one might be able to scoop it off. I have asked several people if they know how much ^3He is contained on Jupiter and Saturn, but nobody seems to know; we must wait until they send atmospheric probes there.

Let me say a word about polarized nuclei. This is particulary exciting for the D-^3He reaction, because we can virtually turn off the *D-D* reaction and the neutrons. How this works. I will outline here.

Suppose we have two nucleus, nuclei that react, we will call them one and two. Let the spin of nucleus one be S_1, and the spin of neucleus two be S_2; just for the sake of making the argument we will take S_1 larger than S_2. Then the spin of total system of two nuclei can take on values from S_1+S_2 to S_1-S_2 in steps of one. Now, let S_t be the spin of one of the members of this set; associated with that spin state are $2S+1$ quantum states, different oreantation the total spin can take. Now, in general, the fusion crossection is dominated by only one total spin state or S_i. The fraction of collision's which result in reactions are the number of states that can react, that is $2S_i+1$, divided by the total number of spin states. If we could line up the nuclear spin, if we could polarized them, so that the total spin is always S_i then we could enhance the reactivity, because every collision could results in a reaction. We would enhance it by the total number of spin states for unpolarized nuclei divided by $2S_i+1$.

Let us just take an example, well, actually two examples but very similar ones. *D-T*, $D-{}^3He$. The spin of Duterium is one and the spin of Tritium or ${}^3He$ is 1/2. The resonant reaction comes from the spin 3/2 state for the total. If we take the spin 3/2 state as the state which gives the reaction, then we find an enhancement of 1.5. That means that one could reduce $n\tau$ for *D-T* by a factor of 1.5, if you could create a plasma of properly spin polarized nuclei. That is some gain, but I think that is not really exciting. What is really exciting is that one could turn off the *D-D* reaction because the *D-D* reaction primarily goes through a total spin states of zero or one. If you lined up the spins of the deuterons(total spin 2) the *D-D* raction is virtually turned off. You would have turned off the production of Tritium. On the other hand, you would have enhanced the $D-^3He$ reactivity by a factor of 1.5

I might just give you a picture why it is that the 3/2 state is responsible for the reasonance. Think of $D+T$ as ^4He , plus an extra neutron in orbit around it. Since the neutron has spin 1/2 and one unit of orbital angular momentum, and because spin orbit coupling enhances the binding when they are parallel it is the 3/2 sate that is most tightly bound for the ^4He neutron system.

A critical question is a whether these polarized nuclei can survive in the plasma for a long enough time for fusion to take place. At first thought it seems crazy, the energy associated with having the spin lined up along the magnetic field, as opposed to the antiparallel case is only equivalent to an energy of 10^{-2} eV or so and this is in a 10 *KeV* plasma. How can this little energy make a difference. The answer is that in the very weak coupling between the plasma and the spin, they are so weakly coupled that, in fact, depolarization is very slow; the crosssection for spinflip during an encounter is like 10^{-30} cm^2 , much smaller than the fusion crosssection. Therefore, if we can create this polarized state to begin with it will survive long enough. If I have time I will say little more about later.

What are other possible advanced fuels; let me give you a partial list.

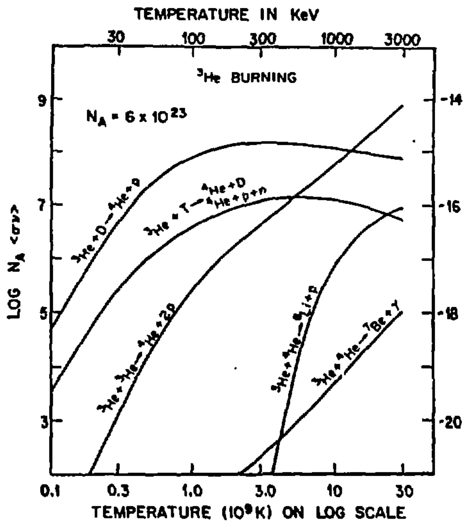
	(1)	P + ^{11}B	→	3^{4}He +	8.	MeV	
	(2)	P + ^{6}Li	→	^{3}He + ^{4}He +	3.865	MeV	
		^{3}He + ^{6}Li	→	2^{4}He + P +	16.6	MeV	
		^{6}Li + ^{6}Li	→	3^{4}He +	20.5	MeV	
	(3)	^{3}He + D	→	^{4}He + P +	18.2	MeV	
		Run 90% ^{3}He, 10% D					
	(4)	^{3}He + ^{9}Be	→	3^{4}He +	18.74	MeV	
		^{3}He + ^{9}Be	→	3^{4}He + n	-1.6	MeV	
83% of Energy Gives Off As Charged Products	(5)	D + ^{6}Li	→	^{7}Li + P +	4.9	MeV	
			→	^{7}Be + N +	3.3	Mev	-Max Neutron Energy 2.89 MeV
			→	^{4}He + T + P +	2.5	MeV	
			→	^{4}He + ^{3}He + n +	1.7	MeV	Max Neutron Energy 1.5 MeV
			→	2^{4}He	22.0	MeV	
		P + ^{6}Li	→	^{3}He + ^{4}He +	3.864	MeV	
		T + ^{6}Li	→	^{7}Li + D +	.9	MeV	
			→	^{7}Li + n + P	-1.2	MeV	Low Neutron Energy
			→	2^{4}He + n +	15.8	MeV	Maximum neutron energy 14 MeV
		^{3}He + ^{6}Li	→	2^{4}He + P +	16.6	MeV	
		^{3}He + D	→	^{4}He + P +	18.7	MeV	
		D + ^{7}Be	→	2^{4}He + P +	16.5	MeV	
		^{7}Be + ^{6}Li	→	3^{4}He + P +	15.0	MeV	
		D + D	→	T + P +	4	MeV	
		D + D	→	^{3}He + n +	3.25	MeV	Neutron Energy 2.4 MeV
		T + D	→	^{4}He + n +	17.4	MeV	Neutron Energy 14 MeV
		^{3}He + D	→	^{4}He + P +	18.2	MeV	

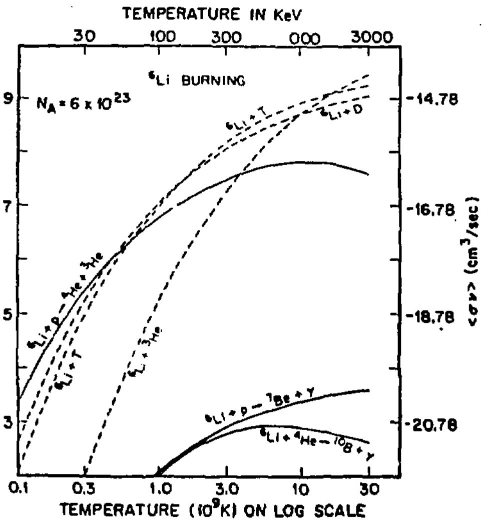
TABLE – SOME ADVANCE FUEL REACTIONS

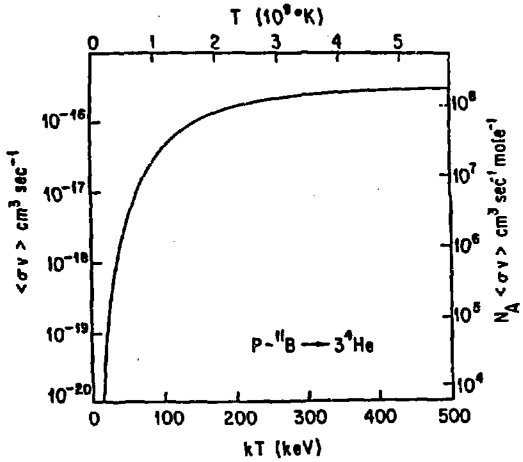
P–^{11}B , this is interesting because it produces virtually no neutrons; this reaction is the one that first interested me in the idea. Unfortunately it looks like, this reaction does not produce quite enough energy to ignite although the idea spin polarization helps here as we will see later. Then there are things like P–^6Li .

that produces $^3He+^4He$ plus almost 4 MeV. The ^3He produced can react with ^6Li to produce two alpha particles plus a proton. Now the proton can come back to react with ^6Li again. So we have a kind of chain going on here. Unfortunately, only one ^3He and one proton are produced, so if any are lost this chain is broken. It is not really a chain which can sustain itself. However, there is the beginning of a chain here and this can help enhance the reactivity. I had really hoped this would be sufficient to make $P-^6Li$ burn very nicely but it doesn't seem to be quite sufficient. Now with the idea of spin polarization perhaps that will change the picture; the calculation remains to be done. As already mentioned there is $D-^3He$; also if we had ^3He, there is $^3He-^9Be$. One reaction that does look like it would go rather well is $D+^6Li$. This produces a huge number of daughter nuclei all of which can react with each other and so one has a kind of stew cooking away and it is a complicated problem to actually figure out the total reactivity for this case. $D+^6Li$, of course, does produce some neutron because of the D-D reactions and also even the $D+^6Li$ reaction produces some neutrons. However 83 % of energy is given of as charged product. Again, if one were to apply the idea of spin polarization that might greatly change this picture.

We might just look at the size of some of these crosssections, because that's what determines whether or not a fuel is a good candidate. We will see that for burning we need $\langle\sigma v\rangle$ around 10^{-16}; somewheres around there.







For D+^3He the ignition temperature is 30 KeV. At that temperature $\langle\sigma\upsilon\rangle$ is just a little bellow 10^{-16}. Let us look at ^6Li reactions, solid curves are based on measured $\langle\sigma V\rangle$, and dashed ones are theoretically derived. From this it looks like P+^6Li

might burn and if you add $^3He-^6Li$ reactions it will burn better. Certainly $D+^6Li$ looks quite favourable. A look at $P+^{11}B$ shows $<\sigma V>$ somewhere above 10^{-16}. Thus it looks like it might go but it is marginal and depends greatly on details: at present it looks like it can't ignite.

Now what I want to talk about are some of the physics considerations. There is a lot of very interesting physics associated with burning advanced fuels: a lot of physics which you don't get into when you just consider $D-T$ reaction because a lot of processes become important which weren't important there. We will look at these one by one, to get a feel for what is involved.

The first thing we look at is the rate of energy production. Suppose we have two ion species A and B. They will produce thermonuclear power equal to $P = n_A\ n_B <\sigma_{AB}\ v_{AB}>\ Q_{AB}$ If we have several species, of course, we have to sum over all different reactions. Now only a fraction of this energy goes to the plasma as we saw with $D-T$ where a good fraction of it leaves with the neutrons. The fraction which stays in plasma to maintain its temperature is that fraction which is given off as charged products. One must keep only that fraction in the energy balance: again for many species you have to sum over the species.

