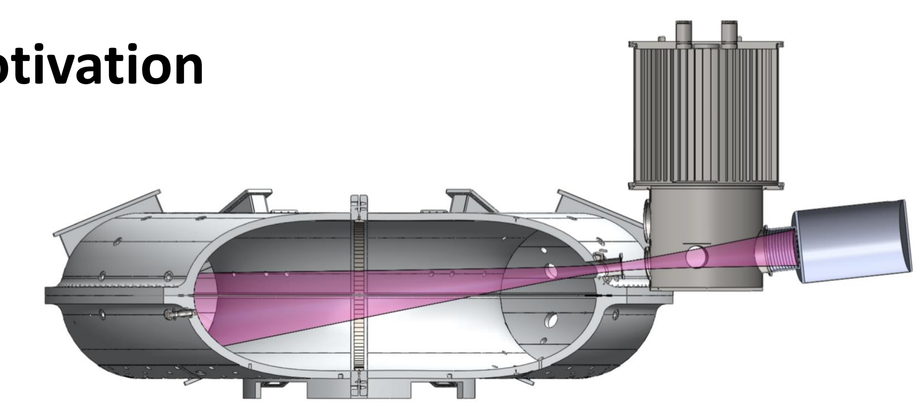
Abstract

Fast ion orbits in the reversed field pinch (RFP) magnetic configuration are well ordered and have low orbit loss despite the stochastic magnetic field generated by multiple tearing modes. Purely classical TRANSP modeling of a 1MW tangentially injected hydrogen neutral beam in MST deuterium plasmas predicts a core-localized fast ion density up to 25% of the electron density and a fast ion beta of many times the local thermal beta. However, neutral particle analysis (NPA) of an NBI-driven mode (presumably driven by a fast ion pressure gradient) clearly shows transport of core-localized fast ions and a saturated fast ion density. The TRANSP modeling is presumed valid until the onset of the beam-driven mode and gives an estimate of the volume-averaged fast ion beta in the range of 1-2% (local core value up to 10%). The development of a collimated neutron detector for fusion product profile measurements will provide information on the energy and spatial distributions of fast ions. This will allow for independent measurements of the fast ion beta to be compared with TRANSP modeling, as well as shed light on the behavior of fast ion transport during onset of NBI-driven modes. Upcoming experiments will further investigate the empirical fast ion beta limit through the use of a deuterium beam into deuterium plasma which will allow for the NPA and neutron flux signals to provide a local and global fast ion beta measurement.

Motivation

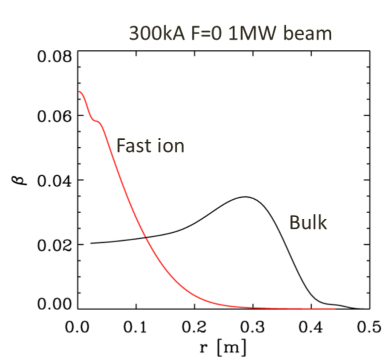


Madison Symmetric Torus
R=1.5 m; a=0.52 m
$I_p \sim 200 - 500$ kA
$|B| \sim 0.2 - 0.5$ T
$T_e(0) \sim 200 - 2000$ eV
$n_e \sim n_D \sim 10^{13}$ cm^{-3}
Pulse length ~ 60-100 ms

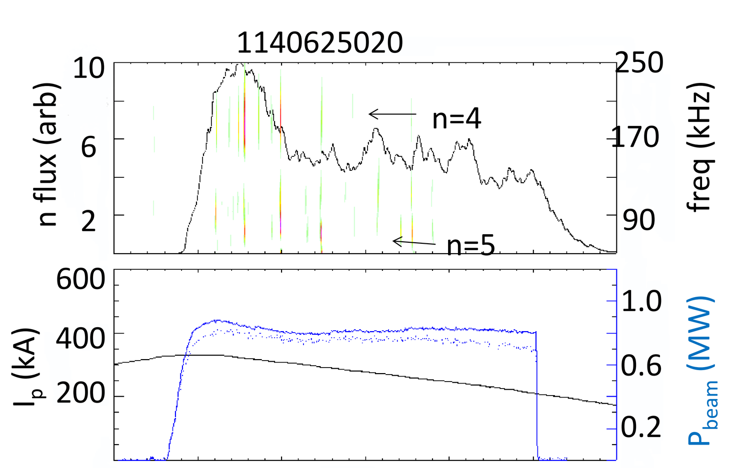
NBI Parameter	Specification
Beam energy	25 keV
Beam power	1 MW
Pulse length	20 ms
Composition	95-97% H, 3-5% D
Energy fraction (E:E/2E/3:E/18)	86%:10%:2%:2%

