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Linear Induction Accelerators for Fusion and Neutron Production

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LINEAR INDUCTION ACCELERATORS FOR FUSION AND NEUTRON PRODUCTION

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Abstract Linear induction accelerators (LIA) with pulsed power drives can produce high energy, intense beams or electrons, protons, or heavy ions with megawatts of average power. The continuing development of highly reliable LIA components permits the use such accelerators as cost-effective beam sources to drive fusion pellets with heavy ions, to produce intense neutron fluxes using proton beams, and to generate with electrons microwave power to drive magnetic fusion reactors and high gradient, rf-linacs.

1. INTRODUCTION AND MOTIVATION

Thirty years ago N. C. Christofilos proposed and built the Astron linear induction accelerator as a means of accelerating high-current electron beams to energies beyond those possible with single stage, high voltage diodes. Christofilos's idea aimed not only at higher voltage beams than diodes, but more significantly, at highly reproducible, long pulses (~300 ns) of nearly constant voltage and current that could be generated at repetition rates of ≈ 1 kHz. Since that time, the evolving needs in the defense and fusion research communities have shaped the development of linacs with pulsed power drives to yield a mature and flexible technology. For example, the FXR linac at LLNL has established the multi-stage induction linac as the ideal X-ray source for flash radiography.

Like flash radiography, inertial confinement fusion requires a driver that can generate high energy, high current beam pulses with high reliability. The heavy ion inertial fusion program centered at LBL has concentrated on developing the physics and technology of induction linacs to meet the specific requirements of fusion pellet ignition. The Induction Linac Systems Experiment (ILSE) now under consideration for Key Decision-1 is the critical step to demonstrate the suitability of induction accelerators of ions.

Several challenging, large scale applications for induction linacs have been suggested over the past ten years based on the use of a free electron laser (FEL) to convert the electron beam energy to microwave radiation for rf-heating of plasmas or powering high gradient rf-linacs. The latter application is still being pursued

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jointly by LLNL and LBL under DOE (High Energy Physics) sponsorship. Unlike flash X-ray production, the generation of microwaves at high average power requires operating the linac at high repetition rates (~1 kHz) and heavily beam loaded to maximize electrical efficiency.

Recently DOE/ER and DOE/DP have considered several applications that require high energy, high average power ion beams. In addition to 1) heavy ion fusion (HIF) these proposed uses are 2) a Pulsed Spallation Source for neutron scattering (PSS), 3) an accelerator-based pulsed reactor for waste transmutation (ATW), tritium production (ATP), electric power, etc.(Axy), and 4) a Fusion Material Test Facility - FMTF. The characteristics of these applications are compared in Table 1 where the duty factor is defined to be the percentage of time that the beam must be delivered on target. Of these activities both HIF and PSS have significant European counterparts. The Japanese have expressed a strong interest in ATW, and FMTF could well be an international project of the magnetic fusion community.

Table 1. Accelerator requirements for high power ion beams

	Ave. Power (MW)	Beam Energy (GeV)	Pulse Current (A)	Macro-Pulse (ns)	Rep Rate (Hz)	Ideal Duty Factor
HIF	50	10	$> 10^4$	~ 50	10	$< 10^{-7}$
PSS	5	1 - 3	$\sim 10^3$	~ 500	10 - 50	$< 10^{-5}$
Axy	500	1 - 3	> 0.1	$> 10^6$	100	$< 10^{-3}$
FMTF	40	0.05	~ 1	CW (?)	-	$\sim 10^{-2}$ (?)

1.1 Inertial fusion

Inertial fusion will require highly complex and reliable drivers capable of producing $>10^8$ pulses per year with several megajoules per pulse. Heavy ion accelerators are well matched to these requirements for fusion power production. The scale, complexity, stored beam energy and cost of existing, high energy ion accelerators are commensurate with ICF driver requirements and constraints. Accelerators can have long life (for example the Bevalac at LBL operated for nearly 40 years), high efficiency (30 - 50%), high reliability, and excellent availability. The high ion current is a new requirement on existing accelerator technology. In particular maintaining high beam quality (low emittance) at high current requires demonstration. This demonstration is a primary goal of ILSE.

