Sustainment of Stable FRC by Neutral Beam Injection and Current Transformer

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Outline

- **Introduction**
  - **Critical issues of FRC research**
  - **Magnetic Reconnection Experiment (MRX) device**

- **The proposed experiments on MRX**
  - **FRC Formation by merging counter-helicity spheromaks**
  - **Current sustainment and amplifications by transformer**
  - **Stabilization and sustainment by neutral beam injection**

- **Summary**

Critical Issues for FRC Concept

"FRC 2001" (Steinhauer et al.)

- **Develop reactor-relevant formation schemes**
  - **Efficient and practical techniques to form large-flux FRCs**

- **Understand and control global stability**
  - **Establish stable, large-s FRCs**

- **Sustain FRC for much longer than the confinement time**
  - **Decouple physics of sustainment from confinement**

- **Characterize and understand transport properties**
  - **Identify main transport mechanisms**

Recent Progress

- **Formation**
  - Slow formation of FRC by spheromak merging on TS-3 and SSX
- **Stability**
  - New understanding of kinetic stability through theory and simulation studies
- **Sustainment**
  - Demonstrated FRC sustainment by Rotating Magnetic Field (RMF) technique
- **Transport**
  - Resistivity and confinement scalings

Proposed FRC Experiments to Address These Critical Issues

- **Formation**
  - **Counter-helicity spheromak merging to form FRCs with much larger flux (~20mWb)**

- **Stability**
  - **Study global stability in wide parameter ranges for shape and ion kinetic effects**

- **Sustainment**
  - **Demonstrate and study FRC sustainment (for ~1ms) by neutral beam injection and current transformer**

- **Transport**
  - **Initial assessments of particle and heat confinement**

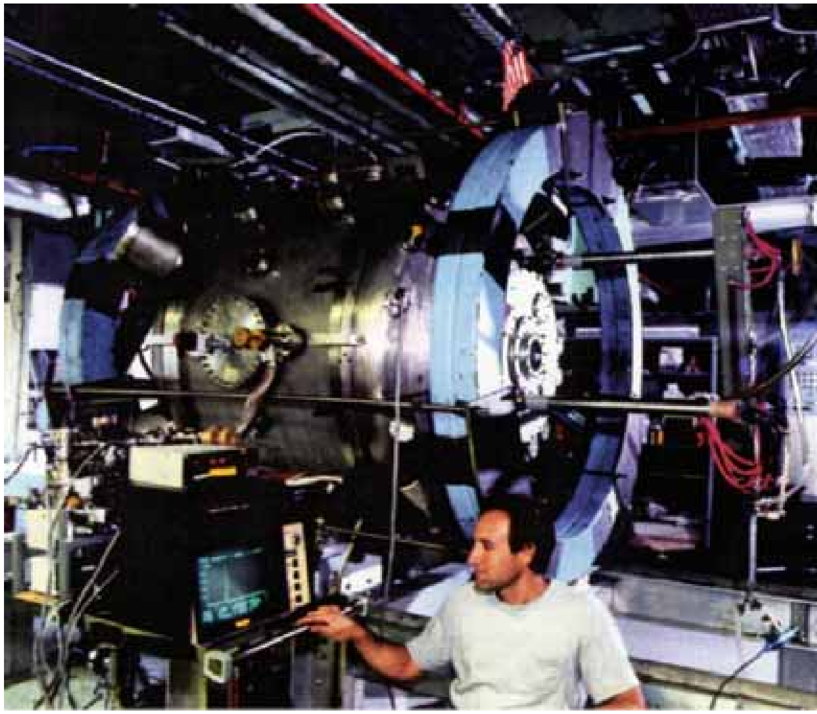
Proposed Experiments Will Be Done on Magnetic Reconnection Experiment (MRX)

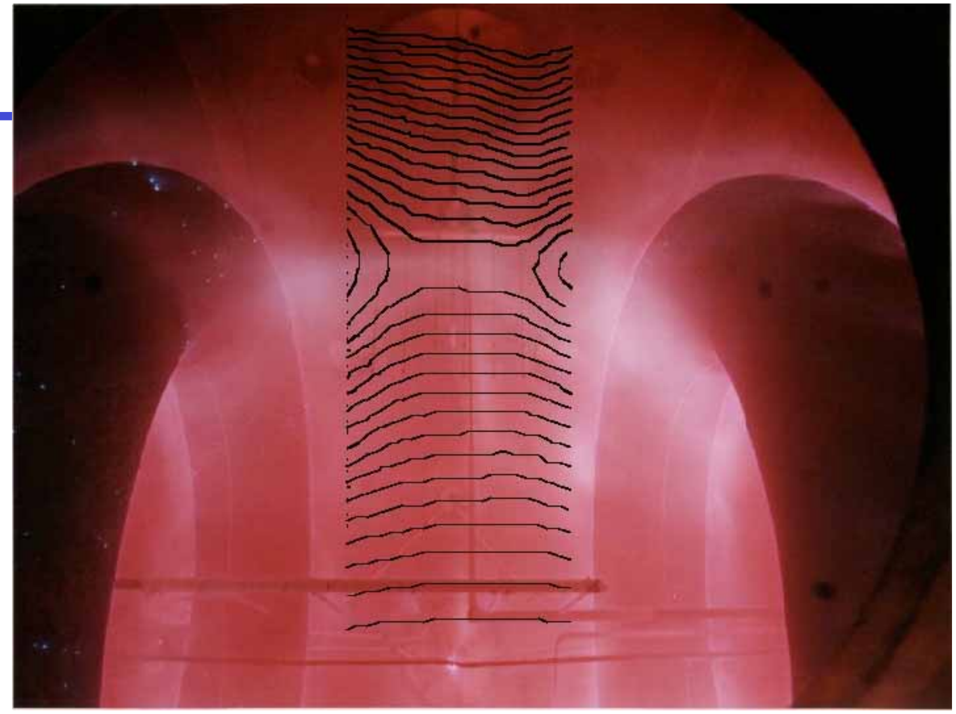
- **A highly-versatile device to study magnetic reconnection and related topics**
  - **also as part of an NSF center on magnetic self-organization**

