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Fast ion physics in the C-2U advanced, beam-driven FRC

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for the TAE Team

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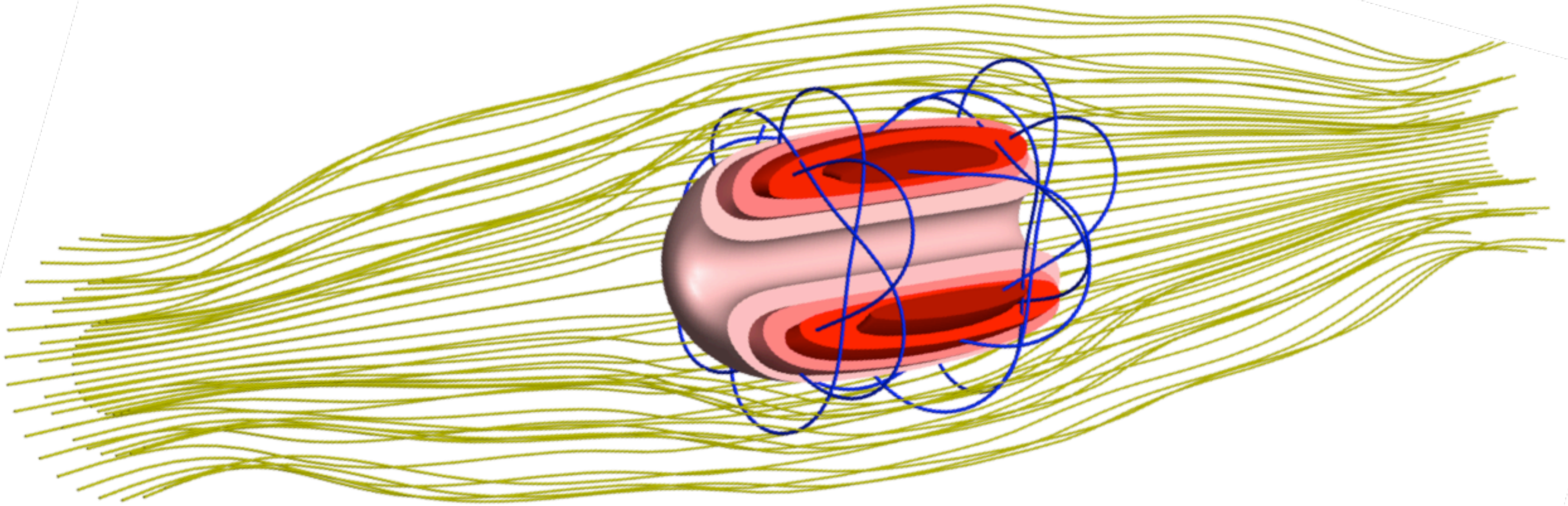
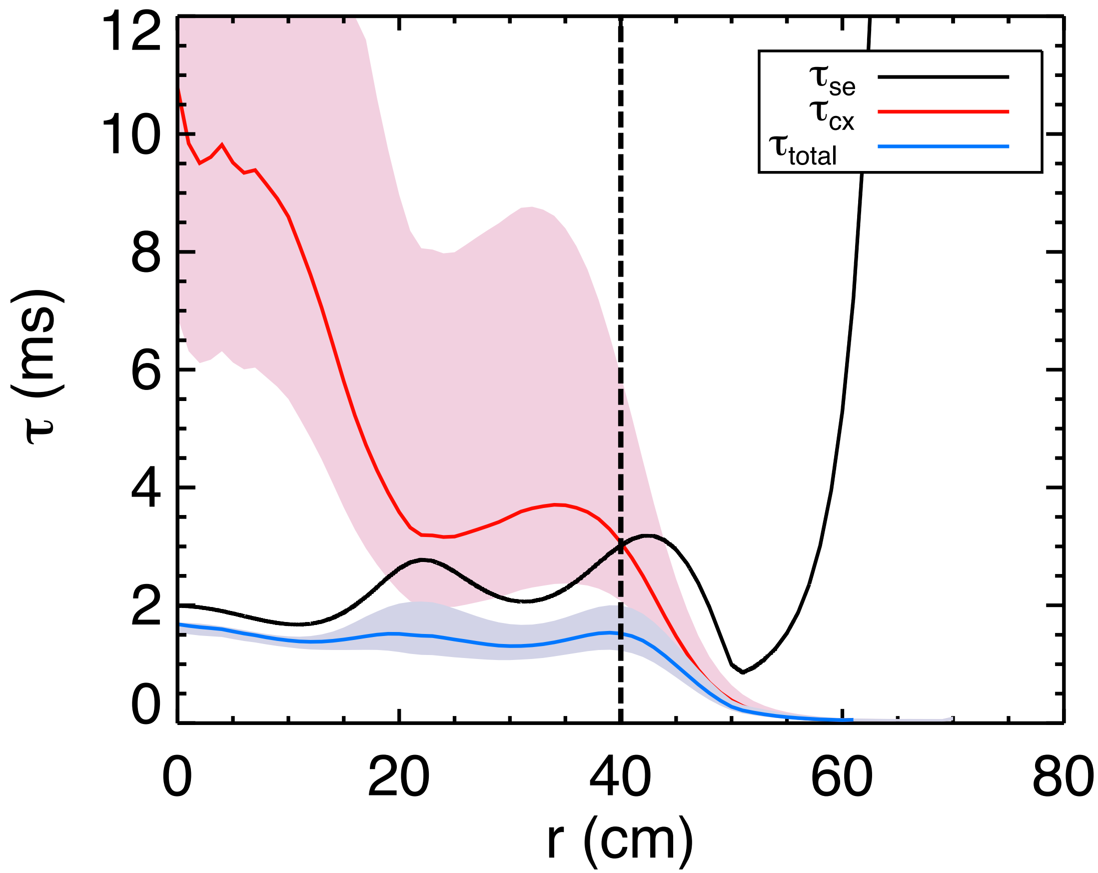
High β FRC embedded in magnetic mirror is a unique fast ion environment



- Tangential NBI + low B field
  - ➢ large, machine sized orbits
- High NB power + compact plasma
  - ➢ high NB power density

Device	Class	NBI (MW/m^3)	ρ/a
ITER	tokamak	0.04	0.005
DIII-D	tokamak	1.4	0.03
2XIIB	mirror machine	5	0.7
C-2U	**FRC**	**10**	**1**
GDT	mirror machine	30	1.5

Dominant fast ion collisional process differs inside and outside separatrix



- In FRC, $\tau_{se} < \tau_{cx}$ ➔ slowing down distribution
- In SOL, $\tau_{se} > \tau_{cx}$ ➔ *df/dv > 0* ➔ beam-driven modes
- Fast ions sample both regions of plasma

