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APPLICATION OF INTENSE RELATIVISTIC ELECTRON BEAMS TO HEATING AND CONFINEMENT OF TOROIDAL PLASMA EXPERIMENTS

by

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ABSTRACT

Because of recently reported successes in the use of intense relativistic electron beams for heating toroidal plasmas, their application in Los Alamos Scientific Laboratory toroidal z-pinch experiments (ZT-40 and ZT-S) is examined. The conclusion is reached that a modestly sized beam ($\sim k\$150$) could be useful for heating an experiment with the size of ZT-S, but that it would require a much larger beam to significantly effect the bulk temperature of larger experiments, such as ZT-40.

I. INTRODUCTION

Intense relativistic electron beams (REB) have been used with some success to create, heat, and confine toroidal plasma configurations.¹⁻³ Experiments to inject an intense REB into magnetic fields that trap the beam in a toroidal configuration have also been successfully performed at several laboratories.¹⁻⁸ In some of these experiments a toroidal-plasma configuration was present, while in others the beam was injected into neutral gas or vacuum.

Intense REB generators have also been suggested as a cost-effective alternative for toroidal-current (poloidal field) generation and plasma heating in a recent spheromak proposal.⁹ Injection of an REB into a toroidal plasma induces return currents in the plasma, which then resistively decay, and thereby ohmically heat the plasma. In addition, the back emf acting on the beam current eventually brings the beam electrons to rest, with the resultant loss of beam energy partitioned between plasma heating and poloidal magnetic-field generation. This partitioning is effected by the initial

current in the toroidal configuration because of its interaction with the induced beam current. These effects modify the confinement physics of toroidal z-pinchs, and this note is intended to indicate to what extent a modest REB could be applied in the CTR-Division reversed-field toroidal-pinch program.

II. BEAM ENERGY PARTITIONING

If the beam does not scatter or directly interact with the plasma by means of the two-stream instability, one can quantify the loss of beam energy as it is stopped by the back emf, and thus arrive at an expression for the energy that goes into joule heating.

At any time the induced loop voltage is $V = L dI/dt = 2\pi RE_0(t)$, where L is the inductance of the beam-plasma torus of radius R , and I is the net current $I = I_{\text{plasma}} + I_{\text{beam}}$. The parallel electric field, E_0 , is unchanged by the transformation to the frame moving with the beam electrons, and, therefore, is related to the rate of change of the momentum by $E_0 = e^{-1} dp/dt$, where e is the electronic charge, and $p = \gamma\beta mc$ is the electron momentum. Here, m is the electron mass, βc is the beam electron velocity, and γmc^2 is the beam electron energy. These equations can be integrated to find the increment in net current, ΔI , as the beam momentum is lost. Assuming a practical situation in which the final momentum is negligible compared to the initial momentum gives $\Delta I \approx 8.5 \gamma\beta \mu_0 R/L$ (kA).

The change in magnetic energy, ΔW_B , during this process is just $\Delta W_B = LI_0 (\Delta I) + \frac{1}{2}L(\Delta I)^2$, where I_0 is the initial current in the plasma. From these expressions the amount of the initial beam energy that goes into the magnetic field can be calculated.

$$\frac{\Delta W_B}{W_B} \approx \frac{\gamma + 1}{\gamma} \frac{I_0}{I_B} + \beta(\gamma + 1) \frac{\mu_0}{L} \frac{4.5 \text{kA}}{I_B}, \quad (1)$$

where I_B is the "wrapped-up" beam current, and W_B is the beam energy. The remainder of the beam energy goes into Joule heating. (Note that for the large initial currents, I_0 , in ZT-40 and ZT-S, the first term in Eq. (1) dominates

for low- γ beams.) This result shows that the fraction of beam energy going into magnetic fields is inversely proportional to the injected current, and consequently efficient heating favors low-impedance, high-current beam generators; while poloidal field generation is best accomplished by high-voltage (γ), high-impedance generators.

III. COMPARISON OF EXPERIMENTAL RESULTS

A number of schemes for injection and trapping of beams in toroidal configurations have been successfully employed. The results of several past experiments were compared with the proposed S-1 spheromak injection startup, and with experiments that might be performed on the ZT-S or ZT-40 toroidal pinches using a relatively modest beam generator. The injection experiments compared included the SPAC-V and SPAC upgrade experiments at Nagoya, which incorporate a foiless-diode injector,¹⁻³ experiments at Physics International using curvature drift injection,⁴ and experiments at Cornell using foil-anode magnetic deflection⁵⁻⁷ or tangential injectors.⁸ The comparisons of the experiments are presented in Tables I and II, and the proposed S-1 Spheromak and ZT toroidal-pinch experiments are compared in Table III.

