Considerations for Addressing TAP FRC Issues

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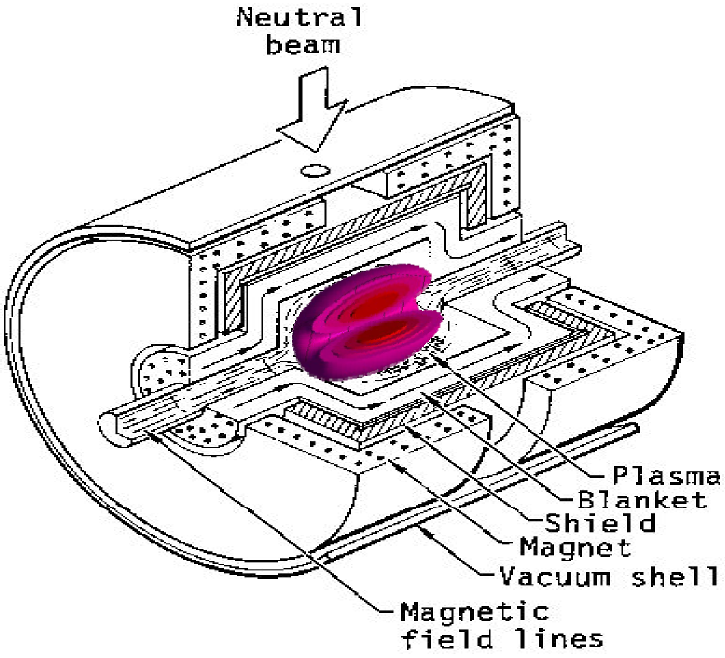
Outline

- Basic FRC Issues
  - Stability (high *s*)
  - Confinement & Sustainment (related)
  - Fast particles (& heating) - TNBI
- A Unified Approach for Addressing all Issues

FRC (& generic CT) Reactor Advantages



LLNL FRM Schematic (1976)

- Studies (U. Wisconsin, EPRI) show tremendous blanket simplifications due to singly connected linear geometry and lowered cost due to simple low field confinement coils. *Aneutronic fuel options?*
- ‘Disruptions’ not a problem for diamagnetic plasmas.
- Divertor loadings can be made as low as desired.
- *Rapid development path possible due to small size & cost.*

- Recent favorable results on low power formation **and sustainment** of hot FRCs, make this the right time for an aggressive effort to address the critical FRC stability, confinement, and sustainment issues.

Tier 1 Stability Issue

- Operating at high *s* is unavoidable unless $D_\perp$ can be made very small!

$$s = \int_R^{r_s} \frac{r dr}{r_s \rho_i} \approx \frac{48 x_s^{1.3}\left(r_s(\mathrm{m}) B_e(\mathrm{T})\right)}{\sqrt{A_i T_i(\mathrm{keV})}} \qquad n\tau_E \approx \frac{n r_s^{\,2}}{8 D_\perp} \propto \frac{(r_s B_e)^2}{T_i D_\perp}$$

At $T_\mathrm{i} = 10$ keV, $r_\mathrm{s}(\mathrm{m})B_\mathrm{e}(\mathrm{T}) = 1.8\{n\tau_{\mathrm{Ereq}}(10^{20}\mathrm{m}^{-3}\mathrm{s})D_\perp(\mathrm{m}^2/\mathrm{sec})\}^{1/2}$.

For $n\tau_{\mathrm{Ereq}} = 5\mathrm{x}10^{20}\mathrm{m}^{-3}\mathrm{s}$, $r_\mathrm{s}(\mathrm{m})B_\mathrm{e}(\mathrm{T}) = 4D_\perp{}^{1/2}(\mathrm{m}^2/\mathrm{sec})$. **$s \approx 28D_\perp{}^{1/2}(\mathrm{m}^2/\mathrm{sec})$.**

- The product **$r_\mathrm{s}B_\mathrm{e}$** is the key engineering parameter for FRCs. A lower flux, $\phi_\mathrm{p} \sim r_\mathrm{s}{}^2B_\mathrm{e}$, is needed at high B_e, but to have a fusion reactor at $s < 5$ requires $D_\perp < 0.03$ m^2/sec, irrespective of magnetic field.

