Magnetized Target Fusion collaboration 2004: recent progress

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http://fusionenergy.lanl.gov
wsx.lanl.gov
abstract

Magnetized Target Fusion (MTF) may be a low cost path to fusion, in a regime that is very different from, and intermediate between, magnetic and inertial fusion energy. It requires compression of a magnetized target plasma and consequent heating to fusion relevant conditions inside a converging flux conserver. To demonstrate the physics basis for MTF, a Field Reversed Configuration (FRC) target plasma has been chosen that will be translated axially to a region where it can be compressed. We show recent and improved FRC formation data, example deformable liner implosions, and a conceptual design for the upcoming translation experiments. We also describe a multi institution collaboration and some physics based estimates of the plasma behavior for this and other compression approaches. Our experimental research focuses on demonstrating MTF with the FRC, but many scientific issues lie on this path. The FRC is an elongated, self-organized compact toroid equilibrium that is extreme among magnetic configurations, apparently relaxed to a non force free state. There is high plasma $\beta\approx 1$, small toroidal field, probably cross-field diamagnetic current and flows, vanishing rotational transform, magnetic shear, helicity and anomalously large resistivity. Related fundamental plasma physics questions extend beyond MHD models, and are relevant to geophysical and astrophysical phenomena.
outline

• Magnetized Target Fusion (MTF): many pulsed approaches to fusion
• Physics & engineering issues
• Community with collaborations
• FRC as a plasma target for compression
• FRC results at LANL
• Summary & list of related presentations
magneto-inertial fusion

- Pulsed, high pressure approaches to fusion
- Inertial + magnetic confinement
- Magnetic field plays essential role
- **Magnetized Target Fusion - MTF examples**
  - Pulsed high density FRC
  - Plasma jet compression of target
  - Field reversed configuration (FRC) in a beer can
MTF physics & engineering issues

- Keep devices, coils, hardware simple
- Advantages vs disadvantages of pulsed scenarios?
- How much gain is sufficient?
- Schemes, technologies for plasma compression
- Physics with large $\beta$, flow, density, collisionality
- Stability of target plasma
- Standoff drivers
- Transport, confinement of target
- Optimize target formation, design & build translation
community wide collaboration

- Attack physics & engineering issues; wide variety of approaches within MTF
  - AFRL Kirtland: Degnan - imploding flux conservers
  - LLNL: Ryutov - edge-wall xport, stability; standoff
  - Univ Wash:
    - Slough - optimize FRXL formation
    - Hoffman - FRC
  - U Wisc: Santarius - plasma jet compression
  - U Nevada Reno: Siemon - wall confinement, z-pinch
  - GA: Parks - standoff drivers, FRC concepts
Converging flux conserver: critical technology for MTF

• Liner = radially imploding cylinder = flux conserver
• Deformable liner
  – Keep the large holes at the ends => ease FRC entry
  – Implode center section
  – Avoid sliding contacts at the ends
  – Reduce impurities
  – Better diagnostic access
• Two approaches
  • Z-pinch: axial current
  • Theta pinch: inductive, non contact drive
Connecting current to the liner
Z-pinching drive

Uniform-thickness liner

Variable-thickness or “shaped” liner

Glide-plane electrodes used in 1999 Shiva-Star experiments would interfere with FRC injection

Shaped liner recently tested
Z-pinch imploded deformable liner radiographs

Static radiograph: liner adjacent to electrode, prior to experiment

simulation contours overlaid on radiographs

$t=22 \mu s$,

$\approx 0.5 \mu s$ before peak compression

Bottom portion of liner includes contacts
Reduced diffusion: collisional, high $\beta$

- MTF plasmas are
  - High beta
  - High collisionality
- Diffusion coefficient is reduced at core
  - Compare gradient lengths $L_n > L_B$
- Strong collisionality stabilizes drift modes, favorable for core confinement

\[ \xi = \frac{\partial \ln B}{\partial \ln n} \]

$D(0) \sim 0.3 D_{Bohm}$

D. Ryutov LLNL
Increase trapped flux: High Power Helicon (HPH) PI

Univ Wash. J.Slough collaboration with FRXL

Improve formation of FRXL FRC:
• Avoid flux limit found with ringing θ PI
• Separate PI from HV θ-pinch coil circuit
• Prevent premature plasma loss from conical coil during translation

