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PIC Simulation of Thermal Distribution Driven Non-Maxwellian by Neutral-Beam Injection in a High Beta Plasma

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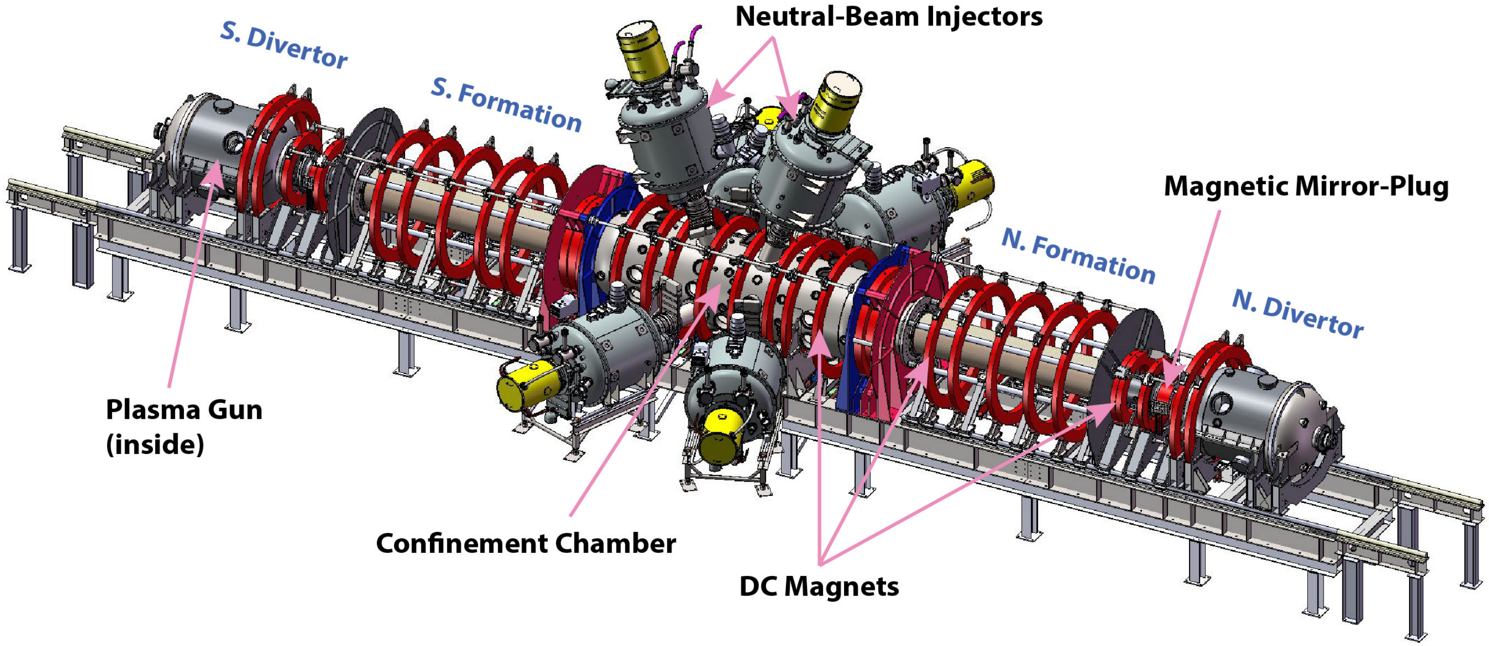
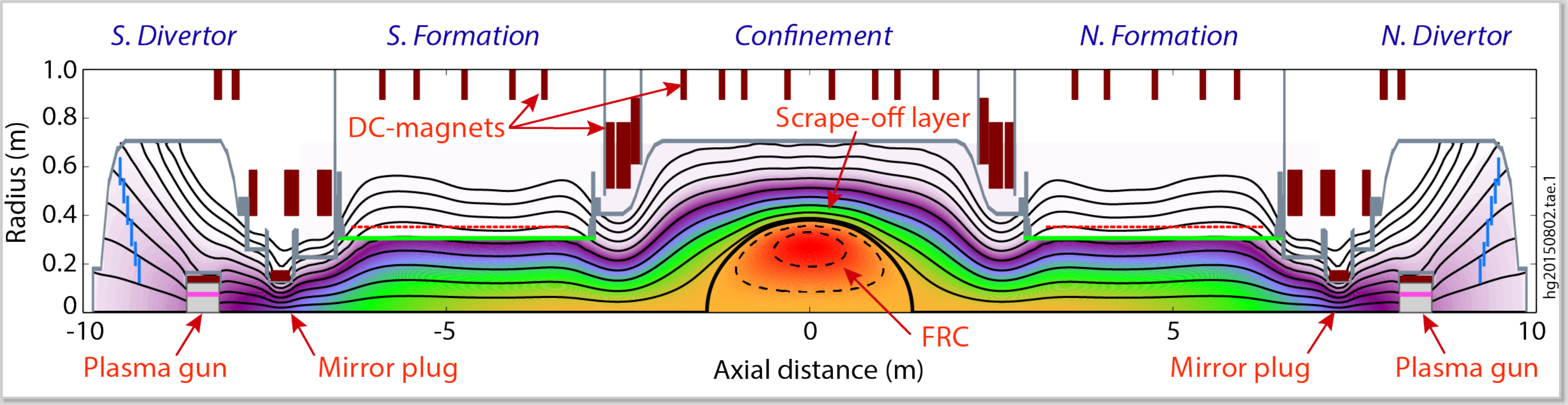
Outline

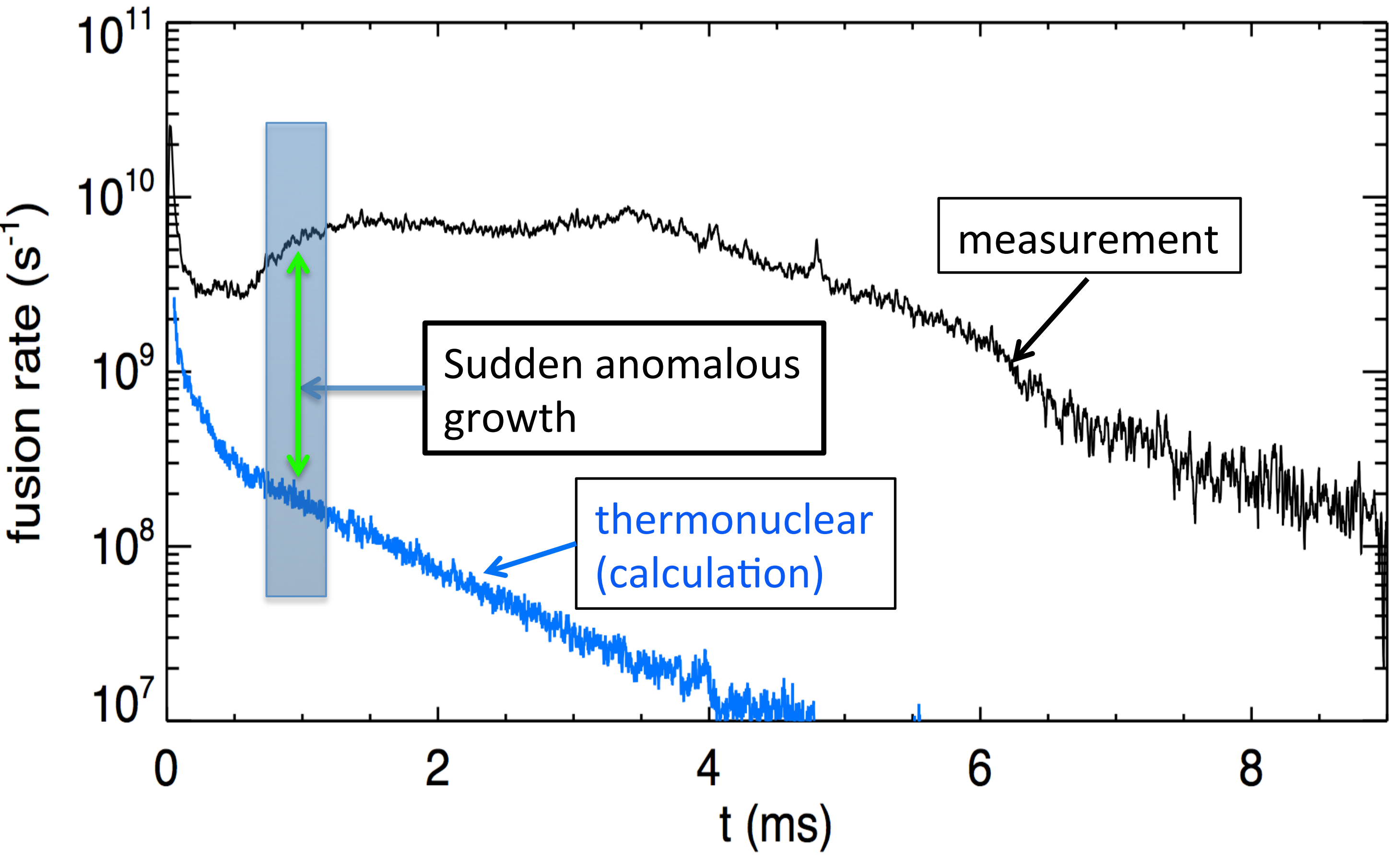
- **Experimental Motivation:**
  - Enhanced neutron yield
- **Theory and computation:**
  - Hypothesis
  - Simulation problem set up
  - ES benchmark
  - Hypothesis verification
  - Klimontovich accounting – neutron generation
  - Comparison between high and low(er) beta – Mode discussion
  - Comparison to Neutral Particle Analyzer data
- **Summary**

