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HEAVY ION INDUCTION LINACS FOR FUSION

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Abstract

In 1976 Denis Keefe proposed the heavy ion induction linac as a driver for inertial confinement fusion (ICF) power plants. Subsequent research has established that heavy ion fusion (HIF) is potentially an attractive energy source and has identified the issues that must be resolved to make HIF a reality. The principal accelerator issues are achieving adequately low transverse and longitudinal emittance and acceptable cost. Results from the single and multiple beam experiments at LBL on transverse emittance are encouraging. A predicted high-current longitudinal instability that can affect longitudinal emittance is currently being studied.

This paper presents an overview of economics and ICF target requirements and their relationship to accelerator design. It also presents a summary of the status of heavy ion induction linac research. It concludes with a discussion of research plans, including plans for the proposed Induction Linac Systems Experiments (ILSE).

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Introduction

In 1974 A.W. Maschke proposed heavy ion accelerators as drivers for inertial confinement fusion (ICF) power plants. Synchrotrons and r.f. linacs were the first types of accelerators studied for this application. In the r.f. linac systems, the linac is followed by storage rings to accumulate enough energy and to produce enough power to drive the ICF targets. In 1976 Denis Keefe proposed using induction linacs rather than r.f. linacs. He recognized that the high current capability of inductions linacs might eliminate the need of storage rings. Subsequent research on both r.f. and inductions linac systems has continued to show that both remain promising ICF drivers.

Economics and Target Requirements

To be economically competitive with future fission or coal power plants, a fusion plant must cost less than about \$2/watt. Thus, a typical 1 GW(electric) power plant must cost less than about \$2B. This cost must cover the reactor, turbines, generators, target factory, and the driver. Detailed systems studies show that about \$600M may be allocated to the driver.[1] The allowable driver cost is roughly proportional to the power plant capacity. Thus, the driver for a 2-GW power plant could cost about \$1.2B and so on. In the U.S. power utilities prefer plants with capacities less than about 1 GW so that \$600M is a desirable goal for a driver.

In addition to cost there is also a requirement on the product of driver efficiency η and target gain G. For power plants using conventional thermal-to-electric energy conversion with an efficiency of 35-45%, ηG must be larger than about 10.[1] If $\eta G<10$, the power required to drive the driver becomes an unacceptably large fraction of the gross power output of the plant, leaving too little power available to be sold at a competitive price. Calculated efficiencies of heavy ion induction linacs are about 25% so that target gain must be larger than 40. Nearly all targets designed for ICF power production use deuterium and tritium as fuel. Target gain depends on total beam energy, ion range, and focal spot radius. Calculated target gain as a function of these variables is shown in Fig. 1.[2] Note that the gain decreases rapidly with increasing focal spot radius so that achieving adequate beam quality to allow a small focal spot is an important consideration in accelerator design. In order to achieve the target gain shown in Fig. 1, the beam pulse must be shaped. The beam power must initially be low, increasing to its peak value for about the last 20% of the pulse. Usually 60-80% of the total beam energy is delivered at peak power. The peak power requirement as a function of beam energy, ion range, and focal spot size is shown in Fig. 2.

For illustrative purposes we consider a single specific case, namely a 3.5-MJ pulse of 10-GeV heavy ions ($A \approx 200$ amu). These ions have a range of approximately 0.1 g/cm^2 in the hot matter of the fusion target. If the beams are focused to a radius of 2.5 mm, Figures 1 and 2 give a target gain of 50 and a peak power requirement of 300 TW. At 10 GeV, 300 TW corresponds to a particle current of 30 kA. Typical quadrupole focusing systems for heavy ion fusion (HIF) power plants produce a beam convergence angle of 10-20 mr so that the beam emittance must be less than 25-50π mm·mr. Since the particle velocity parameter β is about 0.3, the normalized emittance ε_N must be $\lesssim 10\,\pi$ mm·mr. In addition, chromatic aberrations in uncorrected systems limit the longitudinal momentum spread $\delta p/p$ to less than 0.5-1%.[3] A summary of the target and economic requirements is given in Table I. It must be emphasized that these requirements are only one example. Other plant capacities, ion kinetic energies, ion masses, and focal spot sizes would give other requirements.

