CA0500104

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THE INTENSE NEUTRON GENERATOR AND FUTURE FACTORY TYPE ION ACCELERATORS

DL-94

by

W.B. LEWIS

Presented at the IEEE-GNS 15th Annual Meeting, Montreal,
23 October 1968

Chalk River, Ontario
October 1968

AECL-3190

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Le Générateur de flux neutroniques intenses et les futurs accélérateurs d'ions employés comme fabriques d'isotopes

par W.B. Lewis

Mémoire présenté à Montréal le
23 octobre 1968 à l'occasion de
la 15^{e} Assemblée annuelle de
l'IEEE-GNS

Résumé - Les fabriques neutroniques vendront probablement leurs produits sous forme d'isotopes. Aujourd'hui, les fabriques neutroniques sont les réacteurs nucléaires. Les accélérateurs d'ions peuvent également produire des isotopes par interaction directe et aux énergies suffisamment élevées, des mesons et des hypérons. Le défi de la production électrique des neutrons va bien au-delà du marché des isotopes. Il concurrence les deux concepts populaires de l'énergie à grande échelle et à long terme: le réacteur surgénérateur rapide et la fusion thermonucléaire contrôlée. Pour cette utilisation, environ 4% de l'énergie d'origine nucléaire serait communiquée à une boucle de rétroaction engendrant des neutrons supplémentaires. La concurrence jouera en ce qui concerne les frais d'exploitation et de traitement. Le projet de Générateur de flux neutroniques intenses, maintenant abandonné, aurait eu l'ampleur voulue pour une telle utilisation mais d'importants progrès sont nécessaires et prévus en technologie des réacteurs. L'application la plus prometteuse est peut-être celle qui fera appel au principe de la traînée des ions selon lequel des anneaux d'électrons rapides sont accélérés le long de leurs axes en entraînant des ions par attraction électrostatique. Par suite de la masse beaucoup plus grande des ions ils peuvent acquérir une énergie beaucoup plus rapide que les électrons et le processus pourrait être efficace. On n'a pas encore fabriqué de réacteurs de ce genre, mais les études théoriques et expérimentales sont prometteuses.

Chalk River, Ontario
Octobre 1968

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ATOMIC ENERGY OF CANADA LIMITED
CHALK RIVER NUCLEAR LABORATORIES

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ABSTRACT

A neutron factory is likely to sell its product in the form of isotopes. Today neutron factories are nuclear reactors. Ion accelerators may also produce isotopes by direct interaction and, at high enough energies, mesons and hyperons. The challenge of the electrical production of neutrons goes far beyond the isotope market. It challenges the two popular concepts for long term large scale energy, the fast breeder reactor and controlled thermonuclear fusion. For this use about 4% of nuclear generated power would be applied in a feedback loop generating extra neutrons. Competition rests on operating and processing costs. The Intense Neutron Generator proposal now cancelled would have been full scale for such a use, but much further advance in accelerator engineering is required and anticipated. Perhaps most promising is the application of the ion drag principle in which rings of fast electrons are accelerated along their axis dragging ions with them by electrostatic attraction. Due to the much larger mass of the ions they can acquire much higher energy than the electrons and the process could be efficient. Such accelerators have not yet been made but experimental and theoretical studies are promising.

It was almost thirty-seven years ago that the neutron was discovered by J. Chadwick at the Cavendish Laboratory in England. At that time I had the good fortune to be working in the next room. Two years later neutrons were being produced by ion accelerators(1). That was, however, a laboratory rather than a factory type operation. I suppose the stage at which it becomes a factory type operation is when the money received for the product becomes sufficient to pay the salaries and wages of the operators. It is common for factories to produce a range of products. A factory producing neutrons is likely to sell its product as a range of isotopes. We operate a neutron factory at Chalk River but use nuclear reactors rather than accelerators. The main isotope product of the NRU reactor is radio-cobalt, cobalt-60, of which the annual production is 2 million curies. However, a range of other isotopes is also produced.

