This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

20th ICPP, Hico, Gyeongju, Korea
December 1st, 2022

EUROfusion

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

Fulvio Zonca[1] and the DTT Team[2+]

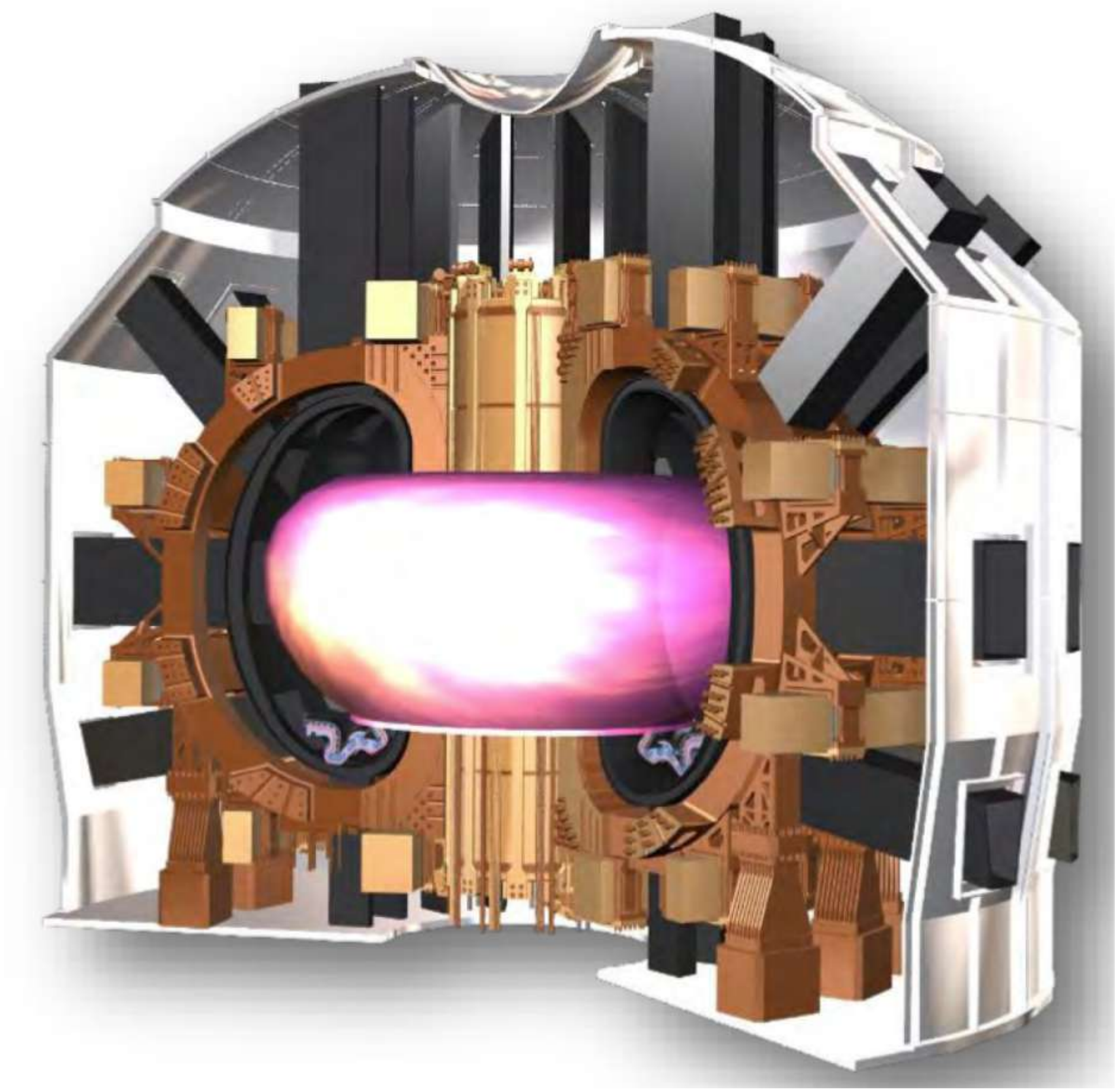
[1]Center for Nonlinear Plasma Science and ENEA FSN Department, Frascati, Italy
[2]DTT S.C. a r.l., 00044 Frascati, Italy

*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

Divertor Tokamak Test facility - I

Divertor Tokamak Test (DTT) facility



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

First plasma expected Spring 2028

EXPECTED COST ~ 500M€

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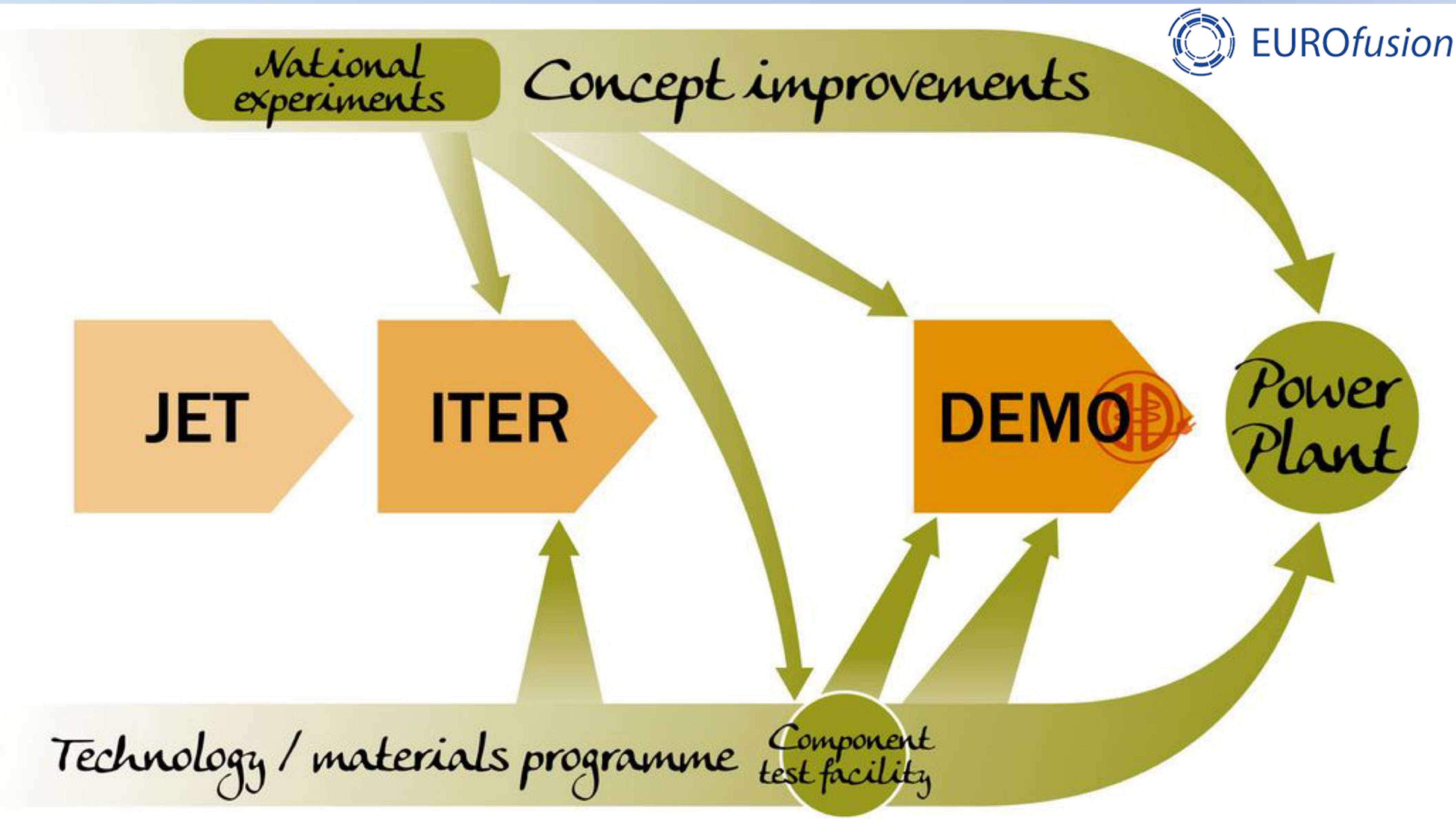
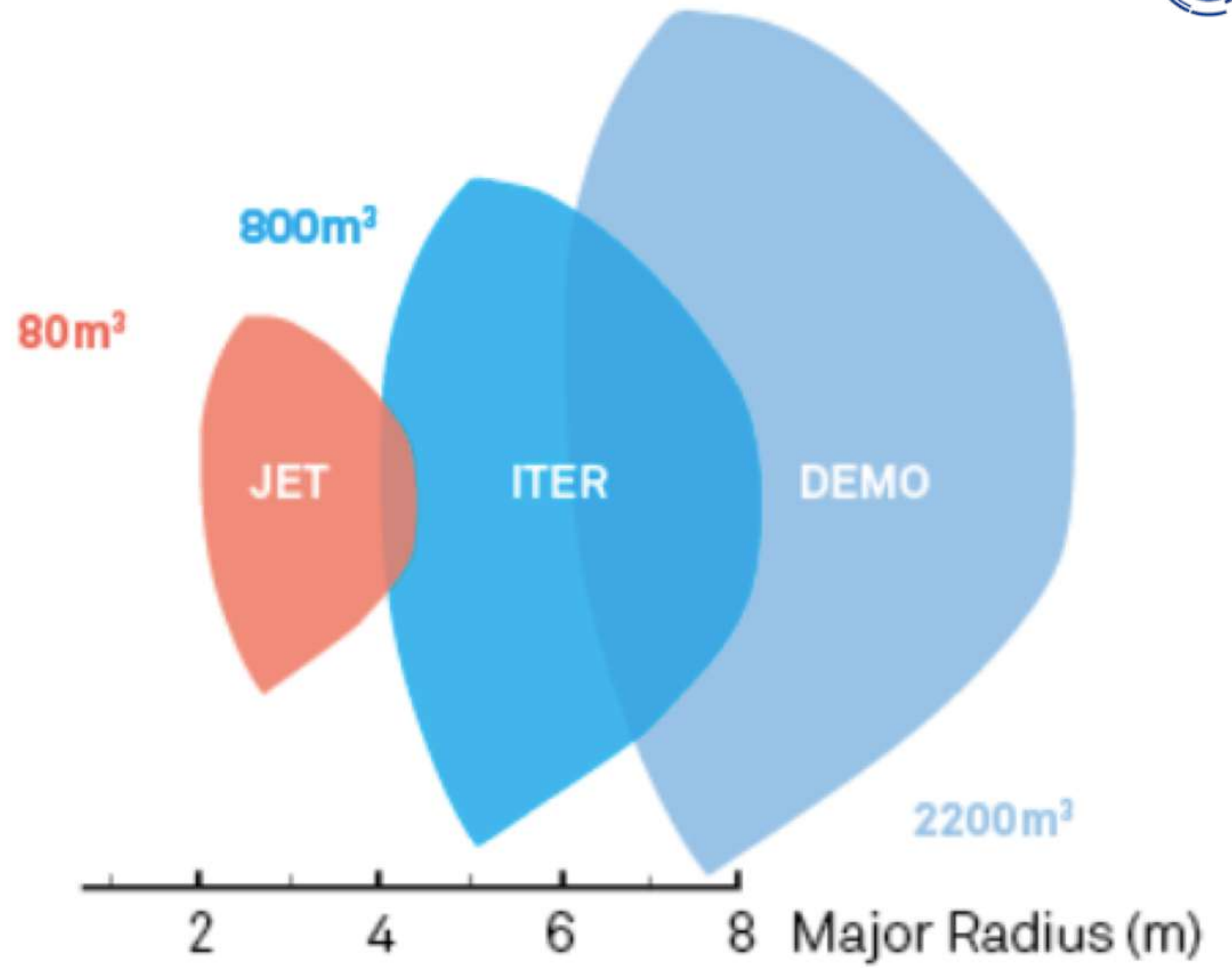
A roadmap to fusion energy…



