Tokamak Energy

THE EMERGING NUCLEAR FUSION INDUSTRY

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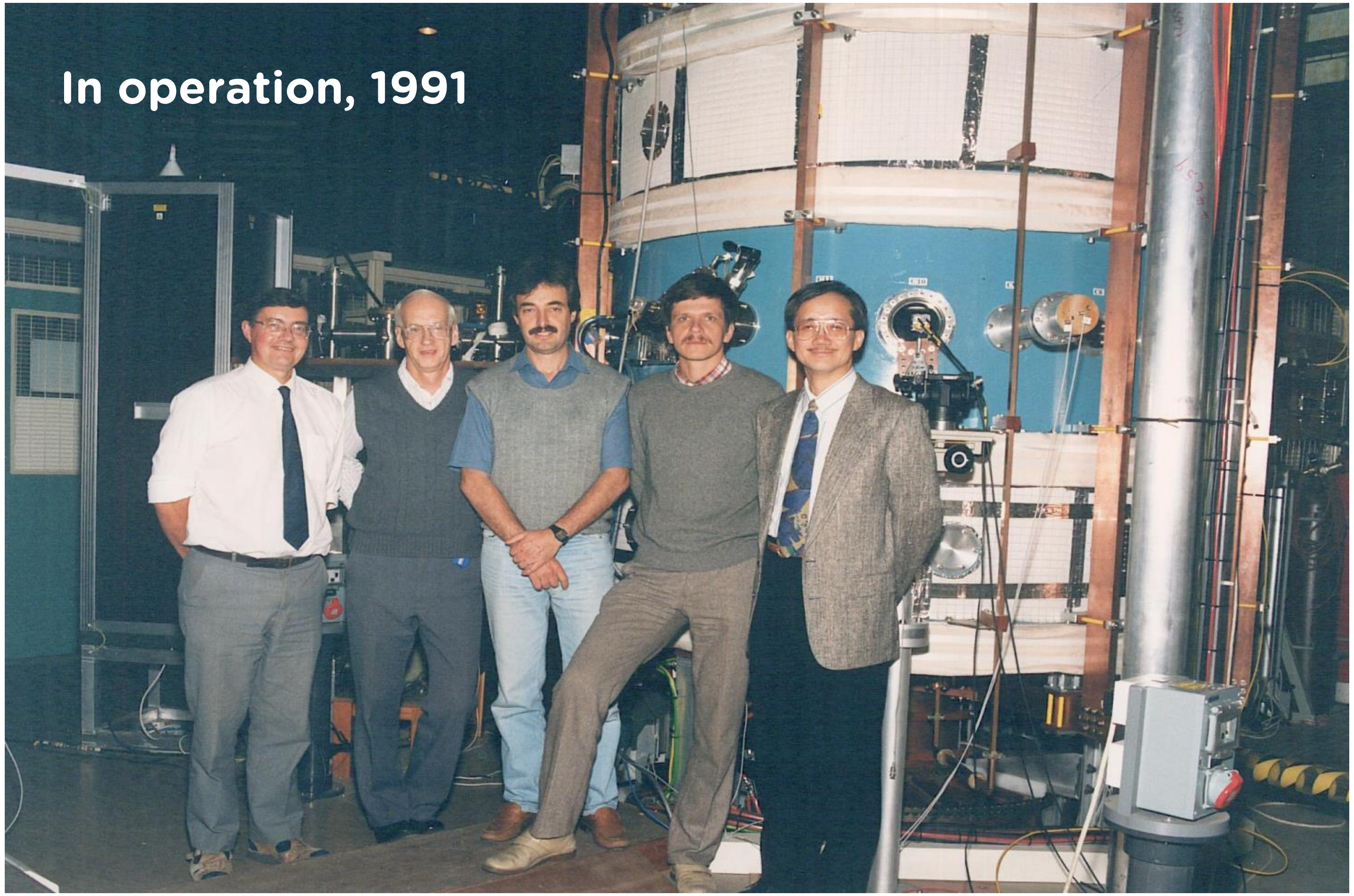
International Summer School INFIERI September 2023 Sao Paulo, Brazil

INFIERI

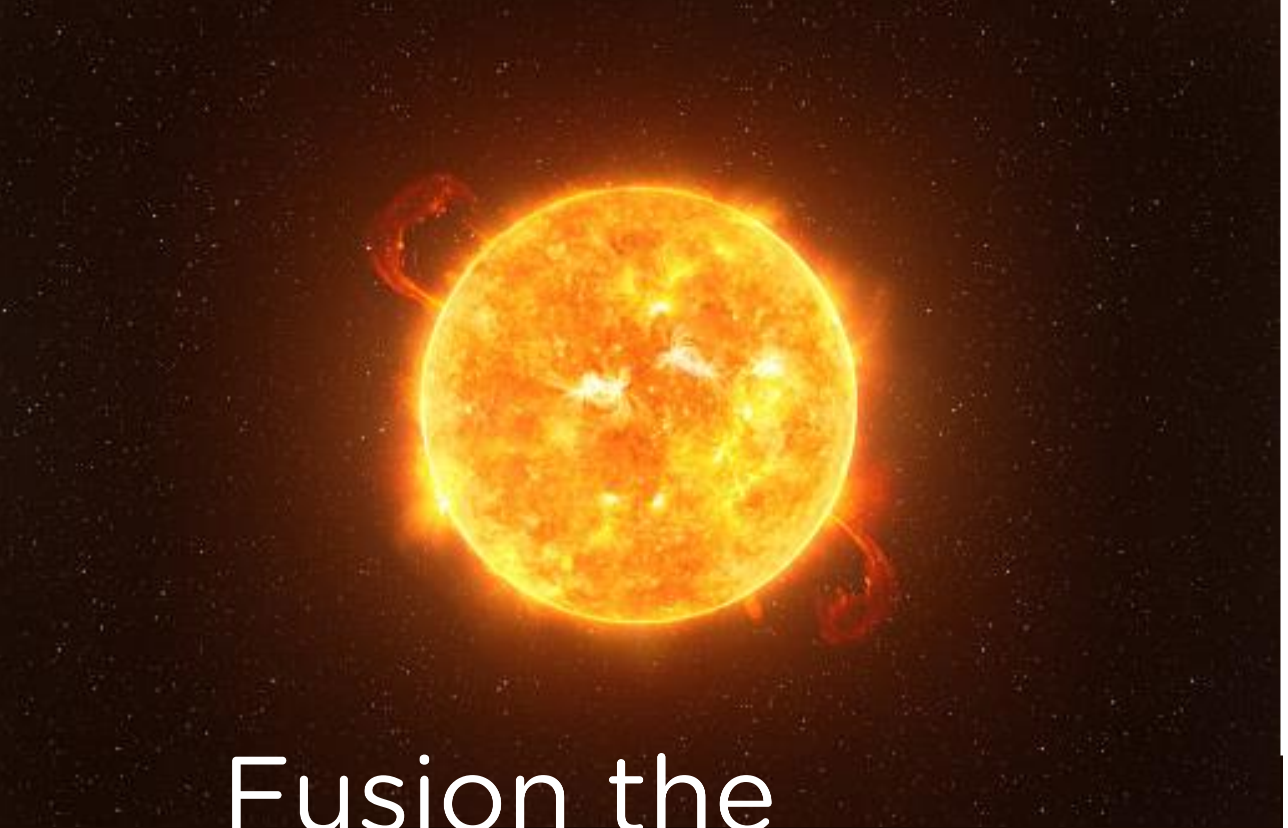
START, UKAEA (1990-1998)