Neutrons are not the only product in prospect from Factory Type Ion Accelerators. Marketable isotopes may be produced by direct nuclear interaction of the ions. Moreover at sufficiently high energies ions produce also mesons and hyperons. The prospective markets for mesons and hyperons are still to be discovered. For neutron products there are many known avenues of development, some well-known and others less known. For example, heat sources to keep divers warm in deep water, heart pace-makers, radiation sterilizers of packaged goods, colloid precipitators with possible application to sewage treatment, polymer grafting in fabrics as well as in chemical syntheses. Mesons may be valuable for cancer therapy, exploiting their special property of delivering energy locally where they are stopped.

One meson generator of sufficient capacity to be classed as a "factory type" is now funded and under construction at the Los Alamos Scientific Laboratory(2). The Intense Neutron

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Generator, (ING)(3) recently cancelled by the Canadian government, was planned to be very similar to the Los Alamos Meson Physics Facility (LAMPF), it would produce mesons as well as neutrons. It was estimated to cost about three times as much as LAMPF and have about sixty times the capacity. Like the NRU reactor mentioned above, it was to have been a multi-purpose facility deriving revenue from the sale of isotopes produced by the neutrons but used also for research in materials science, nuclear science and intermediate energy physics. The neutron production rate would have been about one gram a day or about ten times the current output from NRU.

In essence, the ING was to accelerate a 65 mA beam of protons to 1 GeV. The beam would be turned downwards to plunge into a deep target of flowing lead-bismuth eutectic, that would carry away the heat, while releasing the neutrons produced by the spallation reaction in the heavy nuclei. The neutrons would be slowed down in a surrounding tank of heavy water achieving a thermal neutron flux of 10^{16}n/cm^{2}sec. for a number of targets and beam tubes. Most of the neutrons would then be captured to make isotopes.

One engineering challenge of ING was to attain such efficiency in generating and applying 65 megawatts of continuous radiofrequency power that the neutron products would be competitive in the world market.

The challenge of the electrical production of neutrons, however, goes far beyond the isotope market. It challenges the two popular concepts of how the world of the long term future is going to derive its energy not only much more cheaply than from coal and oil but at a minimum cost. The two popular concepts are the fast breeder reactor and controlled thermonuclear fusion. Let me quote from a paper to the recent World Power Conference in Moscow(4). Translated from the Russian it reads "It should be noted, however, that the method of transforming uranium-238 into plutonium in fast reactors, which is the most developed now, is not the only possible one to create the fuel base for large-scale energy. Physicists propose two more possibilities. One of them is the so-called electro-nuclear method of uranium-238 conversion into plutonium by the capture of neutrons, produced in large quantities in the accelerator target, under the action of particles accelerated to an energy of about 1 GeV. The other method is the utilization (for the same conversion) of neutrons produced in the process of thermonuclear fusion of light elements, explosive or controlled. The acceleration method, though feasible as it was long established, could not be taken seriously before. However, the advance that has been achieved recently in the development of high current and high efficiency accelerators makes it possible to return to these ideas. Investigations of Canadian scientists as well as further new ideas in the field of high current accelerators, including the possibility of using new superconducting materials with high critical temperature, seem to offer some interesting perspectives in this field. However, it is yet far from an economical technological process.

As for the idea of using thermonuclear neutrons for the conversion, which is also clear from the physics viewpoint, I think that we shall not be late to discuss this question at the next international power congress.

Thus, besides the main way, which is the increasing production of plutonium in breeder reactors, there are some reserve ways that may be and will be useful if extremely serious difficulties in obtaining short doubling times of plutonium are encountered."

The speaker was Academician A.P. Alexandrov, Head of the Kurchatov Institute of Atomic Energy, the principal centre in the USSR for research on controlled thermonuclear fusion. I would go further in three respects

- He says conditionally "if extremely serious difficulties in obtaining short doubling times of plutonium are encountered". These difficulties are, I believe, already matters of economic fact, so I conclude with him that "some reserve ways ... will be useful".
- The nuclear properties following the thorium route make it economically far preferable to uranium-238 for the application of the electrically produced neutrons.
- It is the operating, handling and processing costs that will determine the optimum combination of the several possibilities.

