Overview of worldwide ST activities under the IEA Technology Coordination Program
R. Maingi, ST TCP Executive Committee Chair
Magnetic Fusion Science Meeting: April 18, 2022

ST Executive Committee: F. Belloni (EU), S. Diem (US), A. Ejiri (Japan), Z. Gao (China), Y.S. Hwang (S. Korea), D.M. Hwang (S. Korea), J. King (US), R. Maingi (US), J. Menard (US), H. Meyer (UK), Y. Tan (China), Y. Todo (Japan), Z. Yoshida (Japan)

The Spherical Torus Technology Coordination Program (ST TCP) provides a framework for development of the ST concept toward fusion power

- A version of this talk was presented at the Fusion Power Coordinating Committee on 3/3/22, to propose a 5-year renewal to the IEA (provisionally approved)
  - Archive of activities at https://drive.google.com/drive/folders/0B5-iztf28QNJMnFuTVNKTTRYWEU?resourcekey=0-xZy3HRMtvOIgCU-i3NYzkg&usp=sharing
- Introduction and Objectives
- Research Highlights 2017-2021
- Work Plan 2022+

TCP provides framework for development of the ST toward fusion power

- The objective of this agreement, which came into force in 2007, and was renewed in 2012 and 2017, and is sought for renewal in 2022, is:
  - "to enhance the effectiveness and productivity of fusion energy science and technology by strengthening co-operation among spherical torus research programs and facilities,
  - and thus, to contribute to and extend the scientific and technology database of toroidal confinement concepts to the spherical torus physics regime,
  - and to provide a scientific and technological basis for the successful development of fusion power using the spherical torus".

- Fusion energy research is well aligned with the IEA mission and the work carried out under the ST TCP is highly relevant to the IEA Strategy for Energy Research and Technology (range of energy technology options, collaboration, innovation…..)

Three annexes in the ST TCP agreement

- **Annex I – “Co-operation on ST Science R & D”:** Much of the work is carried out under this annex -bi-lateral and multi-lateral research collaboration, joint publications, exchange of equipment and personnel, information exchange at workshops and conferences, organization of the International Spherical Tokamak Workshops, outreach, communication and dissemination to the wider community etc.
- **Annex II – “Co-operation on the Physics and Technology of Future Spherical Torus Devices”:** This work aims to accelerate progress on the physics and technology of future ST devices through co-ordination of activities and exchange of technical information relating to physics and technology challenges which are common to a range of future ST devices.
- **Annex III – “Co-operation on the Steady State Operation of Fusion Devices”:** Here we seek to accelerate progress on the physics and technology of steady state operation of fusion devices through coordinated planning and cooperative research.

Growing number of STs in participating regions, including commercial ventures

- **China:** EXL-50, NCST, SUNIST, SUNIST-2
- **EU(/UK):** MAST-U, Proto-Sphera, SMART, ST-40
- **Japan:** LATE, QUEST, TST-2, TS-6, TS-4U, UTST
- **S. Korea:** VEST, VEST-II
- **US:** LTX-β, NSTX-U, PEGASUS-III

*new or upgraded since 2019

Outline

- Introduction and Objectives
- Research Highlights 2017-2021
- Proposed Work Plan

Perspective on R&D during 2017-2021

- Two largest devices MAST-U and NSTX-U had limited operation during 2017-2020: the ‘community pull’ from these large devices was modest
  - MAST-U first physics campaign conducted in 2021!
- Over the past 2 years, onsite collaborative participation has been nearly impossible – most R&D conducted locally, and shared via virtual meetings
  - Results shown (with a few noted exceptions) are conducted by separate teams
- We look forward to these factors ameliorating in 2022+!

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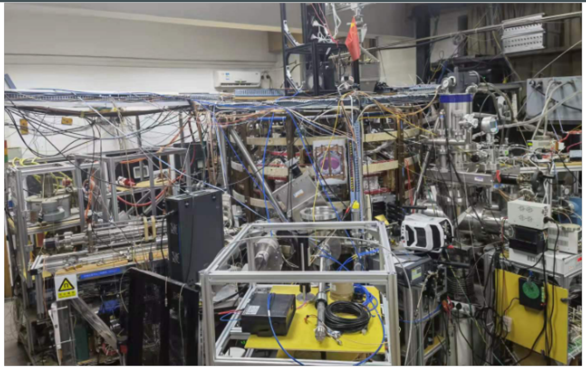
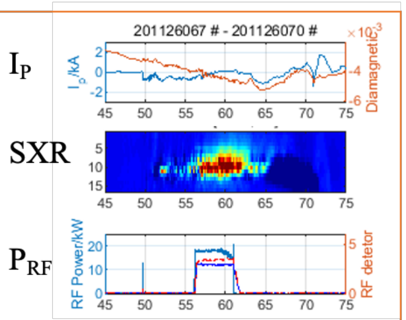
China: Progress in EBW heating, equilibrium reconstruction, and TAE physics in SUNIST



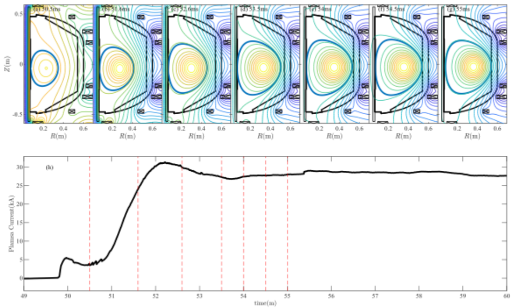
SUNIST (Tsinghua Univ., Beijing)

- R_0: 0.3 m, a: 0.23 m, A: ~1.3, κ: 1.6 – 1.8
- B_{T0}: 0.15 (0.3) T, I_P: 50 (120) kA
- n_e: 0.2 – 3×10^{19}m^{-3}, T_e: ~100 eV
- Black: design, red: achieved

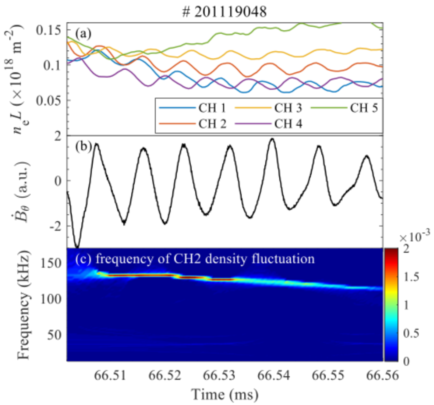


Successful **EBW heating** by injecting 2.45 GHz 30 kW+15 kW microwave into ohmic plasmas. With RF injection, intensities of SXR increased significantly.

n_e@ECR: 1×10^{18}m^{-3}~**13 n_c**!

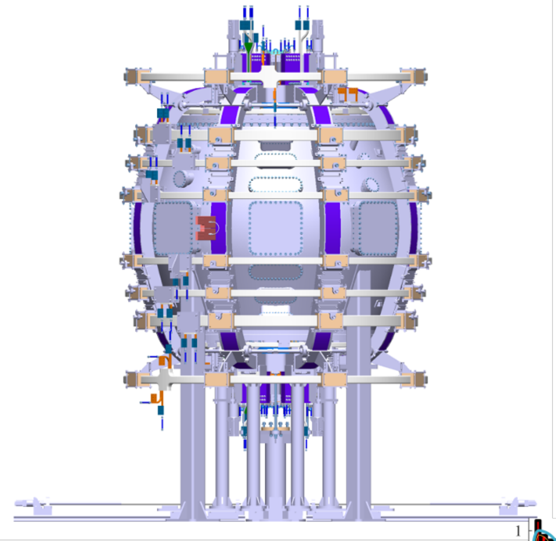


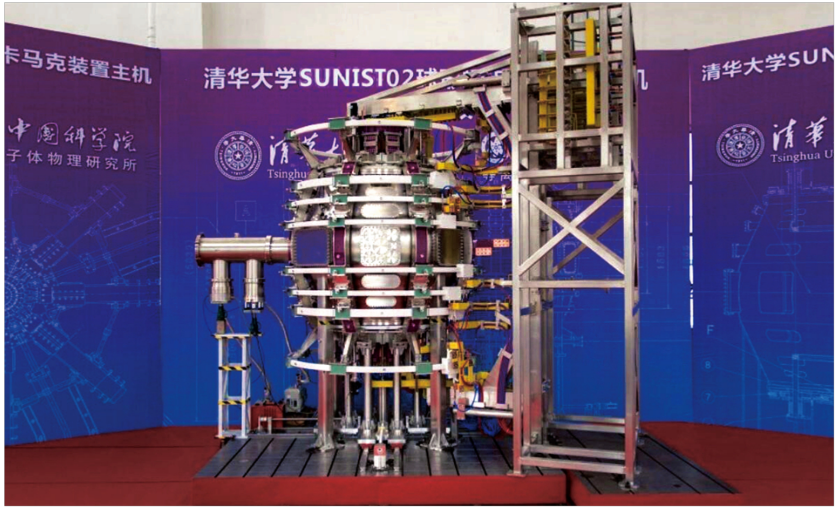
Eddy currents are considered carefully by the **response function** method. Successfully **reconstructed** magnetic surfaces from the very beginning of discharge with **30 MA/s ramp rate** when eddy current effects are huge.



