2nd IAEA TM on Long-Pulse Operation of Fusion Devices
IAEA Headquarters, Vienna, Oct. 14th-18th , 2024

EU-DEMO: pulsed vs. steady-state solution

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with contributions of C. Bachmann, C. Bourdelle, M. Coleman, G. Federici, F. Maviglia, I. Moscato, S. Wiesen, H. Zohm

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.

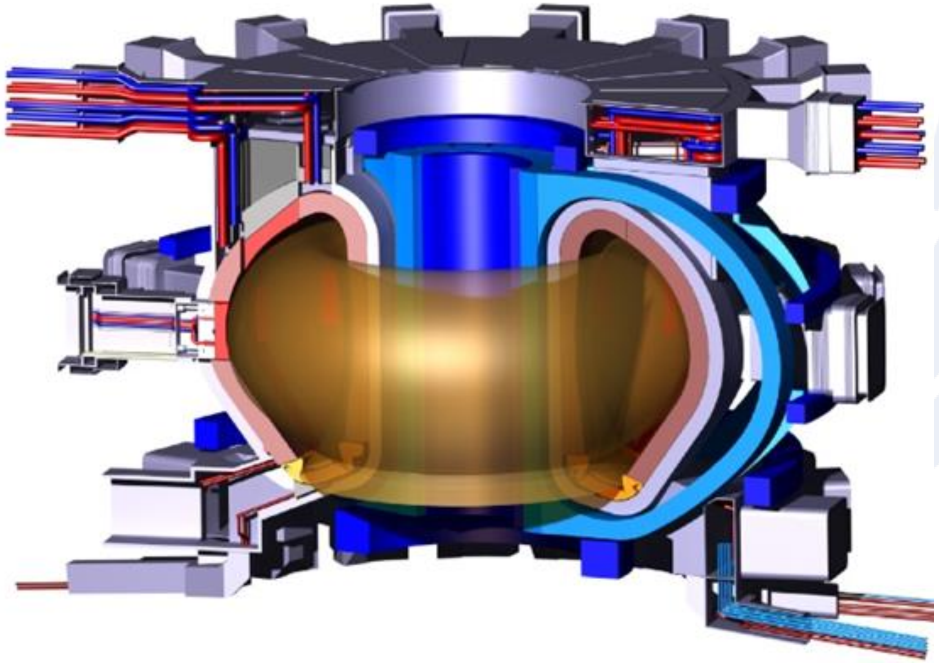
Introduction – EU-DEMO approach

The EU-DEMO approach always aimed at minimizing the leap of physics scenarios and technological solutions from ITER.

In this framework, while ***the importance of looking for new solutions is recognized*** and encouraged, there is still belief that ***relying solely on too speculative scenarios or technological solutions*** may hamper the DEMOnstration of fusion electricity, rather than accelerate it.

In other words: EU-DEMO must be able to ***accommodate innovative solutions*** in its design, if proven to be viable, but at the same time it must be able to ***accomplish its mission also with "modest" extrapolation*** from ITER.

…btw, can we really say that ITER is so low risk?



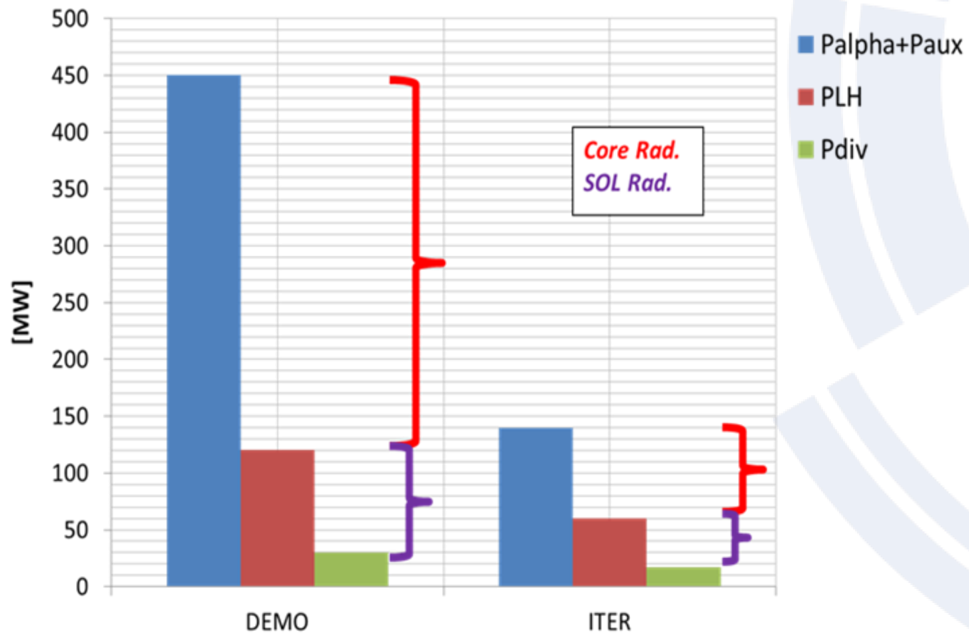
An important caveat

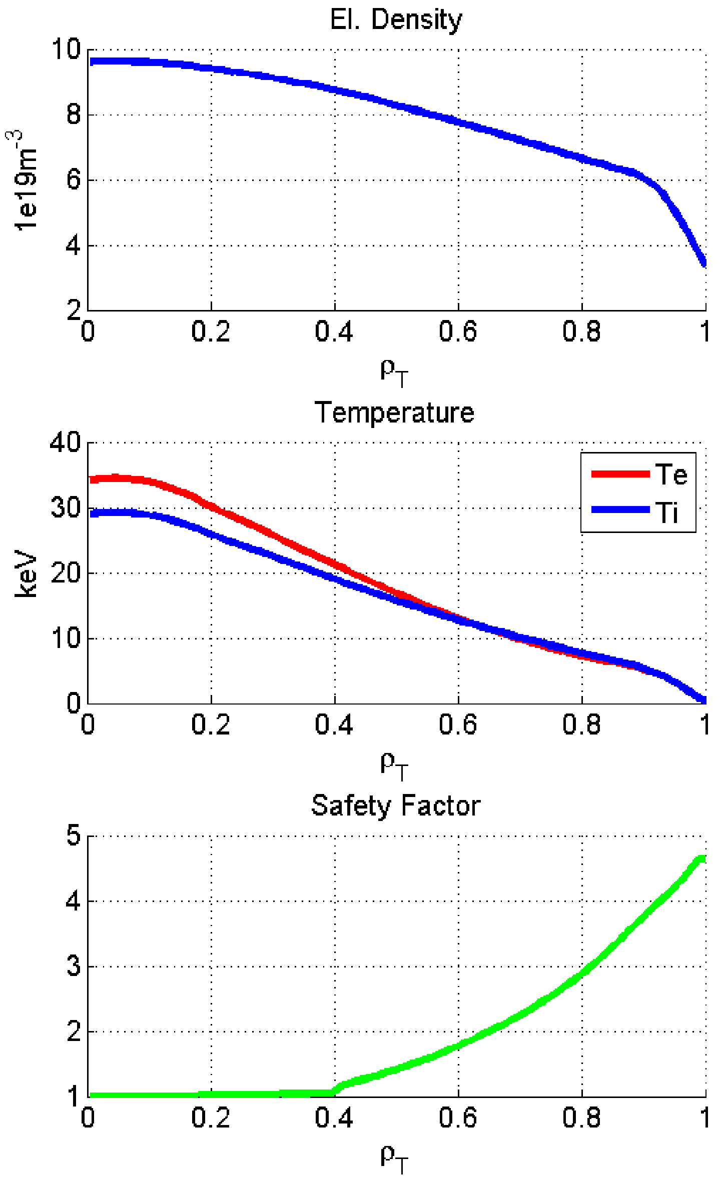
All discussions here refer to DEMO-like devices (i.e. large size tokamak with conventional aspect ratio, moderate field, high fusion power…)

For other machine concepts, conclusions may deviate, but this is not part of this talk.

