Predictions of Neutral Beam Deposition and Energetic Particle Losses in W7-X

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Introduction

Energy production in a nuclear fusion reactor requires that the 3.5 MeV alpha particles generated by D-T reactions be confined long enough to transfer the majority of their energy to the thermal population through collisions. To evaluate the confinement of such particles in the W7-X stellarator a set of neutral beams have been installed. In this work we simulate this heating system using the BEAMS3D code [1]. This allows us to address:

- Shine through estimates
- Particle birth profiles
- Heating and current drive estimates
- Particle loss

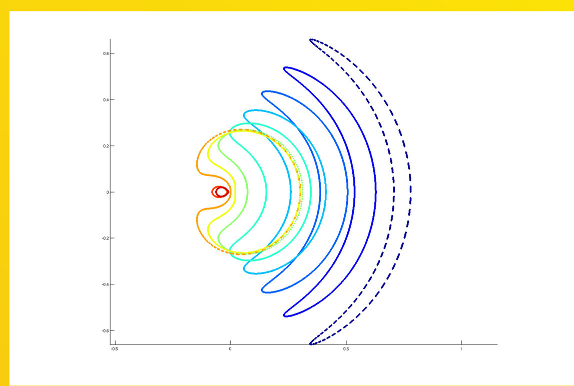
Depiction of the neutral beam injector geometry in W7-X. Ports are shown for reference along with plasma domain and first wall.

Method

The BEAMS3D code provides a comprehensive package for neutral beam injection modeling
- Full neutral beam 3D geometry
- Ioninzation physics: e-impact, i-impact, charge exchange (ADAS) [2]
- Gyrocenter following with slowing down and pitch angle scattering
- All equilibrium quantities specified on cylindrical grid (R,PHI,Z)
- MPI based parallelization over field construction and particle orbits

$$\frac{d\vec{R}}{dr} = \frac{\hat{b}}{qB} \times \left(\mu \nabla B + \frac{m v_\parallel^2}{B} \left(\hat{b} \cdot \nabla \right) \vec{B} \right) + v_\parallel \hat{b}$$

$$\frac{dv_\parallel}{dt} = -\frac{\mu}{m} \hat{b} \cdot \left(\nabla B \right)$$



Example of banana orbits as calculated by BEAMS3D code.

Simulation of neutral beam injection requires handling the detailed physics of the interaction of the energetic particles and bulk plasma
- Charge particle birth profile uses detailed trajectory information and ADAS reaction tables

$$\tau_{fi} = \left[\sum_j n_j < \sigma_j v_{rel} > \right]^{-1}$$

- Particle slowing down
  Slowing down terms are calculated from the Fokker-Plank distribution function [3].

$$\frac{\partial < v >}{\partial t} = -\frac{v}{\tau_s} - \frac{v_c^3}{\tau_s v^2}$$

Electron Term — Ion Term

$$v_c = \left[\frac{3\sqrt{\pi}}{4} \frac{m_e}{m_i} \right]^{1/3} \sqrt{\frac{2T_e}{m_e}}$$

$$\tau_s = \frac{m_i}{m_e} \frac{\left(4\pi\epsilon_0\right)^2}{4\sqrt{(2\pi)}} \frac{3 m_e^{1/2} T_e^{3/2}}{n_e Z_i^2 e^4 \ln\Lambda}$$

- Pitch angle scattering
  At each solution time step, the physics routine takes a new pitch angle from a distribution:

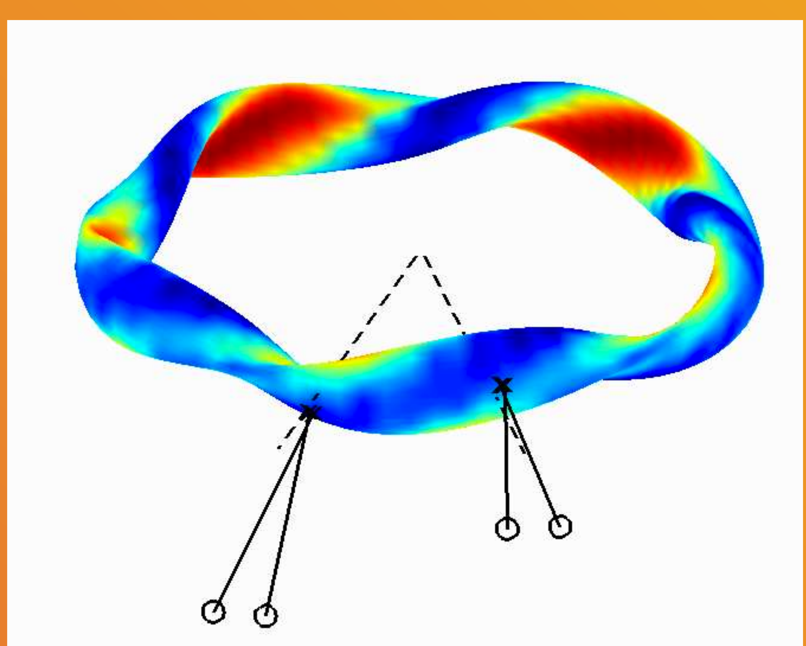
$$P(\zeta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\left(\zeta - < \zeta >\right)^2}{2\sigma^2} \right)$$

$$\sigma^2 = \frac{2 v_s \Delta T}{v^3} \left(1 - \zeta_0^2 \right)$$

$$< \zeta > = \zeta_0 \left(1 - \frac{2 v_s \Delta t}{v^3} \right)$$

$$v_s = \frac{v_c^3}{2\tau_s}$$

The W7-X neutral beam system is a replica of the ASDEX Upgrade system
- 55 eV H (60 eV D)
- 1-2 MW per source
- Two sources per beam line



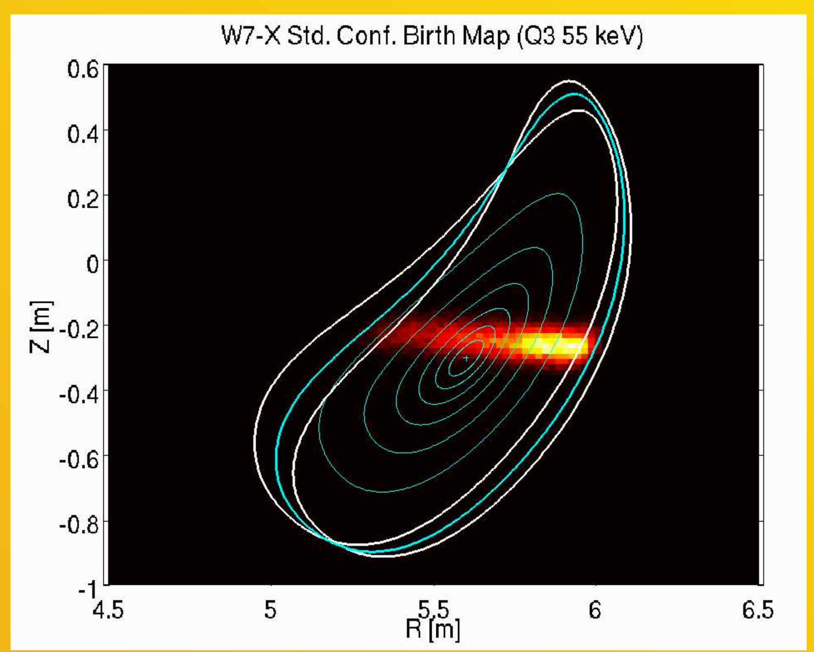
The beam line geometry for the W7-X neutral beam system. Dotted lines indicate the coordinate axis of each neutral beam injector. Circles indicate location of sources for the first campaign. Solid lines are the beam lines.

Source	Q3	Q4	Q7	Q8
Energy [keV]	55			
Power [MW]	1.1	1.3	1.1	1.3
Fraction (E)	54.6%			
Fraction (E/2)	30.9%			
Fraction (E/3)	14.5%			