Kinetic and Hall Parameters

$$\mathbf{E}+\mathbf{u}_e\times\mathbf{B}=\eta\mathbf{j}+\nabla p_e/ne \qquad \mathbf{E}+\mathbf{u}\times\mathbf{B}=\eta\mathbf{j}+\left(\mathbf{j}\times\mathbf{B}+\nabla p_e\right)/ne$$

Non-dimensionalize

$$\tilde{\mathbf{u}}=\frac{\mathbf{u}}{\mathrm{v}_A} \quad \tilde{\mathbf{x}}=\frac{\mathbf{x}}{R} \quad \tilde{\mathbf{B}}=\frac{\mathbf{B}}{B_o} \quad \tilde{\mathbf{j}}=\frac{\mathbf{j}}{(B_o/\mu_o R)} \quad \tilde{p}=\frac{p}{(B_o^2/\mu_o)} \quad \tilde{\mathbf{E}}=\frac{\mathbf{E}}{(RB_o/t_o)} \quad t_o=r/\mathrm{v}_A \quad \mathrm{v}_A=B_o/\sqrt{\mu_o n_o m_1}$$

$$\tilde{\mathbf{E}}+\tilde{\mathbf{u}}\times\tilde{\mathbf{B}}=\frac{1}{S^*}\left(\frac{\tilde{\mathbf{j}}}{\omega_{ce}\tau_{ei}}+\tilde{\mathbf{j}}\times\tilde{\mathbf{B}}+\tilde{\nabla}\tilde{p}_e\right)$$

- $S^* = R/\ell_\mathrm{i}$ where $\ell_\mathrm{i} = c/\omega_\mathrm{pi}$ is the collisionless ion skin depth, of order ρ_i for the high beta FRC.
- S* ~ 5-10*s* for an FRC, depending on flux profile. *S** relates to the Hall term, affecting field-line convection with the electrons, and is thus different from the purely kinetic *s* consideration.

Tier 2 Transport & Sustainment Issue

- Energy confinement and sustainment are related in a diamagnetic plasma.
- In a diamagnetic plasma such as an FRC, in order to sustain the flux by maintaining $E_\theta = \eta_\perp j_\theta + \mathrm{v}_{er} B_z + \langle -\mathrm{v}_{ez} B_r \rangle = 0$, some means must be found of overcoming the negative $\eta_\perp j_\theta$.
  - Fueling, producing an outward v_{er} is helpful, but inoperative where $B_z = 0$.
  - Waves can produce in-phase $\mathrm{v}_{ez} B_r$ oscillations (how Rotating Magnetic Fields - RMF work).
- Tangential Neutral Beam Injection (TNBI) can produce current rings experiencing classical '$\eta_\perp$', thus reducing $\eta_\perp j_{\theta\mathrm{plasma}}$ contribution to flux loss.
- Sustainment power requirements will scale as $\int \eta_\perp \mathrm{j}_\theta^2$, or as $\eta_\perp I_\theta^2$, so having $\eta_\perp$ low is key.

Cross-Field Resistivity & Transport

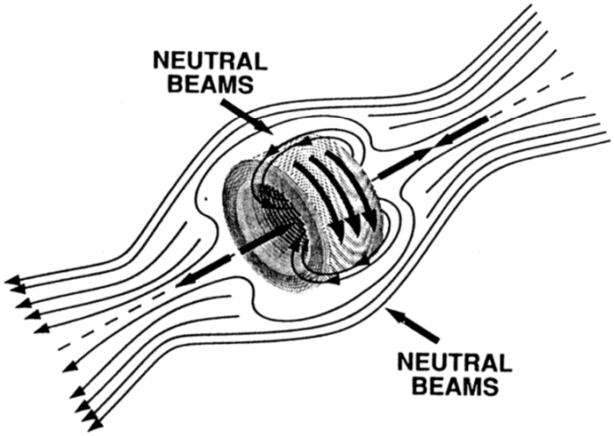
- Many theoretical and numerical calculations show diamagnetic plasma turbulence, and thus transport, strongly dependent on the drift parameter ratio of electron drift speed to ion sound speed, $\gamma_{\mathrm{d}} = v_{\mathrm{de}}/v_{\mathrm{s}}$.
- Present steady-state FRCs have too little flux to study interior thermal conduction, but all transport & energy confinement may be related to the same $D_\perp = \eta_\perp/\mu_o$ governing flux and particle loss rates, which have been measured.

