European Science Meeting (ESM), February 23rd, 2026

VNS design point identifications and physics basis

M. Siccinio

with contributions of: E. Acampora, R. Ambrosino, C. Angioni, C. Bourdelle, E. Bray, Ph. Lauber, F. Maviglia, L. Pigatto, A. Quartararo, K. Särkimäki, A. Snicker, P. Vincenzi, S. Wiesen
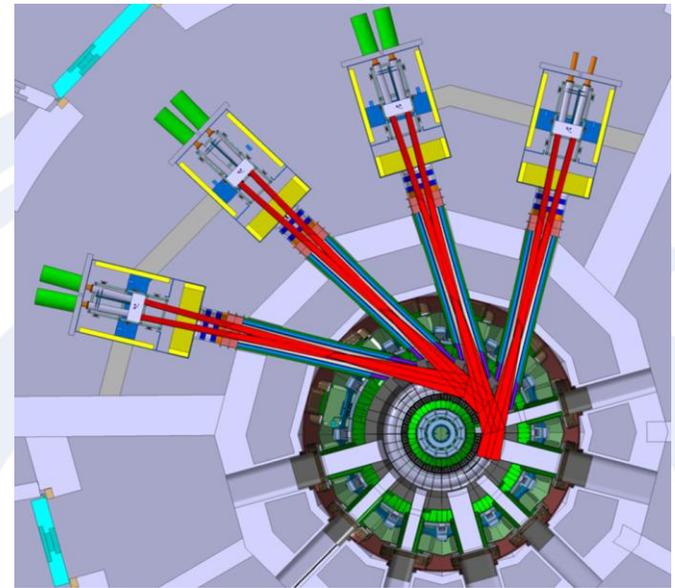
Outline

o   Introduction

o   Design criteria for VNS

o   Present design point and systems code scans

o   Ongoing physics studies

- ✓   Magnetic equilibrium (*R. Ambrosino/E. Acampora*)
- ✓   Integrated modelling and W transport (*E. Bray/C. Angioni/C. Bourdelle*)
- ✓   Power exhaust (*S. Wiesen*)
- ✓   Fast particle physics (*Ph. Lauber/A. Snicker/K. Sarkimäki/L. Pigatto*)

o   Conclusions
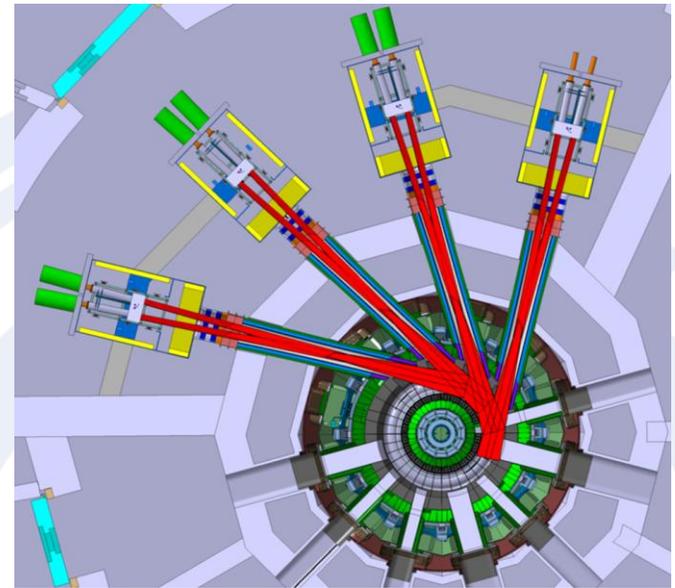
Outline

o **Introduction**

o Design criteria for VNS

o Present design point and systems code scans

o Ongoing physics studies

  ✓ Magnetic equilibrium (*R. Ambrosino/E. Acampora*)
  ✓ Integrated modelling and W transport (*E. Bray/C. Angioni/C. Bourdelle*)
  ✓ Power exhaust (*S. Wiesen*)
  ✓ Fast particle physics (*Ph. Lauber/A. Snicker/K. Sarkimäki/L. Pigatto*)
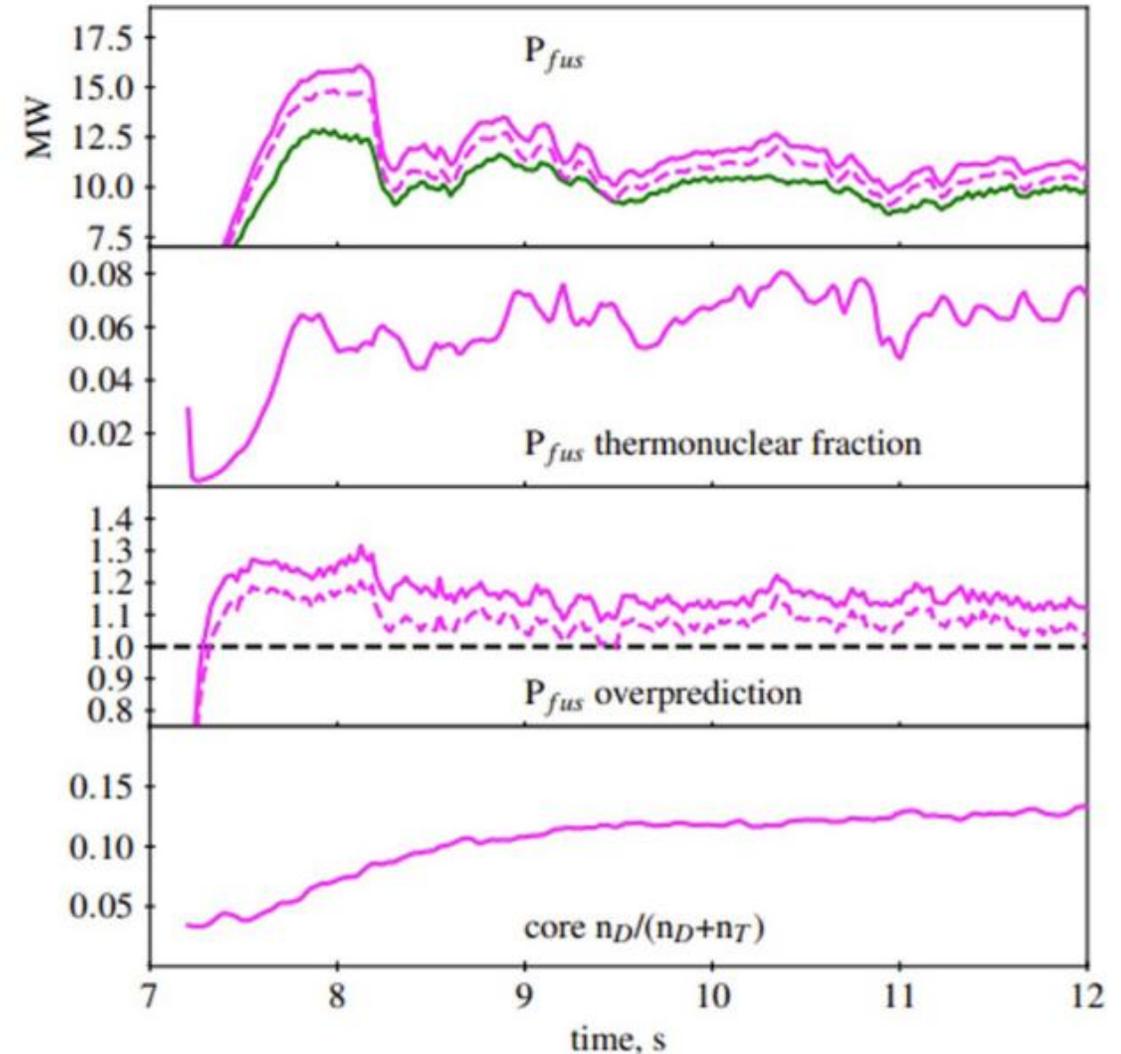
o Conclusions

What is VNS?

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
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, see figure)
- **(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}**

JET shot #99971, T-rich

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

	DEMO	VNS
P_f (MW)	2000	30
NWL (MW/m²)	1	0.5
fpy to reach 20 dpa	2	4
T (kg) consumed to reach 20 dpa	224	6.8

The T consumption constraint *forces* the size of the device to be as small as possible.

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

- **Our device cannot rely on T self-sufficiency** (a machine which tests the blanket cannot work if and only if the blanket works)
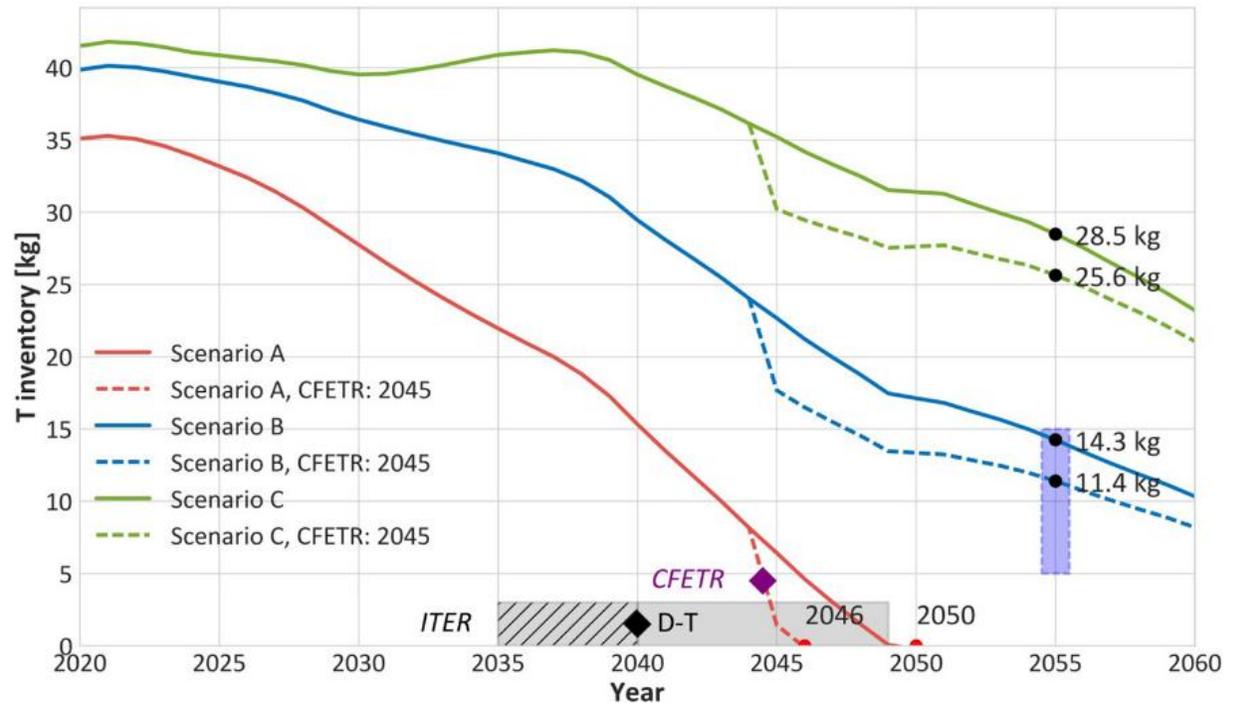
T-consumption must be low!

