TRI ALPHA ENERGY
THE POWER OF INGENUITY

Progress at Tri Alpha Energy

Michl Binderbauer
Tri Alpha Energy

Fusion Power Associates 36th Annual Meeting – Washington, DC
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Dedicated to …

Norman Rostoker (1925-2014)

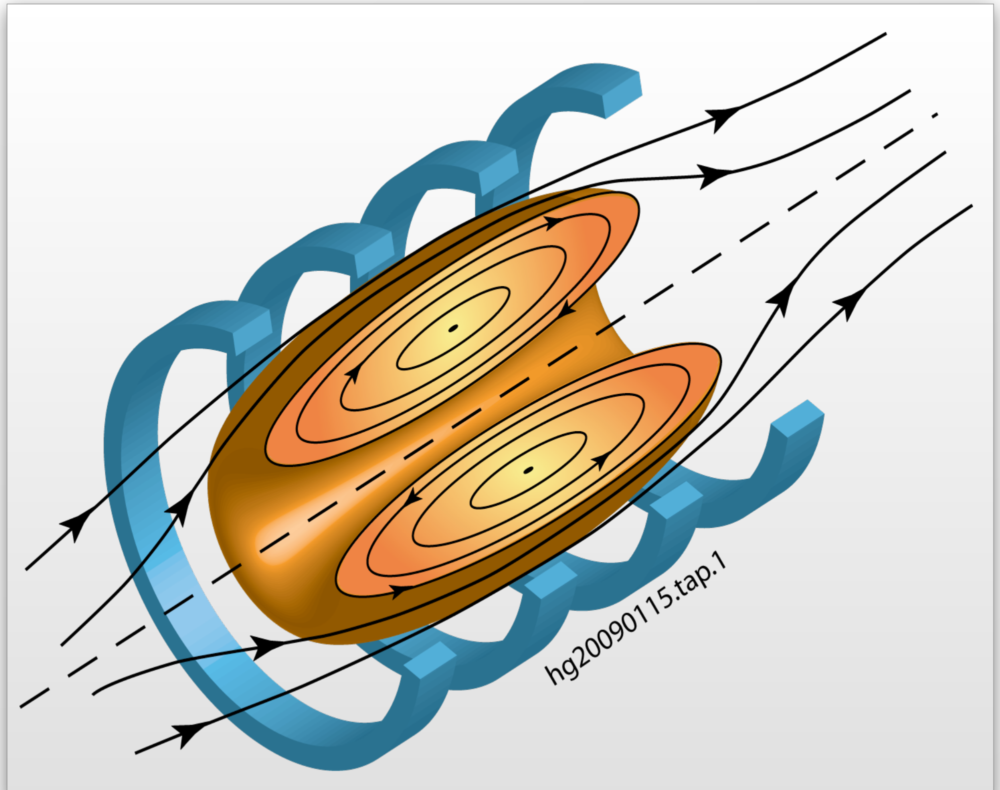
Mentor, Friend, Scientific Genius, Visionary

Agenda

- Introduction
  - Concept and Goals
- C-2/C-2U – a foundational physics testbed
  - Overview
  - Equilibrium profiles and fast particle effects
  - Stability
  - Confinement
  - Sustainment
- Summary of critical accomplishments

FRCs and Tri Alpha Energy's (TAE) Concept

Advanced beam driven FRCs



- High plasma β~1
  - compact and high power density
  - aneutronic fuel capability
  - indigenous kinetic particles
- Tangential beam injection
  - large orbit ion population
  - increased stability and transport
- Simple geometry
  - only diamagnetic currents
  - easier design & maintenance
- Linear unrestricted divertor
  - facilitates impurity, ash and power removal

TAE's Present Goals
Focus of efforts to now

- Test for failure early and at reduced cost while reducing most critical risks
- Establish beam driven high-β, large orbit FRC physics test bed to
  - provide fast learning cycles and large experimental dataset (~50,000 shots)
  - demonstrate sustainment via neutral beam injection (NBI) for >5 ms (longer than critical timescales) with high repeatability
  - study tangential NBI and fast particle effects on stability and transport
  - measure scaling and study fluctuations and transport
- Provide opportunity to
  - tightly integrate theory/modeling with experimentation
  - develop engineering knowhow and integration
- Invite collaboration to accelerate progress
  - Budker Institute, PPPL, UCI, UCLA, LLNL, Univ. of Pisa, Univ. of Wisconsin, Nihon Univ., Univ. of Washington, Industrial partners

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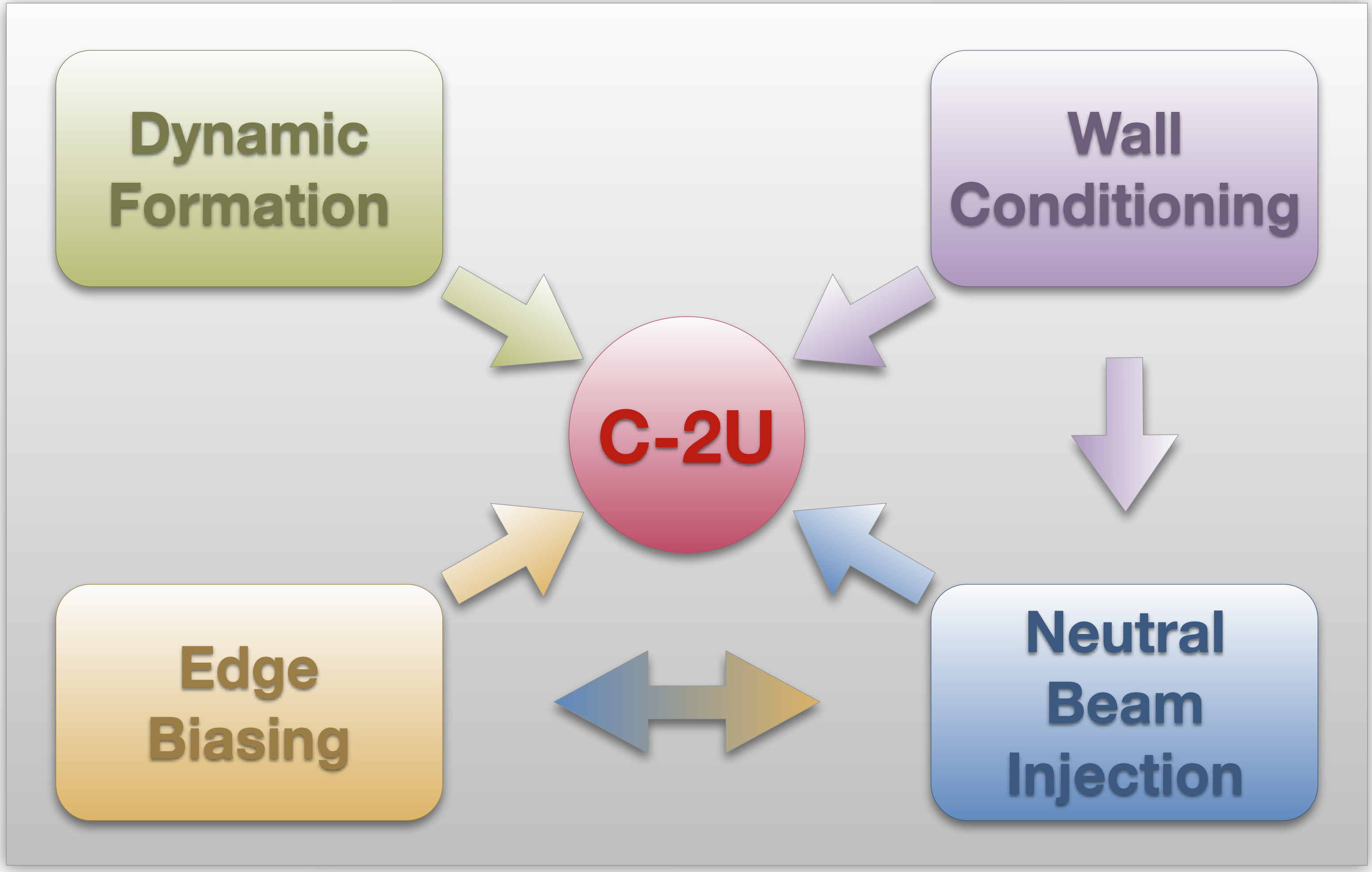
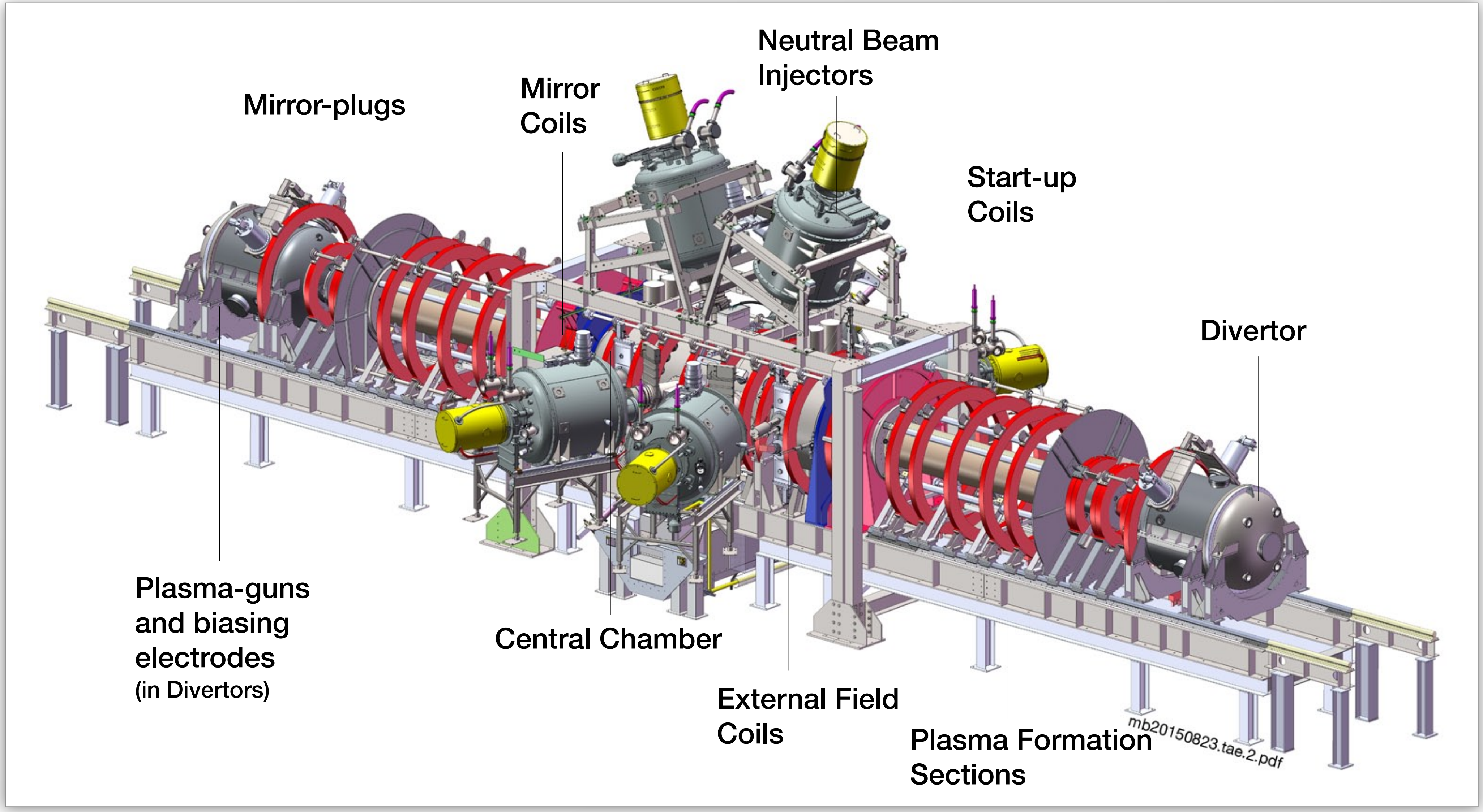
Key Approaches to C-2/C-2U

