UCRL-JC-134014
PREPRINT

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This paper was prepared for submittal to the
Brookhaven National Laboratory
1999 Particle Accelerator Conference
New York City, New York
March 29 - April 2, 1999

April 9, 1999

Lawrence Livermore National Laboratory

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IMPLICATIONS OF NEW INDUCTION CORE MATERIALS AND COATINGS FOR HIGH POWER INDUCTION ACCELERATORS *

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Abstract

Two recent developments enable induction accelerators to achieve better and more consistent performance with higher efficiency. First, better and more consistent performance is achieved with insulating coatings that allow magnetic cores to be annealed after winding. Second, losses are reduced by a factor of 2-3 with nanocrystalline alloys, while the flux swing is only slightly reduced to 2.0 T compared with 2.3 T with economical amorphous alloys. One metric for selecting between the alloys is the cost-of-electricity, COE. A systems code optimizes an accelerator and compares the COE for higher flux-swing amorphous and higher-efficiency nanocrystalline materials and for several variations in assumptions.

1 INTRODUCTION

Heavy ion inertial fusion (HIF) has attractive prospects for generating electrical power at reasonable cost, with high availability, safety, and low activation.[1,2] These advantages are, in large part, due to the use of thick liquid walls of Flibe, a lithium-containing, low-activation molten salt.[2] The liquid walls shield the vacuum chamber solid walls from neutrons and gamma rays and also generate tritium in a continuously replaced blanket that eliminates the need to shutdown for blanket replacement, thereby providing high availability.

Induction accelerators have been selected by the U.S. HIF program because their high current and high power capability eliminates the need for one or more storage rings to accumulate, then rapidly extract the ion beams. Acceleration occurs from pulsing a voltage across the primary winding of a magnetic core, which then couples through an insulating vacuum barrier to induce a voltage along the beam. By timing the pulsers to reach full amplitude as the beam arrives, the ion beam experiences a succession of D.C. accelerating fields.

Induction cores and pulsers form one of the major cost areas[3] for HIF: to achieve GeV range ion energies and several MJ beam energy per pulse requires of the order of 10^7 kg of magnetic alloy tape. The coupling of the cores to the beams is determined by Faraday's Law, which for our purposes is conveniently expressed as

$$V_c \, \Delta t = A \Delta B$$

where V_c is the voltage induced across an insulated gap for a time Δt, by a core with a cross-sectional area (equivalent solid metal area) A, and a magnetic flux swing ΔB.

Short pulse performance is strongly degraded by interlaminar eddy currents, unless interlaminar insulation is provided. By applying Faraday's law to a single lamination (15-25 μm thick and 0.025-0.2 m wide) with a flux swing of ΔB=2.3 T for durations between ~0.2 μs and 20 μs, we find the average interlaminar voltage can reach ~60 V. The difficulty of insulating cores is increased by the necessity of magnetic annealing (at 300-550° C in ~80A-turns/m magnetic field parallel to the laminations and perpendicular to the core axis) in order to maximize ΔB and minimize the core losses. The insulation must not only withstand the temperature but must not apply significant mechanical stress to the alloy during cool-down, or the performance will be degraded.

We have used mica-paper insulation, co-wound with METGLAS 2605SC,[4] and proprietary inorganic insulating coatings supplied by core manufacturers in the tests described here. After surveying a variety of alloys,[5] we selected two distinct types to examine with a driver and power plant systems code.[3] The alloys are 2605SC from Allied Signal, selected for a larger usable flux swing of 2.3 T and moderately low losses, and the nanocrystalline alloy Finemet FT-1H from Hitachi (VITROPERM 800F from VACUUMSCHMELZE is similar), selected for a moderate flux swing of 2.0 T and very low losses, as shown in Fig. 1 and listed in Table 1. Core losses account for most of the pulsed energy losses in an induction linac, so minimizing the core loss decreases the capital costs of

