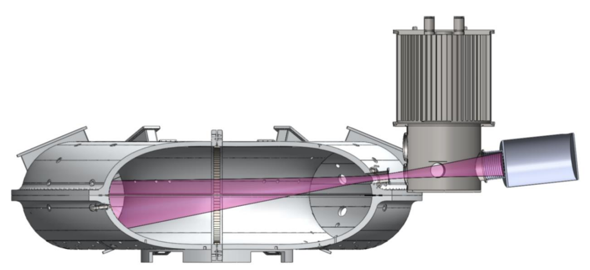
Abstract

Fast ion orbits in the reversed field pinch (RFP) are well ordered and classically confined despite magnetic field stochasticity generated by multiple tearing modes. Classical TRANSP modeling of a 1MW tangentially injected hydrogen neutral beam in MST deuterium plasmas predicts a core-localized fast ion density that can be 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) shows mode-induced 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 initial estimate of the volume-averaged fast ion beta of 1-2% (local core value up to 10%). A collimated neutron detector for fusion product profile measurements will be used to determine the spatial distribution of fast ions, allowing for a first measurement of the critical fast-ion pressure gradient required for mode destabilization. Initial data will be presented. Characterization of both the local and global fast ion beta will be done for deuterium beam injection into deuterium plasmas for comparison to TRANSP predictions.

RFP provides complementary environment to study fast-particle physics

- Weak toroidal field -> large fast-ion beta and stronger drive
- Large magnetic shear -> increased stability
- Energetic particle (EP) driven instabilities observed in MST



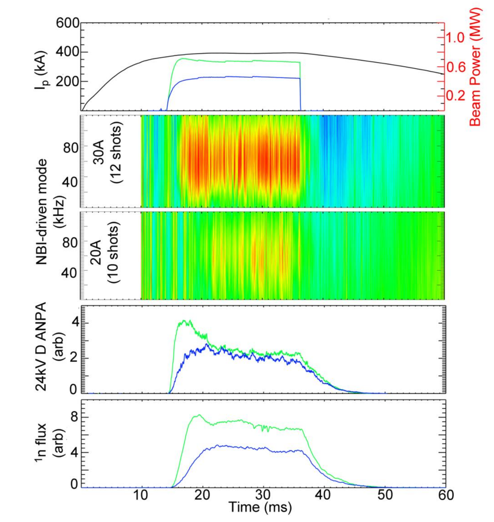
Madison Symmetric Torus
R=1.5 m; a=0.52 m
$I_p \sim 200 - 500$ kA
$\lvert B \rvert \sim 0.2 - 0.5$ T
$T_e(0) \sim 200 - 2000$ eV
$n_e \sim n_D \sim 10^{13}$ cm^{-3}
Pulse length ~ 60-100 ms

NBI Parameter	Specification
Beam energy	25 keV
Beam power	1 MW
Pulse length	20 ms
Composition	100% D
Energy fraction (E:E/2E/3:E/18)	86%:10%:2%:2%

- Large well-confined, core-localized fast-ion population created in MST through tangential neutral beam injection where TRANSP predicts local fast-ion beta in excess of bulk beta

$$\beta = \frac{particle\ pressure}{magnetic\ pressure} \qquad P_{fi} = \frac{1}{V}\int dV \int E\, f_{fi}(E,V)dE$$

- EP modes, driven by fast-ion pressure gradient, result in fast-ion transport, flattening core profile and reducing fast-ion beta
- Experimentally determining the fast ion distribution will help to determine the critical $\nabla\beta_{fi}$ for energetic particle mode (EPM) activity but also give information on fast ion population behavior around magnetic events

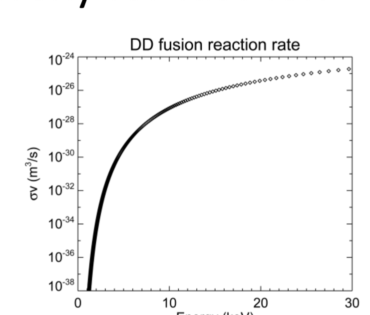


EPM mode onset coincident with ANPA and neutron flux signal saturation

Obtaining fast-ion distribution through neutron measurements

- Due to energy dependence of fusion cross section, measured neutrons are primarily from beam-target fusion, making neutrons a good proxy for fast-ion content