Synergetic effects – High Performance FRC (HPF)



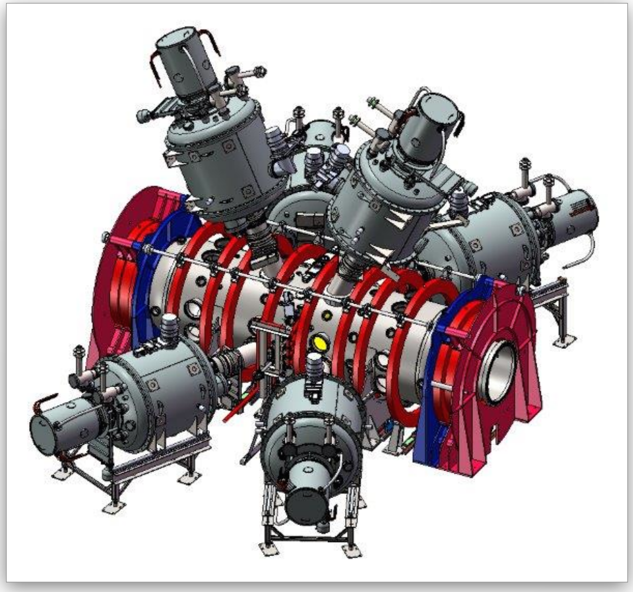
C-2U Research Facility (4th Generation Device)

To study sustainment of advanced beam-driven FRC's



C-2U Neutral Beam System

Performance Markers and Design Philosophy



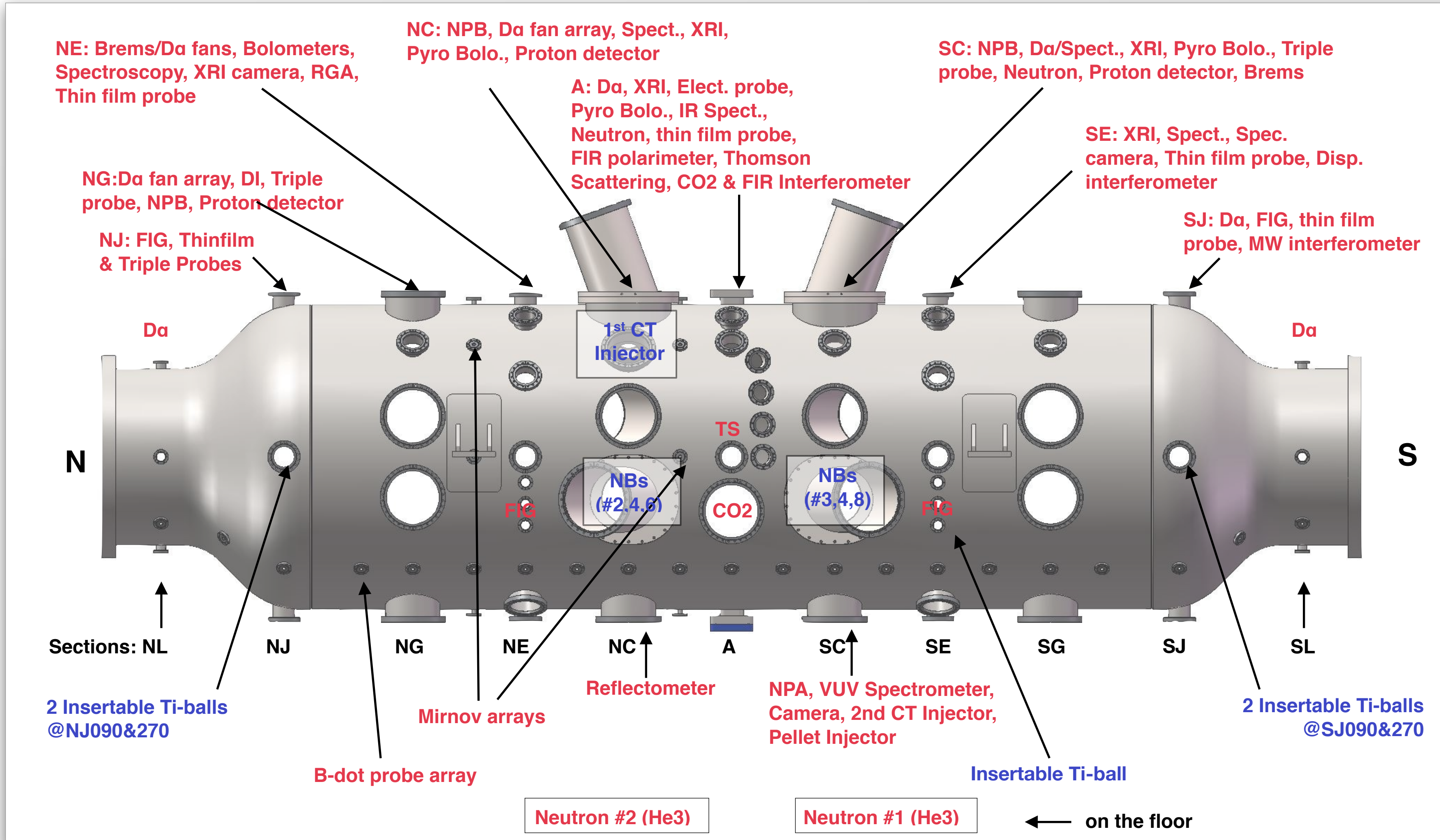
Neutral Beam System Specification

Parameter	Value
Beam energy	15 keV
Total power in neutrals	10+ MW
# of injectors	6
Pulse duration	8 ms flat top
Beam radial e-fold. size	< 10 cm
Beam divergence	< 28 mrad
Ion current per source	145 A

- Centered, angled and tangential neutral beam injection (NBI)
  - Beams aimed at mid-plane to reduce plasma shape impact
  - Simulations suggest optimized injection angle in range of 15°-25°
  - Injection in ion-diamagnet direction to drive current
- High current at low beam energy
  - Reduces peripheral fast ion losses
  - Increases core heating
  - Rapidly establishes dominant fast ion pressure

C-2U Diagnostics

Well diagnosed experiment



- 60+ diagnostics w/ over 1000 channels acquired on every shot (1+ GB/shot)