EU-DEMO – Baseline 2018

R_0, a (m, m)	9, 2.9
A	3.1
B_T,(T)	5.85
Ip (MA), q_{95}	17.75, 3.89
H98	0.98
t_{burn} (hrs)	2
f_{bs}	0.387
fcd	~0
P_{LH} (MW)	120.8
P_{fus} (MW)	2012





[ASTRA Calculations: E Fable]

Flexi-DEMO

In the past, a steady-state EU-DEMO concept, Flexi-DEMO, was proposed *[H. Zohm et al., “A stepladder approach to a tokamak fusion power plant”, Nuclear Fusion 2017].*

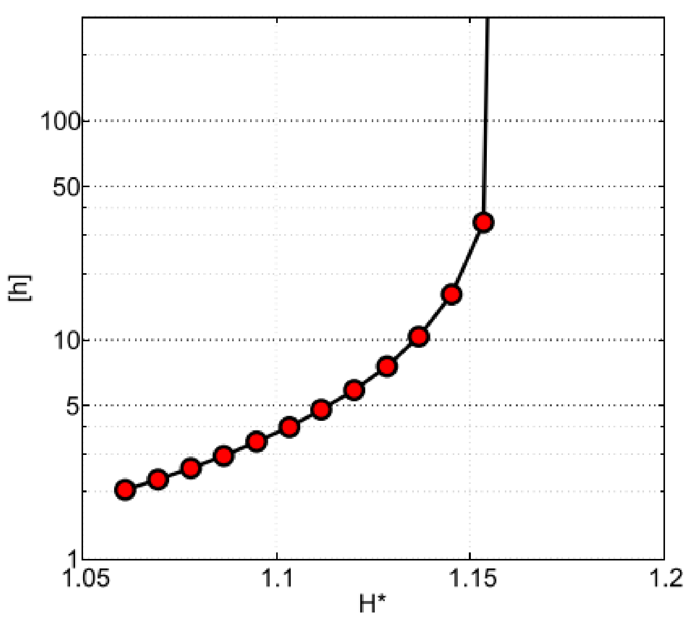
Table 3. Pulse length in DEMO for decreasing H-factor.

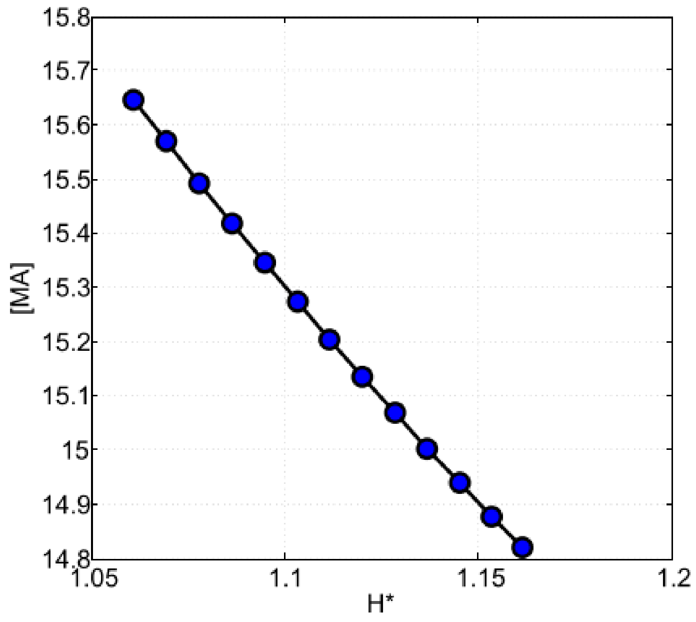
H-factor	I_p (MA)	$n_{e,19}$	I_{ohm} (MA)	U_{ind} (mV)	$\beta_{N,therm}$	t_{pulse} (h)
1.2	14.85	7.81	0	0	2.99	s.s.
1.15	15.15	7.97	1.17	3.65	2.89	10.26
1.1	15.55	8.18	2.19	7.38	2.8	4.94
1.05	16	8.41	3.34	12.58	2.7	2.81
1	16.45	8.65	4.59	17.02	2.6	2.02
0.95	16.8	8.83	5.77	22.76	2.46	1.47

Philosophy: ***fusion power is fixed***, auxiliary power is fixed, ***confinement level (H-factor) is unpredictable***.

The machine ***can be operated both pulsed and steady-state***, depending on which confinement degree one can achieve.

Increasing the current at the price of shortening the pulse length is the way to compensate for low confinement.



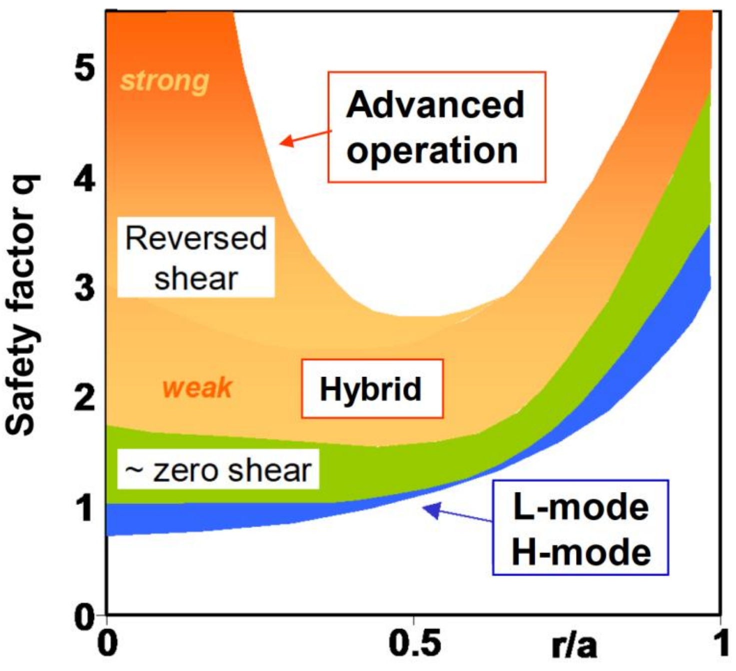


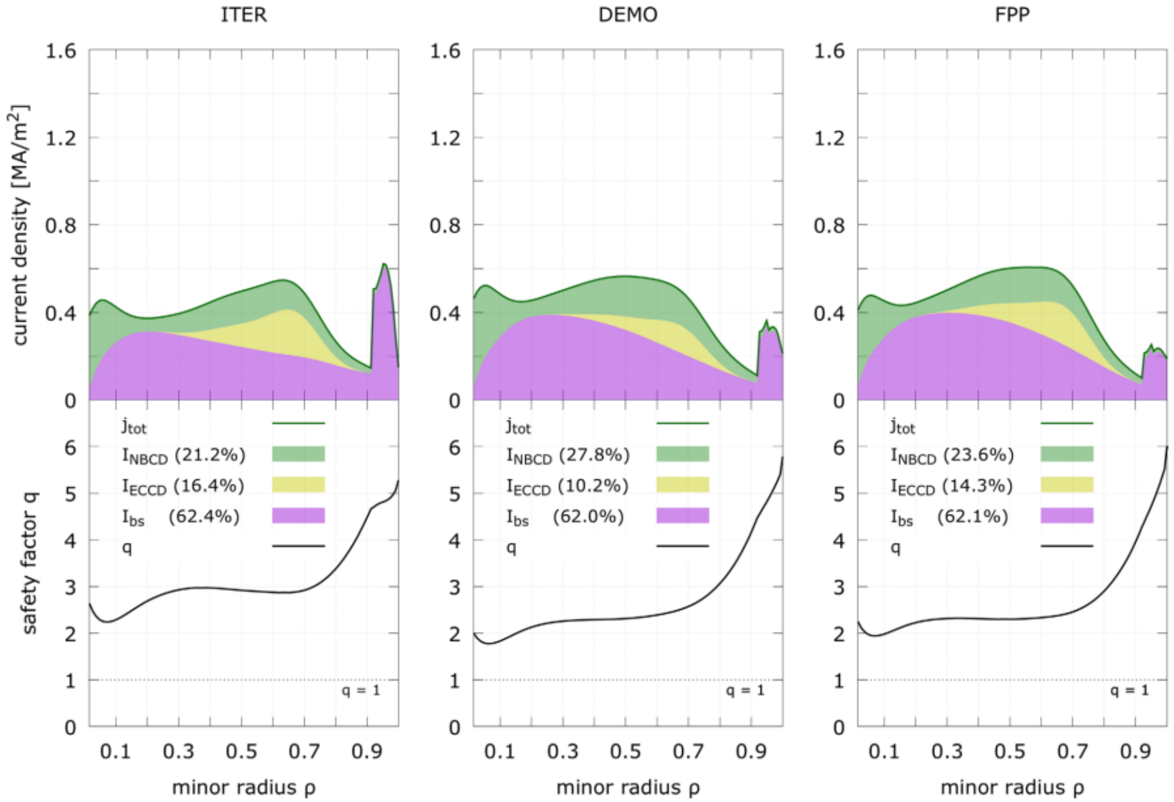
This is an example of how a DEMO can be flexible to “advanced” and “standard” scenarios

Steady State Flexi-DEMO

The Flexi-DEMO Steady-State configuration is based on so-called ***advanced scenarios***, i.e. with elevated q_0 on axis and regions of reversed magnetic shear.

