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October 1988

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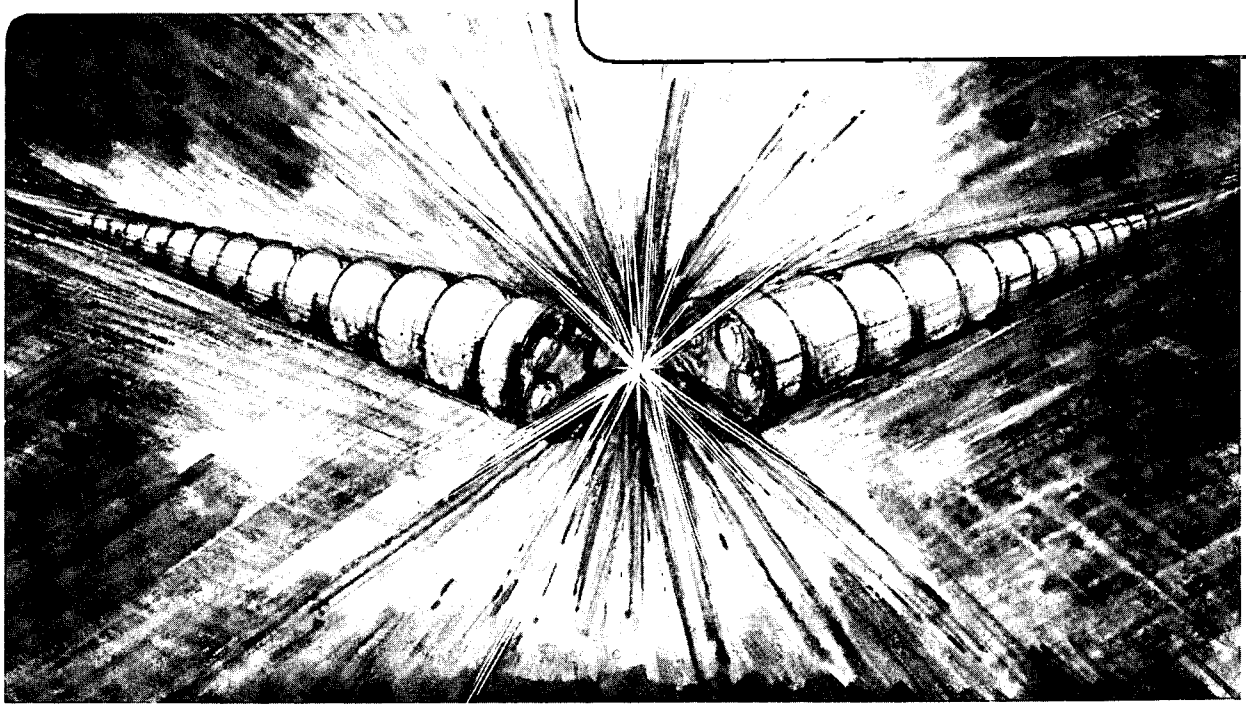

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HEAVY ION INDUCTION LINAC DRIVERS FOR INERTIAL CONFINEMENT FUSION*

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ABSTRACT

Intense beams of high energy heavy ions (e.g., 10 GeV Hg) are an attractive option for an ICF driver because of their favorable energy deposition characteristics. The accelerator systems to produce the beams at the required power level are a development from existing technologies of the induction linac, rf linac/storage ring, and synchrotron. The high repetition rate of the accelerator systems, and the high efficiency which can be realized at high current make this approach especially suitable for commercial ICF. The present report gives a summary of the main features of the induction linac driver system, which is the approach now pursued in the USA. The main subsystems, consisting of injector, multiple beam accelerator at low and high energy, transport and pulse compression lines, and final focus are described. Scale relations are give for the current limits and other features of these subsystems.

