FEC-2023: инженерные и физические вызовы УТС

(по материалам конференции МАГАТЭ)

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ПЛАН доклада

- ВВЕДЕНИЕ: тенденции и формат конференции FEC-2023
- От JET к JT-60SA
- ITER: уроки и планы
- HTS технология для УТС: возможно ли сильное Bt в реакторе?
- Термоядерное «солнце» восходит на Востоке
- Успехи Инерциального синтеза

Заключение

FEC-2023: инженерные и физические вызовы УТС

ВВЕДЕНИЕ: тенденции и формат конференции FEC-2023

- Новое и неожиданное явление в работах по УТС – взрывное увеличение числа частных (private) компаний, вовлеченных в исследования
  1. Ранее «на слуху» были 2 компании: «TAE Technologies Inc.» (C-2W – Field Reversed Configuration), «Tokamak Energy Ltd.» (ST40 – high-field Spherical Tokamak)
  2. К ним добавились еще 15-20: «Commonwealth Fusion Systems» (SPARC – high-field HTS Tokamak), «Type One Energy Group» (High-Field Stellarator), «EX-Fusion Inc.» (High Repetitive laser for IFE reactor), «Thea Energy, Inc.» (Optim. Stellarator Fields w/o costly coils), «Zap Energy» – (Shear-Flow-Stabilized Z-pinch), «HB11 Energy Holdings Pty» (Laser-Driven Proton-Boron fusion), «WS Atkins Plc» (Design of Adv. Tritium Facility) и много др.

- Конференция FEC существенно изменила свой формат:
  1. Не было привычных печатных материалов: Programme, Book of Abstracts …, все материалы – «On-Line».
  2. Вопросы задавались всем докладчикам в конце секции – Q&A (попытка стимулировать обсуждение).
  3. Отменена секция «Summary» (4-5 докладов по основным тематикам). Вместо «Summary» введена секция PWF – «PathWays to Fusion».

     В секции «PathWays to Fusion» предполагались в основном доклады частных компаний.
     В действительности, прозвучали формальные доклады: ITER, EUROFUSION, Japan QST, General Atomics

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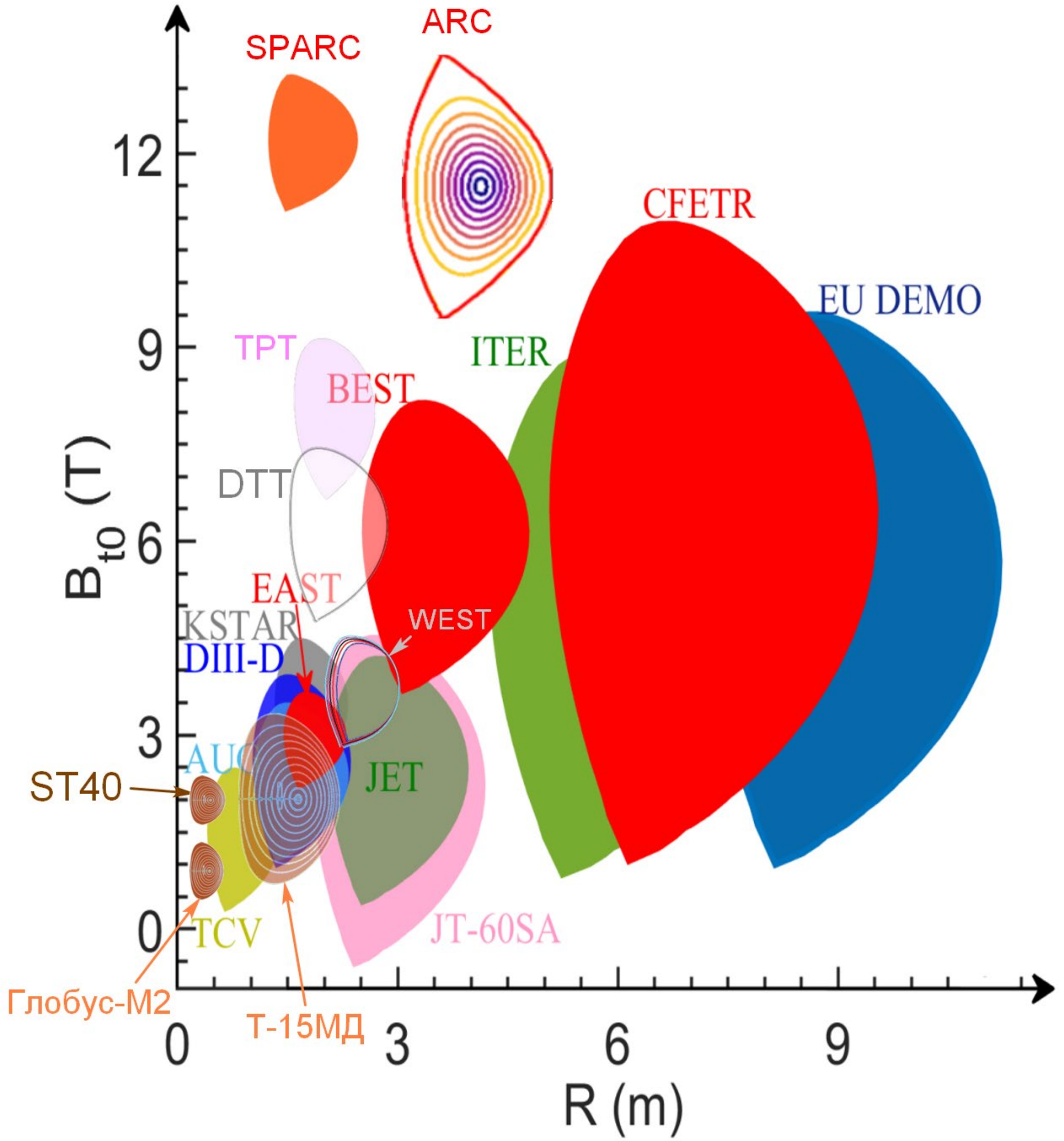
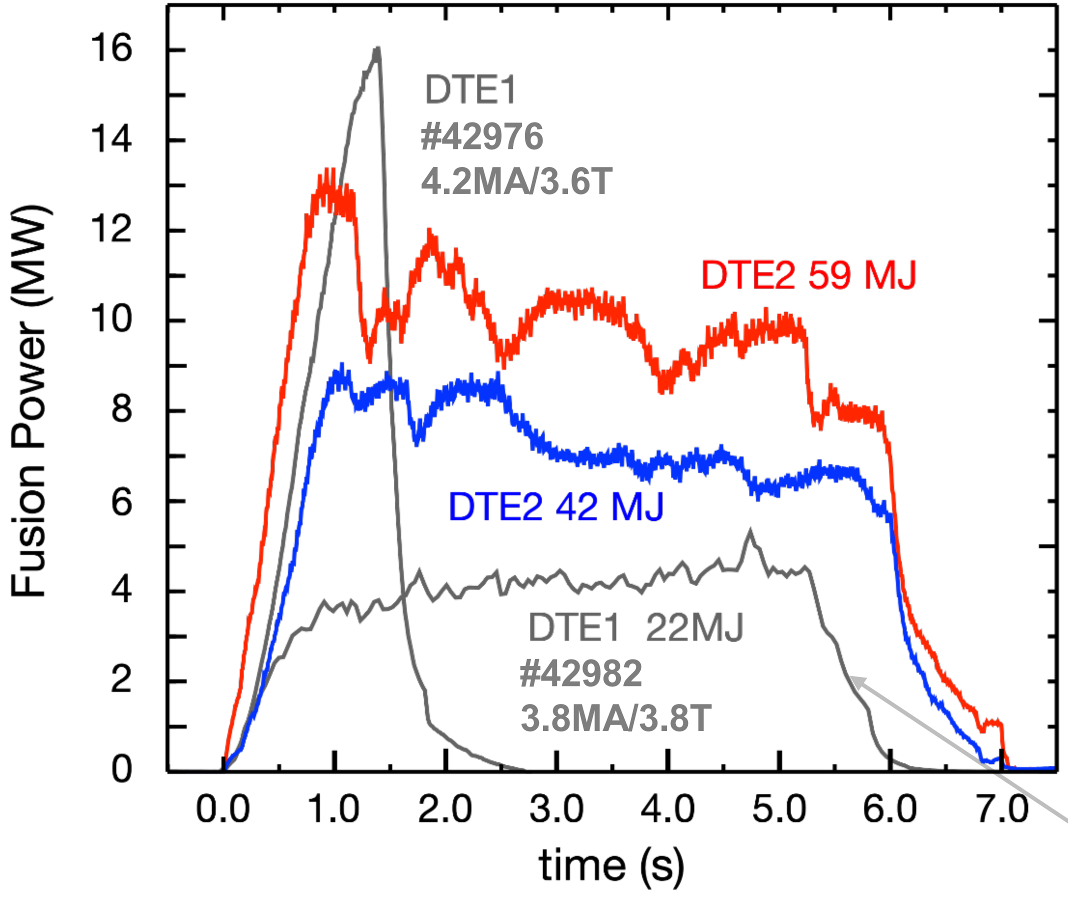
- ☐ Современные токамаки: $R_0 \leq 3.0$ м, $B_T \leq 4.0$ Тл
  (Отсутствуют Alcator C-Mod, FTU с полем до 8 Тл – «теплые катушки», короткий разряд)



World fusion energy records obtained with JET hybrid scenarios

Fusion performance with JET-ILW beyond that of DTE1



- Hybrid plasmas performed in D-T for the first time, with Be/W wall
- **Demonstrate compatibility of JET-ILW with sustained high fusion performance**

[Hobirk et al, NF SI on JET T & D-T 2023]

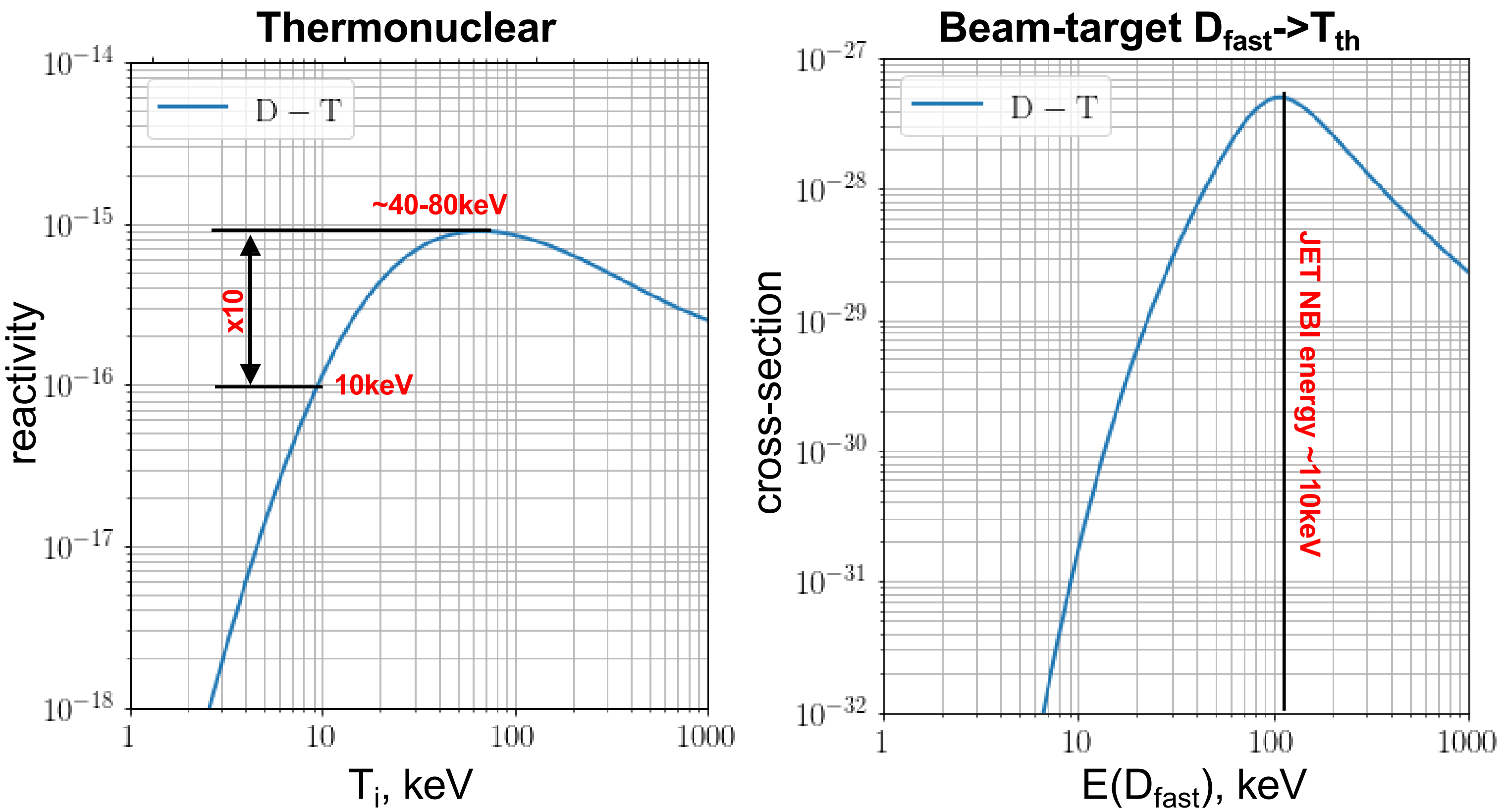
#99869 (2.3MA/3.45T) Hybrid with ~50-50 D-T
#99971 (2.5MA/3.86T) Hybrid with ~15-85 D-T

[Maslov et al, NF SI on JET T & D-T 2023]

Baseline scenario H-mode (JET-C)
[holding world fusion energy record till DTE2]

Non-thermal fusion power

- **T_i ~10keV** at JET - below optimal for the thermonuclear reactivity
- **E(NBI) ~ 110keV** – maximum cross-section for D->T beam-target

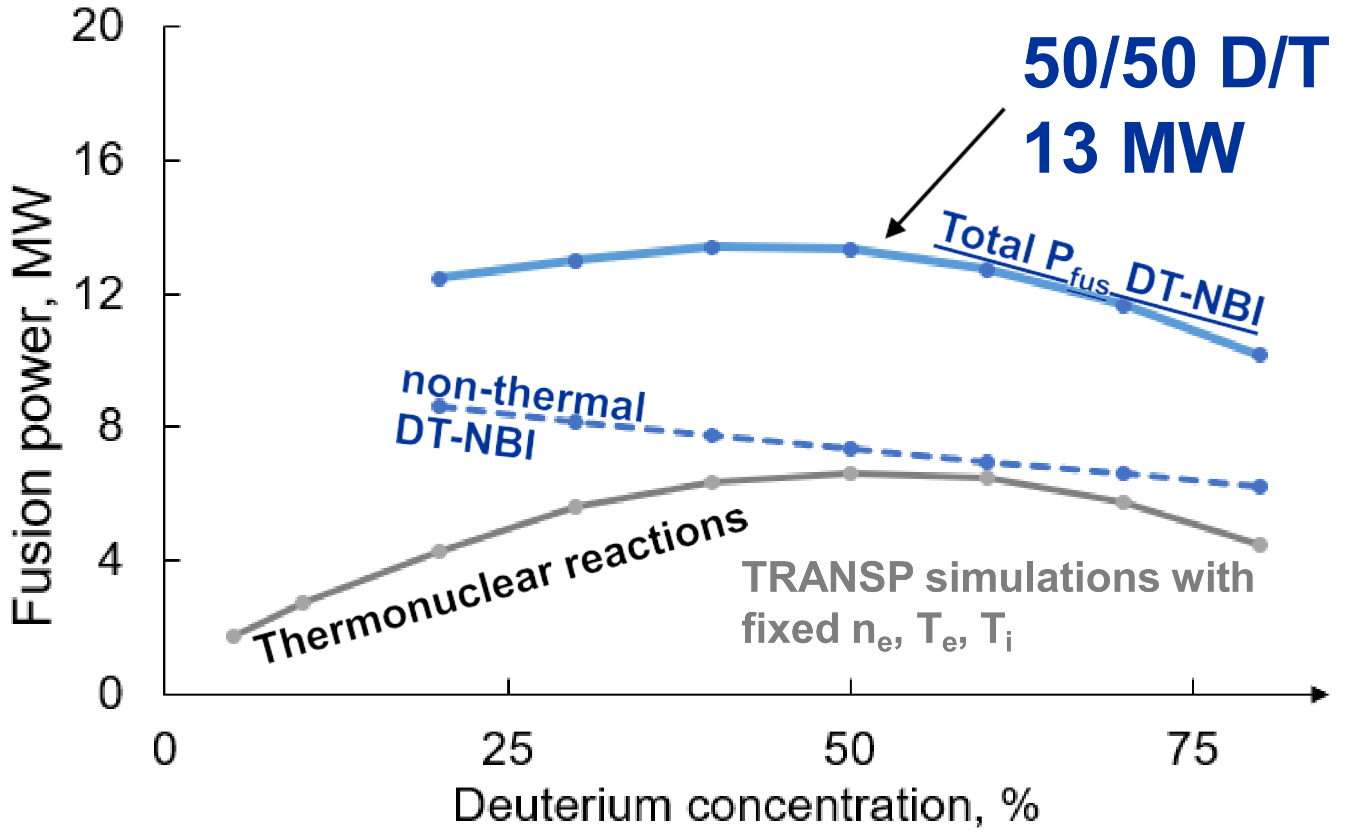


- Non-thermal reactions – beam-target and ICRH driven – always contribute significantly to the total P_{fus} at JET
- Optimizing the balance between thermonuclear and non-thermal reactions for non-symmetric (not 50/50) D/T composition can lead to a net increase of the total fusion power.

Thermonuclear vs non-thermal

- Hybrid scenario: $P_{\text{therm}} \lesssim P_{\text{non-therm}}$

  J. Hobirk this conf.
- Mixed DT-NBI: P_{fus} weakly changes with D/T ratio
- Pure D-NBI: strong increase of P_{fus} towards T-rich plasmas



50/50 D/T
13 MW

- In JET hybrid scenario, up to **50%** more fusion power can be achieved in T-rich plasma with D-NBI
- But the extrapolation assumes the **same T-rich condition in the whole plasma volume**

Thermonuclear vs non-thermal

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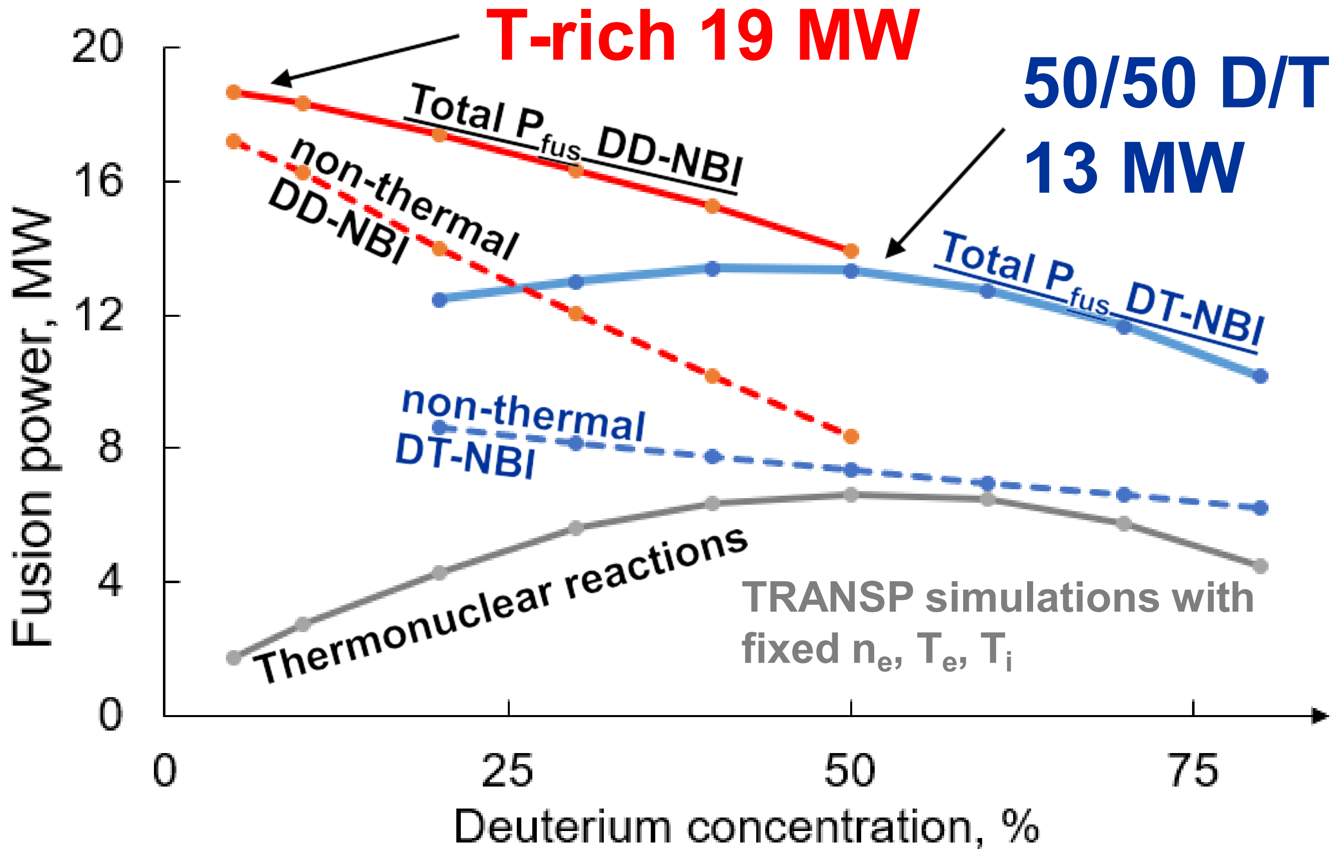

TRANSP simulations with fixed n_e, T_e, T_i

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- But the extrapolation assumes the **same T-rich condition in the whole plasma volume**

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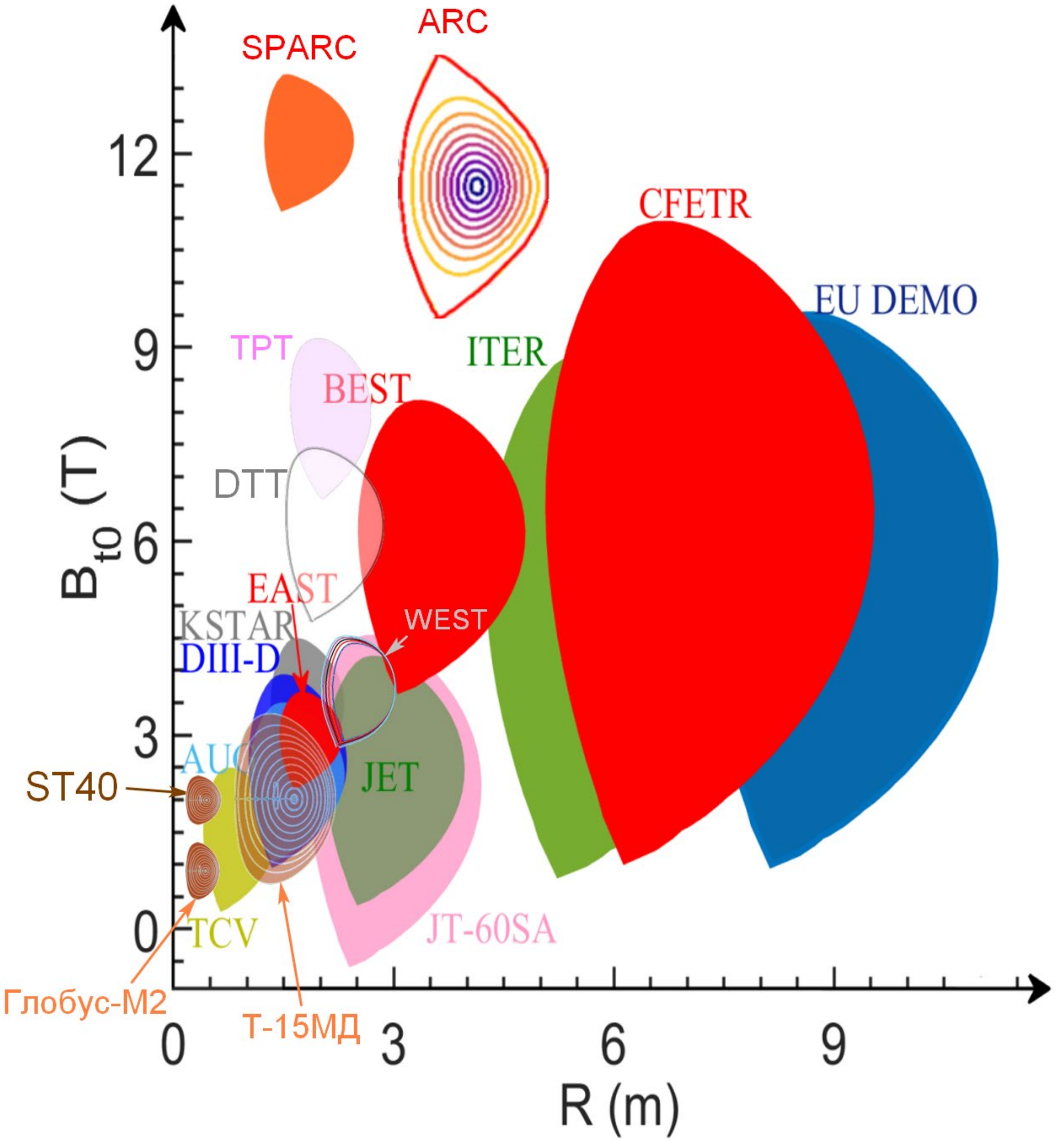
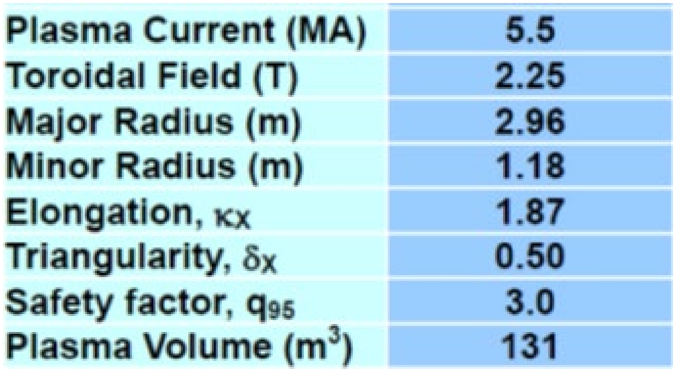
- ☐ На смену JET приходит токамак JT-60SA
  1. Основное отличие – сверхпроводящая магнитная система – длинный разряд!
  2. Магнитное поле меньше, чем в JET: B_T(JT-60SA) = 2.25 Тл, B_T(JET) = 3.85 Тл
  3. Не рассчитан на работу с тритием!

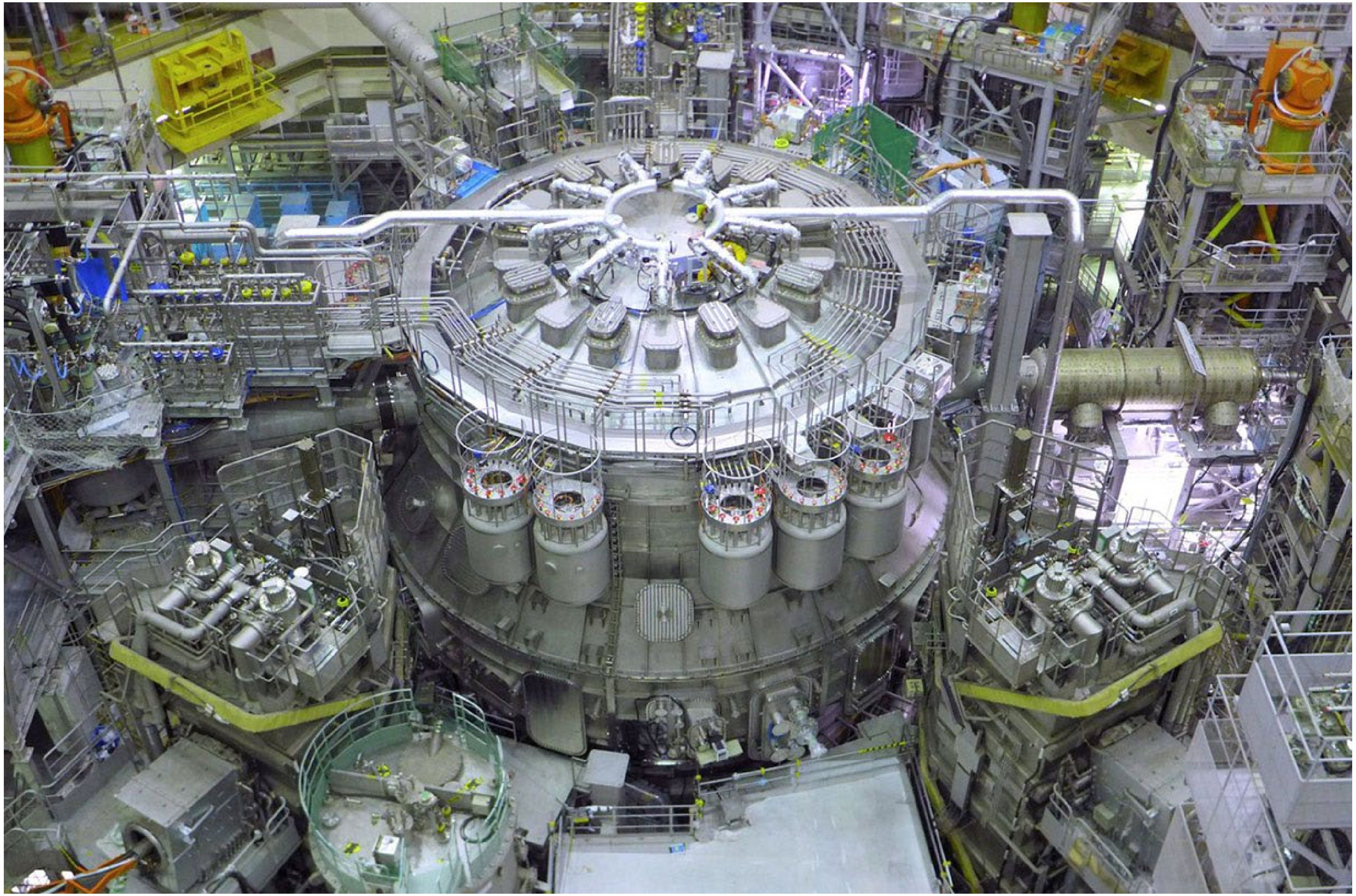


FEC-2023: инженерные и физические вызовы УТС

Параметры JT-60SA



Plasma Current (MA)	5.5
Toroidal Field (T)	2.25
Major Radius (m)	2.96
Minor Radius (m)	1.18
Elongation, κ_X	1.87
Triangularity, δ_X	0.50
Safety factor, q_{95}	3.0
Plasma Volume (m^3)	131



JT-60SA (JT-60 Super Advanced) Project

JT-60SA Project is implemented under the Broader Approach (BA) Agreement between EU and Japan as well as the Japanese national fusion programme.

