Fueling of Tokamaks With Accelerated FRC's

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Introduction

- Tokamaks require deep fuelling primarily to replenish burned fuel while maintaining high central densities for high burn rates.
- Deep fuelling may also be useful to maintain peaked density profiles for high confinement quality.
- Injection of FRC's is a promising approach to deep fuelling.
- The TRAP experiment[1,2] has already demonstrated, on a single shot basis, FRC formation and acceleration sufficient to penetrate to the interior of JET and provide a 5% increase in particle inventory.

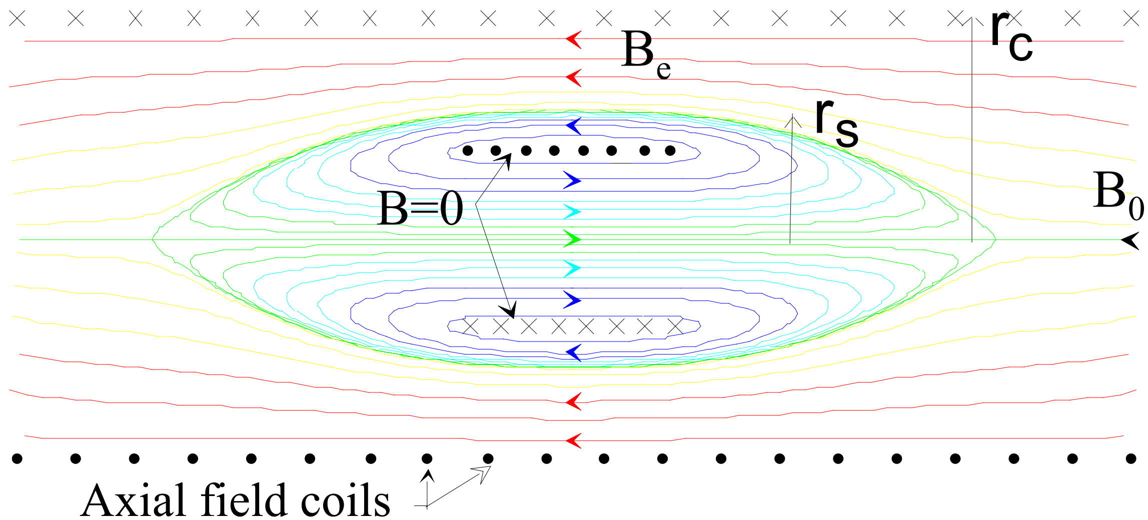
1. A.L. Hoffman et al, to be published in Fusion Technology

