EUROfusion

High-fidelity predictive integrated modeling of the high power (steady-state) plasma in the Volumetric Neutron Source (VNS) tokamak

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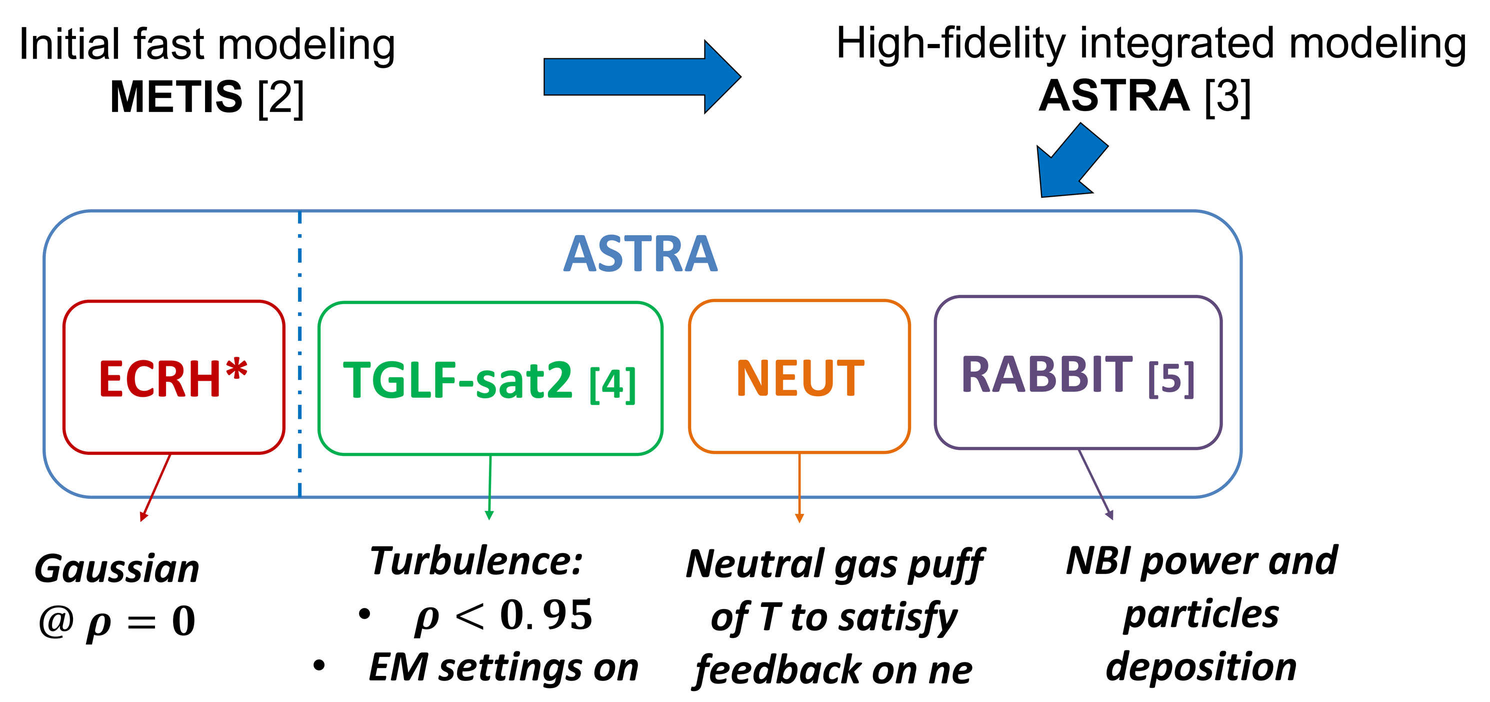
1. Introduction

- The Volumetric Neutron Source **(VNS)** is conceived to be a tokamak for **testing in-vessel components** under **high neutron irradiation** [1].
- Exploits **beam-target fusion** reaction, injecting a deuterium neutral beam into a tritium plasma - (D/T = 10/90), through **NBI** system, also driving the current.

