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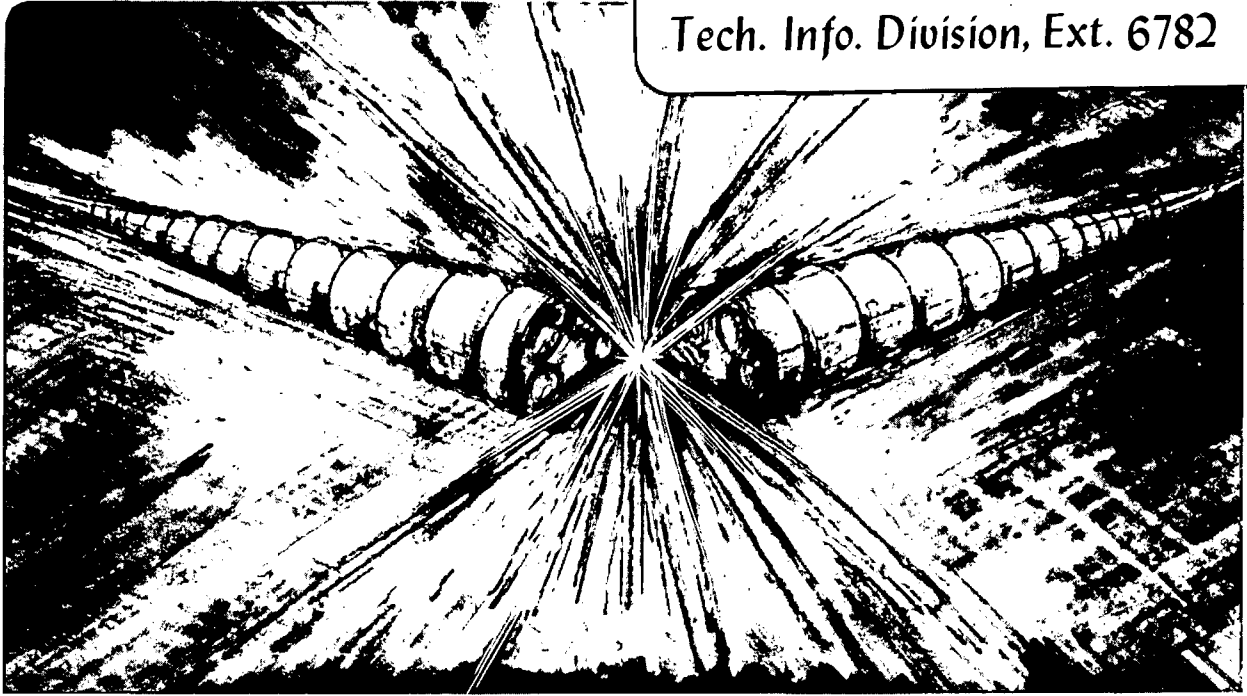
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Denis Keefe and Egon Hoyer

June 1981

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PROTON INDUCTION LINACS AS HIGH-INTENSITY NEUTRON SOURCES\*

I C A N S - V

MEETING OF THE INTERNATIONAL COOPERATION ON  
ADVANCED NEUTRON SOURCES

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June 1981

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Office of Inertial Fusion, Research Division of the U.S. Department of Energy  
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# PROTON INDUCTION LINACS AS HIGH-INTENSITY NEUTRON SOURCES\*

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## Abstract

Proton induction linacs are explored as high intensity neutron sources. The induction linac - concept, properties, experience with electrons, and possibilities - and its limitations for accelerating ions are reviewed. A number of proton induction linac designs are examined with the LIACEP program and general conclusions are given. Results suggest that a proton induction accelerator of the lowest voltage, consistent with good neutron flux, is preferred and could well be cost competitive with the usual rf linac/storage ring designs.

