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Physics basis of a Volumetric Neutron Source (VNS) for component testing and qualification

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The Volumetric Neutron Source (VNS)

What is VNS? *[Federici, NF 2023]*

High Level Objectives

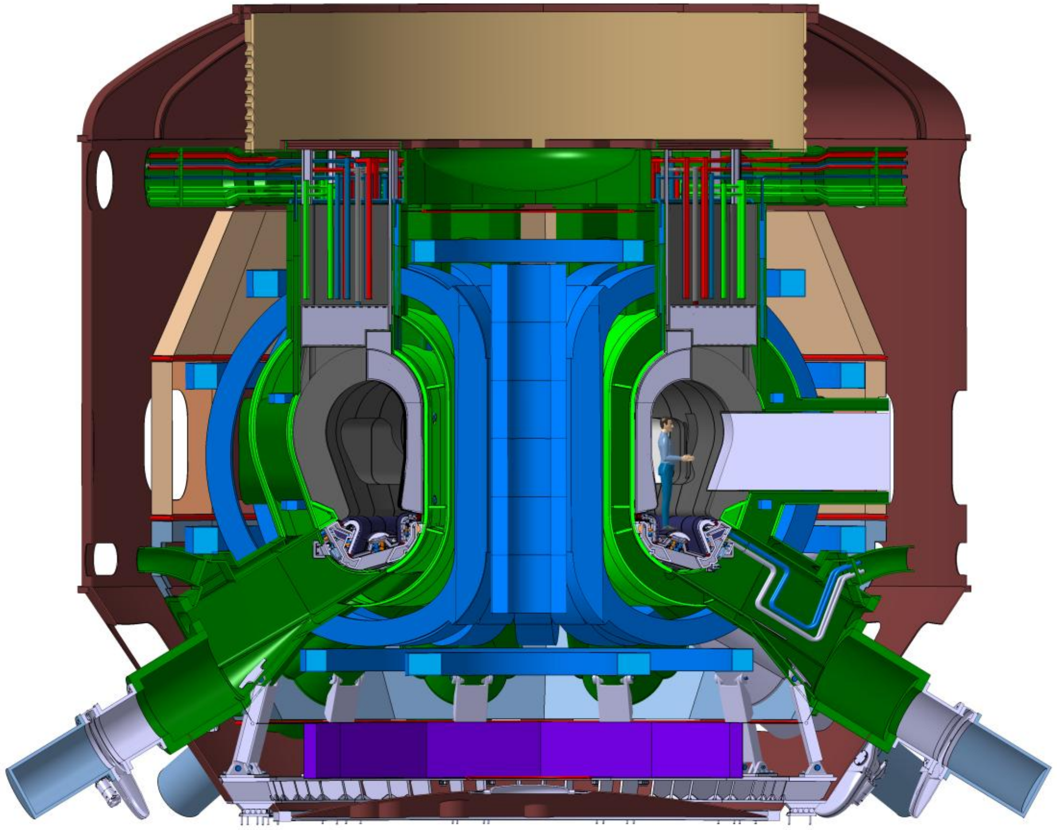
1. To be build in parallel to ITER
2. Nuclear technology mission (DT plasma)
3. Breeding blanket/in-vessel components: concept validation, testing, qualification **in a reactor relevant environment**
4. **Not relying on T self-sufficiency**
5. …

Requirements/ Design Operation Constraints

- **(from 1)** it must rely on a demonstrated physics – **beam-target (Q ≤ 1)** (e.g. JET T-rich plasmas)
- **(from 2, 3)** Sufficient high level of n-flux → **must achieve a relevant NWL ≥ 0.5 MW/m²**
- **(from 2, 3)** Must achieve relatively high fluence levels F= NWL x Irradiation time = NWL x time x Av →(20-50 dpa). **Very long pulses are mandatory**
- **(from 4)** Operate with tritium from external supplies (non self-sufficient) → **must minimize P_{fus}**

T is a very scarce resource – world availability for civil use is few kg/year, with a cost of ~30 k€/g

T-consumption must be low!



Beam-target fusion

VNS relies on **beam-target fusion reactions**, using D-beams on a T-rich plasma, **as demonstrated on JET** in DTE2 *[Maslov NF2023]* and DTE3 *[Maslov EPS2025]*.