Induction Linacs for Heavy Ion Fusion

An example of an induction linac designed to meet the requirements listed in Table I is shown in Fig. 3. This example uses charge state +3 which for 200-amu ions gives a shorter, less expensive linac than charge state +1. In terms of emittance and economics it is advantageous to accelerate multiple beams though common induction cores. The example shown employs 64 beams for ion energies less than 100 MeV. At 100 MeV the 64 beams are transversely merged into 16 beams. The ions in the 16 beams are then accelerated to 10 GeV. Since heavy ions at 10 GeV are not very relativistic, their velocity changes nearly a factor of 10 as they are accelerated from 100 MeV to 10 GeV. Thus, if the beam length were constant, the 225A electrical (not particle) current at 100 MeV would increase to 2.25 kA at 10 GeV. In the example shown there is an additional 4-fold increase in current obtained by longitudinal bunch compression. The longitudinal bunch compression is obtained by accelerating the tail of the beam to a slightly higher speed than the head of the beam. The final current at the end of the accelerator is 9 kA or 3 kA of particle current. A current of 9 kA is well within the demonstrated capability of induction linacs, but it is an order of magnitude less than the 90 kA (30 kA of particles) required for target ignition. Therefore, the acceleration schedule is arranged so that the velocity difference along the beam gives an additional factor of 10 compression as the beam drifts toward the target. Numerical simulations suggest that the velocity profile may also be programmed to give the appropriate pulse shape.[4]

Table I. Example economic and target requirements for heavy ion fusion

• Total beam energy	3.5 MJ
• Ion kinetic energy	10 GeV
• Beam power	300 TW (particle current = 30 kA)
• Ion mass	~200 amu
• Focal radius	2.5 mm ($\varepsilon_N \lesssim 10\pi$ mm·mr, $\delta p/p \lesssim 0.5\%$)
• Driver cost	$\lesssim 0.6$ G$

The scenario just described raises several important issues: Low emittance, high current, reliable heavy ion sources must be developed, preferably with the ability to produce ions in a specified charge state. The complexity of the accelerator and its alignment system are greater for 16 or 64 beams than for the standard 1 or 2 beams in most accelerators or colliders. The emittance growth associated with the acceleration, transport, merging, bunching, bending and focusing of high current beams must be studied. High current beams are also subject to the well known longitudinal instability that arises from the interaction of the beam with the impedance of the accelerating structure. This instability is discussed in the paper by Edward P. Lee and Lloyd Smith given at this conference. It is also discussed in the paper by J.R. Freeman and J.S. Wagner. The longitudinal instability is potentially important because it may give rise to excessive $\delta p/p$. Some calculations show that the instability is quenched by a momentum spread of about 1%; however, for the scenario described here, a 1% momentum spread in the accelerator corresponds to a 10% spread at the final focusing elements because of the longitudinal beam compression after the beam leaves the accelerator. In the opinion of the author some active feedback may be required to suppress this instability. Finally, cost is an issue. Studies show marginally acceptable costs ($500-1000M) for a 1-GWe power plant.[5]

Since the inception of the HIF program in 1976 a number of theoretical and numerical studies and a number of experiments have addressed the issues outlined above. In the late seventies Lawrence Berkeley Laboratory built a 1-ampere cesium source with a normalized emittance of the order of 0.1 π mm·mr or about two orders of magnitude lower than needed at the end of the machine.[6] A grid was used to increase the emittance of this source to 2π mm·mr[7] because of concerns about the stability of low-emittance beams. These concerns have now been alleviated. A single beam transport experiment using 86 electrostatic quadrupoles demonstrated stable beam transport without significant emittance growth for low-emittance space-charge-dominated beams.[8] The space charge forces in these experiments were strong enough to depress the betatron frequency about an order of magnitude below its single particle value. Such strong depression means that the space charge forces are very nearly equal to the applied focusing forces. The Multiple Beam Experiment with 4 beams (MBE-4) started operation at LBL in 1987. It has demonstrated acceleration and bunching of multiple beams. Some details of this experiment are given in the paper by T. Garvey et al. at this conference.