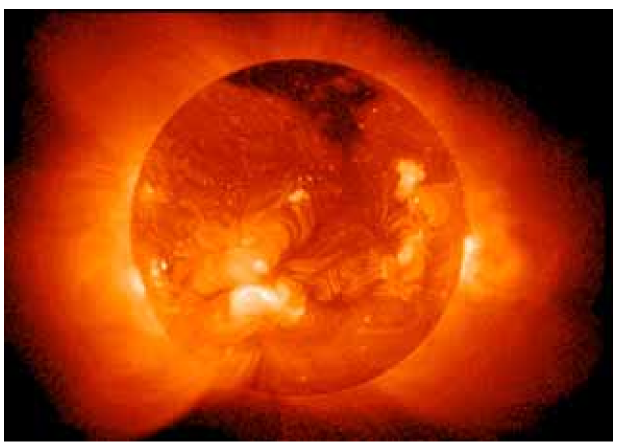
- **Existing facility includes**
  - **Fluxcore systems**
  - **Large power capacitor banks**
  - **An extensive set of diagnostics**

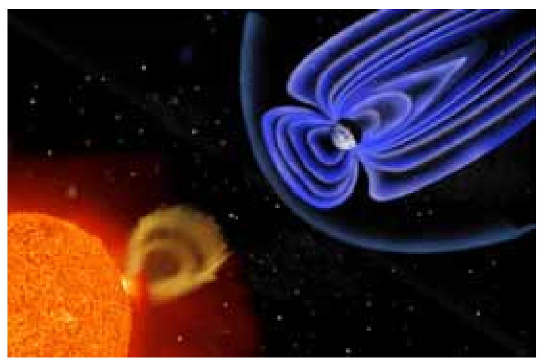
- **Recently upgraded for the purpose of the extended reconnection study**
  - **Highly-leveraged investments for the proposed experiments on FRC**