Graphic: EUROfusion / CCFE

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

…increasing size/cost



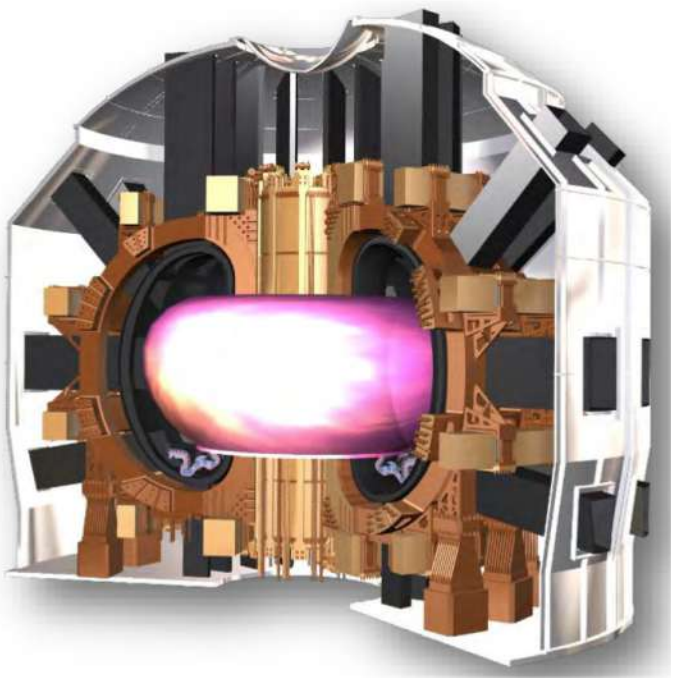
…a challenge for technology

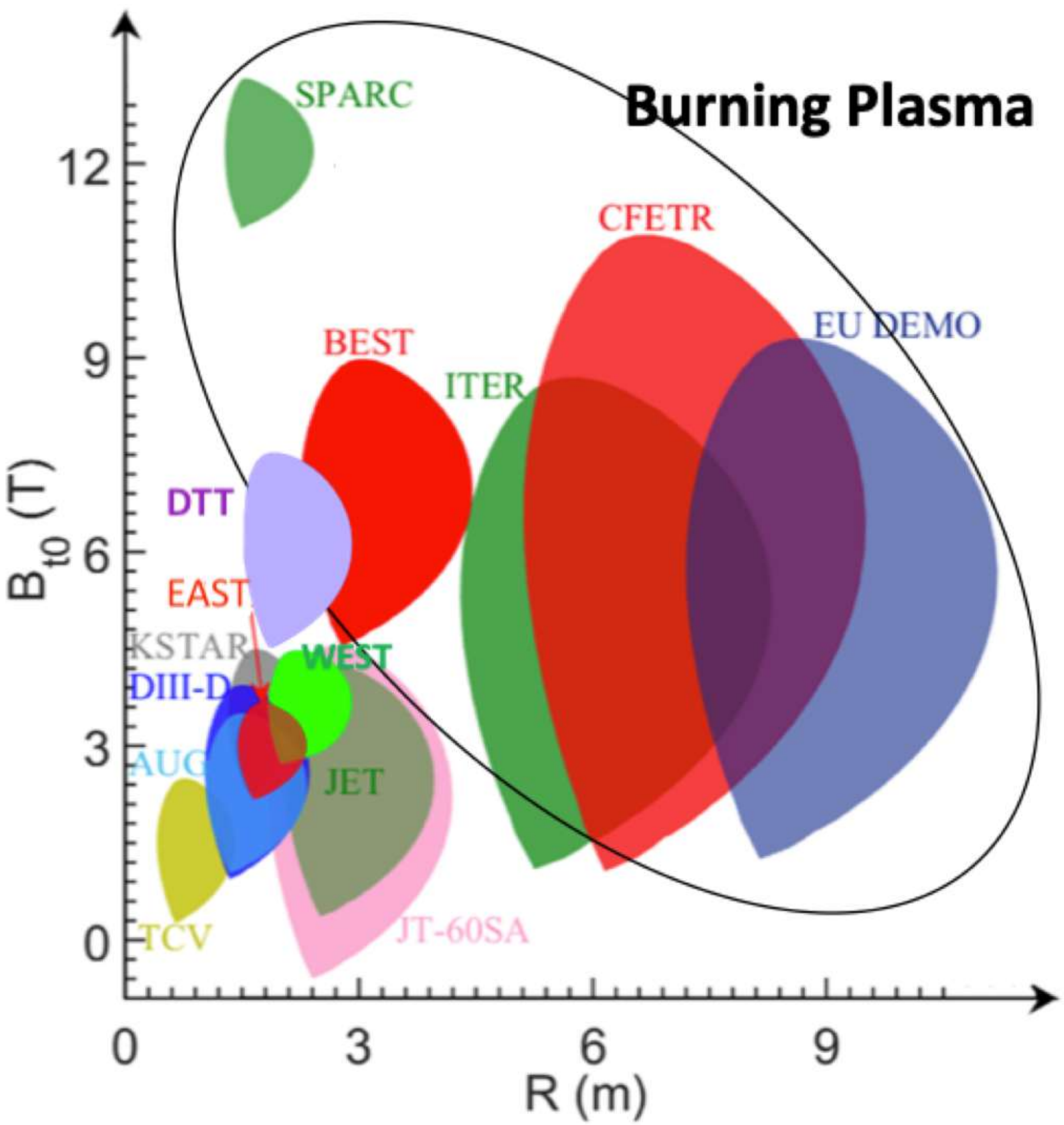
…and for physics

Divertor Tokamak Test facility - II

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

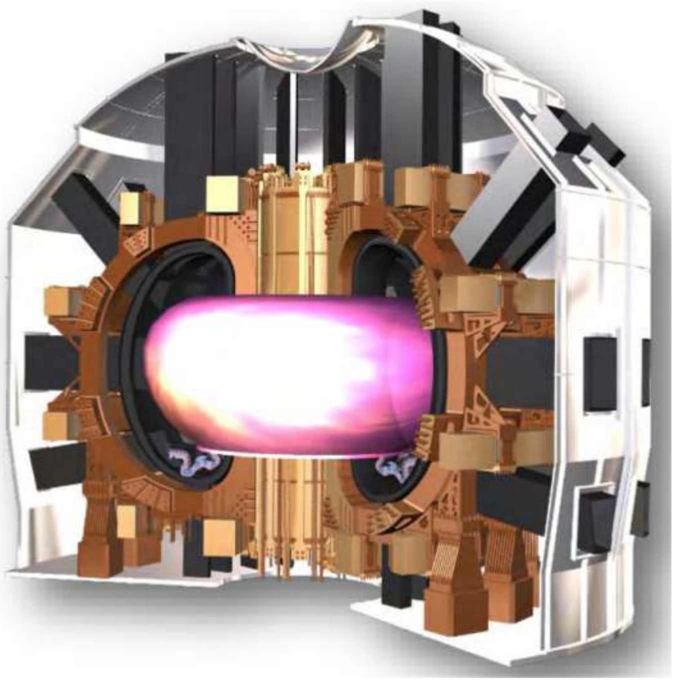
Courtesy of B. Wan
3.rd Trilateral International Workshop on EP Physics, Nov 7-10, 2022

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 (equiv)	10	<1 (~ 1)	($\gtrsim$ 1)

Divertor Tokamak Test facility - III

Divertor Tokamak Test (DTT) facility



- One of the key issues towards demonstration of fusion energy is Power & Particle EXhaust (PPEX)
    - Mission for DTT
- 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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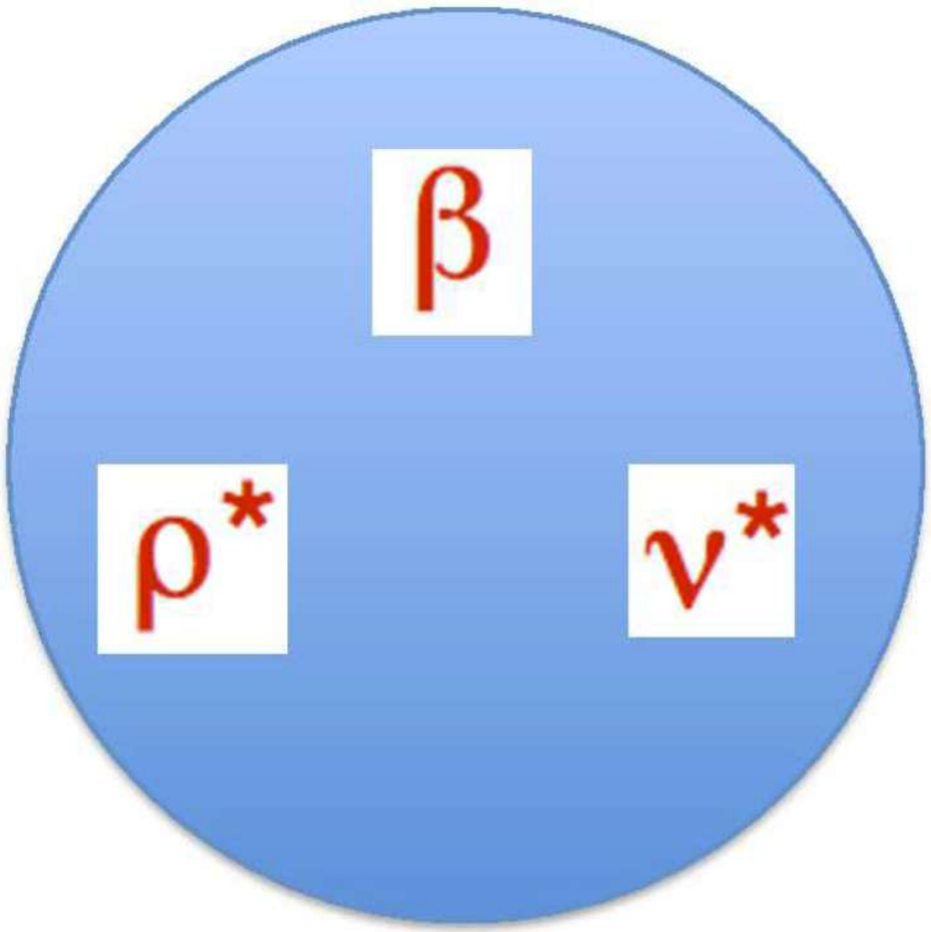
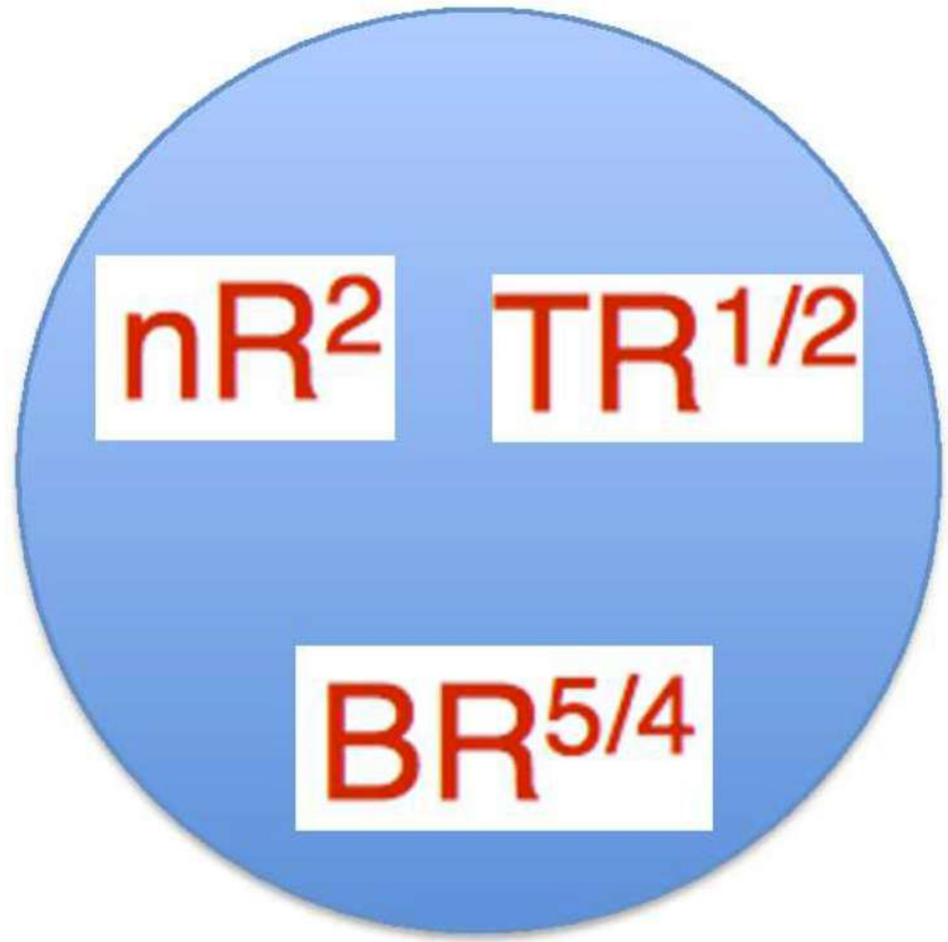
DTT physics rationale - I

- The operation space of quasi-neutral, collisional, finite-β plasmas





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

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

DTT physics rationale - II

- **Weak Kadomtsev scaling** [Pizzuto et al NF2010]:
  ➔ fix $\rho_*^{\epsilon}R$, β, ν_*
  - Weak scaling of $\rho_*^{\epsilon}R$
    - Cross-scale coupling (micro-meso scales) is preserved;
    - Preserve ρ_{*EP}/ρ_* set by T_{EP}/T , given by condition of dominant electron heating
  - Fix β and stability
    - Preserve temporal scale hierarchy: frequency ordering of meso- to macro-scale fluctuations
  - Fix collisionality parameter ν_*
    - Preserve edge physics and PWI (PPEX)
    - Preserve supra-thermal particle content in the core

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DTT physics rationale - III

- 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)	λ_q (mm)	R (m)	$q_{//}$ (GW/m^2)	q_{pol} (GW/m^2)
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
β_N	1.5	2.2	1.5
ν^* (10^{-2})	2.4	1.4	2.4
ρ^* (10^{-3})	1.7	1.5	3.7
ν^*_{ped} (10^{-2})	6.2	4.5	6.3
ρ^*_{ped} (10^{-3})	1.6	3.3	1.3

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

DTT flexibility

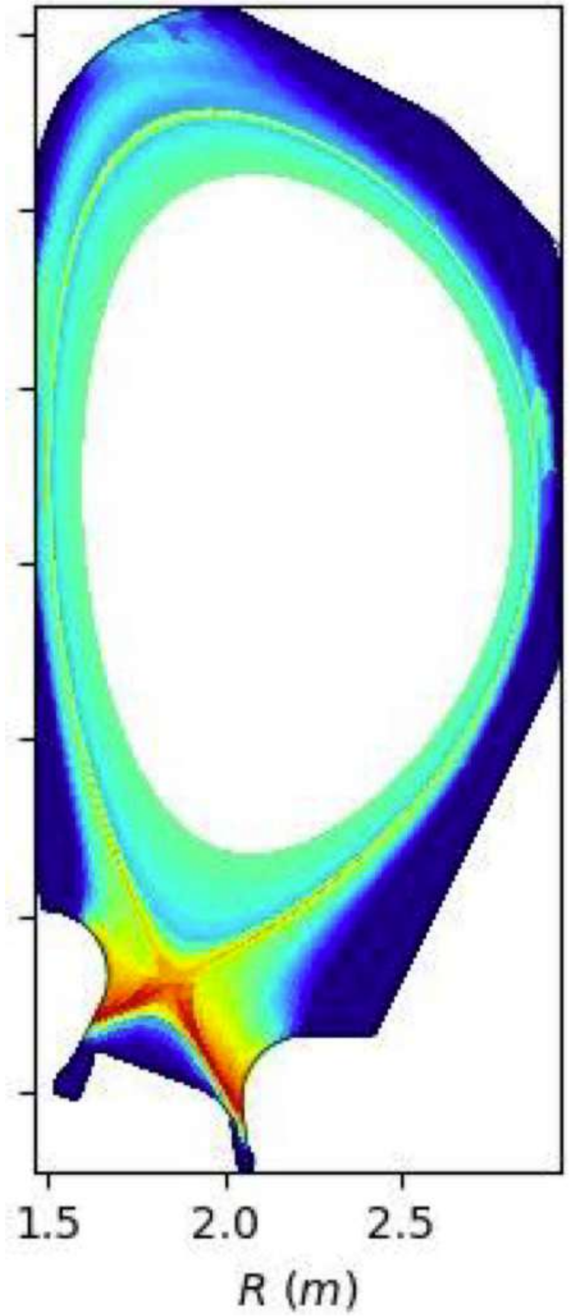
- Flexibility of plasma scenarios - different divertor magnetic topologies: XS(tandard), XD(Second null), N(egative)Triang.
  - a) I_p= 2 MA - B_T= 3 T; P_{add} ~ 8÷35MW
  - b) I_p= 5.5 MA - B_T= 6 T; P_{add} ~ 27÷45MW
- Flexibility in density ➔ study detachment for $\langle n \rangle \sim 1 \div 2 \times 10^{20}\ m^{-3}$
- 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 scenarios

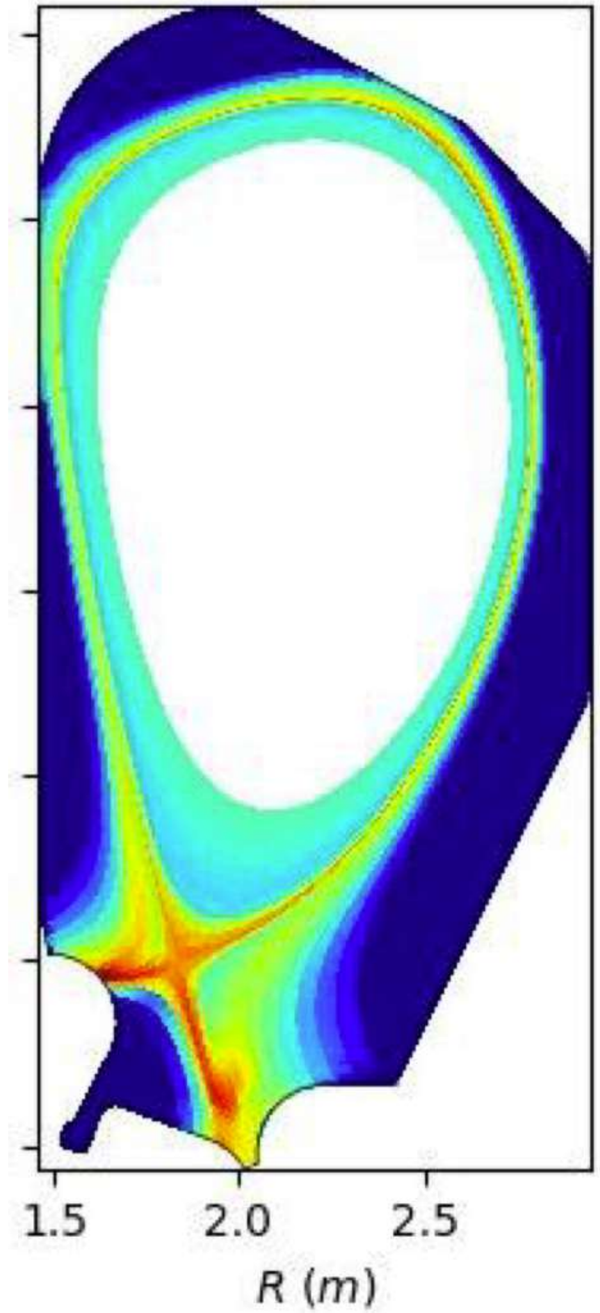
Courtesy of F. Crisanti
DTT RP Kick Off Mtg Jul 8, 2022