Mission:

Contribute to the early realization of fusion energy by addressing key physics and engineering issues for ITER and DEMO.

Major Objectives:

(1) Supportive Research for ITER

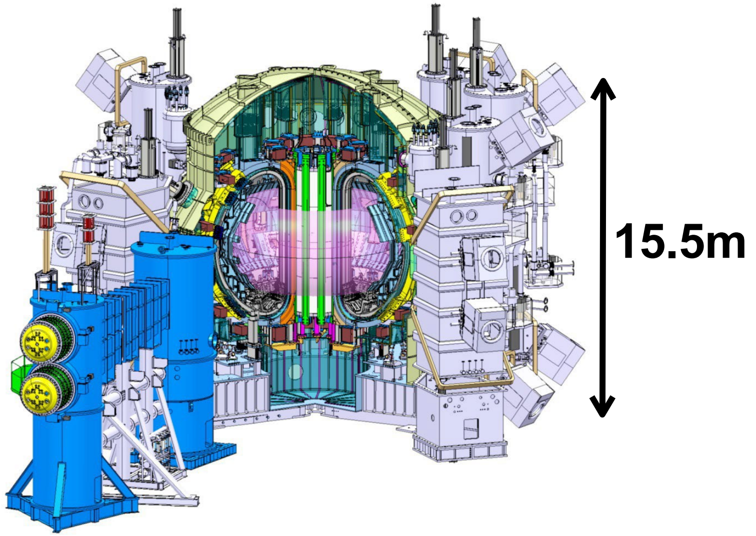
address ITER related issues and optimize the operation scenarios under the break-even condition

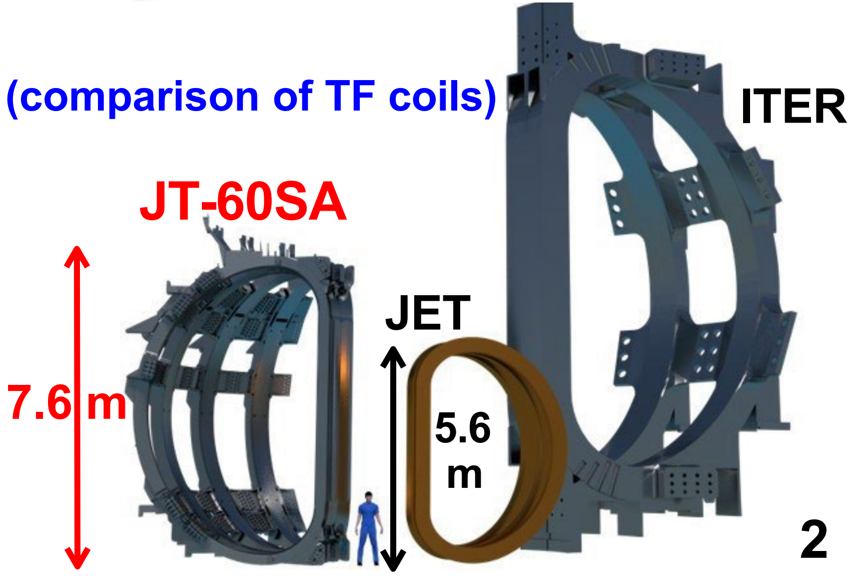
(2) Complementary Research for DEMO

study long sustainment of high integrated performance plasmas with high β_N

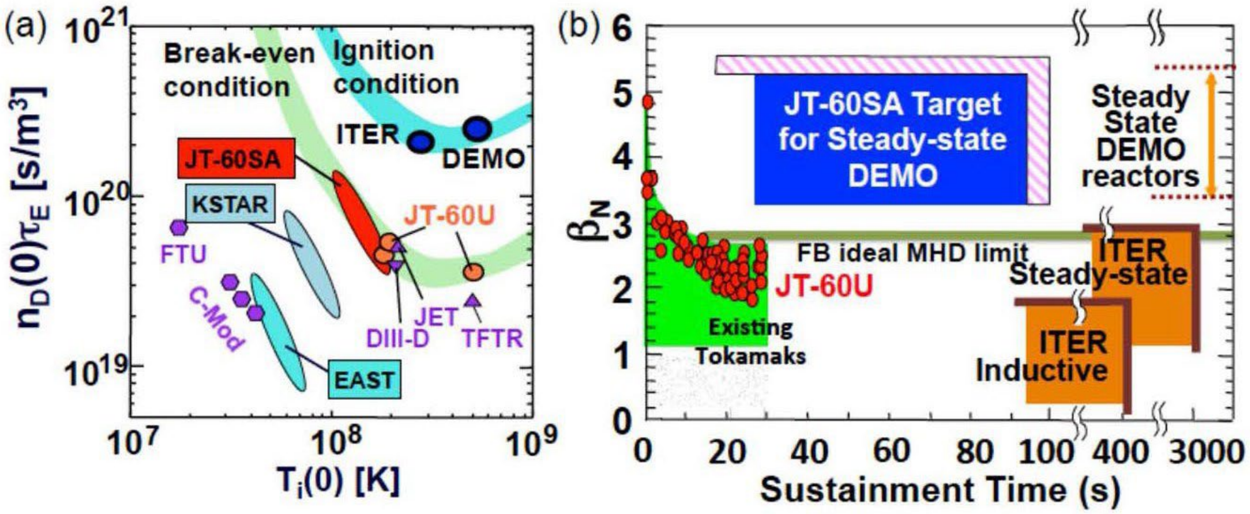
(3) Foster Next Generation

build up experience of young scientists and technicians who will play leading roles in ITER and DEMO.



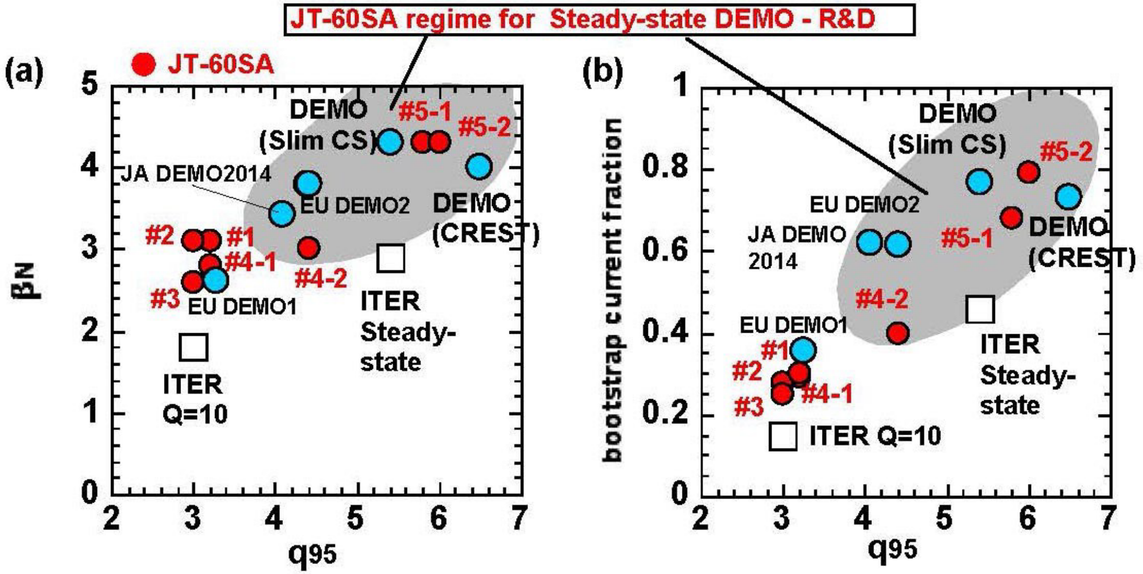

(comparison of TF coils)

JT-60SA Operation Region



JT-60SA can widely cover DEMO target parameter regions.

- high normalized plasma pressure β_N
- low normalized poloidal Larmor radius ρ_p^*
- low normalized collisionality ν^*
- large shape factor S
- high bootstrap current fraction f_{BS}



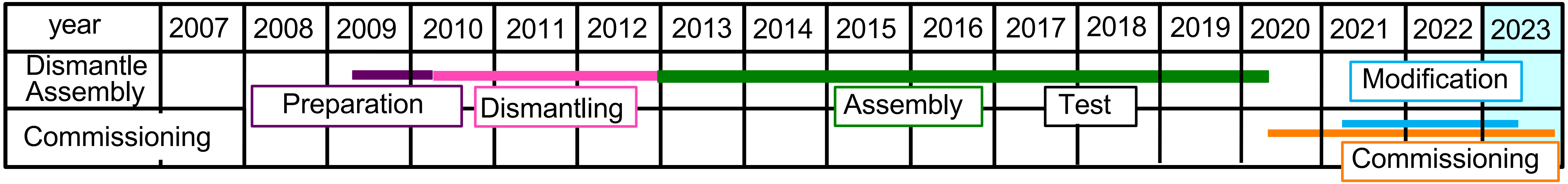
Non-dimensional plasma parameter regions of JT-60SA

Examples of JT-60SA plasma parameters

	Full Ip Inductive	ITER-like Shape Inductive
Plasma Current (MA)	5.5	4.6
Toroidal Field (T)	2.25	2.28
Major Radius (m)	2.96	2.93
Minor Radius (m)	1.18	1.14
Elongation, κ_X	1.87	1.81
Triangularity, δ_X	0.50	0.41
Safety factor, q_{95}	3.0	3.2
Plasma Volume (m^3)	131	122

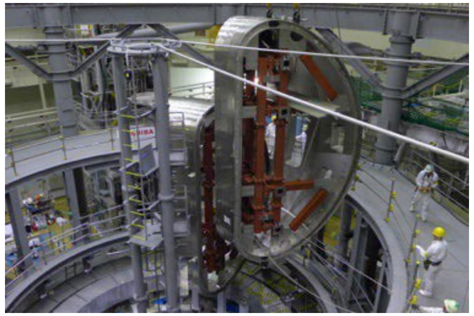
History of JT-60SA Construction

- Tokamak assembly started in January 2013 and completed in March 2020.
- Integrated Commissioning started in April 2020.

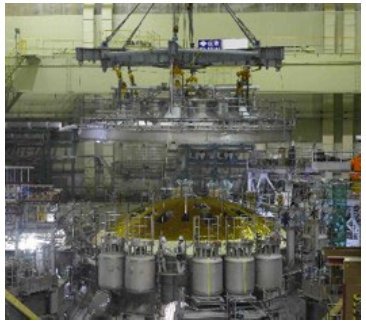



Cryostat base


first 40º VV sector


VV assembly


Cryostat vessel body

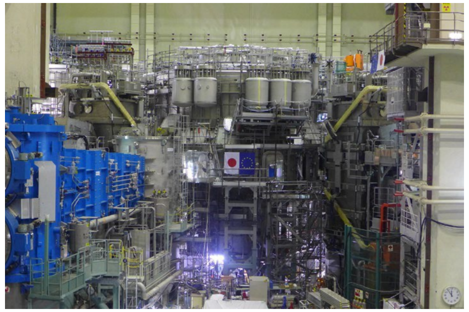

cryostat top lid installation


EF4 coil


First TF coil

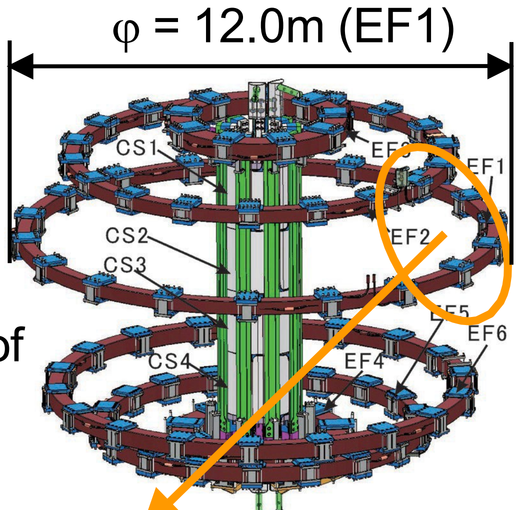

TF installation


CS Installation

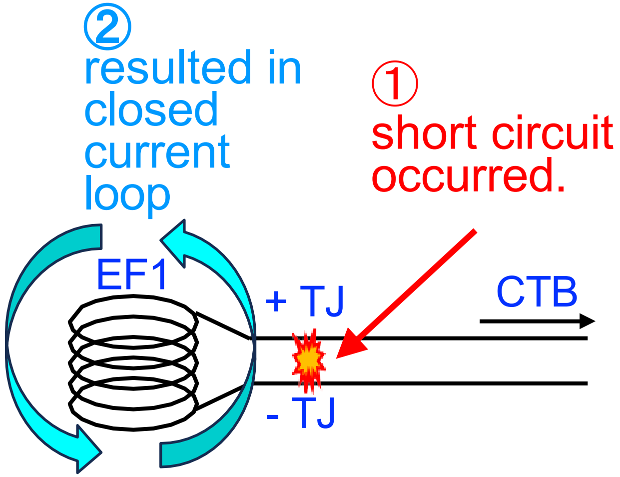

Assembly completion

EF1 Incident on 9 March 2021

- During the EF1 coil test at 5kV, an unexpected increase of current was observed.
- It was found Arc occurred at both +/- Terminal Joints (TJ) of EF1.

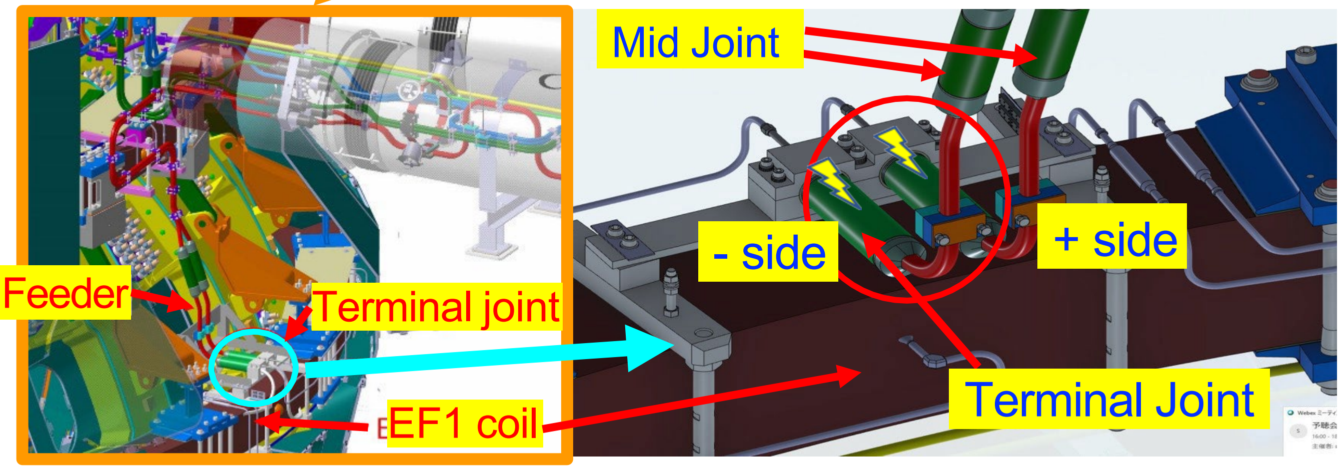


EF coils and CS of JT-60SA



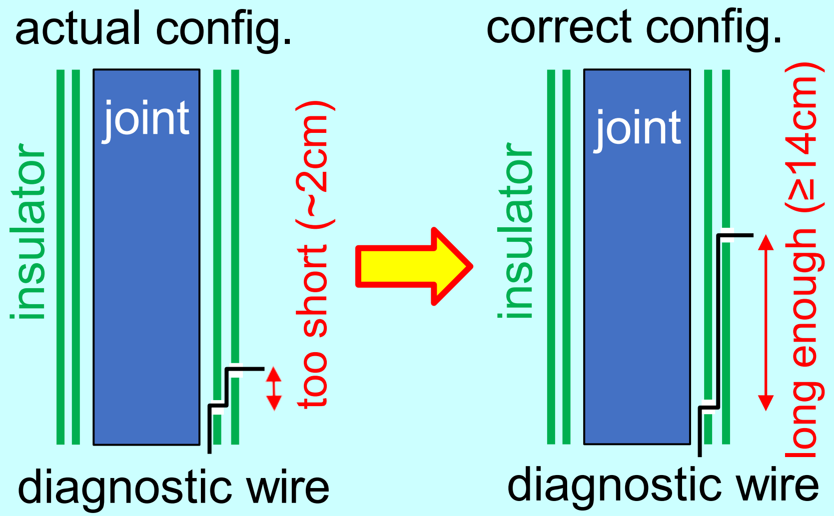
② resulted in closed current loop

① short circuit occurred.



Root Cause

Diagnostic wire was not properly insulated, which resulted in ground faults at TJs.



Summary

- Since the EF1 coil incident in March 2021, the Integrated Project Team have exerted considerable efforts for more than 2 years to ensure safety operation of tokamak without a risk of discharge inside the cryostat.
- The Integrated Commissioning successfully restarted at the end of May 2023. At present, superconducting coil energization test is going on.
- Plasma operation will be carried out to confirm the basic performance of JT-60SA.
- During Maintenance&Enhancement-1 period, JT-60SA will be upgraded with in-vessel components, higher auxiliary heating power, and full sets of diagnostic system to allow high performance plasma experiment, in which maximum plasma current of 5.5MA is foreseen.

Judging from the progress of present coil energization test, the First Plasma of JT-60SA is coming soon.

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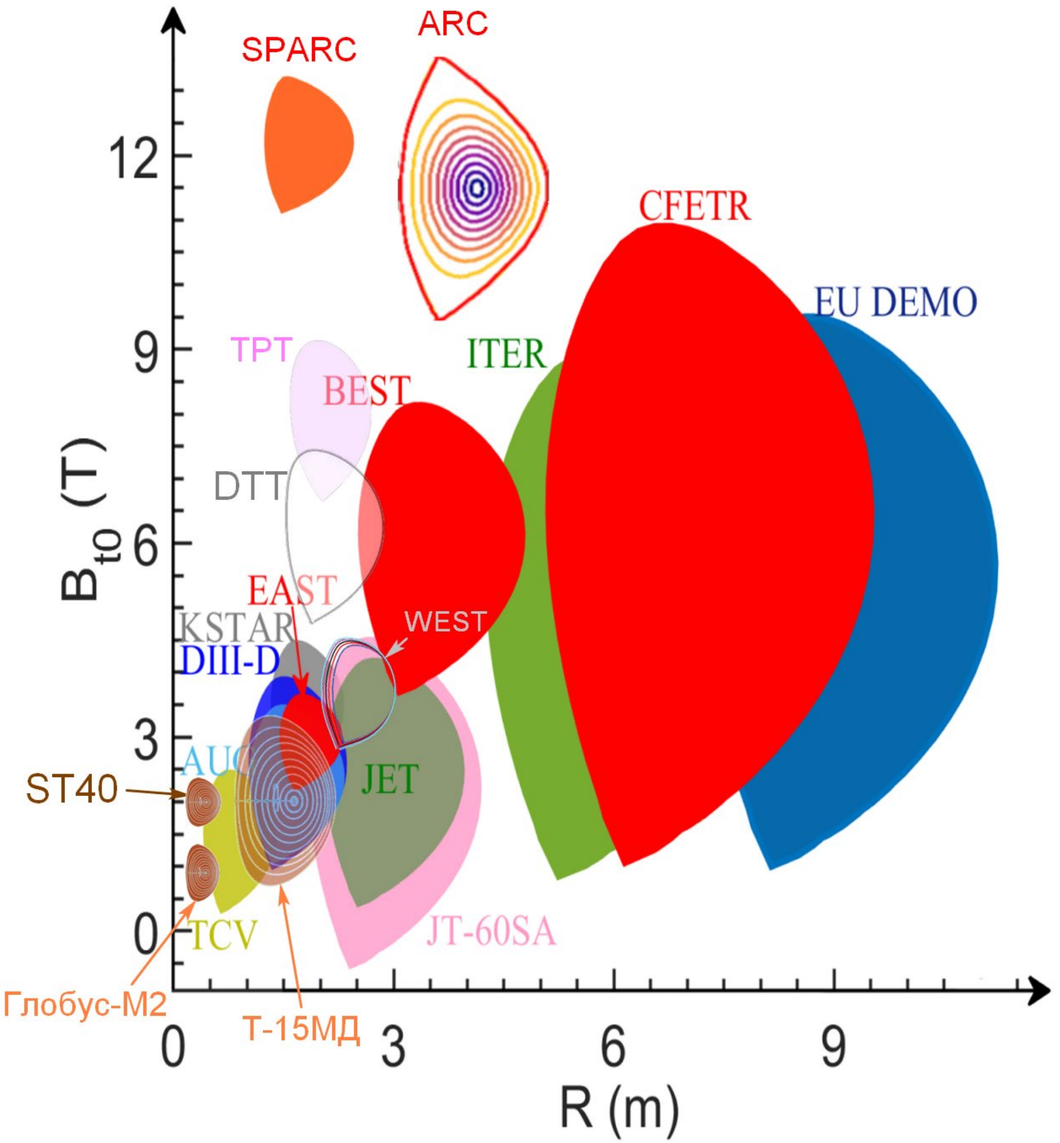
- На смену JET приходит токамак JT-60SA

> “We were fortunate.” To be safe, the JT-60SA team reworked the insulation in more than 100 electrical connections, a task that took 2.5 years, Shirai says.

Первый урок – ликвидация последствий аварий в сложных системах весьма ВРЕМЯЗАТРАТНА!

- В настоящее время JT-60SA уже заработал!

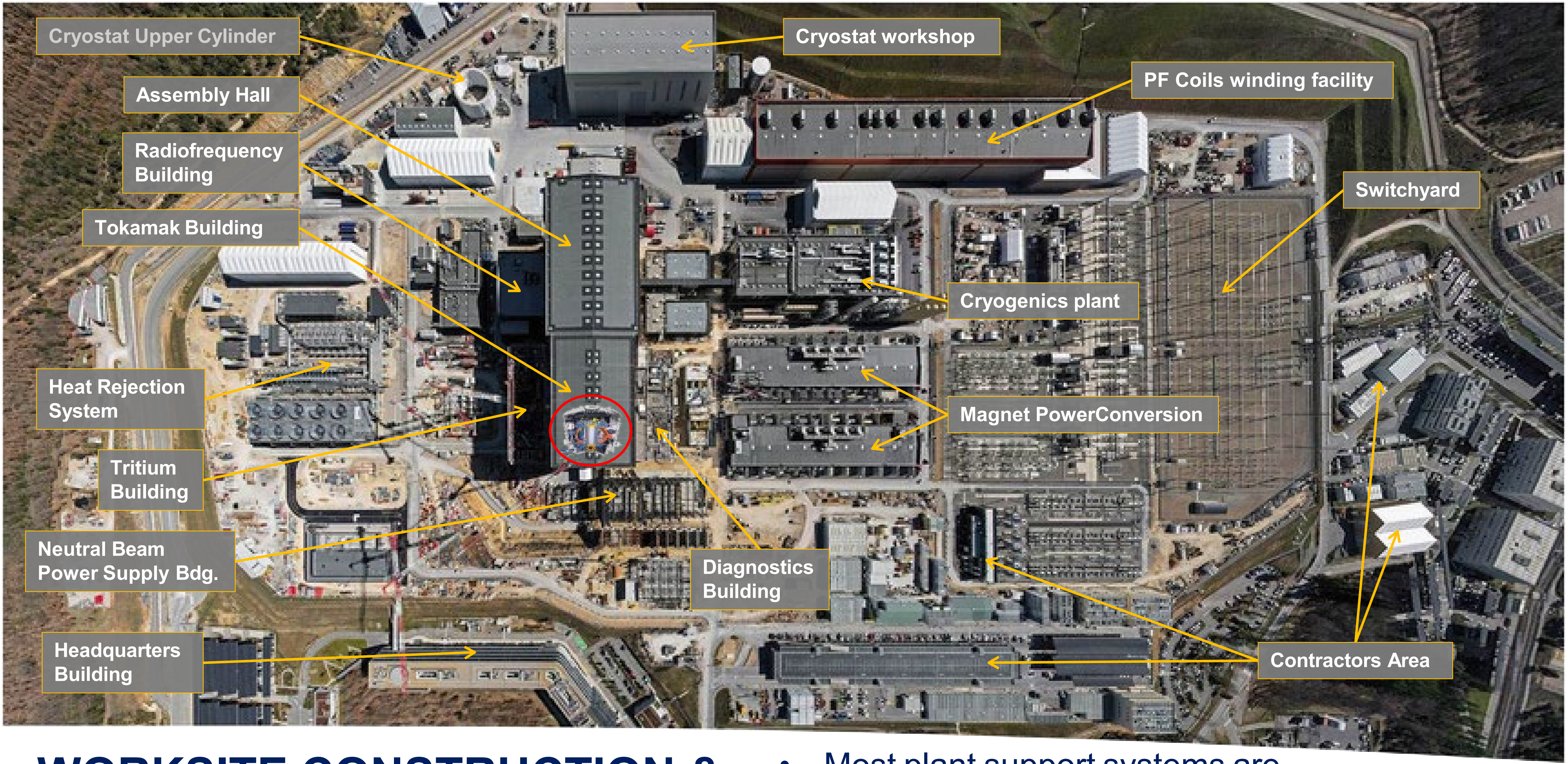


THE ITER PROJECT

Progress on manufacturing, construction, commissioning and an updated baseline

Pietro Barabaschi, Director-General
29th IAEA Fusion Energy Conference, October 2023

china eu india japan korea russia usa



WORKSITE CONSTRUCTION & COMMISSIONING HIGHLIGHTS

- Most plant support systems are operational or in commissioning.
- Civil works are 80% completed.