INTRODUCTION

Inertial confinement fusion (ICF) requires very high power irradiance and energy desposited on the fusion target which are nearly independent of the driver type. In addition, the depth of deposition must be small (typically - 0.1 g/cm^2 in a stopper material) to produce the high fusion yields required for an economically attractive power plant. The range condition can be met, in principle, by any ion species accelerated sufficiently to match the range-energy relation. The large stopping power for heavy ions in matter allows the use of kinetic energies in the range of 5-20 GeV. Required particle currents are therefore very low compared with those for light ions or photons, but they are high compared with those usually associated with ion acceleration. Two conventional, but potentially high current, accelerator technologies are being explored. These are the rf linac/storage ring system now studied in W. Germany, the USSR and Japan and the induction linac approach of the USA. The induction linac, which is described here, appears to be well matched to the requirements of a power plant driver. It is expected to have high electrical efficiency ($\gtrsim$ 20%), high rep rate (>> 1 Hz) and the very long operating life typical of conventional multigap accelerators.

A typical set of final beam parameters suitable for a power reactor are given in Table 1. It must be emphasized that cost tradeoffs among the many components of a complete power plant allow a broad range of system parameters (such as repetition rate) to be considered, with minor effect on the final cost of electricity (COE). The tabulated driver parameters are matched to a 1000 MWe plant with COE of about 60 mil/kWh, and total direct capital cost of 2.2 G$ (1984$).[1,2] The driver contributes 43% of the cost in this case. While the COE is about double that available from existing, on-line coal or fission plants, it is comparable with the estimates from other fusion system studies (e.g. 59.1 mil/kWh for the 120 MWe STARFIRE tokamak in 1984 dollars using current costing methods). The primary concern at present is not so much the COE but the magnitude of generating capacity and capital investment of the plant. A 500-1000 MWe fusion plant with the stated COE is of considerable interest, but it is difficult to achieve, primarily because of the economy of scale associated with all nuclear electric plants. Both the rf linac/storage ring and the induction linac drivers provide a substantial fraction of total

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direct capital costs of a plant and scale poorly for lower net electric power. Magnetic fusion systems are also very large for reasons of economy of scale as well as physical constraints imposed by the use of low density plasma.

Table 1
Heavy Ion Beam Drivers Parameters

Pulse energy	4.0 MJ
Particle energy	10.0 GeV
Particle type	Hg^{+++} (A = 200)
Peak power	400 TW
Pulse length	10 ns
Rep. rate	10 Hz
Number of beams	16
Net pulse charge	1200 μc
Relativistic factor ($\beta\gamma$)	.332
Emittance (unnormalized)	3×10^{-5} m-r
Momentum width	± .1%
Spot radius	4 mm
Convergence half angle	15 mr
Standoff to final magnet	10 m
Target gain	80
Net electric power	1000 MW

The present report gives a summary of the main feature of the induction linac driver system. The main subsystems, consisting of injector, multiple beam accelerator at low and high energy, transport and pulse compression lines and final focus are described. Scale relations are given for the current limits and other features of these subsystems.

GENERAL FEATURES OF THE INDUCTION LINAC SYSTEM

An induction linac driver is now envisioned as a *multiple beamlet* transport lattice consisting of N closely packed parallel $FODO$ transport channels. Each focusing channel is composed of a periodic system of focusing F and defocusing D quadrupole lenses with drift spaces O between successive lenses. Surrounding the transport structure are massive induction cores of ferromagnetic material and associated pulse circuitry that apply a succession of long duration, high-voltage pulses to the N parallel beamlets. Longitudinal focusing is also achieved through the detailed timing and shape of the accelerating waveforms (with feedback correction of errors). A multiple beam source of heavy ions operates at 2 to 3 MV, producing the net charge per pulse required to achieve the desired pellet gain. Initial current and, therefore, initial pulse length are determined by transport limits at low energy. The use of a large number of electrostatic quadrupole channels ($N \sim 16$ to 64) appears to be the least expensive focal option at low energies (below ~50 MV). This is followed by a lower number of superconducting magnetic channels ($N \sim 4$ to 16) for the rest of the accelerator. Merging of beams may therefore be required at this transition. Furthermore, some splitting of beams may be required after acceleration to stay within current limits in the final focus system.