These scenarios are characterised by ***high confinement H > 1*** (sometimes with ITB) and low-ish current, with ***high bootstrap current fraction***, but require a ***careful tailoring of the q-profile*** (see e.g. *[F. Turco, PoP 2015], [A. Garofalo, NF 2015]*).





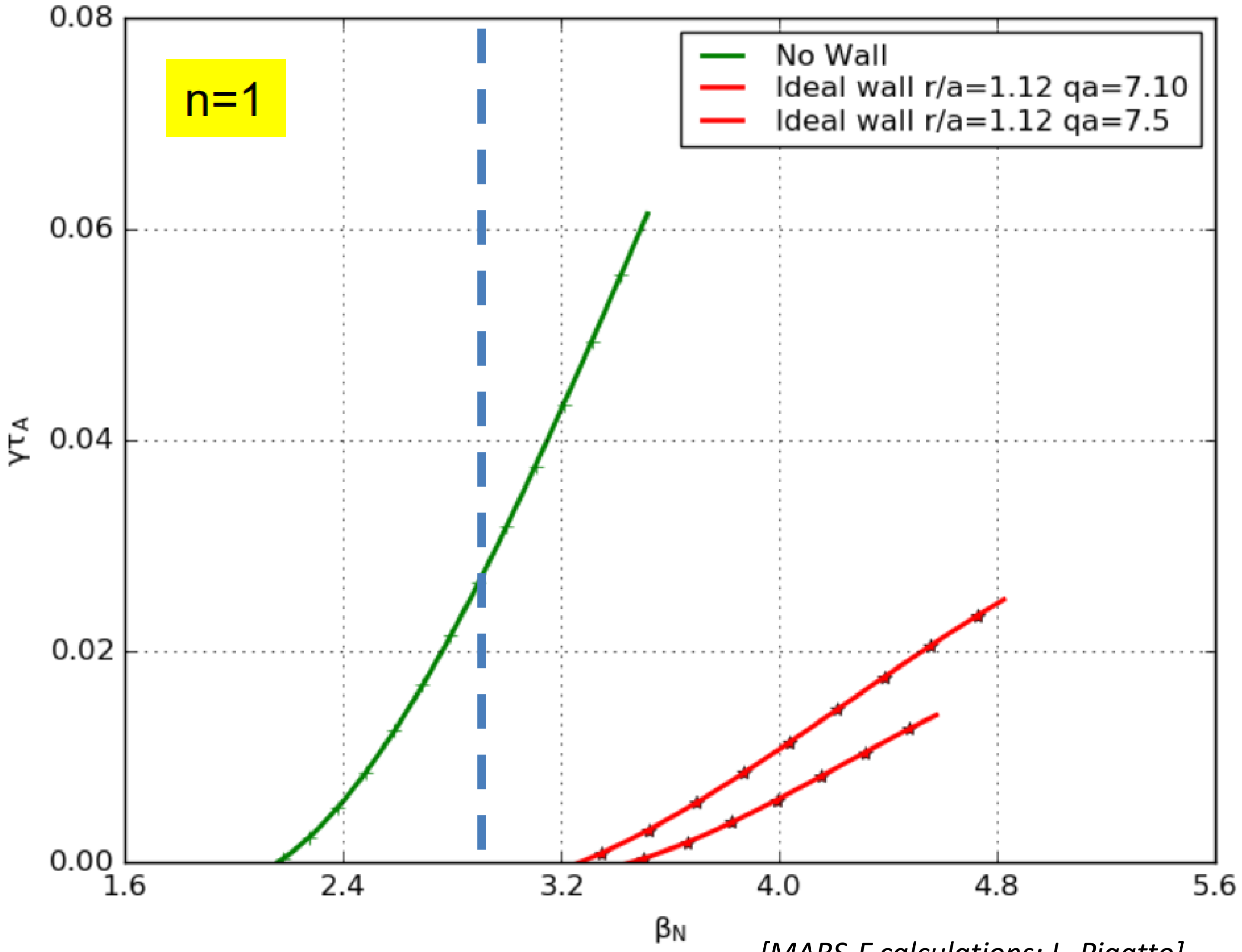
Steady State Flexi-DEMO – why not DEMO baseline?

The steady-state Flexi-DEMO design point has $\beta_N \approx 3$ which is ***above the RWM no-wall limit*** and ***pretty close to the ideal-wall limit*** (i.e. unstable on MHD timescales).

These scenarios require therefore ***active*** RWM control – e.g. with RMP coils, which must be in-vessel, on top of the ***very precise tailoring of the current/safety factor***.

This means that the ***controllability of these scenarios*** is much more cumbersome than in a typical "ITER-like" scenario.

NOT A SELF-ORGANISED PLASMA!



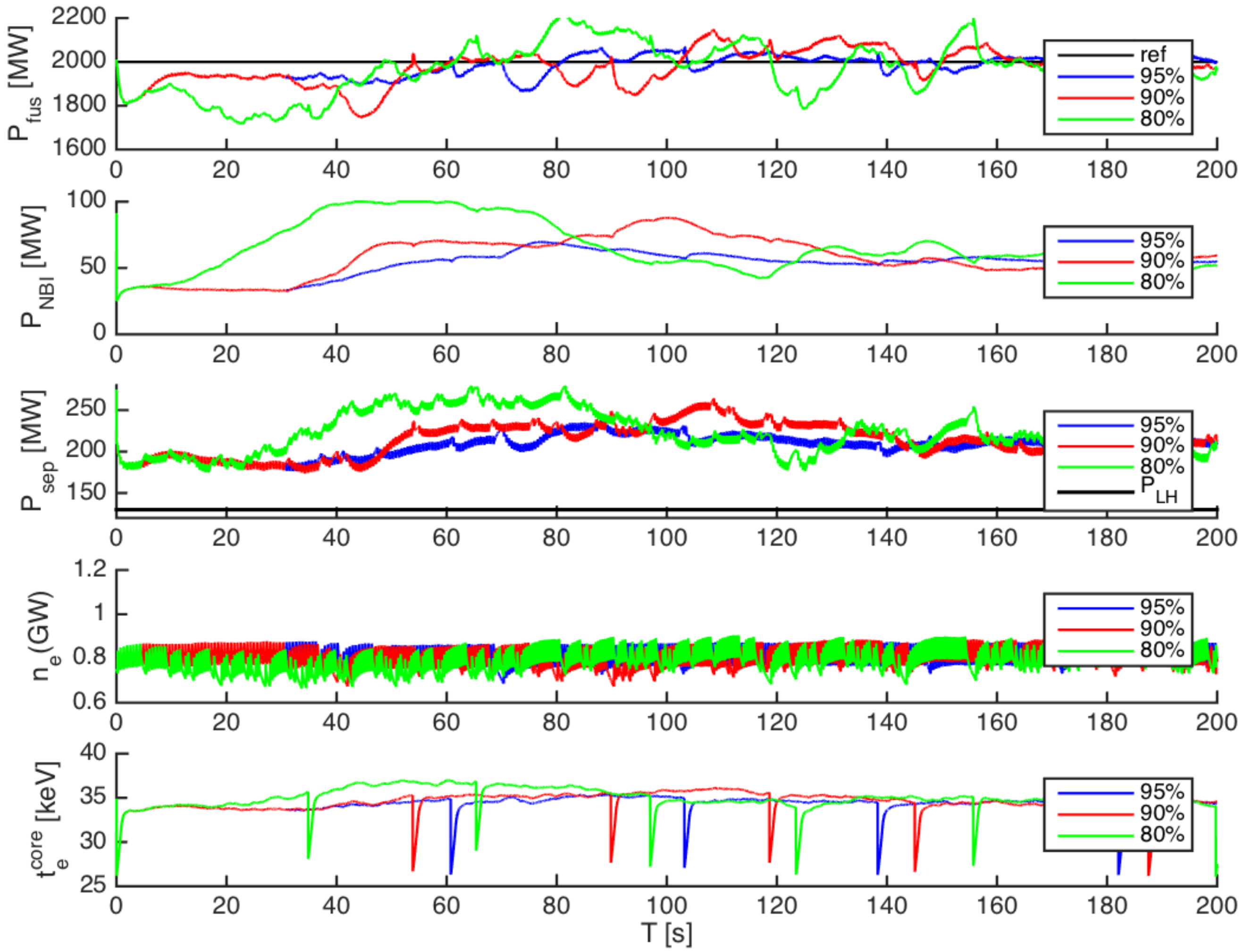
[MARS-F calculations: L. Pigatto]

Steady State Flexi-DEMO – why not DEMO baseline?