- Three main scenarios

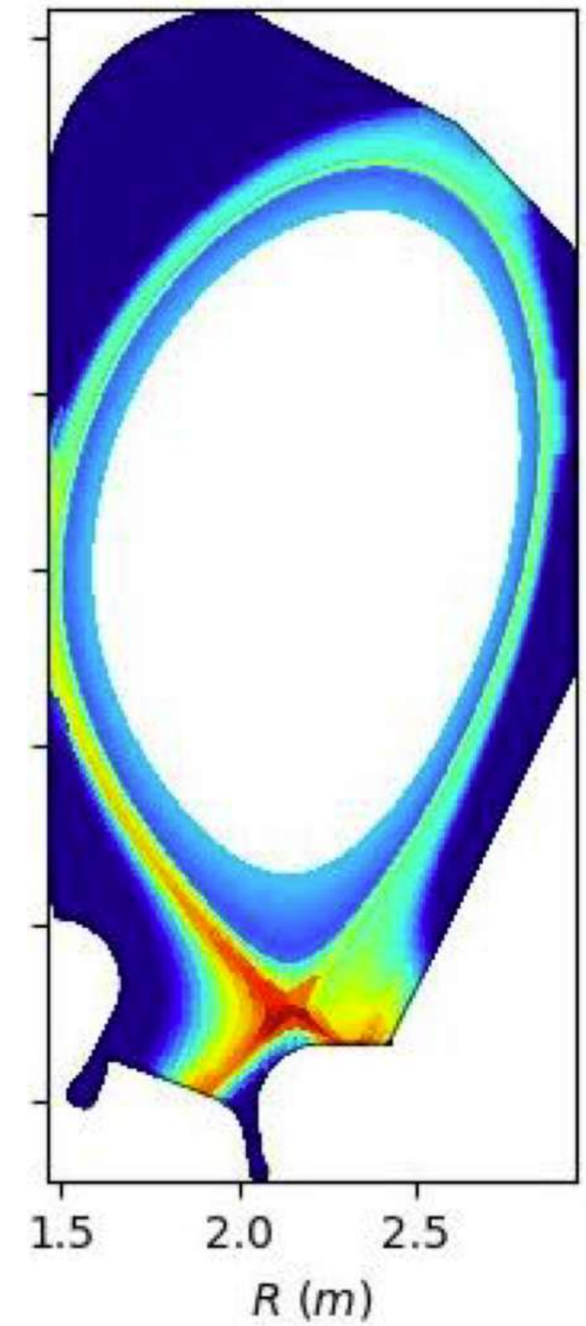
SN 5.5MA



XD 4.5MA



NT 4.0MA

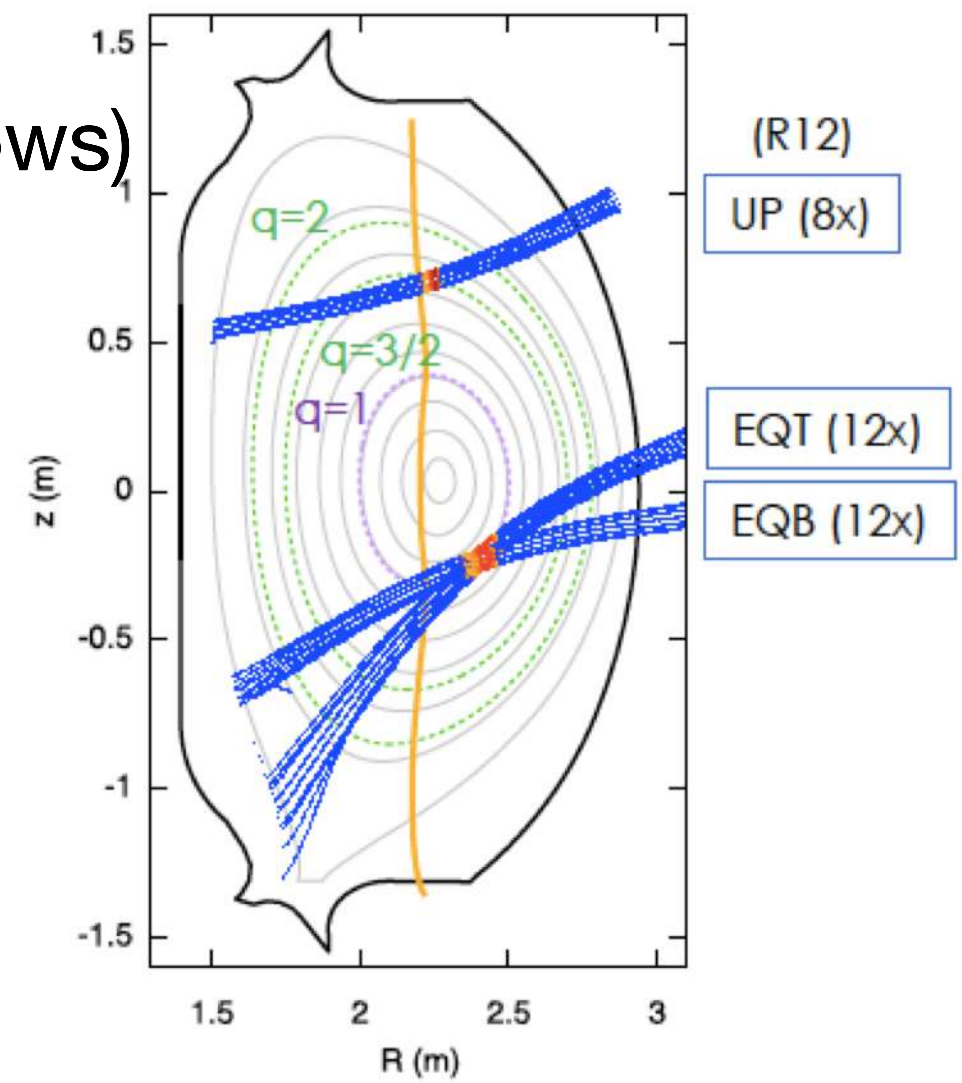


DTT heating mix - I

- 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

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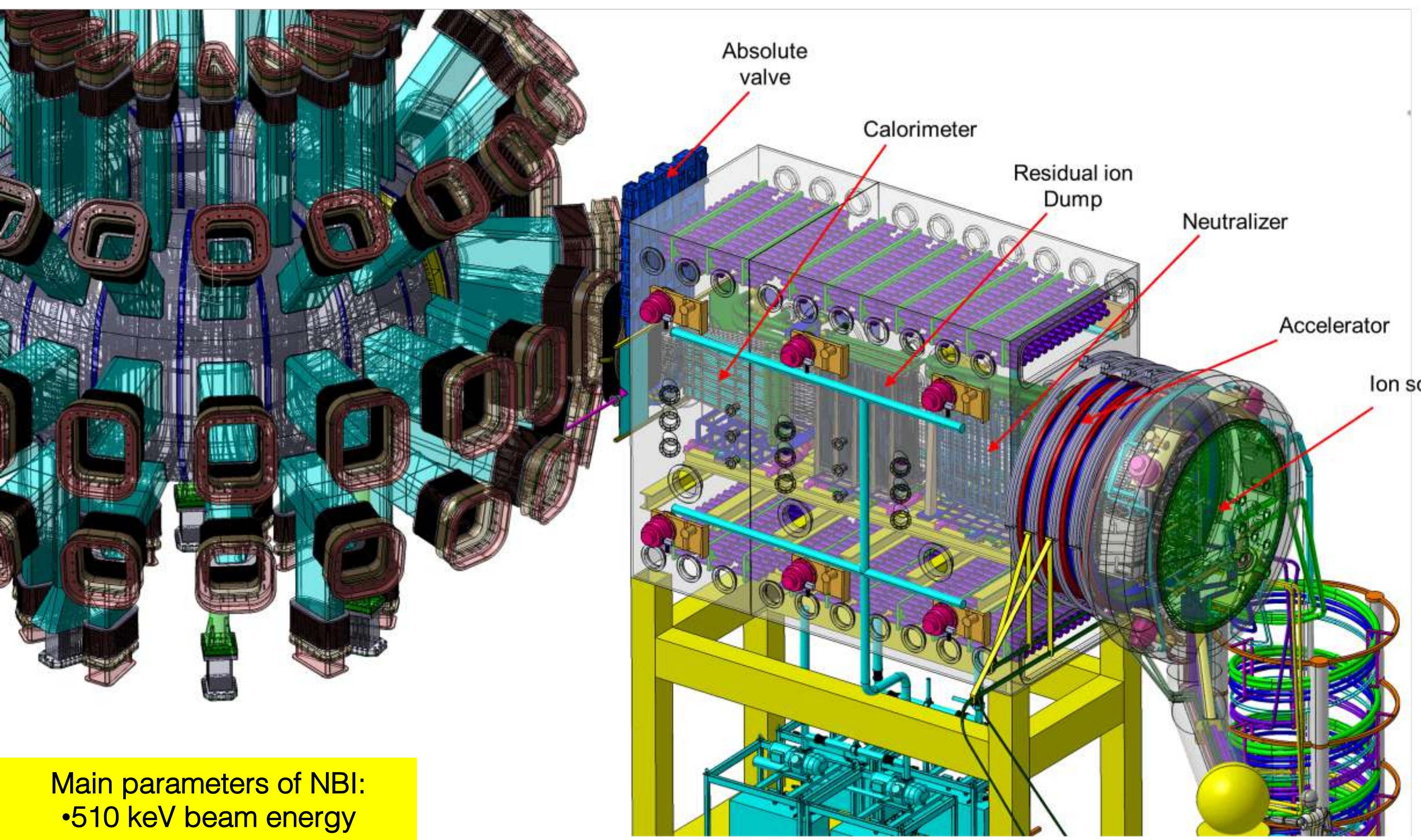
DTT heating mix - II