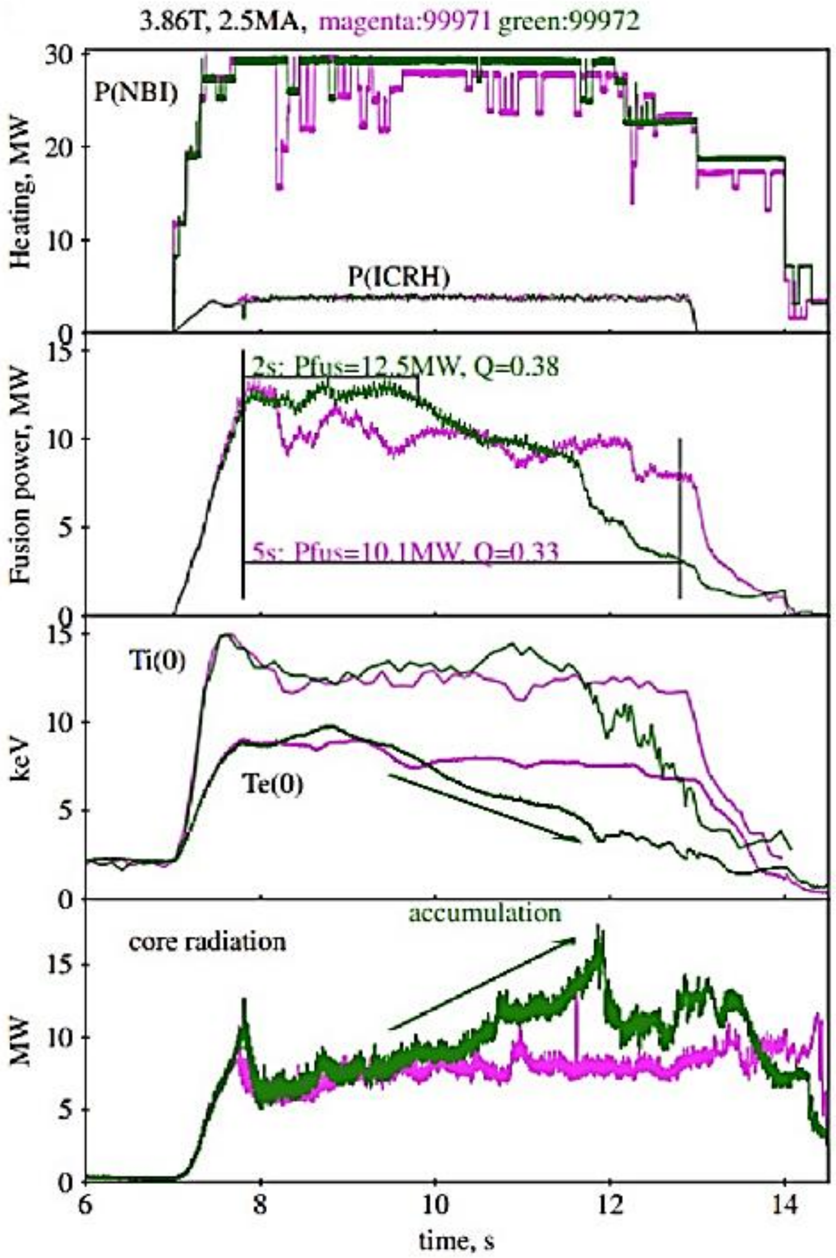
Fusion power generation efficiency in such a plasma relies on:

- **Beam penetration**
- **Beam slowing down time** – *high T_e needed*

Background **plasma profiles have hence a strong impact** in determining the volume in which the beam-target reactions take place, i.e. on the resulting fusion power.

Optimal beam energy: **120-150 keV** range (compromise between good penetration, technological readiness and high neutralization efficiency).

Beams in VNS also drive a substantial fraction of I_p
(fully noninductive scenario)



[Figure: M. Maslov et al., Nucl. Fusion 2023]

