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*Trilateral meeting, Hangzhou*
*26.10.24*

EUROfusion

Center for Nonlinear Plasma Science
CNPS
Since 2020

# The role of the Divertor Tokamak Test facility in the Italian and European magnetic fusion programs*+

**Marco Ciotti[1] and the DTT Team[2+]**

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*Acknowledgments: P. Agostinetti, I. Casiraghi, S. Ceccuzzi, L. Chen, F. Crisanti, M.V. Falessi, L. Figini, V. Fusco, P. Innocente, Ph. Lauber, Y. Li, M. Gobbin, P. Mantica, A. Mishchenko, Z. Qiu, G. Rubino, G. Spizzo, G. Vlad, B. Wan, and the CNPS Team

+With the contribution of the researchers involved in the DTT Physics group and, in general, of all the scientists belonging to the working groups of the DTT program

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# Divertor Tokamak Test facility

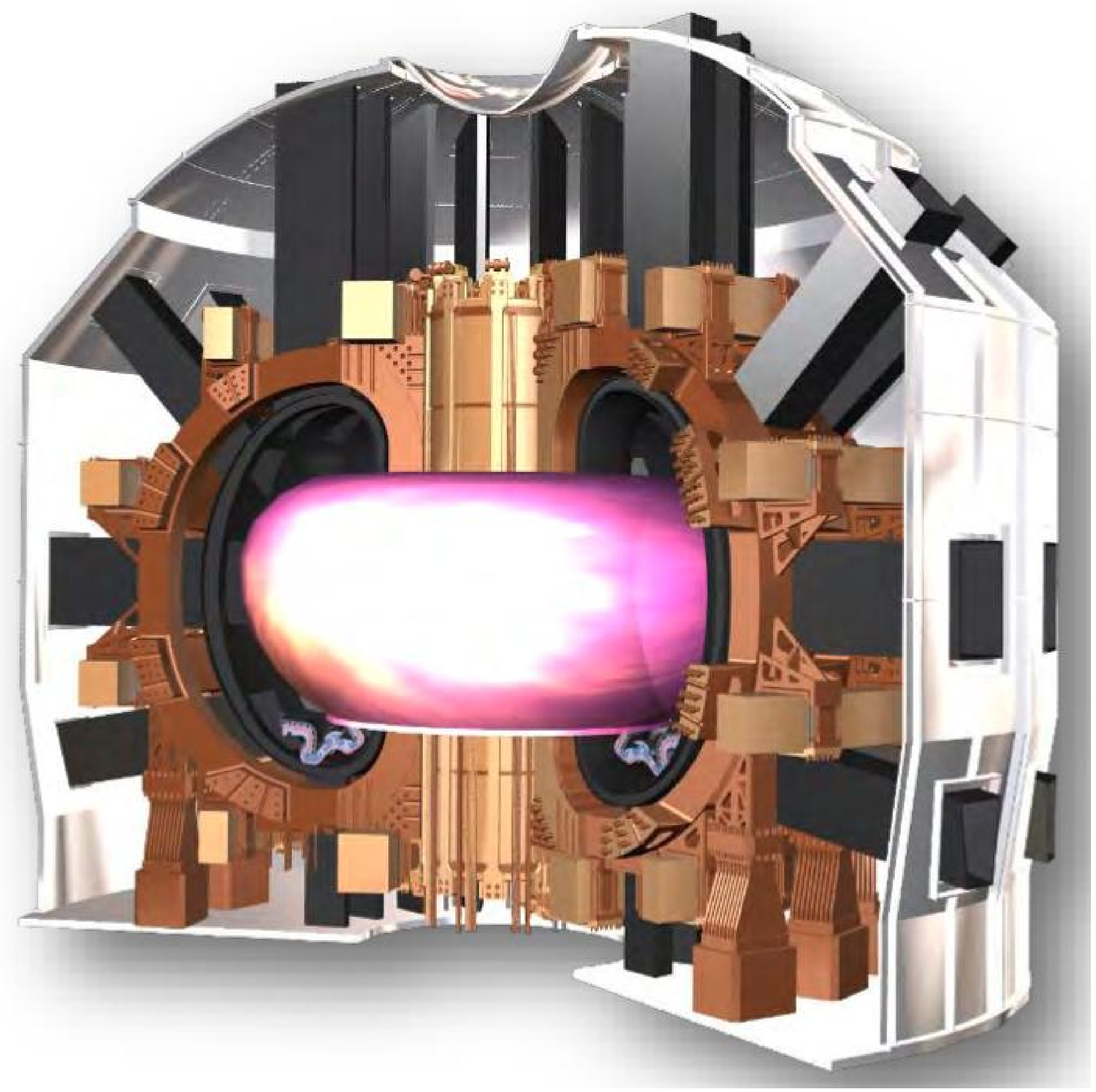
## Outline

Aims of the project
International framework
Parameters choice

First plasma expected end 2030

EXPECTED COST ~ 500M€

# Divertor Tokamak Test (DTT) facility



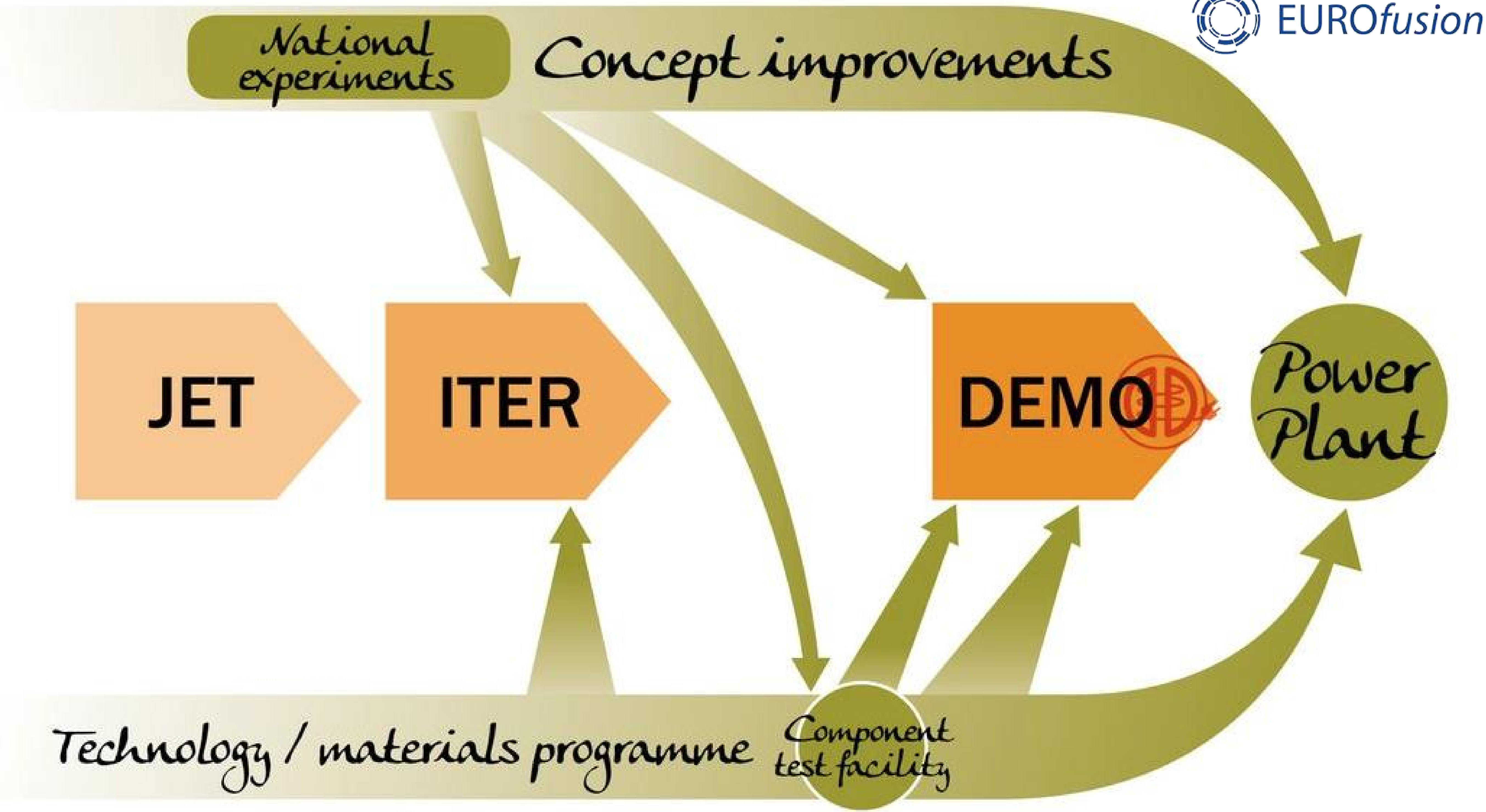
1. Aims of the project
2. International framework
3. Parameters choice
4. 4status of the project
5. conclusion

Superconducting tokamak
Construction at ENEA Labs in Frascati (Rome), Italy

First plasma expected end 2030

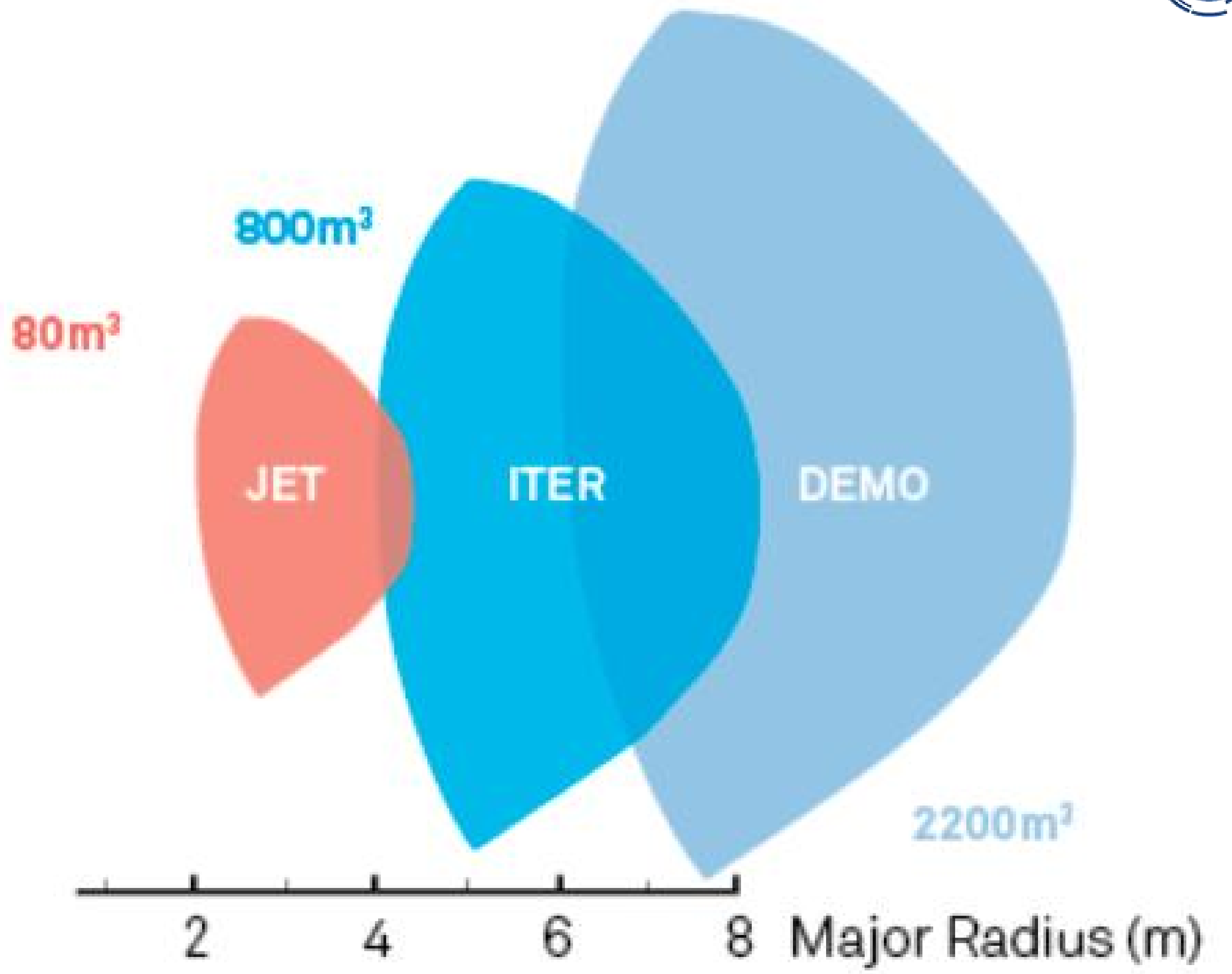
EXPECTED COST ~ 500M€

# A roadmap to fusion energy…




Graphic: EUROfusion / CCFE

# …increasing size/cost

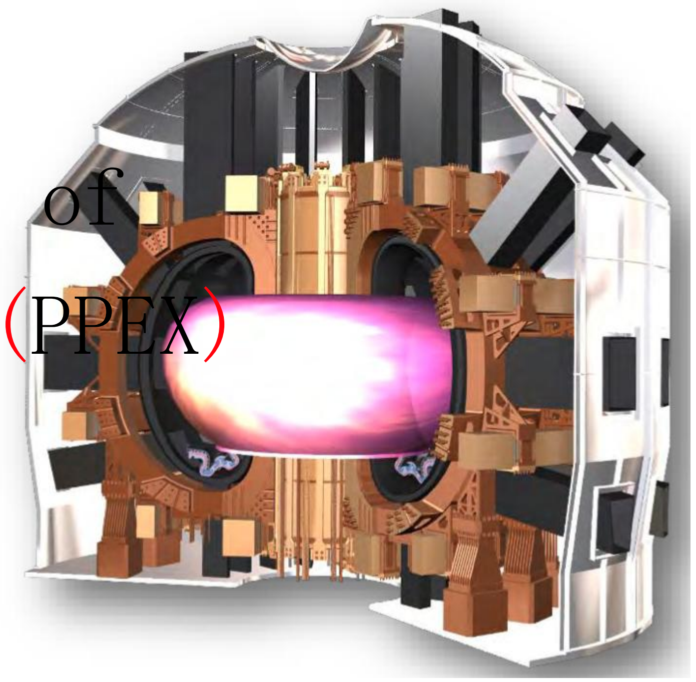


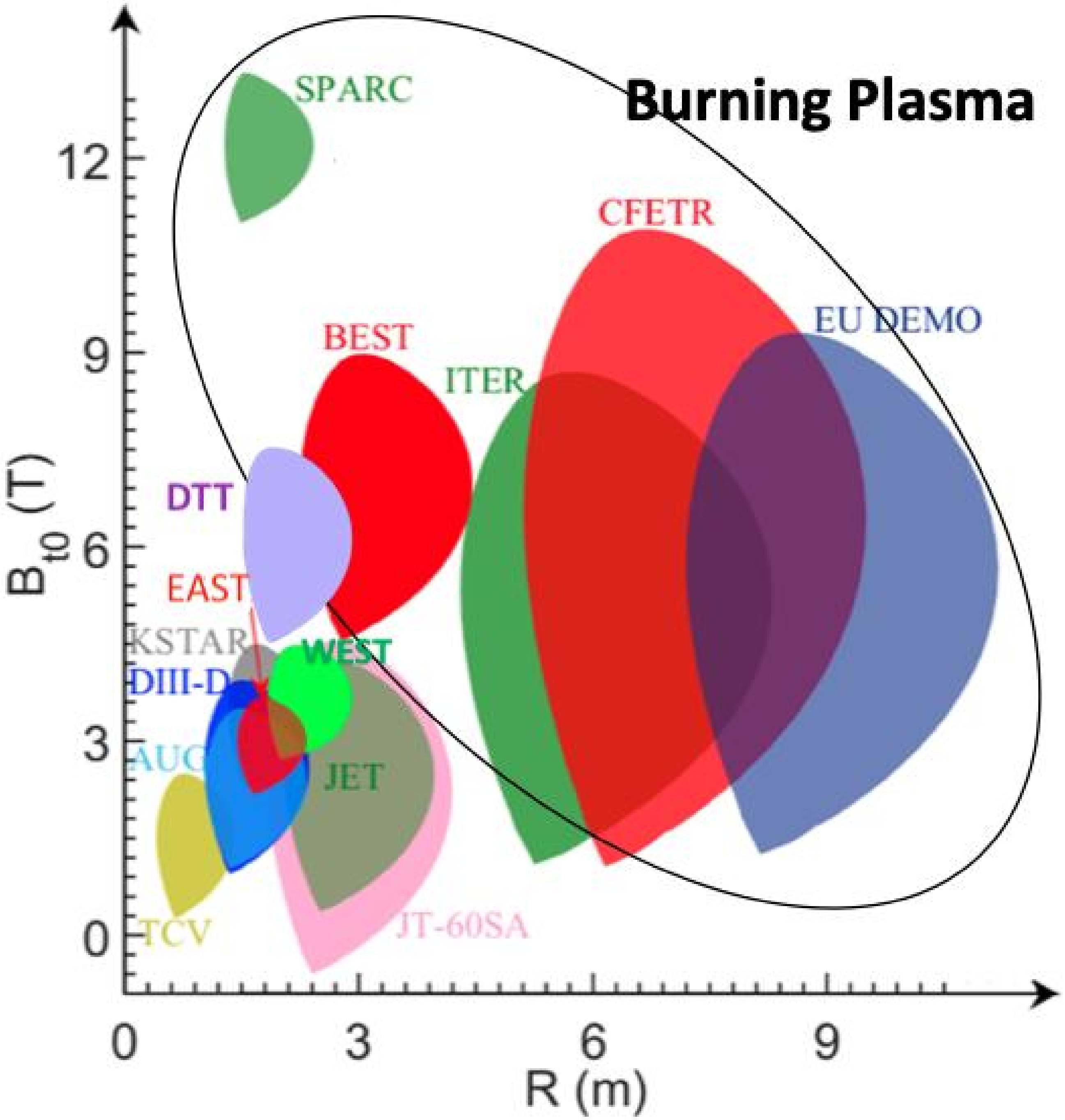

# …a challenge for technology

# …and for physics

# Divertor Tokamak Test (DTT) facility

- One of the key issues towards demonstration of fusion energy is Power & Particle EXhaust (PPEX)