C-2U Machine Configuration





Motivation - search for beam-driven micro-instabilities suggested by enhanced reactivity



- Hydrogen beam injection enhances D-D fusion rate.
- ~ 10 times increase in neutron

Courtesy: Richard Magee

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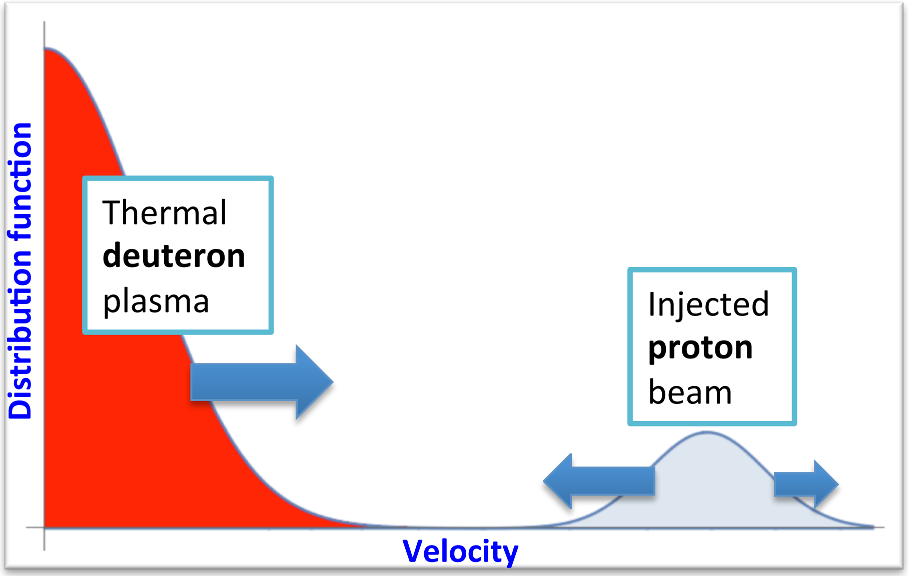
Hypothesis



Presence of proton beam is source of "free energy"

Transfer energy from beam to deuteron

Energetic super-thermal tail in the thermal deuteron plasma

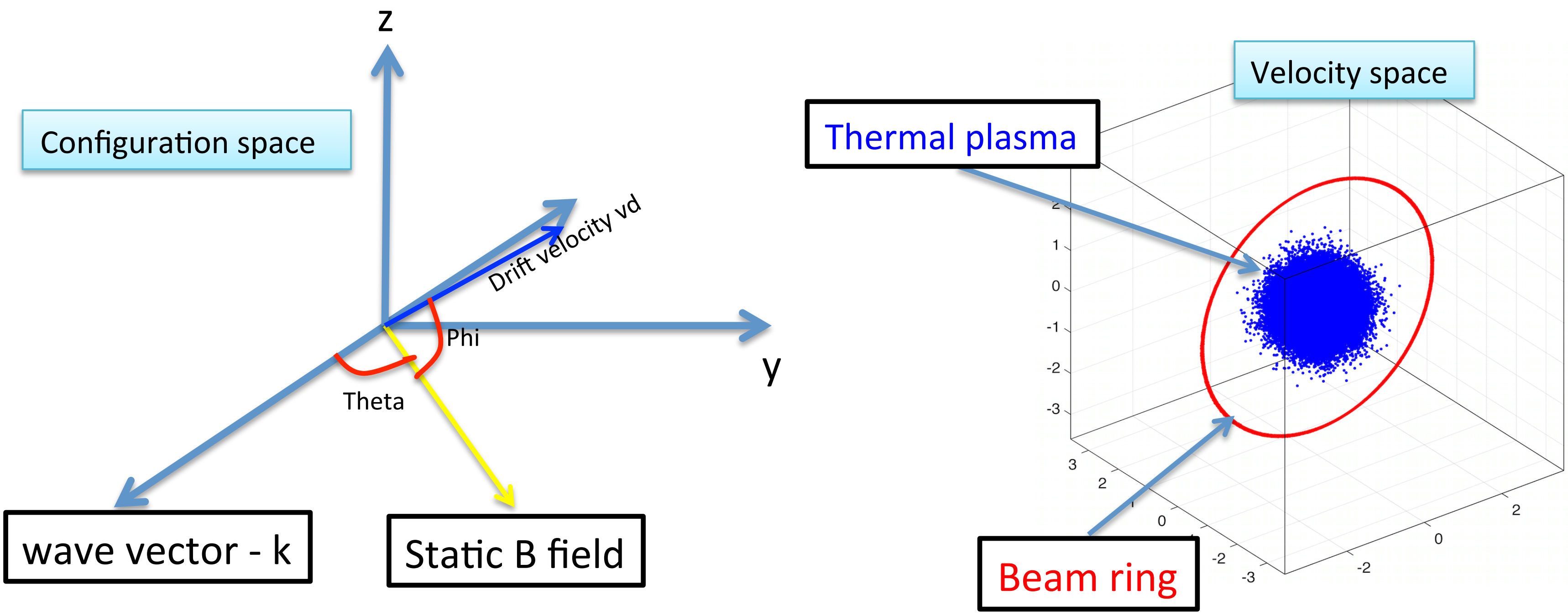
Accelerated deuterons collide with thermal (or super-thermal) deuterons

Enhanced increase in neutron production

Testing the hypothesis

Use a 1D PIC code (EPOCH)

Numerical Problem Set Up



- Fully electromagnetic 1D3V PIC code: Maxwell eqns + Lorentz force
- **Slab model with periodic BC**
- **Initial value problem (introduce beam at t=0)**
- Thermal plasma is Maxwellian, optional: anisotropy, drift
- Beam is set up as a Maxwellian distribution, ring or slowing down distribution – sampling problem. Anisotropy optional.
- Beam set up with velocity parallel and perp to B field
- Particle interaction via collective effects ONLY

Electrostatic Case – Perpendicular Propagation I

Dispersion relation

$$\frac{\omega_{pi}^2}{\lambda_i}\sum_{n=1}^{\infty}\exp[-\lambda_i]I_n(\lambda_i)\frac{2n^2}{\omega^2-n^2\Omega_i^2}+$$ Thermal ion

$$\frac{\omega_{pb}^2}{kv_b}\sum_{n=1}^{\infty}\frac{2n^2\omega_{cb}}{\omega^2-n^2\omega_{cb}^2}J_n(\nu)\left[J_{n-1}(\nu)-J_{n+1}(\nu)\right]=$$ Beam

$$1+\left(\frac{\omega_{pe}}{\Omega_{ce}}\right)^2\left(1+\frac{\omega_{pe}^2}{c^2k^2}\right)$$ Thermal electron

$$\lambda_i=0.5(k\rho_i)^2$$

$$\nu=\frac{kv_b}{\omega_{cb}}$$

- Beta = 1e-4
- Let $\omega=\omega+i\gamma$

Electrostatic Case – Perpendicular Propagation II

Dispersion relation

$$\frac{\omega_{pi}^2}{\lambda_i}\sum_{n=1}^{\infty}\exp[-\lambda_i]I_n(\lambda_i)\frac{2n^2}{\omega^2-n^2\Omega_i^2}+$$

Thermal ion

$$\frac{\omega_{pb}^2}{kv_b}\sum_{n=1}^{\infty}\frac{2n^2\omega_{cb}}{\omega^2-n^2\omega_{cb}^2}J_n(\nu)\left[J_{n-1}(\nu)-J_{n+1}(\nu)\right]=$$

