ST Reactor – new considerations

"Re-thinking of the Fusion Power Plant concept"

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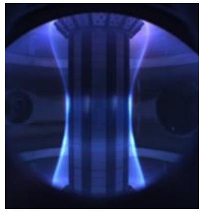
Innovations in Physics and Technologies are the basis for a **new approach** to the design of a **Fusion Reactor**

- What is the fastest path to a **commercial** Fusion Reactor?
- Up to now, designs of Fusion Reactors were based on Physics and Technologies of the last century. **New ideas** are emerging.

- Our approach has many **common ground with** mainstream Tokamak Fusion (e.g. **ITER**, DEMO, STEP). We rely on the **same physics** behind the magnetic fusion concept … but we have a **faster way** to get to a commercially viable device.

The realisation of commercial fusion

ST40



Further validation of ST benefits

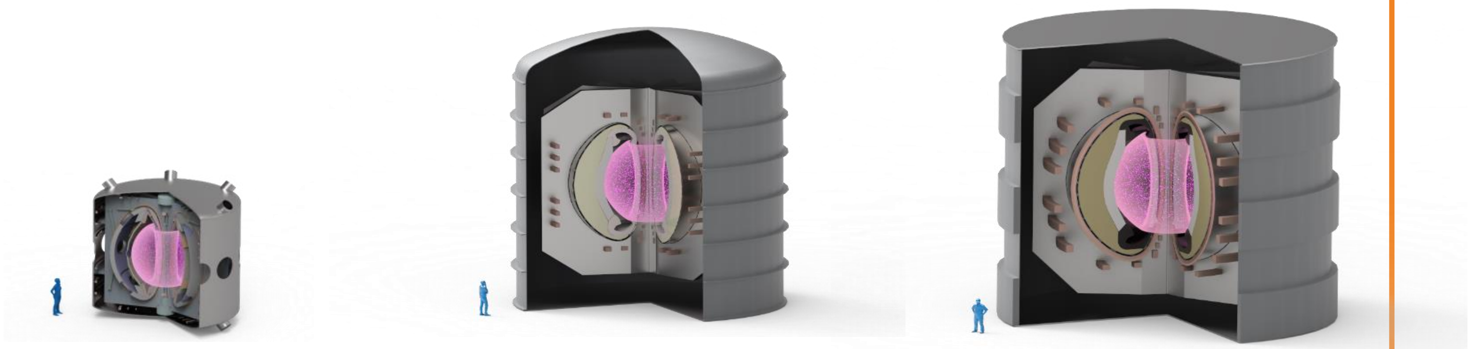
HTS

HTS magnet scale up and demonstration of full ST magnet configuration

ST80-HTS

Commercial Pilot Plant

Commercial Deployment



High performance ST with HTS magnets

Demonstrates technical & commercial capability

Designed for a rapid, global rollout

Mid 2020s

Early 2030s

Mid 2030s

Supporting Technology Development

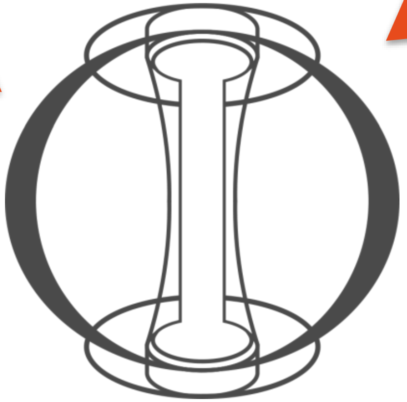
ST80-HTS Mission

- Demonstrate the successful integration of many of the critical engineering technology building blocks.
- Demonstrate long pulse operation with high duty cycle, at high plasma performance

Four Main Innovations:

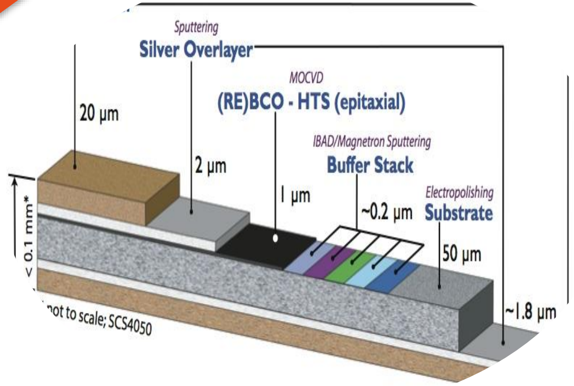
1. Spherical Tokamaks

Squashed shape, compact
Highly efficient, *high β*:
from 12% in DIII-D to 40% in START/NSTX



