NBI fast-ions in the RFP and LTX-β

Studies on well-developed to developing EP populations

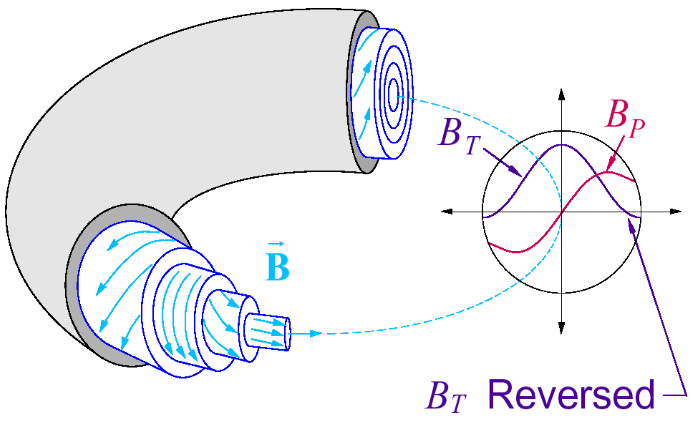
THE UNIVERSITY of WISCONSIN MADISON
MST
U.S. DEPARTMENT OF ENERGY | Office of Science
LTX-β
PPPL PRINCETON PLASMA PHYSICS LABORATORY

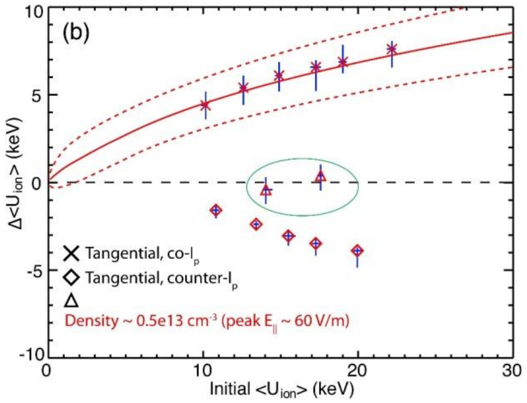
Fast-ion studies* in the RFP and ST

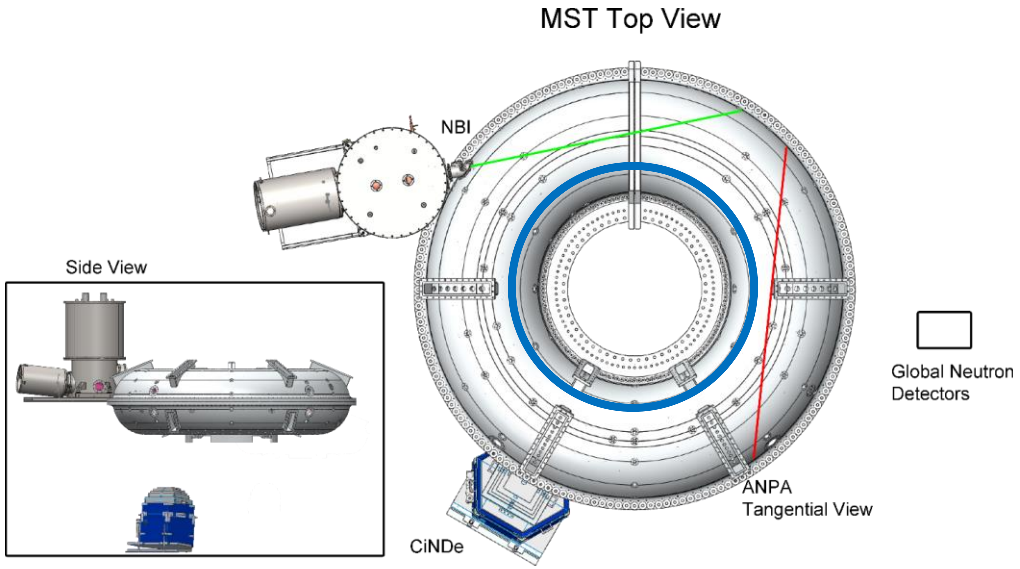
- Critical fast-ion pressure measured on Madison Symmetric Torus
  - Natural fast-ions in RFP
  - Fast-ion dynamics in RFP
  - Large NBI ion population drives Alfvén continuum mode (bursting mode)
  - Collimated D-D neutron flux diagnostic developed to measure fast-ion profile
- Start of fast-ion studies in LTX-β
  - Initial NBI operation- no coupling to plasma
  - Extensive modeling to optimize coupling
  - New higher current equilibria
  - Upcoming work
    - Characterization of beam: NPA, IR thermography, spectroscopy
    - 3d equilibria- large toroidal asymmetry due to shells could drive significant loss
    - Mode activity (?)

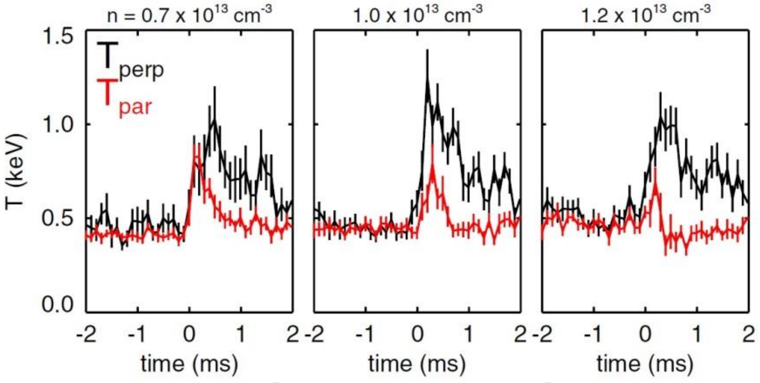
Good EP population to study in RFP

- Madison Symmetric Torus- good testbed for interesting EP physics
  - Low magnetic field → higher fast-ion beta (stronger drive)
  - High shear → Increased stability against continuum modes (EPMs)
- Dynamics influenced by tearing instability
  - Largely impacts evolution of equilibrium, heat/particle transport
  - Ion heating- natural fast ion population
    - Perpendicular heating at sawtooth
    - Runaway ion tail develops during relaxation
    - Large anisotropy in confinement phase space









[Anderson 2016]

Madison Symmetric Torus

R=1.5 m; a=0.52 m

I_p ~ 200 – 500 kA

|B| ~ 0.2 – 0.5 T

$T_e(0)$ ~ 200 – 2000 eV

$n_e \sim n_D \sim 10^{13}$ cm^{-3}

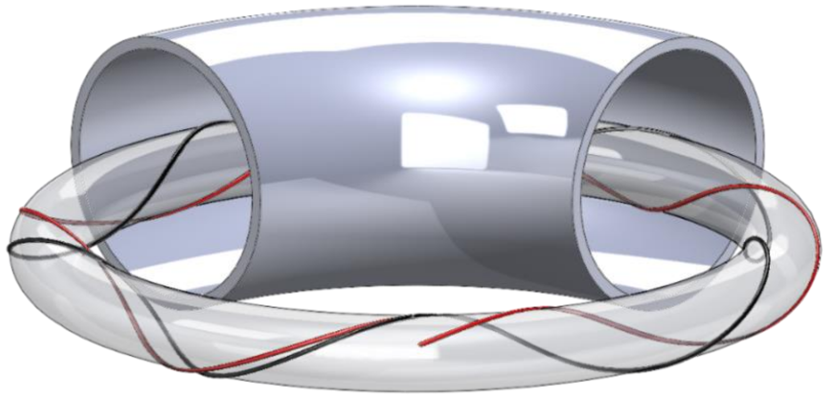
Pulse length ~ 60-100 ms

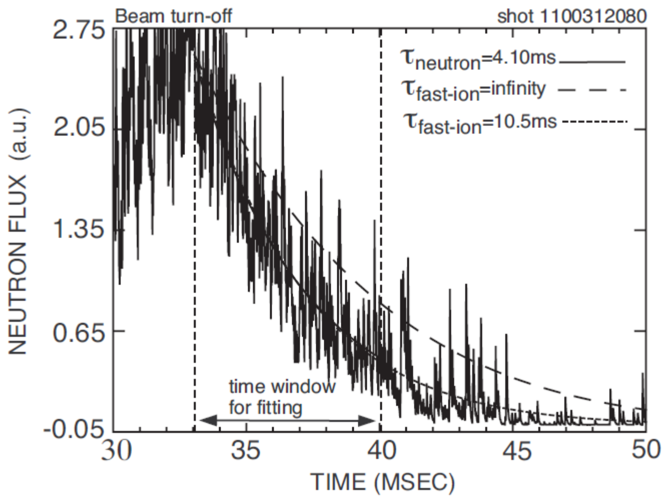
EP motion decoupled from local b_r

- Fast-ion drift velocity stays **on** flux surface

$$v_{GC} = v_\parallel \boldsymbol{b} + \frac{v_\perp^2}{2\omega_c}\frac{\boldsymbol{B}\times\nabla\boldsymbol{B}}{|B|^2} + \frac{v_\parallel^2}{\omega_c}\frac{\boldsymbol{B}\times\boldsymbol{\kappa}}{|B|}$$

- Rational surfaces shifted from locations of tearing mode activity
  - Near classical confinement of co-injected EP (~10ms)
  - (Counter-Ip: ~1ms, perpendicular injection ~4-5ms)





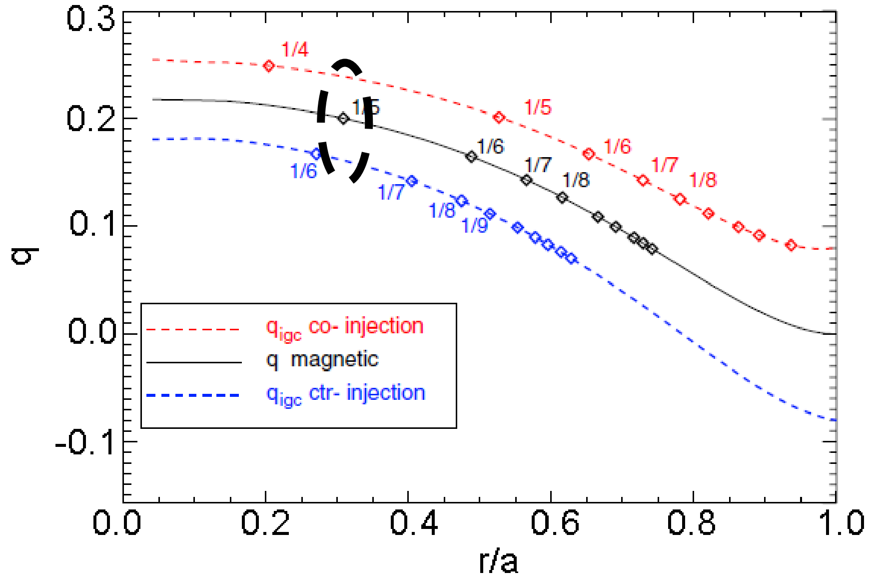
[Anderson et al. 2011]

	$\nabla\boldsymbol{B}$	$\boldsymbol{\kappa}$
Tokamak	$\hat{R}$	$\hat{R}$
RFP	$\hat{r}$	$\hat{r}$

$$q_f = \frac{\omega_\phi}{\omega_\theta} = \frac{r v_\phi}{R v_\theta}$$

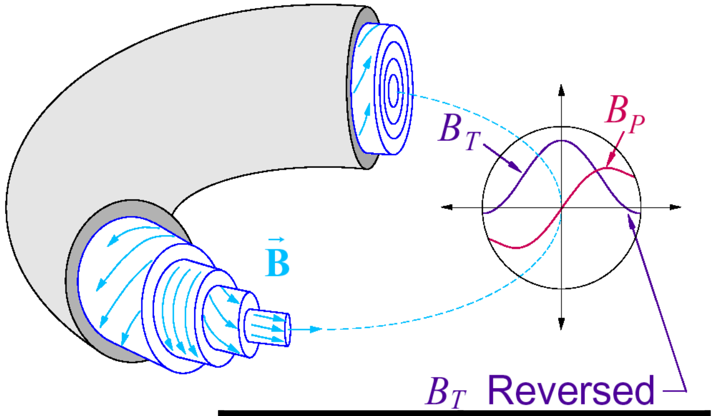
$$q_f \approx q_{mag} + \frac{s_\parallel}{b_\theta^2} r_L \frac{2(1-\mu\Omega)b_\theta^2 - r\mu\Omega'}{2R\sqrt{1-\mu\Omega}}$$

[Hudson 2006]



Good EP population to study in RFP

- Wanted to investigate what limits fast-ion content in RFP
- NBI provides well-confined super-Alfvénic population to study
  - Mode activity is species dependent- ran D-beam into D-plasma
  - Discharge style chosen to isolate single mode activity
    - Removal of m=0 surface eliminates most sawteeth
    - Mode activity observed during NBI then corresponds to an "unavoidable" limit in these discharges