Modeling framework



2. JET validation (#99971)

CONTEXT

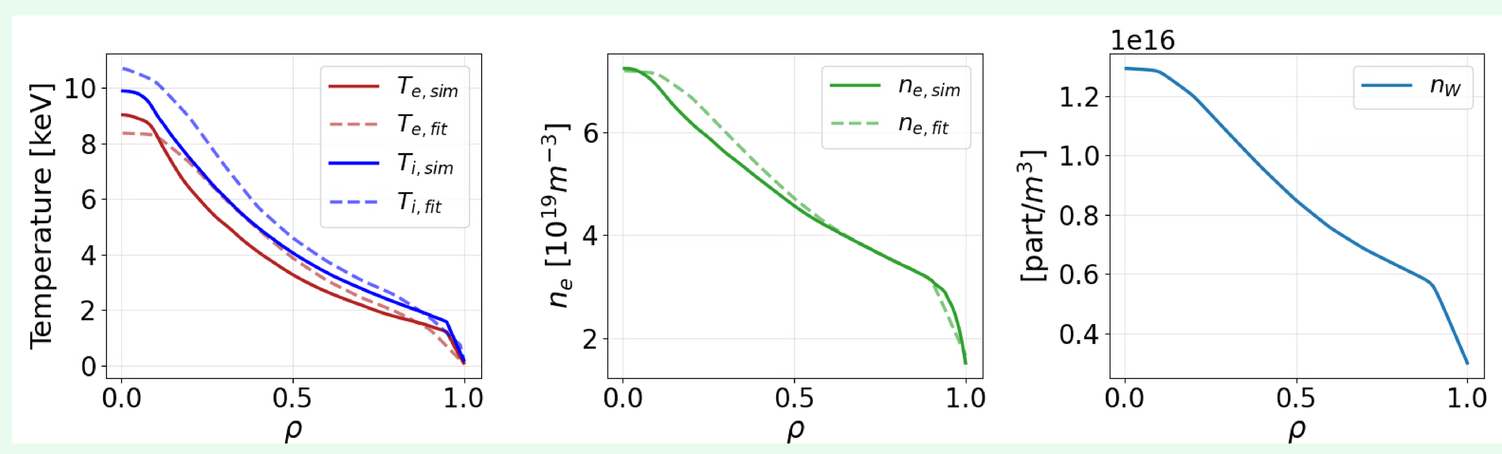
- This ASTRA modelling setup was validated on the **tritium-rich hybrid H-mode discharge** from **JET DTE2 campaign** [5].
- Important features of the shot are:
  - **W accumulation** without radiative collapse
  - **High rotation** induced by NBI torque.

P_{NBI}	29 MW
E_{beam}	108 keV
P_{ICRH}	3.5 MW
$n_{e,avg}$	$4 \cdot 10^{19}$ part/m^3
Z_{eff}	1.8
I_{pl}	2.5 MA
B_T	3.86 T
R/a	3.18
P_{rad}	6/7 MW
P_{fus}	10.1 MW

ASSUMPTIONS

- Ad-hoc extra diffusivity added in the pedestal region, → χ/D_{eff}~3.
- $c_W = 1.8 \cdot 10^{-4}\ part/m^3$ with a fixed profile to satisfy $P_{rad} = 6.45$ MW.

RESULTS



3. VNS predictive simulations

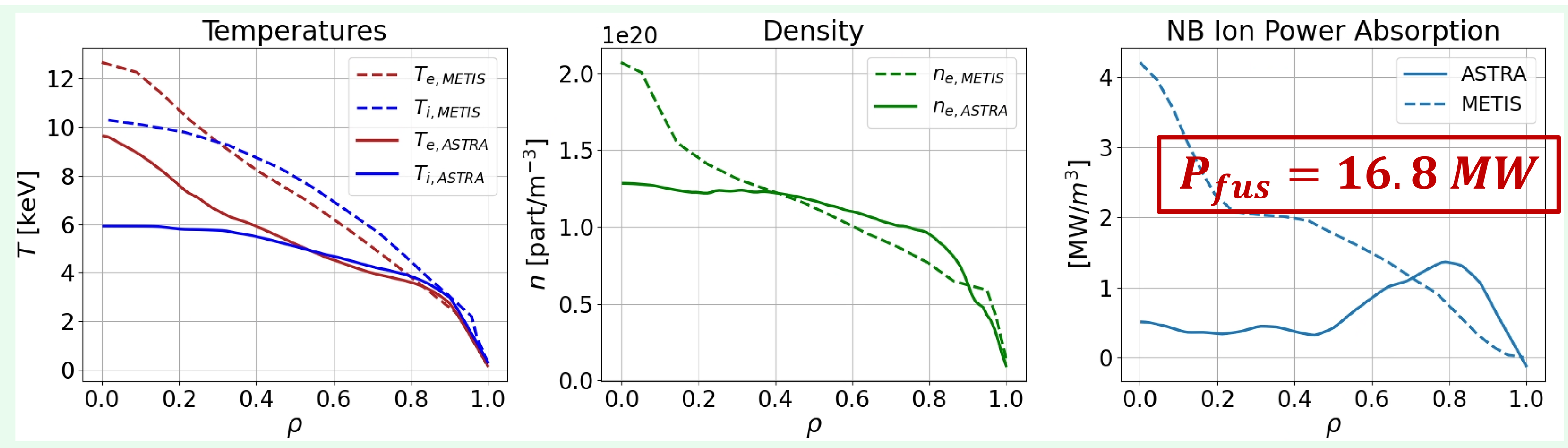
VNS-2025 design point [1]