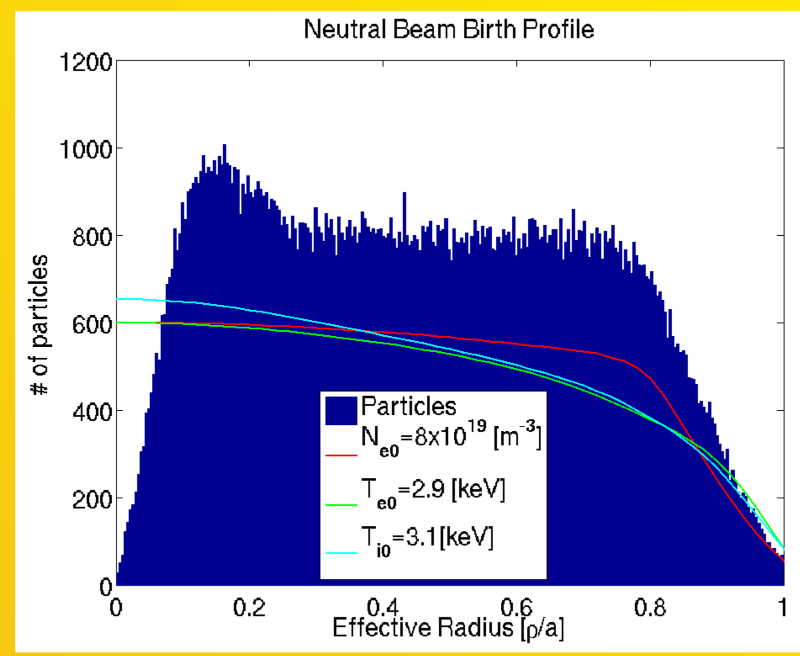
Neutral beam RF source parameters for OP1.2.

Results

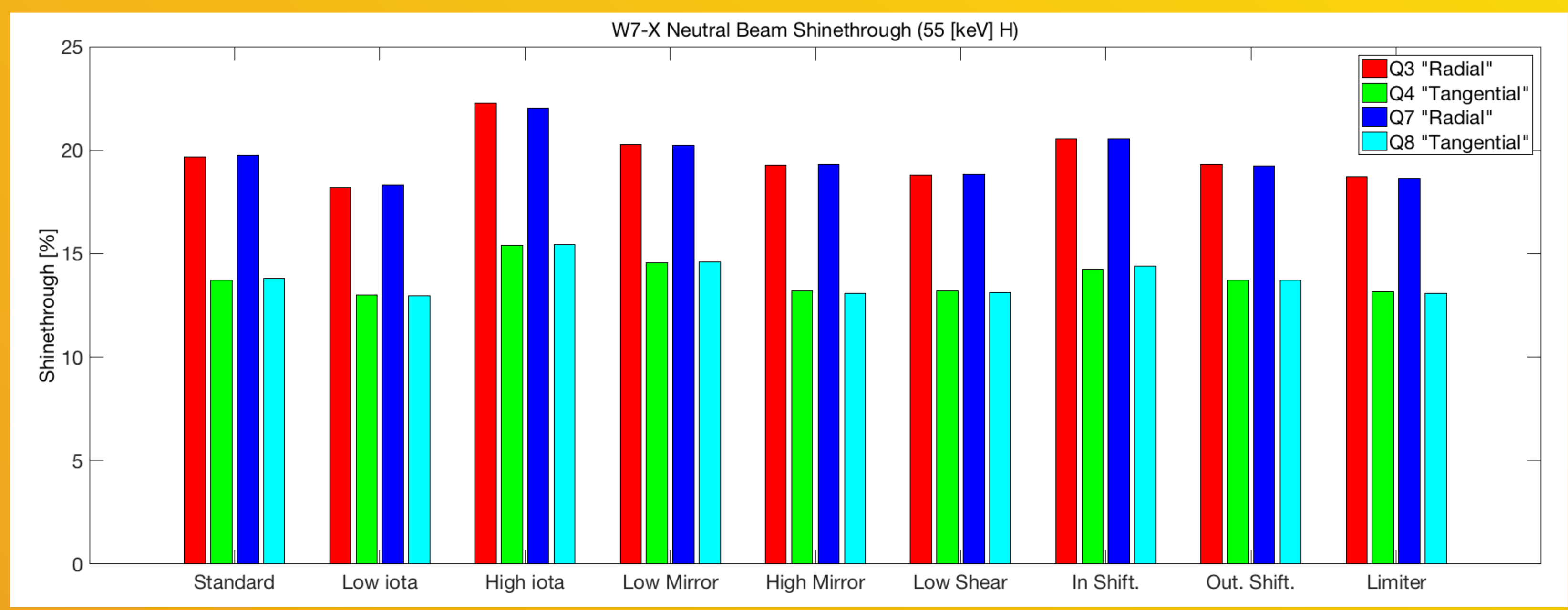
A W7-X 2% beta equilibrium served as the target for the simulations
- Finite beta and zero net current equilibrium
- Profiles from predictive transport calculations