NBI Parameter	Specification
Beam energy	25 keV
Beam power	1 MW
Pulse length	20 ms
Composition	100% D

Madison Symmetric Torus

R=1.5 m; a=0.52 m

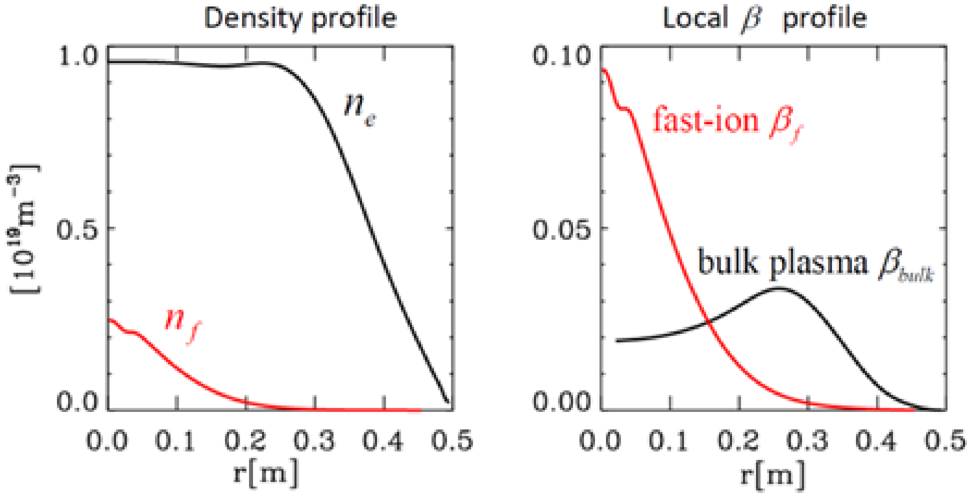
I_p ~ 200 – 500 kA

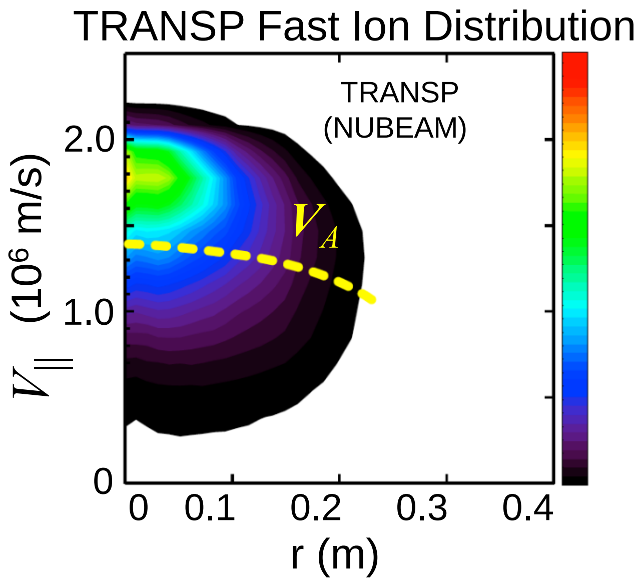
|B| ~ 0.2 – 0.5 T

$T_e(0)$ ~ 200 – 2000 eV

$n_e \sim n_D \sim 10^{13}$ cm^{-3}

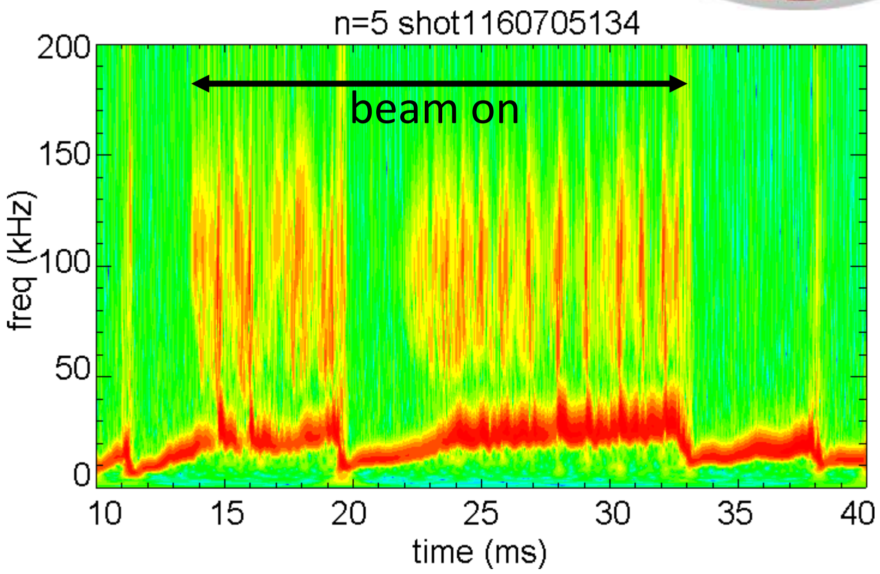
Pulse length ~ 60-100 ms

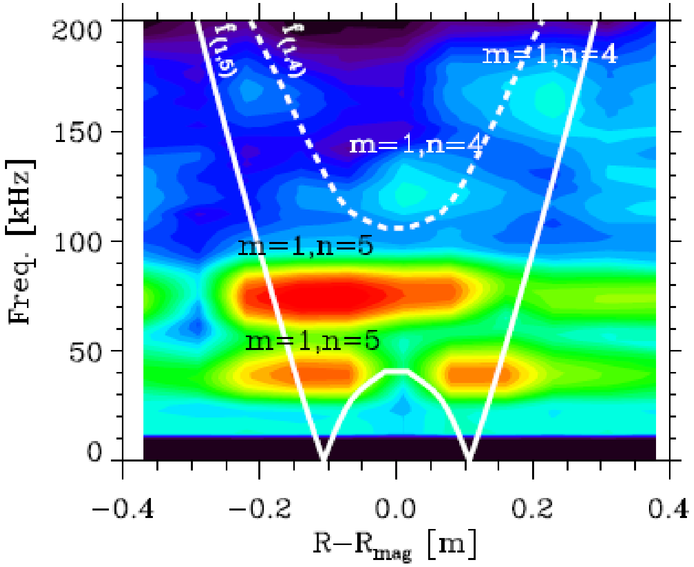




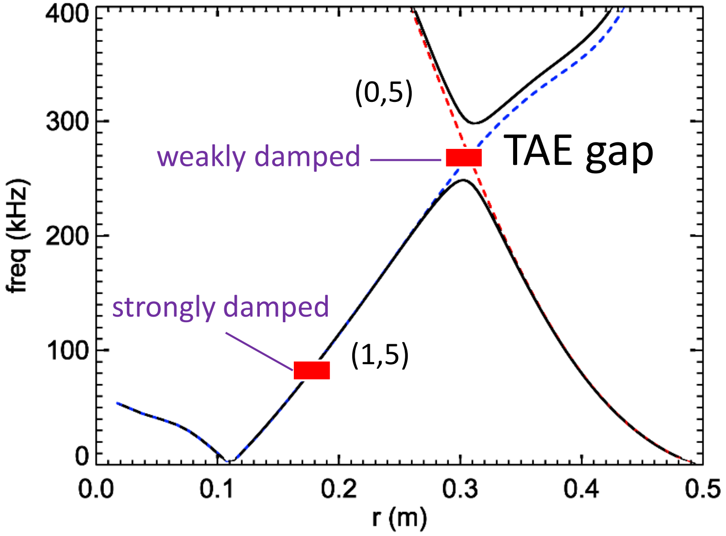
EPM resonant with NBI population

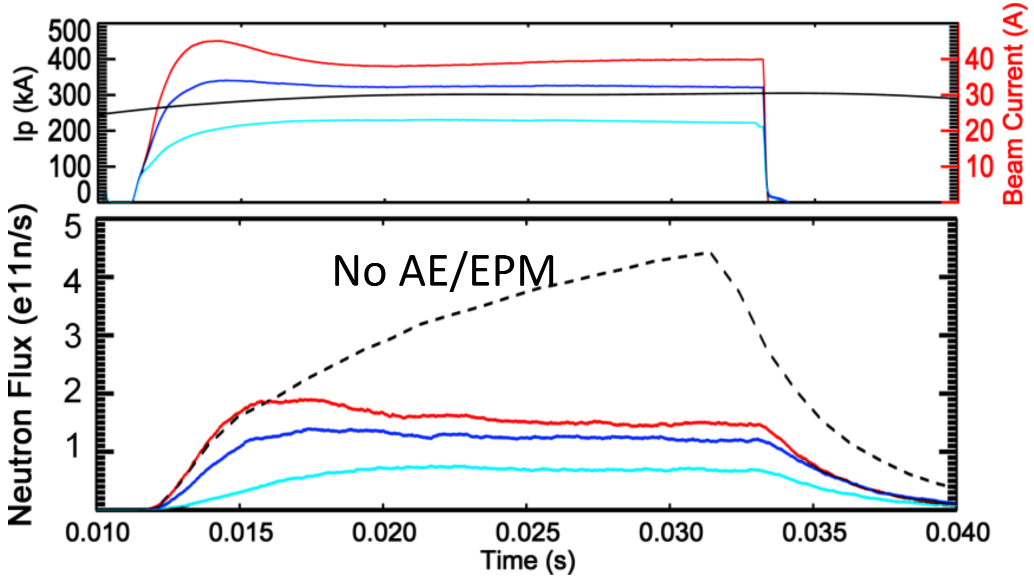
- Periodic “bursting” mode observed during NBI, concurrent with saturation of neutron signal
- Mode indicative of destabilization of Alfvén continuum mode via strong particle drive
    - Alfvén eigenmodes cause resonant transport and were avoided
    - Without AE activity EP population grows until EPM destabilized
    - Isolated mode: only (1,5) activity (prior MST work on n=4 IAE)





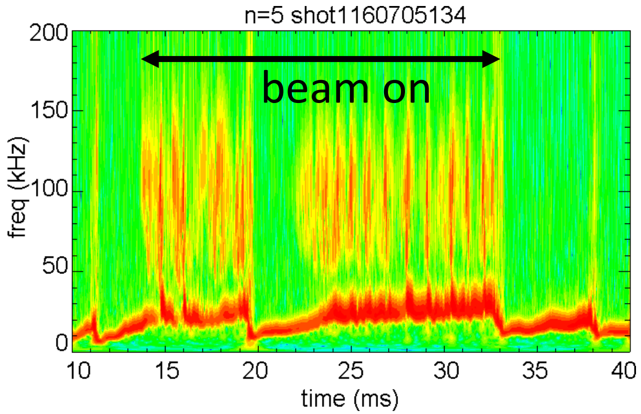
[Lin 2014]

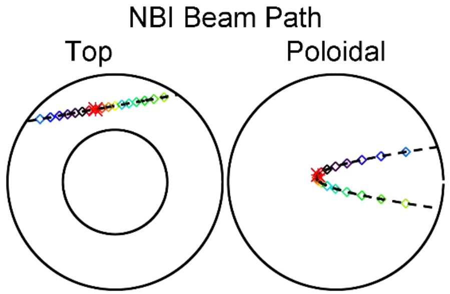


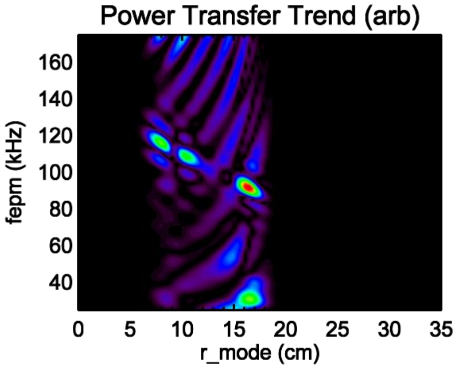


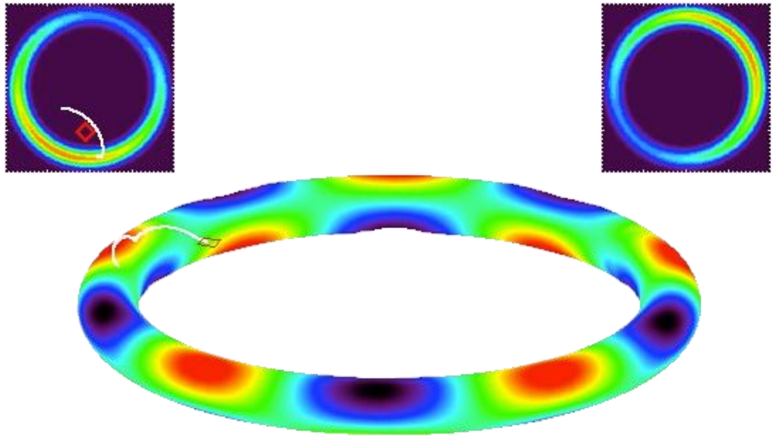
EPM resonant with NBI population

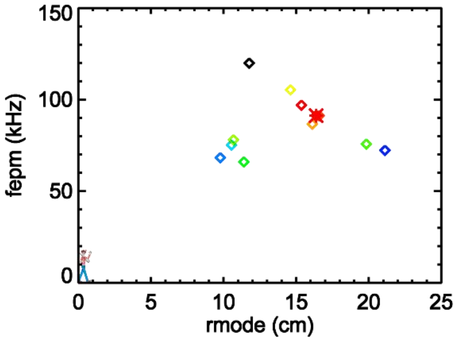
- Full orbit code (POET) developed to probe mode-particle resonance
- Energy transfer to mode:
  - From spatial gradient in fast-ion distribution (NPA shows E constant with r)
  - Transfer via resonant fast-ions
- Resonance observed with mode
  - Power transferred observed using simple (1,5) mode structure
  - Multiple full orbits representative of NBI born ions modeled that showed positive power transfer
  - Consistent with radial location and frequency of observed bursting mode