Outline

- Experimental evidence of classical fast ion confinement
- Experimental evidence of beam-driven modes
- Interpretation

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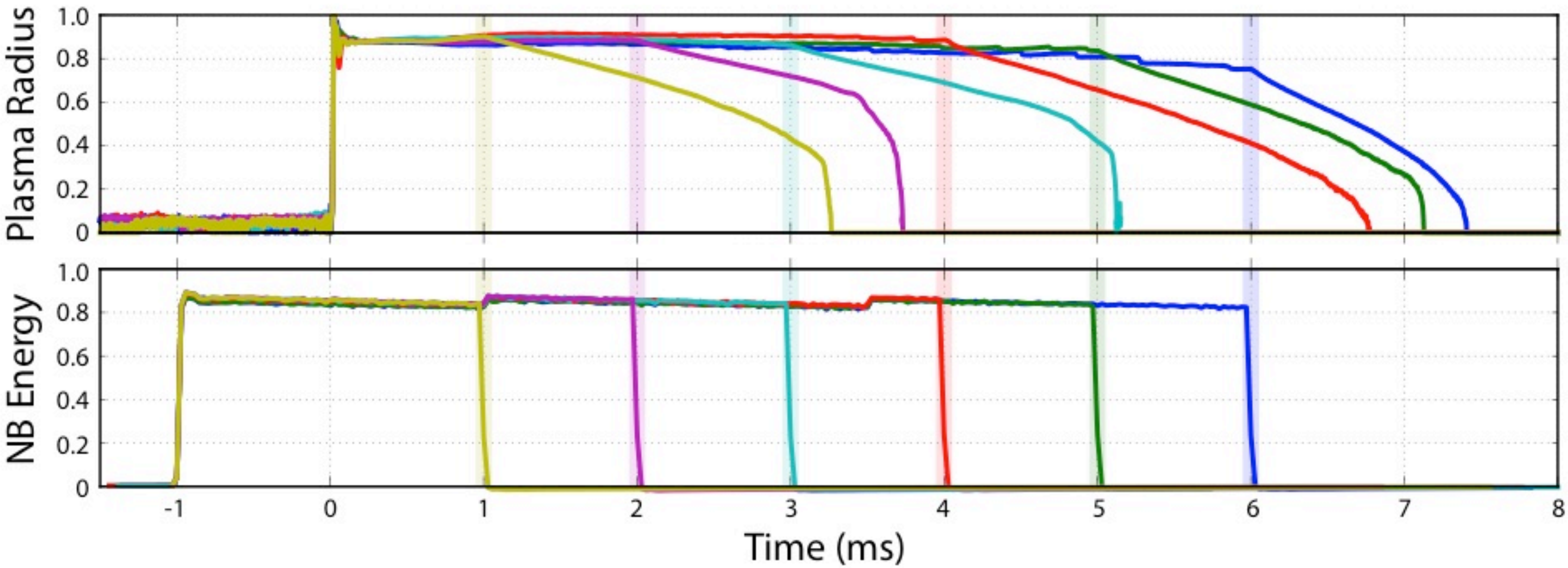
NBI sustains the FRC plasma

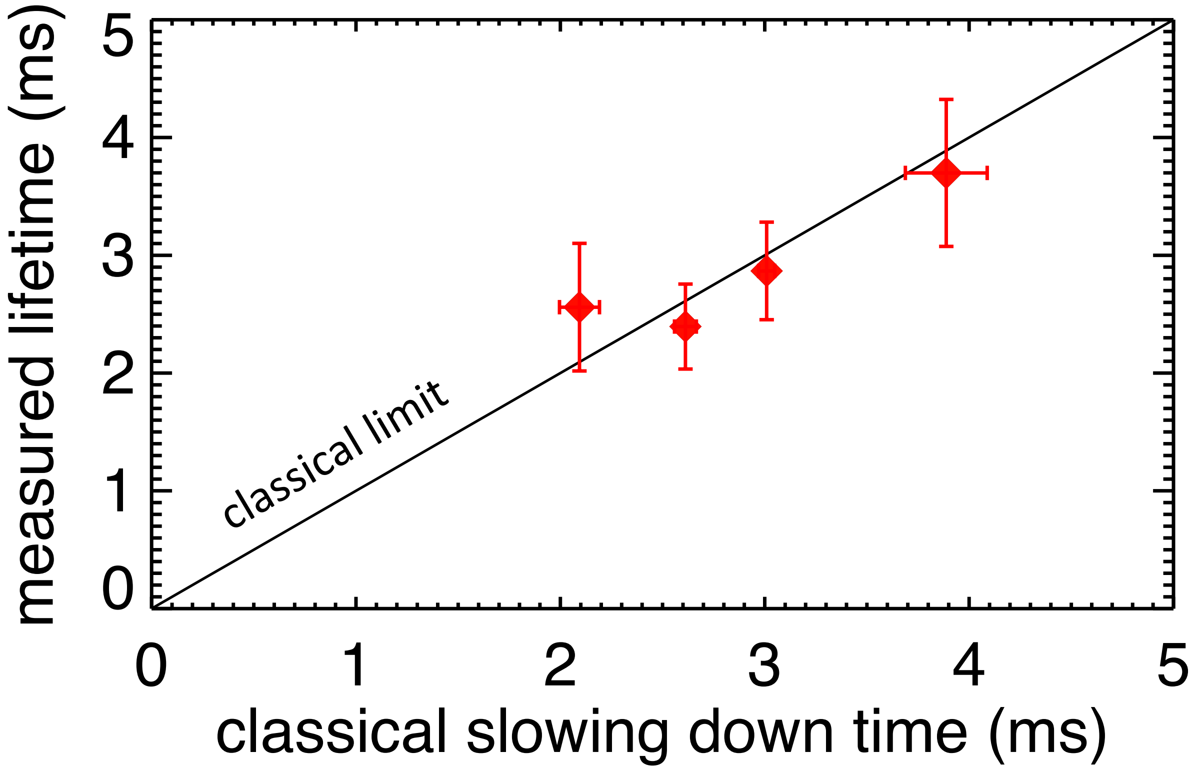
M.W. Binderbauer et. al., AIP Conference Proceedings 1721, 030003 (2016)



- FRC lifetime well correlated with NB pulse length
- Clear evidence of fast ion accumulation