Burning plasmas are an uncharted territory!

Control simulations show that DEMO plasmas (dominated by α-heating) ***are not quiescent***.

Nonlinearity is extremely strong by virtue of the complex interplay between kinetic profiles and heating power.



[FENIX Calculation – F. Janky and E. Fable]

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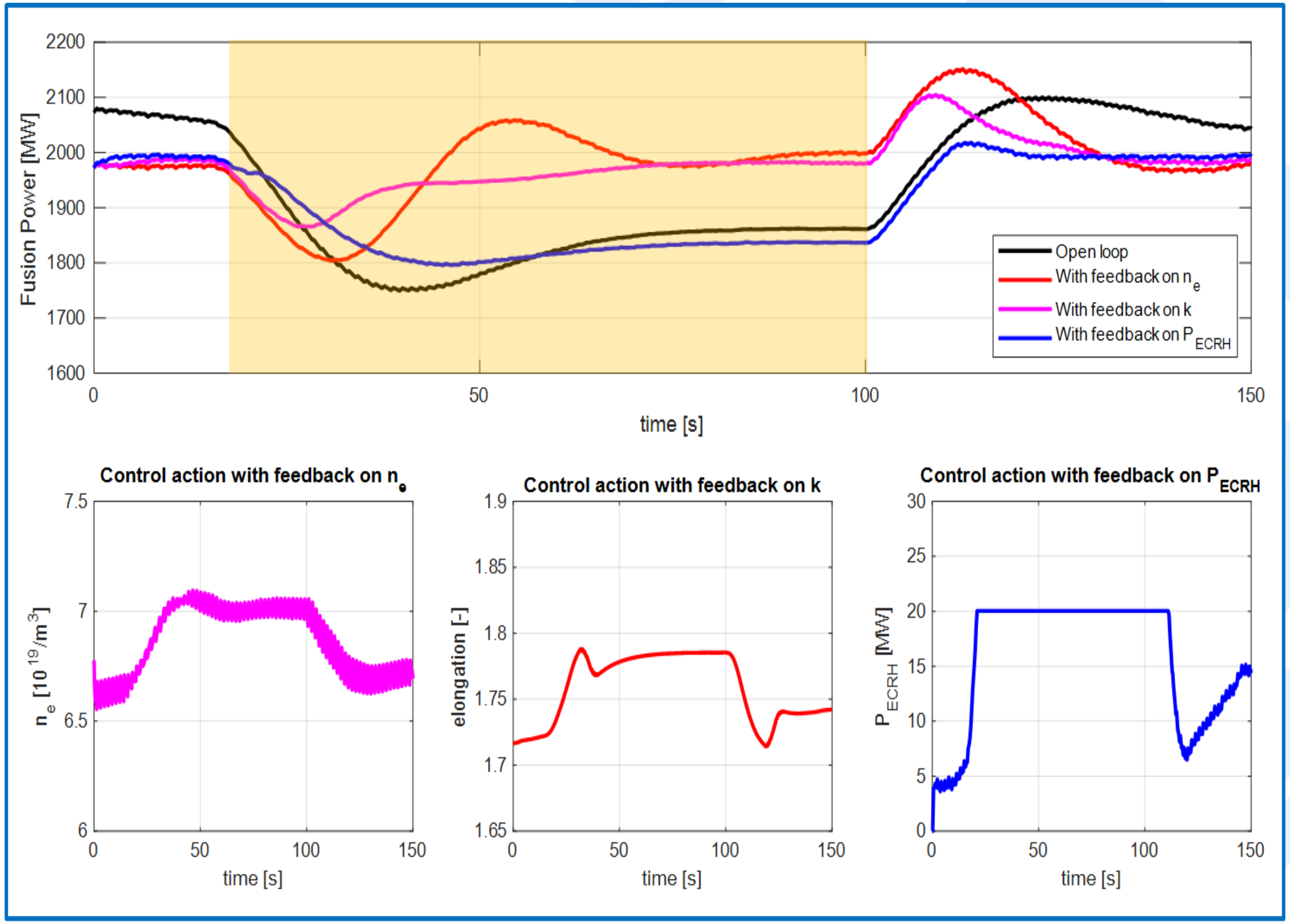
On a reactor, actuators for fusion power control are generally speaking inefficient.

Example: counteracting an excessive Ar influx



[L. Di Grazia et al., SOFT 2024]

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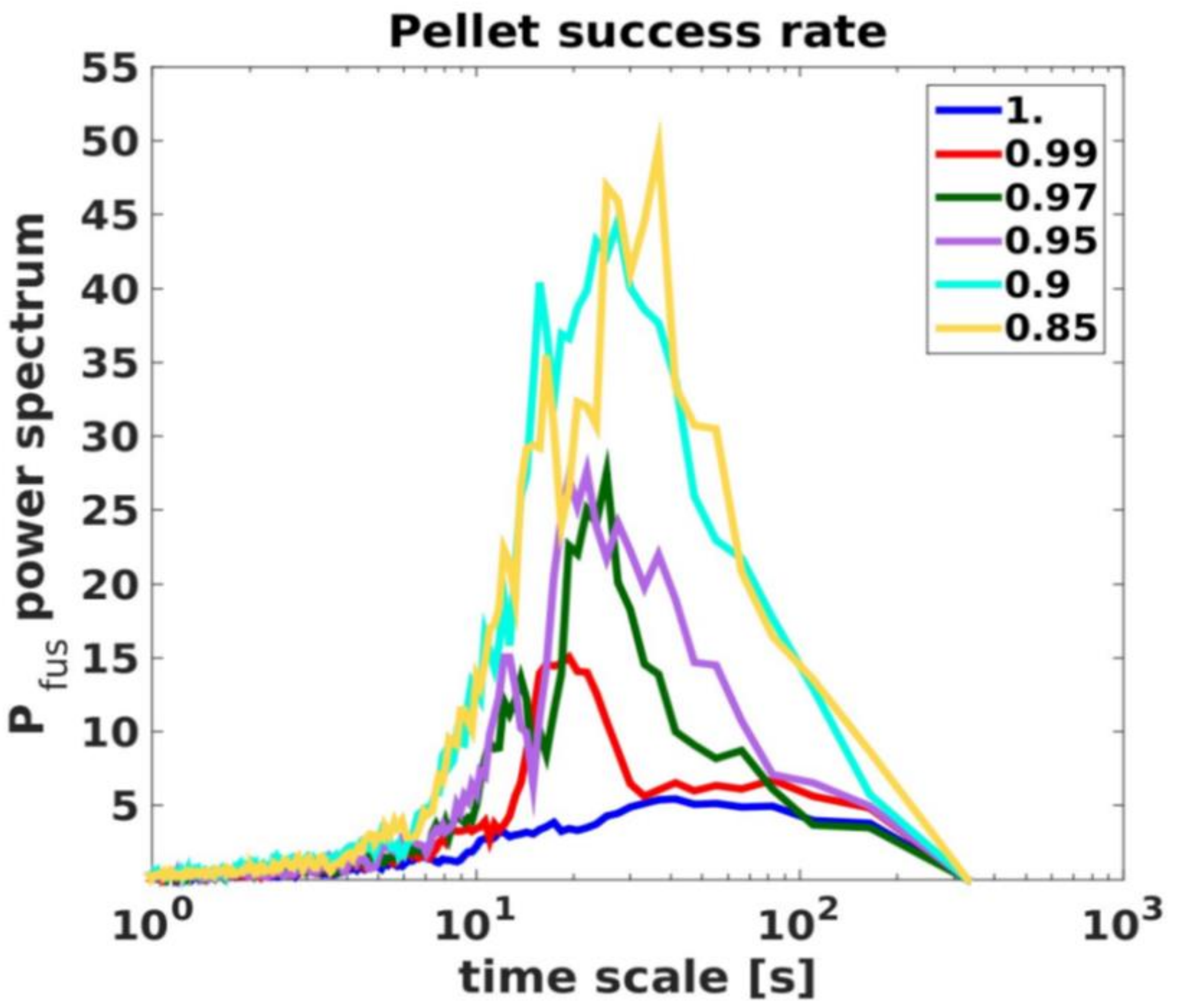
Can such a delicate scenario be safely maintained in presence of these large fluctuations?