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

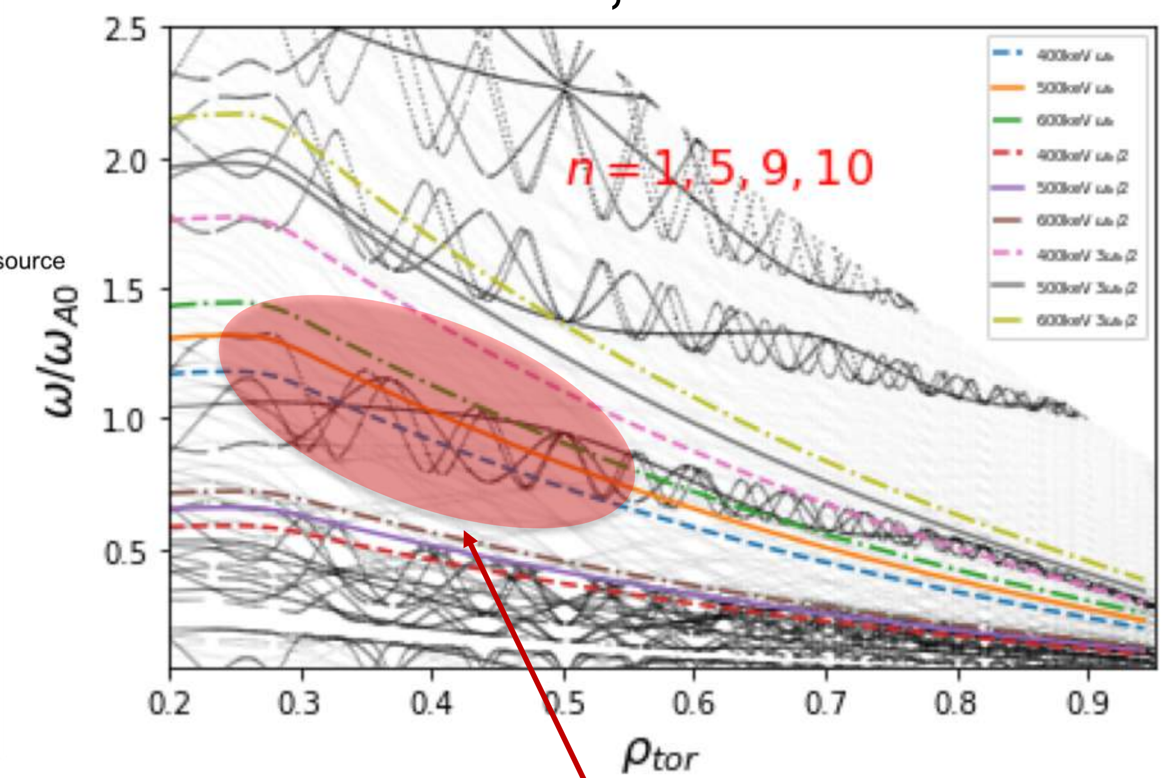
DTT tokamak



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

Courtesy of P. Agostinetti, Oct 14, 2022

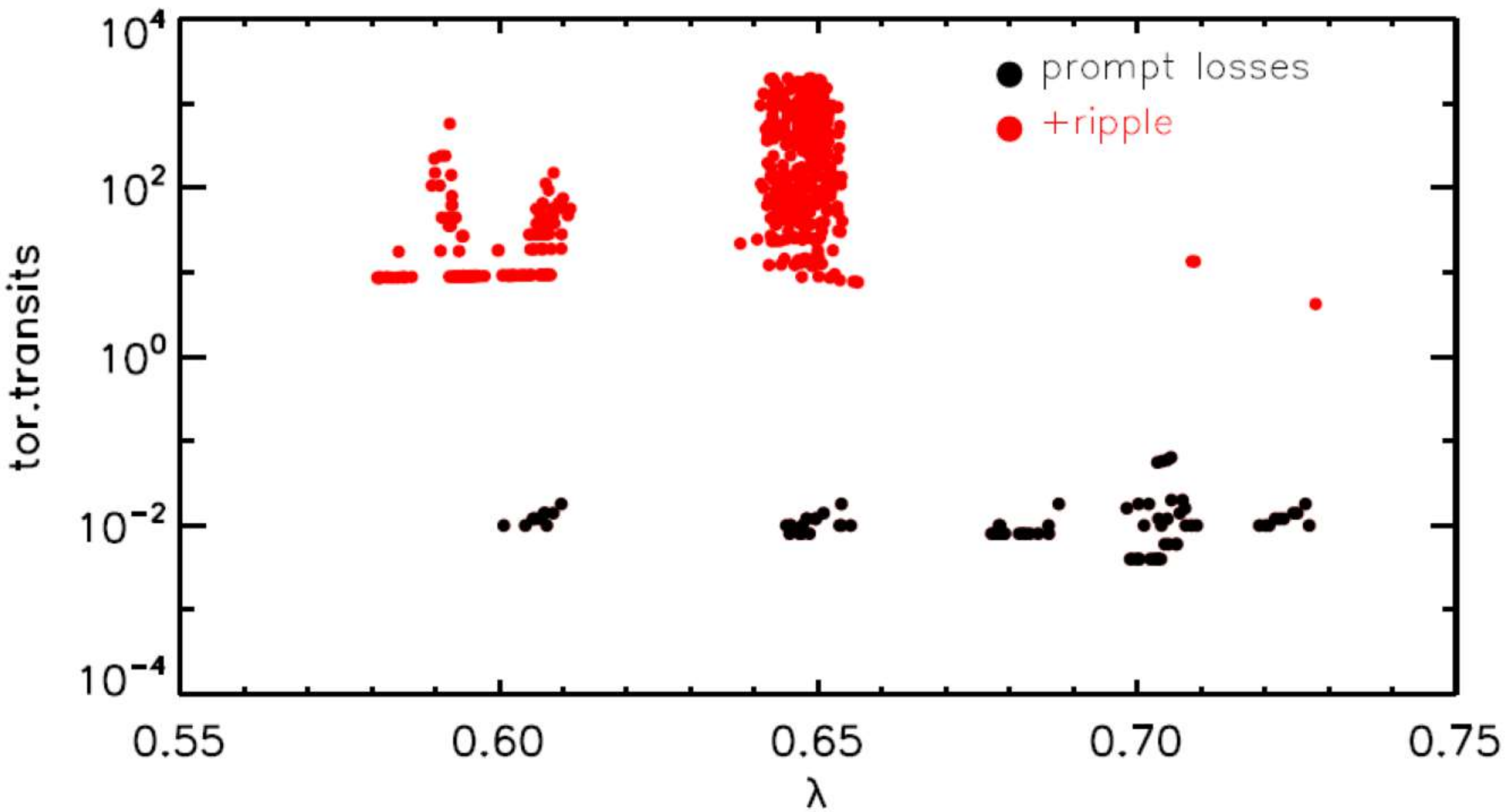
Courtesy of Y. Li, Nov. 15, 2022



Super- Alfvénic Beam

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*

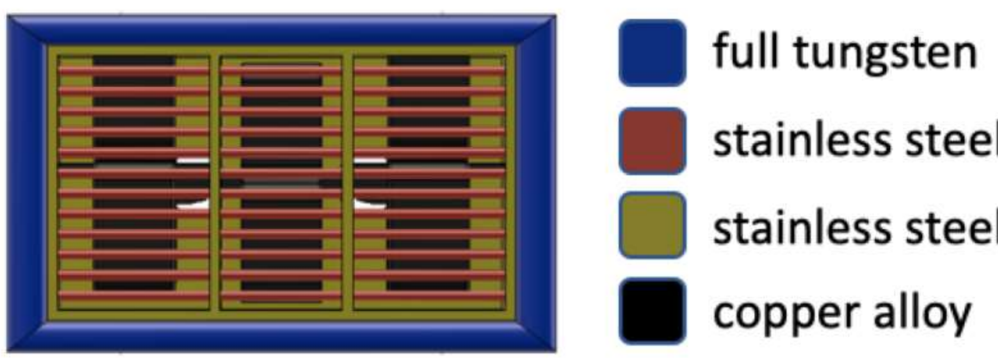
DTT heating mix - III

- 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

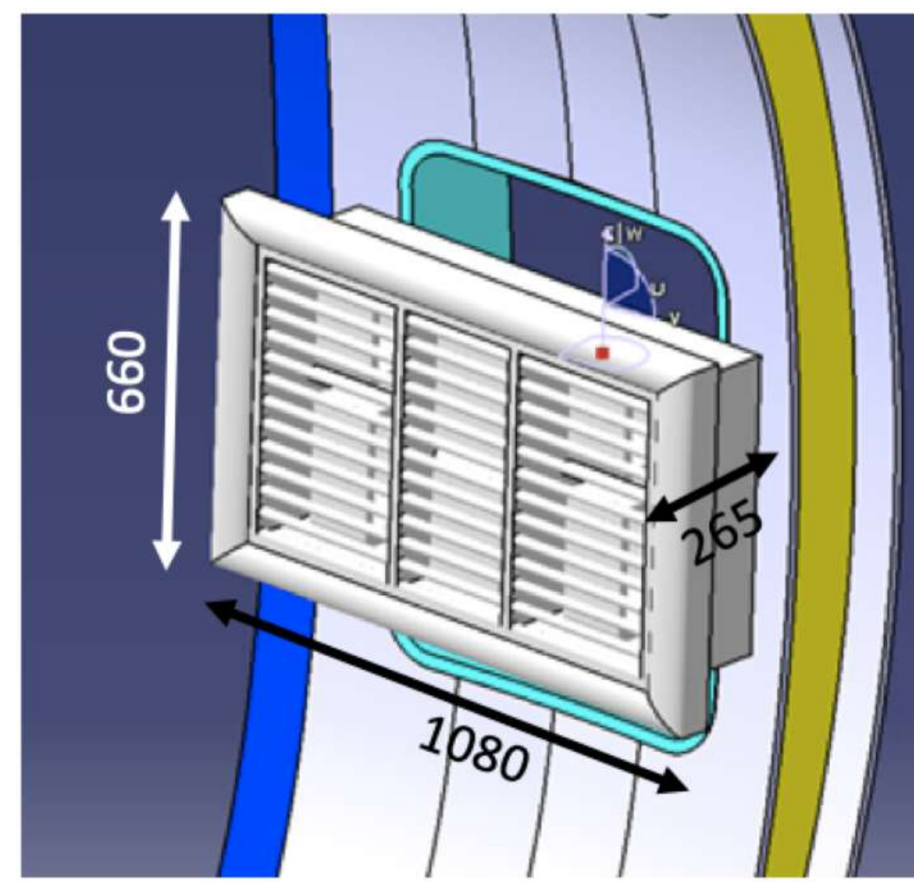
Courtesy of S. Ceccuzzi
24th Topical RF Conf.
Sep 26-28, 2022

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.

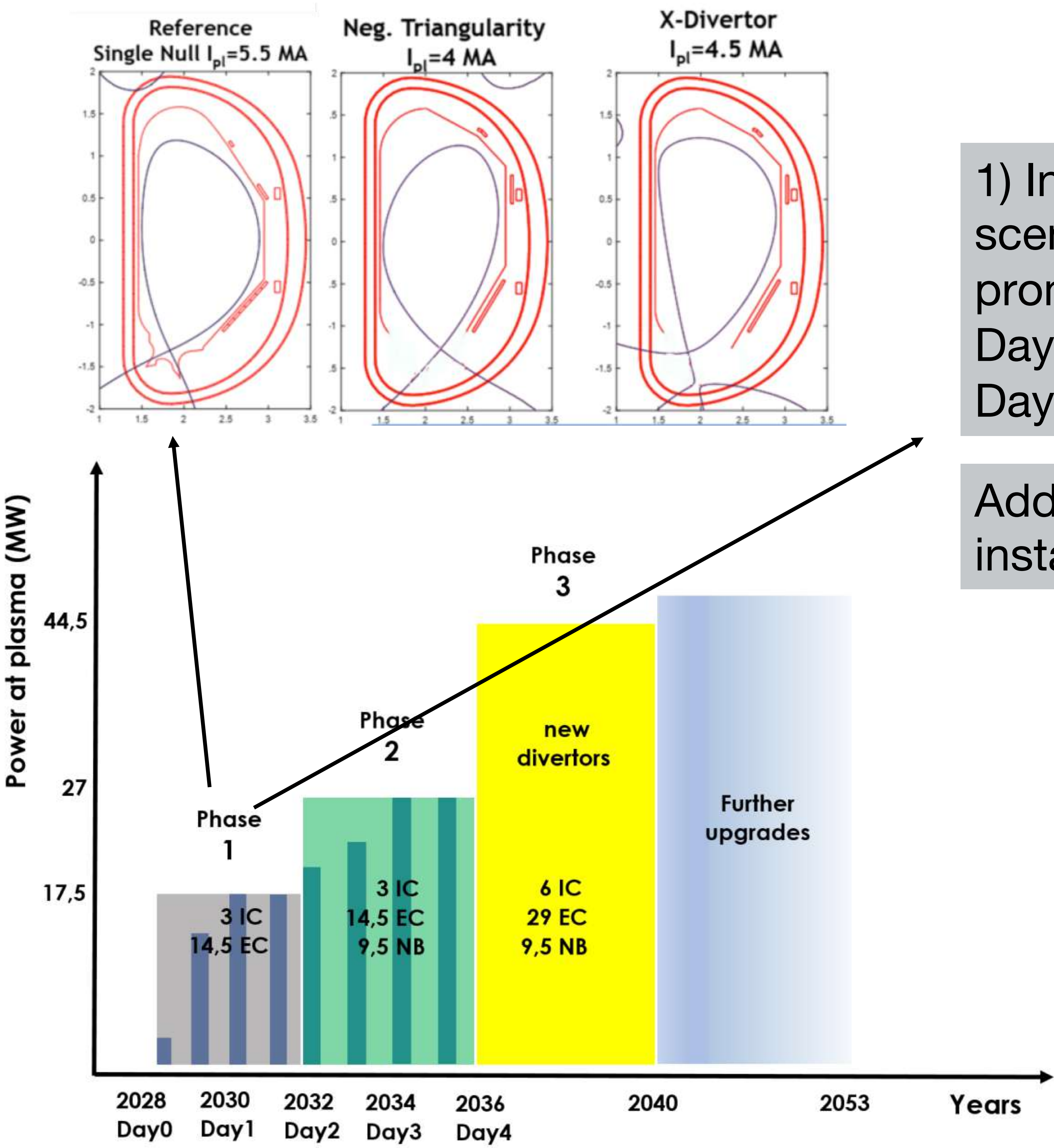
- *Material choice on-going. Preliminary ideas:*



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



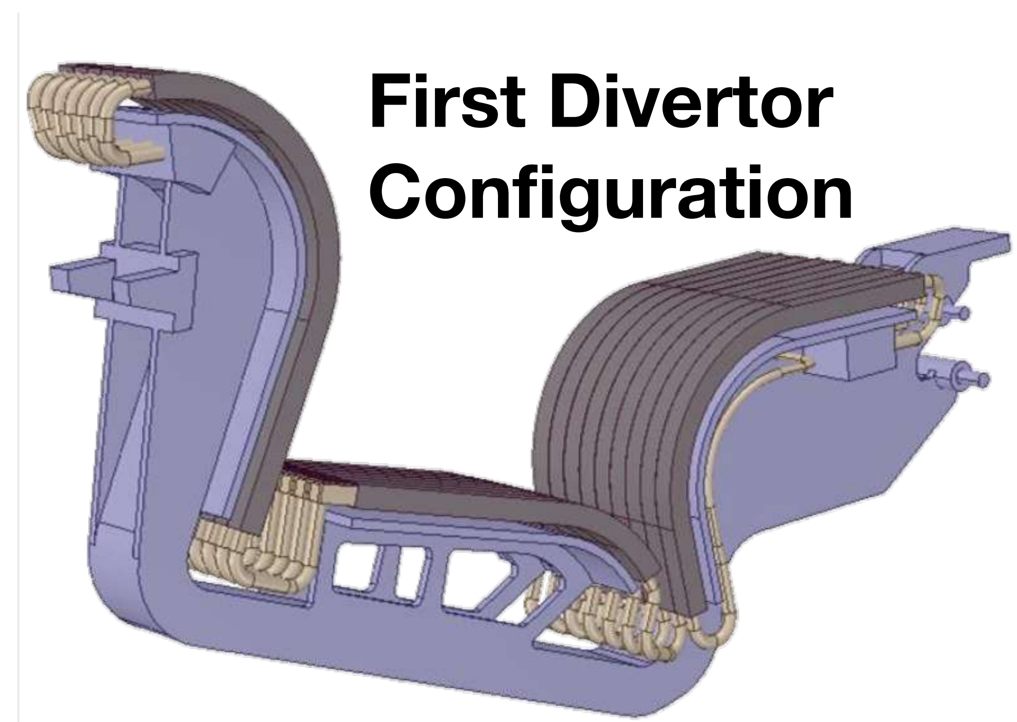
DTT experimental program



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



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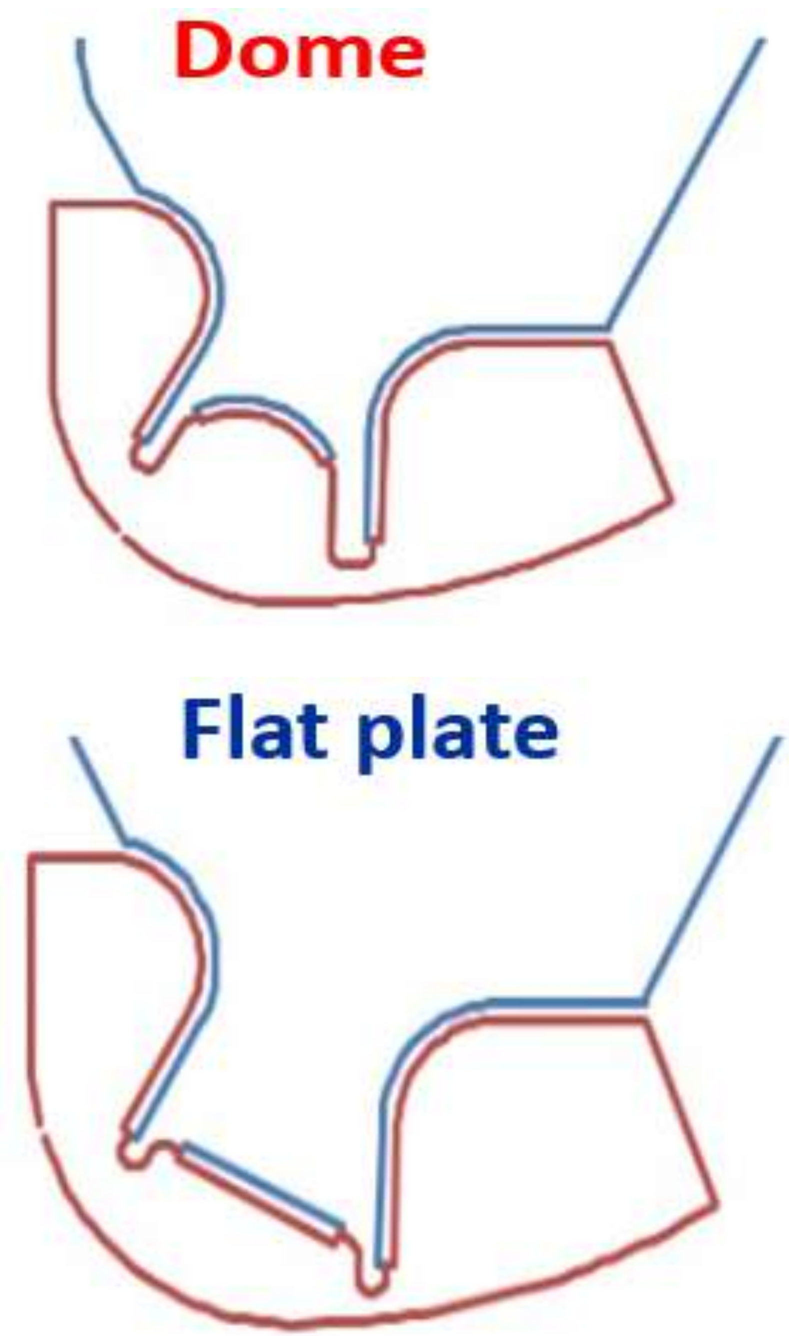
Dome studies with SOLPS-ITER

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 by 10)



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

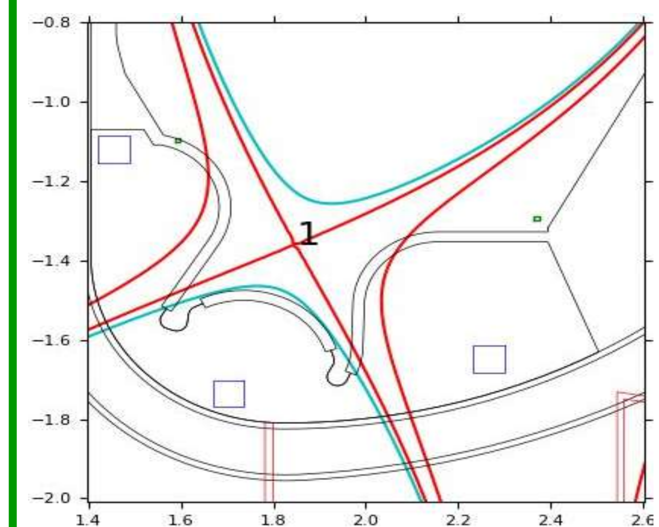
Shape optimization with SOLEDGE2D-EIRENE

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

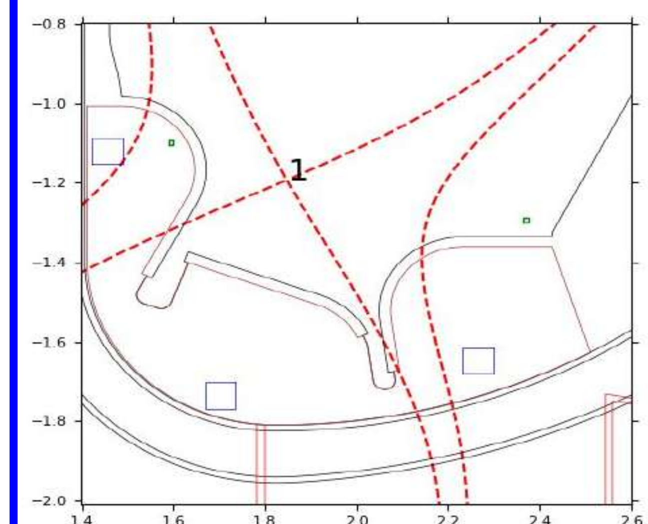
Optimize divertor shape in DTT full power scenario :
P_{AUX} = 45MW with Ne and Ar seeding