Observation of **density fluctuations of TAEs** by a set of mm-wave interferometers with temporal resolution up to 0.5 μs and electron density resolution up to 10^{15} m_2^{-2}.

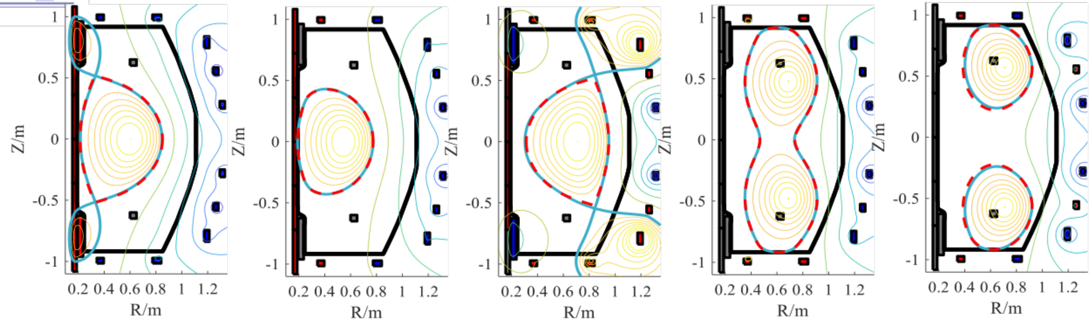
China: SUNIST upgrade in progress





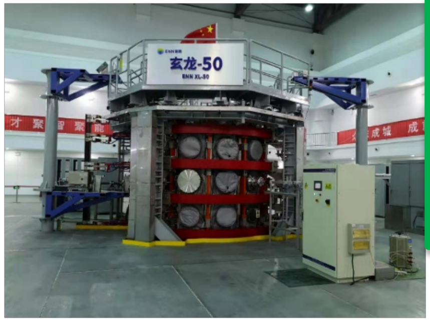
SUNIST-2

- R_0: 0.525 m, a: 0.325 m, κ: ~1.6
- B_{T0}: 0.4 – 1 T, I_P: 500 kA
- Multi-winds solenoids/MC coils for Reconnecting heating
- Pre-assembling finished
- First plasma planned in 2022



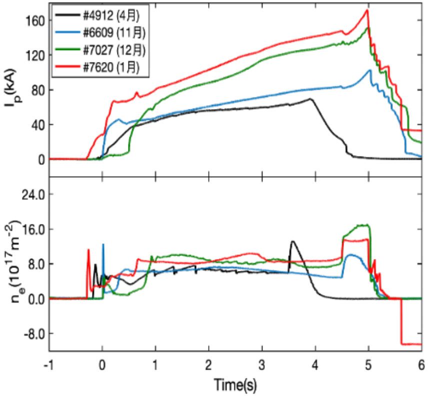
Design configurations: DND, limiter, DND with negative triangularity, doublet,[3] droplet.

China: two more STs have come online – public and private

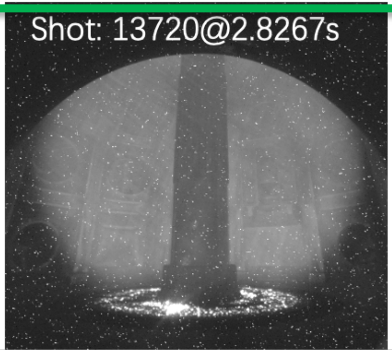


EXL-50 (ENN Group, Langfang)

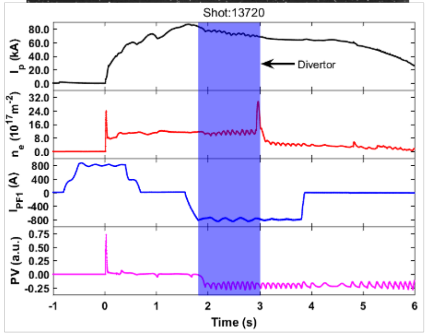
- First plasma at 2019
- R_0: 0.58 m, a: 0.41 m κ: 1.8 – 2.2
- B_{T0}: 0.46 T, I_P: 500 (172) kA



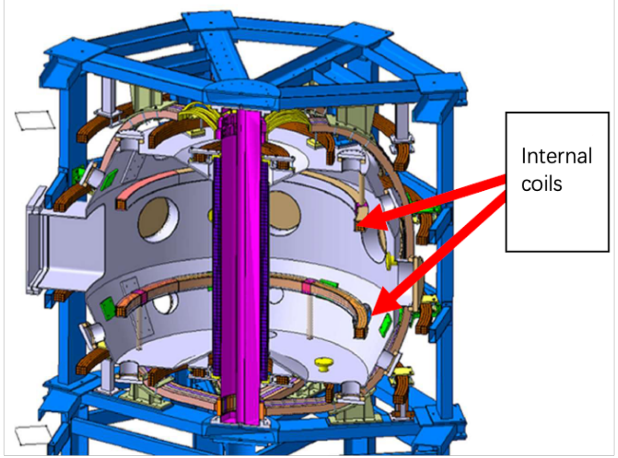
ECW drive w/o CS:~172kA
(including the current outside the LCFS)



Preliminary divertor discharge→



NCST (Nanchang Univ., Nanchang)



- First plasma at 2021 (~0.6kA)
- R_0: 0.40 m, a: 0.24 m κ: 1.5 – 2.0
- B_{T0}: 0.36 T, I_P: 100 (3) kA

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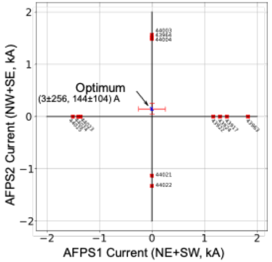
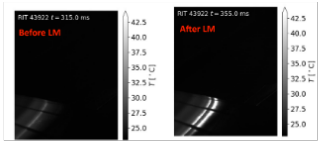
EU: MAST-U 1st physics campaign in 2021 explores features of super-X divertor configurations

UK Atomic Energy Authority

MAST-U successfully completed its 1st physics campaign

Campaign is part funded by EUROfusion work package Tokamak Exploitation

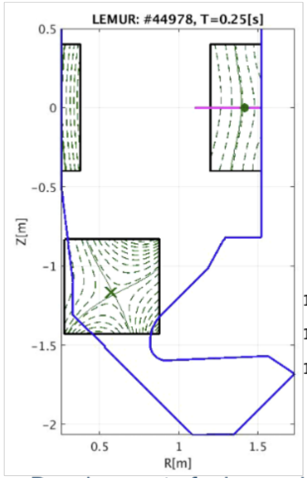




CONSORZIO RFX
Ricerca Formazione Innovazione

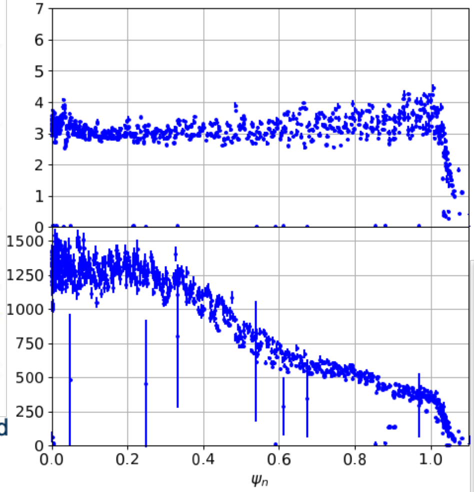
Considerable reduction of the intrinsic error field with respect to MAST despite much larger number of coils.

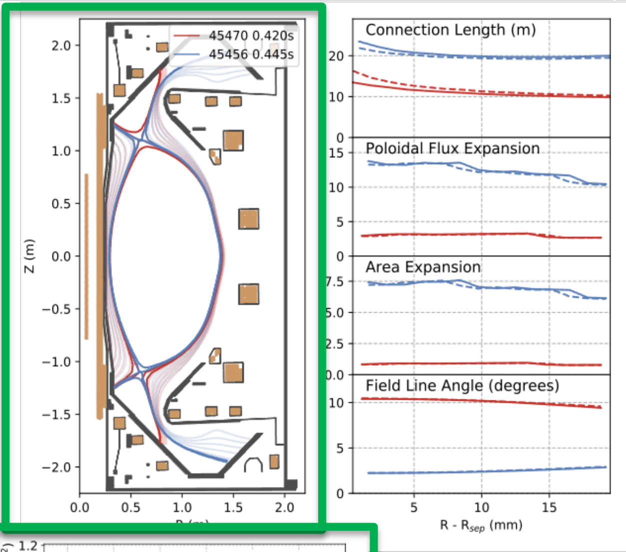
- Improved alignment of old deformed PF coils.
- Enables access to lower density.