$$D_{\mathrm{LHD}} = 0.15 D_{\mathrm{Bohm}} \frac{\gamma_d^2}{1+\frac{\pi}{8}\gamma_d^2} \qquad D_{\mathrm{Bohm}} = \frac{T_e(\mathrm{eV})}{16 B_e(\mathrm{T})}\ \mathrm{m}^2/\mathrm{sec}$$

$$\gamma_d = \frac{0.04\sqrt{A_i T_t(\mathrm{keV})}}{B_e(\mathrm{T})\, r_s(\mathrm{m})}$$

- γ_{d} also depends on the $r_{\mathrm{s}}B_{\mathrm{e}}$ product, and for an FRC $\boldsymbol{\gamma_{\mathrm{d}} \approx 2.5/s}$. *Any high s experiment will thus also be able to test drift wave resistivity scaling, as long as low collisionality is maintained.*

Energetic ion component calculated to enhance FRC stability (and perhaps affect transport)

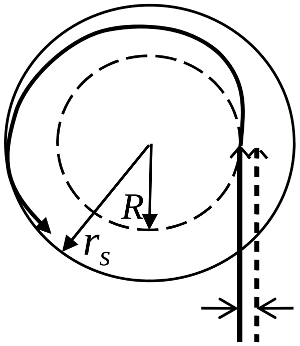


Tangential Neutral Beam Injection (TNBI) can create fast ion ring currents, but how it may sustain flux has not been demonstrated.

- TNBI attempted in 2XIIB Mirror as ‘Q-enhancement’ approach to plug mirror ends, but couldn’t produce field reversal.
- If have pre-existing FRC it will be straightforward to trap fast charge-exchange ions.
- Total azimuthal current is specified by FRC pressure: Fast ions will initially replace some of the bulk electron current thus, at least, reducing the $\eta_{\perp} j_{\theta\text{plasma}}$ contribution to flux loss.
- The fast ion trapping ability within an FRC is also dependent on the $r_s B_e$ product.

TNBI is an ideal complement to RMF since it inserts momentum in the opposite direction.

TNBI Monte-Carlo Calculations



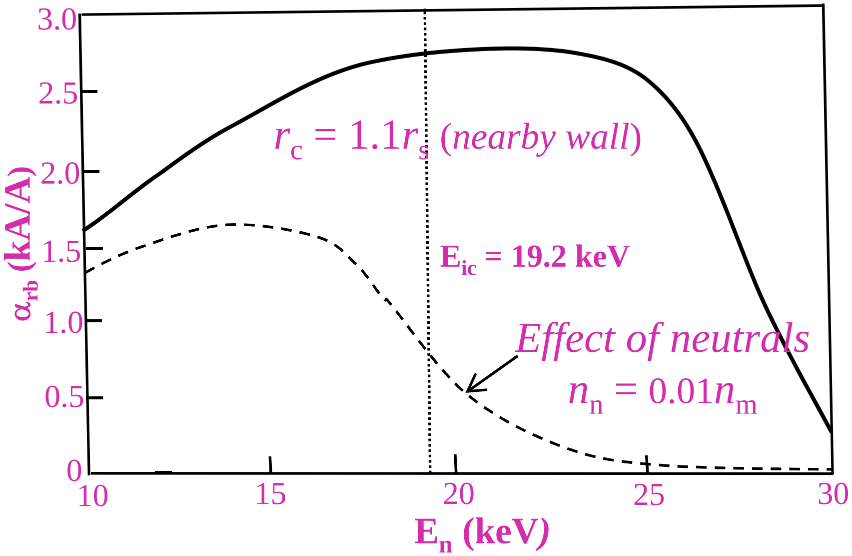
$0.1r_s$ is ideal beam width

Critical orbit:

$$E_{ic}(\text{keV}) = \frac{0.0144}{A_i}\left(\frac{\phi_p(mWb)}{r_s(m)}\right)^2$$

$$I_{ring} = \frac{\tau_s}{2\pi r/v_b} I_{beam} \qquad \tau_s \approx \frac{0.02\, T_e^{2/3}(keV)}{n_e(10^{20}\text{m}^{-3})}\ \text{sec}$$