START, the first tokamak to demonstrate full advantages of an ST

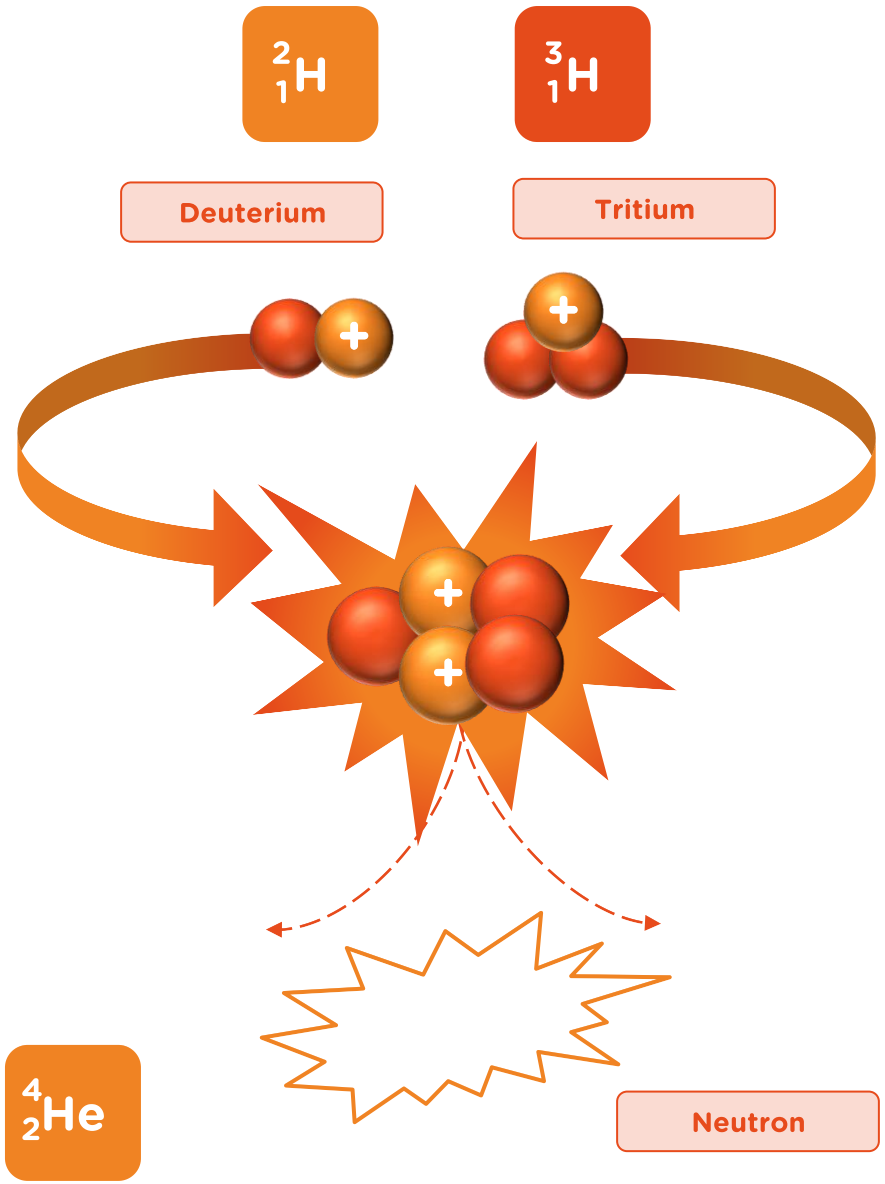


Alan Sykes   Dick Colchin   Edson Del Bosco   Mikhail Gryaznevich   Martin Peng

We hope, not!



Fusion the original source of all energy.