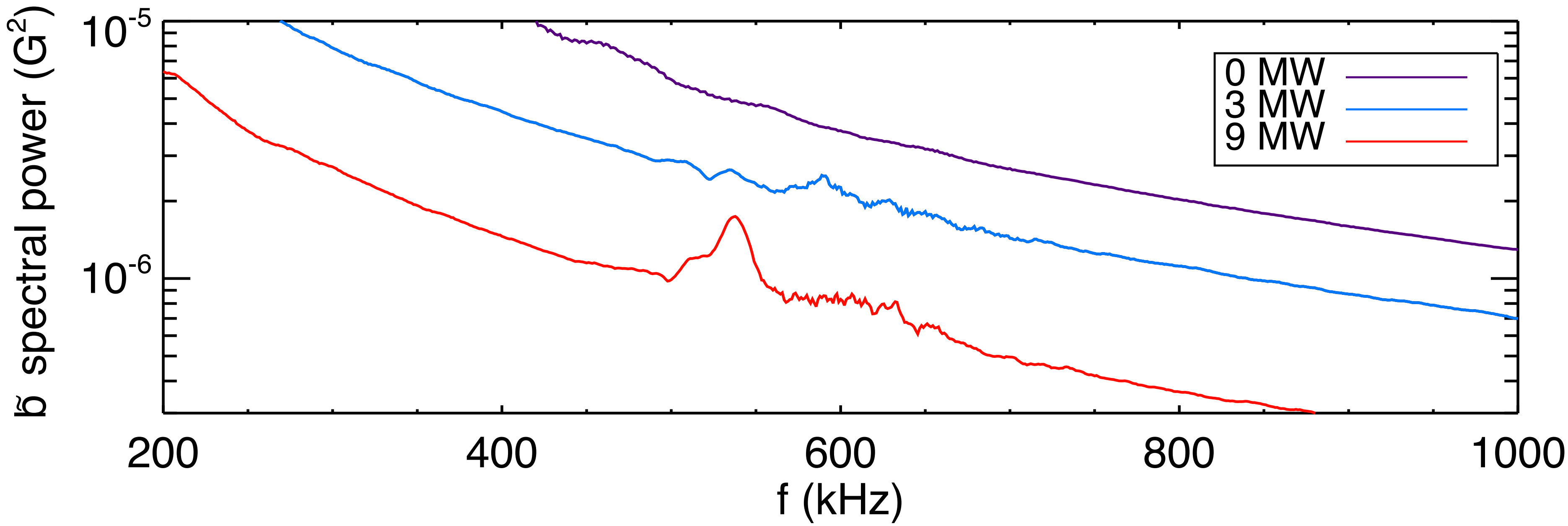
Fast ion lifetime is near classical limit

Phys. Plasmas 22, 056110 (2015)



- Fast ion lifetime inferred from decay in neutron rate after beam termination
- Fast ion lifetime ≈ classical slowing down time for a range of plasma conditions

NBI reduces broadband magnetic turbulence



- Broadband fluctuations decrease with NB power
  - Plasma stabilization
- Resonant peak in spectrum increases with NB power
  - Beam-driven mode

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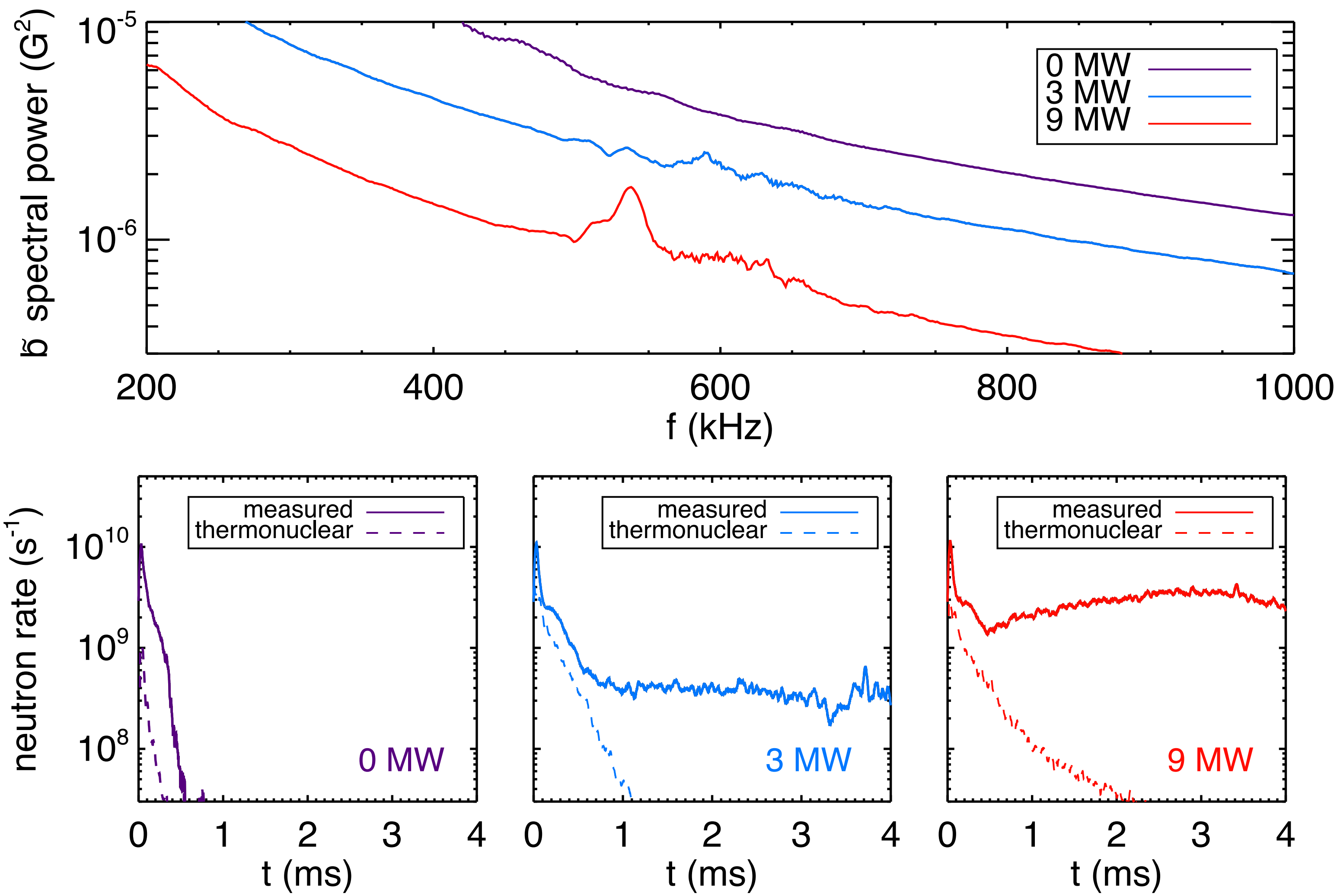
Strong enhancement in neutron production correlated with beam-driven mode