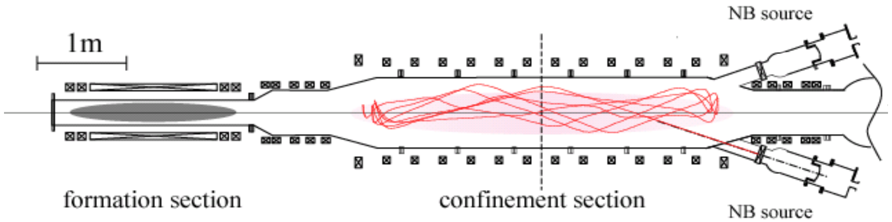
$$\alpha_{rb} \equiv \frac{I_{ring}}{I_b} = 0.75\frac{T_e^{2/3}(\text{keV})E_b^{1/2}(\text{keV})}{A_i^{1/2} n_e(10^{20}\text{m}^{-3})R(\text{m})}\ \text{kA/A}$$



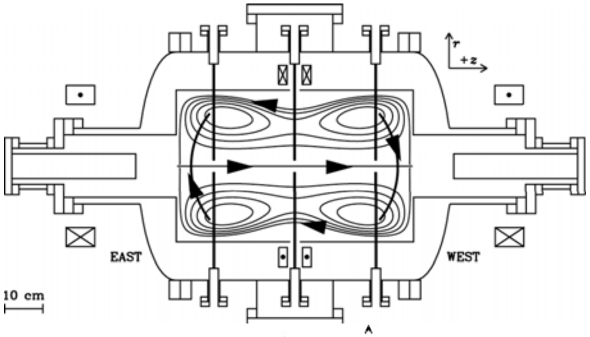
Calculation for 50 mWb, $n_e = 1.5\text{x}10^{19}\ \text{m}^{-3}$, T_e = 325 eV FRC.

- Need $r_s B_e$ product of ~50mT-m to confine charge-exchange fast ions at minimum useful beam energy. Since Δr_{beam} must be of order $0.1r_s$ for good trapping efficiency, r_s should be of order 1 m if beam diameter is of order 10 cm.
- Larger r_s, lower B_e means lower density, which is desirable since $I_{ring}/I_{plasma} \sim n_e^{-2}$.

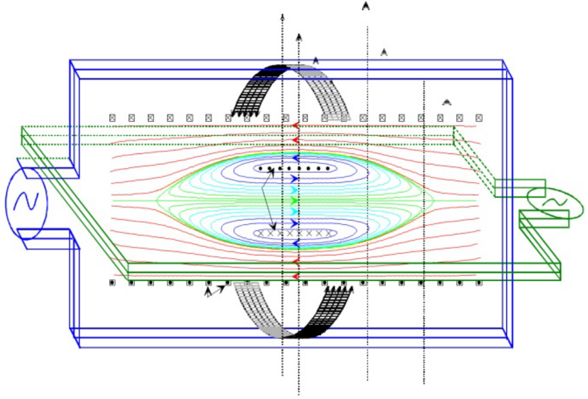
Available FRC Formation Methods



Theta Pinch Formation and
Translation/Expansion
(LSX limited to ϕ_p ~ 10-20 mWb)
(Formation power input ~ 10s of GW)



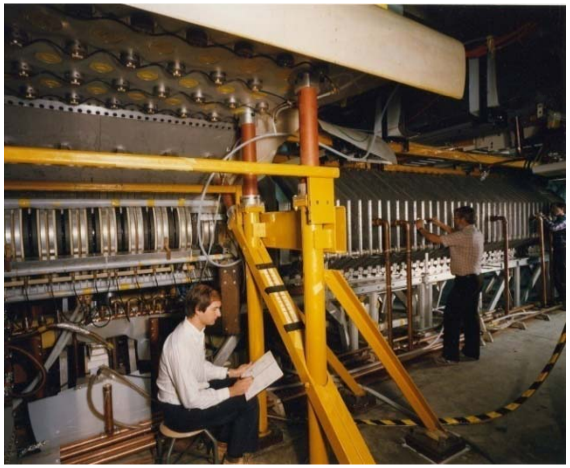
Merging Spheromak Formation
(slower formation – 50 mWb in SSPX)
(Formation power input ~ 100 MW)



Rotating Magnetic Field Formation
(also current drive mechanism – no
fundamental flux limit)
(Formation power input ~ 1 MW)