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Thermal electron

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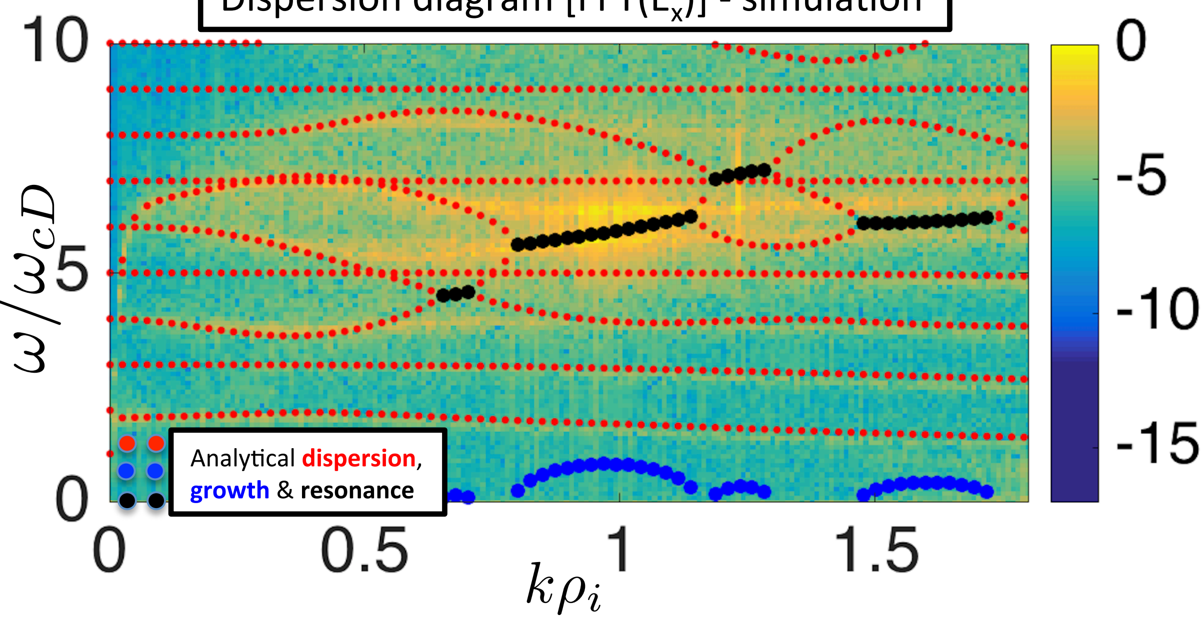
- Beta = 1e-4
- Let $\omega = \omega + i\gamma$
- Coupling of plasma lower hybrid wave and n=6 ion Bernstein harmonic
- Growth rate=0.4 ω_{ci}

Dispersion diagram [FFT(E_x)] - simulation



Electrostatic Case – Perpendicular Propagation III

Dispersion relation

$$\frac{\omega_{pi}^2}{\lambda_i}\sum_{n=1}^{\infty}\exp[-\lambda_i]I_n(\lambda_i)\frac{2n^2}{\omega^2-n^2\Omega_i^2}+$$

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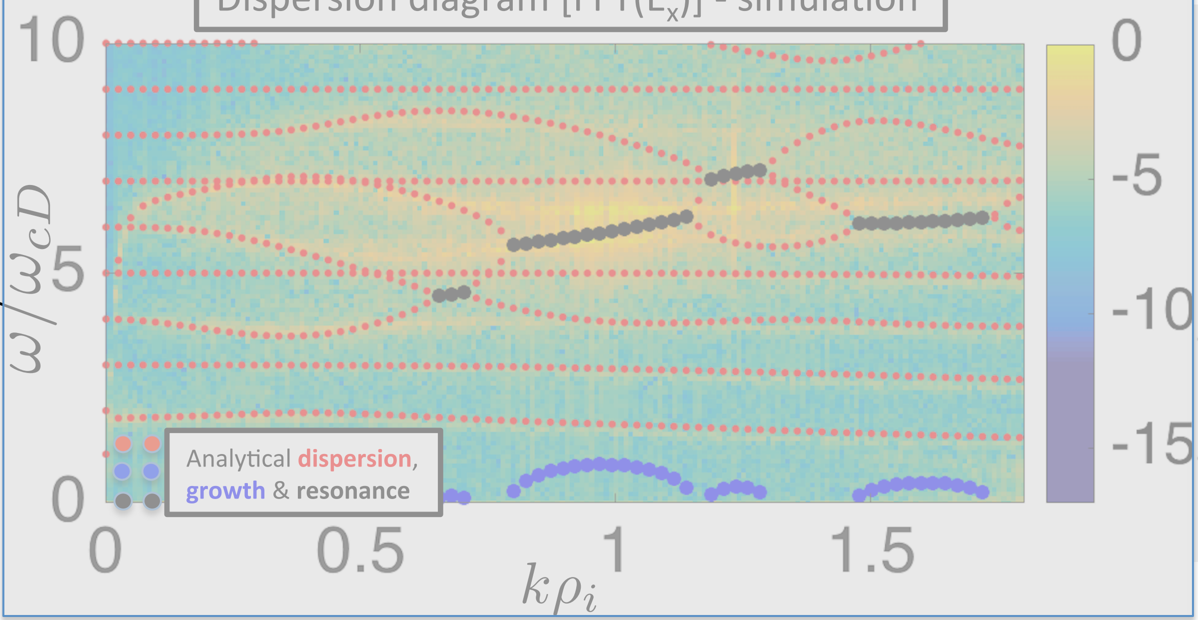

- Beta = 1e-4
- Let $\omega = \omega + i\gamma$
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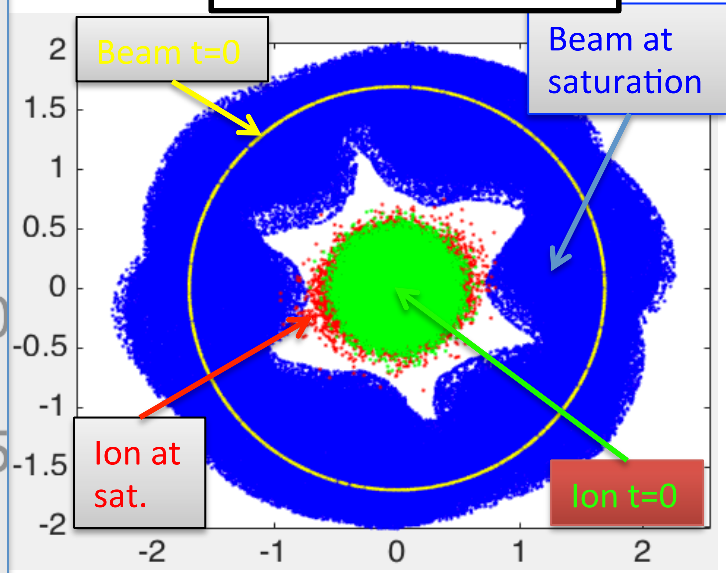
- Good agreement between analytics and simulation

Velocity [x10^6 m/s]



Electrostatic Case – Perpendicular Propagation

Dispersion relation

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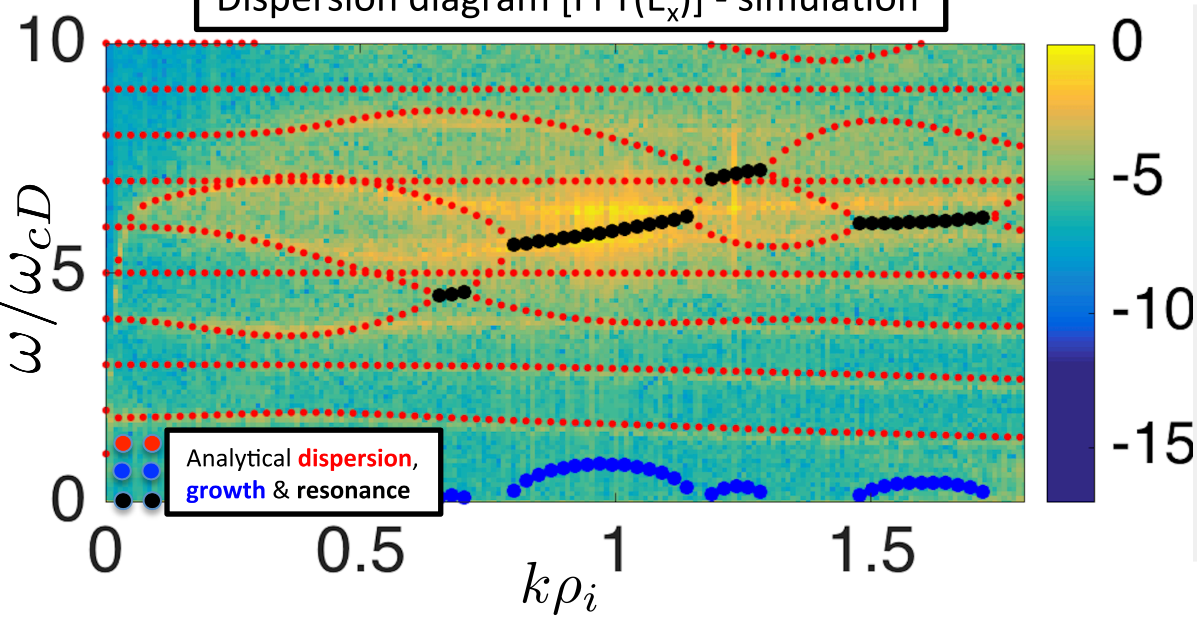