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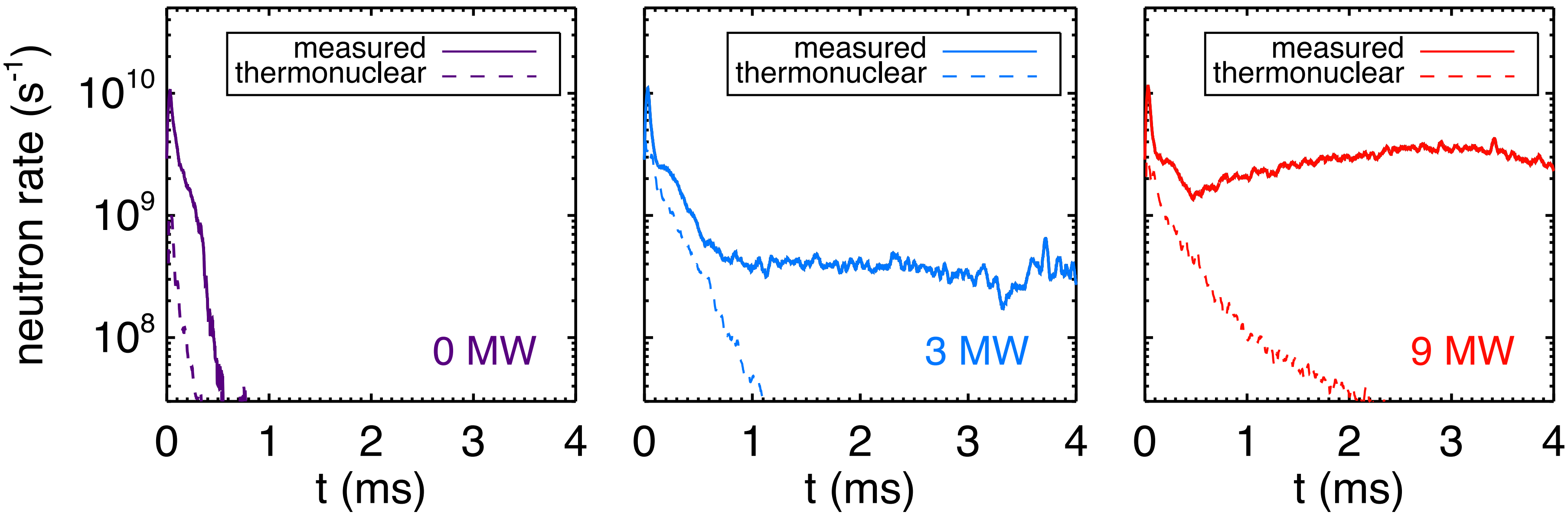
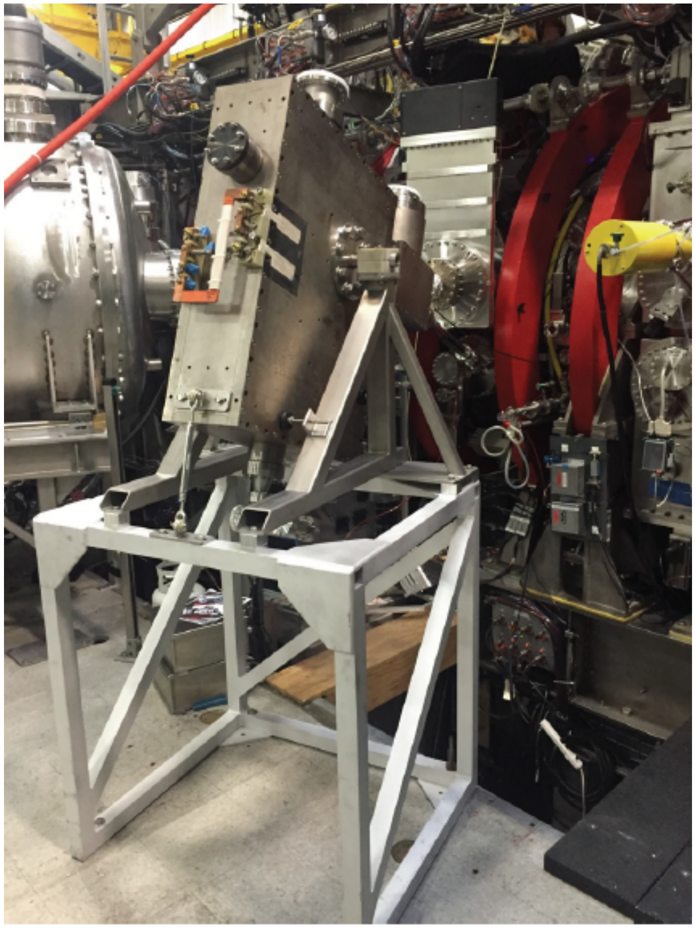
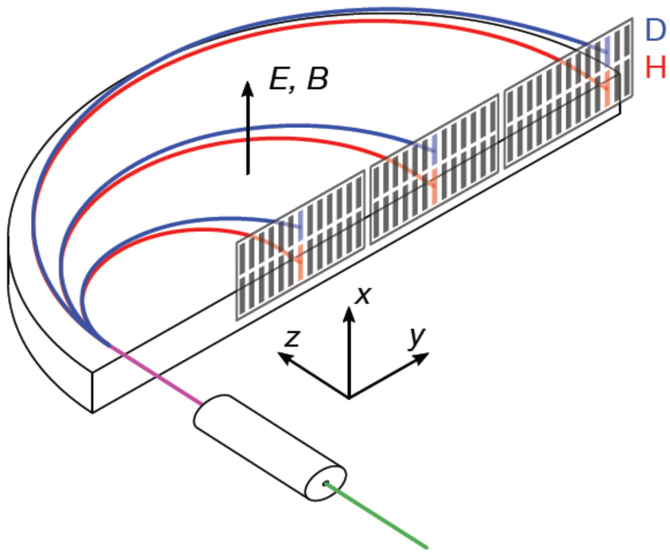


- Pure H beams into D plasma ➔ no beam-target emission
- Neutron production timescale < collisional timescale
- What is the source of fusion rate enhancement?