Carries 20% of the energy produced

Carries 80% of the energy produced

Fusion Energy – One fact

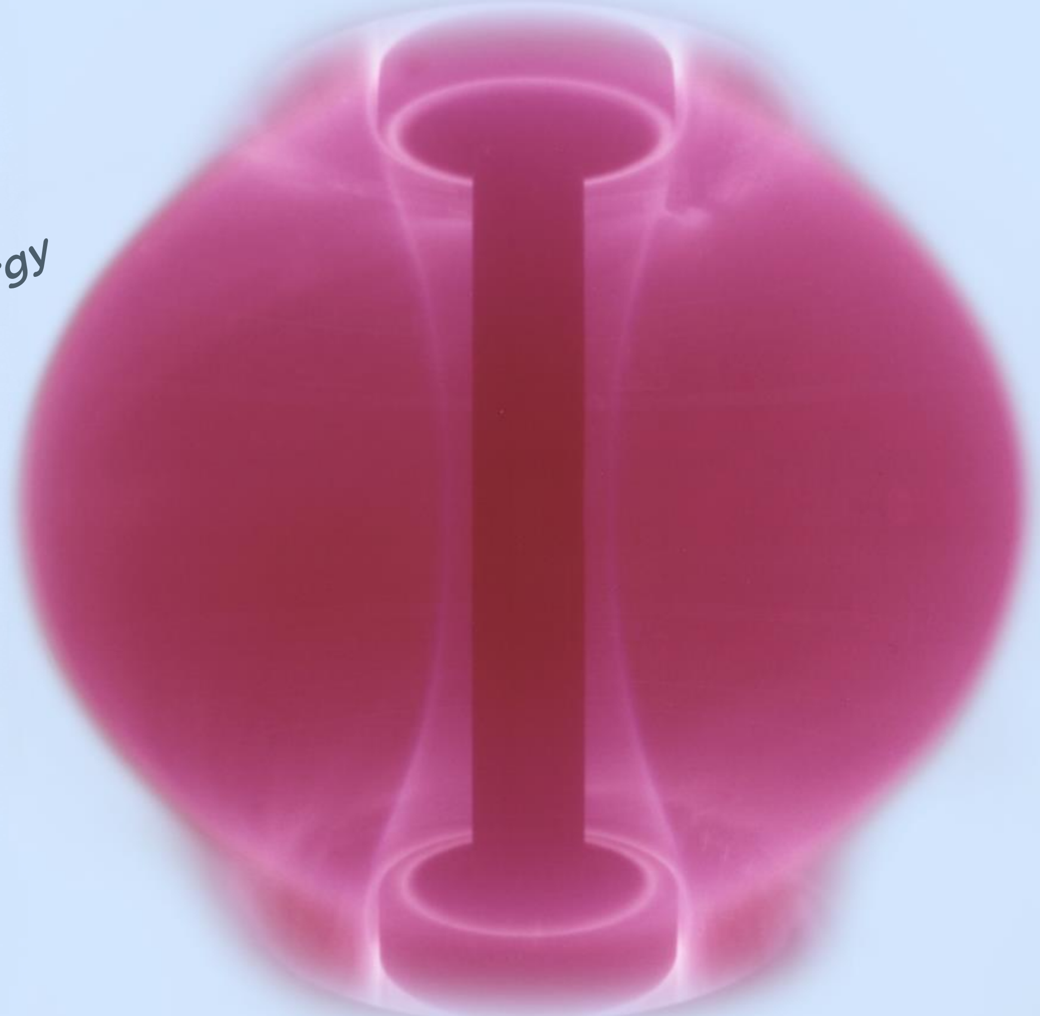
Practically limitless source fuel

One
kg fusion fuel contains as much energy as …

The Global Energy Challenge is Now. Fusion will be the Solution

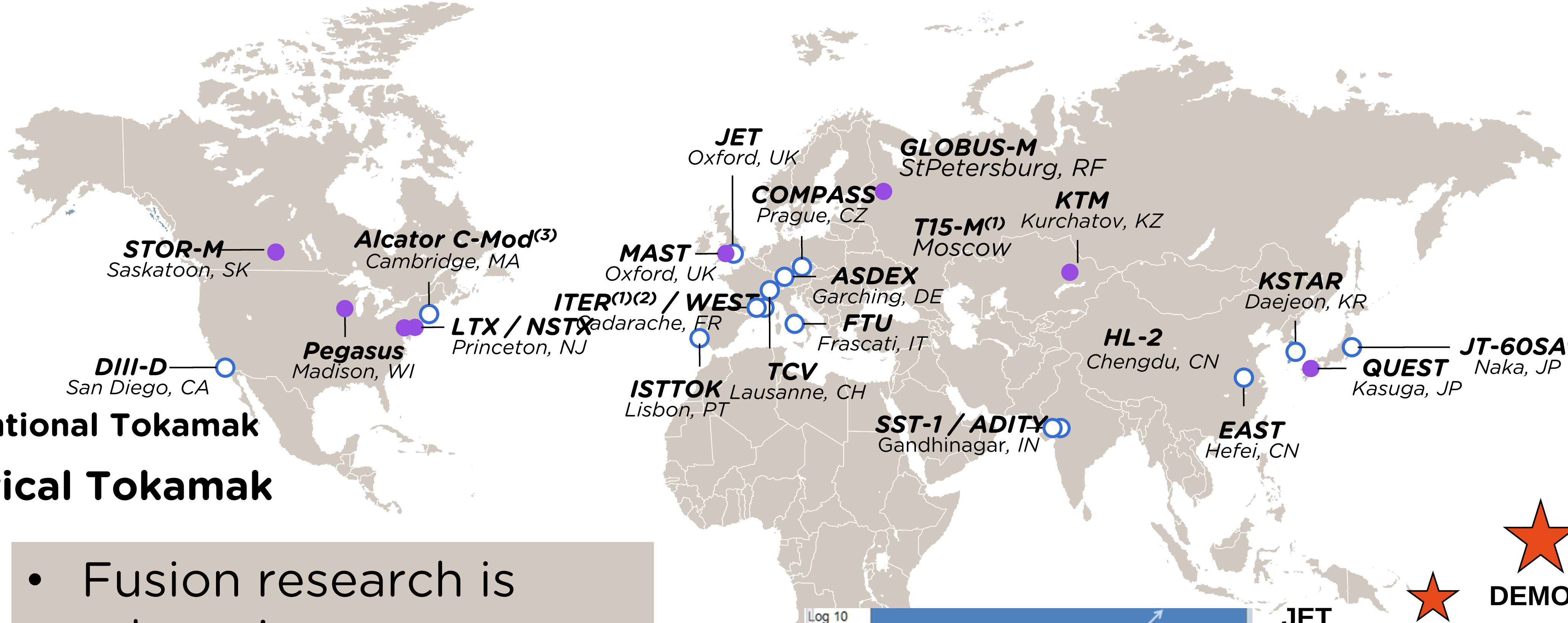
Only fusion can deliver clean, dispatchable energy that is cost-efficient and widely deployable.

	Zero CO_2	Cost-Competitive	Deployable	Dispatchable	Thermal Energy	Secure Energy
Fusion	✓	✓	✓	✓	✓	✓
Renewables	✓	◔	✗	✗	✗	◔
Fossil Fuels	✗	✓	✗	✓	✓	✗
Fission	✓	◔	✗	✓	✓	✗



Plasma inside a spherical tokamak

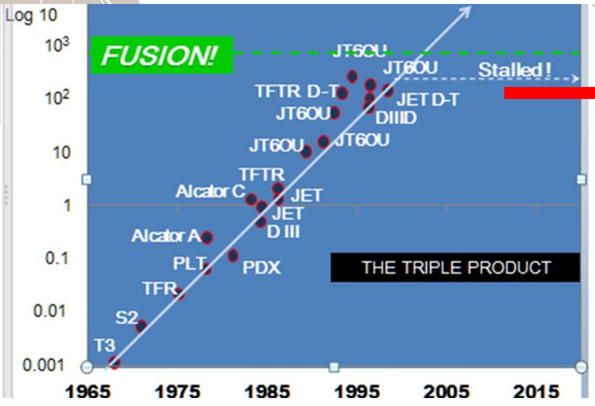
Fusion Research – Public Tokamaks

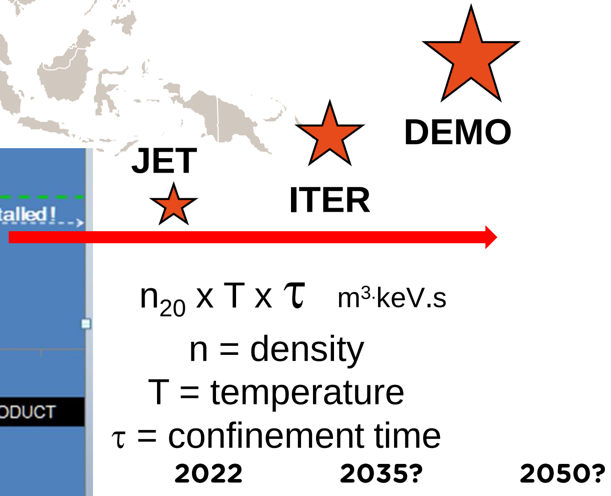


○ **Conventional Tokamak**

● **Spherical Tokamak**

- Fusion research is advancing
- However, progress towards Fusion Power is constrained