…recall that basically no disruptions are allowed in a DEMO…

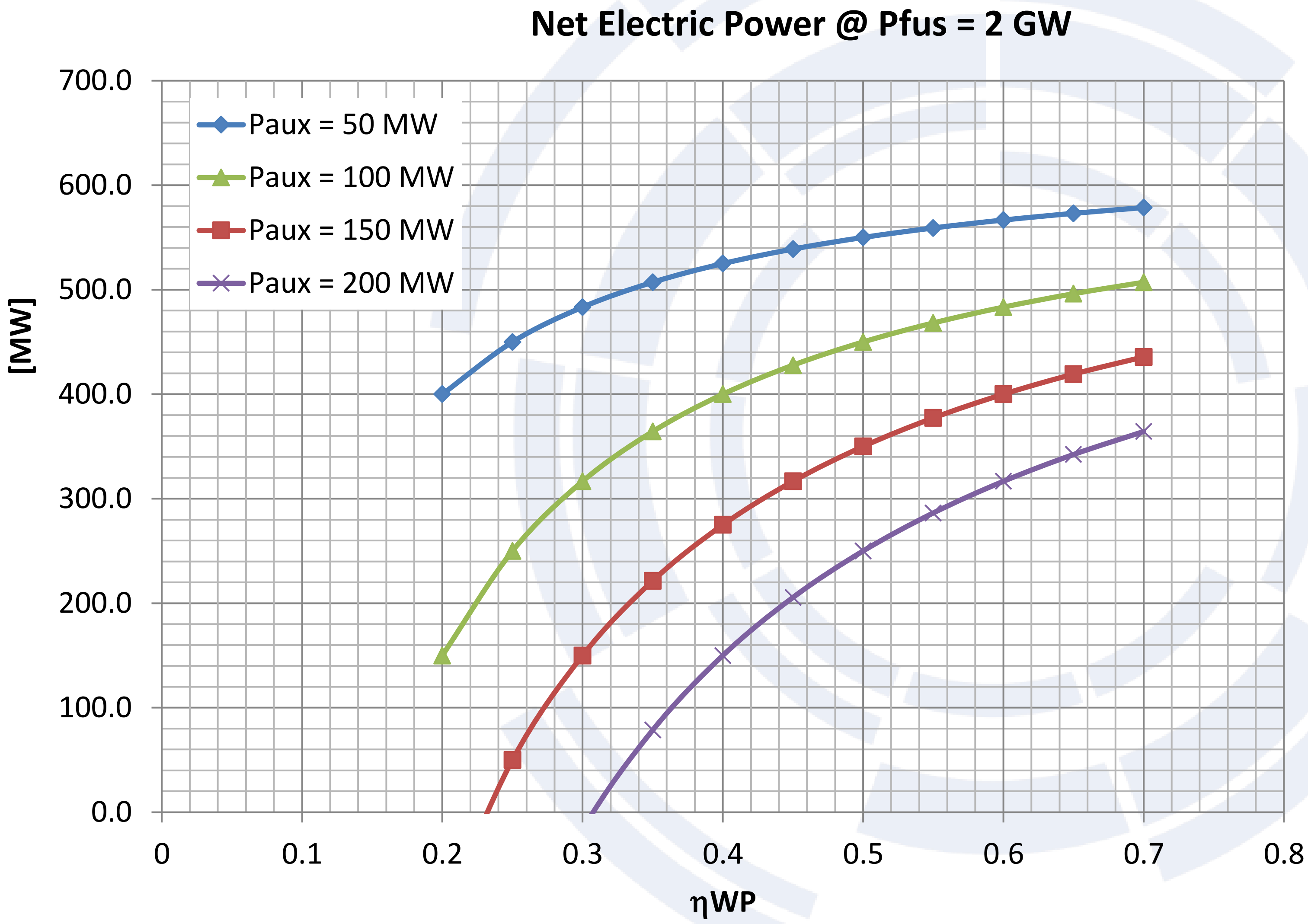
[FENIX Calculation – E. Fable]

Steady State Flexi-DEMO – why not DEMO baseline?

An additional problem is linked to the high recirculating power due to the ***high fraction of auxiliary driven current***.

<u>**Some numbers**</u>: with an efficiency of 50 kA/MW, and $\boldsymbol{I_{p,CD}} \approx$ ***7 MA*** (i.e. $f_{CD} \approx 50\%$), one needs ***140 MW of NBCD/ECCD*** coupled to the plasma, which correspond to ***~400 MW*** to be taken from the grid.

This ***negatively impacts the overall plant performance***, although, admittedly, the problem becomes less severe at higher P_{fus}.

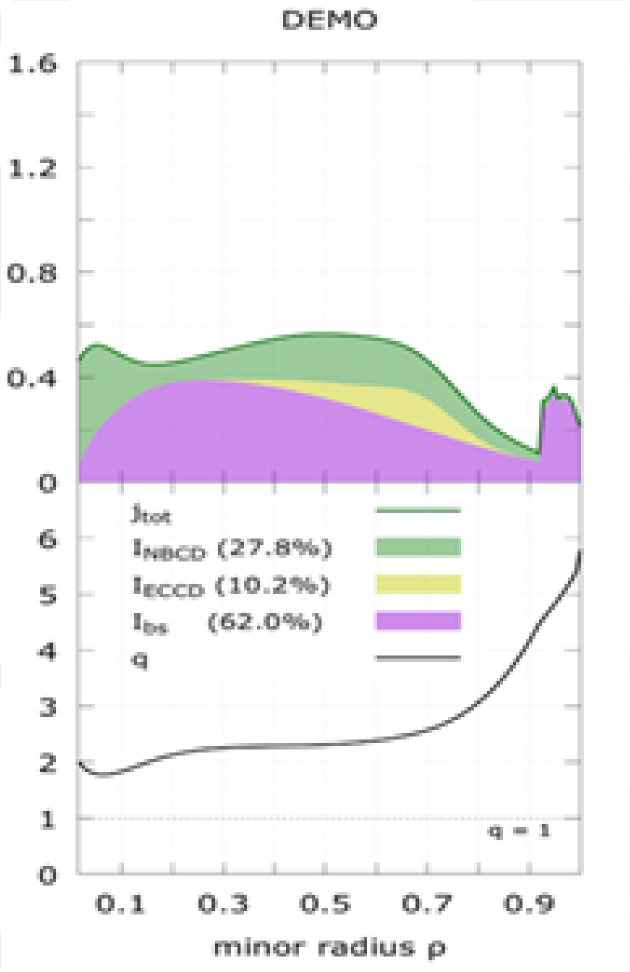


Steady State Flexi-DEMO – why not DEMO baseline?

But you should look at scenarios with more than 60% f_{BS}! They need much less P_{CD}…

<u>Well, yes. But</u>:

- We have ***very limited experimental observations*** of these scenarios *at reactor relevant parameters* (i.e. high density, high current, $q_{95} < 4$, with active RWM control, not during transient phases…).
- Bootstrap current again depends on the plasma profiles. This will make the ***nonlinearity of the burning plasma even stronger.***
- These scenarios anyway require a very careful tailoring of the q-profile and RWM suppression (high $\beta_p \rightarrow$ high β_N). No benefits for the control.
- But especially….