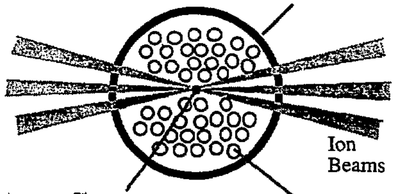

Fig. 1 Schematic representation of protection of a reactor wall with liquid jets

An advantage of inertial fusion vis á vis magnetic confinement fusion is the relative ease of protecting of first wall of the reactor with thick fluid jets of lithium bearing compounds (Fig. 1). The liquid "first wall" prolongs the life of the reactor vessel, permits the use standard engineering materials such as stainless steel, and leads to a low radioactive inventory consistent with shallow burial after decommissioning. On the minus side of the comparison of approaches to fusion energy mass production of fusion targets is an engineering challenge unique to inertial confinement fusion.

1.2 Pulsed spallation sources of neutrons

Advances in neutron scattering science will require new sources capable of producing fluxes of neutrons well above 10^{15} cm^{-2} s^{-1}. The ILL reactor at Grenoble presently produces fluxes approaching 10^{15} cm^{-2} s^{-1}. To move to the forefront in this area the US neutron scattering community has proposed ANS, a new > 300 MW_{th} reactor with an highly enriched uranium core under design at Oak Ridge National Laboratory. ANS aims at fluxes 5 – 10 times higher than ILL.

While spallation sources are not a universal replacement for research reactors and while there is no simple equivalence between beam power on target and flux from a reactor, an optimally moderated source with 5 MW of protons on target is generally considered to be competitive with ANS capabilities for most scattering experiments if the proton pulses are shorter than 1 µs and if the repetition rate is <50 Hz. In fact if the high power could be delivered in 0.5 µs pulses at ≤ 10 Hz, the utility of a pulsed spallation source for scattering would be roughly equivalent to the ANS. It is this philosophy, summarized in Fig. 2, that the motivates the European Spallation Source conceptual design effort aimed at maintaining Europe's lead in neutron scattering facilities. Contemporaneously, DOE has asked LBL to lead a two-year conceptual design effort for a US pulsed spallation source at 1 MW upgradable to 5 MW.

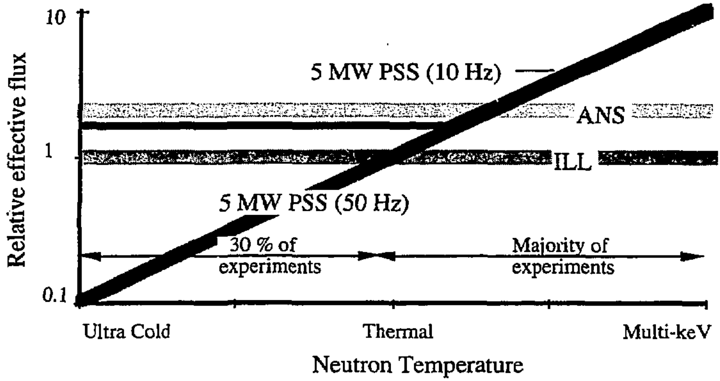

Fig. 2 Comparison of scientific effectiveness of existing ILL reactor (Grenoble) with proposed advanced neutron sources

This remainder of this report addresses the question, "Which type of accelerator technology is the most suitable for meeting the system requirements HIF, PSS, and the other applications of Table 1?" The options considered are fall into two main categories: 1) rf-technology and 2) induction technology.