E||B Neutral Particle Analyzer can make mass resolved fast ion measurement



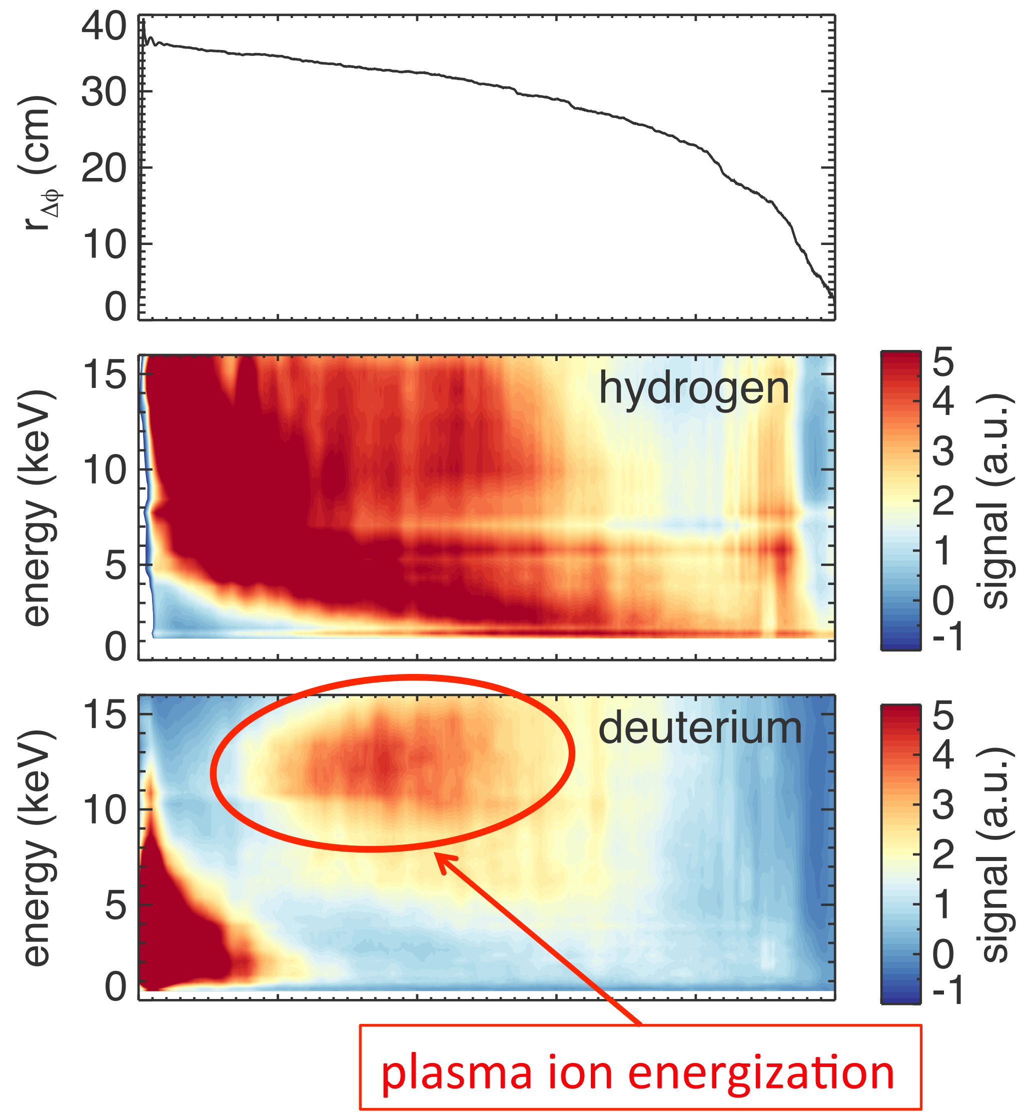


- Formerly installed on TFTR
- Mass discrimination
- High energy resolution (39 ch. / species)
- Adjustable energy range (0.5-40 keV)

Courtesy: Ryan Clary

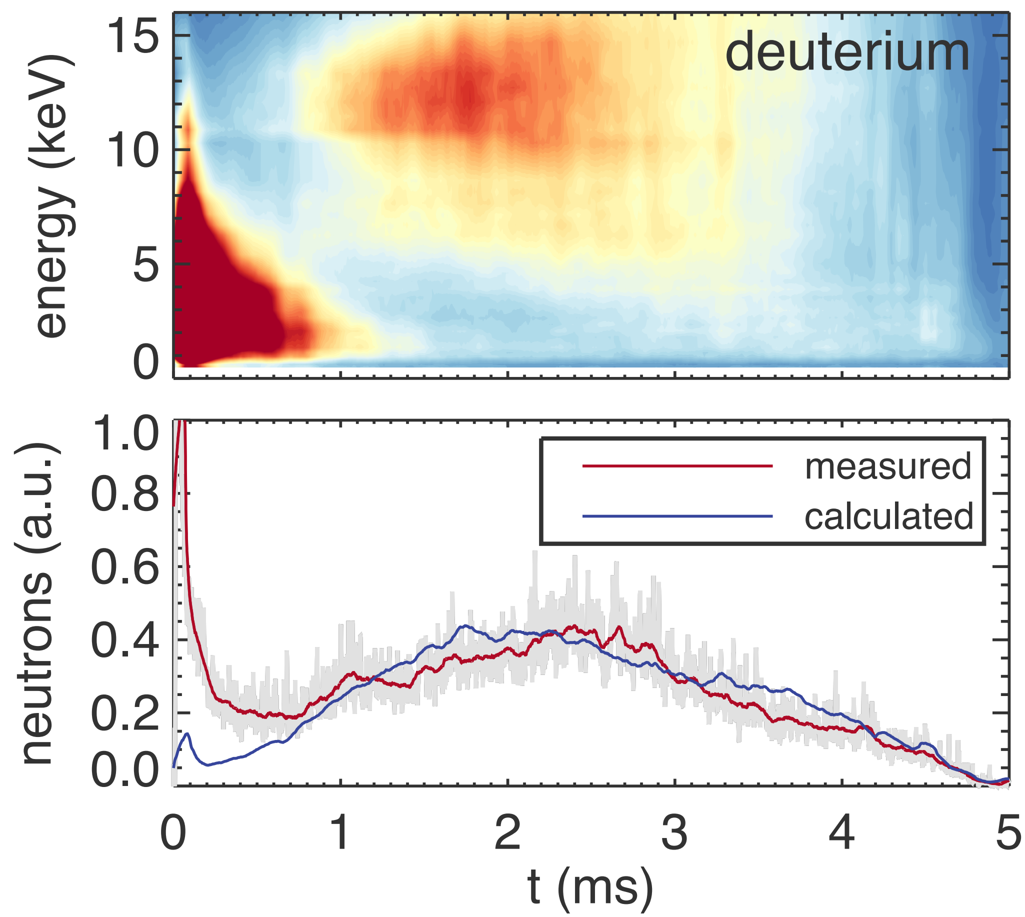
NPA shows high energy deuterium tail develop at *t~1* ms

- Pure HNBI results in fast hydrogen accumulation and slowing down
- High energy deuterons (E~12 keV) appear at *t~1* ms
- NPA measurement from single line of sight at r=49 cm, whereas neutron signal is global
- How does deuterium tail affect calculated neutron rate?