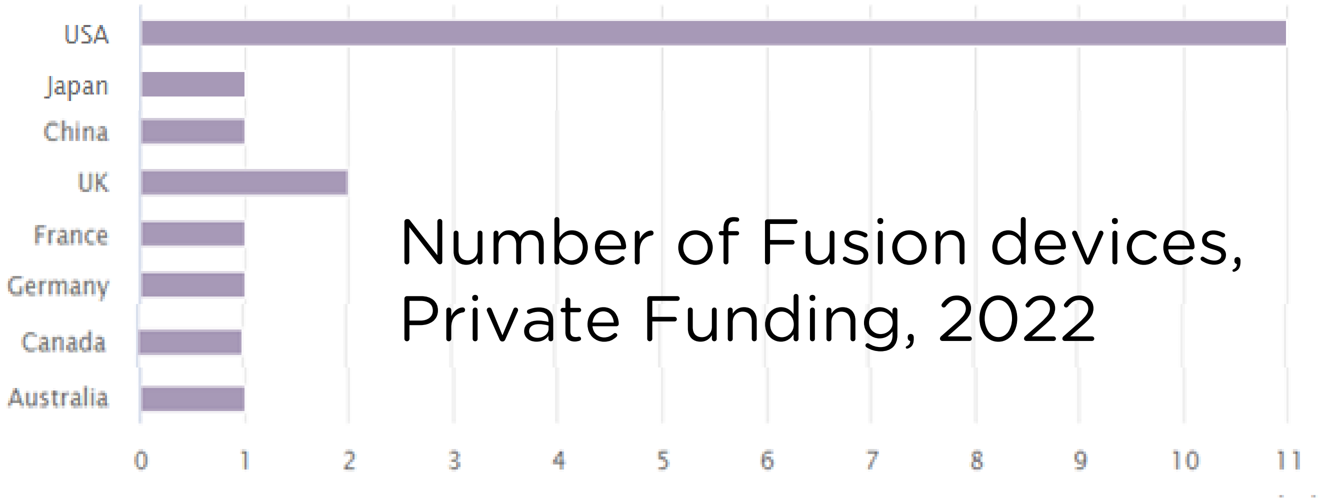
n_{20} x T x τ m^3·keV.s

n = density

T = temperature

τ = confinement time

Fusion Development – Private Funding



Total Private Funding exceeds 4.7B USD

- Common goal of privately and publicly funded Fusion research is to develop Fusion science, technologies and **Fusion Industry**

Private Fusion Competitive Landscape -The emergence of the Fusion Industry

https://www.fusionindustryassociation.org/

Private Fusion Competitive Landscape -The emergence of the Fusion Industry

*There is a nascent fusion industry**

- There are many companies, the list is growing
- They are optimizing for things beyond physics
  - Indicators about the fusion value proposition
- They can be extremely capable organizations
  - Move faster than gov't programs
  - Tight focus on deliverables and milestones
  - With less $ (now) and different resources than gov't
  - High-growth potential
- They are serious and thoughtful

*Private companies investing significantly in fusion R&D, not just performing gov. research.

CFS

Tokamak Energy
a faster way to fusion

tae TECHNOLOGIES

PHOENIX NUCLEAR LABS

LOCKHEED MARTIN SKUNK WORKS 70

generalfusion

HYPERJET FUSION CORPORATION

Helion Energy

MIFTI

Mumgaard, CEO of CFS

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.

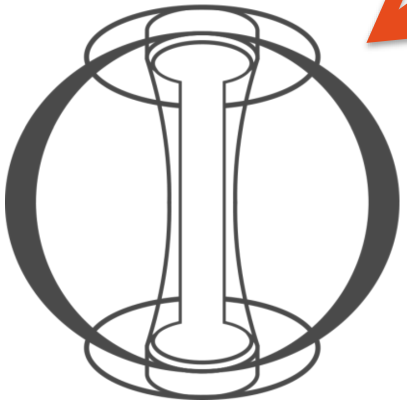
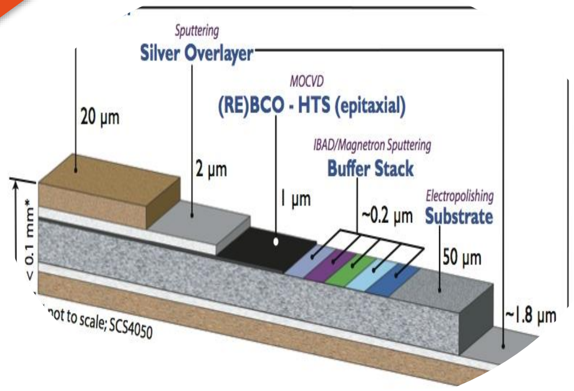
New in 21st century: Four Main Innovations:

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

Tokamak Energy

About Tokamak Energy

250 people

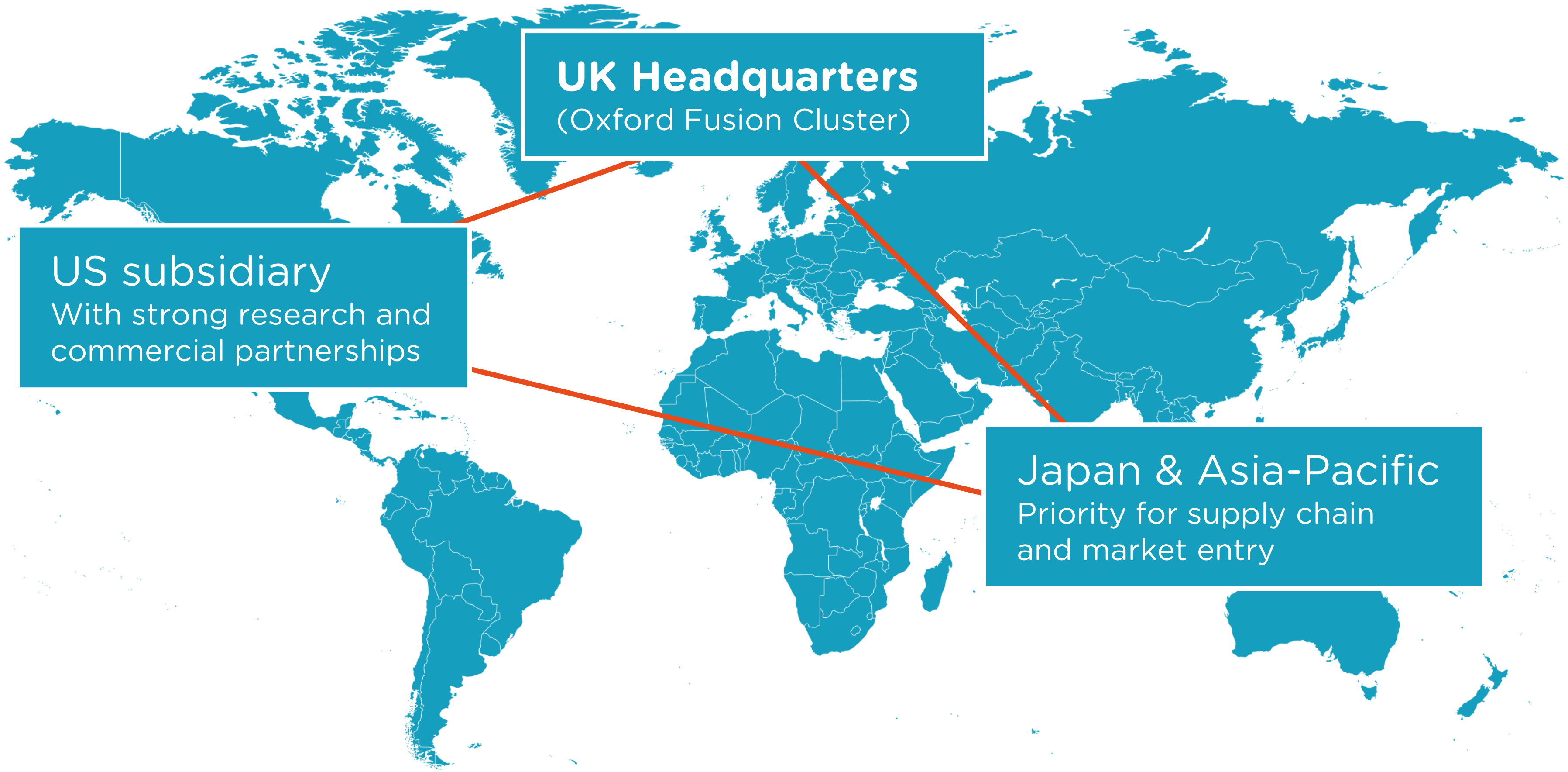
- World-class scientists, engineers and commercial specialists
- 60 PhD, 75 MSc