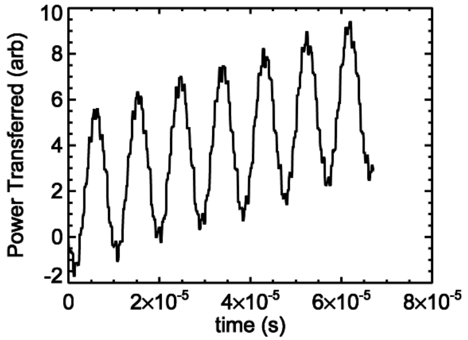










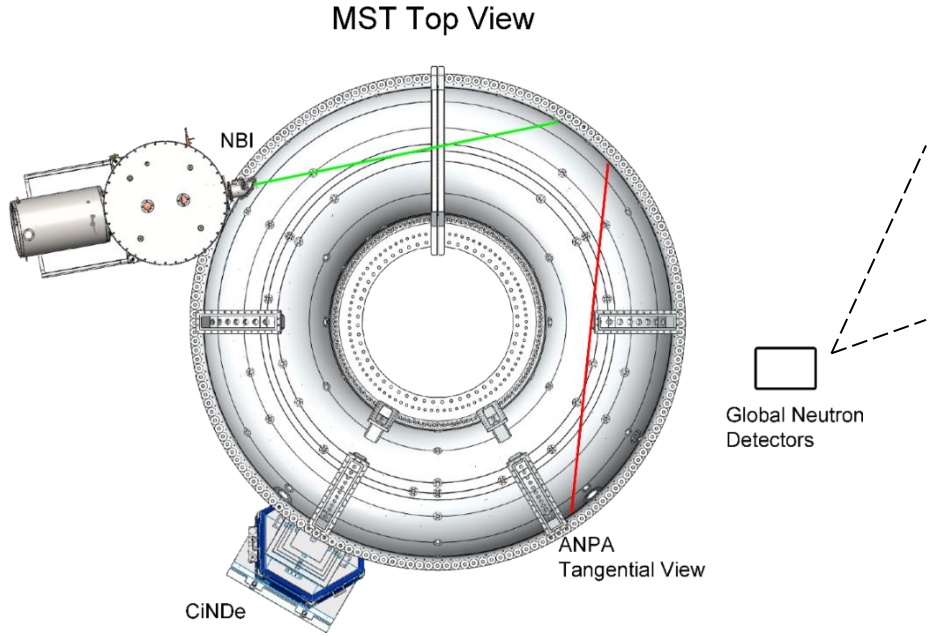


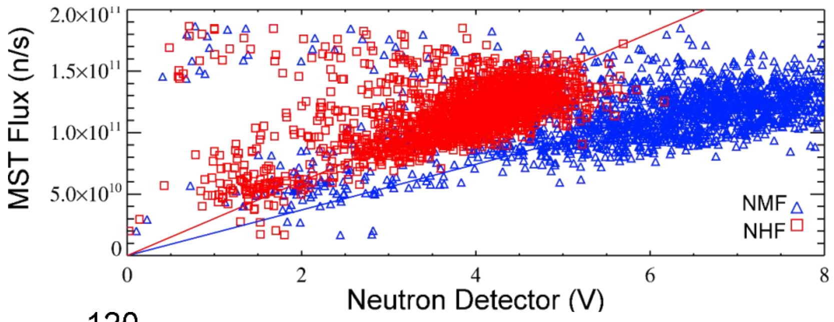
EP profile measured via D-D neutron flux

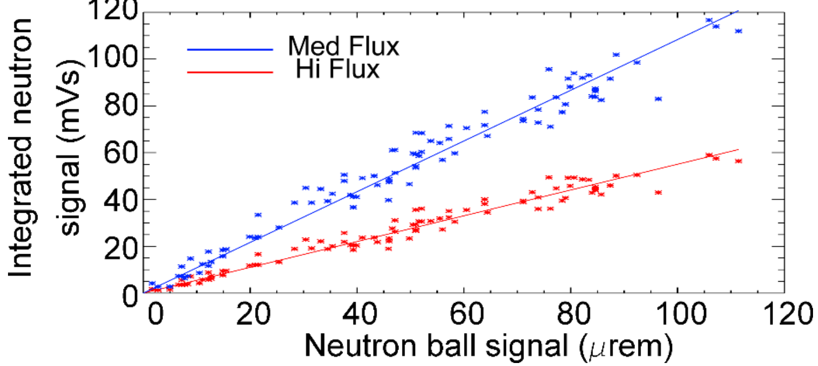
- Full D beam, almost all fusion from beam-plasma interactions

$$\Gamma_{MST} \cong \Gamma_{bt} = \iint f_f n_i \sigma v_f dV dE$$

- Neutron detectors calibrated via multiple methods, good linearity over MST flux range
- Novel collimated neutron detector measured EP profile

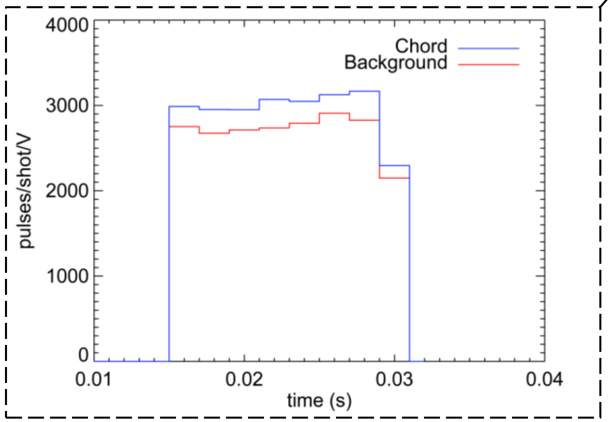


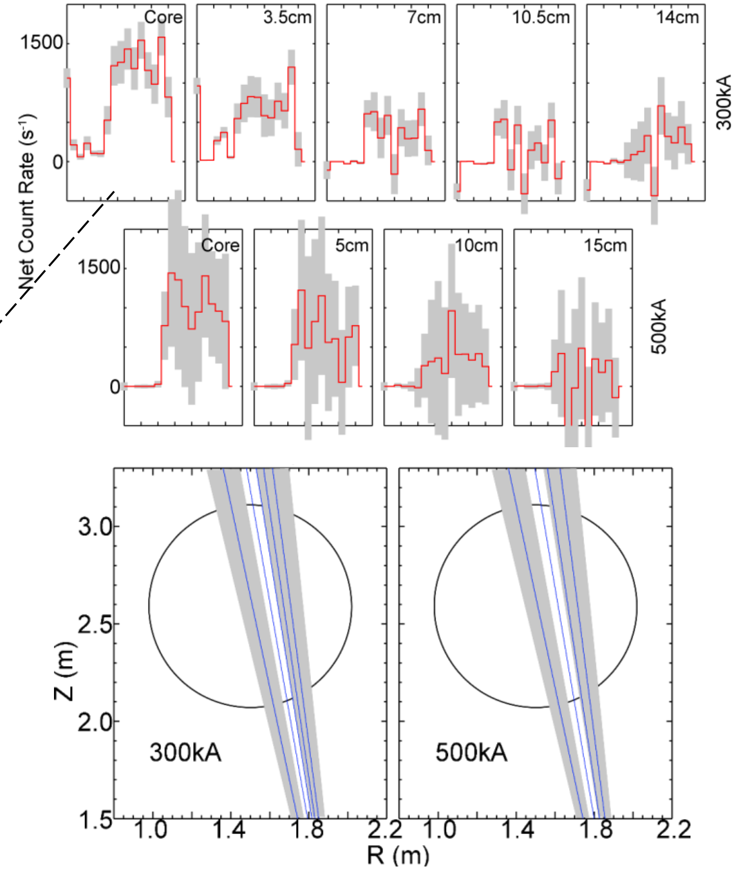


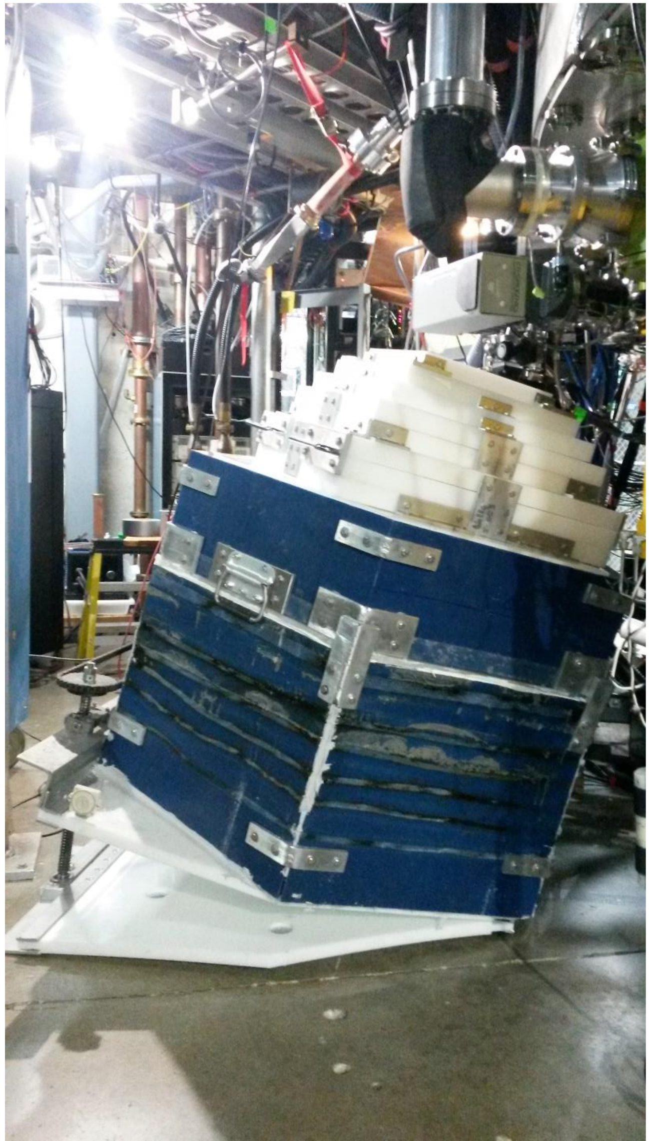


Collimated neutron measure of EP profile

- Code developed to validate collimator design
  - Model of background suppression of moderating material (validated with MCNP)
  - Optimization of scintillator to increase sensitivity to direct capture neutrons
- Large background persisted
  - Scintillator-PMT type detector sensitive to fast neutrons, but also high energy photons
  - Pulse shape discrimination possible
  - Differencing technique on large datasets