Magnetic Reconnection Experiment









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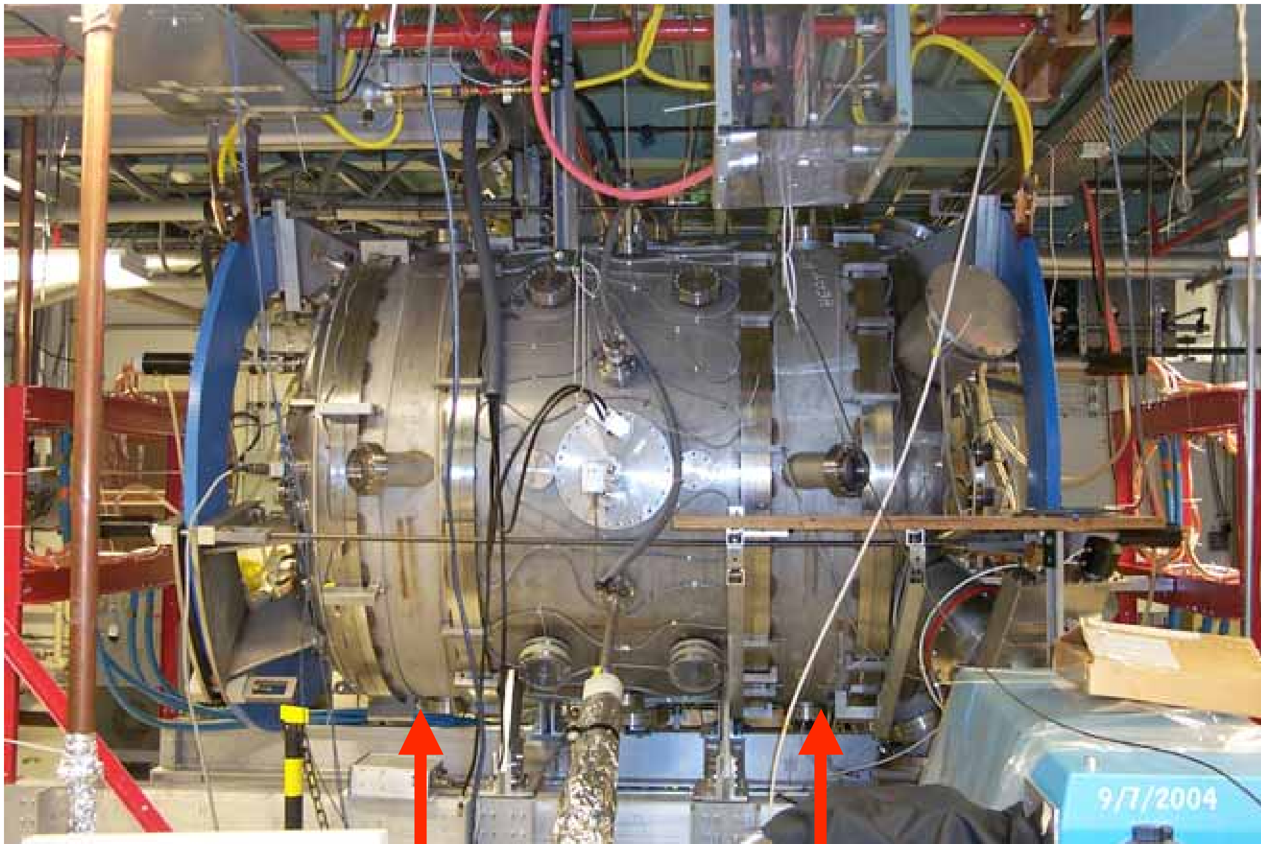