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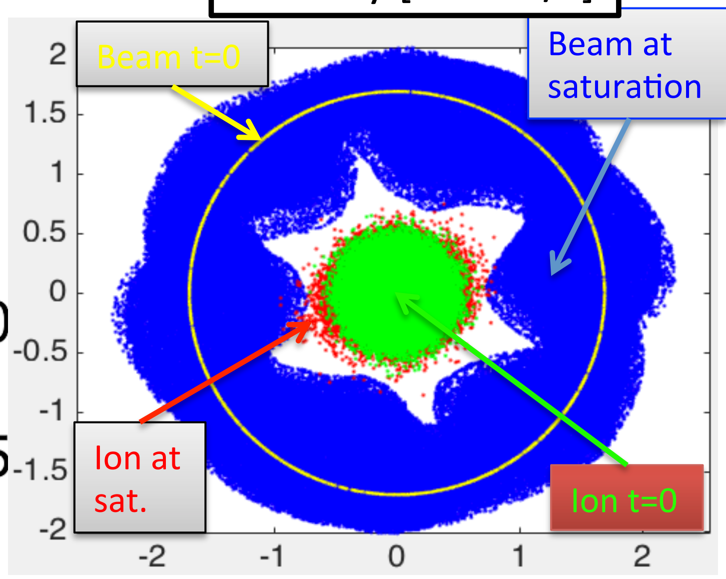
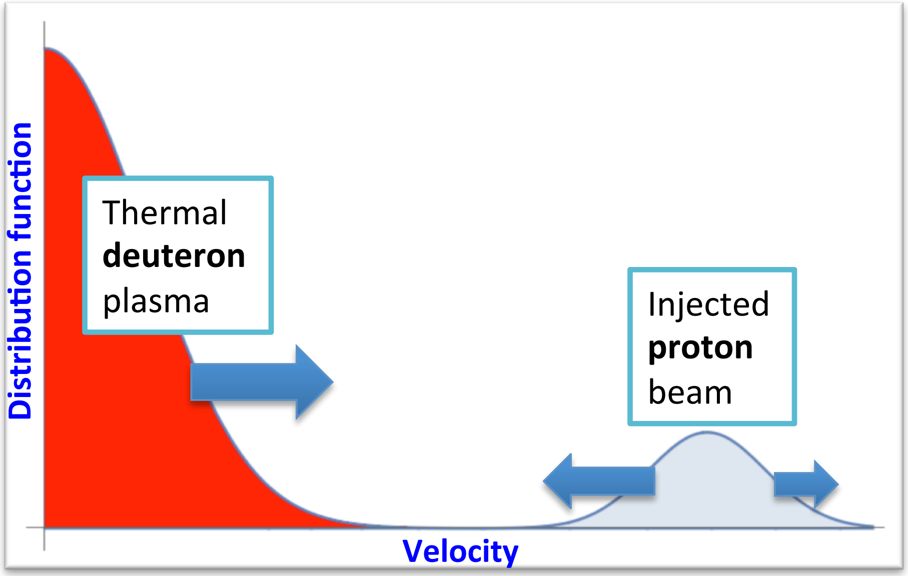


Hypothesis



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↓

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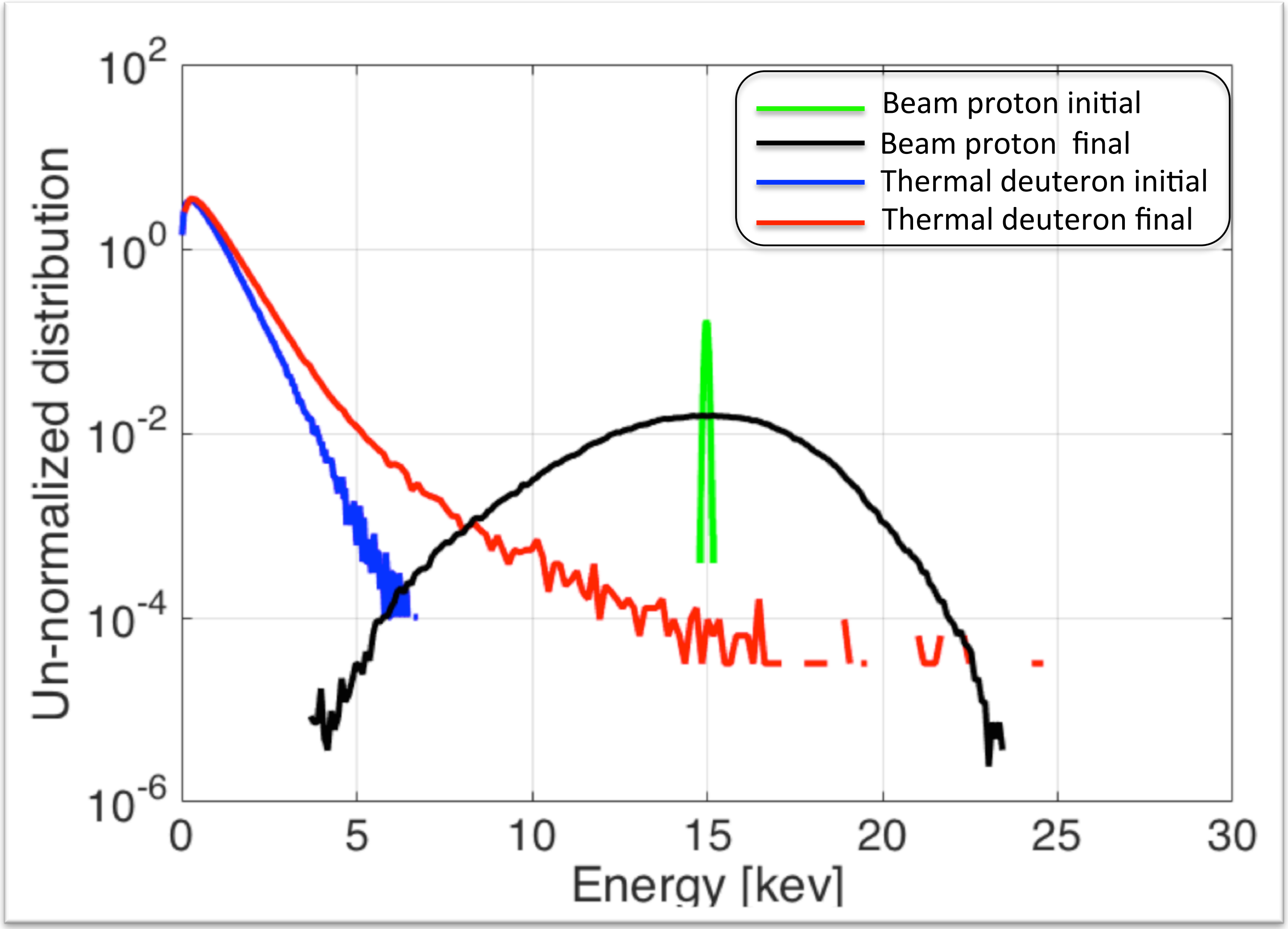
Enhanced increase in neutron production

Testing the hypothesis

→ Use a 1D PIC code (EPOCH)