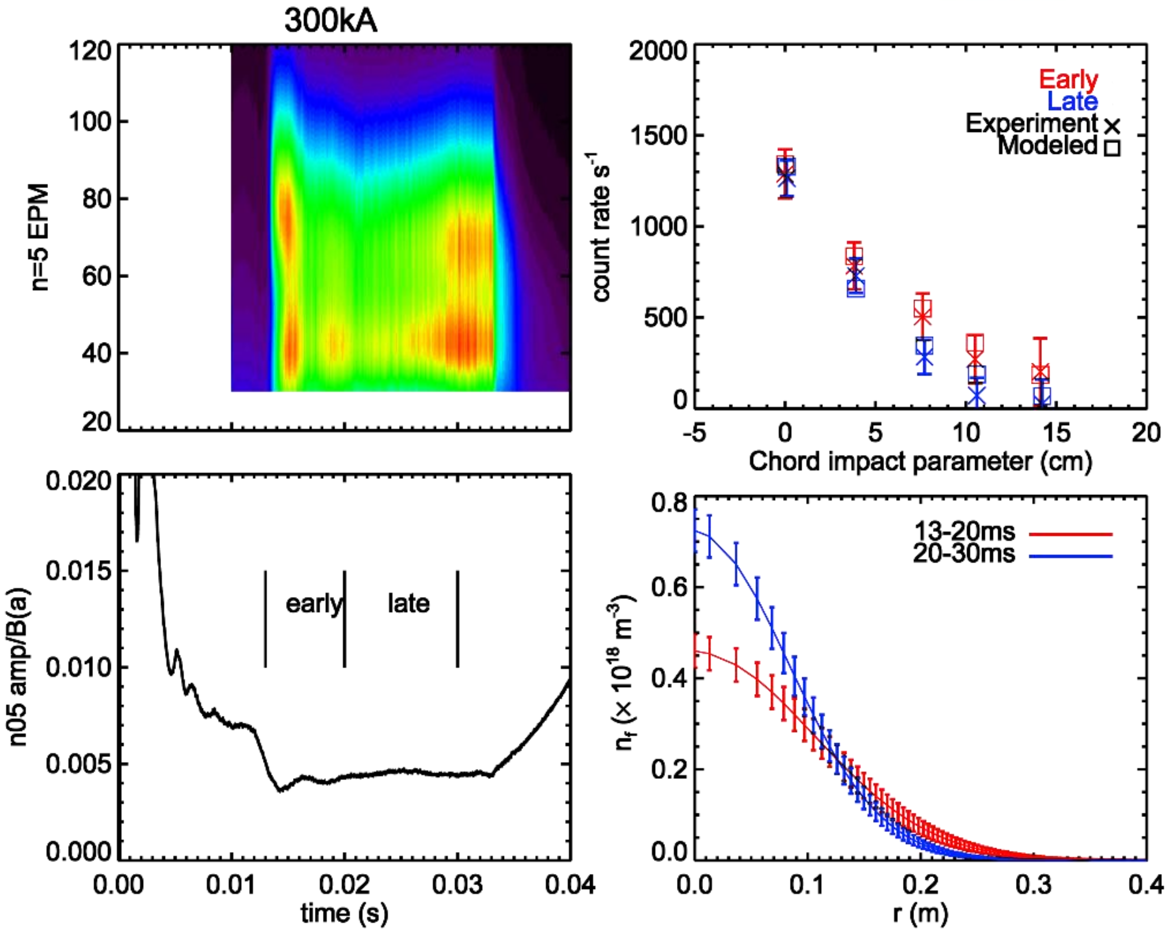






Collimated neutron measure of EP profile

- EP beta profile inverted onto 2-parameter model
  - Good agreement between experimental/modeled flux
  - “early” and “late” time windows were analyzed to provide information on profile development while maintaining good statistics



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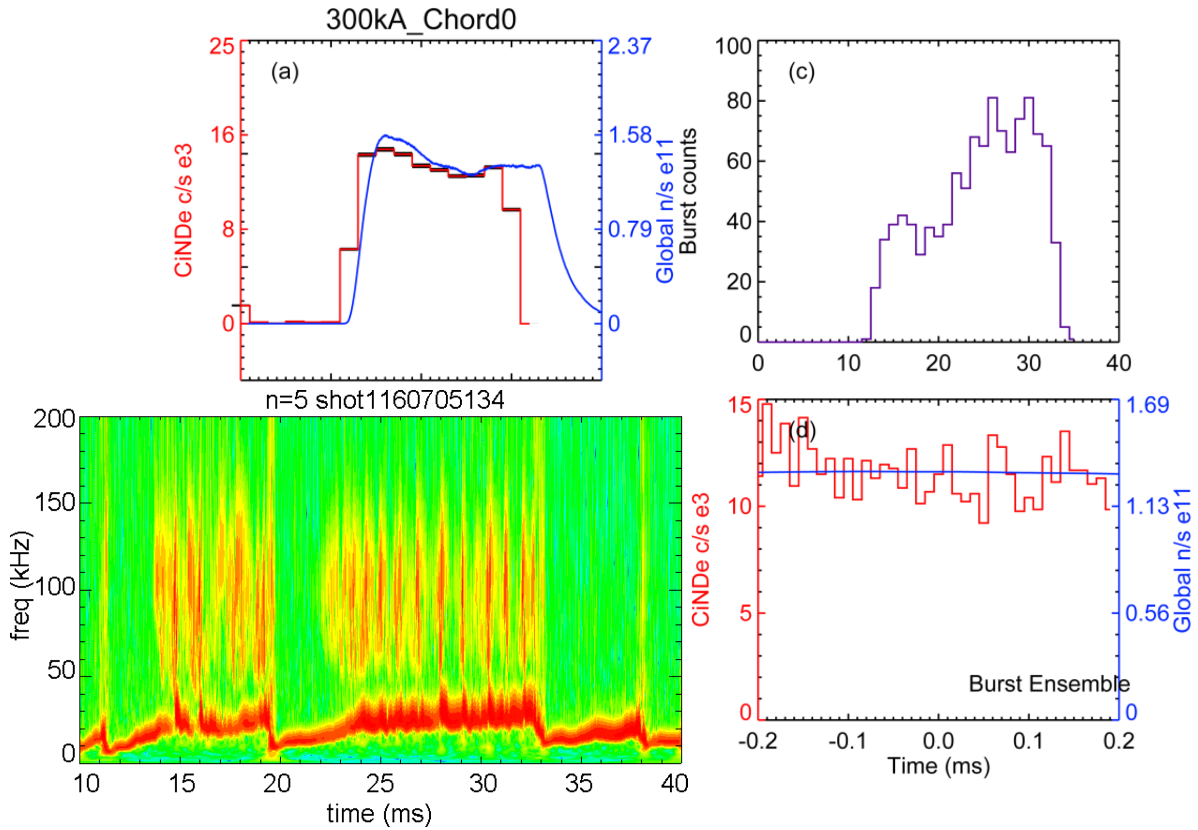
  - Prior work with H-NBI saw drop in NPA signal
    - Triplet mode activity- mode coupling enhanced losses
  - Suggests transport but not loss- local flattening



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- Burst ensemble showed no drop in neutron rate
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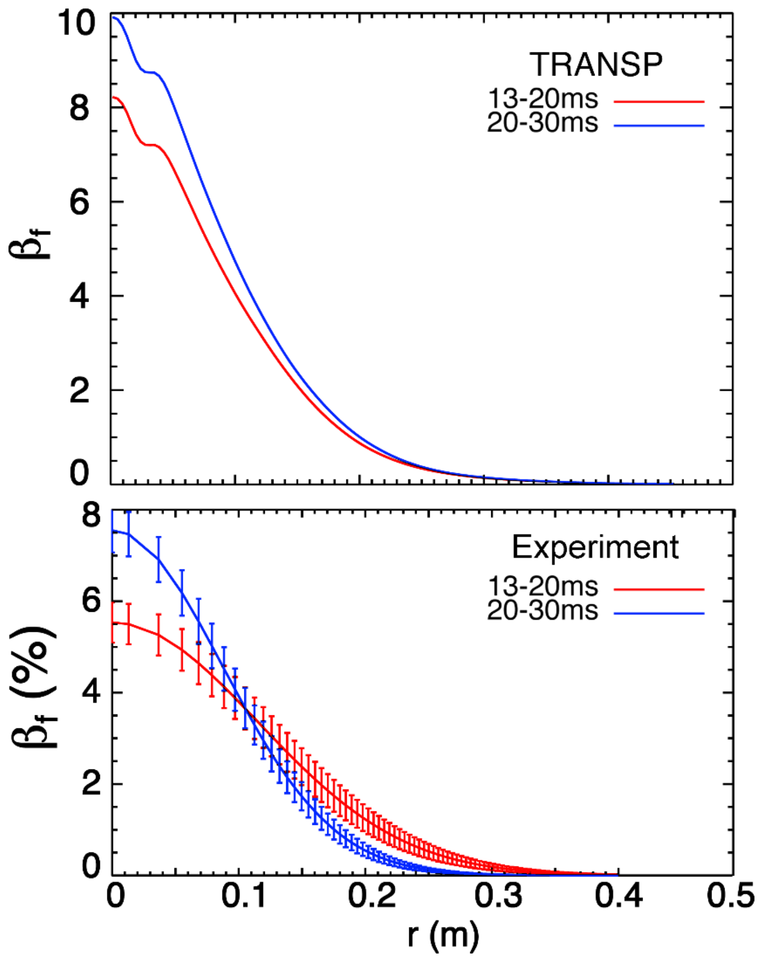
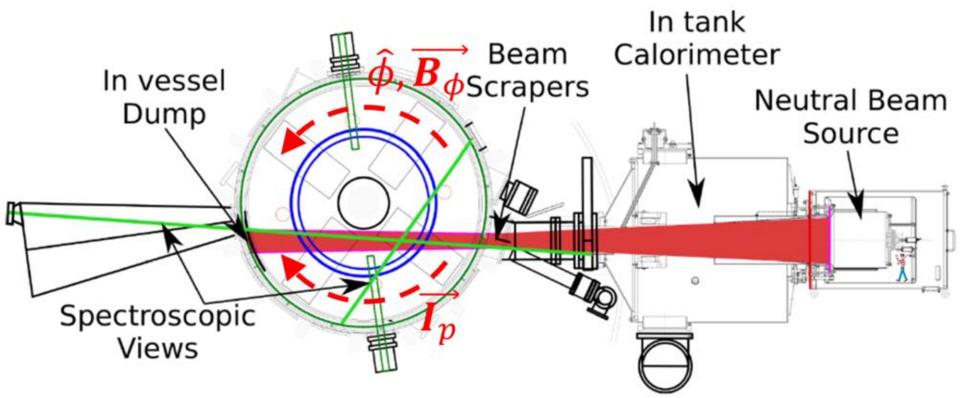
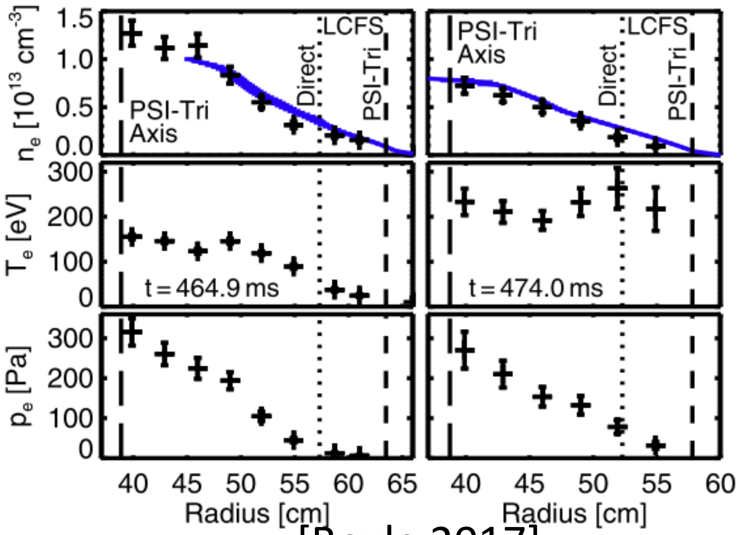
    - Triplet mode activity- mode coupling enhanced losses
  - Suggests transport but not loss- local flattening
- Reconstructed profiles show ~2.5% reduction in core-beta due to EPM activity
  - $\langle \beta_f \rangle = 2.2 \pm 0.3\%$
  - $\nabla \beta_f = 0.52 \pm 0.02\%/cm$



Fast-ion studies in LTX-β

- Flat Te achieved with Li walls
- NBI installed 2019 to further low-recycling boundary studies
  - Core fueling to sustain plasma
  - Heating for study of energy scaling
  - Possible stabilization against density gradient modes





[Boyle 2017]

NBI Parameter	Specification
Beam energy	20 keV
Beam power	700 kW
Pulse length	5-7 ms
Composition	100% H