The first things that we might look at is the time it would take the fusion reaction to heat the fuel up to the burning temperature: (ie. supply its thermal energy) This gives us some idea what kind of $n\tau$'s and also $<\sigma V>$'s are needed. We take the thermonuclear power in the charged products and multiply that by τ and equate it to the energy in the ion and electrons: however I am going to equate it to the only ion energy as I am going to assume that the reaction products heat the ion primarily. It turns out that under the condition we will want to operate the device, we will want the ions to be much hotter than the electrons. The ions react, electrons just radiate and conduct away energy. It turns out that for many advanced fuel reactors this is a good approximation.

$$n\tau = \frac{3}{2} T \,/\, \sum_{ij} \varepsilon_i \varepsilon_j \langle \sigma_{ij} N_{ij} \rangle Q^*_{ij}$$

where n is total ion density, ε_i is the fraction of the ions in species i, Q^*_{ij} is the energy in charged particles from reaction $i-j$ and T is the ion temperature. (assumed to be the same for all ions) Typical temperatures are in the hundreds of KeV as we recall from the graphs. On the other hand, reaction energies are like 10 MeV, which is, thirty times larger. If we consider just two species, say, a fifty-fifty mixture, then if we can get $\langle \sigma V \rangle$ up to 10^{-16}, $n\tau$ comes out to about 2×10^{15}. This tells you, that you must achieve plasma and energy confinement in the $n\tau = 10^{15}$ range which is typically the range we can get as we shall see.

The second things one has to look at is, energy loss. First the one that we can't avoide is bremsstrahlung due to electrons colliding with the ions; this gives the minimum energy loss. Let's first estimate this: the calculation is as follows. The acceleration of an electron in the field of an ion is e^2z^2/mr^2 and then classically the power radiated by such an accelerated electron is $2e^2a^2/3c^3$.

To find the total power radiated by all electron surrounding an ion, we take the number of electron in a little shell and integrate the power radiated from some minimum distance to, well, probably the Debye length but it turns out that it doesn't matter, you can use infinity. The integration must be cut off at some minimum distance or it diverges. The classical calculation fails at very close distance because of the quantum nature of the electron; that is one can't localize electrons to a size smaller than their deBroglie wave length. You can not treat the accelerated electron as a the point particle but really you must think of it as sort of a cloud. If the electron comes closer than the size of this cloud to the nucleus, then we must cut off the integration. This gives us the minimum distances, $\hbar/p$. If we take the monentum, p, as that associated with a thermal particle and then use this cut off in the radiation formula, we get the expression.

$$P = (16\ \pi^2\ z^2\ e^6\ n_e\ /\ 3\ c^3\ m_e\ h\ )\ \sqrt{T_e/m_e}$$

You must add up the contributions from all ions or multiply by n_i .

$$P_T = [\ (4\pi)^2\ e^6\ /\ 3\ c^3\ m_e\ h\ ]\ \sqrt{T_e/m_e}\ n_e \sum_i n_i z_i^2$$

If you go to Spitzer's little book on plasma physics, he gives an expression for the bremsstrahlung from a plasma which has all the same dependences. There is only one thing that's different and that is called the Gaunt factor. That number comes from the quantum mechanical calculation one uses to calculate the bremsstrahlung. One can obviously use many different approximations when calculating the bremsstrahlung and the Gaunt factor depends on the approximation. One never make exact calculations of that. A favorite approximation is the Born approximation and that gives a Gaunt factor of 1.1. Our formula would give a Gaunt factor of 1.08. This little classical calculation which takes five minutes is good to within 2 % of a Born calculation which we probably takes several weeks. Of course, we didn't know the agreement would be so good beforehand, so one really must also do the detail calculations. This is Ok, but once you know that this simple calculation works it becomes a very useful tool.

You can also write the bremsstrahlung formula in terms of the electron density squared times the average z.

$$\bar{z} = \sum_i n_i z_i^2 \;/\; \sum_i n_i z_i$$

This same averaged z enters into the resistivity formula of a fully ionized plasma. Thus the ratio of bremsstrahlung to ohmic heating is constant, independent of the composition of the plasma. This means that if you pass a certain current density through a plasma it will come to a definite temperature independent of it's composition if the energy loss is by bremsstrahlung and the energy input is ohmic heating.

So far, we only talked about the nonrelativistic situation, but actually, if the temperature is 100 KeV, then the electrons are going to be relativistic. Such calculations have been carried out by Maxon, and you can just look up the results. However, again we can get his answer by a simple model which I would like to describe. First of all, suppose we have an ion with an electron going by at some relativistic speed. We would like to know at what rate that electron is radiating.

To do this let's go to the rest frame of electron. We know the power being radiated in the rest frame of electron is given by the simple non-relativistic formula. Next transform that back to the lab. frame. The power radiated is invarient under such a transformation because energy transforms like time and Δt transforms like time so their ratio is independent of the frame. All we have to do is to calculate the acceleration in the rest frame of the electron. That's determined by the electric field that the electron see. The electric field that the electron see is simply the vector sum of electric field parallel to the motion plus γ times the electric field perpendicular to the motion, γ is the relativistic γ. Using the accelertion that this gives in the radiation formula and repeating the earlier calculation gives $(1+2T_e/m_e c^2)$ times the non relativistic bremsstrahlung formula (to order v^2/c^2). One can compare this with the very detailed calculation of Maxon and one finds that it agrees within a per cent or so for temperatures like 300 KeV or below. At such temperatures this correction is already making a factor two differences in the total bremsstrahlung.

Another relativistic correction which we must include is that for electron-electron collisions. At low temperatures we ignore electron-electron collisions; that is because there is no dipole moment for such encounters. Another way to think of it is that each electron radiates, but the radiation fields are out of phase and cancel, and so there is no radiation. However, if you take into acount that the electrons are moving with velocities comparable to the velocity of light, then a phase differences appear and the fields don't exactly cancel out; the correction(in the power is of the order of v^2/c^2 ; one can see that it is essentially the same relativistic correction one gets for ions, however, it is twice as big since two electrons are involved. This gives $(4/\bar{z})\ T_e/m_e c^2$ times the ion bremsstrahlung. This also fits well with Maxon's calculation. Adding these two gives the total bremsstrahlung.

Now how must calculate the bremsstrahlung radiation cooling time to compare with the fusion power. We multiply the bremsstrahlung radiation rate by τ and equate it to the electron thermal energy to find out what $n_e\tau$ has to be.

$$n_e\tau = 1.6\times10^{13}\ T_e^{1/2} / \{\ \bar{z}\ [1+2(\ 1+\frac{2}{\bar{z}}\ )\ \frac{T_e}{m_e\ c^2}\ \}$$

Let's take T_e to be 100 KeV; if we choose $\bar{z}$ to be some reasonable value, $n_e\tau$ is also of the order of 10^{15} . May be this is a good place to quit for today.

------------- question ---------------

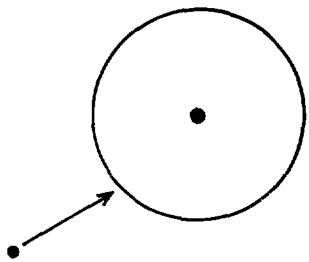
How fast are polarized nuclei depolarized by collisions?

Well, The crosssections, σ, is $\sim 10^{-30}$, it is the same for electrons and icns as far as Coulomb collisions go. You have to take $(n_e<\sigma V>)^{-1}$; thus it's mainly electron which do the depolarizing. V is close to c, so $n_e\tau\sim 1/10^{-30}\times 3\times 10^{10}$ which is 3×10^{19} . Since the reactions equire $n\tau\sim 10^{15}$ this is a long time.

Second Lecture

Last time we looked at bremsstrahlung radiation; today I want to start by looking at impurity radiation. Consider that we have an impurity ion that is not fully stripped.

Fig constant because that's to be determined, in any way, and so



Hot electron transfer heat to cold electron could which immediately radiates it away

Because of the rapid rate of radiation the bound electrons will be in their ground state or in a cold Fermi distribution. When a hot electron collides with an impurity it transfer energy to its electrons which promptly radiate it away. We can estimate the rate of energy transfer from the classical energy transfer rate.

$$P_{imp} \sim n_{imp}\ n_e < \sigma_{ee}\ v_{Te} > T_e \sim \alpha\ 5\times10^{-6}\ n_e\ n_{imp}\ /\ T_e^{1/2}$$

Here α is an empirial constant to take account of the number of bound electrons that can be excited. This formula is found to fit the more detaild calculations of Post reasonably well, within a factor of 3. The constant α depends on the type of impurity ion and varies from 1 for light ions to about 10 for heavy ones.

From this formula we can find the impurity cooling time for the electrons as

$$n_e \tau \sim \frac{1.2\times 10^4 \ T_e^{3/2}}{\alpha} \frac{n_e}{n_{imp}}$$

For $T_e=10^4$ eV and $n_e \tau = 10^{15}$ this gives $n_e/n_{imp} > 8\times 10^4\alpha$ which shows the seriousness of the presence of unstripped impurities.

We don't want to let high z impurity into the plasma, not even into D-T plasma. Low z impurities are not so bad because the ionization energy is not so high and they become striped.

Next we look at synchrotron radiation which is important for magnitized plasmas and particularly for advanced fuels; again we will make a simple estimate. We use the classical rate of radiation for an electron in a magnetic field and this is $2e^2a^2/3c^3$ where the acceleration is ω_c times v. From this formula you can calculate a radiation damping time which turns out to be $2.6\times 10^8/B^2$ seconds. For 10 kilogauss this gives you a radiation damping time of about 3 seconds. Again, we have to find out how important this cooling is, we have to compute $n\tau$ associated with this type of cooling. We need some relation between B and the density, we compute this using pressure balance. If we are thinking of advanced fuels, the number of ions is not equal to the number of electrons and the ion temperature is not equal to the electron temperature. In general, this would be rather complicated, but again we proceed in the sprit of what we are doing, trying to get the feel for sizes. There will be fewer ions than electrons, but the ion temperature will be higher, so we take the electron and ion pressures to be equal. Then we can compute what the electron density is. For B in *Gauss* and T in eV, we have,

$$n_e = \frac{1.24\times10^{10}\ \beta\ B^2}{T_e}$$

Here β is the ratio of plasma to magnetic pressure. We multiply this by the time for cyclotron radiation damping for an electron in vacuum. This gives

$$n_e\tau = \frac{3.2\times10^{18}\ \beta}{T_e}$$

Suppose we have $D-T$, then Te is 10^4 and $n_e\tau$ would be $3\times10^{14}\ \beta$ we know that for $D-T$, $n\tau\sim10^{14}$ is sufficient, so that we see for $D-T$, even if all the synchrotron radiation escapes, you are not in bad shape. However, for advanced fuels, you need larger $n\tau$'s, like 10^{15} , and higher temperatures, like 100 KeV, so the expression shows you that $n_e\tau$ is one hundred times to small or there is one hundred times too much radiation even if β is one. This means that synchrotron radiation will be very serious and we must address this problem. If we can't overcome it, we have no chance of burning advanced fuels in magnetic devices.

