# Merging/ Reconnection Heating for Direct Access to Fusion Reaction

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The fusion reactors can maintain its reaction, once its DT plasmas with $n\tau > 10^{14}$ is heated over 10keV.

A key is how we can increase $T_i$ over 10keV.

Conventional Tokamaks

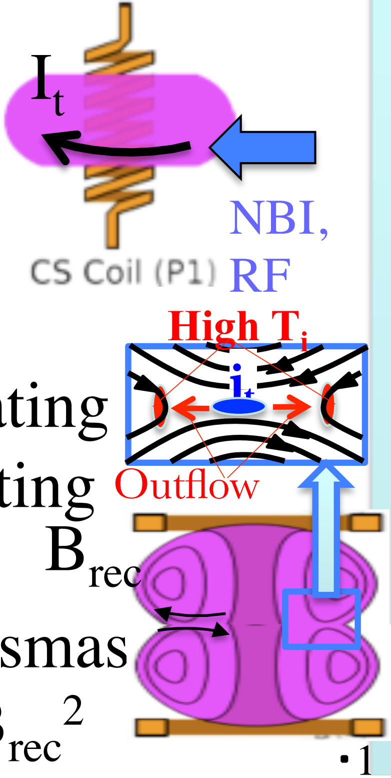
First: Ohmic heating

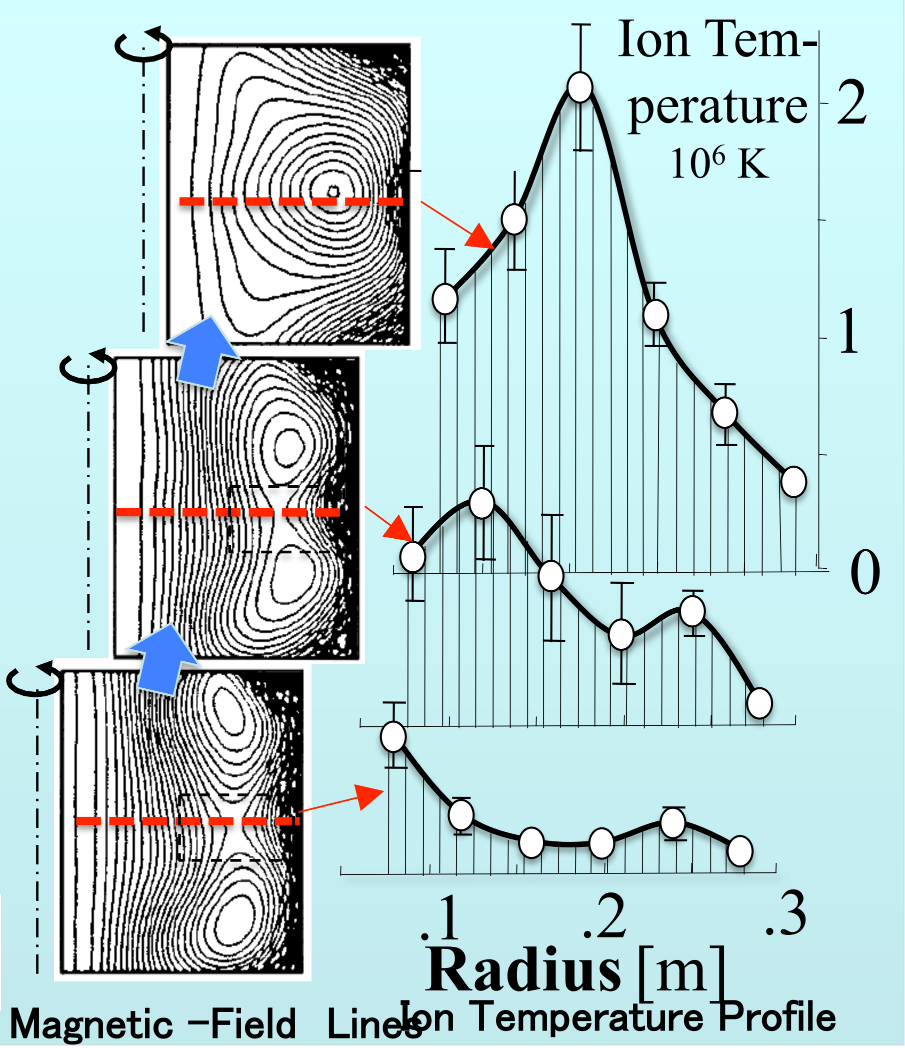
$$W = \eta I_t^2 \propto T_e^{-3/2} I_t^2$$

+Second: Additional Heating

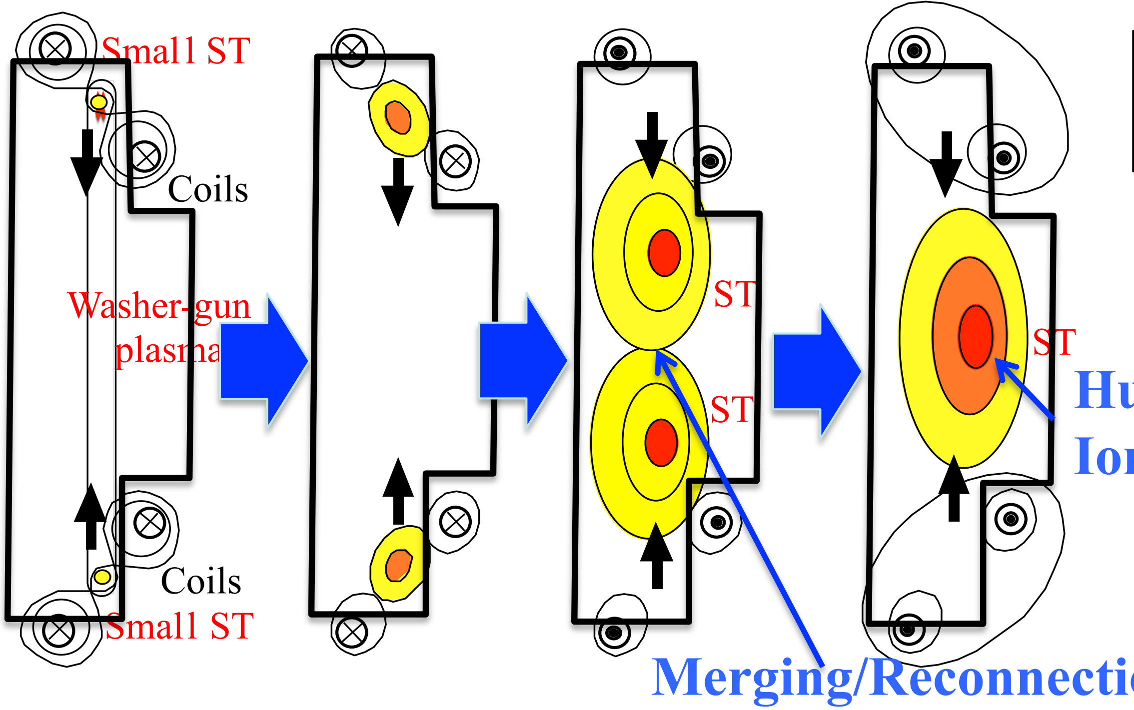
NBI or RF heating

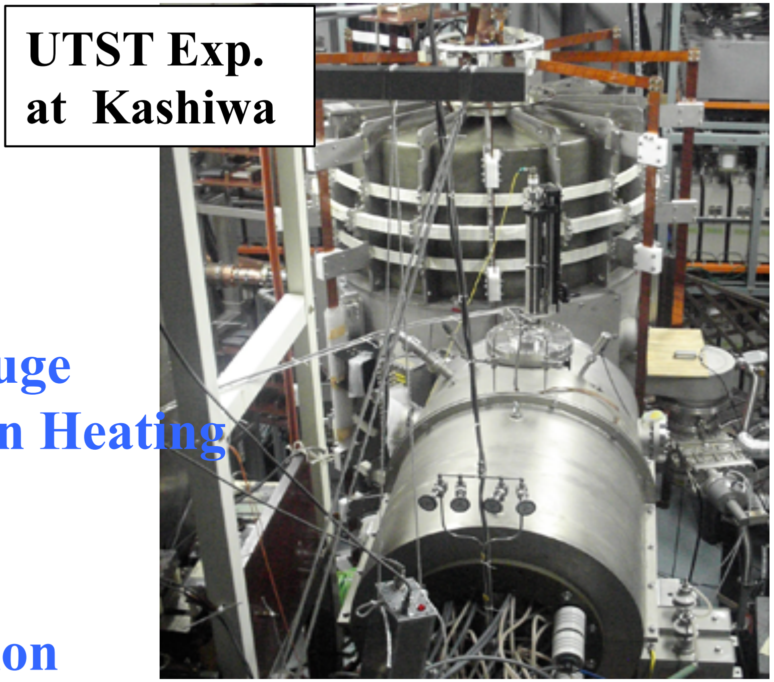
Merging of two torus plasmas can increase their $T_i \propto B_{rec}^2$