$250M raised to date

- Financial backing from private capital and government grants

Collaboration

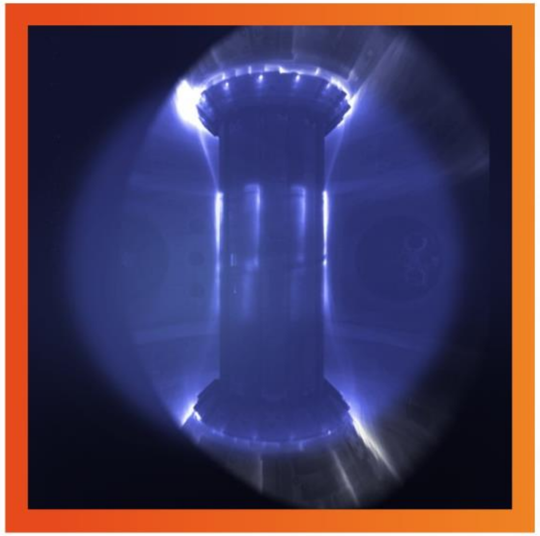
- Governments
- National laboratories
- Strategic partners



Strategic partnerships worldwide

Los Alamos National Laboratory · PPPL Princeton Plasma Physics Laboratory · Oak Ridge National Laboratory · SRNL Savannah River National Laboratory · General Atomics · ATI · UK Atomic Energy Authority · Sumitomo Corporation · 東京大学 The University of Tokyo · Furukawa Electric Group · Fujikura · Kyoto Fusioneering

The Leading Fusion Company: temperatures required for commercial fusion have been achieved!



2022
Highest plasma **'triple product'** of any private fusion company.

2022
First private fusion company to achieve **100M°C plasma** ion temperature in a tokamak.

2020
World-record **24 Tesla** field at 20 K with patented HTS magnet technology.

2017
Designed, built and operate **the world's highest-magnetic field spherical tokamak** (ST40).

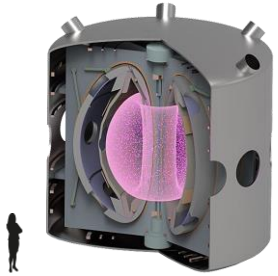
2015
First HTS tokamak sustained pulse for >24 hours (ST25 HTS).

Roadmap to commercial fusion energy

Prototype device de-risks and accelerates

Advanced Prototype Device

LATE 2020s



- Long pulse plasma
- Proves new technology
- Builds IP

Fusion Pilot Plant

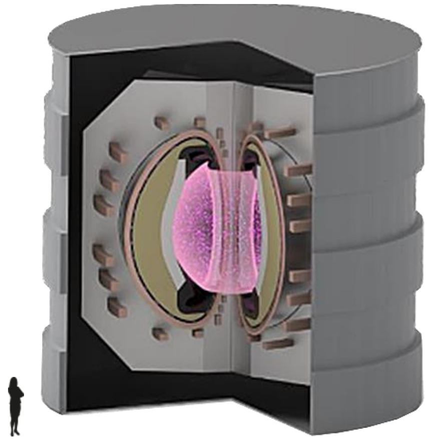
MID 2030s

- Long pulse DT operation required for commercial fusion energy

1st Gen Commercial Plant

LATE 2030s

COMMERCIAL



- Commercial fusion power plant generating 500 MWe

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Together we can make accelerate Fusion!

Our principles:

- **Collaboration** in development of Fusion Science and Technologies
- Use of **multiple compact devices** and demonstrators to validate modelling and progress at a **faster pace** and **lower financial risk**
- Strong focus on **industrial 'deliverability'** and **cost** of the commercial device
- Our approach has **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.

ST Path to Fusion, why High field ST?

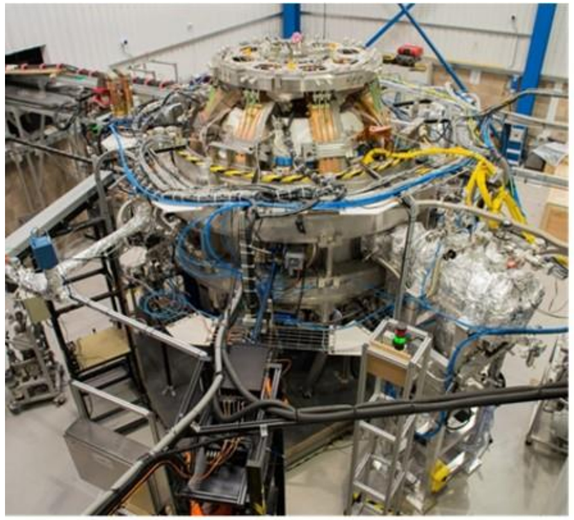
Fusion power	Efficiency	Field strengh	Volume

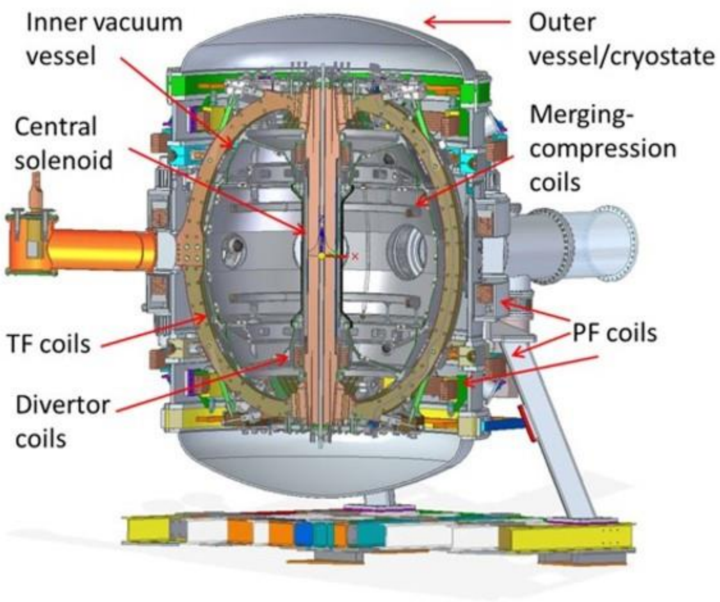
$$P \sim \beta^2 \times B_t^4 \times V$$

- Increase in beta in STs allows significant reduction in plasma volume

- Engineering of **high field** in ST is a real challenge! Physics is good.