<table>
<thead>
<tr>
<th>HPH to date</th>
<th>HPH planned</th>
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<tbody>
<tr>
<td>$P_{\text{abs}} = 20\text{ kW}$</td>
<td>$P_{\text{abs}} = 1\text{ MW}$</td>
</tr>
<tr>
<td>$u_z = 17 - 50 \text{ km/s}$</td>
<td>$u_z = 60 \text{ km/s}$</td>
</tr>
<tr>
<td>$A_p = 4 \times 10^{-3} \text{ m}^2$</td>
<td>$A_p = 8 \times 10^{-3} \text{ m}^2$</td>
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<tr>
<td>$\Rightarrow n = 1.7 \times 10^{20} \text{ m}^{-3}$ (≈ 0.2 – 10^{20} \text{ meas.})$</td>
<td>$\Rightarrow n = 5 \times 10^{21} \text{ m}^{-3}$ (&gt; 30% init. ionized)</td>
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Los Alamos
Rotating Barrier Field for Ion Spin-up Control
Univ Wash. J.Slough collaboration with FRXL

During Field Reversal:
• Counter-rotate ions ⇒ increase FRC stable period
• Increase lift-off flux in FRXL FRC
• Reduce impurity pick-up

Equilibrium:
Provide rotational stabilization
Improve particle confinement

Cell dimensions:
- \( R_{\text{quad}} = 0.17 \text{ m} \)
- \( R_{\text{rings}} = 0.14 \text{ m} \)
- \( R_{\text{wall}} = 0.135 \text{ m} \)
U Wisc. Plasma-Jet compression Modeling Plans

**J. Santarius - Fusion Technology Institute**

- Radiation hydrodynamics using UW’s BUCKY code:
  - Objective: check analytic models and find optimized MTF cases
  - 1-D Lagrangian code; cylindrical or spherical geometry
  - D-T equation-of-state and opacity tables
  - Full burn dynamics, including $\alpha$’s
- $\alpha$ interaction with B-field at boundary layers using SNL’s Icarus code:
  - 2-D discrete simulation Monte Carlo (DSMC) code
  - Collisions; atomic physics
  - Sophisticated gridding; parallelized
UNR experimental plans to study self-organized inverse z pinch for MTF: Poster by Siemon et al.
Flux compression on Atlas to generate megagauss magnetic fields for MTF: Poster by Goodrich et al.

Atlas
23 MJ
20 MA
Magnetized Target Fusion (FRC)

This is a fusion concept where:

- Plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- Plasma density is high $\sim 10^{19}$ cm$^{-3}$
- Current density can be 1000 MA/m$^2$
- Magnetic confining field is 500 Tesla!
- Auxiliary heating power $\sim$ 1000 Gigawatts!
- Heating is “slow” adiabatic compression
- Initial physics research with existing facilities, technology
- Each pulse, in a reactor, has a fresh liquid first wall
- repetition rate is $\sim$ 0.1 Hertz, i.e. there is time to clear the chamber from the previous event
MTF: compress a magnetized target

- MTF uses flux conserving compression
  - metal liners $J_z \times B_0$ driven
  - gaseous or plasma pushers
  - compressible liquid shells

- PdV heat a magnetized target plasma to fusion conditions
  - spheromak
  - field-reversed-configuration (FRC)
Operation between MFE and IFE regimes

- MTF plasma regime \( (n \sim 10^{19}-10^{20} \text{ cm}^{-3}, T \sim 5 \text{ keV}) \)
  - Densities lie between magnetic fusion energy (MFE) and inertial fusion energy (IFE) ranges

- Advantages
  - Fusion reactivity scales as density squared \( \gg \) conventional MFE.
  - Magnetic insulation reduces power compared to ICF
  - High energy efficiency
  - Pulsed-power requirements using existing facilities.
FRX-L Project: present and future

High density FRC’s

STEP 1: Formation

STEP 2: Translation
Design for SHIVA@AFRL

STEP 3: Compression
compression to fusion conditions
Adiabatic ~ cm/µs

FRC Goal Parameters:
- density \(n \sim 10^{17}\) cm\(^{-3}\)
- temperature \(T_{total} \sim 500\) eV
- lifetime \(\tau_E > 10\) µs

Present funded scope 4 years

End of 4 years FRX+L
Excluded flux radius $r_s \approx 3\text{cm}$ at last closed flux surface
Field null radius $R \approx 2\text{cm}$, separatrix length $z_s \approx 30\text{cm}$
$J \cdot B \approx 0$, i.e. not a Taylor relaxed equilibrium
FRC is a good target for MTF