Lithium Tokamak Experiment Beta

R=0.4 m; a=0.25 m

I_p ~ 100 – 150(?) kA

|B| ~ 0.3 T

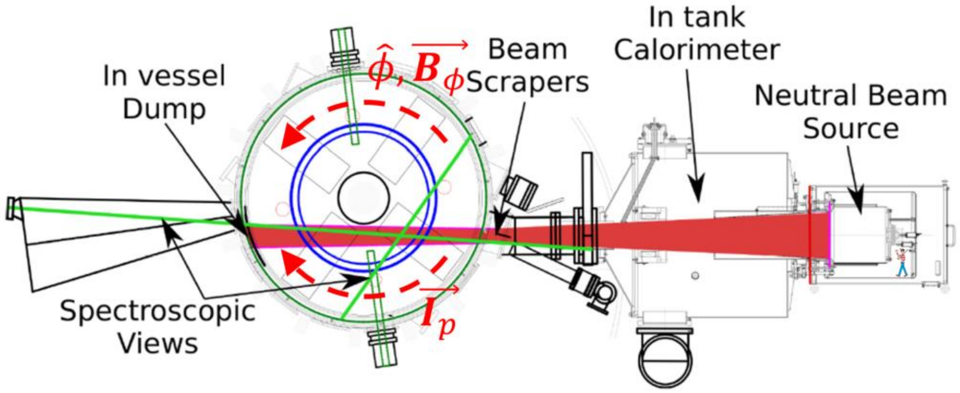
$T_e(0)$ ~ 200 eV

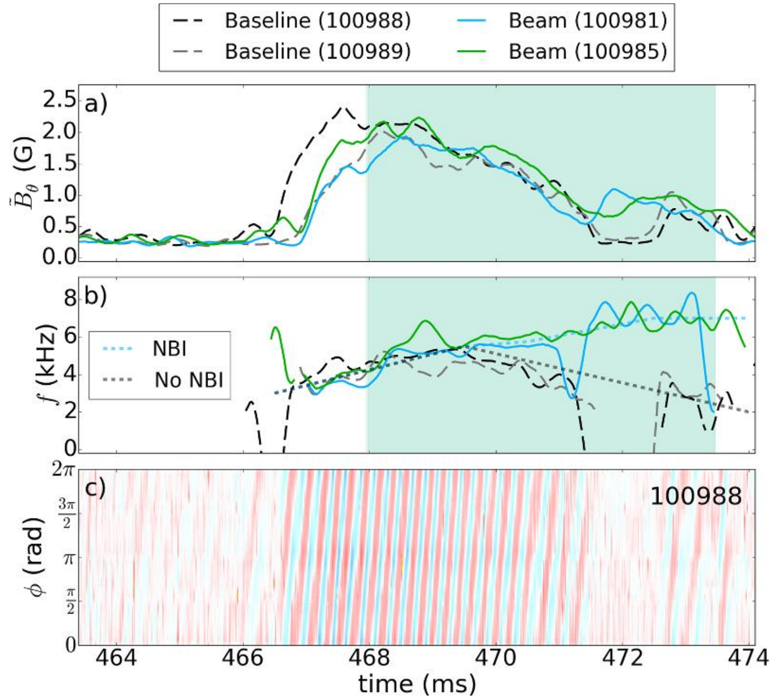
n_e ~ 10^{13} cm^{-3}

Pulse length ~ 50 ms

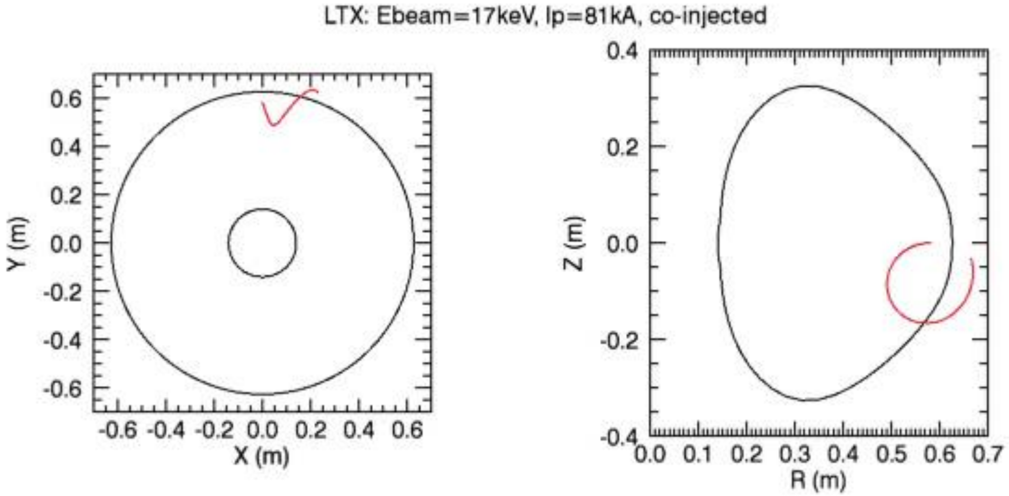
Fast-ion studies in LTX-β

- Flat Te achieved with Li walls
- NBI installed 2019 to further low-recycling boundary studies
  - Core fueling to sustain plasma
  - Heating for study of energy scaling
  - Possible stabilization against density gradient modes
- Initial operation (Ip<100kA) total loss of EPs



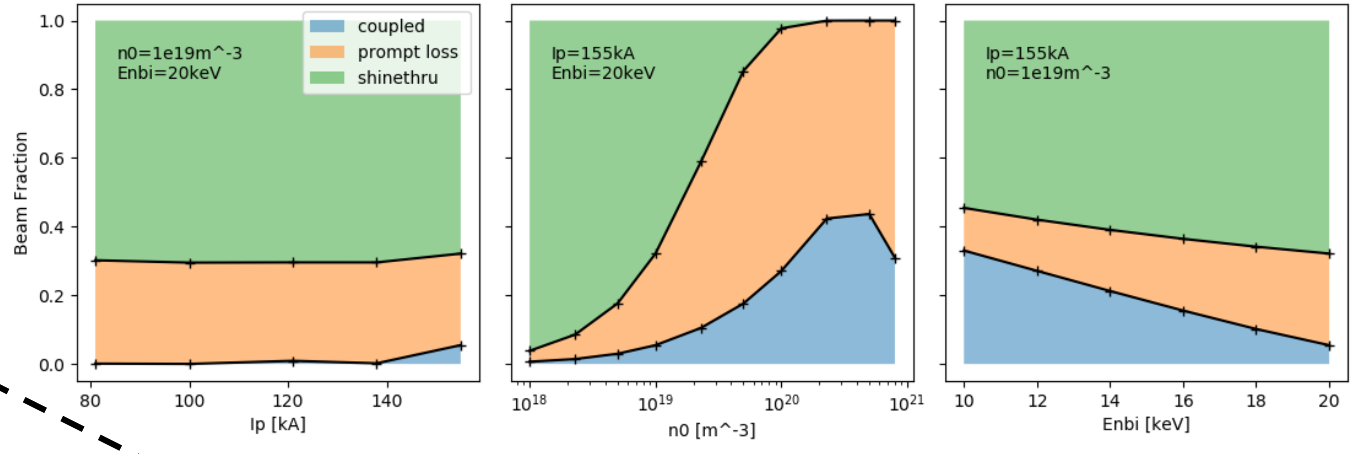


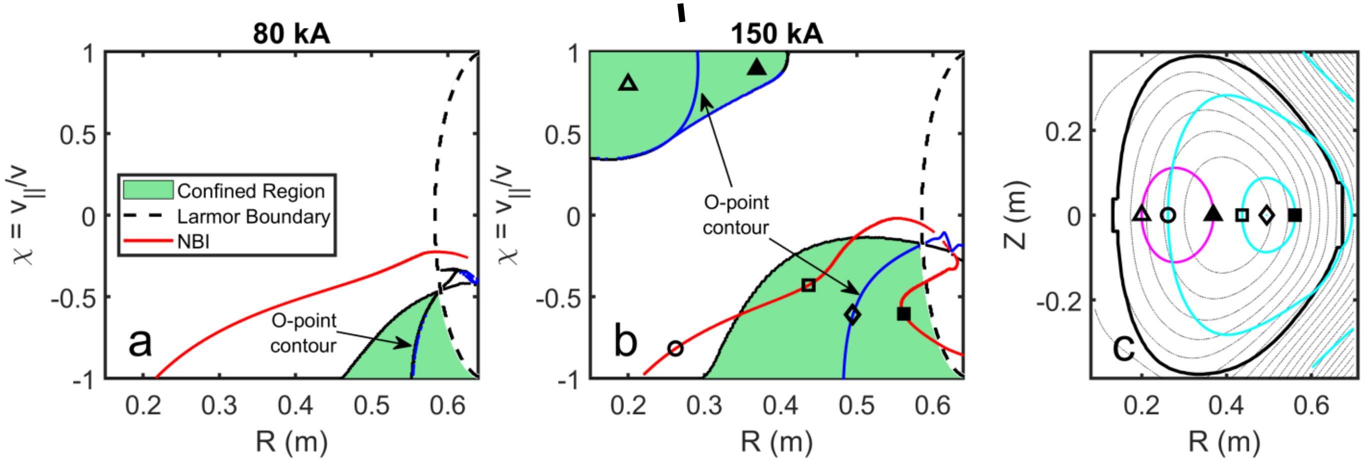
[Hughes et. al, PPCF 2021]

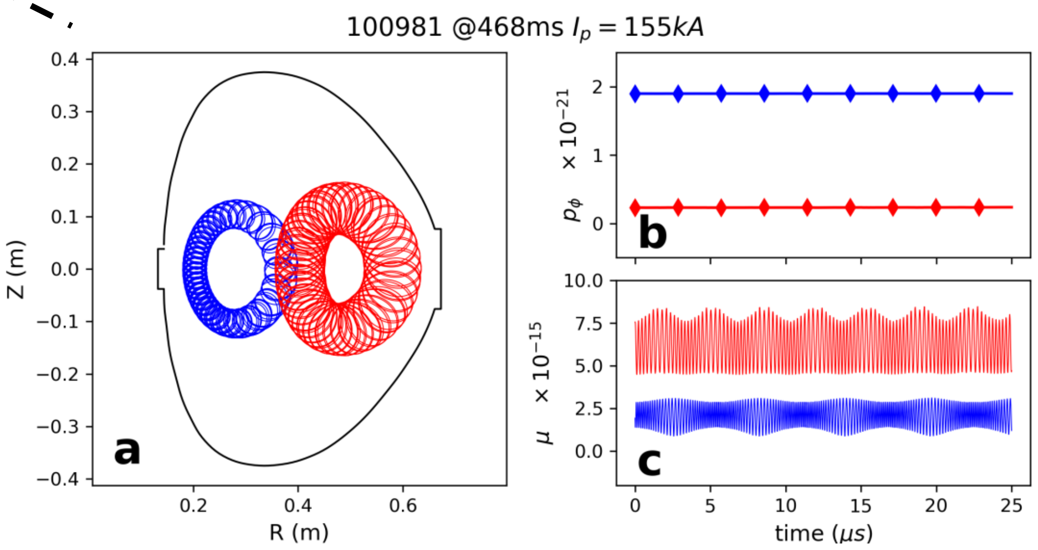


Optimizing NBI coupling

- TRANSP maps potential gains in adjusting n_e, I_p, E_{nbi}
- POET (3d orbits)- FLR effects, non-adiabatic effects unimportant
- CONBEAM- retrofit to ST geometry, illustrates EP confinement regions



