IEA Spherical Torus Technology Coordination Program (TCP) Annual Report

Rajesh Maingi, Chair of the ST TCP Executive Committee
PRINCETON PLASMA PHYSICS LABORATORY

NSTX-U Magnetic Fusion Science Meeting, 27 March 2023

ST TCP work conducted under three annexes

- **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 worldwide, both public and private

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

ST TCP very active in 2022

- *TCP was renewed in 2022 for 5 years*

Outline

- International ST Workshop (virtual) held Oct. 31 – Nov. 4, 2022
- Highlights from worldwide experiments

ST Workshop succeeded in re-connecting the worldwide ST community

Year	Location
1994	Oak Ridge, TN
1995	Princeton, NJ
1996	Culham, UK
1997	St. Petersburg, Russia
1998	Tokyo, Japan
1999	Seattle, WA
2001	Sao Jose dos Campos, Brazil
2002	Princeton, NJ
2003	Culham, UK
2004	Kyoto, Japan
2005	St. Petersburg, Russia
2006	Chengdu, China
2007	Fukuoka, Japan
2008	Frascati, Italy
2009	Madison, WI
2011	Toki, Japan
2013	York, UK
2015	Princeton, NJ
2017	Seoul, Korea
2019	Frascati, Italy
2022	Virtual (Beijing, China)

- ST Workshop (virtual) held 10/31-11/3/22
- Many members from the IEA ST TCP ExCom served on the ISTW Program Committee – thank you!
- Thanks to Prof. Gao for offering Tsinghua Univ. to be the host
- Special thanks to Prof. Tan Yi and Jack Berkery for their coordination efforts
- ISTW 2024 will be in person, site TBD by ST TCP ExCom – stay tuned

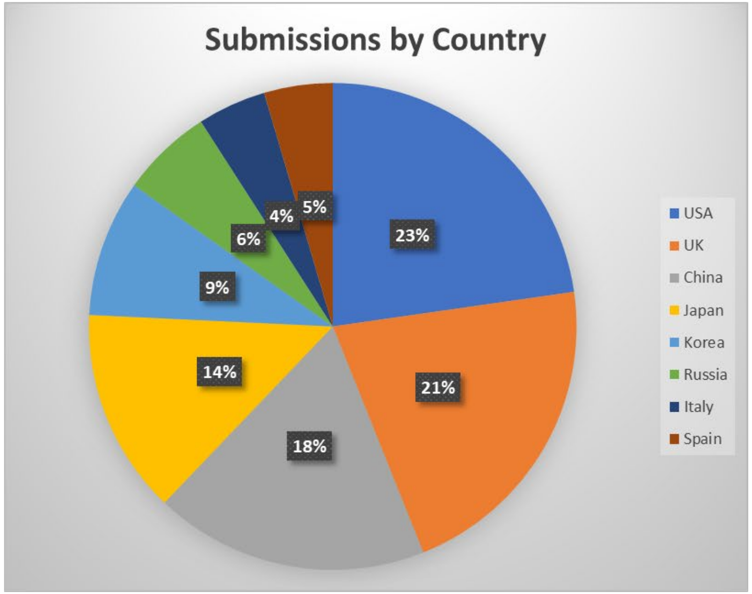
International ST Workshop had excellent worldwide participation

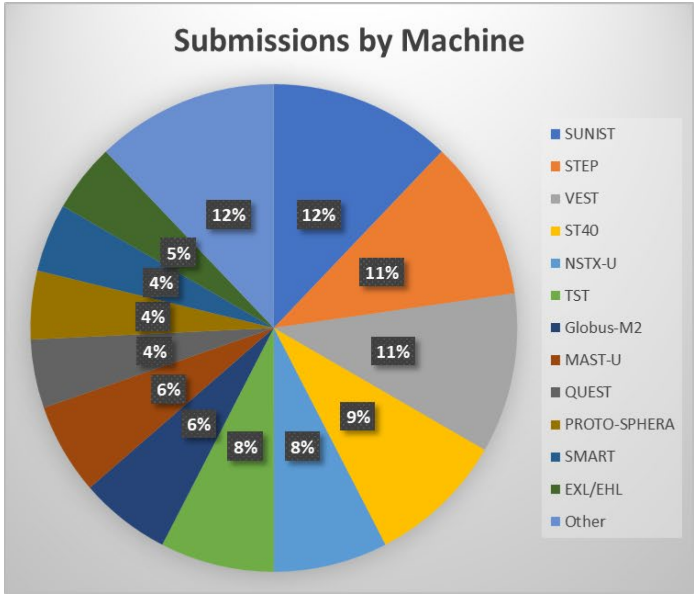
- 92 people registered
  - 43 requested an oral presentation
  - 23 requested a poster
  - 23 requested no presentation (most of these were from Tsinghua U.)
- Eight countries represented
  - 31 from China
  - 19 U.S.
  - 15 U.K.
  - 11 Japan
  - 6 Korea
  - 4 Russia
  - 3 Spain
  - 3 Italy
- ~24 Institutions represented
  - Led by:
  - 25 Tsinghua University
  - 13 PPPL
  - 9 UKAEA
  - 6 Seoul National University

Courtesy of J. Berkery

Abstract submissions received by ST Workshop

- Total number: 66
  - 43 requested an oral presentation
  - 23 requested a poster





Courtesy of J. Berkery

ST TCP very active in 2022

Outline

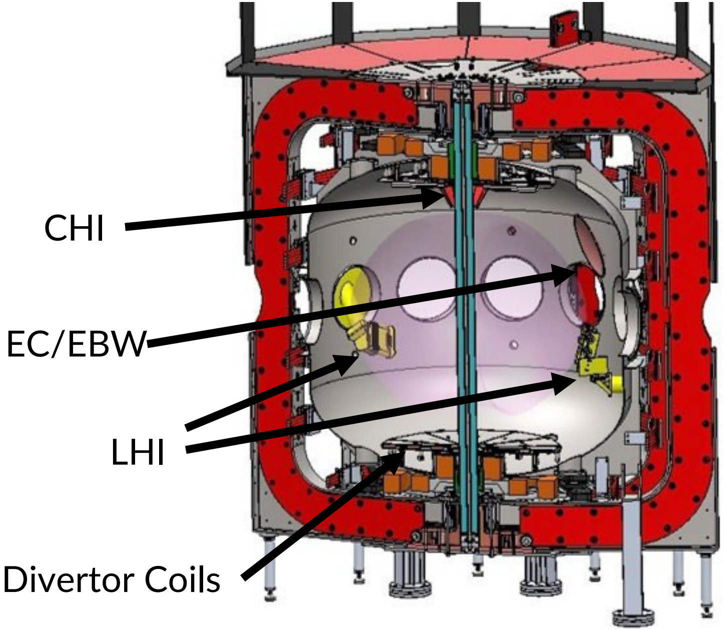
- International ST Workshop (virtual) held Oct. 31 – Nov. 4, 2022
- Highlights from worldwide experiments (in reverse alphabetical order)

US: Next Steps for STs: Elimination of Solenoid to Establish Non-Inductive Startup Pathway for Fusion Energy

- PEGASUS-III Mission: Solving solenoid-free startup for STs (and ATs)
  - Advanced Local Helicity Injection
  - Floating Coaxial Helicity Injection
  - Microwave assist, sustainment and startup
  - Compatibility with NBI heating and current drive
- Research program will provide a predictive understanding of these solenoid-free techniques
  - Extrapolatable techniques to MA-class STs (and ATs)

PEGASUS-III features:

- No solenoid
- 4x toroidal field
- Advanced control
- Expanded diagnostics

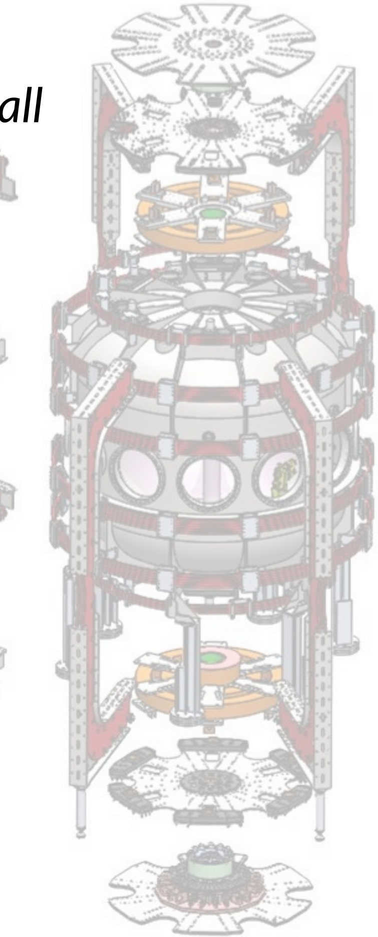


Courtesy of S. Diem

US: All Major PEGASUS-III Upgrade Sub-Assemblies Nearing Completion

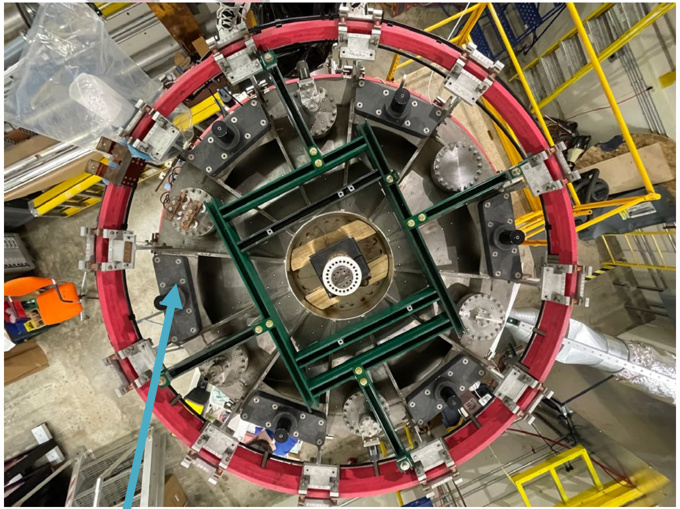
TF bundle installed in vacuum wall

Contact - indexing area



Courtesy of S. Diem

Six pin blocks and pins installed on vessel (top shown here)

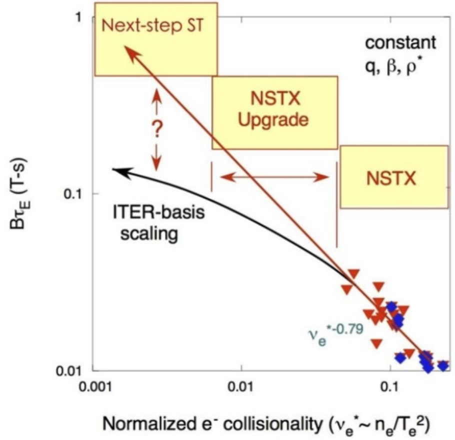


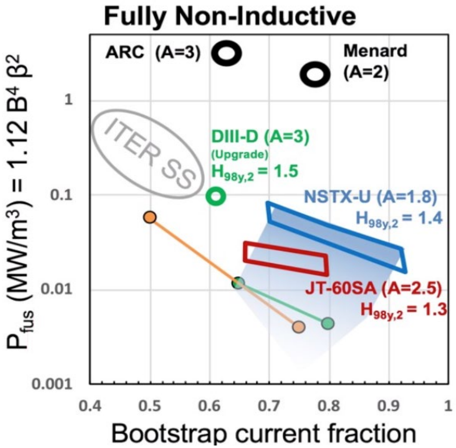
Pin block with pin attached to gusset plate reinforced ribs

Three high-level Objectives comprise the mission-oriented NSTX-U research program

1. Extend confinement and stability physics basis at low aspect ratio and high beta to lower collisionality
   - Enhanced confinement necessary for FPP (of any aspect ratio)
   - Does good ST confinement extend to low collisionality?
2. Develop non-inductive (NI) operation at high-performance and low-disruptivity
   - Steady-state compact ST fusion devices require enhanced confinement, NI operation
   - Develop unique high-beta, strong shaping route to NI operation
3. Develop and evaluate conventional and innovative power and particle handling techniques
   - NSTX-U designed for 8 MW/m^2 for 5 s; can access 50-100 MW/m^2

NSTX-U rebuild continues, First Plasma 3/2025 (early finish)

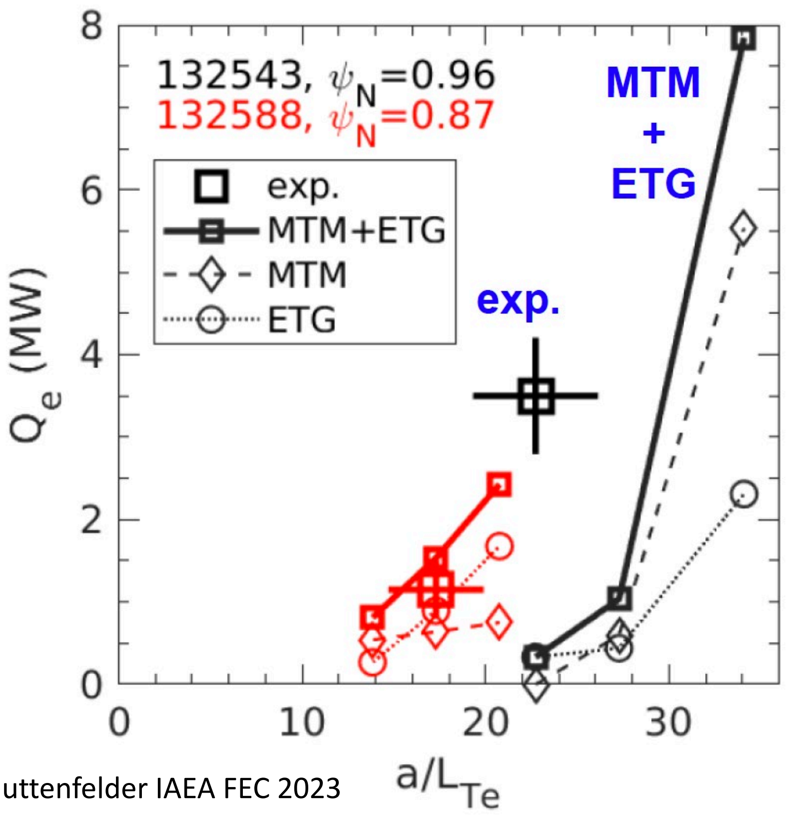




US: NSTX Data Analysis in key objective areas

- Core physics: gyrokinetic simulations of electron heat flux match data
  - Substantial work on developing an R/a independent pedestal model, both on pressure gradient limits and ideal MHD limits
- Evaluating ECCD effectiveness for next step STs based on NSTX-U physics basis
- Developing liquid metal PFCs to be tested in NSTX-U, based on designs for FNSF

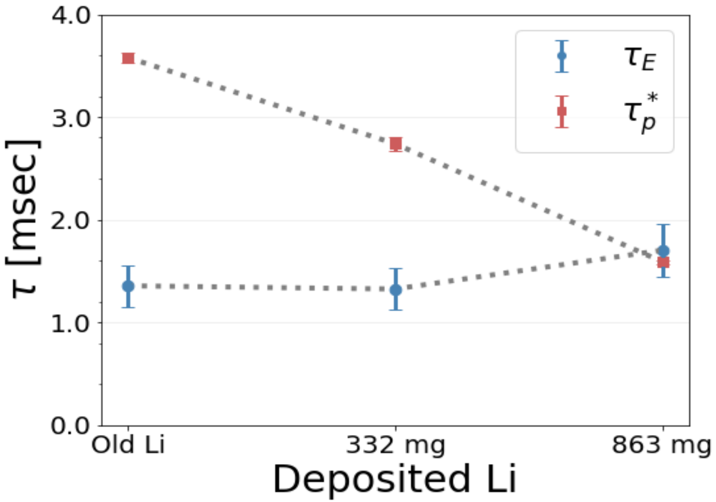
Electron heat flux: Experiment compared to nonlinear MTM + ETG simulations