The advance achieved recently and envisaged for the development of high current and high efficiency accelerators are highly encouraging and I will be discussing some of these in the second half of this paper We need, however, first to establish some perspective of scale and costs.

What is envisaged in the power application is that about 4 per cent of the generated power would be applied in a sort of feedback loop to produce extra neutrons. Suppose the station generates 2000 MWe, then 80 MW would be applied to generate neutrons. The ING was rated at 65 MW in the beam so would have fitted this scale.

The 4 per cent figure is not a rigid figure but represents a judgment of a likely optimum. It can be reduced by more frequent processing of thorium fuel or by improving the reactor design to reduce neutron wastage, also to a limited extent by improving thermal efficiency.

The operating, handling and processing costs, as well as fuel inventory costs in prospect, can be very low using thorium fuel in heavy-water-moderated reactors(5). Fissile uranium-233 builds up in the thorium as well as fission products that must be removed periodically. The value of U-233 at $13/g amounts to about $200/kg thorium and processing costs are not likely to exceed $20/kg thorium. To keep the reactor operating it is necessary not only to recycle the U-233 but also either some extra fissile material such as U-235 or plutonium-239 or some electrically produced neutrons. The value of such neutrons is related to the value of the fissile material saved, together with the difference of the processing and fuel fabricating costs. Several highly ingenious proposals have been made for introducing the neutrons but here we are concerned only with a simplified overall fuel cycle. Since one gram of neutrons can produce 233 g U-233 from thorium the neutrons may be valued at $13 × 233 = $3029/g of neutrons. The ING study showed that 100 MW of power could produce about 1.2g neutrons per day. At a large nuclear power station incremental power may be available at 2 mill/kWh so 2400 MWh would cost $4800 or $4000/g of neutrons. However, the 100 MW is returned to the thermal side of the power station and generates say 30 MWe so the cost of the net power consumed is $2800/g of neutrons. Considering that this is only the power cost and that the capital cost of the accelerator and its target are not negligible, the operation does not look profitable but there is more to come.

The ING reference target was Pb-Bi but for the power application there exists the possibility of almost doubling the neutron yield by introducing U-238 or thorium cooled by Pb-Bi into the target. The long term value of fissile material is linked to the cost of natural uranium and would rise by about $2/g for an increase of $10/kg natural uranium. The efficiency of future heavy-water-moderated power stations may be 40% rather than 30%. Applying all these hopes reduces the power cost to $1200/g neutrons and puts the fissile material up to the equivalent of $3500/g neutrons and possibly higher by the difference of processing costs. There still remains the possibility of reducing the 4% feedback that would reduce the total contribution to the cost of power without changing the ratio between neutron and fissile material values. It would be a mistake, however, to give an over-optimistic picture. It still remains to overcome the many problems of attaining high efficiency and low operating costs for high power accelerators and progress is slowed by the discontinuance of the ING studies. I would still, however, enter the electrical generation of neutrons in the long term low cost power stakes.

Accelerator Development

An early idea in the development of linear accelerators was to form a linear waveguide in which the velocity of a radio-frequency wave could be controlled so that a charged particle riding ahead of the wave crest could be kept there in a stable phase relation to the wave as it was accelerated. It was found, however, that extremely high precision was required in the construction of the disc-loaded waveguide, particularly for the acceleration of protons or heavier ions. Consequently the Alvarez type of structure(6) was preferred and still is for protons up to 100 MeV. In this structure at any instant of time the electric accelerating field is in the same direction across each of the gaps between the collinear drift tubes. The ion spends one or more full periods within each drift tube shielded from the changing field outside. When the velocity βc of the ions is low the wavelength $\beta\lambda$ is short and it may be more convenient to make the drift tube more than one beam wavelength long. The choice still proves controversial. Major improvement in the design of the Alvarez section comes from introducing resonant stubs in the main cavity to give greater stability of operation over a range of beam current and consequent power transfer.