2. High Temperature Superconductors

High field
Quench protection simplified
Lower cryogenic cooling requirements



smaller, cheaper, faster

3. Li technologies

As a path to low recycling regime and sustainable divertor solution

4. Innovative Physics:

new advanced confinement regimes

Some other ideas to boost tokamak performance

- To-day's Fusion reactor concept is based on the thermal DT Fusion and 20th century physics (H-mode). Are there other ways? **Results of recent experiments** are promising:

  - **Low recycling regimes and Hot Ion mode** are now considered as one of promising operation scenarios to get burning conditions in a fusion reactor (FIRE mode, KSTAR, *Nature 2022, SOFT and APS 2022*).
  - Hot Ion mode has been also demonstrated in STs: ST40 (Asunta, Romanelli, S.M. Kaye, this meeting), Globus-M2 (Zhiltsov, this meeting) and suggested on other STs (EHL-2, Huasheng Xie, this meeting)
  - Recent JET experiments also show big advantages of the **low recycling hot ion mode** regime (J.Garcia et al, Ph Pl 2021)

- **Beam-plasma** and beam-beam reactions are known to contribute to Fusion power

  - In big and medium size tokamaks this contribution is known and well determined (~50% on JET, more on MAST/NSTX and ST40)

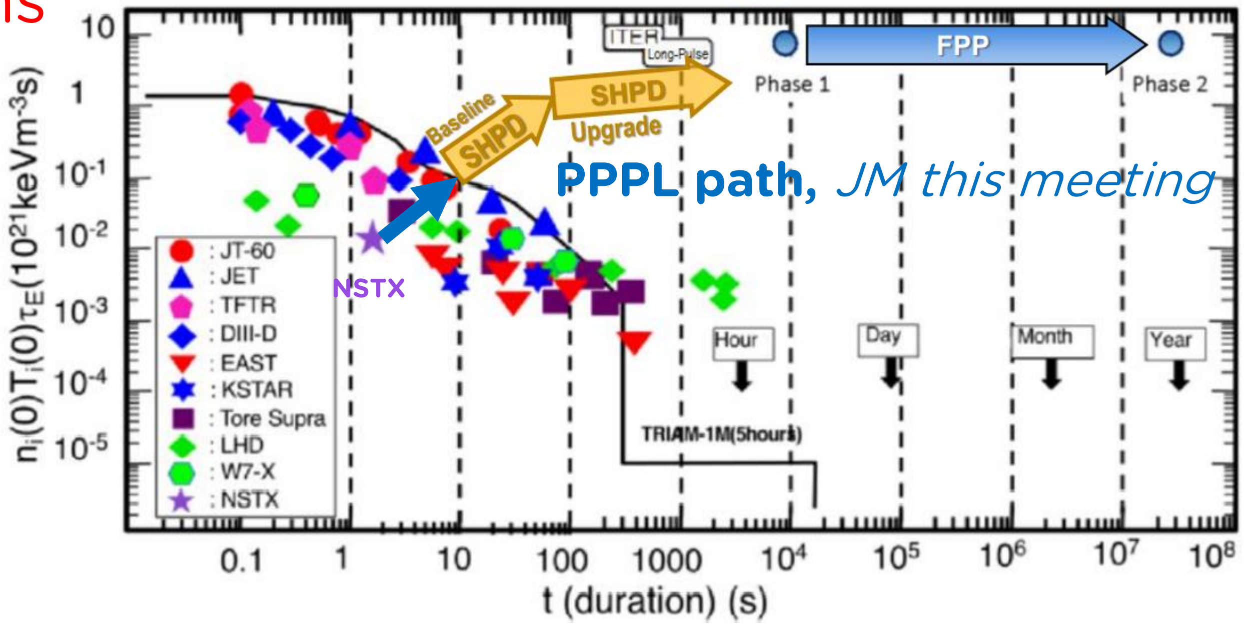
  - Can we boost Q_{fus} optimising **beam-plasma**? And use fast particles for stability improvement (FIRE-type stabilisation, sawteeth stabilisation)

Reality. Are long pulses possible? Not up to now.