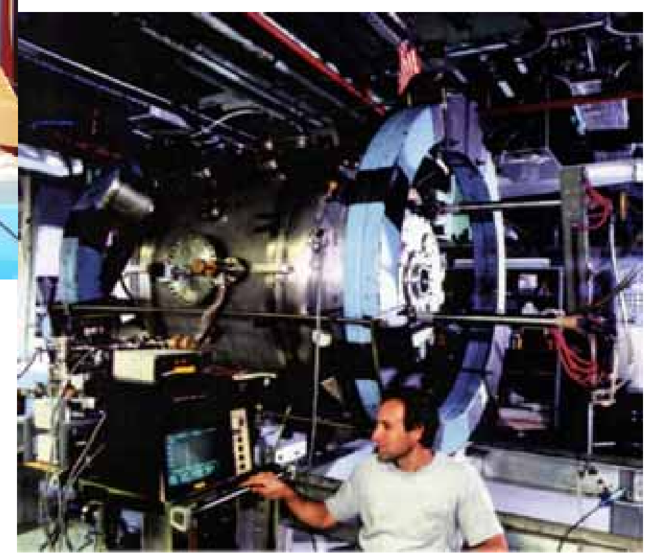
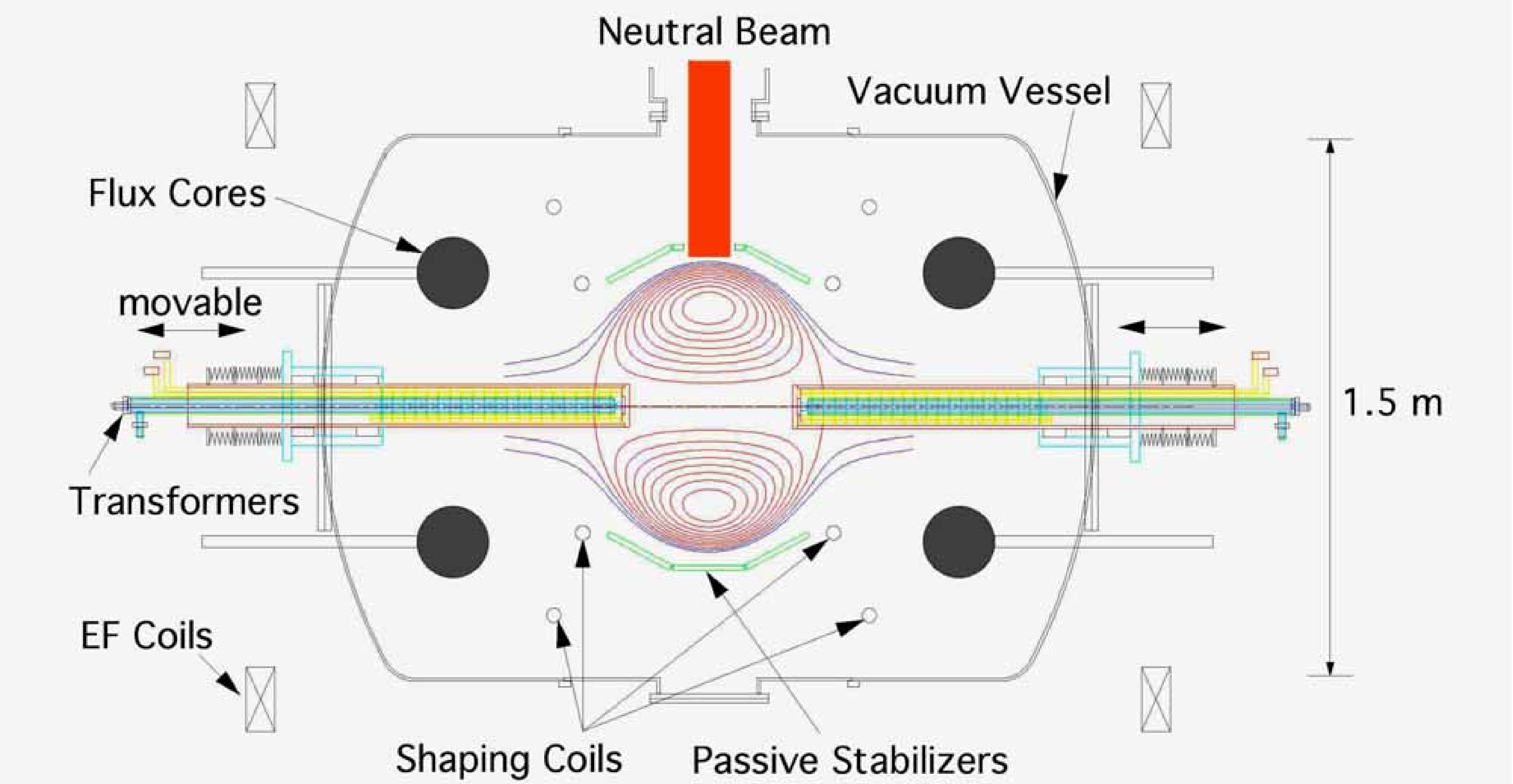
Newly Upgrade Vacuum Chamber