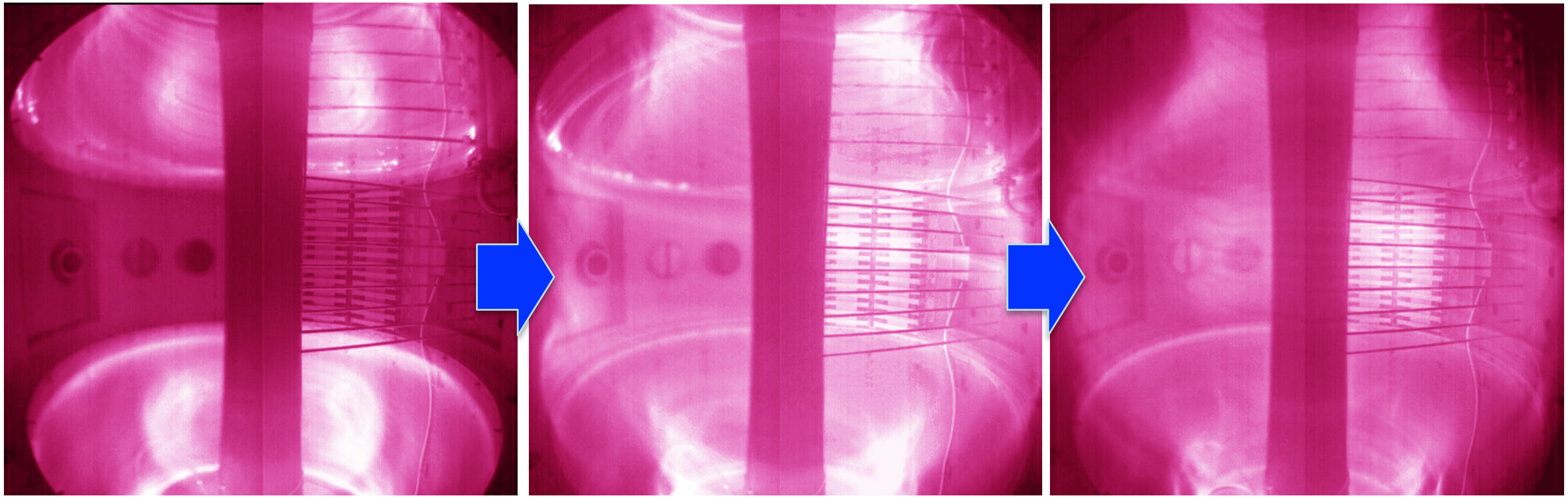




# High-Power Heating of Two Merging Spherical Tokamak (ST) Plasmas for Fusion Energy Development



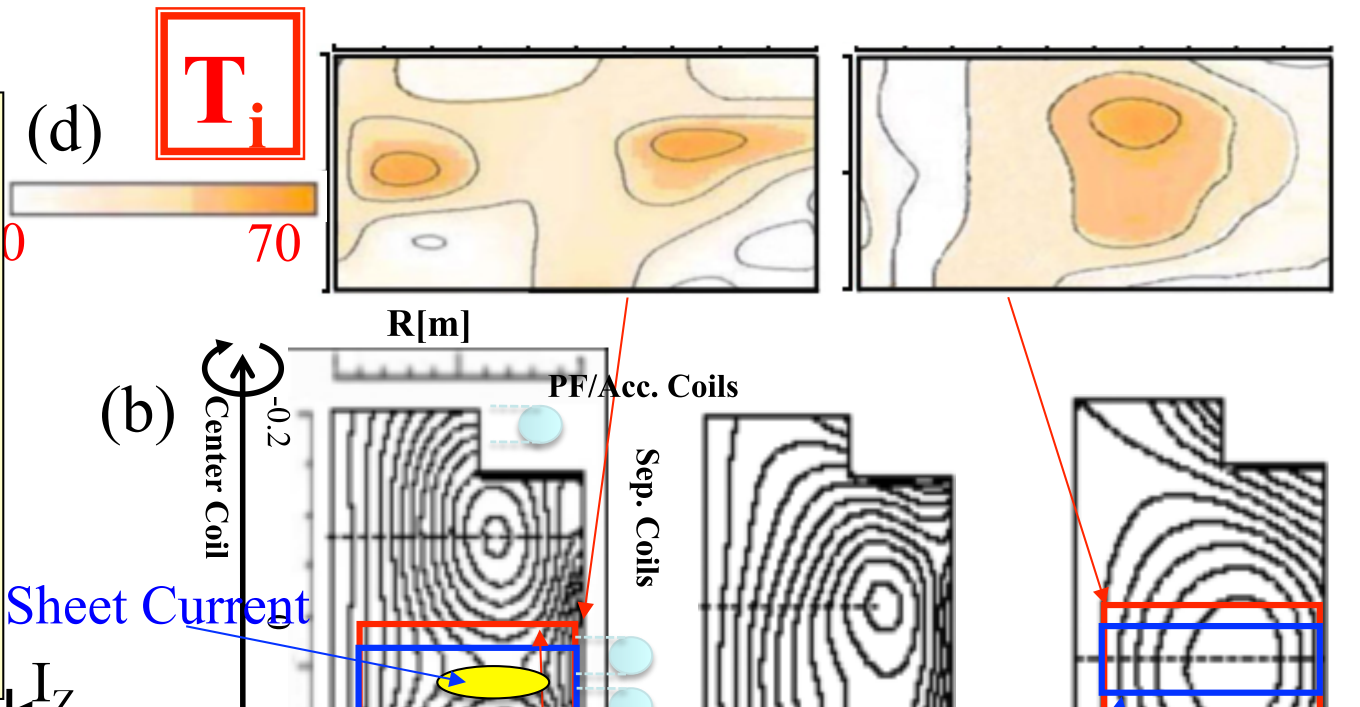


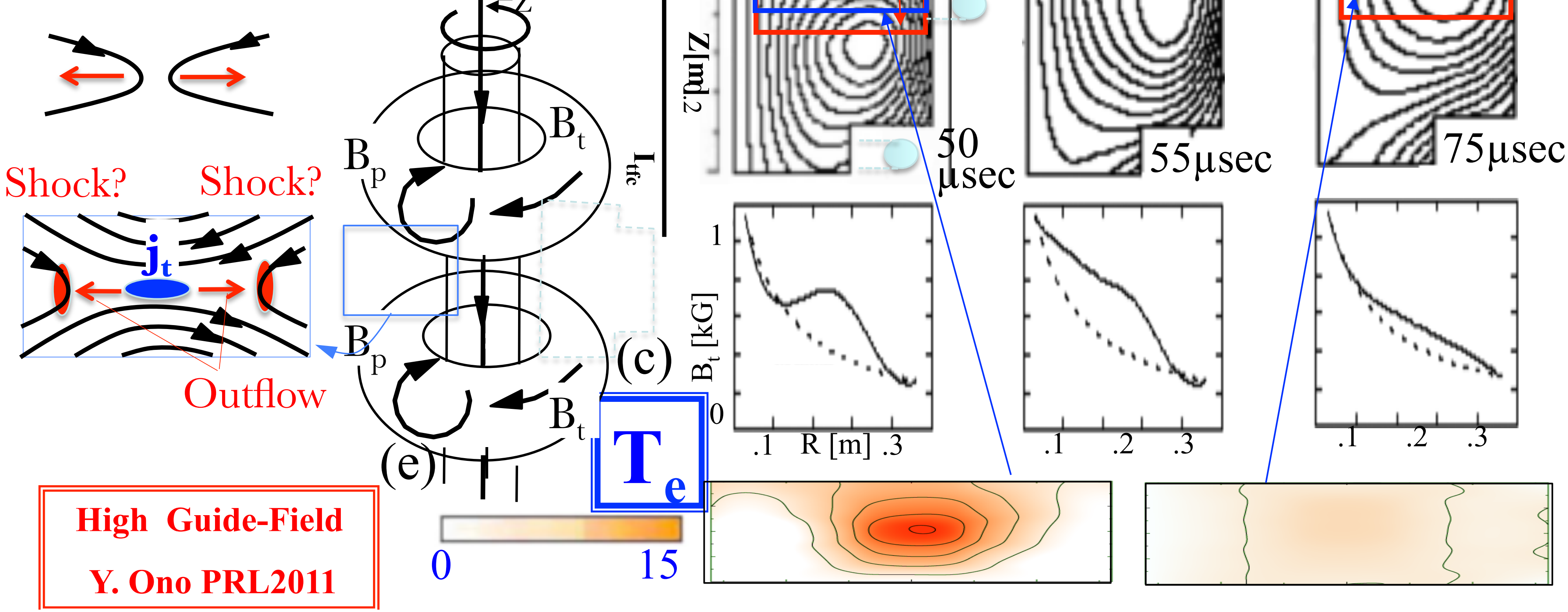


# **TS-3** (U. Tokyo)

**1) Down-stream heating of ions**
**2) X-point heating of electrons**

High power heating suppresses paramag. $B_t$, increasing plasma beta.