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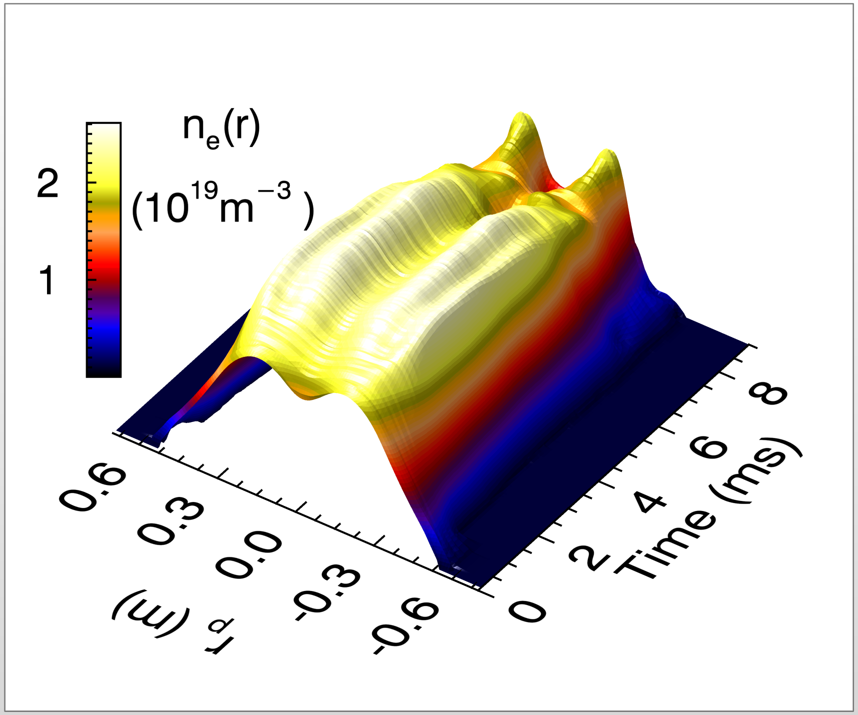
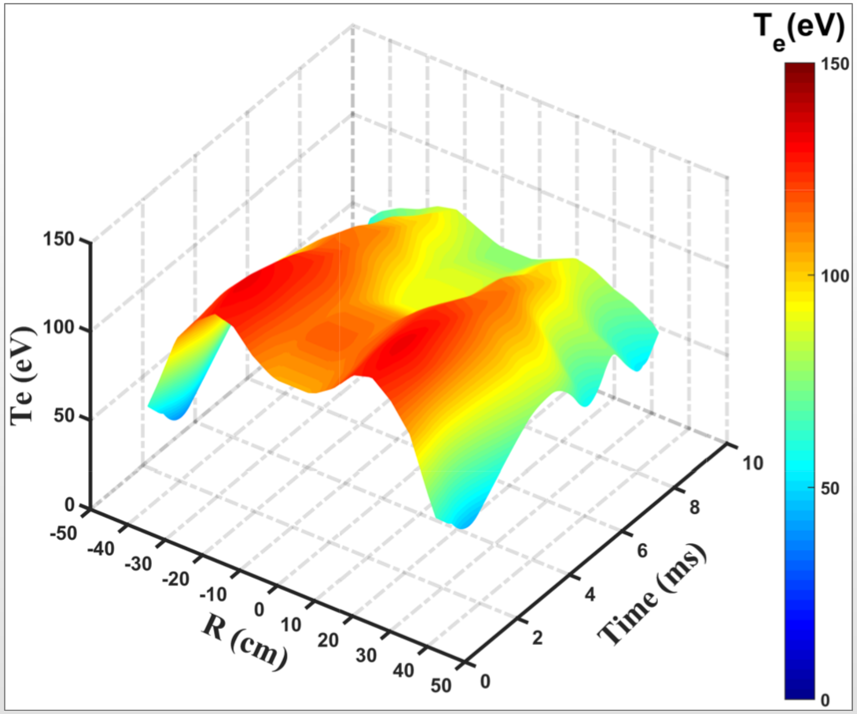
C-2U Equilibrium Profiles

Signatures of advanced beam-driven FRC state

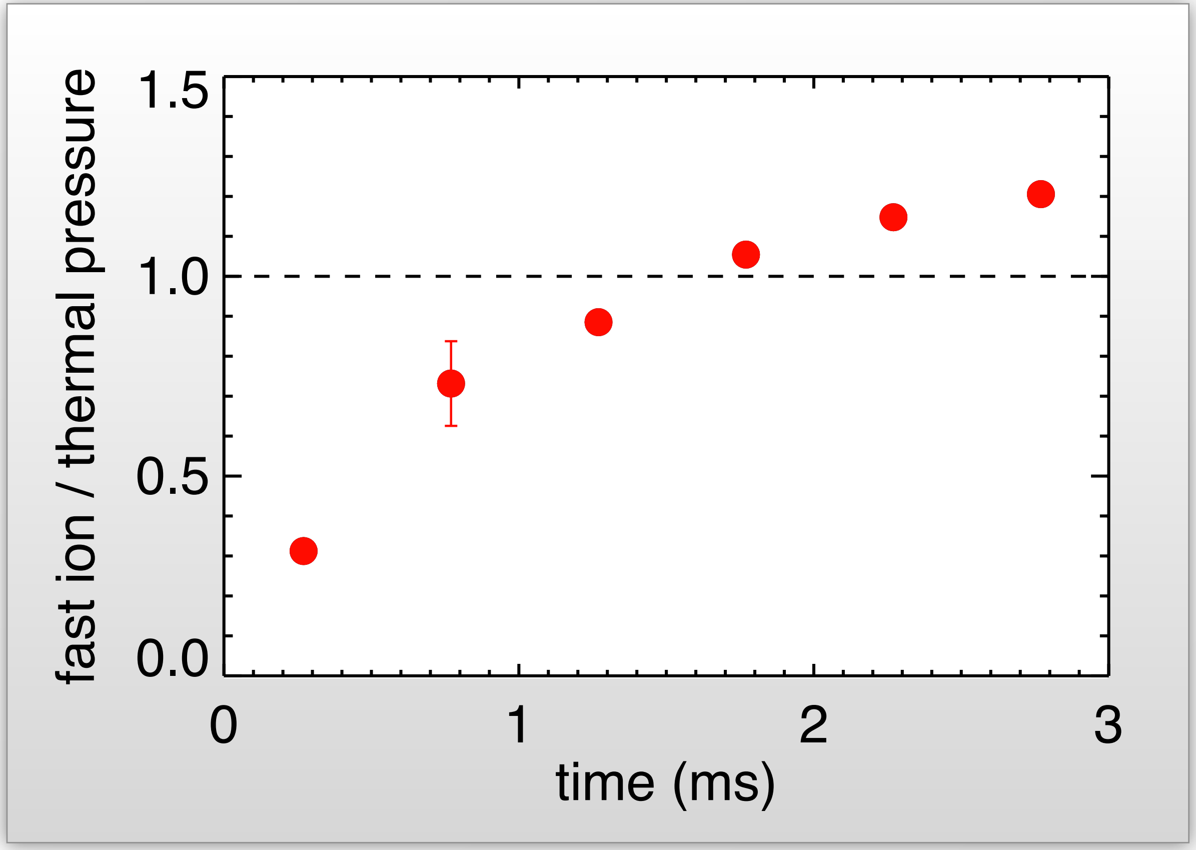




- "Double-humped" electron density and temperature profiles, indicative of substantial fast ion pressure
- Hollow center and steep separatrix gradients consistent with past FRC data and numerical simulations

C-2U Experimental Findings

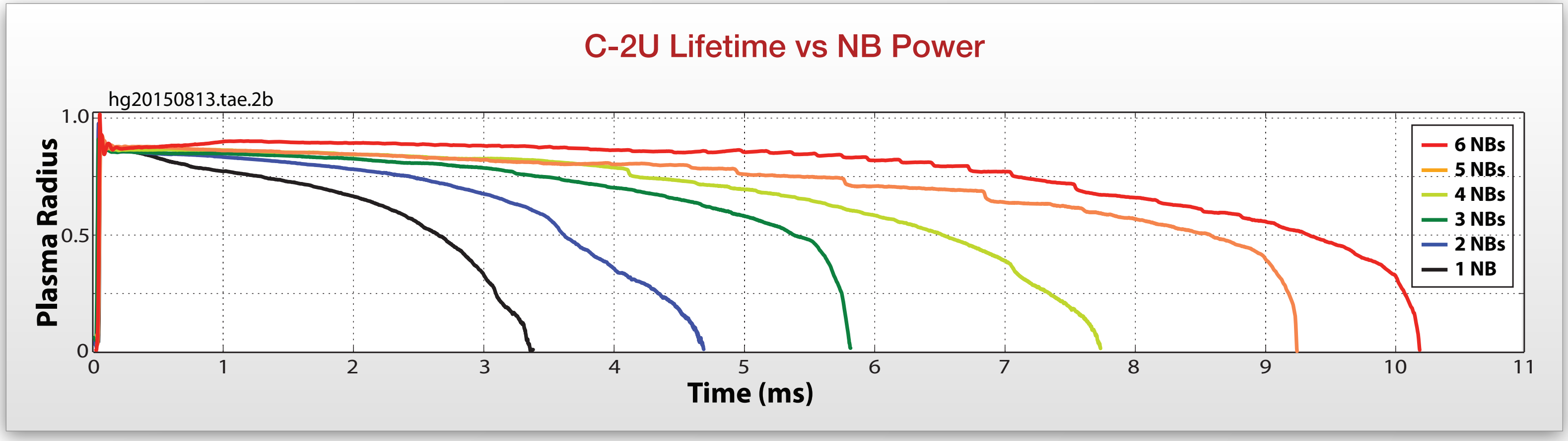
Signatures of beam-driven advanced FRC state