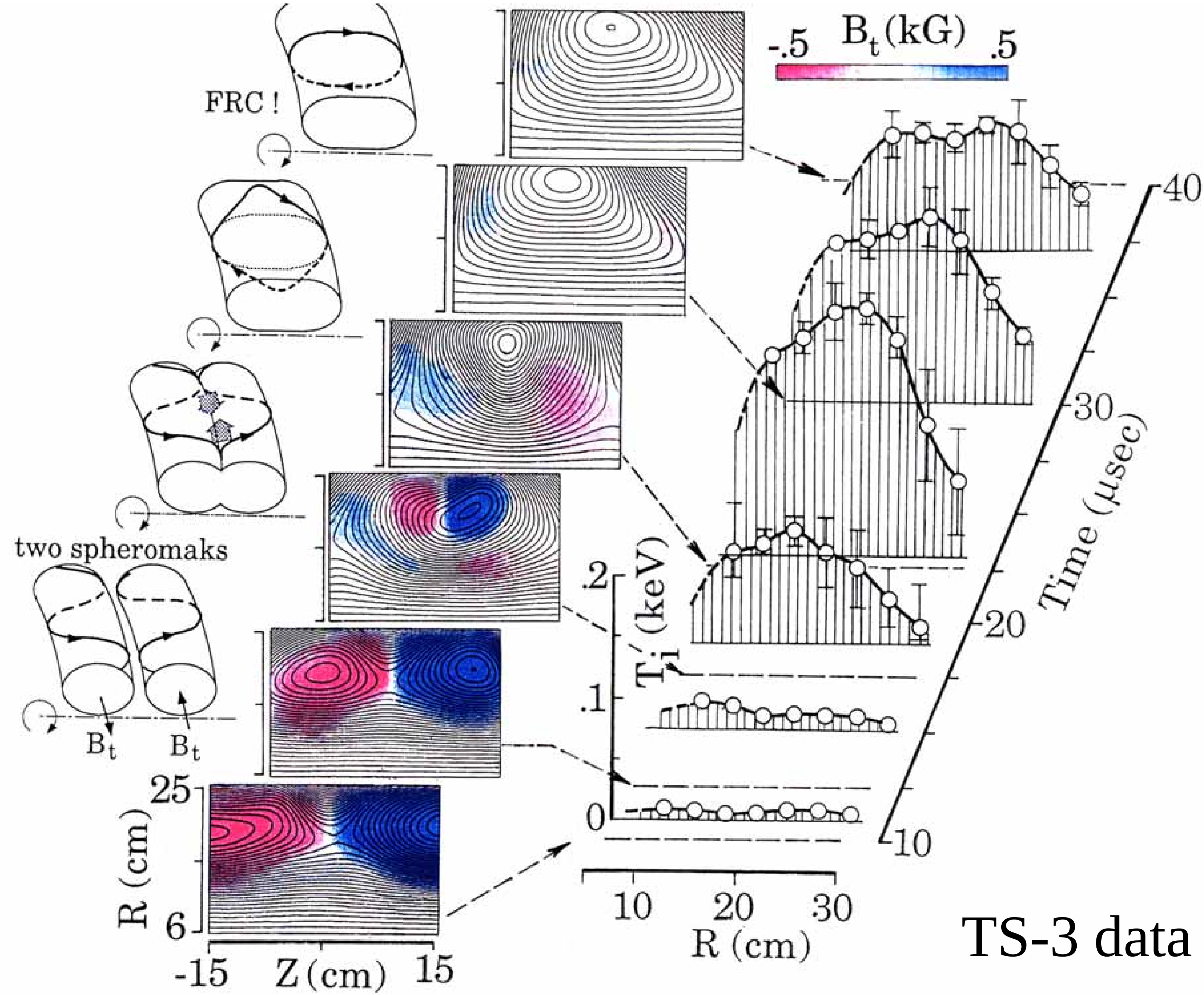
Newly added spool pieces



Proposed Configuration to Study FRC

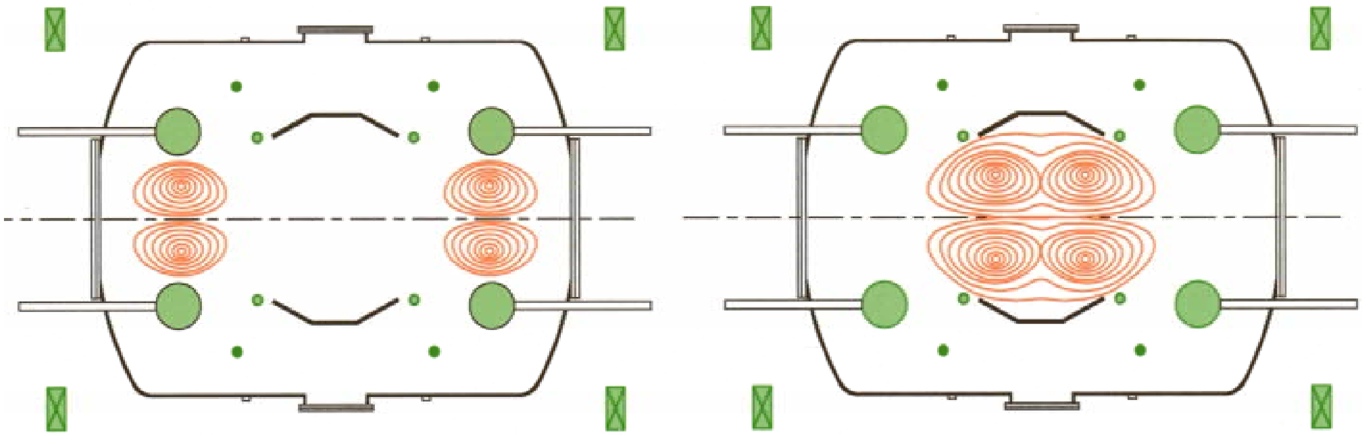


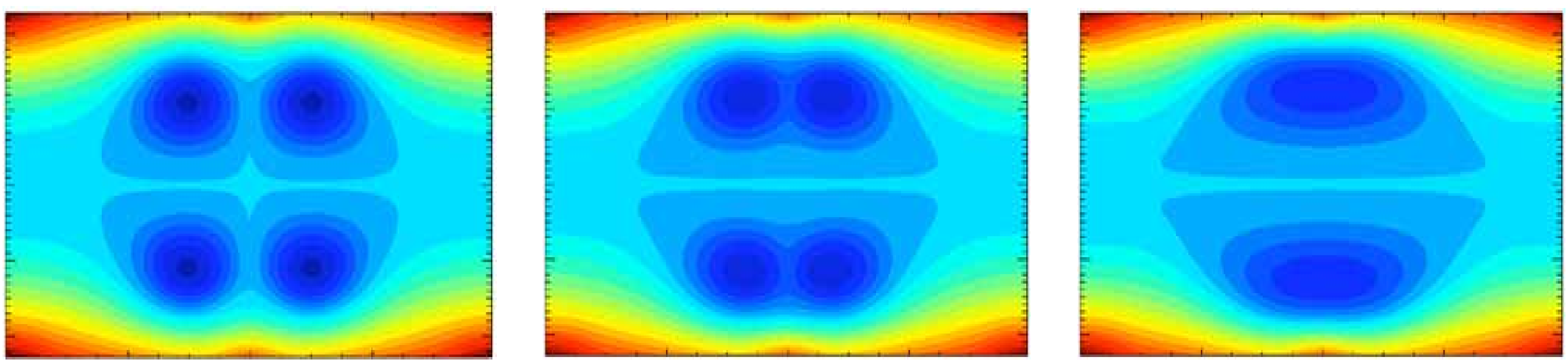
Formation *Sustainment* *Stability*


FRC !
two spheromaks
B_t
B_t
-.5
B_t (kG)
.5
R (cm)
25
6
-15
Z (cm)
15
T_i (keV)
.2
.1
0
10
20
30
R (cm)
Time (μsec)
10
20
30
40