- **A large size device**, independently on how P_{fus} is generated, **would require high P_{fus} and thus high T consumption** (because $NWL \propto \dfrac{P_{fus}}{S}$ and S is large)

[Figure: M. Coleman and M. Kovari, Nucl. Fusion 2018]

Beam-target fusion

The fusion power generated in a beam target device (assuming a D-beam and a T target plasma) can be written as:

$$P_{fus} \propto \dot{n}_{D,beam} n_T \tau_{SD} \sigma(E_D)$$

where $\dot{n}_{D,beam}$ is the injection rate of the D-beam, $\sigma(E_D)$ is the fusion cross section as a function of beam energy and τ_{SD} is the characteristic slowing down time of the beam.

$$\tau_{SD} \propto \frac{T_e^{3/2}}{Z_{eff}^2 n_e},$$

where Z_{eff} is the effective charge of the plasma.

Ion density and temperature profiles are not influential for the fusion power yield. Instead, electron temperature is crucial!


3.86T, 2.5MA, magenta:99971 green:99972
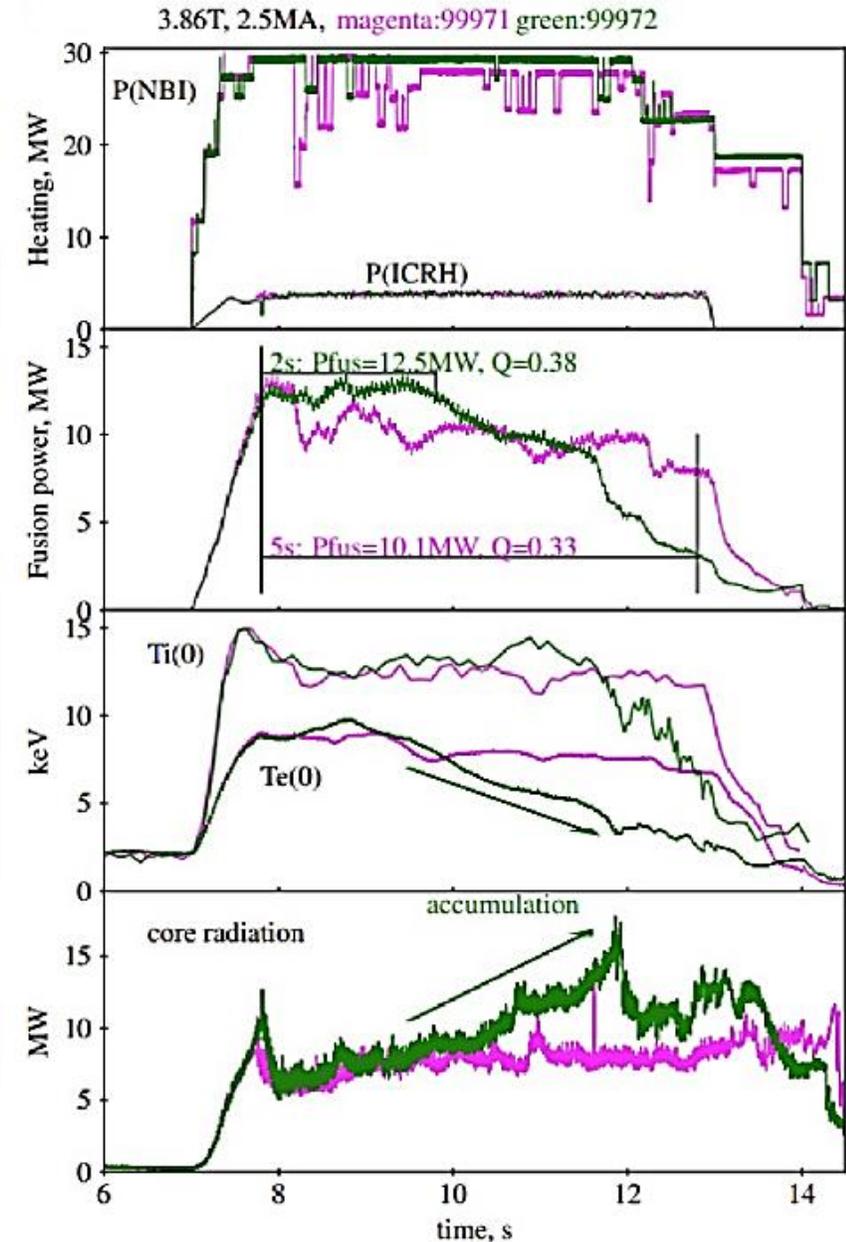
[Figure: M. Maslov et al., Nucl. Fusion 2023]

Outline

○ Introduction

○ **Design criteria for VNS**

○ Present design point and systems code scans

○ Ongoing physics studies

    ✓ Magnetic equilibrium (*R. Ambrosino/E. Acampora*)
    ✓ Integrated modelling and W transport (*E. Bray/C. Angioni/C. Bourdelle*)
    ✓ Power exhaust (*S. Wiesen*)
   ✓ Fast particle physics (*Ph. Lauber/A. Snicker/K. Sarkimäki/L. Pigatto*)

○ Conclusions
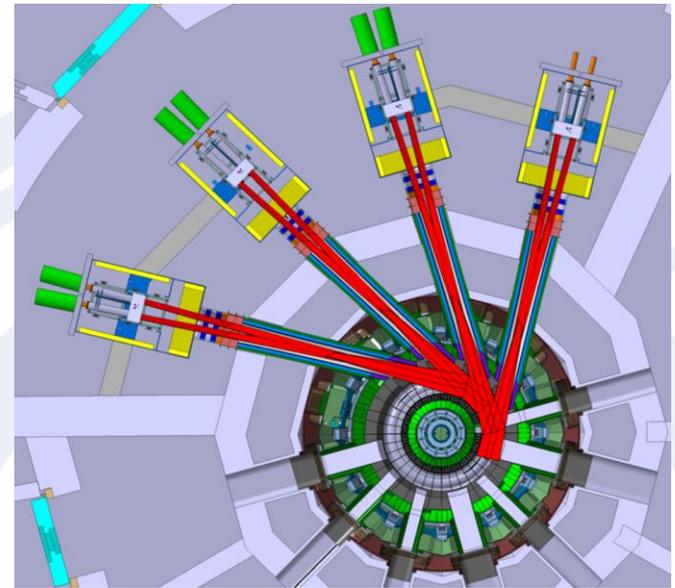
Size and aspect ratio

- **Requiring simultaneously high NWL and low T consumption** (= P_{fus}) forces the machine size to be **small**.

$$NWL \propto P_{fus}/S$$

- Beam-target is the best option!

- In principle, **a high aspect ratio is favourable** for purely geometrical reasons (low surface S and large space on inboard)

- However, a **too high aspect ratio generates problems** in terms of magnetic equilibrium as well as for MHD stability (more on this later).

- **The value of A in the current design point is a result of a trade-off**.
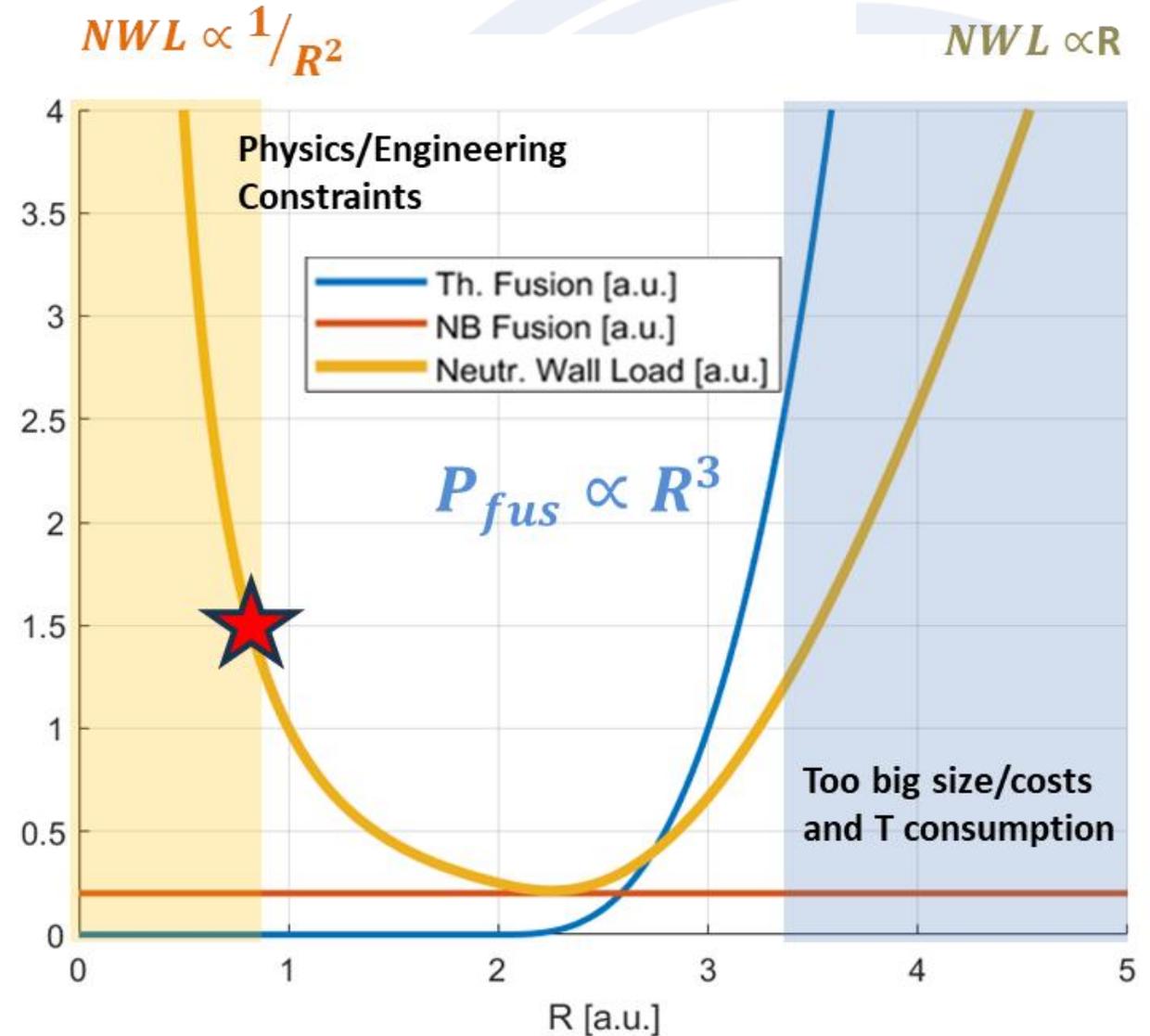
Plasma current

In a nuclear fusion device, high plasma current is required for confinement.
**According to the IPB98(y,2 scaling)**

$$\tau_{E,98y2} \; \propto \; I_p^{0.93} R_{geo}^{1.97}$$

Generally, it is easier to get high T_e than T_i for a given confinement – mainly because it's easier to heat electrons directly. **Confinement is therefore not so critical in a beam-target device (albeit not fully uninfluential)**

Possibly **more stringent reasons why a large current is required in VNS** are:

- ○ Fast particle confinement (α's and beams)
- ○ MHD stability – in particular β-limit

As a consequence, **a high B_T is also necessary to sustain the current** and avoid $q_{95} < 3$.