ST40: Expanding the high field ST physics basis





- B_t =3T (2.3T now), I_p =2MA (0.8MA), R_0 =0.4-0.6m, R/a=1.6-1.8, κ=2.5
- Plasma formation - merging-compression
- 2 – 4 MW auxiliary heating(2 NBI now + ECRH 2024)
- Pellet Injector for fuelling (2024)
- Pulse duration 1s @ 3T, small solenoid, 0.2 – 0.3 volt-seconds, so need efficient bootstrap current (high in STs)

From “toys” to Reactor

PLT

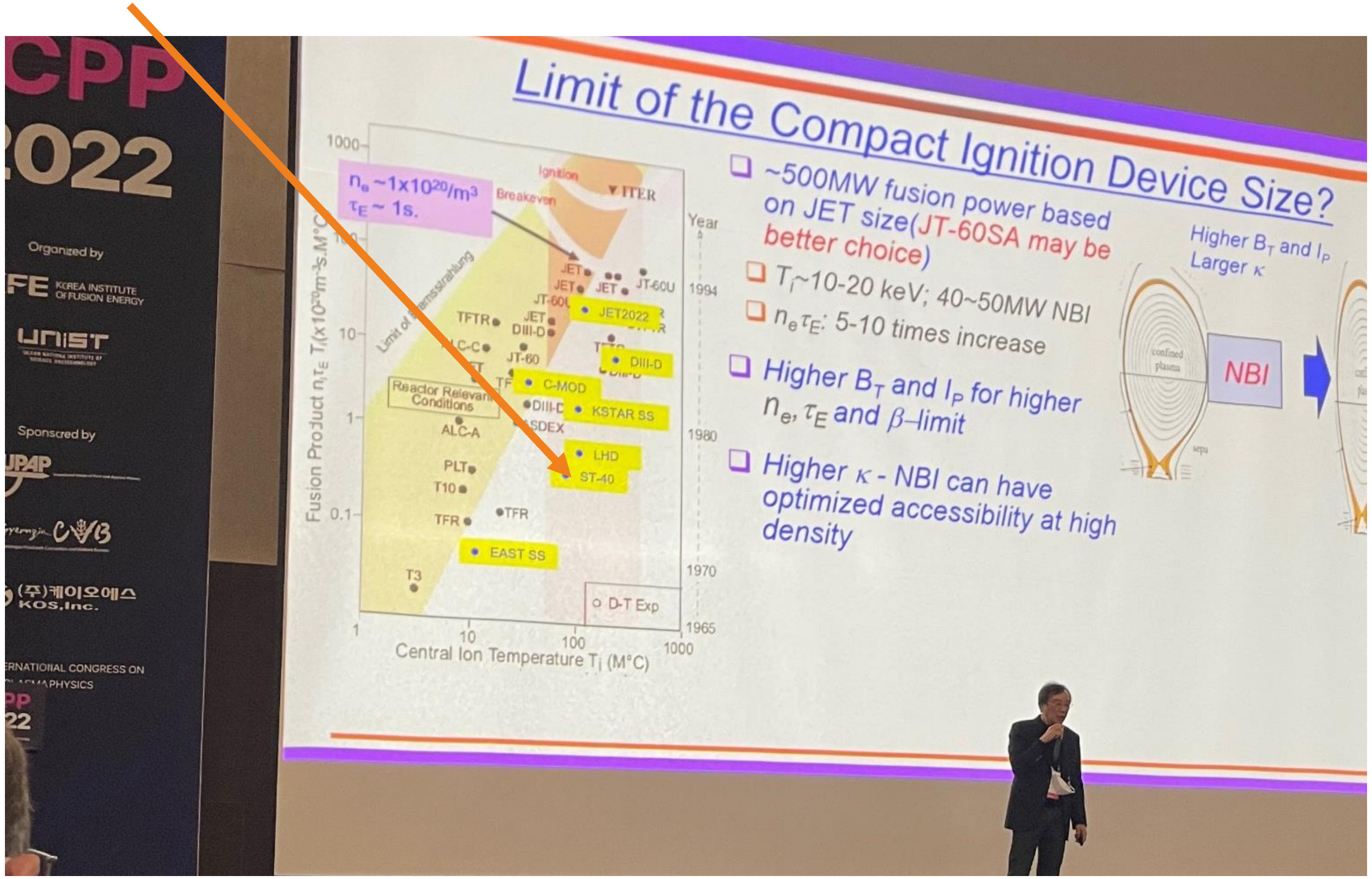
1978

In July, PLT sets a world record for ion temperatures of 60 million degrees C using neutral-beam heating. For the first time, ion temperatures exceed the theoretical threshold for ignition in a tokamak device.

In 2021, ST40: 1m^3, 10 keV (100M ^{o}C)