ASSUMPTIONS

- **Pedestal transport:** JET informed - χ/D_{eff}~3.
- $P_{PT} = 50\ kPa$ – informed by IPED [7] (MHD critical limit)
- Temperature profiles fixed in the pedestal.
- **Toroidal velocity** profile based on **empirical scaling** derived from high rotating AUG and JET discharges.

P_{NBI}	42.5 MW
E_{beam}	120 keV
P_{ECRH}	8 MW
$n_{e,avg}$	$11 \cdot 10^{19}$ part/m^3
Z_{eff}	1.4
I_{pl}	2.5 MA
B_T	5.6 T
R/a	4.25

RESULTS

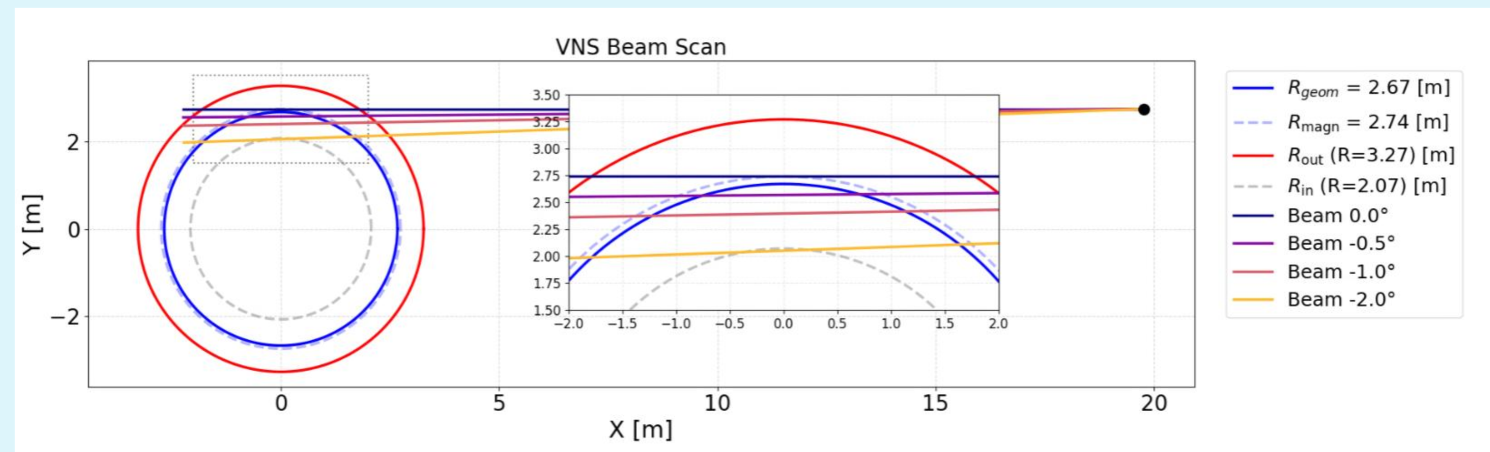


Key parameters limiting achievable fusion power:
- Electron density
- Beam direction and energy

Parametric investigation: $n_e = 7 \div 11\ [10^{19}\ \mathrm{m}^{-3}]$, $E_{beam} = 120 \div 150\ [\mathrm{keV}]$, $\Theta_{inj} = 178 \div 180\ [deg°]$