1) RF-technology:

Ion source [H^- (PSS) or Bi^+(HIF)] *plus*
Room-temperature rf-linac *or*
Superconducting rf-linac *and/or*
Ion synchrotron *plus*
Storage rings

2) Induction technology:

Ion source [H^+ (PSS) or Hg^+ (HIF)] *plus*
Induction linac *or* Induction recirculator

2. CHARACTERISTICS OF LINEAR INDUCTION ACCELERATORS

As illustrated in Fig. 3, the induction linac can be thought of simply as a series of 1–to–1 pulse transformers. The primary circuit is a low impedance pulser network which loops each ferromagnetic core, determining the temporal shape of the voltage waveform. The beam acts as the secondary "winding" of the transformer. The ferromagnetic core and its housing form a non-resonant, i.e., low quality factor cavity with low fundamental frequency (~1 – 10 MHz). As the load current (beam return current) does not encircle the core, it is the pulse driver and beam transport, not the core properties, which limit current that can be accelerated. Indeed, several electron induction linacs have been operated successfully at >1 kA. In general, higher beam currents are desirable for higher operational efficiency and therefore reduced operating costs.

The repetition rate of beam pulses is rate at which the pulse sources can be operated. Typically, rates of 1 - 100 Hz are easily obtainable, although much higher rates (~ 1 kHz) have been demonstrated. Switching networks (with low single pulse energy) with rates of 100 kHz are now under development. As is the case in other linear accelerators, beam quality is determined by the characteristics of the beam source.

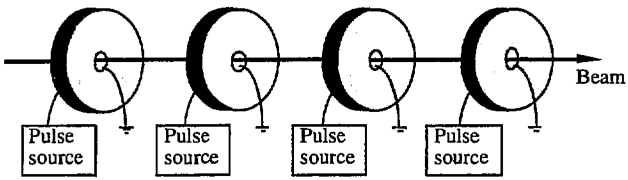

Figure 3. Schematic of an induction linac

Presently available induction linac technology is based on more than 30 years of development for intense electron beam applications. An example of the performance characteristics of some previous machine is given in Table 2. A linear induction accelerator serving as a heavy ion fusion driver or as a pulsed spallation source would be most similar to the Astron.

Table 2. Characteristics of linear induction accelerators

Name	Energy (MeV)	Species	Number of cells	Current (kA)	Pulse T (ns)	Rep rate (Hz)	Total pulses
Astron ('63 - 75)	6	electrons	400	0.8	300	5 1 kHz burst	10^8
ERA-Injector ('70 - 75)	4	electrons	20	1	50	1	10^6
ATA ('83 - 93)	50	electrons	200	10	550	1 1 kHz burst	10^7

With their ability to accelerate high peak currents, induction linacs are ideal for high power, low duty factor applications. The contrast with rf-technology is illustrated in Fig. 4.

In a pulsed, rf-accelerating cavity the sinusoidal accelerating voltage persists for tens of thousands of cycles (macro-pulse). For the beam to have an energy variation less than 1%, the beam can occupy only a small fraction (10^{-3} – 10^{-2}) of the duration of the macropulse even if every cycle is used to accelerate beam. During the macropulse the average current, $\langle I \rangle$, is limited to ~ 0.1 A. If the rf-linac is run in a continuous wave mode the time average duty factor can be as large as $10^{-3} - 10^{-2}$. In the case of the induction linac the accelerating voltage persists for a period of 0.01 – 1 μs. During that time the duty factor is ≈1 and $\langle I \rangle_{max} \sim 10^{3} - 10^{4}$ A. Consequently induction linacs can accelerate a much larger charge per pulse (and usually higher peak currents) than rf linacs. However, as the repetition rate is typically 10 – 100 Hz, the time average duty factor will be $\approx 10^{-6} - 10^{-4}$. As illustrated in Fig. 4a, small variations in the voltage to produce longitudinal (bucket) confinement of the beam bunches are readily produced.

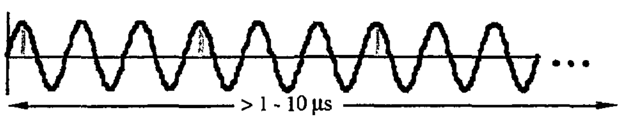

Figure 4 a. RF-voltage (black) and current waveforms (gray) in resonant, rf-accelerating cavity with every third cycle (bucket) filled.