The rationale for the use of multiple beams is that it increases the net charge that can be accelerated by a given cross section of core at a fixed accelerating gradient. Alternatively, a given amount of charge can be accelerated more rapidly with multiple beams since the pulse length is shortened and a core cross section of specified volt-seconds per metre flux-swing can supply an increased gradient. However, an increase in the number of beamlets increases the cost and dimensions of the transport lattice and also increases the cost of the core for a given volt-second product since a larger core volume is required. For a core of given cross sectional area (α volt-seconds per metre), the volume of ferromagnetic material increases as its inside diameter is increased. Hence, there is a trade-off between transport and acceleration costs with an optimum at some finite number of beamlets. The determination of this optimum configuration is a complex problem depending on projected costs of magnets, core insulators, energy storage, pulsers, and fabrication.

The choice of superconducting magnets for the bulk of the linac is mandated by the requirement of system efficiency; this must be at least ~10% in an ICF driver and ideally ≥ 20% to avoid large circulation power fractions [which result in a high cost of electricity]. Induction cores are most likely to be constructed from thin laminations of amorphous iron, which is the preferred material due to its excellent electrical characteristics and flux-swing. At a projected cost of approximately $8.8/kg (insulated and wound), this is a major cost item for the first 2 to 3 GV of a typical linac. At higher voltage, the

cost of pulses and fabrication of the high gradient column with insulators dominates.

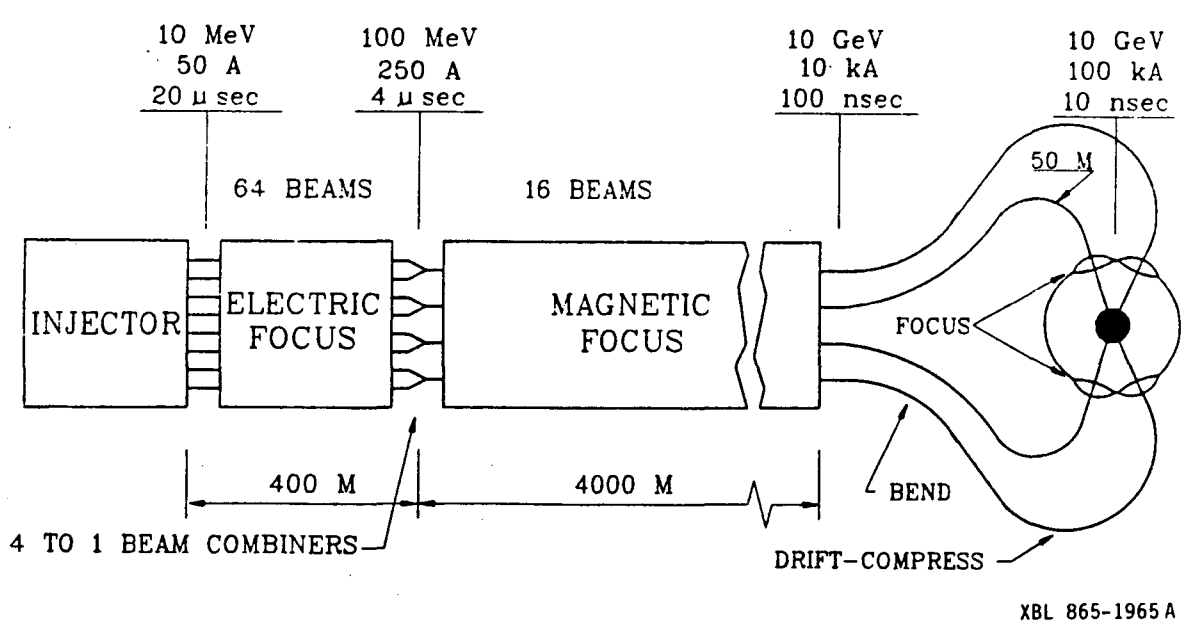
Between the accelerator and the fusion reactor, the beamlets are separated radially in space and, if necessary, split with a kicker and magnetic septum. The drift lines leading to the final focus area are 200 to 600 m long and used for ballistic compression as well as to match the final focus configuration of the reactor. The transport lattice is composed of cold bore superconducting quadrupoles, bends, and possibly higher order elements needed to control momentum dispersion. As the beamlets compress, the transport of the high current becomes increasingly demanding, with the large apertures and the close packing of elements especially pronounced immediately before the final focus train.