TS-3 data

FRC Formation on MRX





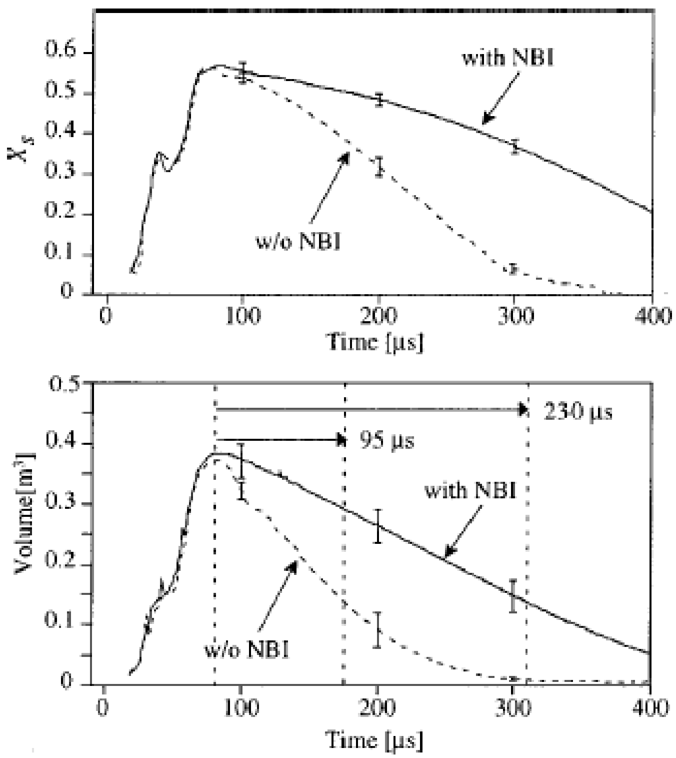
2D MHD simulation for Rs=40cm, S*=18, $n=1\times10^{14}$ cm^{-3}:

1) Bext=1.0kG, Ip=120kA, T=350eV, Flux=15mWb

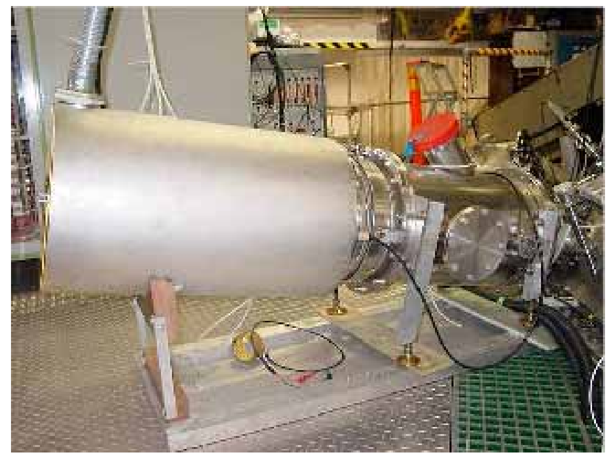
2) Bext=1.5kG, Ip=180kA, T=650eV, Flux=22mWb

FRC Sustainment by Neutral Beam Injection

- Favorable initial results from FIX
- Complimentary to RMF technique



Results from FIX

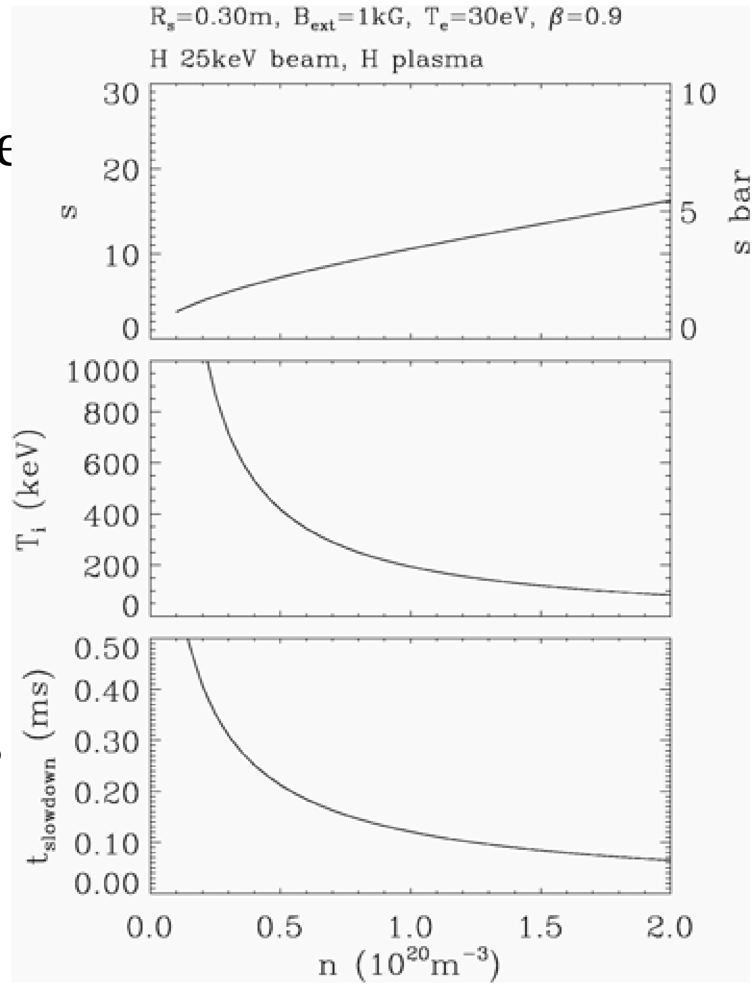


Beam Energy	20-25 keV
Energy stability	< 5%
Beam Power	Up to 1.5 MW for H
Beam Size	4.5"D with <10% losses
Beam Composition	<10% of molecular ions
Current stability	< 10%
Pulse duration	≥1 ms
Repetition Rate	1 pulse per >2 min
Distance from plasma center	1.8 m