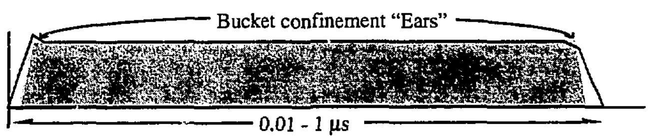

Figure 4 b. Induction linac voltage and current waveforms in non-resonant structure

Because of the close match between the natural duty factor of the induction linac (i.e., large $\langle I \rangle_{max}$ in the macropulse) and the system requirement for the PSS and HIF applications, one can use the beam from the induction linac directly on target without further beam manipulations. In contrast pulse compression is needed to increase the output value of $\langle I \rangle_{max}$ in rf-accelerator based systems. To increase pulse current (lower duty factor) from the rf-accelerator, the usual procedure is to fill one or more storage rings over many turns, and then to extract the beam in single turn. This process may have to be performed more than one time as suggested by Fig. 5.

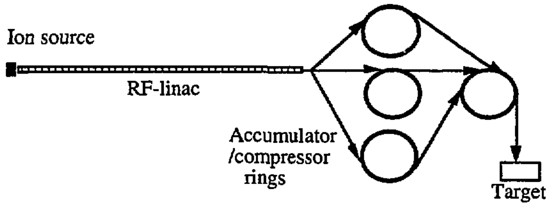

Figure 5. Pulse compression in an rf-accelerator system

Pulse compression is complicated by the fact that sufficient compression may require the trick of changing the charge state of the particles as they enter the storage ring (non-Liouvillian injection). Indeed for the PSS application the approach is to accelerate H^- ions to high energy and then to strip the electrons from the hydrogen to form H^+ in the storage rings. This process exacerbates beam loss during injection into the rings at top energy and consequently leads to accelerator activation and vacuum difficulties. Moreover, suitable negative ion sources (for PSS) are beyond the state-of-the-art.

For the case of pulsed spallation sources the stored current must be raised to the 1 kA level; the largest ion current stored was ~50 A in the ISR (at CERN) at $\gamma \sim 30$. Fortunately, linacs can transport higher currents than can be kept in a storage ring. For a FODO lattice with pole tip field, B, and aperture, a $I \sim 4 \times 10^5 (\beta\gamma)^2 Ba$.

For a 1 GeV proton beam ($\gamma = 2$), and with B = 3 T, a = 6 cm, I = 216 kA, far above the required value. Note that during the acceleration process in the induction linac, the increasing velocity of the bunch raises the 50 A pulse from a 2 MeV injector to 1000 A.

3. APPLICATION OF INDUCTION LINACS TO NEUTRON PRODUCTION

The high peak current, low duty factor output available directly from the induction linac precisely matches the beam requirements for the heavy ion fusion driver and the pulsed spallation source. No technically difficult and expensive beam manipulations are required after the acceleration process as are required with rf-acceleration.

The approach to generating spallation neutrons with a linear induction proton linac is similar to that which would be used for heavy ion driven inertial confinement fusion. For HIF one must deliver 500 μC of heavy ions at 10 GeV to a target in a 10 ns pulse. This 5 MJ pulse is expected to generate 10^{21} neutrons from the fusion capsule. In a power plant, the pulses would be repeated at 10 Hz, which implies the accelerator must deliver 5 mA, 50 MW of beam on fusion targets. The reliability and availability must be > 85% for 3×10^7 seconds per year. Such a fusion plant would be the quintessential pulsed neutron source for scattering experiments.

For the next generation of pulsed spallation sources, pulses of ~100 ns duration are probably optimum with respect to target survival and minimization of cost. Replacing (in concept) the heavy ions with protons and lowering the final beam energy E_{beam} to 1 GeV one would have 5 MW on target.