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# PROTON INDUCTION LINACS AS HIGH-INTENSITY NEUTRON SOURCES\*

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## 1. Induction Linac Concept and Properties

An induction linac is composed of a sequence of independent pulse-power modules each of which adds an increment,  $\Delta V$ , to the beam voltage (kinetic energy/charge state of ion). Within or between the modules, focussing elements -- electrostatic or electromagnetic -- are used to transport the beam.

The evolution of the concept in terms of a transmission-line analogy can be seen by reference to Figure 1. Here, a rectangular voltage pulse derived from a pulsed-power source (pulse-forming network or line, or a Marx generator) will provide an accelerating voltage across the gap (Fig. 1(a)) for the duration of the pulse, provided the shorted end of the transmission-line is far enough away that the inverted reflection does not return too soon. For a vacuum transmission line this transit-time isolation makes a satisfactory system for pulses of the order of 10 nanosec since the dimensions can be kept to the order of 1 meter. For much longer pulses, however, the dimensions can be kept manageable (Fig. 1(b)) by changing the propagation speed through the use of ferromagnetic or dielectric loading. The former is preferred because it presents a higher impedance to the generator. Suitable materials include ferrite, thin iron tape ( $\leq 0.1$  mm to reduce eddy-currents), or the new amorphous iron materials now becoming available.

Instead of simply stacking the cores one behind the other to give incremental voltage increases, various geometrical arrangements of the cores can be made to give voltage step-up per gap -- either axially (Fig. 1(c)), or radially (Fig. 1(d)).

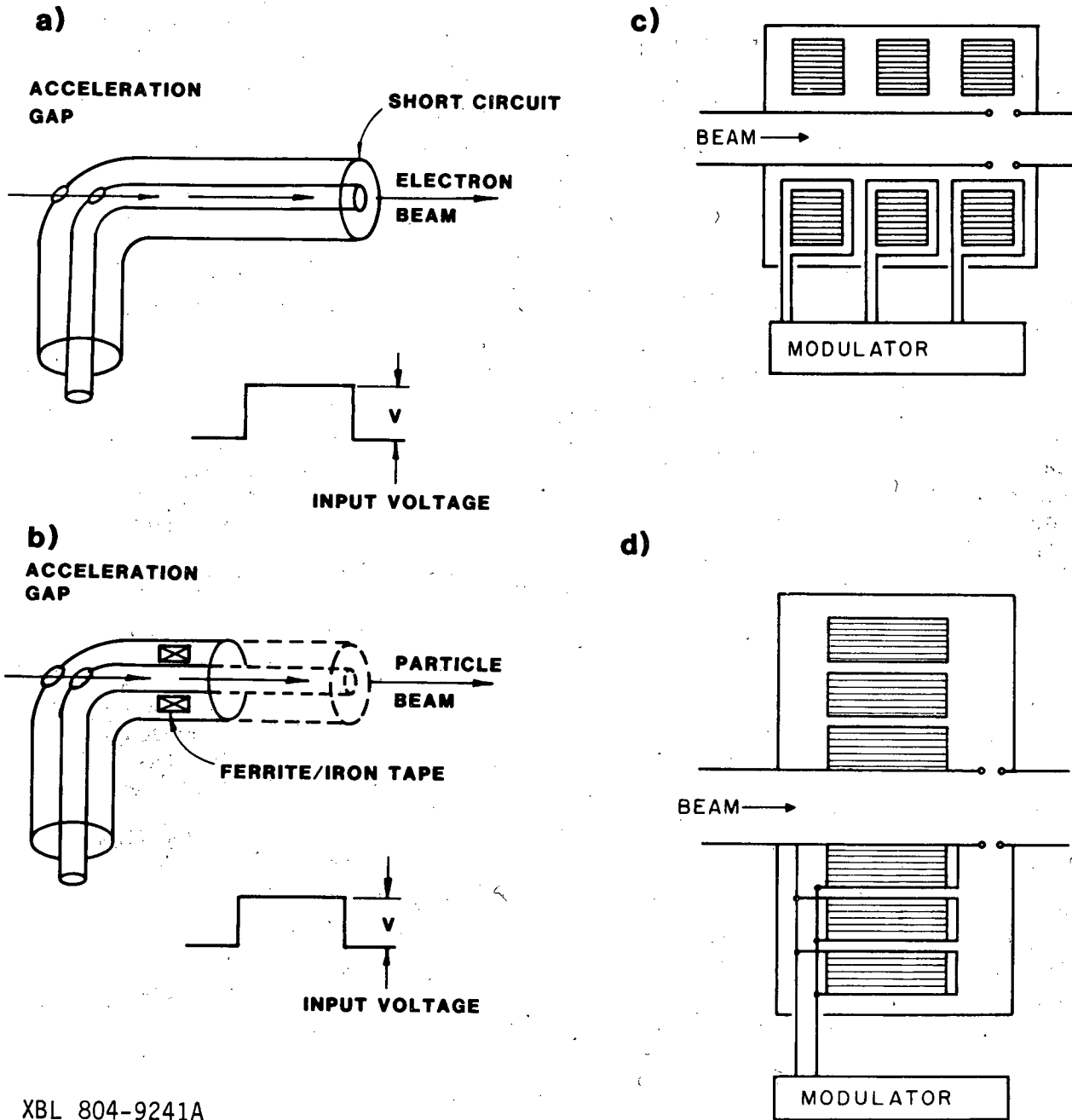
The key utility of this device rests on the ability of pulsed-power systems to supply very high peak-power ( $\sim$  gigawatts) for short periods of time.(1) With a typical operating voltage per module in the range 0.1 - 1.0 MV, beam currents anywhere in the range  $10^2$  to  $10^5$  amperes can be efficiently accelerated. Note that this far exceeds the capability of rf linacs for which a typical beam current is about 1 ampere or less.