The first point is that fortunately, all the synchrotron radiation doesn't really escape from the plasma. In fact, if electrons radiate very strongly this also means that they absorb very strongly. You can calculate the absorption length for the fundamental, that is radiation at the cyclotron frequency. The absorption length is

$$l_{ab}(fundamental) \sim \frac{3\times10^{-4}\ T_e^{3/2}}{\beta\ B}$$

This gives $6\times10^{-2}cm$ for $T_e=10^4\ eV$, $B = 5\times10^4$, and $\beta = 0.1$. Thus little of the fundamental radiation escapes. However, we can allow less than one percent of the synchrotron radiation to escape for advanced fuels; we must not only consider the fundamental, but we must also consider the higher harmonics. If one of those contains one percent of the synchrotron radiation and gets out, we are in trouble.

The formulas for the radiation emitted in various harmonics, I'll give the formula in a few minutes, predicts that the nth harmonics radiate roughly $(T_e e^{2/\gamma}/2m_ec^2)^n$ of the total. For 100 KeV this predicts harmonics up to the 10'th to 15'th are important. We are going to have to absorb frequency up to the 15th harmonics. If we are absorbing them, that means the plasma is black to them, and it radiates like a black body at its temperature for these frequencies. Let's look at what black body radiation tells us, and let see, at how high a frequency, the plasma can radiate like black body before it does us in. If that is larger than the 10th to 15th harmonic then we can hope of overcoming this radiation.

For the estimate we take the Rayleigh-Jeans law for radiation, integrated up to the maximum frequency that we are going to allow the system to radiate at like a black body. The expression for the radiation is

$$P(\nu_{Max}) = \frac{4\pi}{3}\frac{1}{\lambda_{MIN}^3} T_e\ c$$

This formula has a simple physical interpretation. $1/\lambda^3$, is the density of modes of the electromagnetic field which have frequency less than ν_{MAX}, all these modes have energy T_e, and this energy is flowing, out at the speed of light, c.

Now we estimate the allowed ν_{MAX}. To do this we take this power radiated, multiplied by the area of plasma surface, take a cylinder for example, multiply by τ, equate that to the electron energy, that is(3/2) nT times the volume of the plasma: this gives

$$n_e\tau \sim \left(\frac{9}{16\pi}\right)\frac{n_e^2\ \lambda_{MIN}^3\ R_0}{c}$$

For $n_e = 2\times10^{14}$, $B_0 = 50\ KG$, $n_e\tau=10^{15}$ and for λ_{MIN} equal the wave length of the 15th cyclotron harmonic this gives a required R_0 of 25 meters which is pretty large. One thing that we can do is put reflecting wall on the device. in fact, the walls of the reactor would be metalic, and all metals are good reflectors for radiation at the wave lengths we are talking about. A reflectivite, R of 99 % is probably possible. However in a reactor, you will have ports for vacuum pumps and other things and so some radiation escapes out of these holes. A realistic reflectivity for the surface might only be 95 %, or something like that. The time to cool, if one has reflecting walls, is simply multiply by $1/(1-R)$. Including this factor in the critical radius calculation gives $R_0 \sim 1$ meter for the parameters given and 95 % reflectivity. This is also roughly of size we required to make a practical reactor.

The above numbers are not precise so we must make a more detailed calculation of the synchrotron radiation. We go to Landau-Lifshits book on electro-magnetism, they gives an expression for the radiation by an electron gyrating in a circle in the *n* th harmonic. It's given by the expression

$$I_n = \frac{e^4 \ B^2 \ n^{1/2}}{2\pi^{1/2} \ m_e^2 \ c^3} \frac{1}{\gamma^{5/2}} \ (\frac{\gamma-1}{\gamma+1})^n \ exp(2n/\gamma)$$

Most of the synchrotron radiation from the gyrating electron, is given off in narrow cone, like that from a search light from a train, this is particulary true at high harmonics. One might think that all radiation comes out nearly perpendicular to B. However, you must remember that the electron is moving along the B field; if I go to the rest frame of the electron, it's radiating perpendicular to B, but in the lab frame, the reactor frame, that cone gets shifted off the perpendicular direction by an angle $v_{//}/c$. Thus the random motion of the electrons spread that cone though an angle θ^2 which is like $v_{//}^2/c^2$. For 100 KeV, that's 55° , ±55° , to B, or 110 ° out of 180 ° . This is pretty isotropic, so we take it isotropic.

The radiation consists of many different harmonics. For each harmonic the radiation gets Doppler shifted due to the motion along the B field; also, the electrons have different γ's, so the harmonics get smeared out and spread into one another. Rather than treating, the radiation as bands of discrete harmonics we treat it as a continuium. We sum up the radiation in a little band of harmonics about some n and equate that to the intensity emitted at ω times the $\Delta\omega$ that goes with Δn. This gives the expression.

$$I(w,\gamma) = I_n(\gamma)\frac{\gamma}{\omega_{c0}} = I_{\gamma\omega/\omega_{c0}}(\gamma)\ \frac{\gamma}{\omega_{c0}}$$

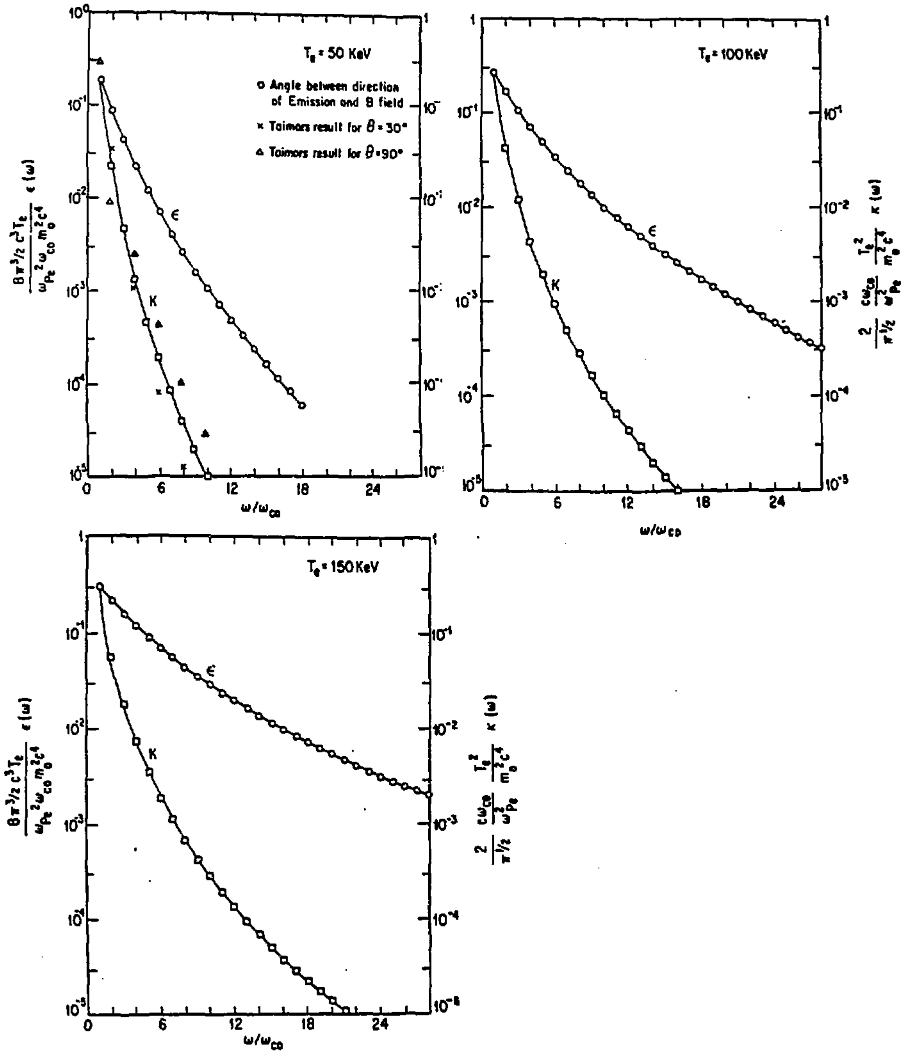
where ω_{c0} is the non relativistic cyclotron frequency.

We want to calculate the emissivity. we assume the radiation goes into 4π steradians and we sum up the radiation from all electrons. We must integrate this over the electron distribution. function: for this we use a two dimensional distribution function, that is we include only the motion perpendicular to the magnetic field for performing this integration. The motion along the field doesn't really effect the amount of radiation emitted very much: it just Doppler shifts it and spreads the frequency which the treatment automaticly includes. This is not totaly correct. but it's roughly true. This gives the expression

$$\varepsilon(\omega) = \frac{1}{8\pi^{3/2}}\ \frac{m_e^2\ c^4}{T_e}\left(\frac{\omega}{\omega_{c0}}\right)^{1/2}\int\frac{d\gamma}{\gamma^2}\left(\frac{\gamma-1}{\gamma+1}\right)^{\omega/\omega_{c0}}\ \exp\left[\frac{zw}{w_{c0}}+\frac{(1-\gamma)m_0c^2}{T_e}\right]$$

We can evaluate this expression numerically.

The other important thing is the absorptivity. For, the absorptivity, we use Kirchoff's Law which says that the absorption coefficient is the emission coefficient divided by the black body intensity. Some curves for the emission and absorption coefficients are shown in the next three figures.