The final focus system itself has parameters determined largely by the requirements of spot size on target, reactor size, and the handling of neutron, X-ray, and gas fluxes from the reactor. The final focus magnet train is composed of six or more magnetic quadrupoles of large bore and several weak bends used to remove line-of-sight neutrons. Its total length is 50 to 100 m per beamline.

Transport within the reactor vessel has, in most studies, been assumed to take place in near-vacuum ($P \leq 10^{-4}$ Torr lithium) to avoid disruption by the two-stream instability, or in a high-pressure window ($P \sim 10^{-1}$ to 10 Torr), where the beam is also thought to be stable.[3] The HIBALL reactor specifies $P < 10^{-5}$ Torr lead vapor to avoid stripping of beam ions, which would lead to reduced target irradiance due to the beam's electric field. Unfortunately, several attractive reactor concepts [CASCADE (Ref. 4), HYLIFE (Ref. 5)] have residual gas pressures in the range 10^{-2} to 10^{-3} Torr lithium at reasonable repetition rates; this pressure must be taken into account both for transport in the reactor and in maintaining vacuum in the final focus lines. Recent calculations[6] show that the two-stream mode is benign at these pressures due to the detuning effects of beam convergence.

Major component systems of the driver are respresented in Fig. 1

Fig. 1: INDUCTION LINAC DRIVER (A=200, q=3)



Multiple Beamlet Injector

The ion source produces the required quantity of ions in the desired charge state, and injects them into the low-voltage section of the accelerator at a voltage high enough for efficient transport (~3 MV). The maximum current density available from a planar diode limited by space-charge effects is given by the Child-Langmuir law[7]:

$$j = \frac{4\sqrt{2}}{9}\left(\frac{e}{m_o c^2}\frac{\varepsilon_o}{\mu_o}\frac{q}{A}\right)^{1/2}\frac{V_s^{3/2}}{d^2}$$

$$= 5.46 \times 10^{-8}\left(\frac{q}{A}\frac{V_s^3}{d^4}\right)^{1/2}\ (\mathrm{A/m^2}), \qquad (1)$$

where

V_s = extractor voltage (typically ≈ 100 kV)
d = source extraction gap width
q = ion charge state
m_o = atomic mass unit.
A = mass number

The normalized emittance $\pi\varepsilon_n$, which is the invariant transverse (x,x') phase volume occupied by a beamlet, is determined by the source characteristics and injector optics. For an ideal injector having no aberations, the emittance can be simply related to the source radius a_s and temperature T_s according to

$$\varepsilon_n \equiv 4\beta\gamma[\overline{x^2}\,\overline{x'^2} - (\overline{xx'})^2]^{1/2}$$

$$= 6.55 \times 10^{-5}\left(\frac{T_s}{A}\right)^{1/2} a_s\,(\mathrm{m\cdot rad}), \qquad (2)$$

where T_s is given in electron-volts.

From the basic Eqs. (1) and (2), the source characteristics and some fundamental limits on the parameters of injected heavy-ion beamlets can be inferred. Using large area diodes (~30 cm^2), heavy-ion curents in the range of 1 to 2 amperes with $\varepsilon_n \approx 10^{-6}$ to 10^{-7} m·rad are plausible, although this capability has not yet been realized in practice. Currents of this magnitude are well matched to the low-energy linac transport capability, while the emittance is 1 to 2 orders lower than the limit imposed by final focus. Hence, there is ample latitude for emittance growth during acceleration and the various beam manipulations.

