Physics basis and progress on a translating FRC for MTF

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for the MTF team

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CURRENT TRENDS IN INTERNATIONAL FUSION RESEARCH: A REVIEW

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abstract

We describe the design, progress and plans for a high density Field Reversed Configuration (FRC) at LANL that will translate in a mirror trapped compression region. A simpler version with fewer diagnostics is being constructed at Kirtland AFB which will be compressed inside a flux conserving cylindrical shell. The experimental goals at LANL include the increase of trapped bias flux during formation, increase of FRC lifetime which should scale with the trapped flux, and studies of a successfully translated FRC. These results are intended to enhance the MTF parallel experiment at AFRL.

This FRC experiment can scan parameters that allow investigations of the physics underlying the anomalous resistivity and the controlled addition of helicity. Even though the ideal FRC has zero helicity and toroidal magnetic field, significant non ideal properties follow from the conical theta pinch formation process. The FRC stability and lifetime properties may improve. A large range of density and pressure can be scanned, allowing unique scientific investigations of this high Lundquist number but collisional plasma. A spread of theta coil conical half angles between 0.5 and 6 degrees is possible, which should allow the first ever systematic investigation of helicity in theta pinch FRC's. At LANL translation and liner region will include radial access for diagnostic insertable probes, so the internal FRC structure can be studied.

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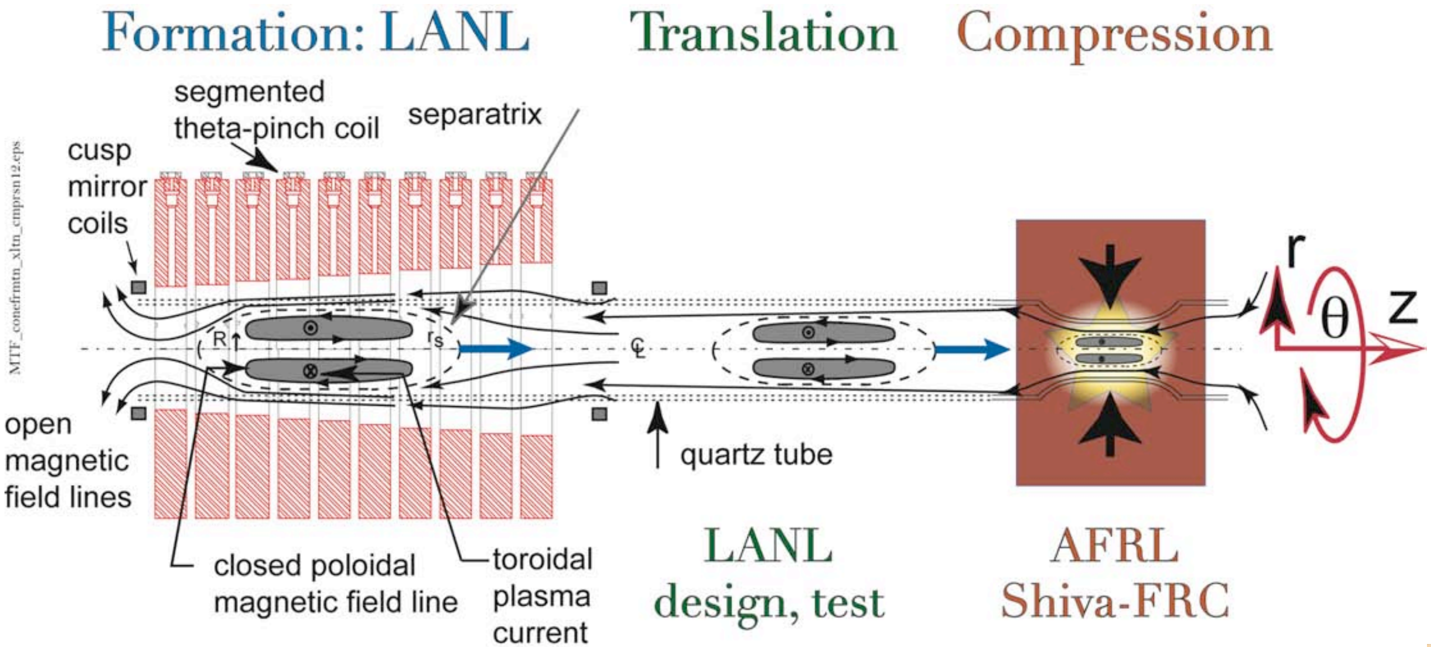
Outline

- What is Magnetized Target Fusion (MTF)?
- Field Reversed Configuration FRX-L
  - High pressure shots in MPa range
- Liner on plasma experiment for mid 2007
- FRC microphysics
  - Anomalous resistivity
  - Helicity

Magneto-Inertial fusion

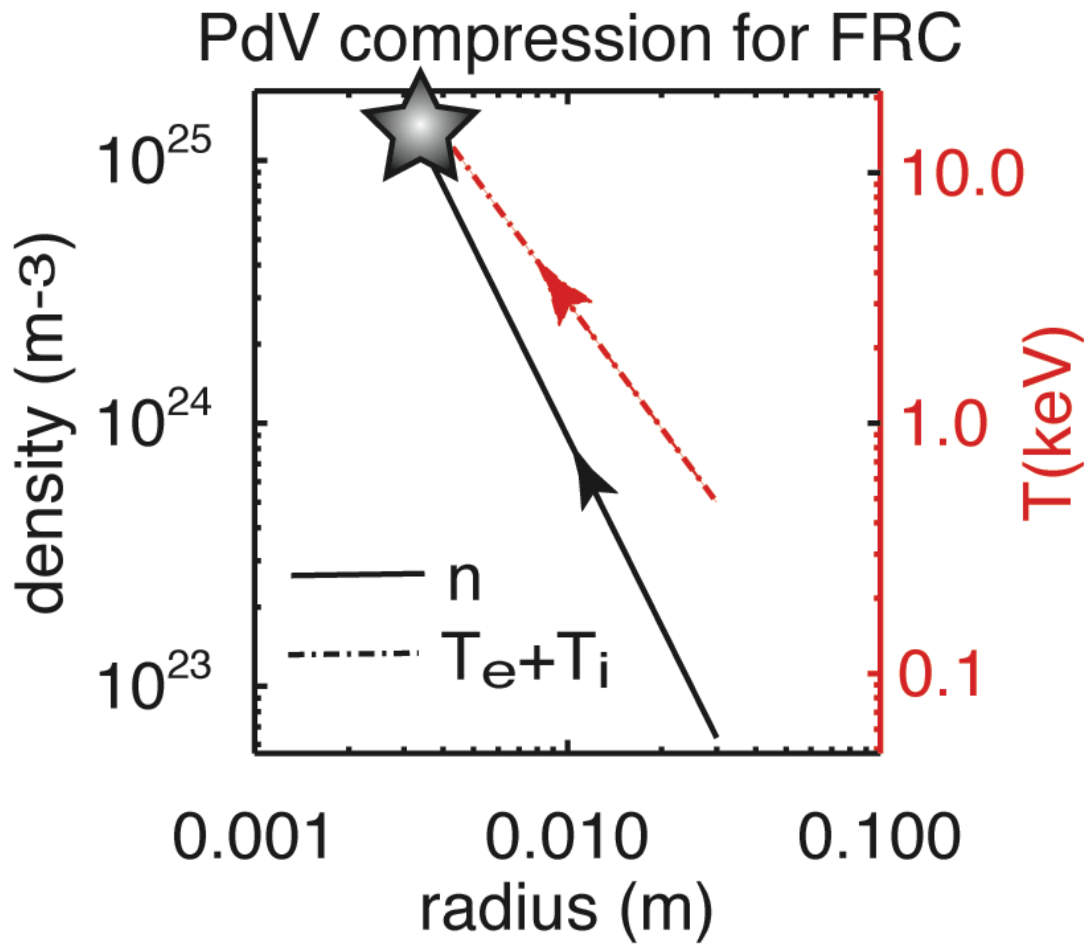
- Pulsed, high pressure approaches to fusion
- Inertial + magnetic confinement
- Magnetic surfaces improve confinement
- Magnetized Target Fusion - MTF example
  - Field reversed configuration (FRC) in a beer can
  - Solid, flux conserving, converging “liner”
  - Magnetized target
  - Other examples: Z, Omega targets ….