I have compaired the results of this calculation with the more detailed calculations of Taimor at $T_e = 50KeV$: his values of the absorption coefficients are shown by the x's and *delta*'s in the first figure. The agreement is quite good. This gives us confidence that we can use our approximation at higher temperatures. Taimor's results only go to 50 KeV. From these curves, recalling that we must absorb all harmonics which contain more than 1 % of the synchrotron emission, we see that for 50 KeV we must absorb out to the 10'th harmonic while for 150 KeV we must go to the 30th harmonic. D-D and D-^3He might be made to work in a Tokamak at 50 KeV but advanced fuels requiring higher temperature will have to opperate in devices with low internal fields which also permit high β, $\beta > 1$ inside the plasma. Electron temperatures above 150 KeV are probably impractical, both because the synchrotron radiation becomes prohibitive and because the bremsstrahlung is increasing rapidly.

Since the electrons are the one losing energy we would be better off if we could run with cold electron; then they would radiate less and the energy loss would be less. On the other hand, it is the ions which are reacting and we would like them at as high a temperature as possible. The best way to run an advanced fuel reactor is in what is called the hot ion mode with the ions hotter than the electron. Now, If the electron temperature is high enough, then it turns out that the reaction products deposit more energy in the ions than in the electrons. Thus, as the temperature runs up, the electron temperature will start to lag behind the ion temperature. It's possible to run an ignited reactor in the hot ion mode. It is also possible to heat the ions, say by an ion beam, or by ion cyclotron heating. If you use a driven machine, then, of course, you have a certain energy multiplication, Q, and the requirement is that Q be sufficiently large that one can get useful energy out of the device. Since the ions are going to be hotter than the electron, we want to know how hot ions are cooled by the electrons. Again, we make a simple estimate of this. Rather than calculate the cooling of the ions by the electron, let's do the inverse calculation and calculate how fast ions are heated by the electrons; then, we use detail balance arguments to calculate the rate at which the ions cool down. Start with an ion which is at rest and calculate how fast it recieves energy from the electrons. As an electron goes by an ion, it gives it a certain momentum kick; this is given by the force times time. Δt

$$\Delta P = (z e^2 / \rho^2) \times \frac{2\rho}{v}$$

where ρ is the impact parameter. The energy given to the ions is $\Delta P^2/2m$. Taking the rate of encounters and integrating over all impact parameters and velocities gives

$$\frac{dE_i}{dt} = \frac{4\pi \; n_e \; z^2 \; e^4}{m_i} < \frac{1}{v_e} > \ln\Lambda$$

The average of $1/v_e$ looks like it diverges, but remembering that in computing the average in velocity space we need the volume element $v_e^2 dv_e$ We see that everything is O.K.

We equate dE_i/dt times τ to the electron temperture and this gives us the electron ion thermalization time. Since $<v_e^{-1}>$ goes like $\sqrt{T_e}$ this gives us a time which goes like $T_e^{3/2}$. This also gives us the ion cooling time on the electrons. That cooling time is almost independent of the ion temperature because of the slow motion of the ions.

One should consider relativistic effects because the electrons are relativistic, it may be that relativistic effects help or hurt us. So far, our formula is actually correct relativistically(though this is not obvious), one just put relativistic velocities in it and takes the proper relativistic averages. It's clear at very high temperature, the average of $1/v$ is going to be c^{-1}, that tells you that at very high temperature the thermalization time does not go like $T_e^{3/2}$, but it goes like T_e. Thus the thermalization time is not such a strong function of electron temperature, as the simple classic formula would predict, but is slightly modified. Detailed calculation were carried out by J.Cordey and the correction is a factor of($1+0.3T_e/m_ec^2$). It increases the power going from the ions to the eletrons by this small factor; for T_e=100KeV, it gives a 6 % increase the energy going from the ions to the electrons.

Using this time, to calculate the power going from the ions to the electrons, it is inversely proportional $T_e^{3/2}$, proportional to the difference between the ion and electron temperatures, we have

$$P_{ie} = \frac{9.4\times 10^{-8}}{T_e^{3/2}}\left(1+\frac{0.3\ T_e}{m_e\ c^2}\right)n_e(T_i-T_e)\sum_i\frac{n_i\ z_i^2}{A_i} \quad in\ \frac{eV}{cm^3\ sec}$$

Now, we have the ion cooling formula, and again, we are interested in the $n\tau$ for the ion density times their cooling time; that will determine whether the reaction is self sustaining or not. Equating the cooling rate times τ_{ie} to the total ion energy, which of course, now depends on what kind of ion species you have and many other complicated things, one can obtain $n\tau_{ie}$. Let's take a single ion species, or say, an average ion species, let's take the ion temperature be twice the electron temperature, and that, gives us the following simple expression for estimating purpose.

$$n_i\tau_{ie} = \frac{7.2\times10^7 T_e^{3/2}}{Z^2(1+0.3T_e/m_ec^2)} \xrightarrow[(T_e\rightarrow 150KeV)]{} \frac{4.2\times10^{15}}{Z^2}$$

Thus this is also of order 10^{15} .

It is funny, but everything in fusion is always marginal. One never seems to find anything where the number really come out greatly in your favor or greatly against you.

We now have to look at how much energy goes to the ions from the reaction products and how much goes to the electons. We must follow a reaction product and calculate the energy loss to the electrons. The loss to the electrons can be calculated using the ion cooling formula, we just calculated, but using the products z and energy. We can generally neglect the electron temperature relative to the product energy in this calculation.

It turns out that from this calculation, you can define a stopping crosssection, this is equlivelent to giving a mean free stopping length for reaction products due to electrons. If you take the electron density times the effective cross section times that stopping length equal one you get the effective crosssection which is

$$\sigma_{eff} = \frac{2.4\times10^{-12}\ z_p^2}{T_e^{3/2}\ w_p^{1/2}}\left(\frac{m_e}{m_p}\right)^{1/2}$$

Pluging in some numbers to get a feel for the size we have for the 14 MeV proton from the D-^3He reaction in a 100 KeV elecron plasma, σ_{eff} = 0.5 barn. This is interesting because that is about the size of nuclear crosssections. That means electrons will not stop the reation products so fast that nuclear elastic processes or secondary reactions don't take place. If you recall that in yesterday's lecture, I pointed out there was a potential chain for the ^3He+^6Li reaction. If those nuclear crosssections are bigger than stopping crosssections, then the chain potentially goes and if they are smaller, then it does not go. This again is an example of how things in fusion come out close to go-nogo.

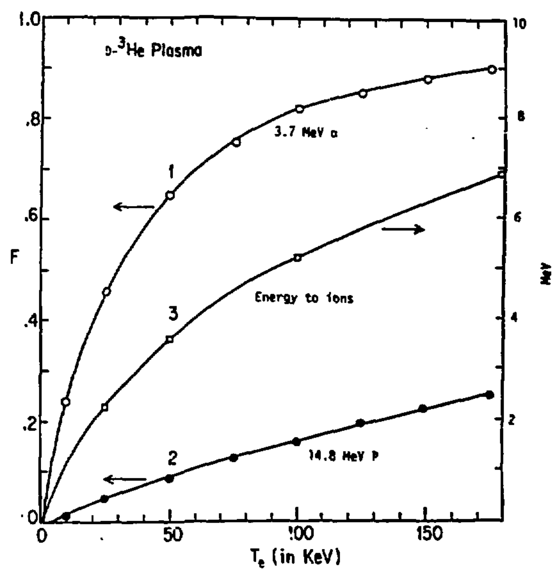
We must also calculate how fast energy is lost to the ions. In this case the reaction products have high energy compare to the ions, so, we can treat the ion more or less at rest and use the energy loss for a fast ion in a cold ion background; that is we neglect the thermal motion of the ions. One can look in Spitzer and obtain the formula.

$$\left(\frac{dw_p}{dt}\right)_i = -(2\pi\ z_p^2\ z_i^2\ e^4\ n_i\ /\ m_i)(2m_p/w_p)^{1/2}\ \ln\Lambda_i$$

There is one point here, there is $\log\Lambda_i$, I use Λ_i for the ions. In the elctron drag there is $\log\Lambda_e$; the reason we distinguish is that Λ is the Deby length over some minimum distance. That minimum distance is the deBroglie wavelength, for the electrons which is rather large. For the ions it is the classical distance of closest approach which is several orders of magnitude smaller and this means that the ion log term is 20~30 %

larger than the electron one.

Of course, one has to add up the energy lost to all the different ion species, and then, to find fraction going to ions, we take the energy going to all ions and divide by the total energy lost; we must integrate this expression from the birth energy down to the temperature of the ions. The result of such a calculation for D=^3He plasma is shown in the figure. There are two products, a 14 MeV proton and a 4 MeV alpha. The plot shows the fraction of the proton and alpha energy going to the ions as a function of the electron temperature as well as the total energy deposited in the ions.



Nuclear elastic scattering might greatly enhance the fraction going into the ions for the 14 MeV proton.

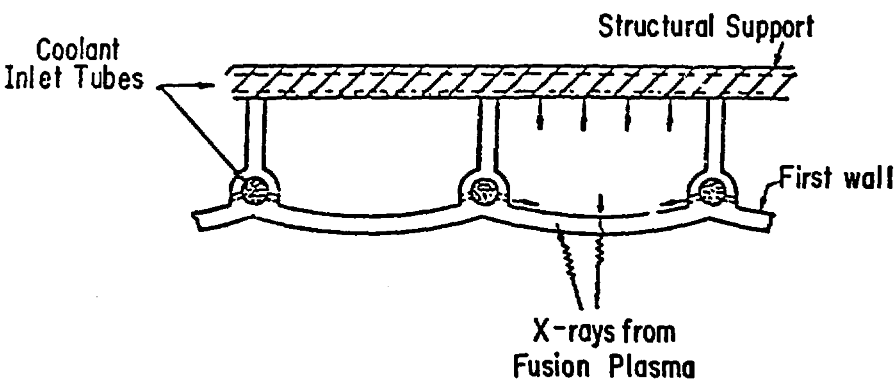
One can also carry out such calculations for other fuels, if this is done for $P-{}^{11}B$, one finds that something like 90 % of reaction energy end up in the ions for electron temperatures above 100 KeV. In that case, it is a good approximation to assume all the energy goes to the ions.