The exact design of the accelerator depends upon the acceleration scenario. In the conventional rf-approach one accelerates many bunches at low, constant current to final energy and then uses rings to strip, store, stack and compress the beam. Transport rapidly get easier as the beam energy (and velocity) increases, but the low energy end of the accelerator limits the current that can be transported. In the induction approach one accelerates a single bunch of constant charge. As the bunch is usually much shorter than the linac, one defers acceleration until entire bunch is contained in the structure. One allows the current to vary (increasing with the beam velocity) along the linac in accordance with beam transport, acceleration, and cost constraints. Hence the design of linac changes gradually along the machine as the pulse length shortens and focusing becomes a weaker constraint. If pulse compression is desired, as for HIF, one can introduce a tilt in the accelerating voltage. This tilt introduces a head-to-tail velocity variation in the beam.

The choice of acceleration scenario influences system cost by trading focusing costs for the cost of accelerating cores. For HIF, the third scenario (pulse compression in the linac) minimizes accelerator cost. The acceleration schedule for protons in a pulsed spallation source needs cost optimization. However, it is likely that 90% of such a linac would be of constant design with as is the case for an electron accelerator. Under this latter assumption one can estimate the cost of a linac delivering 5 MW of protons at 1 GeV as a function of the accelerating gradient. Figure 6 shows such a calculation.

The capital cost of the 5 MW induction accelerator is well below that of the rf-accelerator options. However, a 1 MW spallation source based on induction technology is likely to be only few percent cheaper than the 5 MW version. Consequently, some rf-accelerator options may be slightly less expensive at 1 MW. The operating power for the example of Fig. 6 is ≈ 20 MW roughly the same as for a room-temperature rf-linac. One should note that other technical options being investigated in the HIF program – such as accelerating multiple beam simultaneously (first demonstrated at LBL) or recirculating the beam though the induction cores – have the potential to improve performance and decrease costs further.

In comparing the rf and induction approaches for a PSS one should note that ion source considerations also favor the choice of induction technology. The induction approach eliminates the need to convert negative ions to positive ions before focusing on the target. The smaller aperture (acceptance) of rf-linacs demands a lower emittance ion source to avoid beam losses that will cause activation of the accelerator. While the low emittance, H^- source built by LBL for the SSC injector is a good starting point for a PSS source, pulse current from sources for rf-accelerator approaches must be increased fivefold. The MFE group at LBL has already demonstrated the performance of a high quality, 90 A, continuous H^+ source that exceeds the needs of induction linac approach; some redesign of this source would be needed for pulsed operation. Source availability for HIF applications is not a major consideration in the choice of accelerator technology.

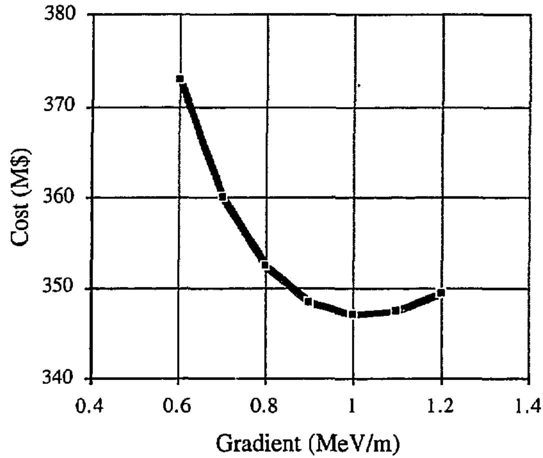

Figure 6. Cost v. accelerating field for a 1 GeV induction linac with I_{beam} = 1 kA and T_p = 100 ns. This estimate includes costs of 10 k$/m for the accelerator building and 33 % for engineering, design and inspection.