- 1MW tangentially injected neutral beam creates population of well confined fast ions in core
- TRANSP predicts fast ion beta a few times local bulk beta

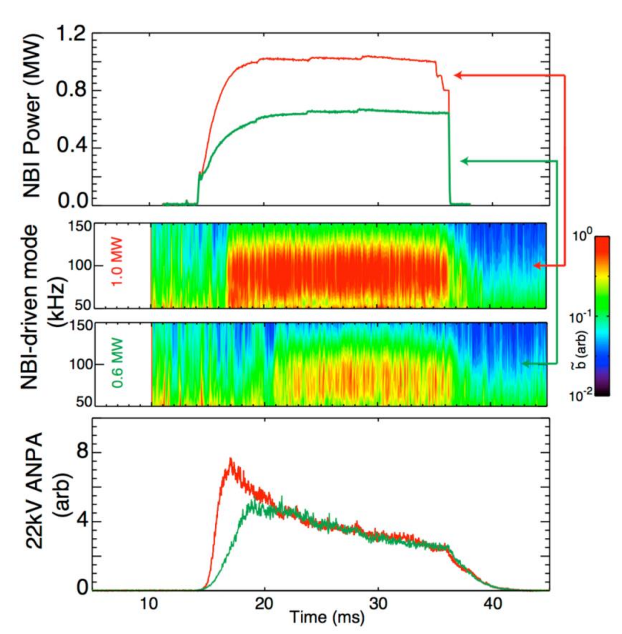
$$\beta = \frac{particle\ pressure}{magnetic\ pressure}$$



- Fast ion pressure gradient drives bursting modes that move or deplete fast population



Bursting modes in full D beam



Saturation of H ANPA channels due to EPMs in D doped H beam

- Experimental goals:
- ➢ Measure fast ion beta profile

$$P_{fi} = \frac{1}{V}\int dV \int E\, f_{fi}(E,V)dE \qquad n_{fi} = \int f_{fi}(E)dE$$

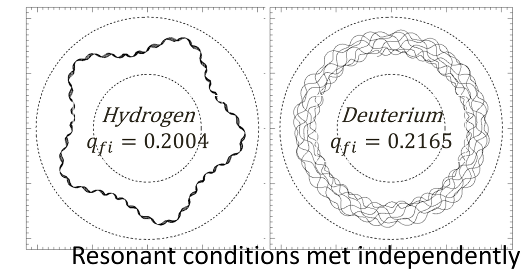
- ➢ Determine behavior of fast ion population around bursting modes and other magnetic events
- ➢ Determine critical $\nabla\beta_{fi}$ for EPM stability

Mode excitation in the RFP

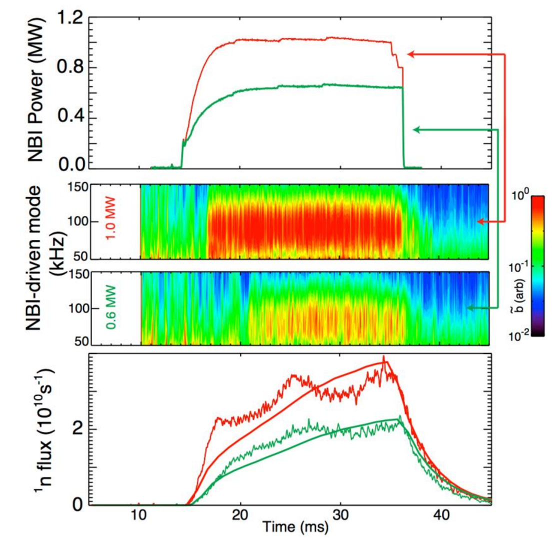
- $\nabla\beta_{fi}$ drives EPM activity
- Resonant condition must be met for magnetic perturbation to tap energy from fast ions