High energy deuterium population consistent with neutron measurement

- Integrate f(E) from NPA with σv, scale to measured neutron rate
- Excellent time history agreement
- First observation of ion energization by a beam-driven mode in a magnetic fusion energy device



Magee, Necas, Tajima, et. al., *Enhanced fusion reactivity in the beam-driven FRC*, Nature Physics (in preparation)

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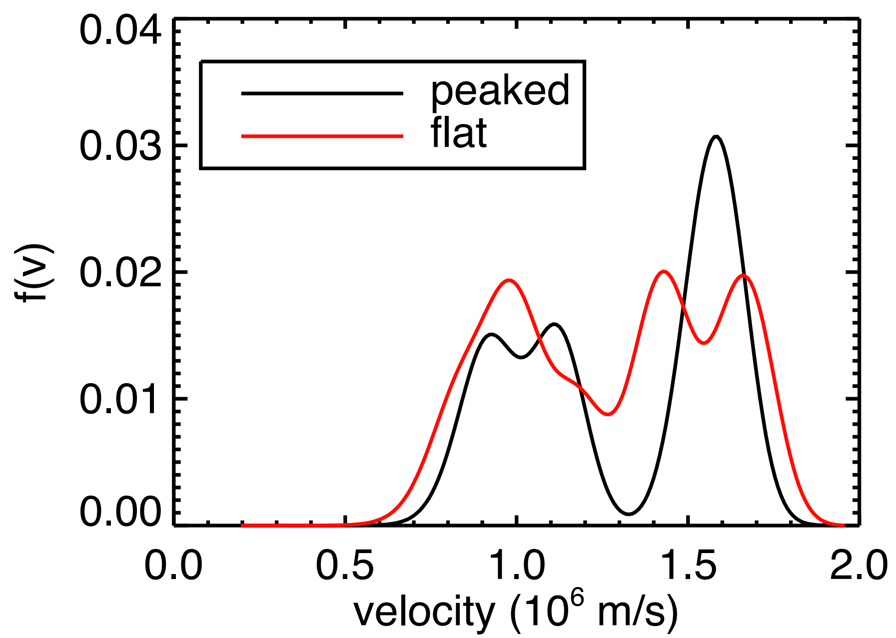
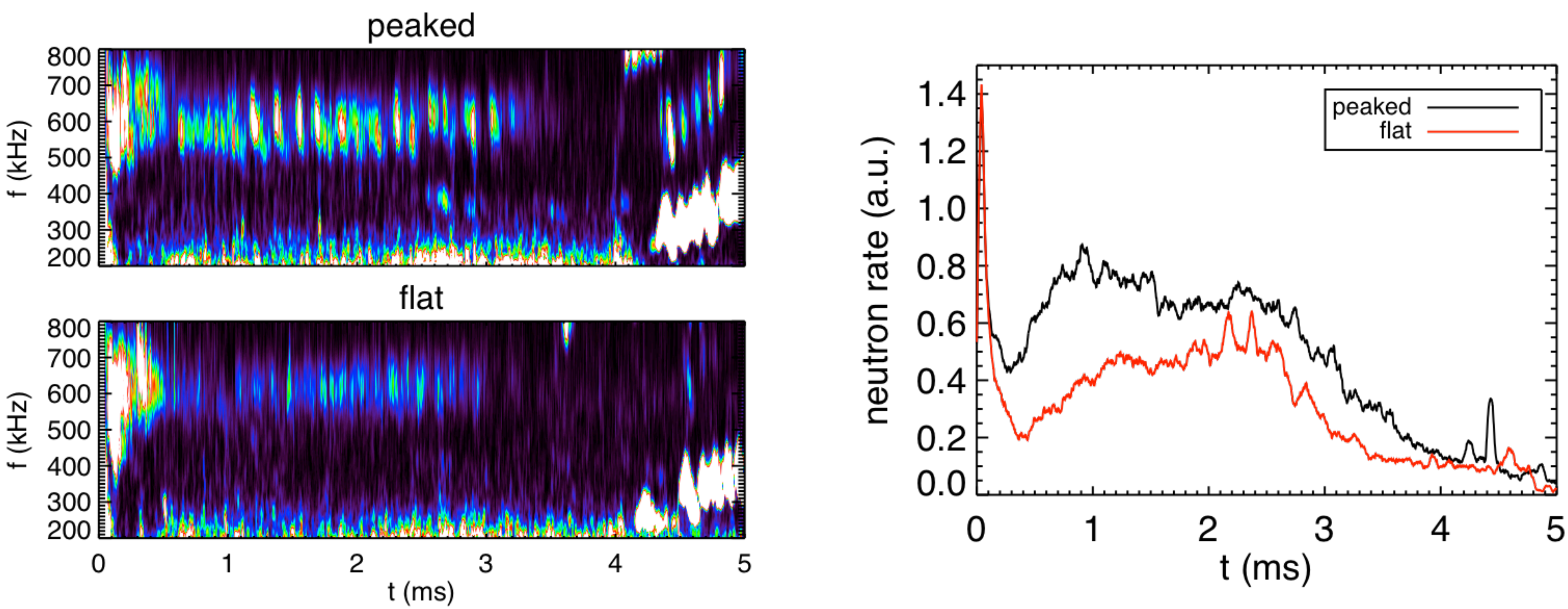
Experiment with staggered beam energies shows velocity gradient is free energy source

- Two cases with equal total injected power (6.8 MW) are compared
  - "peaked" – all beam energies the same
  - "flat" – beam energies staggered
- Free energy source (*df/dv*) reduced in the flat case.