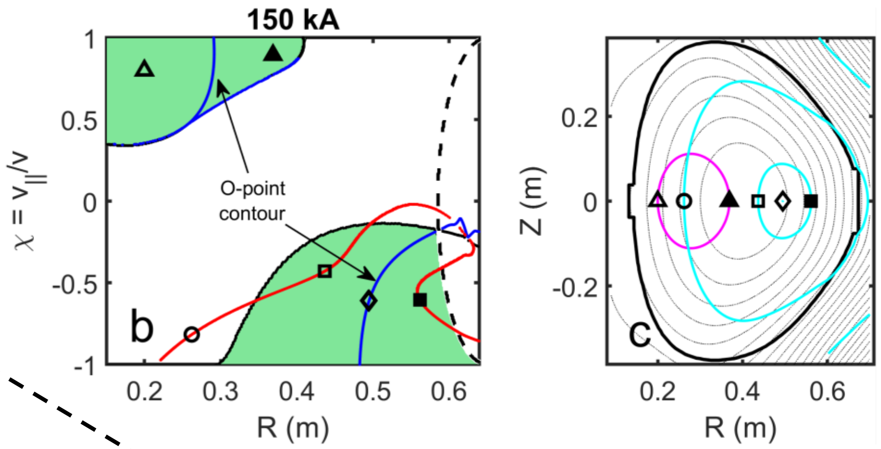




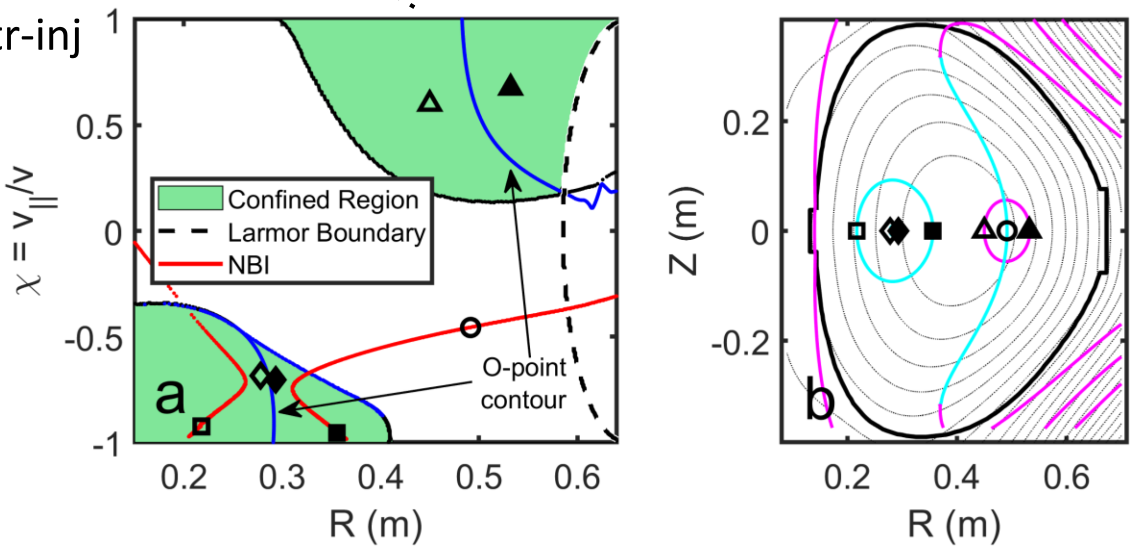
Optimizing NBI coupling

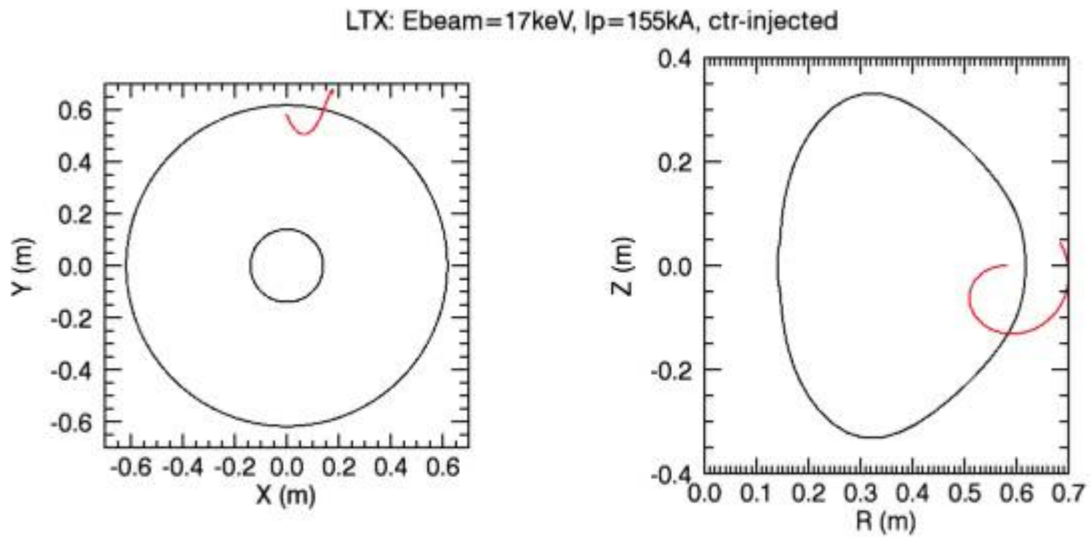
- Preference for HFS/LFS coupling
  - Reversed-current operation for HFS coupling
  - Tangency scan optimum at 35cm
- Large (but very localized) heat flux to walls
- Results very sensitive to equilibrium geometry, data gathering ongoing

Co-inj



Ctr-inj





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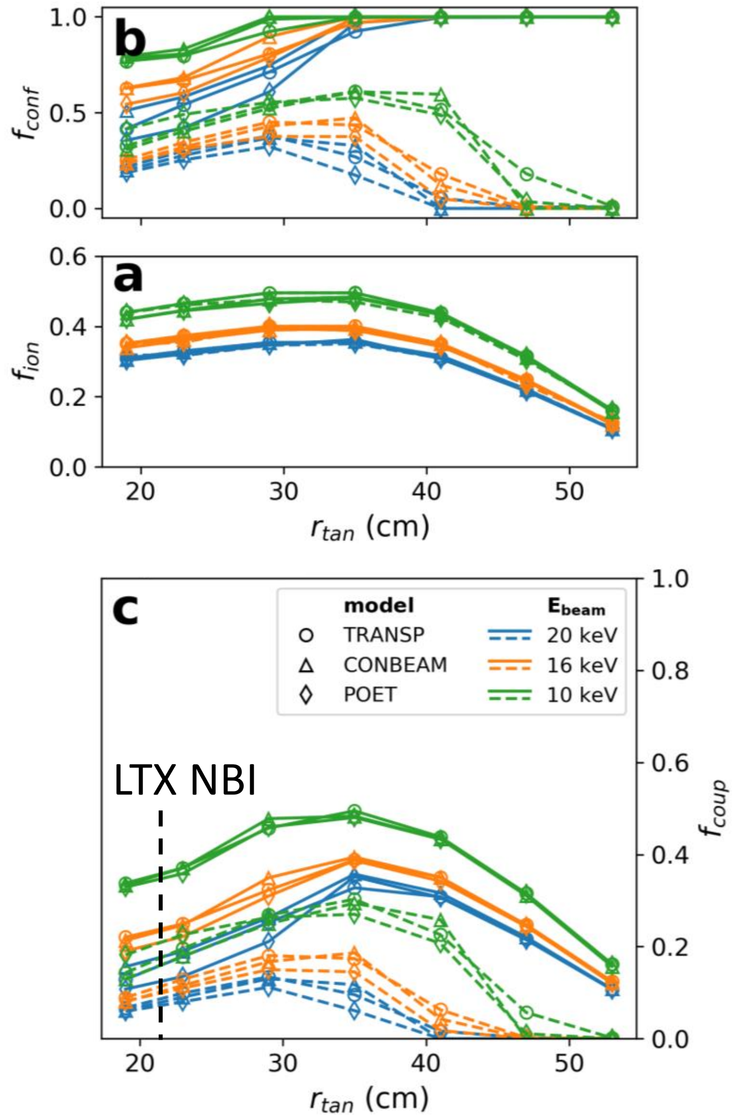
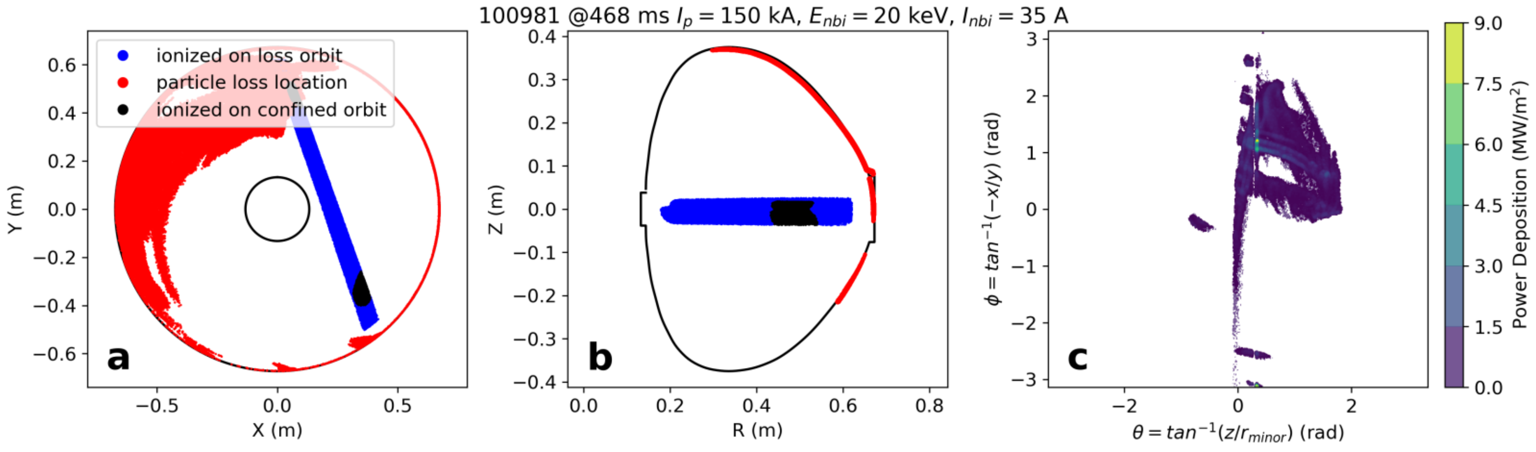
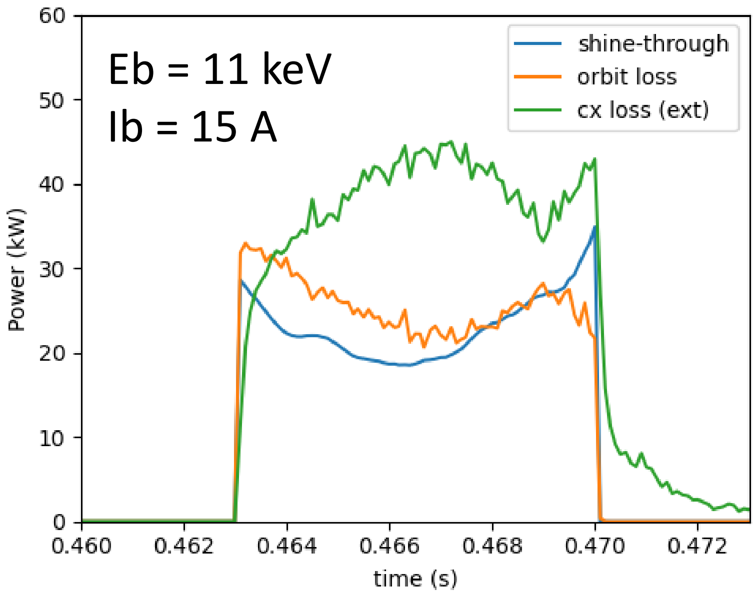


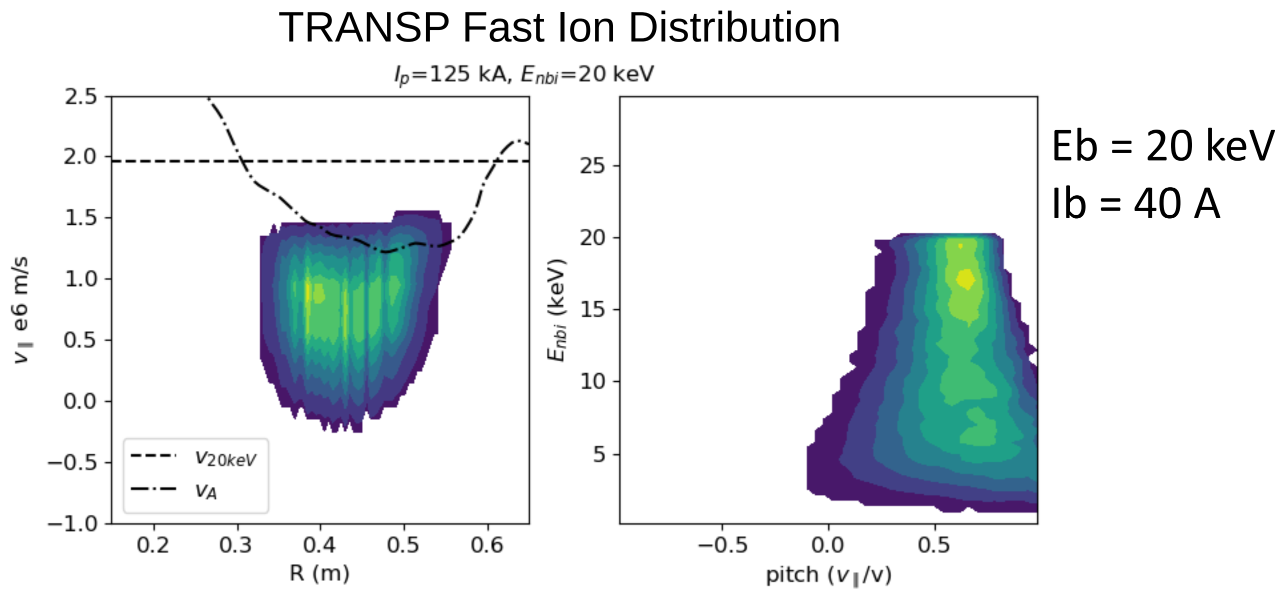


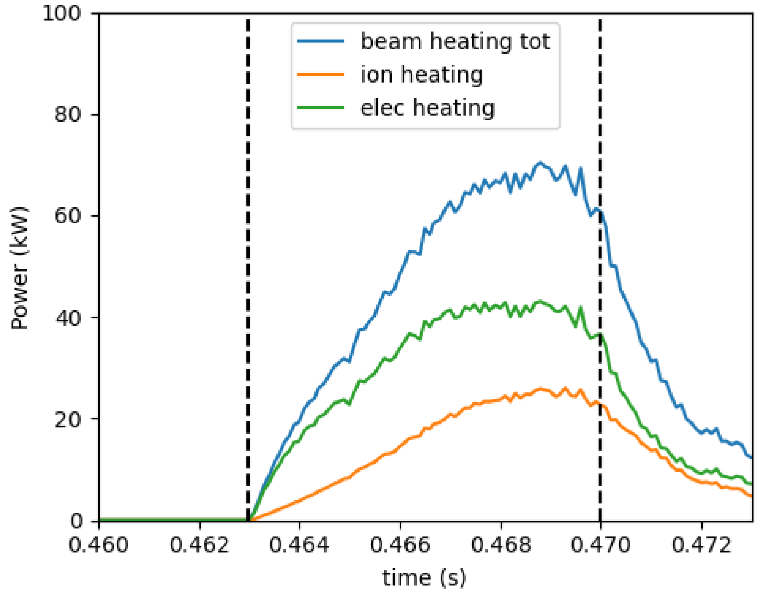
Recent upgrades enable EP population

LTX-β

- Recent shot development Ip~130kA
- Mechanical upgrades
- TRANSP/NUBEAM shows growth of population mid-outboard region
  - Appreciable shine-through, orbit, and cx loss
  - But measurable beam heating (ohmic ~200kW)
  - Just sub-Alfvénic, could see modes in future