$$\omega = n\omega_\phi - (m+l)\omega_\theta$$

- Species-dependent resonant conditions exist due to mass dependence of ion orbit characteristics
- ^{2}H doped ^{1}H neutral beam can excite bursting modes that only effect ^{1}H population



Resonant conditions met independently by species



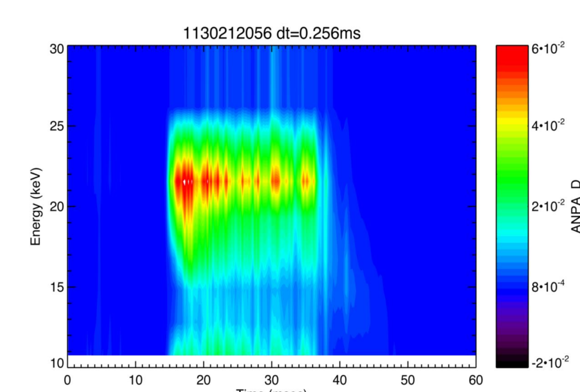
D population (n flux) unaffected by H driven EPM activity

Measure of fast ion distribution

- Measured fusion products predominantly from fast deuterium population due to energy dependence of fusion cross section
- Beam-target fusion dominates over beam-beam and thermal contributions in standard conditions
- Fast ion distribution can then be extracted from global MST neutron flux

$$\Gamma_{MST} \cong \Gamma_{bt} = \iint n_{fi} n_i \sigma v_{fi}\, dV dE$$

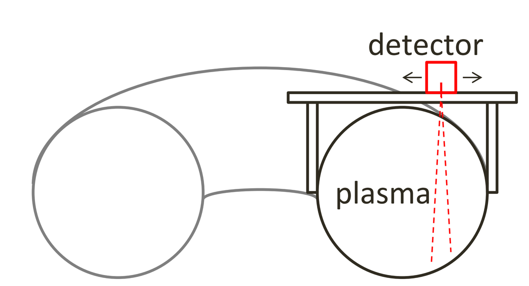
- ANPA provides energy distribution (lacking absolute calibration and radial information)
- Total MST neutron flux for scaling
- Collimated neutron detector provides spatial distribution

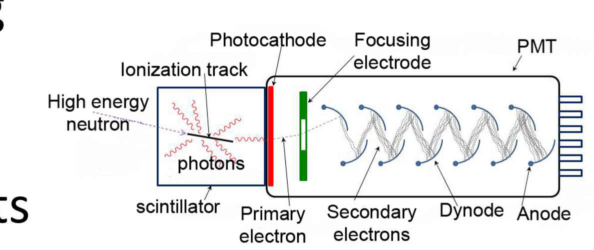


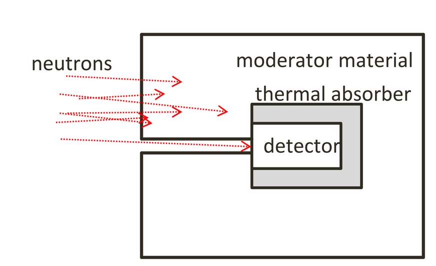
ANPA gives fast ion energy distribution

Collimated detector ideas

- Single camera measures line-integrated neutron signal
- Scanning functionality allows shot-averaging for fast ion profile
- Plastic scintillator-PMT neutron detector: nuclear recoil from neutron collisions imparts energy to scintillator, light collected in PMT sensitive down to a few eV
- Effective neutron shield required to limit collimator signal to sample volume only