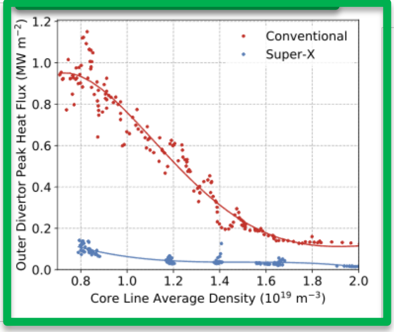


Development of advanced magnetic control for gaps and X-point without full equilibrium reconstruction

Record pedestal temperature of $T_e \sim 0.45\ keV$ in record $t \sim 1s$ ELMy H-mode







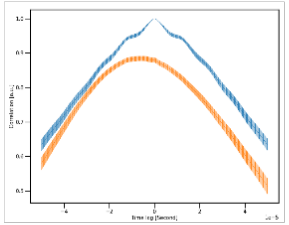
EUROfusion

Super-X gives a substantial reduction of surface power loads and up-stream density for detachment onset

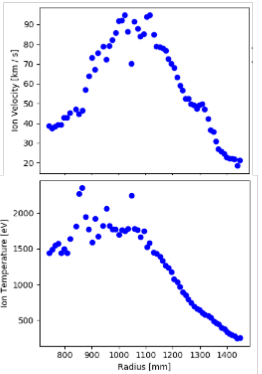
EU: Substantial collaborative upgrades in MAST-U diagnostics!

UK Atomic Energy Authority

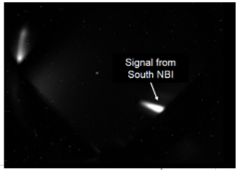
Beam Emission Spectroscopy



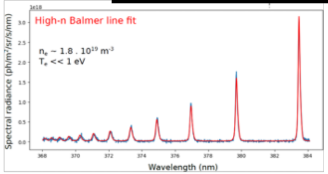
CXRS



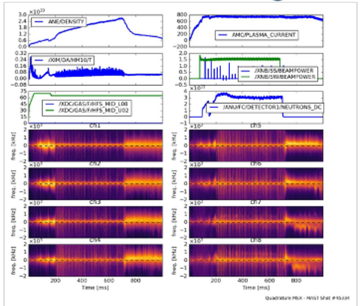
FILD



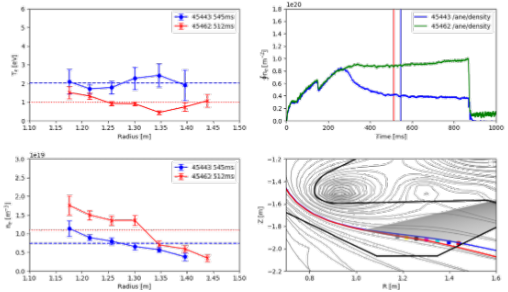
DIBS



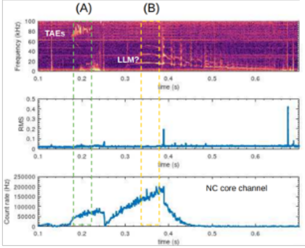
UCLA Doppler Backscattering



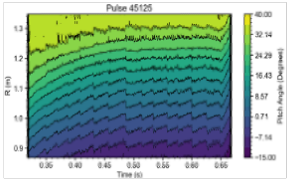
Core & Divertor Thomson Scattering



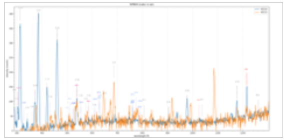
Neutron Camera



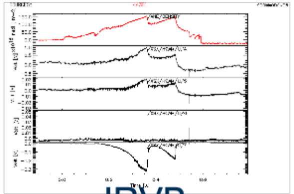
MSE



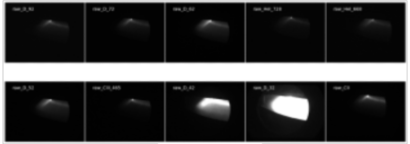
Core SPRED



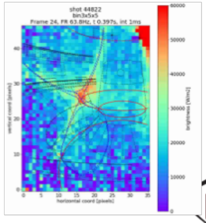
SXR

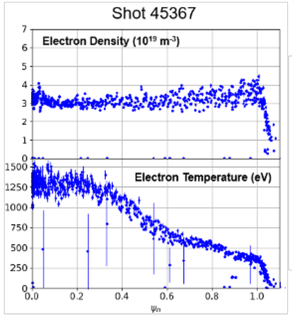


Multi-Wavelength Imaging

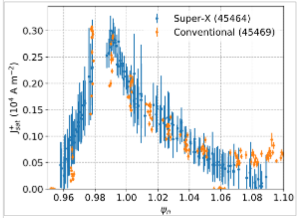


IRVB





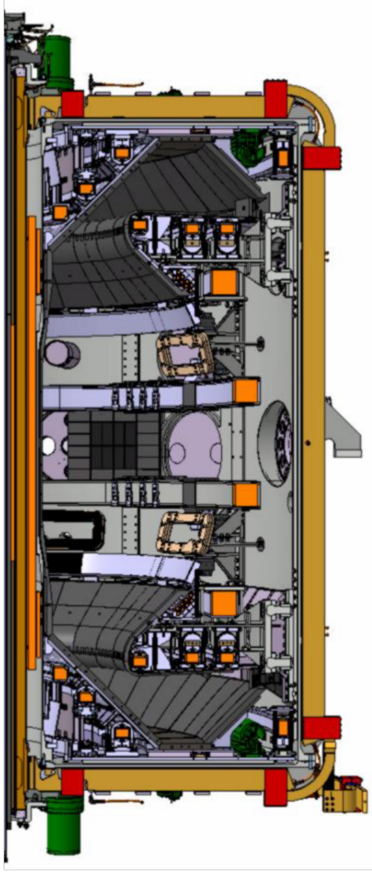
Divertor LPs



& many others

DIFFER Dutch Institute for Fundamental Energy Research
Oak Ridge National Laboratory
SWIP
EUROfusion
University of California UCLA
Durham University
Universidad de Sevilla
Uppsala Universitet
University of Liverpool
Wigner
University of York
Lawrence Livermore National Laboratory

EU: sequence of enhancements available in 2022 on MAST-U



Parameter	1st Campaign	2nd Campaign
R / a (m)	0.7 / 0.5	0.7 / 0.5
Divertor PFC material	Carbon (graphite)	Carbon (graphite)
B_φ (T at 0.8m)	0.65	**0.72**
Max I_p (MA)	0.75	**1.0**
Max κ	2.2	> 2.2
Max δ	0.6	0.6
Divertor geometry	Closed, unpumped	Closed
Max. NBI heating power & duration	3.5 MW for up to 1s	**4.2** MW for up to **2s**
Ohmic Heating	0.2-1MW	0.2-1MW
NBI geometry	1x on axis, 1x off axis	1x on axis, 1x off axis
Fuelling	Gas	Gas, **pellets**

Increasing TF rod current from 100 to 110kA

Building on development of 750kA scenarios

Improving NBI conditioning

HFS pellet injector to be commissioned in MU02

EUROfusion funding ~ 30% of the MAST-U campaign

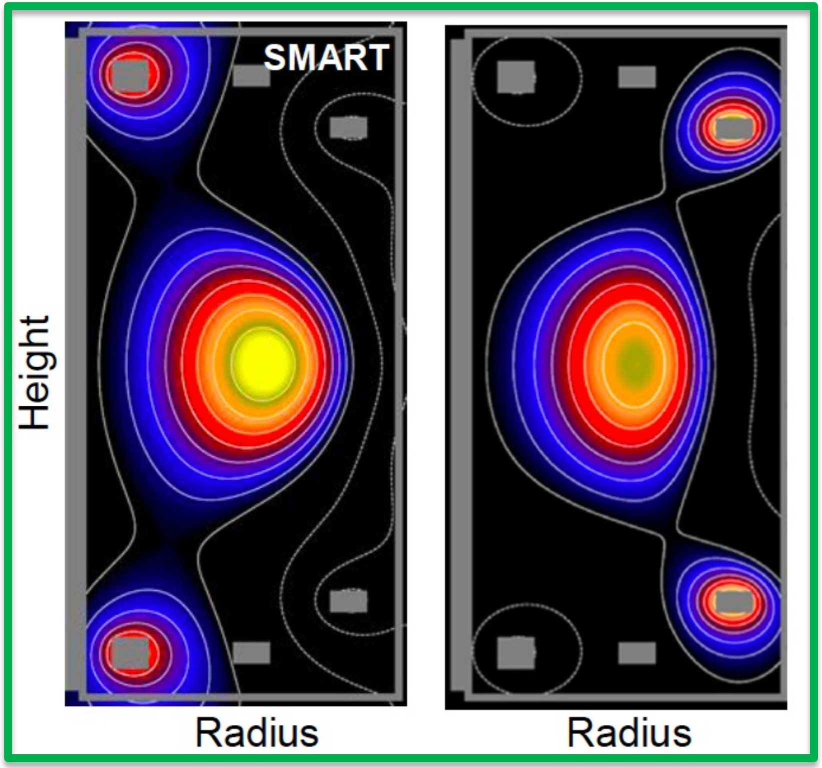
EU: SMART device built to explore science of negative triangularity