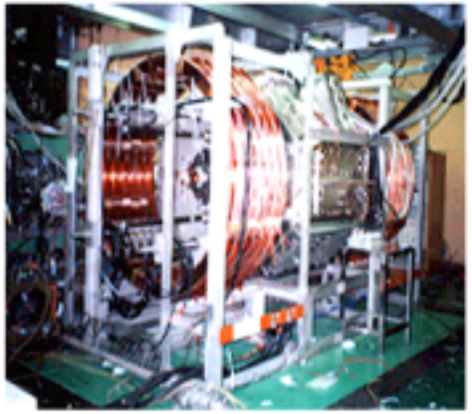
**High Guide-Field**

**Y. Ono PRL2011**

# UTokyo (‘85) & CCFE (‘90) are leading rec. heating experiments.

**1985~ TS-3,4**
**(U.Tokyo)**

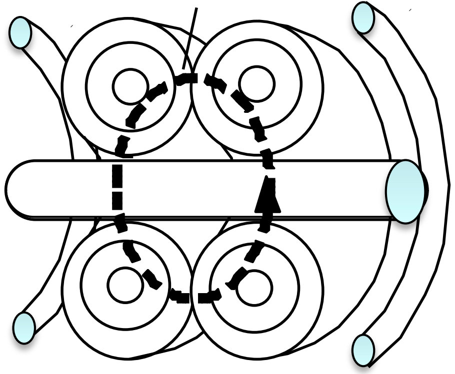
**2010~C-2**
**(Tri Alpha)**



**”Closed Current , Closed Flux”**

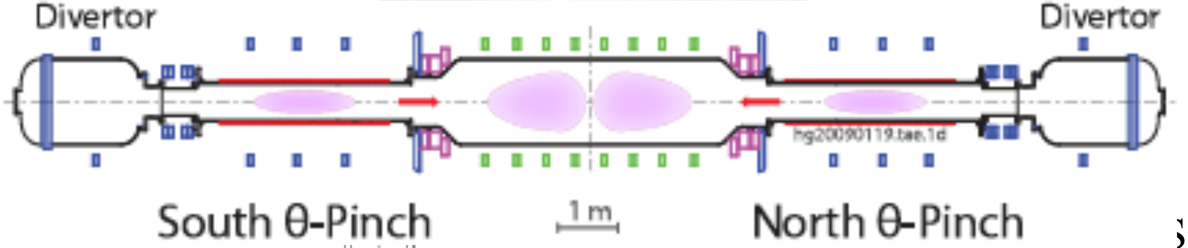
High $R_m$

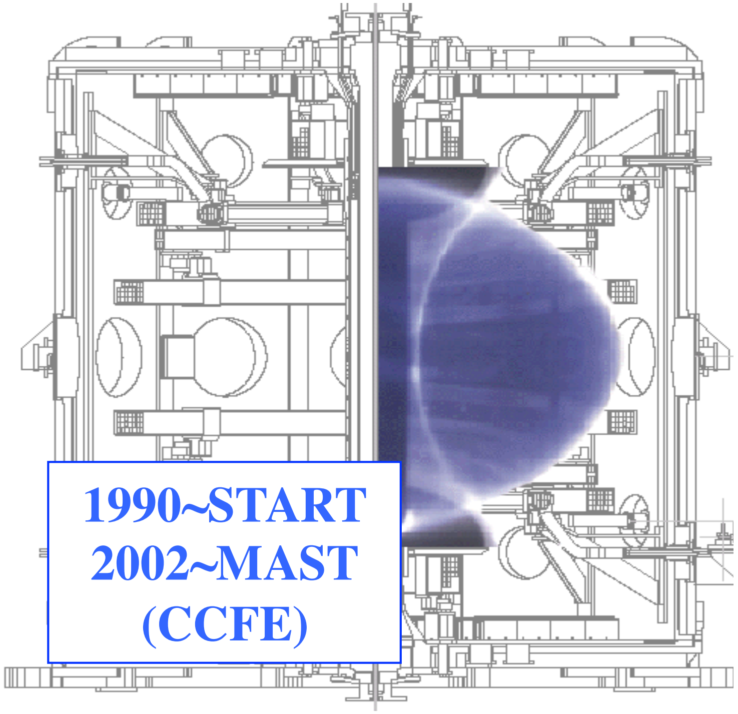
**Closed Flux**
Sheet Current



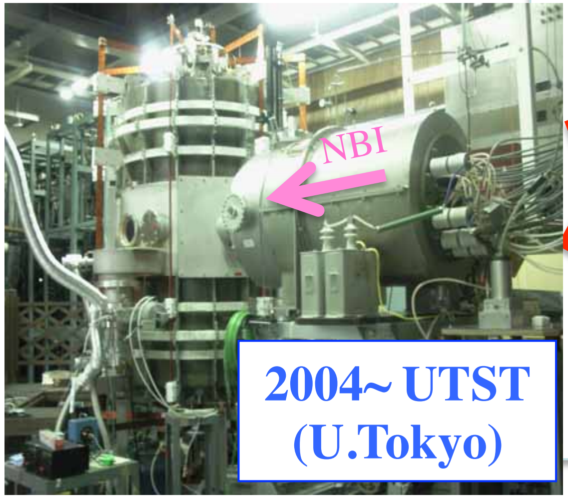
**U. Tokyo TS-3,TS-4(’86~)**

START, MAST (’90~), NASA (‘01~), Colorad FRC (‘07), Try-Alpha C-2 (‘10), Texas A





**1990~START**
**2002~MAST**
**(CCFE)**



**2004~ UTST**
**(U.Tokyo)**

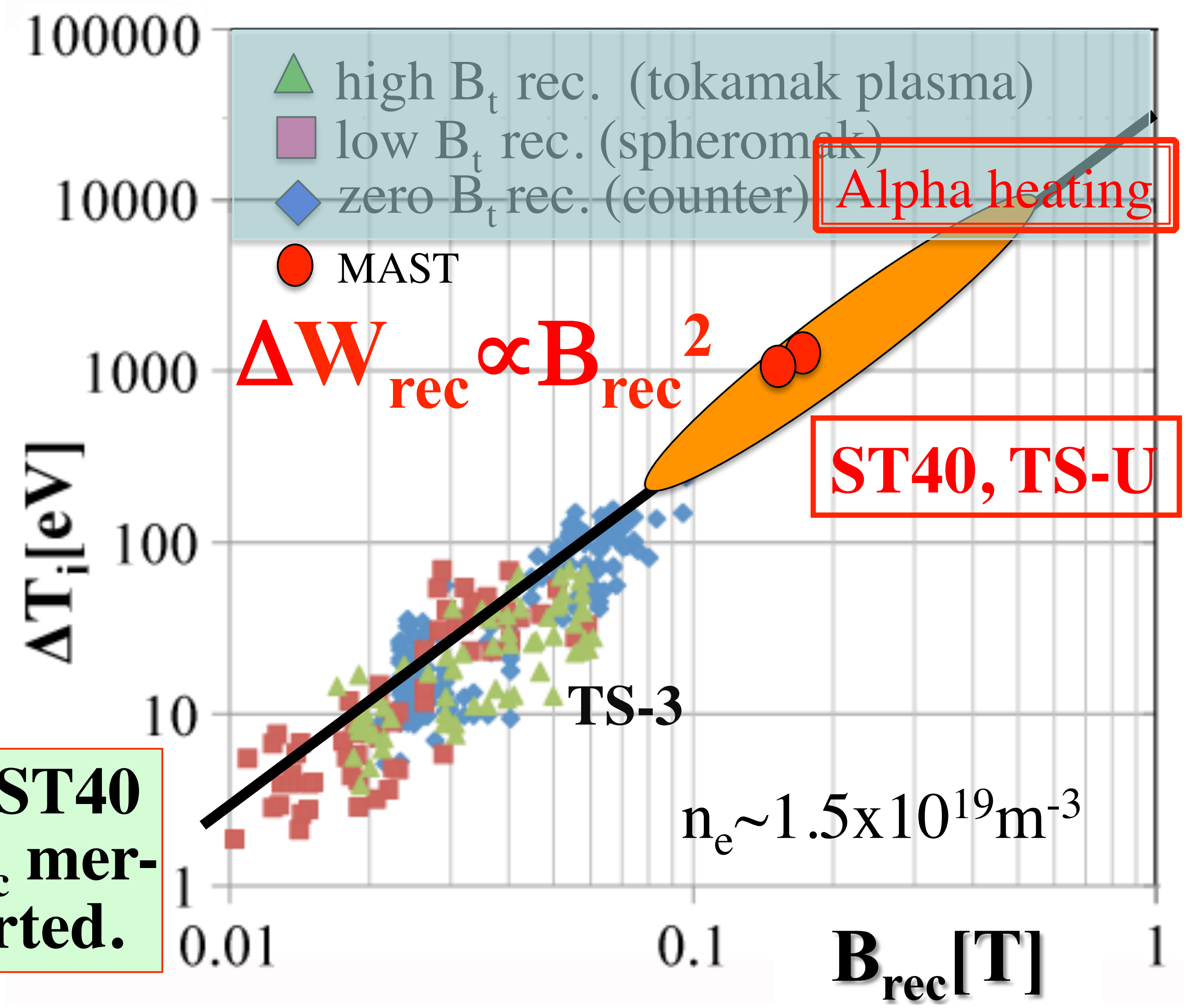
**TS-U Exp**
**(U.Tokyo)**
2016~

**ST-40 Exp.**
**(Tokamak Energy)**
2016~

# The $B_{rec}^2$-scaling of reconnection heating indicates a direct access to alpha-heating without NBI, leading us to a new high-$B_{rec}$ exps.: ST-40 & TS-U.

$\Delta W_{th} \sim \Delta W_{ion}$
$\propto \Delta(nT_i)$
$\propto \Delta T_i$
(n~normalized)
$\propto B_{rec}^2 \propto B_p^2$

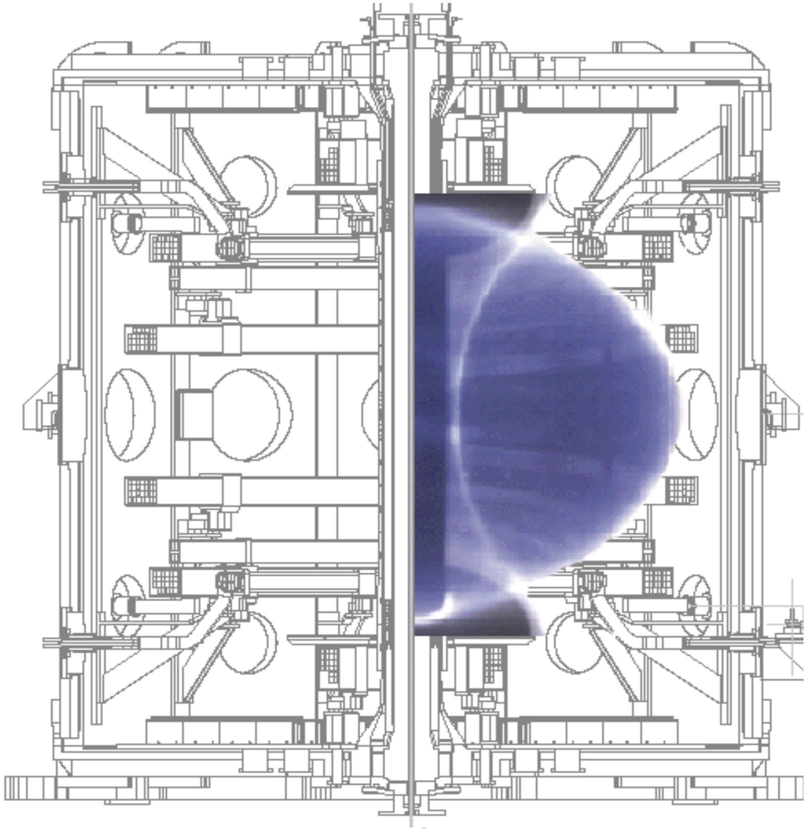
$V_{outflow} \sim$
$V_{pA} \propto B_p/n^{1/2}$



Construction of ST40 &TS-U: high-$B_{rec}$ merging devices started.

$B_{rec}^2$ **-Scaling of Rec. Heating** → **High-$B_{rec}$ Merging Exp.**

# Up-scaled Reconnection Experiment in MAST



**>$10^5$ ← $R_m$ — >$10^3$**

| | MAST | TS-4 | TS-3 |
|---|---|---|---|
| R [m] | 0.9 | 0.5 | 0.2 |
| a [m] | 0.7 | 0.4 | 0.15 |
| $I_p$ [MA] | 2 | 0.1 | 0.07 |
| $B_t$ [T] | 0.4-0.7 | 0.1 | 0.2 |
| $B_p$ [T] | 0.1-0.2 | 0.03 | 0.05 |

1D measurements of $T_i$ and $T_e$ :

1) 130ch. Thomson scattering,

2') NPA

2) 32ch Ion Doppler from UTokyo

*The MAST plasma has higher reconnecting B field than TS-3.*

⬇

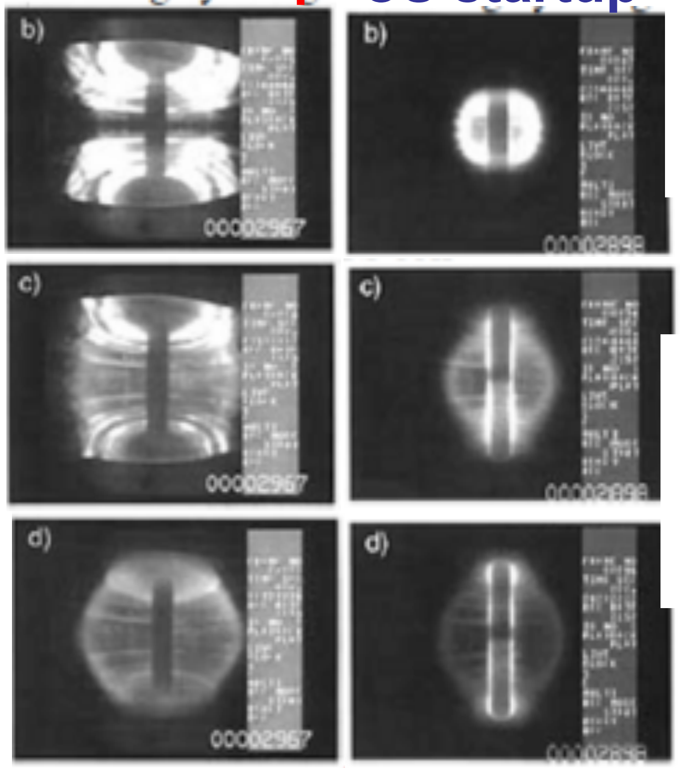
*UK-Japan Joint Experiment supervised by M. Gryaznevich and MAST team*