Since everything is so marginal for advanced fusion reactors we would be better off, if we could recover the energy with high efficiency. In principal, we should be able to do this because the temperature of the fusion plasma is so tremendously high. Now, D.Post at LLL and some other people have looked at direct recovery of the energy of the charged reaction products escaping from a mirror. That is one form high efficiency recovery. However it's only part of the energy coming out of the fusion plasma, and there are a lot of other forms. If we have $D-T$, 80 % comes out as neutrons and you don't recover that with high efficiency. Normally one only consider using this energy to boil water and make steam and run it through a steam turbine; nothing more sophisticate than that. We are going to take this most advanced energy producing device invented by man and we are going to recover its energy with a rather primitive energy convertor. Somehow that is not aesthetically appealing; if one goes to all the trouble one has to to build a fusion reactor you should be able to do better than that.

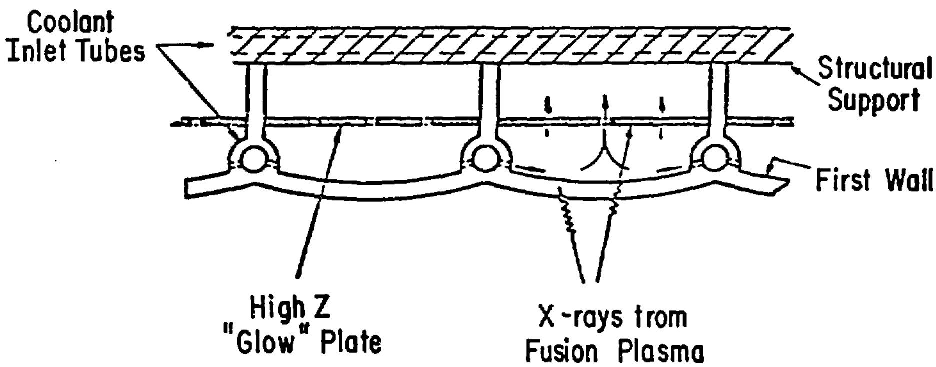
Are there some way to recover the energy more efficiently; in princeple, there are. I will give just one example.

The idea is that one can take the X-ray or neutrons from a fusion reactor and pass them through a first wall into a second region where they heat the material in that second region to a high temperature; as high as is feasible. In this way. fusion reactor can create very high temperatures. they differ from fision reactor where the heat is produced right in the fuel rods and the temperature is limited by the temperature the fuel rods can stand. In a fusion reactor. you can build a region where the energy absorbed which is separated by a cool wall from the reacting plasma. If we use a thermal cycle then the efficiency is determined by the maximum temperature of the working fluid and the temperature of the heat sink. The idea I will present is one for building a very high temperature heat engine. For neutron less advanced fuel reactors. one way you might do this is shown in the figure.

Single Stage Concept (High Z coolant, Low Z wall)



Multiple Stage Concepts (High Z glow, Low Z wall)



You take a wall of low z material, there are many such materials, Be,B,C,Al. You cool this wall: then hard X-rays from the fusion plasma pass through the wall into the region behind where we have a high z gas, say Xenon, with a large absorption coefficient for X-rays. The absorption coefficient is a very strong function of z going something like 4.5 power. Because of this it is possible to pass the X-rays through a low z wall and absorb them in a high z gas. Of course, the X-rays can heat the gas to a higher temperature than the wall: they heat it to any temperature that can be tolerated. Certainly it appears that one can heat the gas to more than 2000 degrees Kelvin, may be even to 5000 degrees Kelvin.

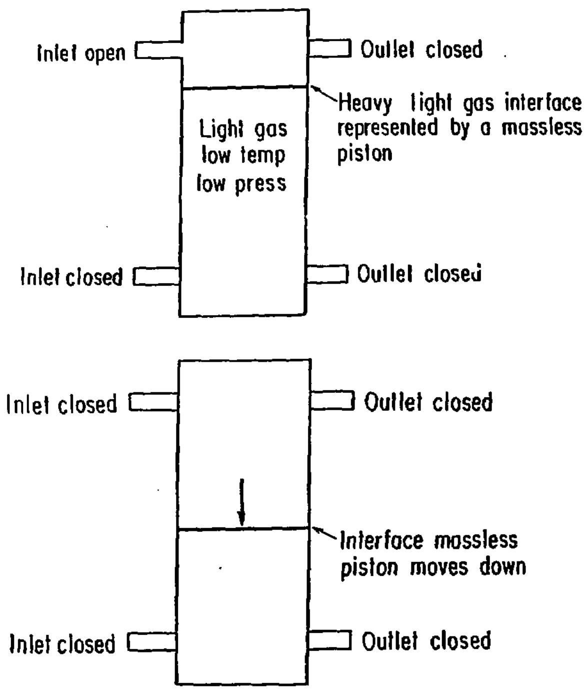
For neutrons the problem is somewhat more difficult, because neutron can go through so much material. What one can do here is that one can put plate behind the first wall which stops the neutrons, and absorbs their energy. The temperature is limited by the temperature the plate can stand. Since the plates need not be under any strain it can be made of high temperature material with the temperature limit being the primary consideration. Graphite blocks are one possibility, a set of tubes filled with liquid *Li* (but not flowing) with equal pressure inside and out is another which would include Tritium breeding. The heat would be removed from the hot plate (or hot tubes in the case of *Li*) by flowing cooling gas by it.

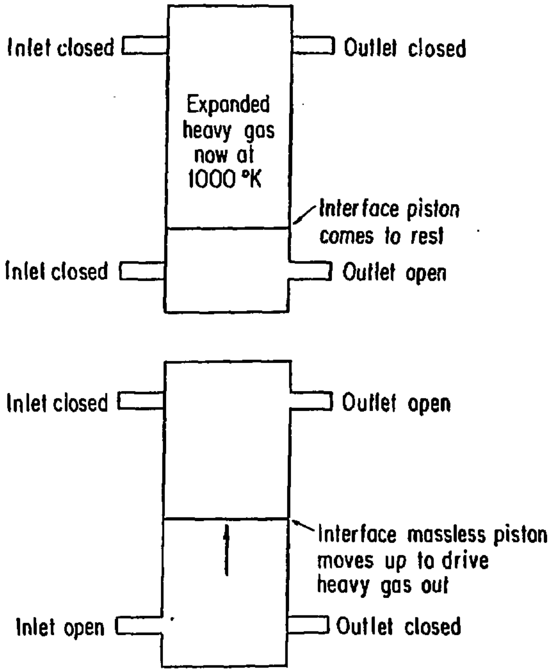
In these ways we can generate gas at several thousand degrees Kelvin. If we try to run such gas through a turbine we will burn the blades off it. We could run it through an MHD generator: that is certainly one possibility which is worth looking into. In the next lecture, I will describe a scheme, worked out by A.Hertzberg of the University of Washington, for a high efficiency, high temperature heat engine. His device has been built and tested. Some similar devices are in use in turbochargers for automobiles.

Third Lecture

Last time, I was talking about the possibility of achieving higher efficiency with fusion device and there are number of ways one might think of doing this. I was considering, high efficiency heat engines because one can convert X-ray and neutron energy into very high temperatures, that is clear. It is not clear how you could convert them directly into useful energy.

The device I want to consider was invented by A.Hertzberg of the University of Washington. The principal of the way it works is shown in the next couple of figures. I will try to describe how it works.





What we imagine is that we heat a gas, a heavy gas, one of high molecular weight, Xe or A would be appropriate, to rather high temperature with, say, by neutrons, or X-rays. We might heat it to say several thousand degrees Kelvin. That temperature is too high to use directly in most energy coverting devices. The devices that Hertzberg invented works more less in the following a way. You imagine that you have a cylinder with various intets and outlets; very hot heavy gas comes from the reactor and is let in at the top. At the bottom we have a low molecular weight, low temperature gas. Now the central point is that we want the process to be isentropic; that is no entropy is generated because any process generating entropy reduces the recoverable energy. We don't want any shock waves or anything like that to develope in the gas channel. To achieve this you require the sound speed in the light gas equal and that in the heavy gas. As the hot heavy gas at high pressure comes in it expands and a compressional wave goes through the light gas but no shock wave is generated and no entropy is generation. Now, picture the interface between the two gases as being separated by massless piston. In realty, there would be no piston, there would be just a gas interface. First the hot heavy gas comes in and the outlets are all closed as well as the inlet for the light gas. The hot heavy gas expands downward compressing the light gas. Since the speeds of sound are the same, the temperature in the light gas is much lower than that in the heavy gas; the speed of sound is $\sqrt{T/m}$

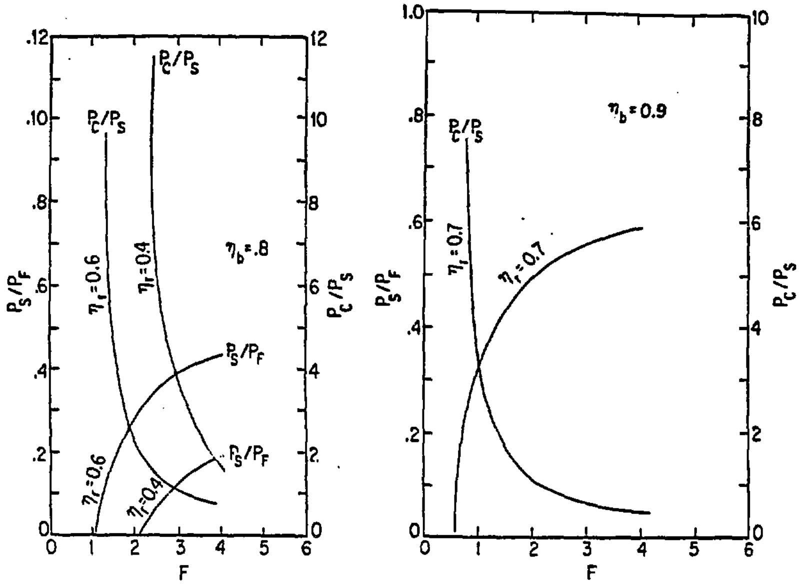
After a charge of heavy gas is let in we close the hot gas inlet, all inlets and outlets are now closed. The hot heavy gas continue to expand against the light gas compresing it, and you adjusted things so that when the interface is half way down the cylinder, the pressures are equal. That implies that there are many more light atoms than heavy atoms, because if the temperature of the heavy gas is high and the temperature of light gas is low and pressure is nT. Thus we are transfering energy from a few hot heavy atoms to lot of light cool atoms in an isentropic way. After the interface reaches the mid point, the inertia of the motion continues to compress the light gas and expand the heavy gas until it is stopped by the build up of the pressure difference. At that point, you open the light gas outlet, and let it out. The heavy gas having expanded adiabatically has cooled; suppose we start it at 2000° K , we might manage to expanded it down to 1000° K . In this case we would have transfered half it's energy to the light gas. The light gas goes out at high pressure but at a low temperature. The hot heavy gas could not be put through a turbine, but the light cooler gas can and in this way the compressional energy is recovered. After we remove the light gas, we must get back to the initial state, To do this we close off the light gas outlet, open the heavy gas outlet and the light gas inlet. Then light gas returning from a turbine forces out the heavy gas which is now at low pressure and temperature. The heavy gas goes to a conventional heat exchanger where more of its energy is removed to run a convetional steam turbine. Then it is returned to the reactor for cooling.