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

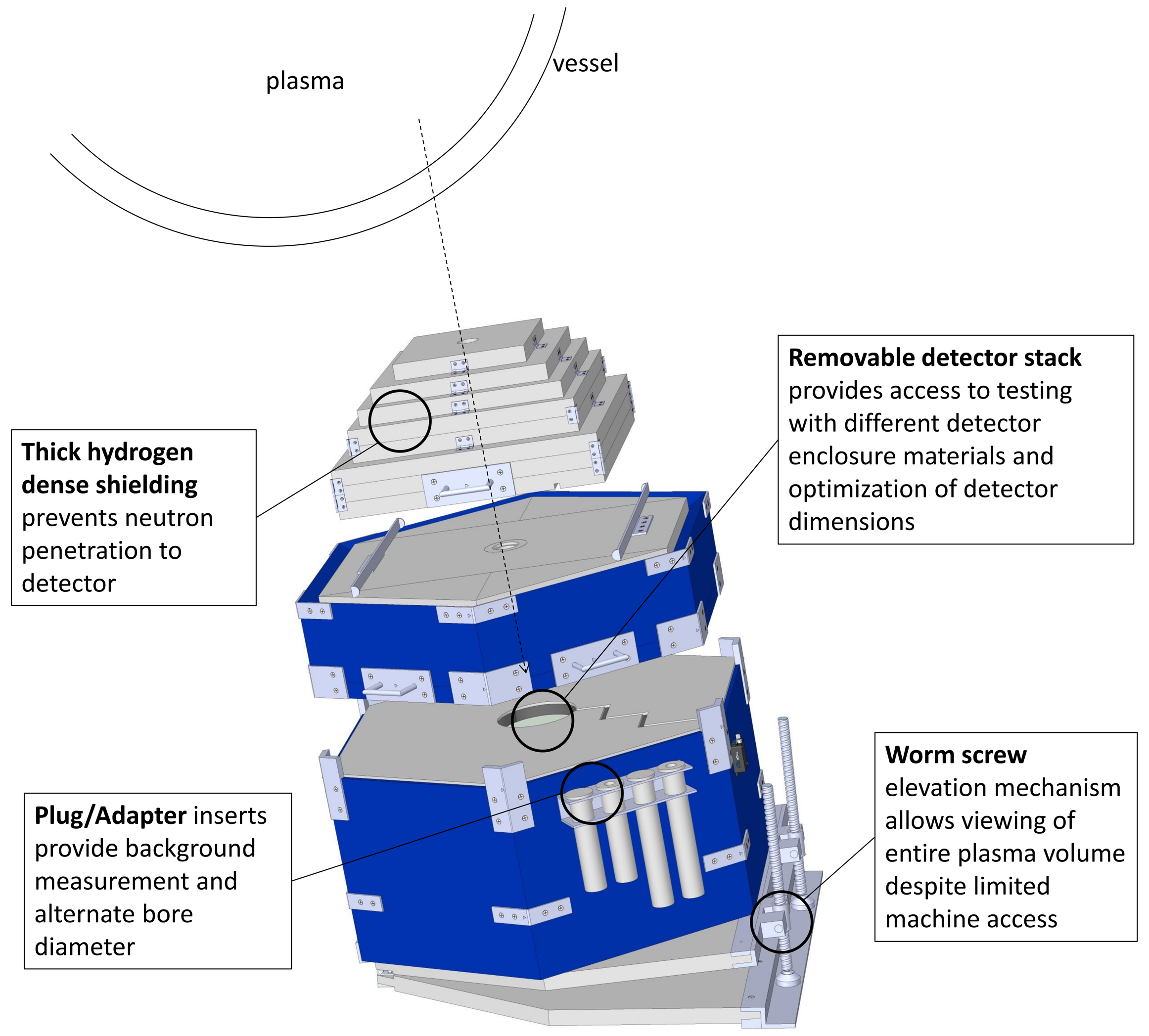


- Detection of neutrons via scintillator-PMT is currently used to provide total neutron flux measurements on MST but as it provides no information on neutron energy spectrum, NPA will be used
- Implementation of new collimated neutron detector in conjunction with a global neutron flux measurement will provide the spatial fast-ion profile the scaling necessary to determine the fast-ion distribution
- Once fast-ion distribution is known calculation of fast ion beta can be done for given magnetic geometry

Collimated neutron detector concept

- Neutron detector embedded within shielding enclosure with a deep bore aperture defining a plasma viewing volume
- Single camera measures line-integrated neutron signal, giving the emissivity profile after inversion of ensembled shots at various viewing cords
- Utilizing Monte Carlo type neutron following code informs design characteristics and behavior