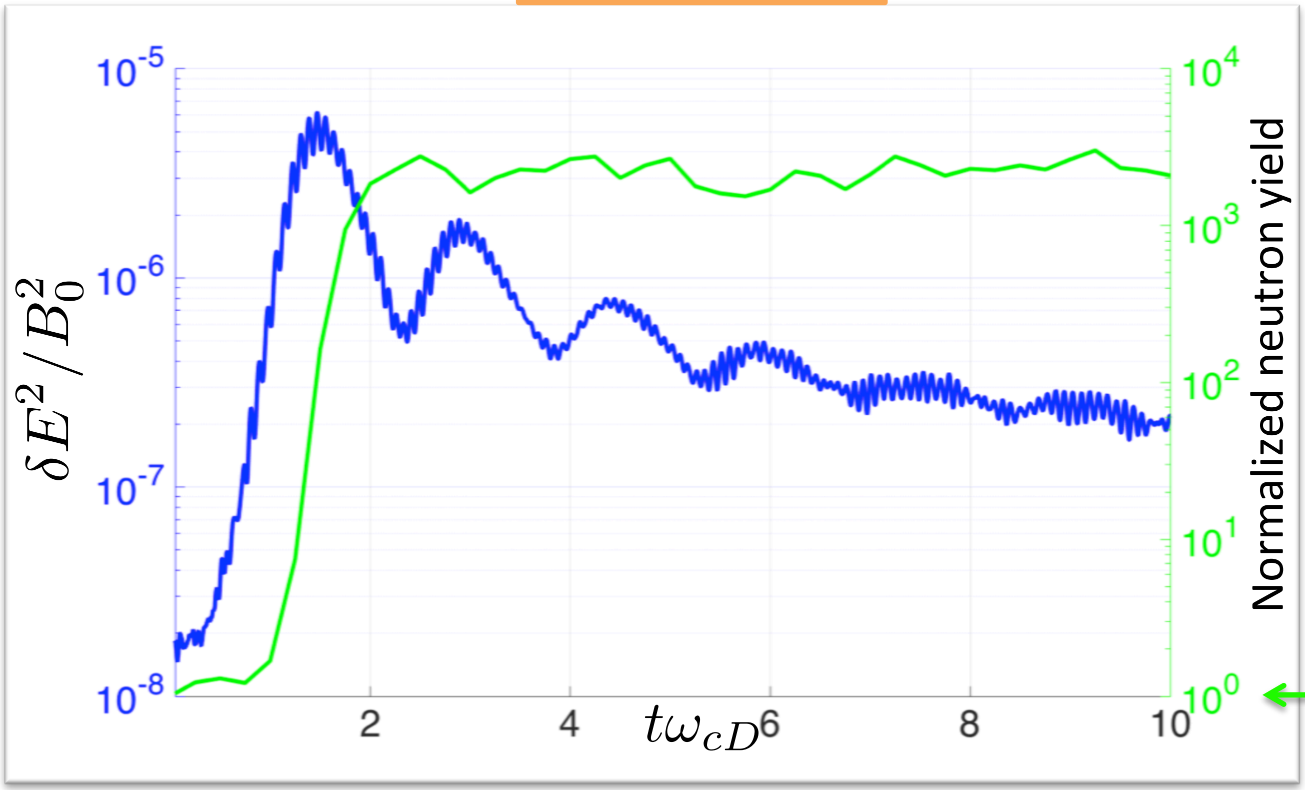
Test our Hypothesis



Klimontovich Reactivity for ES Case

$$\langle \sigma v \rangle = \sum_{i \neq j} \sum_{j} \sigma(\|\mathbf{v_i} - \mathbf{v_j}\|) \|\mathbf{v_i} - \mathbf{v_j}\|$$

DD-cross section



Thermonuclear

Enormous increase in reactivity due to the beam driven collective effects

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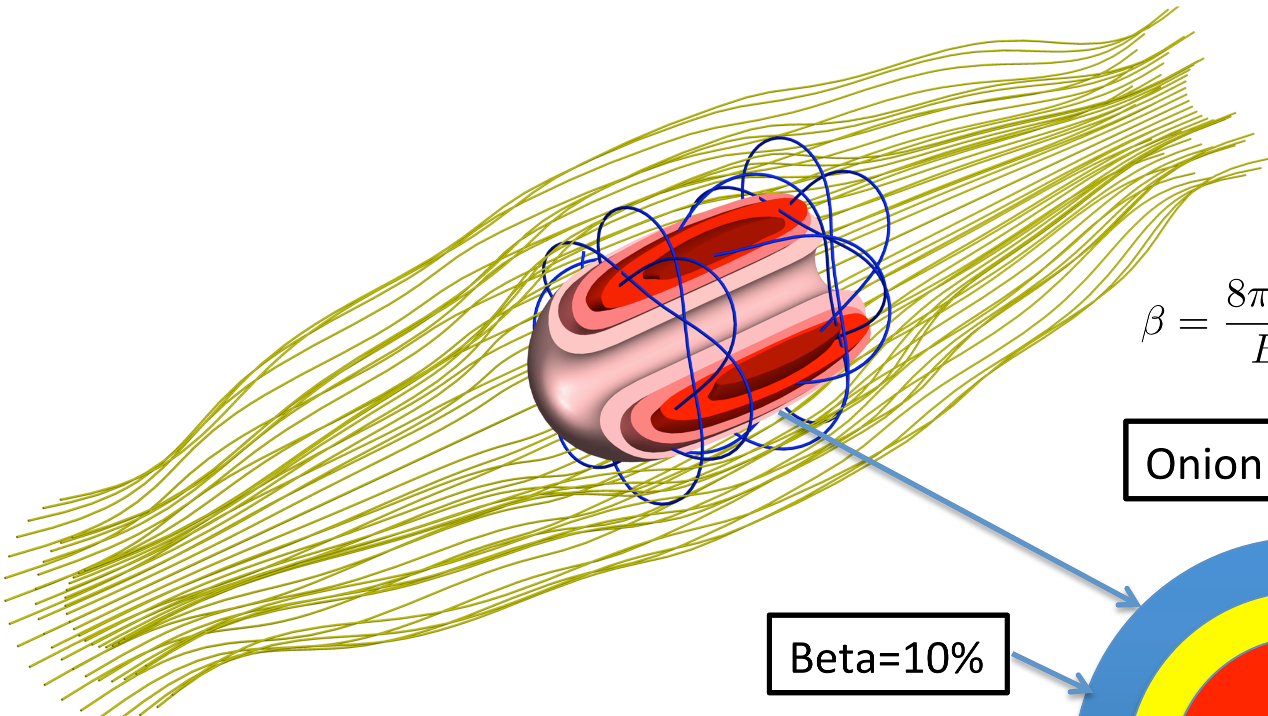
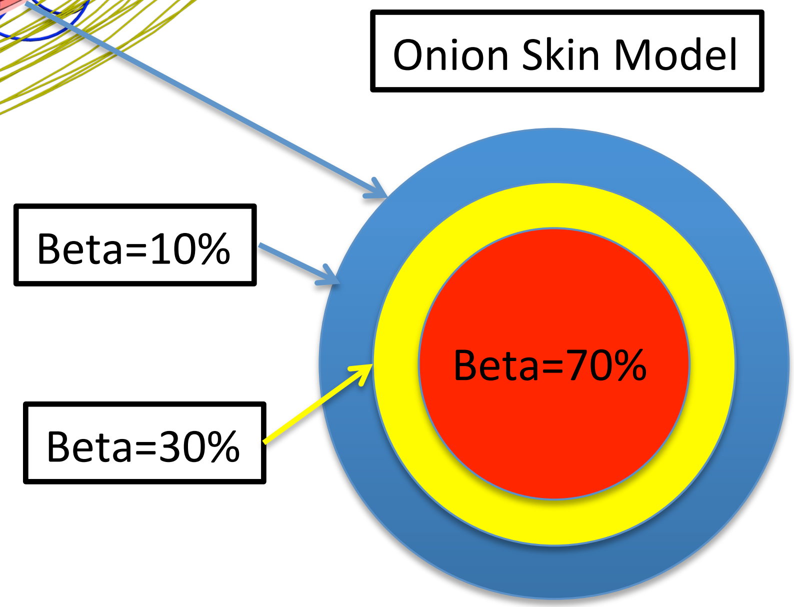
Beam Orbit Samples FRC Volume

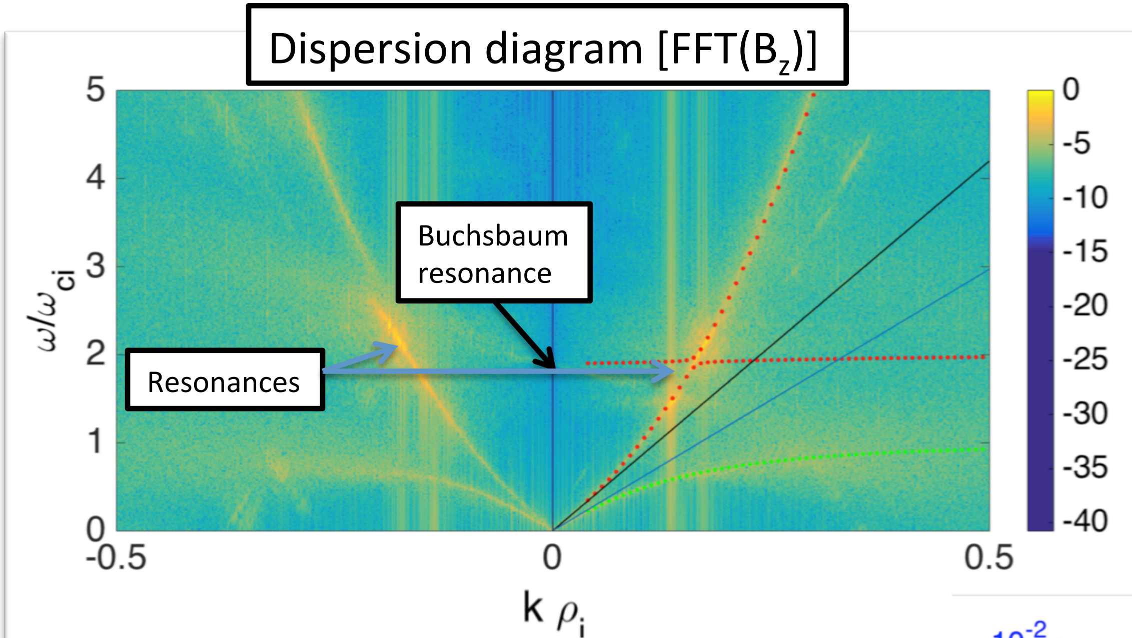


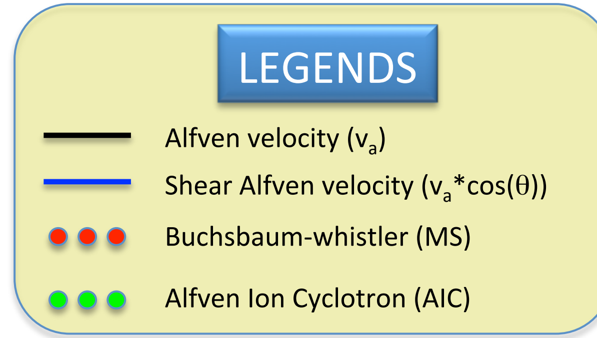
$$\beta = \frac{8\pi n T}{B^2} = \frac{\text{Plasma pressure}}{\text{Magnetic pressure}}$$