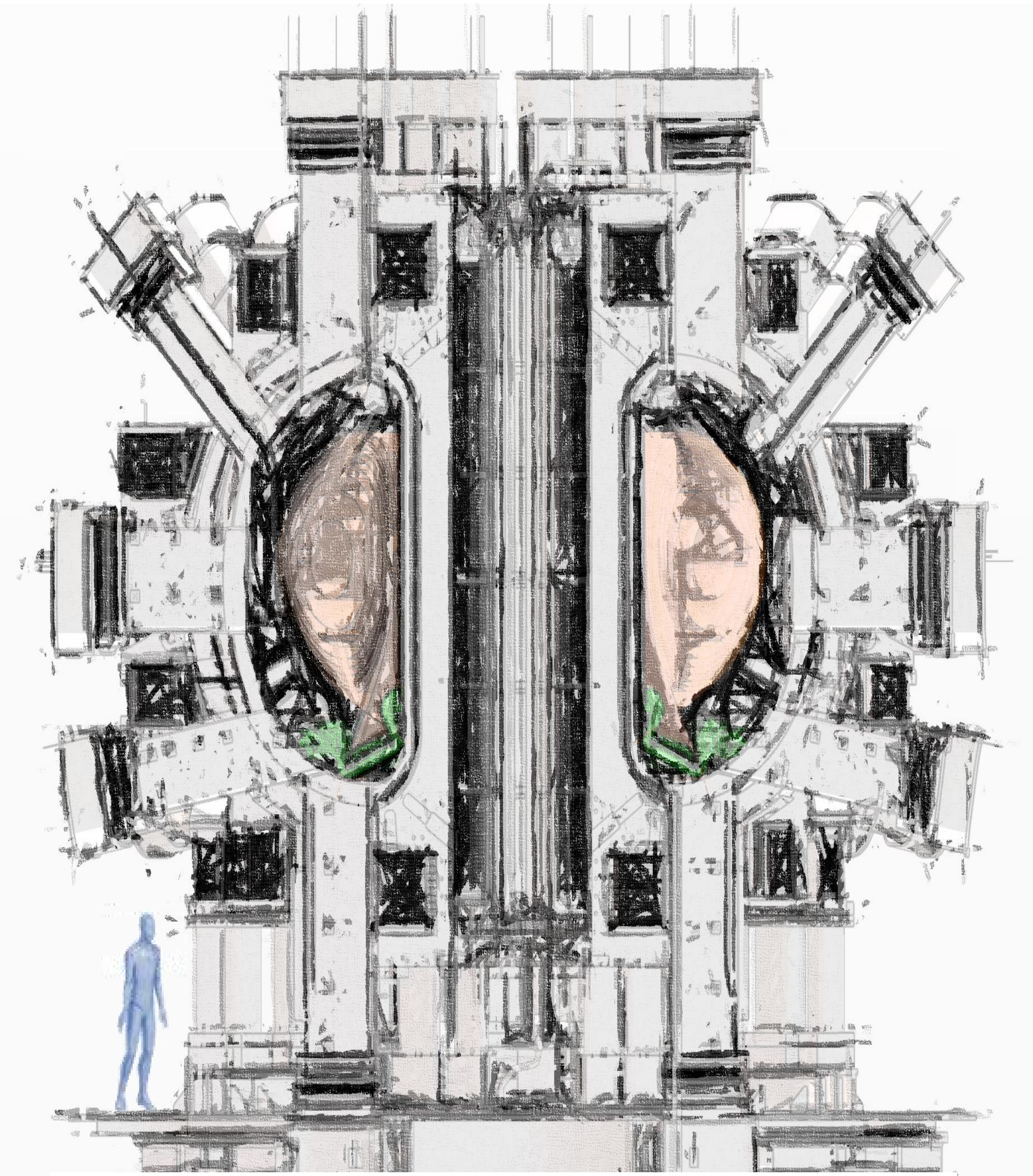

Integration of various physics and technology aspects is crucial

# Main tokamak parameters

| | ITER | JET | DTT |
|---|---|---|---|
| Major radius (m) | 6.2 | 2.96 | 2.19 |
| Minor radius (m) | 2.0 | 1.25 | 0.70 |
| Magnetic field (T) | 5.3 | 3.45 | 6.0 |
| Plasma current (MA) | 15 | <4.8 | 5.5 |
| Q | 10 foreseen | 0.33 Exp | ($\gtrsim$ 1) (equiv) |

# DTT mission

- "European Research Roadmap to the Realization of Fusion Energy" → the **heat exhaust** is one of the **main challenges** towards the construction of a fusion **power plant**. *"The DTT goal is the identification of a reliable solution for the extraction of the heat generated by the fusion process "*
- A dedicated Divertor Tokamak Test (DTT) facility was considered necessary →a **high-field, compact (DD) tokamak** capable of producing plasma conditions **as similar as possible** to those in ITER and DEMO in steady–state conditions
- **Substantial amount of external heating power (up to 45 MW)** to reproduce the level of divertor heat loads foreseen in ITER and DEMO.
- Explore a **variety of different magnetic configurations**
- **Be the first public-private enterprise in fusion in Italy (est. 2020)**



DTT aims at providing a **unique, flexible, integrated environment, relevant to DEMO**



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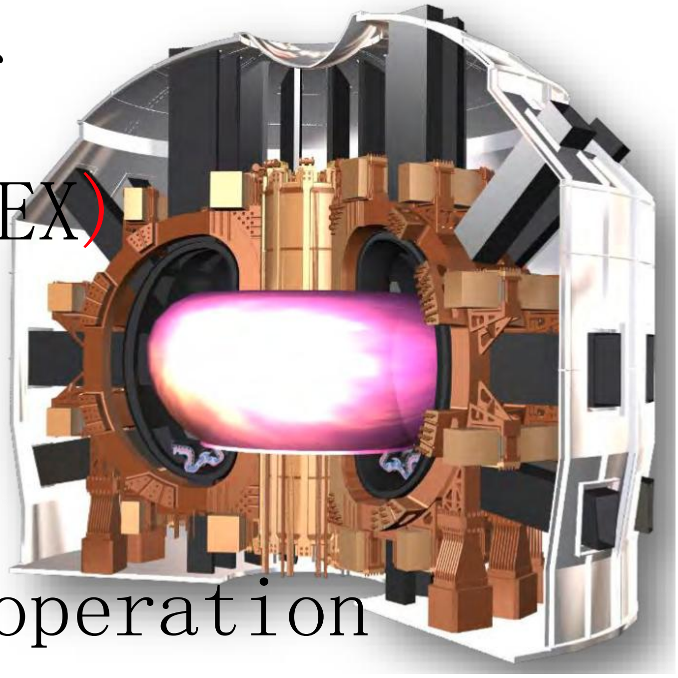
# How to perform such a mission



- One of the key issues towards demonstration of fusion energy is Power & Particle EXhaust (PPEX)
- Integration of various physics and technology aspects is crucial
  - Clear impact on plasma performance and operation
  - Here: focus on physics integration (in general)
  - Need for reliable predictive capability
  - Integrated Modeling crucial for turbulent transport
  - Need for novel approaches and physics understanding:

**fusion is not a mere engineering and technology problem**

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# How to design DTT in order to be as representative as possible for DEMO or any future reactor relevant machine?

- The operation space of quasi-neutral, collisional, finite-$\beta$ plasmas

$\beta$

$\rho^*$ $\nu^*$

$nR^2$ $TR^{1/2}$

$BR^{5/4}$

There exist three dimensionless parameters in the governing equations [Kadomtsev 75]

$\rho_*$=Larmor radius in a units of minor radius
$\nu_*$=ratio connection length to trapped particles mean free path
$\beta$ ratio plasma to magnetic pressure

Three engineering (dimensional) parameters, with R left to vary [Lackner 90]

# DTT physics rationale

- **Weak Kadomtsev scaling** [Pizzuto et al NF2010]:

➔ fix $\rho_* R^{\epsilon}$; $\beta$; $\nu_*$

- Weak scaling of $\rho_* R^{\epsilon}$
    - Cross-scale coupling (micro-meso scales) is preserved;
    - Preserve $\rho_{*EP}/\rho_*$ set by $T_{EP}/T$, given by condition of dominant electron heating
- Fix $\beta$ and stability
    - Preserve temporal scale hierarchy: frequency ordering of meso- to macro-scale fluctuations
- Fix collisionality parameter $\nu_*$
    - Preserve edge physics and PWI (PPEX)
    - Preserve supra-thermal particle content in the core

# DTT physics rationale - II

- **Weak Kadomtsev scaling** [Pizzuto et al NF2010]:
  → DTT parameters chosen to have edge and core dimensionless parameters as close as possible to those of ITER and DEMO

| | $P_{SOL}$ (MW) | $\lambda_q$ (mm) | R (m) | $q_{//}$ (GW/m²) | $q_{pol}$ (GW/m²) |
|---|---|---|---|---|---|
| ITER | ~90 | ~2 | ~6 | ~1.8 | ~0.6 |
| DEMO | ~150 | ~1 | ~9 | ~5 | ~2 |
| DTT | ~30 | ~1.5 | ~2.19 | ~2.1 | ~0.7 |

| | ITER | DEMO | DTT |
|---|---|---|---|
| R (m) | 6.2 | 9 | 2.19 |
| a (m) | 2 | 2.9 | 0.7 |
| Ip (MA) | 15 | 19.5 | 5.5 |
| $B_T$ (T) | 5.3 | 5.7 | 6 |
| <T> (KeV) | 8.5 | 12..7 | 6.2 |
| <n> ($10^{20}$ $m^{-3}$) | 1 | 0.8 | 1.7 |
| $\beta_N$ | 1.5 | 2.2 | 1.5 |
| $\nu^*$ ($10^{-2}$) | 2.4 | 1.4 | 2.4 |
| $\rho^*$ ($10^{-3}$) | 1.7 | 1.5 | 3.7 |
| $\nu^*_{ped}$ ($10^{-2}$) | 6.2 | 4.5 | 6.3 |
| $P^*_{ped}$ ($10^{-3}$) | 1.6 | 3.3 | 1.3 |

Courtesy of F. Crisanti
DTT Research Plan Kick Off Mtg
Jul 8, 2022

# Is it enough?

Divertor is a complex, **active component**, having that should assure to:

1) exaust the He gas;

2) while assuring an effective **impurity** pumping (W, $O_2$, C, etc)

3) preserving the **detatched** status;

4) without punping out unreacted **tritium**;

5) in stationary **burning conditions** for very long time (months?)