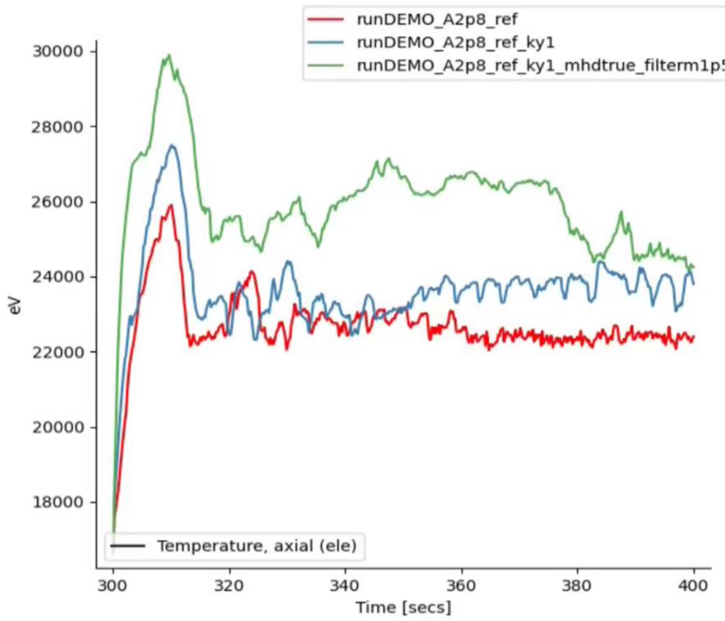


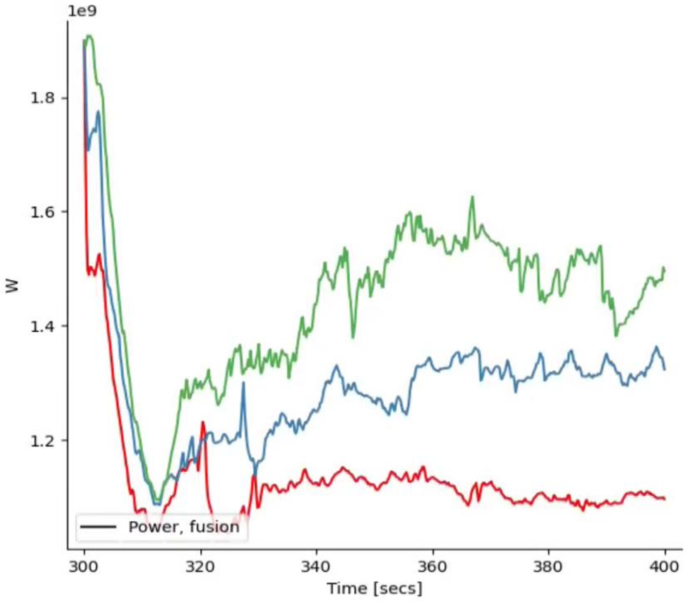
Steady State Flexi-DEMO – why not DEMO baseline?

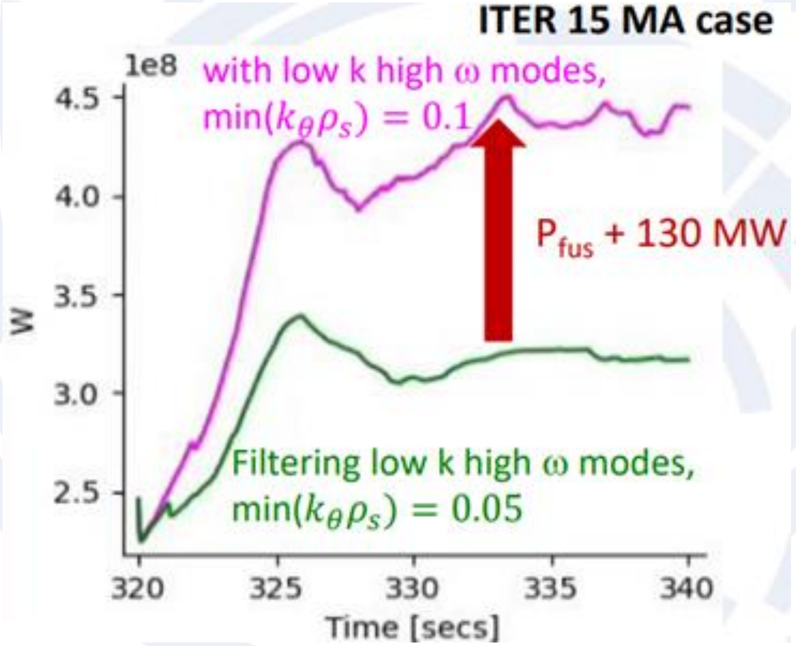
…where would we validate these scenarios?

- ***Burning plasma simulations are extremely unreliable***, exactly because of their nonlinearity (this problem also applies to “standard” scenarios, but they are to some extent easier to adjust). This is an intrinsic feature.

- ***These scenarios will not be seen in ITER as burning plasmas*** (at $Q = 5$ the heating is not α-dominated).



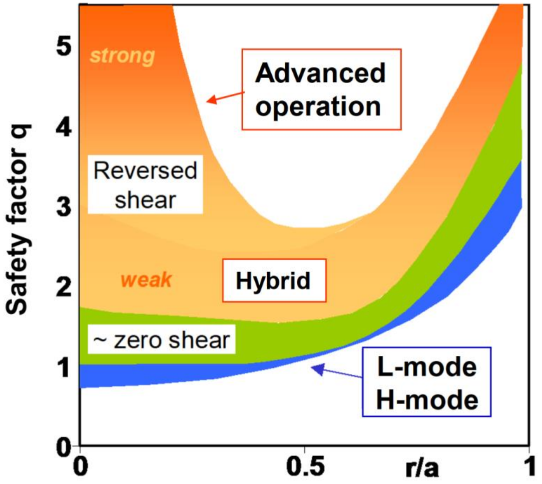




[C. Bourdelle – EPS 2024]