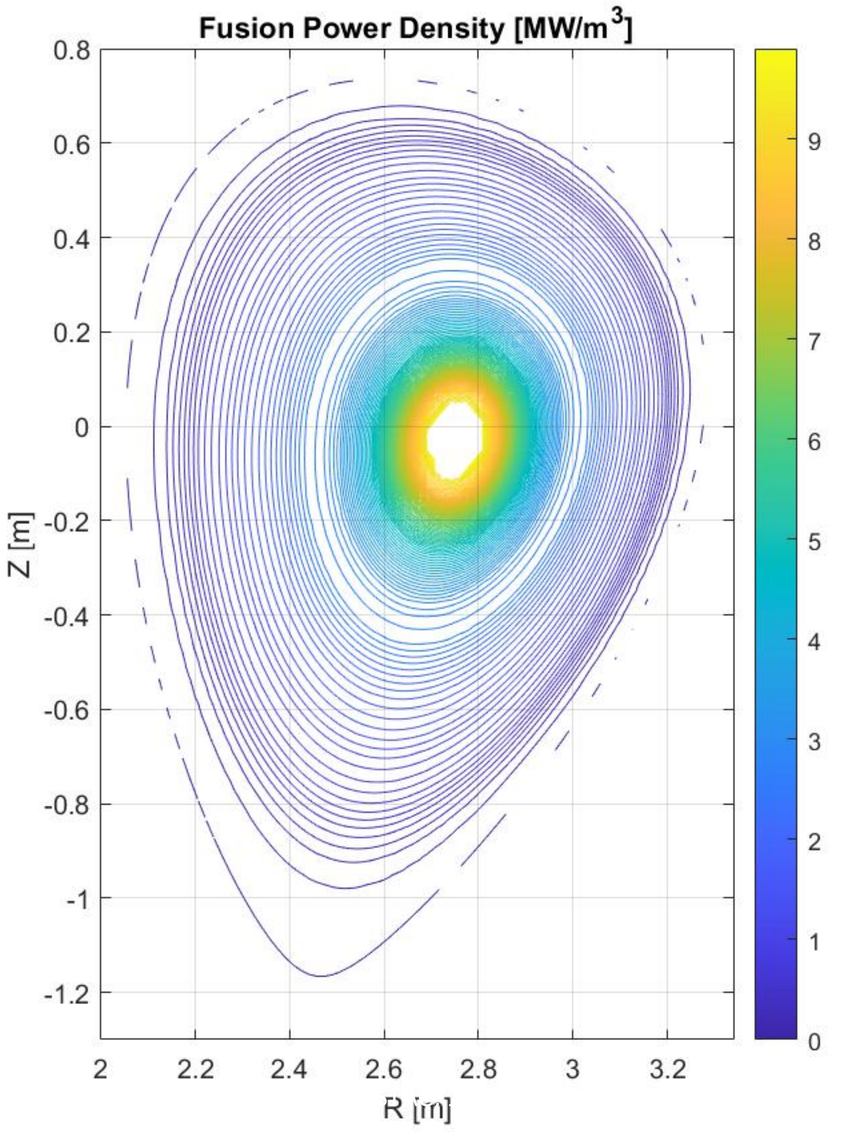
Design criteria – a summary

Quantity	Optimisation
Device size	Small – maximise NWL by lowering the surface and reduce T consumption
Aspect ratio	Trade off – minimize surface to boost NWL w/o compromising MHD stability
Plasma density	Needs to be optimised for power exhaust, fuel dilution and beam penetration
Ion temperature	Irrelevant, as long as electrons are kept warm
Electron temperature	**Crucial – this is what determines the real VNS performance in terms of P_{fus}**
Isotope mix	D beams on T plasma
Plasma current	High – to confine fast particles and MHD stability.
Toroidal field	High – to sustain the current
Beam energy	Limited by technological consideration – **beam penetration to be verified a posteriori**
Pulse length	**Plasma scenario must be fully non-inductive** (at least some tens of minutes of pulse required – small CS can provide only limited flux swing)
Heating mix	**NB for plasma heating, beam-target fusion and CD**, EC for boosting T_e and W control (plus NTM mitigation)

VNS current design point

Parameters (METIS):

Major Radius = 2.67 m
Toroidal Field = 5.6 T
Aspect Ratio = 4.25
Sep. Elongation = 1.6
Triangularity = 0.23
NBI Power = 42.5 MW
Beam Energy = 120 keV
EC Power = 8 MW
Safety Factor q95 = 3.1602
Line average density = 11e19m^{-3}
Plasma Surface = 95.3809 m2
Peak NWL = 0.5114 MW/m2
Av. NWL = 0.32058 MW/m2
BetaN = 2.7209 %Tm/MA
Fusion Power = 38.2219 MW
Centr. El. Temperature = 12.9134 keV
Pl. Current = 2.5401 MA
D Fraction in Bulk Plasma = 0.17006
Power to Divertor = 55.6196 MW



Ideally, one would operate a 100% D-beam on 100% T-plasma to maximize the reaction rate.