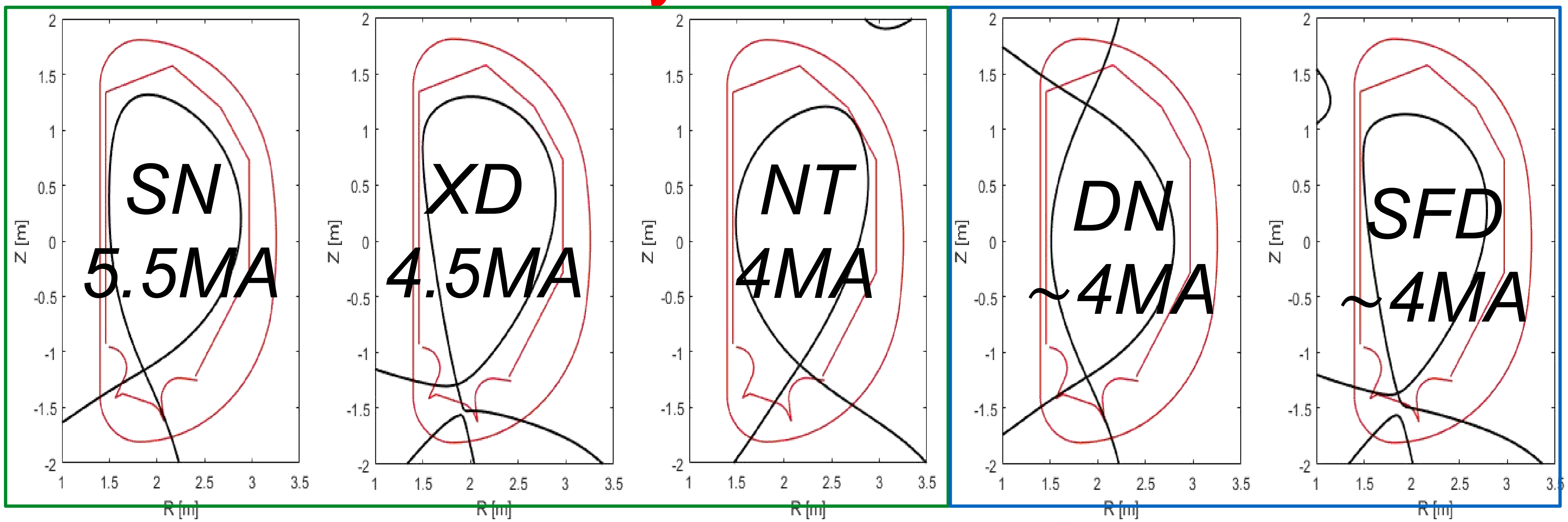
6) while suffering intenses heat loads

# DTT flexibility

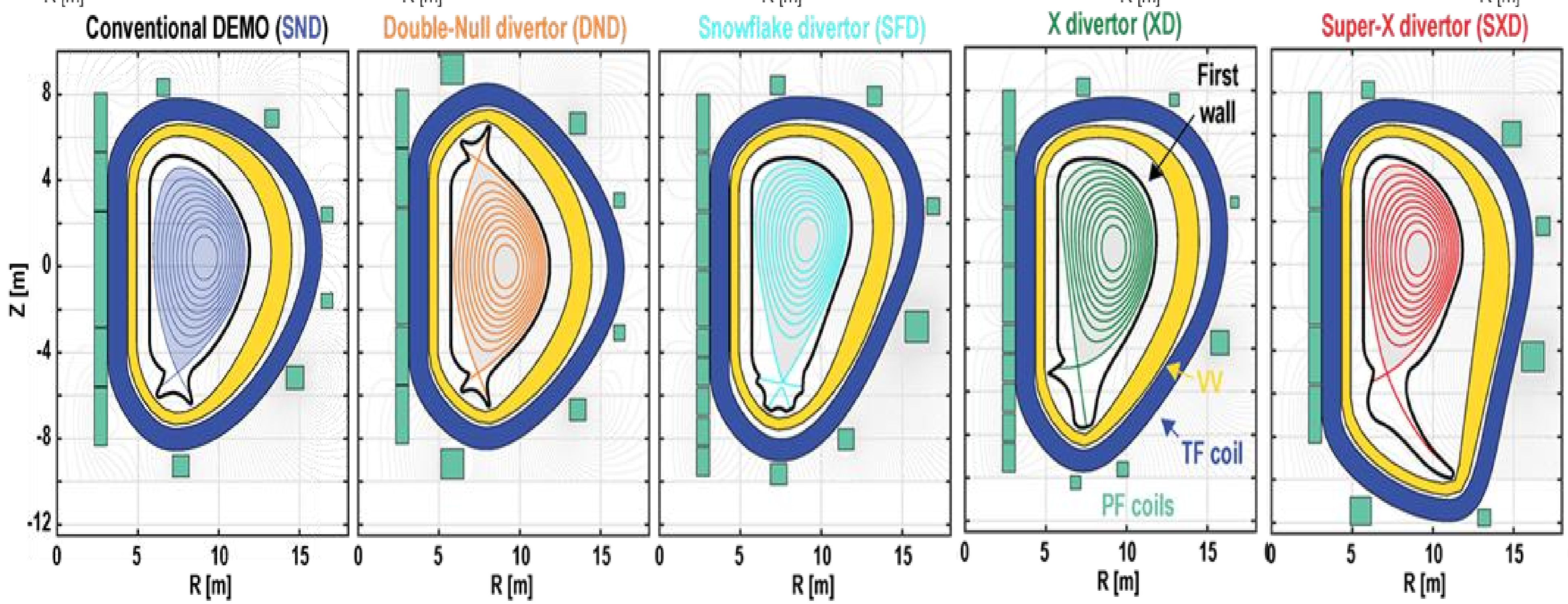
- **Flexibility of plasma scenarios** – different divertor magnetic topologies: XS(tandard), XD(Second null), N(egative)Triang.
  - a) $I_p$= 2 MA – $B_T$= 3 T; $P_{add}$ ~ 8÷35MW
  - b) $I_p$= 5.5 MA – $B_T$= 6 T; $P_{add}$ ~ 27÷45MW
- **Flexibility in density** ➔ study detachment for $\langle n \rangle \sim 1 \div 2 \times 10^{20}\ m^{-3}$
- **Full metal wall** ➔ Tungsten for reactor (DEMO) relevance
- **Relevance to PPEX**
  ➔ The total heating power $P_{SOL}/R$ ~ 7÷15 MW/m
  ➔ Flexible divertor: geometry and material
  ➔ Long pulse ($\tau > 4\tau_R$): aiming at solution without performance degradation

# DTT Main requirements (or challenges) from Physics

**DTT reference scenarios**




**DTT future scenarios not optimized**




**DTT magnetic system can realize all foreseen Alternative Divertor Configurations considered for DEMO**

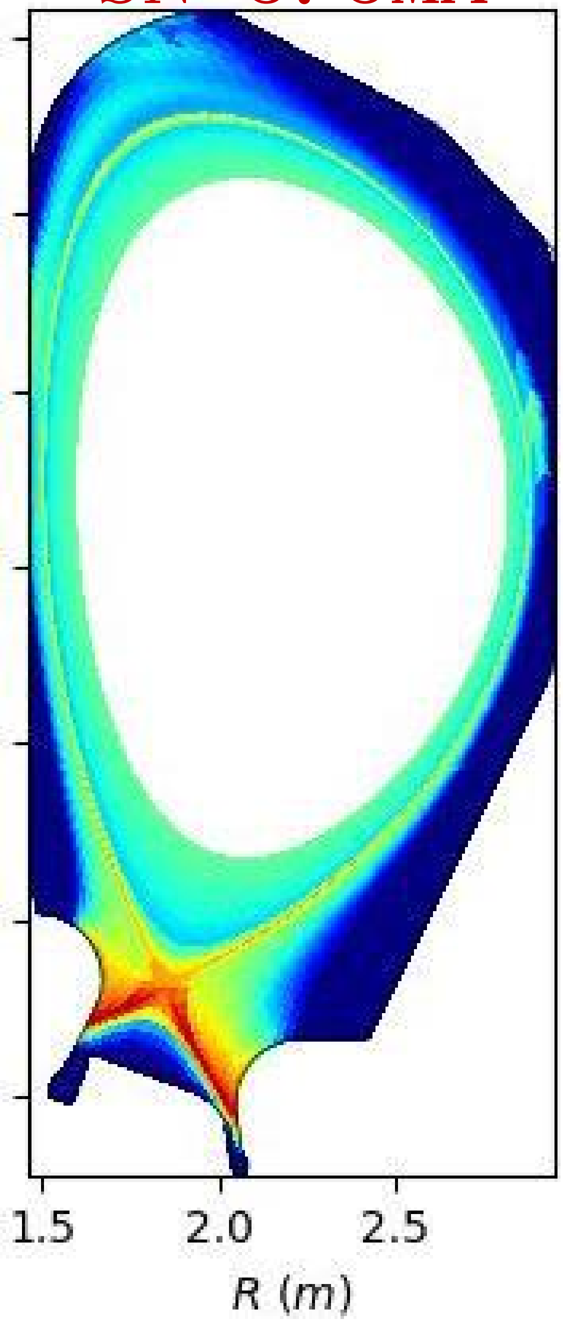
H. Reimerdes et al., “Assessment of alternative divertor configurations as an exhaust solution for DEMO”, Nucl. Fusion 60 (2020) 066030, https://doi.org/10.1088/1741-4326/ab8a6a

# DTT scenarios

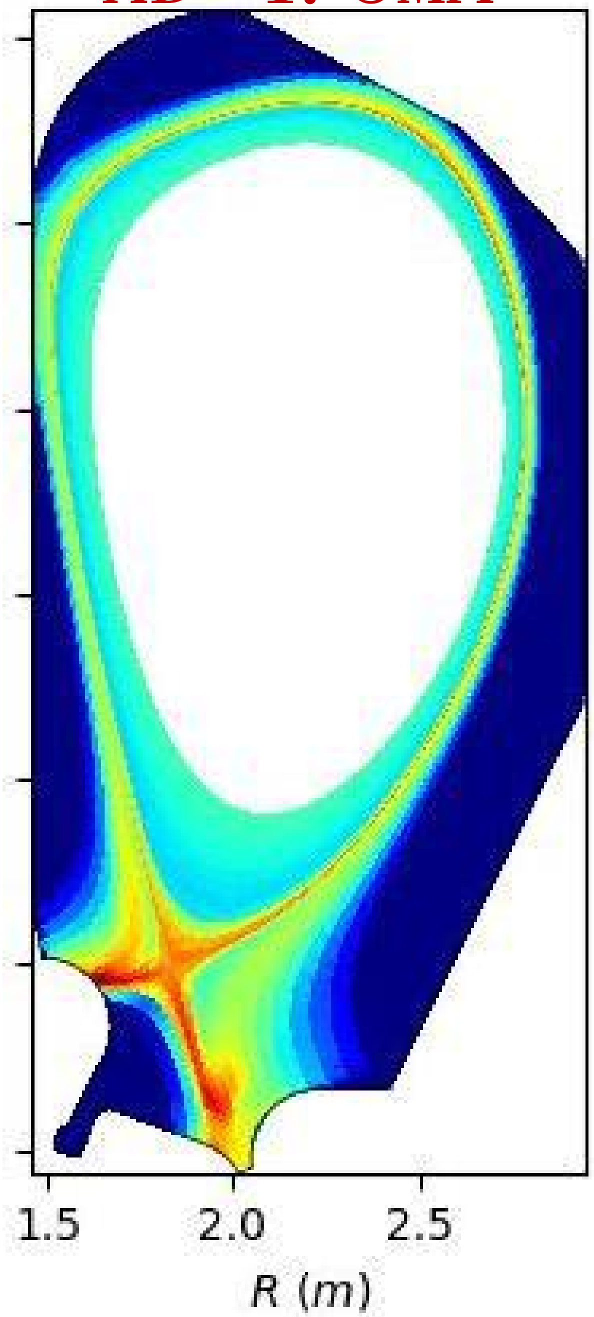
Courtesy of F. Crisanti
DTT RP Kick Off Mtg Jul 8, 2022

- Three main scenarios

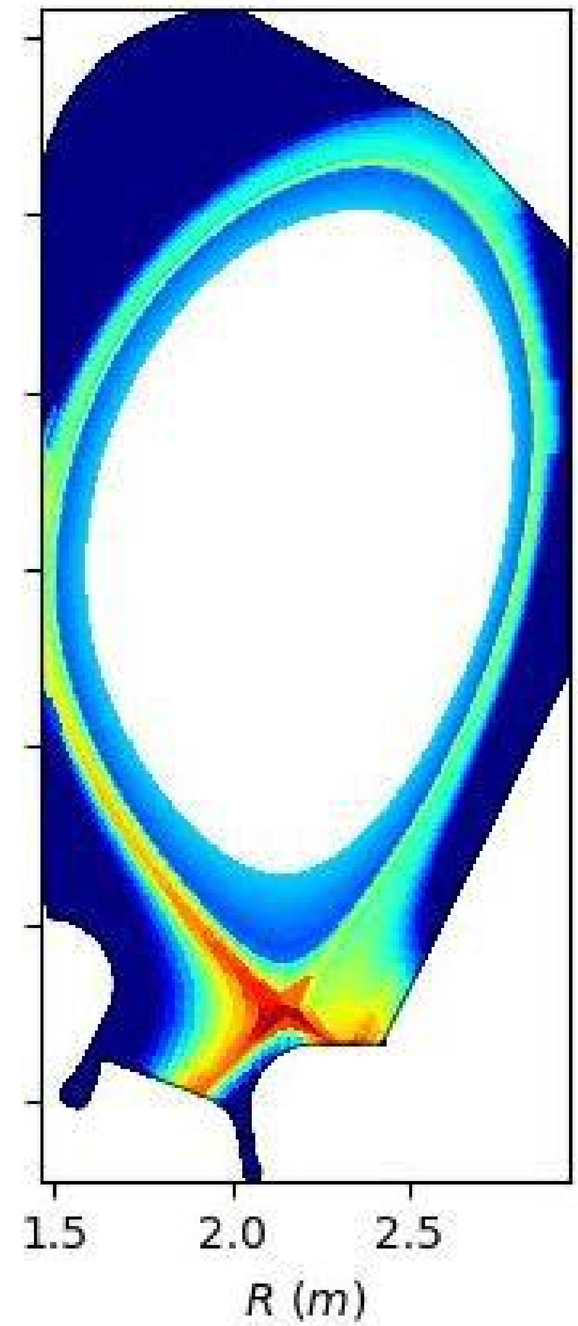
SN 5.5MA



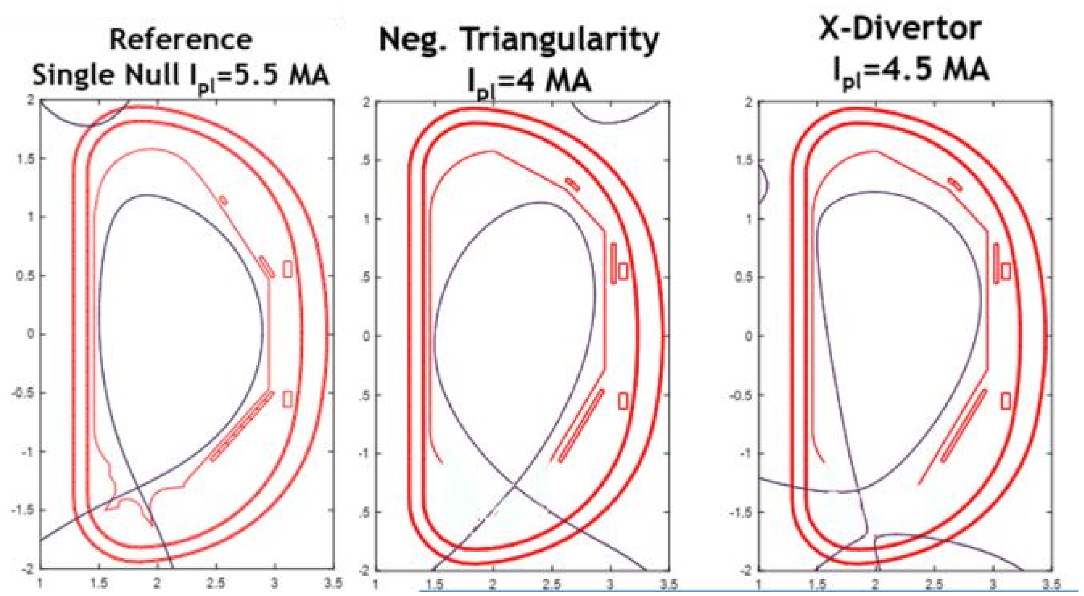

XD 4.5MA




NT 4.0MA



# DTT experimental program



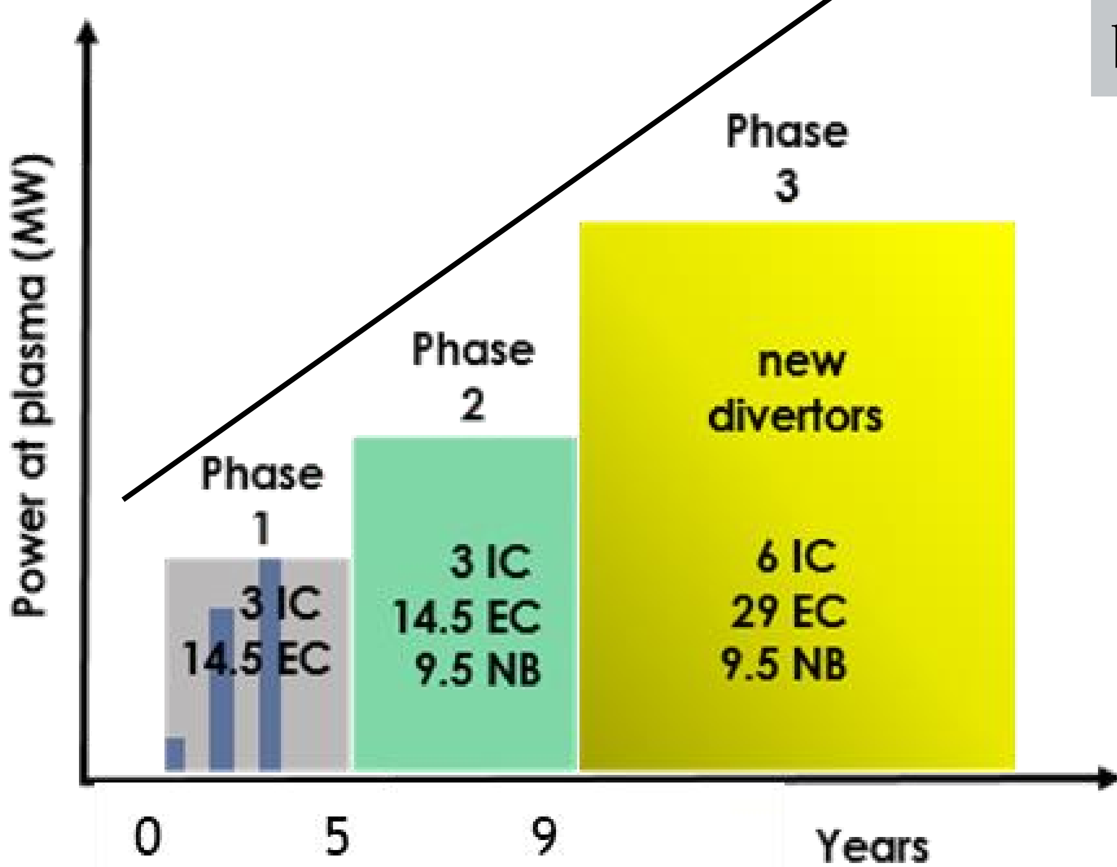

Courtesy of F. Crisanti
DTT RP Kick Off Mtg  Jul 8, 2022

1) In the first phase all the possible plasma scenarios will be tested to identify the most promising following divertor