2. J. T. Slough et al, Physics of Plasmas 6 253 (1999)

Properties of FRC's

$$\langle \beta \rangle = 1 - \frac{1}{2} x_s^2$$

$$x_s = \frac{r_s}{r_c}$$

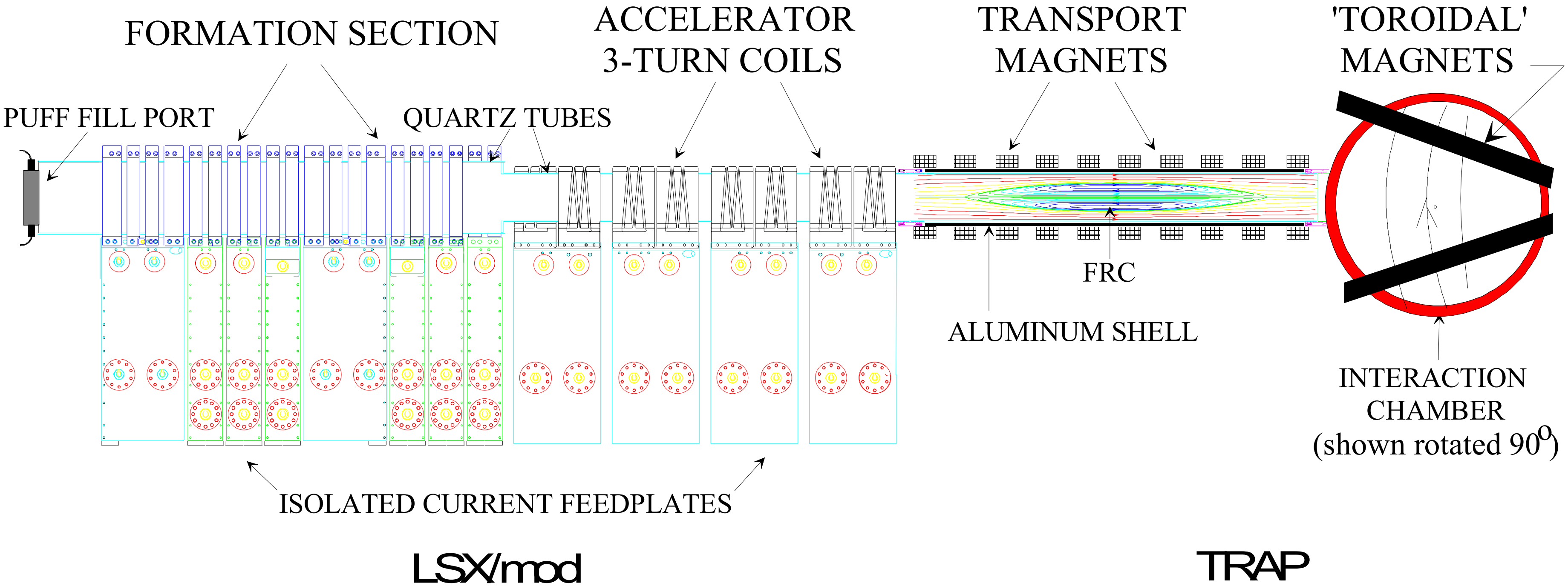


- FRC's are Compact Toroids with no toroidal field.
- $\beta \geq 50\%$ for equilibrium, enabling energy-efficient injection of particles.
- They are formed and accelerated inductively, so that impurity content is very low (< 1% C and O and no measurable heavy metal).

Required Fuelling Rates

- JET requires central particle (total ions) deposition rate of about 1×10^{21} ions/sec to maintain $\bar{n}_e = 0.8n_{GW}$, with no gas puffing.
- Scaling to ITER gives a required central fuelling rate of $N_{D+T} < 5\times10^{21}$, which is consistent with requirements of 1.5GW fusion power with ≈ 20% burnup rate.
- Required repetition frequency given by $N = N_{CT}f_{inj}$, assuming 100% deposition efficiency, where N_{CT} is the particle content of a single injected FRC.
- TRAP achieved $N_{CT} = 1.8\times10^{20}$ particles (0.6mg), $\Rightarrow f_{inj} \approx 5$ Hz for JET.
- Present TdeV spheromak injector is about $N_{CT} \approx 2\times10^{19}$.

TRAP Experiment



Typical TRAP Parameters Experimentally demonstrated (1996)

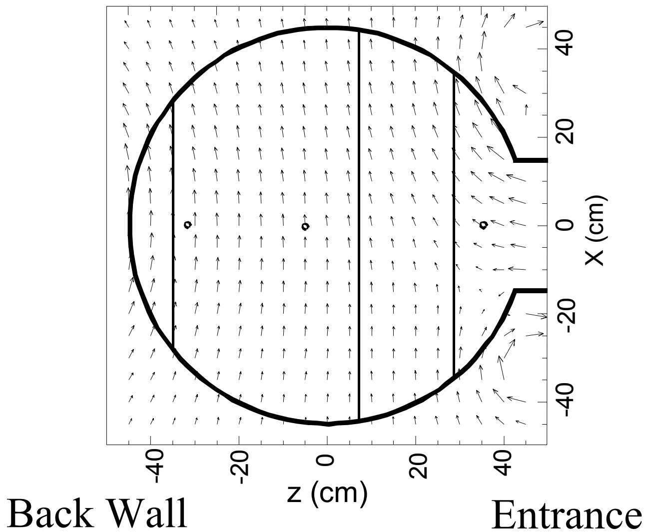
- FRC Density ~ 1.5×10^{22} m^{-3} Temperature ~ 30 eV
- FRC Flux ~ 5 mWb   (s ~ 10)
- FRC Mass ~ 0.6 mg   N ~ 2×10^{20}
- Acceleration Field ~ 0.7 T   (Initially 1.0 T)
- Final Velocity ~ 2×10^{5} m/sec   (200 km/sec)