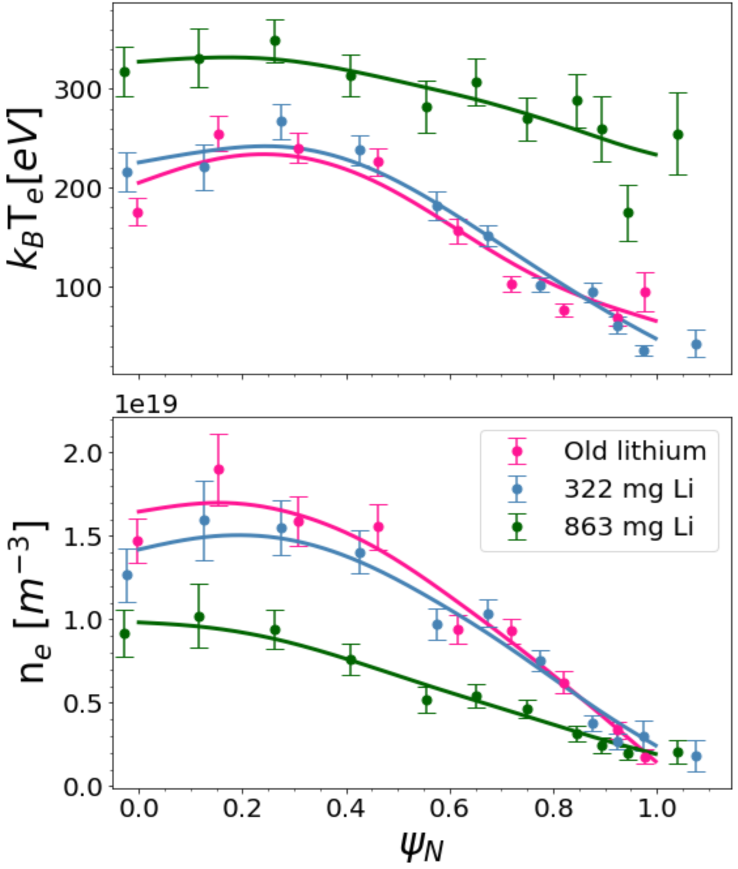
Guttenfelder IAEA FEC 2023

US: LTX-beta sustained flat T_e profiles with lithium PFCs

- Flat T_e profiles sustained: edge Te ~ core T_e
  - Results extended with neutral beam injection to extend core heating beyond ohmic heating
- Recycling reduced with Li PFCs: $\tau_p^* \sim \tau_E$



Maan NME 2022



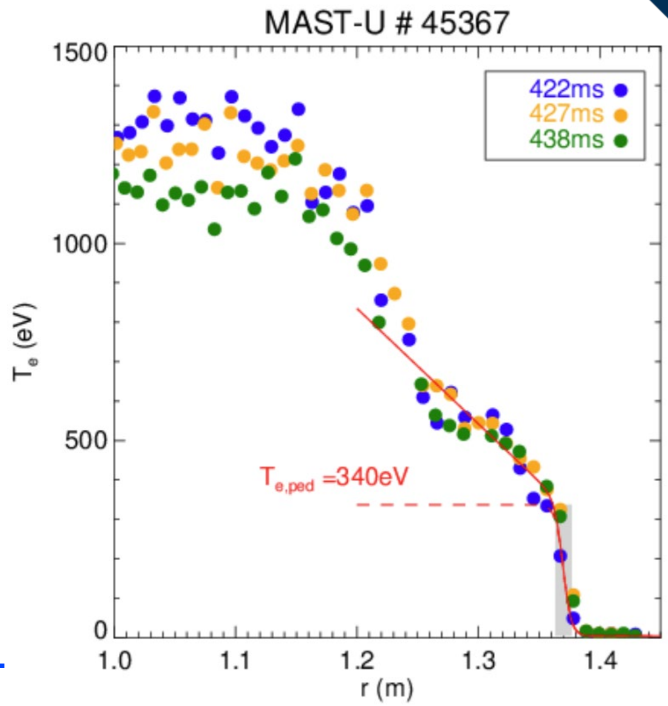
Boyle NF 2023

UK: MAST-U achieved high performance operating scenarios

UK Atomic Energy Authority

- **Developed 1s long type-I ELMy H-mode scenarios**
  - Sustained $T_{e,ped}$ up to ~340 eV, 400 eV transiently
  - $T_{e,core}$ up to 2 keV, $T_{i,core}$ up to 3 keV
  - Injected NBI power up to 3.6 MW
  - ELM mitigation with RMPs observed

- **Developed initial 1 MA plasma scenario**
  - Increased toroidal field from 0.65T to 0.72T on axis

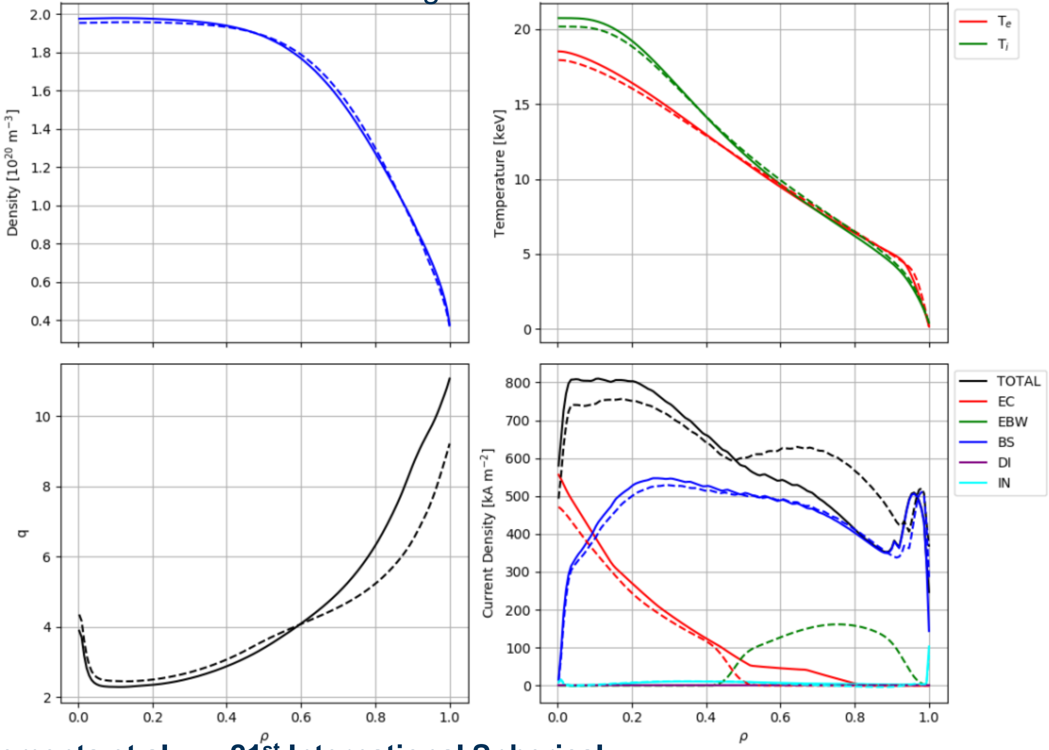


Courtesy of H. Meyer

EUROfusion

UK: Preferred non-inductive operating points on STEP give access to ECCD and EBW

ECCD: Electron cyclotron heating & current drive
EBW: Electron Bernstein wave heating & current drive



H&CD	EC	EC/EBW
R_{geo} [m]	3.60	
A	1.8	
$B_T\,(R_{geo})$[T]	3.2	
I_p [MA]	20.9	22.0
κ	2.93	
δ	0.59	0.50
P_{fus} [GW]	1.76	1.77
P_{net}^{el} [MW]	188	182
P_{ECCD} [MW]	150	154
P_{rad} [MW]	338	341
Q	11.8	11.5
β_N	4.4	4.1
f_{BS}	0.88	0.78
$\bar{n}/n_{GW}$ [%]	100	94
l_i (3)	0.26	0.25
η_{CD}^{EC} [A/W]	0.016	0.027
η_{CD}^{EBW} [A/W]	N/A	0.034
P_{sep}/R_{geo} [MW/m]	41	
$(H_{98}+H_{98}^{\star})/2$	1.35	1.19