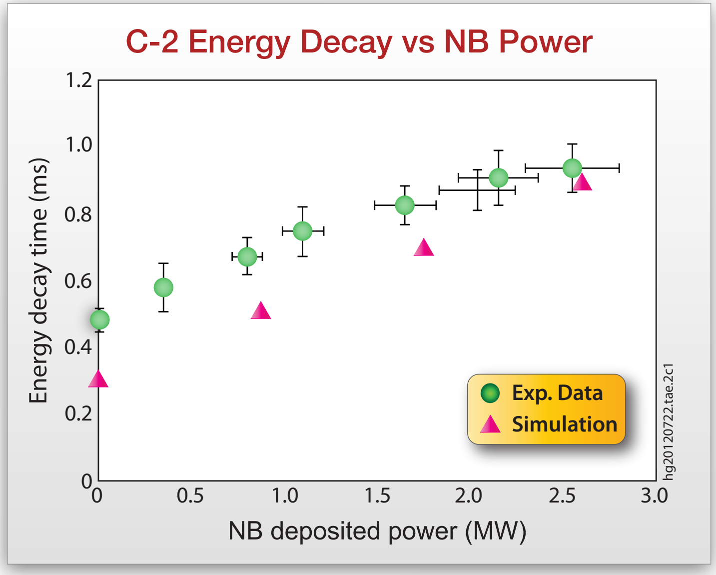


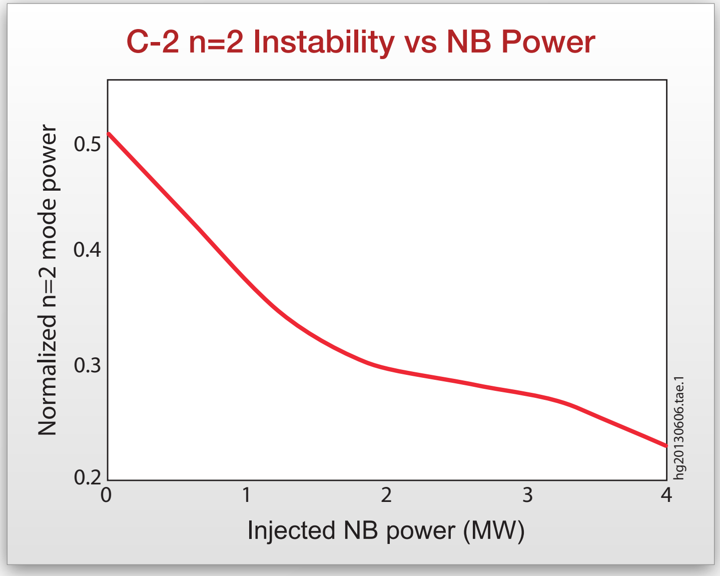
- Dominant fast ion pressure term
  - total pressure is maintained
  - ultimately ~ 60% of thermal pressure replaced by fast particle pressure

C-2/C-2U Fast Particle Effects

Improvements coupled to NBI



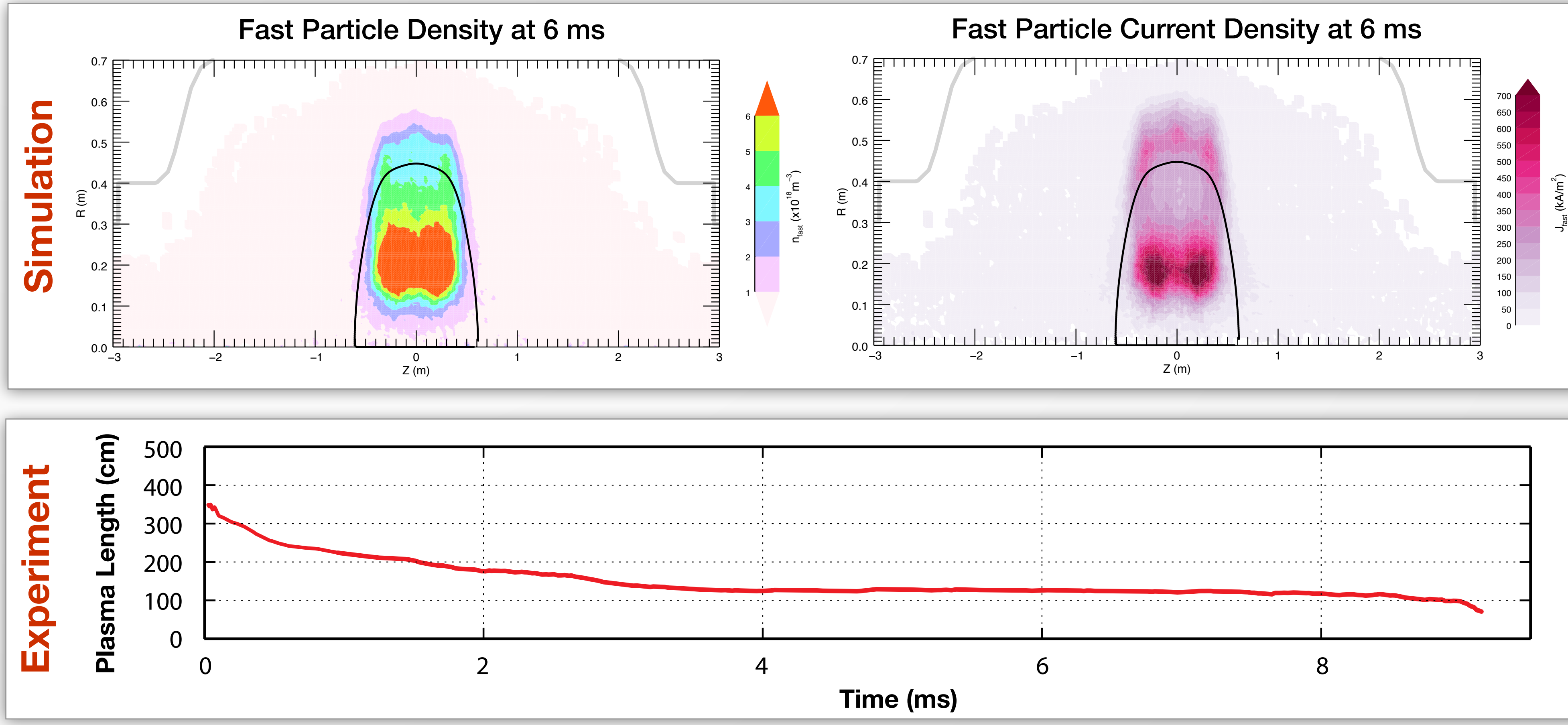




- Positive impact on lifetime, confinement and stability

C-2U Separatrix Length

Fast ions largely determine axial dimension



- Plasma length contracts to fast particle footprint
  - axial dimension of separatrix maintained post transient contraction

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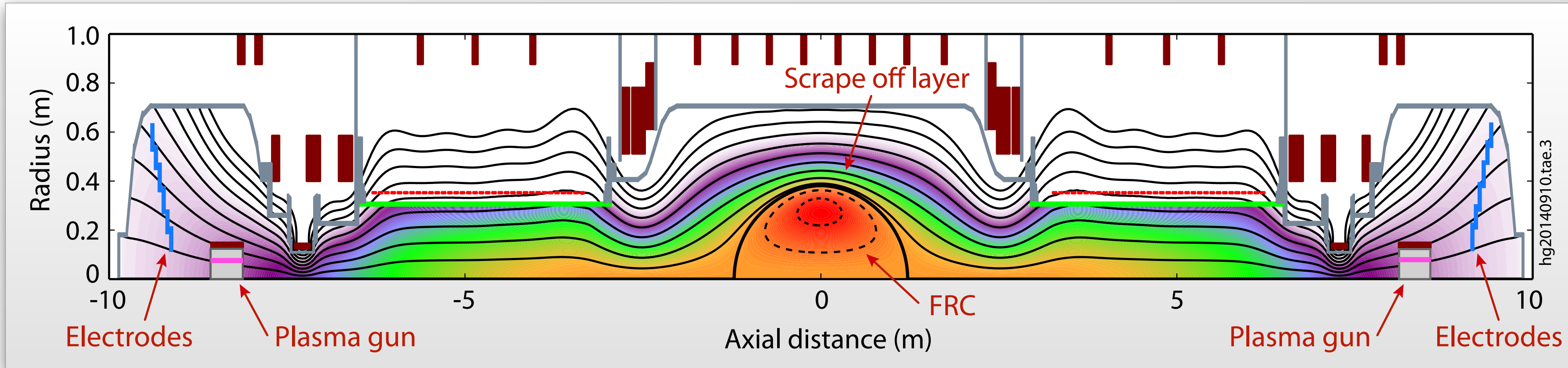
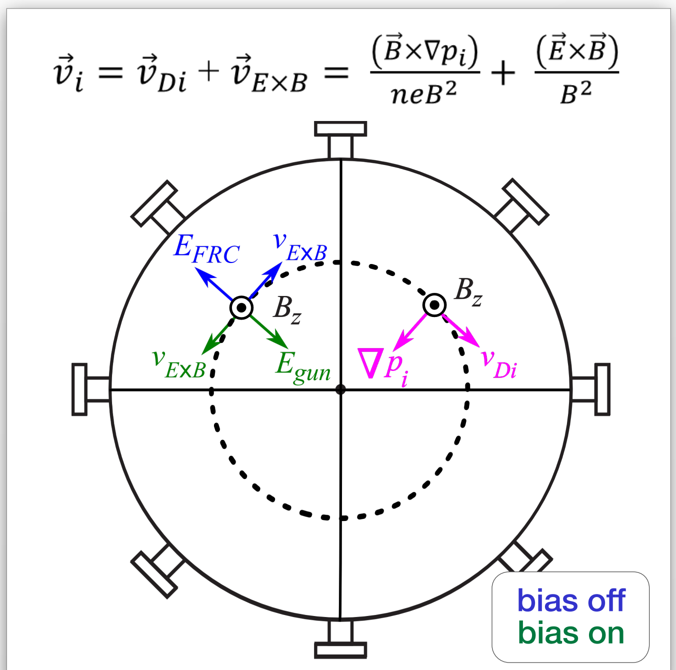
C-2/C-2U Stability