Challenges with steady-state operations

- there **are no steady-state tokamaks or stellarators** with reactor relevant plasma parameters
- There are **no proper experimental facilities** since devices for such studies are **very expensive and risky.**

Adapted from Fig. 4.2 of NASEM report "Bringing Fusion to the U.S. Grid" (2021)



- Although technology issues associated with steady-state magnets, heating and CD auxiliary systems, and requirements for their maintenance could be resolved, there is growing evidence that the **duration of the burning pulse may be limited by other factors**.

  - Even in relatively short pulses unexplained fast disruptions have been observed which can be attributed to **dust** generation, **flaking** of depositions on the **vessel wall** and **central post**, formation of **hot spots** and other plasma-wall interaction phenomena.

Main timescales for performance limitations

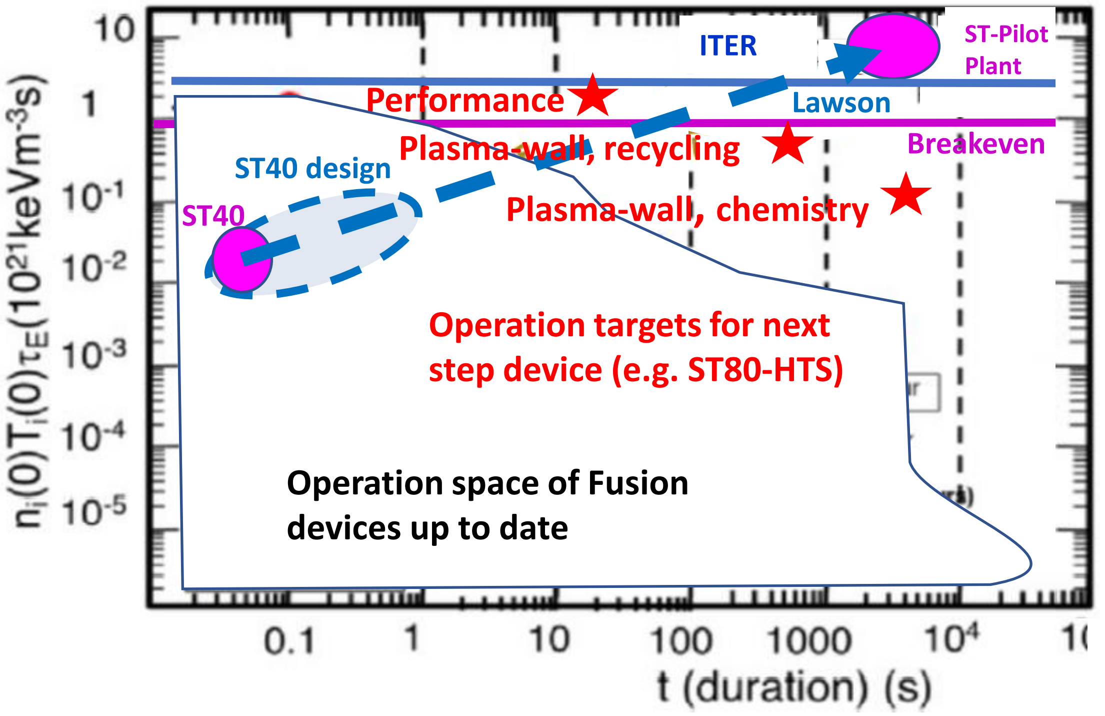
- Several timescales can be considered for possible **pulse duration limitation:**

  - **Fast** due to dust, flaking, hot spots, VDE, MHD

  - Recycling is much slower, from tens of seconds to – **5/15min** w/o / with Li conditioning (*HIDRA, APS 2022*)