Neutral Beam from MST

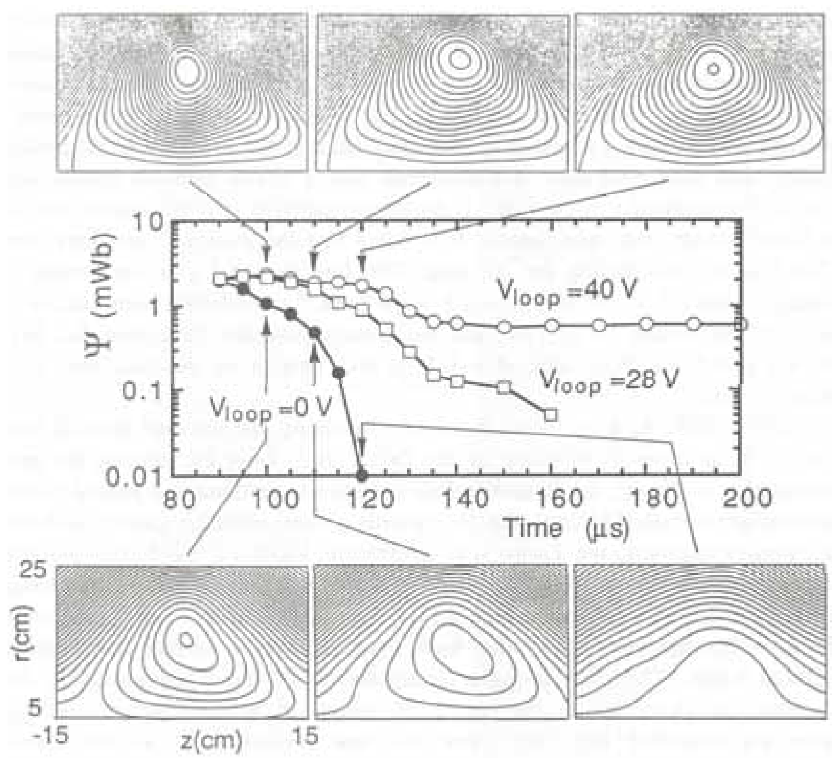
Injection of Low-energy, High-current Neutral Beam

- 25 keV, 60A (1.5MW) beam
- Last ~1.5ms > confinement time
- Short slowdown time (.1-.3ms)
- Heat mostly electrons (97%)
- Favorable beam ion confinement and power deposition
- Additional current drive due to electron thermal-electric effects
  [Hassam et al. PRL **83** (1999)2969]



FRC Sustained and *Amplified* by Current Transformers

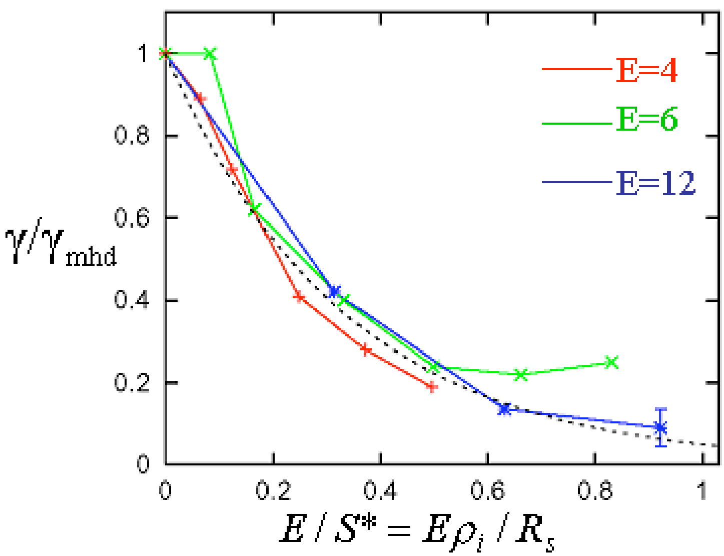
- Two transformers from each end with adjustable distance
- Total available flux of 50mWb (single swing)
- Two uses:
  - Sustain and amplify FRC
  - Amplify spheromaks before merging
- Enable large target FRC plasmas for NBI
- Favorable initial results from TS-3



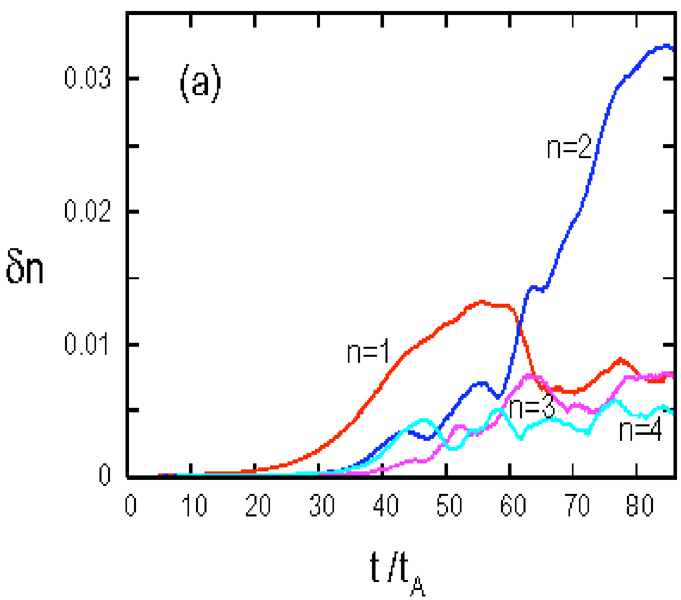
Results from TS-3

Recent Progress by State-of-art Simulations

- **3D hybrid (fluid electrons and full-orbit ions) and MHD simulation codes (HYM)**