n=2 mode suppression via egde biasing



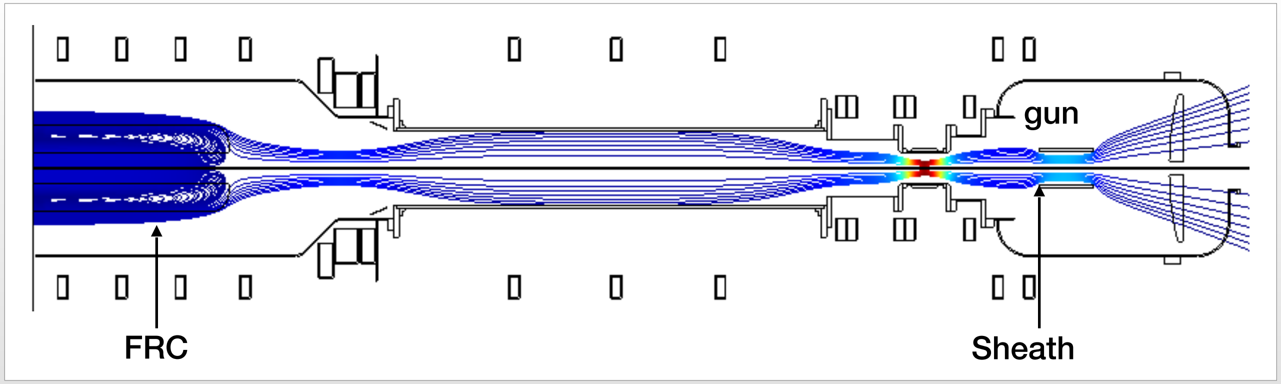


- Biasing field lines in scrape off layer (SOL) can counteract spin-up and suppress n=2 growth
- Without biasing, diamagnetic and E×B term are additive – plasma spins up
- With proper biasing changes E×B term – plasma spins down via shear
- n=2 rotation control without impact on fast particle confinement

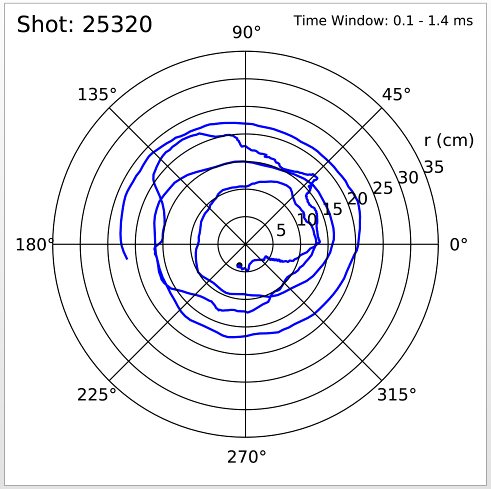
C-2/C-2U Stability

Wobble suppression via line-tying

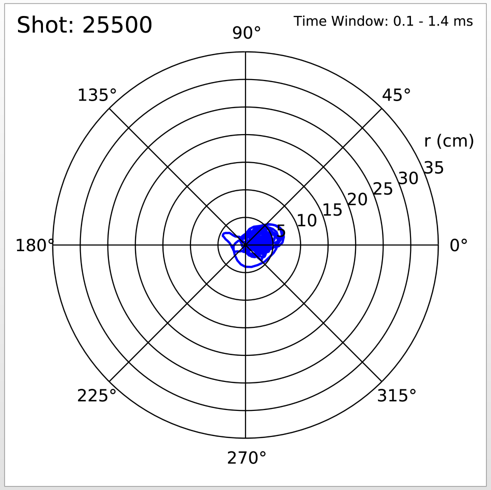
- Mode driven by plasma rotation or end mirror effects
- Line-tying between plasma and conducting end surface (i.e. gun electrode) can stabilize wobble
- Line-tying limited by sheath resistance
- Stability requires sufficiently high (~10^{12} cm^{-3}) gun plasma density (low sheath resistance)
- Active plasma guns and up to 1 kV biasing of central field lines reduces wobble to negligible levels



Plasma Gun Off



Plasma Gun On



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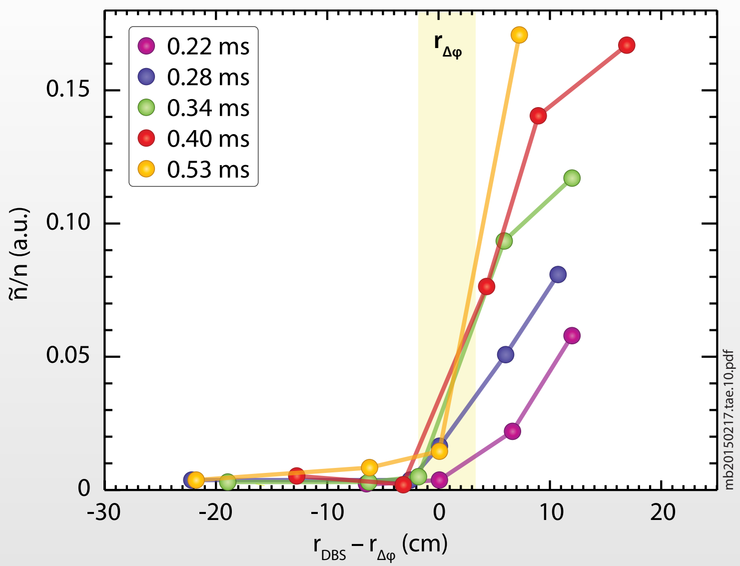
C-2/C-2U HPF Regime Density Fluctuations

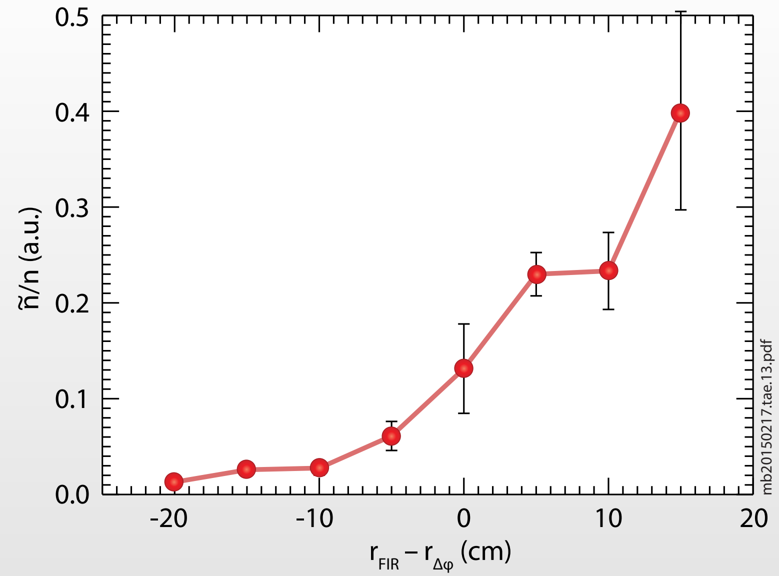
Quiescent core, turbulence located outside