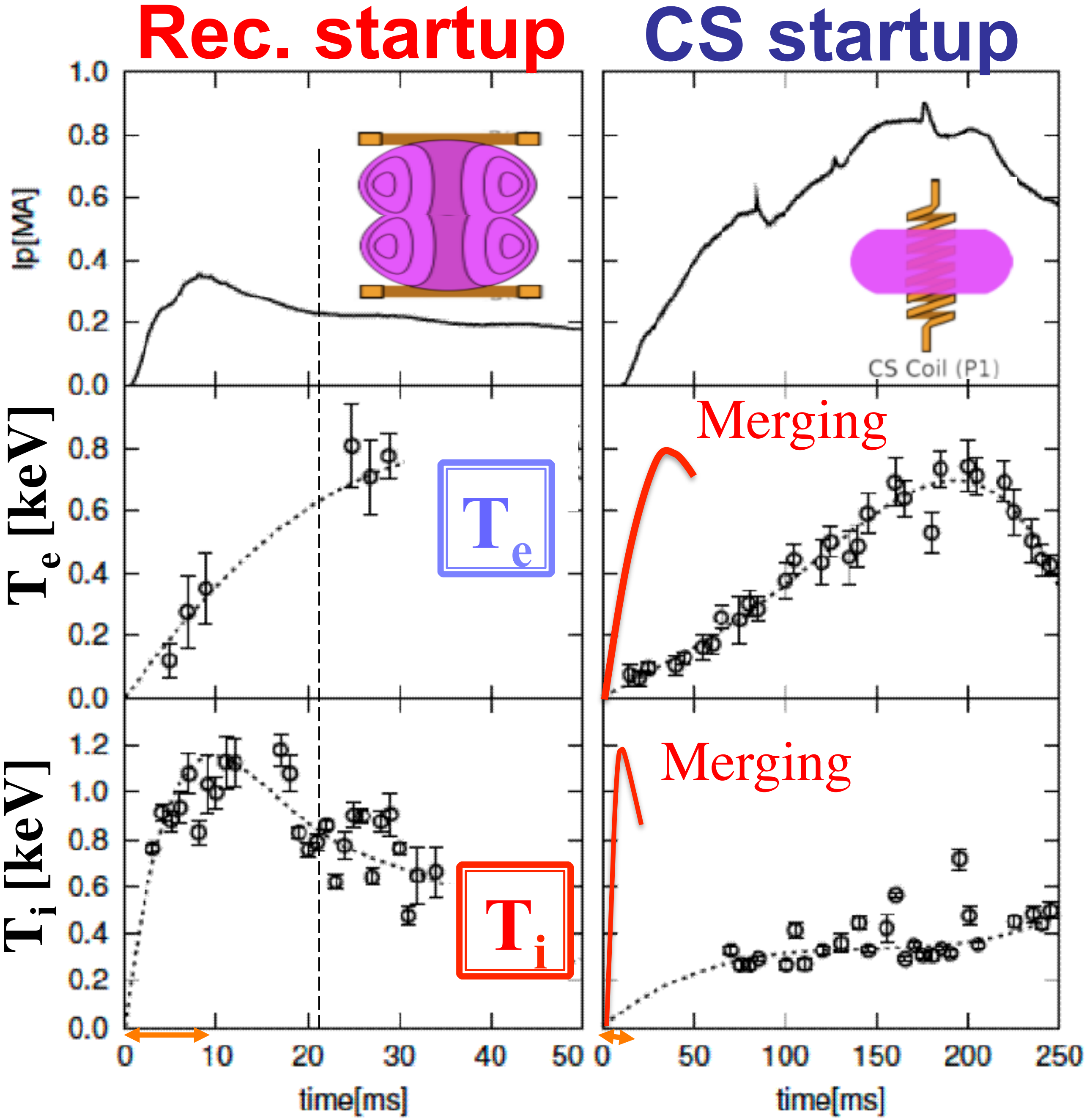
# MAST (UK)

**MAST Merging Exp.**
The merging/reconnection of two ST plasmas heats ions to 1.2keV within 10 msec.

## Significant Ion Heating in MAST Rec.

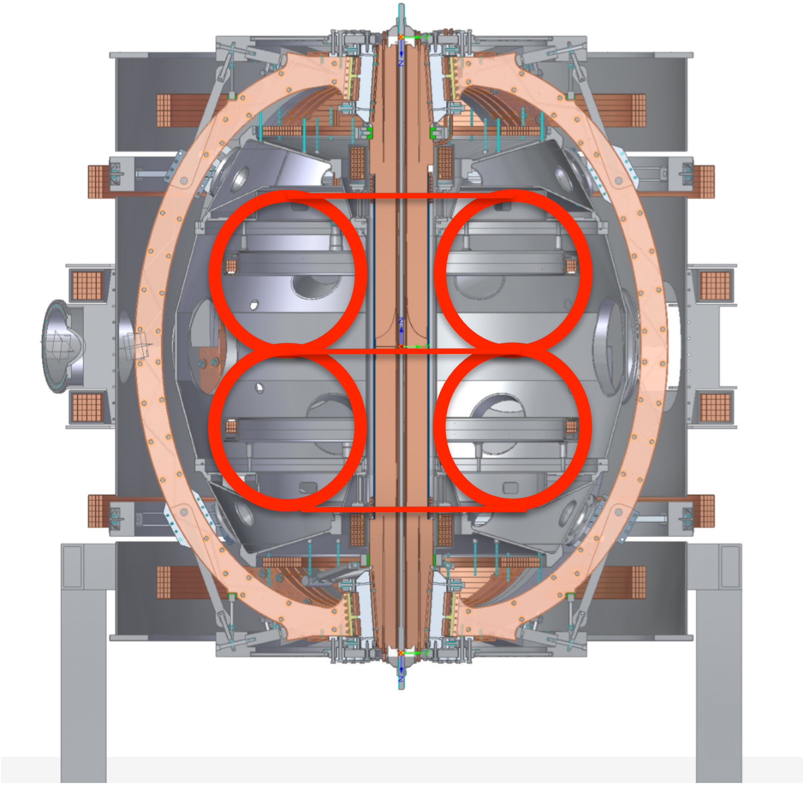
Rec. startup CS startup

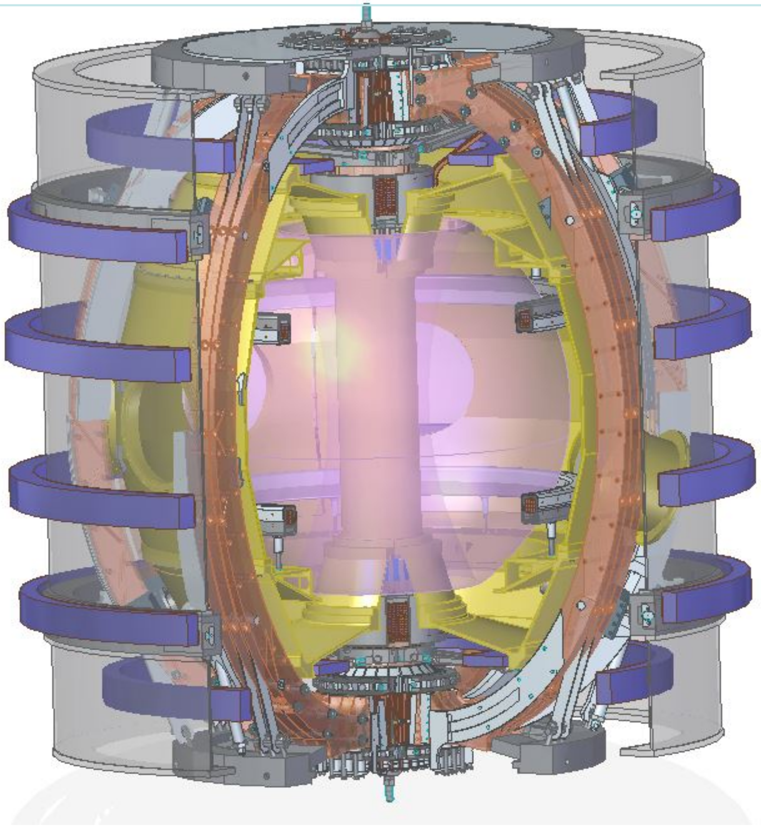




# High-Magnetic Field Merging ST Device: ST40 (Tokamak Energy Ltd.)

**ST40:** 3T/2MA, water or LN2 cooled copper magnet; $R_0$=0.4 - 0.6m, R/a = 1.6-1.8, k~2.5, DND, NBI and EBW/ECRH/RF heating at Phase II





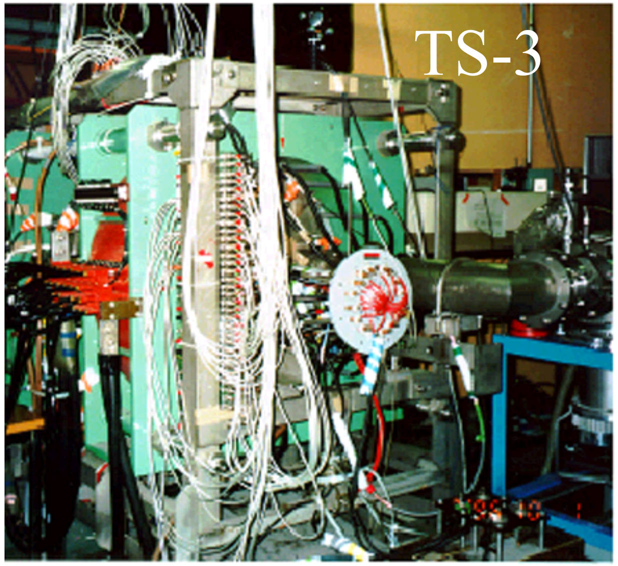
- ST40 has, like START&MAST, in-vessel merging-compression coils and only small solenoid

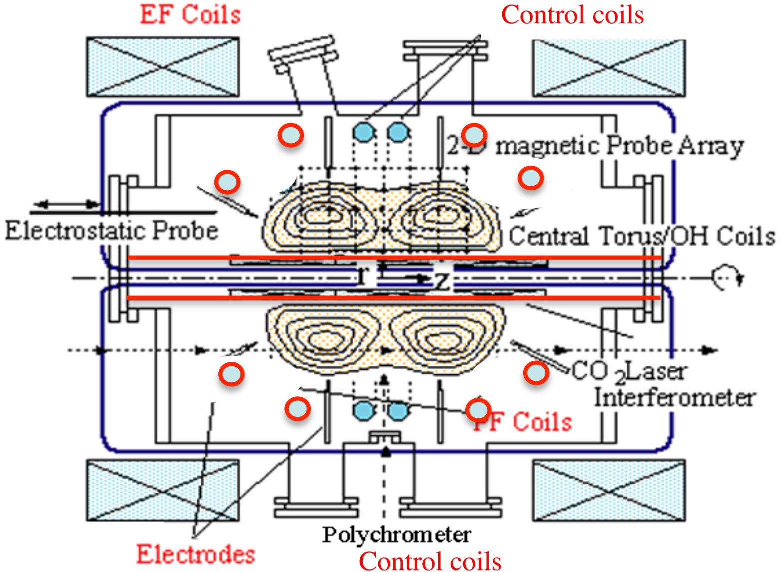
## Upgrades of TS merging exps. were accepted by JSPS:

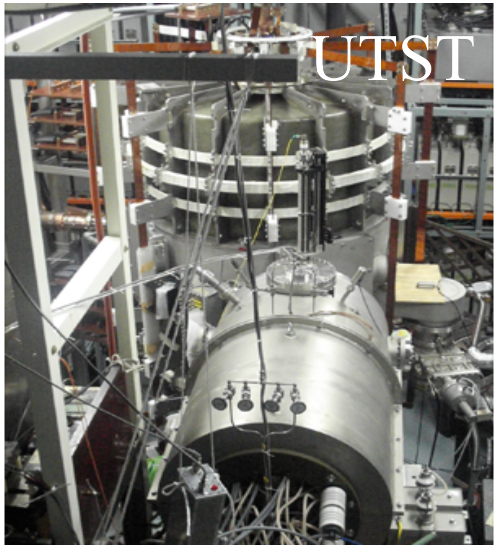
TS-3 (R=0.2m) $B_{rec} < 1kG$ ⟹ $B_{rec} > 5kG$

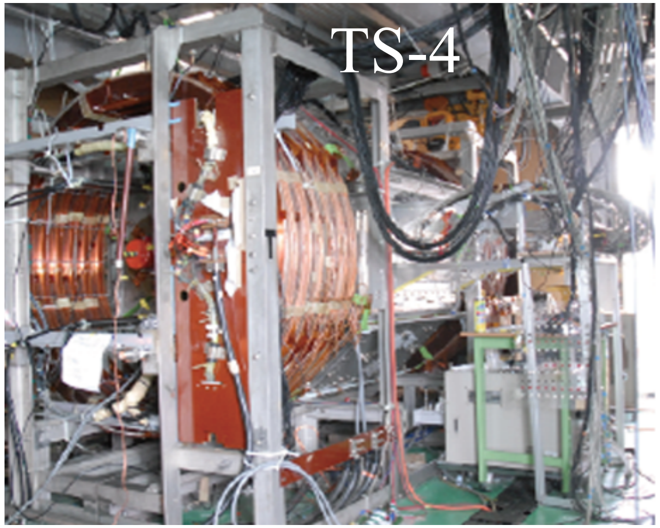
TS-4 (R=0.5m) $B_{rec} < 0.5kG$ ⟹ $B_{rec} > 3kG$

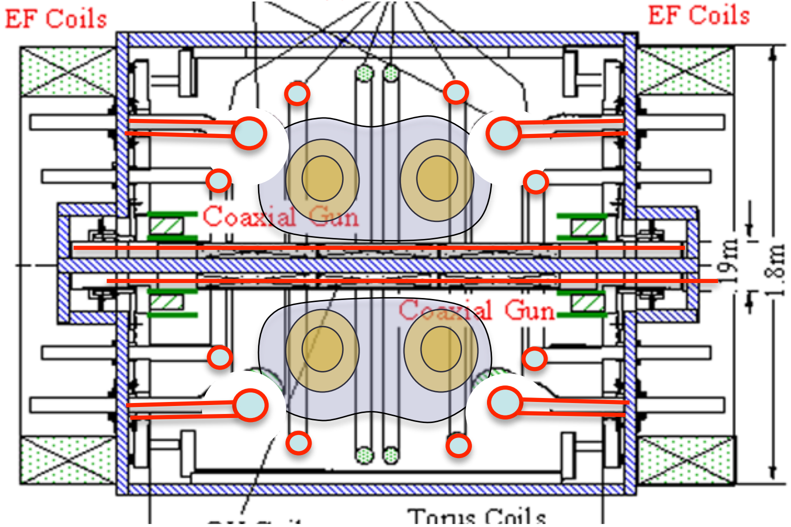
UTST (R=0.45m) $B_{rec} < 0.2kG$ ⟹ $B_{rec} > 1kG$

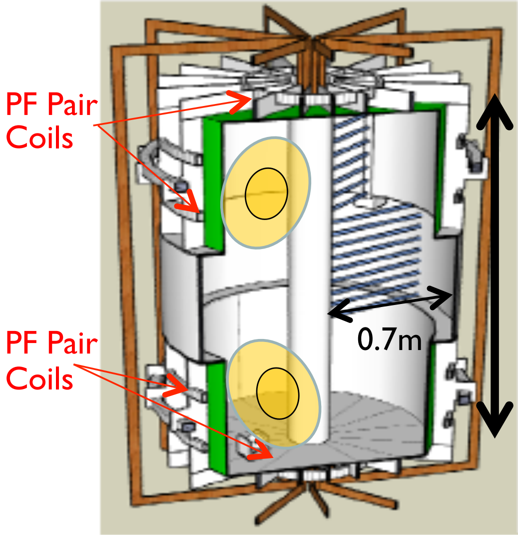












# Summary and Conclusions

A series of ST/ FRC merging experiments reveal:

1) Significant rec. heating of ions MAST **$T_i$ > 1keV**

2) 2D images of $T_i$ and $T_e$ indicate

   Downstream heating of ions MAST,TS-3, PIC, Solar

   X-point heating of electrons MAST, TS-3, PIC

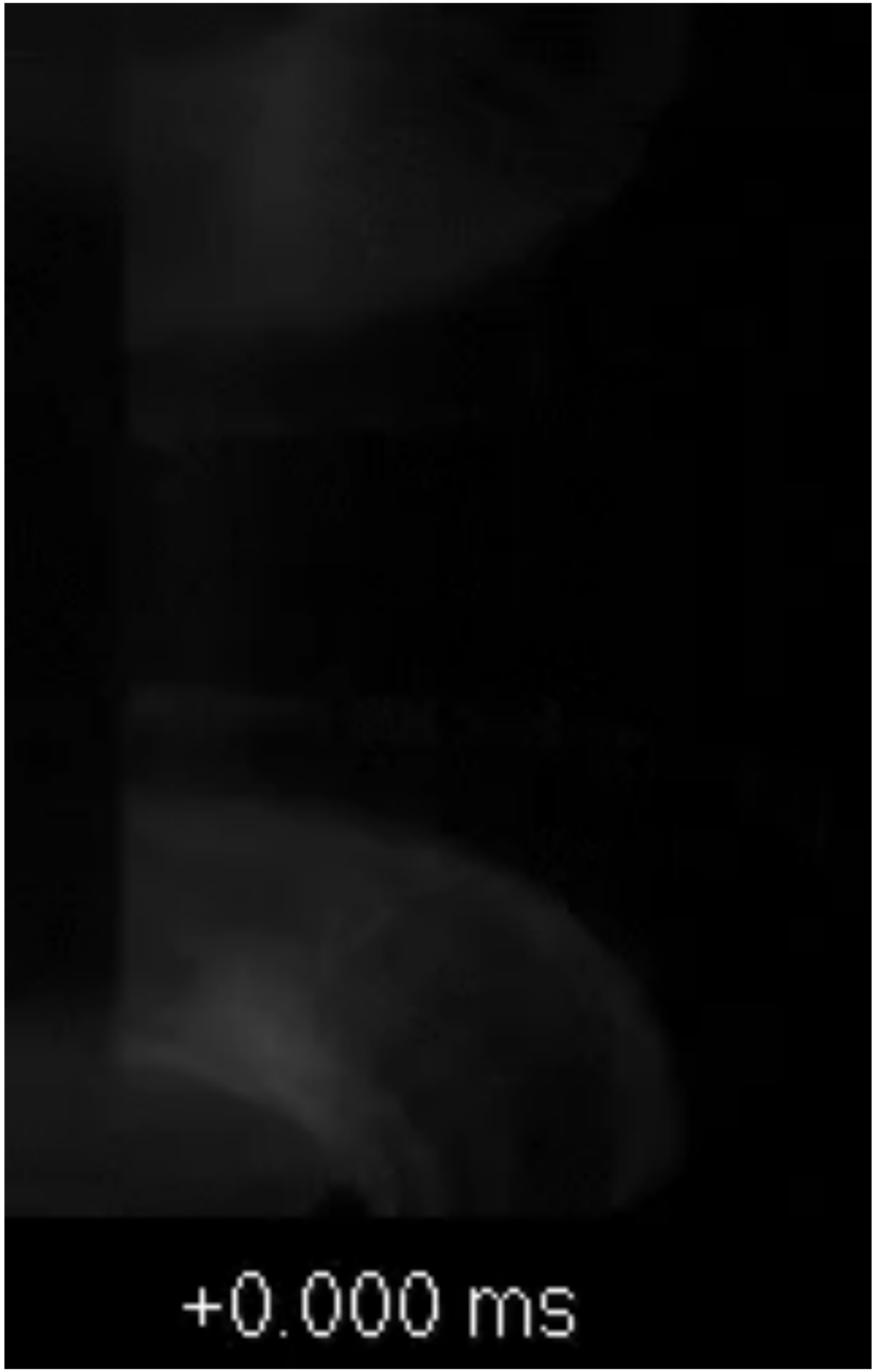
3) Ion heating energy >> electron heating energy.

4) Ion heating energy and $T_i$ increase with $B_{rec}^2$.

UK-Japan team extended the $B_{rec}^2$-scaling to $T_i$~1.2keV ($T_e$~0.8keV) using MAST merging exp with $B_{rec}$~0.15T.

The rec. is a promising method for heating ions > 10keV: direct access to alpha heating planned by UK-J team.