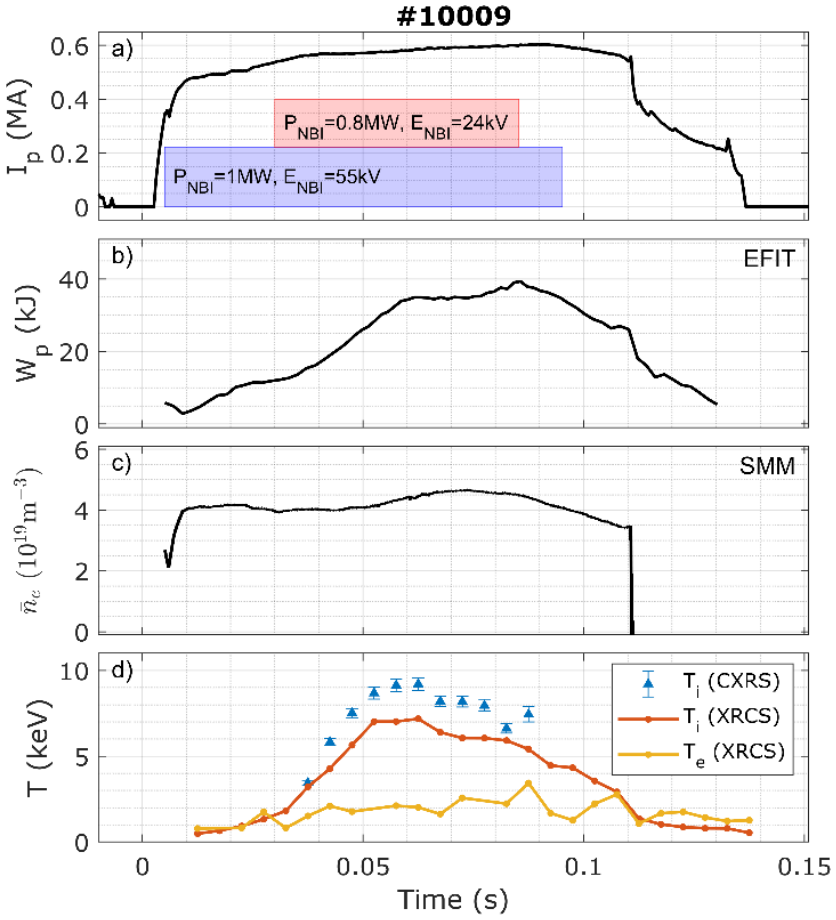
From "toys" to Reactor

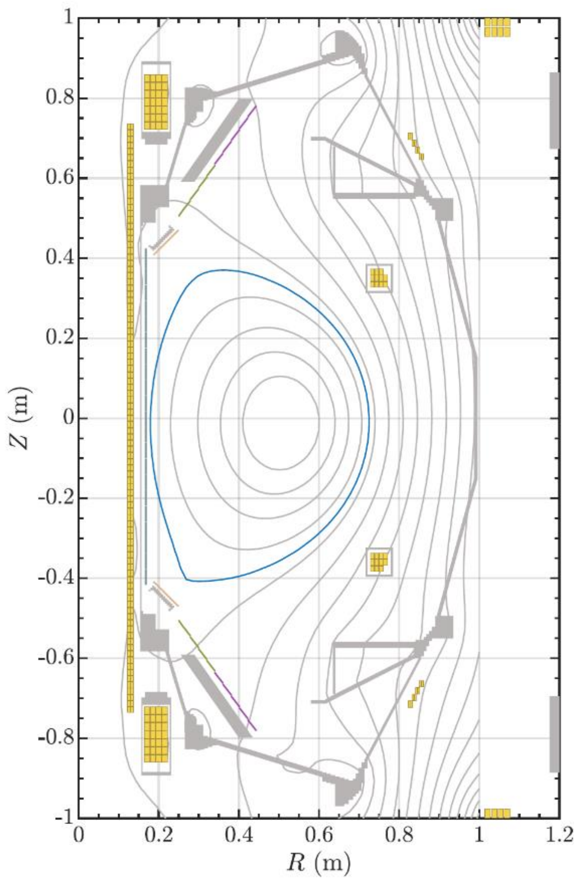
ST40: 1m^3, 10 keV

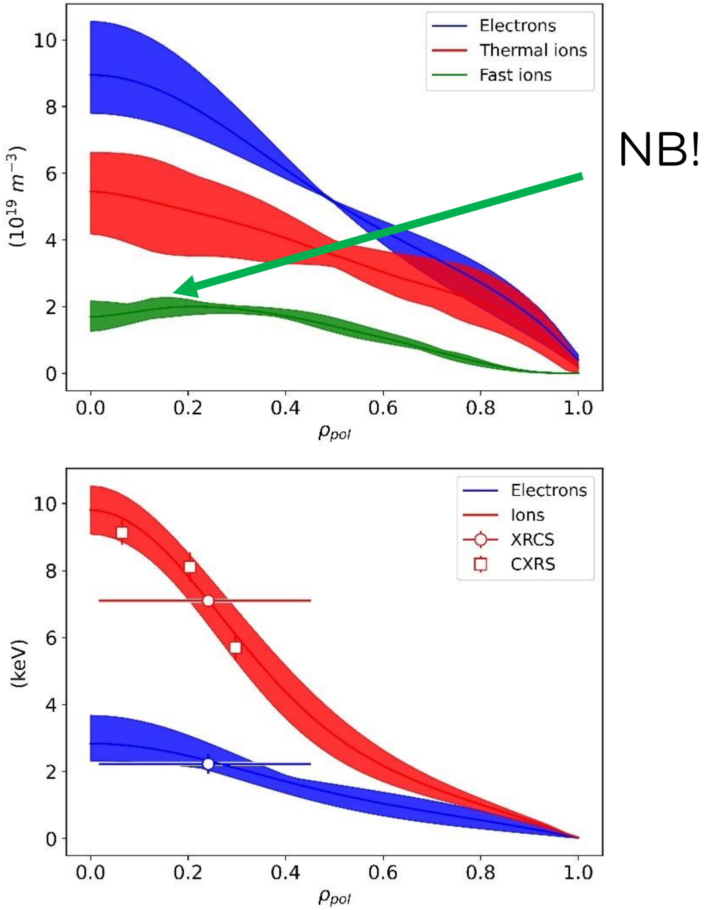


- **ICPP 2022: Compact** Ignition device size: ***ST40***: 1m^3, 10 keV. ***Cmod*** 1m^3 8 keV, record pressure in a tokamak, vs ***JET*** – 80 m^3.

Achievement of ion temperatures in 10 keV range in **Hot Ion mode** with **high fast ion fraction**







Typical waveforms and EFIT reconstruction for #10009, D-D, double null divertor

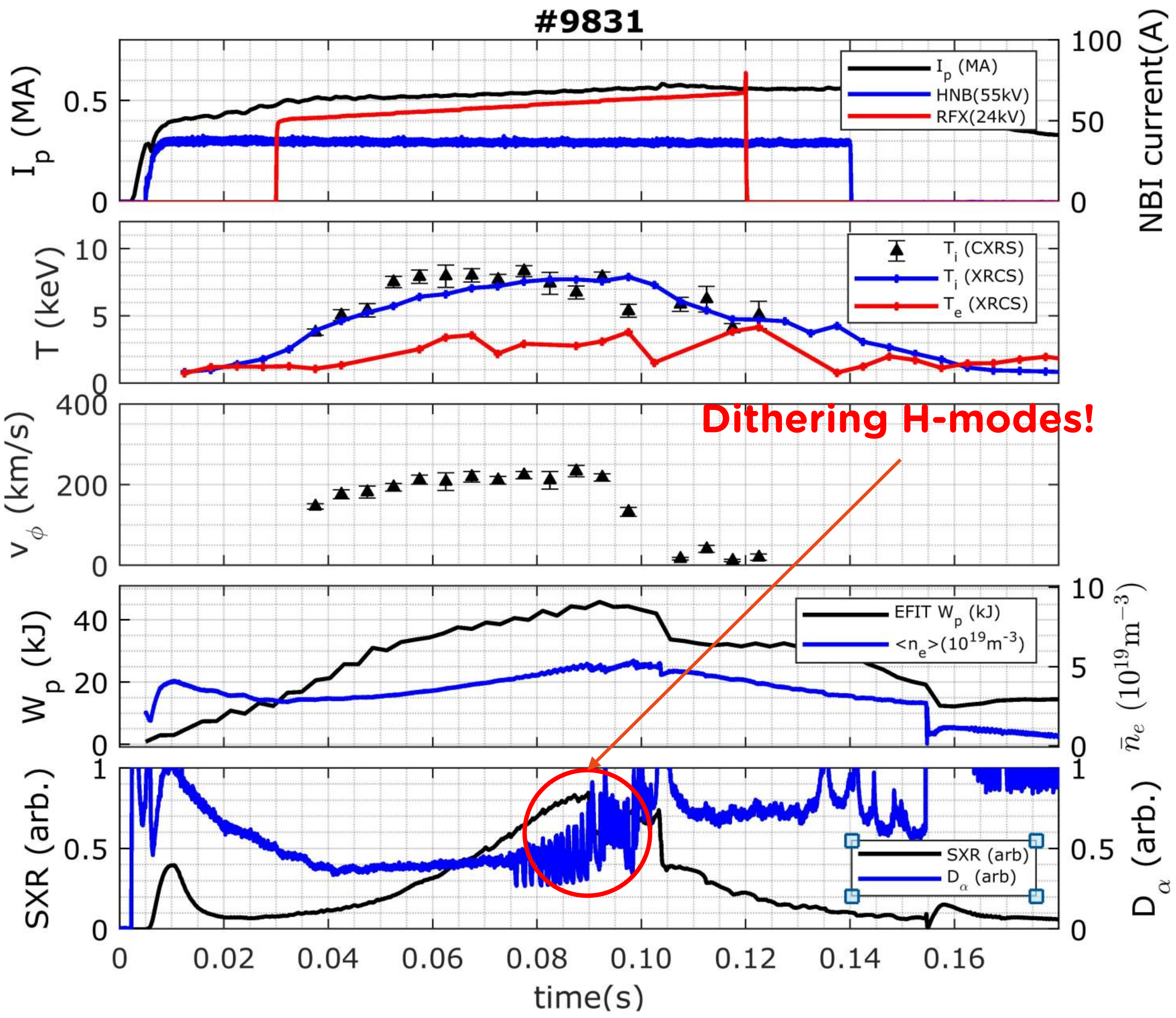
(top) electron density, ion and fast particle densities, (bot) ion and electron temperature determined using the integrated analysis approach for pulse #10009 at time of maximum ion temperature