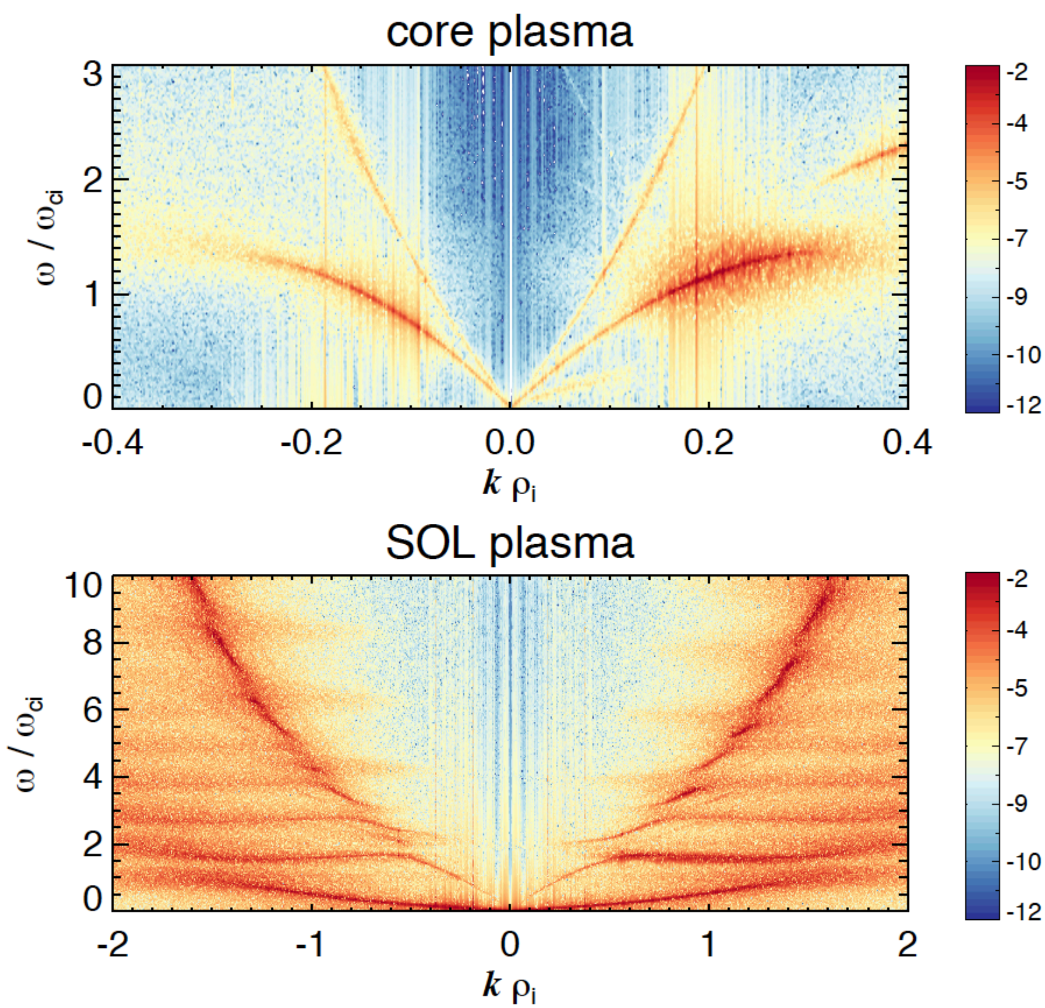
Staggering beam energies reduces fluctuations and fusion rate



- Strong evidence for velocity space instability
- What does theory predict?

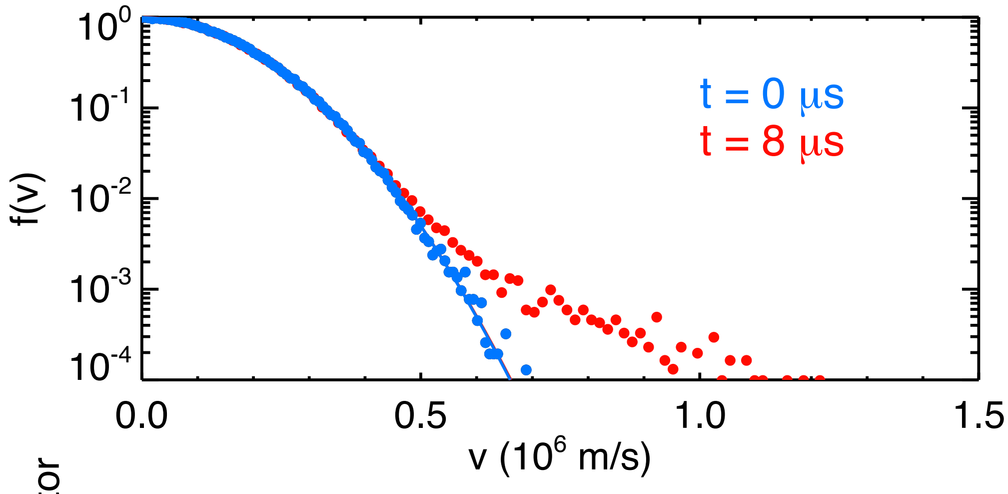
Particle-in-cell simulation shows much stronger mode activity in SOL than in core

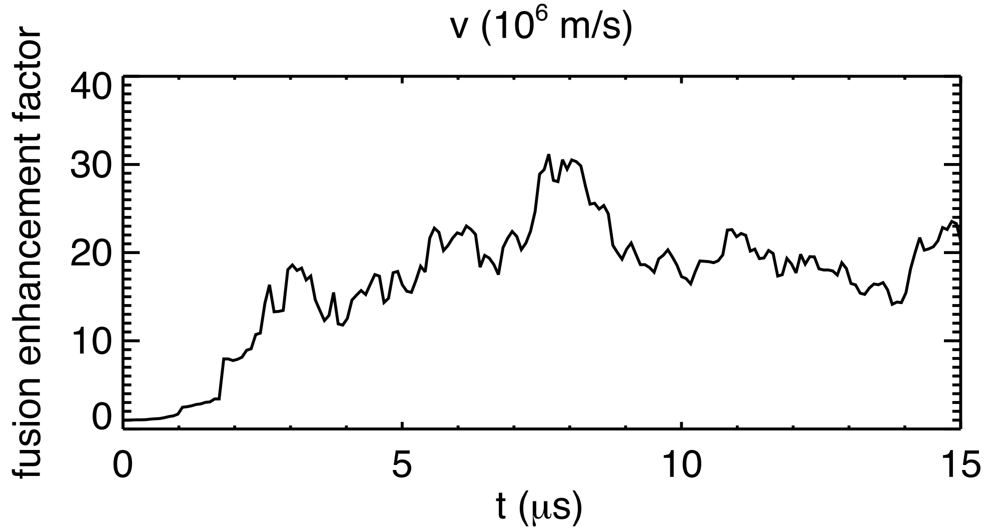
- EPOCH code used to analysis beam-plasma interaction in a simplified geometry
- In the core plasma, the AIC mode has the largest growth rate
- In the SOL plasma, the Ion Bernstein mode appears at multiple harmonics of the cyclotron frequency