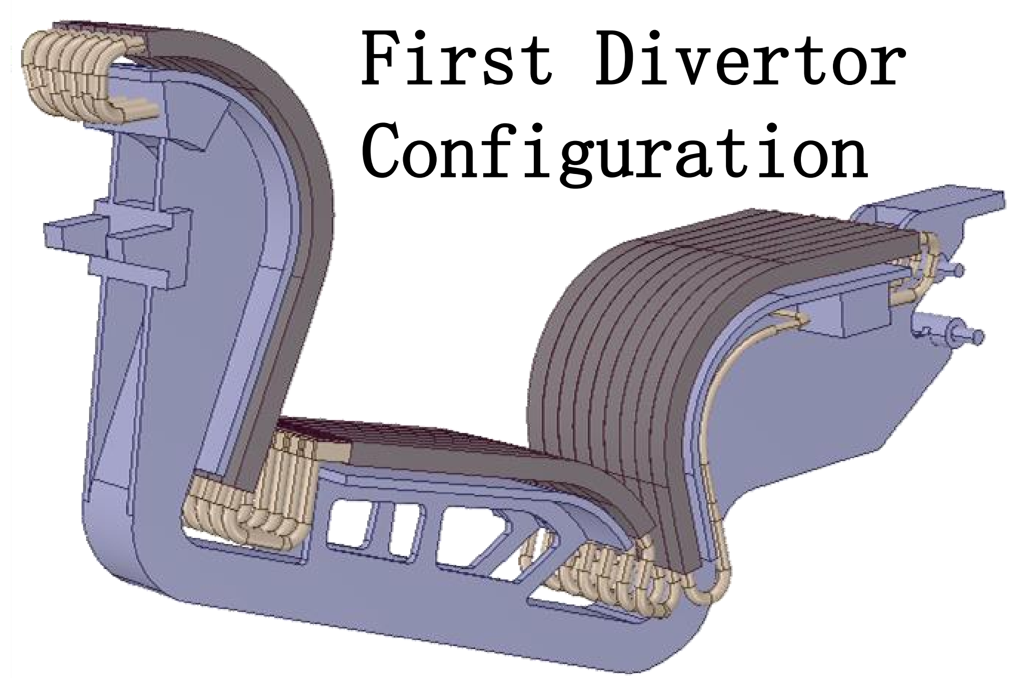
Day0: $I_p$= 2 MA – $B_T$= 3 T

Day1: $I_p$= 4 MA – $B_T$= 6 T

Additional heating power to be installed in three steps




First Divertor Configuration



# DTT Research Plan: Theory and Simulation

Coordinator: M.V. Falessi

CNPS Center for Nonlinear Plasma Science Since 2020

## Main Topics and Timeline

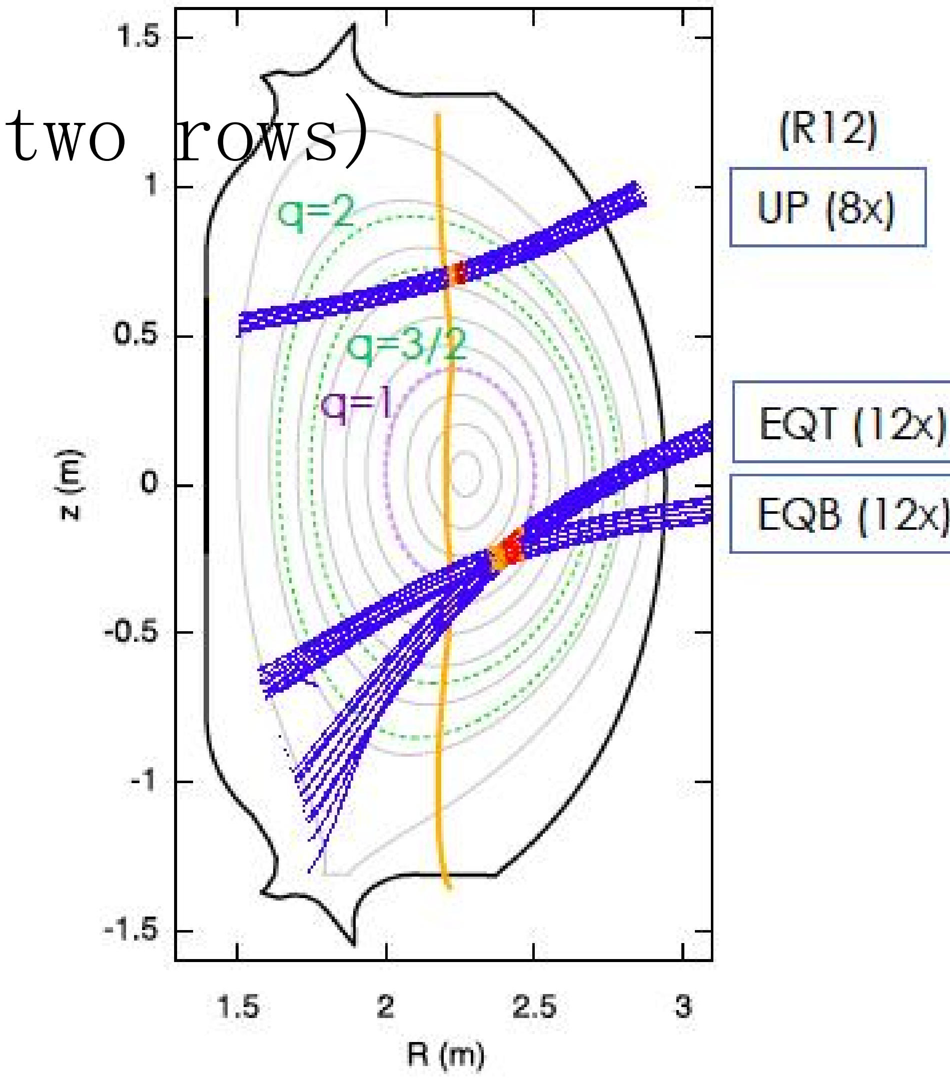
| Headline number | Headline contents | Priority (+,++, +++) | ITER | DEMO |
|---|---|---|---|---|
| **Construction Phase 2022-2029** | | | | |
| C.8.1 | Verification of Phase 1 scenarios and extended/kinetic MHD modelling with high fidelity theory-based tools. Predict and prepare Phase 1 Experimental programme. | ++ | * | * |
| C.8.2 | Set up IMAS infrastructure and workflows, e.g. ATEP code | +++ | | |
| **Phase 1 2029-2034** | | | | |
| 1.8.1 | Verification of Phase 1 scenarios and extended/kinetic MHD modelling with high fidelity | ++ | * | * |
| | theory-based tools. Predict and prepare Phase 2 Experimental programme. | | | |
| 1.8.2 | Validation of IMAS workflows under Low EP (ICRH) Pressures and Currents and scenario optimization | ++ | | |
| **Phase 2 2034-2038** | | | | |
| 2.8.1 | Verification of Phase 2 scenarios and extended/kinetic MHD modelling with high fidelity theory-based tools. Predict and prepare Phase 3 Experimental programme | +++ | * | * |
| 2.8.2 | Validation of IMAS workflows description of new EP transport regimes with NNBI and high current and scenario optimization | ++ | * | * |
| 2.8.3 | Development of reduced models for describing DTT's full power EP transport | ++ | * | * |
| **Phase 3 2038-...** | | | | |
| 3.8.1 | Verification of Phase 3 scenarios and extended/kinetic MHD modelling with high fidelity theory-based tools. Predict and prepare Phase 3 Experimental programme | +++ | * | * |
| 3.8.2 | Validation of IMAS workflows with full power plasmas and scenario optimization | ++ | * | * |
| 3.8.3 | Development of reduced models for describing DTT's EP transport | ++ | * | * |

# DTT heating mix - I

- Electron cyclotron resonance heating: 170GHz, $B_{res}$=6.07T
  - ➔Flexible coupling with dominant e-heating
  - ➔Reliable profile control

- 32 x 1 MW, 170 GHz beams, 28.8 MW at the plasma
- 4 Upper launchers x 2 mirrors
- 4 Equatorial launchers x 6 mirrors (two rows)
- Poloidal & toroidal steering

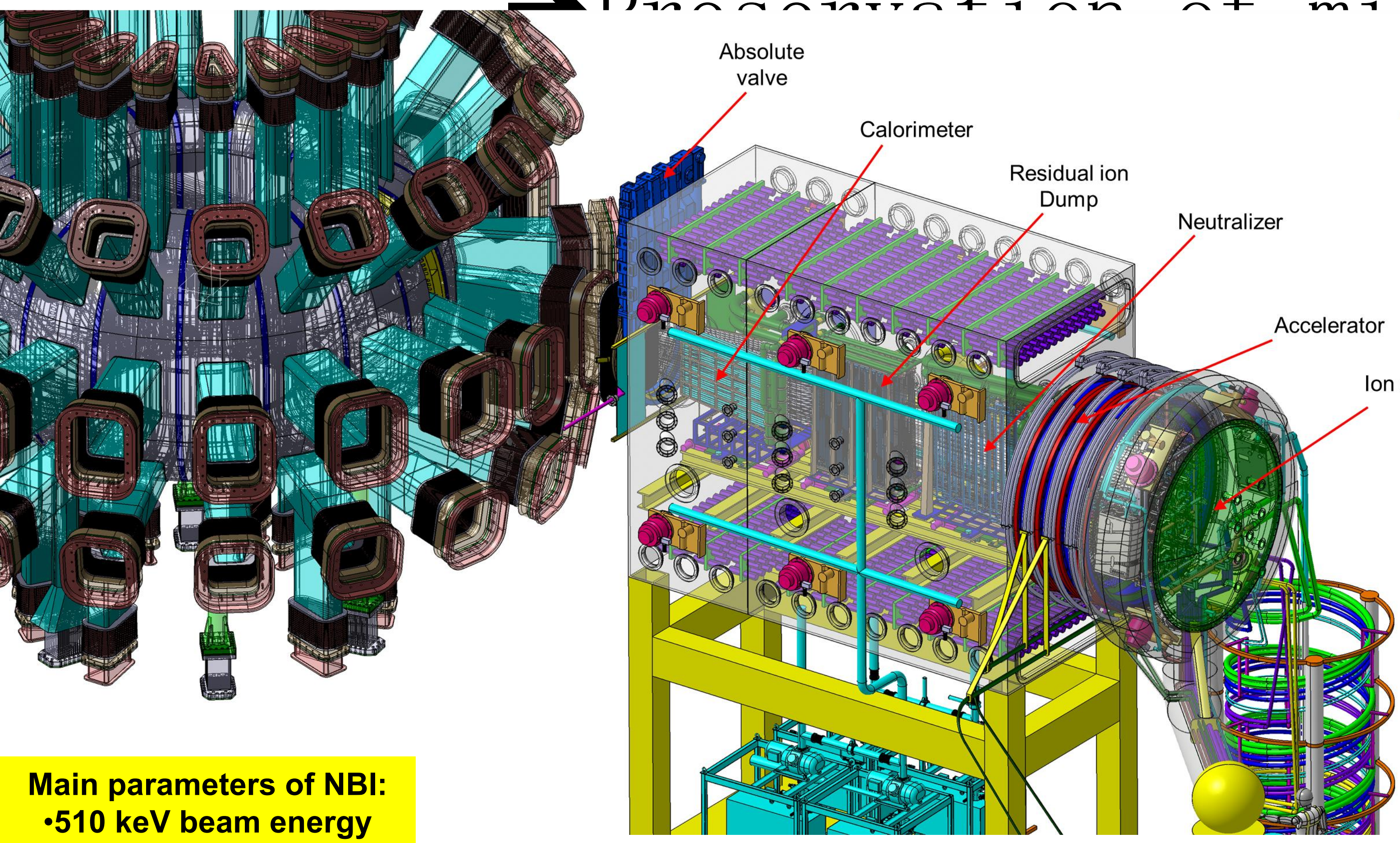
| | # beams | R (m) | z (m) |
|---|---|---|---|
| UP (2020) | 8 | 2.939 | 0.895 |
| UP (2021, R12) | | 2.854 | 0.980 |
| UP (2021, R13) | | 2.988 | 1.115 |
| **UP (2021, R13-09)** | | **3.070** | **1.200** |
| **EQ Top** | **12** | **3.126** | **0.179** |
| **EQ Bottom** | **12** | **3.126** | **-0.079** |




Courtesy of L. Figini,
Jan 13, 2022

# DTT heating mix - II

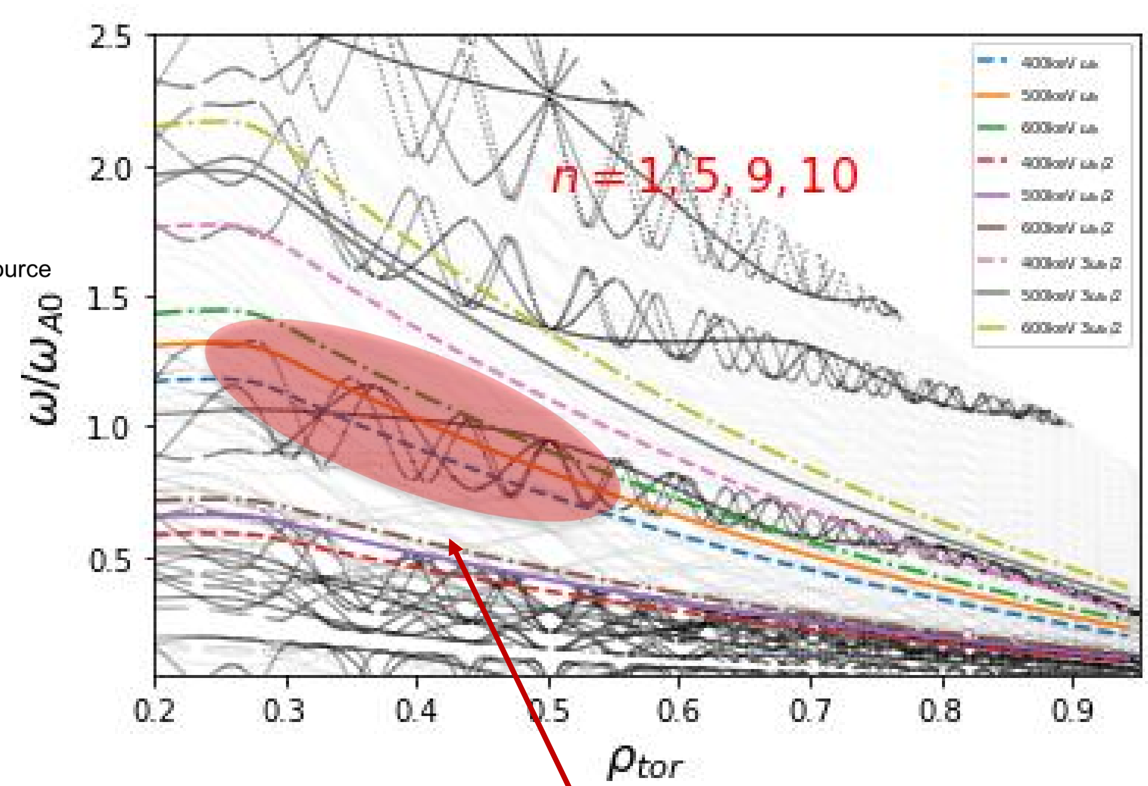
- Negative neutral beam injection (10 MW @ 510 keV):
  - ➔Plasma heating @ $E>E_c$
  - ➔Preservation of micro- to meso-scale