IV. SCALING AND PROPOSED EXPERIMENTS

The bare cost of this high-voltage technology is estimated to be in the range of a few tens-of-dollars per Joule of delivered beam energy. The price of commercially produced generators reflects this scaling as shown in Fig. 1. The calculated heating efficiencies for the small generator (~150 k\$) assumed for the ZT comparison are rather good for ZT-S with its low plasma current, but poor for ZT-40 where much work must be done to establish the return current in the presence of the large plasma current. Thus, although beam heating appears to be attractive for a small experiment, such as ZT-S, the application to large experiments would require much more energetic beams. Even if ZT-40 were heated in a different mode (e-beam pre-heat, or two-stream heating) to improve the transfer efficiency, the large volume of plasma to be heated would restrict the

TABLE I

RESULTS OF REB INJECTION EXPERIMENTS
AT PHYSICS INTERNATIONAL AND CORNELL UNIVERSITY

		PHYSICS <u>INTERNATIONAL</u>	CORNELL <u>RACETRACK</u> <u>CHRISTA</u>		
Major Radius	R_o (cm)	20	135	135	12
Wall Radius	a_w (cm)	10	6.5	6.5	30
Toroidal Field	B_t (kG)	1.5-4	3.8	3.8	1.0
Vertical Field	B_v (kG)	0-.8	0		0.4
Plasma Radius	a_p (cm)		3.8	7	
Plasma Density	n_p (cm ⁻³)		10 ¹³		
Gas Pressure	P (Torr)	~10 ³			0.4
Plasma Temperature	T_e (eV)		5	15-20	
Initial Plasma Current	I_o (kA)	0	0	0.5	0
Beam Voltage	V_B (kV)	1750	400	400	2500
Electron Energy/mc ²	γ	4.4	1.78	1.78	5.9
v/c	β	0.98	0.83	0.83	0.99
Injected Current	I_{inj} (kA)	10	24	20	30
Beam Radius	r_B (cm)				
Pulse Length	τ (ns)	40	50	50	80
Wrap-up Factor	N	9.4	1.5	1.5	31.5
Circulating Current	I_B (kA)	94	35	30	945
Injected Energy	W_B (kJ)	0.7	0.5	0.4	6.0
Current Increase Observed	ΔI (kA)		5.6		30
Calculated Current					
Increase	ΔI (kA)	40-150	6-50		30
% Beam Heating Calculated	$\Delta W_L / E_B$		88%		98%
Temperature Increase	ΔT_e (eV)		100	~40	60
Lifetimes Observed			0.3 μ s	>100 μ s	

temperature increase to less than 80 eV for the beam generator assumed in this study.

TABLE II
RESULTS OF REB INJECTION EXPERIMENTS
AT NAGOYA

		<u>SPAC-V</u>	<u>SPAC UPGRADE</u>
Major Radius	R_o (cm)	15	
Wall Radius	a_w (cm)	35	
Toroidal Field	B_t (kG)	3.7	30
Vertical Field	B_v (kG)	.56	
Plasma Radius	a_p (cm)	5	
Plasma Density	n_p (cm ⁻³)	7×10^{13}	
Plasma Temperature	T_e (eV)	<10	
Initial Plasma Current	I_o (kA)	0	
Beam Voltage	V_B (kV)	500	1800
Electron Energy/mc ²	γ	1.98	4.5
v/c	β	0.86	0.98
Injected Current	I_{inj} (kA)	80	400
Beam Radius	r_B (cm)	3	
Pulse Length	τ (ns)	70	65
Wrap-up Factor	N	19.2	
Circulating Current	I_B (kA)	1530	
Injected Energy	W_B (kJ)	2.6	40
Current Increase Observed	ΔI (kA)	28	
Calculated Current Increase	ΔI (kA)	6-58	
% Beam Heating Calculated	$\Delta W_{\perp} / E_B$	98%	
Temperature Increase	ΔT_e (eV)	1.5×10^3	
Lifetimes Observed		1.0 ms	

This does not mean, however, that a modest REB could not be employed on ZT-40 to some advantage by heating or otherwise modifying the parameters of localized regions (such as a thin outer layer) of the pinch. The physics issues involved in the use of REB's in this manner are more complicated than the simple estimates given in this note, and should be investigated.

Fig. 1.
Intense relativistic electron beam generator commercial prices in 1979. Prices for comparable generators in 1972 are shown as open circles to indicate the inflationary trend.

TABLE III
PROPOSED REB INJECTION EXPERIMENTS

		<u>S-1 Hot</u>	<u>S-1 Cold</u>	<u>ZT-S</u>	<u>7T-40</u>
Major Radius	R_O (cm)	50	50	40	114
Wall Radius	a_w (cm)	29	29	7.7	20
Toroidal Field	B_t (kG)	36	3	15	25
Vertical Field	B_v (kG)	0	0	0	0
Plasma Radius	a_p (cm)	25	25	5	13
Plasma Density	n_p (cm ⁻³)	3×10^{13}	3×10^{13}	2×10^{15}	10^{15}
Plasma Temperature	T_e (eV)	300	10	25	200
Initial Plasma Current	I_O (kA)	400	0	65	440
Beam Voltage	V_B (kA)	700	700	500	500
Electron Energy/mc ²	γ	2.37	2.37	1.98	1.98
v/c	β	0.91	0.91	0.86	0.86
Injected Current	I_{inj} (kA)	160	160	250	250
Beam Radius	r_B (cm)	5	5	2.5	5
Pulse Length	τ (ns)	65	65	70	70
Wrap-up Factor	N	5.6	5.6	7.2	2.9
Circulating Current	I_B (kA)	900	900	1800	733
Injected Energy	W_B (kJ)	7.28	7.28	5	5
Calculated Current Increase	ΔI (kA)	9-46	9-46	10-22	9-22
% Beam Heating Calculated	$\Delta W_l / E_B$	33%	96%	94%	9%
Temperature Increase	ΔT_e (eV)	400	1.2×10^3	740	7

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