VNS optimization analysis

INJECTION ANGLE



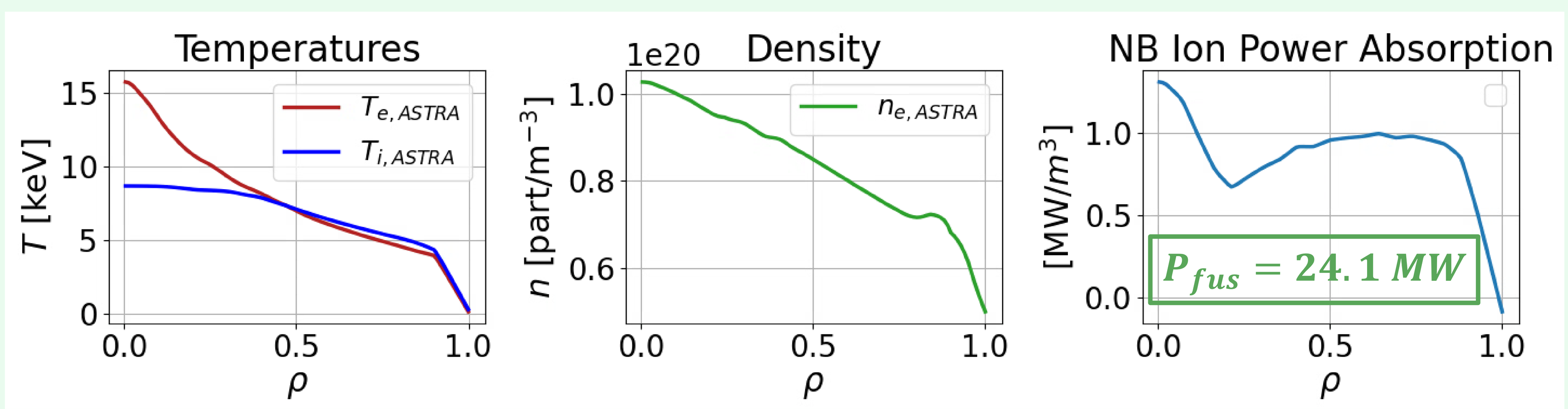
RESULTS

Case	Injection angle	NBI power [MW]	NBI beam energy [keV]	ECRH power [MW]	P_{fus} [MW]	V_{loop} [mV]	Rot losses [MW]	$V_{tor,0}$ [km/s]
Design	180°	42.5	120	8	**16.80**	**14**	8.73	740
150 keV	180°	42.5	**150**	**10**	**21.54**	**-10**	8.10	665
-0.5 degree	**179.5°**	42.5	**150**	**10**	**24.11**	**1.1**	7.72	646
-1 degree	**179°**	42.5	**150**	**10**	**28.62**	**10**	7.07	620
-2 degree	**178°**	42.5	**150**	**10**	**32.05**	**18**	5.7	550

Optimal configuration: $n_e = 7 \cdot 10^{19}\ [\mathrm{m}^{-3}]$, $E_{beam} = 150\ [\mathrm{keV}]$, $\Theta_{inj} = 179.5\ [deg°]$

P_{NBI}	42.5 MW
E_{beam}	**150** keV
P_{ECRH}	**10** MW
$n_{e,avg}$	**7** $\cdot 10^{19}$ part/m^3
Z_{eff}	1.4
I_{pl}	2.5 MA
B_T	5.6 T
R/a	4.25

- Increasing the beam penetration, increases the fusion power, but against the V_{loop}.
- To ensure steady-state scenario: → $V_{loop} \in [0 \div 2]\ [mV]$



4. Conclusions & further studies

- High-fidelity modeling revealed key physical challenges, including inefficient beam penetration and high loop voltage.
- **Scenario optimization**: defined a new $n_{e,avg} = 7 \cdot 10^{19}$ target and NBI injection angle and settings to optimize current machine limits.
- New design validated with **METIS**, to **accelerate parameter exploration** targeting a NWL = 0.5 MW/m^2 (~ 38 MW of P_{fus}).
- **Expand physics models** to include self-consistent **ECRH**, improve descriptions of **pedestal transport**, **MHD** stability, **EP** modes, impact of **W**.

References

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