The new high $B_{rec}$ ST merging exp. started in Tokomak Energy & UTokyo for economical heating/fusion reactor.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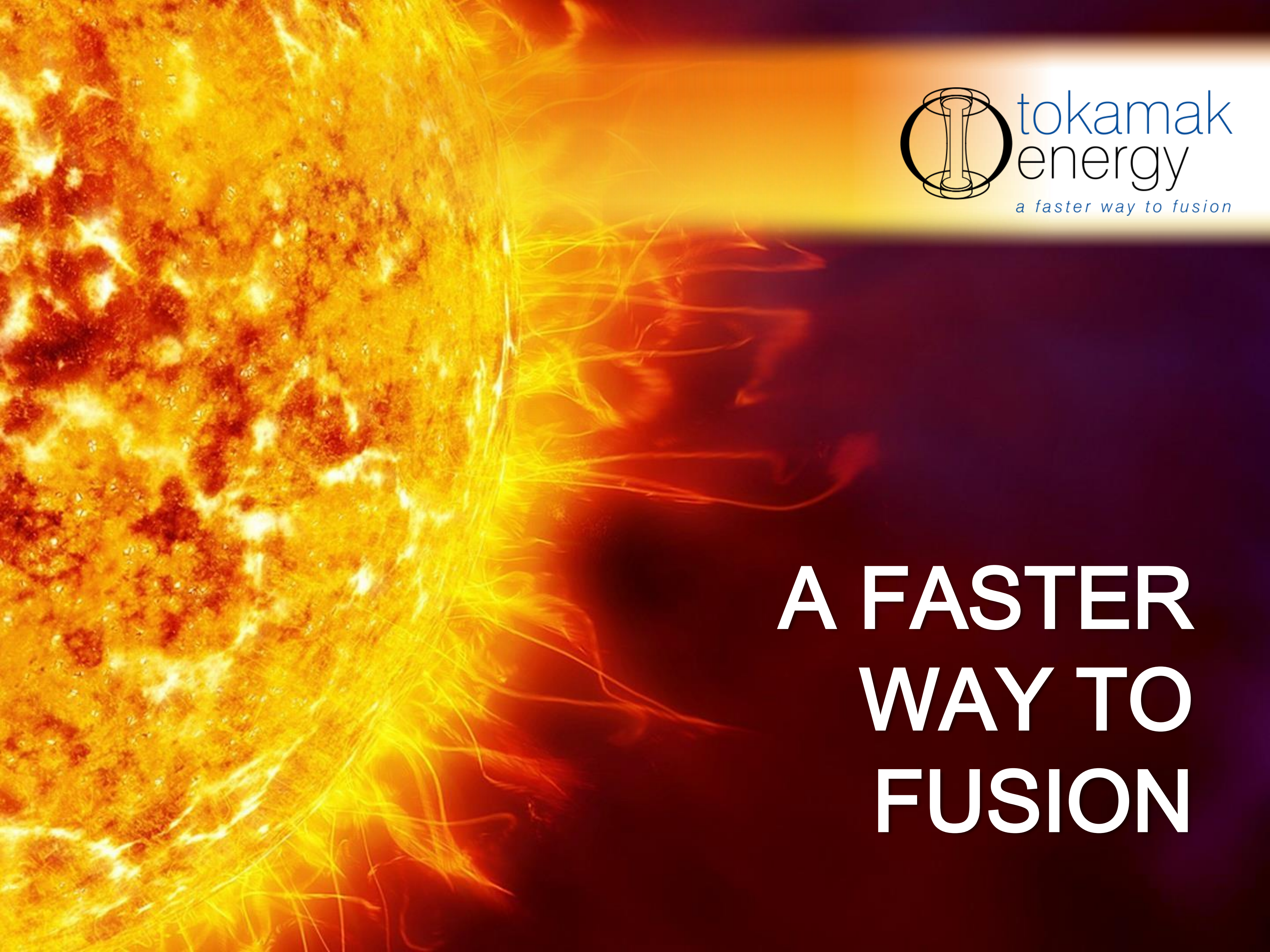