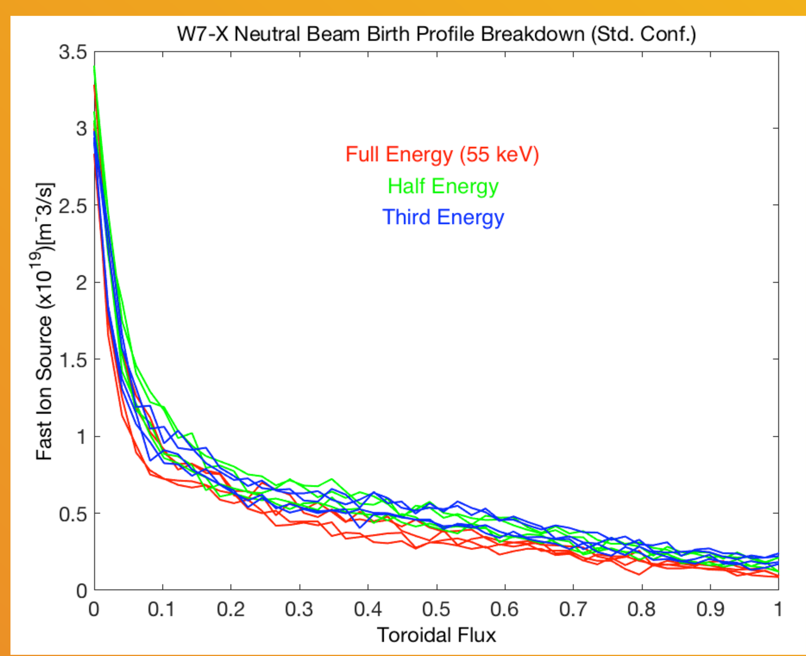
Distribution of 55 keV H fast ions born in the standard configuration. Equilibrium surfaces depict toroidal extent.



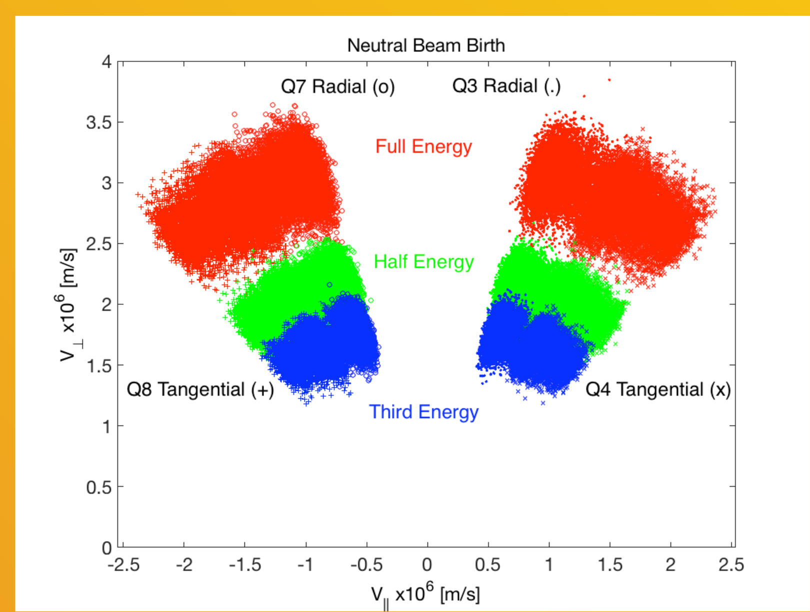
Radial location of particle births in simulation of the standard configuration. Plasma profiles used in simulations are plotted.