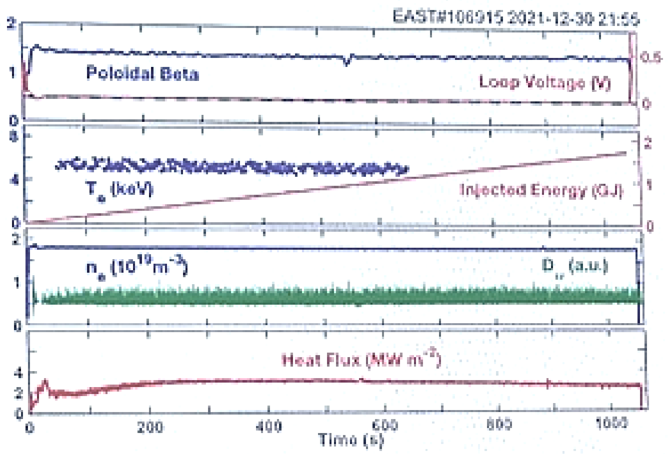
  - Accumulation of **chemistry** on and in the wall (**30 – 40 min**)

- *These timescales determine necessary pulse durations in next step experimental devices and test beds to find recipes for mitigation and achievement of long discharges in future devices*



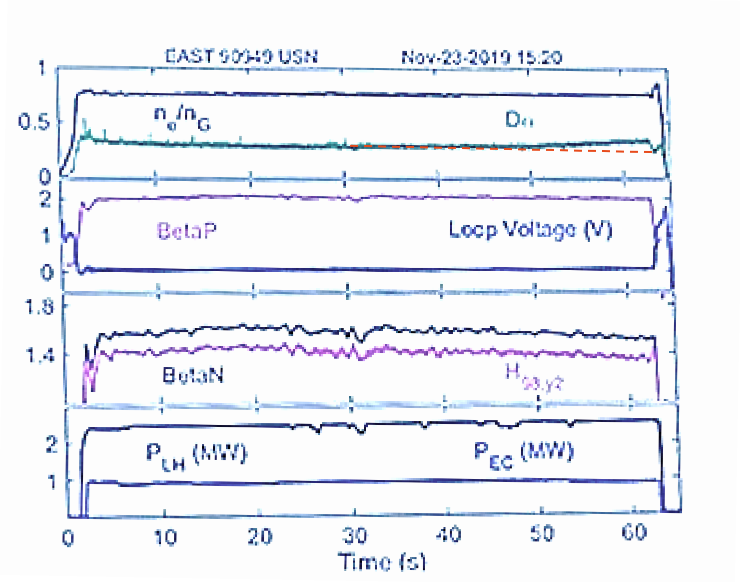
- Engineering and **thermal cycle** (blanket, divertor etc) **timescales** should also be taken into account

Are **longer** pulses possible? Yes *(SOFT, APS 2022).*



- Fully non-inductive plasma with dominant e-heating
  - Zero injected torque
  - P_{inj}~1.65 MW (P_{LHW}~1.1MW, P_{ECH}~0.55MW) with E_{inj}~1.73GJ
  - H_{98}~1.3
- Stable control of plasma equilibrium configuration
- Good control of particle recycling and heat load

Te(0)~6.5keV, T_i(0)~1.0keV, n_i(0)~2.2x$10^{19}m^{-3}$, τ_E~60ms



EAST 1056 sec discharge **w/o** expected recycling or chemistry **limitation**

- The secret is “Control of recycling”, i.e. Li conditioning

But **EAST H-mode** shot was limited to 60 sec.

- Note “hardly visible” increase in D_α around 50 sec
- **KSTAR** performance degradation was mitigated with reducing wall recycling due to injection of Boron Nitride, hot vessel, wall conditioning.
- Boronisation resulted in significant increase in pulse duration on **W7X**

- But we need to demonstrate long pulses at **10 – 100 times higher** performance ($nT\tau$)

Could pulsed pilot plants overcome long pulse challenges?

- Recent studies *(Segal et al, NF 2021)* have shown potential advantages of a **pulsed** fusion reactor over a conventional **steady-state** reactor:

  - **reduced** need of very expensive non-inductive **current drive**;

  - lower risk, as the steady state operations may have limitations;

  - broader range of possible plasma parameters (not limited by the CD requirements or H-mode, *Frank et al, NF 2022*);

- **Pulsed ST reactors** have even more advantages due to:

  - possibility of **high bootstrap current**,
  - stronger increase in the **confinement** with the toroidal field,
  - good stability,
  - lower requirements on the volt-second capability of the central solenoid for the plasma current sustainment.

How long should be burning phase in a Reactor?