Accelerator System

The acceleration of the ion beam takes place in the drift sections of the FODO lattaice. The linear induction accelerator is equivalent to a transformer with the beam acting as a single-turn secondary. A toroidal core of ferromagnetic material is excited by a primary winding from a high-power pulser/modulator. Combining Faraday's law with Stokes' theorem, the change in the magnetic flux in the core is accompanied by an electric field across an acceleration gap

$$\int E\cdot dl = -\int_s \frac{dB}{dt}\cdot dS\ , \qquad (3)$$

where

E = electric field intensity
dl = elemental path length
B = magnetic induction
dS = elemental portion of the cross section of the core.

Since

$$\int E\cdot dl = V_c\ , \qquad (4)$$

where V_c is the voltage applied to the core, Eq. (3) can be written as

$$\tau V_c = S\Delta B, \qquad (5)$$

where

S = cross-sectional area of the core
= $\pi(r_2^2 - r_1^2)$

ΔB = magnetic flux swing in the core

τ = temporal duration of the pulse including the rise and fall time.

The essential role of the core is to permit a series of high-voltage pulses of up to tens of microseconds duration (instead of nanoseconds) to be applied to the beam at successive acceleration gaps.

The acceleration system consists of a focal subsystem, the magnetic core subsystem as well as the modulator subsystem. Other major subsystems of the accelerator include the heat removal, beam alignment, control and diagnostics, insulation, supporting structure, and safety. A brief discussion of the major components follows.

The lens subsystem consists of electrostatic or magnetic lens sets. In general, the lens configurations may include quadrupoles, sextupoles, higher order multipoles, and solenoids. Magnetic solenoids, in principle, may allow higher current densities per beam than quadrupoles at low ion kinetic energies, but are not under consideration for low-energy transport at present due to a perceived economic disadvantage. At moderate to high beam voltages, the quadrupoles clearly allow a higher current density than the solenoids, and have been used in most conceptual driver designs. The selection of quadrupoles over higher order multipoles is based in part on the linearity of the quadrupole fields, which is desired to conserve emittance. The focusing quadrupoles can be either electrostatic, or magnetic. Due to the factor of velocity in the magnetic force law, magnetic quadrupoles are the choice at high energy and electrostatic quadrupoles at low energy. In a typical conceptual HIF driver, the magnetic focusing system allows a higher beam current density than an electrostatic focusing system for voltages above some 10 to 100 MV. Several types of magnetic focusing quadrupoles can be used; for example, they can be either pulsed or steady devices. The pulsed quadrupoles and water-cooled steady-state electromagnets tend to be too inefficient for extensive use in a power plant. The steady-state magnetic quadrupole transport system has an option of using either permanent and/or superconducting magnets. The achievable pole-tip field strength for permanent magnets is, at the most, ~25% of that for superconducting magnets. This yields a transportable current density through a permanent magnet quadrupole set that is <16% of that using a superconducting magnet quadrupole set of comparable dimensions, and makes them unattractive for most scenarios.

The vacuum required in the beamline is determined by the allowable beam losses from interaction of the beam ions with the residual background gases. The stripping cross sections tend to decrease with the ion kinetic energy, so the vacuum requirement is more severe at the low-voltage end of the accelerator. To keep the total beam losses from interaction with the background gas <5%, the background gas number density must be $<10^7$ to 10^9 particle/cm^3. These densities can be achieved in a well-designed system using turbomolecular or cryogenic pumps.

The accelerator cores can be fabricated from either dielectric or ferromagnetic material. Since the ferromagnetic material has a higher electrical impedance to the driving source than a dielectric, the ferromagnetic cores are preferred. The cores are wound from thin tape, with insulation between the layers to allow for rapid field penetration and to decrease the eddy current losses, which ideally scale as the tape thickness squared divided by resistivity. Several cores can be driven in parallel, utilizing either radial or longitudinal stacking arrangements to increase the acceleration gap voltage.