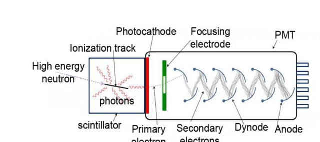
CiNDe: Collimated Neutron Detector

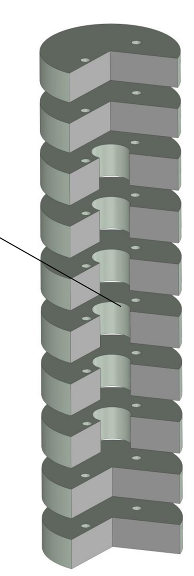


Weight: 1460lbs
Dimensions: 42x42x42”
Bore: 2” diameter w/plugs and 1” adapters

Detector stack:

- Plastic scintillator-PMT, proton recoil from neutron collisions imparts energy to scintillator, light then collected in photomultiplier

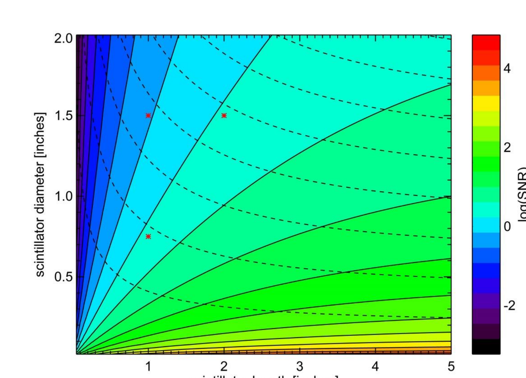




- Large gamma radiation background due to Tritium-branch fusion protons striking vessel wall

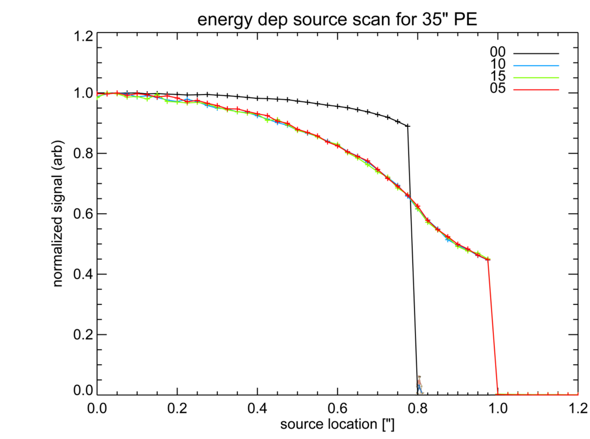
$$D + D \rightarrow {}^{3}He + n(2.45MeV)$$
$$\rightarrow T + p(3.01MeV)$$

- Lead detector sheath provides x-ray shielding and reduces gamma flux
- Modeling of the energy deposition of ‘signal’ neutrons (bore-originated) to ‘noise’ neutrons (through shielding) informs optimal scintillator geometry

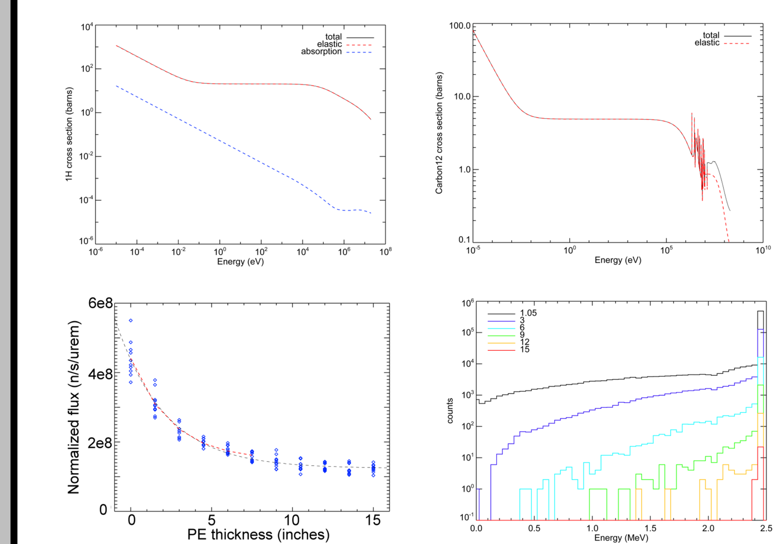


Deep bore:

- Scintillating detector material sits at bottom of a ~35” bore, defining the plasma viewing volume
- 2” bore results in ~7cm beam width on midplane
- Due to imperfect shielding, simulations of a source scan across the bore aperture give a measure of the effective viewing angle



Shielding:



Direct thickness only (no side/rear shielding)