Doppler Backscattering



Toroidal wavenumber
$2 \leq k_\theta \rho_s \leq 10$

FIR Forward Scattering

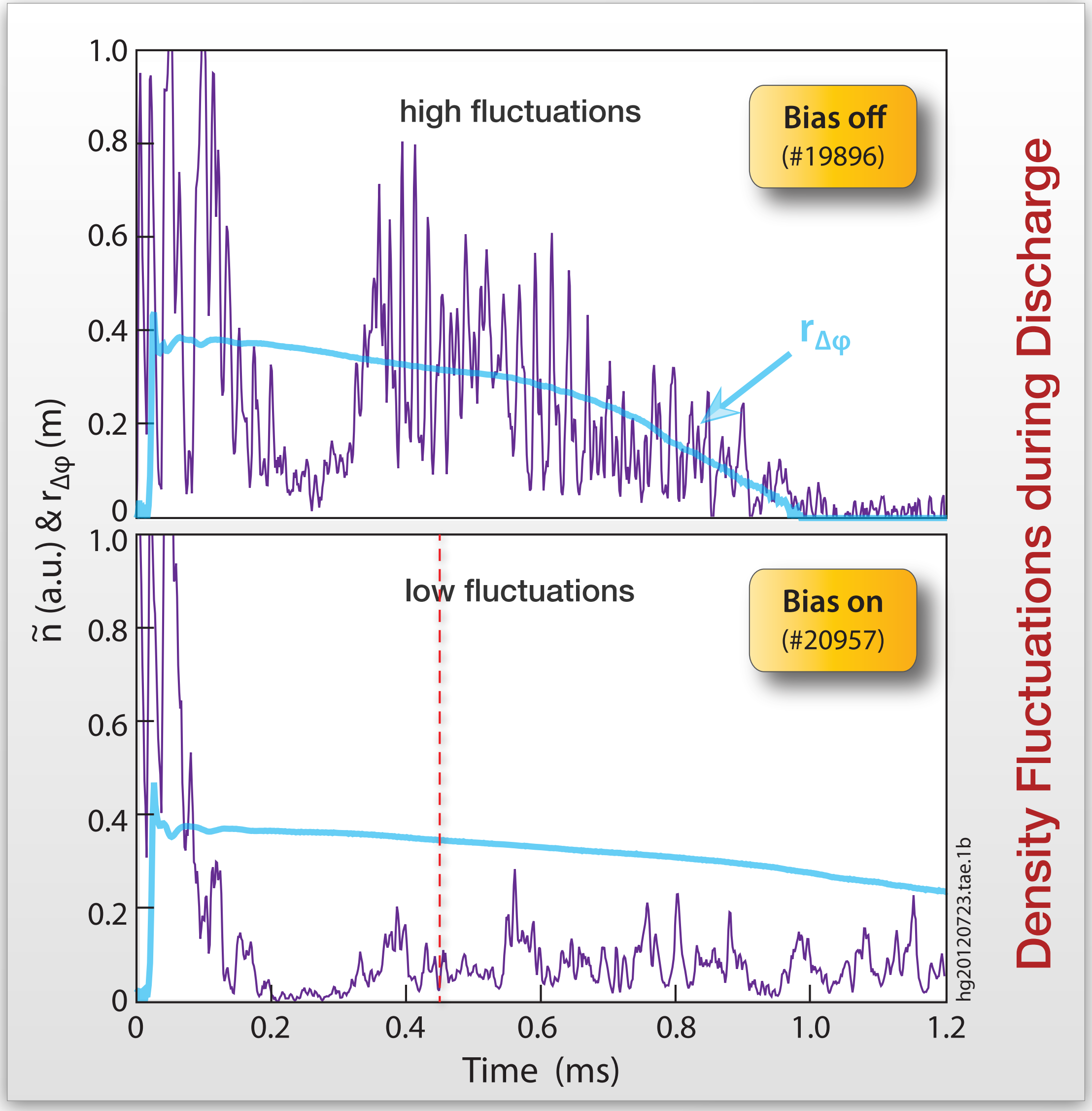


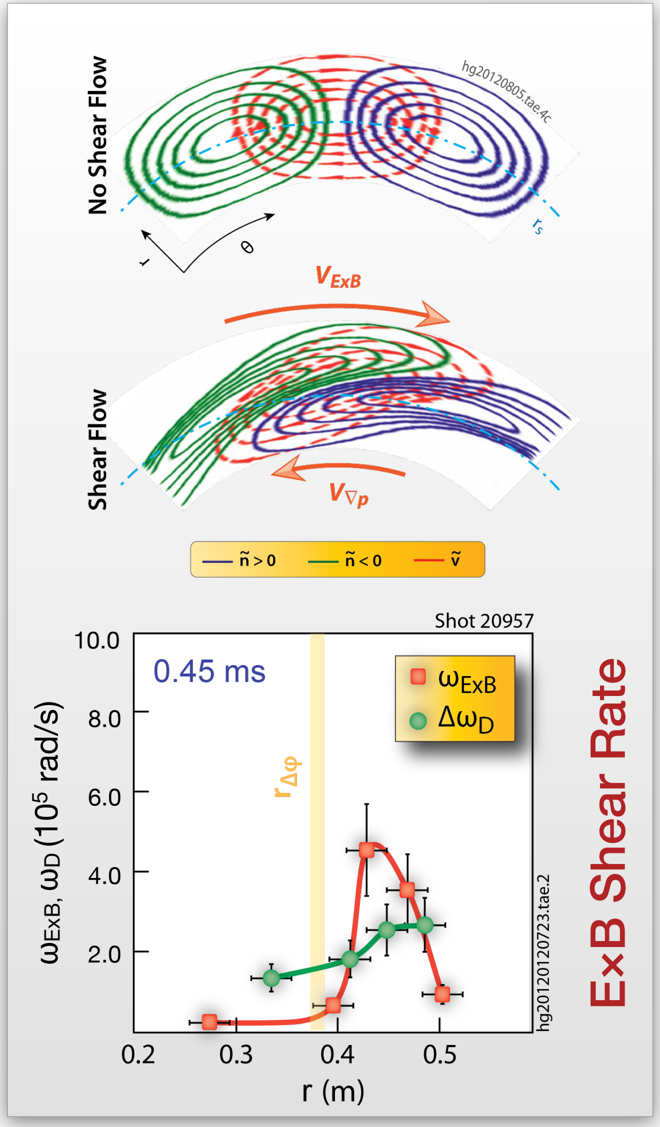
Perpendicular wavenumber
$k_\perp \rho_s \leq 4$ (low k)

- Absolute fluctuation levels peak just outbound of separatrix
- Relative fluctuation amplitude increases with radius outside the separatrix
- HPF plasmas have very low fluctuation levels in the FRC core

C-2U Fluctuation Suppression in HPF regime

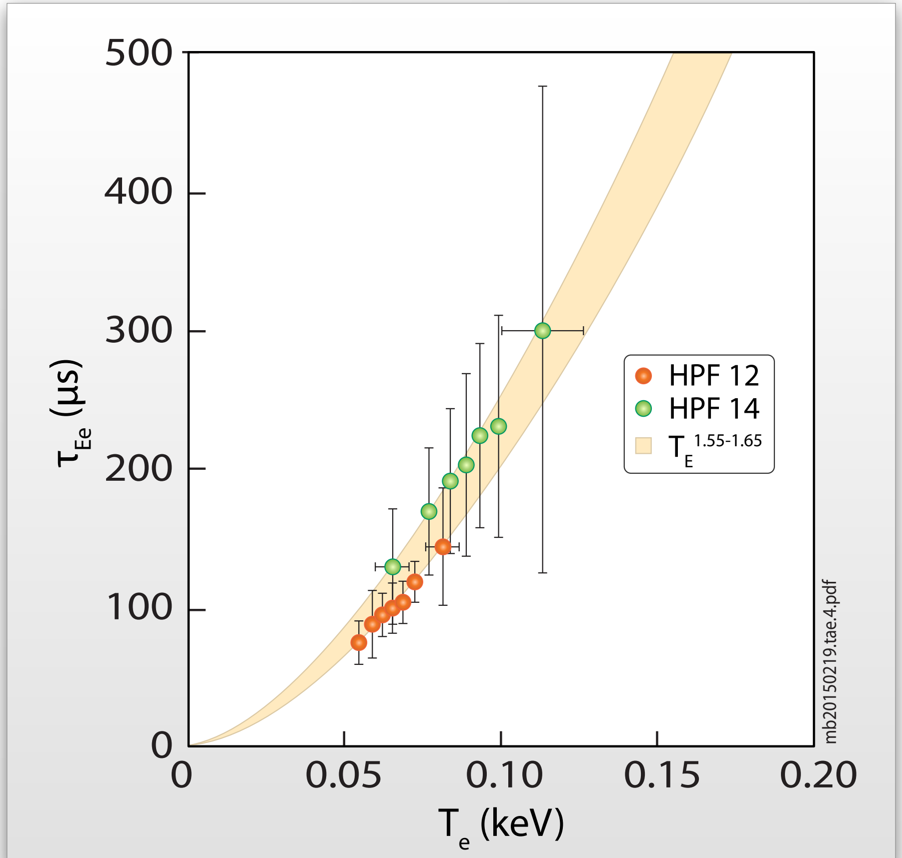
Substantial localized shear near separatrix