MTF: high risk high payoff route to fusion



- Pulsed, high pressure approach to fusion
- Inertial + magnetic confinement
- Magnetic field plays essential role

MTF: pulsed compression



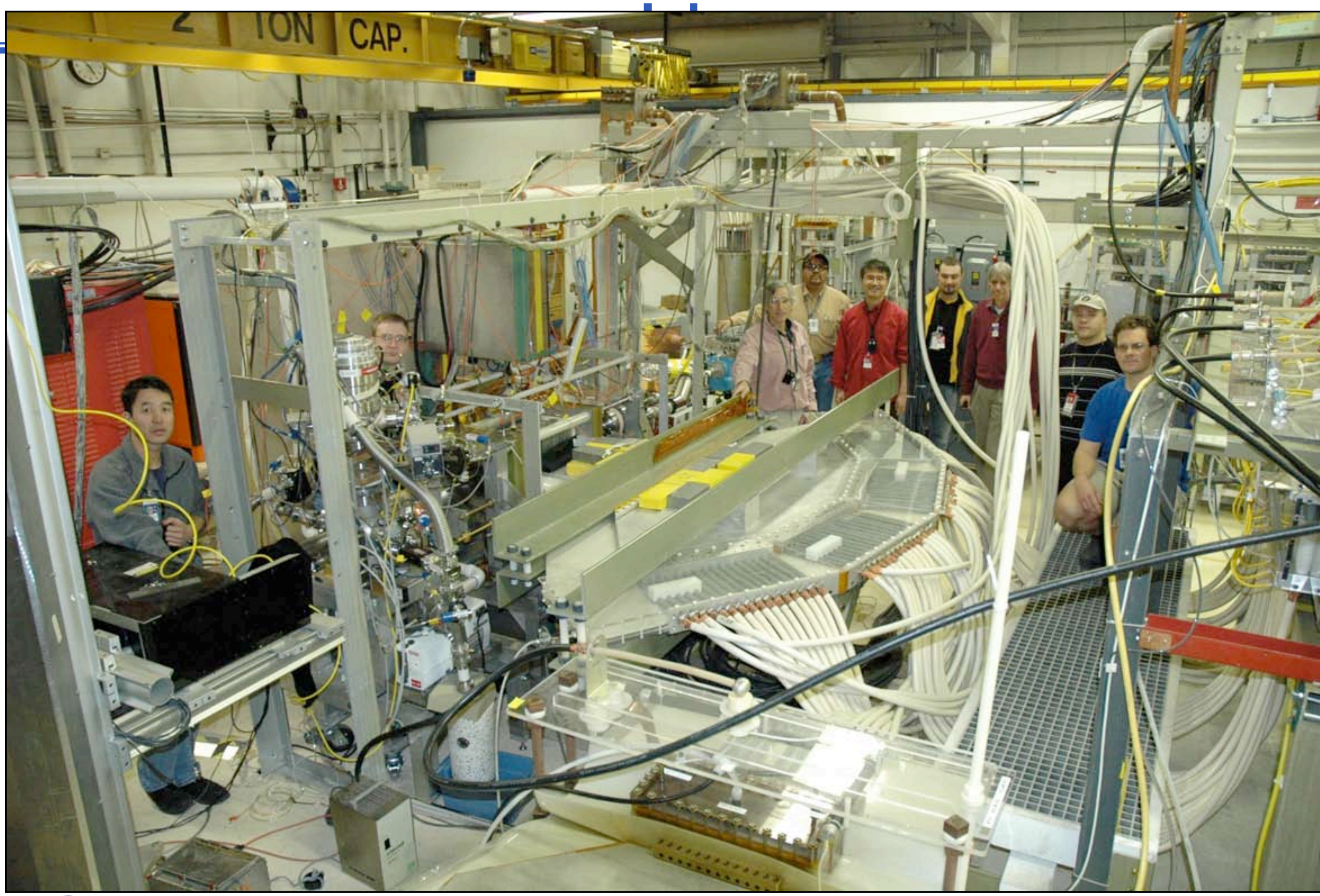
Why Field Reversed Configuration?

- Plasma parameters
  - High energy density, $\beta \approx 1$ at 3-5 Tesla
  - Advanced fuel potential at high β and large T_i
  - Target pressure $\rightarrow$ 20-30bar = 2-3 MPa
  - Huge current density $\rightarrow$ $J_{tor} \approx 0.5$GAmp/m^2
  - High density 200xCMOD tokamak $\rightarrow$ clean plasma, low Z_{eff}
- geometry
  - Simply connected … geometric simplicity
  - Lower development cost
  - Natural divertor $\rightarrow$ Heat exhaust handling
- Physics
  - Experimentally demonstrated resilient, closed flux surfaces during compression, translation

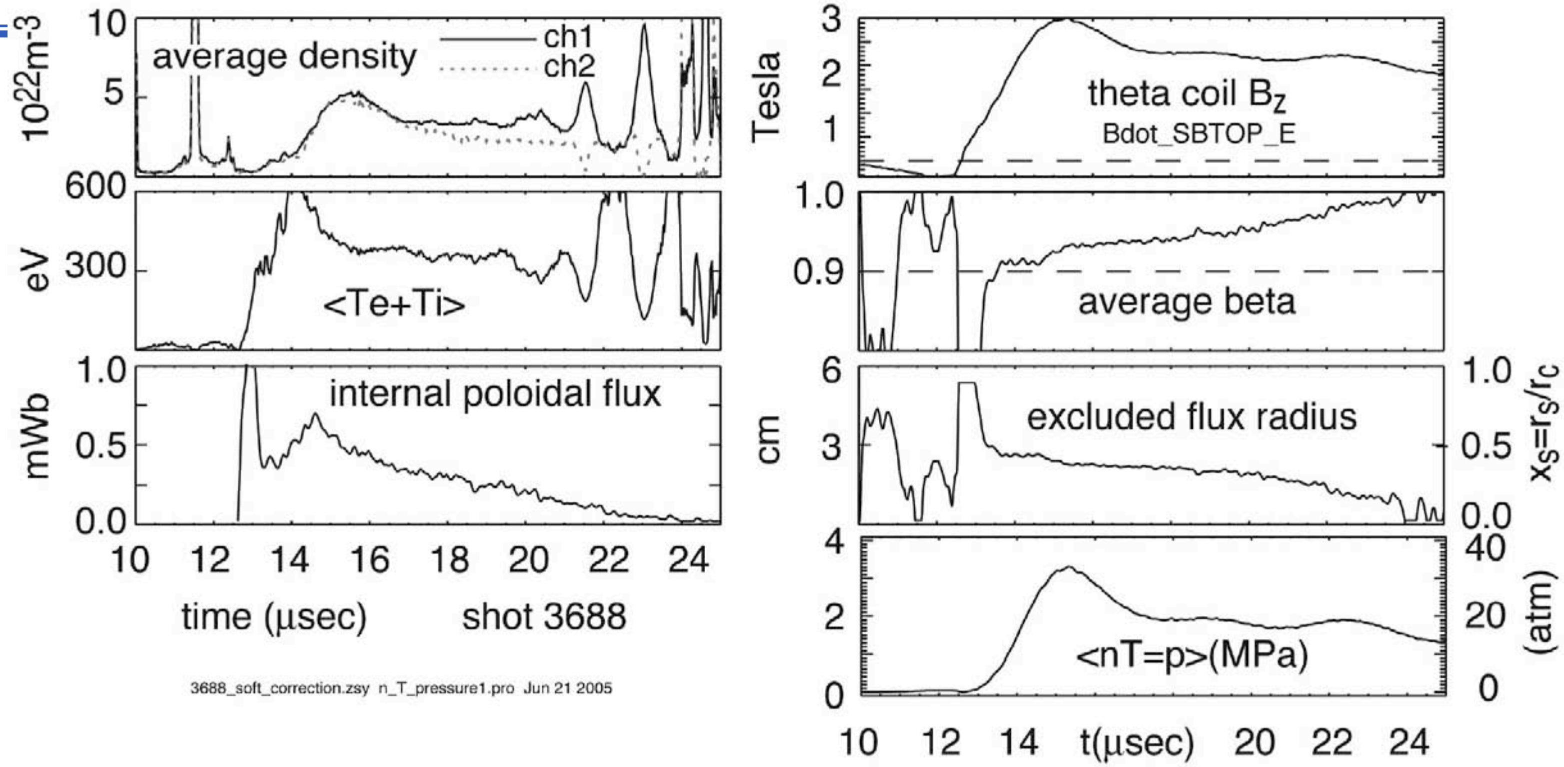
FRC + MTF

- Poor man's high energy density plasma (HED)
- Radial 1D compression 10x $\rightarrow$ 2.4D volume x $10^{2.4}$
- B $\approx$ 4 Tesla & Flux conservation $\rightarrow$ B x $10^2 \approx$ 4MG
- Pressure nT $\rightarrow$ 20-30 atm x 10^4 $\rightarrow$ 0.2-0.3Mbar
- Compression "auxiliary heating" power $\approx$ 3MJ/25µsec $\rightarrow$ 100GW
- Efficient capacitor banks: wall plug to liner kinetic energy $\approx$ 30%
- How to diagnose this experiment? Tough problem