- Reactor efficiency criterion *E Rebhan, van Oost, Fusion Science and Technology 2017* :

$$\frac{\tau_b}{\tau_E^*} = \frac{(1+\tau_h/\tau_{E,h}^*)}{5\eta_a\eta_{eff}(1-\eta/\eta_{eff})},$$

τ_b is burn time, η is efficiency of power station, $\eta_{eff} \sim \eta_{th}$ ~ 1/3, $\eta_a\eta_{eff}$ ~ 1/20 => **τ_{burn} ~ 160τ_E**

- **Burn time of 2h** would allow 100 000 cycles for 25 years of reactor life time tor typical conventional reactor with τ_E ~ **3.5 sec**

- Another estimate *Segal et al, NF 2021:*

- 500 cycles per month, assuming 15000 maximum N_{cycle} before SC replacement, or

$$\tau_P = 720\frac{N_{ON}\tau_{OFF}}{N_{CYC}} = 1.44 \sim 1.5 \text{ hours per pulse}$$

- 1 – 2 h pulses are assumed for most of today's DEMO proposals
- **ST reactor** may be smaller and confinement time ~ 1 sec, so needed pulse (burn) duration may be just 30 – 60 min

Could pulsed pilot plants overcome long pulse challenges?

- For these pulse durations, **central solenoid** can be the most efficient tool to sustain plasma current, replacing expensive RF CD

  - Steady state reactor needs about 50% higher fusion gain than a pulsed reactor due to its low RF conversion efficiency (*Segal et al, NF 2021*)

  - However, **non-inductive** methods should be used for plasma **current ramp-up** (H Idei, N Tsujii, Y Ono, M Ono, K Kuroda, M Inomoto, E. du Toit, H. Tanaka, K. Iwasaki, N. Tsujii, S.J. Diem, Tan Yi, etc this meeting) **to save solenoid flux for the flat-top**

- Pulsed operations may allow solutions for chemistry treatment between shots (e.g. GDC, boronisation, Li conditioning and re-conditioning)

- Steady-state energy production can be achieved by **keeping blanket temperature high** enough between plasma pulses

  - Typical **blanket** full **cooling time** ~ 100 sec, assuming 20 – 30 sec needed to recharge solenoid, loss of CoE is not substantial. Only 3 MW needed for EU DEMO to keep blanket hot (SOFT 2022)

Advantages of an ST pulsed pilot plant

- The analysis described in (*Segal et al*) has been extended to STs. It can be concluded that pulsed reactors have some extra favourable properties, including :

  - Broader range of possible plasma parameters (not limited by the CD requirements);

  - Potentially simpler, faster, and cheaper development path as operations with the CS are well established;

- These advantages are even **more pronounced in STs** due to several specific features:

  - Possibility to operate at a higher beta;

  - Possibility to achieve a higher bootstrap current fraction;

  - Stronger increase in the confinement with the toroidal field;

  - Better stability, both for micro-pressure-driven micro instabilities and for the current-driven instabilities.

  - Lower requirements on the volt-second capability of the CS due to the ability to reach full plasma current without using the CS.

Further option – recharging of SC during steady-state

- Although the bootstrap current in an ST is expected to contribute up to high levels of ~90% of the total plasma current at the flat-top, the remainder (~10%) must be driven by other means and the **CS is an efficient** solution.

- Given that the CS is used only for the I_p sustainment and **not for the I_p ramp-up**, the **needed CS volt-seconds can be much smaller.**

  - When the limited CS volt-second capability is exhausted during the burning stage, it may be **recharged without plasma termination.**

  - Keeping plasma current constant during CS recharge significantly **reduces** engineering **challenges** from the **thermal cycling** of pulsed operation.

- RF and microwave auxiliary systems that were used during the ramp-up phase can be **re-applied during recharging**.

  - This will reduce the efficiency of the energy production because of the increased re-circulating power, but only for a considerably short period.