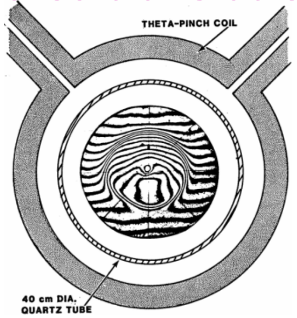
High Power (GW) θ-Pinch Facilities

(historical approach, but now mostly of interest for high density pulsed approaches)



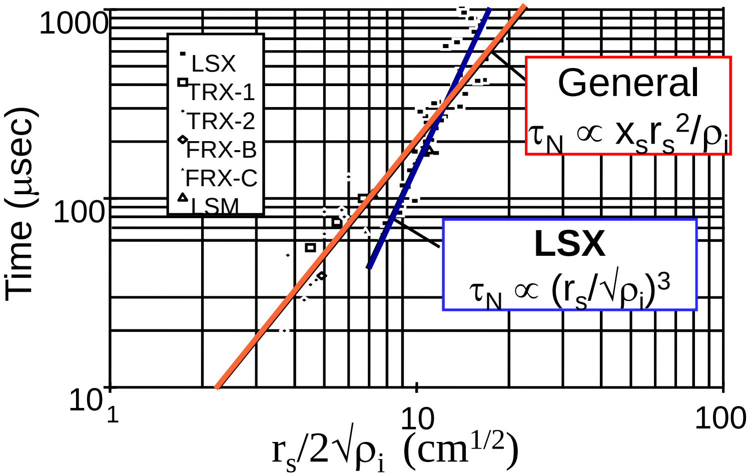
FRXC/T (LLNL - early 1980s)

Studied translation & adiabatic compression



Interferogram taken on FRX-C using holography

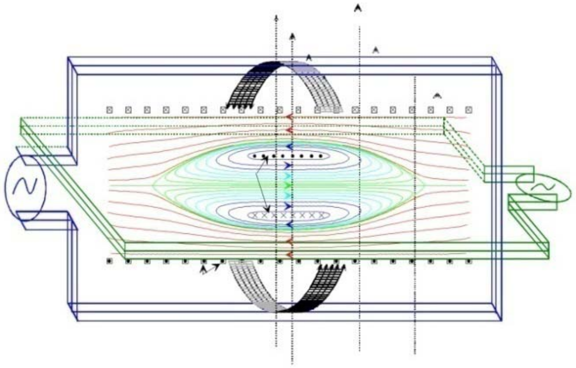
LSX (Large *s* Experiment) (STI - 1991)



Much better than Bohm confinement ($D_\perp \sim 5$ m^2/s when $\gamma_d < 1$).

Demonstrated stability up to *s* = 4.

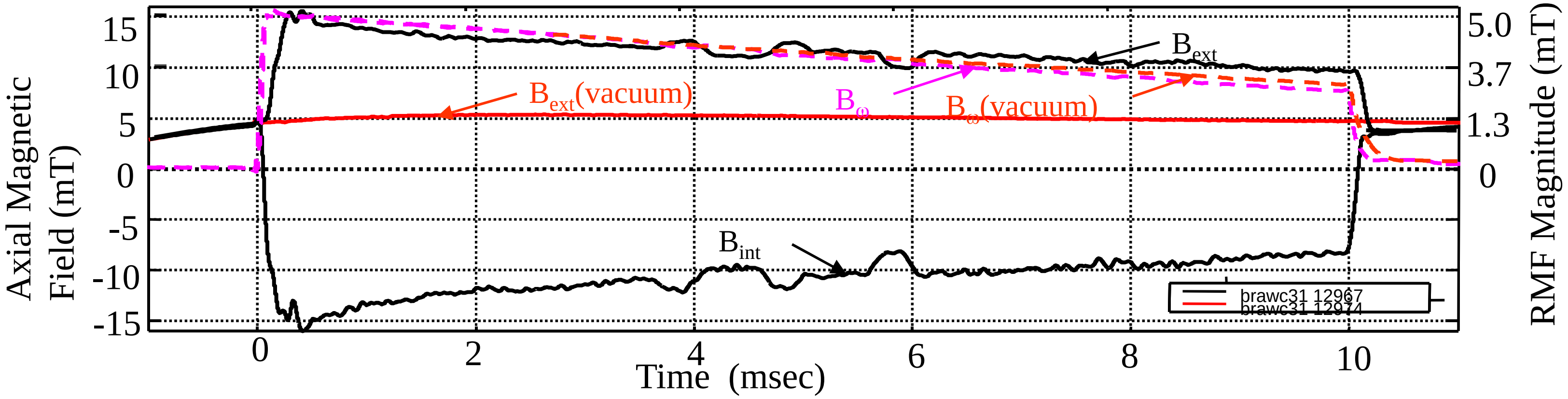
Rotating Magnetic Field (RMF) Current Drive