**Main parameters of NBI:**
- 510 keV beam energy
- 10 MW coupled with plasma
- Equatorial injection

Courtesy of P. Agostinetti, Oct 14, 2022

Courtesy of Y. Li, Nov. 15, 2022




Super-Alfvénic Beam

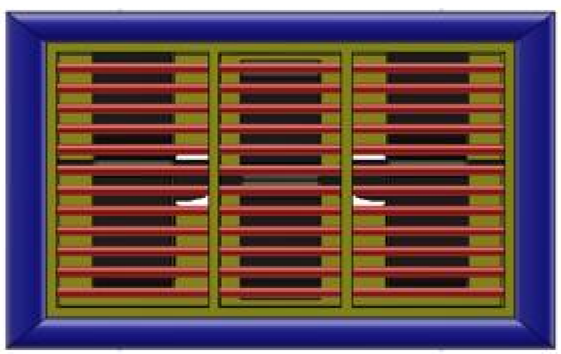
# DTT heating mix - III

- Ion cyclotron resonance heating: 4 antennas, 6 MW, 60-90 MHz (on axis D n=2, He$^3$ n=1)
  - ➔ H-mode access/ion heating
  - ➔ Fast ion generation
  - ➔ Wall cleaning/conditioning

Courtesy of S. Ceccuzzi
24th Topical RF Conf.
Sep 26-28, 2022

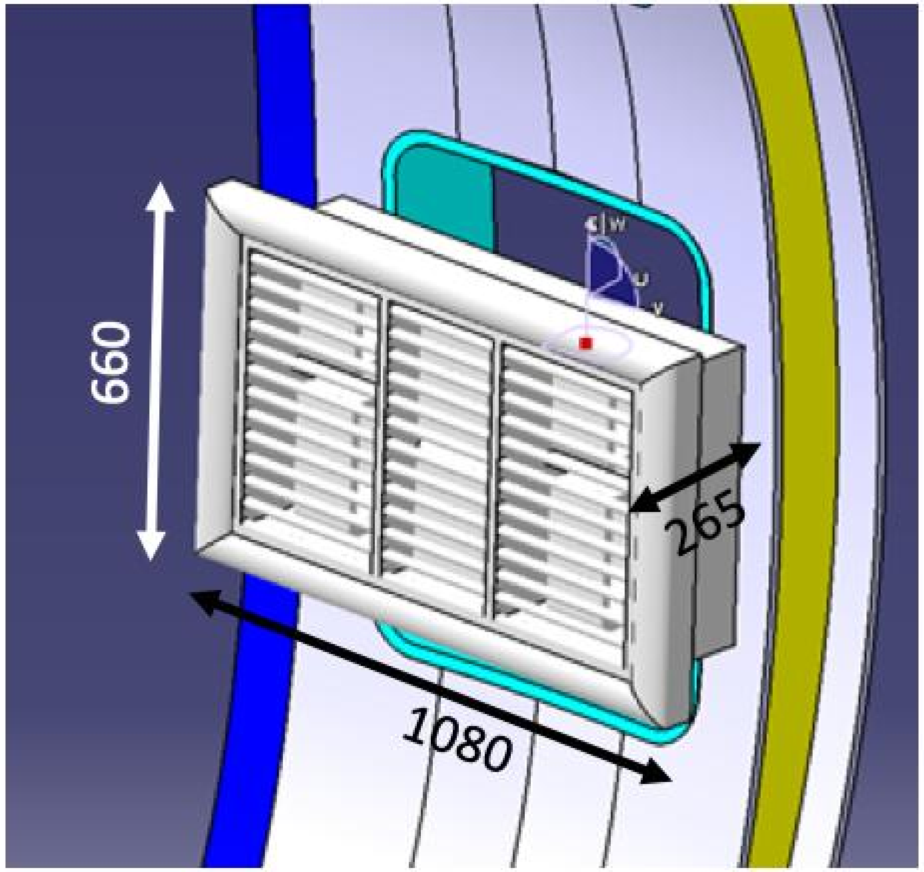
**1st option (baseline): 3-strap antenna** with lateral folded straps and central end-fed, centre-grounded strap to be installed/maintained via remote handling system.

- *Material choice on-going. Preliminary ideas:*



- full tungsten
- stainless steel
- stainless steel
- copper alloy

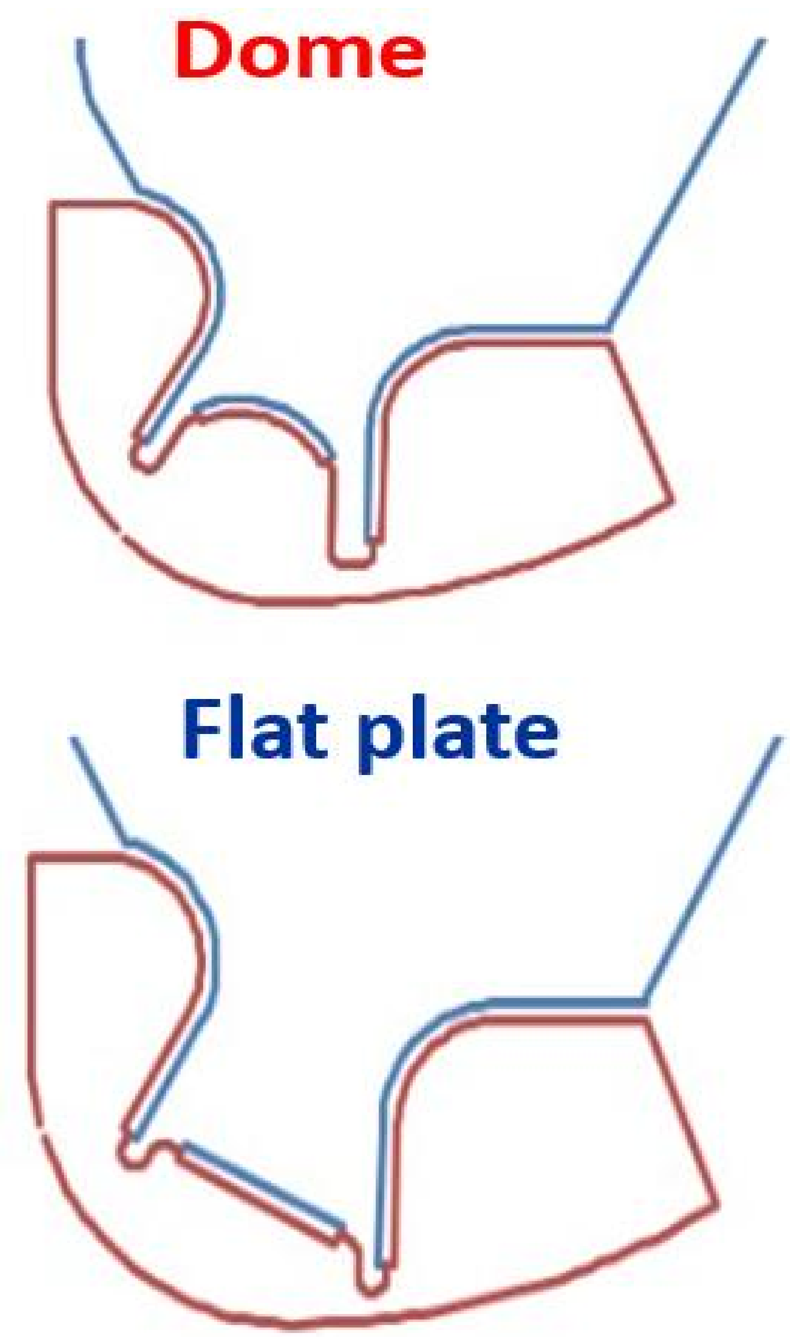
- Compatibility with field alignment but increase of complexity to be preferably addressed later on or w.r.t. the 2nd antenna pair



# Dome studies with SOLPS-ITER

**Assessment of the effect of dome in DTT full power scenario : $P_{AUX}$ = 45MW and Ne seeding**

- Dome adds complexity of the divertor cassette design and increase machine cost
- SOL modeling and kinetic neutral description with SOLPS-ITER code suite (B2.5+EIRENE)
- Small impact on the performance in terms of divertor performance (power loads onto divertor targets, plasma density and temperature, radiation fraction, etc…)
- **Small effect on Deuterium pumping** with dome increase in both D throughput by 30% and sub divertor neutral pressure by < 2, in line with previous ITER studies (*Kukuskhin 2002,2007*)
- **Strong effect is seen on the impurity pumping capability** (➔Increase in the sub divertor Ne pressure by a factor 5 and
  ➔ Increase in the Ne puff




Courtesy of G. Rubino
AAPPS-DPP Conf, Oct. 9-14 2022

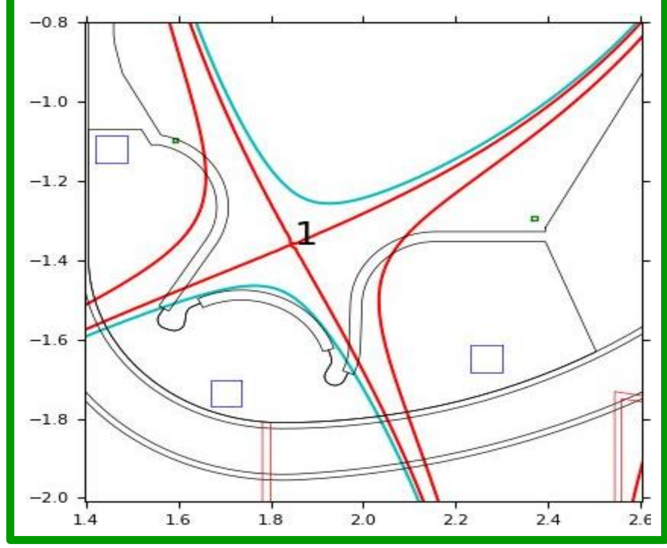
# Shape optimization with SOLEDGE2D-EIRENE

Courtesy of G. Rubino
AAPPS-DPP Conf,
Oct. 9-14 2022

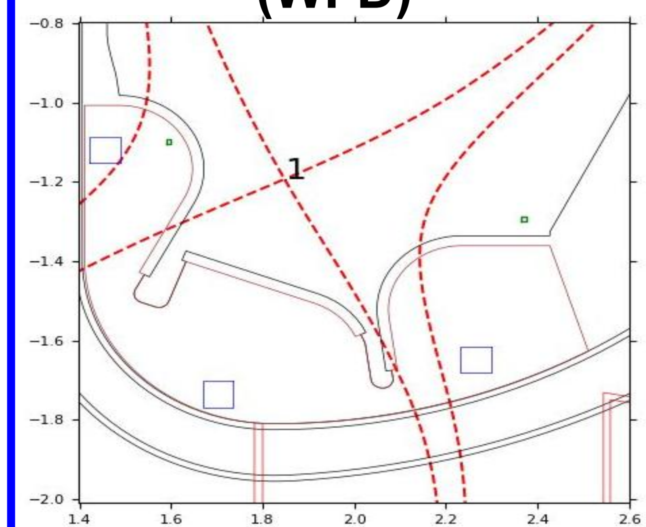
**Optimize divertor shape in DTT full power scenario : $P_{AUX}$ = 45MW with Ne and Ar seeding**

- SOL modeling and kinetic neutral description with SOLEDGE2D-EIRENE
- Verify the compatibility in terms magnetic configuration, no X-point radiation, X-point and strike point position flexibility
- Fulfill engineering constraints: minimum bending radius, cooling pipes shielding, grazing angle for reference SN (2°) and Pumping speed (100 $m^3/s$) requests
- The wide divertor can provide reliable operation for SN and XD configurations in pure deuterium at reduced power and with seeding at full power
- **The wide divertor provides better exhaust performance than a standard narrow divertor**

**Std/narrow divertor (ND)**




**Wide flat-dome div (WFD)**



# Integrated modeling in support of DTT

Courtesy of I. Casiraghi EPS-DPP 2022

...specifically
- the design of **diagnostic systems**
- the estimate of **neutron yields**
- the assessment of **fast particle losses**
- the definition of the **heating mix**
- the design of the **neutron shields**

**Integrated modelling** allows us to predict **radial profiles** of:
- Te
- Ti
- ne
- J
- power depositions
- $P_{rad}$
- impurities...

using

state-of-art modules for
- heating
- fuelling
- magnetic equilibrium

&

- **first-principle multi-channel quasi-linear (QL) transport models**

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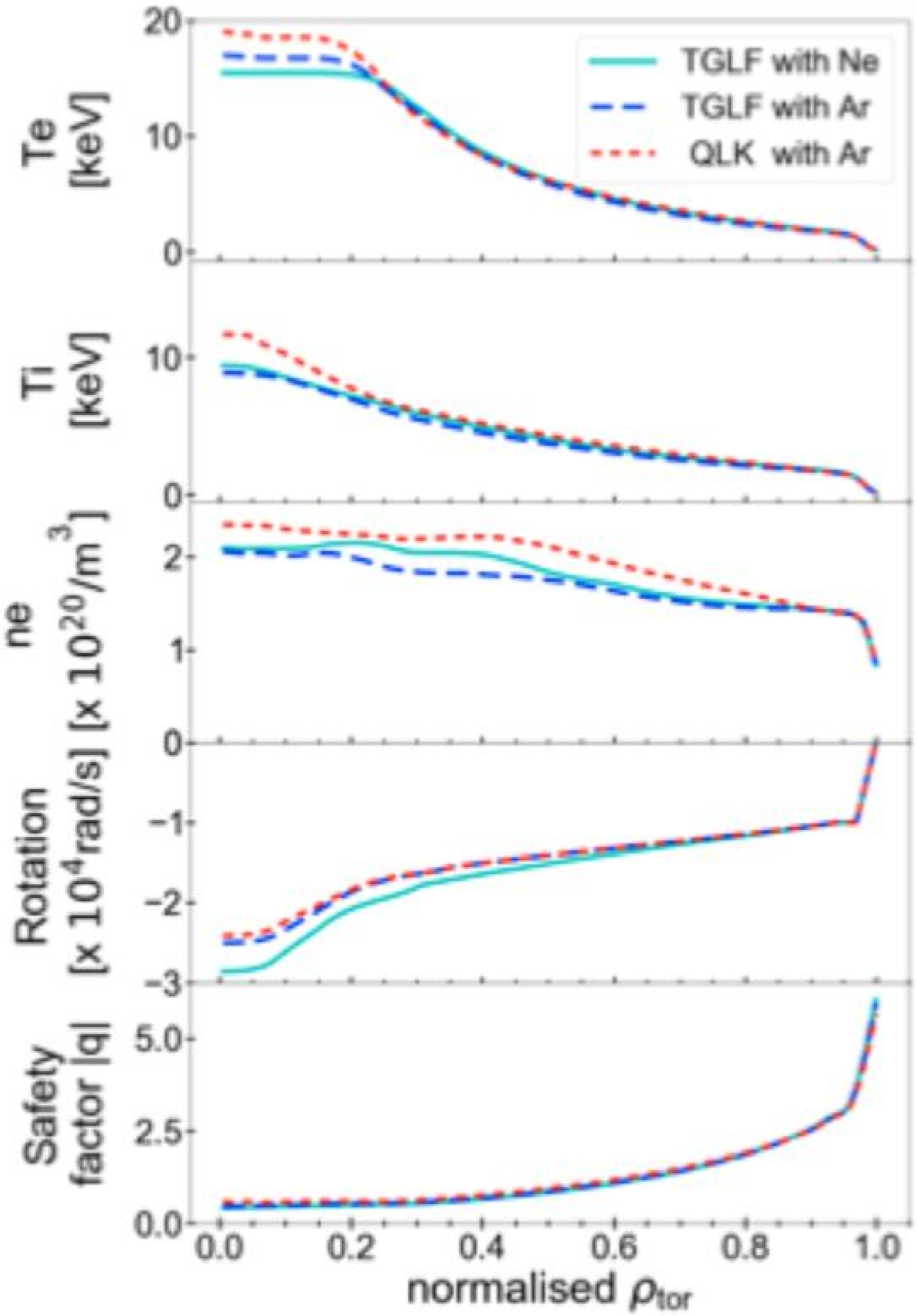
# Full power flat-top phase