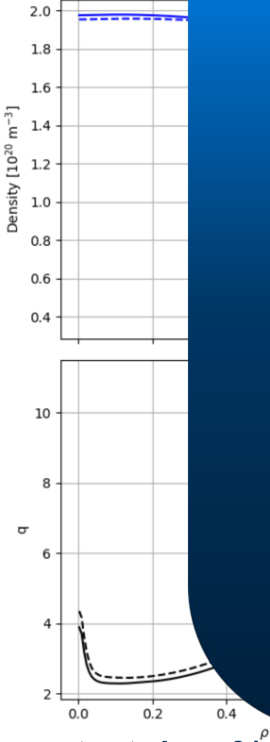
Courtesy of H. Meyer

F. Casson, F. Koechl, S. Marsden, G. Szepesi, E. Tholerus, T. Wilson

UK: Preferred non-inductive operating points on STEP give access to EC

ECCD: Electron cyclot

EBW: Electron Berns



STEP now has a site

The Step Prototype Plant will be built in West Burton-U ~200 km from Culham Science Centre

H&CD	EC	EC/EBW
[m]	3.60	
	1.8	
₀)[T]	3.2	
A]	20.9	22.0
	2.93	
	0.59	0.50
W]	1.76	1.77
MW]	188	182
MW]	150	154
MW]	338	341
	11.8	11.5
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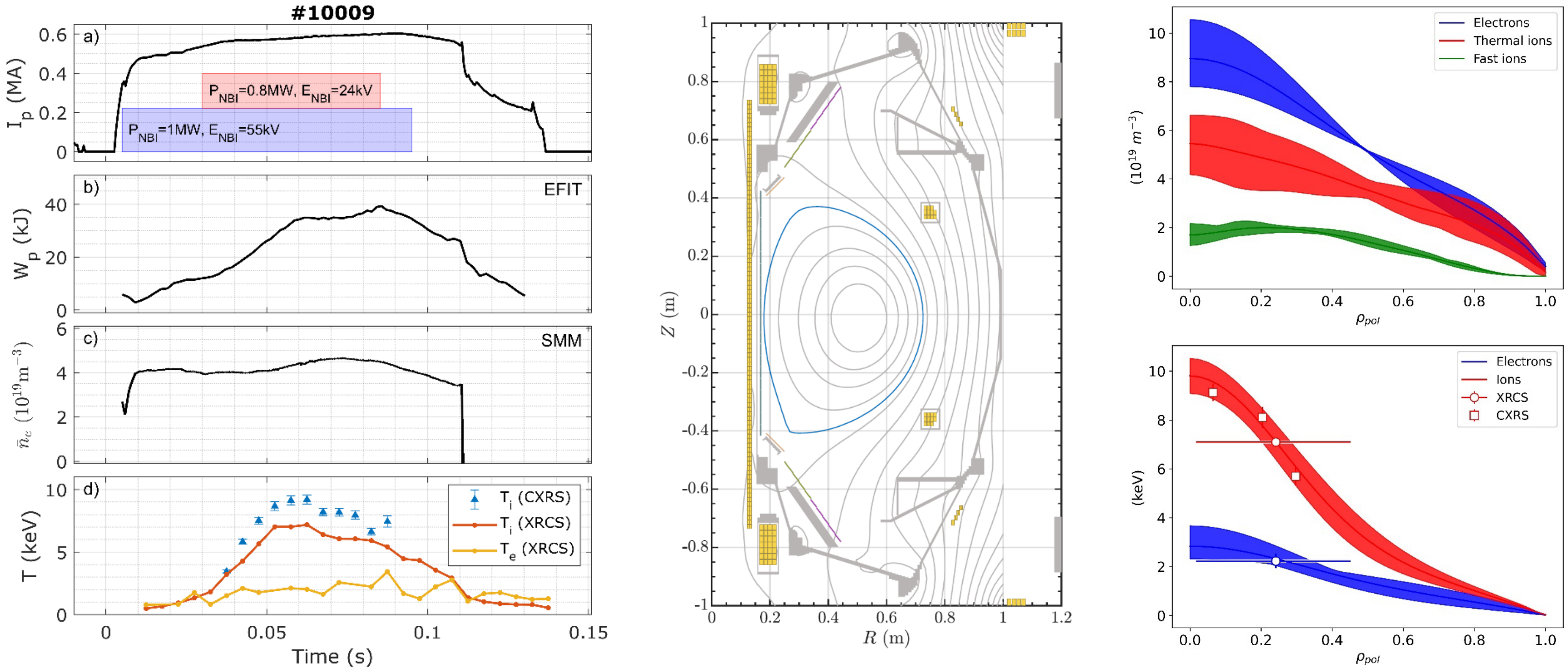
Courtesy of H. Meyer

F. Casson, F. Koechl, S. Marsden, G. Szepesi, E. Tholerus, T. Wilson

UK: ST-40 achieved T_i in excess of 100 million Kelvins

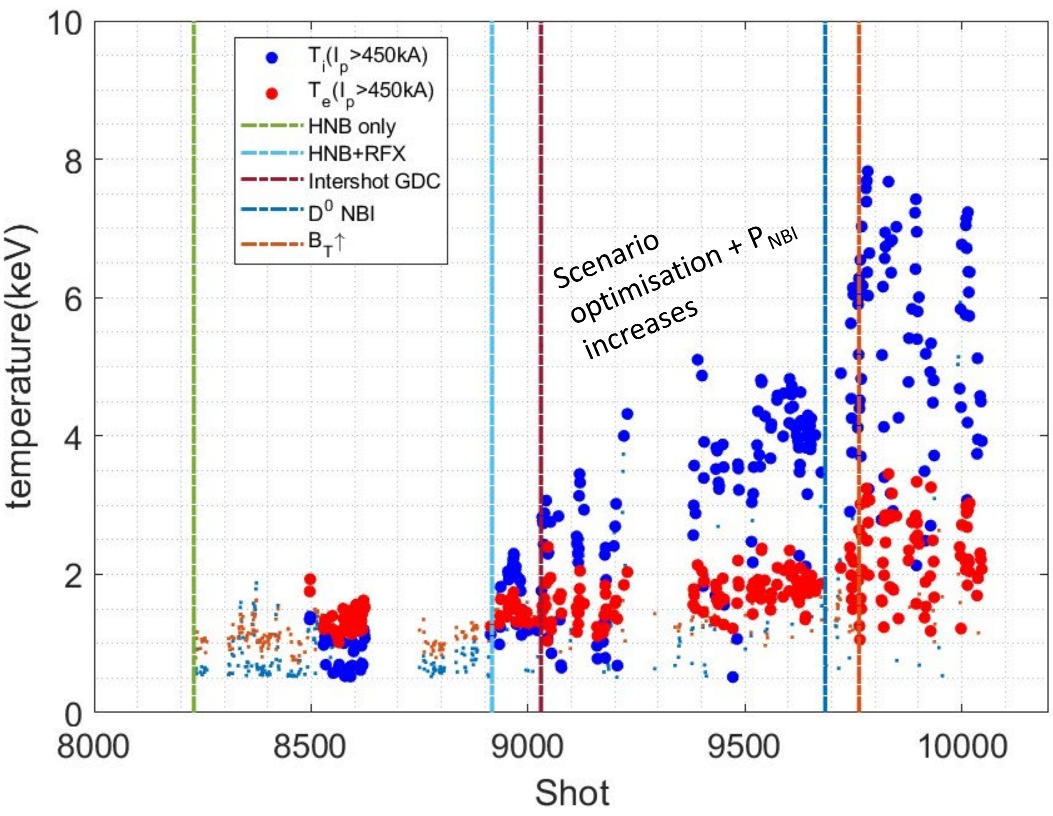


Profiles of (a) electron density, ion and fast particle densities, (b) ion and electron temperature determined using the integrated data analysis approach (#10009, t=58 ms at maximum T_i)