$D^0 \Rightarrow D^+$: High temperatures and dithering H-modes

- If target density raised slightly, dithering H-modes observed.
- T_i sustained at ~8keV until 90ms and does not decrease in H-mode
- Density is slightly above the minimum value for H-mode[1] from multi-machine database[2] :

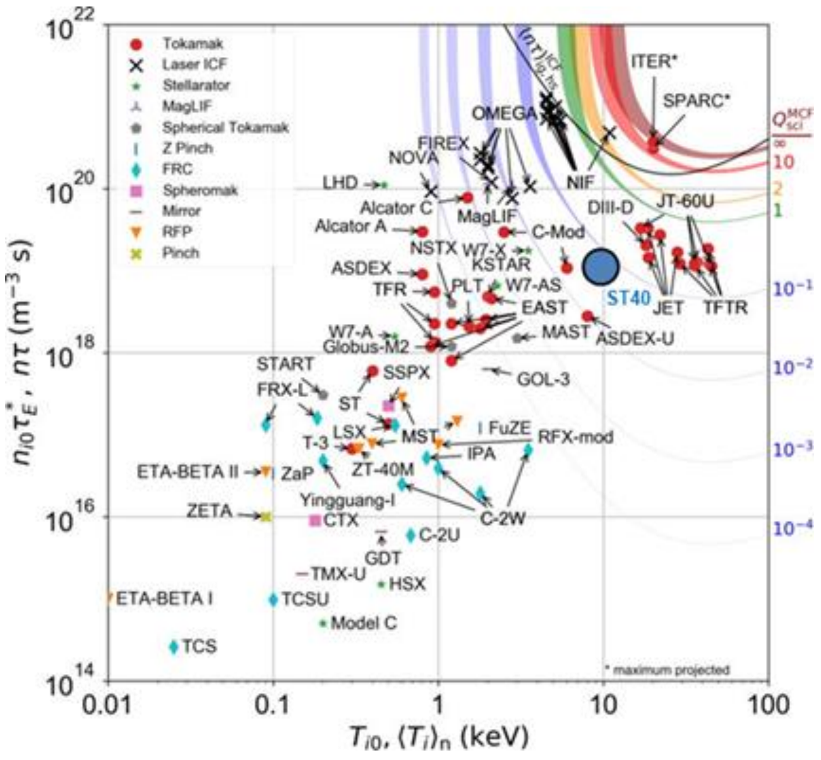
$$n_{e,min}^{scal} = I_p^{0.34} B_T^{0.62} a^{-0.95} (R/a)^{0.4}$$

- *More results presented at International Fusion Conferences 2022 - 2023*

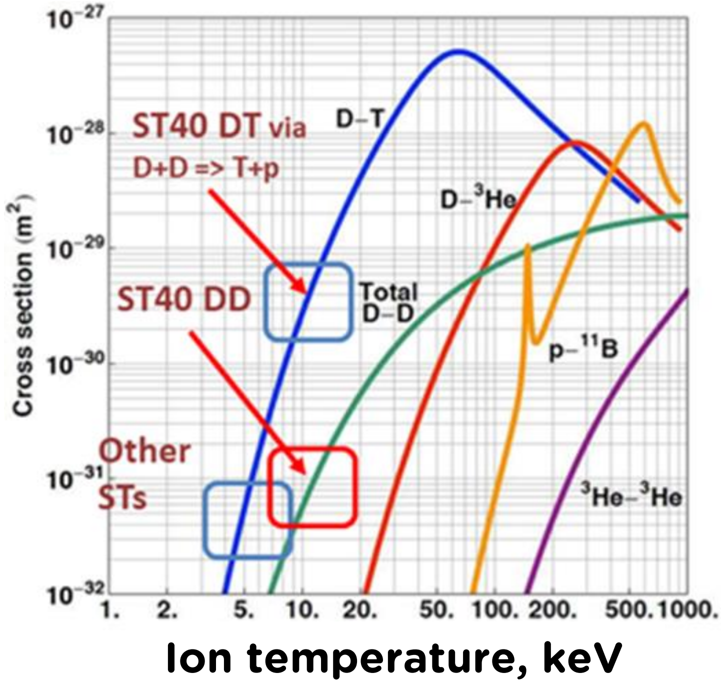


[1] *Y. Andrews et al., Phil. Trans. A, DOI:10.1098/rsta.2021.0225.R2*
[2] *F. Ryter et al.., Nucl. Fus.,**54** 083003*

New challenges for ST research: close to burning plasma conditions



Triple product vs plasma temperature for the number of tokamaks, stellarators, other magnetic fusion devices and inertial fusion.



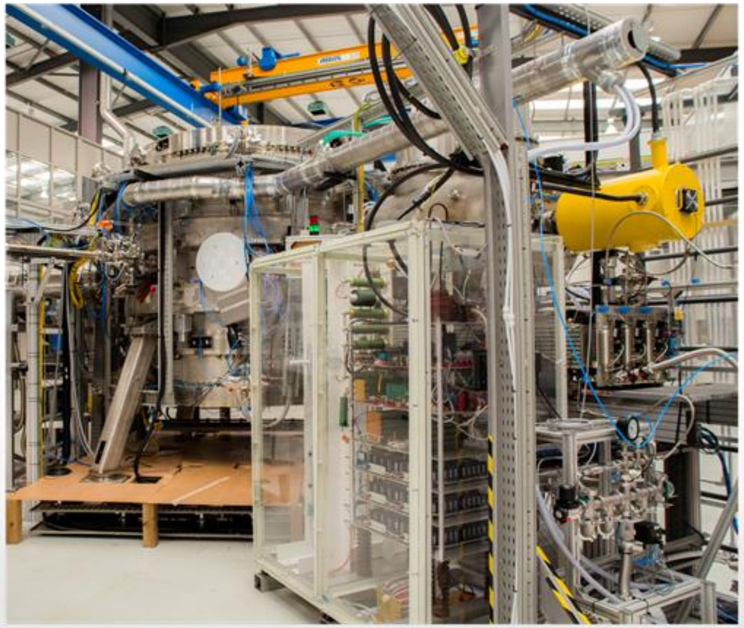
- All previous STs operated at T_i < 5 keV, with DT and DD cross-sections 1 – 2 orders lower than at 10 keV.
- Although ST40 operates without tritium fuelling, high T_i boosts the **secondary D-D reaction** that produces T, and at ~ 10 keV the cross-section of D-T reaction is high enough to contribute to the Fusion production, upper blue box.

Conclusions

• Demonstration of burning plasma in a compact high-field ST is the current challenge for Fusion and results from ST40 show Fusion relevant performance in a high field compact ST

• The ST path to commercial application of Fusion can start from Compact ST with R as low as 0.4 m

• 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. Innovations can make Fusion sooner and cheaper



• **ST40** is the first high field Spherical Tokamak

Tokamak Energy

Thank you

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