FRX☼L Field Reversed eXperiment



FRX-L high plasma pressure shots

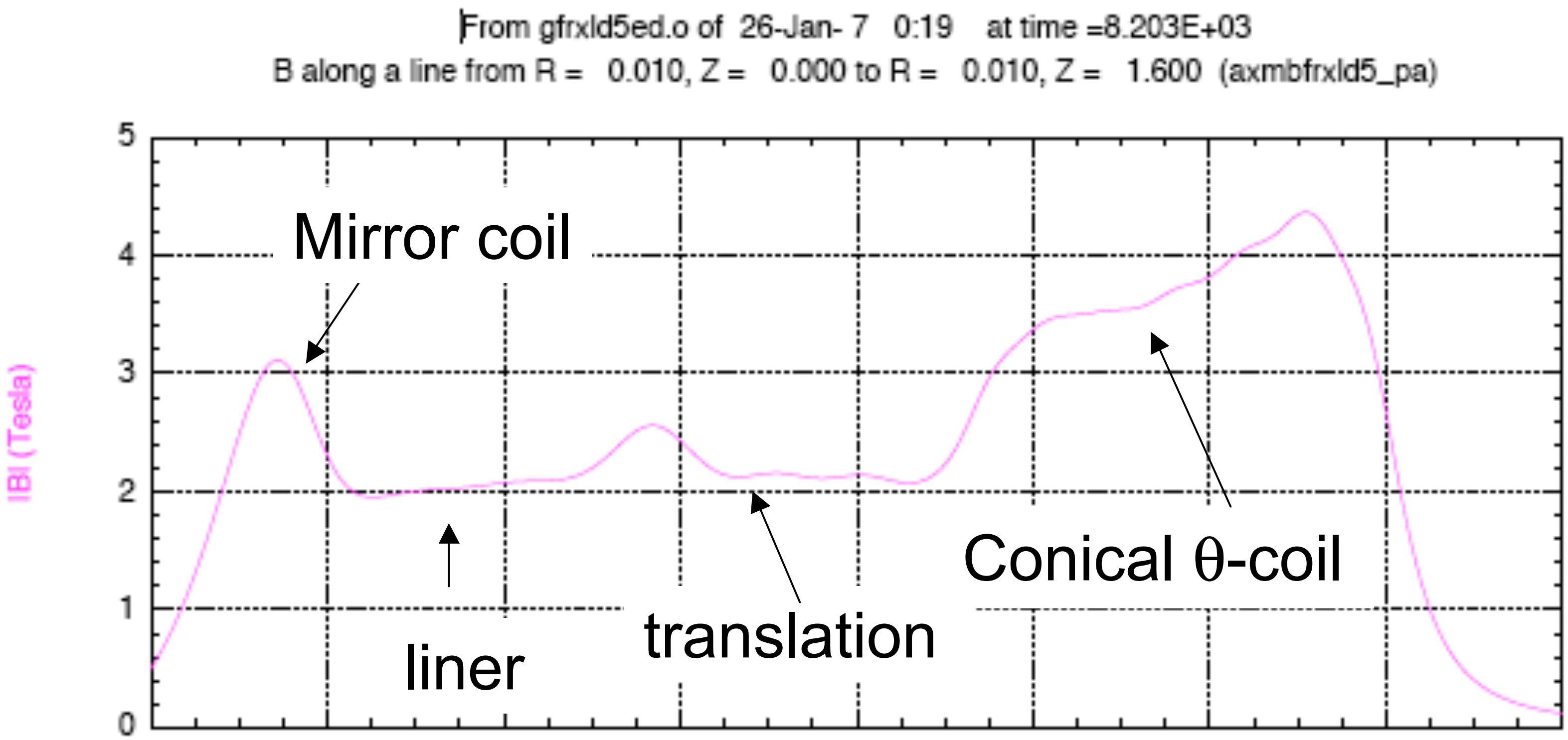


- Large plasma pressure ≈ 2-3 MPa (volume averaged)
- Radial profiles can be obtained from interferometer array

Physics requirements drive MTF design

- Diagnoses of FRC during formation, translation, fake + real liner implosion
- Use LANL tested formation scenario & technology
- Translation speed
  - minimize deadtime
  - Sufficient energy to squeeze into liner region
- Conical theta coil is the simplest scheme
  - Forces reconnection during formation
  - Cone angle imparts helicity, robustness
- FRC scaling laws predict formation and translated parameters

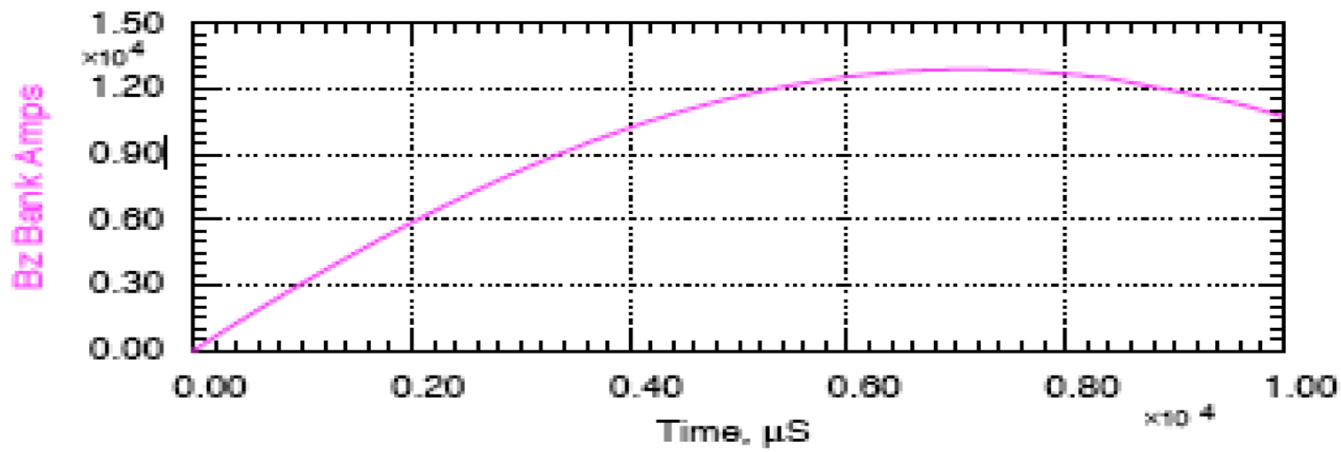
$B_z(z)$ during main bank



$B_z(t)$ slowly soaks into liner

Low current slow bank: $\tau_{1/4} \approx 7ms$

Jan 25 frxld5e.sct from frxld5.par. Revised per
Tom/Reass. Units: mH,mF,Ohms,Volts,Amps
Coils:Mirror 1,2;Bz 3-8;Cusp 9,10;LinerTop 11-14:Liner
15-25;Shiva 26-31;ThetaP 32-36:SS 37-40
Bz:12mF/-6kV/0.5mH/5.2mW; Cusp1:1mF/-
5.1kV/0.79mH/16.7mW; Cusp2:-9.8kV;
Bias:6mF/9.8kV/7.2mH/5.5mW; Main:36mF/70



Design point for experiment

- Solve scaling relations using applied external magnetic field
  - B(translation) ≈ 0.7 B(formation)
    - B(formation) < 4 Tesla
    - B(translation) < 3 Tesla
    - B(end mirror) ≈ 4 Tesla
  - Translation speed approaches upstream ion acoustic speed
  - Temperature ≈ 70% of formation
  - Separatrix size grows slightly: x_s(translation) ≈ 1.1 x_s (formation)
- Long pulse (7 msec), large energy (MJ), translation circuit to penetrate liner conductor
- Conical theta coil allows knob on helicity injection
- Diagnostic access, at least at LANL

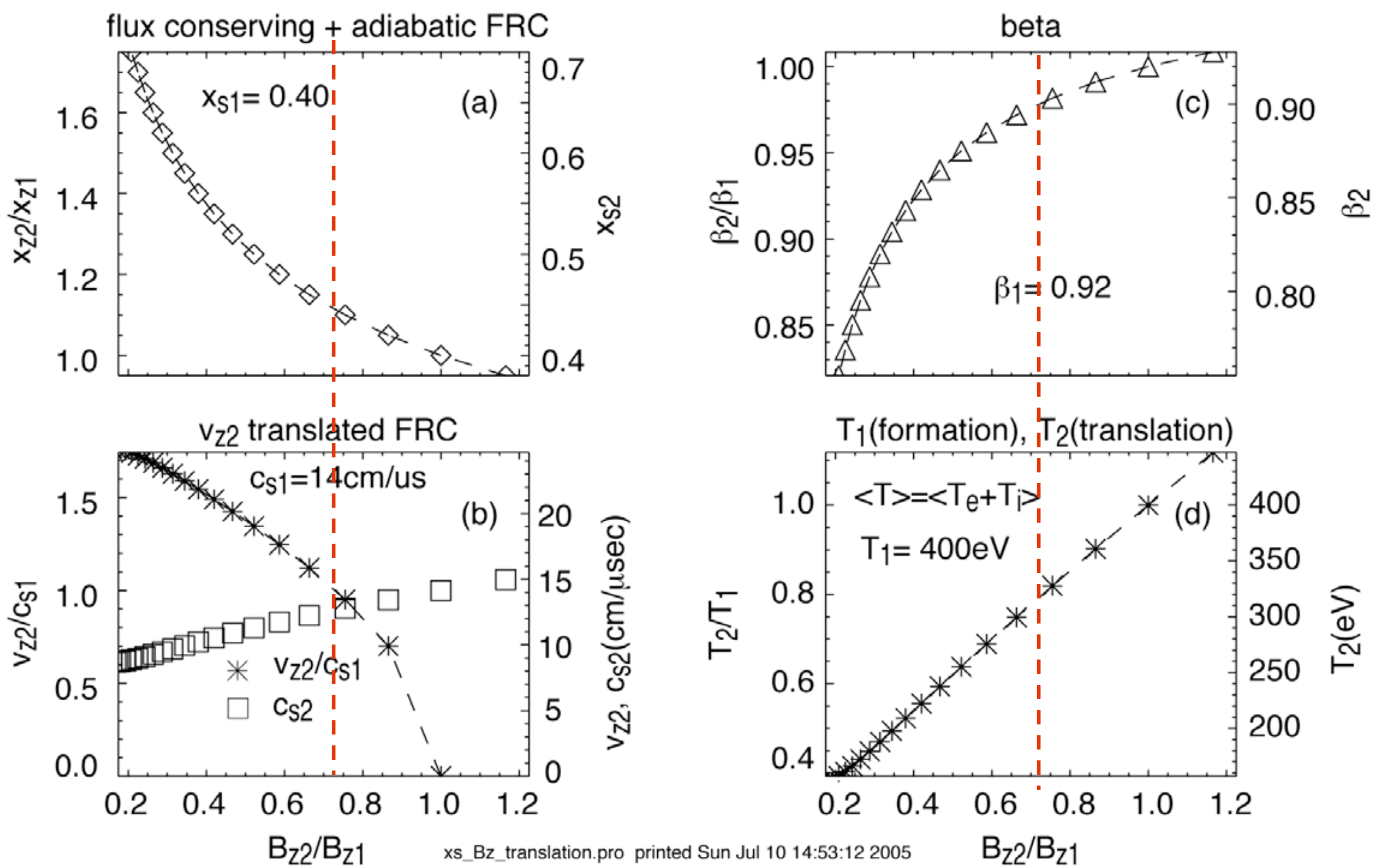
FRC scaling can predict translation parameters