New development and experiments are needed to resolve the remaining issues. Development of sources of ions other than cesium is needed. Transport of heavily space-charge-dominated beams has been demonstrated in electrostatic quadrupole systems but requires demonstration in magnetic systems. Bending, merging, bunching, and focusing have been studied analytically and numerically but experiments are needed. Characterization of large induction cavities and their associated circuitry is necessary to understand and control longitudinal dynamics. Finally, technology development is needed to achieve low cost.

Lawrence Berkeley Laboratory has proposed an integrated series of experiments, the Induction Linac Systems Experiments (ILSE)[9] to address many of the remaining issues. The present preliminary design of ILSE is shown in Fig. 4. The total length from injector to focus is roughly 100m. ILSE, at small scale, tests many of the features of a full-scale driver. ILSE has been favorably reviewed by DOE and Congressional review committees. A high voltage injector for ILSE is now being assembled at LBL. If funding is available, assembly of the remainder of ILSE will begin in about a year. One feature that ILSE cannot test well is the longitudinal instability. A large induction cavity is currently being built to provide an experimental determination of the longitudinal coupling impedance. The AMOS code is being used to simulate induction cavities for HIF. At this conference the papers by J.F. DeFord, C.C. Shang, G.D. Craig, and G. Kamin describe simulation of induction cavities and the AMOS code.

Cost remains an important issue. Lawrence Livermore National Laboratory and Lawrence Berkeley Laboratory are evaluating recirculating induction linacs as a potential way to reduce cost. If this evaluation is favorable, it may be possible to test recirculation on ILSE by providing an additional 180° bend.

If the ILSE experiments are successful we hope to construct a larger intermediate facility in the latter half of the decade so that we can be in a position to construct a full-scale ICF driver early in the next century.

In conclusion, theoretical and experimental results to date are encouraging. It appears that HIF is potentially an attractive commercial energy source; however, significantly larger experiments such as ILSE are required to resolve remaining issues.

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Figure Captions

Figure 1. Target gain as a function of driver energy, focal spot radius (r), and ion range (R). Curves of constant energy yield (Y) are also shown.

Figure 2. Peak power requirements for the gain curves shown in Fig. 1.

Figure 3. Example induction linac concept.

Figure 4. Diagram of the preliminary design of the Induction Linac Systems Experiments (ILSE).