## 2. Experience with Induction Linacs for Electrons

The first induction linac was conceived by N. Christofilos and built at Livermore more than twenty years ago as an injector for the Astron experiment.(2) After successive modifications, it operated reliably for many years with a beam current of about 1 kA, a pulse-length of 300 nanosec., a voltage of 6 MeV, and a repetition rate capability of 30 Hz. A simpler and more elegant machine based on

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Fig. 1: Evolution of the induction linac geometry. In (a) it can be seen that a shorted transmission line with a hollow center conductor can accelerate particles across the gap shown; the voltage disappears, however, when the inverted reflection returns, from the shorted end to the gap. For pulses much longer than a few nanoseconds this would provide a very low accelerating gradient. In (b) ferromagnetic material increases the electrical line-length and thus allows long pulse-length without sacrificing gradient. Several cores driven in parallel can provide increased gap voltage; they may be stacked axially (c) or radially (d). The latter was the choice for the NBS 2  $\mu$ sec induction linac.

TABLE 1: SOME ELECTRON INDUCTION LINACS

Accelerator	Astron Injector Livermore, 1963	ERA Berkeley, 1971	NEP 2 Injector Dubna, 1971	ATA Livermore, 1976	NBS Proposed, 1971
Kinetic					
Energy, MeV	3.7	4.0	30	50	100
Current, Amps	350	900	250	10,000	2,000
Pulse					
Duration, ns	300	2-45	500	50	2,000
Pulse					
Energy, J	0.4	0.1	3.8	25	400
Rep Rate,					
pps	60	0-5	50	5	1
Number of					
Switches	300	17	750	200	250

ferrite cores, better matched to a shorter pulse length requirement, was operated for many years at Berkeley.(3) The U. S. National Bureau of Standards pioneered the development of long pulse (2  $\mu$ sec) modules.(4) A selection of induction linacs for electrons is included in Table 1 which shows some of their important parameters. The reader is referred to Reference 5 for a description of some other classes of induction linac that do not use ferromagnetic loading.