- 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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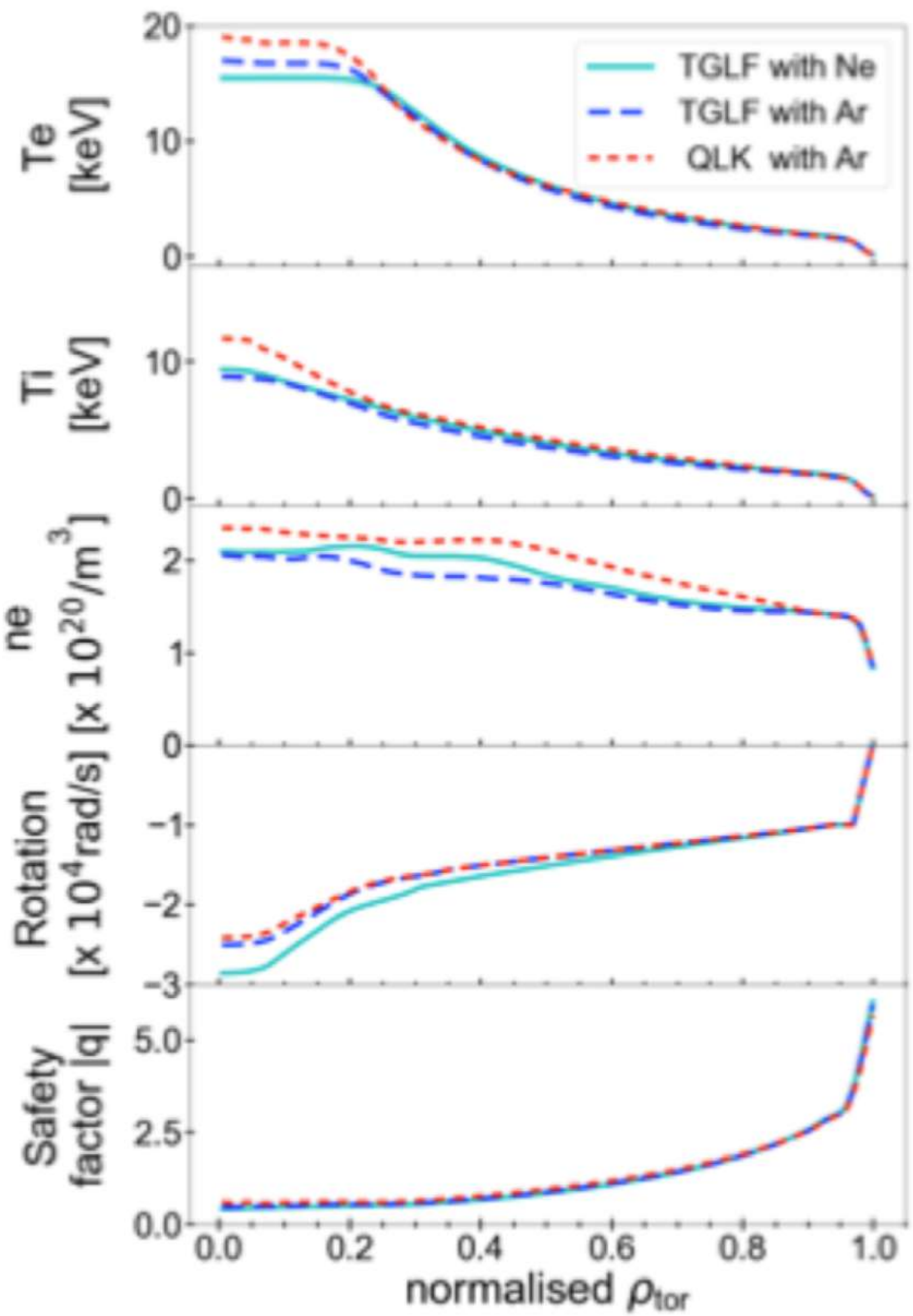
Full power flat-top phase



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 ≲ 1.2×10^{17} neutrons/s
- H_{98} = 0.8–1.0, τ_E = (0.41–0.45)s, βN_{tot} =1.3–1.6

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Integrated simulation hierarchy

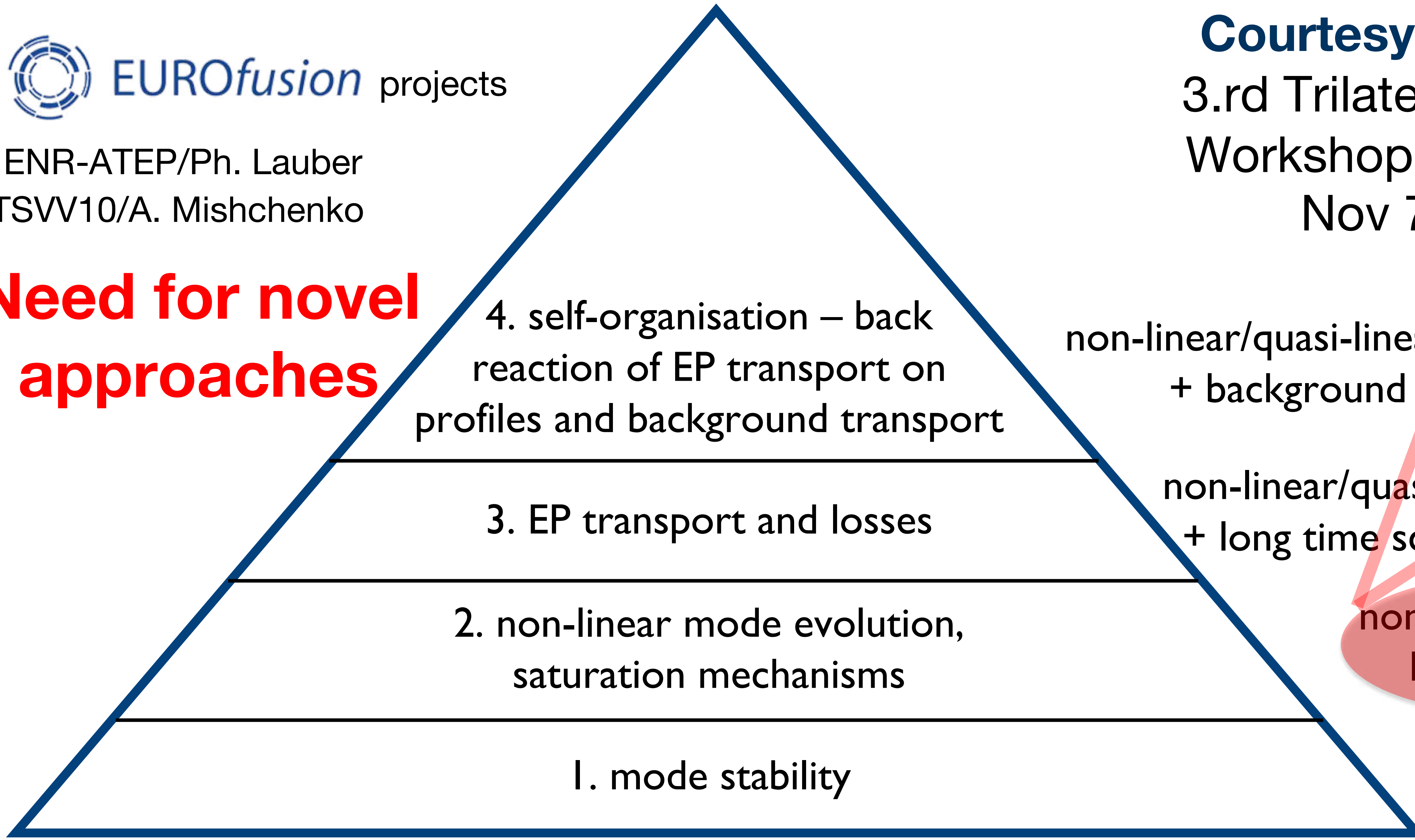
- Integrated simulation hierarchy for plasmas with significant EP energy density ➔ **Drift Alfvén Waves & DWT**

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

Plasma and fusion reactivity profiles

Turbulence & fluctuation driven fluxes

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

Conclusions and discussion

- The Divertor Tokamak Test facility, in 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

Thank you for your attention!

Your questions are welcome

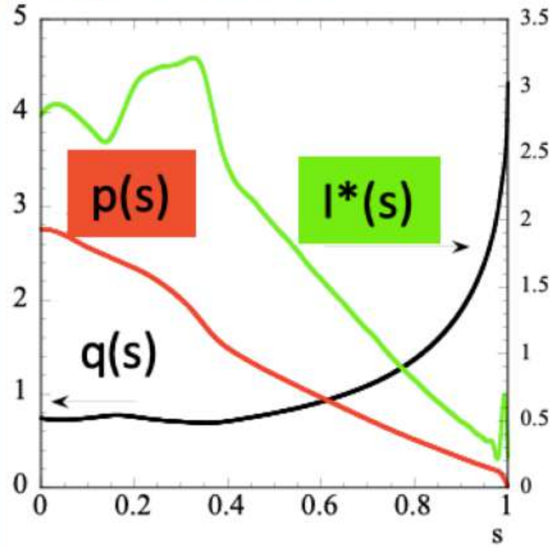
Backup slides

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. Giovannozzi

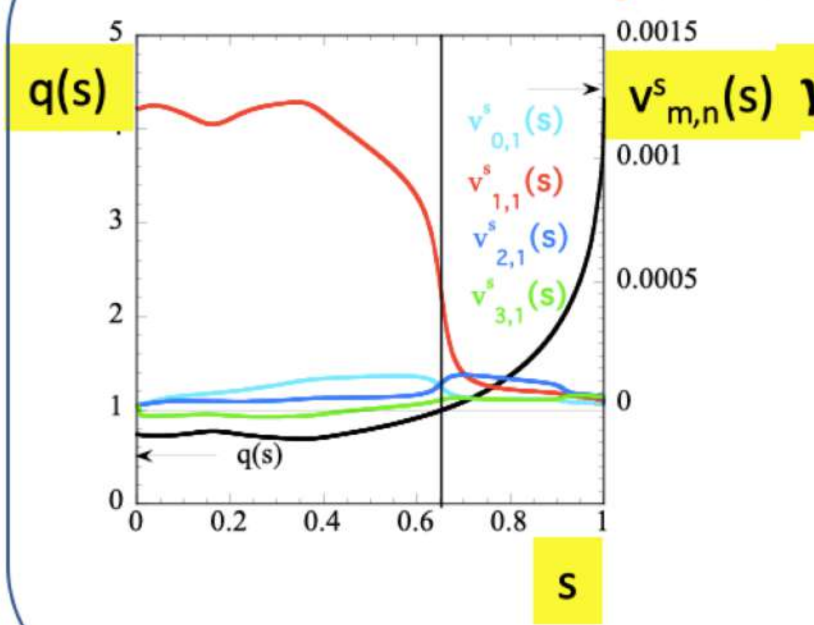
Equilibrium

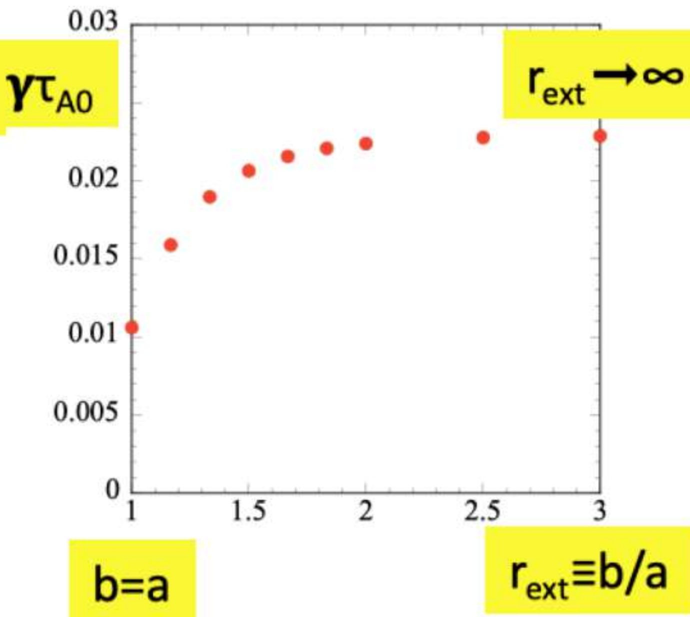


	DTT
I_{tot} MA	5.489
q_0	0.74
$q_{95\%}$	2.84
q_{edge}	4.3
β_{tor}%	1.89
β_N	1.20
p_0/<p>	4

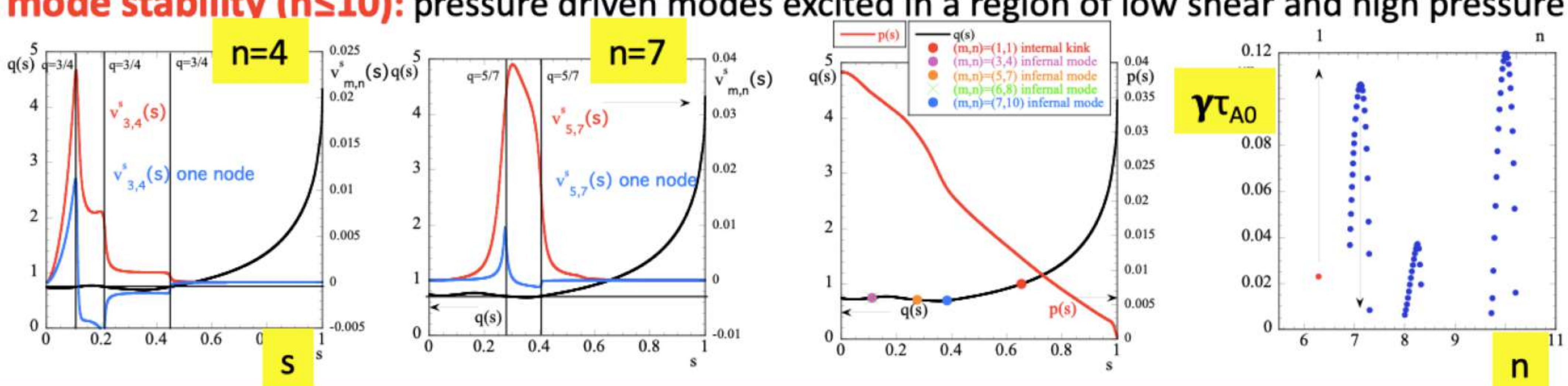
- The q=1 is located around s≈0.64 (no sawtooth model included so far)

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.