- SMART device coming online in 2022, U. Sevila (EU)
- Nascent US-EU collaboration on SMART

- Vacuum vessel dimensions: 1.6 x 1.6 m
- 12 toroidal field coils, 8 poloidal field coils, 1 solenoid
- Major radius R = 0.45 m
- Minor radius a = 0.25 m

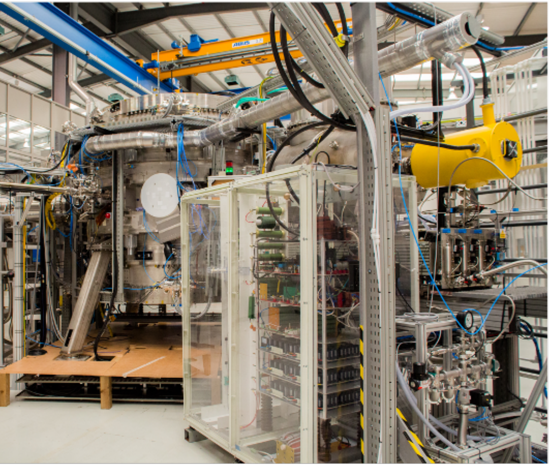
- 3 operational phases foreseen

Parameters	Phase 1	Phase 2	Phase 3
Plasma Current [kA]	100	>100	<500
Toroidal field [T]	0.1	0.3	1.0
Flat-top duration [ms]	150	>150	500
Microwave heating [kW]	6	6	200
Neutral beam injection [MW]	-	1	1

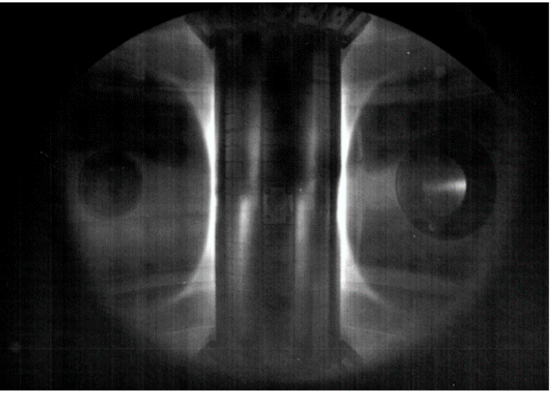


EU: ST40 (private co.) expands the ST basis to higher B_t

tokamak energy
a faster way to fusion



Parameter	Achieved Range
Bt [T]	1.8 – 2.3
Ip [MA]	0.5 – 0.8
R_{Geo} [m]	0.4 – 0.55
A	1.6 – 1.8
P_{NB}/E_{NB} [MW/kV]	0.6/25, 0.7/50
ψ_{sol} [Wb]	0.2
Start-up	Merging-compression



ST40 is equipped with a comprehensive set of diagnostics and activities are focused on optimising **hot ion mode** regimes to maximise central ion temperature

ST40 is uniquely placed to study physics of high field STs:

- **Investigate confinement at high field**
  Strong scaling of confinement observed on other STs with increasing toroidal field (reducing collisionality)
- **Characterise divertor performance**
  Extend scrape-off layer width scalings to high poloidal field
- **Demonstrate solenoid-free start-up methods**
  Exploring merging compression and RF driven start-up (EBW + ECRH)
- **Develop reactor relevant high-performance operating scenarios**
  High bootstrap, high performance regimes with minimal NBI heating

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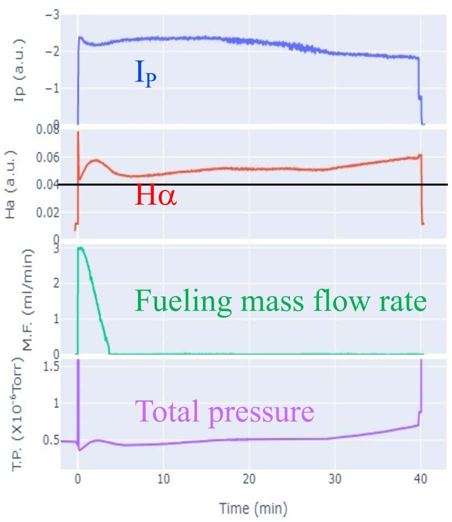
*new or upgraded since 2019

Japan: progress in both QUEST and TST-2

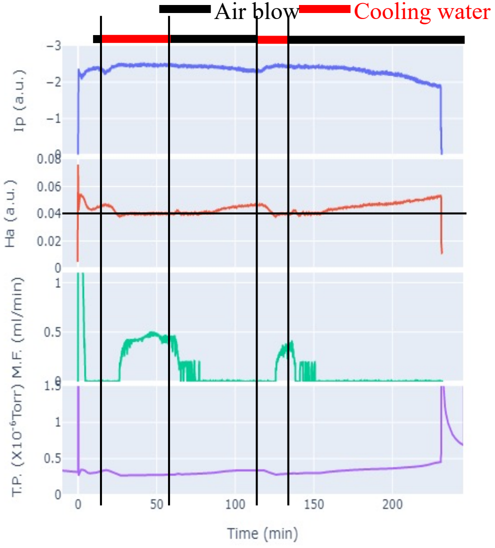
- **QUEST (Kyushu Univ.)**

Long discharge period operation **with hot walls**
Increase in the wall temperature 474 K ->673 K

40 min. op. @673 K

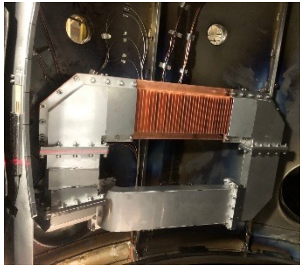


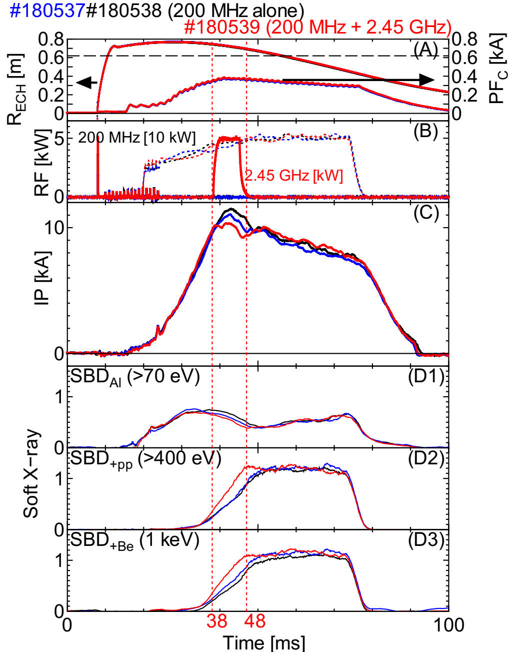
3 hr. op. @673 K
with transient cooling



- **TST-2 (Univ. Tokyo)**

Installation of a new antenna **to excite LHW** (5kW/2.45GH)
Increase in the soft X-ray, when injected to LHW (50 kW/ 200 MHz) sustained ST plasma



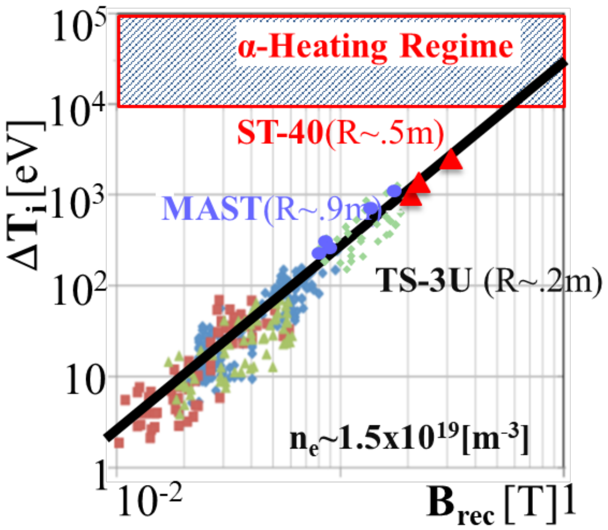


Japan: magnetic reconnection studies in TS-6 TS-4U, UTST

- TS-6, TS-4U, UTST (Univ. Tokyo)