It will be seen from Table 1 that the pulse length has typically ranged from several nanoseconds to several microseconds. Applications have normally demanded high peak power and low average power. Below a repetition rate of several tens of Hertz, spark gaps offer the least expensive switch solution; higher repetition rates are achievable, if desired, by the use of more expensive thyratrons or vacuum tubes.

Finally, it should be noted that an advanced technology accelerator (ATA) under construction at present will advance the voltage and current achievements by an order of magnitude apiece beyond those of the earlier accelerators, namely, to 50 MV and 10,000 A respectively.

A common feature of electron induction linacs is that, because the particles are launched from the gun area with relativistic speeds, it is not possible to accomplish any significant bunching thereafter. Thus the current and the bunch length remain the same throughout the accelerator. The design of an electron machine is thus rather simple since it requires the sequential placement of identical modules each with the appropriate number of volt-seconds of core. Solenoid lenses are adequate to handle the beam focussing.

### 3. Induction Linacs for Ions

When the possibility of using short pulses of high-intensity heavy ions to drive the implosion of small deuterium-tritium pellets to achieve inertial-confinement fusion was first proposed,(6) it seemed a natural choice to examine the induction linac as a candidate.(7) An immediate apparent difficulty is that at low energies currents of only several



amperes can be transported whereas a current of 10-20 kA is needed at the target. A striking new feature in this application, however, was recognized,(7) in that the ions travel, by and large, with sub-relativistic speeds ( $\beta \approx 0.3$ ); thus bunching and consequent current amplification becomes a new degree of freedom not available in electron devices.

In any linac, if the accelerating fields have been established prior to entry of the bunch of charge, the head of the bunch will experience acceleration at the moment of its entry, and earlier in time, than the remaining parts of the beam. In this case the bunch becomes extended in length and continues to do so in such a way that the beam-current remains constant throughout the entire linac. If, instead, in an induction linac, the entire bunch length (perhaps 20-30 m long) is inserted into the linac structures and then the fields are pulsed on, the head and tail of the bunch (and parts between) can all observe the same acceleration at the same time and the bunch length will remain a constant throughout the whole acceleration process. In this case the bunch duration,  $\tau = L/\beta c$ , decreases directly as  $1/\beta$  and the current increases proportional to  $\beta$  during the acceleration process. Because the voltage waveforms applied to the induction modules can be chosen to have a variety of shapes, a further strategy becomes possible, viz., by introducing a modest ramp on the voltage the rear portions of the bunch can be accelerated somewhat more than the front. Thus, the bunch length can in fact be gradually compressed and the current amplified during acceleration at a rate proportional to  $\beta^k$ , where  $k > 1$ .

A major consideration in the design of an ion induction linac is that the beam current is limited to inconveniently low values by the inability of the quadrupole transport system to handle large amounts of space-charge. As pointed out by Maschke,(8) for magnetic quadrupoles the current limit is

$$I_M = 1.7 \times 10^6 (A/Z)^{1/3} (\epsilon_N n B)^{2/3} (\beta\gamma)^{5/3} \text{ amps} \quad \text{Eq. (1)}$$

where  $A, Z$ , are the atomic weight, number, of the ion,  
 $\epsilon_N$  = normalized emittance (meters),  
 $B$  = quadrupole "pole-tip" field (maximum  $\approx 5T$ ),  
 $n$  = fraction of length occupied by quadrupoles.

For a heavy ion fusion driver ( $A \approx 200$ ),  $I_M$  varies from a few amperes at injection, to a few thousand amperes at full energy ( $\beta \approx 0.3$ ). To make best use of the induction linac it is important to choose a design that can handle a current as high as possible (within reason) at all points along the accelerator. Thus it is advantageous to arrange for some pulse-length compression so that the current amplification exponent,  $k$ , defined in the previous paragraph, can approach the value 5/3 (see Eq. 1). Other constraints, however, can enter; for example, the bunch compression must be halted if the longitudinally defocussing self-fields at the bunch ends become too strong.