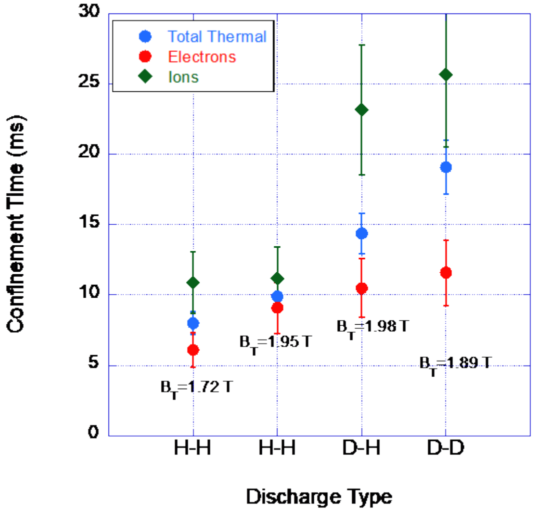
S. McNamara, NF 2023

UK: Higher B_t and NBI enables access to higher T_i and T_e on ST-40

Tokamak Energy



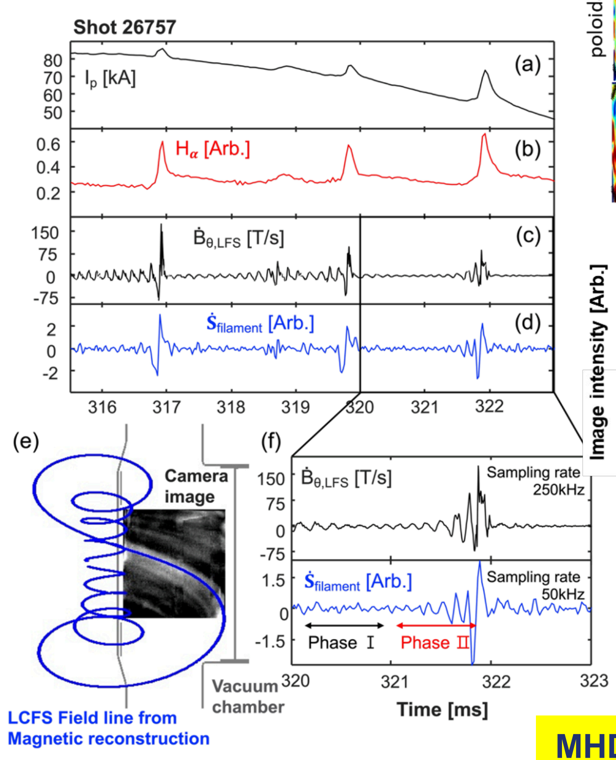
- Increased power B_T acts to suppress sawteeth, which contributes to increase in T_e
- TRANSP analysis shows that increase in T_e and T_i to confinement improvement in both channels

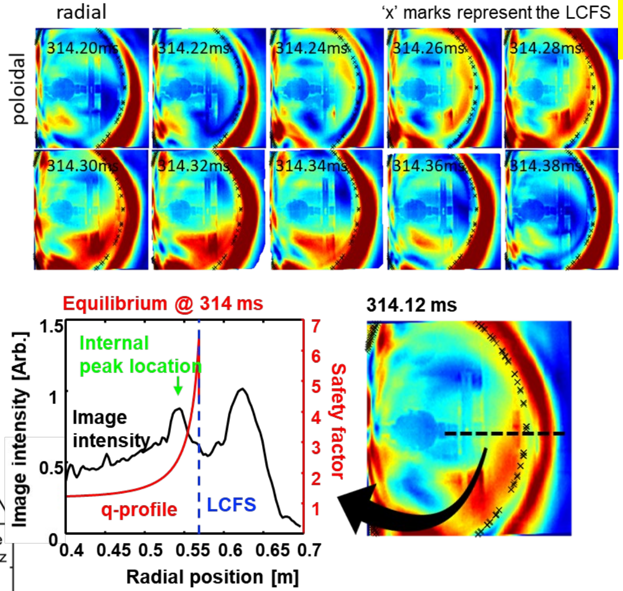


Courtesy of Tokamak Energy

KO: Interaction between external Blobs and internal MHD modes during IRE

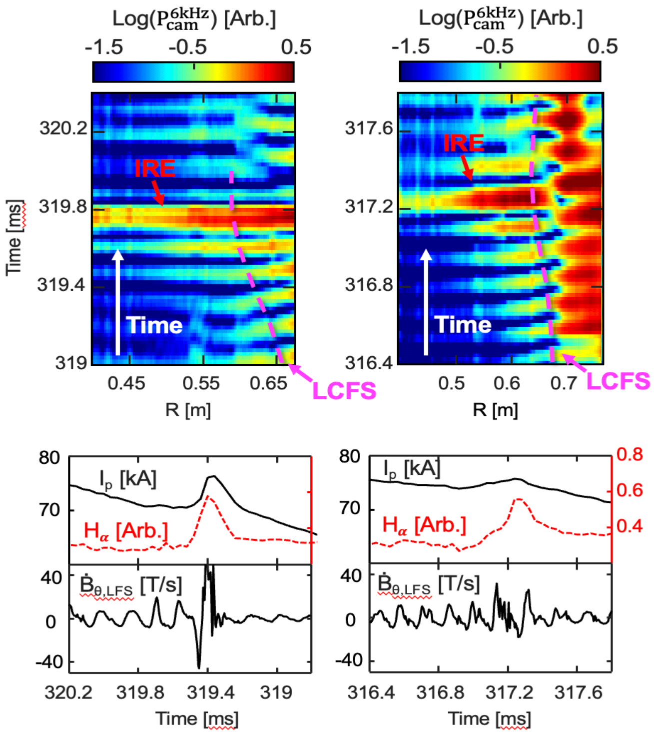
Internal Reconnection Event (IRE)





MHD-correlated blobs before IRE

Phase alignment between MHD and blobs



Courtesy of Y.S. Hwang

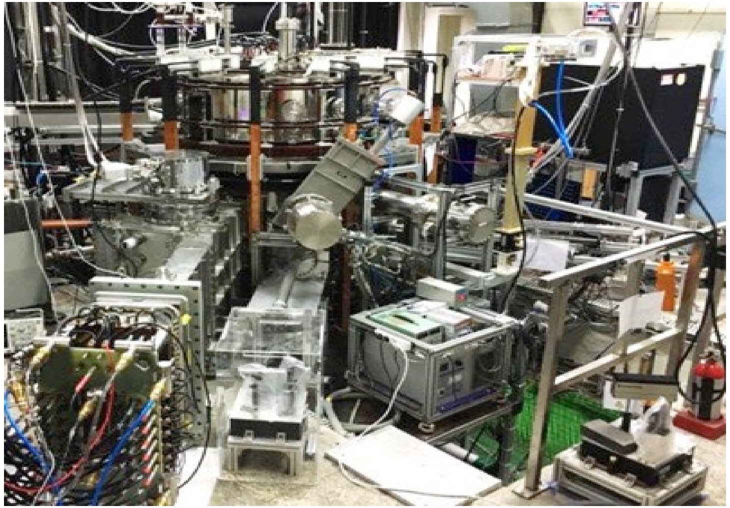
E.C. Jung et al, Nucl. Fusion 62 (2022) 126029

KO: Center for ST Fusion Metaware Research (7/2021-12/2025)

국가과학난제도전융합연구개발사업
National Science Challenge Initiatives
ST핵융합메타웨어연구단

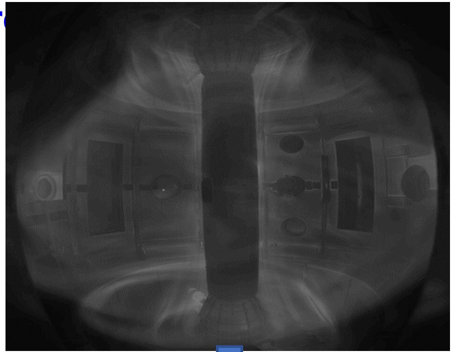
Establish Cyber Physical ST System
for the realization of compact ST fusion reactor