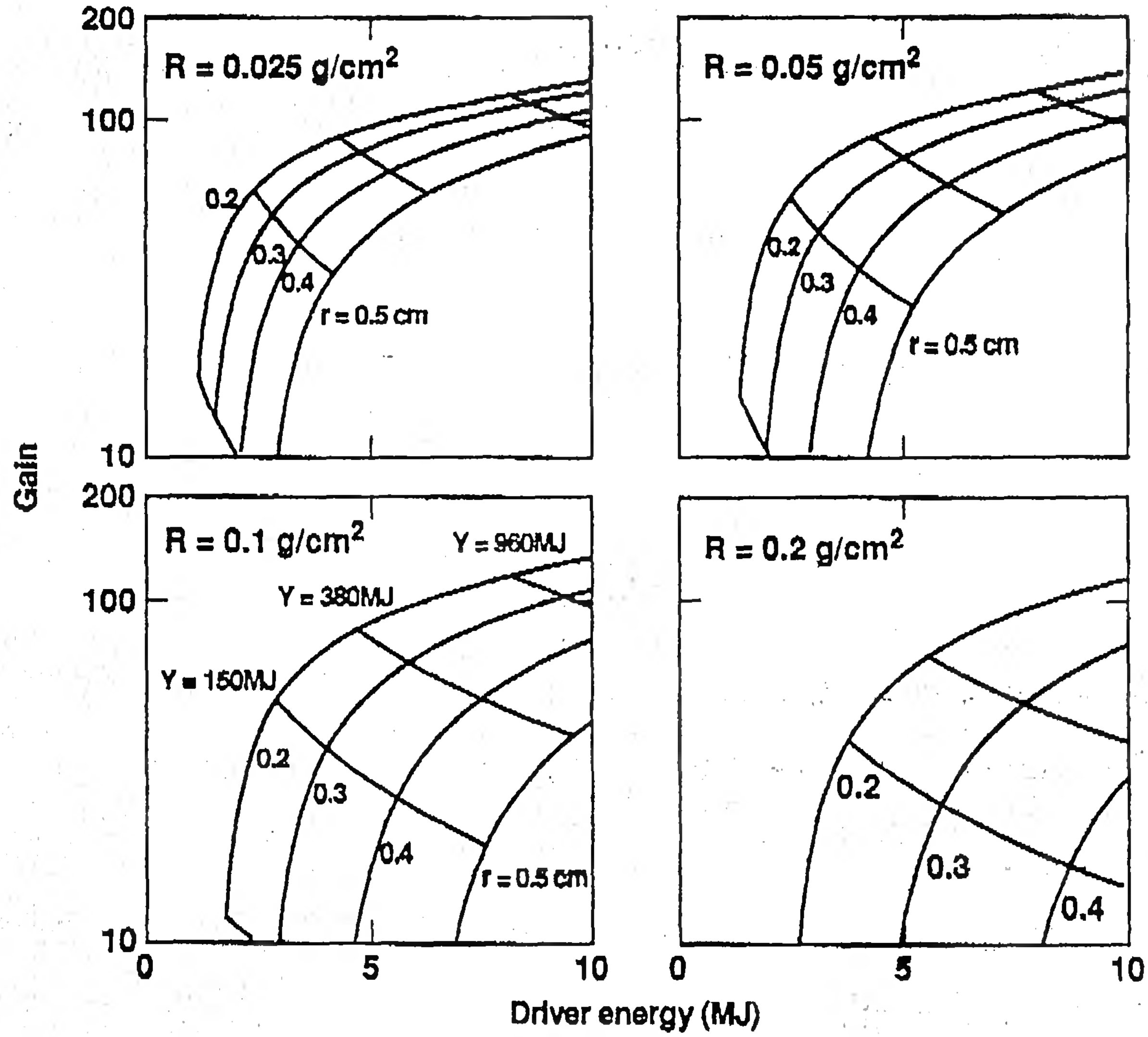
200
100
10
Gain
R = 0.025 g/cm²
0.2
0.3
0.4
r = 0.5 cm
R = 0.05 g/cm²
0.2
0.3
0.4
r = 0.5 cm
200
100
10
R = 0.1 g/cm²
Y = 960MJ
Y = 380MJ
Y = 150MJ
0.2
0.3
0.4
r = 0.5 cm
R = 0.2 g/cm²
0.2
0.3
0.4
0
5
10
0
5
10
Driver energy (MJ)