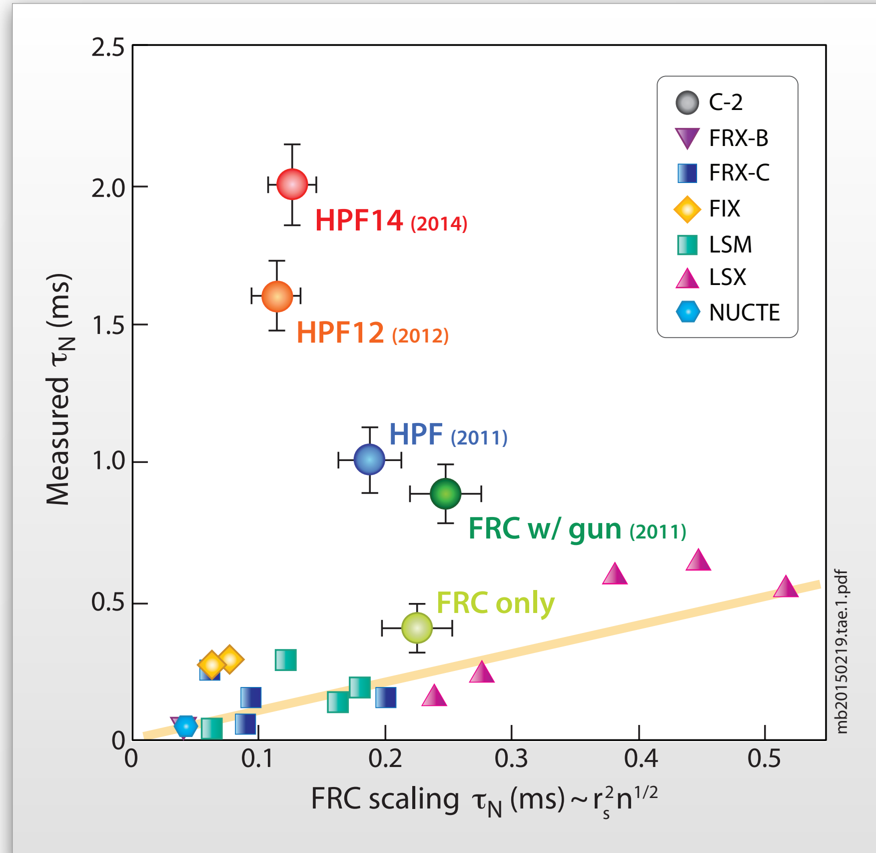




Confinement Scaling

Dramatic improvement in current regime



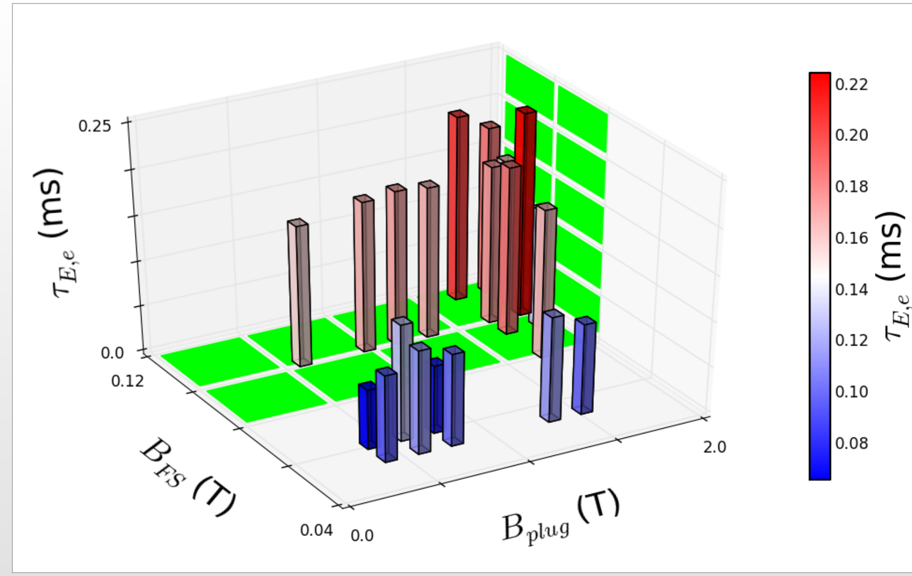


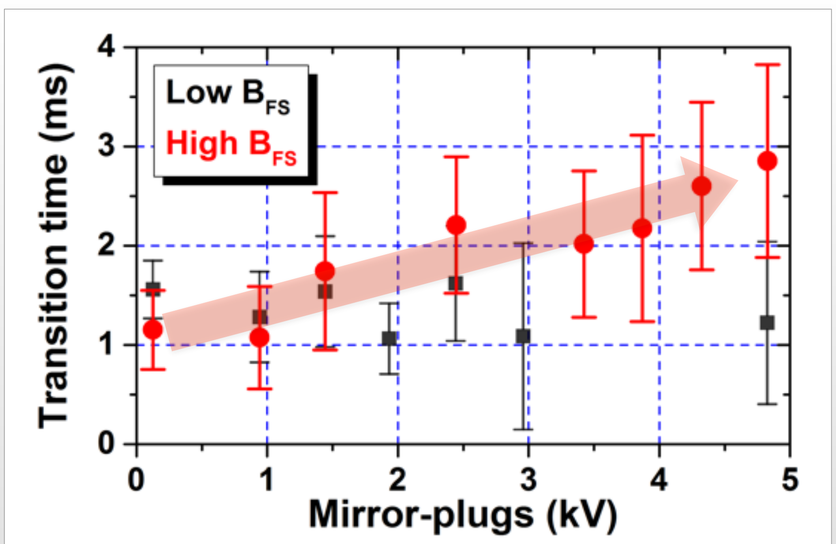
- Strong positive correlation between T_e and τ_{Ee}
- Good fit: $\tau_{Ee} \propto T_e^{1.6}$
- Confinement dramatically better than conventional FRC scaling prediction
- ~10× improved particle confinement

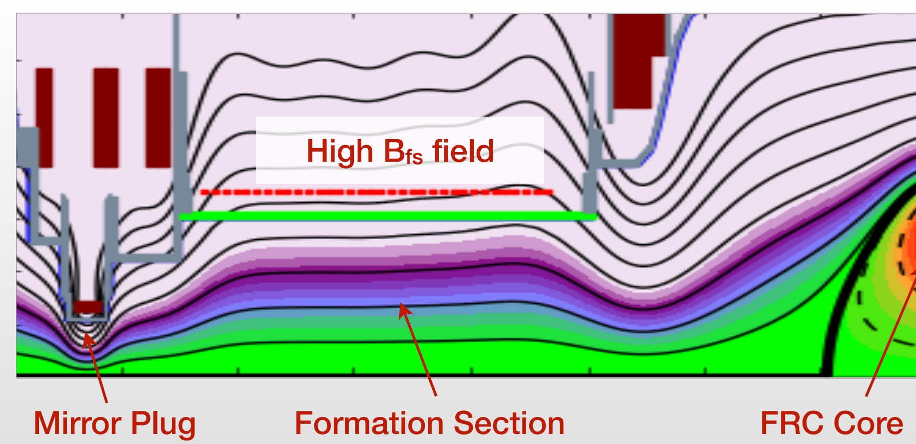
SOL-Core Confinement Coupling

Edge knobs effect overall confinement

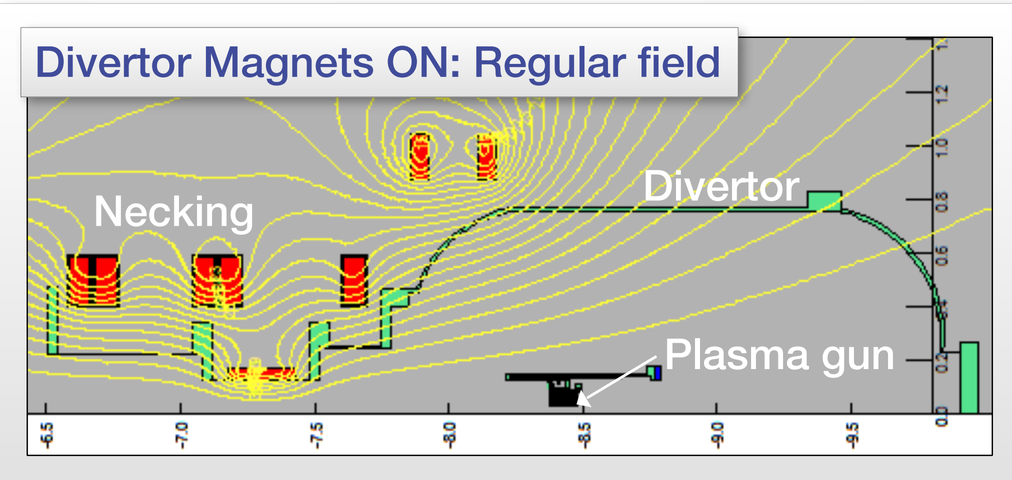
- FRC transport is determined by sequential but coupled effects between core and scrape-off layer
- High formation and mirror plug fields improve SOL and core confinement
- HPF14 demonstrates clear coupling between SOL and FRC core

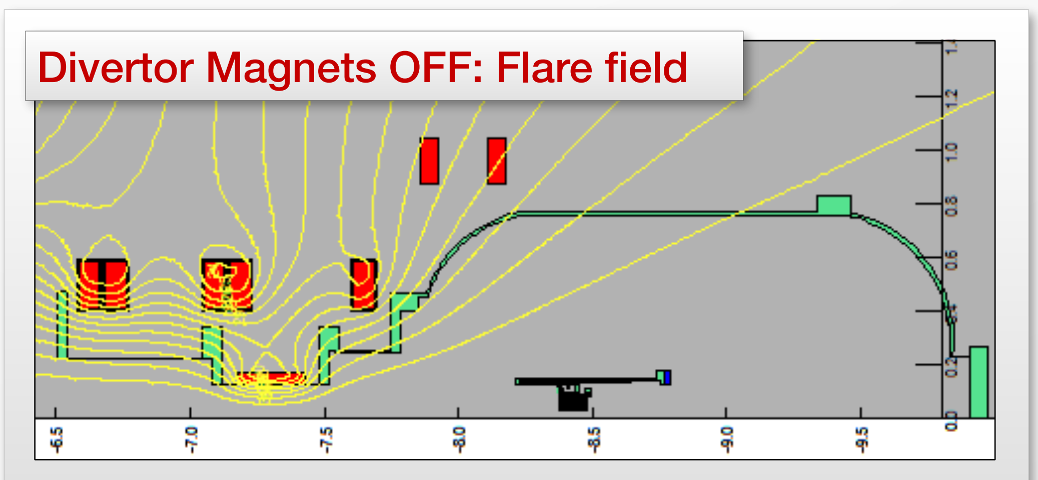


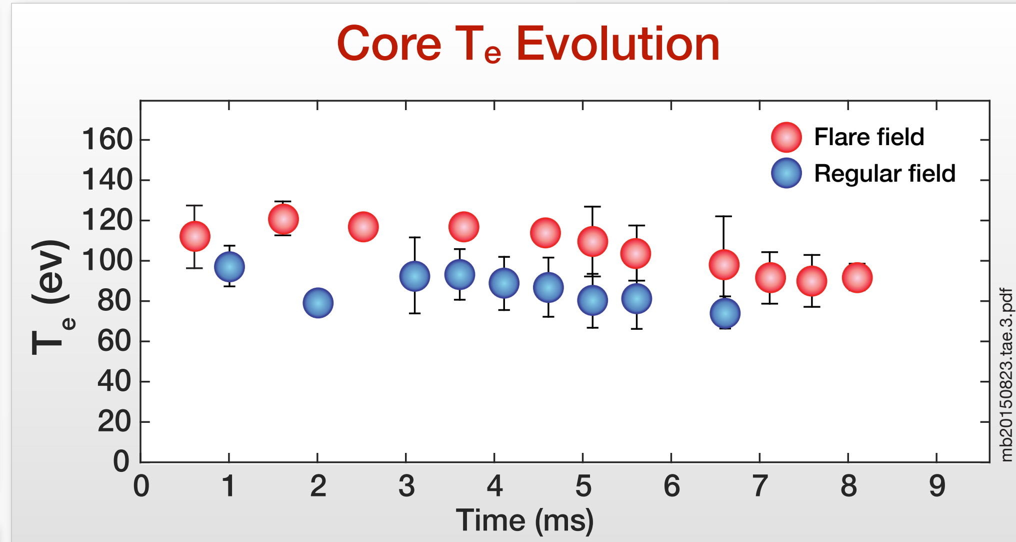




SOL-Core Confinement Coupling
Edge knobs effect overall confinement (cont.)