Recharging of SC during steady-state

- If needed, solenoid may be recharged during the pulse using combination of RF CD schemes that were used during ramp-up

  - ST has big advantages on this route – lower inductance, high bootstrap fraction

  - High neoclassical resistivity controversially helps

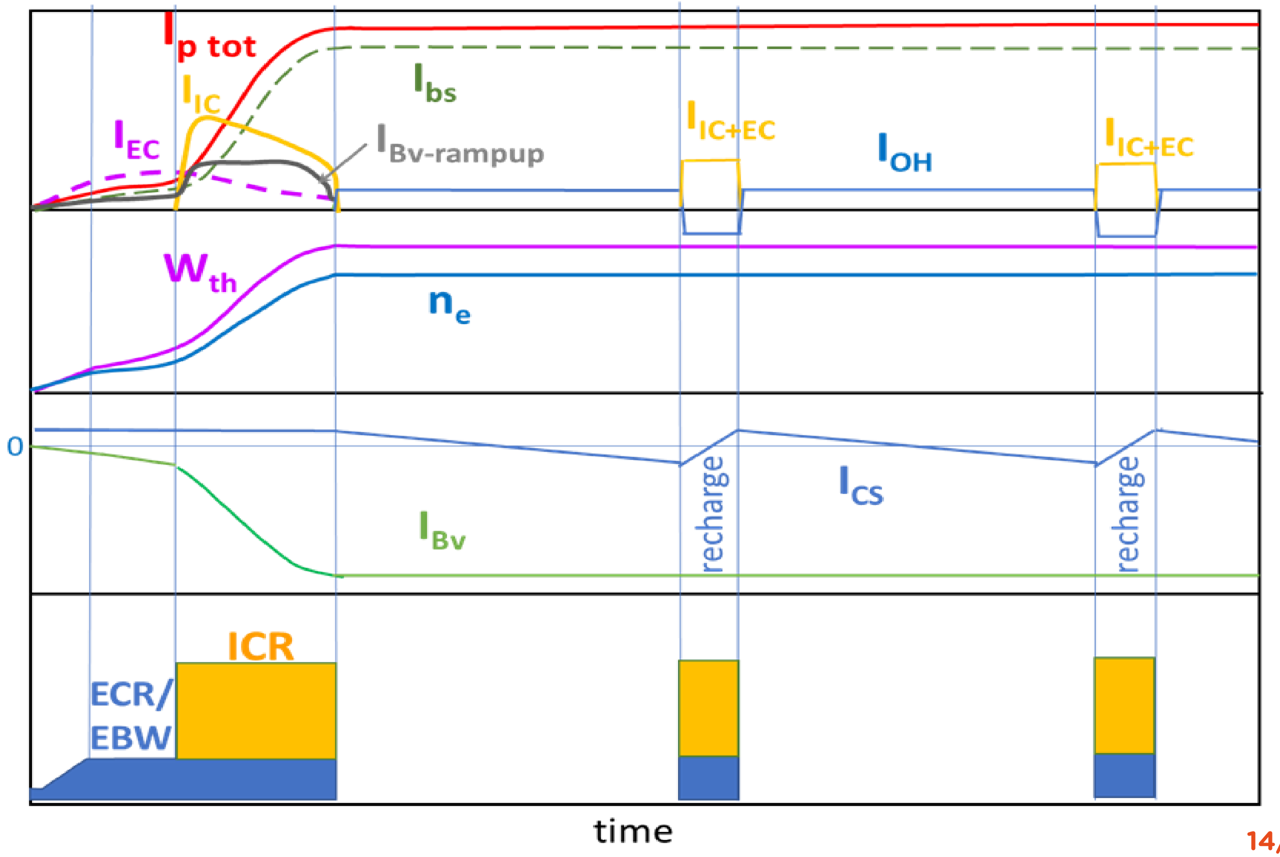
Proposed time sequence:

$I_{p\ tot}$ - total plasma current and its components: I_{EC}, I_{IC}, I_{bs}, and $I_{Bv\text{-}rampup}$ (not to scale);

W_{th}- plasma thermal energy and n_e- electron density;

I_{CS} - CS current and I_{BV} - vertical field coil current;

and auxiliary CD and heating power application periods (schematic).