This process actually amounts to a toping cycle; may be, you get 50 % of the energy of the hot gas without going through a conventional steam generator and 40 %. of the remainder is recovered in the conventional way for an over all efficiency of above 70 %. Values of 70 % are consistent with the calculations and experiments of Hertzberg.

What's the importants of high efficiency; well, if you have an advanced fuel, not quite ignited then you may have to drive it. We get a certain energy multiplication or f. Let us imagine we drive the device with a beam. We supply certain beam power P_B ; let the fusion power that is generated be f times P_B and let η_r be the energy recovery efficiency. Let the effeciency of generating the beam be η_B. Then the device will be just self sustaining. if the efficiency of energy recover times total energy that comes out of the reactor(the fusion power plus the beam power) is just enough to generate the beam. That has to be the beam power divided by η_B This means that multiplication factor f must exceed

$$f \geqq \frac{1}{\eta_T \eta_B} - 1$$

If you take typical thermal efficiencies of 40 % and if you assume η_B equals 60 % (rather conservative values) then you find that you need an $f > 3$. On the other hand, if we take very optimistic values of, say, 70 % for thermal recovery (Hertzberg believes he can get up to 75 %) and assume you can generate beams at 90 % efficiency, then the multiplication factor doesn't even have to be as large as 1; an f of 0.59 will make the plant self sustaining. One can, plot the power for sale, P_s, and the circulating power, P_c, vs f; such plots are shown for various η's in the next two figure.

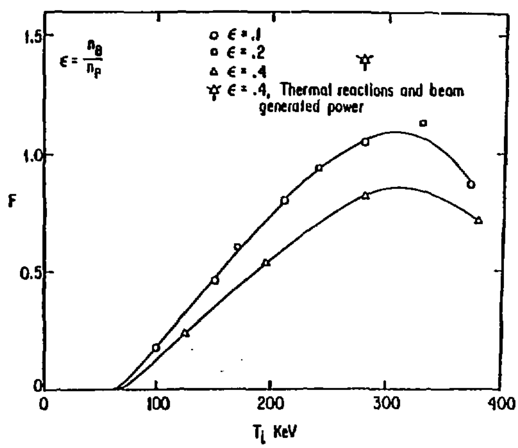


The power has been normalized to the fusion power, P_F. For our optimistic case an f of 2 already makes roughly 40 % of the fusion power available for sale and the circulating power is less than the fusion power. These conditions require high technology and are unconventional and not considered by most fusion researchers. However, fusion already requires high technology and is an unconventional devices so one should also consider such possibilities.

There are other advantages to high efficiency energy recovery. The walls of *D–T* reactors are subjected to neutron bombartment, and the total usefull energy that you can get out during the lifetime of the reactor depends on when you have to replace the wall. Thus the more efficiently, you can recover energy the longer the lifetime of that first wall (the more MW years m^2 This itself could substantially increase the effective MW years of the wall.

Of course activation, radioactivity, the amount of Tritium, all get reduced by increased efficiency. These are goals of the fusion program and should be pursued by all means that appear promising.

Let us now look at some specific advanced fuel reactors. The first reaction we look at is $P-{}^{11}B$. This reaction produces virtually no neutron and looks like it would be good. I have calculated the multiplication factor vs ion temperature assuming only bremsstrahlung loss and did this for various ratios of Boron to proton density: the optimum ratio is 0.2, but the reactivity is not very sensitive, for values around this. The result are shown in the following figure.



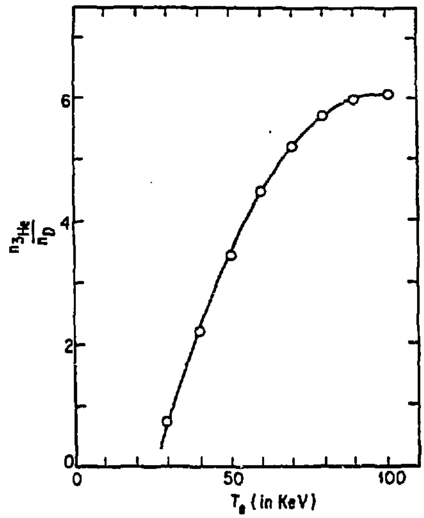
We see, we can get multiplication factors just slightly above one which means the fusion power would be just slightly more, than the beam power, required to sustain it. Now there is one point on the figure which is at about 1.3; this point includes energy generated by the beam as the beam slows down in the plasma. These values are not good enough to be interesting at the present time.

Recently, the idea of spin polialized nuclei has come up so I took a another look at what effect this might have. First of all, I should say that the fact that $f = 1$ means that to sustain the plasma the beam power has to be equal to the fusion power; that means if we could some how double the fusion crosssection, the fusion power could maintain the reaction. It's right on the edge of burning. The idea of spin polarization gives you a chance to achieve that larger crosssection. Unfortunately we don't get factor 2, but we do get subsantial improvement. The spin of Boron eleven is 3/2, the spin of the protron is 1/2, and that means that total spin of a ^{11}B nuclius plus a proton is either 2 or 1. In the earlier lecture, I gave you an expression for the enhancement of the reactivity from spin polarization. To apply this formula we must first find out which one of these total spin states it is that contributes to the resonance, at 800 KeV which gives most of the reactivity. From tables of excited states of carbon 12 we find it is a spin 2 state. According to our enhancement formula we could get an enhancement of 1.6, not 2. Nevertheless a gain of 1.6 reduces the requid beam power to 0.4 of the total power and the theoretical energy multiplication is now 4. If one includes enhanced reactivity due to the beam it looks like energy multiplication of 6 are possible. With high efficiency energy recovery, both of these would be adequate for interesting devices with a little to spare for effects we have ignored. Because this reaction would be very clean it may be worth looking deeper into this.

The achievement of controlled fusion presently is a dream (though I believe one that can be achieved): one should try to look at how far that dream might be able to go. In fusion we are working on what we hope will be a superior energy source. It is clear that fusion offers many possibilities from a fission fuel breeder (probably the easiest to build) to rather clean advanced fuel reactors. I see no reason to stop at the *D-T* stage.

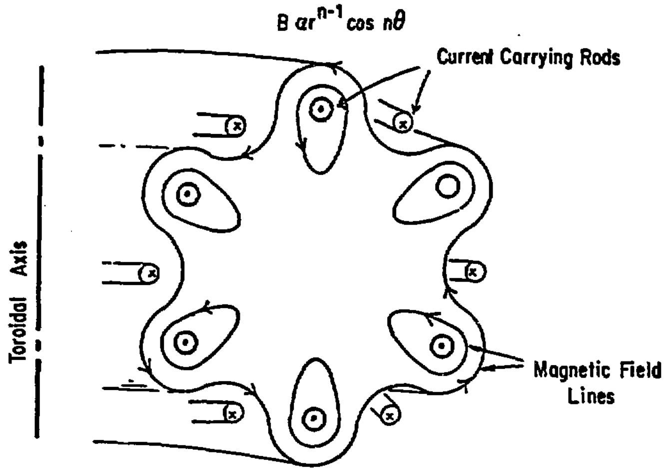
The advanced fuel which looks easiest to make go is $D\text{-}^3He$. The problem is the ^3He supply. I personally believe that we can get ^3He if we decide to go this way. There is ^3He around, in fact, you can buy it, and there are a lot of experiments in low temperature physics done with ^3He. The price of it is $90 for a liter at STP (standard temperature and pressure). That sounds expensive, but that is equivalent to buying gasoline at 0.1 $/gallon or 6.75 *yen*/litter. It is pretty cheap energy; of couse, if you start to burn it in a big way the price will raise rather rapidly.

The next figure shows the ratio of ^3He density to Deuterium density at which you can burn $D\text{-}^3He$ as a function of electron temperature; the minimum ignition temperature is right around 30 *KeV* and at that point the ^3He to D ratio is I think half, some thing like that.

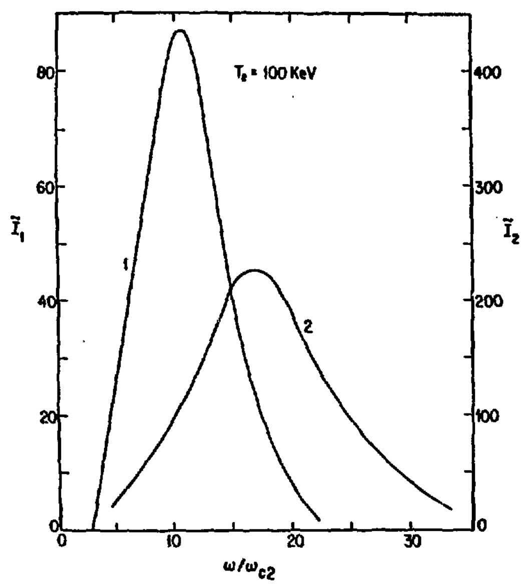


If you raise the temperature, you can increase the consentration of ^3He and decrease the consentration of D. The point of doing this is, it minimizes neutron production: the neutrons from the D-^3He reaction comes from D-D reactions and secondary D-T reactions. If you can reduce the density of D, and increase the density of ^3He, you run down the neutron production. If we get up to 60 KeV, some thing like that, which might be practical even in a Tokamak (B.Coppi believe it is quite feasible) and you can get a ratio of five to one,(five times much ^3He as D), that reduces the neutron production greatly. There have been a number of estimates of this; it looks like, you might get two order of magnitude reduction in the neutron production,(and in particular, in 14 MeV neutron production) per unit of energy produced. This is interesting because it is an order of magnitude fewer neutrons than are produced by fission. Here again the idea of spin polarized nuclei can help. If you can polarize the spins you can turn off the D-D reaction, and that means you may be able to reduce the neutron production by another 1 to 2 orders of magnitude. It also means that you may be able to opperate with a richer D to ^3He ratio and still have low neutron production. Also it enhances the D-^3He crosssection by a factor of 1.5 which helps.