shape factor spans high/low flux sharp boundary

ε scaling (adiabatic, $\varepsilon \approx 0.25$)

x_s	$(r_c^2 B_e)^{-1/(3+\varepsilon)}$ scales with applied flux
$2z_s$	$x_s^{2(4+3\varepsilon)/5} \langle\beta\rangle^{-(3+2\varepsilon)/5}\, r_w^{2/5}$
z_s/r_s	$x_s^{3(1+2\varepsilon)/5}\, r_w^{7/5}$
n_m	$x_s^{-6(3+\varepsilon)/5} \langle\beta\rangle^{-2(1-\varepsilon)/5}\, r_w^{-12/5}$
T	$x_s^{-4(3+\varepsilon)/5} \langle\beta\rangle^{2(1-\varepsilon)/5}\, r_w^{-8/5}$
B_w	$x_s^{-(3+\varepsilon)}\, r_w^{-2}$
$\langle\beta\rangle$	$1 - x_s^2/2$

Translation predicted parameters

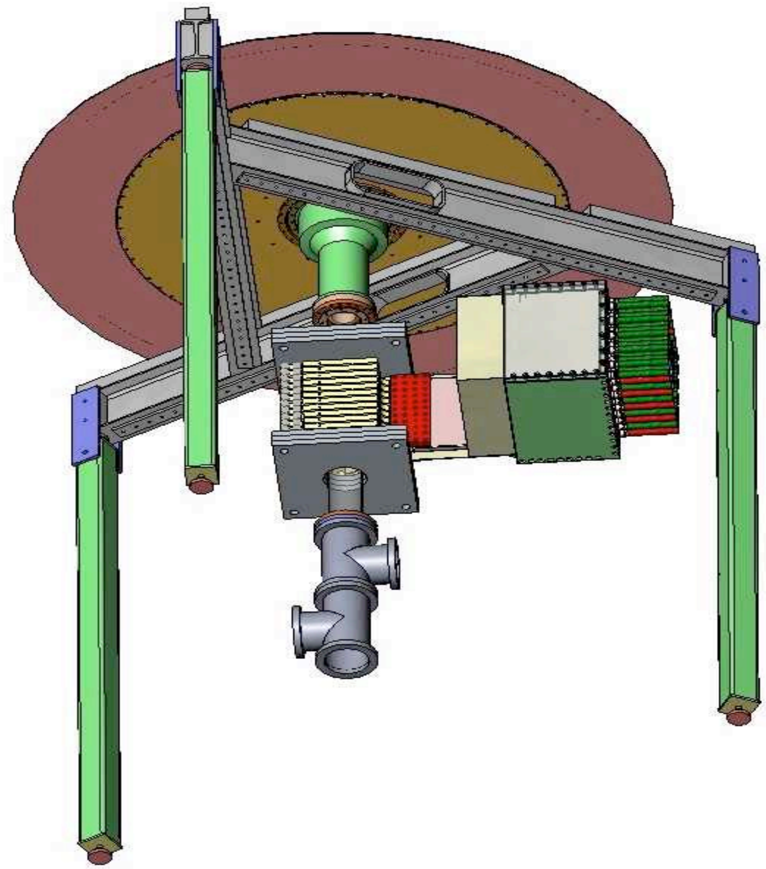


Hardware fab for MTF: 30%

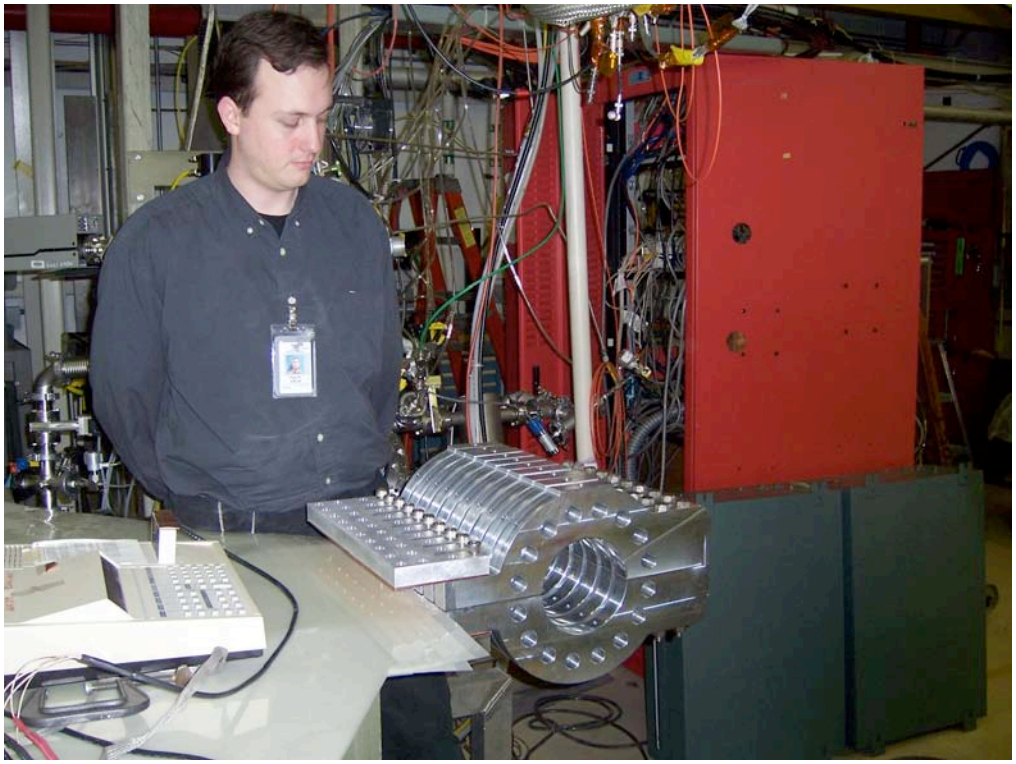
- Liner on plasma at AFRL, physics basis at LANL
- Capacitor banks & coils
  - Translation & mirror (0.6MJ)
  - Increased bias (bank only)
  - Fast cusp
  - Switching, monitors, failsafe features
- Vessel stand- compatible FRXL & SHIVA
- Conical theta coils
- Fake liner section + diagnostic spools
- MDS+ hook to ethernet + CAMAC
- Diagnostics
- Experiment and vacuum control