A procedure has been developed at LBL to examine at any given point along the accelerator how one can choose the design of accelerator modules and associated transport system to minimize the cost,  $\Delta C/\Delta V$ , to add a further unit increment in voltage.(9) In brief, one can see from

Eq. 1 that one would tend to choose values for  $n$  close to unity in order to achieve high current, but that would result in leaving no space for accelerating modules. On the other hand, making  $n$  small decreases the current and, for a given charge,  $[I\tau]$ , in the beam, leads to a long pulse duration,  $\tau$ , thereby necessitating a large investment in volt-seconds of core to achieve the next increment of voltage. Thus, one can see how a reasonable optimum solution must exist between these extremes. In the computer program, LIACEP, one specifies, to begin with, the ion mass and charge state, the emittance, the allowed betatron tune depression (usually from  $60^\circ$  to  $24^\circ$  in terms of phase advance per period), the pulse repetition rate, and proceeds with optimization at each voltage point along the machine for a wide variety of assumed total beam charge,  $[I] = 30 \mu\text{C}, 60 \mu\text{C}, \dots$ , etc. A pre-chosen set of engineering design options and a variety of ferromagnetic material are cycled through to find the most suitable solutions at each point.

The region of parameter space that has been most explored has been centered on  $A > 200$ ,  $Z < 6$ ,  $\epsilon_N \approx 3 \cdot 10^{-5}$  rad-m,  $Z_{\text{eV}} \approx 10$  GeV, final energy  $\approx 1$ -10 MJ,  $[I\tau] \approx 200$ -600  $\mu\text{C}$ , pulse rate 1-10 Hz. Almost all of these are quite far from the parameters of interest for a proton induction linac to produce neutrons but the procedure is still applicable even if the results need more caution in interpretation. Three important differences between the heavy-ion driver and proton INS cases should be borne in mind:

(i) The heavy ions are in essence non-relativistic throughout the course of acceleration ( $\beta < 0.3$ ). Bunch length compression is accomplished at quite low speeds ( $\beta < 0.1$ ) and the bunch-length held at a constant value thereafter until a final impulsive compression stage in the final transport system to the target. By contrast, protons can be considered as non-relativistic when their kinetic energy is less than 100-200 MeV for bunch-length compression purposes. Thereafter, if one assumes a final energy of 1 GeV, current amplification can occur significantly only through the  $\beta$ -factor which saturates as  $\beta$  tends towards unity.

(ii) Creation and preservation of a low-emittance beam is crucial in the design of a heavy-ion driver for which it is essential that the beam ultimately be focussed, at a stand-off distance of some 10 m, to a spot a few millimeters in radius. Taking into account the difference in  $\beta\gamma$  and the relaxed target conditions, it would seem to us that, perhaps, two-orders-of-magnitude greater normalized emittance could be tolerated for a proton induction linac for an INS. Since the normalized emittance,  $\epsilon_N$ , occurs to the 2/3 power in Eq. 1 this could alter the space charge limit by a factor of twenty!

(iii) The zero-th order cost-determining factor in our heavy-ion driver studies turned out to be simply the beam energy in joules,  $[I\tau]V$ . There is a weak dependence upon emittance within the narrow range allowed (bigger  $\epsilon_N$  is better), weak dependence on charge-state -- within a narrow range -- (higher  $Z$  is better), and substantial gains observed by incorporating several independently focussed beams within a single induction-linac accelerator structure. For reasons we do not yet fully understand, the result for the example proton linacs examined had quite dramatically different indications, namely, that the cost seemed to be more significantly related to the final beam voltage and not to the final joules in the beam. This is probably because of the significantly lower charge accelerated.