Figure 1

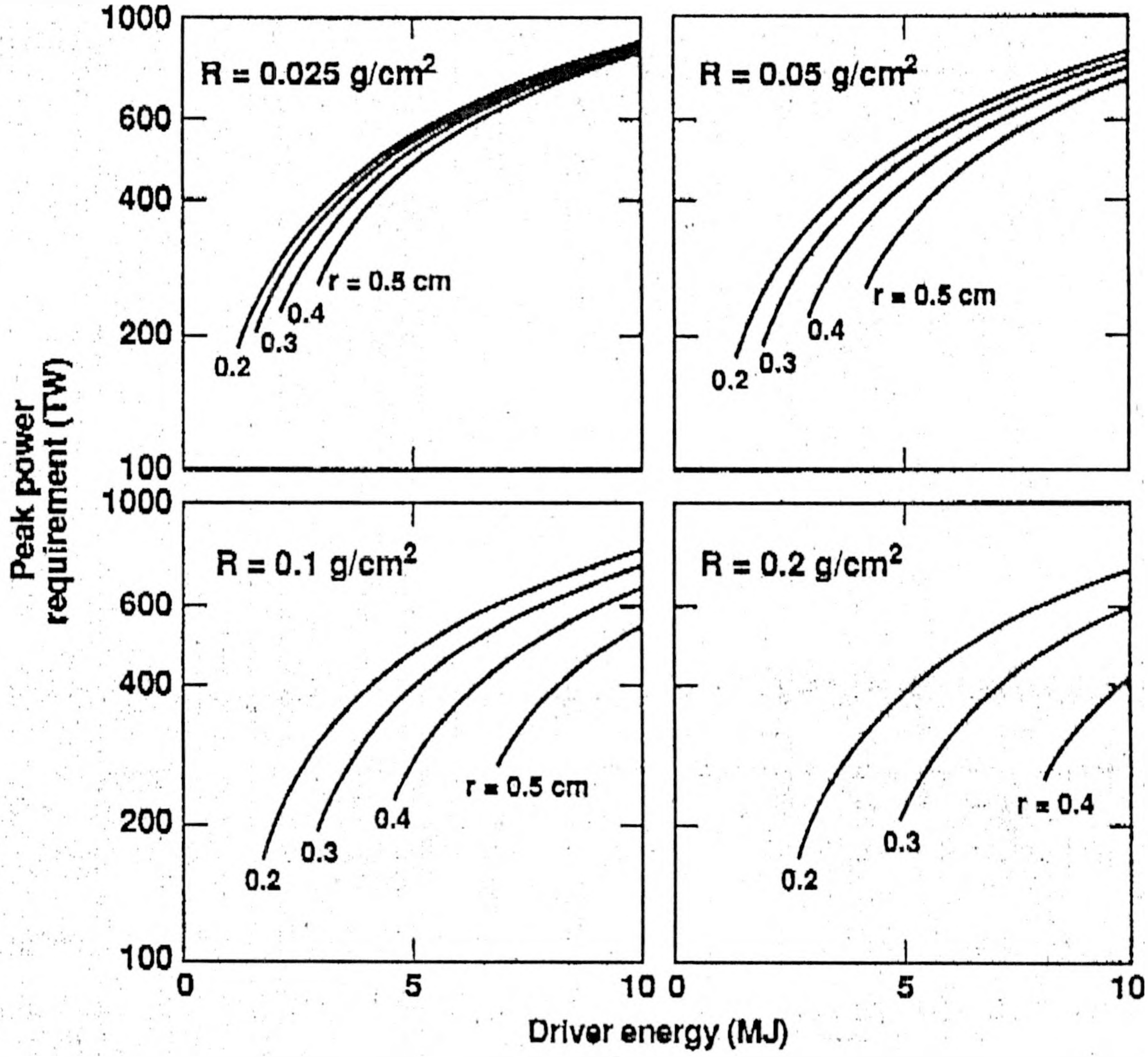
R = 0.025 g/cm²
R = 0.05 g/cm²
R = 0.1 g/cm²
R = 0.2 g/cm²
r = 0.5 cm
0.4
0.3
0.2
r = 0.4
Peak power requirement (TW)
Driver energy (MJ)
1000
600
400
200
100
0
5
10