TOROIDAL FIELD COILS

- 18 coils
- 41 gigajoules
- 11.8 Tesla

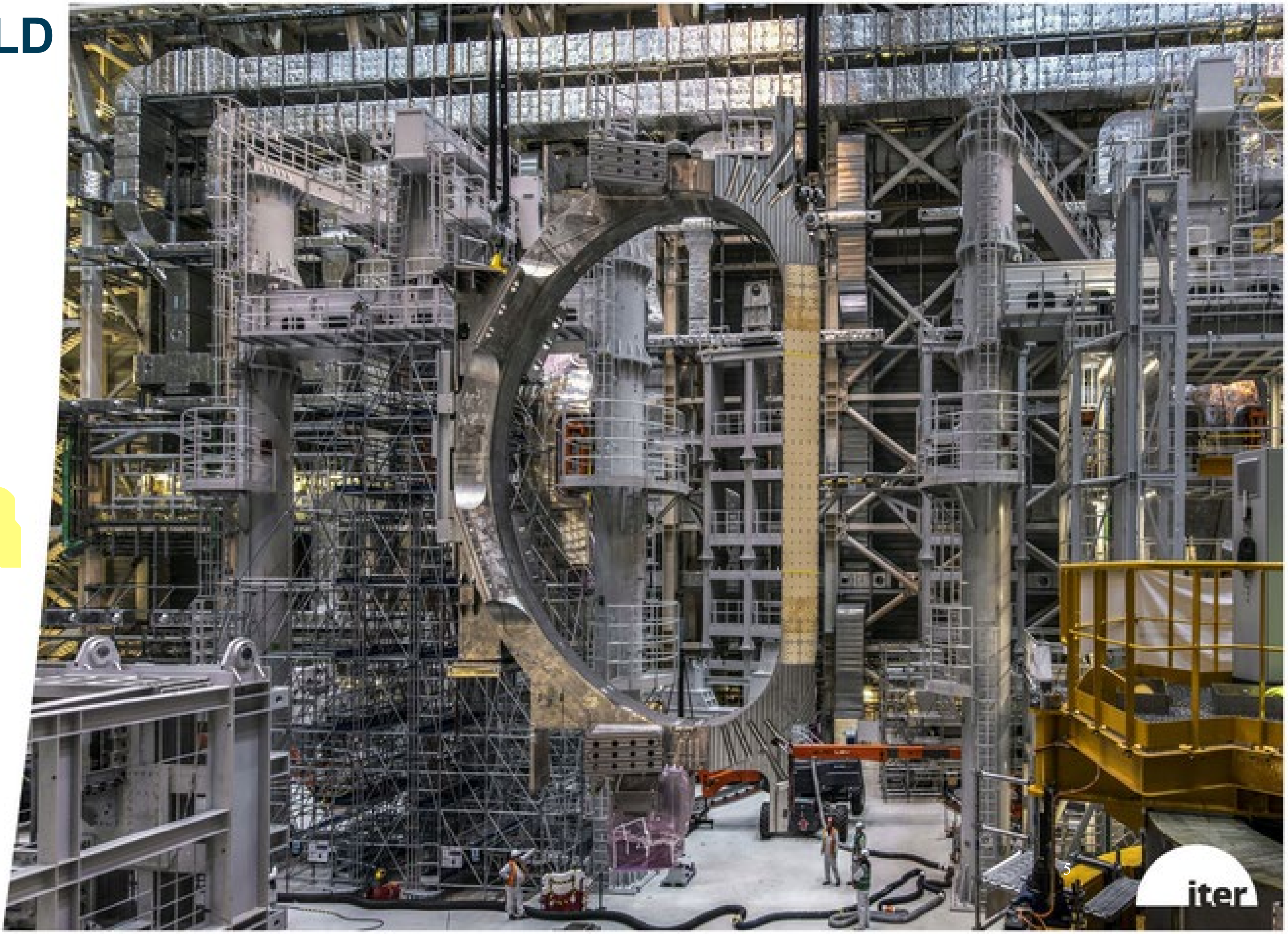
Each coil:
- 360 tonnes
- 9 x 17 metres

Status:

Manufacturing of all 19 coils completed.

17 coils already onsite

#18 and #19 are in transport



POLOIDAL FIELD COILS

Six coils, the largest with a diameter of 24 metres, weighing 400 tonnes.

Total magnetic energy: 4 gigajoules

Maximum magnetic field: 6 Tesla

Status:

PF6 (EU/CN) and PF5 are installed;

PF1 (RF) is onsite;

PF2 and PF4 (EU) are completed;

PF3 **to be finished by the end of 2023.**

CENTRAL SOLENOID

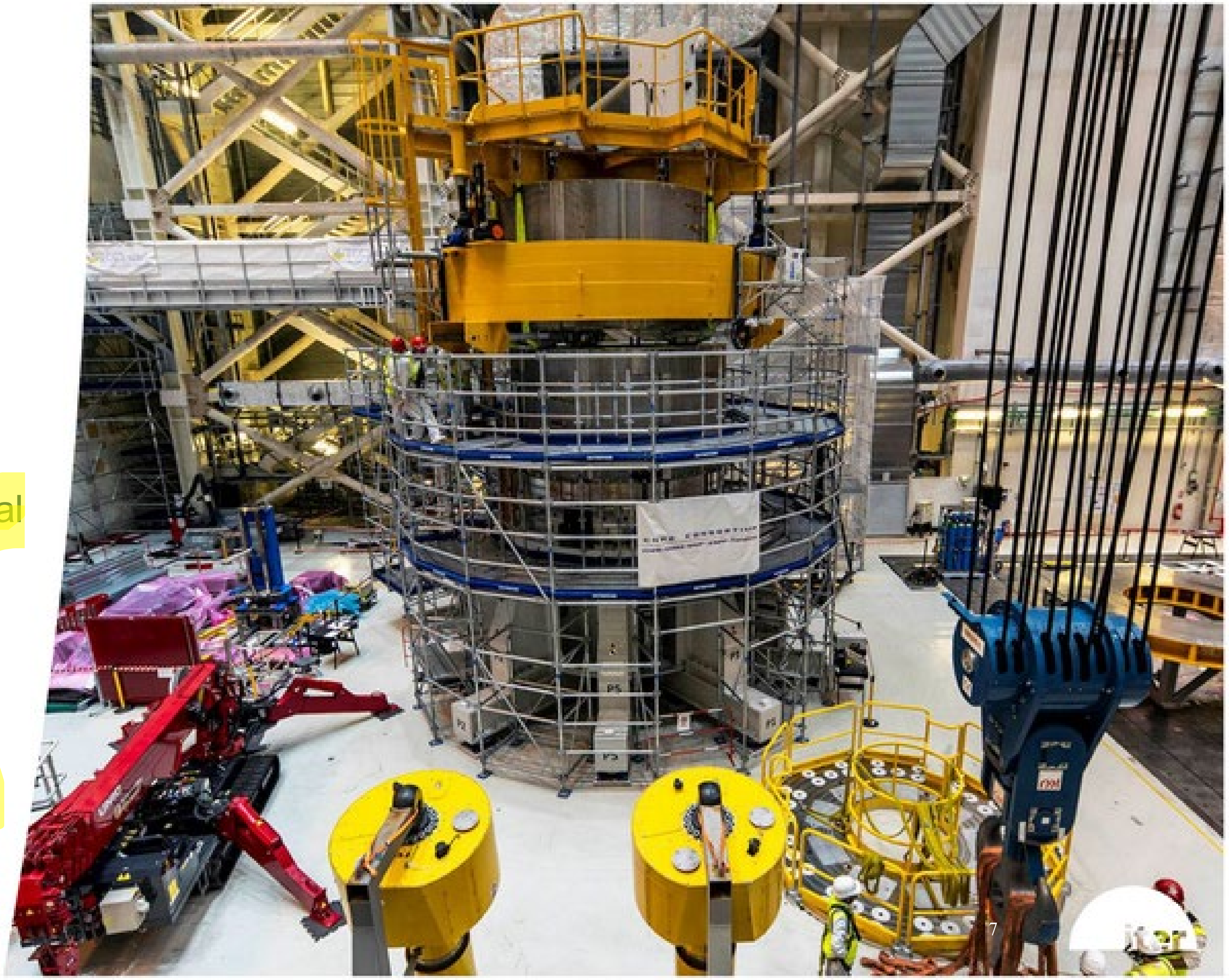
Height: 18 metres
Diameter: 4.13 metres
Total weight: 1000 tonnes
Peak field strength: 13.1 Tesla
Operating voltage: 14 kV
Operating current: 45 kA
Stored energy: 5.5 gigajoules

Status:

The second module of the Central Solenoid has been installed on the assembly platform.

A third module (#4) has safely arrived from San Diego.

#3 module was damaged during testing, now being repaired, will be used as a spare.



OTHER MANUFACTURING HIGHLIGHTS

The Domestic Agencies have completed the fabrication and delivery of a substantial portion of ITER's First-of-a-Kind components.

3 of 4 Vacuum Vessel sectors complete

Cryostat Manufacturing is complete

Bottom correction coils installed

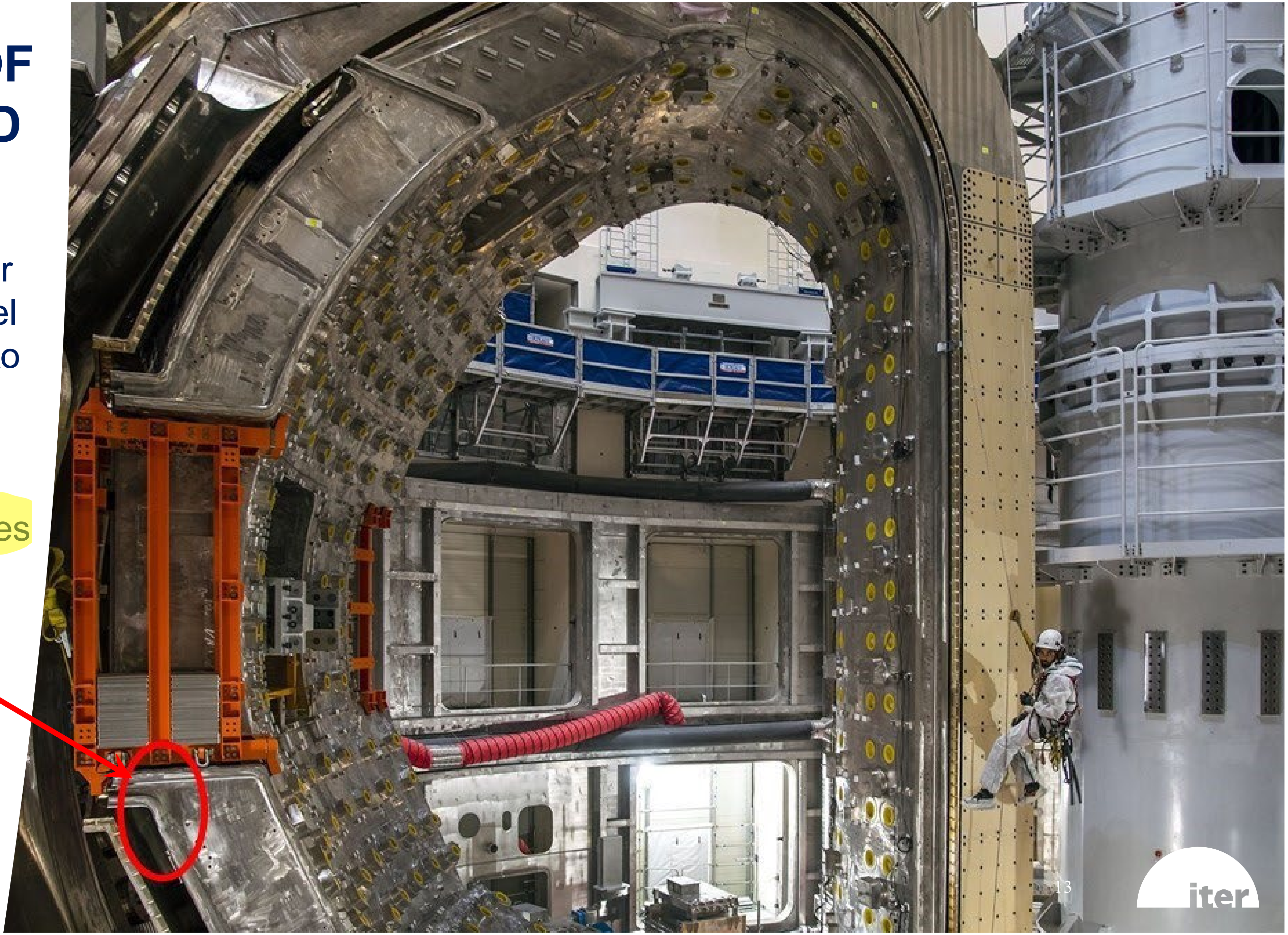
5 Vacuum Vessel sectors in advanced stages of production

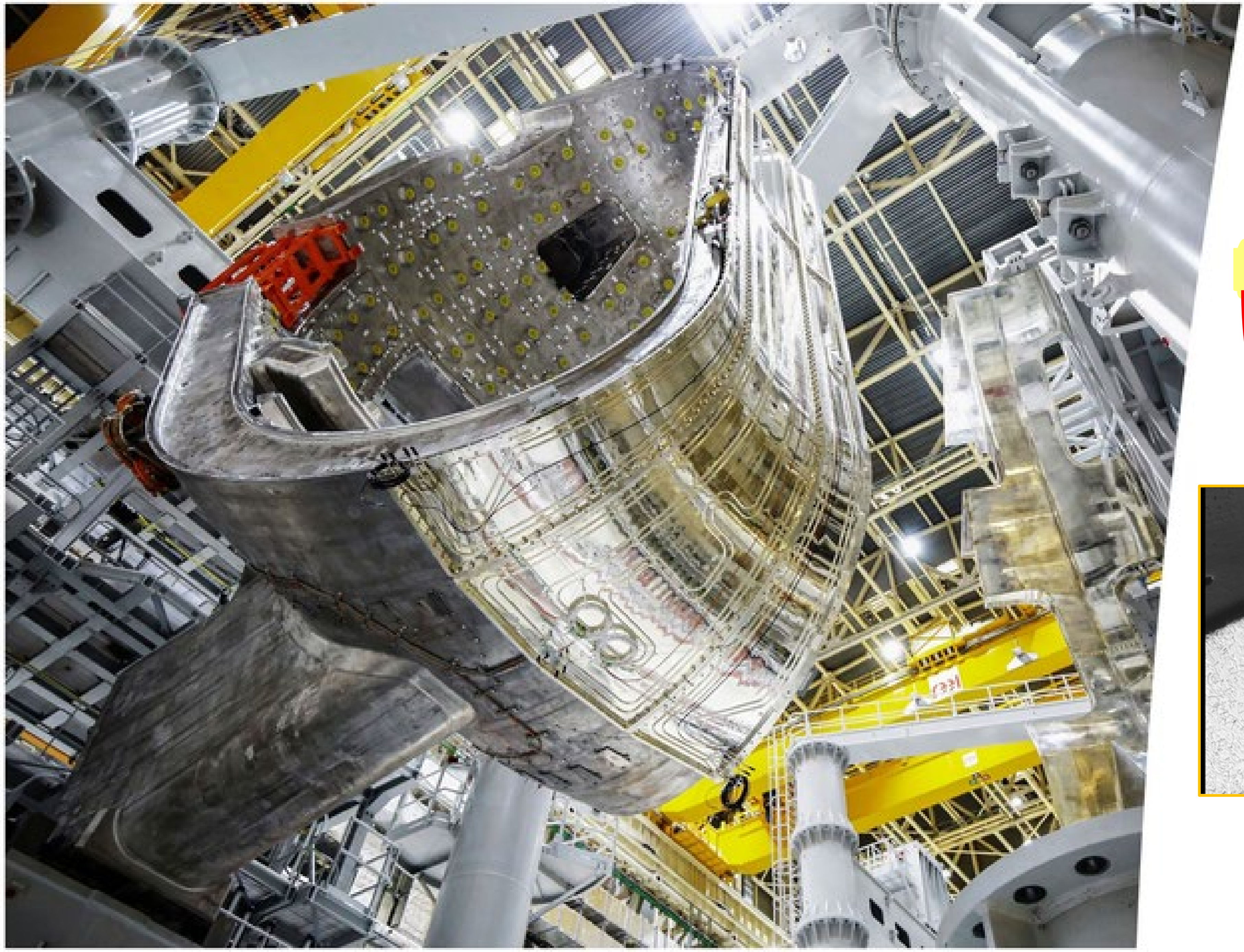
CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

The first complete Vacuum Vessel Sector Module was lifted into the tokamak pit in May 2022 ...

CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

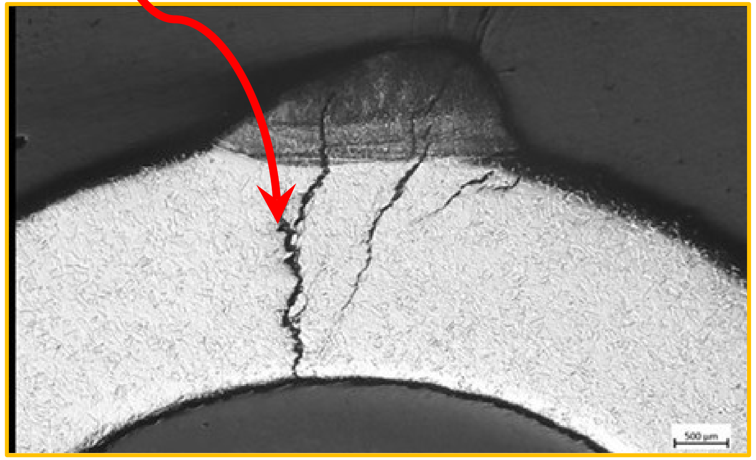
… but the sector-to-sector welding of Vacuum Vessel sectors was reassessed to be too challenging to perform *in situ*, based on the previously identified geometric non-conformities in the field joints.





CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

Leakage was also identified in thermal shield cooling piping due to chloride stress corrosion.



CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

Repair contracts to address these non-conformities have been awarded, and teams have been deployed on site executing the first steps of the repair campaign.

PREPARING AN UPDATED BASELINE by Mid-2024

The current ITER cost and schedule “baseline” was set in 2016. A review of the baseline is underway, and a new baseline proposal will be presented to the ITER Council in 2024.

Overall objective: to achieve Q=10 as soon as possible, with a plan that includes contingencies.

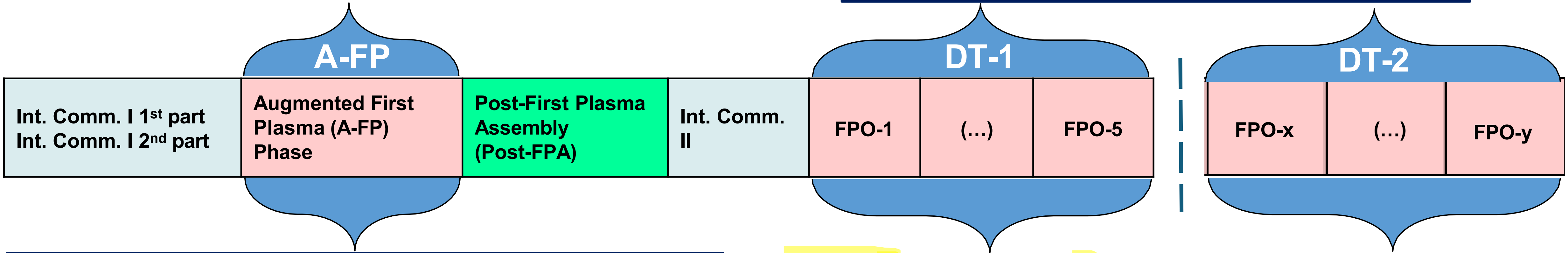
Key challenges and considerations include:

- Known delays created by the Covid-19 pandemic and First-of-a-Kind technical challenges.
- Repairs to the Vacuum Vessel sectors and Thermal Shield cooling pipes, as described.
- Ensuring alignment with ASN, the French nuclear safety regulator, in part by implementing a stepwise approach to safety demonstration.
- Reconsideration of Vacuum Vessel welding sequence, to control deformations.
- 4 Kelvin testing of some Toroidal and Poloidal Field coils.
- Realistic timing for assembly and commissioning.
- First Wall Material Beryllium → Tungsten.
- Adjustments to scope of First Plasma campaign, followed by two DT operational phases.

NEW BASELINE MACHINE CONFIGURATION

- 40 MW EC heating power (4 Upper + 1 Equatorial Launchers)
- 10 MW of ICWC & ICH
- Boronization system (Glow Discharge Cleaning + *dropper*)
- Full in-vessel coil system (ELM control and VS)
- 4 Pellet injectors (fueling + ELM control)
- W divertor (water cool.) + inertially cooled W wall in key areas

- **All A-FP systems, plus FW, TBM, …**
- 67 MW EC heating power (4 Upper + 2 Equatorial Launchers)
- 33 MW Neutral Beam (NB) heating power
- 10 → 20 MW IC heating (depending on A-FP tests)
    - 50 MW NB upgrade for DT-2



- Fully commission tokamak system (including divertor)
- Demonstrate H-mode (DD) plasmas **5.0-7.5 mega-amperes (MA) / 2.65 Tesla (T).**
- Commission Plasma Control, Protection and Mitigation Systems (including DMS) to **15 MA / 5.3 T.**

- **Q = 10, 300-500 second pulses.**
- 1% of total fluence
- Confirm safety demonstration for DT-2

- Confirm reliable operation
- **Q=5, to 3000 seconds**
- Full TBM qualification
- 100% of total fluence

ITER SAFETY DEMONSTRATION:

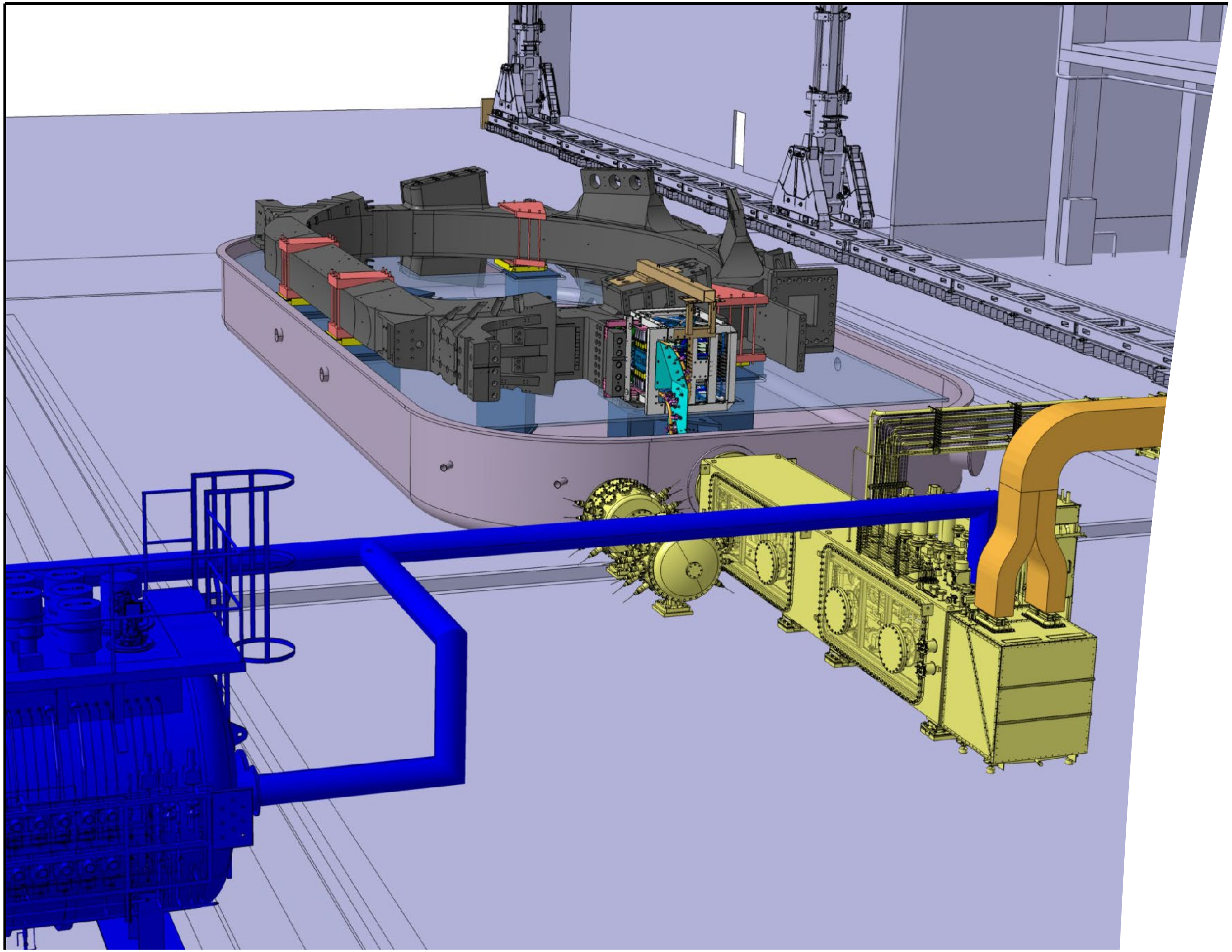
what are the key uncertainties?

- Neutron transport calculations
- Activated Corrosion Products generation, impact on occupational radiation exposure (ORE)
- Mechanical and thermal loads on vessel and in-vessel due to plasma transients
- Superconducting magnets, reliability of insulation, impact on VV in case of failures
- Dust formation
- Hydrogen formation due to in vessel Loss-of-Coolant Accidents
- Tritium retention
- Effect of neutrons on electronics
- Reliability and maintenance requirements, impact on ORE
- Maintainability of in-vessel components and impact on hot cell
- Etc. ..

ITER SAFETY DEMONSTRATION:

what will we learn from DT-1?

- At the end of DT1 we will know, for example:
  - Effect of disruptions and Vertical Displacement Events, with measurement of mechanical and thermal loads.
  - Magnet insulation reliability confirmed, mitigations measures developed
  - Neutron flux will be measured, any additional shielding needs confirmed
  - Actual Activated Corrosion Products will be measured and any needed controls determined
  - Reliability of systems and maintenance requirements well understood
- This knowledge will allow us to prepare a DT-2 safety demonstration without being over-conservative.
  - Example: for occupational radiation exposure at the end of DT-2, conservative assumptions would require extensive dose reduction measures (e.g., extra shielding). This will induce cost and delays that may well be unnecessary.
  - With our strategy during DT-1 we will actually measure neutron flux and gain experience on needed maintenance areas; therefore, shielding may be added only where needed and we will still have the option to add more isolators if needed.



TF/PF COLD TESTING

… to mitigate risks of superconducting magnets

- Cryostat to accommodate TF coils and PF1 coil.
- A complete unit of energization (up to 67kA for TFs) and associated fast discharge unit.
- Connection to ITER’s existing Cryogenic plant, using 1 of 3 Helium refrigerators to cool the coils at 4 Kelvin.

THE QUESTION OF FIRST WALL MATERIAL: Beryllium or Tungsten?

The question of First Wall (FW) Material remains key: today we have no proven material for FW that is compatible with a power production fusion device.

Explaining the ITER team decision to change the FW material from Beryllium (Be) to Tungsten (W):

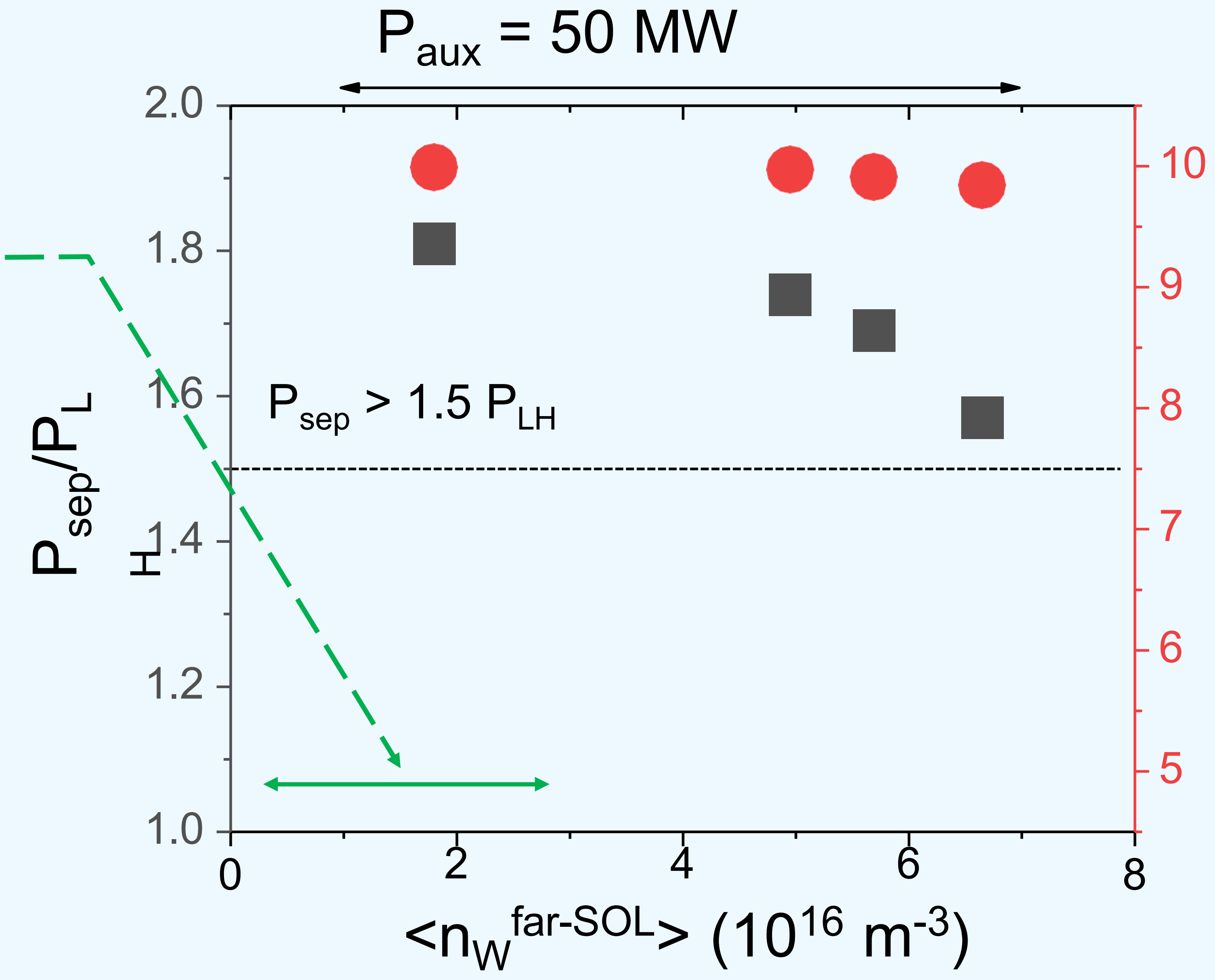
1. Is ITER's *raison d'etre* to reach Q = 10 and a conduct a set of experiments? Or to serve as precursor to DEMO?
   - Answer: **both**

2. Concerns regarding excessive erosion of Be (first wall lifetime, dust production and tritium retention)
3. Concerns regarding structural integrity after disruption damage due to FW design
4. Concerns on maintainability in the commissioning phase, due to Be toxicity

All fusion devices designed for a burning plasma plan to use W as armour material; therefore, the remaining concerns of W, related to plasma compatibility and suitable risk mitigation (e.g., boronization) must be further developed.