3.1 High duty factor applications

The FMFT and the accelerator-driven reactor (Axy) applications appear to require a high duty factor output from the accelerator. While achieving high duty factor (~ 10^{-2}) is not impossible with induction technology, the required, continual repetition rate of well over 1 kHz will lead to severe engineering difficulties in cooling the ferromagnetic cores. The ideal match to the required beam waveform is provided by a rf-linac operating in a continuous wave mode. Superconducting rf-linacs are likely to be less expensive to build and to run in this mode than room temperature rf-linacs. If one can show that lower duty factors do not compromise the application, then the induction linac could be reconsidered especially for FMFT which requires a high average current (≈ 1A).

3.2 Linac reliability

Given such technical advantages for HIF and PSS why isn't the induction accelerator widely accepted as the technology of choice for these applications. First, rf-technology is far more familiar to most accelerator groups. In particular, Europe has no experience with induction accelerators with the exception of a small group at a defense laboratory in France. Secondly, all high energy accelerators use rf-technology. Finally, the association of induction technology with pulsed power raises fears of short component lifetimes or lack of sufficient reliability. On closer inspection, however, one sees that the induction linacs satisfy lifetime requirements. The principal components are as follows:

- Induction cores - ferrites or metal/metallic glass tapes
- Induction cavities - stainless steel and aluminum
- Insulators - ceramics at power feeds
- Pulse forming networks - lumped and distributed elements
- Primary switch - Thyratron, FET, or SCR stack
- DC power supplies
- Ancillaries - cooling, vacuum

This list is similar to that for an rf-linac. With respect to lifetimes, one finds

- Cores - *no known limit*; Astron cores still in use
- Cavities - no known limit; benign faults (easier than rf)
- Insulators - Needs quality control, derate 2 × for faults
- Pulse Forming Network - With derated, pulsed capacitors $>10^{11}$ pulses (SLAC)
- Primary switch - $>10^9$ derated (exactly the same as the thyratron in a modulator for an rf-system)
- DC supplies - > 10 years (the same as for rf-system)
- Cooling, vacuum - easier than rf

If the system is not "red-lined", then the lifetimes of both rf and induction systems should be the same; i.e., both will be acceptable. What is needed is 1) an integrated demonstration of induction system reliability and 2) a full, system-level demonstration of linear induction acceleration of ions. The latter is the aim of ILSE

ILSE is a fully integrated, low energy demonstration of the technology for HIF at full beam characteristics needed in an inertial fusion driver. The ILSE accelerator consists of a four beam system with 2 MV injectors (K^+), an electrostatic quadrupole (ESQ) front end, a 4-into-1 beam combiner, and magnetic transport to 10 MeV. The accelerator is followed by a long transport line for beam stability tests. Recirculation tests are expected to be part of latter experiments. Mechanical and electrical performance requirements of ILSE are at the full fusion driver level. Prototypes of critical components have already been tested. The conceptual design has passed a full technical and cost validation review by the US DoE and is judged to have low technical risk and to be ready for a FY95 construction start.

4. SUMMARY

The induction linac offers a radically different approach to deliver high power ion beams. Any potential technical problems in this approach are at low energy and will be addressed by ILSE. The major differences between the induction linac and rf-based approaches to HIF and PSS are

1) H^+ instead of H^-; hence, minimal source development (PSS only),
2) No problems of injection into and extraction from storage/accumulator rings,
3) Produces short, high current pulses (no need for beam manipulation "gymnastics"),
4) Allows very large beam apertures and clearances (minimizes beam loss at high energy).

The key reliability question for induction technology is the mean time to failure or overhaul for the primary switch (FET, thyratron, etc.); this issue is no different than that for pulsed rf-accelerators.

For PSS the machine design and cost is relatively independent of average power. Raising P_{beam} from 0.1 to 5 MW requires changing the repetition rate from 1 Hz to 50 Hz. Hence, induction technology becomes ever more attractive as the power level required for the application is raised. Clearly this technology deserves more study. While ILSE is the essential next step to resolve the beam physics and technology issues at the fusion driver level, reliability tests and lifetime demonstration of components is the key to community acceptance.

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