tokamak
energy
*a faster way to fusion*

# A FASTER WAY TO FUSION

# Fusion

## Clean

ZERO CARBON

## Abundant

Deuterium & Lithium

1Kg Fusion Fuel
=10,000,000 Kg Oil

## Safe, Reliable

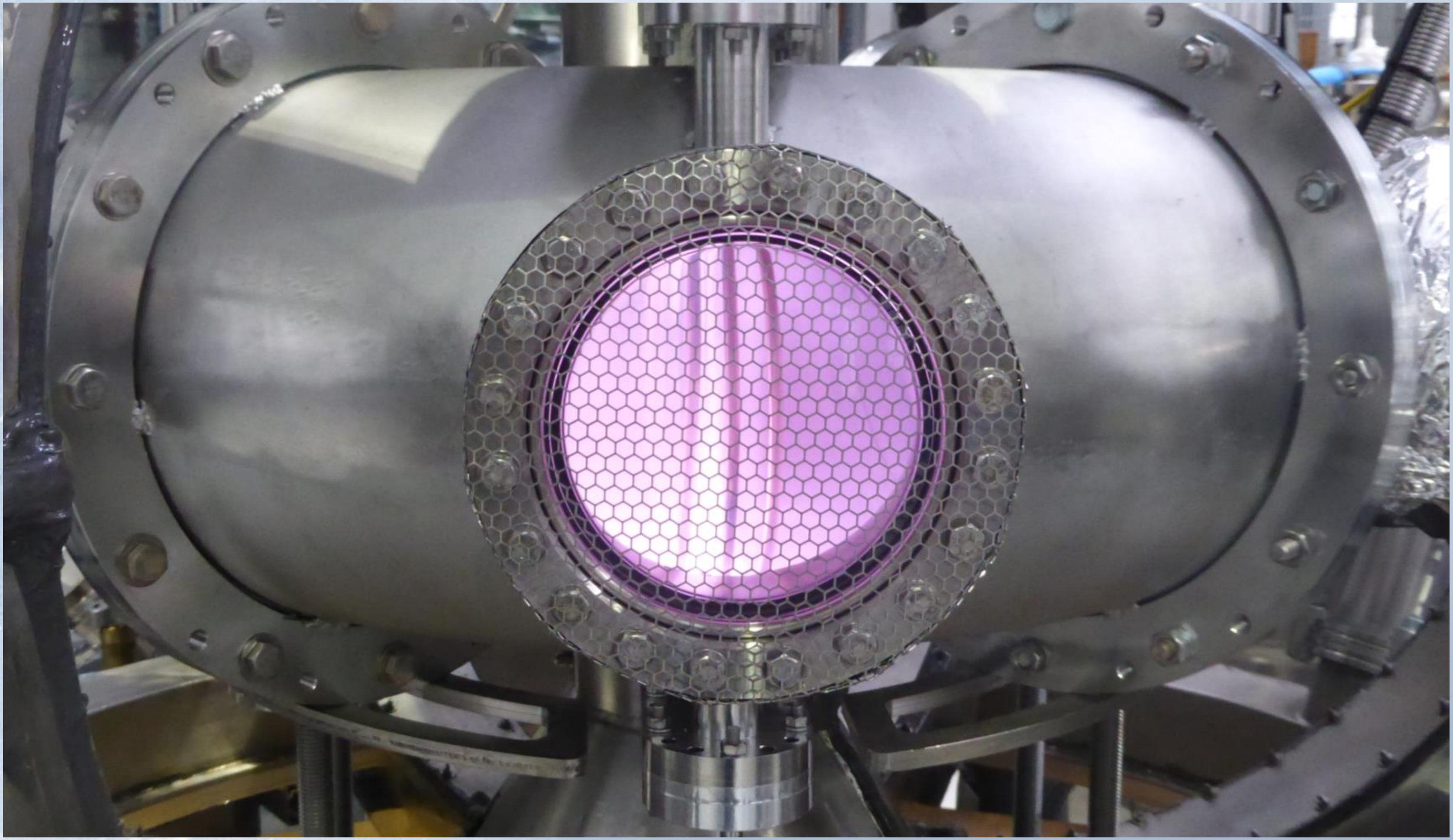
No long term radioactive waste

No risk of meltdown

## Competitive

Economics of fusion power highly favourable

# Tokamak Energy



# The Technology

## Spherical Tokamaks

Squashed shape

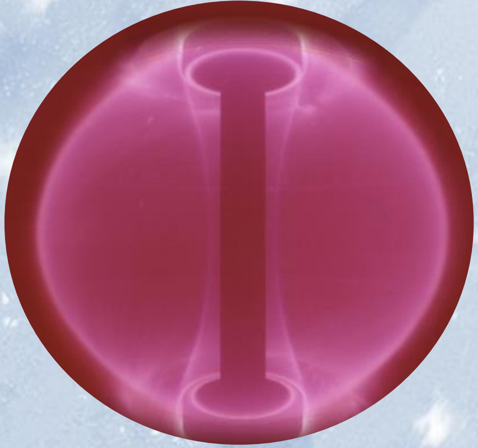
Highly efficient

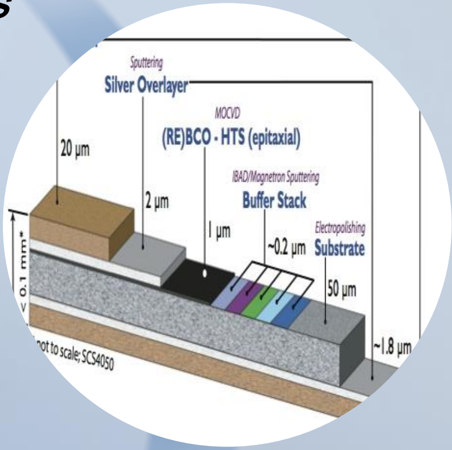
*From 12% to 40% efficiency*

## High Temperature Superconductors

High current at high field

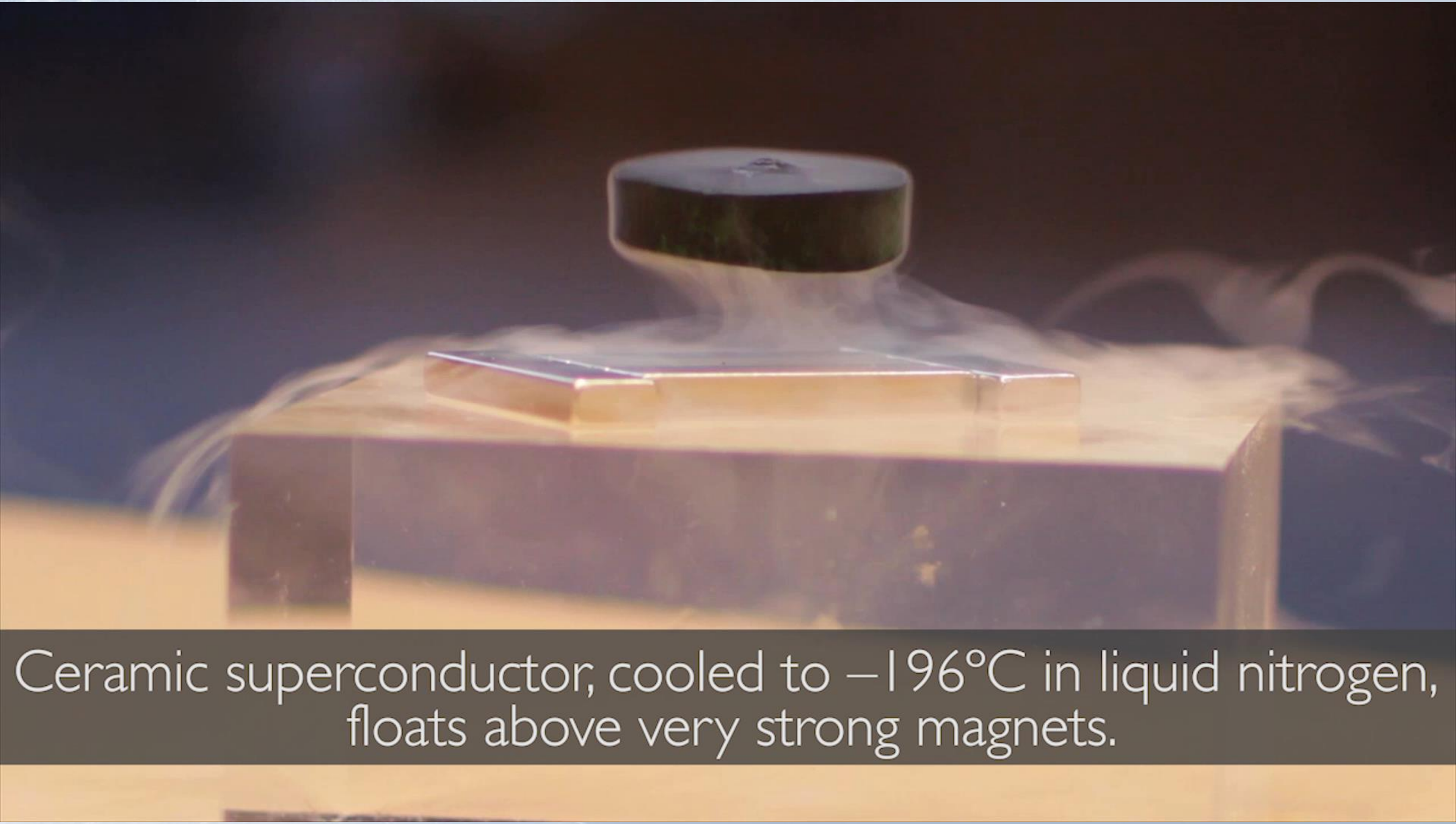
*Lower cryogenic cooling requirements*





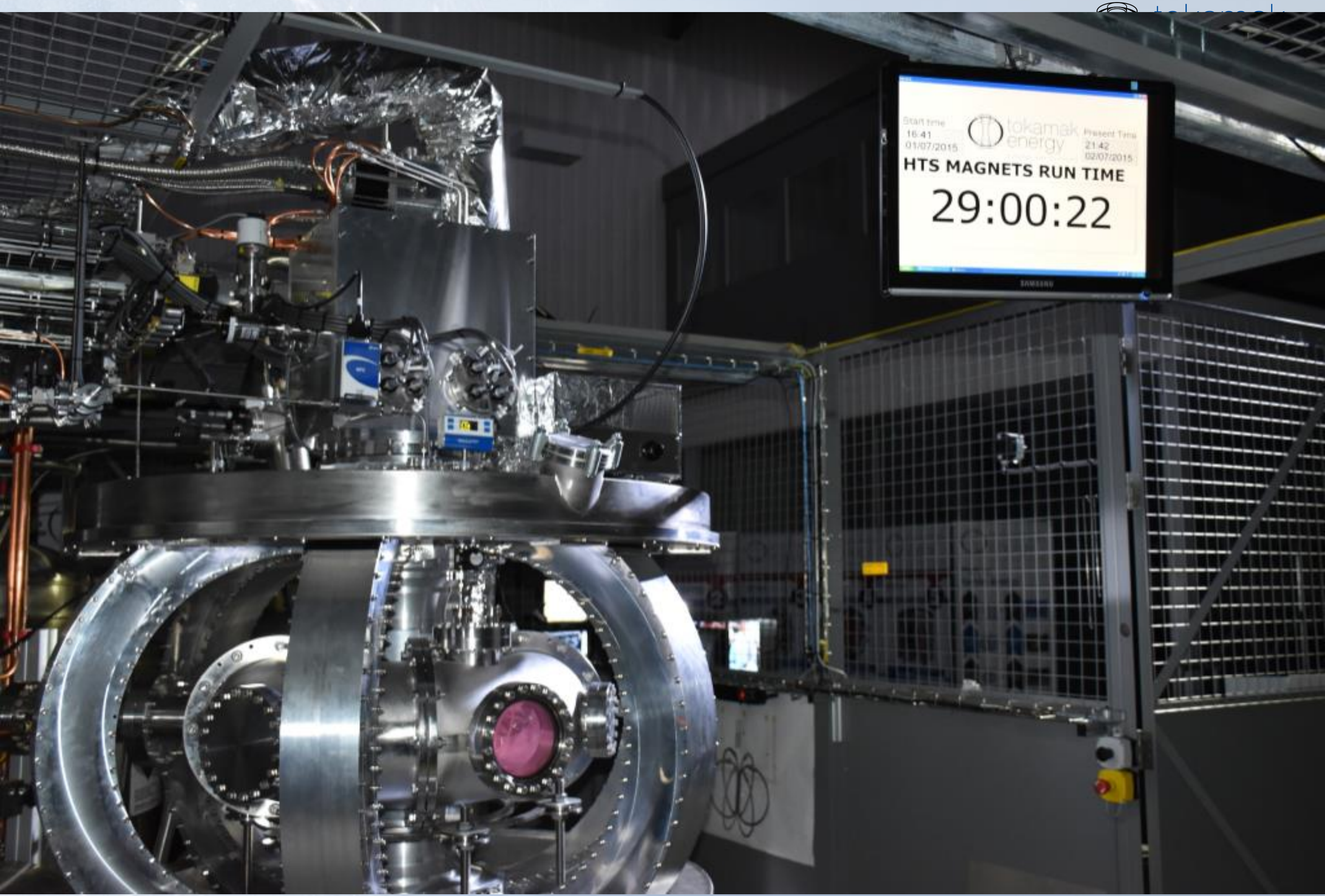
# smaller, cheaper, faster

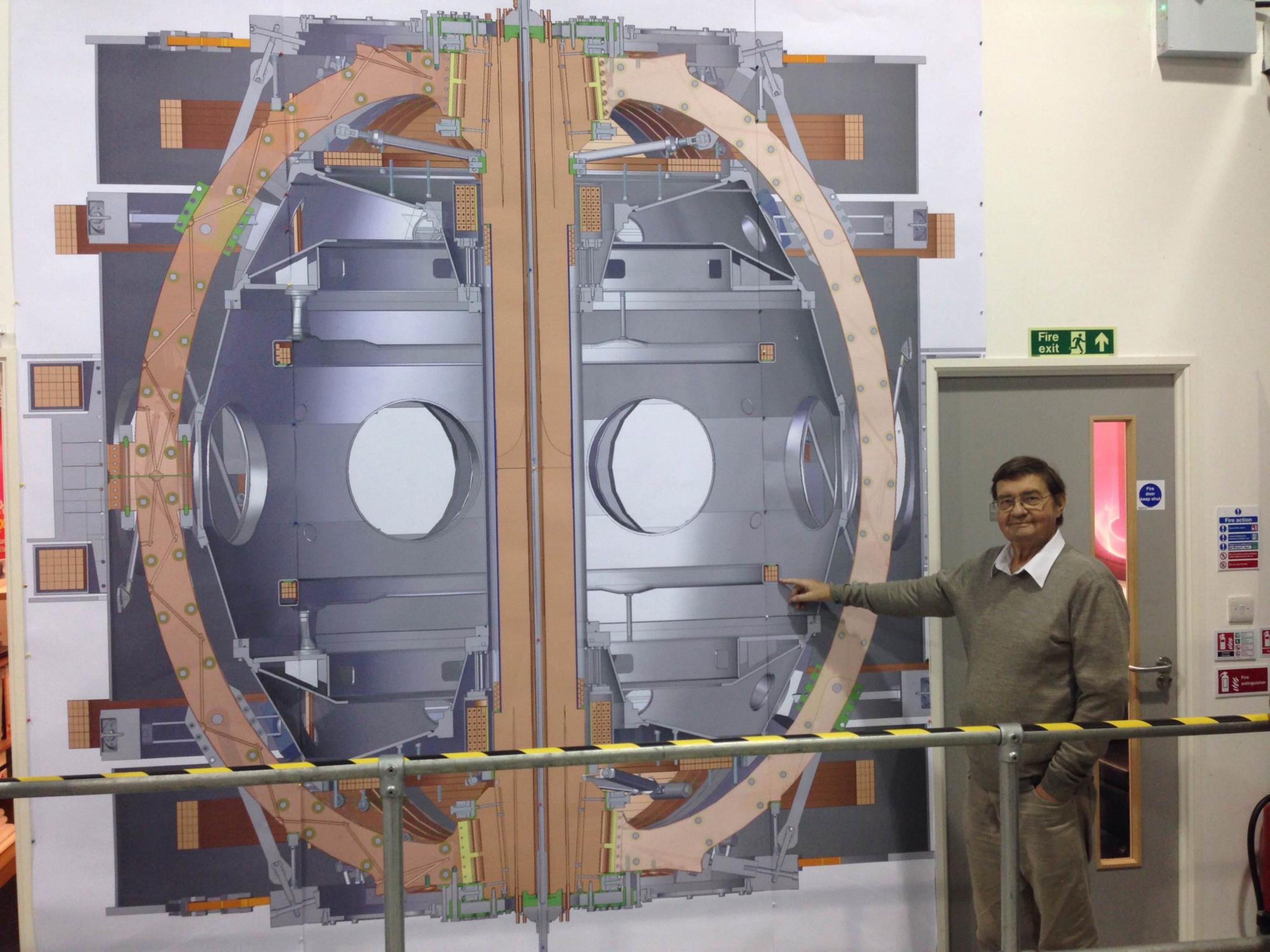
# Superconductivity



Ceramic superconductor, cooled to –196°C in liquid nitrogen, floats above very strong magnets.