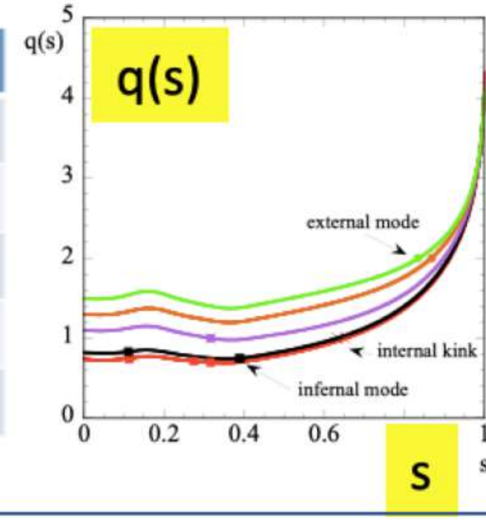


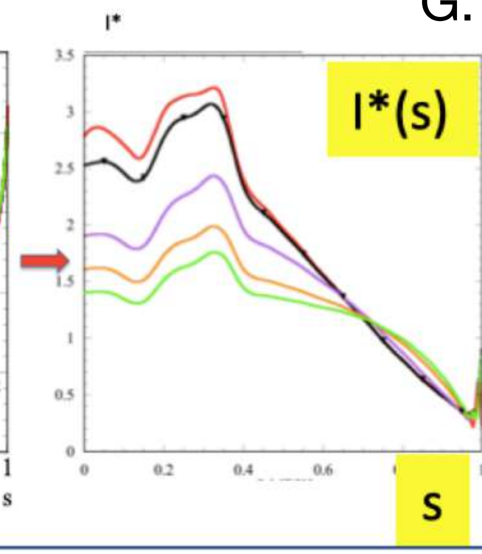
Low-n MHD stability studies - II

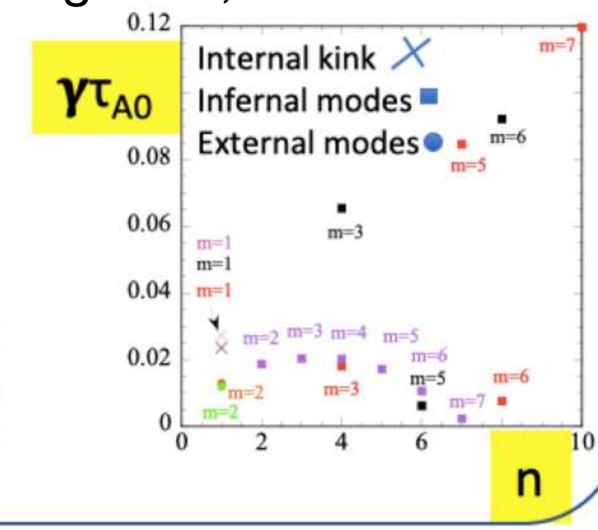
Sensitivity analysis

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

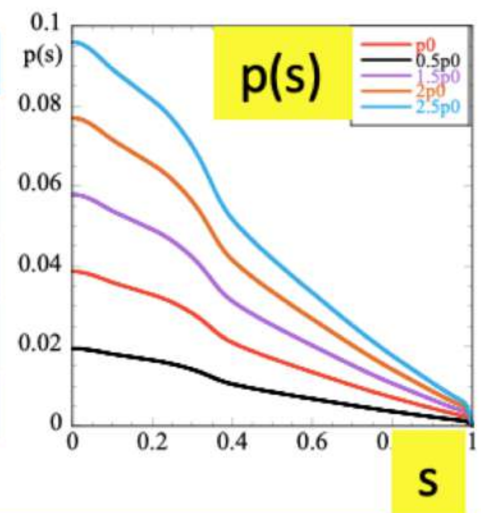
q	I_{tot} MA	q_0	$q_{95\%}$	q_{edge}	β_{tor}%	β_N%
(red line)	5.489	0.74	2.8450	4.3	1.89	1.20
(black line)	5.487	0.82	2.8747	4.0016	1.866	1.191
(violet line)	5.327	1.10	2.9072	3.999	1.803	1.328
(orange line)	5.315	1.3	2.9636	4.0067	1.675	1.263
(green line)	5.131	1.5	2.9965	4.0087	1.606	1.086

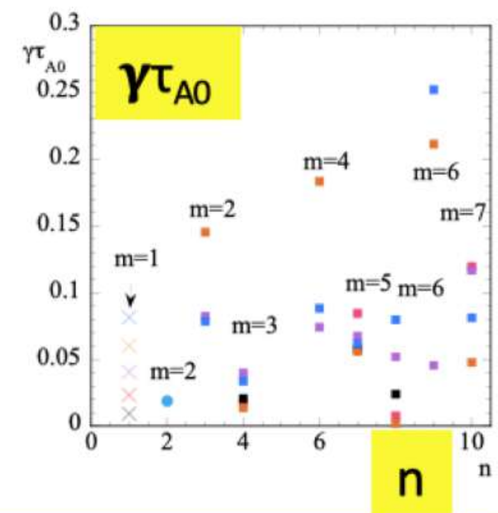






p	I_{tot}MA	q_0	$q_{95\%}$	q_{edge}	β_{tor}%	β_N%
p0	5.489	0.74	2.8450	4.3	1.89	1.20
0.5p0	5.505	0.75	2.82	4.2	0.0096	0.73
1.5p0	5.475	0.71	2.87	4.4	2.81	1.81
2p0	5.459	0.69	2.90	4.5	3.72	2.43
2.5p0	5.444	0.67	2.93	4.6	4.64	3.04





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

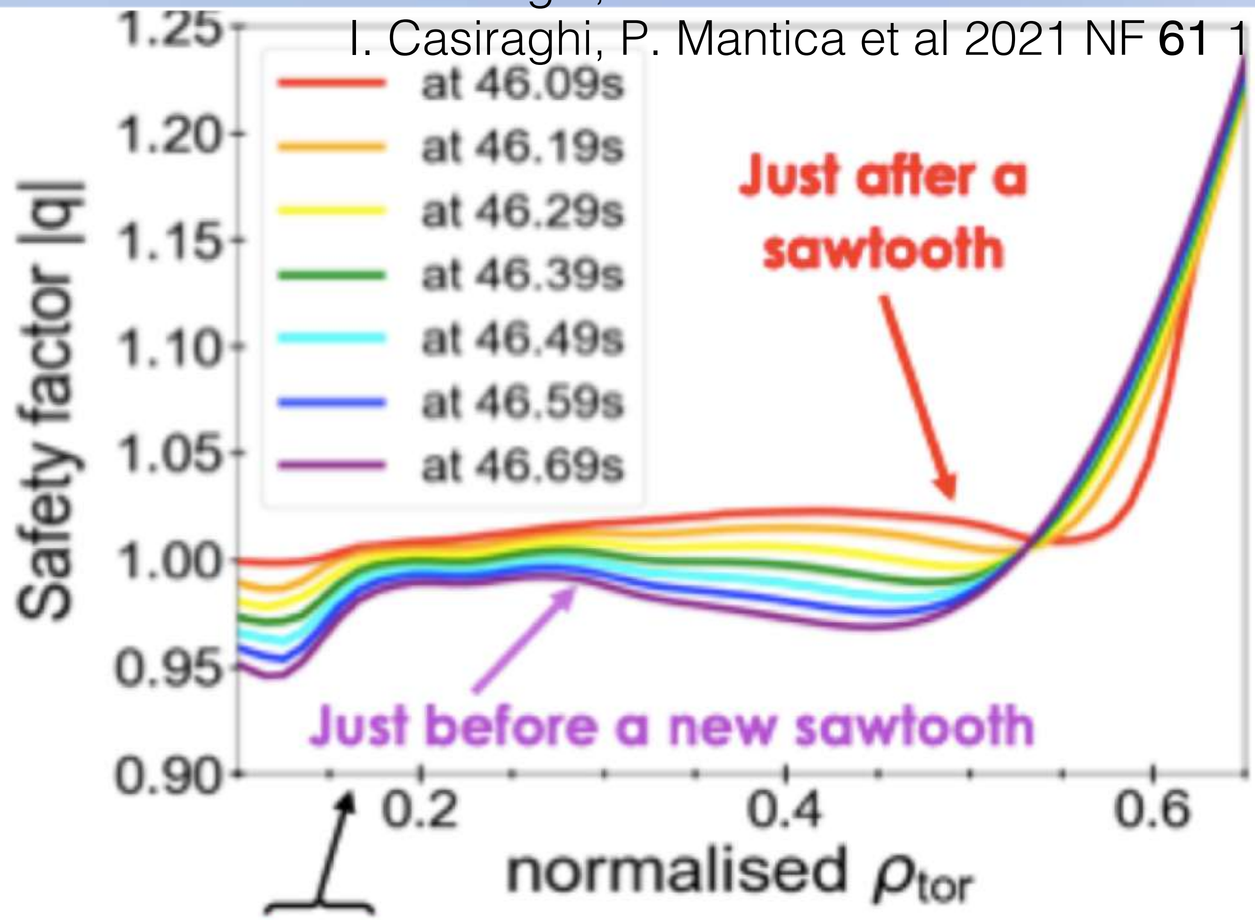
Full power including sawteeth

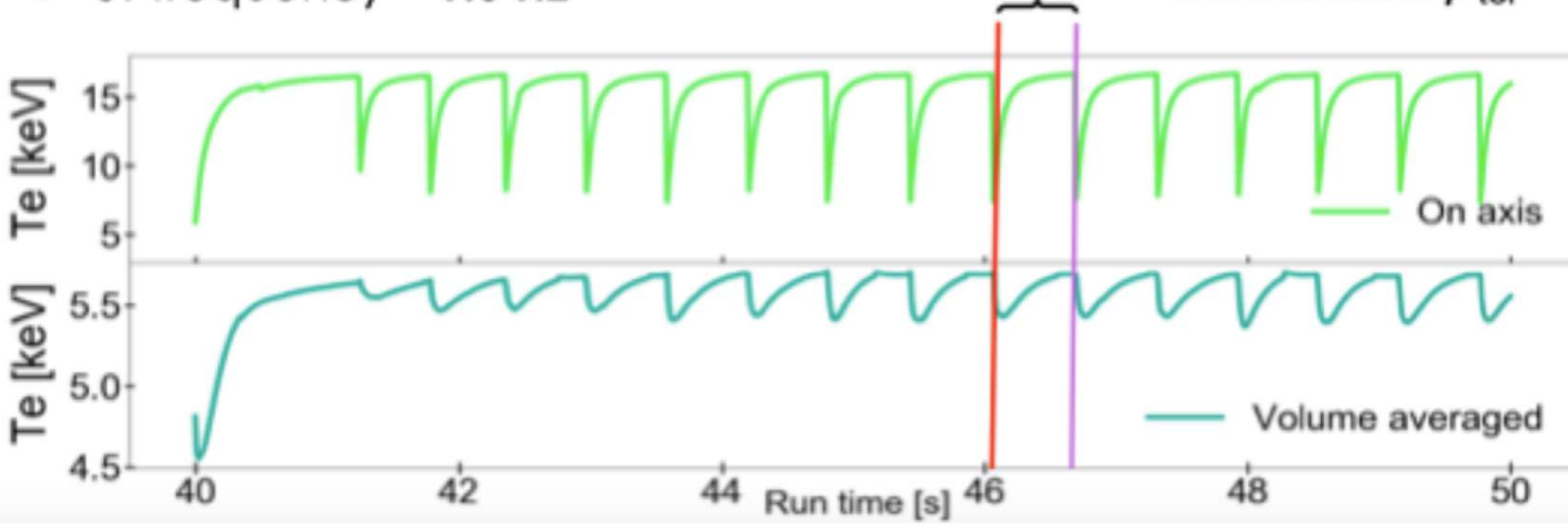
I. Casiraghi, P. Mantica et al EPS 2022
I. Casiraghi, P. Mantica et al 2021 NF **61** 116068

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**





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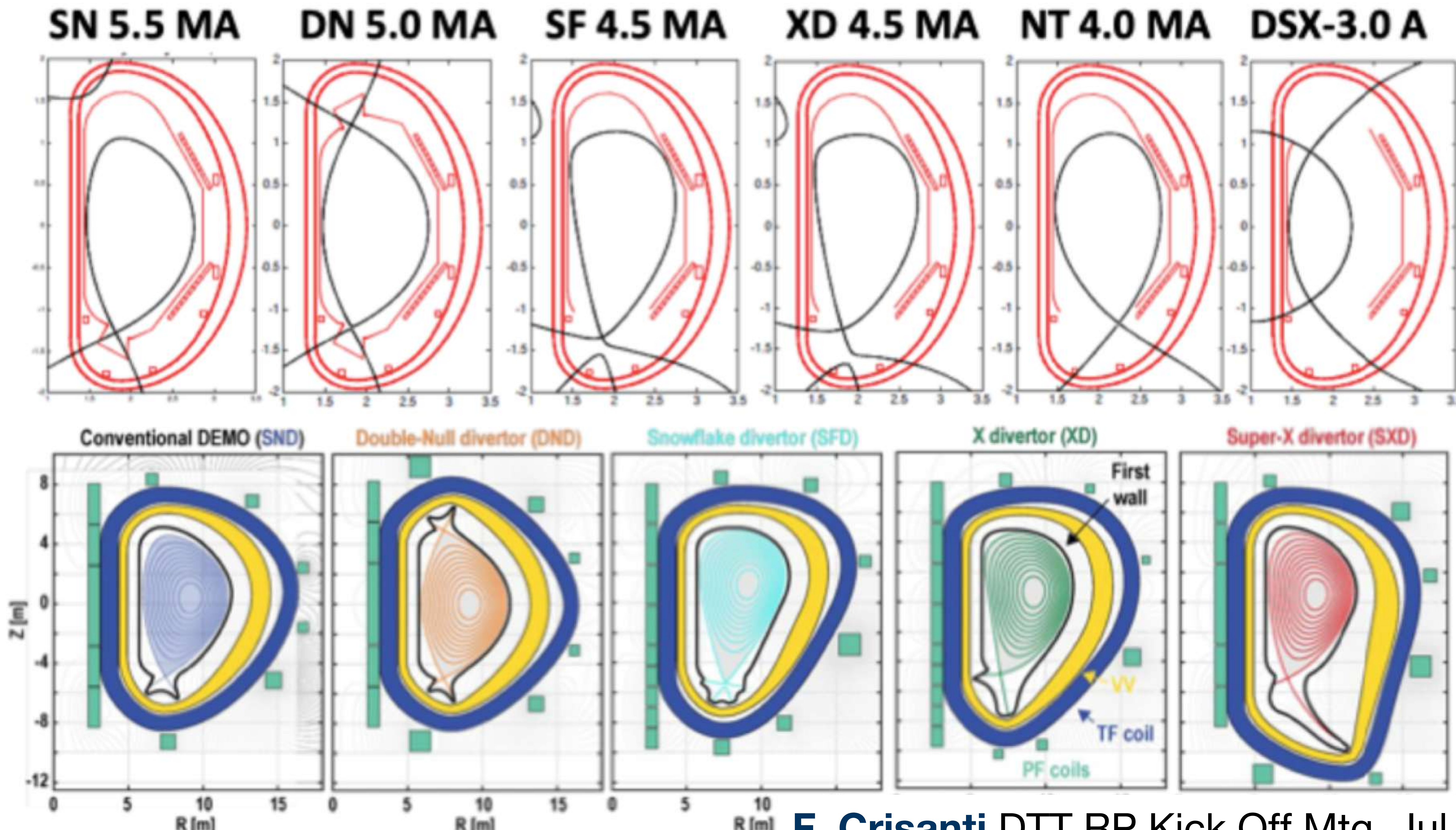
DTT as a step towards DEMO



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

DTT can test all foreseen ADCs DEMO configurations

A set of small internal coils will allow **playing with local magnetic topology**