Finally, it should be remarked that a major program element in the LBL efforts towards heavy-ion fusion has been research and development on long-pulse (several micro-second) induction modules suitable for the front-end of an ICF driver. Despite support and encouragement from the U. S. Department of Energy, financial support for this basic R D has not been forthcoming and we have been able to pursue only small-scale model tests to seek out the more prospective candidates for ferromagnetic core material. Part of that low-level program has included a cooperation with Allied Chemical who are the producers of the amorphous-iron material registered as Met-Glas.

To conclude this section, it should be recorded that Nation has reported accelerating several hundred amperes of protons with an induction linac module.(10) The beam probably had a large component of electrons, which, while supplying space-charge neutralization, also provided a drain on the generator and a backward bombardment of the ion source.

#### 4. Induction Linacs for Intense Neutron Sources

To our knowledge, the first person to draw attention to the possibility of using the very large current, short pulse capability of the induction linac for neutron production was C. Bowman.(11) He proposed that a 10 MeV, 1000 ampere electron induction linac with a 30 nanosecond pulse could produce an average neutron rate of  $3 \times 10^{14}$  per second by bombarding a suitable target containing beryllium or deuterium. To achieve this rate would require a pulse repetition frequency of 1000 Hz; except in this one respect his suggested parameters are well within past and tried technology. At 1000 Hz, spark-gap switches are probably inappropriate but thyratrons and vacuum tubes are viable alternatives.

From studies for heavy-ion fusion drivers the two major candidates have been identified as the low-current rf linac followed by a current-amplifying storage ring, on the one hand, or the single-pass induction linac in which current amplification is accomplished during acceleration. Recognizing the correspondence between the similar - if less demanding - requirements for a spallation source and, also, that only the former candidate has so far been considered, Foss has recently looked at the induction linac as a possible design concept alternative.(12) His goal was not to develop dimensions, gradients or any engineering features of a design but rather to establish the feasibility of bunching the proton beam in a "buncher" section - in which the current is kept just below the space charge limit and then to enter a purely "accelerating" section in which the current remains more or less constant throughout. His single-particle bunching calculations parallel those done by Laslett (13) for a heavy ion test bed - which, in addition, included longitudinal space-charge effects - but have the advantage of being explicitly for protons.

Our approach taken in this early examination of the problem is different, however, and starts from an engineering evaluation of how the beam can be most economically accelerated and transported from point to point down the length of the accelerator (see previous section regarding LIACEP program). Whether the physics of the implied bunching process to meet the minimum-cost goals is reasonable or not must be examined as a separate issue. While we are confident in knowing that solutions exist

for the heavy ion driver case ( $\beta=0.3$ ,  $\gamma=1.05$ ), some caution is needed in accepting the results for the present examples where  $\beta=0.875$  and  $\gamma=2.07$ . As noted earlier, ultra-relativistic electrons cannot, in practice, be bunched whereas non-relativistic ions can; for a proton accelerator of 1 GeV we are dealing with an intermediate case. Most of the bunching by modestly ramping the voltage pulses is carried out at low velocities. Later, the degree of difficulty - in terms of the magnitude of the ramp - is essentially determined by the relativistic increase in longitudinal mass,  $m\gamma^3$ ; one could thus assume that any voltage ramps needed would still be of reasonably modest proportions up to  $\beta$  between 0.6 and 0.7 ( $T \sim 230 - 370$  MeV) where the  $\gamma^3$  factor is about 2. Beyond that, however, current amplification of more than a factor of two becomes very difficult.

We were gratified to note that the economically most advantageous strategy of pulse-time compression by a factor of 1/10, between 1 and 10 MeV, is in agreement with the physics-based estimates by Foss. Since this is well within the non-relativistic domain, which had been examined for various heavy-ion scenarios in detail, it is not surprising.