RMF antenna
$I_z = I_o \cos\omega t$

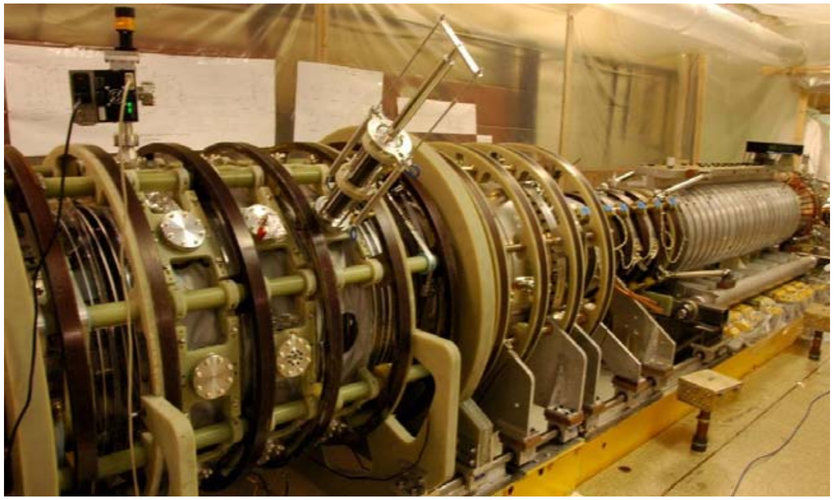
RMF antenna
$I_z = I_o \sin\omega t$

- Technique developed by Ieuan Jones‘ group in extensive ‘rotamak’ experiments.
- ‘Drag’ electrons to produce toroidal current. (*Reverses negative resistive* E_θ).

