THEA ENERGY

The Scoping, Design, and Plasma Physics Optimization of the Eos Neutron Source Stellarator

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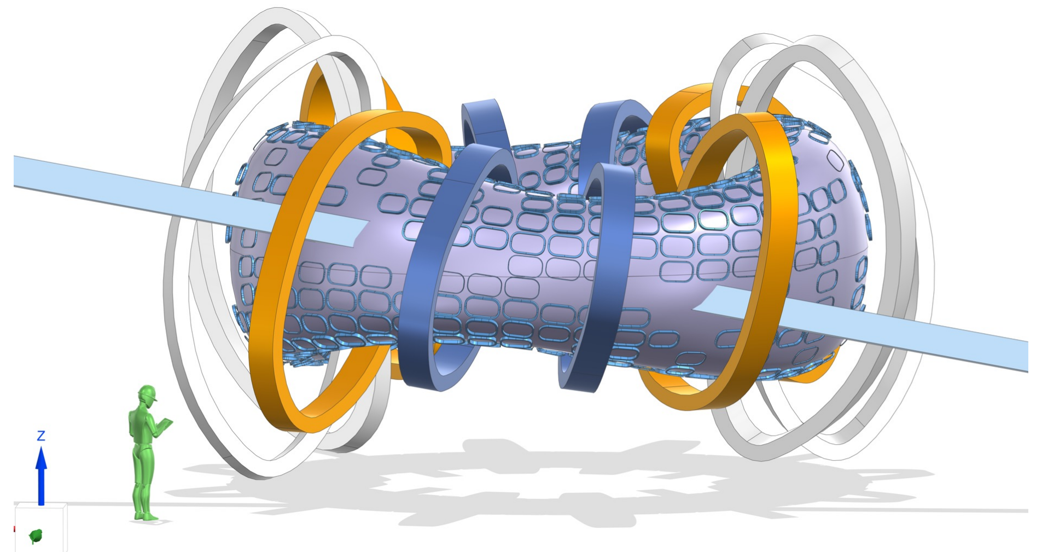
Introduction

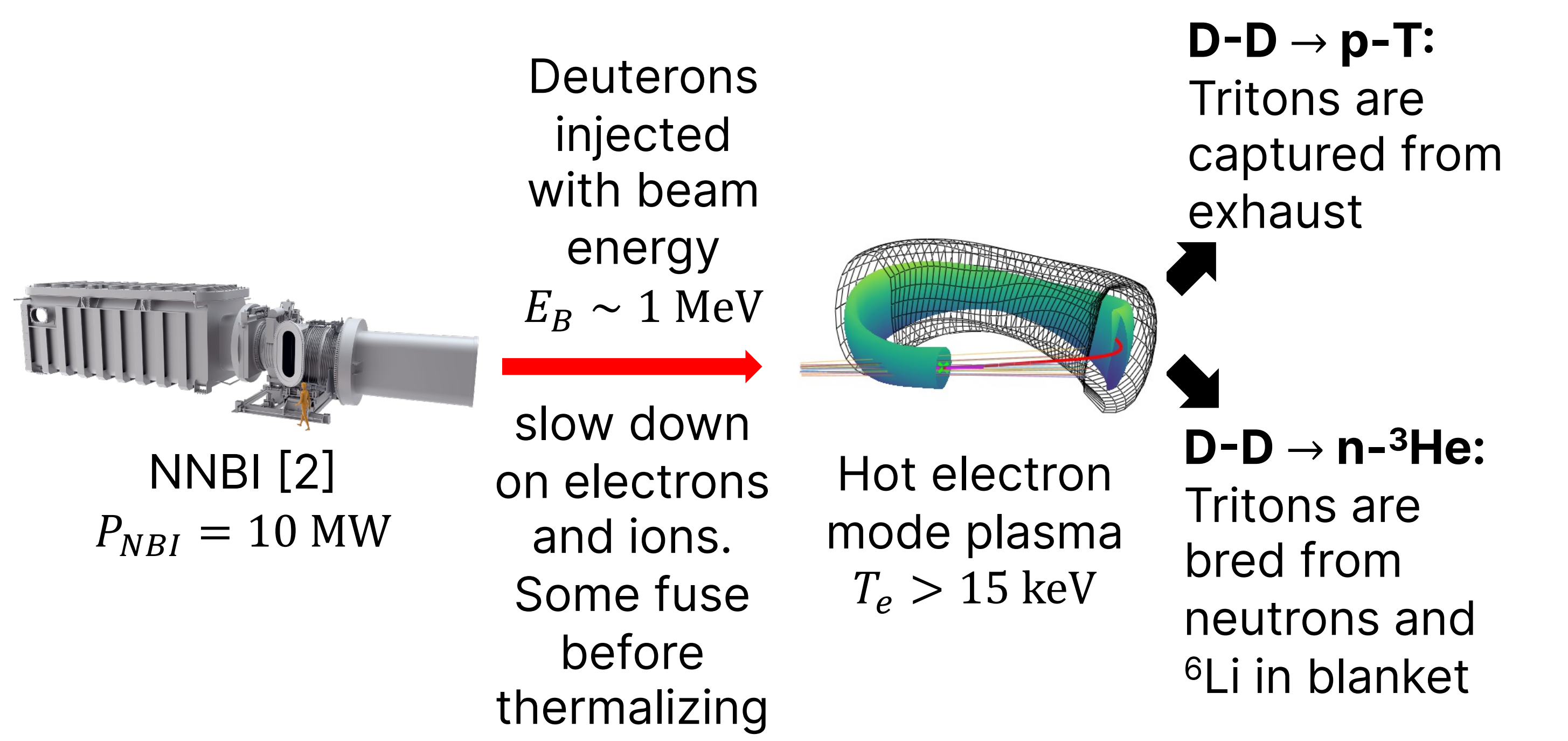
On the path to a fusion pilot plant, Thea Energy plans to build Eos, a sub-breakeven, deuterium-deuterium, beam-target fusion, stellarator neutron source facility for producing tritium and other valuable radioisotopes. In this paper, a set of 1-D plasma physics models are coupled and used to design the operating point of the facility and predict performance. Models of 1-D profile-dependent neutral beam stopping, ion beam slowing down, beam-target fusion, electron-ion classical heat transfer, energy confinement (ISS04), beam pressure, beam heating of ions and electrons, beam-beam fraction, and neutral beam injection and gyrotron heating electrical efficiencies are included. A numerical optimizer is used to determine the minimum required facility electric power to generate tritium at a given rate. A stellarator facility requiring 40 MWe would produce as much tritium as a CANDU reactor. Manuscript submitted to Nuclear Fusion.[1]