Data: L. Pigatto
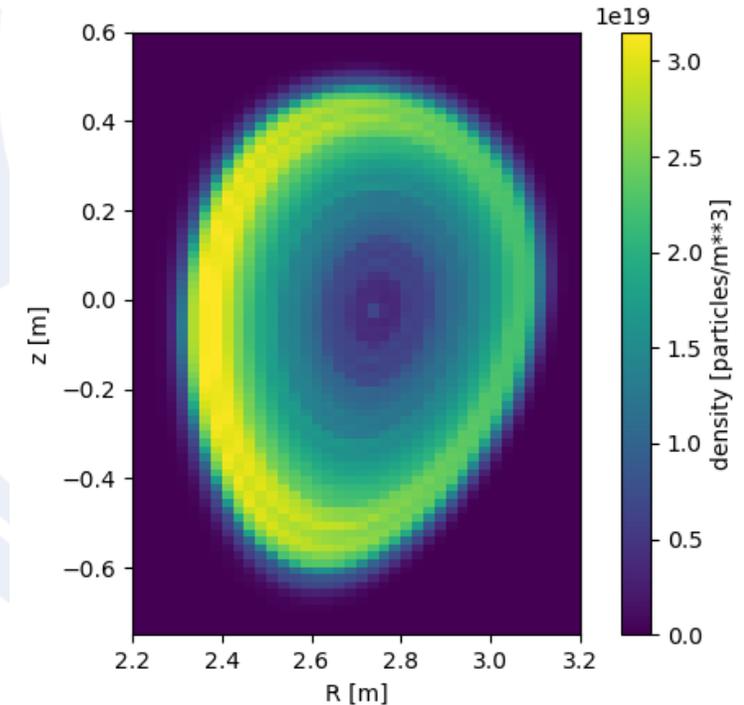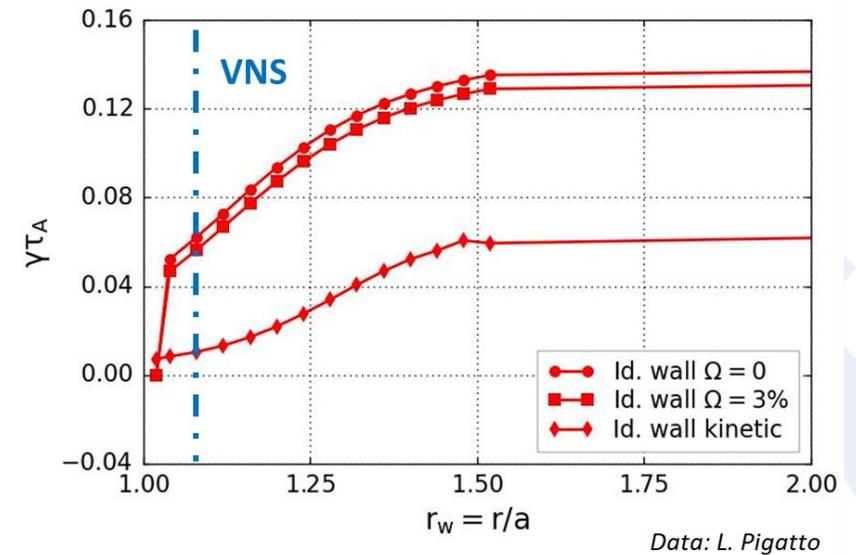
Plasma density

o At zeroth order, the fusion power (or the NWL) is independent on the background plasma density.

o In reality, **there is a non-monotonic dependence**. The current VNS design point has been chosen in correspondence of the maximum.

o At too low density, **the D-dilution in the T plasma** becomes strong (the D source is NB -> fixed).

o At too high density, **the electron temperature drops**, negatively impacting the beam slowing-down time.

o The VNS density value may still be adjusted in view of **power exhaust**, or **beam penetration** related considerations – see in the following.
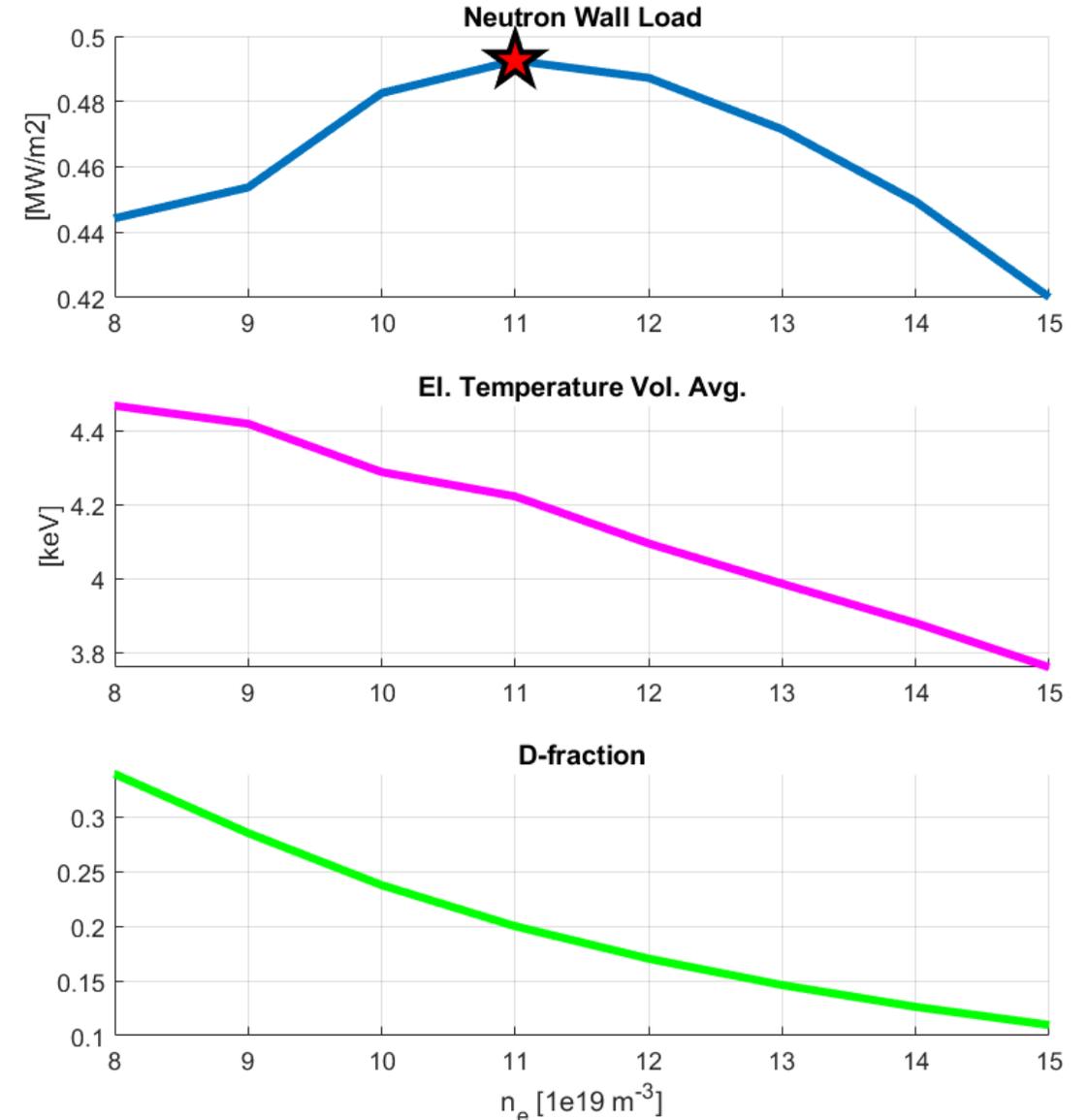
Energy of the beam

The fusion cross section decreases quite fast for E_b $> \sim 120\ keV$.

If a proper beam deposition is granted, **higher beam energy has therefore only marginal impact on the fusion power** generation, at the price of technological complications.

High beam energy can however be beneficial for:

- Reducing rotation at given beam energy (which affects W transport)
- Improve beam deposition
- Improve NBCD

The choice of $E_b = 120$ keV has been made to remain in the positive ion beam realm.
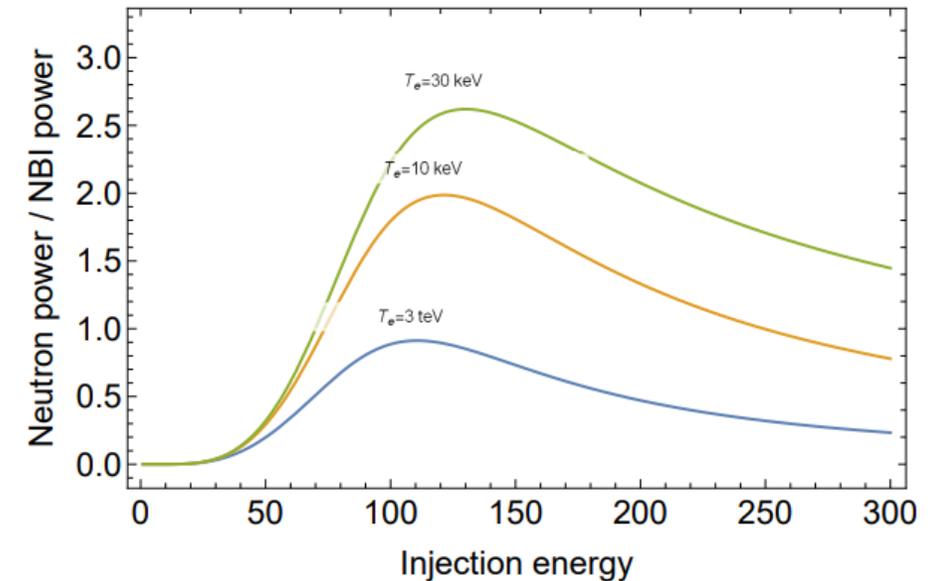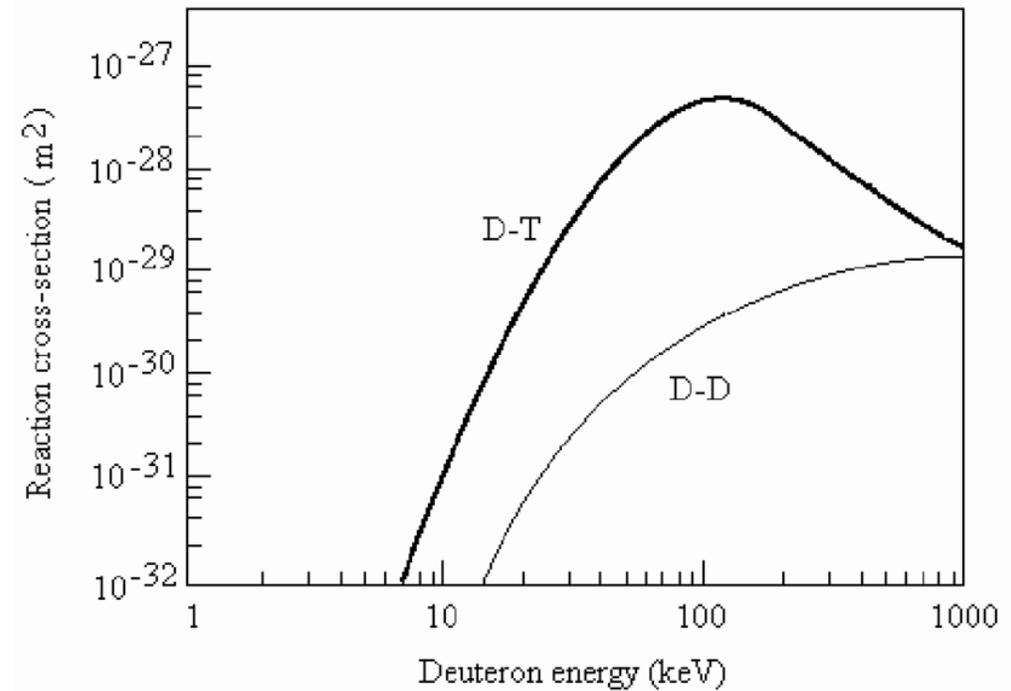
Pulse length

VNS **requires long pulses** for the qualification of the components – at least tens of minutes to reach thermalization and enforce $t_{pulse} \gg t_{dwell}$, ideally steady-state to achieve large fluence with limited number of cycles.