Ion Bernstein modes create high energy tail that increases neutron rate 30x

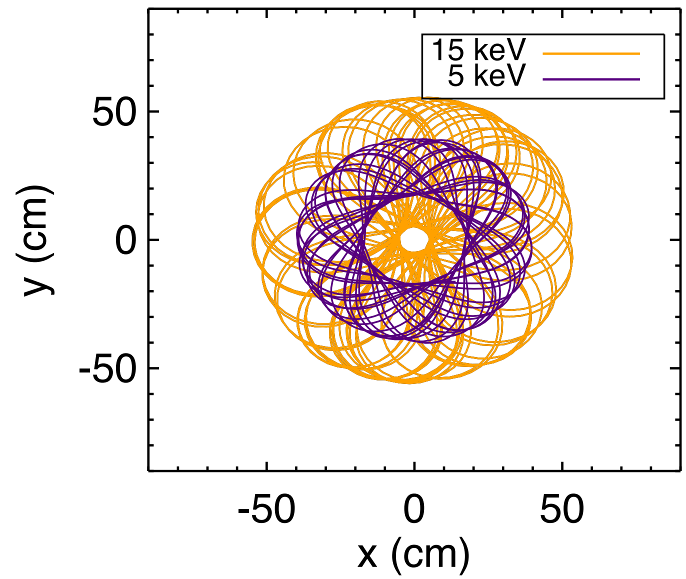
- The code reproduces the tail on the plasma ion velocity distribution and the enhanced neutron production.
- Code is an initial value problem, so the mode saturates very quickly.
- *See talk by A. Necas Wed. afternoon.*

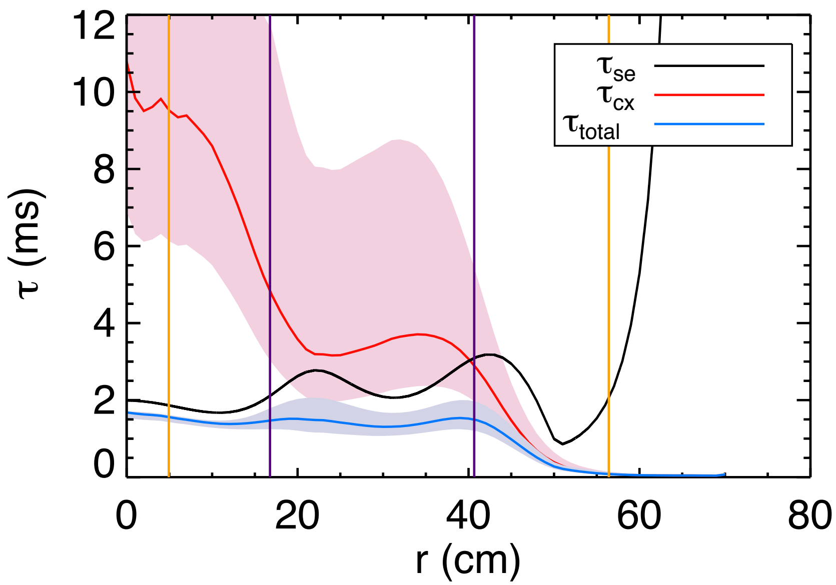




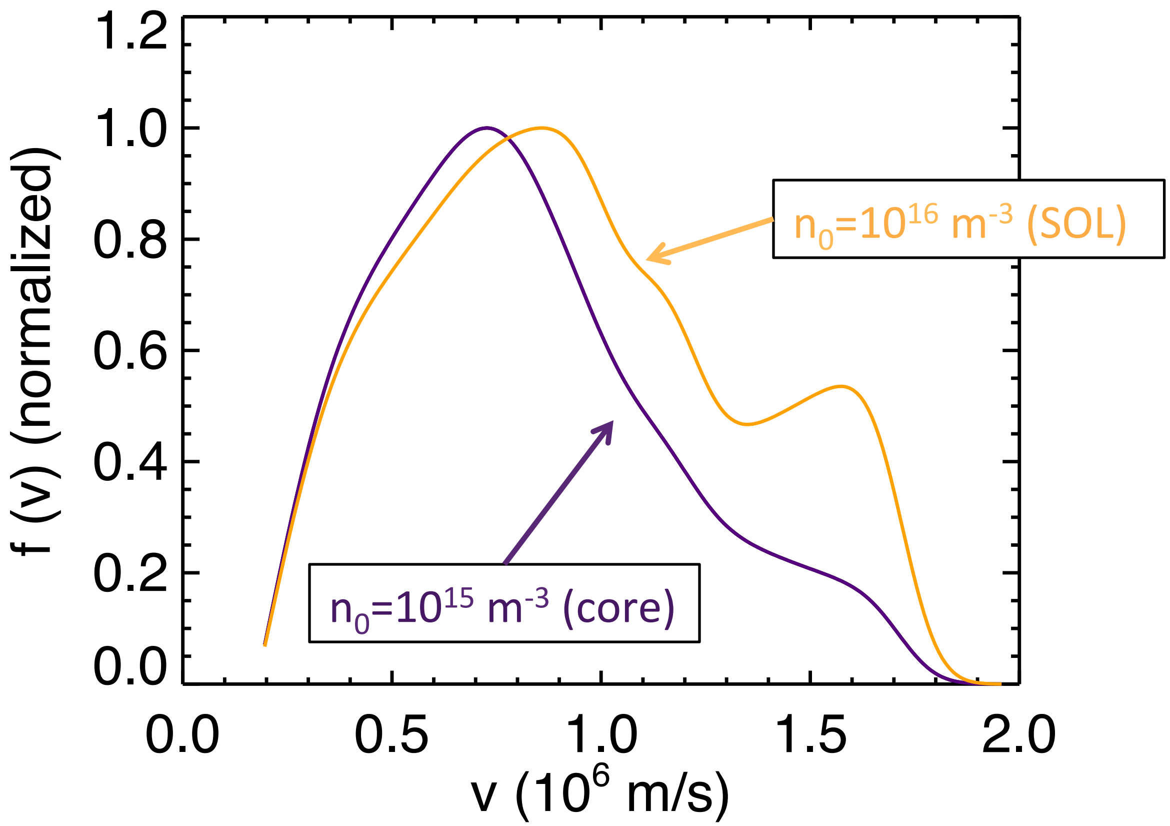
Putting it all together

- Source of free energy is velocity space gradients (staggered beam energy experiments)
- Optimal plasma conditions to support beam-driven mode are in the SOL (PIC simulation)
- Are there velocity gradients in the SOL? Look to 1D Fokker-Planck solver…





Charge exchange creates *df/dv>0* in SOL plasma



- Source of free energy and optimal plasma conditions to support the mode are both largest in SOL
- Beam-driven mode in SOL does not destroy the plasma because $v_{beam} >> v_{T,i}$

Summary

- **Beam-driven mode accelerates plasma ions and enhances fusion rate, but does not destroy the plasma**

- **Fast ions sample two distinct plasma regions:**
  - **FRC – $\tau_{se} < \tau_{cx}$ ➔ slowing down distribution**
  - **SOL – $\tau_{se} > \tau_{cx}$ ➔ *df/dv > 0* ➔ beam-driven modes**

- **Fast ion free energy is larger in SOL where beam-driven modes are supported**

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Thank you!