- Improving open-field-line plasmas key for better core confinement
- 20-30% higher core T_e with flaring divertor magnetic field

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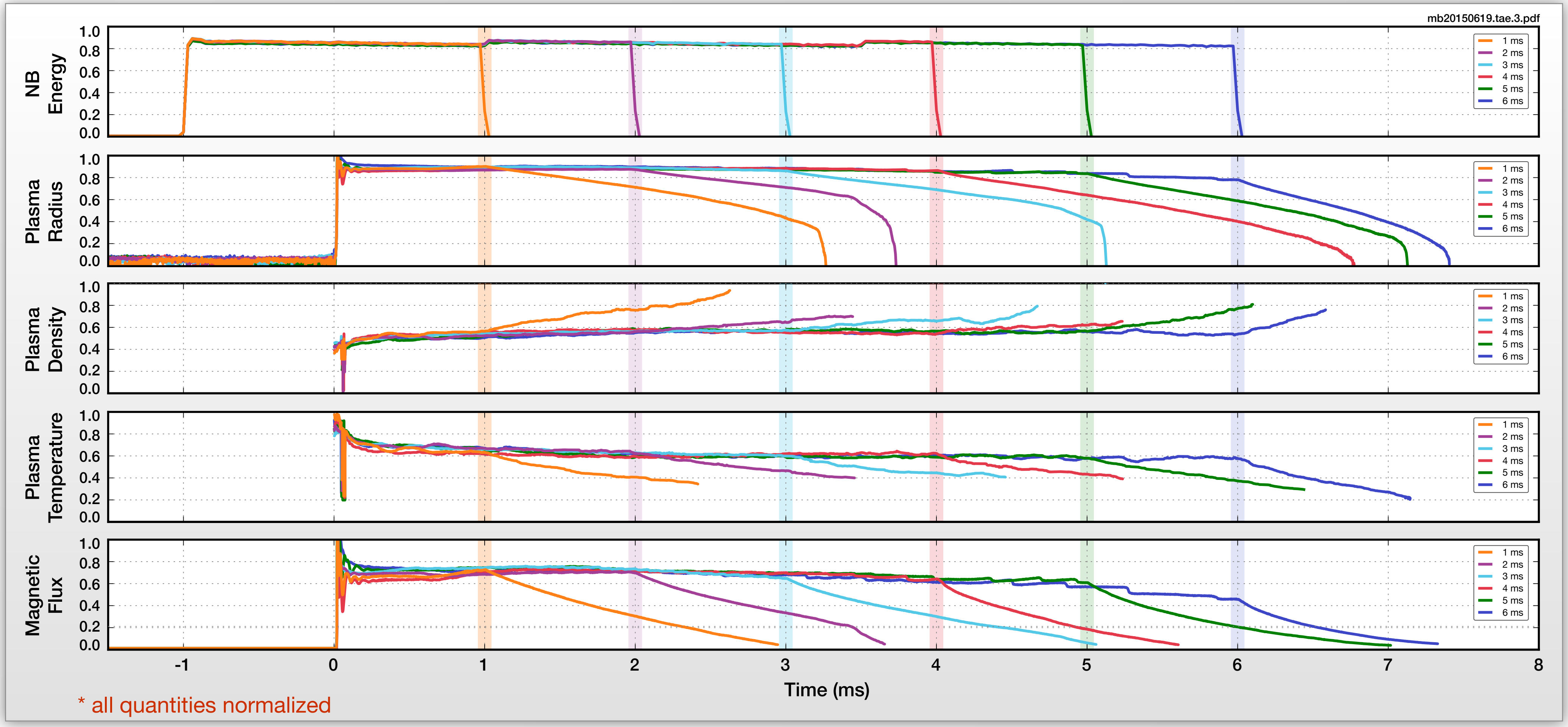
C-2U Sustainment Experiments

Correlation between beam drive and plasma characteristics



- pulse length limited by hardware and stored supply energy (biasing, beams)
- flux maintained (up to 5-5.5 ms) – showcases ability to drive current by beams
- electron and ion temperatures maintained (T_e~120 eV, T_i~500 eV)
- no active feedback to control anything – very robust physics

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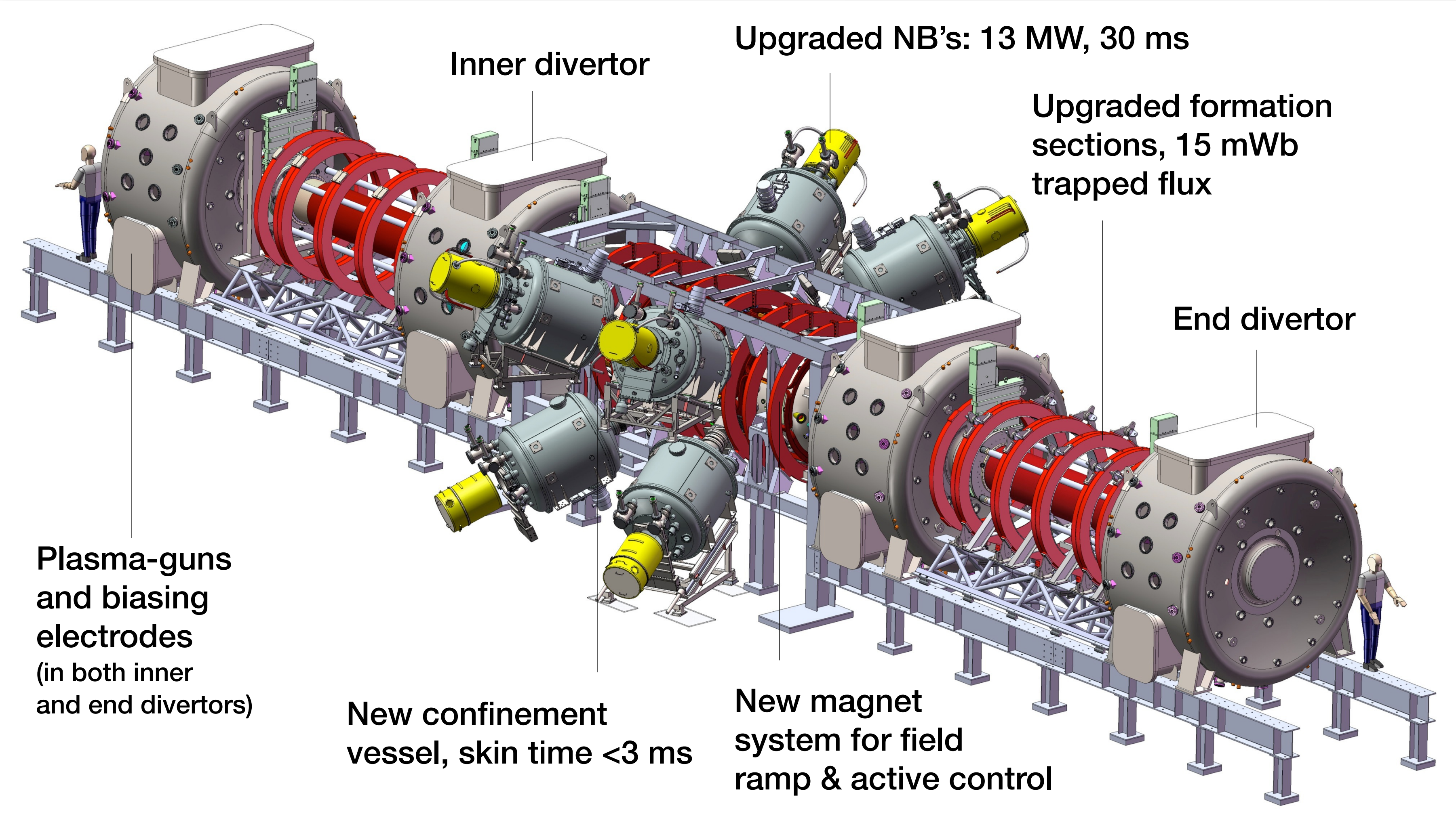
- Next Steps and Summary

C-2W

Next device at 10× stored energy



Summary

Essential accomplishments

- Successfully operated and studied advanced beam driven FRCs
  - dynamic formation and fast ion pressure dominated equilibria
  - achieved engineering integration of major system components
- High Performance FRC regime demonstrated
  - edge biasing, neutral beams and gettering (low Z_{eff}~1.28 in core) produce HPF regime with excellent shot-to-shot reproducibility
  - improved FRC stability and confinement
  - record FRC lifetimes (> 11 ms), limited only by transport
  - beneficial emerging confinement scaling and coupled core-SOL transport
- Advanced beam driven FRC sustainment breakthrough
  - current drive and plasma sustainment in excess of characteristic system and plasma time scales, correlated w/ NB pulse – 5+ ms
  - Performance limited by hardware and stored energy constraints
- Compelling foundation for success with C-2W