Fit up to SHIVA-STAR

- Stand must fit underneath SHIVA-Star
- See talk by
  - Ruden



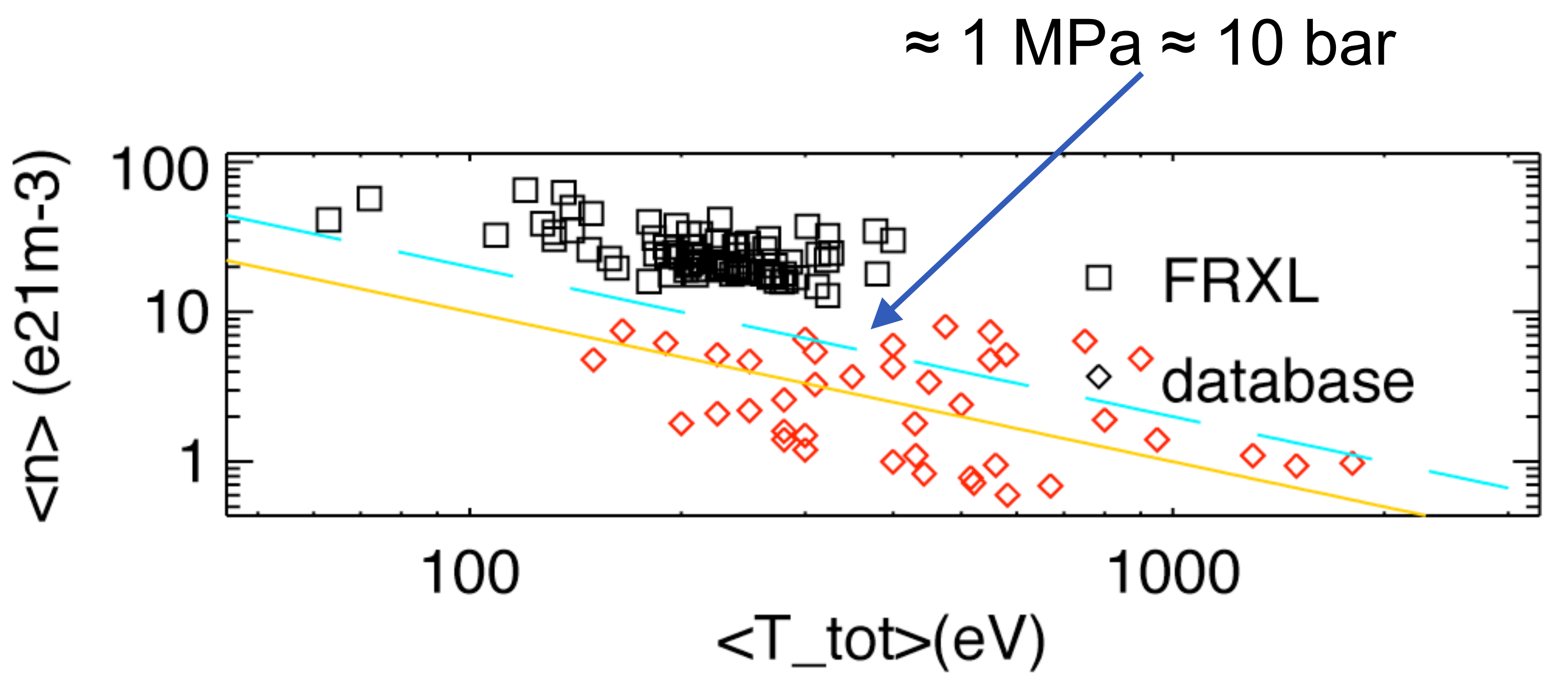
Conical theta coil assembly



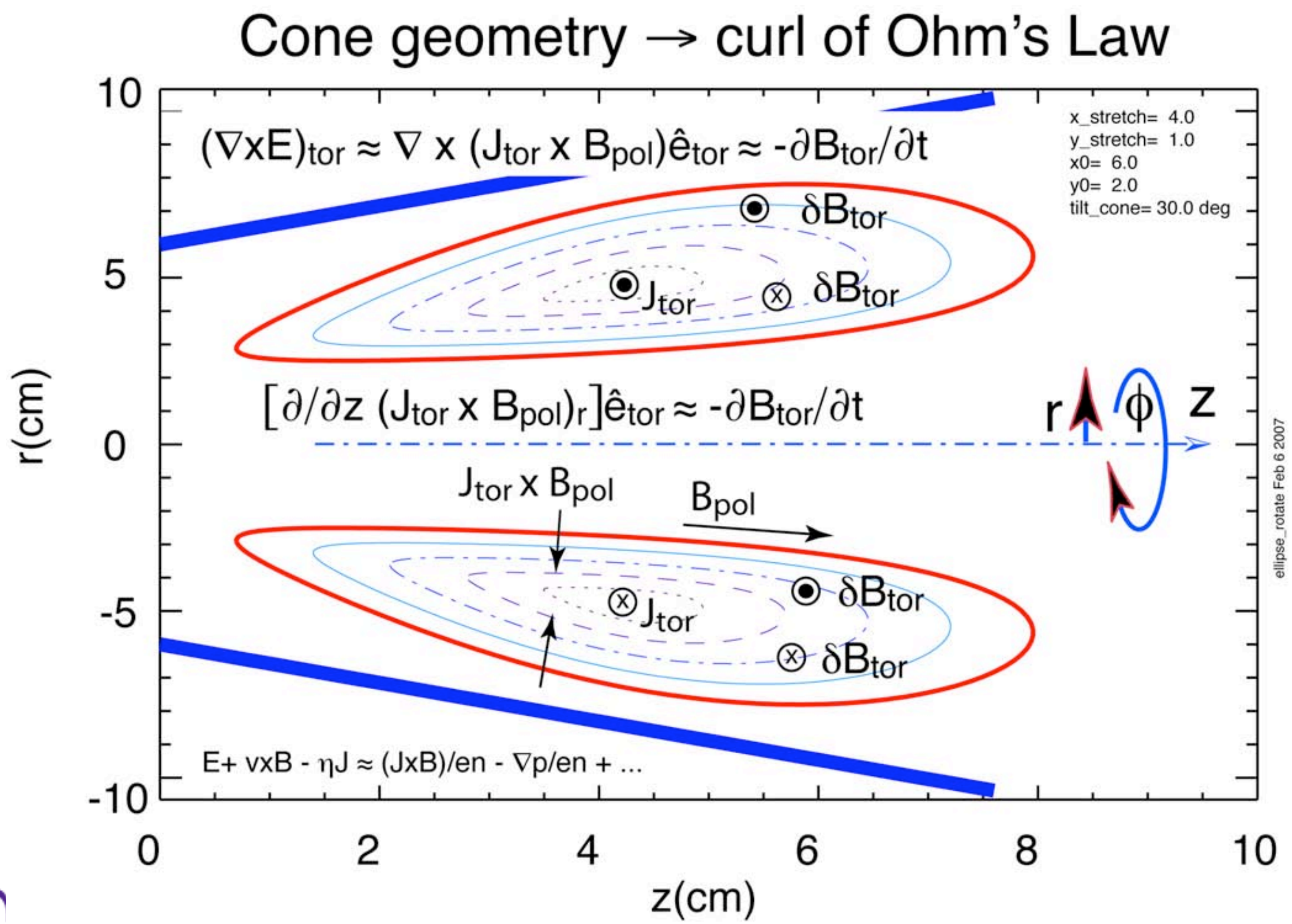
FRC: Basic plasma science

- FRC: elongated, self-organized, compact toroid
  - toroidal plasma current + poloidal magnetic field.
  - FRC J•B $\approx 0 \rightarrow$ extreme magnetic configuration
- large beta $\beta = nT/(B^2/2\mu_0)$
  - high plasma pressure / B field coils
  - Compare to $B_{poloidal}$ in tokamaks
- vanishing rotational transform, magnetic shear, toroidal field, helicity
- Anomalous resistivity
  - FRXL can scan collisionality & Lundquist number
- Helicity

FRX-L has high pressure

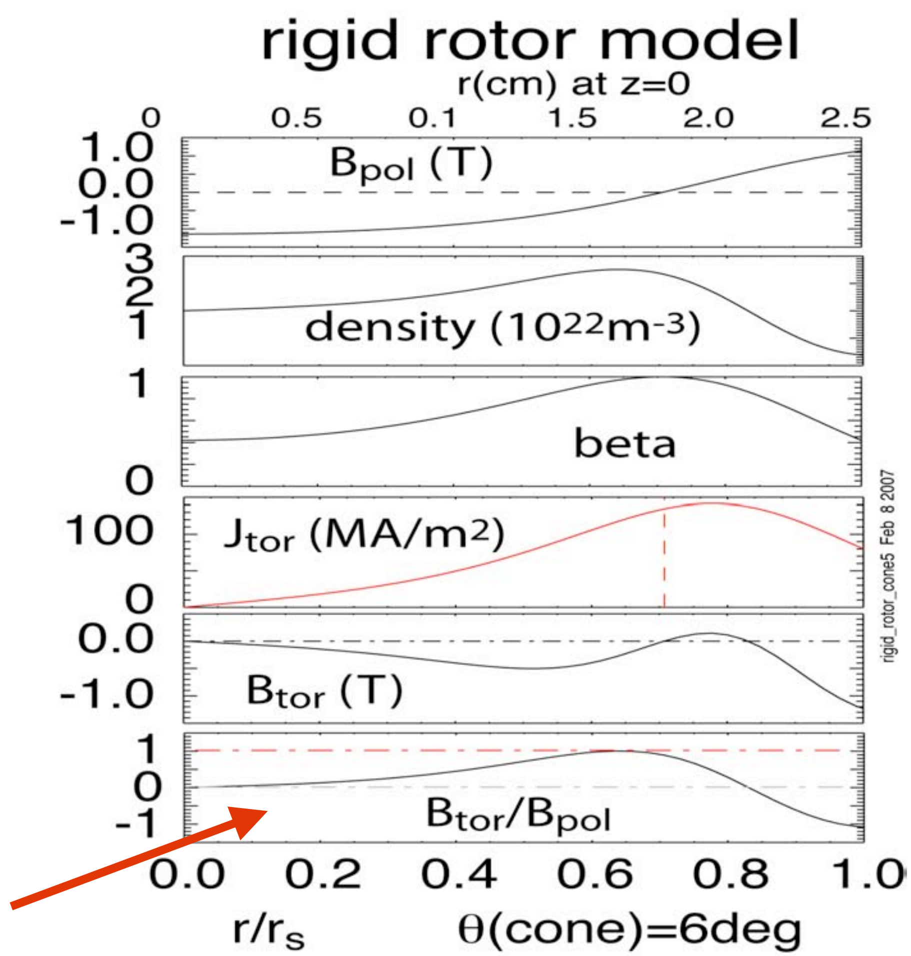


Conical θ-pinch => Controlled helicity injection



Conical formation => radial profiles & helicity

- Start with a rigid rotor model
  - deform to conical
  - then tilt z axis
- Harris sheet like profiles <=> equilibrium forces $J \times B = \nabla p$
- JxB forces are radial and give rise to a radial E_r field
- Cone imparts z (poloidal) derivative to the curl of E_r field
- $(\nabla \times E_r) e_{tor} = -\partial B_{tor}/\partial t$
- Allow B_{tor} to grow for a poloidal flux confinement time