Returning to the P-^{11}B reaction the only loss that was included was bremsstrahlung. Since it is so marginal we must reduce other losses to a minimum if it is to have a chance. We must somehow reduce the synchrotion-radiation to a low level: to do this we should reduce the magnetic field inside the plasma. One possibility is to use a multipole configuration. A multipole has current carrying rings, and some are actually inside the plasma as shown the figure.



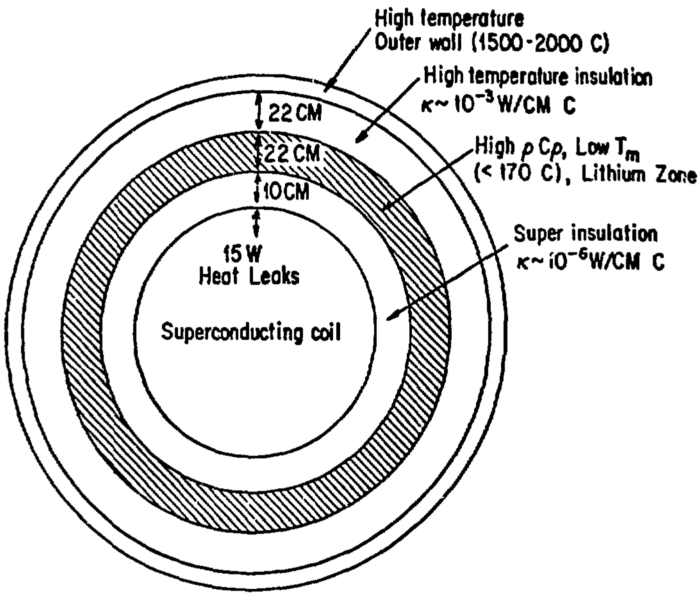
It's possible to have such rings floating (therefor levitated) without suports. I will talk about that in just a minute. This has rather complicated magnetic geometry but the B field in the bulk of the plasma is now rather low. In order to estimate the synchrotron radiation from this plasma we average the absolute value of the B field in θ. The magnetic field varies as r^{n-1} times $\cos n\theta$, where n is the order of multipole. We then go back to the emissivity and absorption coefficients that we looked at before and calculate the synchrotron emission as if B were a function of r only. The result of such a calculation are shown in the figure.



Two curves are shown for an electron temperature of 100 KeV. Curve 2 goes with the right hand scale and is for a β = 1 plasma with the B uniform through out it. Curve 1 goes with the left hand scale and is our calculation for an octopole. Both curves are for plasmas of 200 cm radi and wall reflectivities of 0.9. You should notice that curve 2 has a peak value of about 230 while curve 1 has a value of 85, so there is about a factor 3 difference in hight. Also the width of curve 2 is about twice that of 1 so the total reductionis about 6. The synchrotron radiation is equal to half the bremsstrahlung for this case. Now, in making this calculation I assumed that the electron temperature was uniform though out, but if you have a B field that is varying from very weak at the center to strong at the outside region, then it would be radiating strongly, from it's outer regions and weakly, from its interior. A temperature gradient would be set up with the outside cooler and hence radiating less. I think you would actually gain more than a factor of 6.

There is a second reasons why you would like to use a multipole, it is that you need very good plasma confinement because not only must you get the radiation down but you must have very good plasma confinement. Experimentaly multipoles seems to have very good confinement. At Wisconsin they have done experiment on floating multipoles which give values of β in the region where the magnetic field is strongest of about 38 %; the value of β everywhere else would be much higher than this. 38 % is interestingly more than 4 times the theoretical MHD limiting value against ballooning modes. They only get those high β's at low magnetic fields and it turns out that under those conditions they also have rather low temperatures and high densities. Some, people argue that this is not a good test because of the high collision rate but I think these make the MHD approximation better. However, Wisconsin and also UCLA have also gotten 10 % β for collisionless plasmas which also exceed the theoretical MHD stability values.

The other problem you face with multipoles is how do you have current carrying conduvtors inside the plasma. If you don't have any neutron, it turns out that it is possible. The next figure shows the designs of possible ring.



On the outside you have, Tungsten or a high temperature wall that runs at about 2000° K where it radiates 100 W/cm^2 which is a kind of power incident on it as X-rays. This tungsten layer is like a fusion lamp. It's absorbs X-rays from the plasma and reradiates it as optical light. This would make a super light bulb. The tungsten radiates most of the heat it absorbes. Now at the center you have a super conducting coil at $4 dgreeK$ which must be insulated from the $2000^{\circ} K$ outside wall. There are various kind of insulation in the ring. You put in graphite wool next to the tungsten followed by a layer of Litium, or something that melts and absorbs a lot of heat. This is followed by super insulation that is used in exsiting superconducing coils. After all this you find about a 15 Watt heat leak into the super conductor. People at TRW calculated this, and they calculate that such a ring can be levitated for several days. Thus if you could get rid of the neutrons you really could have such rings. It's also possible to include region of neutron absorbers and make this thing works with some neutron production. The TRW people calculated that they could work with $D{-}^{3}He$ with this kind of devices, and get perhaps 8 hours of opperation before cool down is required. With polarized nuclei we should be able to do better. However, in that case we must provide enough toroidal B to keep the spins adiabatic at the center. A few KG should suffice.

There was one other point associated with multipole which I want to make. There are several things we are trying to do in fusion research. One is that we are trying to make a practical reactor. This is of course the over all objective. However, at the present time we need to learn all we can about reacting plasmas, to get experience with them and also about the engineering problem associated with reactors, and what happens to material subjected to a reactor environment. For these latter purposes we don't need a device which will in the end will be a practical reactor. In fact, what we really need is a relatively cheap device, which is easy to work with. If we had such a device we might build several of them to gain experience and data at a faster rate. Different devices might be used for different purposes, plasma physics, engineering, materials tests etc. To me the multipoles appears to be a candidate for such devices. They are rather stable with good confinement. One could create ignited plasmas in them with, say, normal conducting rings although perhaps cooled to increase their conductivity. We would float the rings; we would choose the size so they would sustain current for some minutes. We could create ignited plasma in these, let it burn some tens of seconds while the rings heat up. One should be able to get sufficiently long burns to be interesting. I believe you can probably build such devices cheaper than you can build complicated Tokamaks. Of course there are other possible devices. The big advantage that Tokamaks have (it is an important one) is that there is much more experence on them. However, considering the cost of reacting Tokamaks I believe these possibilities merit serious consideration. As soon as you cut lose from the fact that your experimental device has to be a practical reactor you gain a lot of freedom.

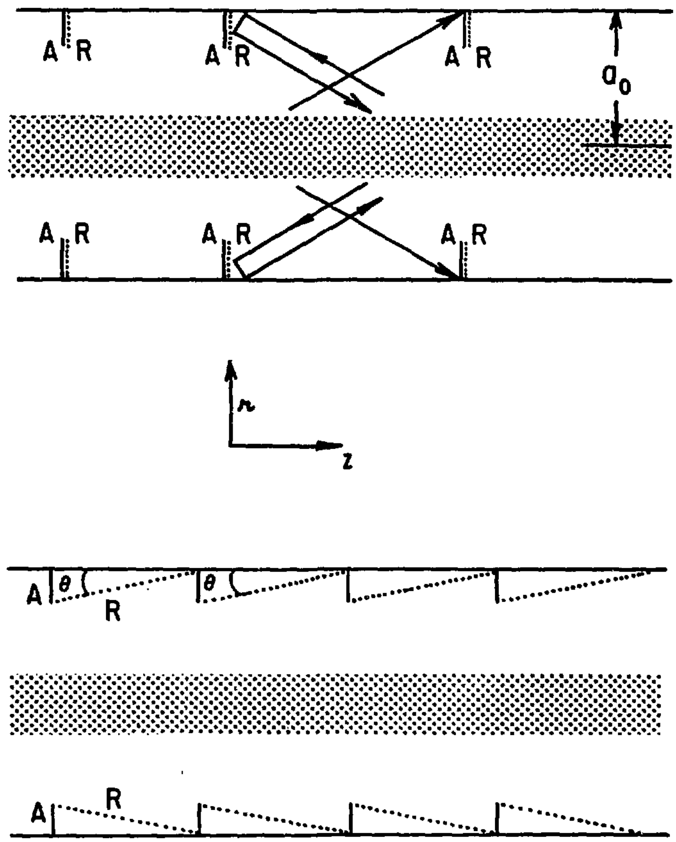
There are two other topics I want to say a little about. The first is the idea that we could maintain current in a Tokamak by using its own synchrotron radiation. As you are quite aware there is a lot of work going on both theoretical and experimental on current drive in Tokamaks. I think most of this effort is going into RF current drive and Nagoya is a pioneer in this area with probably the first experiment dedicates to it. It is also possible to drive current with particle beams and some thought has gone into this. I personally think that both of these methods are practical and deserve attention.

With RF current drive we must supply power from outside the device. This certainly has some disadvantages, because, you have to generate the RF, which means a lot of hardware which costs money; you have to maintain it, there is a loss in efficiency from extracting energy and converting it to RF. It would be nice if you could find a way to make a plasma generate its own current. Such methods I call passive current drive as opposed to external drives which I call active.

I think one can conceive of more than one passive current drive scheme. However, I will give one example, hopefully this will stimulate others to think about these problems. The idea is to use the synchrotron radiation coming out from the plasma itself; as we saw earlier the synchrotron radiation can be significant, particulaly for advanced fuels with temperatures of 50 KeV or more. At high temperatures we will get several %, in fact, may be even 10's of %, of the energy coming out as synchrotron radiation. That means there is a lot of this radiation for high temperature devices. For Tokamaks it works best for, say, D-D, cat. D-D or D-^3He reactors. If we had say a power plant producing a few GW of thermal power then we would be producing a few 10's to 100's of MW of synchrotron radiation and that's comparable to the powers consitered for RF current drive. Thus the power is all right if the efficiency of current drive is right. We have seen that the dominant synchrotron harmonic is between the

10'th and 20'th harmonic of the cyclotron frequency which means wavelengths of $10^{-1}mm$. In this range, radiation is strongly reflected by the wall and is also strongly absorbed and emitted by the plasma. This means that both the wall and plasma interact strongly with this radiation. It forms a nice medium for interaction of the plasma with the walls and vice-versa. It provides a means for the exchange of momentum between the plasma electrons and the wall. I have often been asked if this does not violate the second law of Thermodynamics. The answer is no: for this you must rely on the fact that the plasma and wall are not in thermal equilibrium. For thermal equilibrium, current drive would violate the second law of Thermodynamics. Obviously the wall is not at the same temperature as the plasma so that condition doesn't give us any problem.