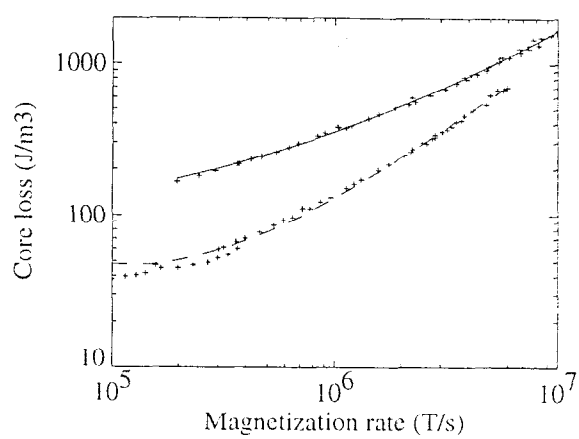

Figure 1: Loss data (plus) and fits for 2605SC amorphous (solid line) and FT-1H nanocrystalline (dashed line) cores.

*Work performed under the auspices of the U.S. Department of Energy under contract No. W-7405-ENG-48 (LLNL) and DE-AC03-76F00098 (LBNL).
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Table 1: Loss coefficients and loss in J/m^3 for two pulse durations 0.42 and 1.0 μs.

Alloy	Loss coef.	Loss(0.42,1.0)
2605SC	81, 193, 119	1044, 577
+bias	89, 213, 132	1433, 782
FT-1H	51, -49, 200	565, 241
+ bias	55, -54, 220	855, 363

pulsers and increases the accelerator efficiency. Core losses are fit by[6]

$$U\left(\frac{J}{m^3}\right) = C_1\left(\frac{\Delta B}{2.5}\right) + C_2\left(\frac{\Delta B}{2.5}\right)\left(\frac{dB}{dt}\right)^{0.5} + C_3\left(\frac{\Delta B}{2.5}\right)^2\left(\frac{dB}{dt}\right)$$

where B is in Tesla, dB/dt is in T/μs, and the coefficients are listed in Table 1.

We use \$5/kg as a cost goal for assembled cores of 2605SC. Based on estimated niobium costs of ~\$30/kg, the 3% Nb in nanocrystalline materials would add ~\$1/kg to the cost, so we assume \$6/kg for assembled nanocrystalline cores.

2 ACCELERATOR SYSTEMS STUDY

The accelerator design parameters are chosen to satisfy constraints imposed by the fusion target design. For this paper, we design to a close-coupled target[7] which minimizes accelerator costs by requiring less beam energy (3.3 MJ) to deliver a yield of 430 MJ vs. 5.9 MJ to deliver a yield of ~400 MJ with a previous distributed radiator design.[8] The disadvantage of using the close coupled target is that each elliptical beamlet must be focused to an area with an equivalent circular spot radius of 1.7 mm, as compared with 2.7 mm for the distributed radiator target. The close-coupled target calculation used a lead ion beam, but the systems code finds lower costs with lower mass ions.

Systems studies have shown that lower M/Q ions with their lower ion energy will shorten the accelerator and reduce costs.[9] The target performance is essentially invariant to the beam-ion mass, if the ion energy is adjusted to keep the range (stopping distance) constant, and the pulse duration and beam energy (MJ) remain the same. The optimum is below M/Q=50, but the higher beam current requires better space-charge neutralization[10] in order to focus the beam to the 1.7 mm spot radius required on target. Kr^+ was chosen as a compromise: it is near the minimum cost for present concepts of induction linacs, without requiring the maximum neutralization. The target requirements are met with a 1.3 GeV Kr^+ main pulse ion beam to deliver 2.8 MJ in 8 ns and a 0.85 GeV Kr^+ prepulse ion beam to deliver 0.5 MJ in 30 ns. A lower ion mass could further reduce the costs by ~20%.

The accelerator architecture is simplified by transitioning to magnetic quadrupole focusing at a low energy of 1.6 MeV, and omitting beam combining.