For protons above about 100 MeV the design of travelling wave tube has undergone many changes so that now in function but not in form it is very like the Alvarez section. It is best described as a series of resonant coupled cavities operating in a standing wave mode. By these changes it has proved possible to improve the efficiency and the frequency characteristic. The reference design (Table I) for the ING accelerator was essentially the same as developed at Los Alamos for LAMPF and operating at the same frequency 805 MHz.

TABLE I

ING REFERENCE ACCELERATOR, MARCH 1968

Output energy 1 GeV

Current - positive ions 65 mA
- negative ions 0.5 mA

Length 1540 m

Injection

Current - positive ions 120 mA
- negative ions 1 mA

D.C. Acc. Voltage 750 kV

	Alvarez Sections	Coupled Cavity Sections
Output energy	106 MeV	1000 MeV
Frequency	268.3 MHz	805 MHz
Length	110 m	1430 m
No. of tanks	9	322
Total R.F.power	10 MW	80.5 MW
Total R.F. losses	3.5 MW	22.4 MW

It should be noted that for a given output voltage the R.F. losses are almost inversely proportional to the length. The longer the accelerator the lower the voltage gradient. For a single cavity the losses are proportional to the square of the voltage. The long length 1430 m and large number 322 of tanks each comprising 31 to 22 accelerating cavities were chosen to keep the losses a small fraction of the beam power. Incidentally, this should have the advantage of reducing electrical breakdown and X-ray production, but it does increase the capital cost.

The table indicates that a subsidiary beam of negative hydrogen ions was also to be accelerated. This trick was proposed by C.H. Westcott as being simpler than schemes for deflecting pulses out of the beam for some of the experimental work, particularly with mesons. This explains why the frequency of the Alvarez section has broken away from the traditional 200 MHz. The transition of the two beams from the Alvarez to the Coupled Cavity Sections is simple when the ratio of frequencies is an odd number, three in this case.

Throughout the history of accelerators it has happened that many choices of design have seemed basically secure and sound, only to be overtaken by a major improvement in another design. At the start of the ING study the linear accelerator was rejected on the grounds of unacceptably high R.F. losses in favour of a new type of synchroton identified as the Separated Orbit Cyclotron(7) devised by F.M. Russell. A switch was made later largely from fears of maintenance difficulties with the S.O.C. under the very high radiation fields expected from the residual radioactivity excited in the materials. The switch, however, could not have been made without the advances in linac efficiency introduced at Los Alamos.

Another prospect for the linac ING was that when operating as a factory with a fairly high cost for power there would be an incentive to change the accelerator in sections a few tanks at a time to a more efficient design if it should be developed. In particular there are developments at Stanford University(8) and elsewhere of superconducting linacs in which the R.F. losses would be negligible, although cryogenic power would be required. It should prove possible to make such an accelerator much shorter. It seems that development still has some way to go before all the requirements of ING could be met by such technique. The beam power is high and even temporary beam spill could overload the cryogenic system.

There are, however, several other possibilities. The problem of continuous faultless R.F. power has not yet been solved. By having 322 tanks the power to each is reduced to about 250 kW, which seems low enough not to introduce window breakdown as a serious limit to availability. On the other hand the proposed use of 500 kW tubes to generate the power, makes tube failure a significant problem. Two or three possible lines of development seem worth mentioning. The reference R.F. generator tube was the Amplitron (9) or amplifying multi-anode magnetron, chosen largely because very high efficiency is in theory attainable in the range of 80 to 90% or even higher. In practice, however, as the output power is increased so is the tendency to excite unwanted R.F. modes. Although suggestions have been made for improvement, it is early to make predictions. The back-up choice was the klystron. Although of limited life, klystrons have shown good stability in operation, but were initially ruled out because of low efficiency in the range of 35 to 40%(10). More recently efficiencies of over 60% have been obtained(11) and the prospect appears good for something better. Moreover klystrons have mostly been developed for pulse working at very high peak power. It seems not impossible that very special long klystrons with many cavities and output windows could be developed for total continuous power outputs of 10 MW or more.