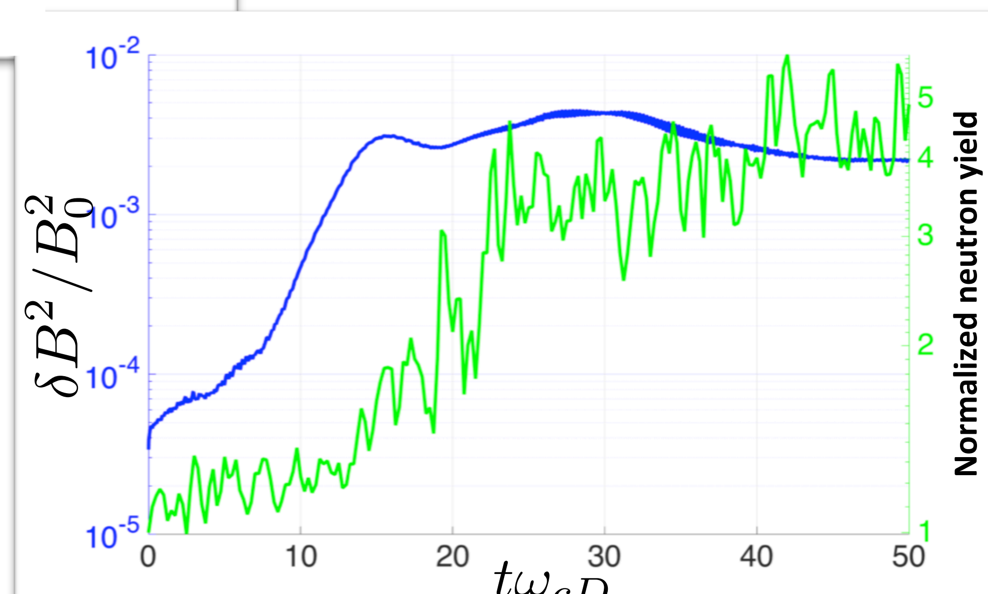
- Study each onion layer separately
- Moving radially inward, increases beta

Beta=10 % -- Open field line Case

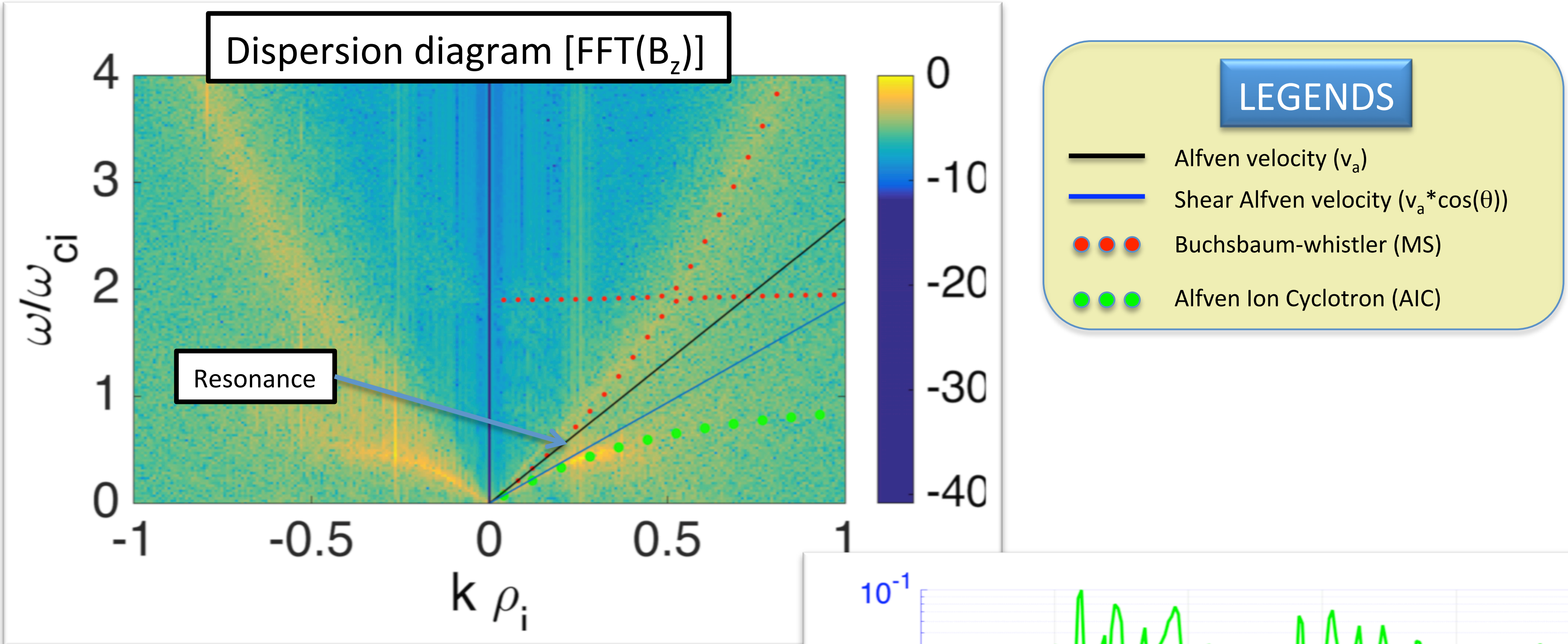




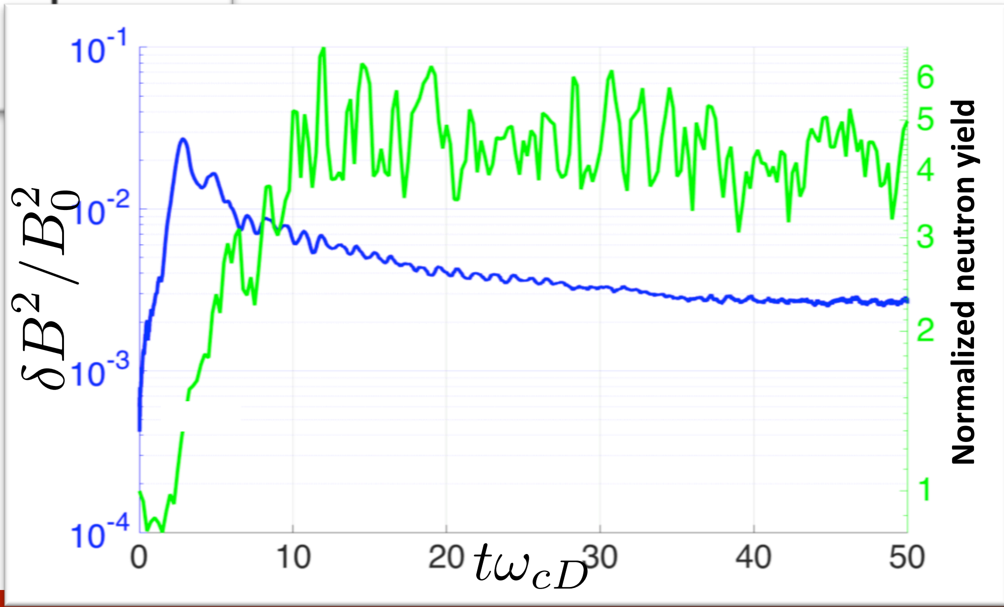
- Buchsbaum-whistler coupling facilitated by beams in presence of two q/m ion species.
- Letting m_t=m_b results in the excitation of AIC mode
- Various resonances/modes are excited as beam slows down
- Slow growth (γ~$0.03\omega_{cD}$)
- Enhanced neutron signal