## 5. Results

Some parameters proposed for neutron sources appear in Table 2. It would be nice to report that we can present cost estimates for a variety of induction linac scenarios. Unfortunately, we can not, but have arrived at the important conclusion that the proton induction linac is a candidate worthy of careful scrutiny for the pulsed neutron source application. Major uncertainties in cost stem from several main reasons:

TABLE 2: PARAMETERS OF SOME OPERATING OR PROPOSED NEUTRON SOURCES

Neutron Spalla tion Source	Kinetic Energy (MeV)	Repeti- tion Rate (Hz)	Pulse Length ( $\mu$ sec)	Charge per Pulse ( $\mu$ C)	Normalized Emittance mm-mrad.	Average Beam Power (MW)
IPNS-1	500	30	01.00	0.5		0.01
KENS	500	20	< 1	0.1	20 $\pi$	0.001
SNS	800	50	0.100	4	80 $\pi$	0.17
PSR	800	12 (720)	0.250 (0.001)	8 (0.01)	30 $\pi$	0.1
SNQ	1,100	100	500 (< 1)	50 (45)	15 $\pi$	5.5

a) No very large induction linac system has been built which one can use as a calibration point. The largest in the U.S. is the ATA, still under construction; it will provide a  $500\mu$ C beam at 10kA and 50 MeV.

b) The level of effort in exploring this question for ions has been confined to the part-time activity of two or three people at Berkeley.

c) We have used two quite different cost bases for exploring a cost-minimum optimization routine;

(A) Assume you must proceed immediately with a low-energy accelerator on the basis of conservative assumptions and proven technology. Examples: (i) assume 250kV per Marx generator—a proven technology of more than a decade ago for rep-rated induction linacs; (ii) Silicon steel tape in 0.001 ins thickness is not immediately an economic choice; use 0.002 in. thick material at current prices. The origin of this cost basis, labelled "conservative" or C, derives from the urging by the U.S. DOE Office of Inertial Fusion in 1979 to proceed rapidly to a 10–50 MeV test bed for Heavy Ions.

(B) Estimate the future(F) cost of a heavy ion driver in the megajoule range – an accelerator that will cost several hundred million dollars. Here, one must assume some years of research, development, and prototyping to develop cheaper insulators, better ways of fabricating and packaging cores, development of better ferromagnetic materials, e.g. amorphous iron materials, and higher voltage for reliable and rep-rateable pulse-power generators. (In the last case, the present rep-rated performance is regularly in the 350 kV – 400 kV range at LBL).

For the purposes of this discussion, unfortunately, the differences between Cost Basis C and Cost Basis F are too far apart to allow us to give any really meaningful cost estimates. We have run several examples with the following parameters:

BEAM CURRENT ( $\mu\text{C}$ ) =	5	10	20	80
BEAM ENERGY (GeV) =	1 and 2	1	0.5	0.125

with a variety of values of  $\epsilon_N$  in the range 20 to  $80\pi$  mm-mrad. We have assumed that only a single-beam is transported through the accelerator (multiple beams would be cheaper). We adopt a reference repetition rate of 20 Hz (spark-gap switches can be used up to  $\cong 100$  Hz if that is desirable – beyond that thyratrons would be better).

Some general conclusions were:

- Whether the "Conservative(C)" or "Future(F)" cost basis was used the derived prescriptions for how the beam current (and pulse duration), the magnet occupancy factor, quadrupole field and beam size turned out to be very similar (see figure 2, for one example). The biggest difference was that the final pulse-length for the F-basis, i.e. using amorphous iron, was at most a factor of two larger than with the C-basis.

- While the initial pulse was several microseconds long it could be dropped to 1/10 of this by the 10 MeV point

- Increase in  $\epsilon_N$  reduced costs some ( $\cong 10$  between 40 and  $80\pi$  mm-mrad).

- The F-costed accelerators always turned out to be about one-half the length of the corresponding C-costed cases – a direct reflection of the higher module voltage assumed. The corresponding gradients were about 2 MV/m and 1 MV/m, respectively.