Several optimizations by the systems code for 2605SC are shown in Fig. 2, where the cost multiplier is plotted vs. the reference value multiplier. The nominal energy at which the beam radius becomes fixed at 0.01 m, rather than continuing to decrease with energy, is 500 MeV. Allowing the radius to decrease further reduces costs by decreasing the core volume at fixed area, but magnetic quadrupole construction and beam alignment become more difficult. Even the minimum radius of 0.01 m, assumed here, is quite challenging. Increasing the number of beams to beyond 140 (30 in the prepulse and 110 in the main beam) does not decrease costs because not only is the minimum beam radius fixed, but the beam-to-wall distance, and the thickness of cryo-insulation are also fixed. The cost vs. initial pulse duration apparently optimizes near 24 μs, but beyond 20 μs, the spot size on target exceeds the required 1.7 mm, so 20 μs is the usable optimum. (The beam duration is reduced to 200 ns as rapidly as possible after injection. It then remains constant for the rest of the accelerator, where the core pulse duration has a minimum of 420 ns.) Finally, increasing the quadrupole magnetic field decreases the core inner radii, until the superconducting cable thickness builds up faster than the beamlet radius decreases.

The current per beamlet of the prepulse (main pulse) is 1.0 A at the injector, 96 (97) at the end of the accelerator, and 650 (2450) at the target. The prepulse beam is separated from the main pulse beams at 0.85 GeV. The main pulse beams are then accelerated further to 1.30 GeV. A velocity tilt is applied to the beams near the end of the accelerator to compress them to 30 (8) ns over a drift compression distance of a few hundred meters. During drift compression, the beams are also split into 2 groups that impinge on the target from opposite directions.

The core geometry is optimized, subject to constraints on the axial voltage gradient. The core costs scale with the core mass or metal volume V, which is given by

$$V = \pi\, \varepsilon_{PF} L\, \Delta R\, (2R_i + \Delta R)$$

where ε_{PF} is the packing fraction, L is the length, R_i the inner radius, and ΔR the radial build up. Since the cross-sectional area $A = \varepsilon_{PF}\, L\, \Delta R$ must satisfy Faraday's Law, the acceleration voltage V_C from a core is

$$V_C = (\varepsilon_{PF}\, L\, \Delta R)\, \Delta B/\Delta t$$

The core efficiency η_c in terms of core loss is

$$\eta_c = (I\, V_C\, \Delta t)/(I\, V_C\, \Delta t + \mathrm{Loss}(\Delta B, \Delta t)\, V)$$
$$= (I\, \Delta B) / (I\, \Delta B + \mathrm{Loss}\, \pi\, (2R_i + \Delta R)),$$

so high beam current and low losses increase efficiency. The pulser efficiency η_p is taken as 75% or 50%.

Our results, comparing 2605SC with nanocrystalline materials, are shown in Table 2. We find that, as expected for its higher flux swing, 2605SC requires less mass of cores, and has lower direct costs; whereas nanocrystalline materials have lower losses for higher efficiency and reduced circulating power in the driver. These effects