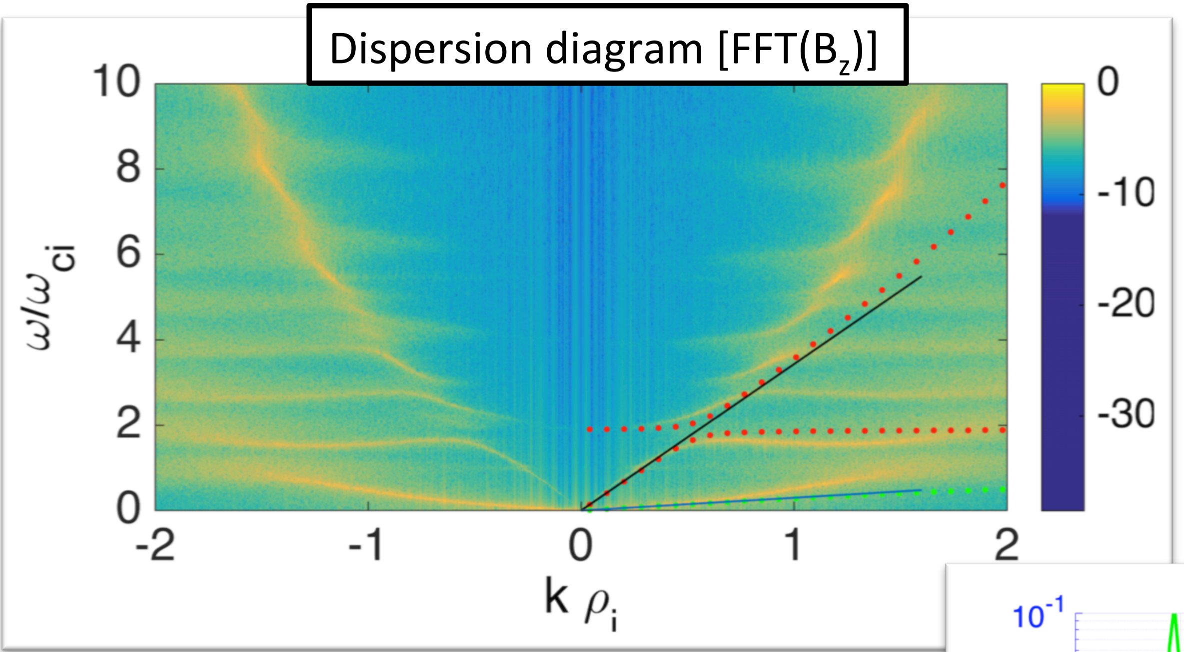
Beta=70 % -- Core

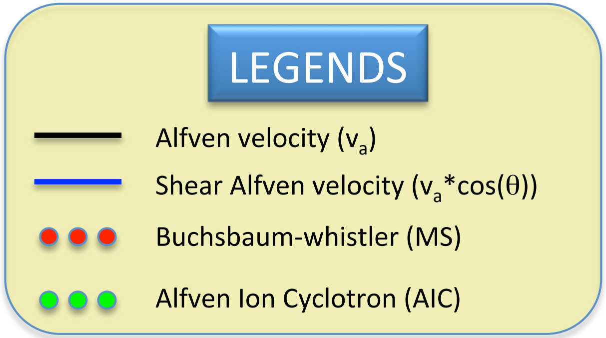


- **AIC mode excited due to the presence of anisotropic (W_{perp} >$W_{||}$) beam population**
- **Proton beam and deuteron thermal**
- **Only one mode excited**
- **Fast growth (γ~0.13ω_{cD})**
- **Enhanced neutron signal**

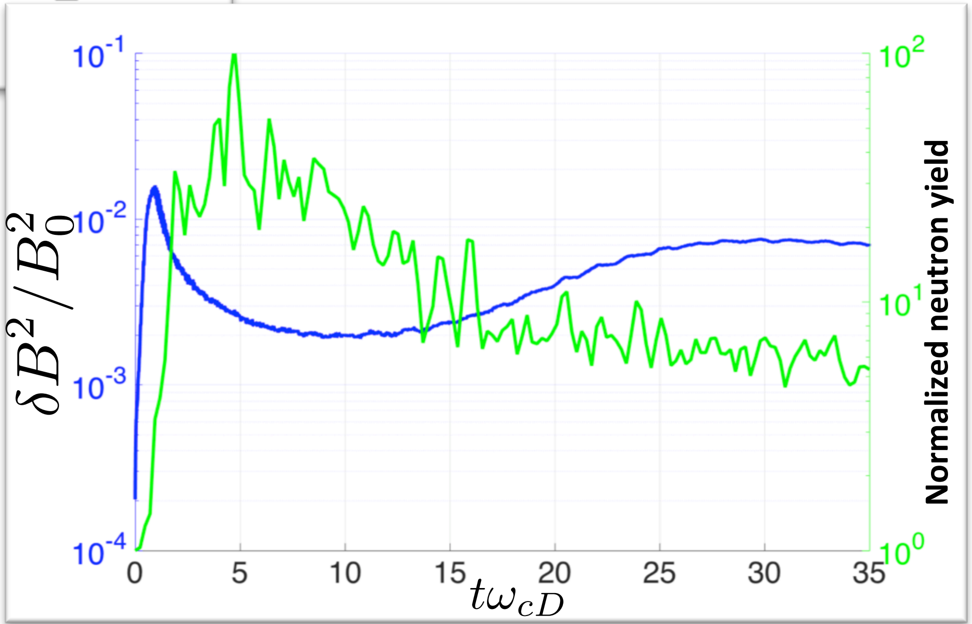


Beta=30 % -- SOL (~impact par. of NPA)

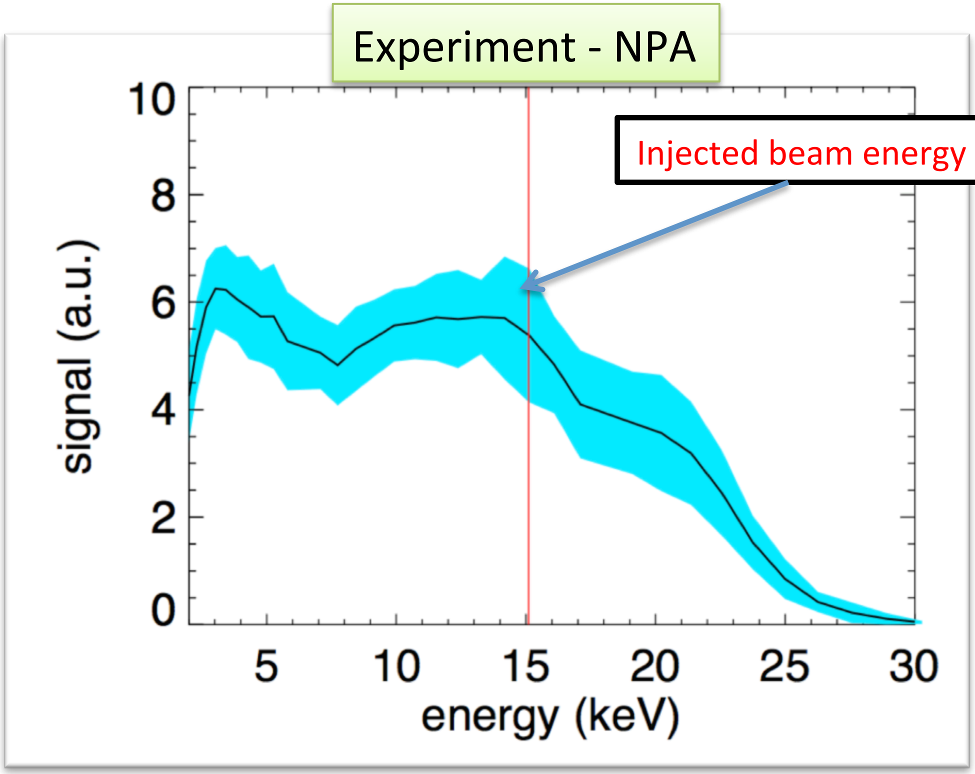


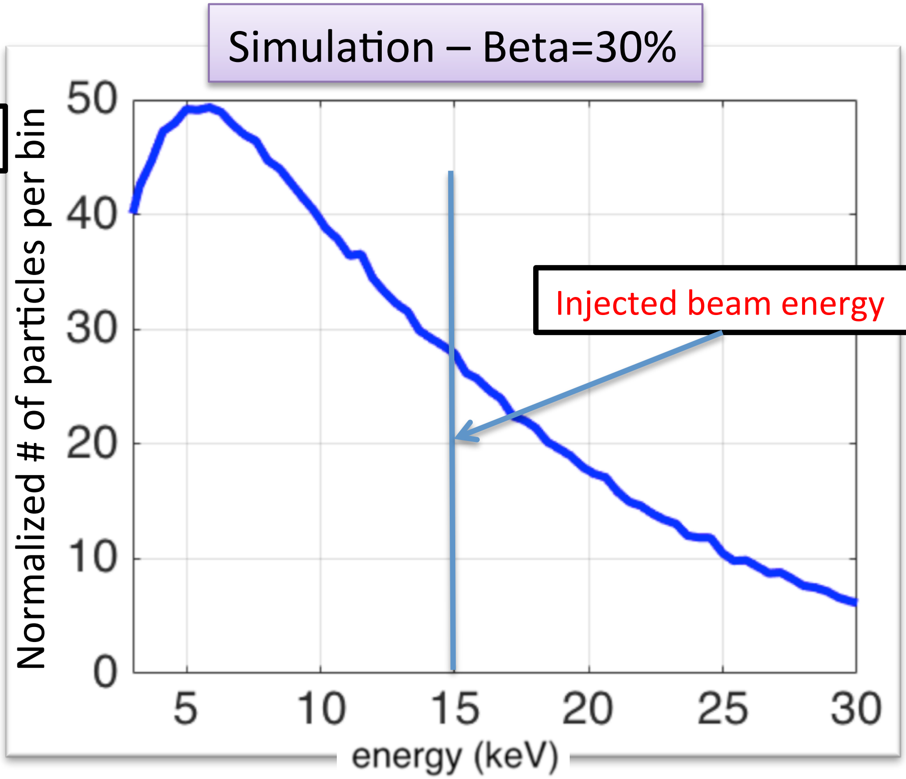


- Allow $k_{||}<k_{perp}$
- Broadband
- Ion Bernstein harmonics
- AIC mode
- **Enhanced neutron signal**
- Fast growth ~ 0.2 ω_{cD}
- **Proton beam and deuteron thermal**