# High temperature superconductors

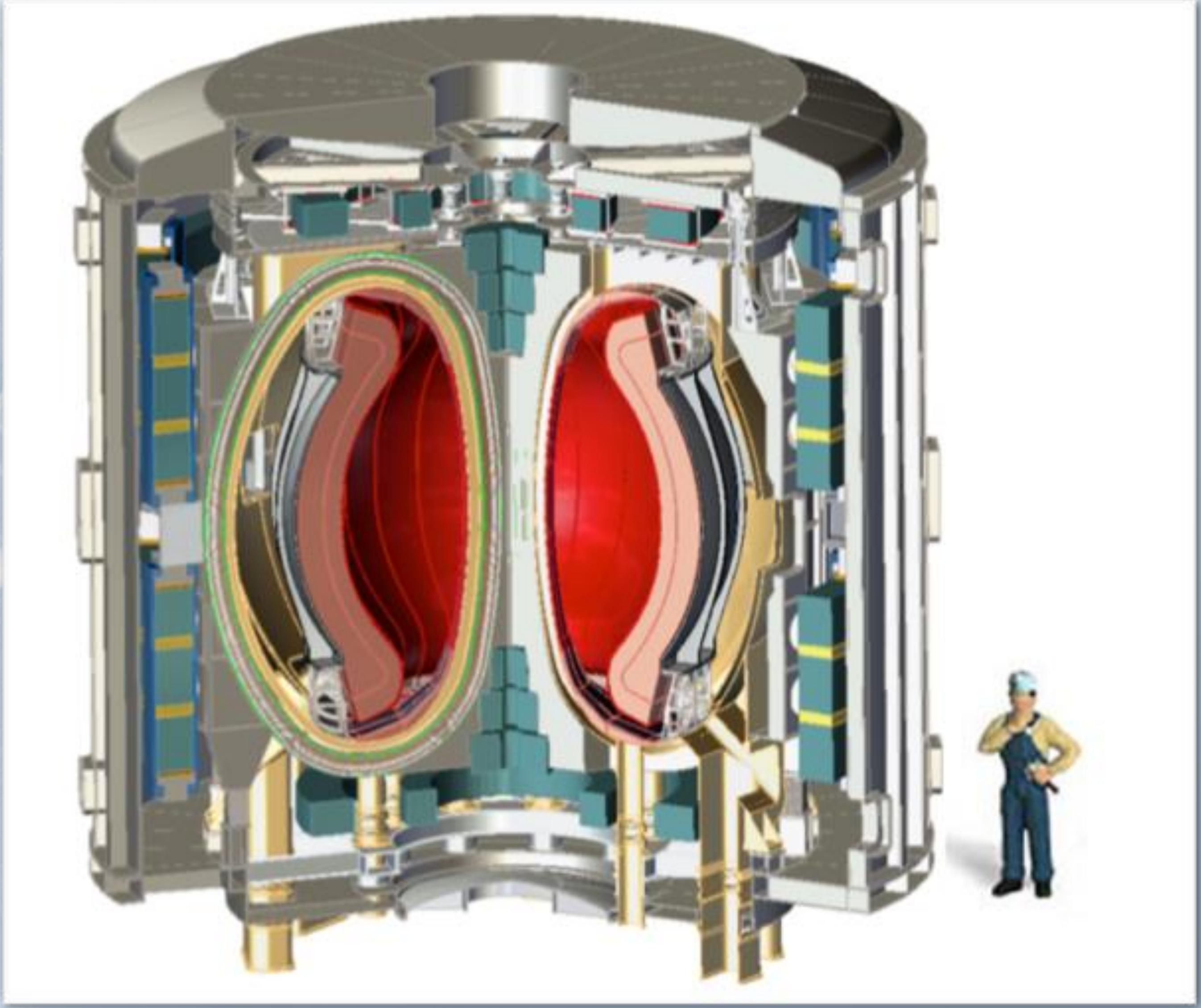

Start time
16:41
01/07/2015
tokamak energy
Present Time
21:42
02/07/2015
HTS MAGNETS RUN TIME
29:00:22


Fire exit
Fire door keep shut
Fire action
Fire extinguisher

# Reactor considerations

Materials

Engineering



# Tackling the challenges

1 HTS tokamak

2 Fusion temperatures

3 Energy breakeven

4 First electricity

5 Power plant

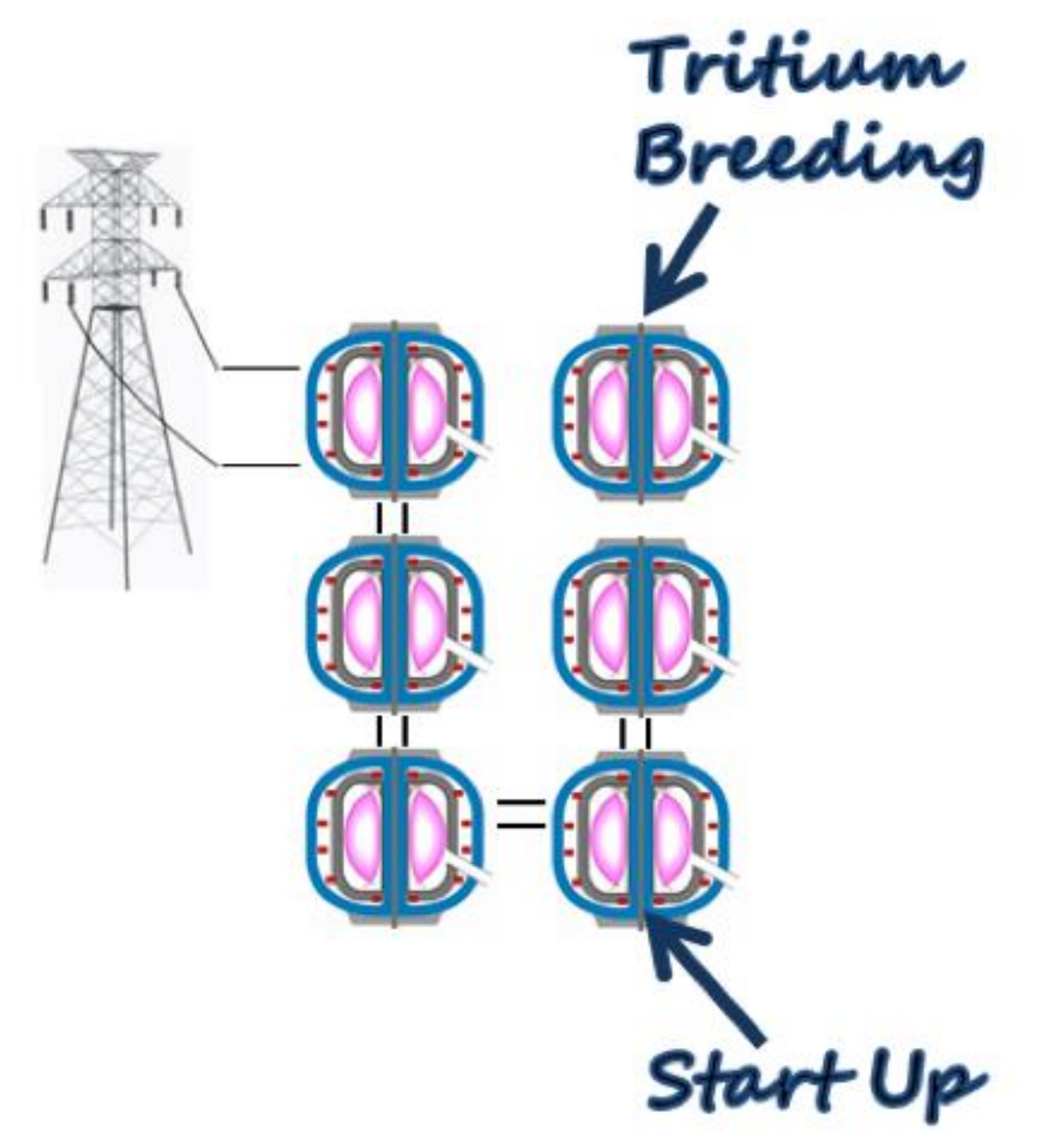
Magnet engineering

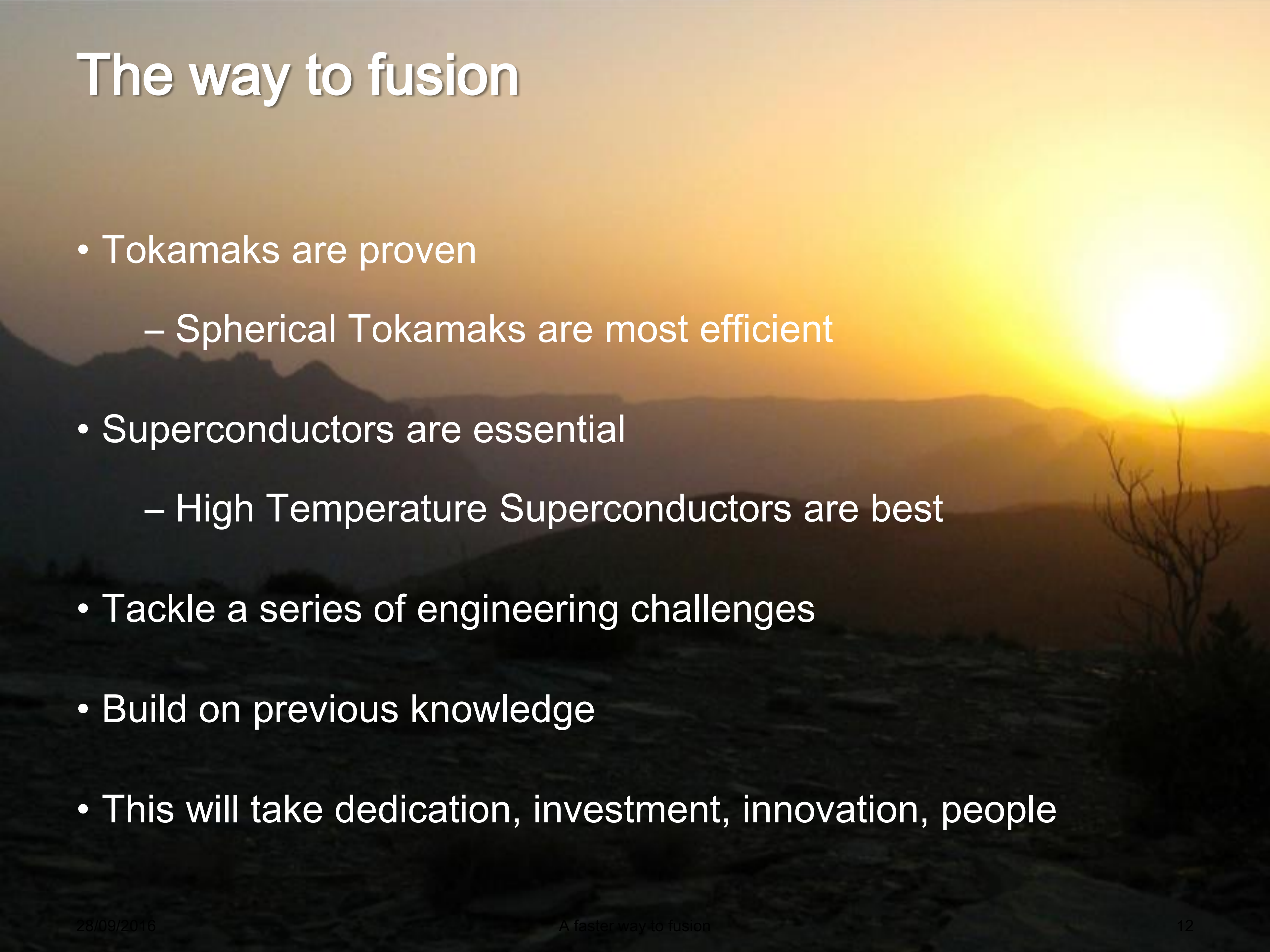
Tokamak engineering

Measurement & control systems

# Compact & modular = flexible

tokamak energy
*a faster way to fusion*





# The way to fusion

- Tokamaks are proven
  - Spherical Tokamaks are most efficient
- Superconductors are essential
  - High Temperature Superconductors are best
- Tackle a series of engineering challenges
- Build on previous knowledge
- This will take dedication, investment, innovation, people

tokamak energy

*a faster way to fusion*

**#fasterfusion**

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