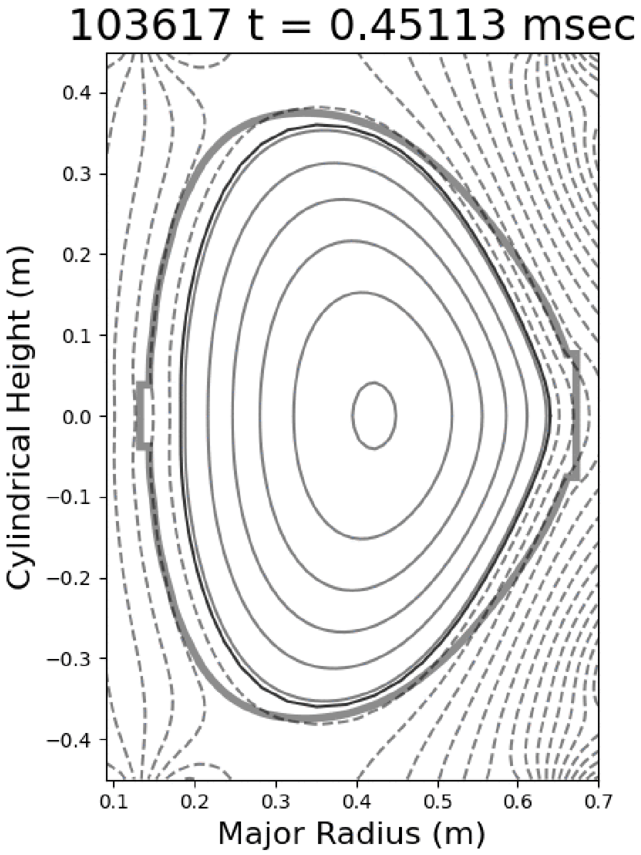


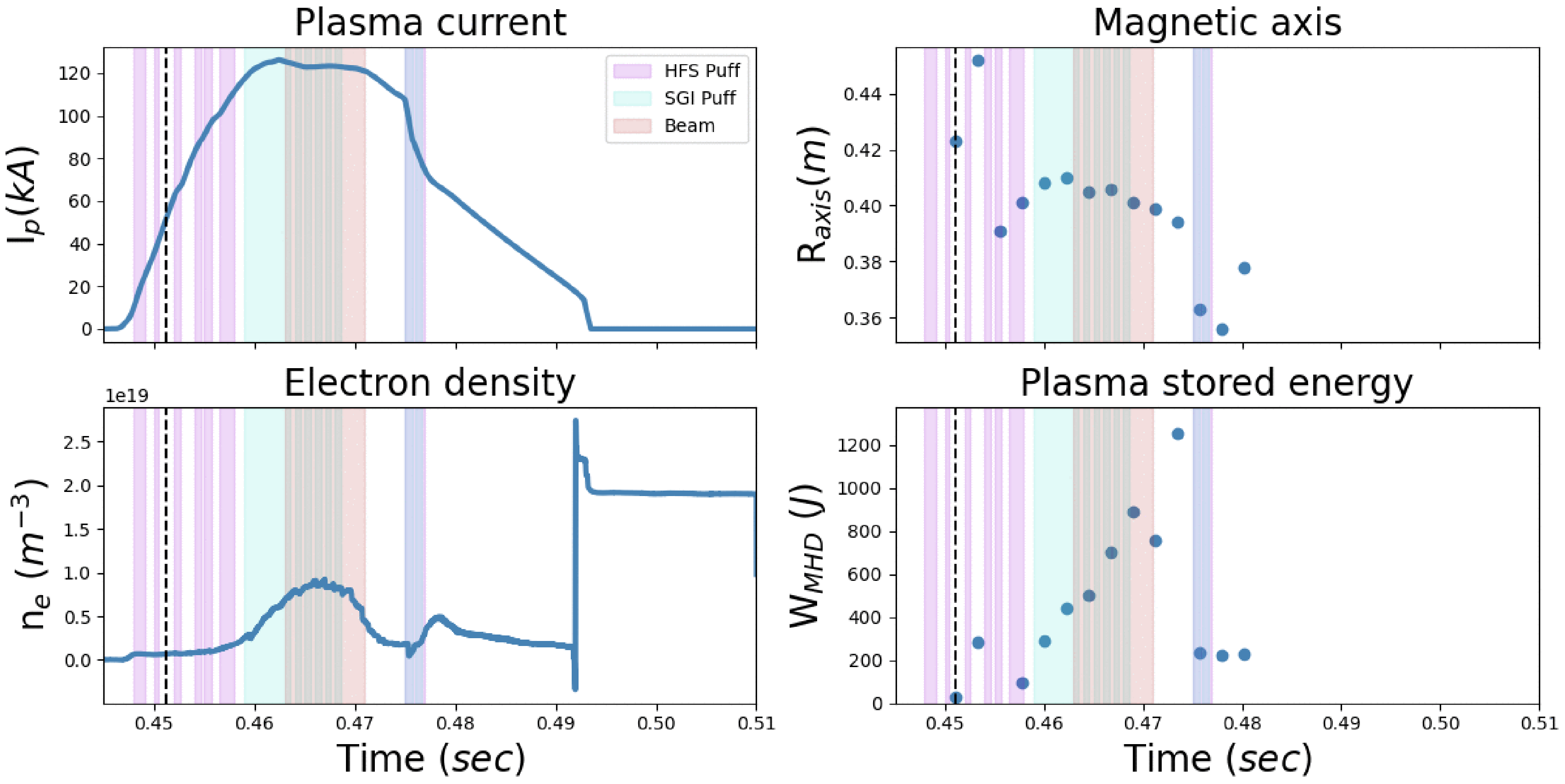


Post-discharge tools for NBI coupling data

LTX-β

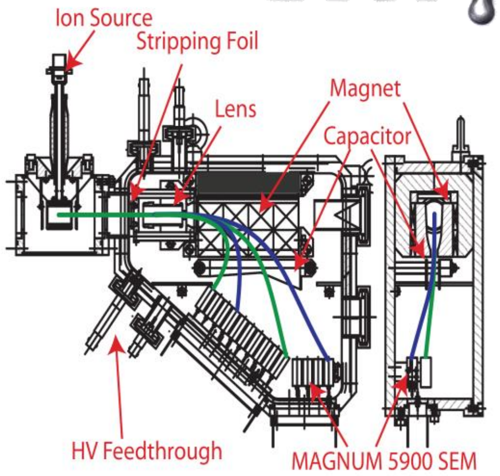
- Equilibrium reconstruction is (semi) automatic
- Equilibrium is dynamic
  - Amassing data on coupling as mag axis shifts
  - CONBEAM set up to analyze equilibria (no TS data)



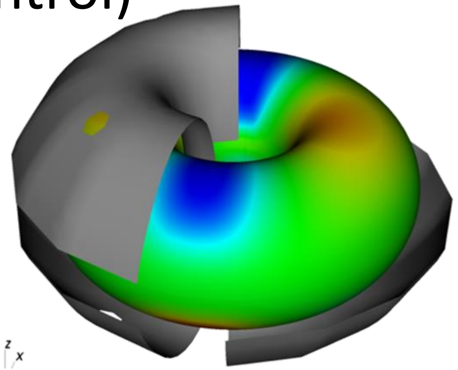


Fast-ion studies in LTX-β

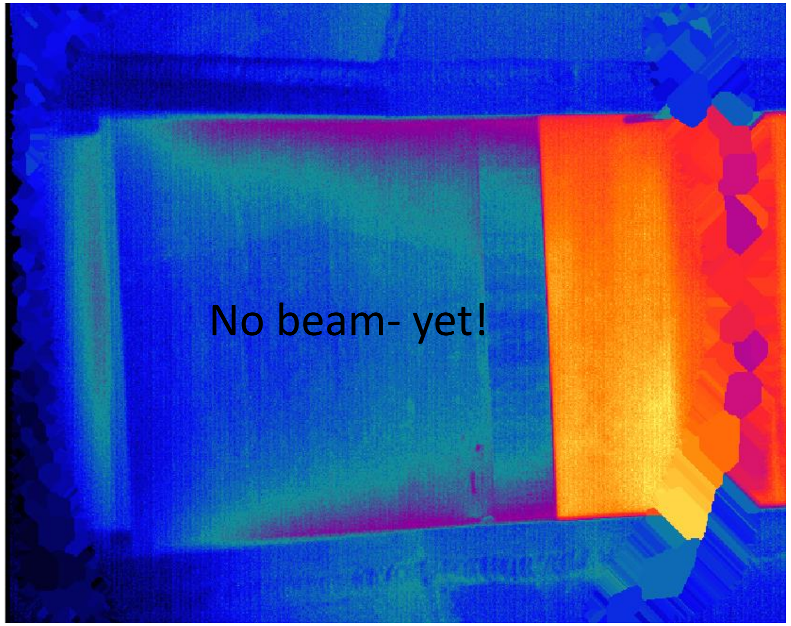
- Upcoming: IR thermography, spectroscopy
- NPA: diagnose EP pitch/energy distribution
  - Degas2 modeling underway
- Inter-shot beam analysis (no real-time plasma control)
  - “tangency” scan data
  - Assess impact of reversed-current ops
- Fast-ion transport in 3D fields

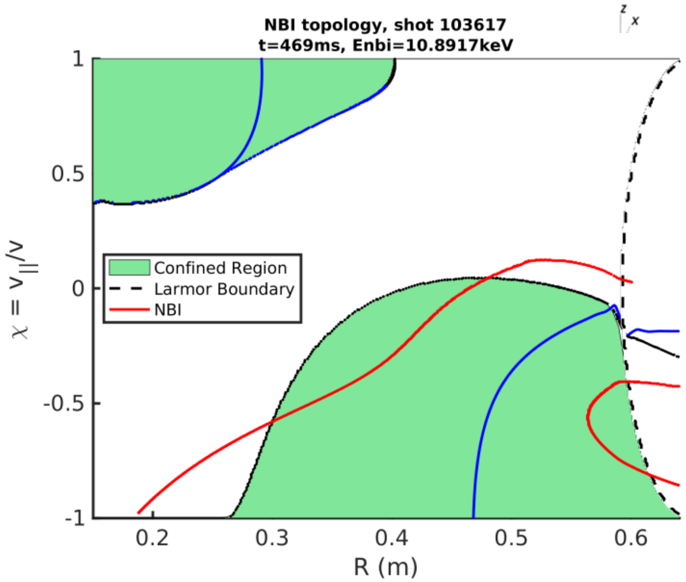


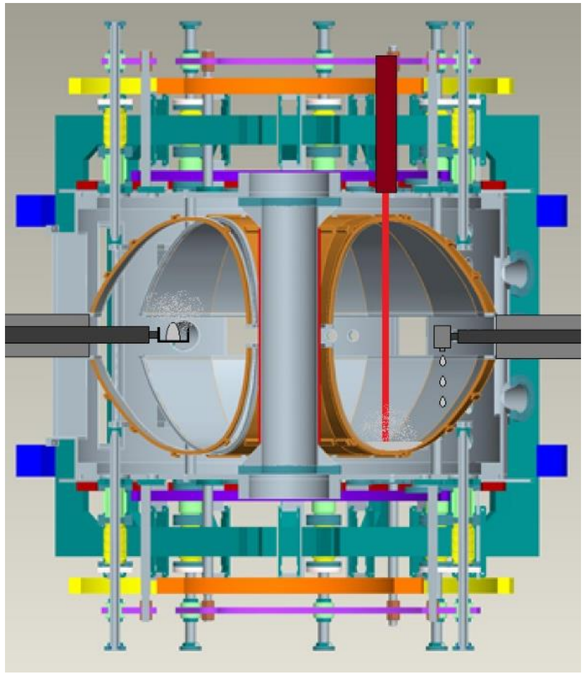
[J. Reusch 2012]