The power delivered to the cores is increased from that delivered by the primary energy source by a series of pulse energy compression steps. A power supply charges a pulse generator such as a Marx generator or pulse-forming network (which includes a high-power switch). The output from this modulator drives the load current, which is a parallel combination of the beam current (assumed constant during the pulse), and the core currents, which increase during the pulse. A network consisting, for example, of a resistor and capacitor in series can be used to compensate for the increase in the core eddy current such that the total impedance of the core plus compensator is nearly constant.

TRANSPORT

In the absence of focusing, space-charge and emittance effects would cause the ion beam to expand radially. To control the transverse motion of the ions, lenses are used along the length of the driver and subsequent transport lines. For this study, these lenses, which are either electrostatic or magnetic quadrupoles, are arranged in a *FODO* (focusing-drift-defocusing-drift) periodic lattice. A simple set of scale formulas relates the principal parameters of a

magnetic *FODO* lattice (average beam radius $\bar{a}$, field at average beam radius B, and half-period length L) to the principal beam parameters (electric current I, normalized emittance ε_n, and relativistic factor $\beta\gamma$). It is also necessary to specify the fraction of the lattice occupied by quadrupoles η, the phase advance per lattice period or tune σ_0, and the depressed value of the tune σ resulting from the partial cancellation of the focal force by the beam's self-generated field. These relations may be cast into the approximate form[8]

$$I = (2.89\ \mathrm{MA})\left[1 - \left(\frac{\sigma}{\sigma_0}\right)^2\right]$$

$$\times\left[\sigma_0^4 (\beta\gamma)^5 \eta^2 \left(\frac{A}{q}\right)\left(\frac{\epsilon_n}{\sigma}\right)^2 B^2\right]^{1/3}, \qquad (6)$$

$$\bar{a} = (2.32\ \mathrm{m})\left[\left(\frac{\sigma_0}{\eta}\right)\left(\frac{1}{\beta\gamma}\right)\left(\frac{A}{q}\right)\left(\frac{\varepsilon_n}{\sigma}\right)^2\left(\frac{1}{B}\right)\right]^{1/3}, \qquad (7)$$

and

$$L = (2.68\ \mathrm{m})\left[\left(\frac{\sigma_0}{\eta}\right)^2 (\beta\gamma)\left(\frac{A}{q}\right)^2\left(\frac{\varepsilon_n}{\sigma}\right)\left(\frac{1}{B}\right)^2\right]^{1/3}, \qquad (8)$$

where B is given in Tesla, ε_n in metre-radians, and the tunes in radians per period. From Eqs. (6) and (7), the beamlet current density is

$$j = \left(0.171\ \frac{\mathrm{MA}}{\mathrm{m}^2}\right)\left[1 - \left(\frac{\sigma}{\sigma_0}\right)^2\right]$$

$$\times\left[(\sigma_0)^2 \eta^4 (\beta\gamma)^7 \left(\frac{q}{A}\right)\left(\frac{\sigma}{\varepsilon_n}\right)^2 B^4\right]^{1/3}, \qquad (9)$$

From Eq. (6), we anticipated that operation at low values of σ results in high values of transportable current I. However, this strategy also results in large values of the beam radius $\bar{a}$ In general, a cost minimum can be found, typically with σ in the 8- to 24-deg range, depending on the number of beamlets, total charge accelerated, emittance, and, especially, ratio q/A.

Compression

At the end of acceleration, the ion pulse is typically 100 to 400 ns long, which is well matched to the bandwidth of the pulse forming system. Subsequent reduction to the desired 5- to 20-ns length desired for the fusion pellet impolsion dynamics is achieved by the mechanism of drift compression in the transport lines leading to the final focus system. If the initial pulse length (in metres) is l_0 and the drift lines have length z_0, then a head-to-tail velocity tilt (at a fixed time) of approximately

$$\frac{\Delta v}{v} = \frac{l_0}{z_0} \qquad (10)$$

must be applied in the final stages of acceleration. If, for example, l_0 = 20 m and z_0 = 400 m, then the pulse tail must move 5% faster than the head in the transport lines.