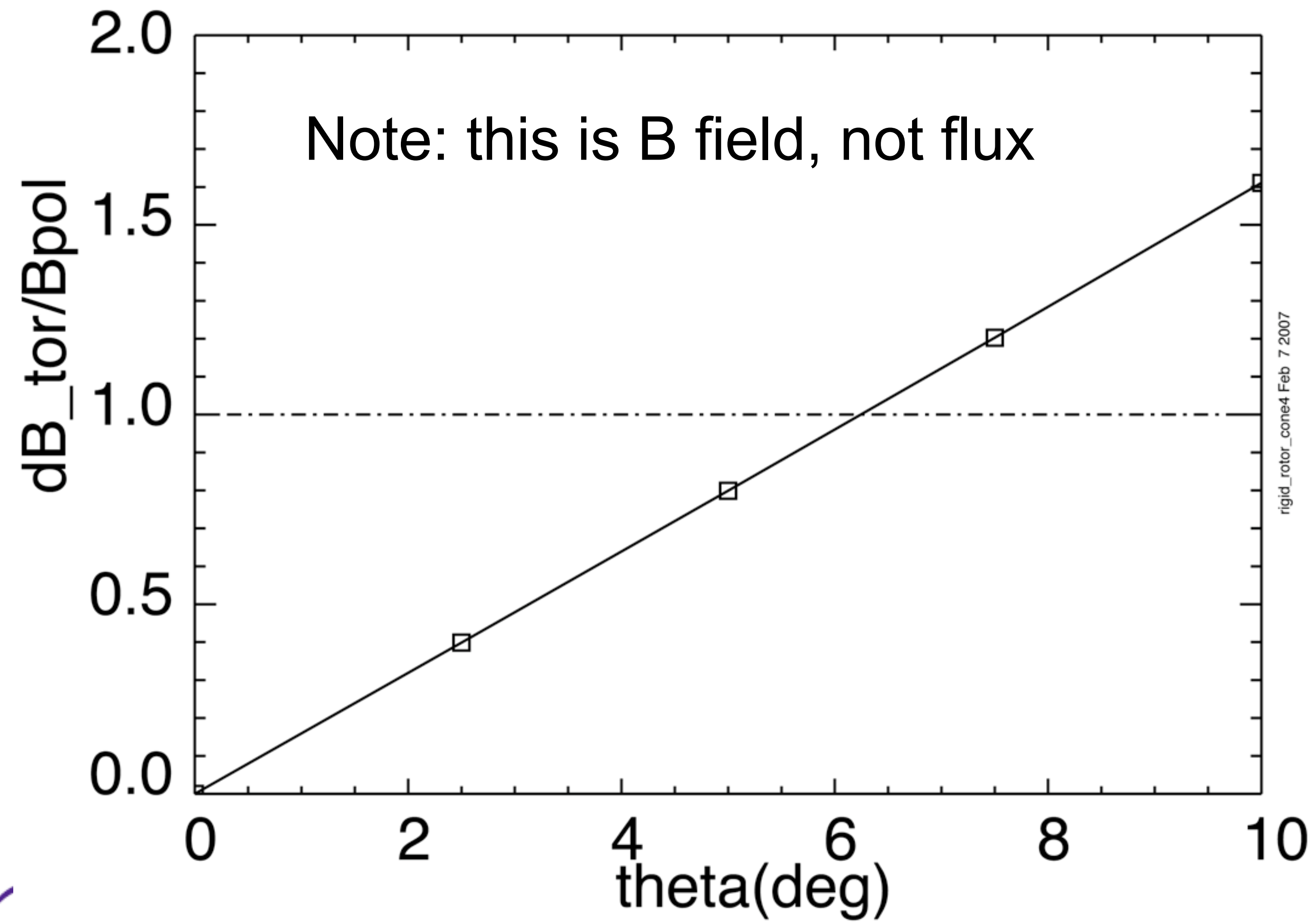


Significant $B_{tor}/B_{pol} \approx 1$

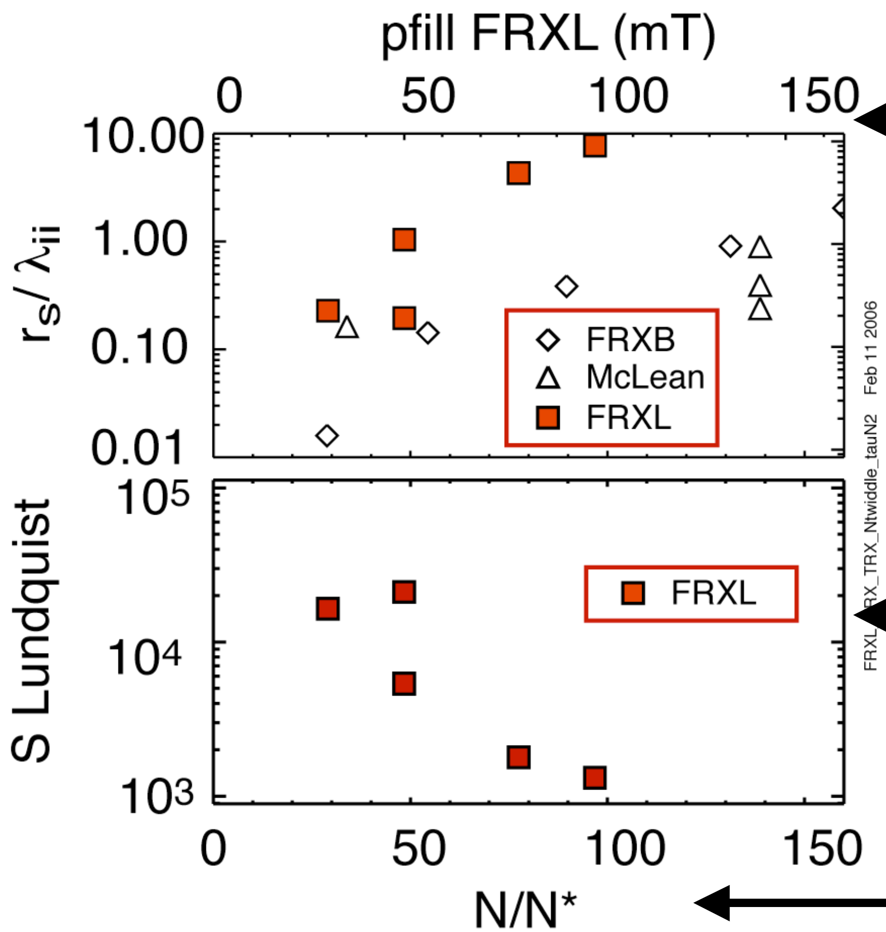
Simple model of conical FRC

- Rewrite Ohm's Law
- $E = \eta J - vxB + JxB/en + \nabla p/en \ldots$
- $\nabla xE = -\partial B/\partial t$ … look at time changing $B_{toroidal}$
- $\nabla xE = \nabla xE(JxB) = [(B\bullet \nabla)J - (J\bullet \nabla)B]/en$
  - curl in cylinder coords, $B_\phi(t=0)=0$
  - $-\partial B_\phi/\partial t \approx B_r\, \partial J_\phi/\partial r + B_z\, \partial J_\phi/\partial z - B_r J_\phi/r$
  - Integrate over flux dissipation $\Delta t \approx \tau_{flux}$
  - $\Delta B_\phi(r) \approx -B_{pol}\, \partial J_{tor}/\partial z\, \tau_{flux}$
  - Where $r_s=r_s(z)$ conically expands in z

Peak $\delta B_{tor}/B_{pol}$(max) proportional to cone angle



FRX-L: highly collisional FRC



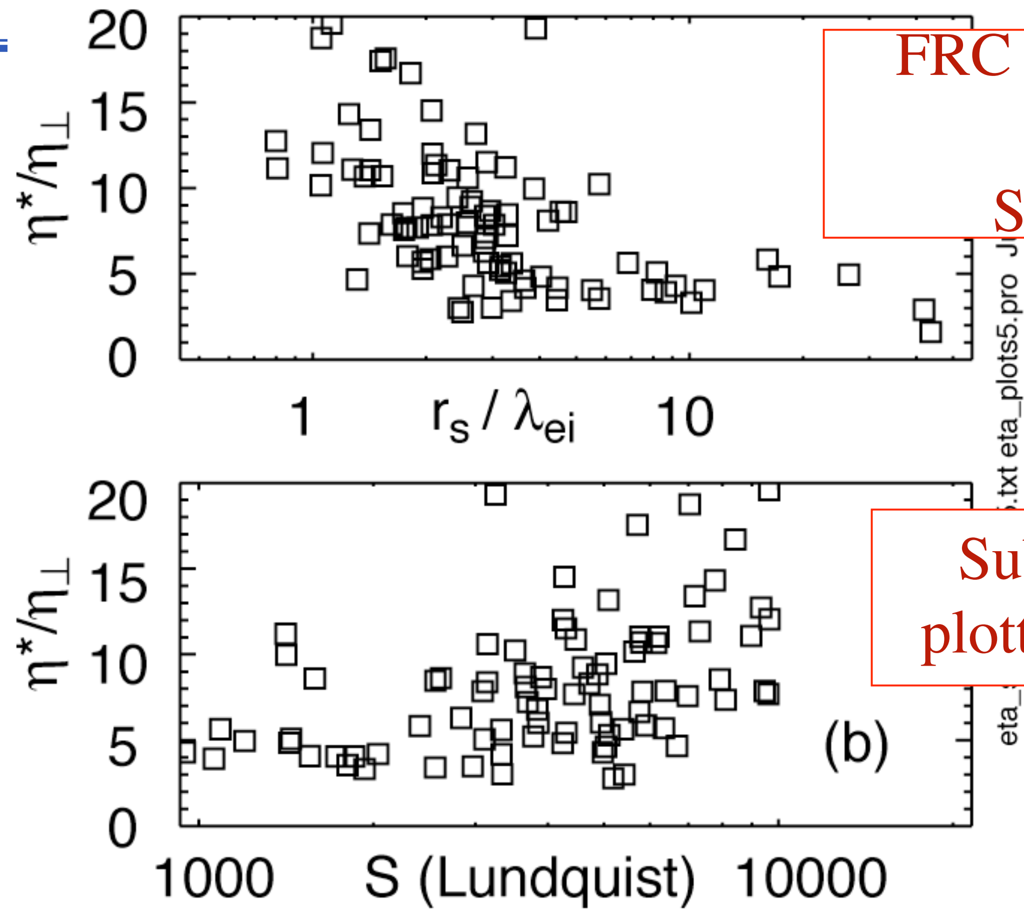
...$\lambda_{ii}=\lambda_{ee}$

- coulomb collisionality Radius / λ_{ii}

- Lundquist number

dimensionless density parameter compares several experiments

Resistivity anomaly shows trends + scatter



FRC size /mean free path

$\lambda_{ei} \approx \lambda_{ii} \approx T^2/n$

Substantial scatter

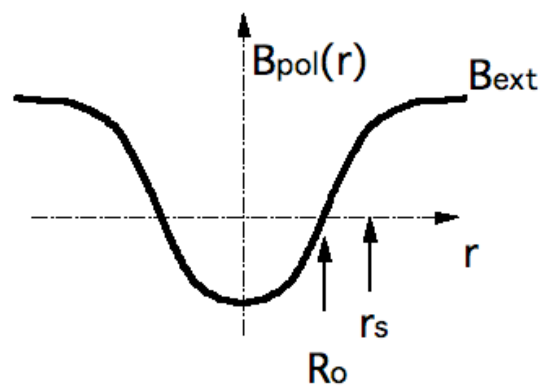
Substantial scatter when plotted against Lundquist #