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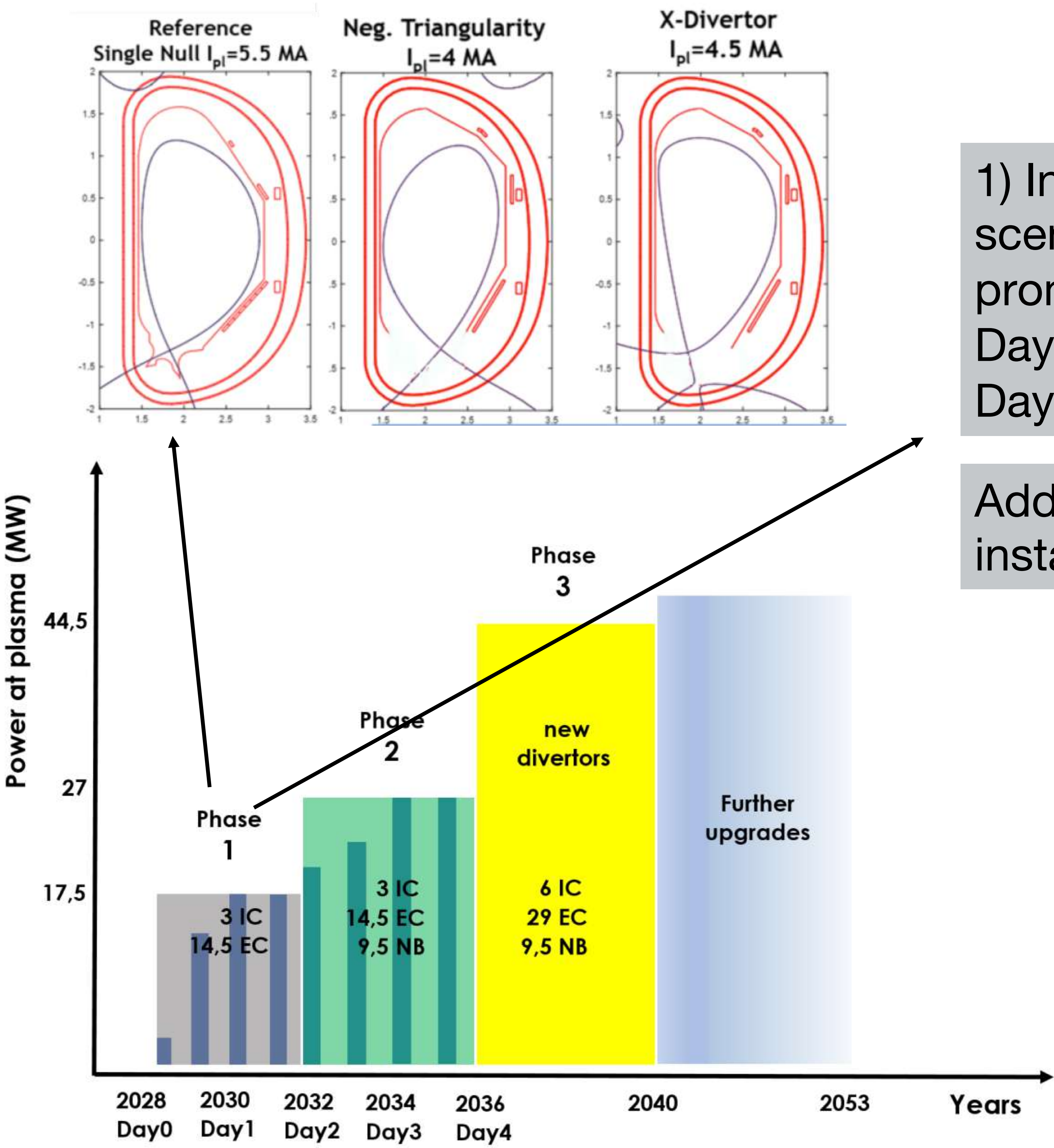
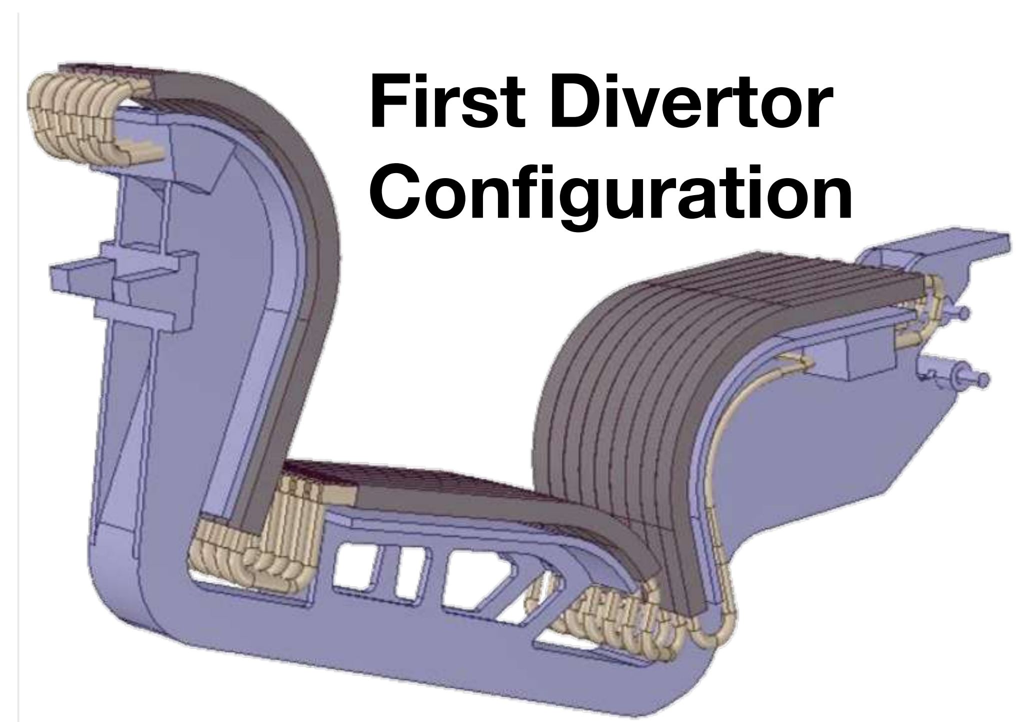
DTT experimental program - I

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



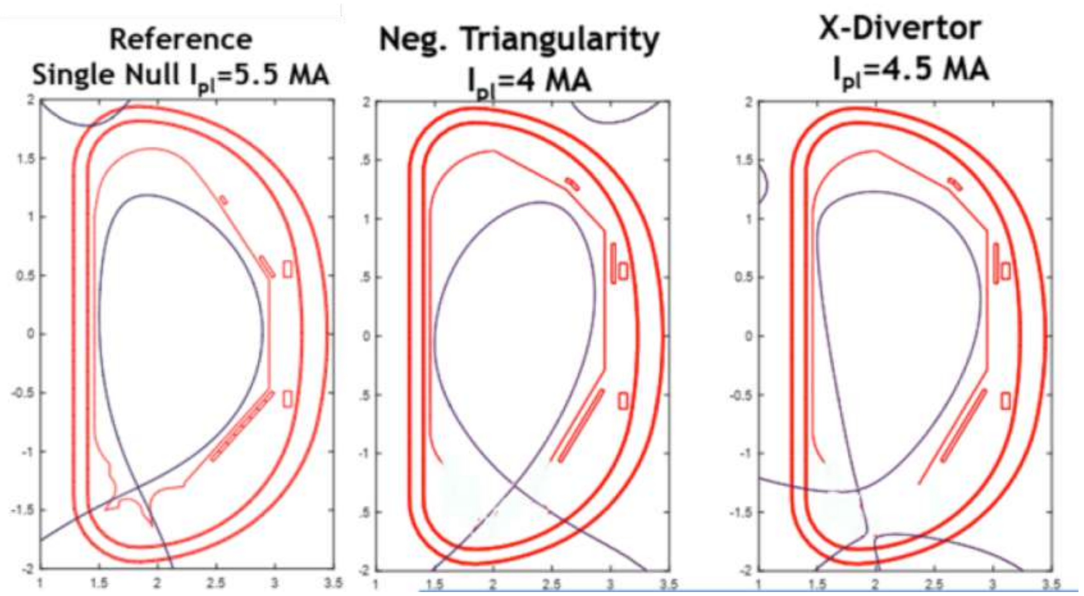
1) In the first phase all the possible plasma scenarios will be tested to identify the most promising following divertor
Day0: I_p= 2 MA - B_T= 3 T
Day1: I_p= 4 MA - B_T= 6 T

Additional heating power to be installed in three steps

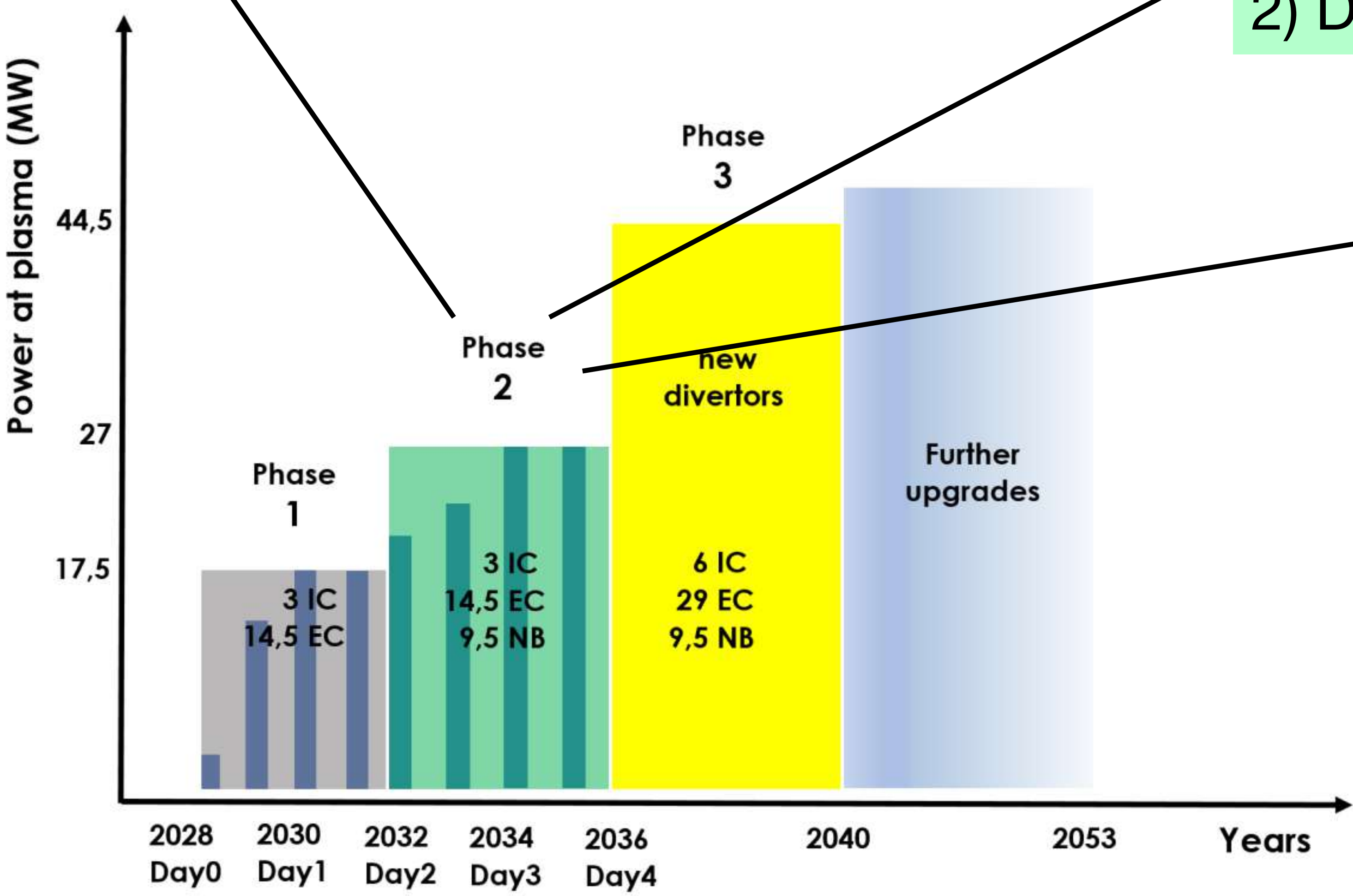


DTT experimental program - II

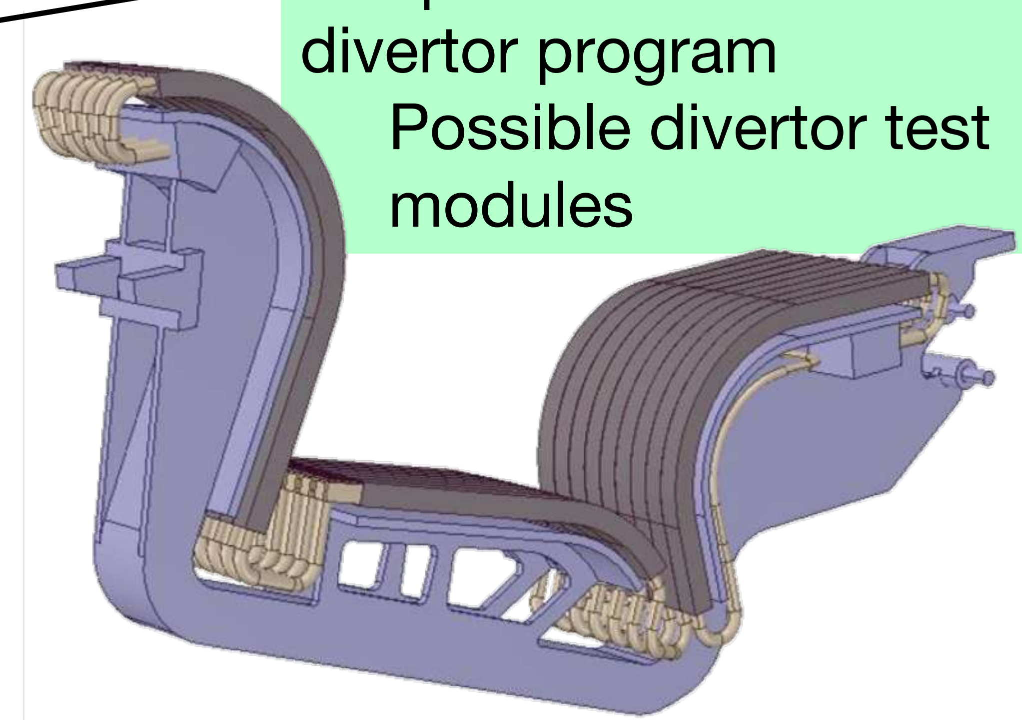
Courtesy of F. Crisanti
DTT RP Kick Off Mtg Jul 8, 2022



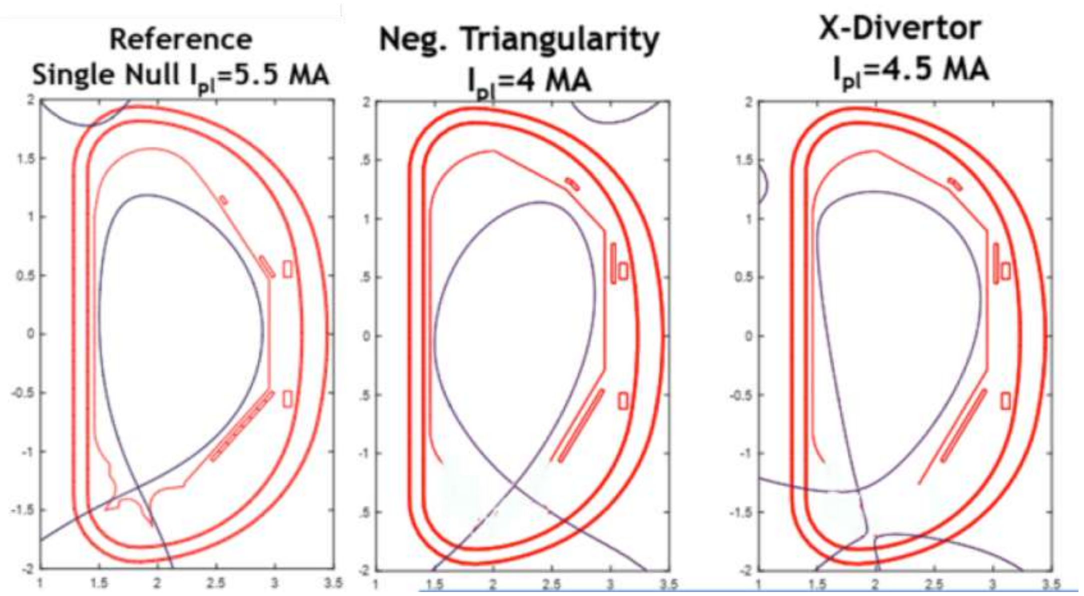
1) In the first phase all the possible plasma scenarios will be tested to identify the most promising following divertor
Day0: I_p= 2 MA - B_T= 3 T
Day1: I_p= 4 MA - B_T= 6 T
2) Detachment studies (test divertors)