Final Focus and Transport within Reactor

To focus the beamlets to a small spot radius (r) at the fusion pellet, a special final focus system is employed. It must convert the matched beam envelope of the transport lines into large radii with appropriate convergence angles at the chamber entrance. The final focus quadrupole triples described by Martin[9] are well-suited as the basic beamline components and not described here.

The minimum number of final beamlines N_0 required to transport the beam ions to the fusion pellet with radius r can be estimated from the consideration of space-charge effects in the reactor chamber. First, consider that the beamlets traverse the chamber in vacuum and that space-charge is the only defocusing effect. Then the beam envelope equation is

$$\frac{d^2a}{ds^2} = \frac{K_0}{a}, \qquad (11)$$

where K_0 is the beamlet perveance

$$K_0 = \frac{2Iqe}{(\beta\gamma)^3 m_0 c^3 A 4\pi\varepsilon_0} \approx \frac{2Iq}{(\beta\gamma)^3 A(31 \times 10^6\ \mathrm{A})}.$$

(12)

The perveance is a dimensionless measure of beamlet current. The minimum beam radius resulting from Eq. (11) is

$$r = a_{lens}\exp\left(-\theta^2/2K_0\right), \tag{13}$$

where θ is the convergence cone half-angle and

$$a_{lens} = L\theta \tag{14}$$

is the beam radius at the final lens. For a power reactor, we expect standoff length $L \approx 5$ to 10 m, $\theta = 10$ to 20 m-rad, and $r = 2$ to 4 mm. To make space-charge negligible, we therefore require, in the absence of neutralization,

$$K_0 \leq (0.1)\theta^2 . \tag{15}$$

This condition leads to unacceptably large numbers of beamlets when the charge state exceeds $q \approx 2$ to 4, so some degree of neutralization must be invoked in general, either from the ionization of residual gas or coinjection of electrons. Recent calculations by Olson[10] indicate that the ion pulse is able to trap an electron cloud of sufficient density and low enough temperature to accomplish this. Thus, we allow $K_0 \leq \theta^2$. The number of beamlets N_0 can be related to the total energy delivered to the pellet W by

$$N_0 = \frac{W}{It_pT_0/qe} = \frac{4We^2q^2}{K_0(\beta\gamma)^5A^2m_0^2c^5 4\pi\varepsilon_0 t_p}$$

$$= (0.138)\left(\frac{q}{A}\right)^2 \frac{W_{MJ}}{K_0(\beta\gamma)^5 t_{ns}}, \tag{16}$$

where final pulse length is t_p (or t_{ns} in nanoseconds). For the typcal case ($q = 3$, $A = 200$, $W_{MJ} = 4$, $t_{ns} = 10$, $K_0 = 2.25 \times 10^{-4}$, $\beta\gamma = 0.33$), we get $N_0 \geq 14.1$, which rounds up to $N_0 = 16$ for symmetric two-sided illumination.

To produce a small radius r on the target, the normalized beamlet emittance ε_n must satisfy

$$\varepsilon_n < \beta\gamma r\theta . \tag{17}$$

Allowance must also be made for the effect on spot size of momentum dispersion, various forms of jitter, and residual space-charge-induced blowup. A final focus system composed of quadrupoles and weak bends has momentum dispersion at the target, which leads in a practical design based on a pair of triplets to increased spot radius

$$\Delta r \approx 8F\theta\frac{\Delta p}{p}, \tag{18}$$

where F is the distance from pellet to the center of the final quadrupole. Without compensation by high order elements, it is desirable to keep the momentum variation $\Delta p/p \leq 10^{-3}$. This is a severe requirement to be met by the accelerator system. Combining Eqs. (15) and (16), the spot radius on target is

$$r = \left[\left(\frac{\varepsilon_n}{\beta\gamma\theta}\right)^2 + 64\left(F\theta\frac{\Delta p}{p}\right)^2\right]^{1/2} . \tag{19}$$

Equations (1) through (19) constitute a brief summary of the physics foundation of drivers for ICF based on linear induction accelerators. Further descriptions can be found in the literature.[11-17]

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