For all R.F. generators the power is basically supplied as D.C. power. The power is transferred to become kinetic energy of electrons and is passed by them to become oscillating radio-frequency currents on the inner surfaces of resonant cavities, which do not necessarily collect the electrons. The process of recovering the residual energy of the electrons is often a major cause of inefficiency. The klystron seems to offer design possibilities for using high energy electrons and achieving still higher efficiency.

Several proposals have been made for combining the R.F. generator with the ion accelerator.(12)(13) In an ordinary triode it is designed that the electron stream is modulated to deliver current to the anode at a phase when the D.C. and R.F. fields are in opposition so the electrons arrive with little kinetic energy. If a proton took the same path at the same time it would transfer power from the R.F. to the D.C. system and also would suffer little change in kinetic energy. Since over this part of their paths neither the protons nor the electrons are accelerated, I suggested the name "staticelerator" to describe the action. The proton, it may be noted, would have reached a point of high D.C. potential, the anode, and passing on would be accelerated to a zero potential electrode. By repeating the process many times the proton could in principle be taken to any desired voltage many times that of the D.C. supply. Ideally, the only transfer of power to the R.F. system is that to make up for the conductor losses. However, the scheme is still complex and limited by the electric potential gradients that can be maintained between conductors. I mention it only to lead to simpler ideas.

Much higher electric fields, even 10^9 volts per meter or more can be experienced in finite electron clouds(14) or bunches by charged particles moving in magnetic fields. Most directly the field

$$E = v \times B = 10^9 \text{ V/m}$$

$$\text{if} \quad v \approx c = 3 \times 10^8 \text{ m/s}$$

$$\text{and} \quad B = 3{\cdot}3 \text{ Weber/m}^2 \ (= 33 \text{ kG})$$

Electrons with nearly the velocity of light and magnetic fields of 30 to 40 kilogauss are familiar.

The field at the edge of a cylindrical electron bunch of radius r and uniform electron density ρ is

$$E_r = \rho e r / 2\varepsilon_0$$

$$= 10^9 \text{ V/m for } r = 1 \text{ cm}$$

$$\rho = \frac{2 \times 8{\cdot}854 \times 10^{-12} \times 10^9}{1.602 \times 10^{-19} \times 10^{-2}}$$

$$= 10^{19} \text{ electrons/m}^3$$

$$(10^{13} \text{ electrons/cm}^3)$$

Since the cross section $\pi r^2 = \pi$ cm^2 the current for $v = c$ is $3\pi \times 10^{23}$ electrons/s = 15100 amperes.

Electron currents of such magnitude are produced in electron pulse generators (15) that deliver single pulses of tens or even hundreds of thousands of amperes of electrons typically at 2 to 4 MeV of 20 to 50 nanosecond duration. These pulses or streams 6 to 15 metres long are remarkably stabilized in gases at low pressure. Theory developed by J.D. Lawson(16) and by G. Budker(17) suggests a limiting current of several times 8500 $\beta\gamma$ amperes, where γ is the familiar relativistic mass multiplier $1/\sqrt{1-\beta^2}$ and $\beta = v/c$. Recent experiments by S. Graybill J. Uglum and S. Nablo support this.(18) The stability is essentially due to the relativistic velocity of the electrons relative to positive ions they produce in the gas. This was explained originally by Willard H. Bennett in 1934(19) and is often referred to as the Bennett pinch effect. It is relevant to several possible means of acceleration. The phenomenon was very neatly described by G. Budker in a paper to the 1956 CERN accelerator conference.(20) He notes that given the presence of the positive ions the electron beam can be a potential well for electrons in their frame of reference, while the presence of the electrons makes it also a potential well for the positive ions in their frame of reference and this arises simply from a direct application of the Lorentz transformations between frames of reference moving relatively at high velocity.