PHYSICS ASSESSMENTS OF TUNGSTEN (W) WALL IMPLICATIONS

- W wall source and impact on plasma performance modelled by WallDYN + JINTRAC, as shown.
- Q = 10 can be sustained up to highest W wall source modelled (including Ne and C-X sputtering with Ne being dominant)
- Ne essential for radiative divertor operation at high Q



Risk mitigation → Increased Electron Cyclotron Heating power and boronization

CONCLUSIONS

- ITER construction and commissioning has made significant progress since last IAEA FEC.
  - Serious issues have been identified, related to the Vacuum Vessel sectors, Thermal Shield piping, integrated assembly and licensing strategy.
- To address these issues while also providing a robust approach to licensing, safety demonstration and scientific exploitation, an updated Baseline will be presented to the ITER Council in 2024.
  - Augmented First Plasma (nuclear operation in DD);
  - DT-1 (Q = 10 with low fluence);
  - DT-2 (full achievement of all project goals).
- Cold tests of TF coils and PF1 will be carried out before in-pit installation.
- Change of First Wall material from Beryllium to Tungsten will lead to other changes:
  - Modified mix of Heating & Current Drive power, optimized for DT-1
  - Boronization system
- **Support from ITER Members is essential as we refine New Baseline Research Plan and to address outstanding R&D issues!**

MORE ITER @ FEC 2023 (oral presentations)

Tuesday / Technology session

*ITER PHYSICS BASIS AND TECHNOLOGY DEVELOPMENT FOR THE ITER **DISRUPTION MITIGATION SYSTEM***

Presenter: LEHNEN, Michael – IO

LESSONS LEARNED** FROM EUROPEAN AND JAPANESE PRODUCTIONS OF ITER **TOROIDAL FIELD COILS

Presenter: HEMMI, Tsutomu – JA-DA

***LESSONS LEARNED** FROM ITER **CENTRAL SOLENOID** MANUFACTURING*

Presenter: WOOLEY, Kyle – US-DA

*CHALLENGES AND **LESSONS LEARNT** DURING MANUFACTURING, TRANSPORTATION AND ASSEMBLY OF THE ITER **CRYOSTAT***

Presenter: BHARDWAJ, ANIL KUMAR – IN-DA

***LESSONS LEARNED** IN THE MANAGEMENT OF THE PRODUCTION OF THE **POLOIDAL FIELD COILS** (AND OTHER COILS)*

Presenter: Mr BONITO OLIVA, Alessandro – EU-DA

CORRECTION COIL** AND **MAGNET FEEDER** / **LESSONS LEARNED

Presenter: Prof. LU, Kun – CN-DA

Saturday / Pathways to fusion energy

THE ITER CONTRIBUTIONS AND VIEWS

Presenter: BECOULET, Alain – IO

FEC-2023: инженерные и физические вызовы УТС

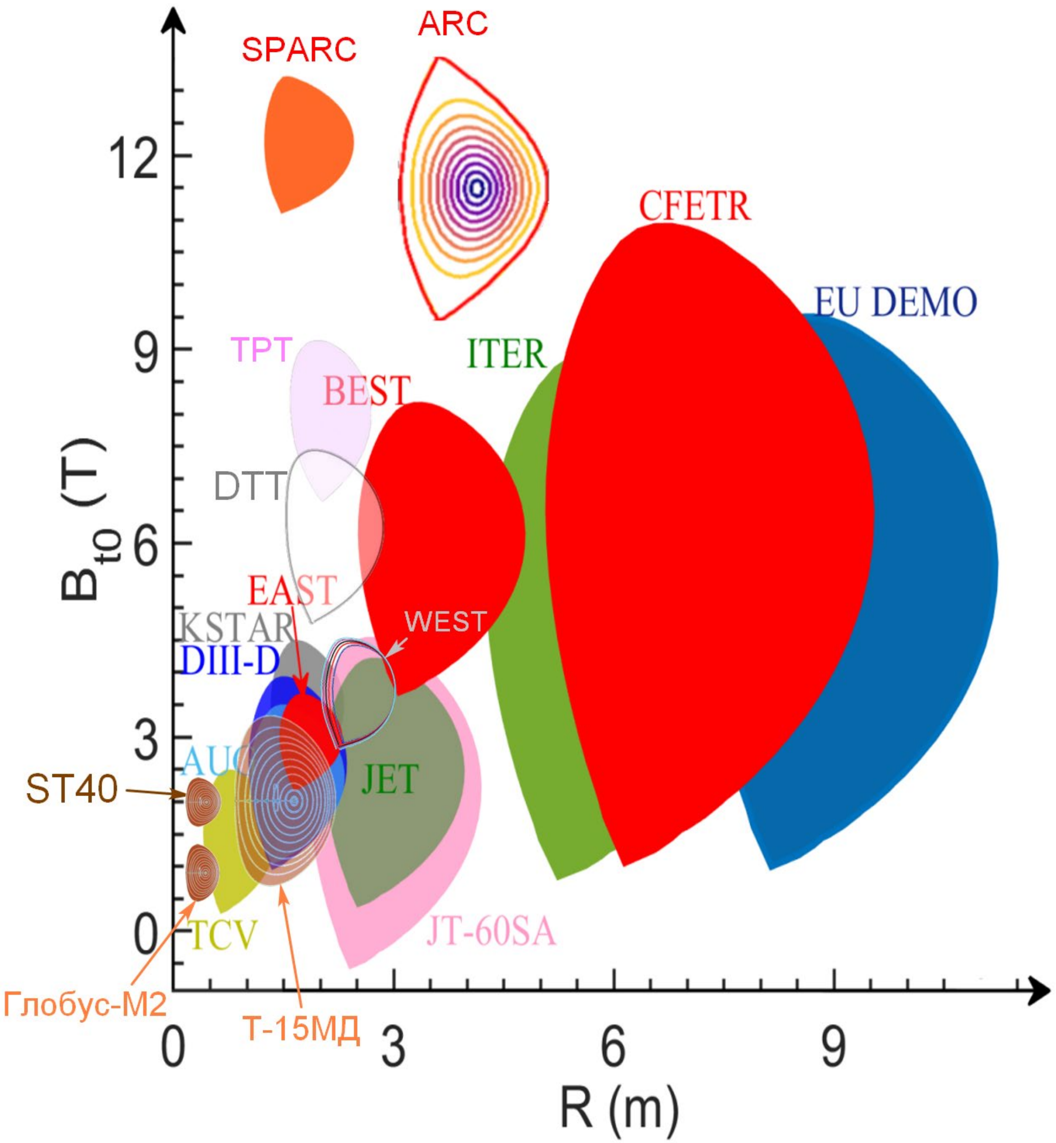
ТОКАМАКИ:
СОВРЕМЕННЫЙ ЛАНДШАФТ И ТЕНДЕНЦИИ РАЗВИТИЯ

- ☐ Современные токамаки: $R_0 \leq 3.0$ м, $B_T \leq 4.0$ Тл *(Отсутствуют Alcator C-Mod, FTU с полем до 8 Тл – «теплые», короткий разряд)*

HTS технология для УТС: сильное Bt в реакторе?

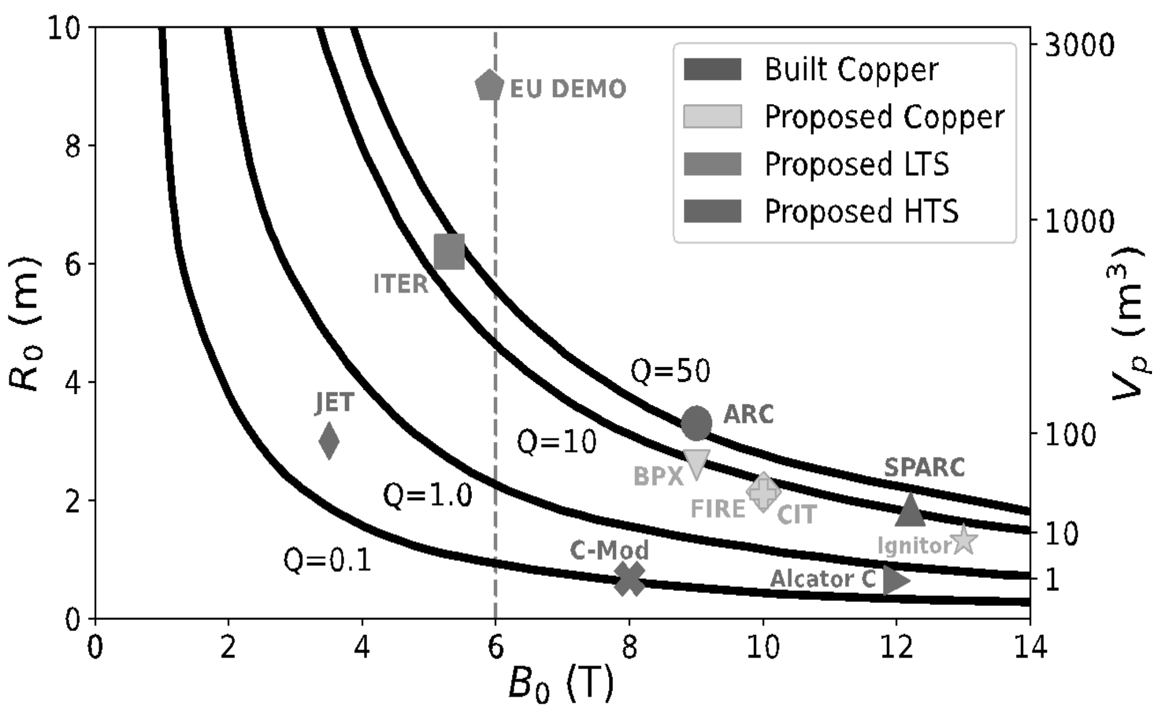
- ☐ Следующее поколение: $R_0 \leq 6.2$ м, $B_T \leq 6.0$ Тл, LTS – низкотемпературные СП катушки
- ☐ Альтернатива: $8.0 \leq B_T \leq 12.2$ Тл, $R_0 \leq 4.0$ м

  Надежды на реализацию $B_T \geq 8.0$ Тл связаны с HTS – высокотемпературными СП магнитами
- ☐ Наиболее амбициозные планы у частной компании CFS (Commonwealth Fusion Systems, > 600 сотр.)



SPARC leverages compact size enabled by high field

Compact size: $P_{fusion} \sim B^4$



SPARC: R_0=1.65m, B_0=12.2 T

High physics performance

- $Q>1$ ($H_{98,y2} \sim 0.7$), $Q \sim 10$ ($H_{98,y2} \sim 1$)

Experimental demonstrated physics

- SPARC-JET similarity: n/n_G, q_{95}, ν^*, β_N, and τ_E

Minimize size, cost, schedule

- KSTAR-size, cost O($1B), ~10yr design-to-DT

Less organizational complexity

- 1 company, 1000 people, streamlined, culture

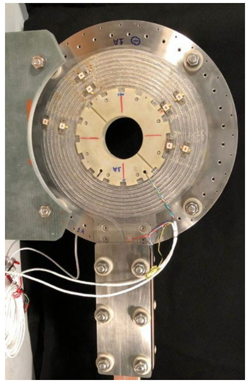
Superior siting and regulation

- Licensed w/ existing state-level regulations

What was the SPARC Toroidal Field Model (TFMC) Coil Program?

1. Developed REBCO conductor technologies (2017-2019)

Cables

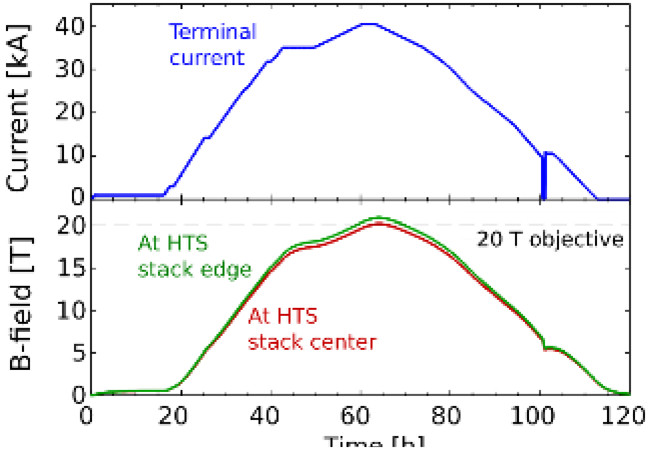


Coils

2. Designed and built the TF model coil (2019-2021)

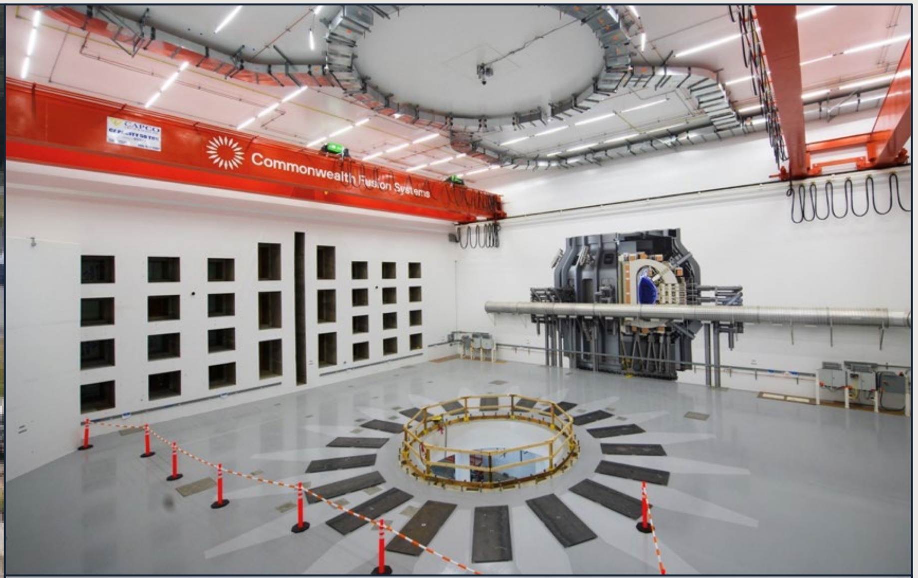
3. Built and commissioned the test facility (2020-2021)

4. Achieved 20 tesla full performance test (2021)



Six papers submitted to IEEE Trans. Appl. Superconductivity, 2023.

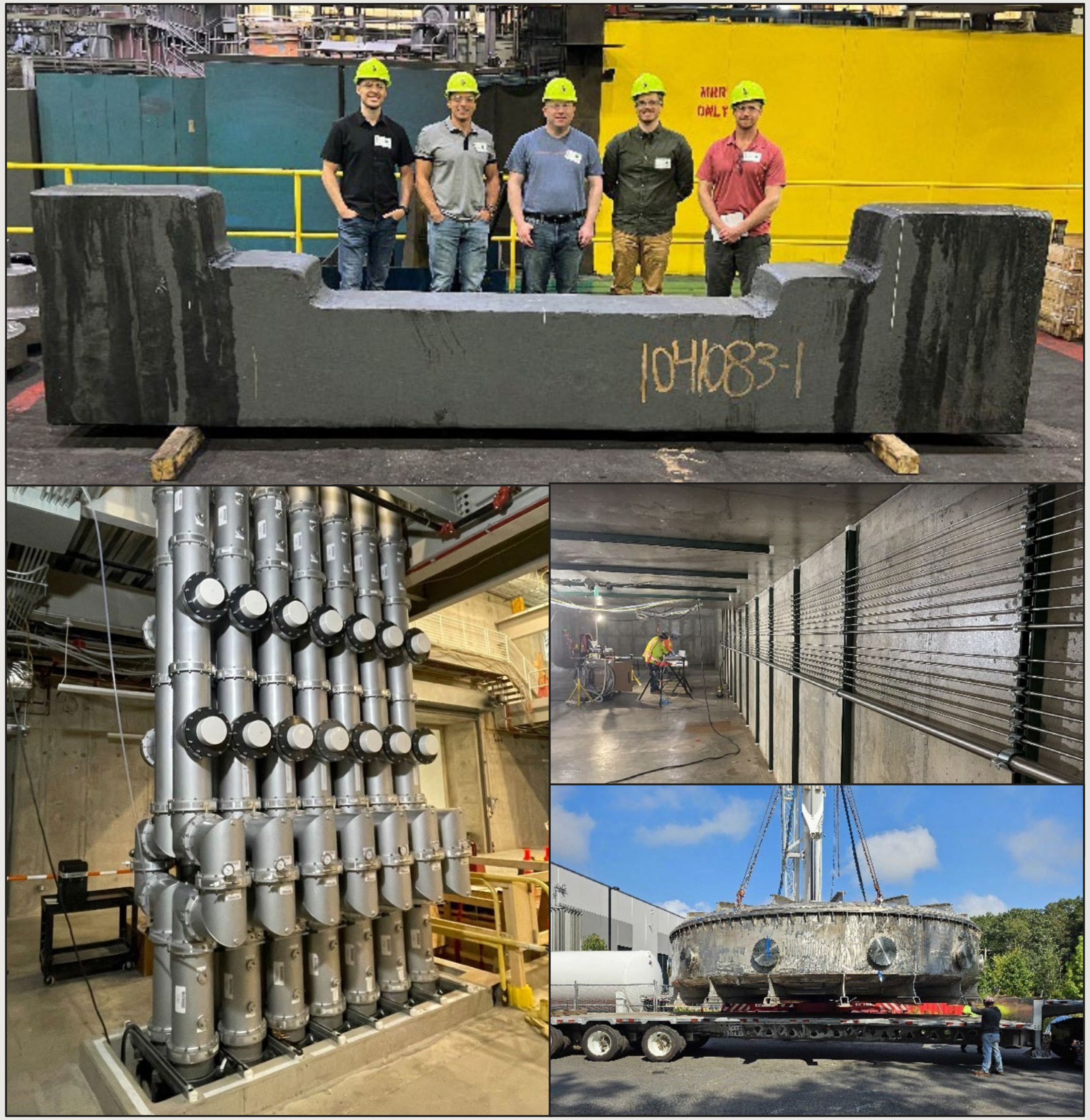
SPARC construction proceeding at a rapid pace from greenfield in 2.5 years ago to today:



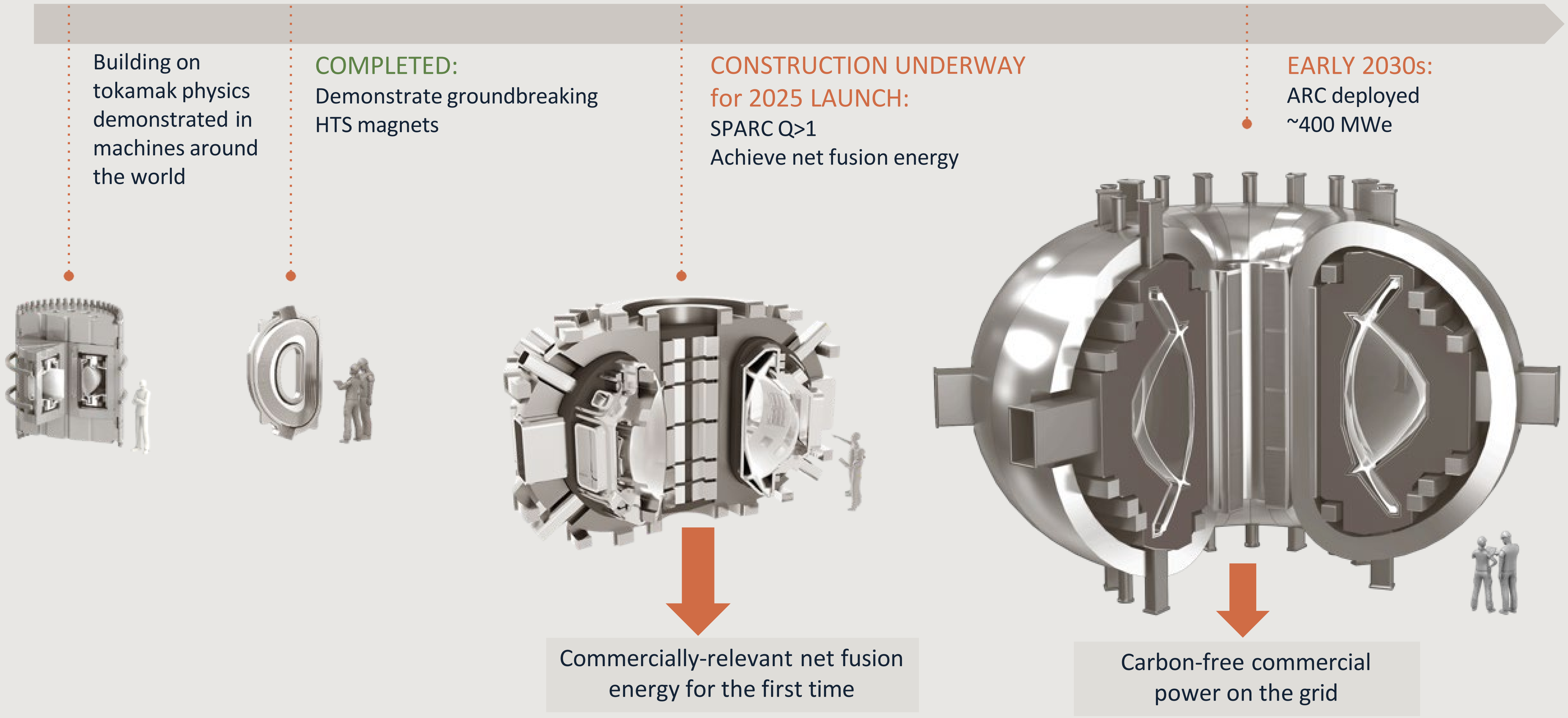
SPARC manufacturing and procurement are in progress

- In house magnet production
  - All HTS is ordered, >40% on site now
  - First TF in production
  - HTS cabling line in final commissioning
  - All magnets are tested at temperature and current before SPARC installation

- Long lead procurements from vendors
  - >60% of all orders placed
  - Vacuum vessel, cryoplant, power supplies, plasma facing components, etc.
  - First systems arriving at SPARC now



High-field tokamak path to fusion energy



Building on tokamak physics demonstrated in machines around the world

COMPLETED:
Demonstrate groundbreaking HTS magnets

CONSTRUCTION UNDERWAY for 2025 LAUNCH:
SPARC Q>1
Achieve net fusion energy

EARLY 2030s:
ARC deployed
~400 MWe

Commercially-relevant net fusion energy for the first time

Carbon-free commercial power on the grid

Status and Prospects of DEMO-related Activities in Europe

Gianfranco Federici

Acknowledgements to: Mattia Siccinio, Matti Coleman and Hartmut Zohm

29th IAEA Fusion Energy Conference (FEC 2023)
16-21 October 2023, London, United Kingdom

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.

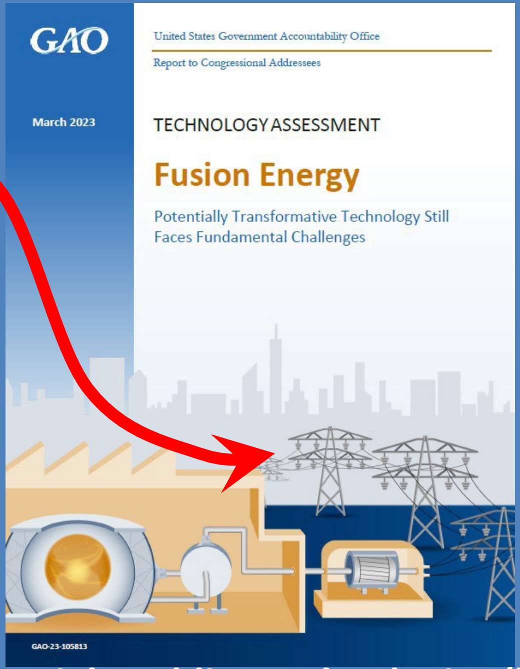
New Context

Change of the fusion landscape

- ✓ Increased perception of **urgency to address clean baseload electricity and energy security**
- ✓ Unprecedented rate of formation of so-called **fusion energy startups** (private investments)
- ✓ **Overly ambitious claims** (through barrages of press releases) of fusion electricity production as early as 2030
- ✓ **ITER** is a cornerstone but is facing **further delays**
- ✓ **Low TRL of essential enabling technologies** (breeding blanket, T-fuel cycle, Divertor, Materials, RH)

There is an urgent need to:
- ✓ align public and private investor objectives/ investments towards priorities
- ✓ strengthen involvement of industry
- ✓ address regulatory uncertainties
- ✓ address the skill gap problem

Recent US assessment Fusion Energy March 2023 Report US Government Accountability Office



GAO

United States Government Accountability Office

Report to Congressional Addressees

March 2023

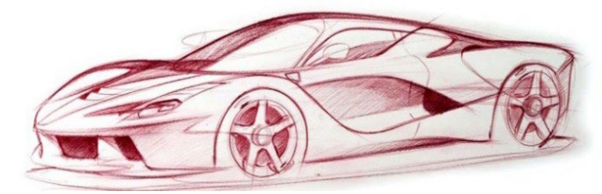
TECHNOLOGY ASSESSMENT

Fusion Energy

Potentially Transformative Technology Still Faces Fundamental Challenges

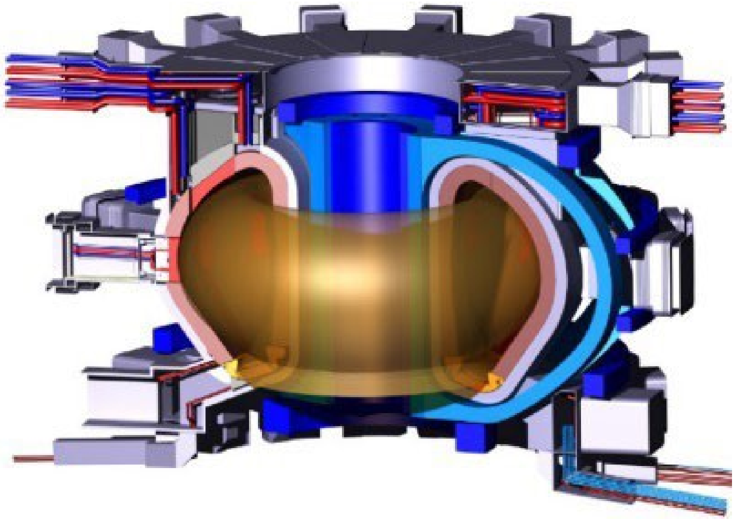
GAO-23-105813

Low TRL of essential enabling technologies (breeding blanket, T fuel cycle, Divertor, Materials, RH)



Design Activities

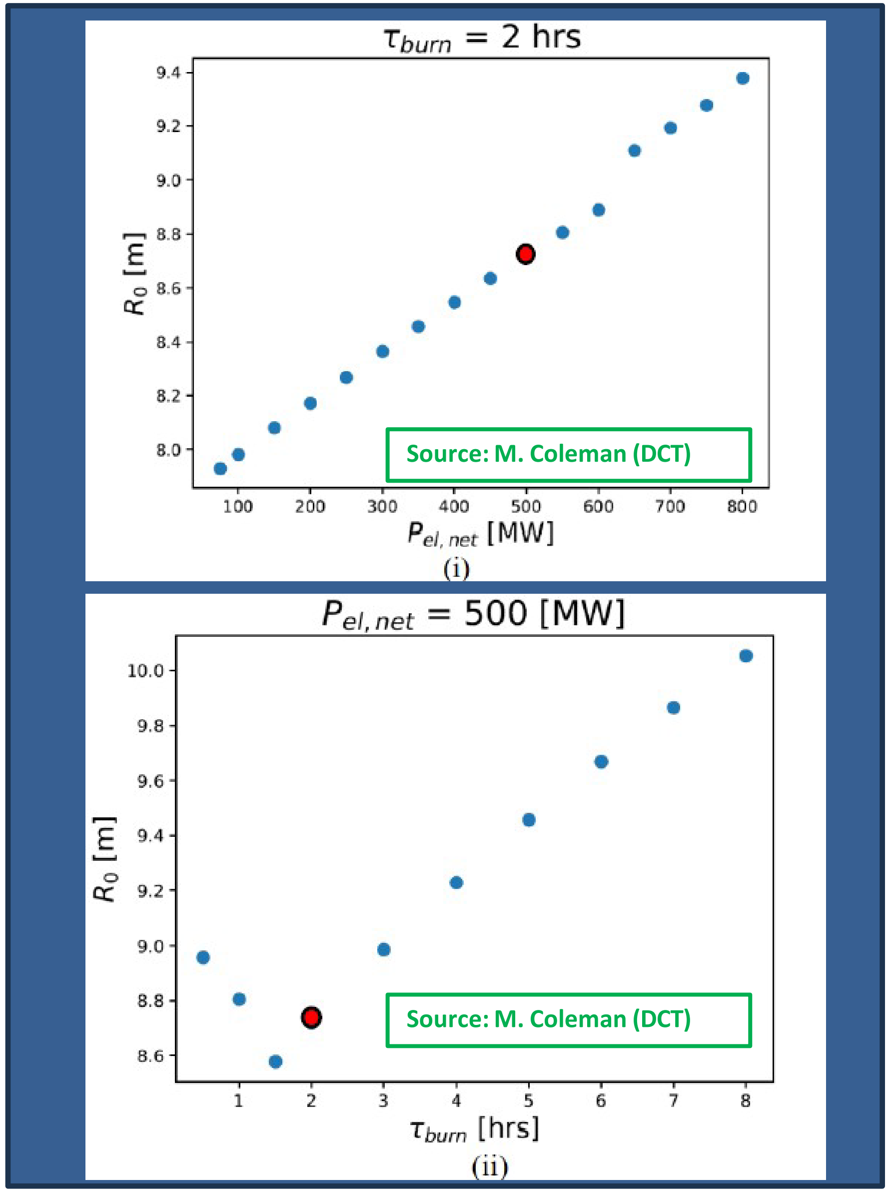
After 2020: Advance the DEMO concept design by addressing main technical issues emerged during the Gate Review G1



Recent studies

✓ Studies to explore DEMO design and operating space, which is heavily constrained by physics and technology limits.