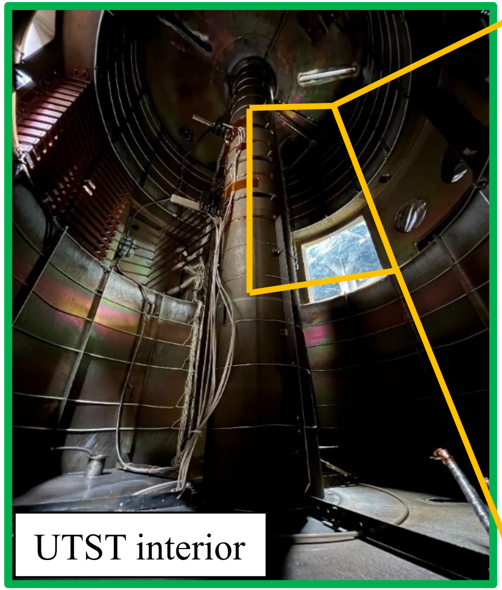
ST merging experiments for heating and for magnetic reconnection study

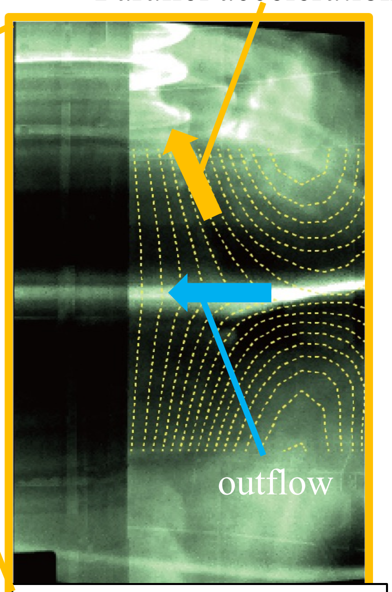
Collaboration between TSs, ST-40, MAST showing ion temperature scaling $\Delta w_{ion} \propto B_{rec}^2 \propto B_p^2$



Distributed limiter to control reconnection downstream condition in UTST

Alternation in energy conversion process





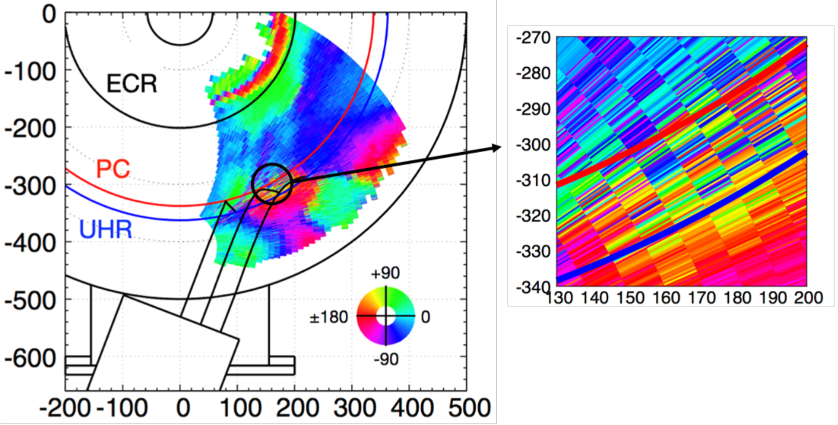
Japan: evidence of EBW heating pattern in LATE device

- LATE (Kyoto Univ.)

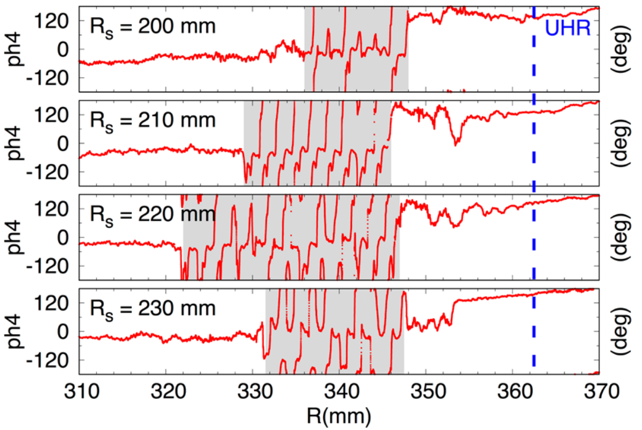
Direct measurement of 2-D wave pattern of Electron Bernstein Wave (EBW) by using five-pin probe antenna

Measurement of (obliquely injected) microwave (1.5 GHz) in an over-dense plasma, produced by ECH (2.45 GHz)

EBW-like wave pattern near the UHR layer



EWB features: short-wavelength (2 mm), backward, electrostatic, are confirmed



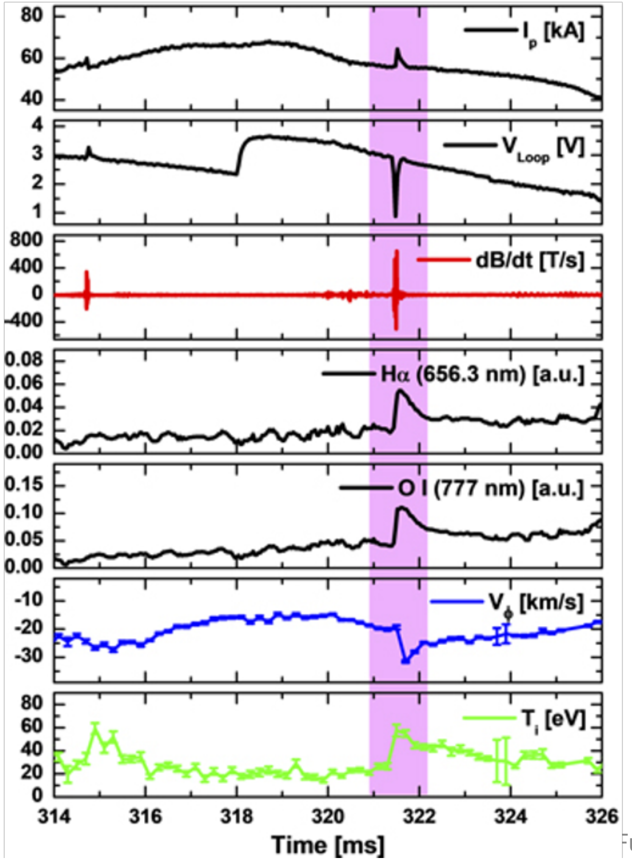
Growing number of STs in participating regions, including commercial ventures

- **China:** EXL-50, NCST, SUNIST, SUNIST-2
- **EU(/UK):** MAST-U, Proto-Sphera, SMART, ST-40
- **Japan:** LATE, QUEST, TST-2, TS-6, TS-4U, UTST
- **S. Korea:** VEST, VEST-II
- **US:** LTX-β, NSTX-U, PEGASUS-III

*new or upgraded since 2019

S. Korea: VEST characterized rotation dynamics during reconnection events

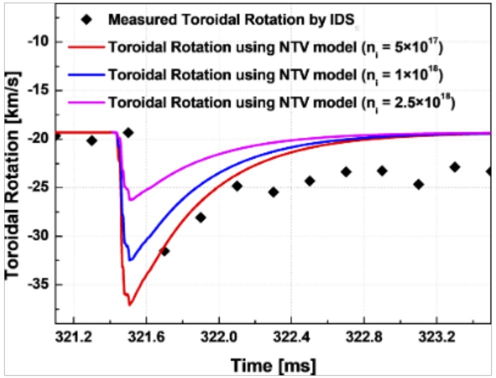
VEST



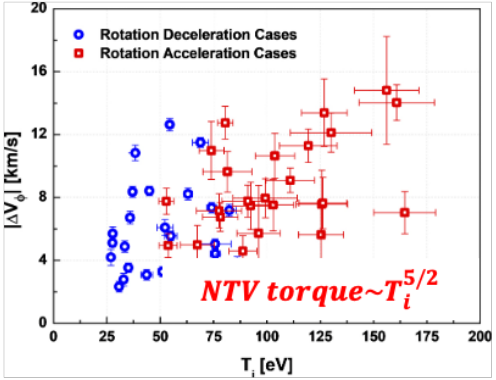
Accelerated rotation during Internal Reconnection Event (IRE)

Kim et al., NF 2021 61, 126011

- Accelerated rotation as well as ion heating is observed during IRE by Ion Doppler Spectroscopy, helping discharge recovery from IRE.
- NTV (Neoclassical Toroidal Viscosity) is thought to provide torque, which is supported by a simple modelling of momentum balance for the experimental results of enhanced plasma rotation.



