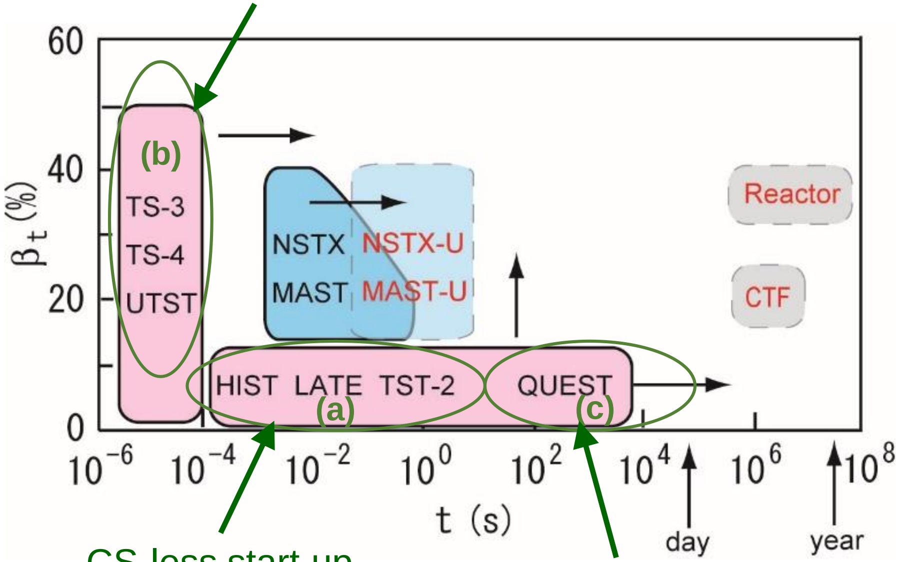
Overview of Coordinated ST Research in Japan

Y. Takase for the Japanese ST Research Programme

very high β



CS-less start-up

steady-state operation

Presentations:

P4 (Wed)

- Y. Ono (Merging ST)

P7 (Fri)

- K. Hanada (QUEST)
- T. Onchi (QUEST)
- A. Ejiri (TST-2)
- N. Tsujii (TST-2)
- H. Tanaka (LATE)
- H. Tanabe (TS-6)
- M. Akimitsu (TS-3U/TS-4U)

P8 (Fri)

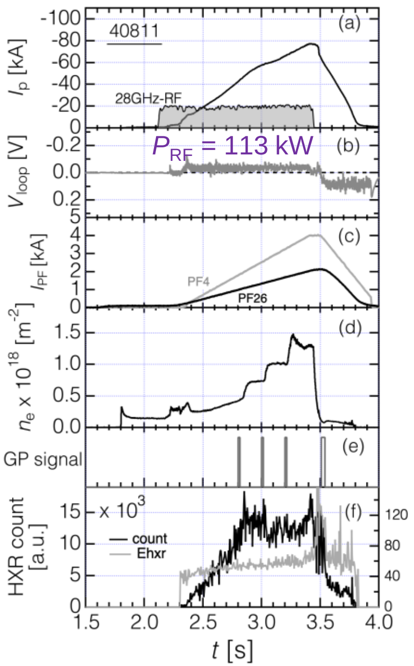
- M. Nagata (HIST)