Quantitatively

	Laboratory system ions at rest	Moving system electrons at rest
Defining		
Density of electrons	n_e	n'_e
Density of ions	n_i	n'_i

$$\text{Then } n'_e = (1/\gamma)n_e$$

$$n'_i = \gamma n_i$$

If $n_e > n_i$ there is a potential well for ions in the laboratory system and if

$$n'_i > n'_e \quad \text{i.e. } \gamma n_i > (1/\gamma)n_e$$
$$\text{or} \quad n_i > (1/\gamma^2)n_e$$

there is a potential well for electrons in the moving system.

Since γ can be a large number, a very wide range of the relative number of ions can exist over which the electron bunch does not explode.

Ion Drag Acceleration

The process by which an electron bunch can drag and accelerate ions is known as ion drag acceleration. If the ions are travelling axially along a magnetic field and a bunch of relativistic electrons is constrained to travel a helical path with the same axial velocity, the ions will be attracted to the local centre of the electron bunch. Transfer of energy from the electrons to the ions can be rapid and efficient. For the ions to acquire a high energy from the electron bunch, it must move like the carrot in front of the donkey but also accelerate to keep pace with the ions. Because of the complexity of the motions and interactions I like to think, also, of another analogy. The ions are like marbles in a saucer on a railway train. Given a sufficiently gradual acceleration the marbles will stay in the saucer and acquire the velocity of the train.

To accelerate protons to 1 GeV suppose we start with 20 MeV electrons ($\gamma = 39$) and 20 MeV protons ($\beta = 0.2c$). At 1 GeV protons $\beta = 0.875c$ and for the same velocity electrons have a kinetic energy of about 600 keV. The axial velocity of the electron bunch then has to change from 0.2 c to 0.875 c. Suppose the number of protons is 1% of the number of electrons, then to give the protons 1 GeV the electrons must lose 10 MeV. So far everything seems quite practicable and it could all be accomplished in a static magnetic field that over a distance of 10 to 20 metres along its axis falls off from 40 kg to 4 kg.

The formation of such an electron ring and its acceleration by such a magnetic field is the subject of experiment at Dubna in the U.S.S.R.$^{(21)}$ and at Berkeley and Livermore in California.$^{(22)}$ These experiments are of the nature of "zero power" experiments with somewhat elaborate and slow methods of forming the energetic electron rings one at a time. If they are successful, however, it should not be difficult, given the necessary power source, to accelerate the electrons to 20 MeV before forming the rings.

In these concepts we are engineering with plasma and some bitter experience warns us to expect a wide range of possible instabilities. On the other side there seem still to be equally many tricks we can play in return and we may be encouraged by the experience of the stability of the relativistic electron streams.

It is unwise to speculate too far ahead but, noting that caution, we may consider what would be envisaged to adapt electron ring acceleration, if successful for single rings, to the megacycle repetition rate required for a 60 MW 1 GeV proton accelerator. The electron bunches and proton bunches might be formed by R.F. bunchers, controllable in relative phase, and launched into the magnetic field at controlled energies - so that the marbles would be caught and stay in the saucer - even though damping of their relative motions may be slight, and when out of balance radiation may be severe.

It would be most efficient if most of the power could be delivered at 20 MV as D.C. The late Dr. Van de Graaff was interested in extending mechanical generators to these voltages and higher powers. We are supporting a study$^{(23)}$ aiming at 4 MW 20 MV with power transmitted mechanically by one or more insulated shafts.$^{(24)}$ The main problems appear to be windage drag and cooling at high D.C. potentials. The generators are high frequency alternators designed around permanent magnets, barium and strontium ferrites have been studied but new Cobalt-Copper-Samarium alloys$^{(25)}$ with a coercivity of 28 kOe may well offer a reduction in size.

I think we can feel we are living at the right time to see advances in accelerator designs for large power and their application to factory-purposes. Within the next thirty years we may see them applied also to large scale nuclear energy.

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