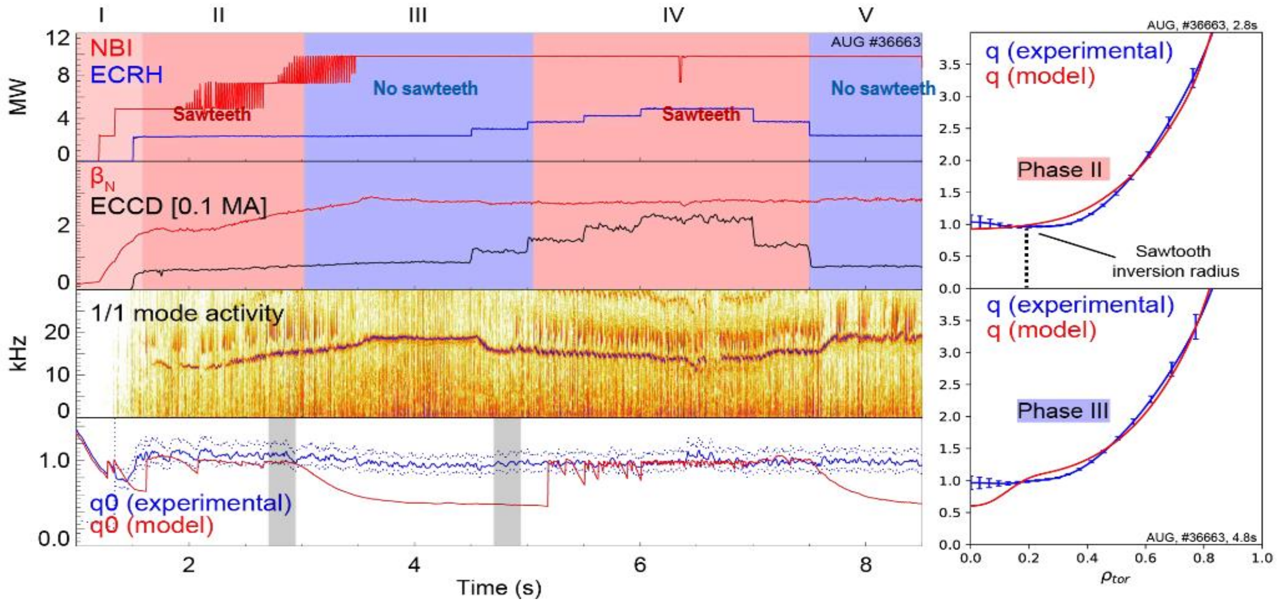
Flux Pumping

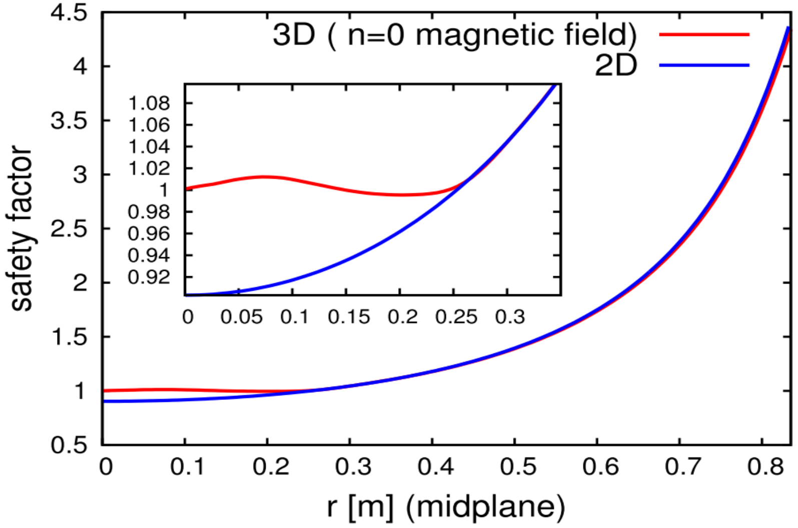
A long pulse is however advantageous.



EU-DEMO is at moment considering scenarios which are not fully steady-state but may allow for longer pulses. They are based on ***hybrid scenarios*** (i.e. $q_0 \approx 1$, no reversed shear) and exhibit the so-called "flux pumping" mechanism *[C. C. Petty, Phys Rev. Letters 2009]*).

Main advantage: self-organised plasma, no need for additional profile control

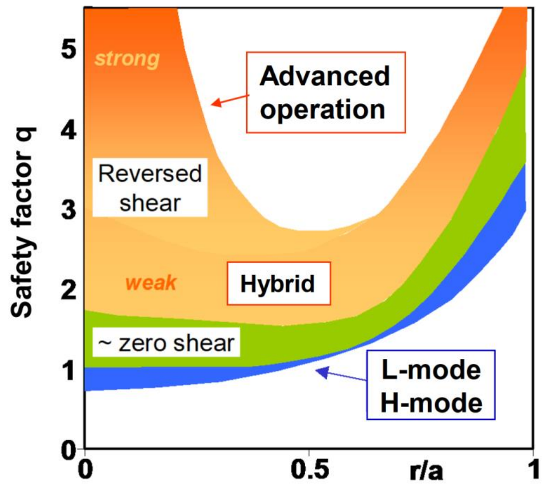




[I. Krebs, PoP 2017][A. Burckhart, NF 2023]

Flux Pumping

While these hybrid scenarios are not intrinsically steady-state, they exhibit advantages with respect to both non-advanced and advanced scenarios.



Benefits (w.r.t. "non-advanced" scenarios):

i) Safety factor on axis clamped at $q_0 \approx 1$

ii) Full suppression of ST crashes (!!)

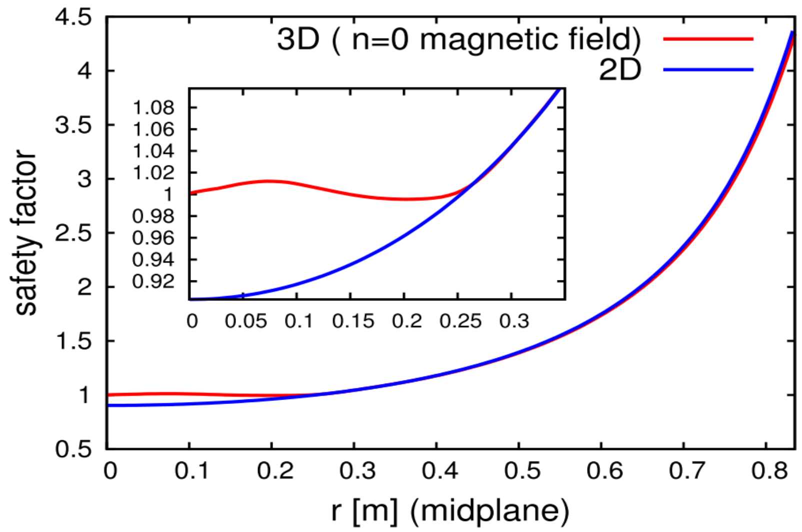
iii) Redistribution of flux: allows for on-axis CD (high efficiency) leading to off-axis q-profile tailoring -> **higher bootstrap current drive**.

Benefits (w.r.t. advanced scenarios):

i) ECCD current generated on axis, where efficiency is high, but „pumped" to off-axis nonlinearly

ii) Self-organised state, no $j(r)$ control needed

iii) Stable scenarios against RMW (i.e. far from beta limit).



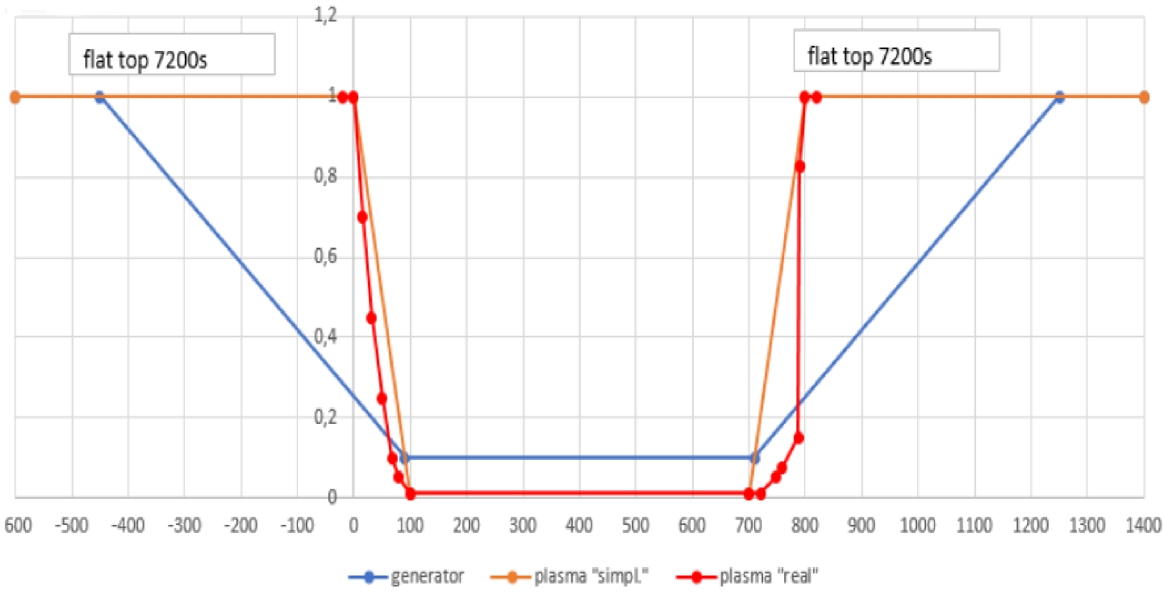
Also, these scenarios can potentially be tested in ITER at high Q.