Electromagnetic coils



Eos will confine plasma in a quasi-axisymmetric magnetic field produced by a set of planar electromagnetic coils. Planar plasma-encircling coils: White, orange, and blue. Planar shaping coils: Rounded rectangles. NNBI beamline: Light blue rectangular prism.

Beam-target DD Fusion Neutron Production:



NNBI [2]
$P_{NBI} = 10$ MW

Deuterons injected with beam energy $E_B \sim 1$ MeV

slow down on electrons and ions. Some fuse before thermalizing

Hot electron mode plasma
$T_e > 15$ keV

D-D → p-T: Tritons are captured from exhaust

D-D → n-^{3}He: Tritons are bred from neutrons and ^{6}Li in blanket

The Model

The model is 1D: Resolved in radial profiles, beam chord length, and beam-ion energy.

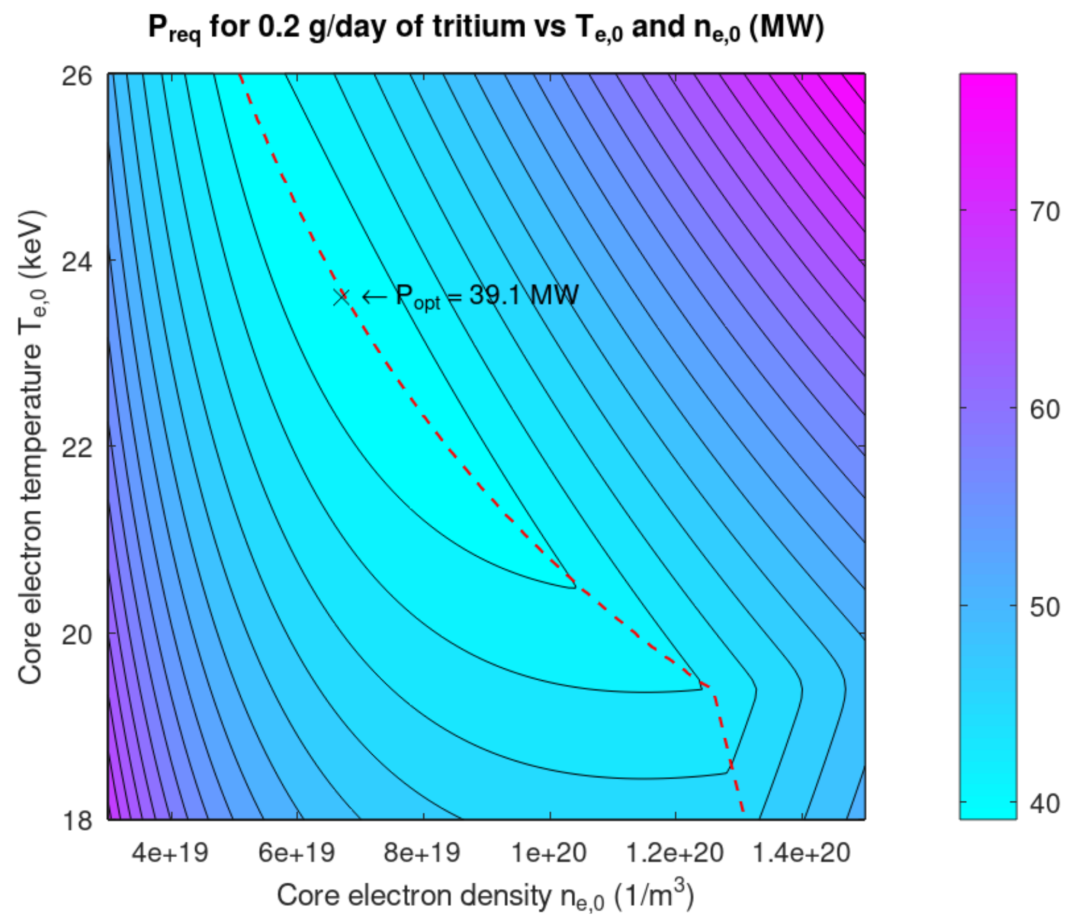
The following phenomena are resolved:

- 1D Plasma profiles
  - Parabolic power-law profiles: $n, T \propto (1-\rho^2)^{\alpha_{n,T}}$
- Plasma conditions along the beam chord:
  - Parabolic plasma axis, circular cross section:
  - $\rho(L) = \left|\frac{L^2}{2R_{c,min}a} - \frac{\Delta R_t}{a}\right|$
- Neutral beam stopping:
  - Power law fit to Suzuki [3]: $\sigma_{stop} \propto E^{-0.767}$
- Beam-target slowing from beam distribution
  - Energy-resolved fusion cross section, deterministic classical slowing on electrons and ions [4]:
  - $p = \int_0^{E_b} dE \, \frac{n_i \sigma(E) v_b(E)}{-((\partial_t E)_i + (\partial_t E)_e)}$
- Electron-ion thermal transfer
  - Classical collisions
  - $\overline{\tau_e} \propto T_e^{3/2}/n_e$
- Beam heating of ions and electrons
  - $P_{b,h,i/e} = \int_0^{E_b} dE \, \frac{(\partial_t E)_{i/e}}{((\partial_t E)_i + (\partial_t E)_e)}$
- Energy confinement
  - ISS04 empirical scaling, τ_{ISS04} [5]
  - Confinement enhancement factor $H_{ISS04} = 1.5$
- Excess electron or plasma power made up with ECRH, gyrotron tubes
- Facility power
  - Beam efficiency $\eta_b = 0.3$
  - ECRH efficiency $\eta_g = 0.45$
  - Balance of plant $P_{BOP} = 5\ MW$

Equilibrium parameters		
Major radius	R	3.24 meters
Aspect ratio	A	6
Rotational transform	$\overline{\iota_{2/3}}$	0.66
Axial magnetic field	B_0	5 T
Max radius of curvature	$R_{c,min}$	5.84 m