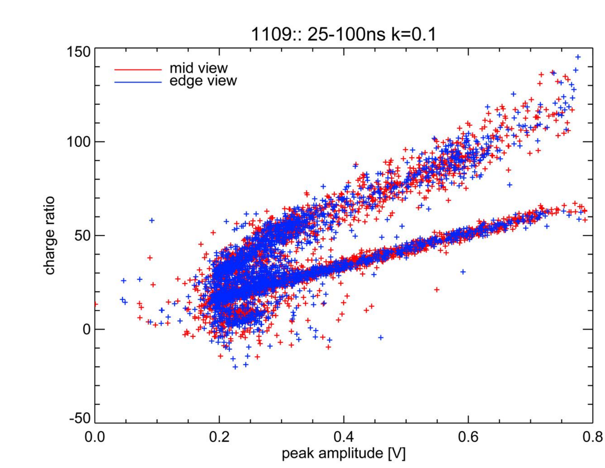
- Elastic collisions dominate nuclear interactions at high neutron energy making highly hydrogenous material suitable for shielding

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

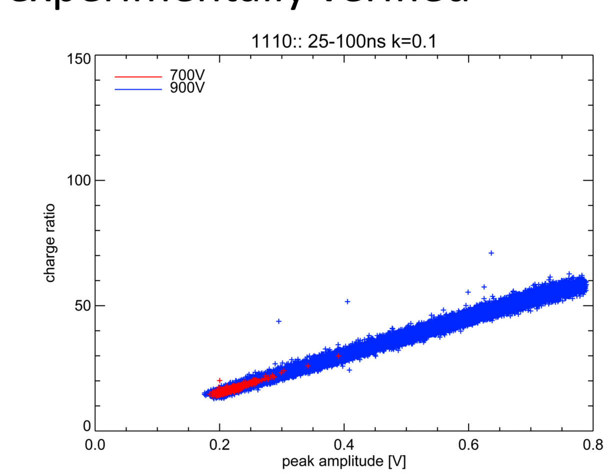
- Polyethylene $(C_2H_4)_n$ test confirms neutron signal mitigation but reveals large scattered signal component, requiring 360° enclosure of collimated detector
- Thermalization of neutrons requires on average 27 collisions, though elastic (and absorption) cross sections increase as energy is lost
- Modeling confirms transmitted population largely full energy neutrons

Neutron counting achieved through gamma pulse shape discrimination

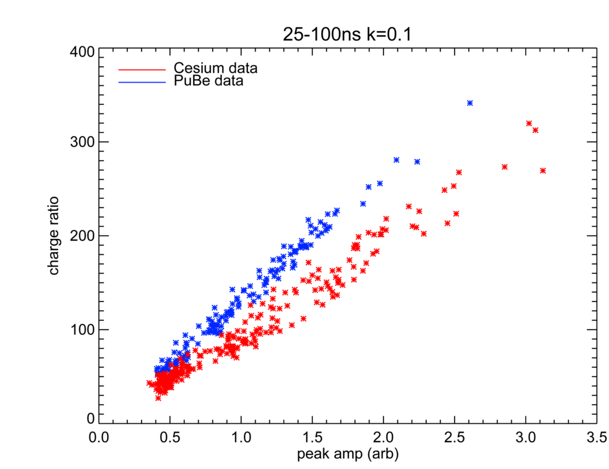
- Fast (5ns rise time) transimpedance amp and fast digitization allows for discrimination between neutron and gamma pulse shapes
- Comparison of the charge collected in the PMT anode during the initial pulse rise vs total charge collected during pulse can characterize the particle responsible due to:
  - free electrons created by gamma interaction preferentially excite scintillator molecules into singlet state where photon emission due to decay is prompt
  - recoil protons from neutron collisions excite more atoms into triplet state leading to delayed fluorescence and a more elongated pulse shape
- Identification of neutrons has been experimentally verified



CiNDe data from full D NBI into MST plasmas shows two trend lines as expected in presence of both neutron and gamma radiation



Cesium data on fast digitizer shows single trend line, in agreement with gamma-only radiation



Cesium data compared to PuBe source confirms the dual trend lines corresponding to neutron and gamma radiation

Summary of work

A collimated neutron detector has been designed and built for measuring the fast-ion spatial distribution in MST

Initial results show gamma pulse discrimination can be achieved, providing a means of neutron flux measurements via neutron counting through various plasma viewing volumes

Future measurements of the neutron emissivity profile by 2D tomographic inversion of CiNDe data will provide the first measurement of the fast-ion beta profile in MST

Investigating the fast-ion beta in various plasma parameters will yield a measure of the fast-ion beta limit in MST

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