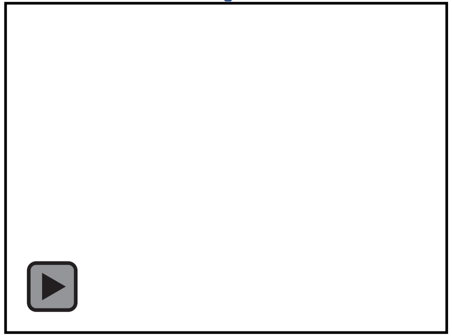
VEST will be upgraded by doubling Ohmic power and NBI power as well as diagnostic capabilities



VEST (Versatile Experiment Spherical Torus)

Real experimental r





Digital Twins (DT)

Virtual ST plasma model

GPU-based 6-D full PIC simulation code

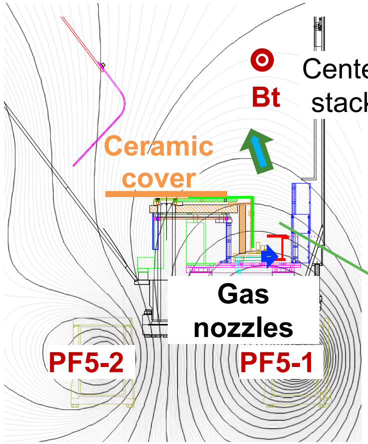
Courtesy of Y.S. Hwang

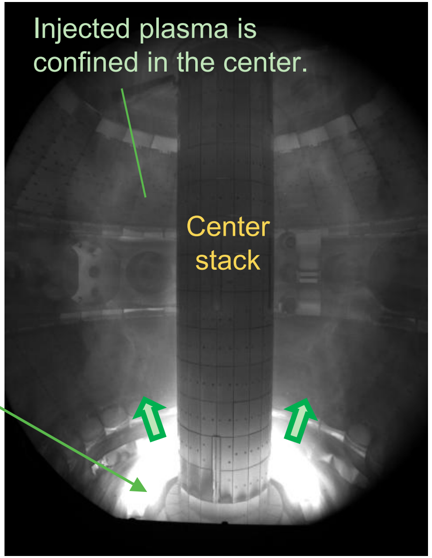
JA: progress on QUEST and TST-2

- QUEST (Kyushu Univ.)

Transient CHI start-up operation on a single biased electrode configuration.

Single biased electrode incorporated on lower divertor for Transient CHI start-up

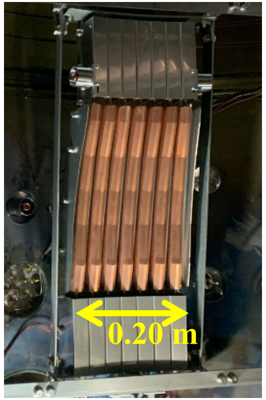


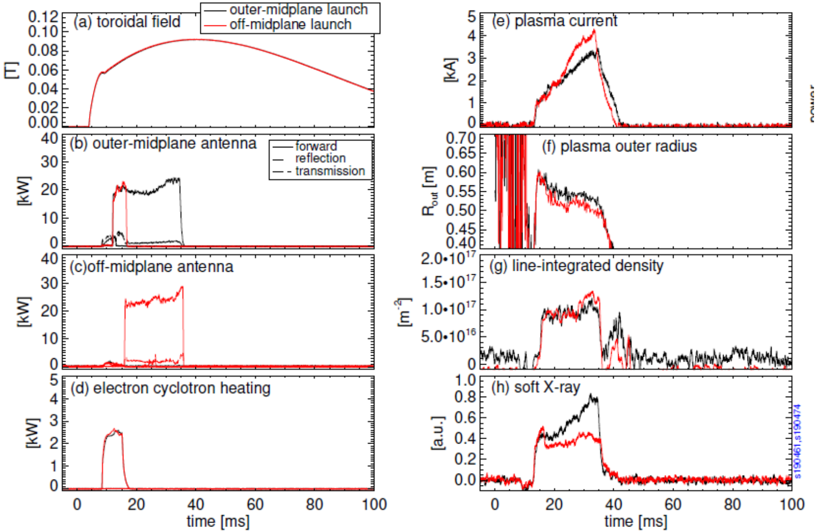


Courtesy of A. Ejiri

- TST-2 (Univ. Tokyo)

Installation of a new off-midplane comb line antenna to excite LHW (100kW/200 MHz) (see the right photograph).
Preliminary results showed better efficiency than an old antenna.





Comparison of plasmas sustained by the outer-midplane(black) and the new off-midplane (red) antennas.

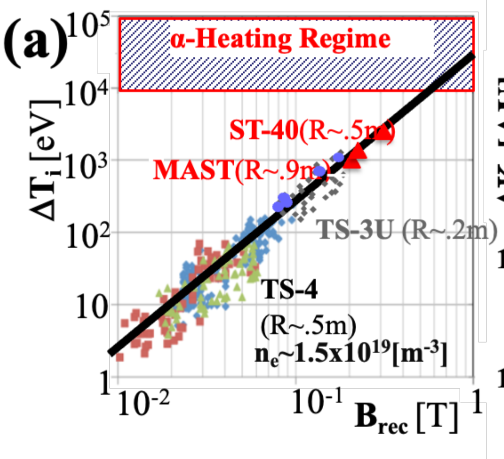
JA: progress on TS-6, TS-4U, UTST

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

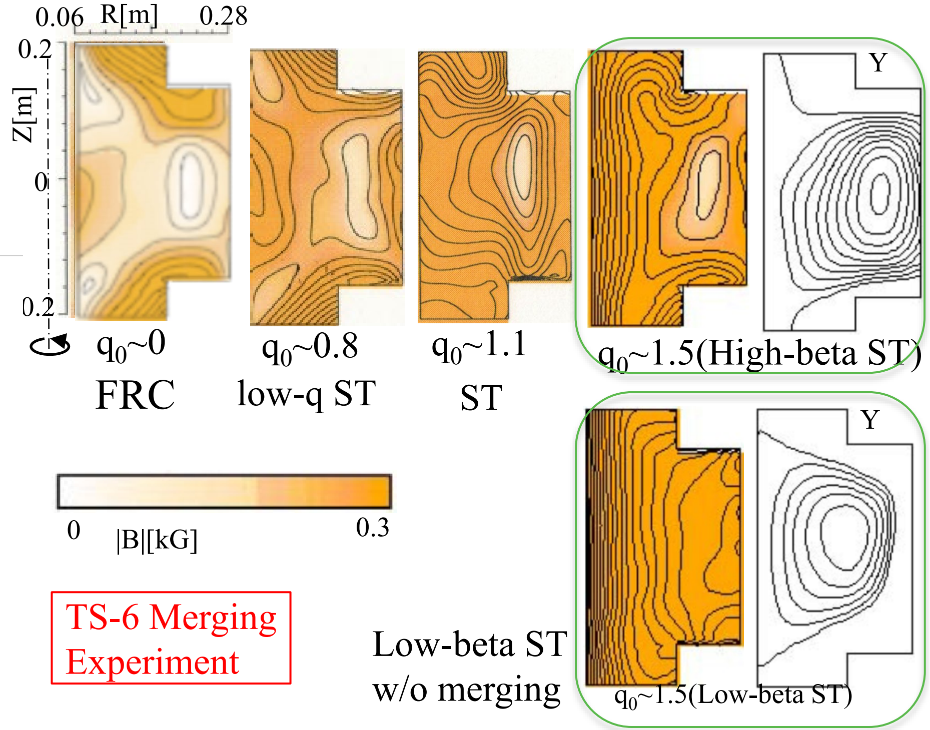
The ST reconnection heating experiments TS-6 and TS-4 studied the ion temperature scaling $\Delta w_{ion} \propto B_{rec}^2 \propto B_p^2$ for direct access to the burning plasms.

Based on collaboration between TSs and ST-40, high-field merging experiment is being made in TS-40 and documented 10^6K ion temperature using both of merging and NBI.

The high-power reconnection heating experiments TS-6 successfully formed ultra-high beta STs with absolute minimum-B configuration.