Anomalous resistivity $\eta^* J^2$ ohmically heats FRC

Los Alamos

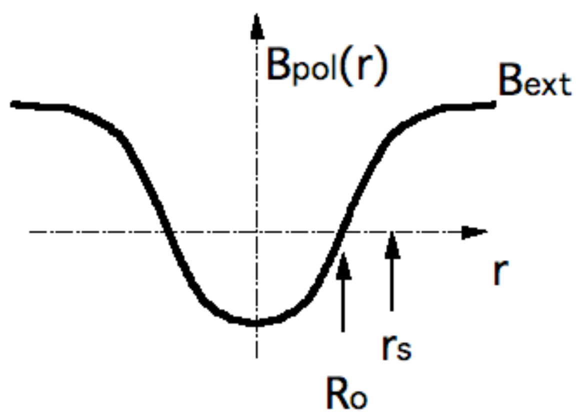
Scattering proportional to magnetic energy?

- If resistivity is due to wave scattering
  - $\eta^* = \nu^*/(\omega_{pe}^2 \varepsilon_0)$ … ν^*= collision frequency
  - Force balance $eEn = \eta^* Jen = -\nabla_\perp W(r)$
- Scattering off magnetic wave energy W proportional to internal poloidal fi
  - $W(r) \approx B_{pol}^2/2\mu_0$
  - $\nabla_\perp W(r) \approx B_{pol}^2/(r_s - R_0) \approx B_{ext}^2/(r_s - R_0)$
    - Where $B_{pol}(r) \approx B_{ext}(r_s - r)/(r - R_0)$
  - $\mu_0 J = \nabla \times B_{pol} \rightarrow J \approx B_{pol}/(r_s \mu_0)$

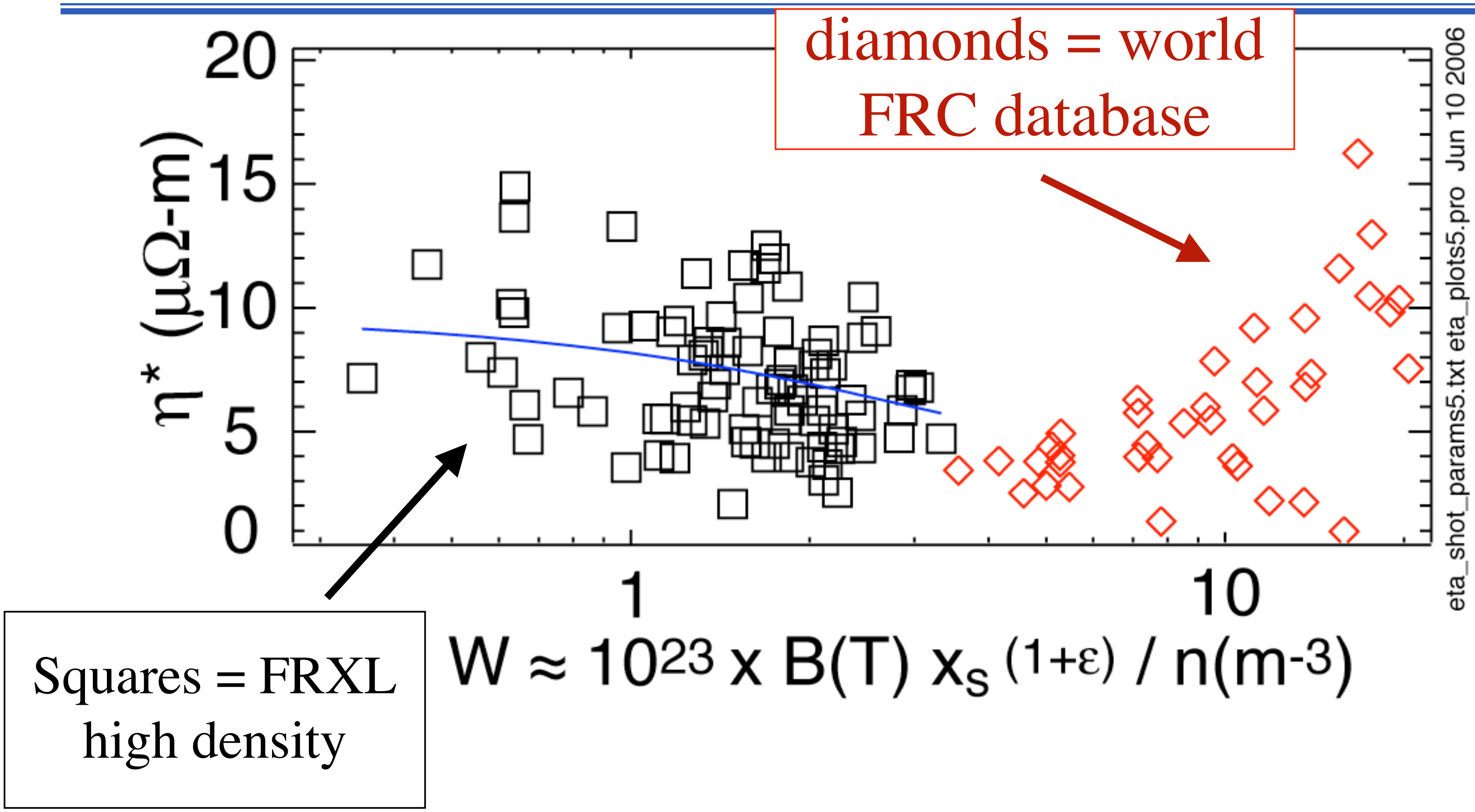


Use FRC scaling laws to find η^* dependence

- $\mu_0 J = \nabla \times B_{pol} \rightarrow J \approx B_{pol} / (r_s \mu_0)$
- η^* in terms of internal energy
  - $\eta^* = -\nabla_\perp W(r) / Jen$
- scaling relates internal flux to external B field
  - $\Phi_{pol} = \pi r_c^2 B_{ext} \bullet x_s^{1+\varepsilon}$
  - ε is an edge shape factor
- η^* then scales external B field
  - ***$\eta^* \approx C_{wave} B_{ext} (1 + x_s)^{1+\varepsilon}/n$***
    - Where $B_{pol}(r) \approx B_{ext} (r_s - r)/(r-R_0)$