Figure 2

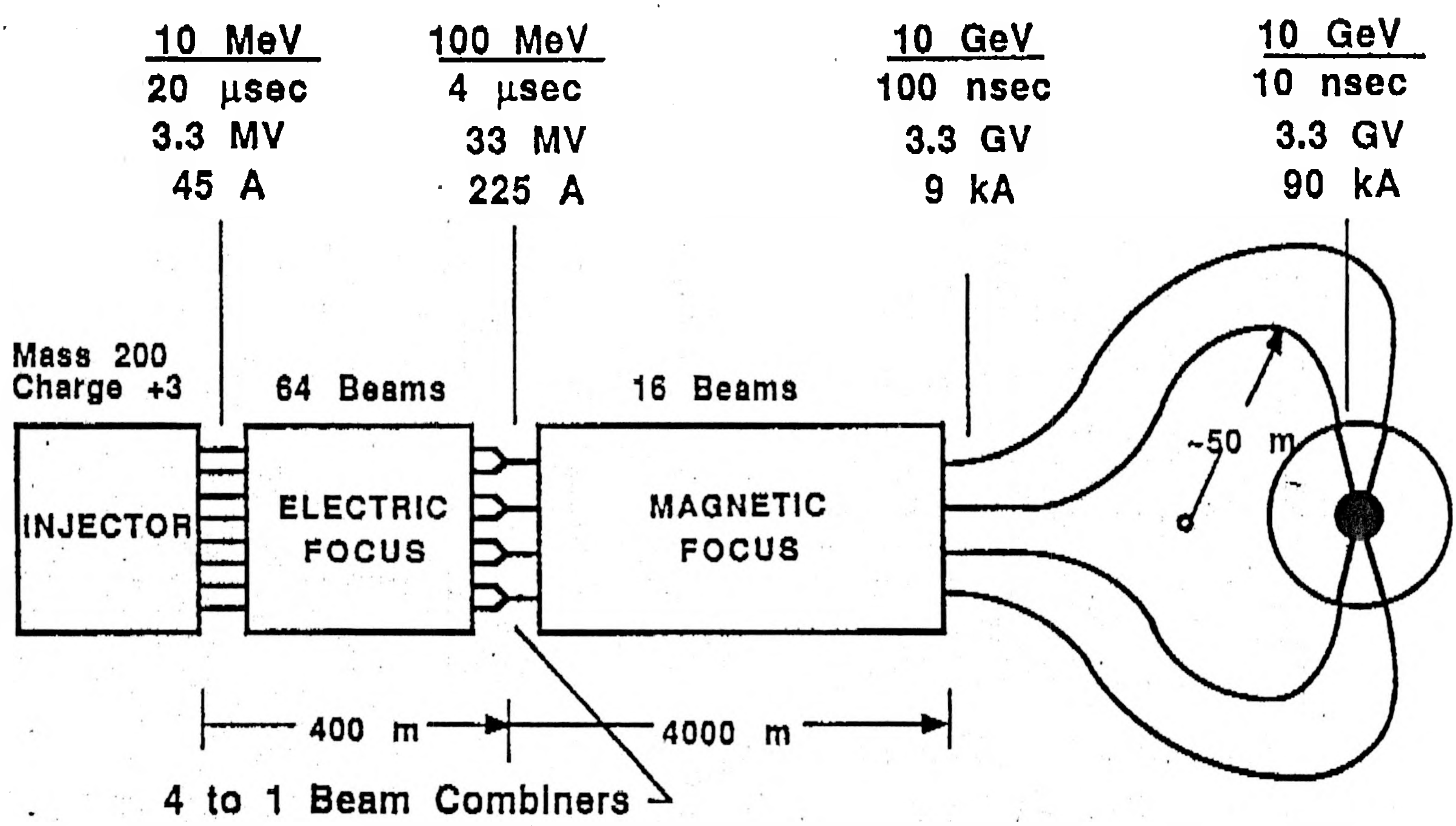
10 MeV
20 µsec
3.3 MV
45 A
100 MeV
4 µsec
33 MV
225 A
10 GeV
100 nsec
3.3 GV
9 kA
10 GeV
10 nsec
3.3 GV
90 kA
Mass 200
Charge +3
64 Beams
16 Beams
INJECTOR
ELECTRIC FOCUS
MAGNETIC FOCUS
~50 m
400 m
4000 m
4 to 1 Beam Combiners