This is an impossible target to reach with a CS (even if $V_{loop} = 10$ mV, one would require 18 Wb of flux consumption *only* to sustain the flat-top for 30 minutes -> *not enough space for such CS*)

VNS must therefore be designed with a fully non-inductive scenario. In other words, the duration of the plasma pulse will be determined by testing needs.

Currently **– only NBCD required**.
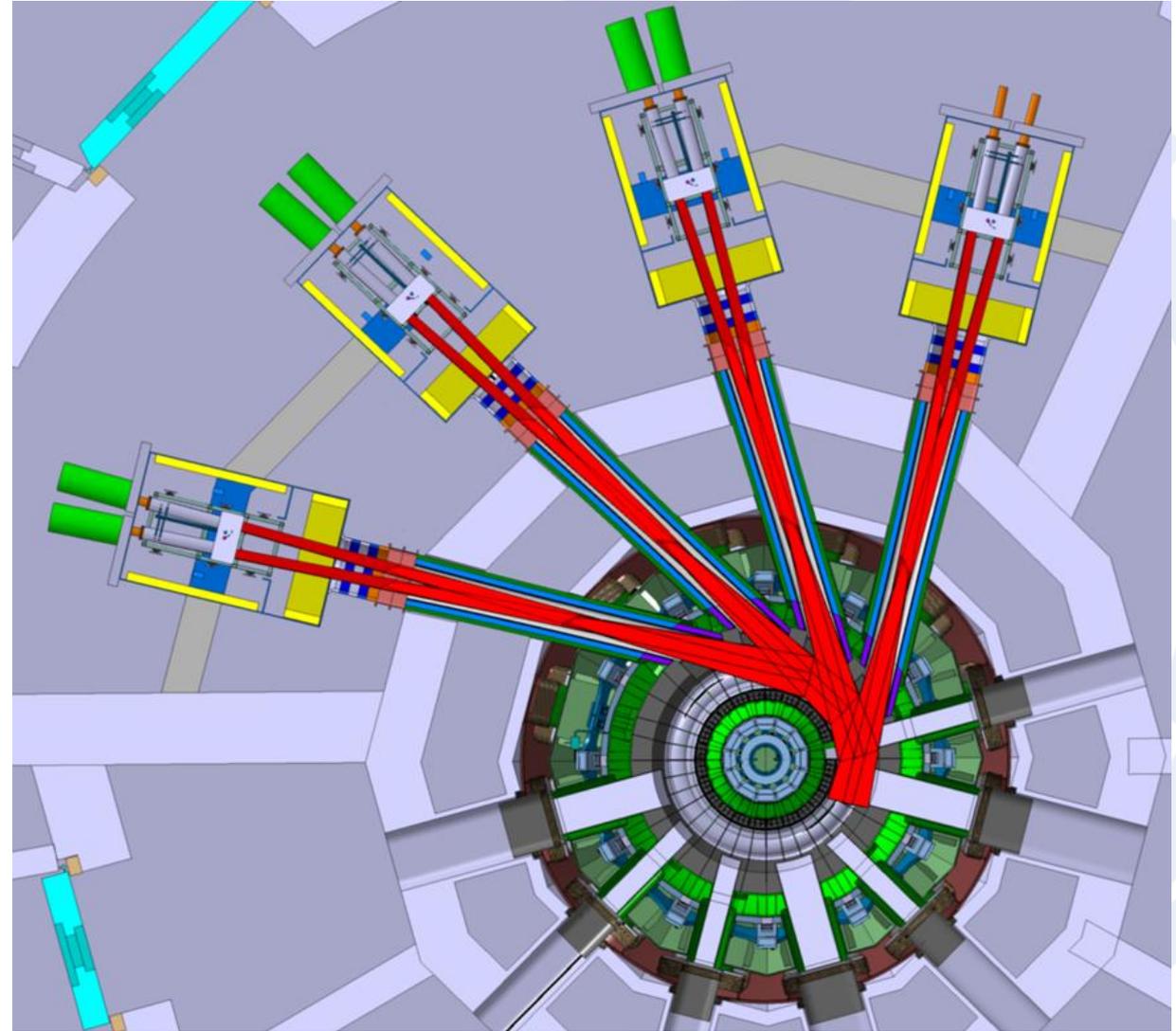
Design criteria – a summary

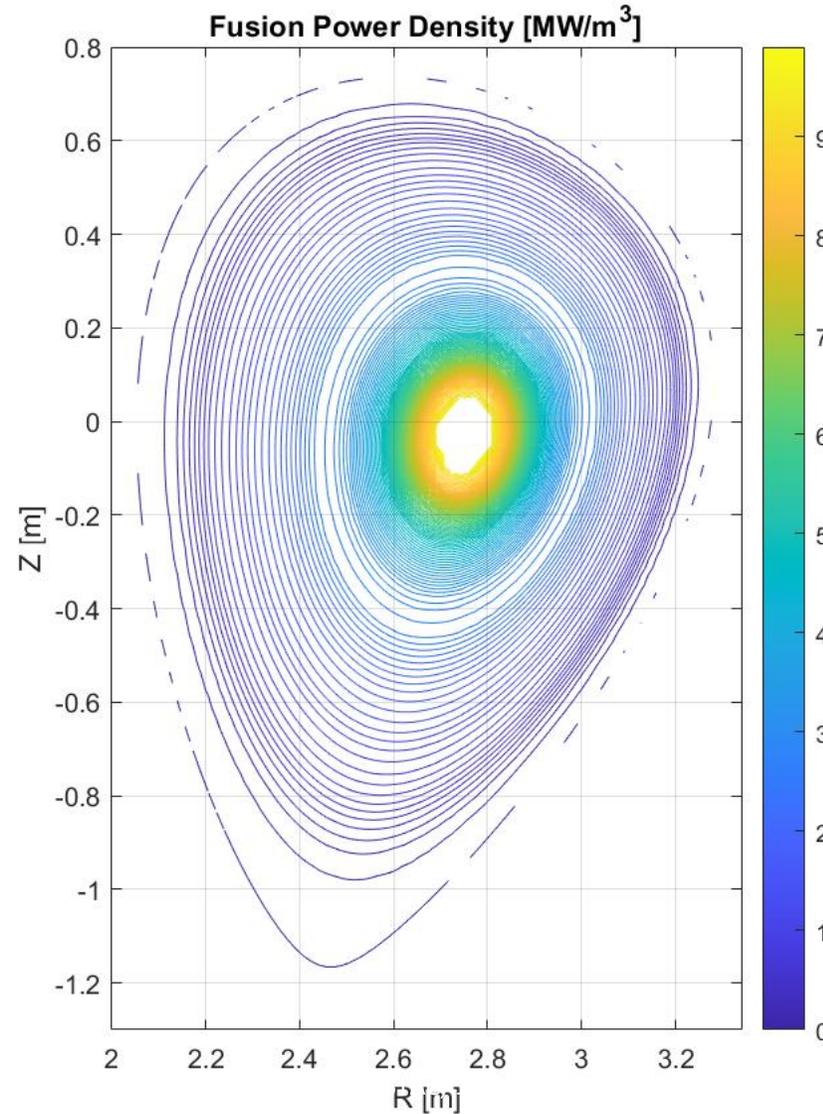| Quantity	Optimisation
Device size	Small – maximise NWL by lowering the surface
Aspect ratio	Trade off – minimize surface to boost NWL w/o compromising MHD stability
Plasma density	Not relevant for Pfus – needs to be high for power exhaust and for fuel dilution
Ion temperature	Irrelevant, as long as electrons are kept warm
Electron temperature	**Crucial – this is what determines the real VNS performance in terms of Pfus**
Isotope mix	D beams on T plasma
Plasma current	High – to confine fast particles and MHD stability. Confinement and high density (= Greenwald limit) not as crucial as in "thermal" devices à la ITER
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
Heating mix	NB for plasma heating, beam-target fusion and CD, EC for boosting Te and W control (plus NTM mitigation) - IC explored as alternative
Elongation/shaping	Magnetic equilibrium to be a posteriori verified -> *more on this later*