- The most dramatic difference between the two cost bases showed up when the beam energy was fixed at 10kJ/pulse, and the charge varied from  $5\mu\text{C}$  to  $80\mu\text{C}$ . On the C-basis the cost decreased sharply to

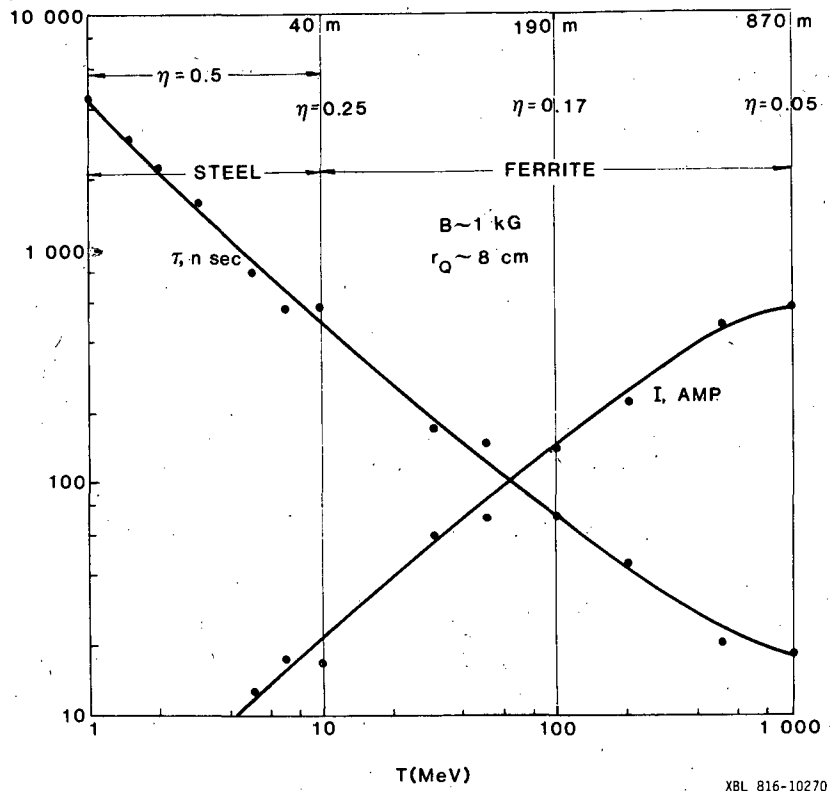


Figure 2: An example of how the current and pulse duration should vary to minimize the overall cost (on the conservative (C) basis). The fraction of space occupied by magnets,  $\eta$ , is indicated and can be seen to be small over most of the length. With the F cost-basis the length is halved.

one quarter with increasing charge. On the F-basis the change was less - to one half. This suggests strongly that choice of the lowest voltage machine, consistent with a good neutron flux, is preferred.

- If we fix our attention on a particular beam voltage, e.g. 500 MeV, we find for both the C and F scenarios that whether one accelerates  $5\mu\text{C}$  or  $10\mu\text{C}$  the cost is the same (a "single-particle" approximation), and to accelerate  $80\mu\text{C}$  is less than a factor of two more in cost.

Table 3 gives some representative results.

TABLE 3 - Proton Induction Linacs ( $f=20\text{Hz}$ )

$I\tau$ $\mu\text{C}$	T (MeV)	L (m)	$\epsilon_N$ mm mrad	$\tau_j$ $\mu\text{sec}$	$\tau_f$ $\mu\text{sec}$	$I_f$ amps
5	1000	470-890	25	5	.014	200-350
10	1000	460-870	80	5	.018	300-550
20	500	360-700	40	14	.05	375
80	125	235-365	80	33	0.3	250-280

Our final guess, based on a cursory survey, is that a 500 MV accelerator delivering 50 kJ per pulse can be built for significantly less than 100 M\$, given a serious design study and some aggressive research, development, and prototype work.

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