Toroidal rotation: model vs. experiment



Rotation change vs. ion temperature

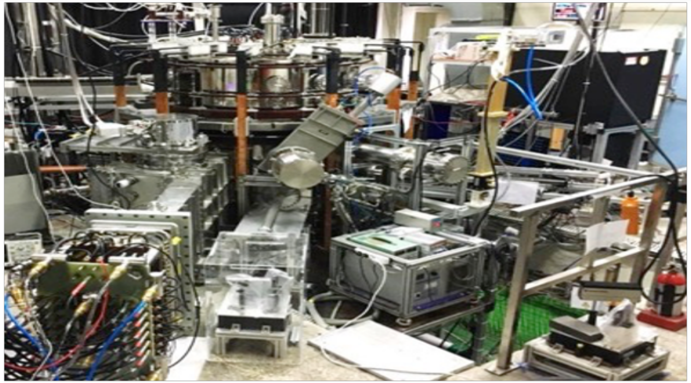
→ Accelerated rotation helping IRE recovery may provide a clue to stabilize disruptive MHD crash such as minor/major disruptions.

S. Korea: VEST-II upgrade entails wider parameter range and increased model development toward predictability

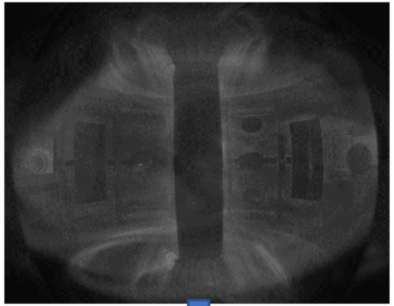
National Science Challenge Initiatives
Center for ST Fusion Metaware Research
July 2021 – December 2025

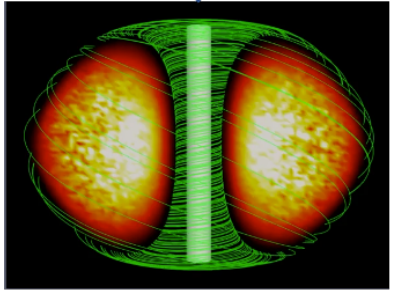
국가과학난제도전융합연구개발사업
National Science Challenge Initiatives
ST핵융합메타웨어연구단

[Hardware] VEST→ VEST II Upgrade
- ✓ $R=0.4m/a=0.3m$, $P_{NBI}=1MW/20keV$
- ✓ $I_p=0.17MA$ → $>0.3MA$, $B_{TF}= 0.18T$ → $0.3T$
- ✓ Improved diagnostics



Real experimental results





Virtual ST plasma model

Objective:
Compact Fusion Reactor by Solving the Fusion Plasma Challenge

Stability
Confinement

SEOUL NATIONAL UNIVERSITY

KU LEUVEN

[Software] ECsim (6D full PIC code)
- ✓ CPU-based : ~300M particles (Present)
- ✓ GPU/CPU hybrids : 1 trillion particles
- ✓ Real-Time AI Diagnostics

Growing number of STs in participating regions, including commercial ventures

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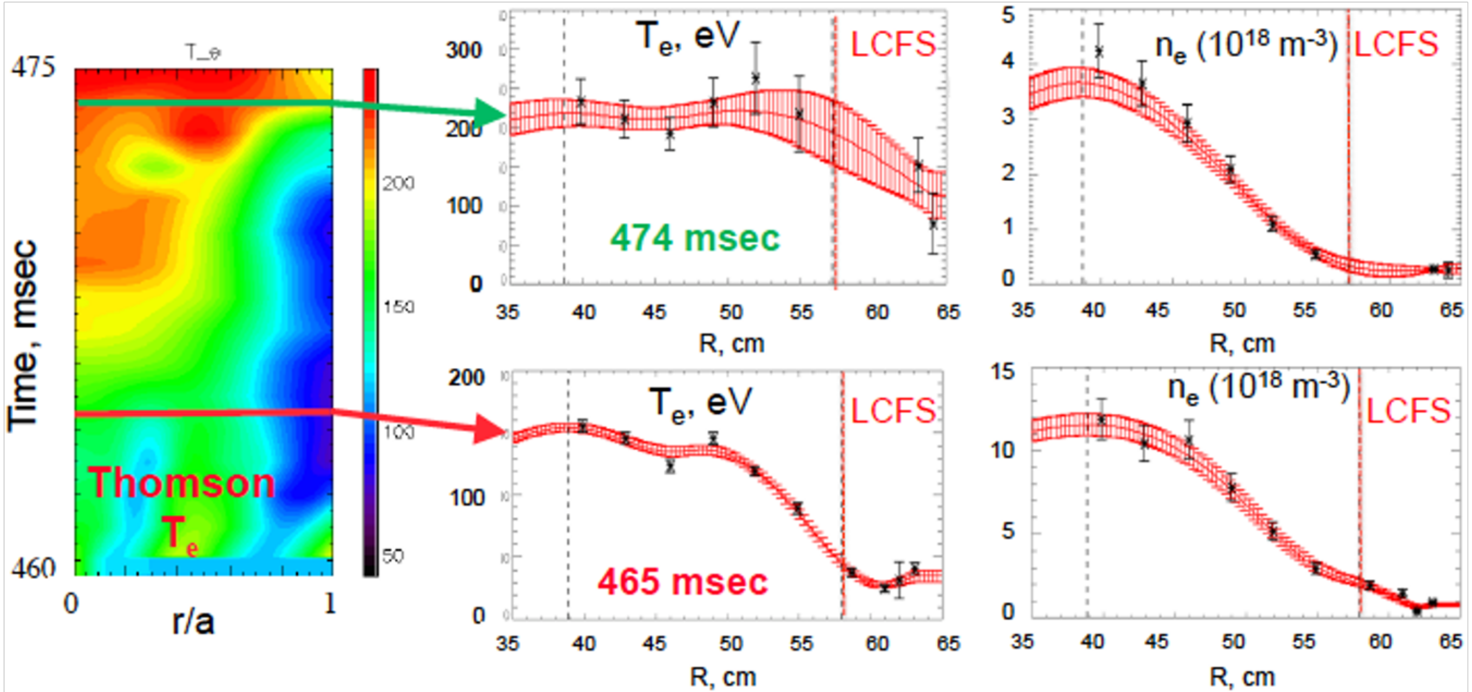
- **US:** LTX-β, NSTX-U, PEGASUS-III

*new or upgraded since 2019

US: LTX-β achieved flat, high temperature profiles with liquid Li walls

- Flat T_e profiles observed with no gas puffing and Li walls
- Impact: Prediction that flat T_e profiles reduce transport, increase τ_E; less sputtering for Li at the wall (above the peak T_e)