28th IAEA Fusion Energy Conference (FEC 2020)
10–15 May 2021

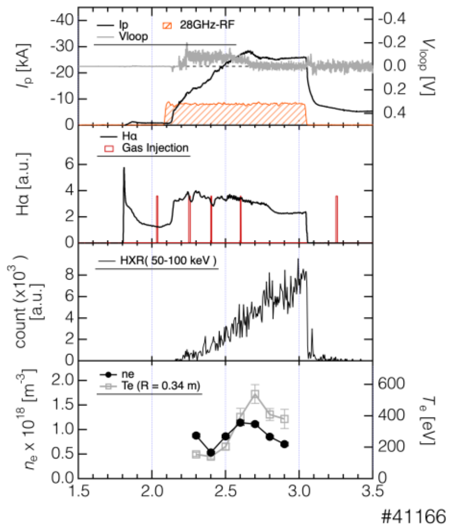
I_p start-up by RF waves

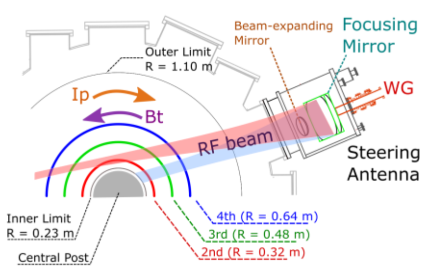
- ECW/EBW (LATE, QUEST)
  - Efficient CD at low $N_{||}$
  - Bulk e heating at high $N_{||}$
- LHW (TST-2)
  - RF induced transport model and X-ray emission model reproduce measured spectra
  - Extended MHD equilibrium with kinetic electrons show important modification due to fast electrons

$N_{||}$ = 0.75 at $2\Omega_e$

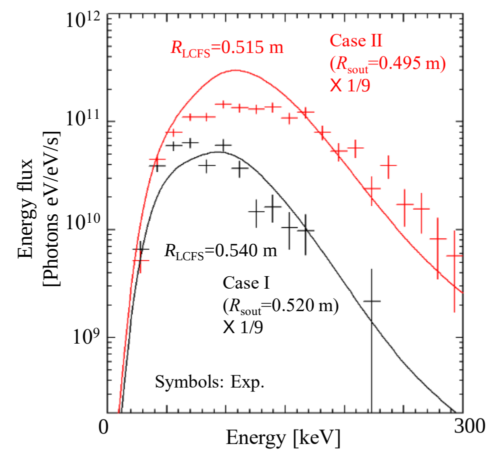


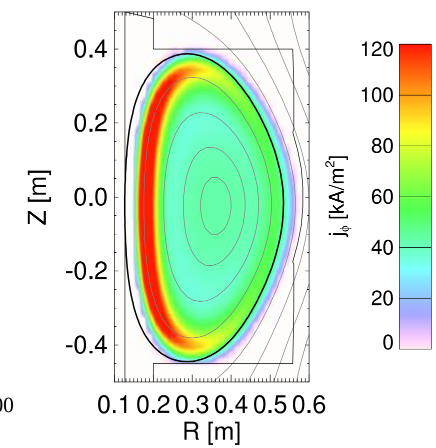
$N_{||}$ = 0.26 at $2\Omega_e$





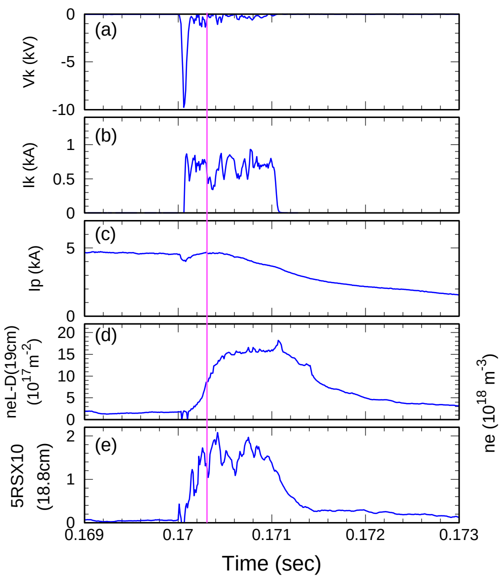
Extended-MHD
(70 % fast electrons)