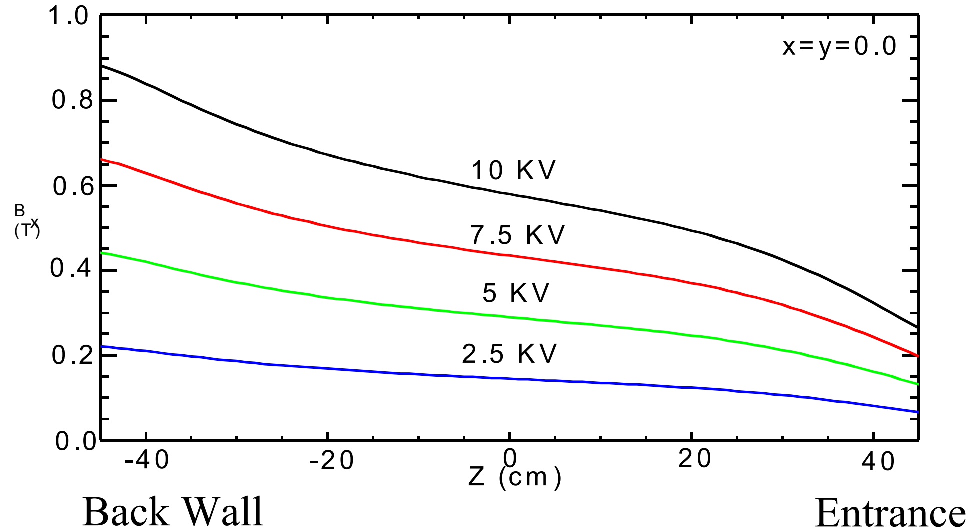
Fueling Parameters For JET & ITER

	ITER(95)	JET	TRAP results to date:	TRAP (var. voltage accel.)
			20 mTorr	20 mTorr
Toroidal field on axis	5.68 T	4.0 T	0.8 T	-
$\rho v^2/2$ (MJ/m^3) Required Available	6.4	3.2	0.13 1.0	3.5
$\langle n \rangle$ (m^{-3}) injected FRC	4.0×10^{22}	3.0×10^{22}	1.5×10^{22}	2.7×10^{22}
penetration velocity (km/s)	280	250	200	280
injected mass	1 mg D-T	0.6 mg D	0.6 mg D	0.55 mg D
injected particles	2.4×10^{20}	1.8×10^{20}	1.8×10^{20}	1.6×10^{20}
½ Mv^2	40 kJ	20 kJ	12 kJ	22 kJ
% inventory	0.3%	10%	-	-

Up to 5×10^{21} particles/sec. must be injected into ITER depending on replacement of burn-up or total particle loss.
This requires a rep. rate of up to 20 Hz.

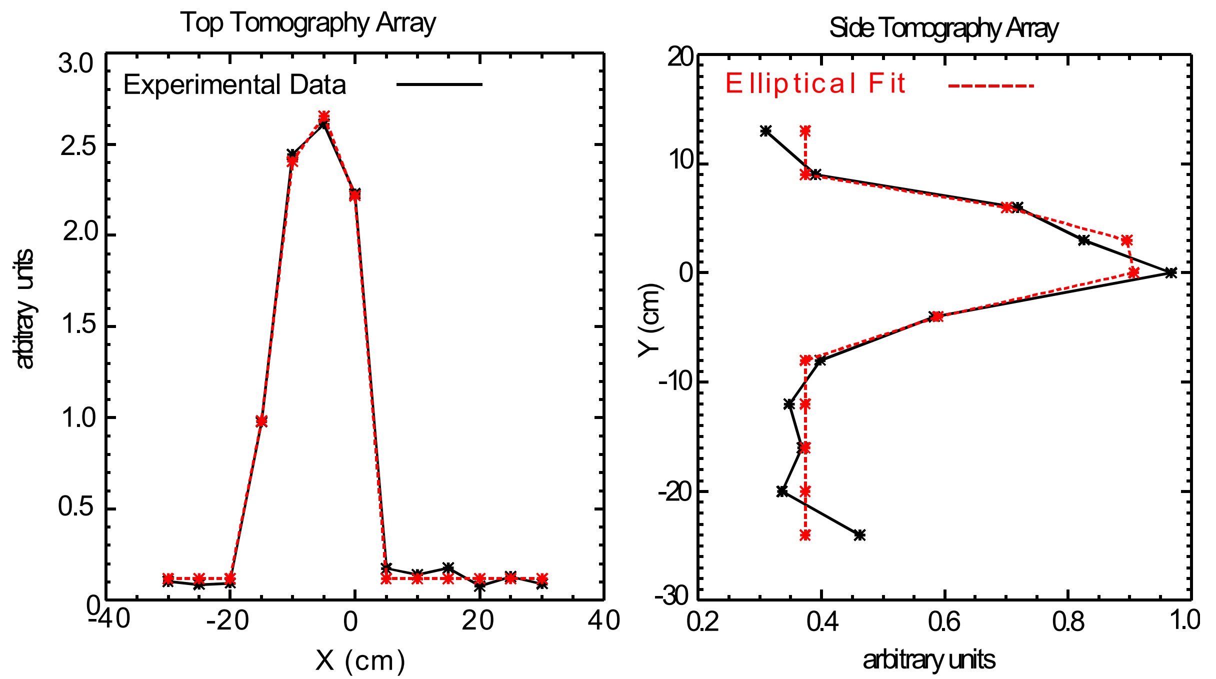
Interaction Geometry and Magnetic Fields





- The combined FRC guide field and 'Tokamak' cross field directs open field line plasma to the right, but pushes the FRC to the left.
- This 'tilt-like' behavior could be useful in helping overly robust FRCs dump their contents.