Courtesy of I. Casiraghi EPS-DPP 2022

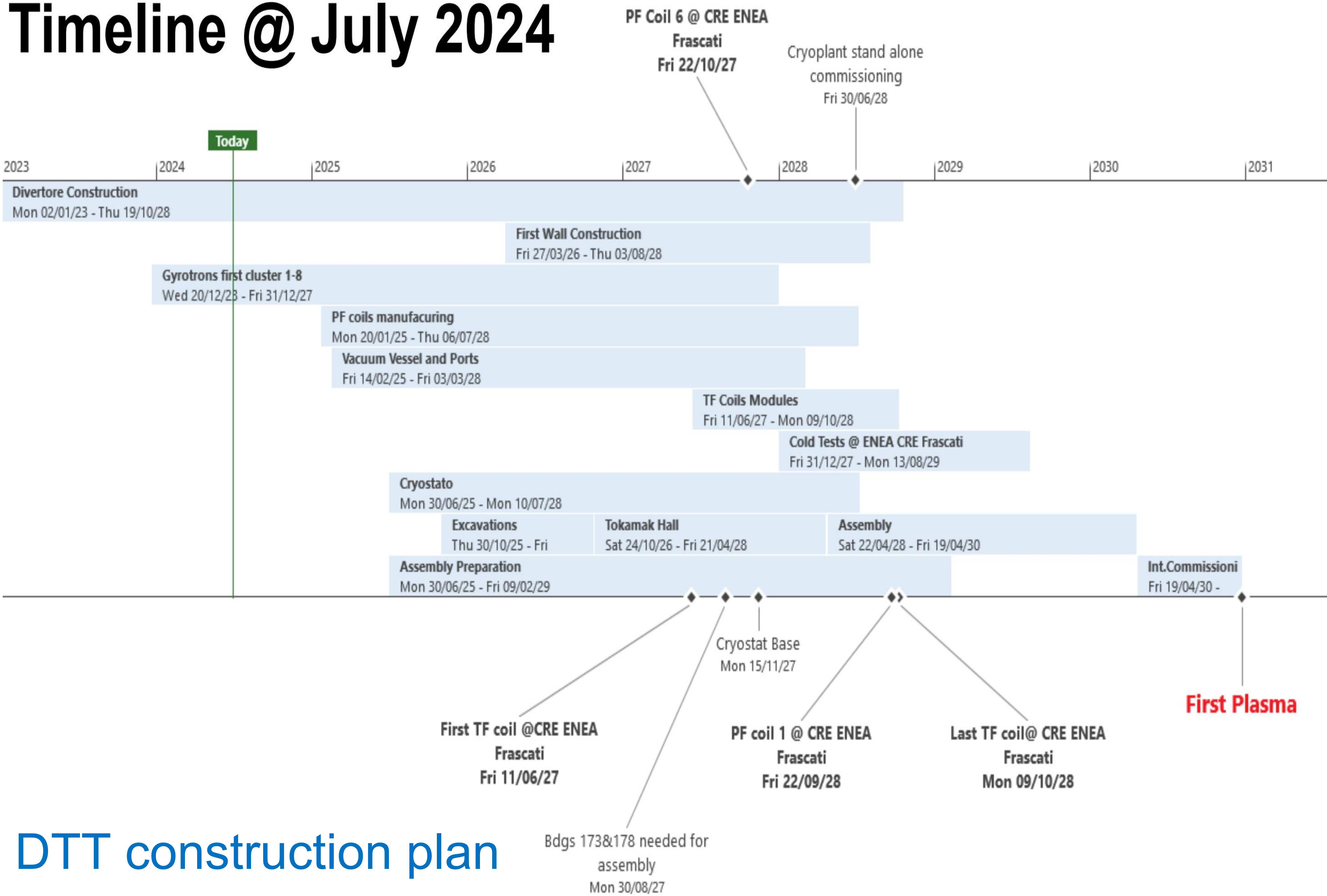



- ➔ Integration with **Scrape-Off Layer** runs
  - $n_{e,sep} = 0.8 \times 10^{20}/m^3$
  - $T_{sep} = 130$ eV
  - Ar or Ne as seeding gas
- ➔ Checked consistency between the control **coil system** capabilities and plasma profiles

---

- **Good agreement** between the 2 QL models (TGLF vs QLK)
- Te>Ti over most of plasma radius
- Neutron rate ≤ $1.2 \times 10^{17}$ neutrons/s
- $H_{98} = 0.8–1.0$, $\tau_E = (0.41–0.45)$s, $\beta N_{tot} = 1.3–1.6$

# Timeline @ July 2024

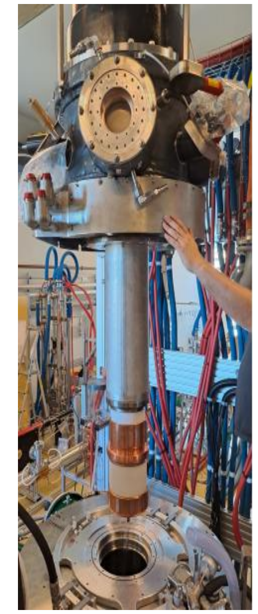



## DTT construction plan

# Heating and Current Drive systems: main procurements on- going

*ECH GYROTRON*: 16 (1MW each 170 GHz)
*Procured **jointly with F4E for ITER***

- ✓ *pre-serie gyrotron successfully overcome Interim FAT in Dec. 2023*
- ✓ *Contract#2 for 15 series gyrotrons signed in January 2024.*
- ❑ *First series gyrotron expected to be delivered to DTT in 2025.*
- ❑ *Last one in 2031.*

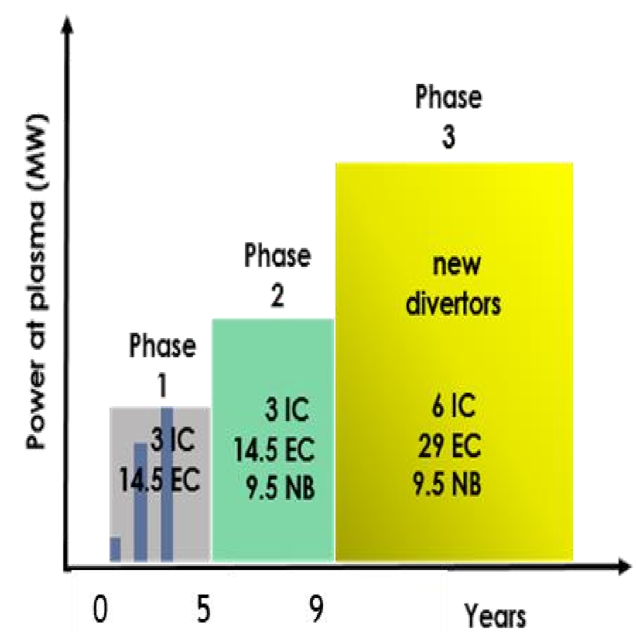


THALES
Building a future we can all trust


**ICH TRANSMITTERS**: 2 solid state transmitter 60 -

90 MHZ

- ✓ 27/02/2024 **Contract Awarded** to OCEM/SYES
- ✓ 09/05/2024 **Kick-Off Meeting**
- ❑ **11/11/2025** first transmitter delivery
- ❑ **14/04/2026** second transmitter delivery




Courtesy of G. Granucci & HCD team

# Conclusions and discussion

- The Divertor Tokamak Test facility, under construction at ENEA Frascati, focuses on power and particle exhaust issues, integrating physics and technology aspects
- Flexibility is a key element of DTT
- Integrated modeling is in progress and new theory and simulation approaches are being developed by international collaboration network to address key physics issues
- The DTT research plan is being developed consistent with machine mission and vision/objectives: collaborations are welcome
- Tokamak are becoming more and more complex, **a deeper comprehension is needed,** primarily to simplify configurations

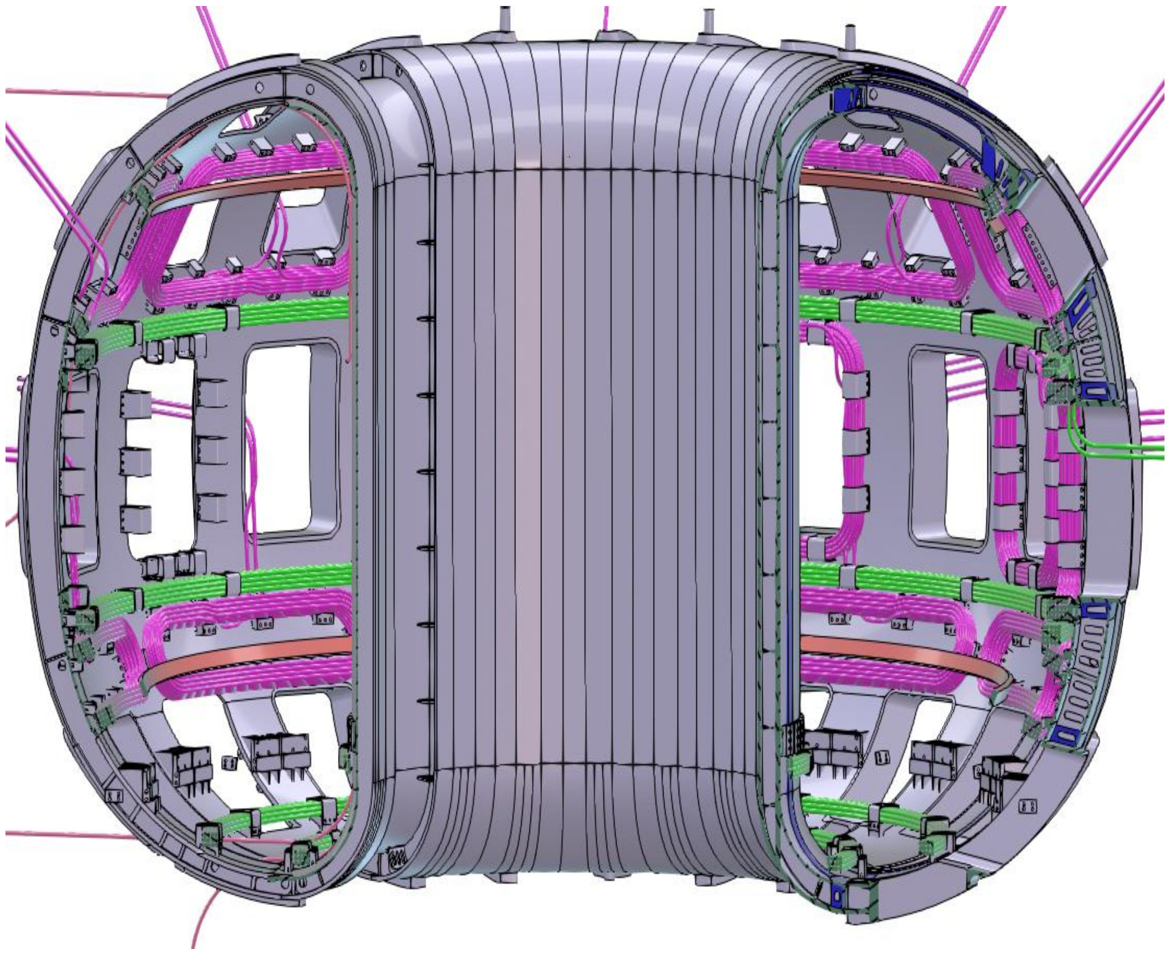
Thank you for your attention!

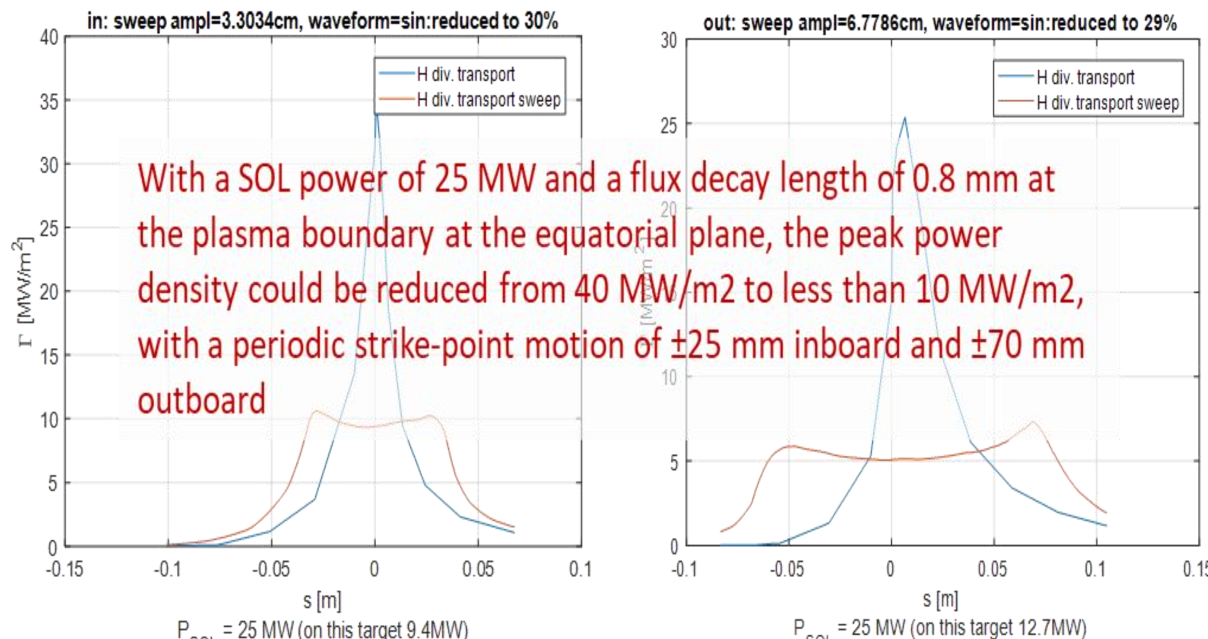
# Backup slides

# In-vessel coils and related power supplies

| Parameter\PS | DIV | VS | NAS |
|---|---|---|---|
| N. | 3 | 2 | 27 |
| Nominal current | ±5 kA | ±6 kA | ±2.5 kA |
| Nominal voltage | ±600 V | ±4 kV | ±550 V |
| Nominal duration | 40 s | 100 s | 100 s |

| PS | Contractor | Contract sign | Delivery |
|---|---|---|---|
| VS | OCEM | 08/05/2024 | Feb 2026 |
| DIV | OCEM | 08/05/2024 | Nov 2025 |
| NAS | EEI | 28/05/2024 | Oct 2025 |






For further detail please refer to the following paper:
- E.Acampora et al.Conceptual design of in-vessel divertor coils in DTT, FED, 2023

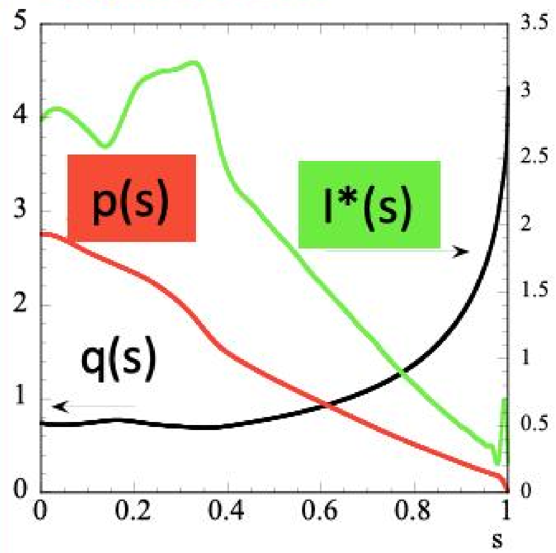
Courtesy of M. Dalla Palma & OVC team
A. Lampasi & PSS team

# Low-n MHD stability studies - I

Input data and profiles from JETTO steady state Full Power time snapshot (Casiraghi et al. EPS 2022)

Courtesy of V. Fusco, G. Vlad, G. Fogaccia, E.