Outline
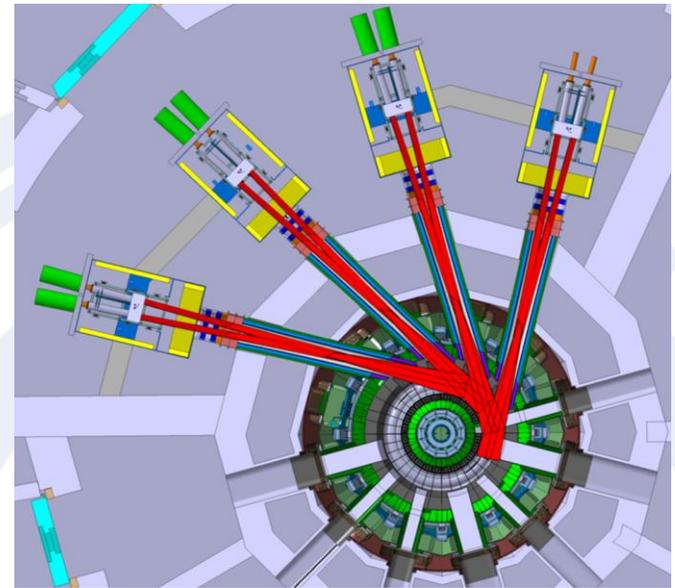
VNS current design point

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
Tot. Beta Poloidal = 1.8749
D Fraction in Bulk Plasma = 0.17006
Power to Divertor = 55.6196 MW
```


Fusion Power Density [MW/m^3]

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!

Systems code scans: assumptions

- P_{ECRH}=10 MW (heating only)
- n_e=11·10^{19} m^{-3}
- **q$_{95}$ is fixed**, so the code iterates on I$_p$ to reach the desired safety factor

3 main free parameters

- **P$_{NBI}$ is varied to drive the entire plasma current non-inductively, to have a steady-state machine**

- **B$_t$ (and thus TF thickness) is iterated until the CS flux available at the CS matches the required flux for current RU -** to avoid wasting space at the inboard. Flux consumption is roughly estimated based on the plasma internal inductance, calculated by METIS.

- CS and inboard TFCs are sized in the iteration loop, while the thickness of neutron shielding structures (inboard) is kept constant.

- Elongation and triangularity are kept constant.

3 iteration variables

Systems code scans: post-processing

After the calculations are completed, the main outcomes are collected:

- The **NWL is the main output** of the code, and it is free to vary depending on the input parameters
- **P_{NBI}** is both an iteration variable and an output parameter. It strongly influences plant cost and equatorial port availability for testing.
- Post-processing checks are performed to **exclude points violating constraints on β_N** (lower than 3.3% Tm/MA)**, electron density, and magnetic equilibrium** feasibility (a < 0.6 m).
- Finally, an indication of free ports available for the TBM is provided, starting from the following assumptions on port occupation:
    - 12 TF coils
    - Maximum 15 MW NB power through one NB port
    - 1 additional NBI (regeneration)
    - 1 blind port
    - 2 ECRH ports
    - 2 diagnostic ports

Results – fixed q_{95}
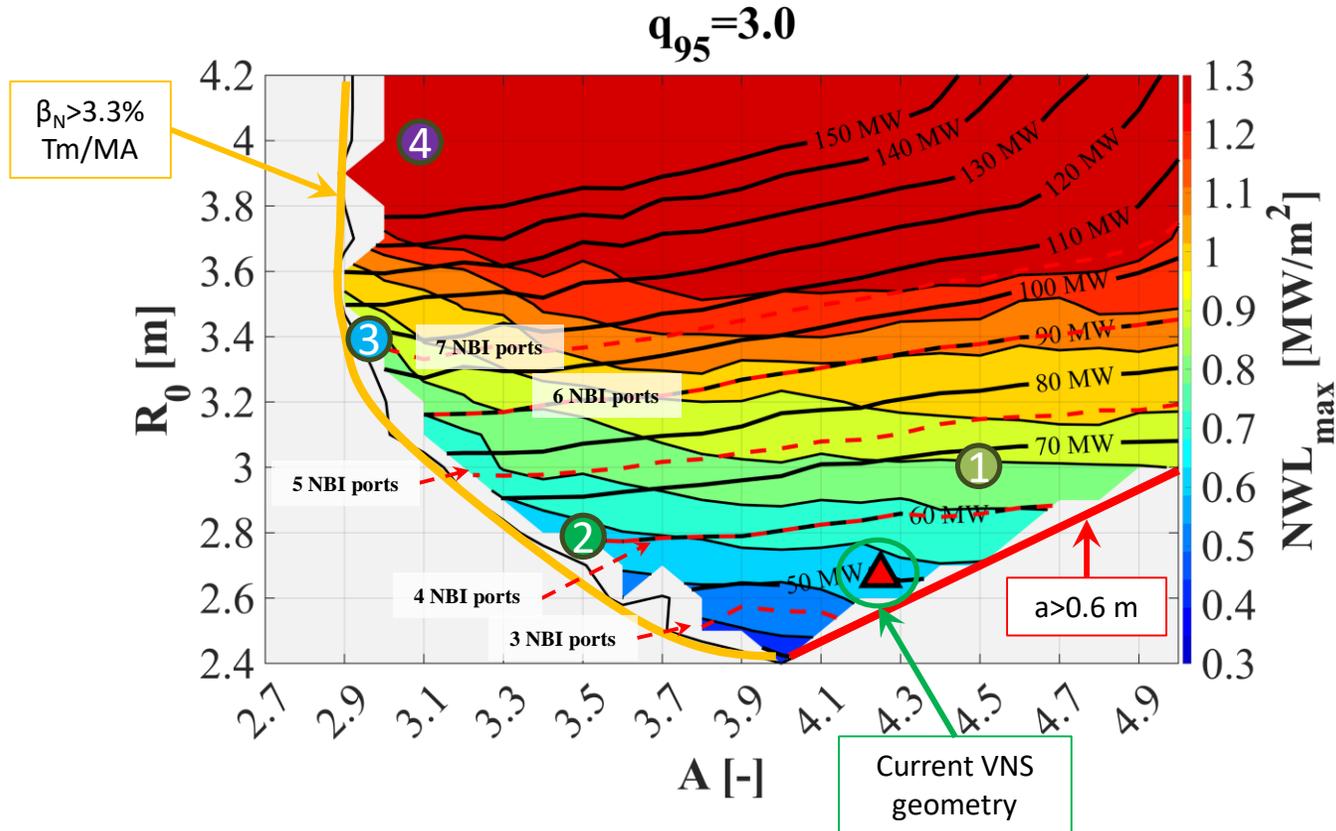
Comparison between current VNS design and **four candidate points @q_{95}=3.0**.

	Ref. VNS*	①	②	③	④
R_0 [m]	2.67	3	2.8	3.4	4
A	4.25	4.5	3.5	3.0	3.1
q_{95}	3.2	3.0	3.0	3.0	3.0
NWL [MW/m²]	**0.51**	**0.89**	**0.67**	**0.90**	**1.63**
q''_{div} [MW/m²]	80.4	133.5	100.4	135.4	226.0
β_N [Tm/MA]	2.7%	3.0%	3.2%	3.3%	3.2%
P_{NBI} [MW]	42.5	66.7	61.7	107.8	176.2
P_{EC} [MW]	8.0	10.0	10.0	10.0	10.0
P_{fus} [MW]	38.2	76.3	62.7	138.6	331.8
B_t [T]	5.60	6.48	4.55	4.41	5.70
I_p [MA]	2.54	3.12	3.52	5.80	8.22
T_{cons} [kg/FPY]	2.13	4.25	3.49	7.72	18.49