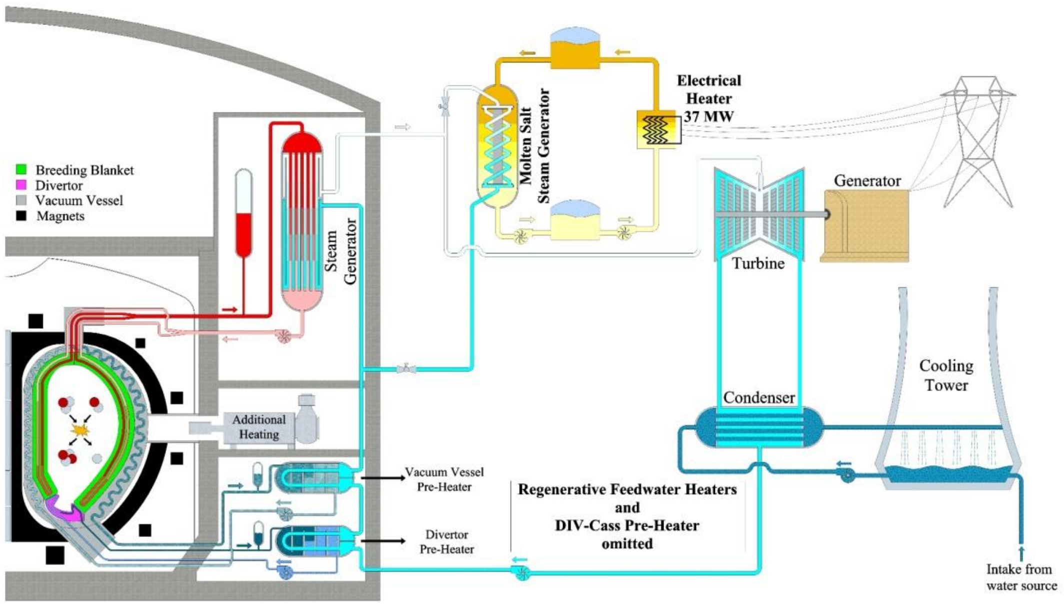
[I. Krebs, PoP 2017][A. Burckhart, NF 2023]

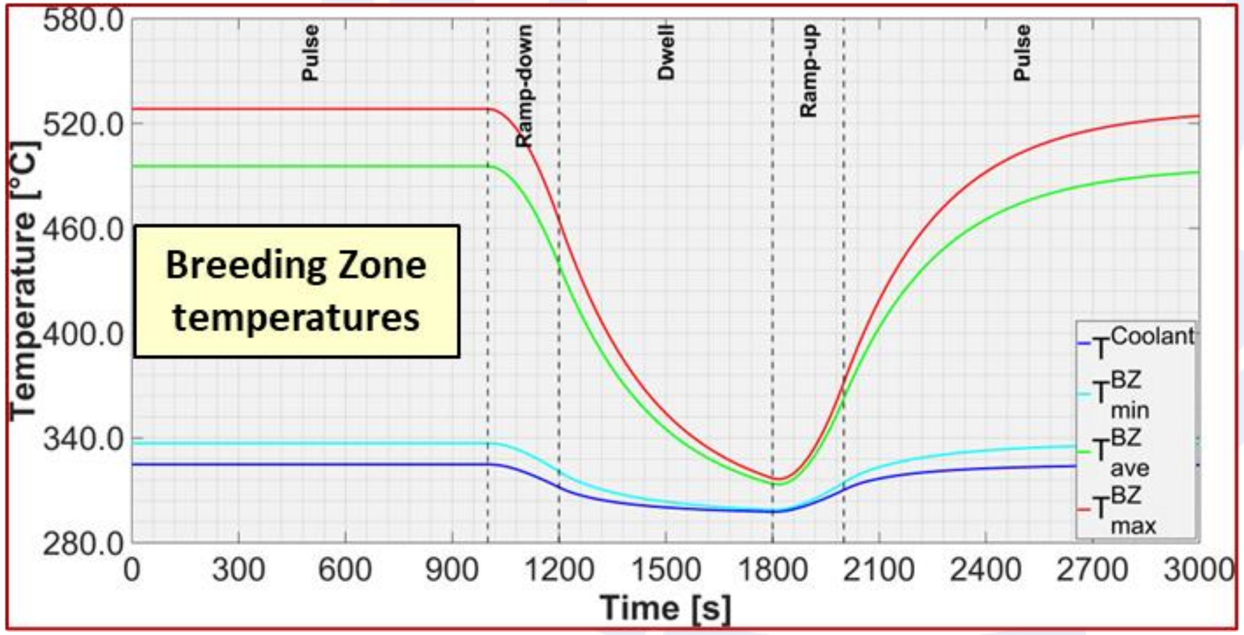
Balance of Plant for pulsed solutions

Molten salt small energy storage **(1200 m³)** electrically heated to produce 10% of steam flow and keep the turbine spinning. ***Size of the storage about 1/10 w.r.t. the indirect cycle solution*** (i.e. decoupling heat generation and turbine).

Thermal inertia of BB significant, but effects of thermal fatigue to be explored. The effect more pronounced on the divertor components.

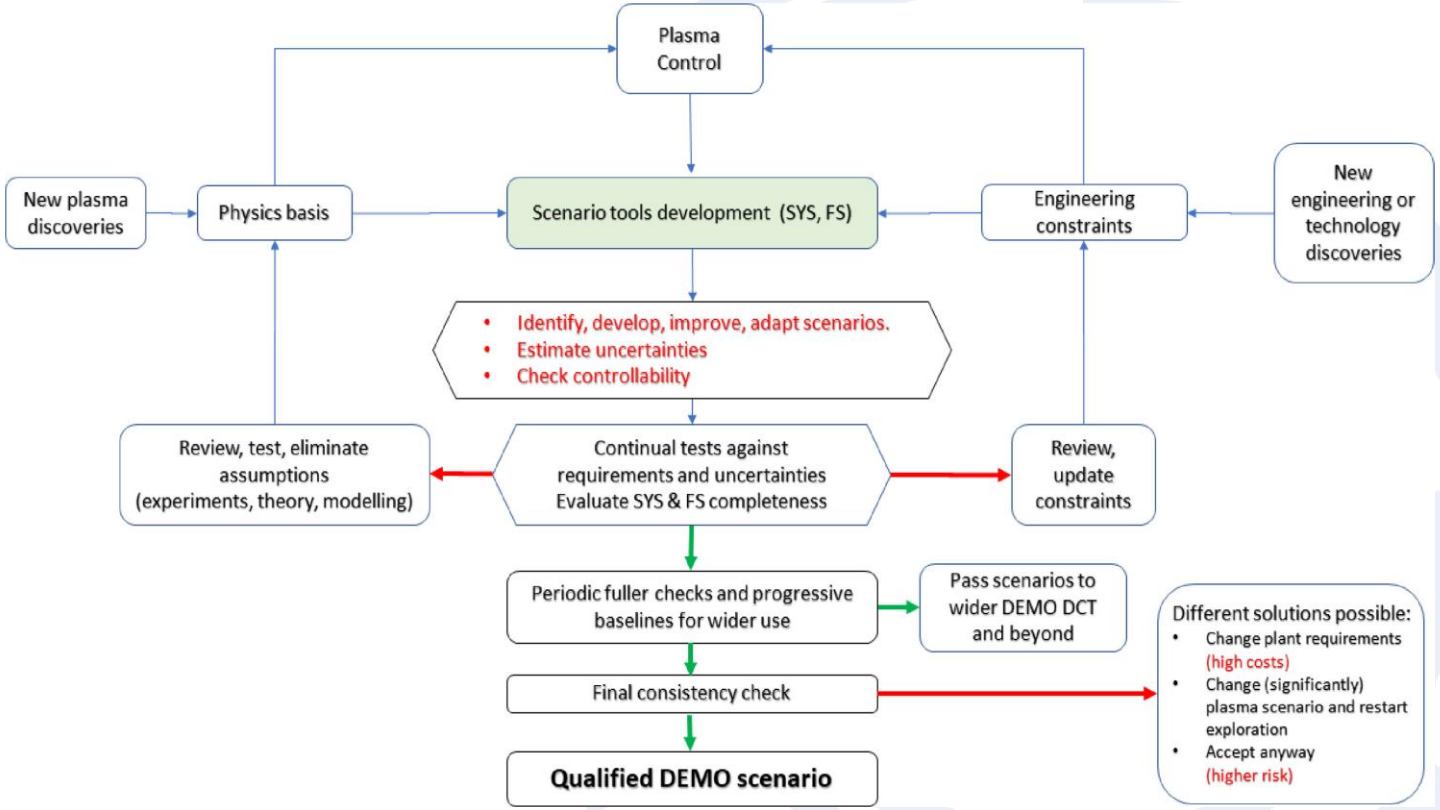






Conclusions

- ***EU-DEMO is based on a pulsed scenario*** because steady-state scenarios are considered too speculative for the time being.
- The EU-DEMO approach however allows to ***take on board innovation*** starting from the early design stages. ***The development of advanced scenarios is thus welcome***.
- ***This approach fundamentally differs from designing a machine which can accomplish its mission *only if* innovation works.***
- This is especially relevant in the nuclear branch, where reactor operation requires well-established solutions to be licensed.



[M. Siccinio, FED 2022]