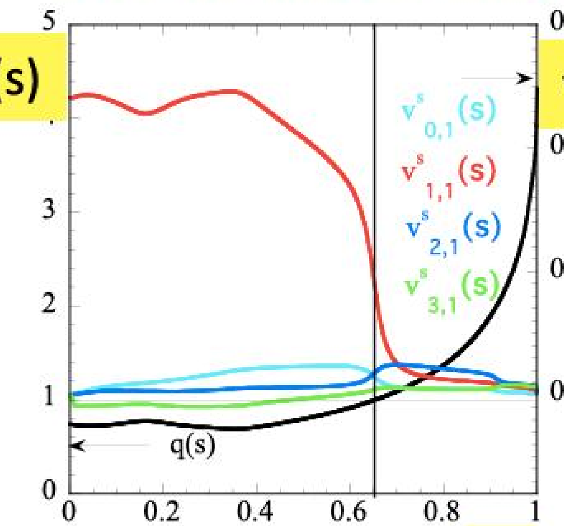
## Equilibrium

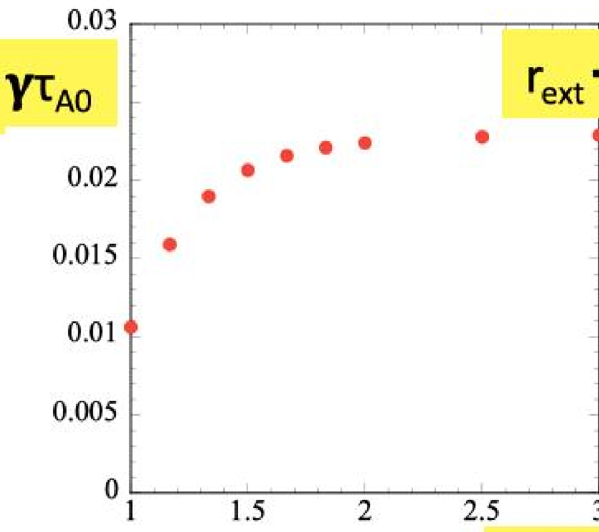



| | DTT |
|---|---|
| $I_{tot}$ MA | 5.489 |
| $q_0$ | 0.74 |
| $q_{95\%}$ | 2.84 |
| $q_{edge}$ | 4.3 |
| $\beta_{tor}\%$ | 1.89 |
| $\beta_N$ | 1.20 |
| $p_0/<p>$ | 4 |

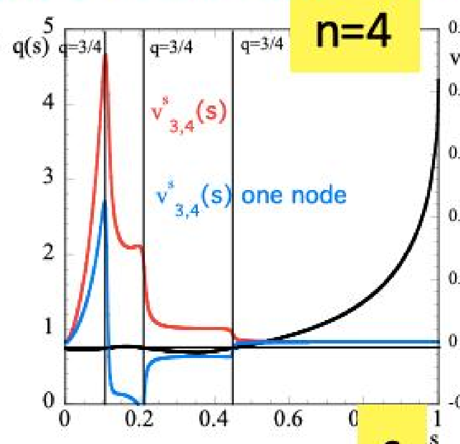
- The q=1 is located around s≈0.64 (no sawtooth model included so far)

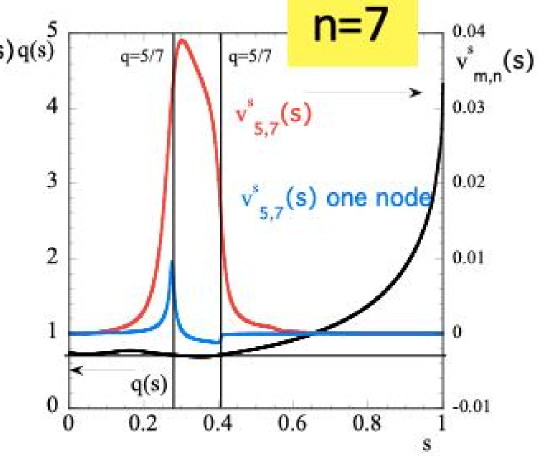
## Internal kink stability (m,n)=(1,1)

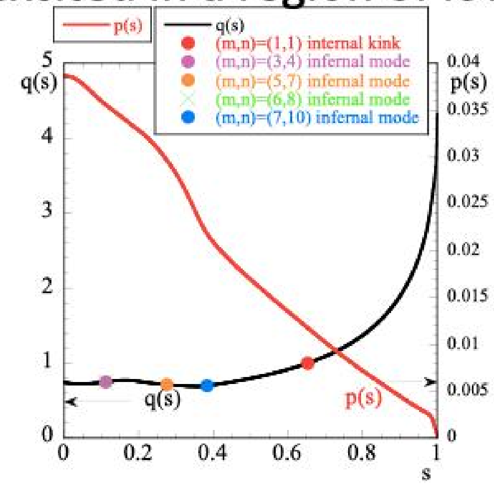


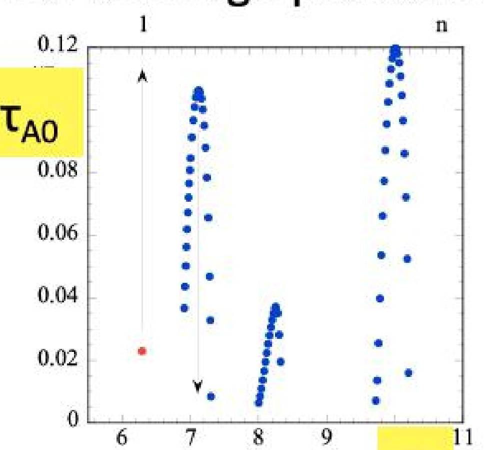




**Infernal mode stability (n≤10):** pressure driven modes excited in a region of low shear and high pressure gradient.



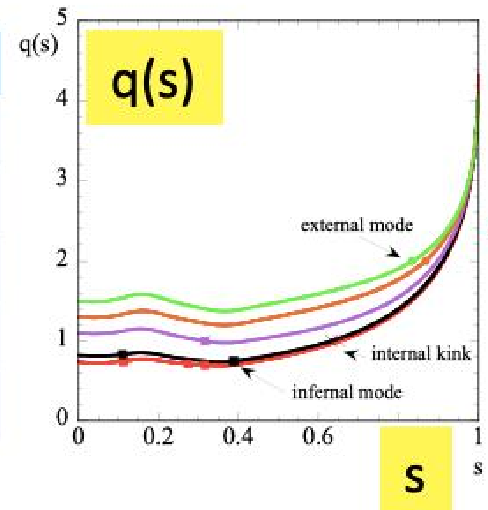



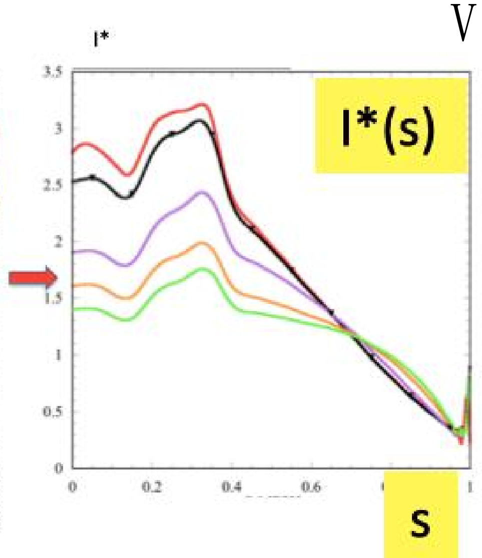
# Low-n MHD stability studies - II

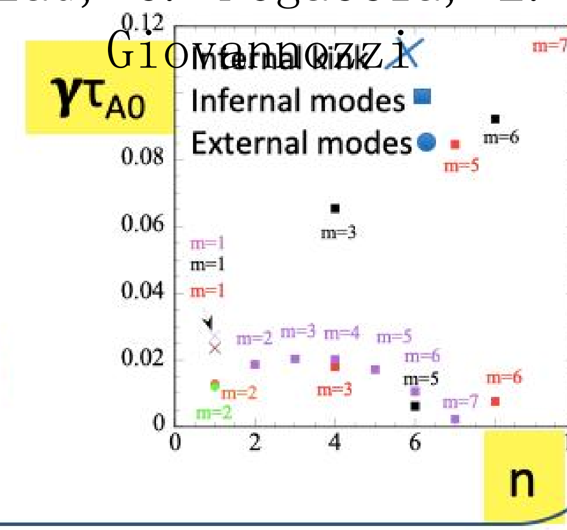
## Sensitivity analysis

Courtesy of V. Fusco, G. Vlad, G. Fogaccia, E. Giovannozzi

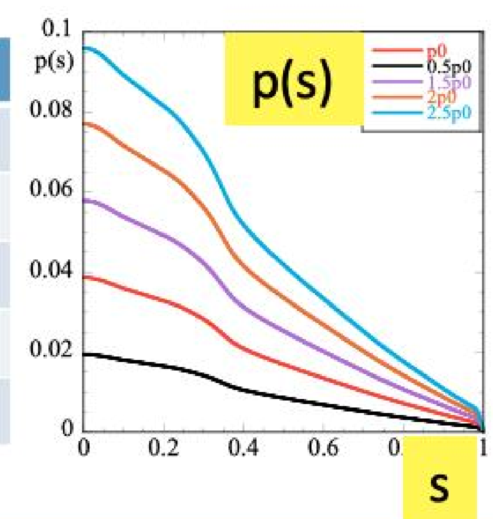
| q | $I_{tot}$ MA | $q_0$ | $q_{95\%}$ | $q_{edge}$ | $\beta_{tor}\%$ | $\beta_N\%$ |
|---|---|---|---|---|---|---|
| | 5.489 | 0.74 | 2.8450 | 4.3 | 1.89 | 1.20 |
| | 5.487 | 0.82 | 2.8747 | 4.0016 | 1.866 | 1.191 |
| | 5.327 | 1.10 | 2.9072 | 3.999 | 1.803 | 1.328 |
| | 5.315 | 1.3 | 2.9636 | 4.0067 | 1.675 | 1.263 |
| | 5.131 | 1.5 | 2.9965 | 4.0087 | 1.606 | 1.086 |

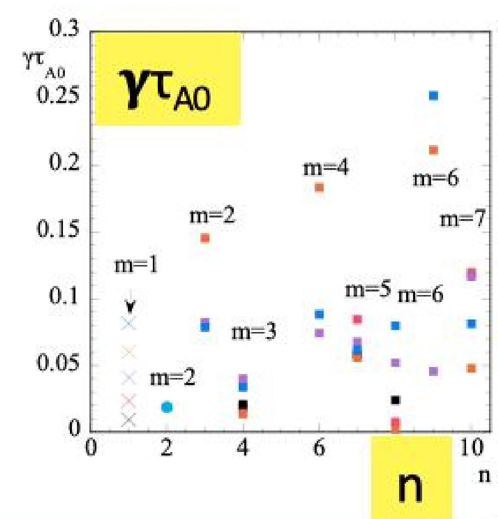



| p | $I_{tot}$MA | $q_0$ | $q_{95\%}$ | $q_{edge}$ | $\beta_{tor}\%$ | $\beta_N\%$ |
|---|---|---|---|---|---|---|
| p0 | 5.489 | 0.74 | 2.8450 | 4.3 | 1.89 | 1.20 |
| 0.5p0 | 5.505 | 0.75 | 2.82 | 4.2 | 0.0096 | 0.73 |
| 1.5p0 | 5.475 | 0.71 | 2.87 | 4.4 | 2.81 | 1.81 |
| 2p0 | 5.459 | 0.69 | 2.90 | 4.5 | 3.72 | 2.43 |
| 2.5p0 | 5.444 | 0.67 | 2.93 | 4.6 | 4.64 | 3.04 |




## Conclusion

- The internal kink exists as long as $q_0 \lesssim 1$ and the infernal modes are observed when q rational surfaces lie in the zone of low shear and high pressure gradient
- The appearance of external modes occurs for parameters far from the nominal scenario

# Full power including sawteeth

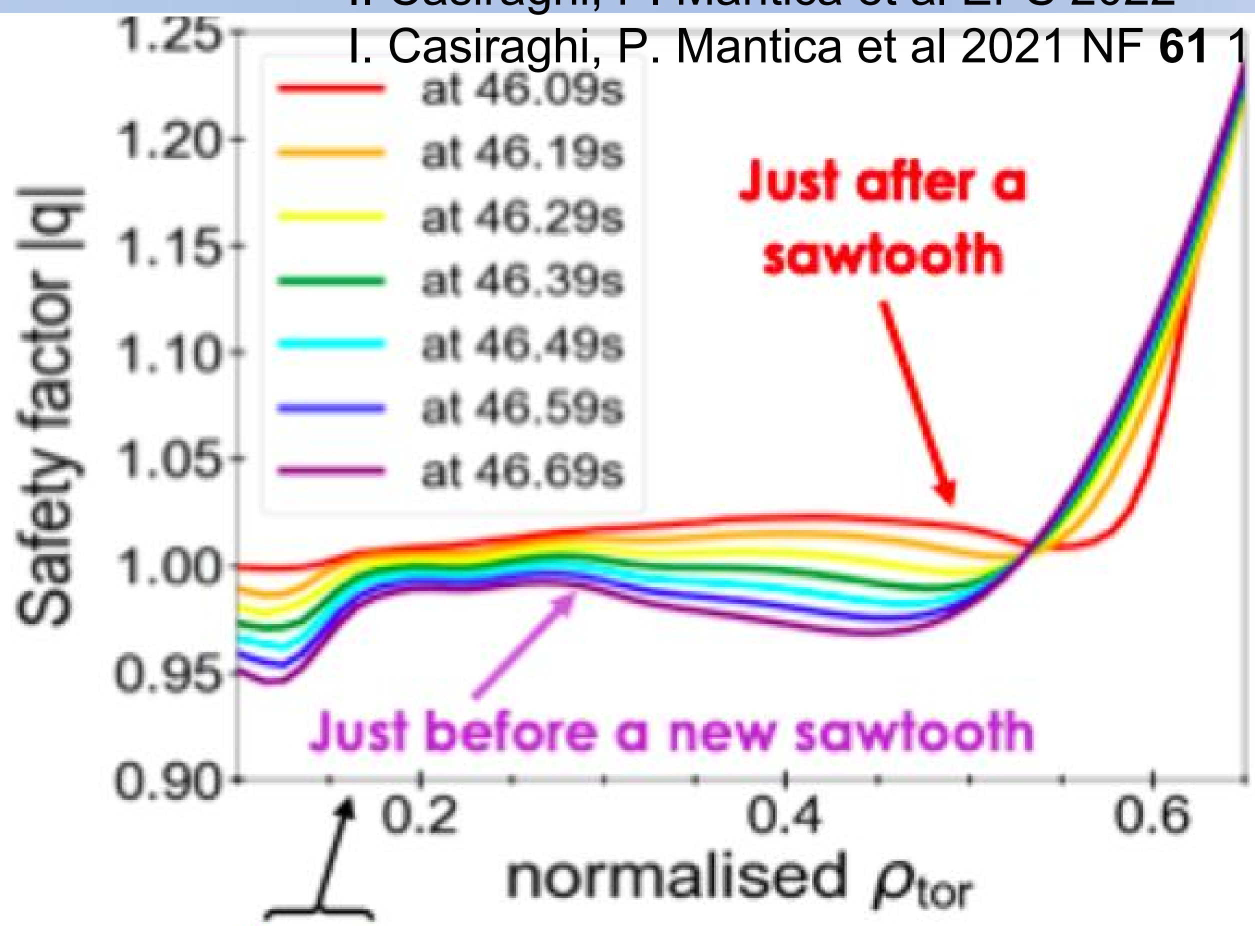
I. Casiraghi, P. Mantica et al EPS 2022

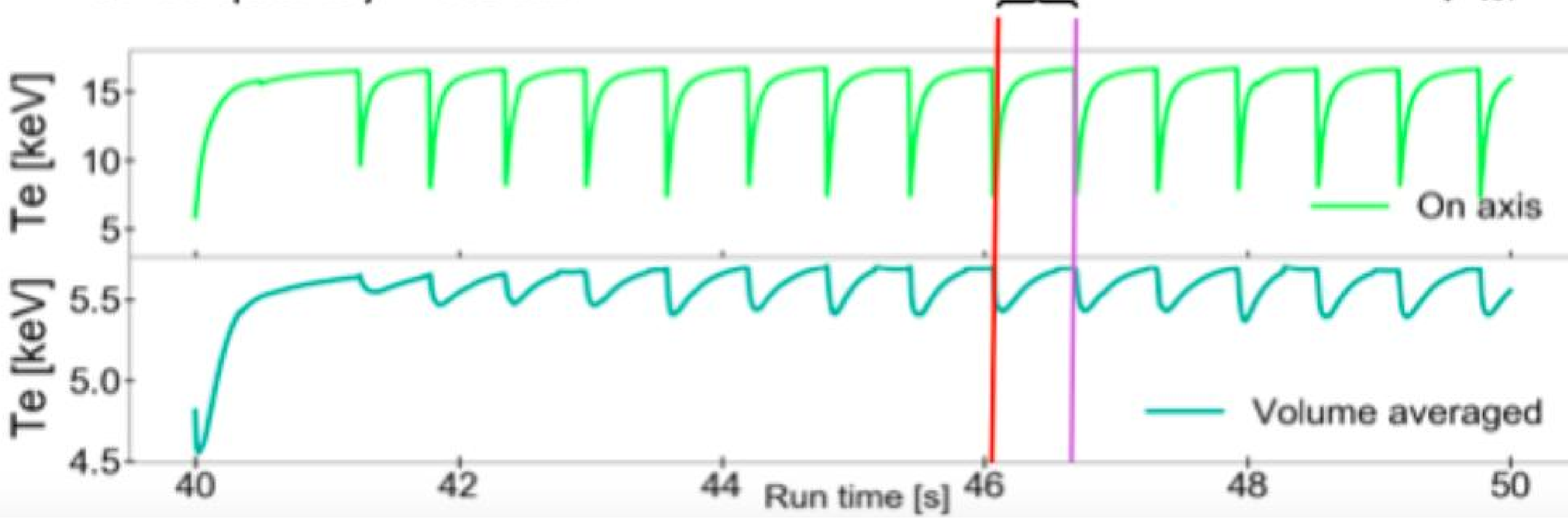
I. Casiraghi, P. Mantica et al 2021 NF **61** 116068