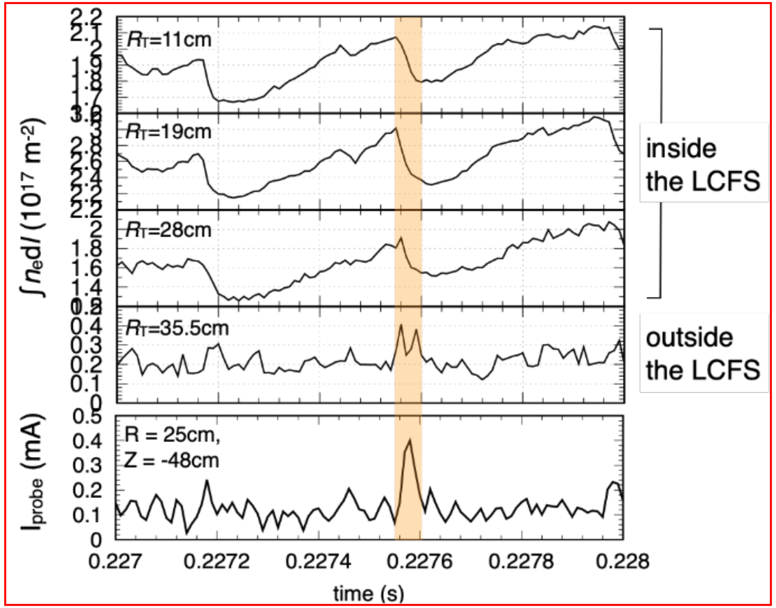
Courtesy of A. Ejiri

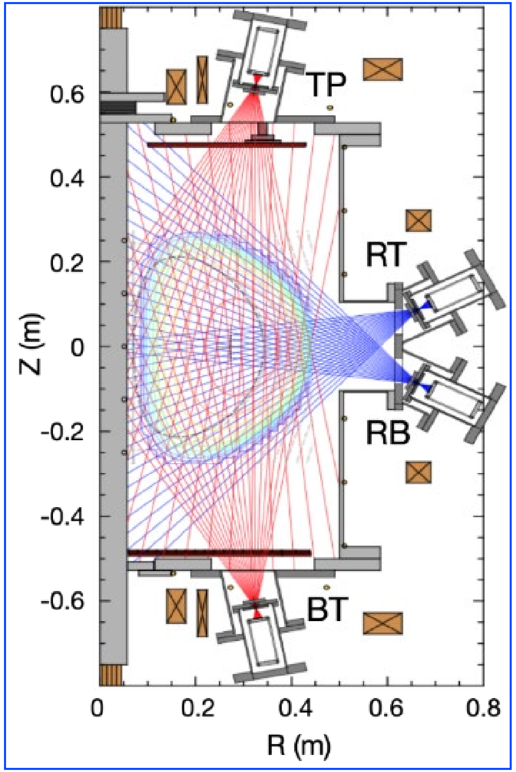


JA: progress on LATE

- LATE (Kyoto University)

Non-inductive formation of overdense ST plasma by exciting electron Bernstein wave (EBW) via O-X-B mode conversion process.
* Soft X-ray CT system is under development to investigate the plasma ejection phenomena in the overdense ST plasma.

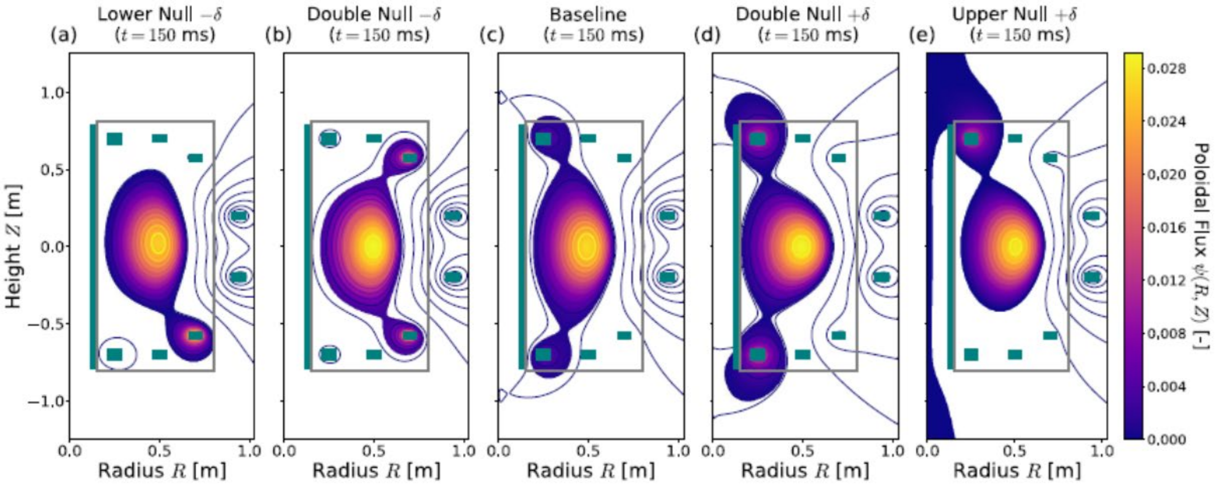




Courtesy of A. Ejiri

EU: SMART Will Explore a Wide Shaping Range at Relatively High I_p / B_t

SMART aims at high confinement regimes in Spherical Tokamaks (STs) with flexible shaping, high β, and fusion-relevant T_i, T_e, n_e, and collisionalities



Parameters	Phase 1	Phase 2	Phase 3
I_p [kA]	100	500	>500
B_t [T]	0.1	0.3	1.0
τ_{pulse} [sec]	0.15	0.5	>1
R/a (m)	0.45 / 0.25		
Aspect Ratio	1.4 – 3.0		
κ	< 3		
δ	-0.6 – +0.6		
P_e[kW]	6	6	200
P_{NBI} [MW]	-	1	1

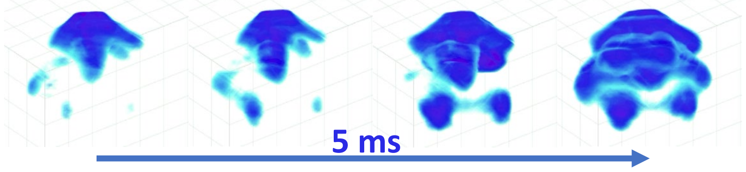
- Exploiting novel diagnostic and exhaust and plasma control techniques
- Training next generation of fusion physicists and engineers

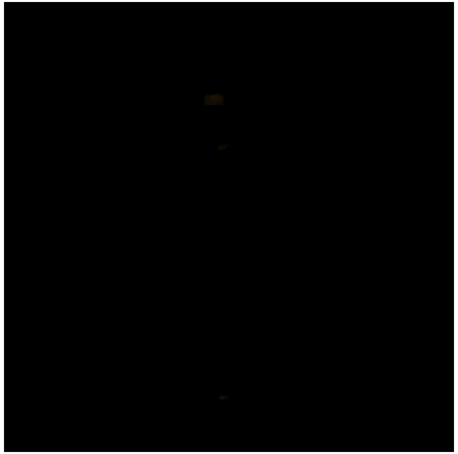
A. Mancini *et al*, Fus. Eng. Des. **171** 112542 (2021)

EU: PROTO-SPHERA confined torus sustained for up to 1 sec

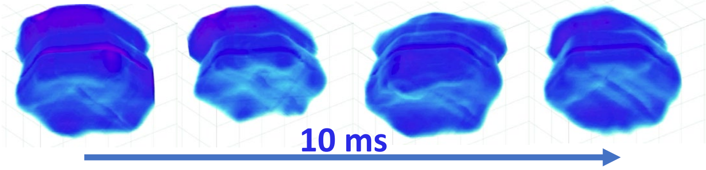
Preliminary (still with some artifacts) 3D tomographic reconstruction from 6 cameras around main plasma

PROTO-SPHERA Plasma Torus forms in 5 ms, as the Centerpost Plasma current & toroidal field grow