- Stakeholder Requirements
- Use of high field (TF) coils
- Configurations with low A



Source: M. Coleman (DCT)

Source: M. Coleman (DCT)

P_{fus}=2 GW, P_{el}=0.5 GW
TBR> 1 consumes > 110 kg-T/ FPY
Pulse duration=2 hr
R= 8-9 m, **a = 3 m**
B_o=5.9 T, B_{leg}=13 T
I_p=20 MA
**NWL= 1 MW/m², **
N-Fluence = 20+(50) dpa

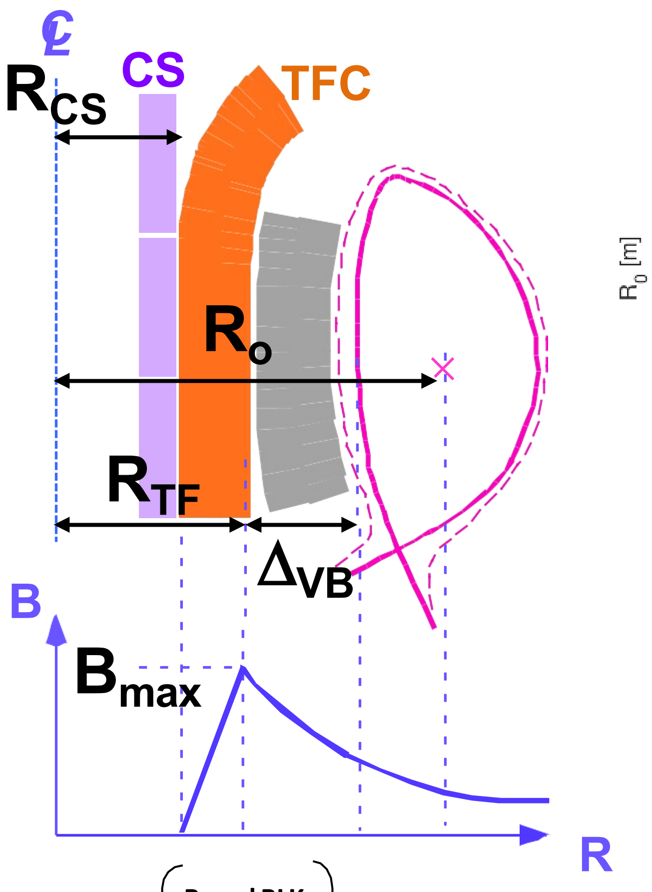
Risks

- ITER delays/ possible descoping of TBM programme.
- DEMO risks due not fully qualified blanket.
- DEMO as a qualifying device would need to operate very long times: 20 dpa 1st blanket; 50 dpa 2nd one.
- Delayed industrial ramp up of commercial FPPs.
- EUROfusion is doing ***a feasibility study of a VNS.***

Limited Spaces AVALIABLE

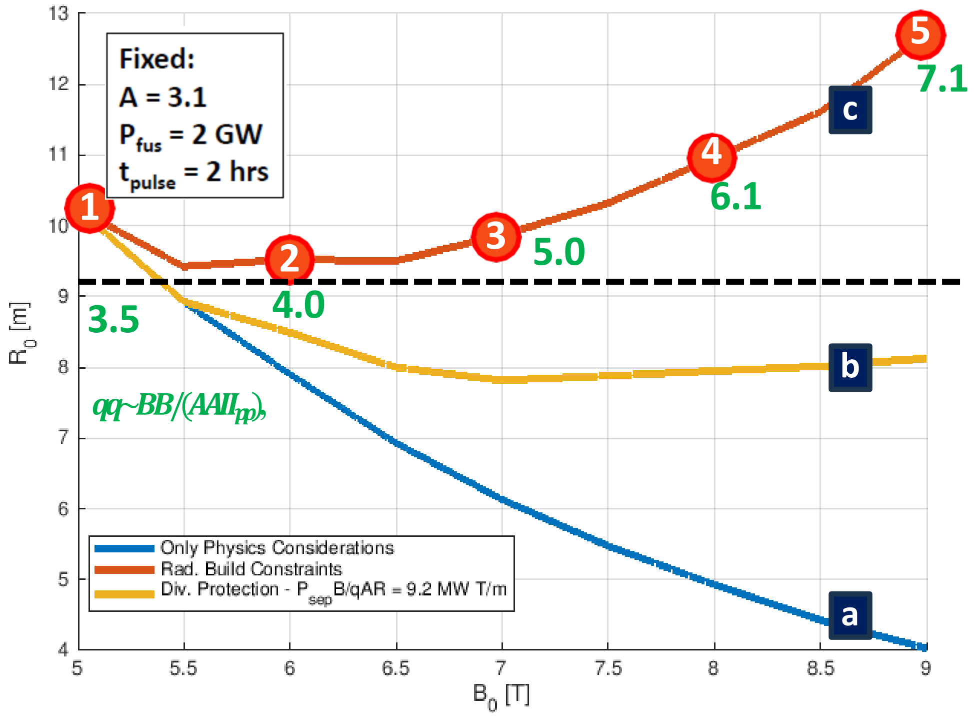
Exploration of high field TF coils

TF Inner Leg Space Allocation

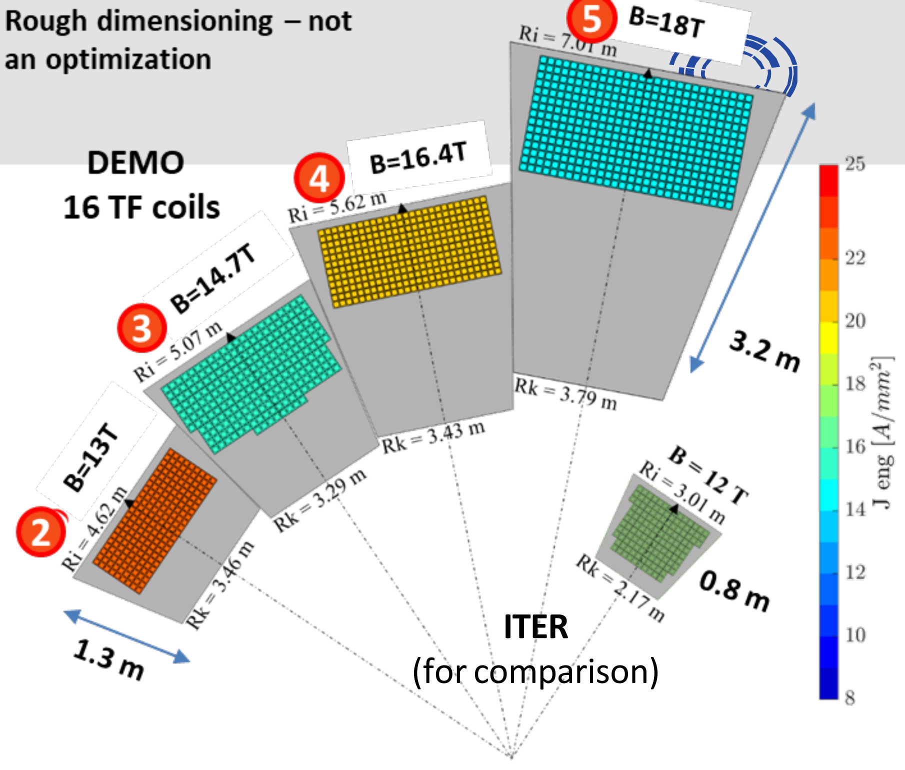


Δ_{VB} { Breed BLK, n-shield, VV, TH-Shield }

Rule of thumb
1.3-1.4 m



- **High field: for our set of requirements & design assumptions, no advantage going to higher B**
- **Higher field advantage offset by larger size of mechanical structure**



However, HTS still attractive, even if we do not operate at high field:

- **Simplify magnet cooling design/ improved margins thanks to increase temp margins.**
- **Simplify coil construction** and **minimize High-Voltage risks** at the terminals by decoupling coolant and current-carrying functions of the conductor.
- Potential to increase flux in **CS coil.**

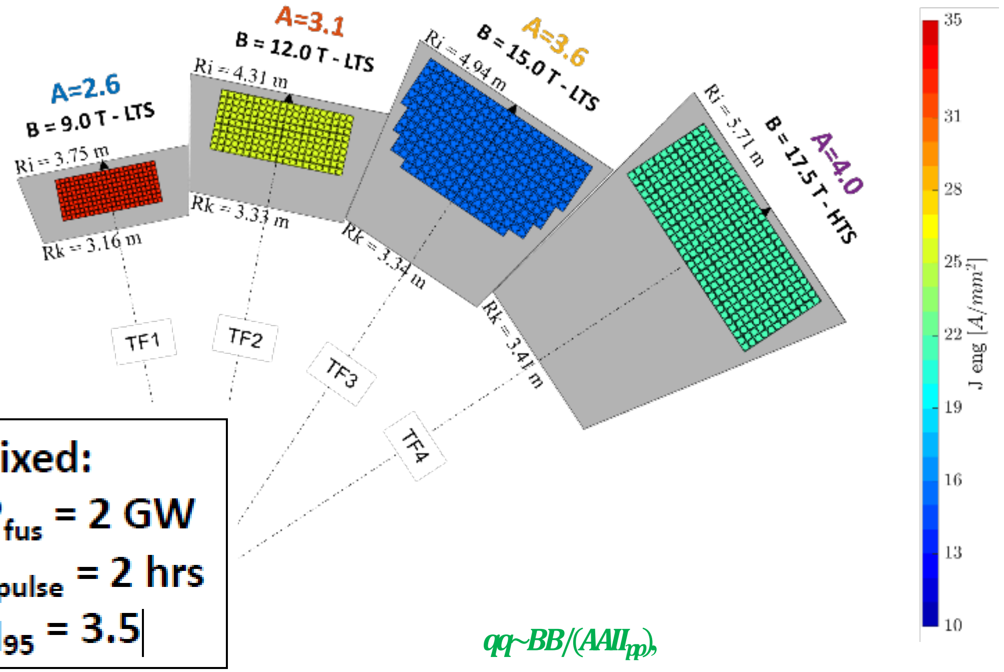
Exploration of low aspect ratio

- much-reduced reattachment heat flux
- magnet technology is proven and readily available
- ↑ k → a larger P_F for a given machine radius. This is due to the higher natural k, and the relative distance between plasma and passive structures, thus enhancing passive vertical stability.

P_{fus} = 2 GW	B_o [T]	B_{max} [T]	Heat Flux @reatt [MW/m²] P_{sep}=1.2 P_{LH}
A=2.6	4	9	34
A=3.1	5.55	12.0	61
A=3.6	7.45	15.0	92
A=4.0	9.25	17.3	127

Benefits from coil designs that minimises TF structures

- There is a practical limit to the **max. thickness of the TF nose based on manufacturability** (given by size of forgings)
- There is also a **limit to weldability of segments and weld deformation**, which becomes hard to control in large and thick structures. Mock-ups are required
- For DEMO-sized machines, **the cost of the structures alone** (just the coil case) is a **significant fraction of overall cost of TF coils**



Fixed:
P_{fus} = 2 GW
t_{pulse} = 2 hrs
q_{95} = 3.5

$qq \sim BB/(AAII_{pp})$

Design basis of a VNS

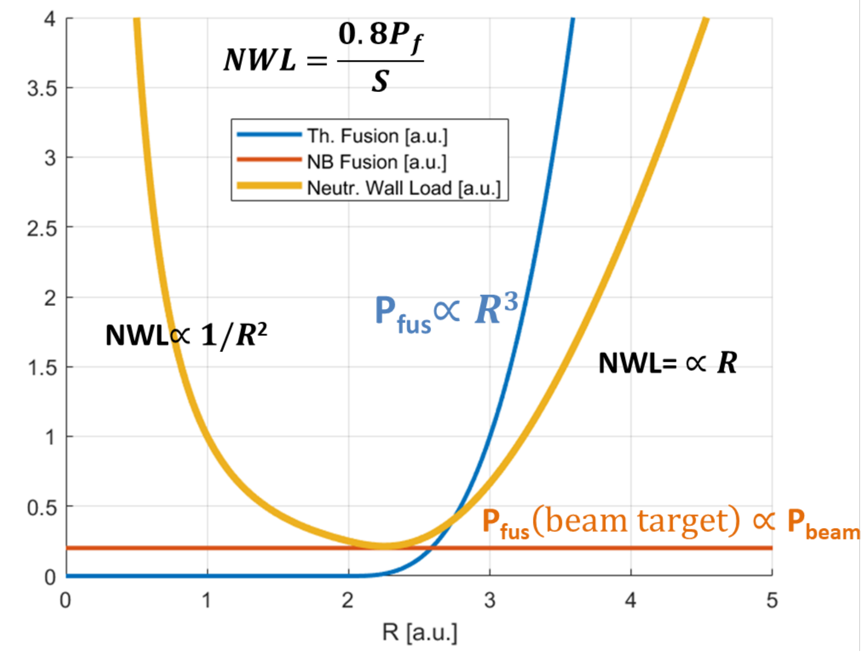
See G. Federici: Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO, Nuclear Fusion

The device should be a plasma based 14 MeV n- source

- **Minimized T-consumption:** < 50 MW
- **Peak NWL** > = 0.5 MW/m²
- **Testing surface:** available equatorial ports and outboard wall > 10 m² of exposed first wall

Large fusion power required by a "thermal" bulk plasma to get a sufficient NWL.

By "non-thermal" (beam-target), fusion power depends on beam power – no volume dependence → a compact device is conceivable



Physics Challenges:

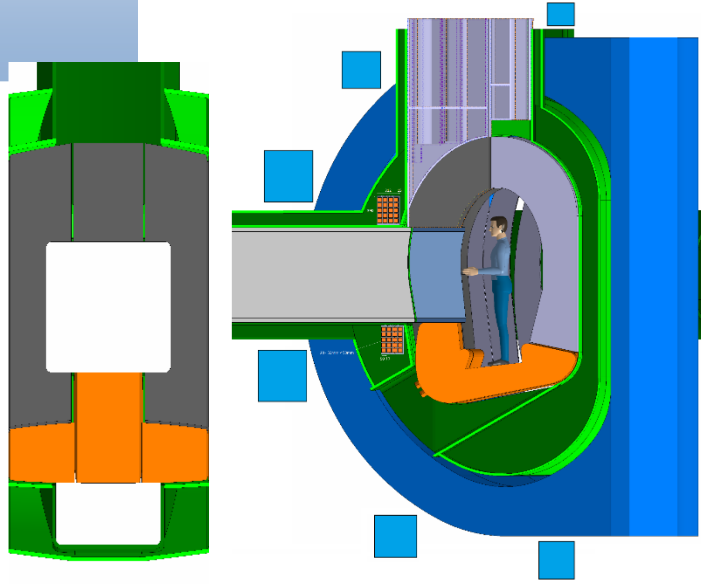
- ✓ **Equilibrium and VS**
- ✓ **β-limit becomes an issue**
- ✓ **Fast particle confinement**
- ✓ **Divertor/ power exhaust**

Design issues:

- ✓ **n- shielding inboard TF coils and NBI ports**
- ✓ **Magnets / Equilibrium:**
- ✓ **Neutral beam: pumping/ regeneration and availability/maintainability**
- ✓ **Integration/ maintenance IVCs**

P_{fus}<50 MW, P_{el}=0. GW
Steady state
P_{NBI}= 30 MW
R= 2.5 m, a =0.5 m
B_o=6 T, B_{leg}=14 T
I_p=1.5 MA
NWL= 0.5 MW/m²,
Fluence = tbd > 20 dpa

It should also be noted that a tokamak-based VNS option is presently explored, **but alternative plasma configurations like stellarators and mirrors will also be investigated,** if deemed attractive. As for the latter, important work is ongoing in the US



Key Takeaways

- ✓ **ITER remains a cornerstone project for Europe.**
- ✓ **A lot of discussions** about **making fusion smaller, cheaper, and faster**, but there is no magic bullet to solve the integrated design problem.
- ✓ **Do not postpone integration**. If you do, you risk developing design solutions that cannot be integrated in practice. Integration of multiple design drivers and systems interdependencies with key nuclear systems are often ignored.
- ✓ **Still large plasma physics and technology uncertainties that strongly impact the design.** Need to be cautious with physics assumptions.
- ✓ **High-B TF magnets, don't lead to a reduction in size,** as large structures are needed to withstand enormous forces.
- ✓ **Large technology gaps remain** (i.e., breeding blanket) and an aggressive technology R&D programme is needed
- ✓ RoX from the past show that **typically 15-25 years of R&D cycle** are needed for the development, testing and qualification cycle **especially of fusion nuclear technologies**.
- ✓ **Fusion is a nuclear technology and as such will be assessed with scrutiny by a regulator.**

FEC-2023: инженерные и физические вызовы УТС

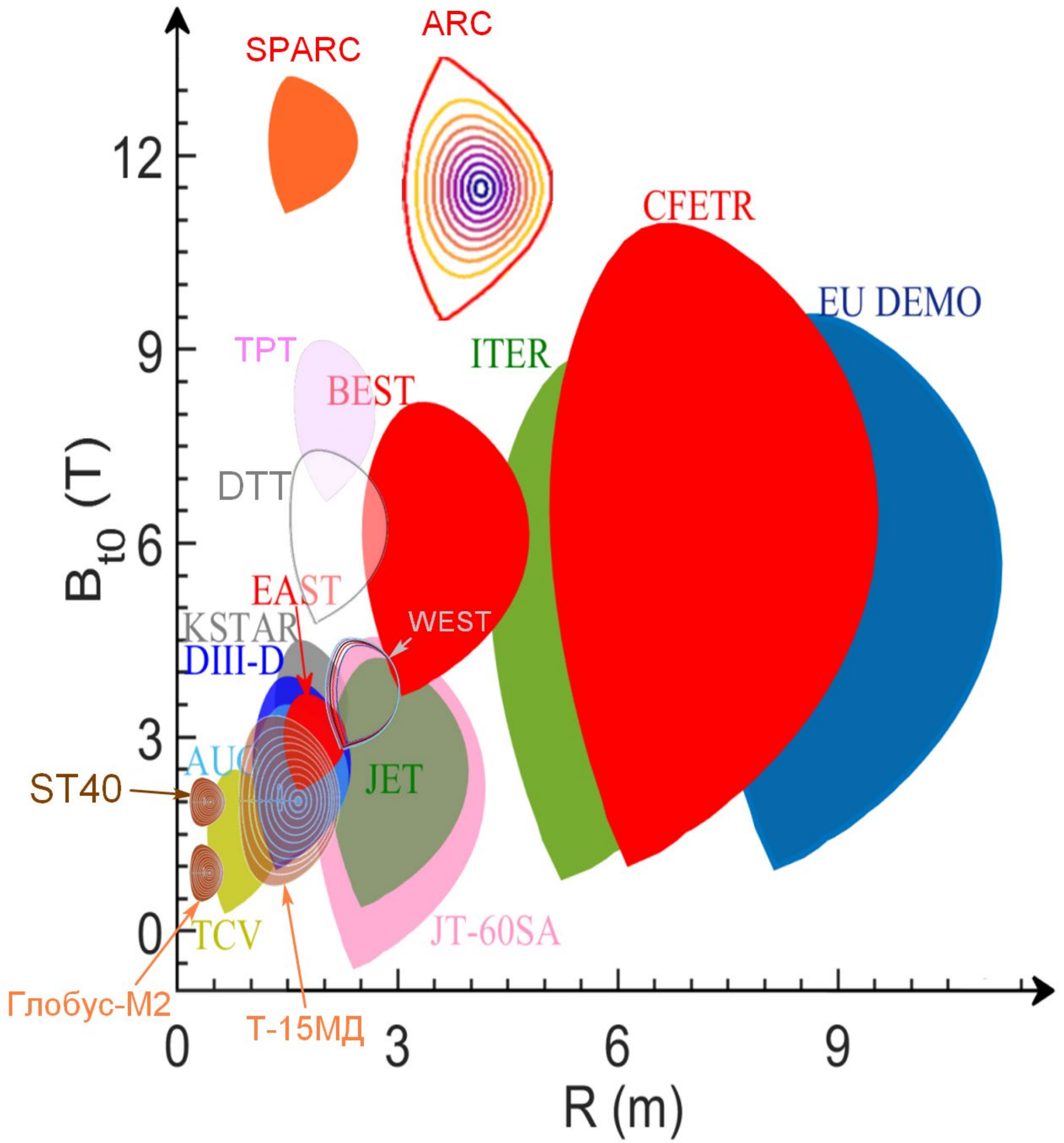
ТОКАМАКИ:

СОВРЕМЕННЫЙ ЛАНДШАФТ И ТЕНДЕНЦИИ РАЗВИТИЯ

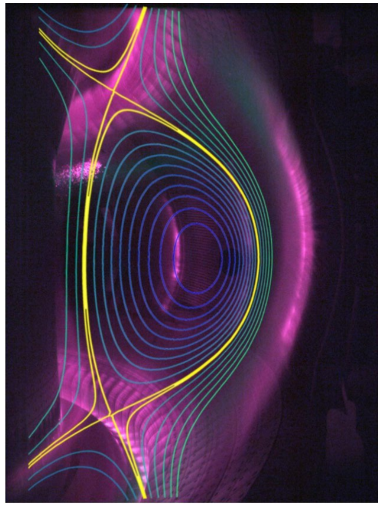
- Современные токамаки: $R_0 \leq 3.0$ м, $B_T \leq 4.0$ Тл

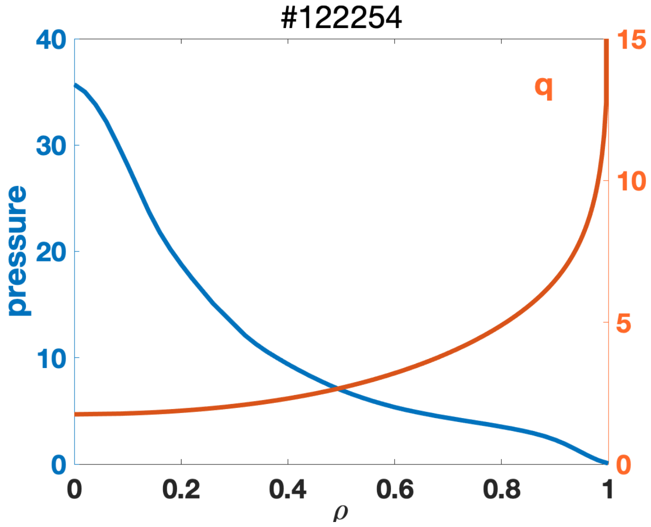
Термоядерное «солнце» восходит на Востоке

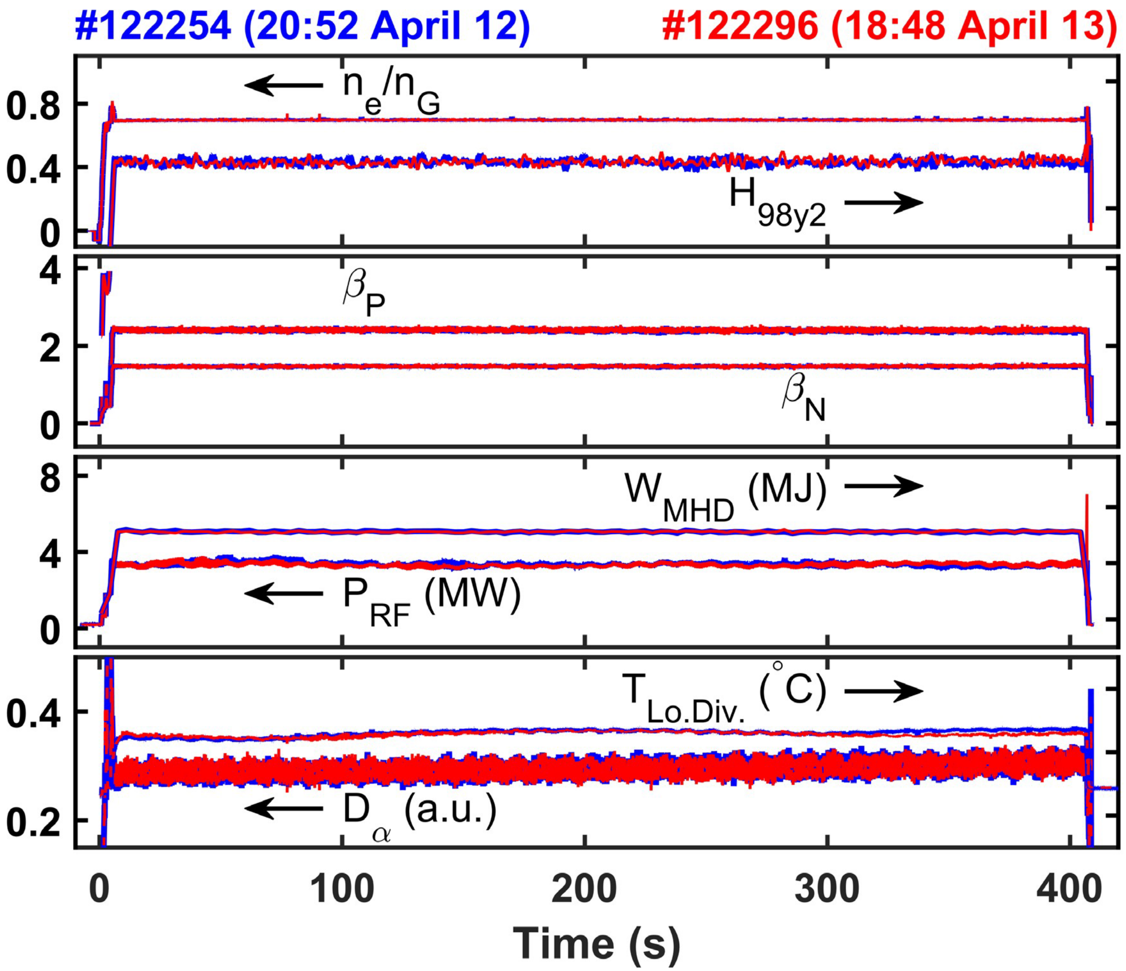
- JT-60SA – важный шаг вперед!
- Китай приступил к активному проектированию и разработке реактора CFETR
- На 2027 год запланирован запуск токамака BEST
- Рекордные длительности разрядов на EAST
- Режим улучшенного удержания FIRE на KSTAR



New Record of Reproducible 403 Seconds H-mode Plasmas Demonstrated on EAST with Tungsten Divertor