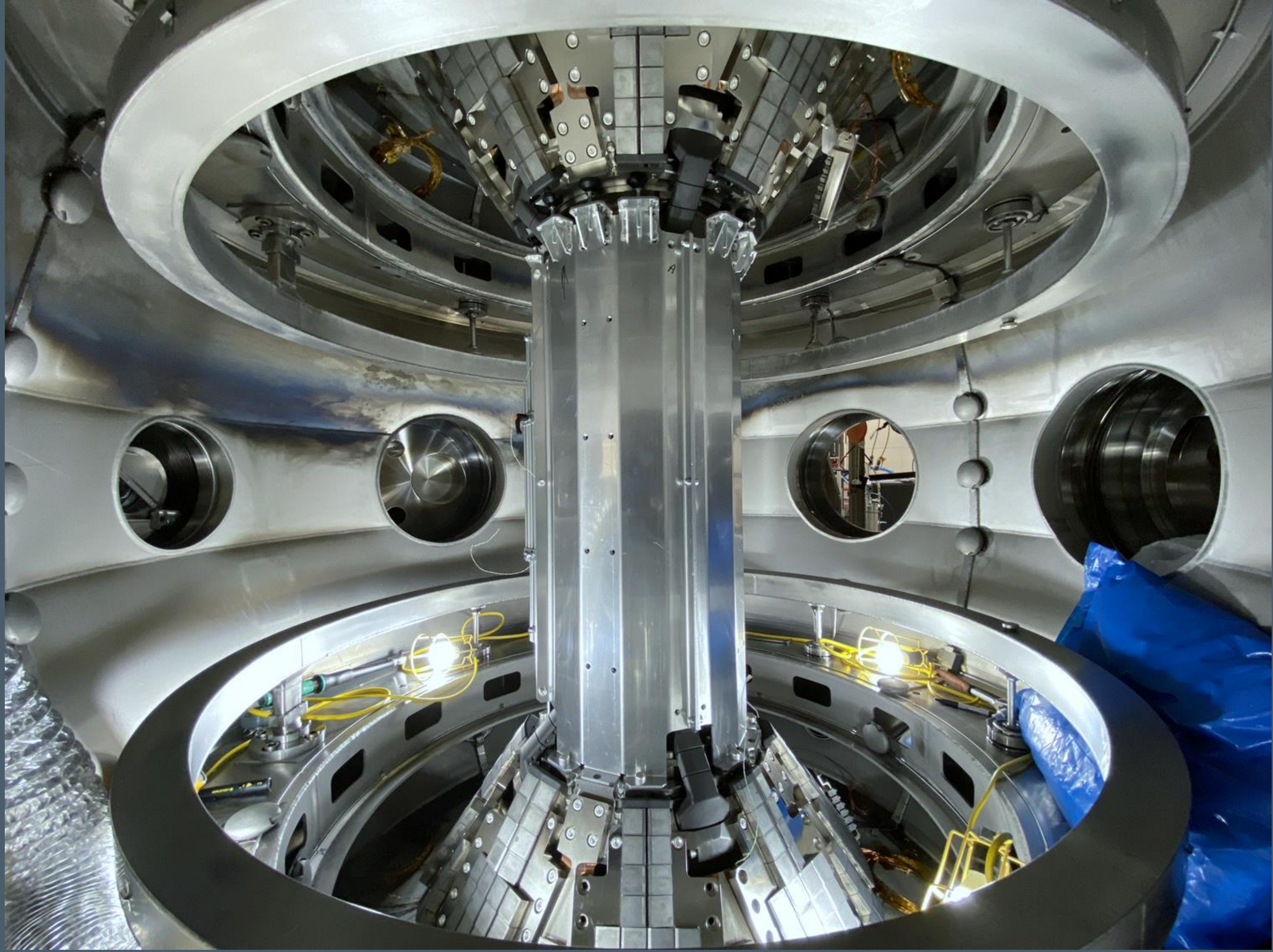


Conclusions

- Recent advances in Physics and technologies allow **re-thinking** of **Fusion Power Plant** concepts
- With the new approach, a pulsed device can be technically and economically feasible
- An ST **Fusion Pilot Plant** that has **competitive advantages for commercialization and cost reduction** and a strong economy of scale, leading to a **Power Plants** that are still small on an absolute scale

ST40: World Firsts

- Achieving a plasma temperature of 100 million degrees Celsius, the threshold
- This is by far the highest temperature ever achieved in a spherical tokamak and by any privately funded tokamak
- The triple product achieved is the highest by a private fusion energy company in a spherical tokamak with a plasma volume of less than one cubic meter
- This is 15 times less volume than any other tokamak which has achieved this temperature.



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