• Robust magnetic equilibrium during compression
  – Survives translation, bounce, shock heating, compression
    • Because of equilibrium + field line tension, radial compression contracts FRC axially, 2.4D compression
    • Stability properties are ≈ constant during compression
  – Natural divertor, particle exhaust, direct energy conversion
  …

• high density FRC has advantages
  – Fusion reactivity increases as n²
  – pulsed FRC is easy path to high energy density=> high fusion reactivity
FRX-L Experimental Bay at LANL
FRX-L theta coil & Diagnostics

Half FRX-L theta coil, flux loops

8-chord laser interferometer beams, vertical view through slotted theta-coil
FRX-L FRC 2003 data

- FRC plasma
- high \( n \approx 1 \times 10^{22} \text{m}^{-3} \)
- hot
  \( T_e + T_i \approx 250 \text{eV} \)
• Increase
  • Lifetime $\tau_\Phi \approx 10 \, \mu\text{sec}$
  • Density $n \approx 2-3 \times 10^{22} \text{m}^{-3}$
  • Temperature $T_e + T_i \approx 300 \, \text{eV}$

• Diagnostics
  • 8-chord interferometer
  • magnetics probes
  • visible spectroscopy
  • two optical tomography side-on arrays
  • (almost) operational multi-point Thomson scattering system.
FRX-L: a highly collisional FRC

High coulomb collisionality $r_s \gg \lambda_{ei}$

$r_s$/Coulomb mean free path vs $N/N^*$ reference line density

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

• So far, similar to conventional wisdom
  – Resistivity is anomalous, 10-20 x Spitzer, and not dominated by Coulomb collisions … published
  – Flux trapping and retention is well characterized by FRC scaling laws … show data here

• Things not investigated yet
  – Flow
  – Relaxation
  – Particle, flux loss mechanisms
flux retention wrt other FRC’s

Theoretical/empirical scaling favors large devices

- $f_\Phi = 0.85 r_{\text{wall}} (m) p_0 (mT)^{1/2}$
- FRXL is small, expect collisionality to change the physics eventually
- Normalized equilibrium FRC flux $f_\Phi / r_{\text{wall}}$ vs fill pressure & predictions

Very high $n > 10^{17} \text{cm}^{-3}$, $p_0 = 150 \text{mTorr}$, non optimized
trapped lift off flux $\Phi_{LO} \Rightarrow$ equilibrium $\Phi_{equil}$

$\Phi_{equil}/\Phi_{LO} = 0.85 \ p_{0}(mT)^{1/2}$

- Scatter plot of >100 shots
- Recent shots have better main bank timing, more bias and lift off flux

$\Phi_{equil}$ scales with $\Phi_{LO}$
flux retention fraction: other FRC’s & model

\[ f_{\Phi} = \frac{\Phi_{\text{equil}}}{\Phi_0} \]

\[ 0.85 \, r_{\text{tube}}(m) \, p_0(\text{mT})^{1/2} \]

\[ f_{\Phi} \text{ for high density FRC fits conventional scaling} \]
Enhance ohmic over radial shock heating

\[ \frac{T_{\text{impl}}}{T_{\text{model}}} = 143, 278 \text{eV} \]

- \( \frac{T_e + T_i}{T_{\text{impl}}} \) vs \( G_{\text{LO}} = \Phi_{\text{LO}} / \Phi_{\text{GN}} \)
- \( G_{\text{LO}} = \text{lift off} / \text{Green Newton flux} \)
- Main bank field modulation affects nominal implosion temperature \( T_{\text{impl}} \)

Large \( G_{\text{LO}} \)

- dissipate trapped flux
- ohmically heat high density FRC
Other MTF related presentations

• Poster session #2
  – Wurden  FRXL status, diagnostics
  – Zhang    FRXL data details
  – Siemon   inverse Z pinch
  – Ryutov   plasma liners
  – Santarius plasma jet MTF

• Poster session #3
  – Ryutov  magnetic transport, field perturbations
  – Slough  PHD pulsed high density FRC
summary

• MTF pulsed approach to fusion is very different from mainstream and most ICC scenarios
• Several collaborators investigate physics & engineering
• Improved high density FRX-L target plasmas scale with conventional FRC wisdom
• 2004: New diagnostics, design FRX-L translation exp’ts, growing theory support
• Four year plan => physics demonstration of MTF FRC implosions Shiva Star, Kirtland AFRL
Zeroth announcement

New developments in compact torus plasma research

Santa Fe, NM
20-22 Sep 2004

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