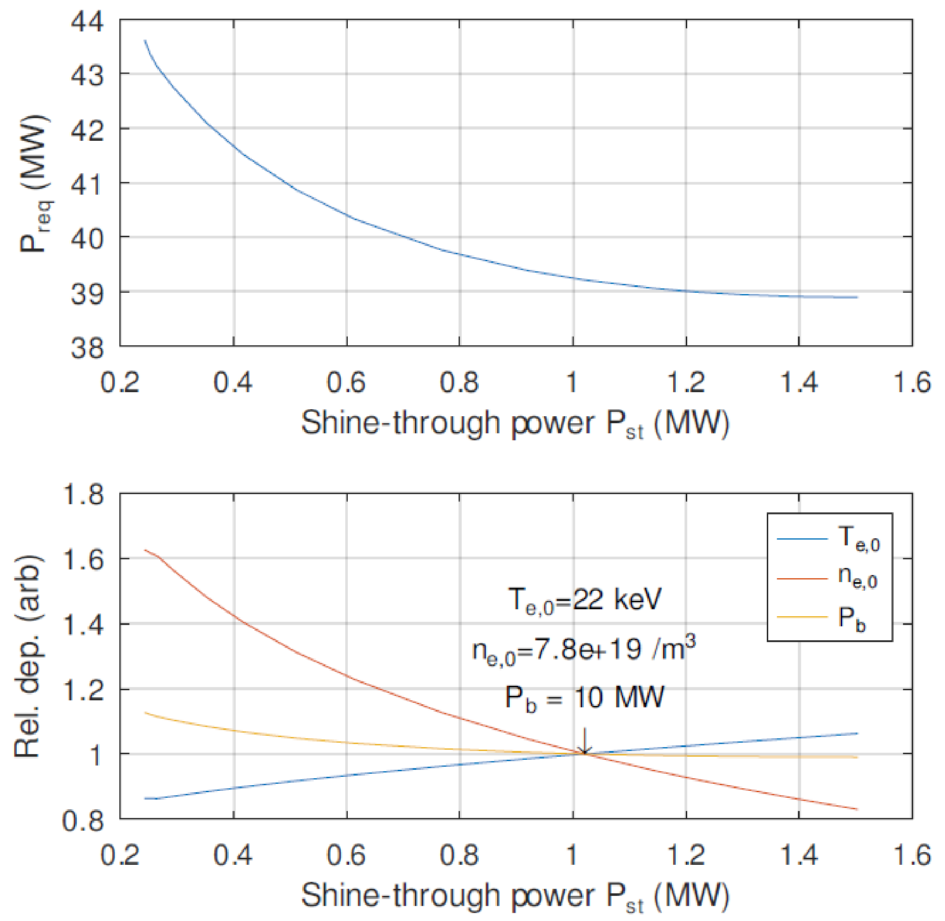
Parametric Results

Assuming $E_b = 1\ MeV, \Delta R_t = 0.1\ m$, producing $2.5{\times}10^{17} n/s$ or 0.2 grams/day of tritium or 73 grams/year of tritium.



Total facility power has a minimum at $P_{req} = 39\ MW, T_{e,0} = 23.5\ keV, n_{e,0} = 6.5{\times}10^{19}/m^3$. Minimum is broad and extends along the contour at which the beam power is *just sufficient* to balance transport power (rad dashed line).

However, this optimum has impractically high shine-through power and beam beta. Pareto front of facility power and shine-through power:



Moving to colder / denser plasma decreases the shine-through while having little effect on the required facility power

Equilibrium parameters				
Quantity	**Symbol**	**E_b free**	**E_b = 1 MeV**	**P_{st} = 500 kW**
Required facility electric power	P_{req}	38 MW	39 MW	41 MW
Core electron temperature	$T_{e,0}$	22 keV	24 keV	21 keV
Core electron density	$n_{e,0}$	$7.6{\times}10^{19}/m^3$	$6.5{\times}10^{19}\ /m^3$	$1.0{\times}10^{20}\ /m^3$
Beam energy	E_b	1.3 MeV	1.0 MeV	1.0 MeV
Beam tangency radius inward shift	ΔR_t	0.14 m	0.14 m	0.16 m
Injected beam power	P_b	10 MW	10 MW	11 MW
Beam shine-through	P_{st}	17%	15%	4.80%
Ion-electron thermalization power	P_{ie}	2.4 MW	1.7 MW	4.4 MW
ISS04 transport power	P_{ISS04}	8.2 MW	8.6 MW	10 MW
Beam ion heating	$P_{b,h,i}$	3.0 MW	3.9 MW	4.0 MW
Beam electron heating	$P_{b,h,e}$	5.3 MW	4.7 MW	6.0 MW
Electron cyclotron heating	$P_{g,h,e}$	~ 0	~ 0	~ 0
Neutron rate	R_n	$2.5{\times}10^{17}\ n/s$	$2.5{\times}10^{17}\ n/s$	$2.5{\times}10^{17}\ n/s$
Average target plasma beta	$\langle\beta_p\rangle$	0.67%	0.63%	0.85%
Average effective beam beta	$\langle\beta_{eff,b}\rangle$	3.40%	3.90%	2.50%

3 cases are evaluated: In which the beam energy is free to change, in which the beam energy is limited to 1 MeV, and in which the shine-through power is constrained to 500 kW. The low-shine-through case requires a colder, denser target plasma but not much higher total facility power.

Conclusion

Simple 1D plasma physics models have been coupled to evaluate the design of a beam-target DD stellarator neutron source for the production of radioisotopes including tritium. The analysis indicates that a facility including a medium-scale stellarator and NNBI using 40 MWe could produce as much tritium as a CANDU reactor.

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