f_{boot}	49.6%	55.0%	55.0%	55.1%	54.8%
f_{GW}	53.7%	49.2%	62.9%	76.5%	70.0%
Φ_{cons} [Wb]	6.7	8.4	8.9	16.6	26.2
R_{CS} [m]	0.63	0.68	0.68	0.94	1.10
$P_{el.req}$ [MW]	175	259	242	401	637
Time [years] @ 10 dpa	8.49	4.88	6.50	4.83	2.65
TBM ports available	3	1	1	0	0

*The current VNS design point has been selected not considering the exact same assumptions.

- A **first parametric scan at constant NWL** has been performed starting from the reference point and moving at **constant A** and varying R_0.

- Points at higher R_0 have higher I_p, higher NB power and a lower number of available ports.
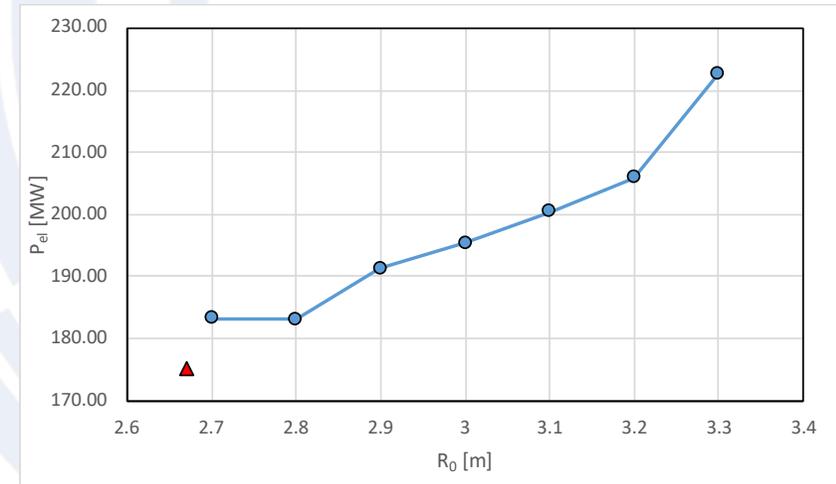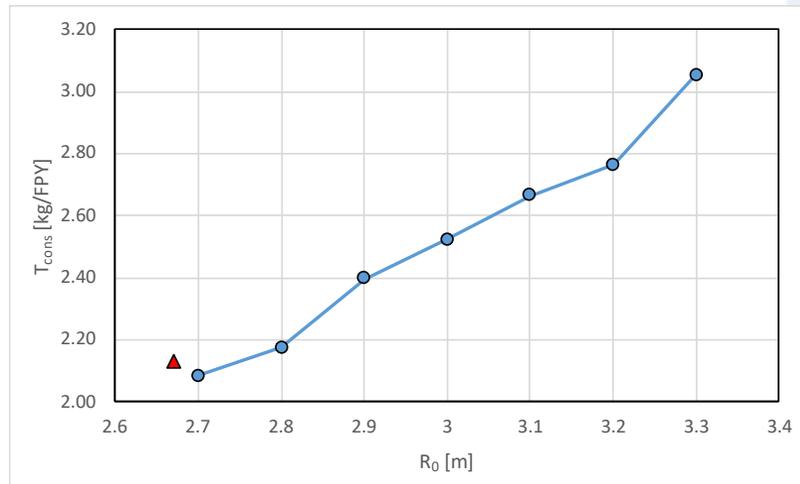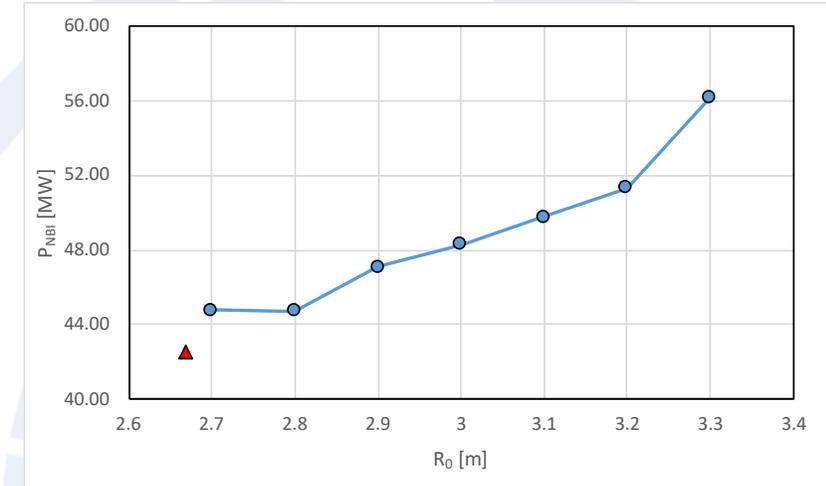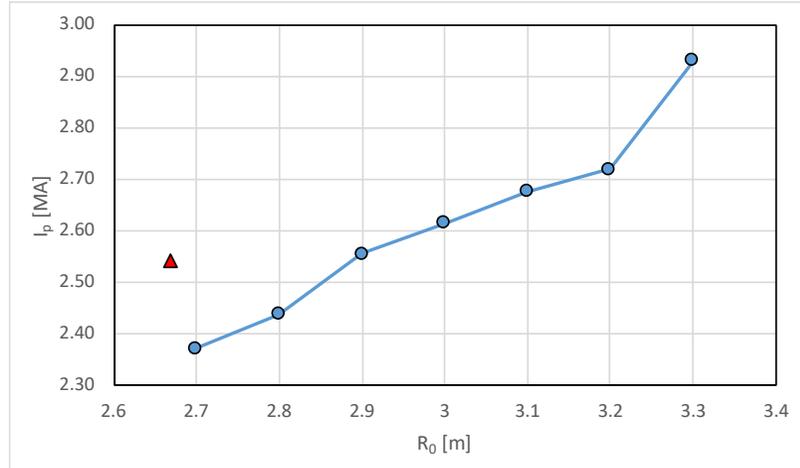
Results – fixed NWL

- A **second parametric scan at constant NWL** has been performed starting from the reference point and moving at **constant R_0** and varying A.

- Points at higher A have lower I_p, lower NB power and a higher number of available ports
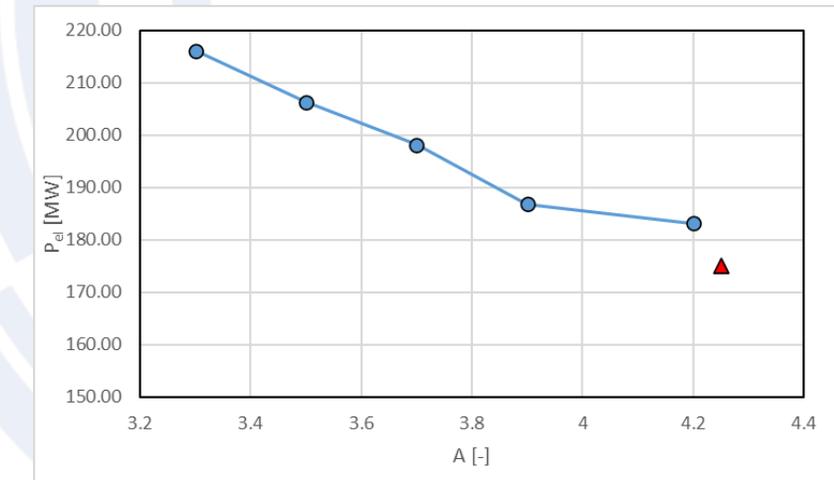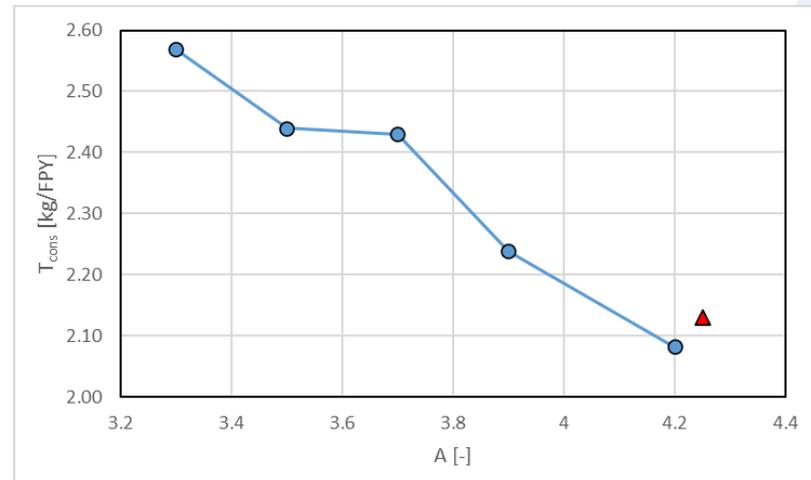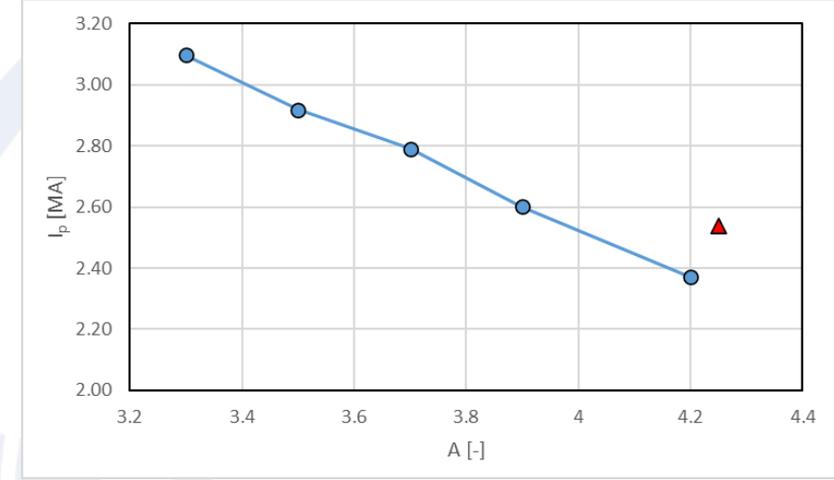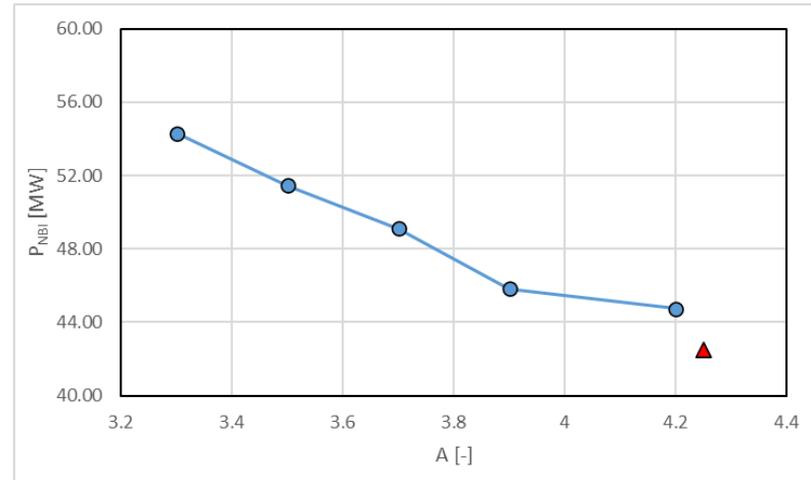
Outline

o   Ongoing physics studies

   ✓   Magnetic equilibrium (*R. Ambrosino/E. Acampora*)
   ✓   Integrated modelling and W transport (*E. Bray/C. Angioni/C. Bourdelle*)
   ✓   Power exhaust (*S. Wiesen*)
   ✓   Fast particle physics (*Ph. Lauber/A. Snicker/K. Sarkimäki/L. Pigatto*)
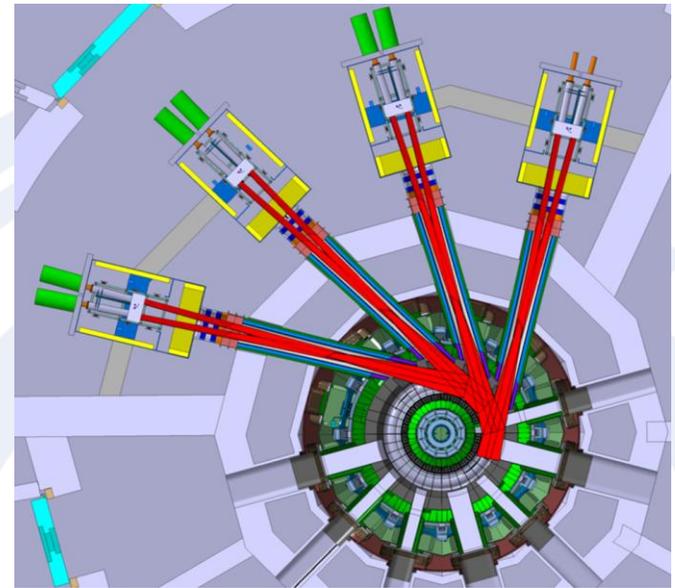
VNS design context and control challenges

VNS current design is characterized by a relatively **small major radius** , but **with a relative** <u>large dimension</u> **B**lanket and **V**acuum **V**essel. This bring the following **challenges**:

High currents in the equilibrium coils (*i.e.* **5** to **8MAt**, versus a 2.6MA plasma current) due to the <u>large PF/CS coils to plasma distance</u>.
Poor shape controllability: Relative distance of: • **coils↔plasma core**,   • and **coils↔plasma boundary**,   is <u>very comparable</u> in VNS: equilibrium coils "see" plasma more like a point from afar, with less degrees of freedom to control the shape.

**ITER, VNS enlarged to ITER** major radius R_0 and inflated to the ITER minor radius *a*
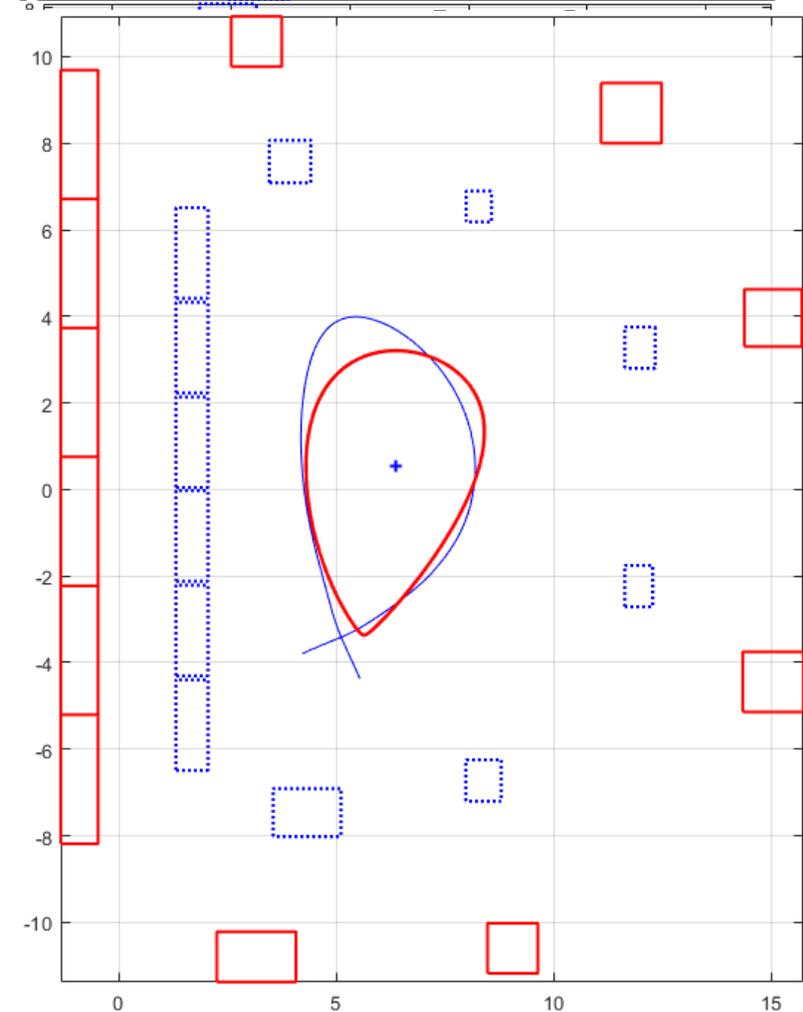
e.g. Ratio between distance (plasma boundary↔coils) / (plasma core↔coils), in **ITER** (≈1.5) and **VNS** (≈1.2)

VNS 2D Passive vertical stability

Only **2D toroidal continuous VV** (no ports) and **triangular support** considered.

	2s	3s	4s	7s	9s	11s	*20s	*39s