Neutron moderation

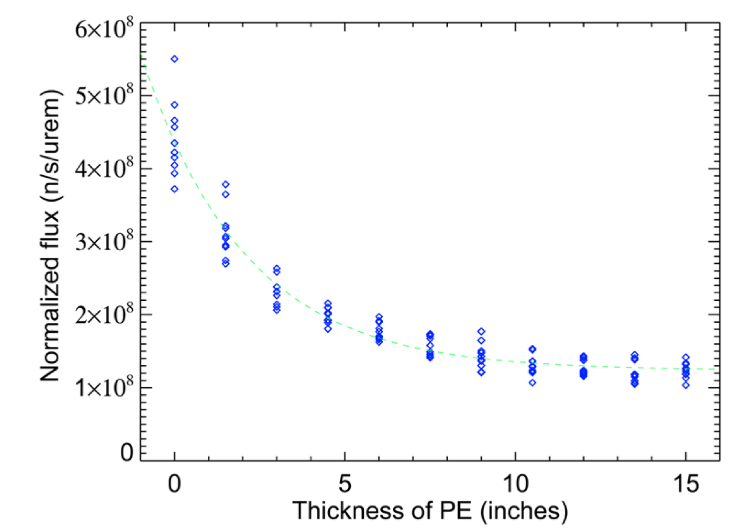
- Hydrogenous material most effective moderator of neutrons

$$E_R = \frac{4A}{(A+1)^2}\cos^2\theta\, E_n$$

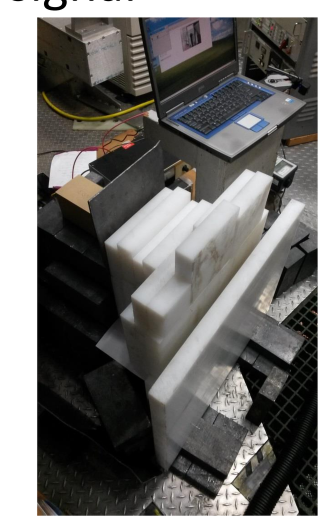
- Energy disparity: neutrons start at high energy and must be moderated to below scintillator sensitivity to be shielded from detector

$$D + D \rightarrow 3He + n(2.45MeV)$$

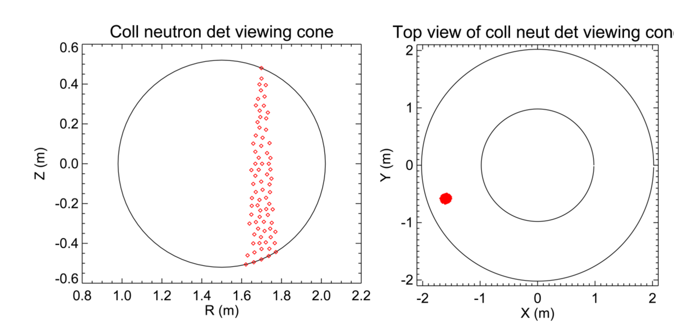
- At high energy neutron interactions dominated by elastic collisions requiring, on average, 27 collisions to thermalize
- However, as energy decreases, elastic (and absorption) cross section increase which shortens neutron mean-free-path
- Polyethylene $(C_2H_4)_n$ experimentally tested for shielding capability
  - Forward facing shield only, no scatter protection
- Results show effective mean free path of $\lambda_{mfp} = 7.7cm$
- Scatter shown to contribute ~30% of unshielded signal



Fit results:
$f = Ae^{Bt} + C$
A=3.133e8
B=-0.3272
C=1.238e8



- Modeling of collimator (100% absorptive shield) used to determine thickness of PE shield required



Typical values (n/s)	
MST Total neutron flux	2e11
Collimator (shielded)	2e4
Collimator (un-shielded)	1e6

- Factor of ~70 moderation required near core (~13” PE shield equivalent)

Design and build of collimator

- Design provides minimum 12” shielding to scatter, additional moderation to direct neutron flux
- Paraffin wax $(C_{31}H_{64})$ used to fill cavities
- Pb shielding required for γ,X-ray shielding, not shown
- Thermal neutron absorber surrounding detector could further improve shielding, improving signal to noise
- Before drilling the collimator bore the effectiveness of the neutron shield will be validated for background noise levels