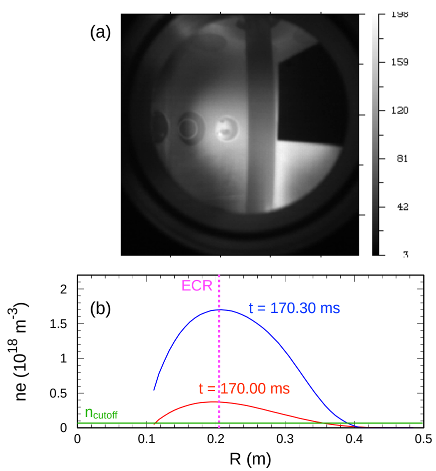


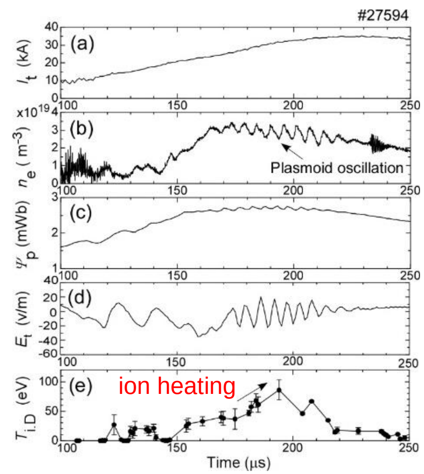


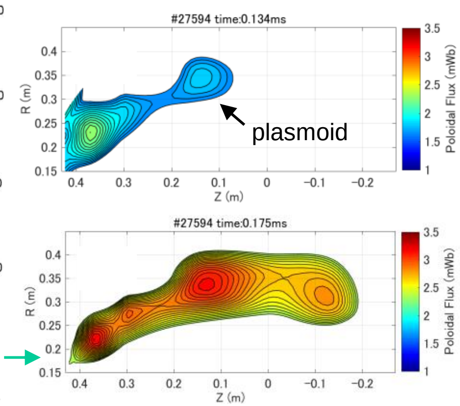
I_p start-up by non-RF methods

- e-beam injection (LATE)
  - e-beam injected to EBW-driven ST plasma resulted in density increase up to $30 \times n_{cut\text{-}off}$
  - Significant core heating was observed but not I_p increase.
- T-CHI (HIST)
  - Multiple plasmoids are formed by tearing instability in the elongated current sheet
  - Flux closure and ion heating by plasmoid-mediated fast magnetic reconnection were observed.





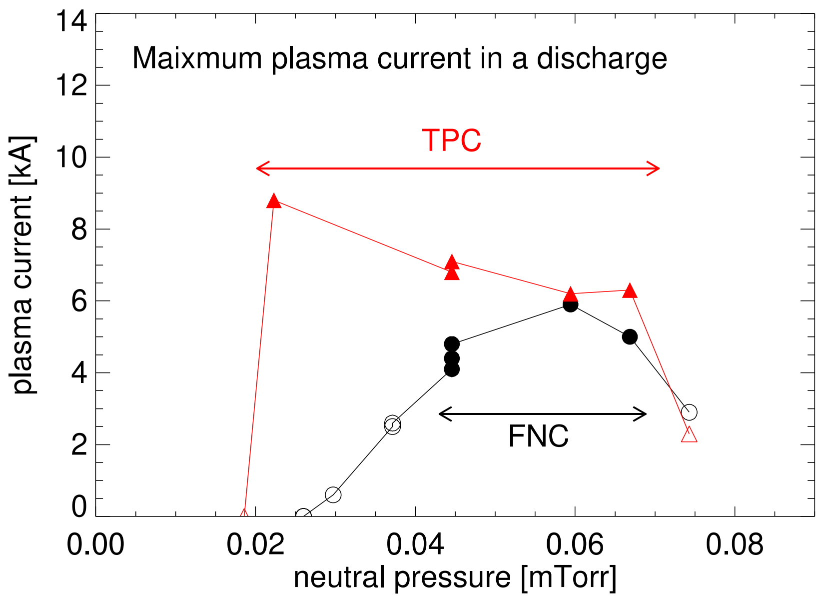




coaxial plasma gun

Inductive operation

- Optimization of I_p start-up (TST-2)
  - Low pressure limit for I_p start-up is extended to lower pressure region in TPC.
  - I_p ramp-up rate is higher for TPC.