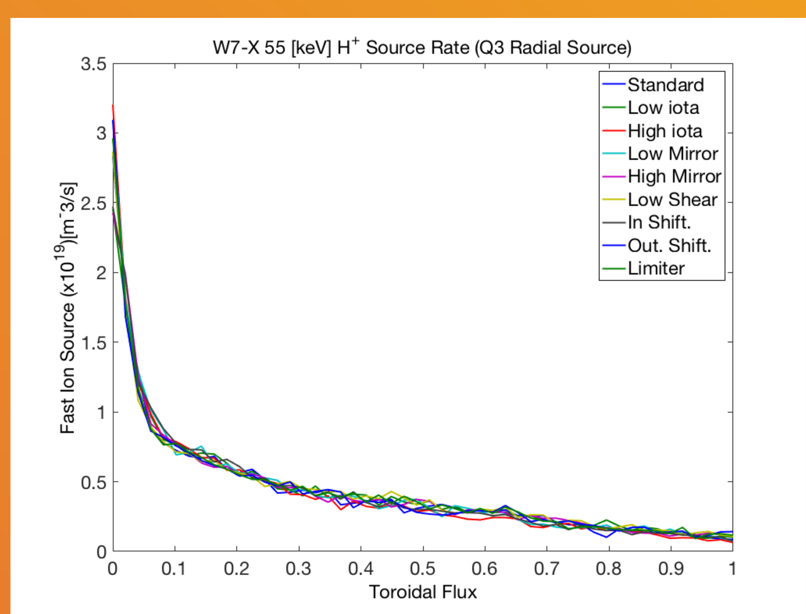
Estimations of beam shine-through for the 55 keV H component of the beams for the nine baseline configurations of W7-X. The 'tangential' sources show a consistent 5% better coupling to the plasma than the 'radial' beams which is consistent with their longer path through the plasma.



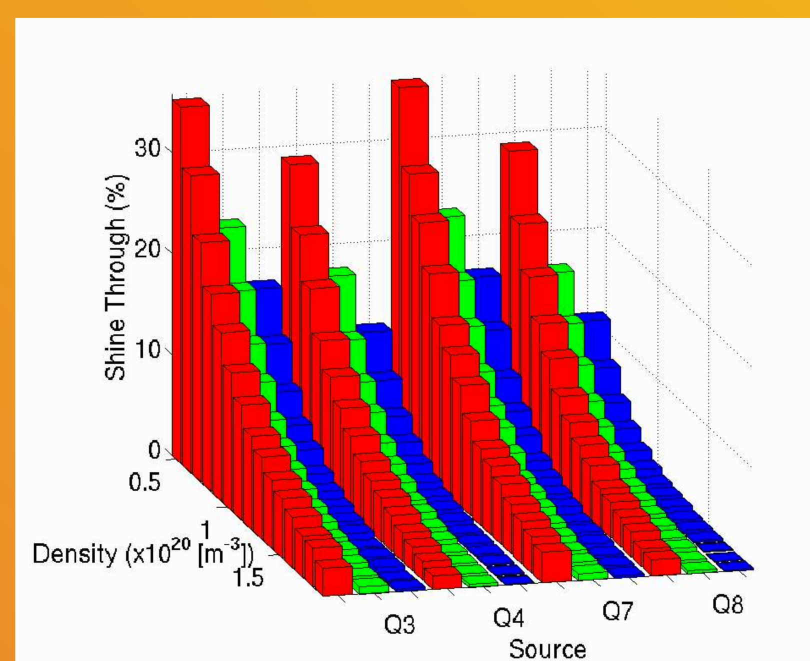
Fast-ion birth profiles for the standard configuration at the full, half and third energies. Slower particles appear to be ionizing at larger radii which is consistent with assumptions about neutral beam birth profiles.



Pitch angle space plot of particle birth locations in the standard configuration. The 'radial' beams larger pitch angles than the 'tangential' beams, consistent with the beam-line geometries. Some overlap between the half and third energy pitch angles is present.



Comparisons between configurations show little variation in the birth rate of fast ions in the plasma.



Shine through dependance on density for the standard configuration in W7-X.

Discussion

The BEAM3D code has been used to simulate neutral beam deposition in W7-X providing estimates for shine-through and neutral beam deposition for OP1.2 and beyond
- Shine-through estimates show little dependence on magnetic configuration.
- Radial beam lines show a consistently high level of shine-through
- At low density beam shine through appears large for the full energy component of each source.
- Work is underway to incorporate a wall and neutral beam duct model into the simulations.

References

[1] McMillan M and Lazerson S Plasma Physics and Controlled Fusion 56, 095019 (2014)
[2] Summers H P *et al.* 5th Int. Conf. on Atomic and Molecular Data 902, 239 (2006)
[3] Callen J D Fundamentals of Plasma Physics (Lecture Notes) (2003)

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