Tomographic Imaging Data ($B_t = 2$ kG)



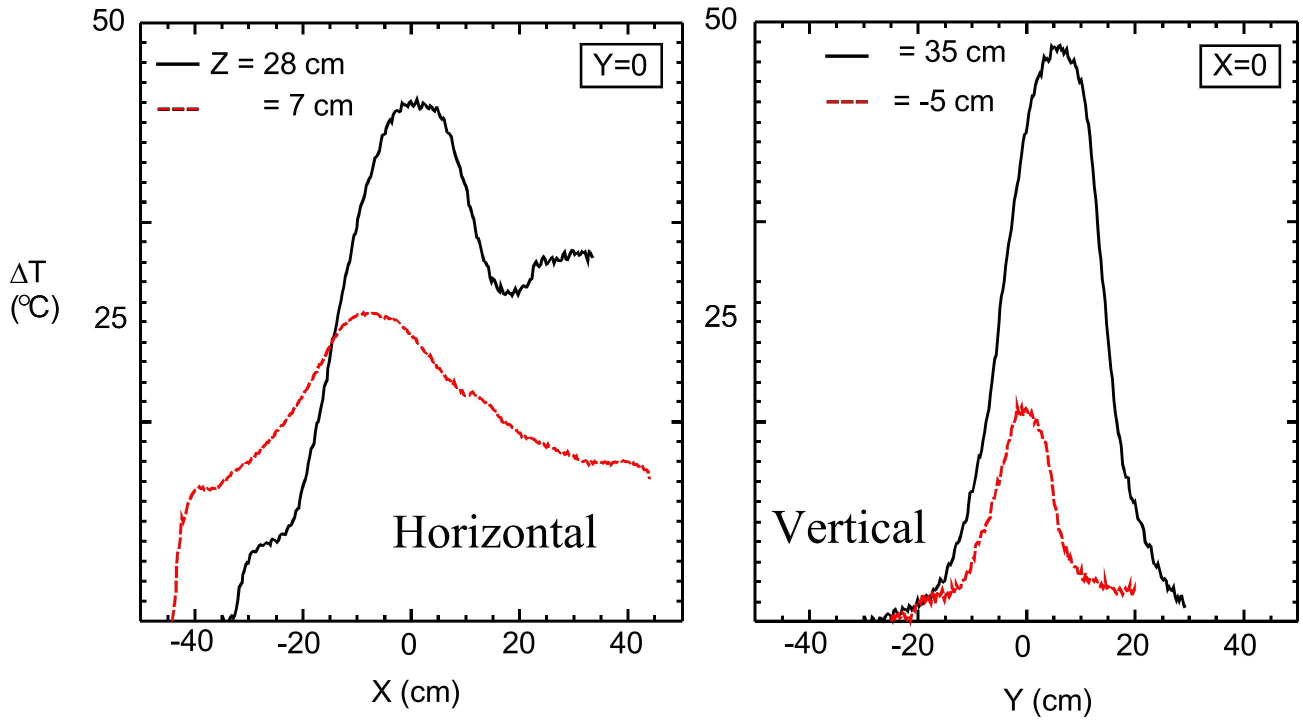
- The tomographically measured FRC shape appears to be an ellipse with E ~ 2.
- The dimensions of the ellipse can be calculated using averaged x and y forces.

Needed Developments for an FRC Fueller

- I. Scientific:
  - A single pulse FRC injection experiment on DIII-D or JET to study interaction with an energetic tokamak plasma.
  - A 3-D simulation of an FRC interacting with a tokamak plasma.

- II. Technological:
  - Development of circuitry for repetitive pulsing with high energy recovery. This requires very long life capacitors and high current, high voltage switching components.

Thermocouple Measurements of Deposited Energy (B_t = 5 kG)



- The FRC spreads in the horizontal (toroidal) direction, but still remains collimated.
- The FRC is deflected to the left, resulting in a smaller signal on the vertical probe at z = -5 cm

Work In Progress

- Source optimization is important for an FRC fueller. High energy recovery circuitry will be necessary for high efficiency formation.
- Analytic scaling laws are being developed for the source and acceleration sections to give a better understanding of which parameters are important in the optimization process.
- Low voltage techniques are being studied that would allow the use of IGBT switches. Use of these devices would greatly enhance the energy recovery, efficiency, and ability to rep-rate the fueller.
- The 2D MOQUI code is being used to simulate various design concepts and test relative efficiencies during the optimization process.
- Liaison has been established with JET & ITER to design device specific FRC fuellers.