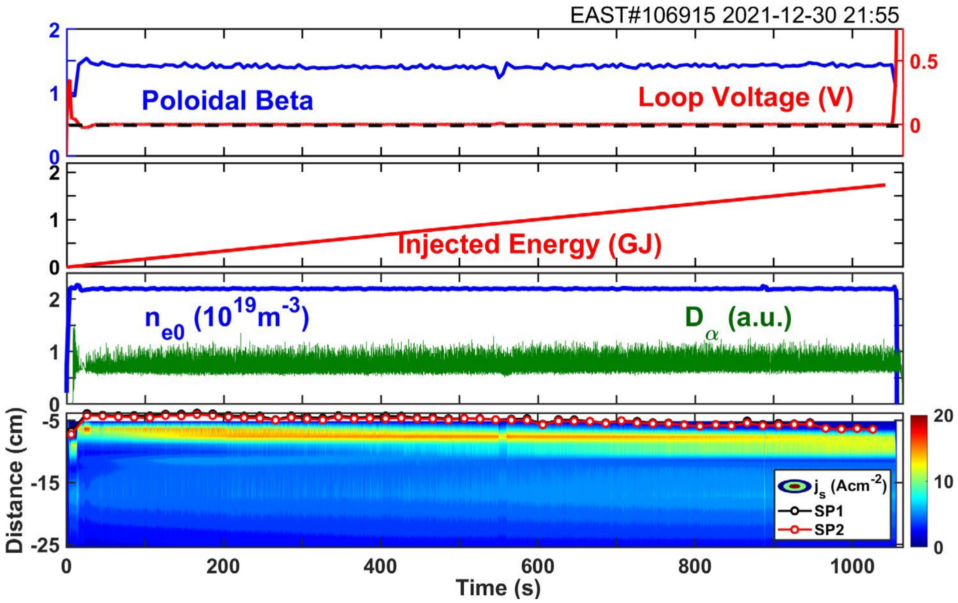




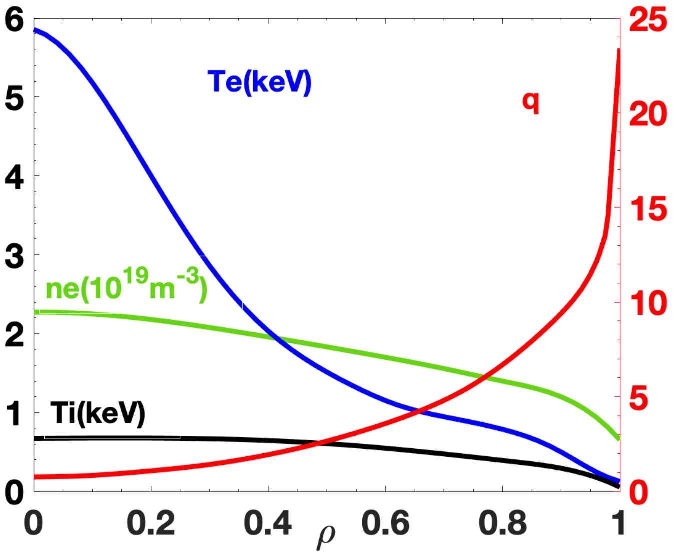
- A full non-inductive at f_{GW}~0.7 with f_{BS}>50% by RF heating with zero torque injection
- $H_{98,y2}$ ~1.35 with ITB by electron dominant heating
- Stationary control on particle exhaust and heat load with actively cooling W-divertor
- Small ELMs throughout discharges with high core performance

New Milestone and Tremendous Step Forward

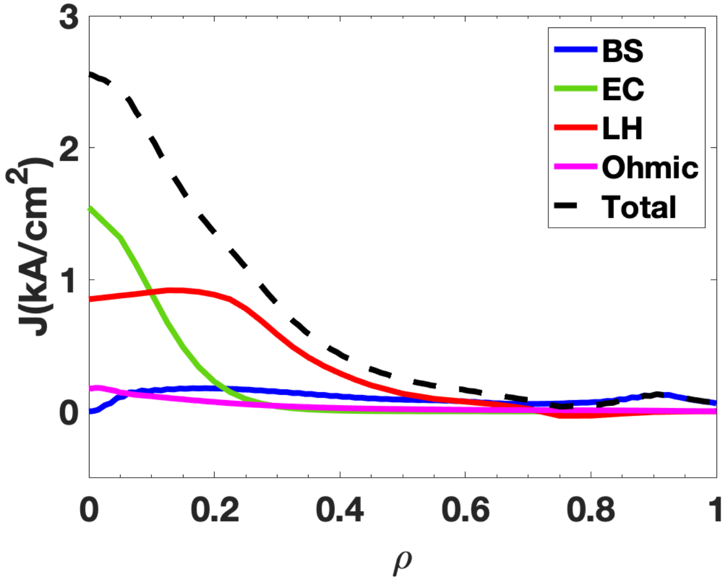
Demonstration of 1056-second Steady-state Plasma with Improved Confinement on EAST



Total injected energy ~ 1.73 GJ



Y. Song, Sci. Adv., 2022

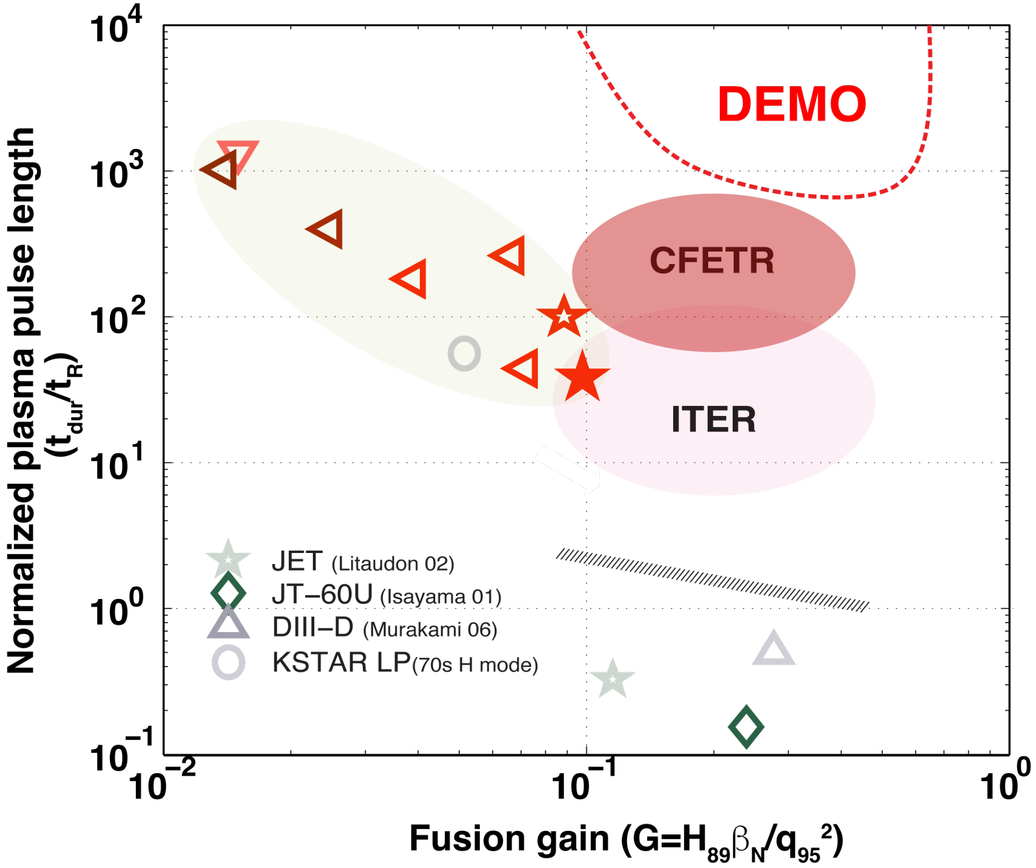


https://www.iter.org/newsline/-/3740

- Fully non-inductive f_{RFCD}~70%, f_{BS}~30%, H_{89} ~1.3, V_{loop}~0 with feedback control by LHW
- Enhanced power exhaust with new water-cooled lower W-divertor
- Lower recycling control with real-time wall conditioning
- Good control of plasma equilibrium and position over long time scales

A Steady-state Tokamak Research Aims at Efficient Low Cost Fusion Reactors for a Sufficiently Long Duration

- **Steady state operation requires fully non-inductive current $I_P = I_{CS} (\rightarrow 0) + I_{BS} + I_{AUX}$**
- **High self-driven current requires high-β_P**
- **High fusion power requires high pressure β_T**
- **Long pulse operation requires stationary particle control and heat flux exhaust**



ITER aims at Q≥5 long-pulse (~3000s) steady-state operation (SSO)

ASIPP

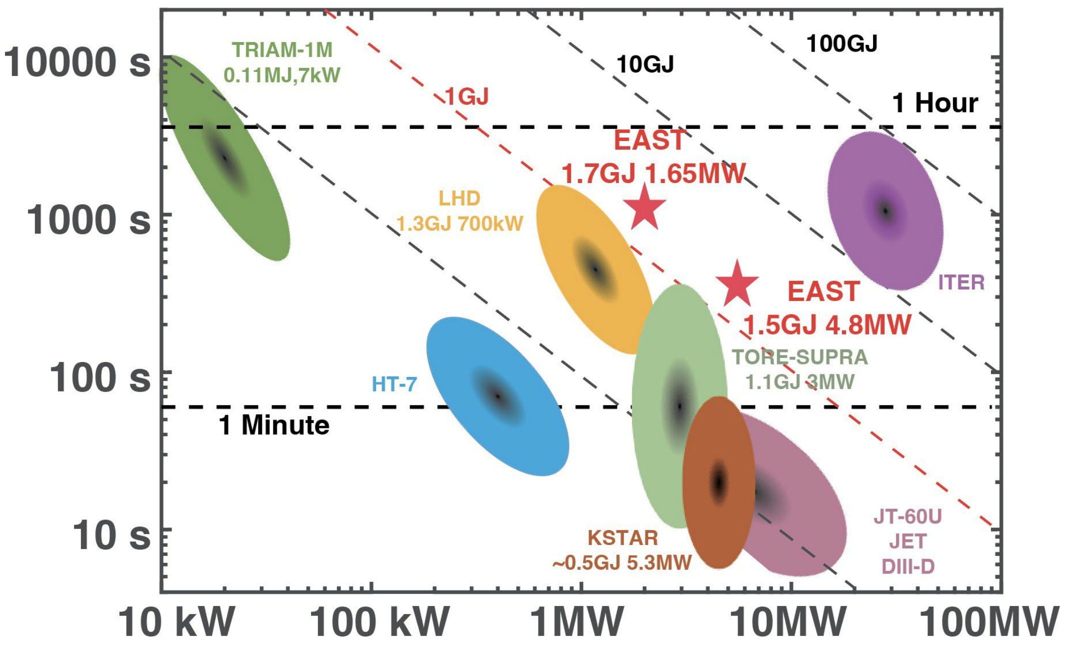
Strategies to Establish the Scientific Basis Integrated Solutions of for SSO in Support of Future Fusion Devices

S1: Enhance H/CD efficiency & relevant fundamental physics understanding and key diagnostics

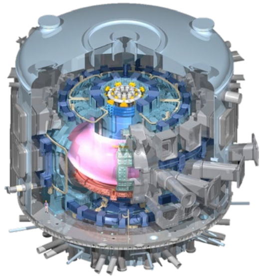
S2: Demonstrate long-pulse (≥400s) H-mode plasmas and develop fully non-inductive high-β scenarios

S3: Extend EAST operation regime to demonstrate steady-state high performance plasmas and deliver relevant physics for ITER and CFETR

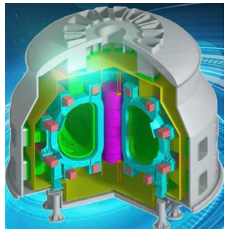
Total injected energy up to 1.73GJ



ITER



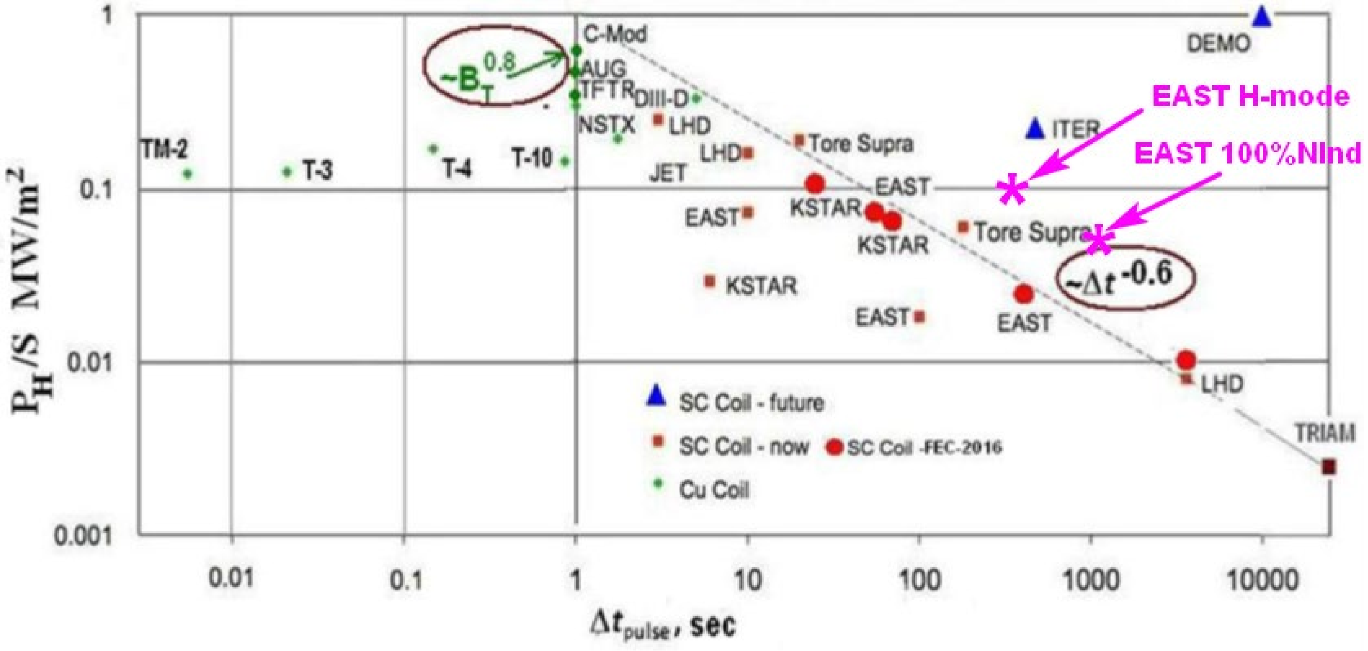
BEST



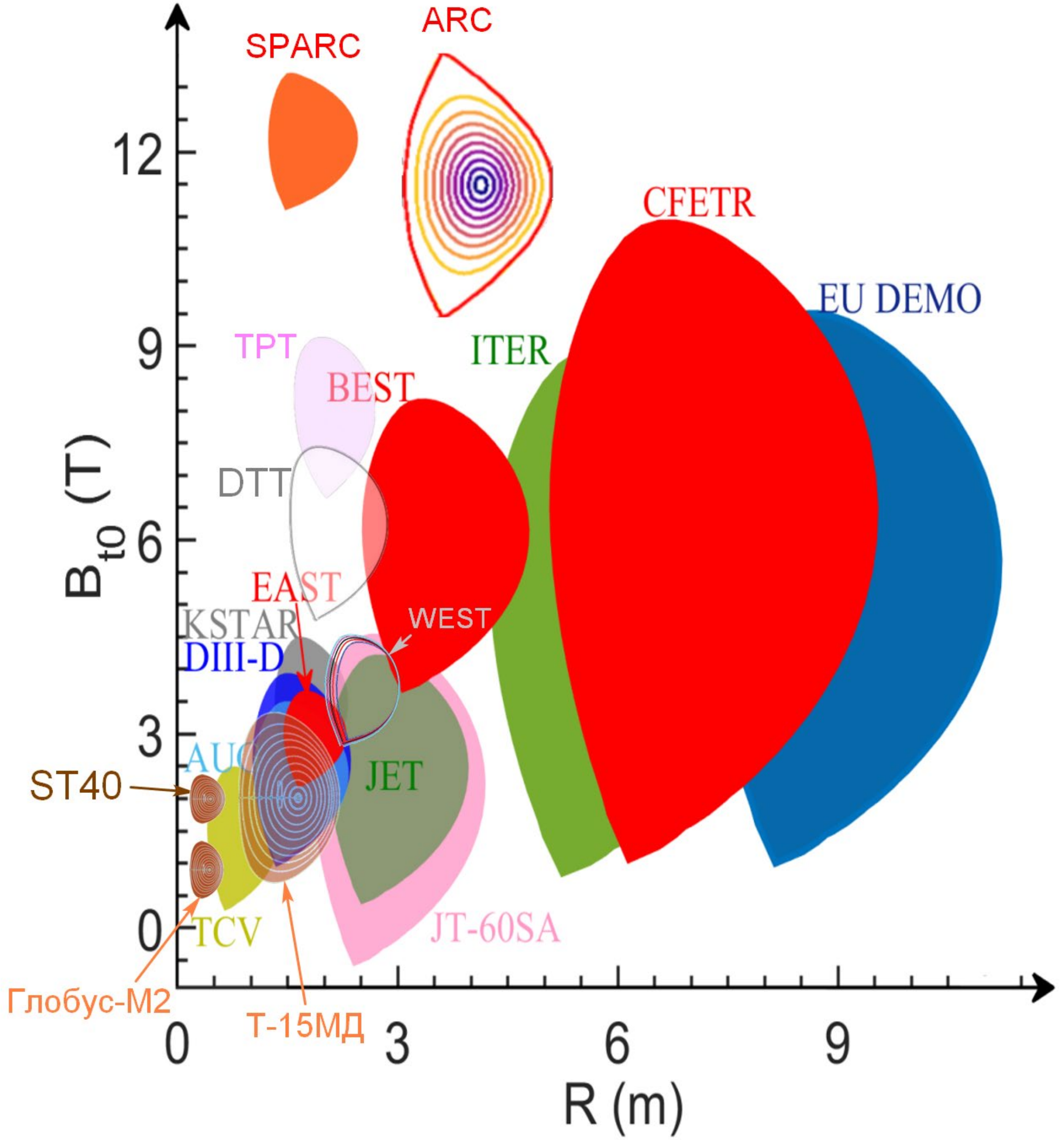
CFETR

FEC-2023: инженерные и физические вызовы УТС

Термоядерное «солнце» восходит на Востоке



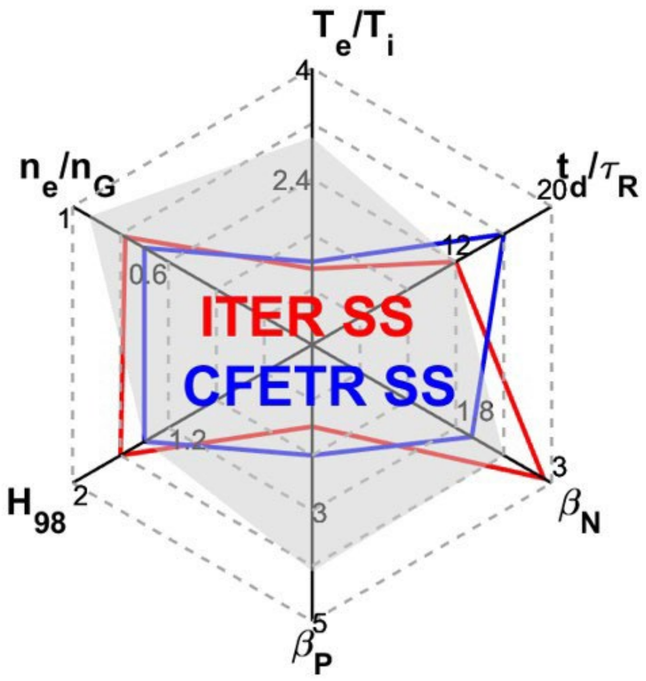
На графике, предложенном С.В. Мирновым [*NF, **59** (2019) 015001*], разряды EAST существенно превышают предел $\Delta\tau^{-0.6}$.



Exploiting the Potential of EAST to Close the Gaps towards ITER and CFETR Steady-state

- **Need to develop innovative physics understanding & approaches towards ITER&CFETR SS LPO:**
  - Handle particle and heat load, materials erosion, elimination of damaging with long pulse
  - Solve divertor/SOL, pedestal, confinement & transport and its trade-off with H&CD

Challenges and Future Plans



Challenge/Goal	Approaches	Capabilities
Solve fully non-inductive high-β_p scenario with T_e~T_i at lower q_{95} and zero-torque, efficient H&CD at high density, β–limits,	• Discover high performance core solutions. Validate models in burning-plasma-relevant regimes • Major H&CD upgrade with shape, B-field • High current for ICRF ion heating and enable lower q_{95} • Transport for various Te/Ti , electromagnetic effects, magnetic shear and Shafranov shift, and ExB shear	• **6MW ICRF (2-antenna)** • **6MW EC (2-gyrotrons, dual Freq.)** • **4MW LHW PAM-4.6GHz** • **2MW NBI RF-sources** • **New modular limiters & Div.** • **New Control and DIAs upgrades**
Expand range of j(r) & P(r) to improve performance to find high confinement high-β_p regime with large radius ITB & high f_{BS}	• Develop integrated simulation tools to test fundamental physics of q_{min}>2 for ITB and f_{BS} • Increases in ECH&ICRH to access to ITER and CFETR relevant β_N & q_{95} • Focus on profile requirements for ideal MHD limits, good EP & global confinement	
Demonstrate long pulse with high power (P_{loss}/R) operation to extend fusion performance	• Improve particle and power handling, elimination of damaging from hot spots • Recycling and heat flux control etc. in real-time • Identify path to integration with divertor and core solutions	

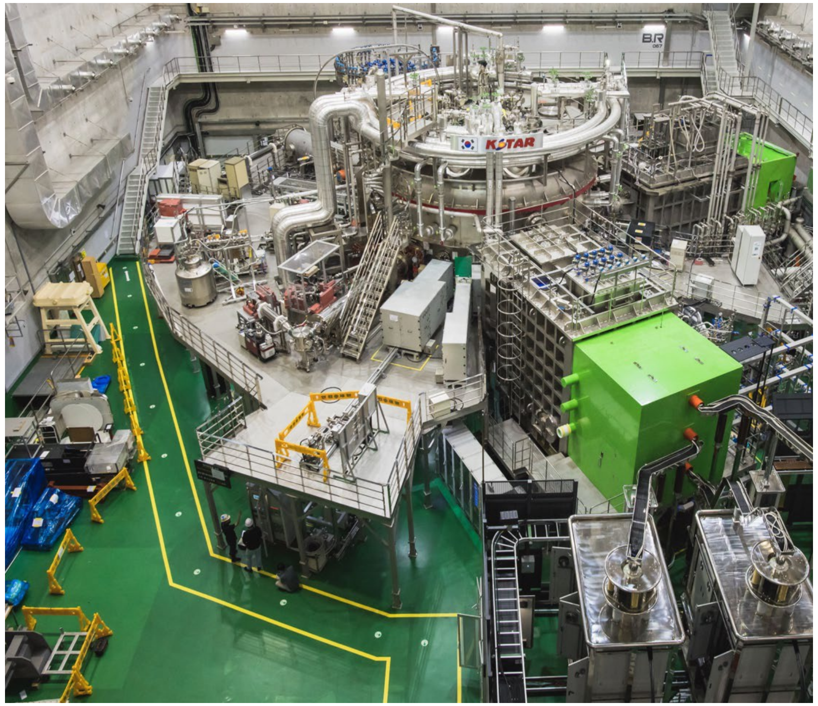
Summary

- **Significant progress has been made in long-pulse SSO on EAST**
  - Record of duration ~403s H-mode and a 1056s time scale fully non-inductive plasma demonstrated
  - Development of state steady high-β_p scenarios up to 100s with zero torque injection (β_p~3.0/β_N~1.8, f_{BS}>50%, n_e/n_G~0.82, H_{98y2}~1.5)
  - Extension of fusion performance with high confinement at high density (H_{98y2}~1.5 at n_e/n_G~1.0) and β_N =2.5~4*li near no-wall limit

- **Advances on the key issues essential for long pulse SSO, providing supports to ITER and CFETR steady state operation**
  - Improved confinement with stability, broad j(r), Shafranov shift, e-ITB, high efficiency of H&CD at high density, active controls of radiative divertor, small ELM, plasma control, etc.

- **Near-term plan with upgrade of inner components and augmented H&CD systems**
  - 1000s long-pulse H-mode operation with high bootstrap current fraction
  - Demonstrate SSO with **extended fusion performance** at 15-20 MW power injection

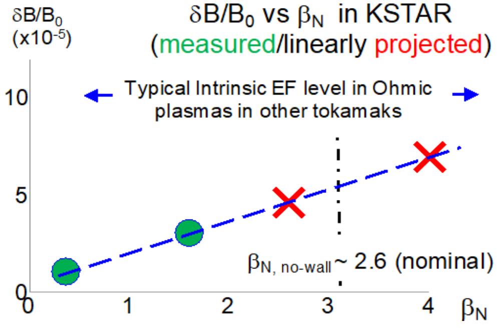
Improvement of KSTAR for High Beta Steady-state Operation



Major radius, R_0	**1.8 m**
Minor radius, a	**0.5 m**
Plasma current, I_P	**~ 1.2 MA**
Toroidal Field, B_T	**~ 3.5 T**

▶ Improved Plasma Symmetry

- **Lowest error field ($\delta\delta B/B_0$~$1x10^{-5}$)**
- **Lowest toroidal ripple (~0.05 %)**

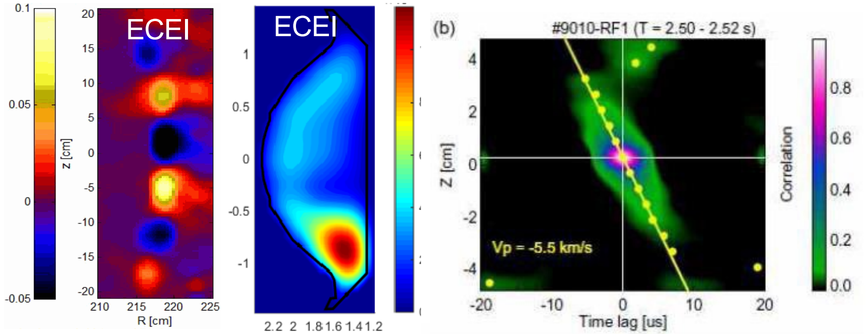


▶ Improved Control with IVCC

- **Uniquely top/middle/bottom coils**
- **Reliable ELM suppression (>45s)**

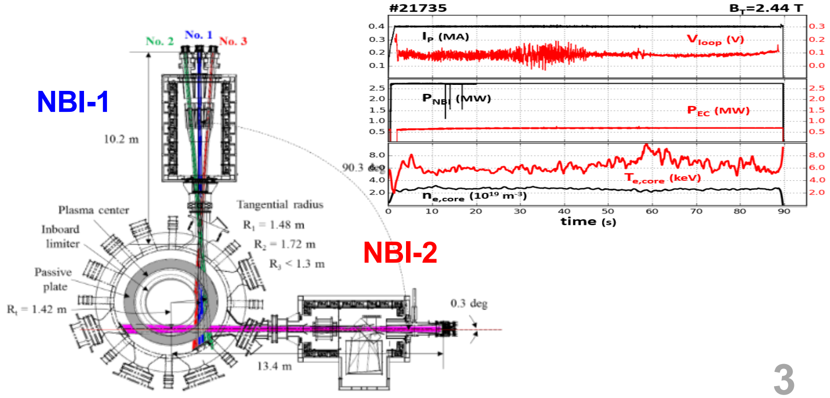
▶ Advanced Diagnostic

- **2D/3D imaging diagnostics**
- **Physics validation**



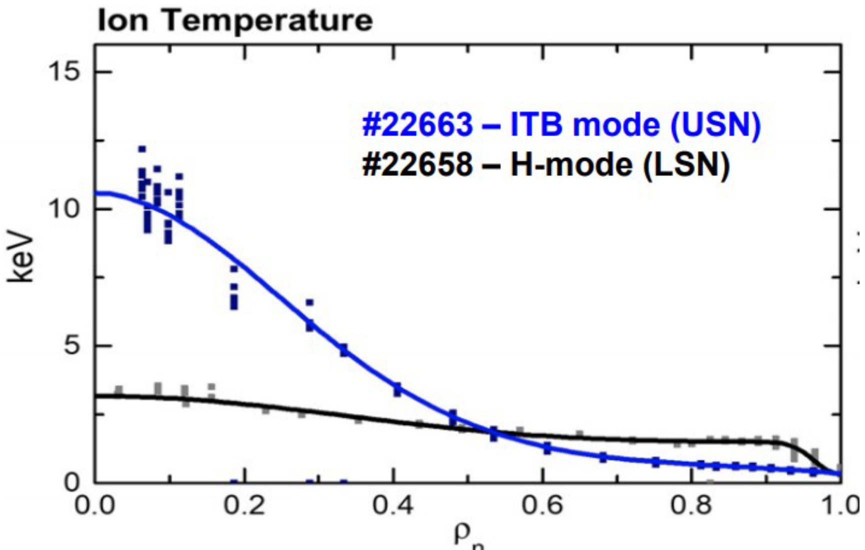
▶ Improved Efficiency in H/CD

- **Long pulse using NBI (>90s)**
- **2nd NBI system is operated**



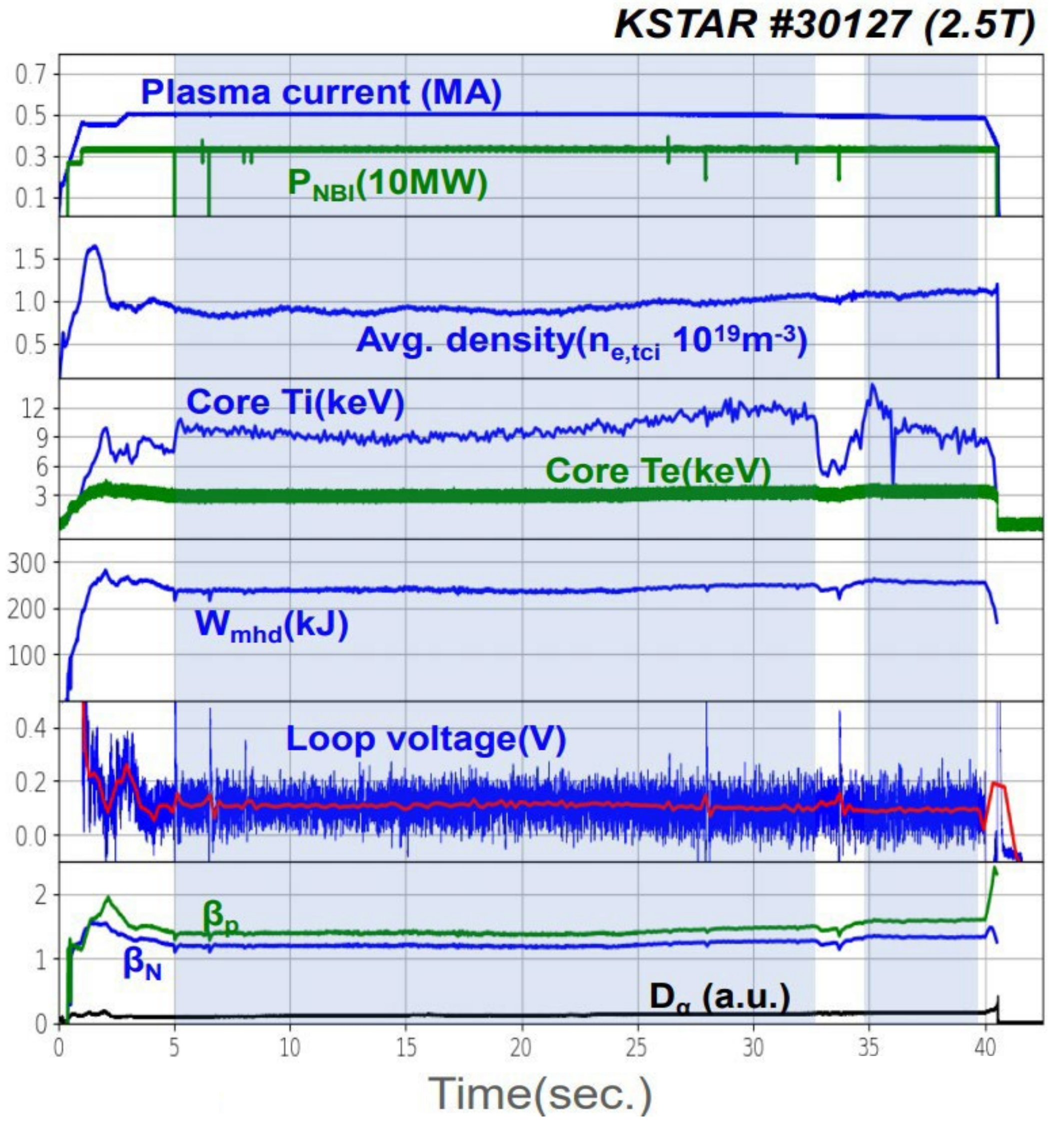
Scenario Development : a New Stationary ITB Formation in KSTAR