But, since the burn-up is very low, the contribution of the beams to fueling (and thus to density) is non-negligible.

High plasma current and toroidal field are required for MHD stability (beta limit) and for fast particles confinement

Fully non-inductive plasma! Neutral Beams providing both P_{fus} and NBCD

Impact of various modelling fidelity levels

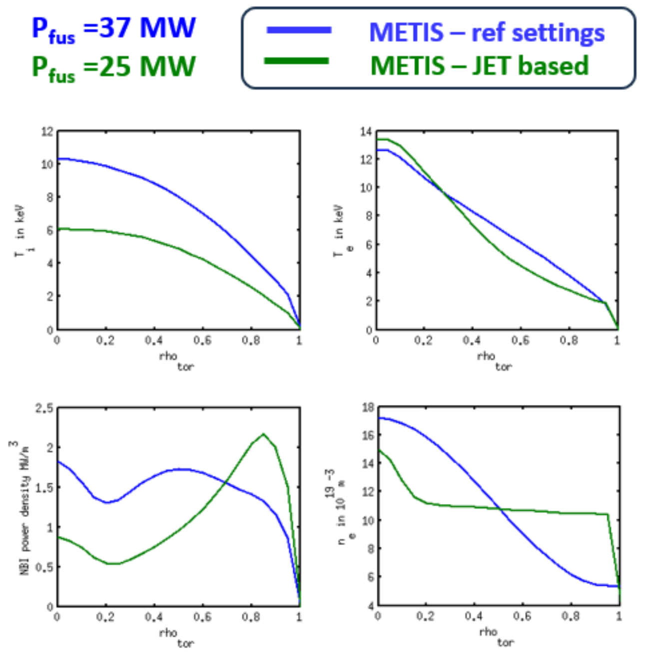
VNS shows a high sensitivity on the background plasma profiles. *It has been soon realised that the first METIS results were inaccurate.*

High fidelity simulations are mandatory

	0.5D integrated modelling (ASTRA-0.5D, METIS)	**High fidelity integrated modelling (ASTRA, HFPS)**
Density profile	ad-hoc parameters	Physics based: Turbulent transport reduced model & pedestal model [*see poster of E. Bray*]
Temperature profile	ad-hoc pedestal & heat diffusion shape	
	Constrained by energy scaling law	

For the parameter space exploration, METIS has been calibrated vs:

- **JET shot 99971** and
- **High fidelity simulations** (few cases)



This provides confidence for the exploration of the parameter space and **the identification of a new, more robust point.**

VNS beam target comes with a number of challenges

- **Magnetic control :** large ratio between the plasma to PF coils distance and the plasma minor radius (neutron shielding)
- **High Neutron Wall Load comes with exhaust challenge**
  - Cannot increase Z_{eff} (affects beam penetration, dilutes the fuel and increases V_{loop})
  - T rich plasmas, hence larger fueling means high T throughput
- **Exhaust requirement and NBI penetration** [***see poster of S. Wiesen***]
  - Target protection through large flux, means large n_{sep}
  - NBI penetration needs low density at separatrix/pedestal
- **NBI torque comes with NBI CD**
  - NBI torque vs. W neoclassical transport compatibility
  - NBI CD vs MHD stability
  - NBI power lost for fusion via mechanical energy transferred to the torque
- **NBI penetration vs loss of CD efficiency**
  - NBI less tangential, better penetration, but less CD [***see poster of E. Bray***]
  - Can be compensated by ECCD on axis, MHD stability to be verified
- **NBI penetration vs drive for Energetic Particle modes**
  - Larger pressure gradients of fast D from NBI : more unstable EP modes
  - Interplay with NBI CD efficiency see KSTAR long pulses with NBI *[Kim et al., Nucl. Fusion 2024]*

To be explored with integrated modelling

Conclusions

A design point for the VNS has been identified, and the criteria for its definition have been illustrated.

While simplified models are acceptable for a preliminary definition of the plasma scenario, the **need of increasing fidelity and integrated modelling** becomes apparent when trying to assess the device performance and consolidate the design.

VNS is very sensitive to profile details!

(…like every device with significant P_{fus}…)

With calibrated models, it is possible to gain **confidence for the exploration of the parameter space** and identify robust design solutions.

[*see poster of E. Bray*]