We repeated simulations of the FP SN PT scenario with

- the **BgB model** as turbulent transport model
- the **Porcelli model** to trigger the sawteeth (included fast ions)
- the **Kadomtsev model** for reconnection

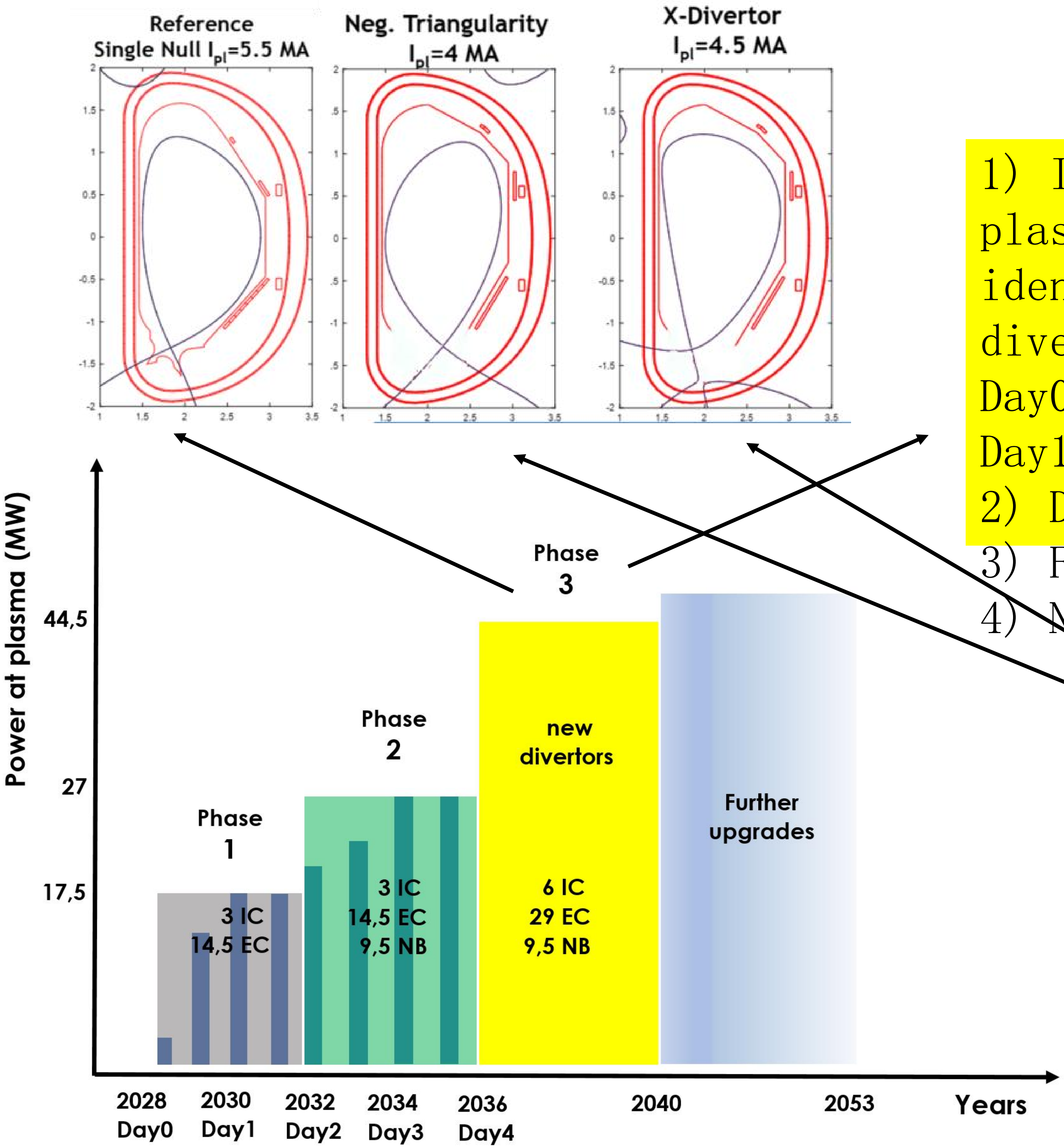
→ ST frequency ≈ **1.6 Hz**



# DTT experimental program - IV

Courtesy of F. Crisanti
DTT RP Kick Off Mtg Jul 8, 2022




1) In the first phase all the possible plasma scenarios will be tested to identify the most promising following divertor

Day0: $I_p$= 2 MA - $B_T$= 3 T

Day1: $I_p$= 4 MA - $B_T$= 6 T

2) Detachment studies (test divertors)

3) Full heating power

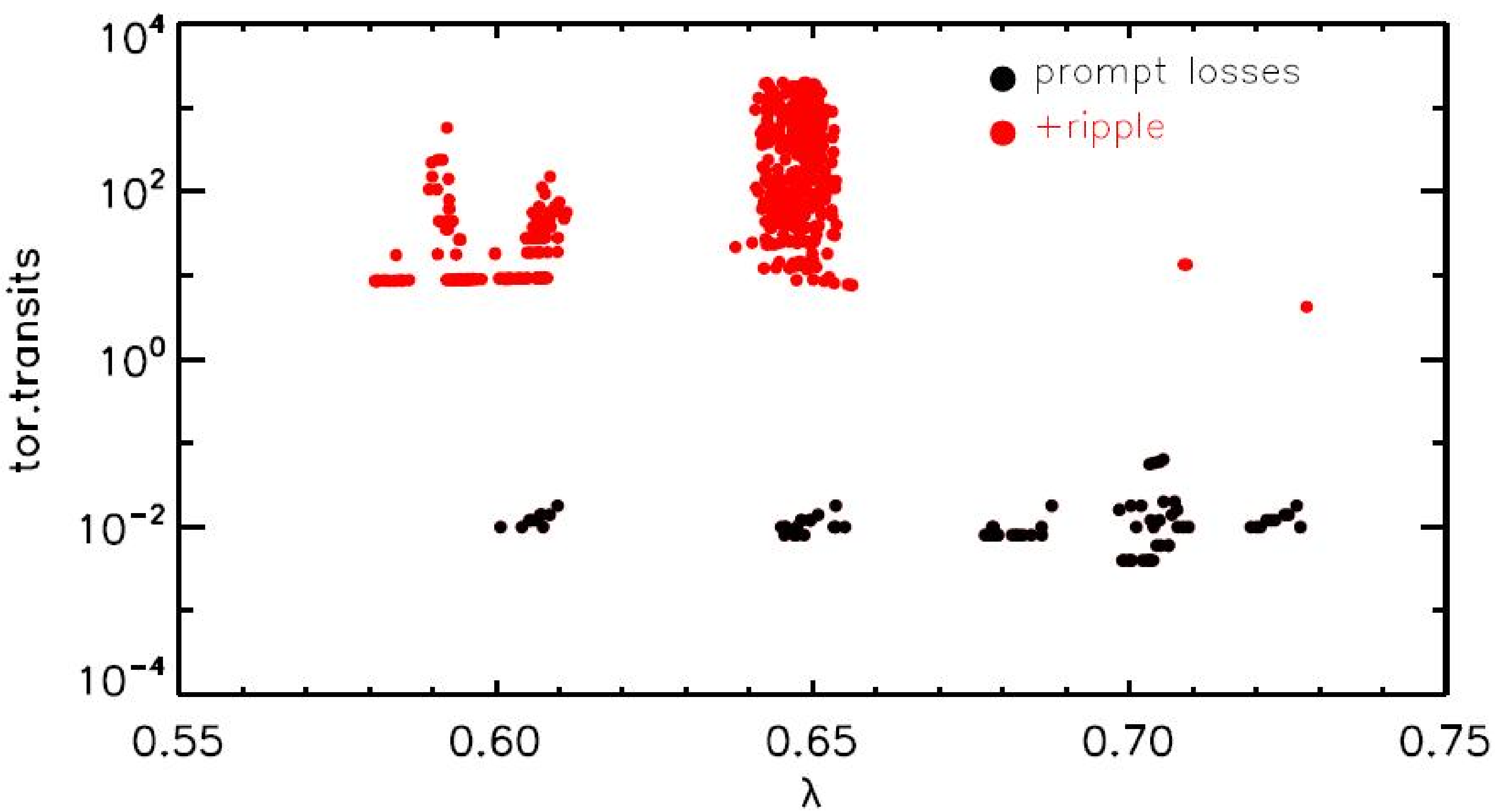
4) New divertor

**New divertor**

1. Shape?
2. Double null?
3. Negative triangulariry
4. Liquid metals
5. Others? …

# EP prompt and ripple losses

- Ripple losses amount to 0:07%, prompt losses ~0.01% (ORBIT run with 1M particles)
- Pitch angle of lost particles $\lambda_{res} \approx 0.65$ & 0.6




**Courtesy of G. Spizzo, M. Gobbin**
To be submited to *PPCF*

# Integrated simulation hierarchy

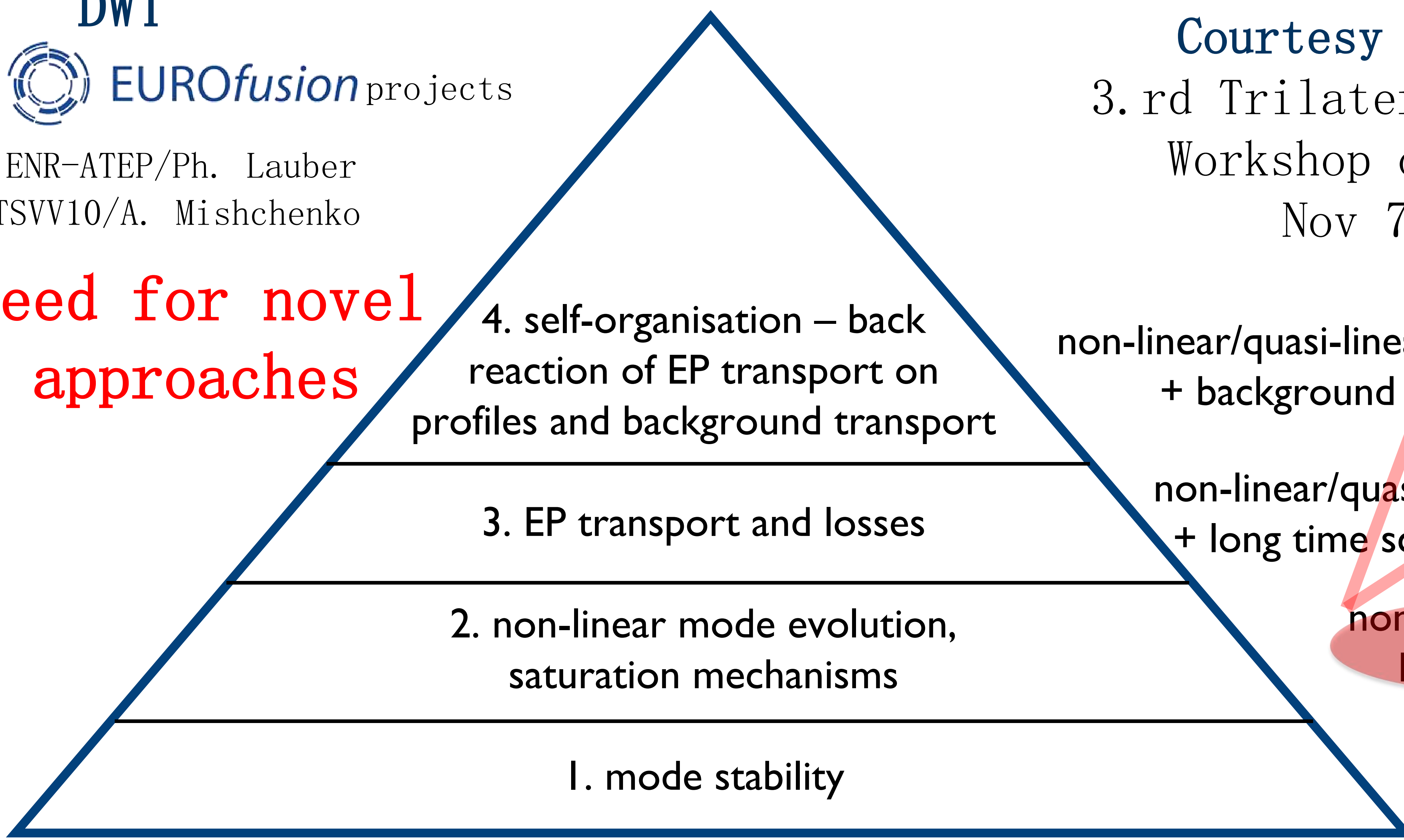
- Integrated simulation hierarchy for plasmas with significant EP energy density ➔ **Drift Alfvén Waves & DWT**

EUROfusion projects

ENR-ATEP/Ph. Lauber
TSVV10/A. Mishchenko

Courtesy of Ph. Lauber
3.rd Trilateral International Workshop on EP Physics, Nov 7-10, 2022

**Need for novel approaches**




non-linear/quasi-linear global kinetic + background transport

non-linear/quasi-linear global kinetic + long time scales (source + sink)

non-linear global kinetic e.m.

linear global kinetic e.m.

# The physics of burning plasmas

- Integrated simulations ➔ must address burning plasmas as complex self-organized systems

EUROfusion projects
ENR-ATEP/Ph. Lauber
TSVV10/A. Mishchenko

L. Chen & FZ, RMP 88 015008 2016
FZ, L. Chen et al, NJP 17 013052 2015

Multi-spatiotemporal scale fluctuations

Turbulence & fluctuation driven fluxes

Plasma and fusion reactivity profiles

Drift Alfvén Waves
MHD & DWT

Meso & macro-scale distortion of equilibrium

NL wave-particle

NL wave-wave

M. V. Falessi & FZ, POP 26 022305 2019
L. Chen, Z. Qiu, FZ, NF 62 094001 2022
L. Chen, Z. Qiu, FZ, POP 29 050701 2022