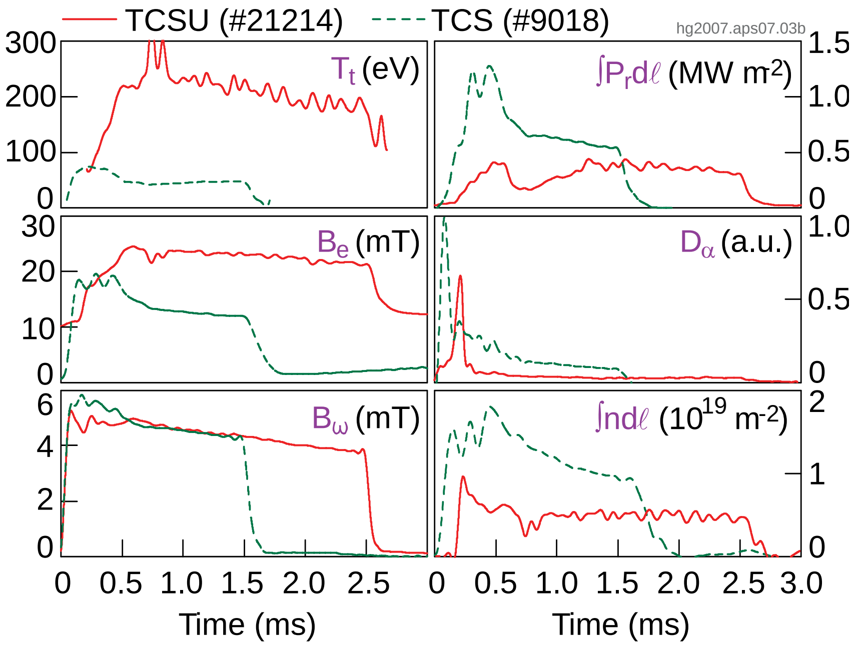


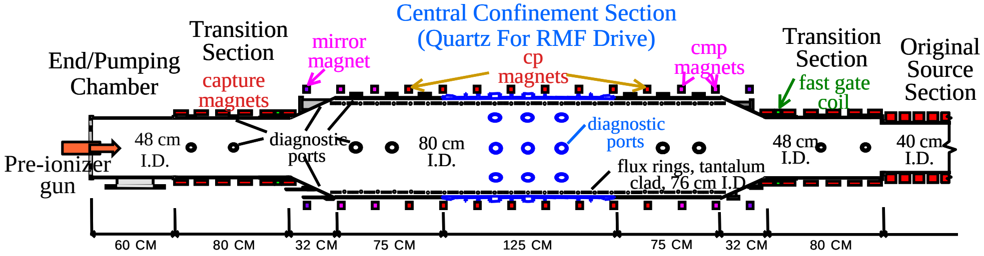
- FRCs formed and sustained for ~100 Alfven times, limited only by RMF power supply.

TCS-upgrade built to control recycling of impurities and D_2



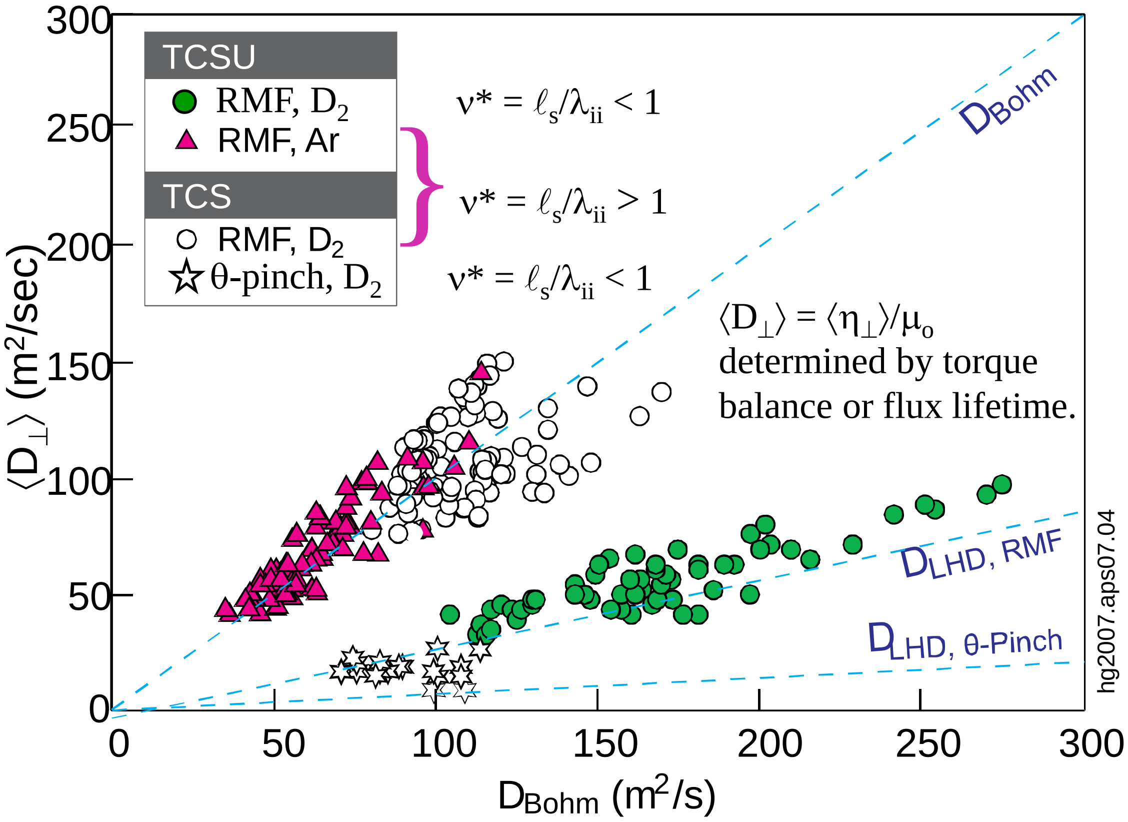
Completed early 2007





- Can now overcome low *Z* impurity barriers with low power inputs.
- Don’t use θ-pinch translation capability.