Linear tilt stability



Nonlinear evolution of prolate FRC with S*=20

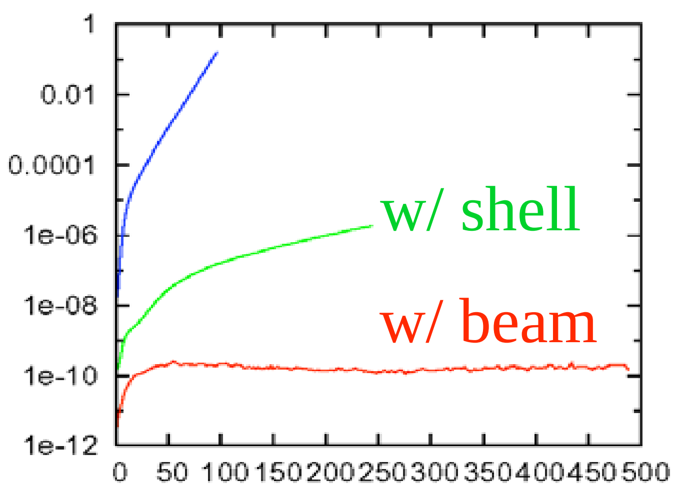
Stability Study in Wide Parameter Ranges
(Guidance from and Comparisons to Simulations)

- Experimental study of stability as functions of
  - Plasma shape (0.5 < Elongation < 2)
  - Kinetic parameter (5 < S*<40)
  - Boundary conditions (close-fitting conducting shells)
  - Flow and beam ions (neutral beam injection)

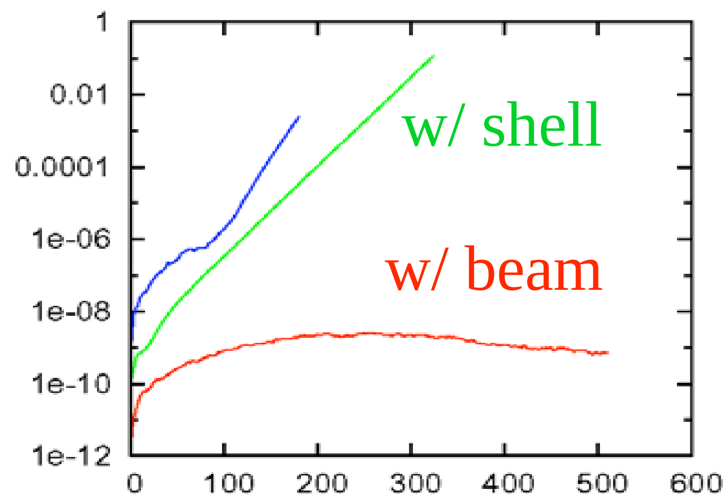
Mode	**Prolate** (E>1)	**Oblate** (E<1)
Internal tilt, *n*=1	MHD Unstable, stabilized by FLR, rotation and nonlinear effects for S*<20-30	MHD Stable
External tilt and radial shift, *n*=1	MHD Stable	MHD Unstable, stabilized by conducting shell
Co-interchange, *n*>1	MHD Unstable, stabilized by FLR	MHD Unstable, requiring velocity shear or NBI
Interchange, *n*≥1	MHD Unstable, stabilized by compressional effects	Same as left
Rotational, *n*=2	MHD Unstable, stabilized by quadrupole field and conducting shell	Same as left

Favorable Preliminary Results with Conducting Shells and Beam Ions

- **FRCs with $S^*=18$ and $0.5<E<2$ are highly unstable without conducting shells and beam ions**
- **Conducting shells are effective to reduce growth of n=1 modes**
- **Beam ions, when injected properly, suppress residual low-n modes**



n=1



n=2

Summary

- The proposed FRC experiments on MRX will explore
  - Formation of large-flux FRC
  - Sustainment by NBI and transformer
  - Global stability in wide ranges of parameters, including shell and beam ions
  - Initial assessments of transport in quasi-steady state plasmas

- The proposed FRC program based on MRX
  - Highly-leveraged on the existing facility and technologies
  - Unique and exciting opportunities to advance the FRC concept
  - Cost-effective, staged approach:
    - FRC Formation
    - Suatainment/amplification by transformer
    - Installation of NBI
  - State-of-art simulations available for guidance and comparisons

Field-Reversed Configurations (FRCs)

- **Highest possible beta**
  - **Cost-effective and high-power-density reactors**
- **Simple geometry**
  - **Advantages in engineering requirements**
- **Uncertainties in formation, stability, sustainment and confinement properties**
  - **Require more exploratory studies**