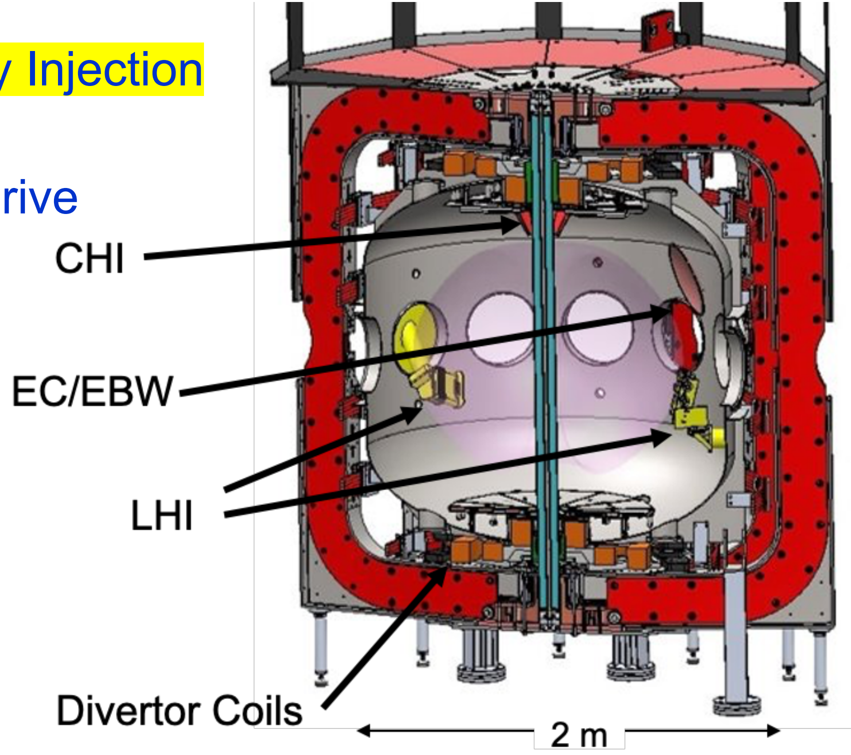


R. Majeski, *Phys. Plasmas* **24** (2017) 056110

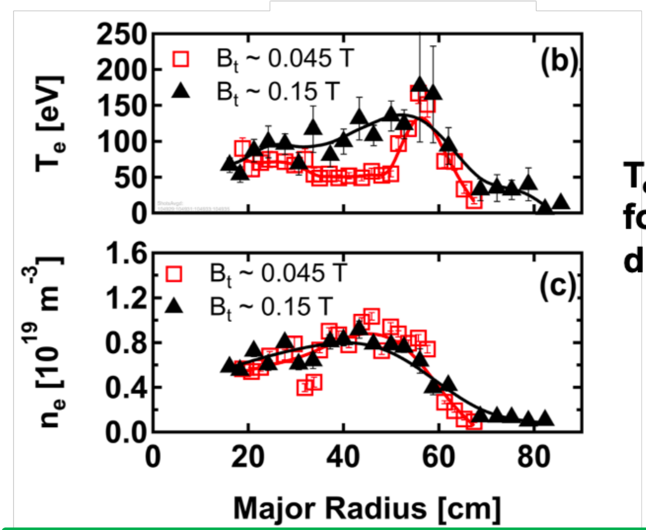
US: PEGASUS-III extends capabilities with emphasis on helicity injection

- Future ST designs call for solenoid-free operation
- Mission: Solving solenoid-free startup
  - Advanced Local Helicity and Coaxial Helicity Injection
  - RF assist, sustainment and startup
  - Compatibility with NBI heating and current drive

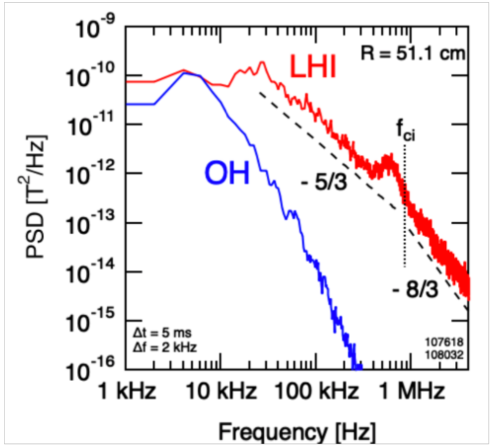
Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18



US: Final PEGASUS campaign produced seminal results during helicity injection studies



T_e, n_e profiles for LHI discharges



Magnetic power spectral density in plasma edge

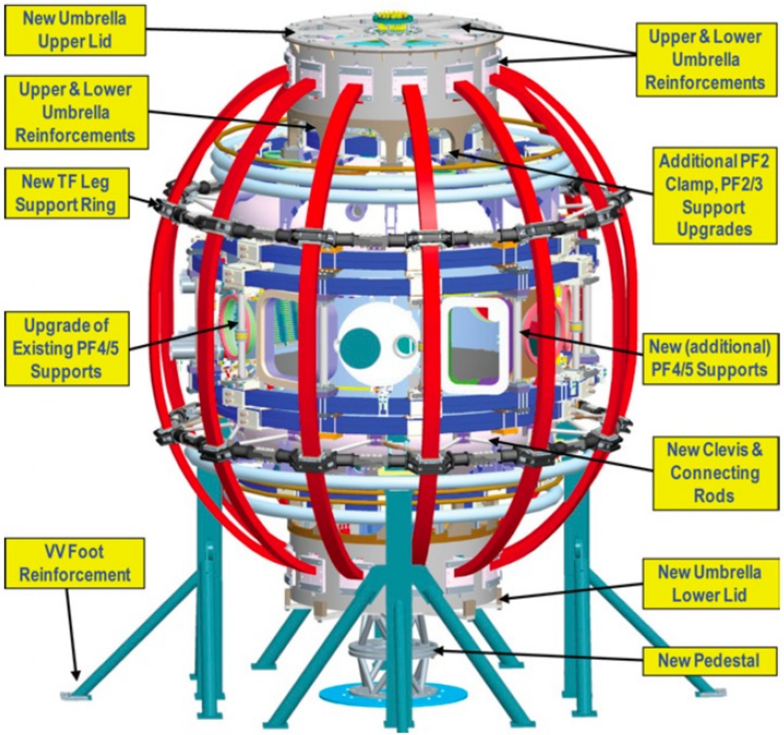
- First systematic measurements of T_e profiles during LHI selected as **Editor's Pick** by the Physics of Plasmas Editors
- T_e(R) profiles hollow at low B_T, flat-peaked at highest B_T available (B_T = 0.15 T)
  - Peak T_e comparable to central T_e in Ohmic discharges

G.M. Bodner, et. al, Physics of Plasmas 28, 102504 (2021)

- First systematic measurements of small-scale magnetic turbulence accepted by **Physical Review Letters (2022) article by N.J. Richner**
- Injected electron beams excite short-wavelength Alfvenic turbulence & reconnection activity – correlated to give local magnetic dynamos that drive toroidal current locally
  - Sum of current driven over magnetic spectrum comparable to total I_p

US: NSTX-U rebuild continues

- NSTX-U had a ten-week run in 2016 during which time some of the PF coils started to behave unpredictably
  - Problems with insulation – decision was to rebuild 6 PF coils
  - Data analysis from first run completed in 2017
- As project was nearing completion in 2021, the TF bundle turn-to-turn resistance started to decline
  - Problem with AquaPour compound used in VPI process
  - Assessing if "cleaned" bundle can be re-used (late CY 2023) and prepring to build a new bundle



Outline

- Introduction and Objectives
- Research Highlights 2017-2021
- Proposed Work Plan

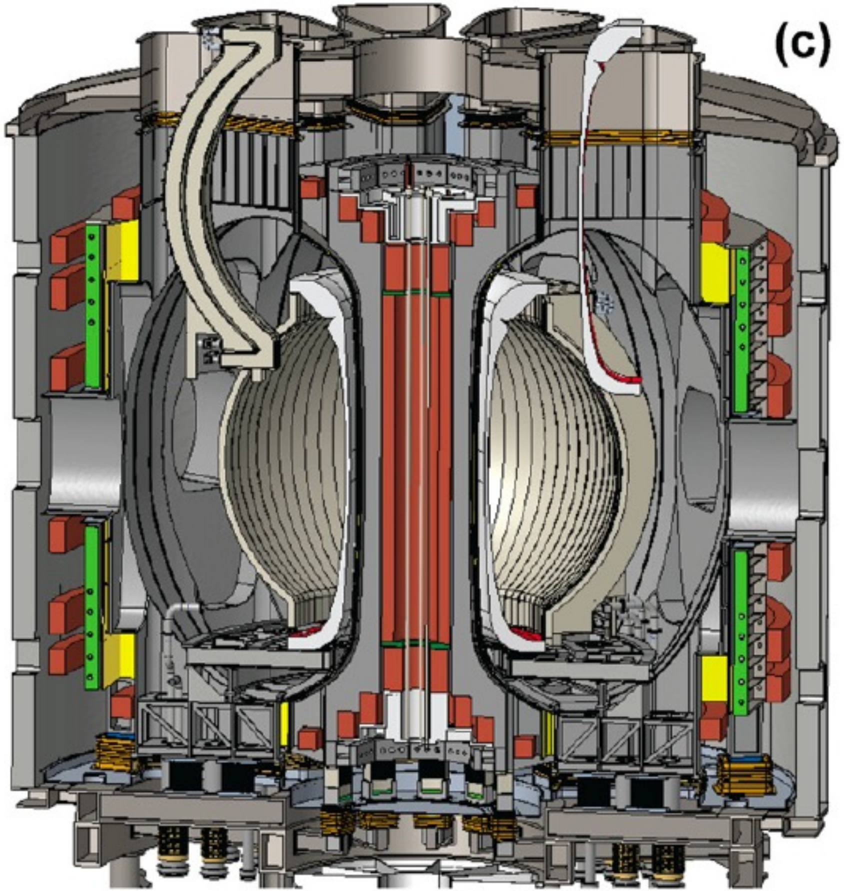
ST ExCo partners expanded during 2017-2020