- **Characteristics of new ITB mode**
  - Self-organized with high performance **(T_{icore} > 10 keV)** without sophisticated control
  - No significant impurity accumulation
  - Reduced maximum heat load on divertor
  - **High NBI power** applied to lower density plasma in order to avoid the H-mode transition at the diverted USN



H. HAN, S.J. Park, Y. Na, *Nature* (2022)

Y. NA(EX-S-1925), EX/5-2[Oct.19(**Thu**) 2PM]



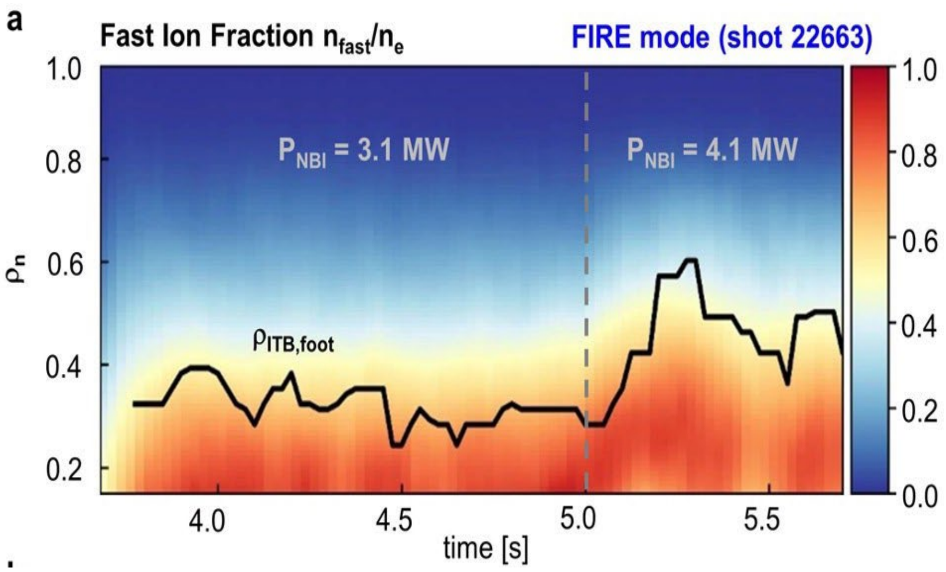
Scenario Development : Gyrokinetic Simulation Gives Understanding Key Mechanism for High Ti Operation as a New ITB

C. SUNG(TH-C-1865), TH/2-2 [Oct.17(**Tue**) 11AM]
Y. NA(EX-S-1925), EX/5-2 [Oct.19(**Thu**) 2PM]

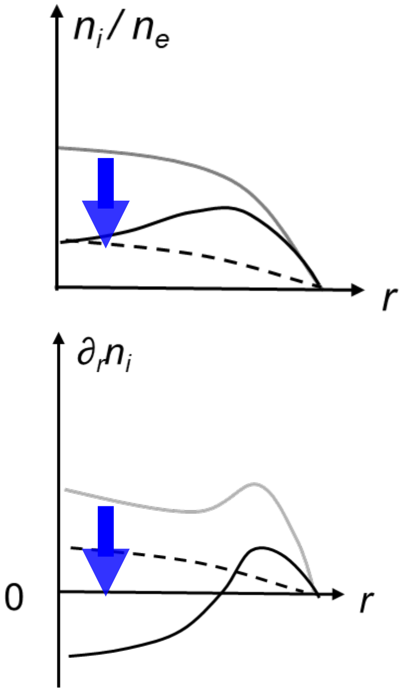
▶ Understanding key mechanism for high Ti operation

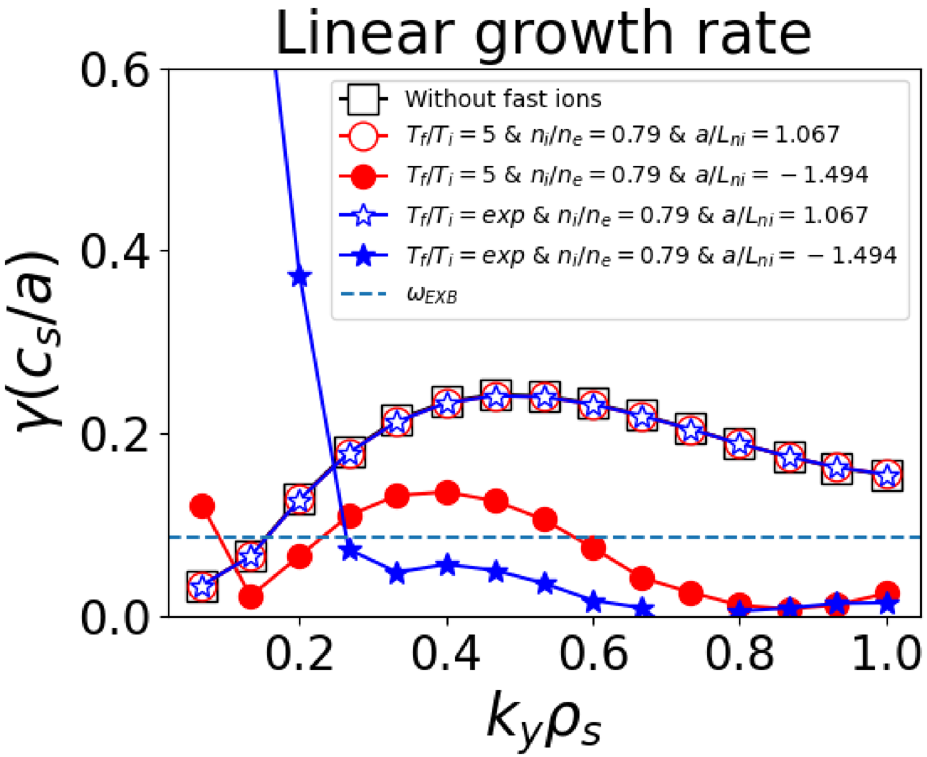
- Gyrokinetic simulation for New ITB discharge shows **higher fast ion fraction** compared to H-mode may affect ITB formation and improving confinement
- The Inverted main ion density gradient (a/L_{ni}) is reduced and the linear growth rate decreases from CGYRO simulation which shows dilution effects by fast ions mainly responsible for **turbulence suppression**

→ **Fast Ion Regulated Enhancement (FIRE) mode**



H. HAN, S.J. Park, Y. Na, *Nature* (2022)



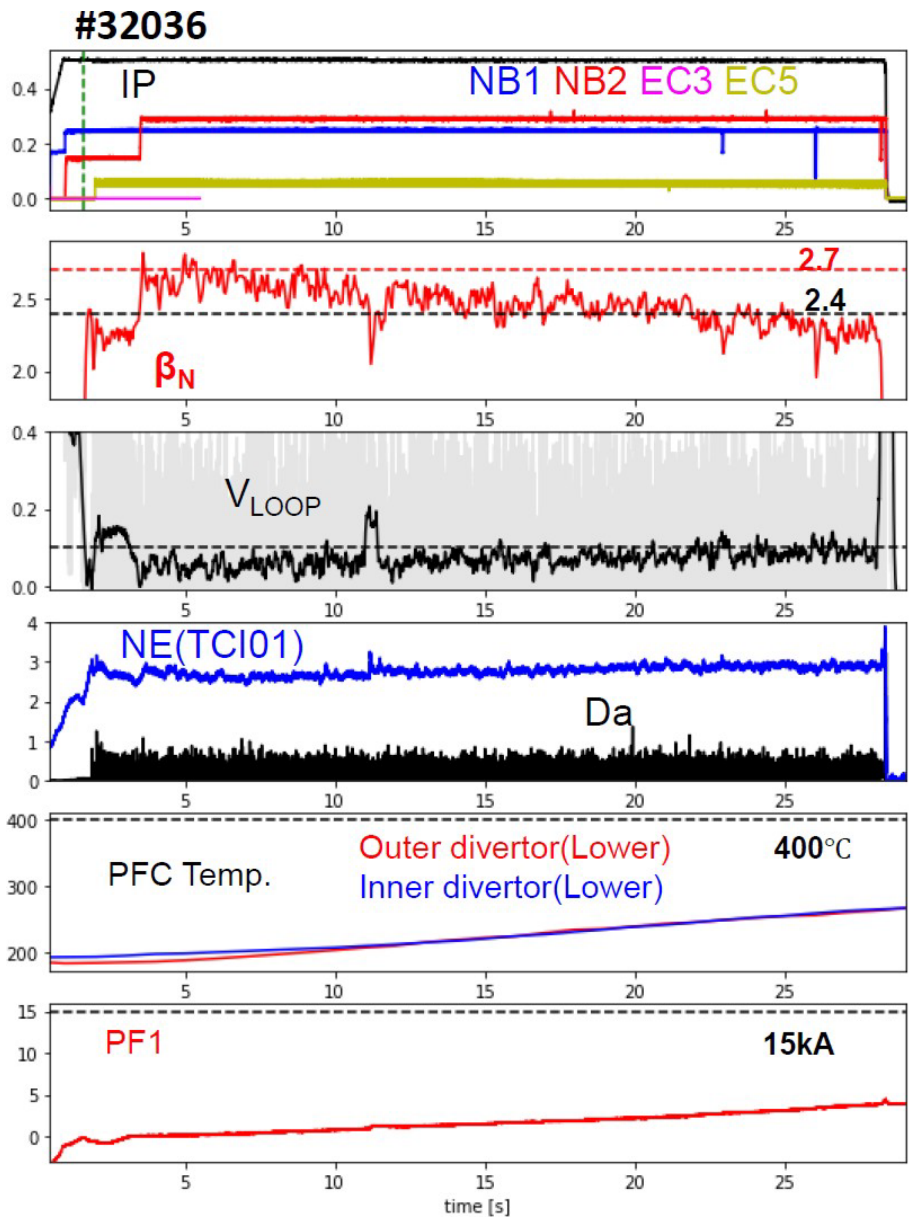


D. KIM, C. Sung, *Nucl. Fusion* (2023)

Scenario Development : Toward to Quasi-steady State Hybrid with β_N >2.4 for 20 s

- **Hybrid obtained by improving the edge stability and core performance of the H-mode plasma**
- **By controlling fueling, external heating and current overshooting, plasma shaping and deep reinforcement Machine Learning of scenario control *[J, Seo, Nucl. Fusion (2021)]***
- **From high $\beta_N \sim 2.7$, slow degradation rate: $\beta_N \geq 2.4$**
- **Confinement degradation in Hybrid long pulse**
  1) **Shaping control missing for sudden change**
  2) **Density rise affected by increasing outer gap**
  3) **Occurrence of MHD activities, AEs…**

Y.S. NA, FY2022 KSTAR summary



Target gain >1 from inertial confinement fusion experiments at the National Ignition Facility

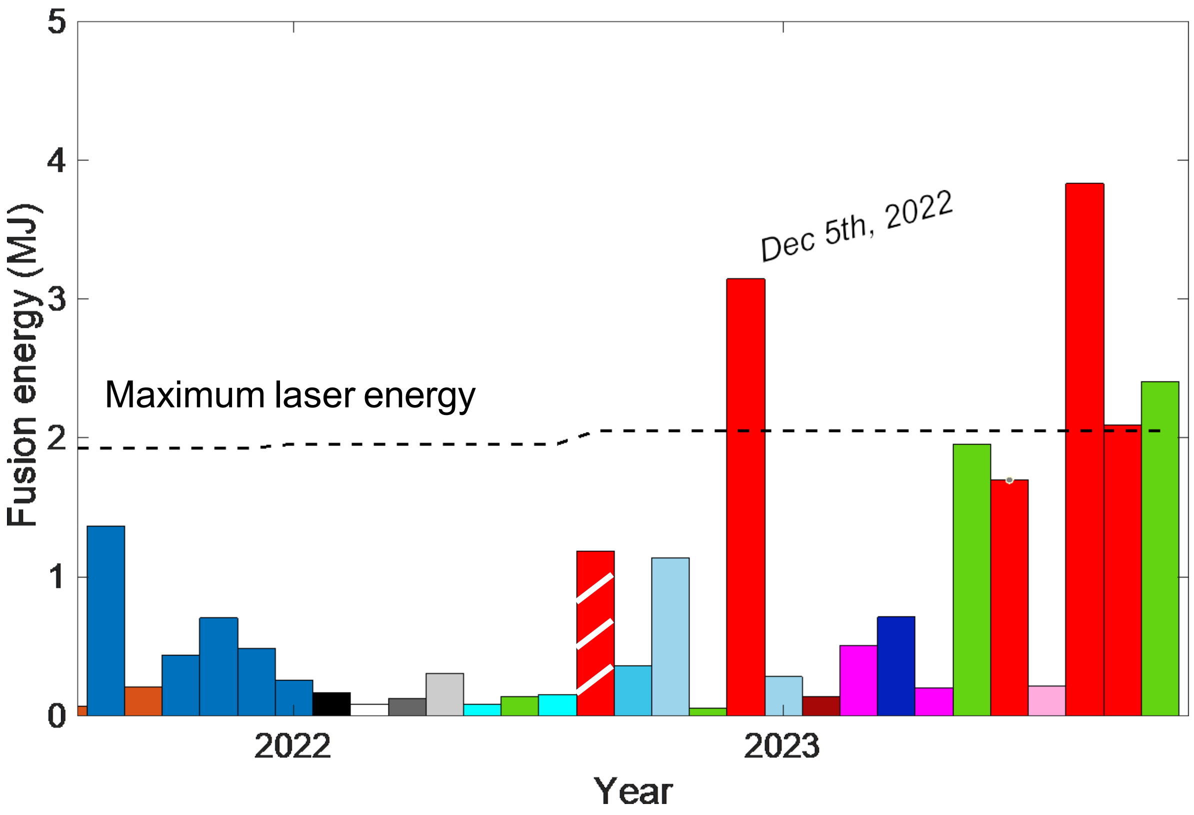
Arthur Pak on behalf of the indirect drive inertial confinement fusion collaboration

IAEA Fusion Energy Conference, Oct 16th, 2023

LLNL-PRES-1084645
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Our program is focused on developing paths to higher target gains and understanding the origin of variability in fusion output



- Conducted 3 near repeat experiments of Dec. 5th experiment
- Fusion yields of up to 3.88 MJ and target gains of 1.9X have been achieved.
- Target gain ≥ 1 achieved 3 out of 4 times.
- A second approach has now also achieved target gain > 1.

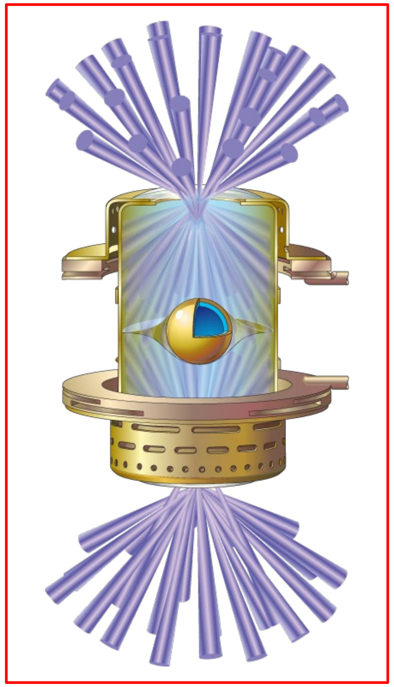
There are several complementary approaches to ignition in inertial confinement research

Laser Indirect Drive

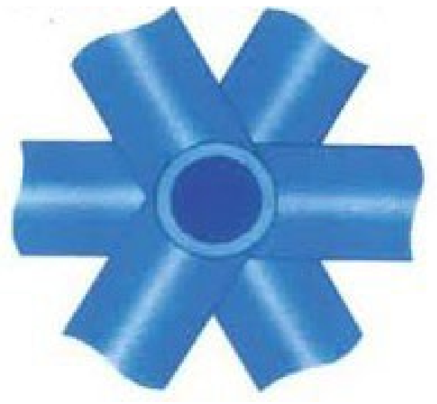
Laser Direct Drive

Magnetic Drive

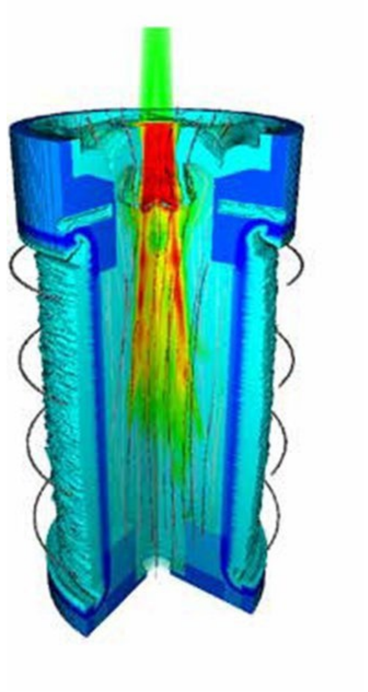
Double Shells



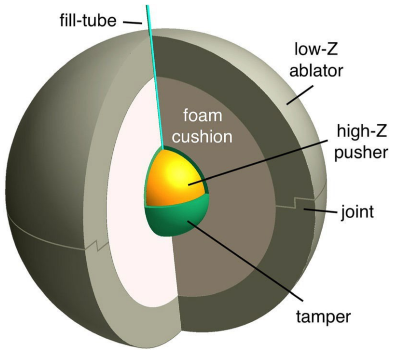
Lindl,
Phys Plasmas 1995, 2014



Craxton,
Phys Plasmas 2015



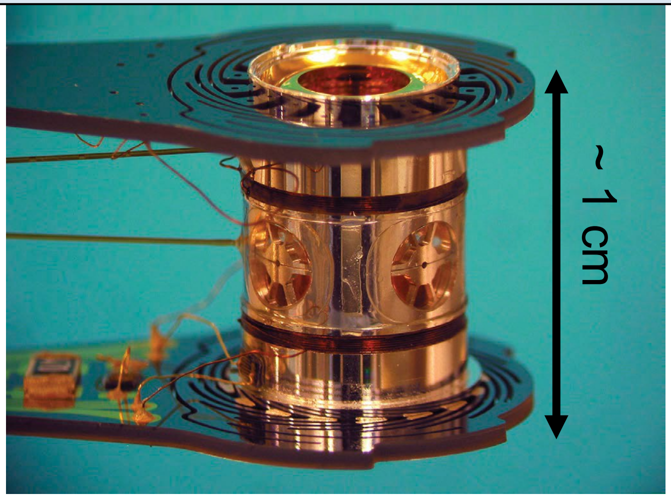
Slutz,
Phys Plasmas 2010



Montgomery,
Phys Plasmas 2018

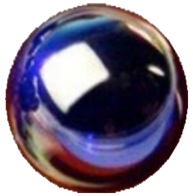
Targets require state-of-the-art microfabrication precision

Gold lined uranium hohlraum



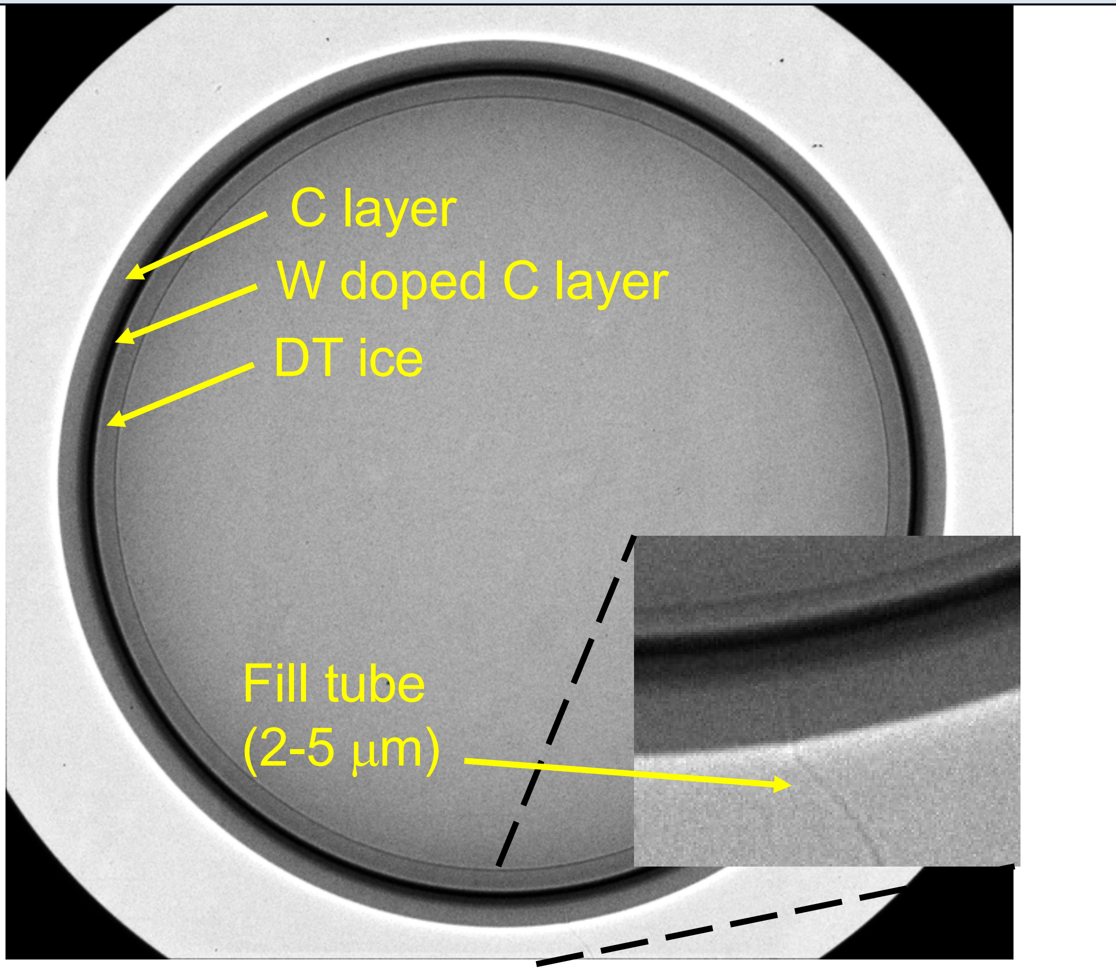
Cryogenic (19 K)
0.3 mg/cc He fill

Diamond Nanocrystalline Capsule
(High Density Carbon – HDC)



≈ 2 mm diameter,
smooth to 10 nm

In-situ radiograph of capsule with DT layer



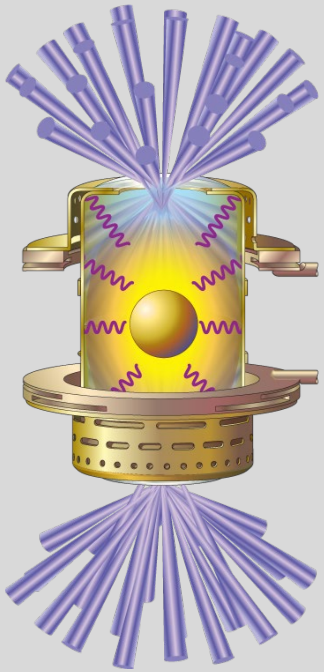
We perform ~15 experiments with cryogenic DT fuel a year at full laser energy.
It takes ~1-2 days to grow the DT ice layer and 1 day to execute the experiment

The National Ignition Facility (NIF) is the world’s most energetic laser enabling the study of extreme conditions

- 192 Beams,
- 2.05 MJ Energy, 500 TW Power (300 MJ electric)
- Matter temperature >10^8 K
- Radiation temperature >3.5×10^6 K
- Densities >10^2 g/cm^3
- Pressures >10^{11} atm
- Number of Diagnostics >120

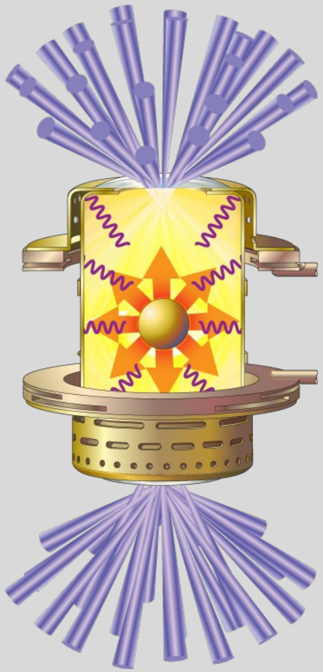
The NIF uses a laser driven high Z enclosure "hohlraum" to compress a fuel pellet filled with DT fuel to achieve the conditions for ignition

Laser beams rapidly heat the inside surface of the hohlraum creating x-rays



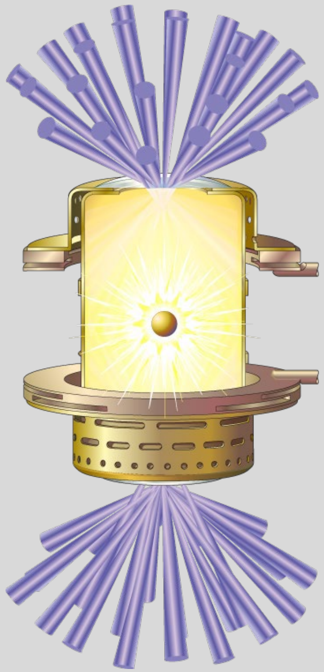
2.05 MJ of laser energy

The x-rays blow off the fuel capsule wall, accelerating the fuel inward to 1 million MPH



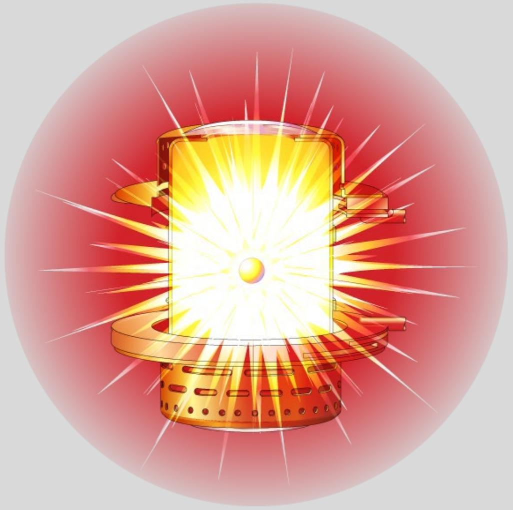
~250 kJ absorbed by capsule

The fuel is compressed to 100x the density of lead, its center heating and igniting at 100,000,000° C