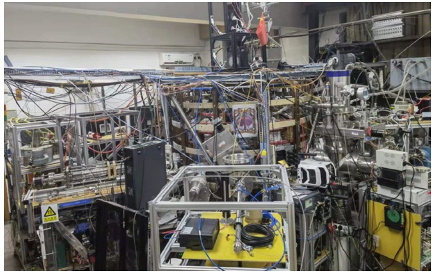
The Plasma Torus is a slightly oblique rotator maintained by 3D magnetic reconnections toroidal Plasma current enters torus in bursts



The Plasma Torus grows from a kinked filament, formed inside a pre-existing purely Magnetostatic Field:
→ a toroidal ~ axisymmetric confined plasma could be produced and maintained in steady-state by permanent magnets only

Courtesy of H. Meyer and P. Micozzi

Spherical Tokamaks in China

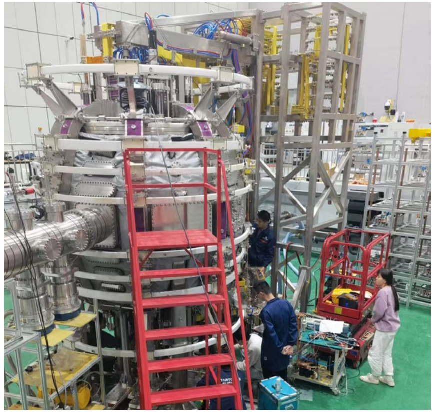


SUNIST

- Tsinghua University, Beijing
- Construction started at 2000, first plasma in 2002
- R_0 / a: 0.3 / 0.23 m
- B_{T0}: 0.15 (0.27) T
- I_P: 50 (120) kA
- Black: design, red: achieved

Research topics

- Basic properties of spherical tokamak plasmas
- EBW heating / Alfven eigenmodes



SUNIST-2

- Tsinghua University, Xi'an
- Construction started at 2020, first plasma in 2022 (expected)
- R_0 / a: 0.525 / 0.325 m
- B_{T0}: 1 T, I_P: 500 kA

Research topics

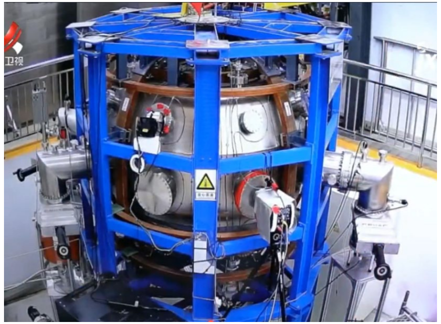
- Confinement of spherical tokamak at 1 Tesla
- Reconnection heating

EXL-50

- ENN, Langfang, Hebei
- Construction started at 2018, first plasma in 2019
- R_0 / a: 0.58 / 0.39 m
- B_{T0}: 0.5 T, I_P: 500 (160) kA
- EC waves: 1.75 MW 28 / 50 GHz

Research topics

- Solenoid-free current drive up to 140 kA by 115 kW 28 GHz EC
- p-B^{11} ST reactor



NCST

- Nanchang University, Jiangxi
- Construction started at 2018, first plasma in 2021
- R_0 / a: 0.4 / 0.24 m
- B_{T0}: 0.36 T, I_P: 100-300 (30) kA

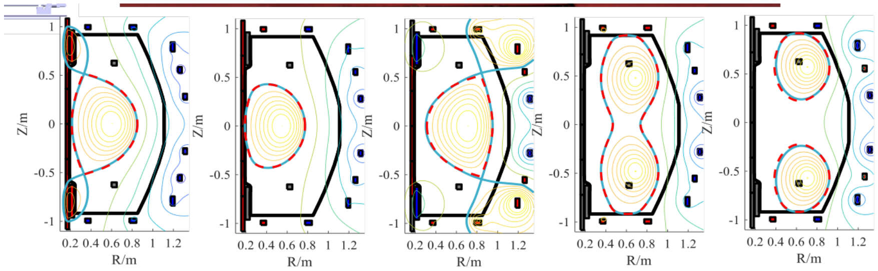
Research topics

- Solenoid-free startup by merging
- Basic properties of spherical tokamak plasmas

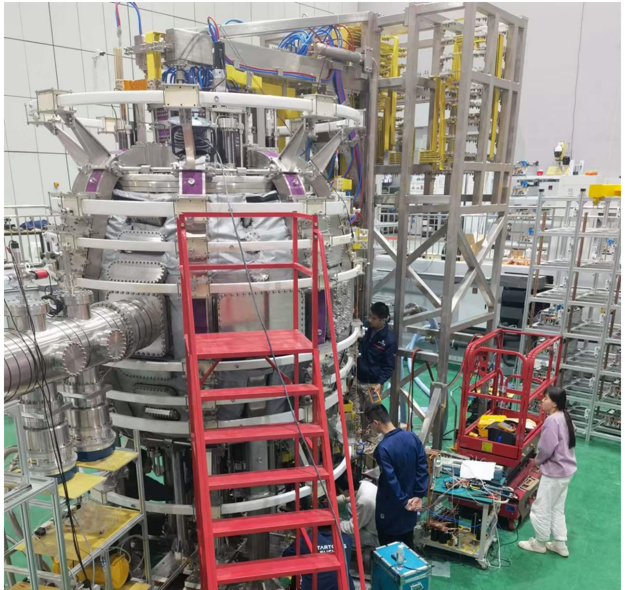
Courtesy of T. Yi

China: SUNIST-2 device construction nearly completed

- R = 0.525m, a = 0.325m, κ ~ 1.6
- I_p ~ 500 kA, B_t from 0.4 – 1.0 T
- Substantial shape flexibility
- Construction delayed by COVID-19, completion imminent



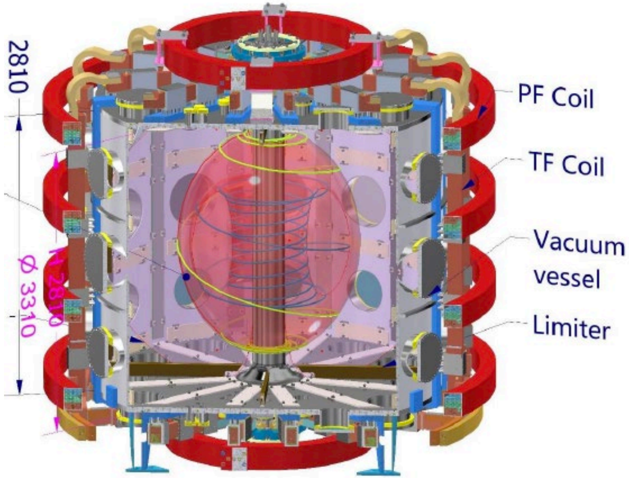
Design configurations: DND, limiter, DND with negative triangularity, doublet, droplet.

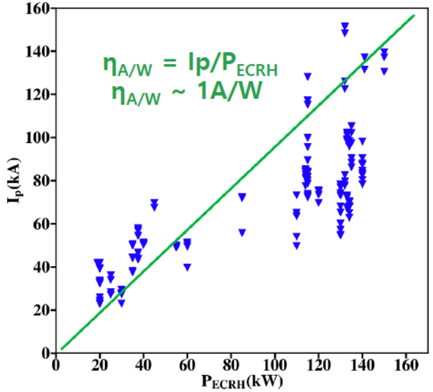


Courtesy of T. Yi

China: EXL-50 achieved efficient CD

Parameters	Values
Plasma current	0.5 MA
Thermal ions major radius R_i	0.58 m
Energetic electron cloud radius	0.7m
Thermal ions aspect ratio (LCF S)	1.5
Energetic electron cloud aspect ratio	1.3
Toroidal magnetic field (at R_i)	0.5T
Elongation	≈2
Thermal ions temperature	1 keV
Energetic electron temperature	0.23 MeV
Electron density	$2 \times 10^{19}/m^3$
Discharge TF flattop duration	5s @ 0.5T 20s @ 0.3 T





Ip versus P_{ECRH} for 200 successful shots in EXL-50

Very productive year in the ST TCP!

Looking forward to 2023, with several device upgrades coming online