Ipl [MA]	0.42	0.63	0.80	1.39	1.79	2.18	2.54	2.54
β_p	0.26	0.27	0.30	2.12	2.47	2.46	2.30	2.20
l_i	1.03	0.97	1.03	0.71	0.58	0.53	0.58	0.62
k	1.18	1.18	1.41	1.50	1.56	1.61	1.64	1.62
$\gamma(s^{-1})$	58.98	21.93	64.11	68.85	72.60	52.60	56.61	55.43
m_s	0.61	1.30	0.54	0.46	0.44	0.56	0.53	0.54
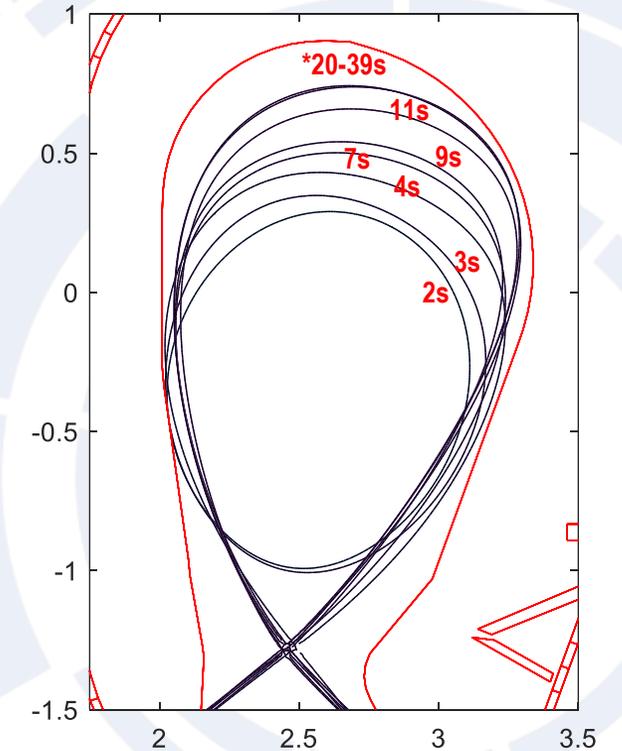
Empirical stability criterion $m_s \geq$ 0.2-0.3 [A. Portone 2005 Nuc.Fus.]

The VNS **Ramp up trajectory** of (static) equilibrium points considered have a **stability margin within control limits**.

Impact of various modelling fidelity levels

P$_{fus}$ =37 MW
P$_{fus}$ =25 MW
P$_{fus}$ =17 MW

ASTRA-TGLF
METIS – ref settings
METIS – JET based

	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
Temperature profile	Ad-hoc pedestal & heat diffusion shape	
	Constrained by energy scaling law	
CPU time	~ minute per operation point	~ 1 day on 48 procs for 100s of plasma
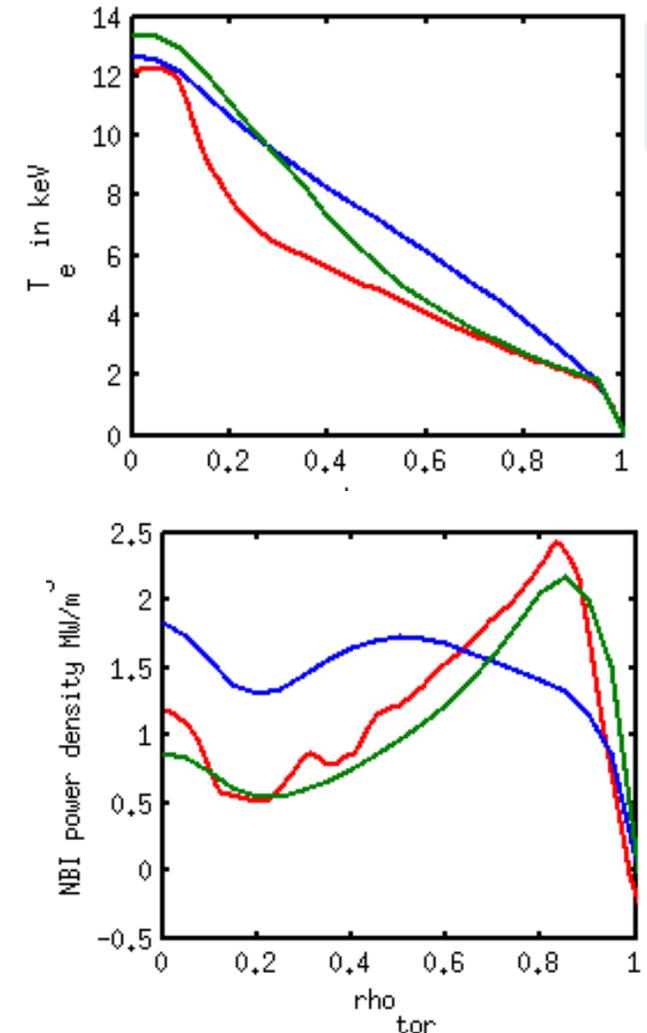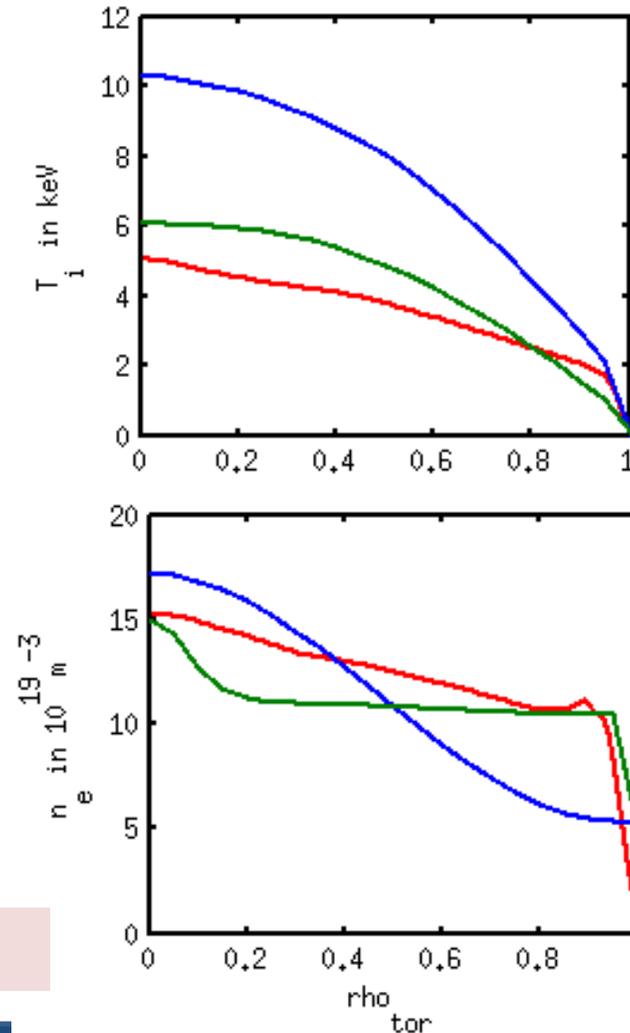
To maximize P$_{fus}$: Key role of NBI absorption and T$_e$

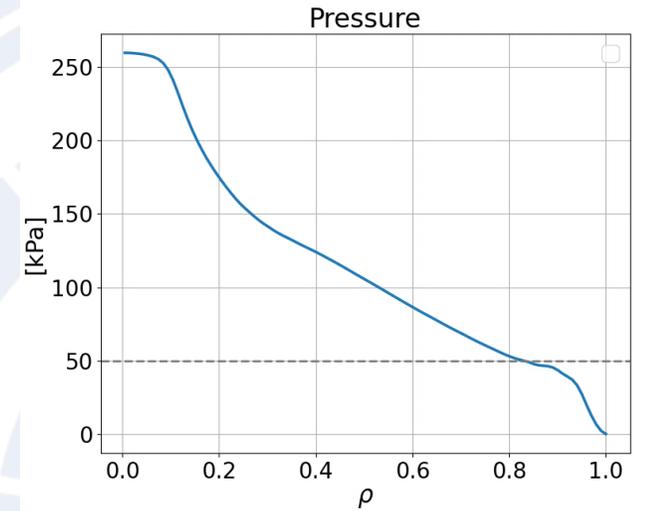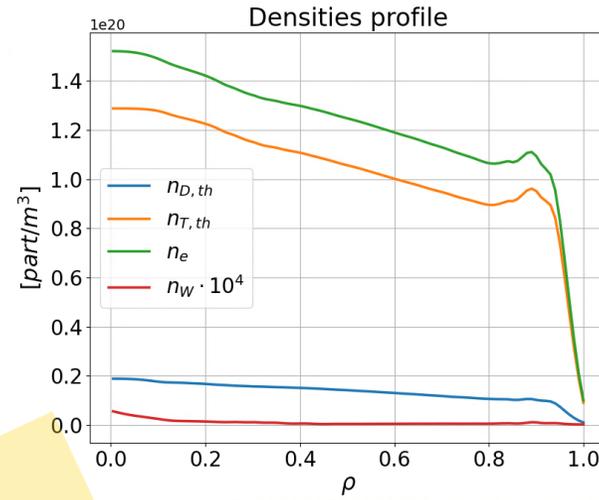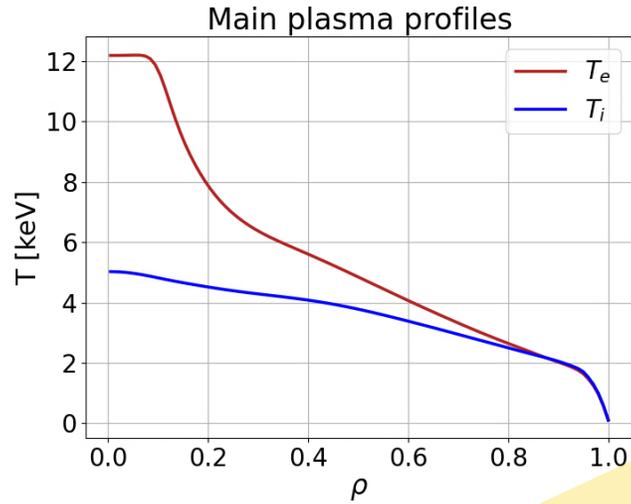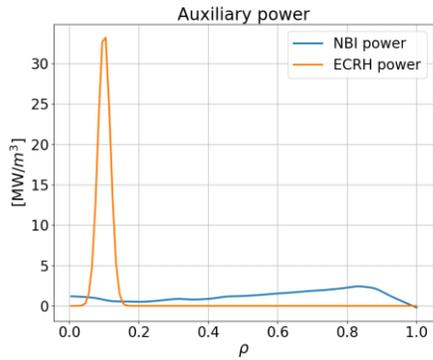# Integrated modelling example: W accumulation

Plasma species:

- **D/T** plasma with ratio **10/90**
- $n_\alpha = 10^{-3} \cdot n_{e,in}$
- n_W → **scan of source at separatrix**
- n_e : feedback on line average density $= 11 \cdot 10^{19} \; part/m^3$

n_D: injected with NBI, with energy of 120 keV

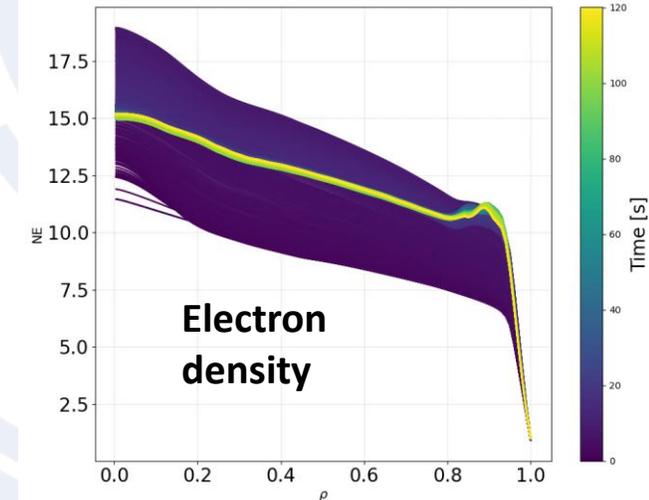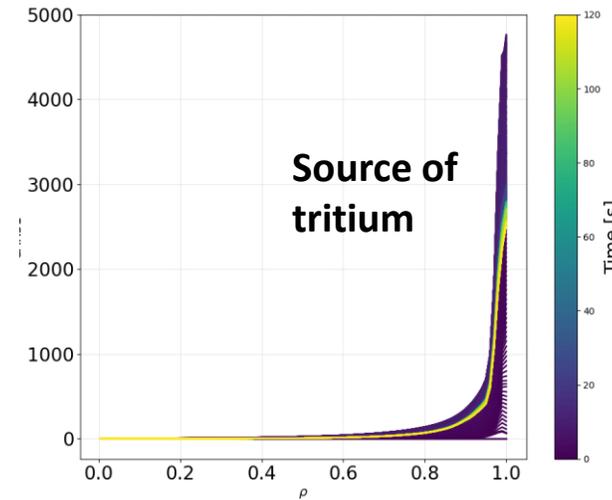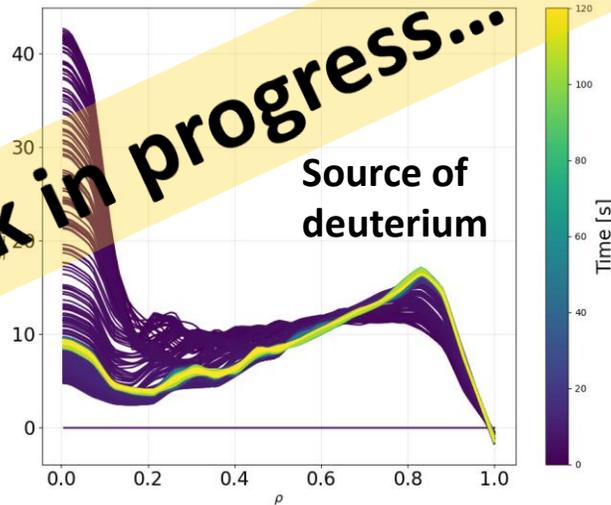n_T: injected with **gas puff,** to satisfy the $n_{e,avg}$

High-fidelity, integrated modeling

ASTRA

TGLF-sat2 — Turbulence of impurity and main plasma $\rho < 0.95$

FACIT — Neoclassical transport of W

NEUT — Neutral particles from atomic processes

RABBIT — NBI power and particles deposition

$$v_{tor,PT} = 250\,km/s$$
$$P_{ECRH} = 8\text{ MW}$$
$$P_{NBI} = 42\text{ MW}$$
$$c_W = 2 \cdot 10^{-6}$$

…work in progress…

Source of deuterium

Source of tritium

Electron density

An extended operational space has been found for operating VNS with Kr seeding compared to Ar seeding with a detached divertor at tractable peak heat-load densities $q_{pk,LFS} \leq 10\ MW/m^2$.

- Both, Kr-seeding and T-fuelling help to reduce $q_{pk,LFS}$

- Compared to Ar, seeding with Kr allows lower levels of $Z_{eff} < 2$, and is thus more compatible with core requirements (i.e. beam slowing down time $\tau_s \sim 1/Z_b^2$)