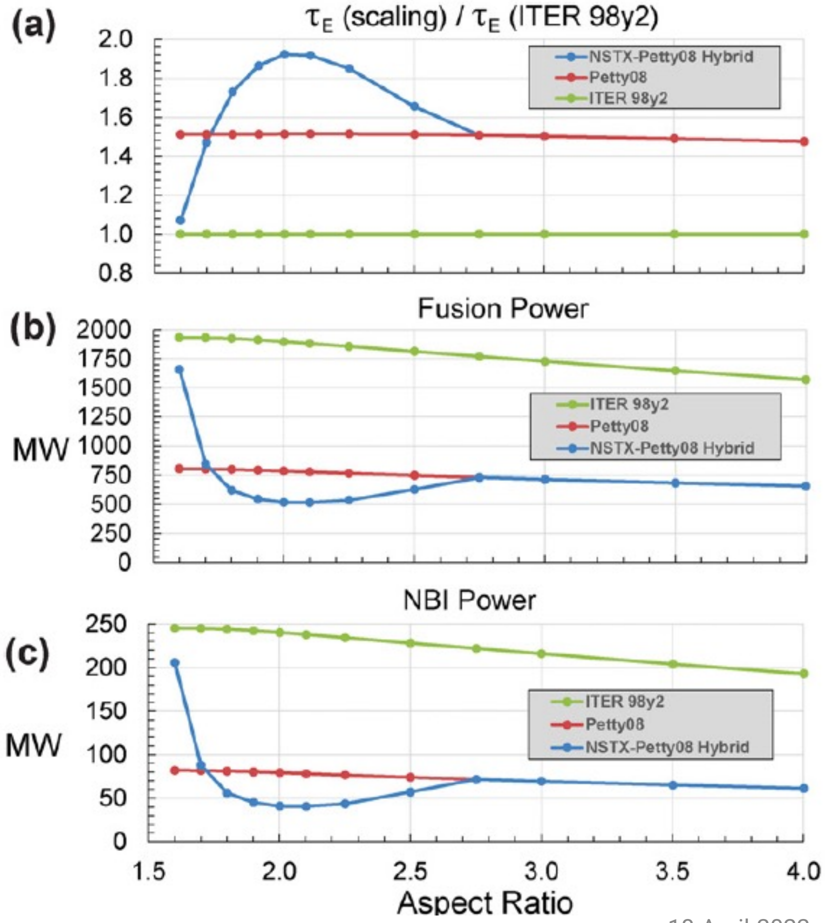
- S. Korea and China joined as TCP partners in 2018 and 2020 respectively
- There were 5 ExCo meetings from 2017-2022
    - In-person at ST Workshops, others virtual
- ST workshops were held in 2017 (SNU, Seoul, S. Korea) and 2019 (Frascati, Italy) respectively, but the one scheduled for 2021 was delayed until 2022, due to COVID
    - Will have option for a virtual meeting, given unpredictable COVID evolution and future quarantine requirements
- Modernization of the ST TCP agreement in progress

Proposed Work Plan

- Extend collaborative R&D through bilateral and multi-lateral agreements
  - 12 US groups were funded to collaborate on MAST-U in the areas of fast particle physics, plasma exhaust, real-time control, core and edge confinement, MHD; a follow-on solicitation is being considered to continue the work (US-EU)
  - There is a PPPL-UKAEA postdoctoral program that has supported at least 8 fellows on ST R&D
  - Bilateral agreements between CN and UK have enabled collaborative diagnostic deployment
  - MAST-U exploitation is ~30% driven by the EU task leaders
- Continue to organize biennial international ST Workshops
- Continue to collaborate on ST reactor designs, e.g. US studies and the STEP program

US: Pilot Plant Study targets optimization of aspect ratio





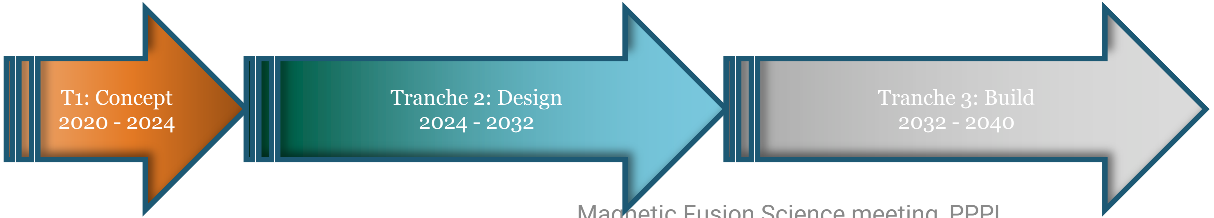
J.E. Menard et al., *Nucl. Fusion* **62** (2022) 036026

EU: Spherical Tokamak for Energy Production (STEP) started!

- From 2019 onwards the UK embarked on a programme to:

Deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion.

- About ~40 conceptual flat top operational points have been evaluated and a preferred operating point has been identified that deliver $P_{el} > 100\ MW$
  - 1D+ integrated modelling (JETTO) to integrate the system code assumptions (Bohm-gyro Bohm transport) + MHD, α-particle loss, pedestal and vertical stability assessment.
- Entirely microwave heated with access for both ECCD and EBW current drive.
- Non-inductive ramp-up from a seed (~ 1 MA) inductive target plasma can be achieved within ½ h.
- Exhaust challenge can be handled with alternative divertor concepts for all divertor legs.



ECCD operating point	
$\boldsymbol{R_{geo}}$ **[m]**	***3.60***
$\boldsymbol{A}$	***1.8***
$B_t\ (R_{geo})$ [T]	*3.2*
$I_p\ [MA]$	*19.9*
κ	*2.93*
δ	*0.50*
$\boldsymbol{P_{fus}}$ **[GW]**	***1.76***
$\boldsymbol{P_{ECCD}\ [MW]}$	***150***
$P_{rad}\ [MW]$	*340*
$\boldsymbol{Q}$	***12***
β_N	*4.4*
f_{BS}	*0.81*
n/n_{GW}	*99.6*
l_i (3)	*0.32*
q_{min}	*2.1*
q_{95}	*8.5*
$\eta_{CD}\ [A/W]$	*0.024*
$\langle n_i \rangle\ [10^{20} m^{-3}]$	*1.35*
$\langle T_i \rangle\ [keV]$	*10.3*
$P_{sep}/R_{geo}\ [MW/m]$	*42.2*

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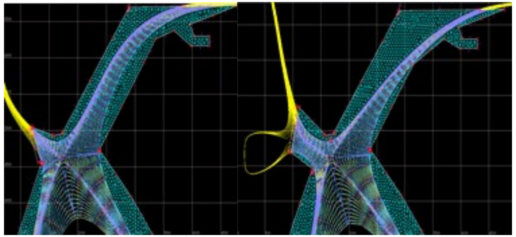
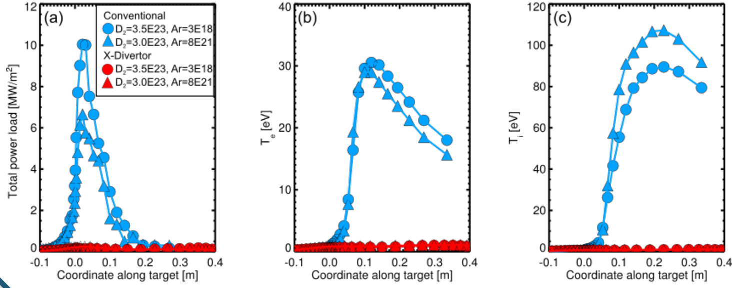
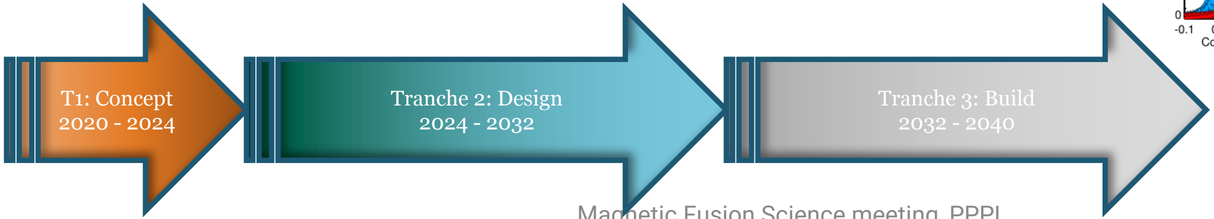
Inboard divertor magnetic geometry







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  - MAST-U exploitation is ~30% driven by the EU task leaders
- Continue to organize biennial international ST Workshops
- Continue to collaborate on ST reactor designs, e.g. US studies and the STEP program
- **With the full operation of large ST's (MAST-U and NSTX-U) serving as a pull, the world ST community is poised to fully benefit from the TCP enabling framework!**
  - MAST-U focus on super-X divertor, NSTX-U will move to liquid lithium PFCs

Thank you for your attention