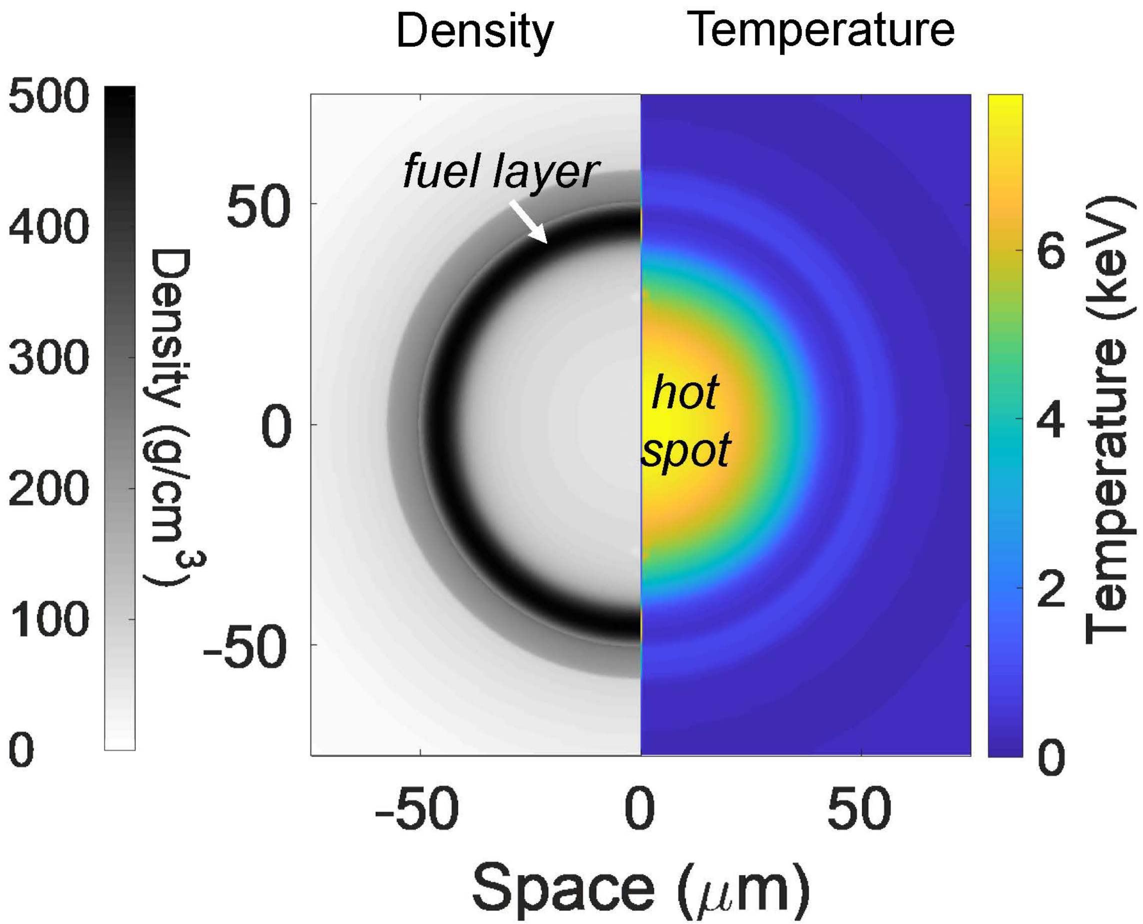
~20 kJ given to the DT fuel

Fusion burn spreads rapidly through the compressed fuel, yielding many times the input energy



3.14 MJ fusion energy output on Dec. 5th,2022

The hot spot temperature and yield depends on the competition between heating and loss rates



*Number of DT reactions in hot spot**

$$\gamma \propto n_D n_T \, T_{DT}^4 \, \tau \, V$$

DT temperature dependence / energy balance

Radiation losses

Conduction losses

$$C_{DT}\frac{dT}{dt} = Q_\alpha - Q_{rad.} - Q_{cond.} - Q_{PdV}$$

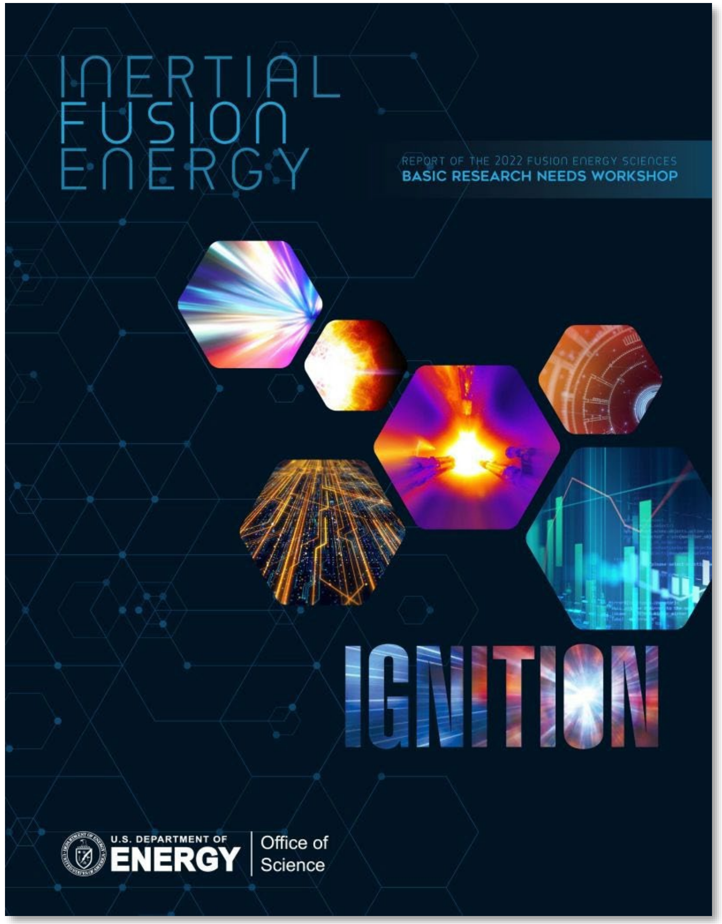
α-particle heating

Compressive work / Expansion losses

When Q_α > all losses and $dT^2/dt^2 > 0$ a sustained chain reaction occurs leading to ignition

*DT reactivity in temperature range of experiment scales approximately as T^4

Fusion Energy Sciences Basic Research Needs 2022 identifies priority research opportunities for IFE



INERTIAL FUSION ENERGY

REPORT OF THE 2022 FUSION ENERGY SCIENCES
BASIC RESEARCH NEEDS WORKSHOP

IGNITION

U.S. DEPARTMENT OF ENERGY | Office of Science

Goals for 4 key research areas identified

1) **Target Physics and Ignition**
   - Target gain ~50

2) **Driver and Target Technologies**
   - Rep. rate ~10 Hz, high efficiency, low cost

3) **Fusion Power Plant Integrated Systems**
   - Tritium breeding / 1st wall

4) **Cross Cutting:**
   - Theory and Simulation
   - Artificial Intelligence and Machine Learn
   - Workforce

U.S. DOE has launched public-private partnership milestone program and an IFE Science & Technology Accelerated Research (IFE-STAR) program

Milestone Program: 46 M$

“Within five to 10 years, the eight awardees will resolve scientific and technological challenges to create designs for a fusion pilot plant that will help bring fusion to both technical and commercial viability.”

Commonwealth Fusion Systems

Tokamak Energy

FOCUSED ENERGY

TYPE ONE ENERGY

Princeton Stellarators

XCIMER

REALTA FUSION

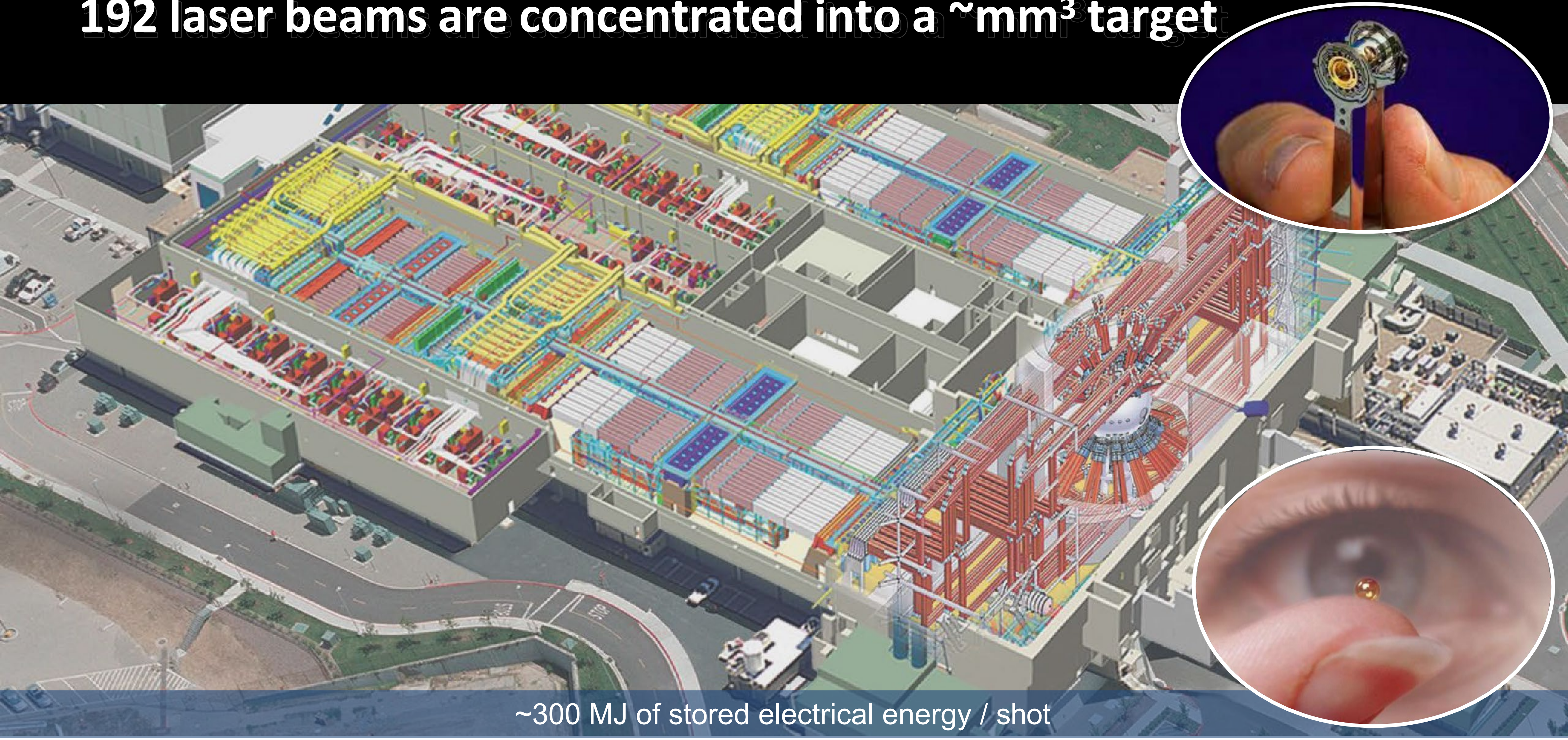
ZAP ENERGY

IFE-STAR Program: 45 M$

“The objective of IFE-STAR is to provide an IFE framework that leverages expertise and capabilities across national laboratories, academia, and industry to advance foundational IFE S&T using integrated and self-consistent solutions as outlined in the BRN report “

Awards will be announced in early FY24

192 laser beams are concentrated into a ~mm^3 target



~300 MJ of stored electrical energy / shot

FEC-2023: инженерные и физические вызовы УТС

СПАСИБО ЗА ВНИМАНИЕ !

FEC-2023: инженерные и физические вызовы УТС

ДОПОЛНИТЕЛЬНЫЕ СЛАЙДЫ

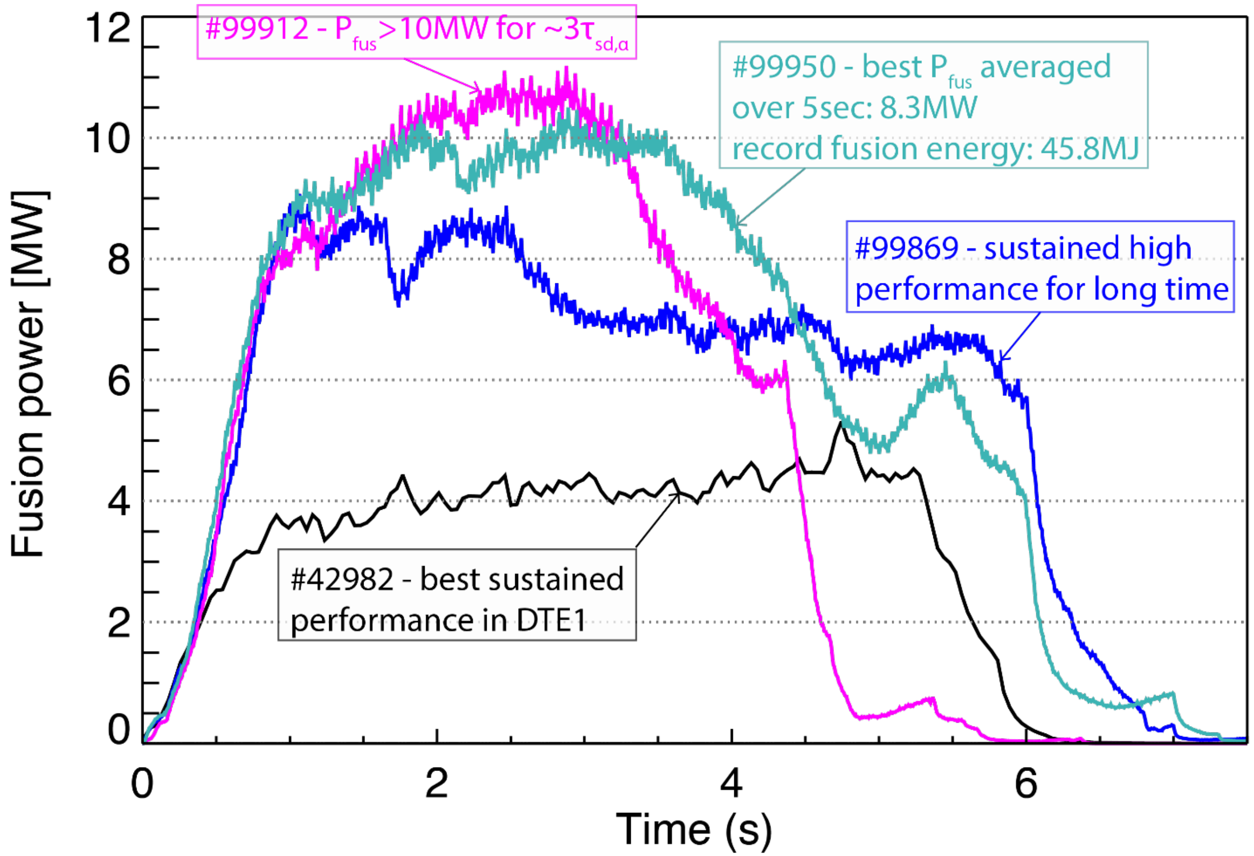
JET 50-50 D-T hybrid scenario achieved record, sustained P_{fus}

Hybrid scenario run for the first time in 50-50 D-T and Be/W wall

- **2.3MA/3.45T**, q_{95} ~ 4.8, β_N ~2.5, β_{pol} ~ 1.4
- Gas injection only (type I ELMy pedestal)
- Lower density, $T_i > T_e$

[Hobirk et al, NF SI on JET T & D-T 2023]

Hobirk, EX-C #1880 (Friday)



- Sustained high fusion power for long time
- Record 50-50 D-T fusion power averaged over 5s ~ 8.3 MW and record D-T fusion energy ~45.8MJ
- D-T fusion power >10MW for > 3 α-particle slowing down times

H-T Kim

Stancar

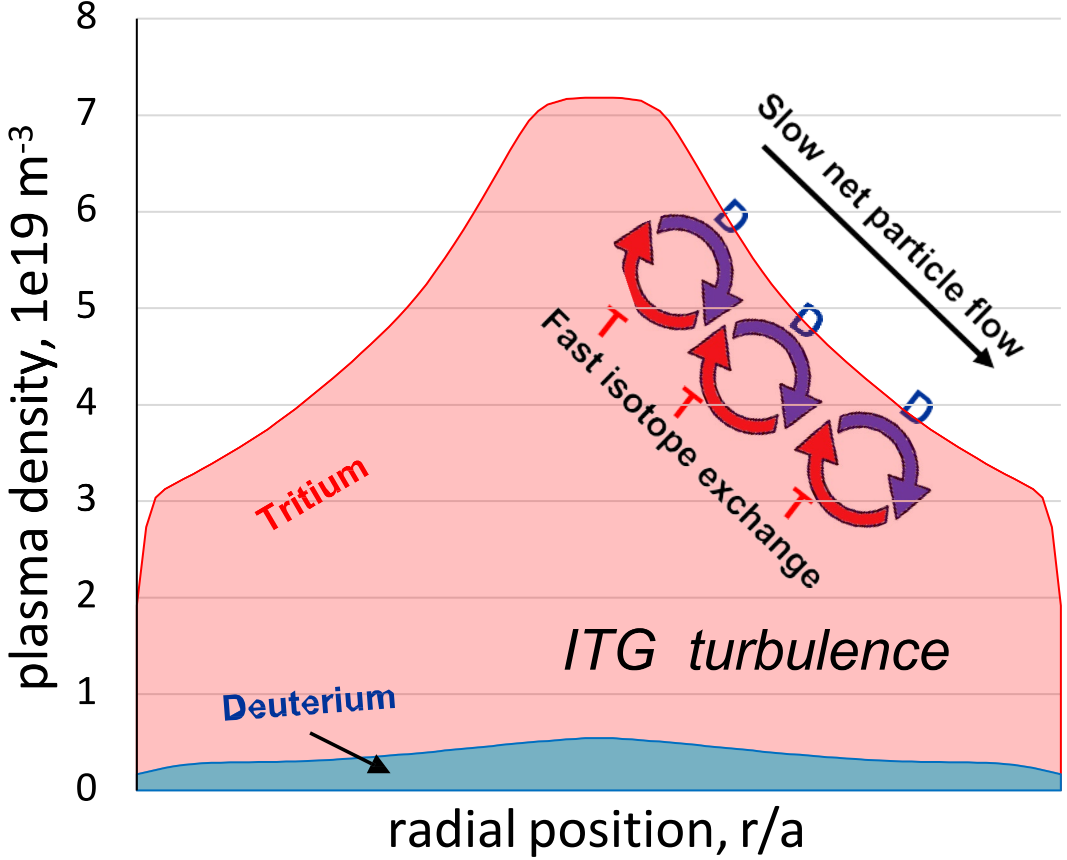
Ivanova Stanik

Alessi

Core isotope control

- D-NBI particle fuelling: **~2.7*10^{21}** atoms/s, the plasma content: **~3*10^{21}** electrons
- Deuterium ions must be removed from the plasma core at τ<<1s

#99972 (T-rich) t=48.5s, P(D-NBI)=30MW, **τ_E=200ms**



Fast isotope transpor

- For plasmas with strong ITG **equilibration time << Particle con**
- Ions easily move across the plasma the same everywhere
- In case of an intense D-NBI source but not of the Deuterium isotope

M. Maslov et al 2018 Nucl. Fusion 58 076022
C. Bourdelle et al 2018 Nucl. Fusion 58 076028

High-field tokamak path to fusion energy

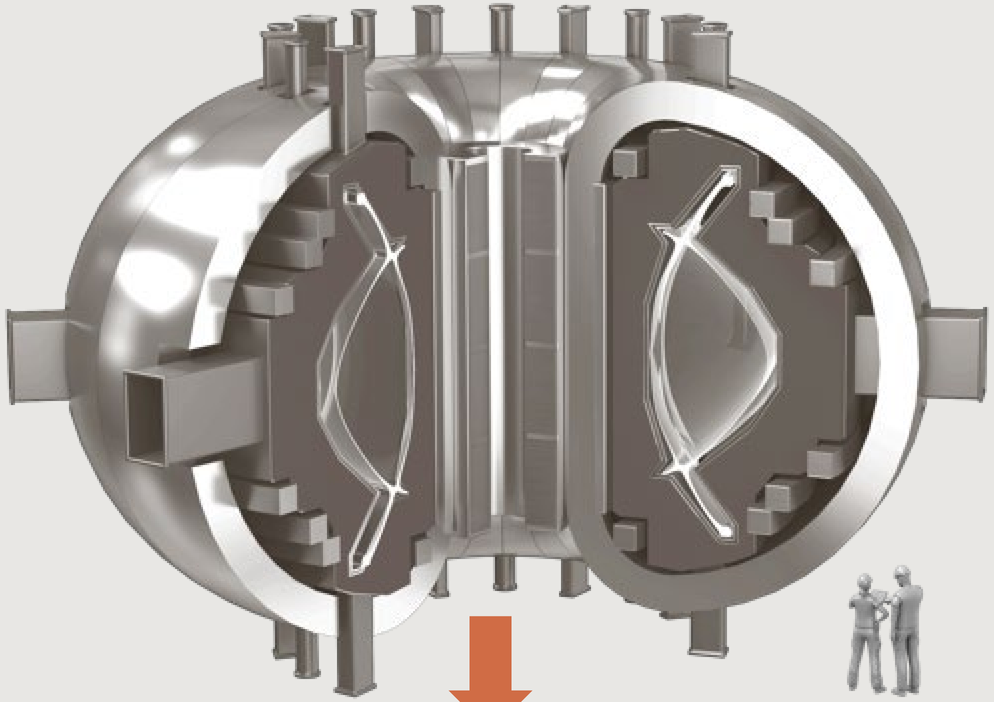
Building on tokamak physics demonstrated in machines around the world

COMPLETED:
Demonstrate groundbreaking HTS magnets

CONSTRUCTION UNDERWAY for 2025 LAUNCH:
SPARC Q>1
Achieve net fusion energy

Commercially-relevant net fusion energy for the first time

EARLY 2030s:
ARC deployed
~400 MWe

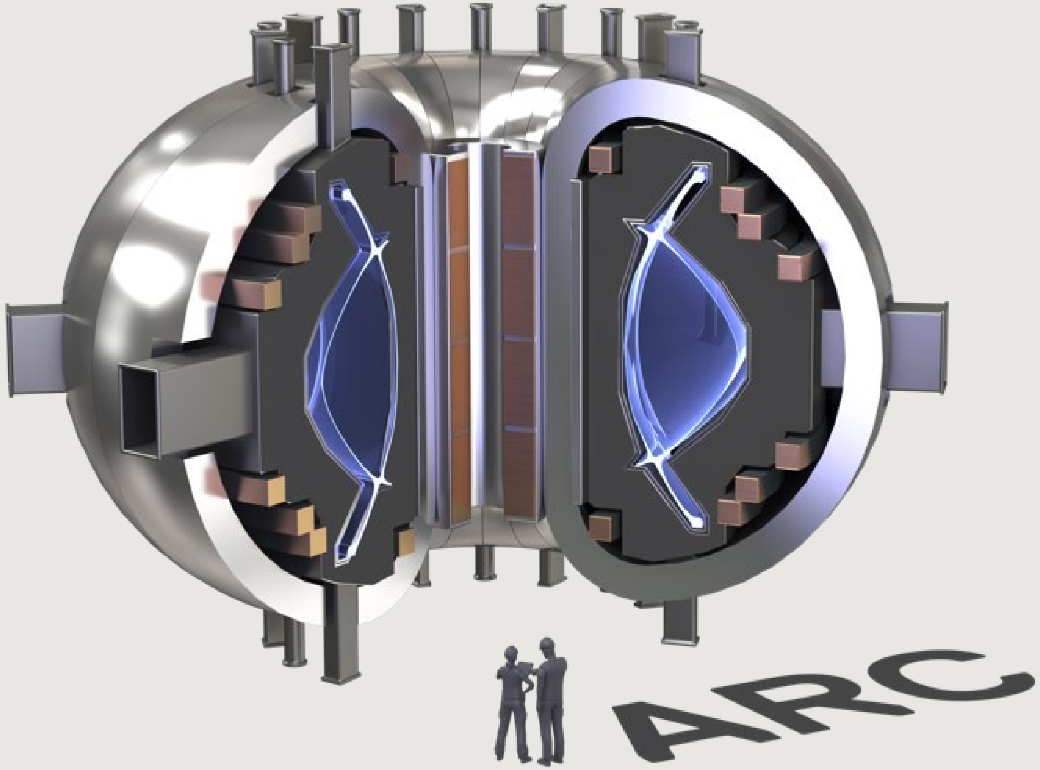


Carbon-free commercial power on the grid

CFS' fusion pilot plant: ARC

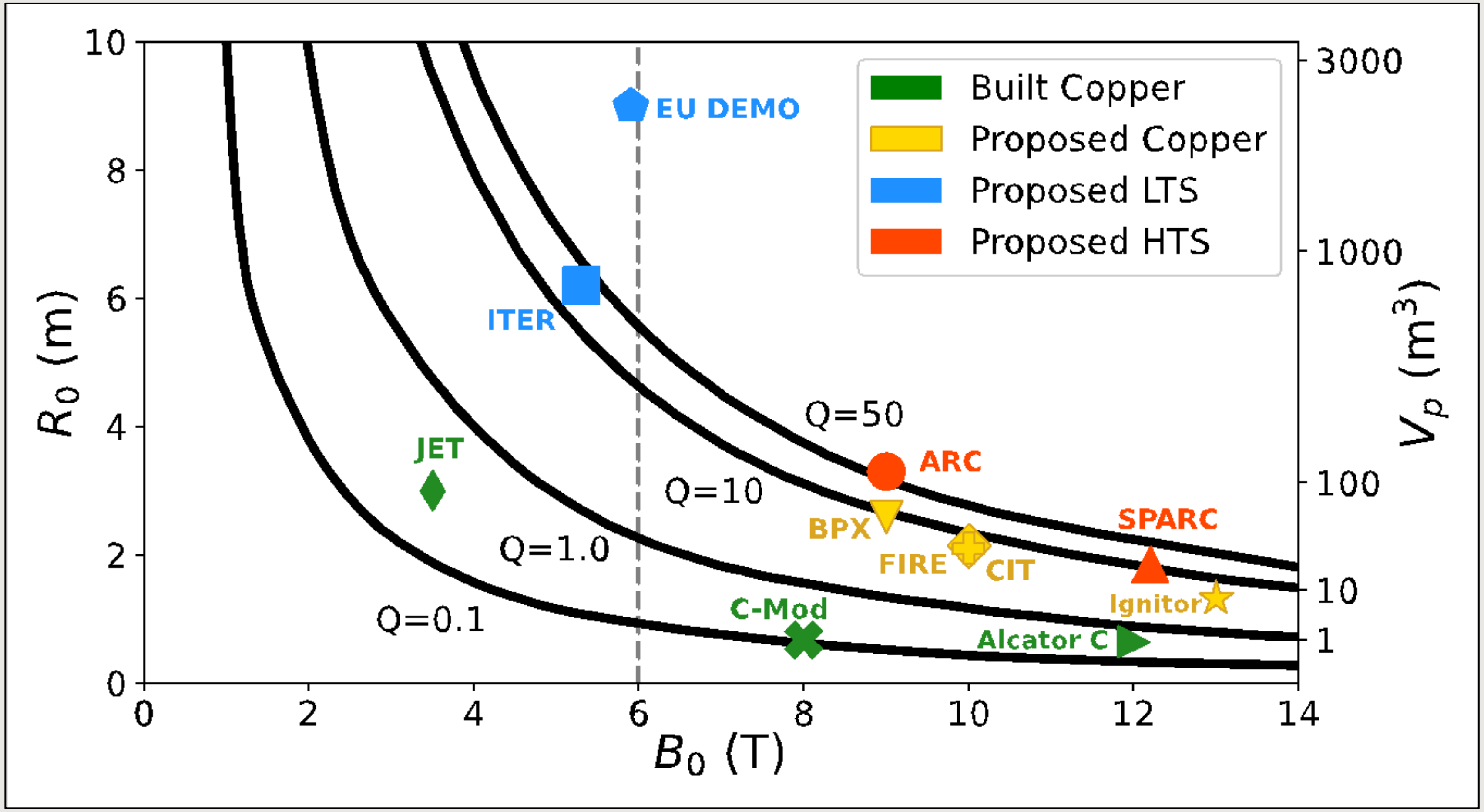
ARC is a high-field, standard aspect ratio tokamak

- High-field: B_0=11.5 T, I_p=10.1 MA
- Compact size: R_0=4.08 m, a=1.06 m
- Standard aspect ratio: R_0/a=3.85
- ICRF heated: <25 MW
- CS-pulsed: 15-minute flattop
- Conservative physics: $H_{98,y2}$=1.0, $\beta\beta_N$=1.7, f_G=0.85
- High-power: Q=50, P_{fus}=1 GW, P_e=0.4 GW
- Tungsten first-wall
- Demountable HTS magnets
- Liquid immersion FLiBe molten salt blanket



High magnetic field enables smaller machines

- 170+ tokamaks gives solid physics foundation for prediction of machine performance
- Field and size are major design levers for increasing Q
- Low-temperature superconductors were limited in magnetic field, result in large machines
- Copper was the only option to go to high field, with many high-Q machines designed, until now…



Other device data from [Parker et al. 1985, 1988; Hutchinson 1989; Neilson 1992; Coppi et al. 1999, 2001; Keilhacker et al. 2001; Meade 2002b; Shimada et al. 2007; Sorbom et al. 2015; Federici et al. 2018]