Proton (Beam) Energy Spectrum

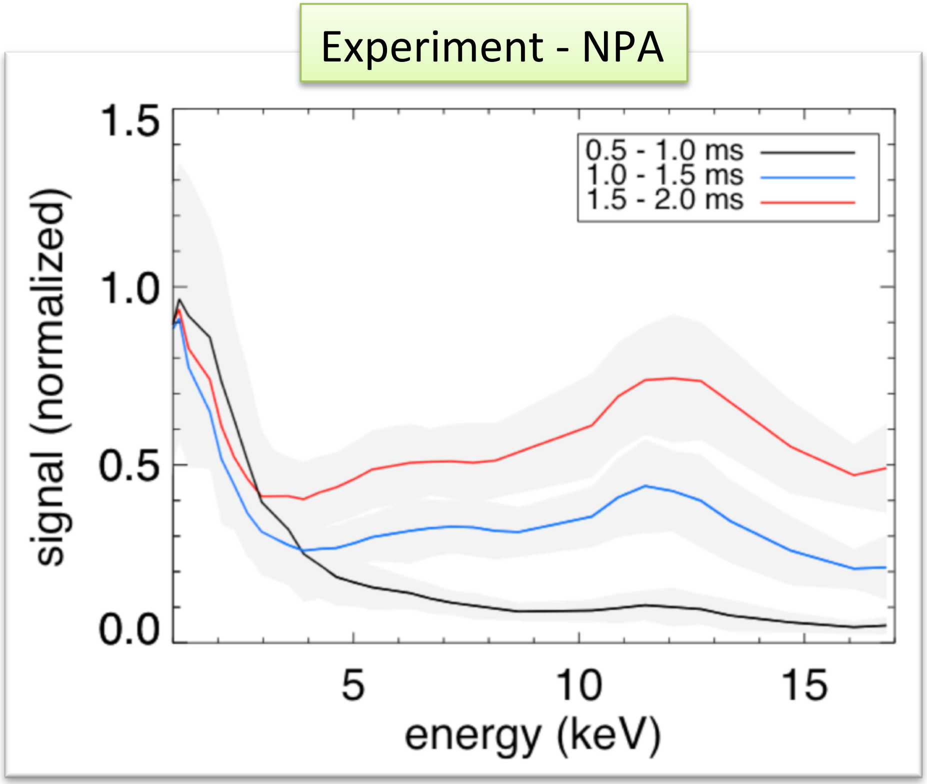


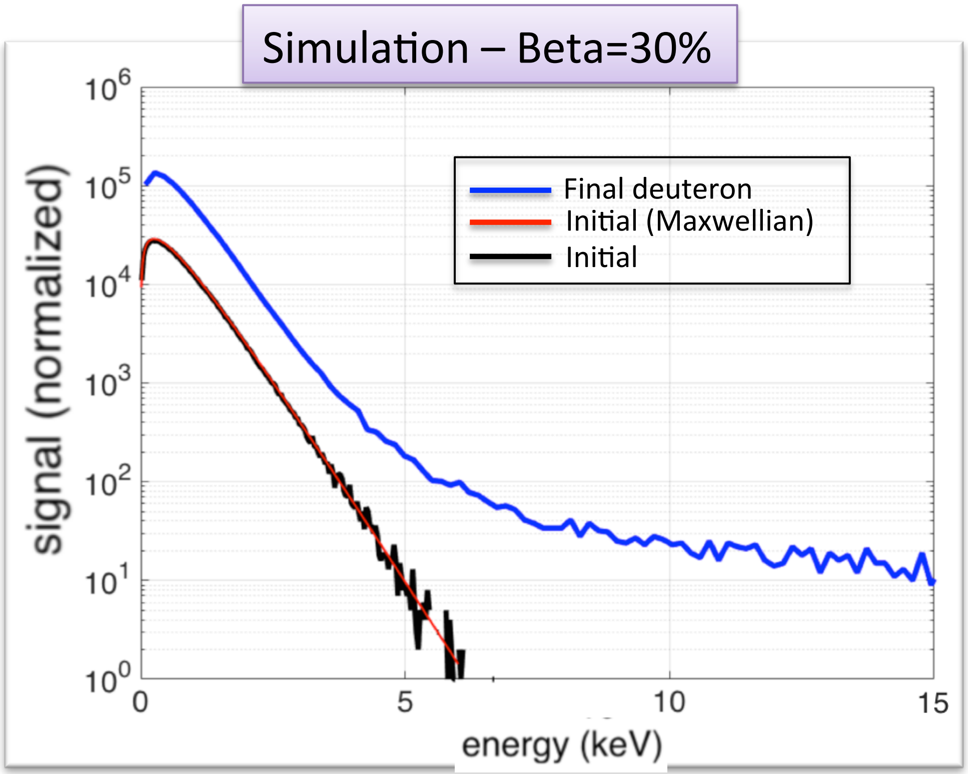


Courtesy: Ryan Clary

Experimental observation and simulation show scattering of beam proton to higher than injected energy

Deuteron (Thermal) Energy Spectrum





Courtesy: Ryan Clary

Experimental observation and simulation show energetic tail in the deuteron distribution

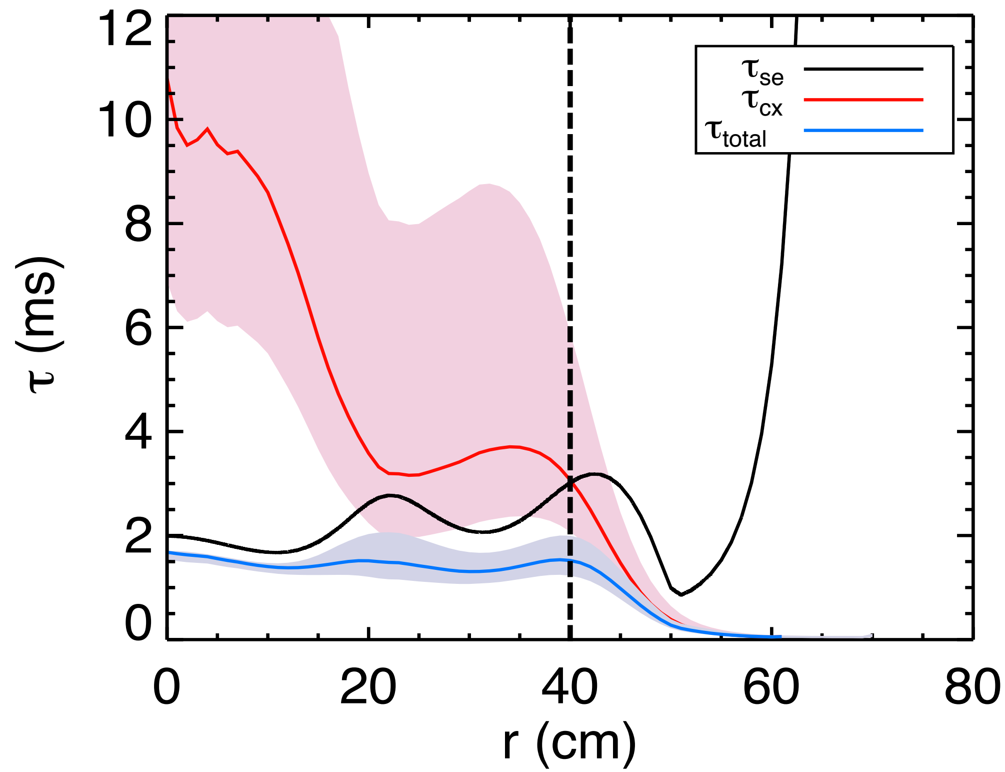
Summary

- Introduced hypothesis for enhanced neutron observed experimentally
- ES used for an analytical benchmark
- Studied three different regimes => each generating enhanced neutrons
- Concentrate on a regime near the impact parameter of the NPA
- ~10x increase in neutron yield compares well to experiment
- Despite the presence of possible robust μ-instabilities, FRC plasma remains robust and undestroyed.

Future Work

- Study beam anisotropy
- Field and density inhomogeneity
- DC steady state beam injection and modulation
- 1D3V longer runs (Perform at NERSC)
- 2D3V simulation to relax angle of propagation (Perform at NERSC)

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