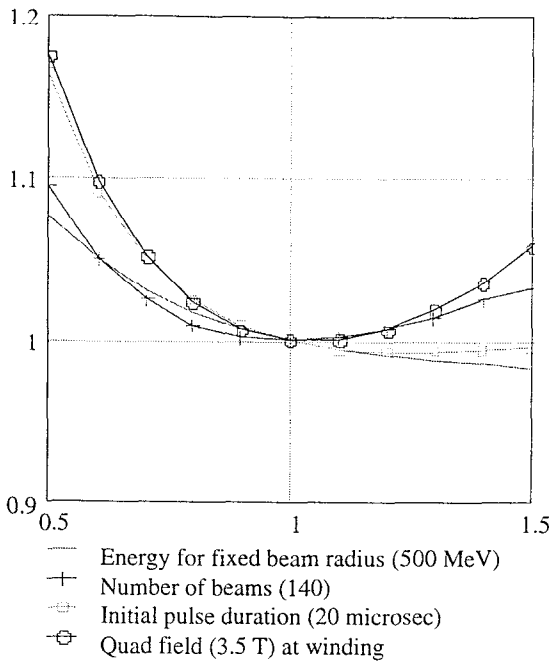

Figure 2: Accelerator optimizations

partially cancel, leaving 2605SC with a lower cost-of-electricity, COE, by 3.3%. Increasing the flux swing slightly by back-biasing the cores reduces the COE for 2605SC by 0.4%, and for FT-1H by 1.1%, resulting in 2605SC still 2.6% lower. The COE, quoted in Table 2, are relatively low for a 1 GWe fusion plant. Economies of scale reduce the COE to 3.3 cents/kWh for a 2 GWe plant. These are competitive with other sources of power except natural gas without carbon sequestration.

Three design choices lead to the low costs with an increase in the technical risk: (1) The low-mass ion Kr+ requires a lower energy, higher current accelerator, only 1000 m long; but requires 99% beam neutralization at final focus. (2) The close-coupled target has lower beam energy requirements, but a demandingly small focus radius of 1.7 mm and tighter tolerances on beam-target aiming. Focus and neutralization are costed at $8 M.[3] Target injection experiments to date show an ability to determine target position in the target chamber to within 0.22 mm.[11] (3) The beam radius is only 0.01 m in the accelerator. The minimum beam radius is determined by alignment accuracy, cryo-insulation thickness, quadrupole magnet design (typically 0.05 m radius), and other issues.

The direct costs for the driver are $600 M, compared with $1400 M for a 5.9 MJ Pb^+ accelerator.[3] This shows the high cost-leverage of developing effective beam-neutralization techniques combined with a precise final focus and target injection and steering techniques.

The sensitivity of the COE to our assumptions about the core and pulser parameters is listed in Table 3. Engineering studies, by industry, of thyratrons and capacitors concluded that redesign for quantity production could reduce costs by factors of several. Pulser costs then drop from $10/J [3] to $2/J, both values are listed in Table 3. With these changes, the pulsed power accounted for only

Table 2: Systems code results, second value is for back-biased core.

	2605SC	**FT-1H**
Flux swing, Tesla	2.3, 2.43	2.0, 2.15
Core mass 10^6 kg	15.5, 14.4	18.5, 16.9
Ave. core eff., %	50.4, 47.9	57.5, 54.4
Accelerator direct costs, $M	612, 602	669, 650
COE, cents/kWh	4.55, 4.53	4.70, 4.65

Table 3: Sensitivity of COE (Cents/kWh) to core alloy, pulsed power efficiency η_p and cost C, and back-biasing .

	COE	% Change
Base case 2605SC, η_p=75%, C=$2/J	4.55	0.0
Lower pulser efficiency, η_p =50%	4.62	+1.5
Higher pulser cost, C=$10/J	4.79	+5.3
Both, η_p =50%, C=$10/J	4.99	+9.7
Base case, back-biased 2605SC	4.53	-0.4
Use Finemet FT-1H @$6/kg	4.70	+3.3
Use FT-1H with η_p =50% and C=$10/J	5.08	+11.6
Finemet FT-1H @ $5/kg	4.62	+1.5
Back-bias FT-1H @$5/kg	4.58	+0.7

12% of the costs in the magnetic focus portion of the accelerator, down from 40% in earlier studies.[3]

Core efficiency becomes more important with more expensive and lower efficiency pulsers, as shown in Table 3. The lower flux swing of the nanocrystalline material is as important as its higher price in increasing the COE: at core costs of $5/kg, the COE still increases by 1.5%. Back-biasing either material results in a slight decrease in the COE, assuming that the pulser cost increase is only due to increased energy storage. Because the COE difference is small between amorphous and nanocrystalline materials, and because their magnetic performance and impedance variations are distinctly different, these other characteristics may also play a significant role in the selection decision.

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