Cooperation with DEMO divertor program
Possible divertor test modules

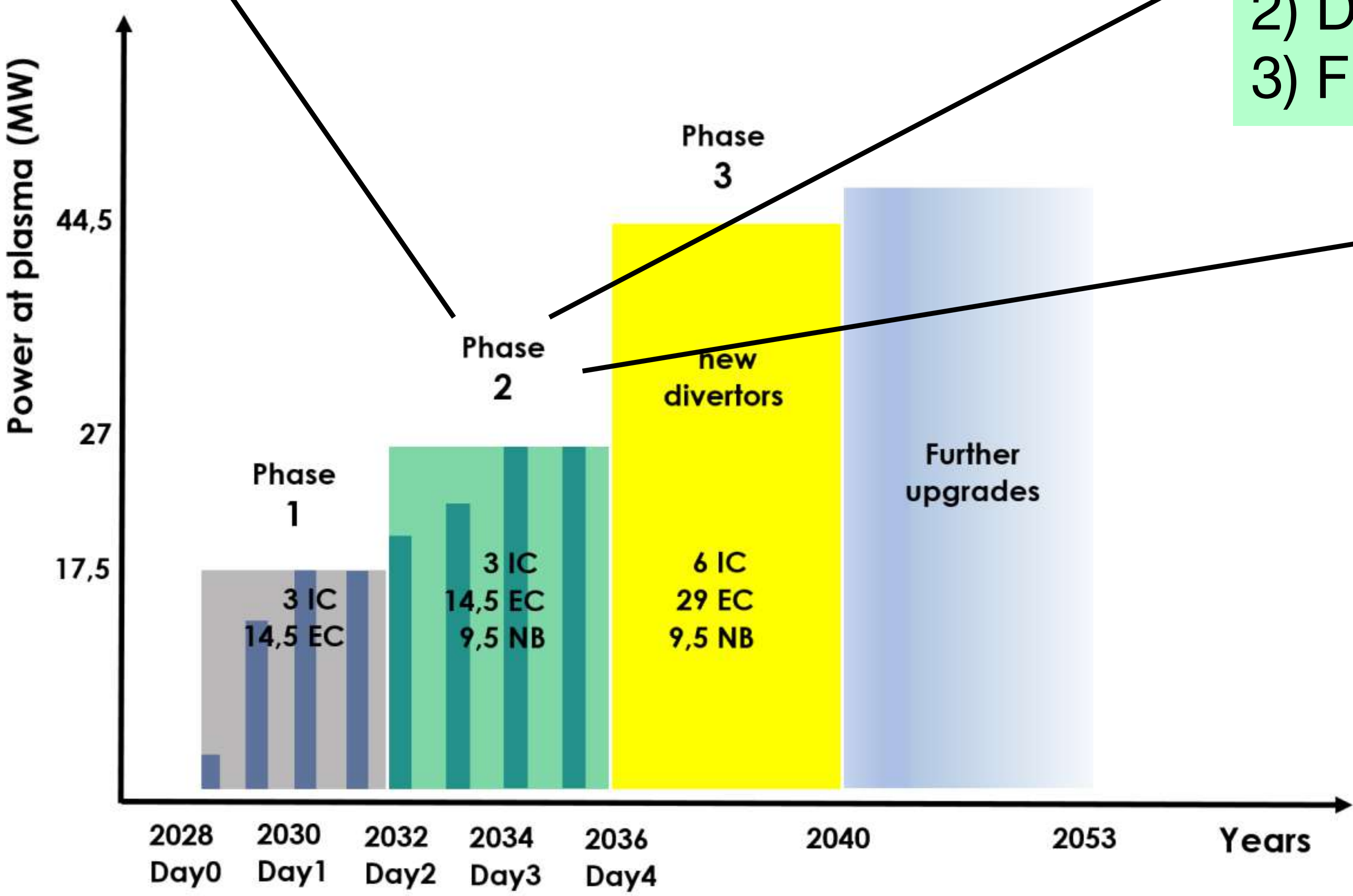


DTT experimental program - III

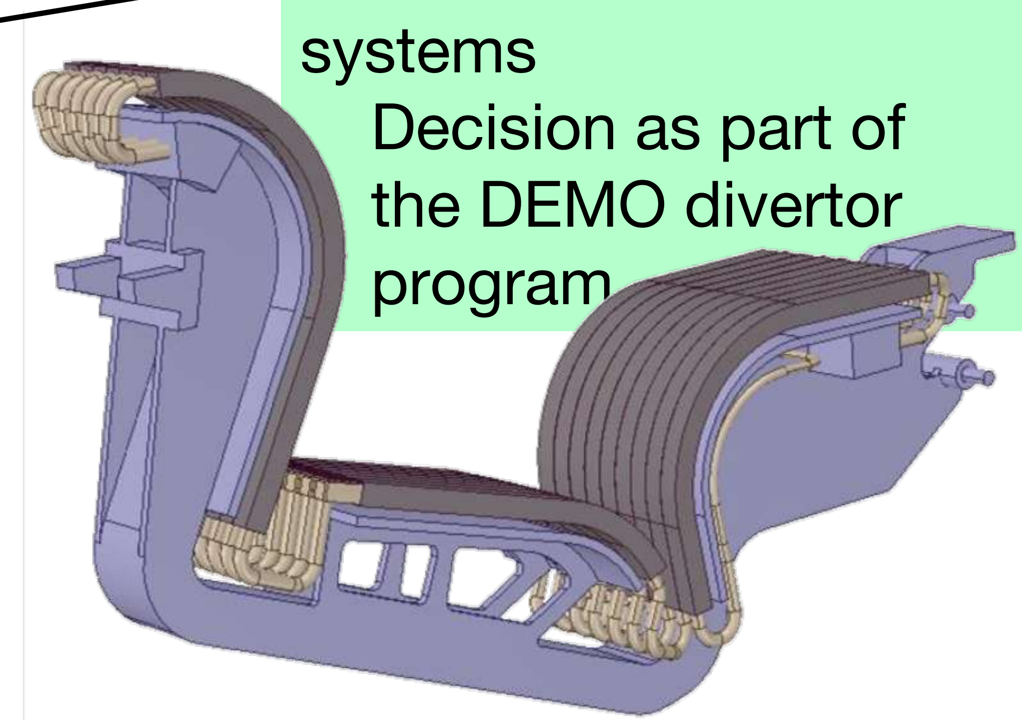


Courtesy of F. Crisanti
DTT RP Kick Off Mtg Jul 8, 2022

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

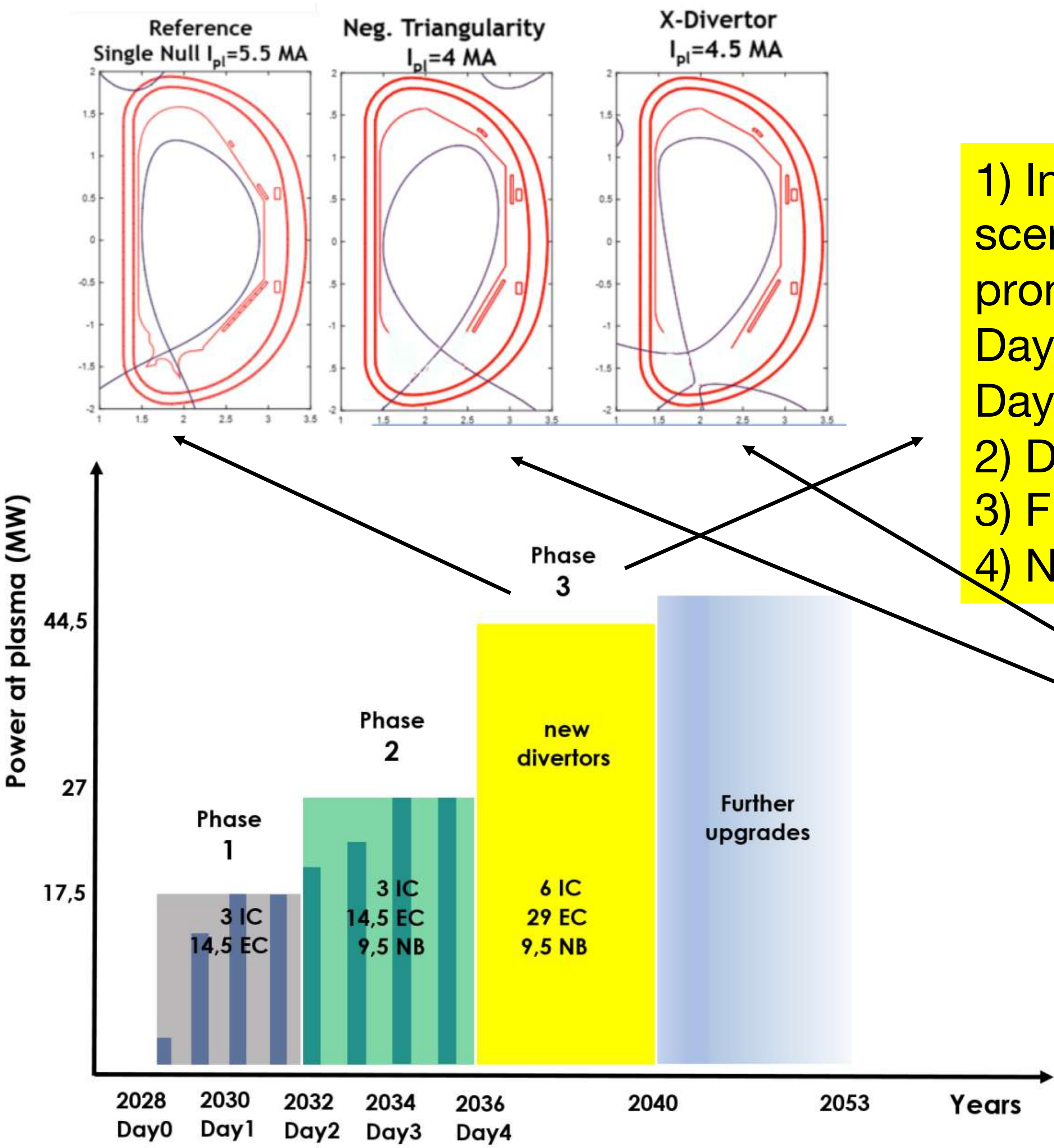


Final choice of last heating systems
Decision as part of the DEMO divertor program



DTT experimental program - IV

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

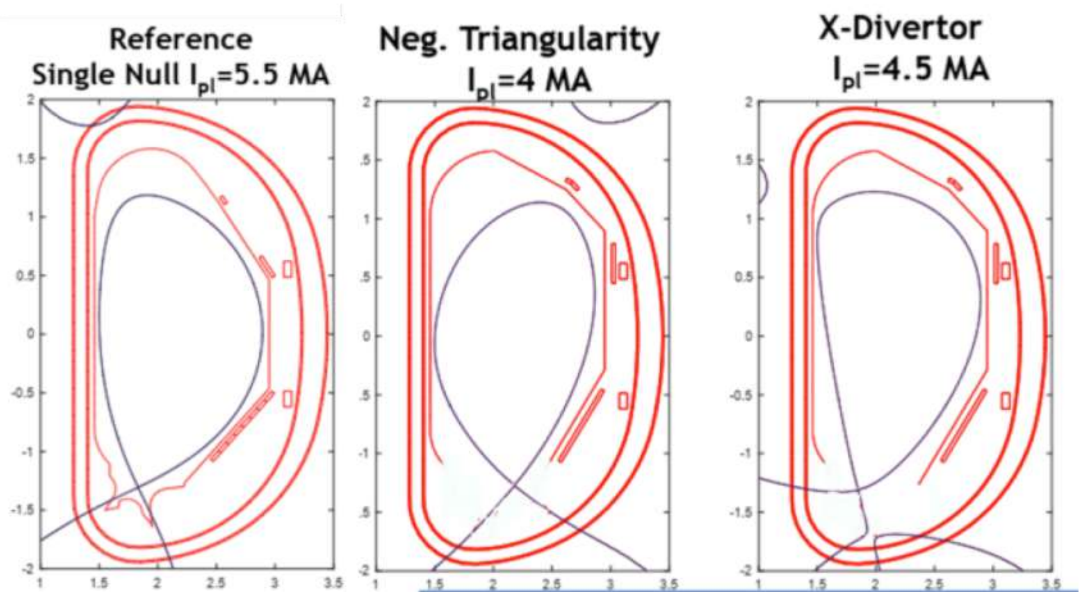


1) In the first phase all the possible plasma scenarios will be tested to identify the most promising following divertor
Day0: I_p= 2 MA - B_T= 3 T
Day1: I_p= 4 MA - B_T= 6 T
2) Detachment studies (test divertors)
3) Full heating power
4) New divertor

New divertor

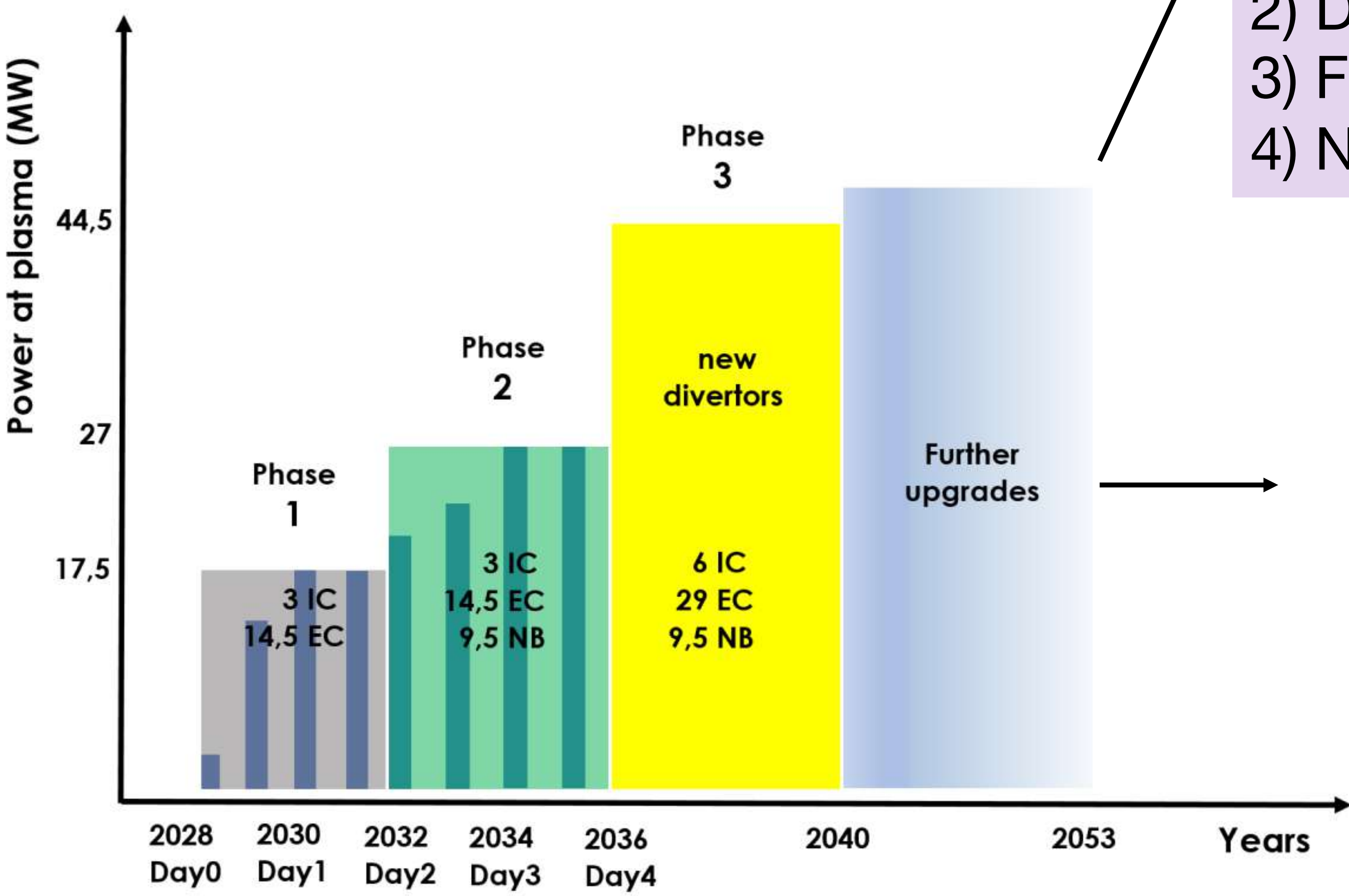
1. Shape?
2. Double null?
3. Negative triangulariry
4. Liquid metals
5. Others? …

DTT experimental program - V



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



- Experimental program will run in parallel with ITER and JT60SA
- Strong cooperation will be mandatory.
- DTT mission will be mandatory to assist DEMO in divertor design

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