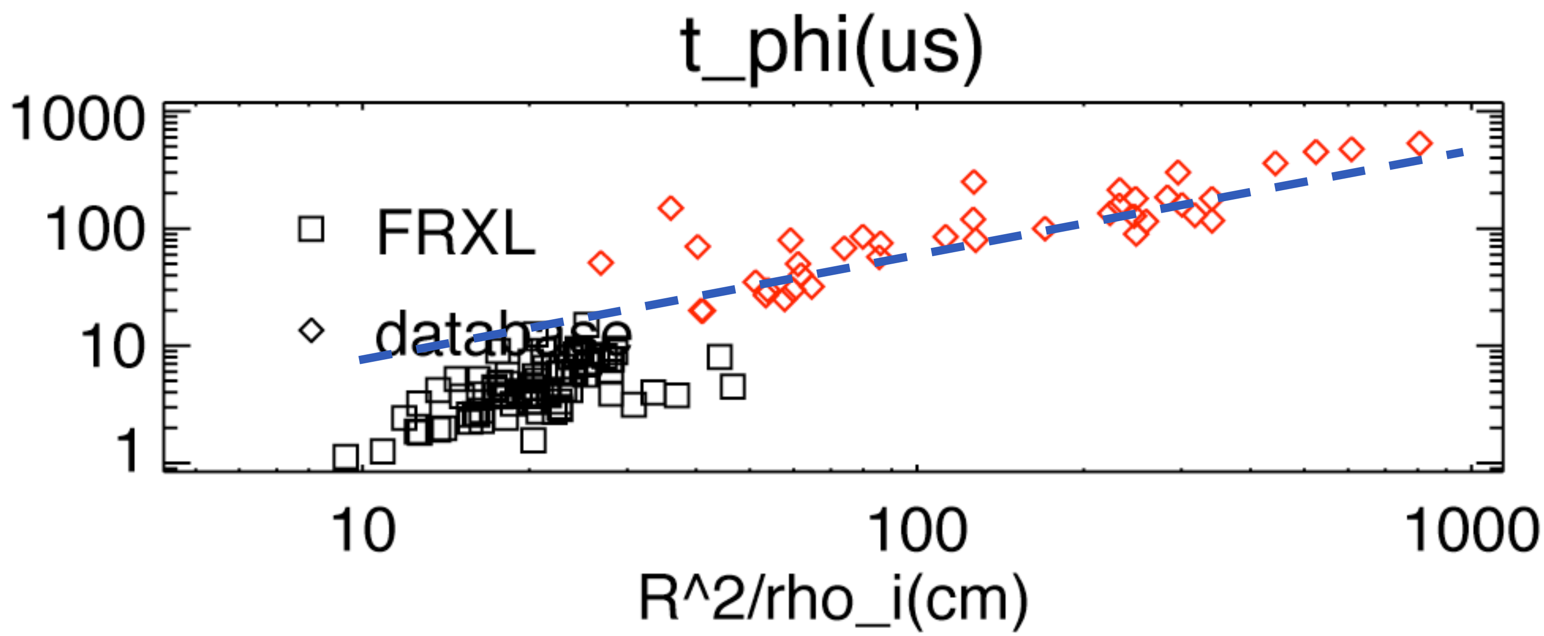
Resistivity plotted vs wave energy



Flux confinement time fits "standard" model

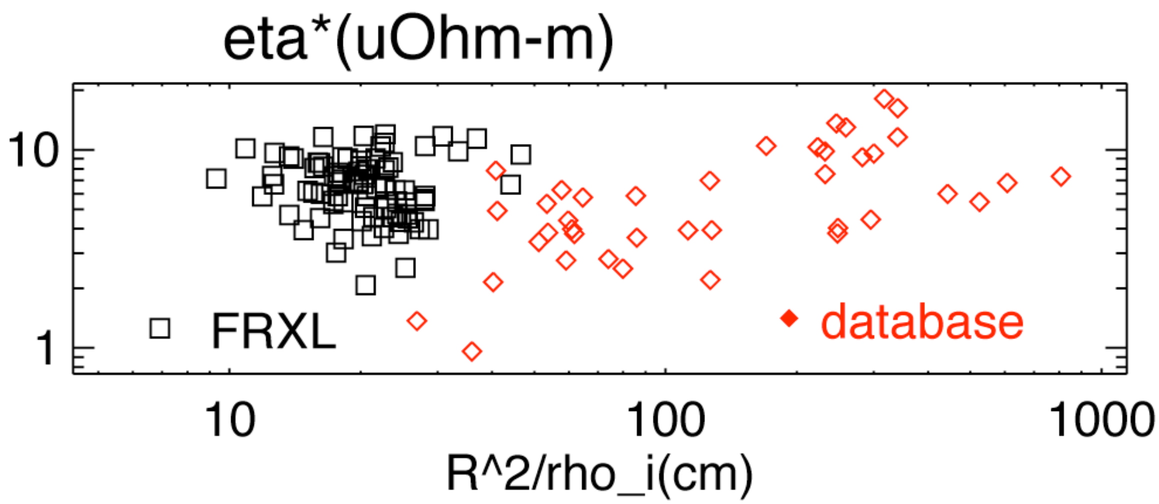
Red diamond = FRC worldwide database (no FRXL)

Black square = FRXL high n: High flux FRXL has longest lifetime

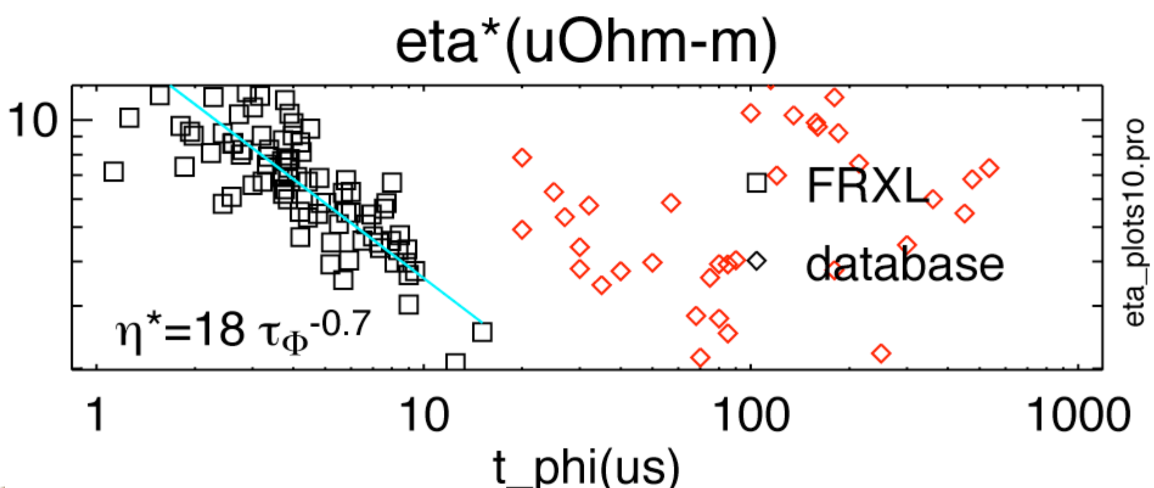


$\tau_{\Phi}(\mu s) = 0.5 \bullet R^2(cm^2)/\rho_i(cm)$

FRC resistivity scales differently at high n

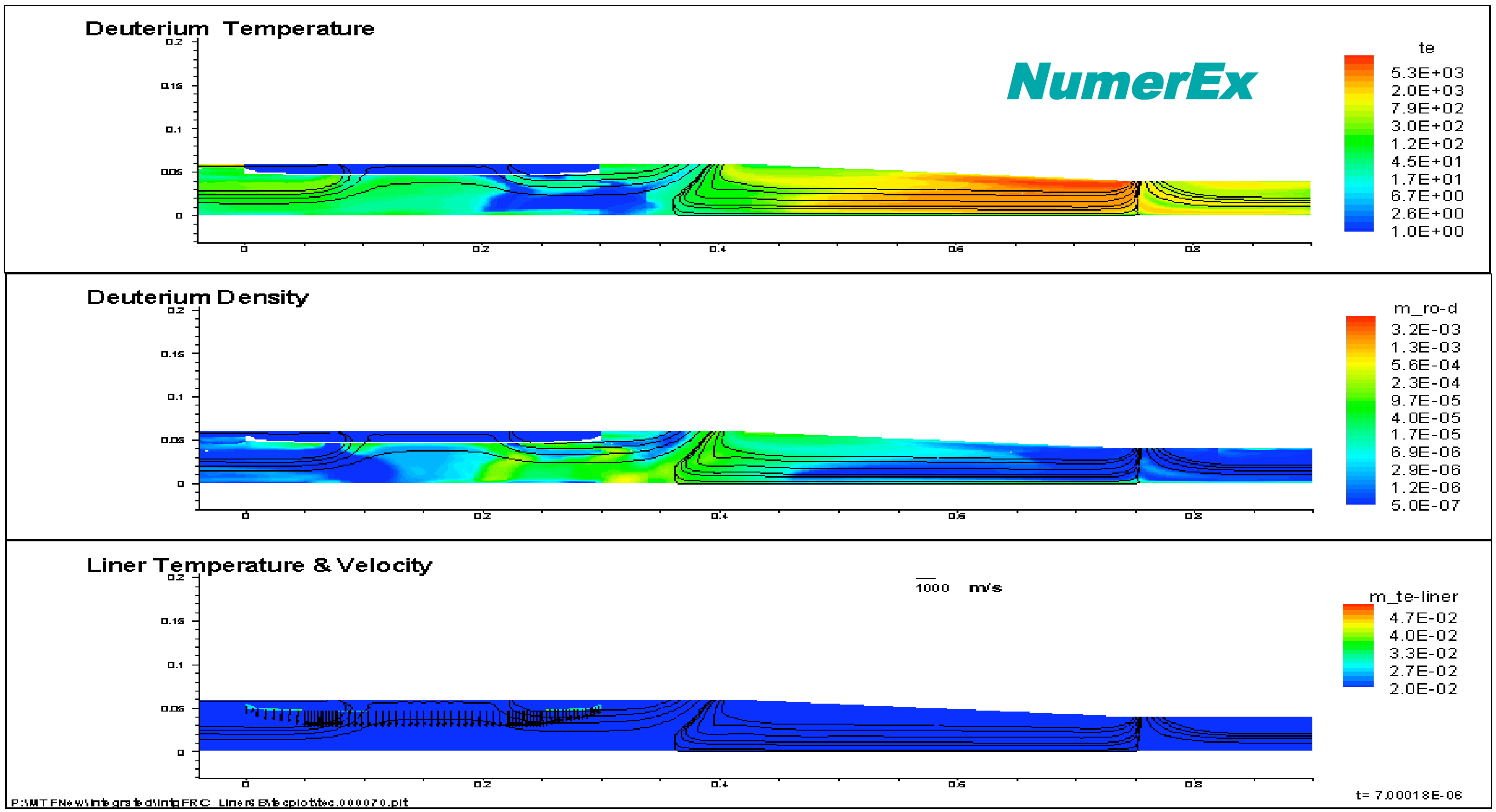


World FRC database $\eta^* \approx R^2/\rho_i$



FRX-L database $\eta^* \approx \tau_\Phi$

MACH2 integrated FRC simulation formation, translation, liner compression



Movie

Summary

- MTF … high risk high pay off adventure
- FRXL data → Physics design for MTF
- Hardware in fabrication for 2007
- Conical theta coil and translation allows physics window on FRC
  - MHD mysteries: helicity, resistivity