Can study confinement in low collisionality regime - LHD-type scaling rather than Bohm



- Higher temperature, collisionless FRCs experience LHD-like, drift-wave resistivity scaling.
- Drift-wave resistivity is calculated to scale as $1/\gamma_d^2$.
- **It is essential to obtain such improvement for steady-state FRCs to scale to reactor parameters!**

$\gamma_d = v_{de}/v_i$ is ~2.5 near edge for TCSU and scales as $1/(n_e^{1/2} r_s)$, **which points out the need for a larger, more powerful machine to make dramatic improvements!** ($D_\perp$ is much lower in FRC interior where γ_d is smaller).

Minimum ‘POP-level’ parameters to investigate critical FRC physics issues

Parameter	**TCSU**	**‘POP-level’**		**Reactor**
	B_ω = 5 mT	**B_ω = 10 mT**		
$\langle\eta_\perp\rangle$ =	**85 μΩ-m**	**120 μΩ-m**	**30 μΩ-m**	**~ 1 μΩ-m**
f_ω (kHz)	150	30		10
r_s (m)	0.37	0.9	0.9	2.0
B_e (T)	0.03	0.06	0.12	1.8
ϕ_p (Wb)	0.0035	**0.045**	**0.090**	4.5
T_i, T_e (keV)	0.12	0.32	0.65	10
n_e (10^{20}m^{-3})	0.1	0.15	0.3	4.0
s (in deuterium)	1.0	**3.0**	**4.2**	30
λ_{ii} (m)	25	150	300	5,000
ρ_{ci} (m)	0.06	0.04	0.03	0.01
$\gamma_d = v_{de}/v_s$	2.5	**0.77**	**0.54**	0.1
E_{ic} (keV)	0.6	18	72	24,000

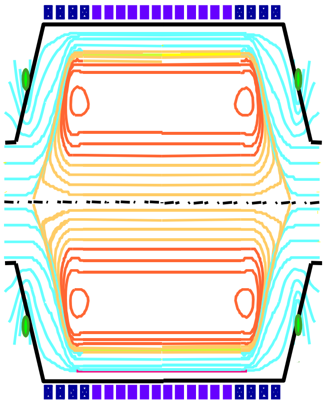
} Parameters relevant to RMF formation & sustainment

Need ~50 mWb flux level to study basic confinement

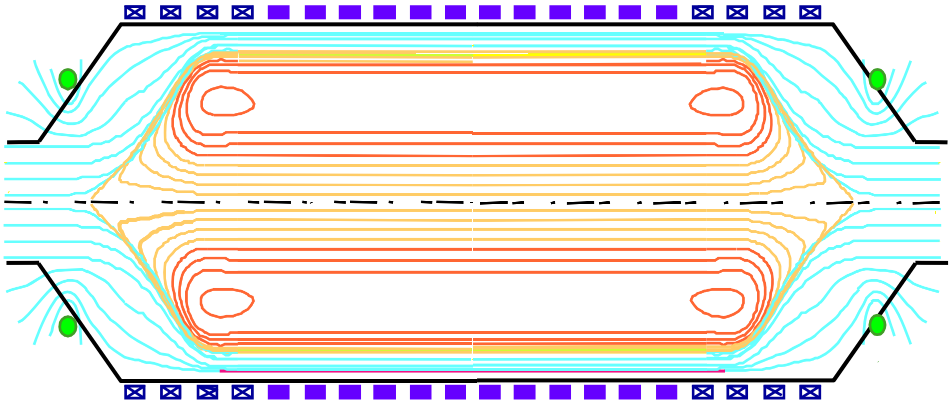
Initial s is in previosly stable regime, and can be increased by √2 using hydrogen

Need $\gamma_d < 1$

Oblate vs. Prolate



Elongation $E = 2r_s/\ell_s \le 1$



Elongation $E = 2r_s/\ell_s$ typically 1.5 - 5

- Usual for merging spheromaks and rotamaks.
- Can be tilt stable with close fitting walls.
- Minimum reactor size.
- Difficult to utilize ‘odd-parity’ RMF

- Usual for θ-pinches and RMF.
- MHD growth rate ~ E^{-1}, and kinetic and flow shear effects may have greater influence on stability. (S^*/E boundary?)
- Small B_{toroidal} will result in q > 1.

Conclusions

- FRCs are a high risk, high reward approach to fusion.
- Present facilities cannot address the critical knowledge *gaps*.
- A 50 mWb steady-state facility is an essential research *thrust*. It would cost less than LSX (~$25M in today's dollars).
- There is such great reactor promise and enough encouraging results to justify this thrust.