Figure 3

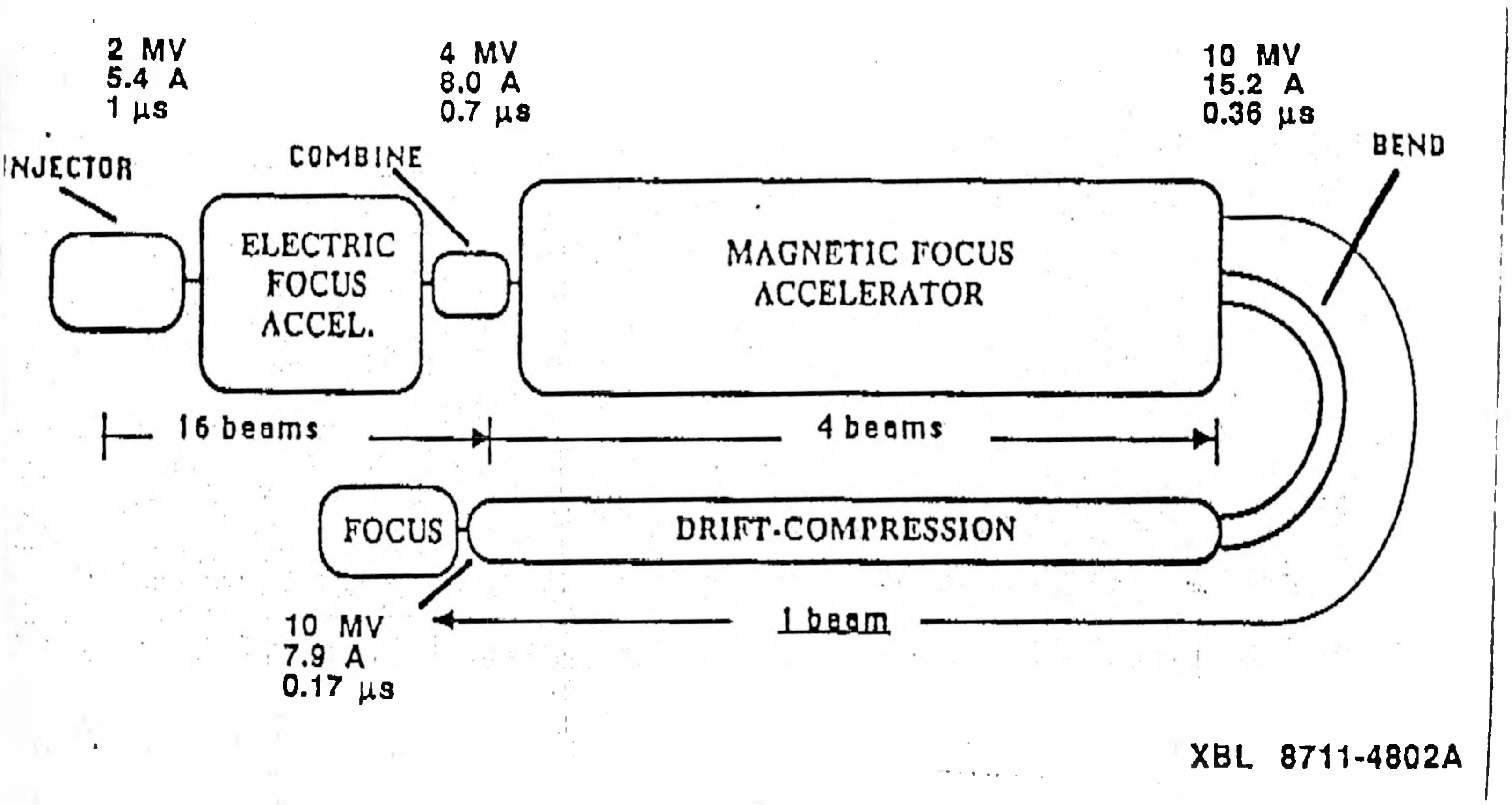
2 MV
5.4 A
1 µs
4 MV
8.0 A
0.7 µs
10 MV
15.2 A
0.36 µs
INJECTOR
COMBINE
BEND
ELECTRIC FOCUS ACCEL.
MAGNETIC FOCUS ACCELERATOR
16 beams
4 beams
FOCUS
DRIFT-COMPRESSION
10 MV
7.9 A
0.17 µs
1 beam
XBL 8711-4802A

Figure 4

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