C. Hansen



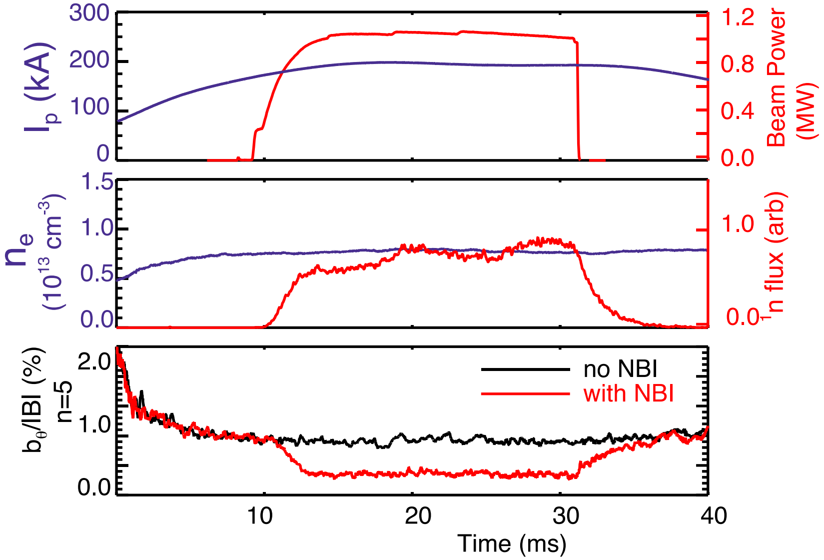


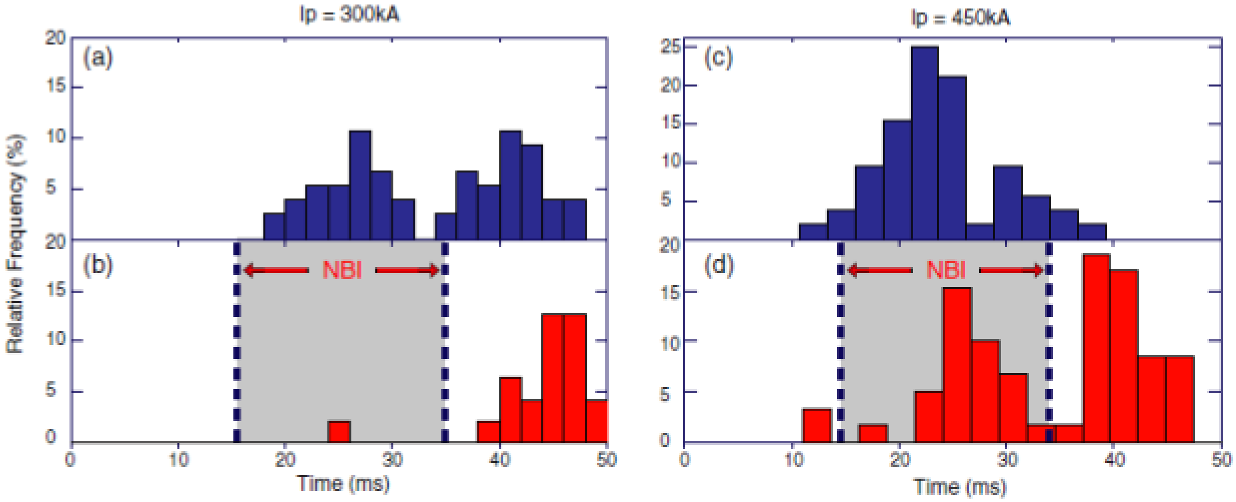


Thank you!

Extras

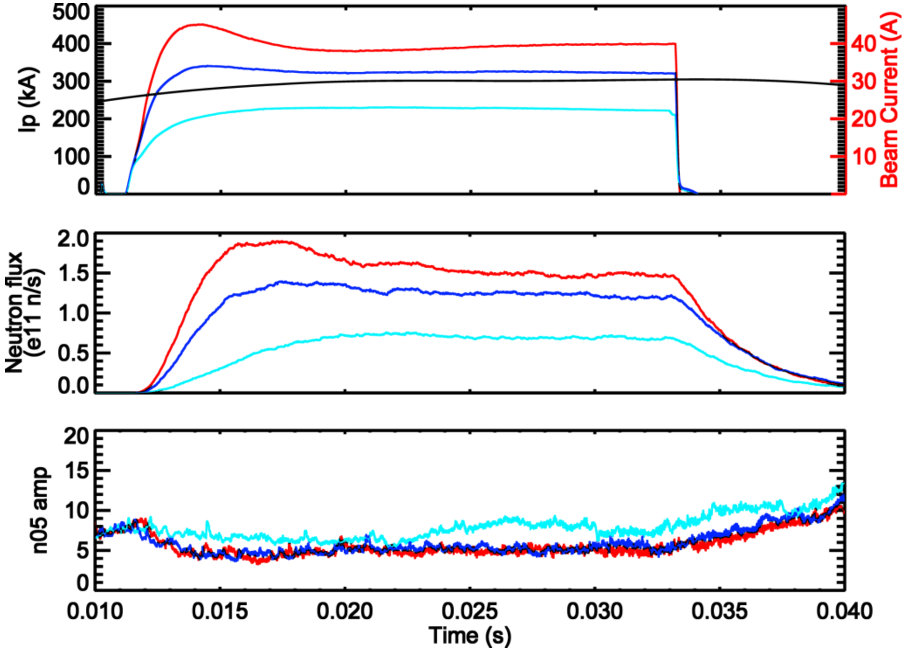
- EPs stabilizing effect on core tearing mode, suppress transition to QSH

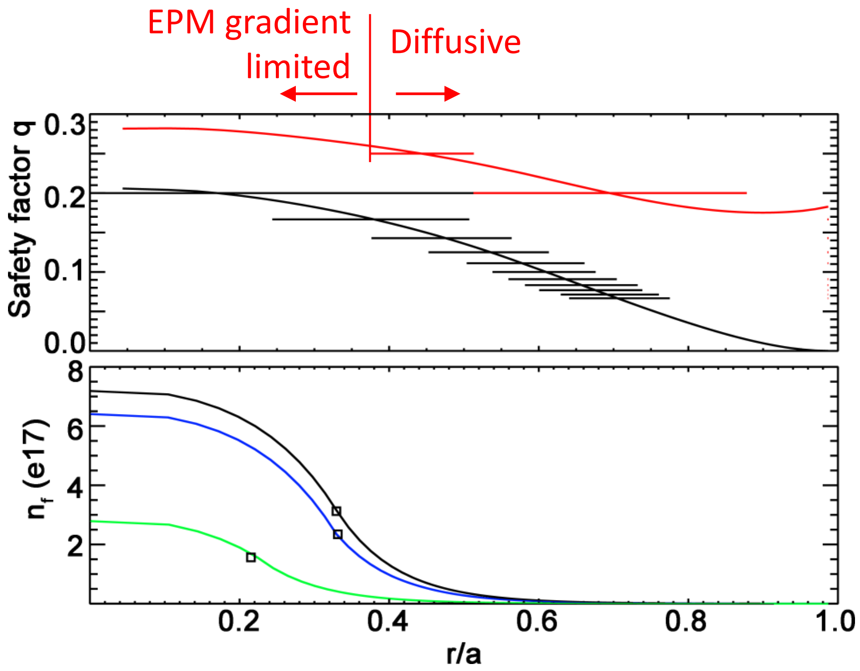




Extras

- Explanation of differing neutron flux saturation
  - Diffusive boundary at mid-radius set by fast-ion island overlap
  - Lower Ip reduces particle flux, slowing lowers average energy
  - This reduces qfi moving diffusive boundary inward





Extras

- Beta->pressure->density
- E spatially constant, B fields well known

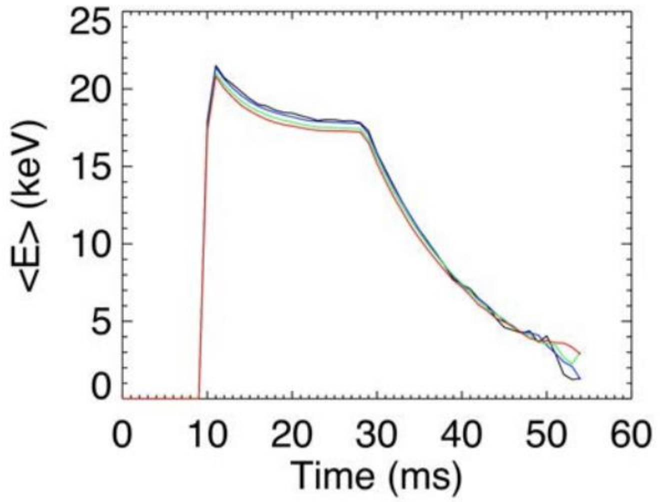


Fig. 5.13: TRANSP average fast-ion energy vs time at four radii from r = 0-0.2 m shows near constancy with radius.

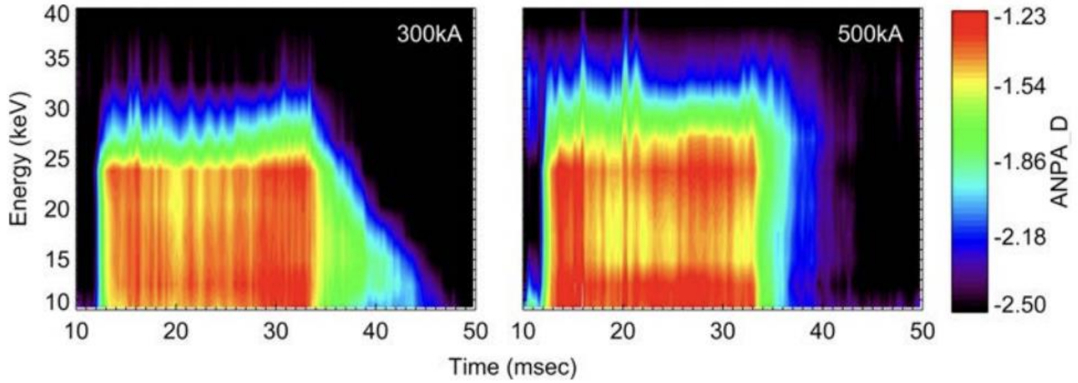
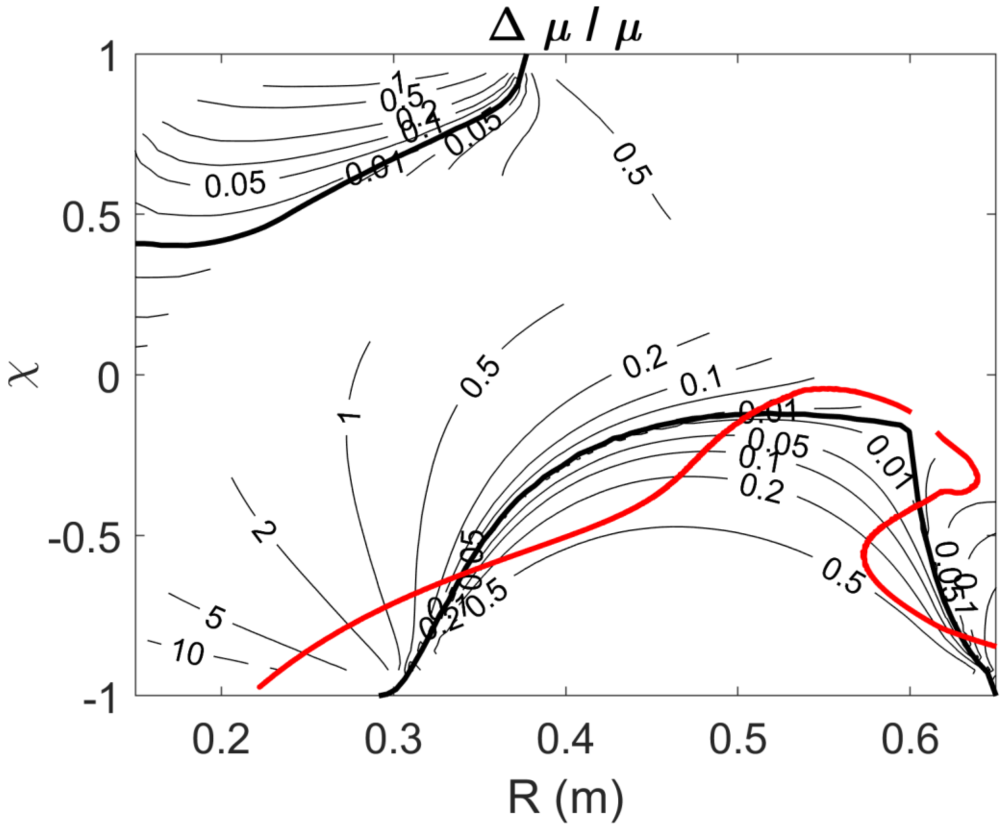


Fig. 5.14: ANPA spectrogram for 300 and 500 kA datasets. Injection near 25 keV connects through a broad profile to the lower energy channels.

[Capecchi thesis, TRANSP, Liu, Anderson et al]

Extras

- Very small EP population sensitive to chances in magnetic moment



Extras

- TRANSP scan shows good beam heating at higher Eb despite increases to orbit loss/shine-through
- Assumes identical beam optics