- With Kr, the required total T-particle throughputs $\phi_{T,total} = \phi_{T,core} + \phi_{T,gas} \sim 3 - 4\ 10^{22}\ s^{-1}$ (c.f ITER $\sim 10^{23}\ s^{-1}$)

- A forward optimization attempts to minimize Z_{eff} → $Z_{eff} = 1.6$ can be achieved with a symmetric power sharing between inner and outer target $<\ 10\ MW/m^2$


$Z_{eff,core}$ vs LFS peak heat flux $[MW/m^2]$
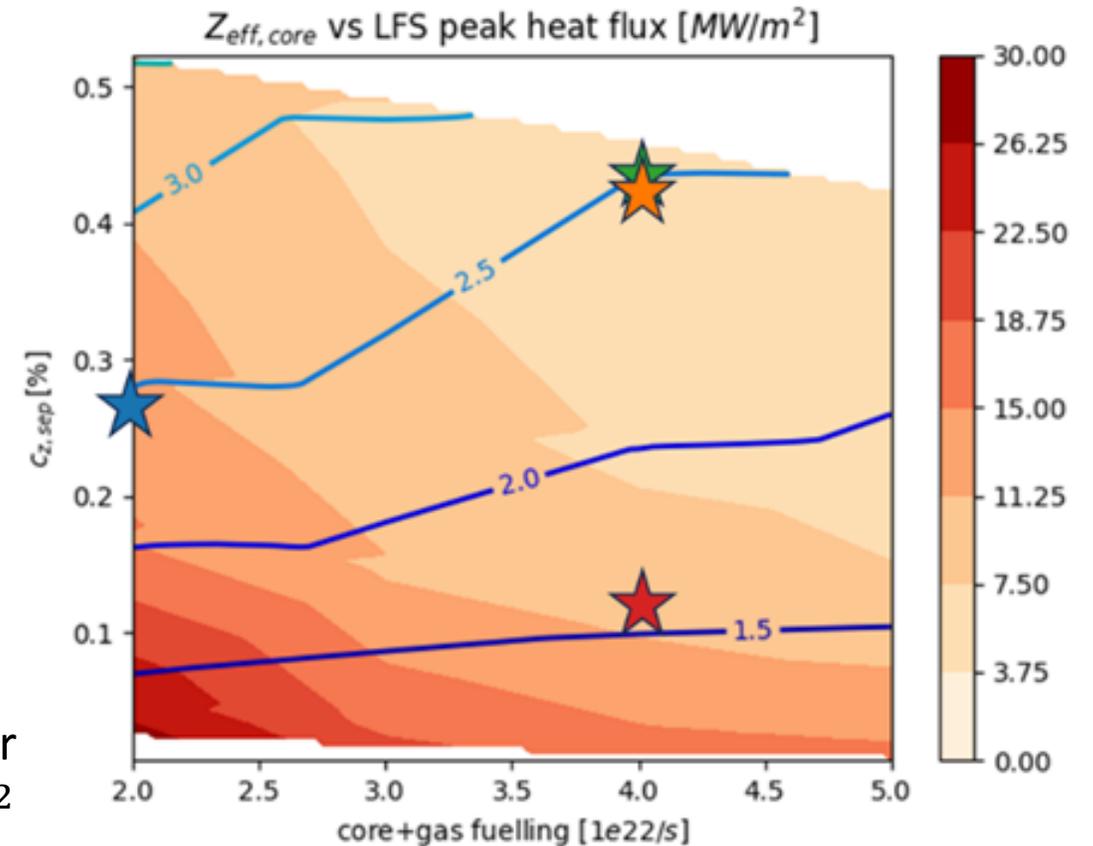
Fast particle physics

Open points

VNS is characterised by a very large fast particle population (both α's and beams), which numerous implications.

1. **Optimisation of the beam injection:** ASCOT simulations have shown that the current architecture does not ensure a proper beam penetration.

2. **Fast particle losses** and their distribution on the FW.

3. **Global MHD stability:** fast particles pressure is ~30% of the total pressure. This can have an impact e.g. on the dynamics of RWM.

4. **Alfvén Eigenmodes** and EP modes.
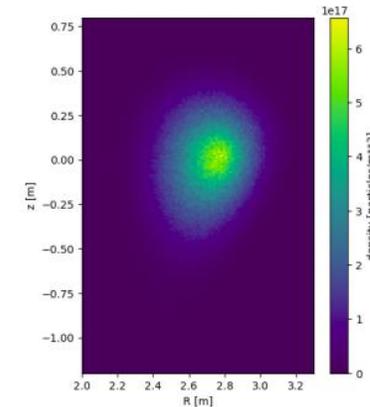

Ionization source
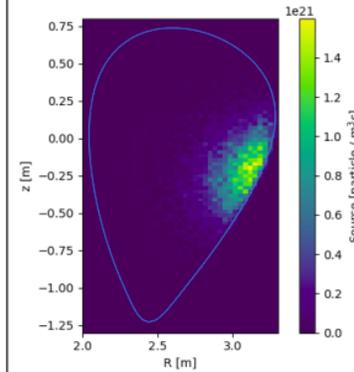
- Shinethrough 1.9 %.
- Beam ionized on the low field side
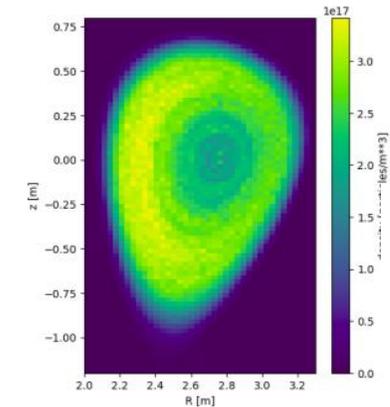 - Some particles even miss the plasma

Slowing-down density
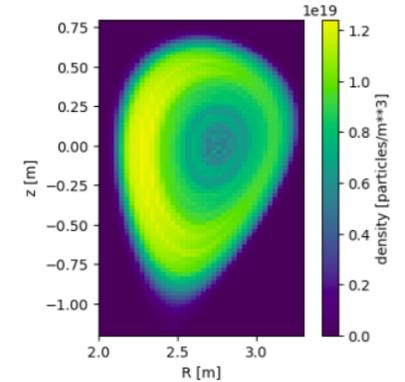
- No beam ion losses.
- Density peaked towards the edge.
  - Reducing nominal density to 25 % produces centrally peaked profile

- Thermal alpha power: 1.12 MW

- Beam-thermal alpha power: 3.44 MW

Outline

o   Introduction

o   Design criteria for VNS

o   Present design point and systems code scans

o   Ongoing physics studies

   ✓   Magnetic equilibrium (*R. Ambrosino/E. Acampora*)
   ✓   Integrated modelling and W transport (*E. Bray/C. Angioni/C. Bourdelle*)
   ✓   Power exhaust (*S. Wiesen*)
   ✓   Fast particle physics (*Ph. Lauber/A. Snicker/K. Sarkimäki/L. Pigatto*)
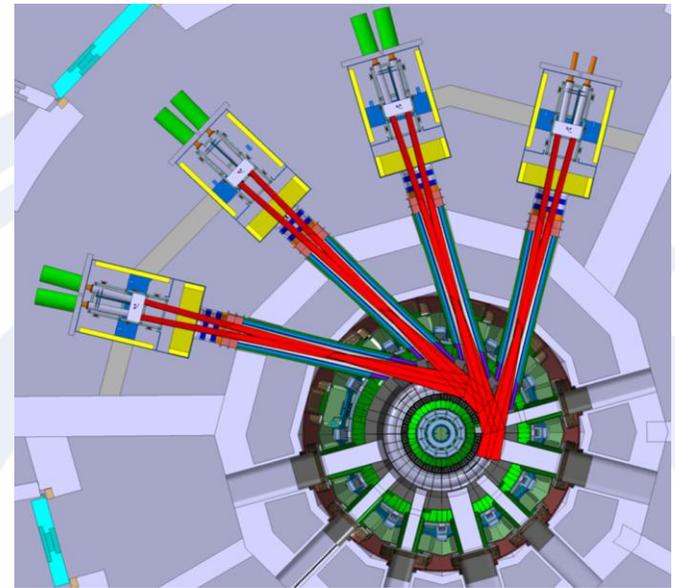
o   **Conclusions**

Conclusions

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

- o The driving constraint is the T consumption, which favours small device size at high aspect ratio – as long as compatible with engineering and physics constraints

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.

- o Areas of particular interest are: plasma and impurity transport, magnetic equilibria, fast particle physics and power exhaust.

Experiments in support of the plasma scenario definition and validation would be very welcome – JET beam target offers ideal validation platform and is already being used actively (E. Bray). High β_{fast} scenarios are instead less explored.

Thank you for your attention!