The figure illustrates how the current drive works.



The top drawing shows the simplest conceptual configuration; one sticks little fins out perpendicular to the wall. They are absorbing on one side and reflecting on the other. The synchrotron radiation emitted in one direction is absorbed, but synchrotron radiation emitted in the other is reflected back and pushes on the electrons and drives a current. The top configuration would not be very efficient because radiation going perpendicular or almost perpendicular to the wall will not be reflected so as to drive current. We can do better if we make a sort of sawtooth or fishscale, (Uroko), wall on the inside of the Tokamak. We have reflecting surfaces the faces of the scales and absorbing ends to them. The radiation slides around torus one way easily but not the other. The electrons pick up the radiation momentum when they reabsorbes it giving a current.

The details of the calculation can be found in J.M.Dawson and P.Kaw. Phys. Rev. Letters. 48, 1730(1982). Let me just write down the expression for the current.

$$I = \frac{\pi a_0^2}{3} e n_e \left\{ \frac{T_e}{m_e c} \frac{\tau_{ei}}{\tau_{syn}} \right\}$$

Here a_0 is the minor radius of the torus, T_e is the electron temperature, τ_{ei} is the ion electron collision time and τ_{syn} is the electron cooling time due to synchrotron radiation loss.

There is a simple physical interpretation of this expression. Let me explain it. T_e/c^2 is the mass associated with the thermal energy that the electrons radiate in a synchrotron cooling time τ_{syn}. Now if all that energy were going in one direction, then, it would carry momentum(T_e/c^2) c. Dividing this by the mass of the electron gives the drift velocity the electrons would acquire; this is the first term in brackets.

Now, the electrons are continually colliding with the ions so they don't, acquire that full drift velocity. they gain only the fraction they would get in a time between electrons ion collisions.Thus, we must multiply this drift velocity by that ratio τ_{ei}/τ_{syn} The rest of the factors are of co rse the density. the area, the charge and some geometric factor.

For the synchrotron cooling time we use the expression of Trubnikov.

$$\tau_{syn} = \left(\frac{2.6\cdot 10^{8}}{B^{2}}\right)\left(\frac{1}{60}\left(\frac{m_e c^2}{T_e}\right)^{3/2}\left(\frac{a_0\ \omega_p^2}{c\ \omega_c\ (1-R)}\right)^{1/2}\right)$$

For the electron ion collision time, we use Spitzer: we just look this up in his little book.

$$n_e\tau_{ei} = \frac{6.6\cdot 10^{4}\ T_e^{3/2}}{z}$$

$$z = \sum_i n_i z_i^2 \Big/ \sum_i n_i z_i$$

We plug all of these into the current formula and you get the rather long expression.

$$I = \alpha\ 9.4\times 10^{-7}\ a_0^{3/2}\left(\frac{T_e}{m_e c^2}\right)^{5/2}\frac{T_e^{3/2}\ B^{5/2}(1-R)^{1/2}}{z\ n_e^{1/2}}$$

The quantity α appearing here is a numerical factror which we realize should be there because the energetic electron do most of the radiating and absorbing, and also they collide less strongly. You should not use the actual thermal energy, but you should use some multiple of it in this calculation. I have estimated the value of α to be somewhere between 5 and 10. We see the current is a very strong function of temperatrure, it goes as T^4. That is because the synchrotron radiation is a strong function of temperature and also because the resistivity decreases strongly with temperature.

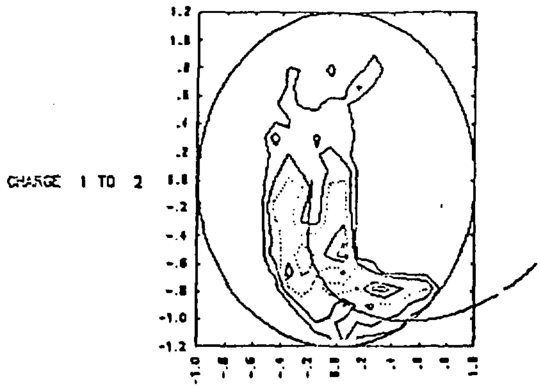
We can plug in some typical Tokamak value that one might expect to have. Let's imagine burning *D-D* or D–^3He , so we need a high temperature, we take 50 KeV; we take a density of 10^{14} , a 100 KG field and a radius of 1.5 meters. All these are not unreasonable values. For the wall reflectivity we take 90 %. These values give a β of 5 % which is a little larger than what people have achieved. However, if Tokamaks don't achieve β's of 5 %, they are not practical reactors: you wouldn't care if current dive worked or not if Tokamaks were not a success, so we assume success. With these values we find a current of $(6\alpha/\bar{z})$ million Amps. If we take an α of 5 and $\bar{z}$ of 2, that would gives us 15 MA. This is more than enough current. Of course, this is just one set of numbers, can take different set of numbers and get more or less current.

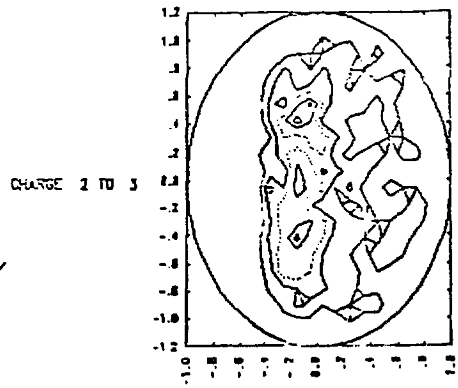
Thus indeed it looks like we could make the Tokamak current selfsustaining. If you think about this, it is somewhat revolutionaly. Many years ago, Tokamaks were dismissed on the grounds that they could not have a steady current. For years people considered Stellarators superior, because they were the only toridal devices that requires no current drive to run in stady state. Now we see that in principal this is not the case. You might even want to add such a current drive to Stellarators. One possible advantage of a steady current in a Stellarator is to use it in combination with a vertical B field so that $j\times B$ cancels the hoop forces and thus minimize the secondary currents. This might allow you to simplify coil design. That might have some advantages. It gives you one more thing that you can vary to to optimize the Stellarator. One wouldn't need 6 MA in a Stellarator, one could get away with much less, say a few hundred KA. I think, you can get that at temperatures of 10~20 KeV by this scheme. This possibility allowes you to free up yor thinking on what types of device can be steady state.

I've one more topic.

This is an idea for another way to heat fusion plasma besides RF and neutral Deuterium beams. The idea is to take singly charged ion of an atom with nuclear charge greater than one, and accelerate them to one or two MeV per nucleon. Such atoms can enter the plasma along a curved orbit, once they enter the plasma additional electron get stripped off by the plasma just as for neutral injection. The stripped energetic ions are trapped inside plasma and heat it. Now, this would have a lot of advantages. First of all, It should be very efficient, because no neutralization is needed, so there is no loss of particle in a neutralizing cell. The beam can be guided by magnetic fields; this means you can put the accelerator some distance back from the reactor and guide the beam into it. The path can be curved so the beam source and accelerator don't have to be looking square into the reactor and catching neutrons in the face. The accelerator can be put far away where it can be well shielded. This complicated piece of apparatus does not become radioactive and is not hot so maintenance should be easy. Further more, you can focus the beam, because it is deflected by magnetic forces. You can focus it through a relatively small hole. Calculation show the beam will penetrate to the center of the plasma and get trapped. We are going to use very energetic ions, in the multi MeV range. Thus very few of them we needed, to heat the plasma so the impurity problem is totaly neglegible. Once the plasma is burning we turn off the beam and the beam particles which have entered the plasma diffuse out just as the He ash. We can inject ^3He, singly ionized ^4He, or singly ionized Li, Be, or Boron, these things can burn, so they are not really impurities. In that case, we can actually get some fusion power from beam plasma interactions. Finally, the beam carries in momentum, this momentum is mainly transfered to the electrons and can drive an electron current. It appears feasible to drive the Tokamak current in this way.

The critical thing is whether you can contain the energetic ions. This depends on the ratio of the Larmor radius to the size of the device. That just depend on v/ω_c, and since ω_c is proportional to z/m and the ratio z/m is nearly the same for all atoms once they are stripped we see that nearly all stripped atoms with the same velocity will be trapped. Since we must confined α particles which have one MeV per nucleon we can certainly inject ions at 1 MeV per nucleon. More detailed calculation actually show you could injected at several MeV per nucleon, may be, up to 10 MeV per nucleon, depending on what kind of atom you are using. The following figure shows results of detailed calculations made at Princeton for injecting 24 MeV Li into a Tokamak.





The solid curve shows the center the beam, where the center of beam goes. For the orbit choosen it passes through the center of the plasma. The dashed curves are contours the density of second ionized *Li* at a certain time after injection. You see, they are nicely going into the center. The right hand diagram shows contours of triply ionized *Li* density after a long time. You see they are nicely trapped inside the device. In fact, they are concentrated toward the center which is another advantage of this type of injection, because it means, you can heat the center of plasma. You can ignite the center without having to heat up the outside. Of course, the outside tends to cool, lose the energy, faster, and if all you have to do is ignite the central region, then it's fusion energy can heat the outer regions to ignition. One would need less energy which is a big consideration. Now, what do you need, what kind of beam do you need; at 20 *MeV*, if you want 100 *MW* which a reactor might require you need 5 Amps of beam. For experimental devices where several MW are interesting several hundred mille Amps would be sufficient. These might be broken up into a number of smaller beams. No one has made such beams but there do not seem to be any serious technological problems to their production. Well, I think that more or less gives you the geneal idea here. There are of course many more details. Some of these can be found in "*MeV* Ion Heating of Tokamaks" by J.M.Dawson and K.Mackenzie, Proceedings of the Second Joint Grenoble - Varenna International Symposium on Heating Troidal Plasmas, Como, Villa Olma, Italy, Sept. 1980. Also other methods for heating Tokamaks were examined by a U.S. DOE (Magnetic Fussion) panel chaired by Don Kerstin 1981. I believe there is a report on this which you could get: I don't know its number.

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