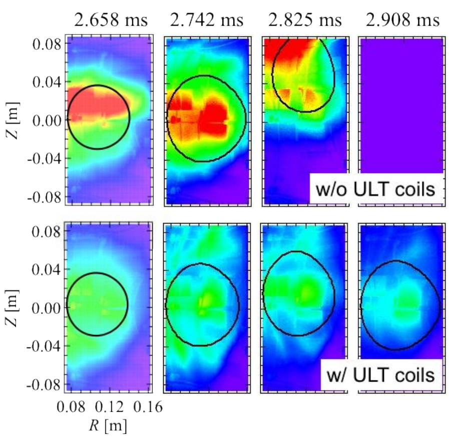


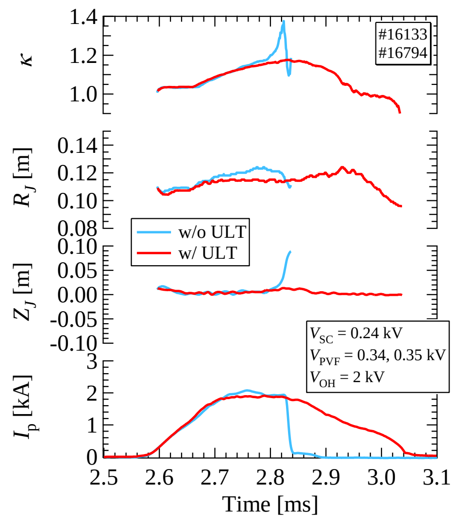
- Reconnection heating by plasma merging (TS-∗, MAST, ST40)
  - Reconnection heating energy increases proportional to B_{rec}^2 (B_{rec}: reconnecting B field).
  - T_i = 2.3 keV was achieved on ST40.
  - Promising for direct access to burning plasmas.

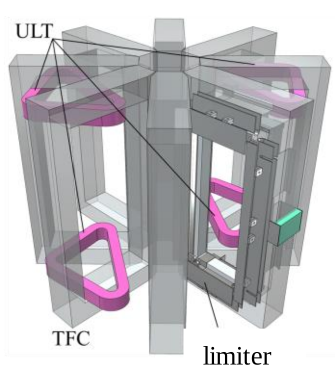
(see Y. Ono, et al., paper IAC/P4-3)

Towards steady-state

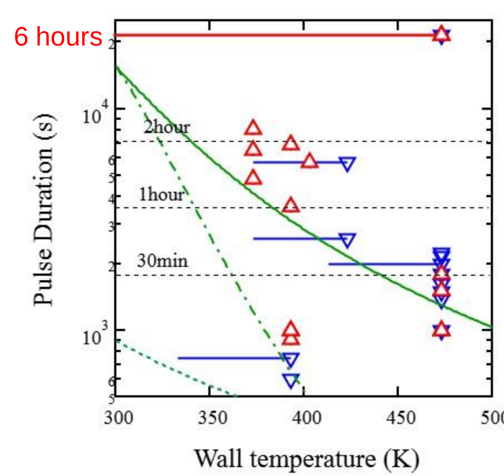
- VDE stabilization by local helical field (TOKASTAR-2)
  - VDE was stabilized by only a set of upper and lower triangular (ULT) coils.

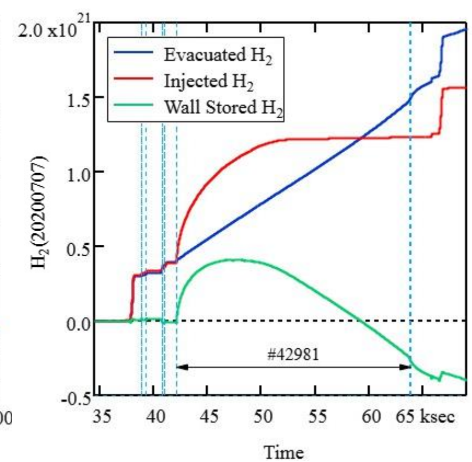






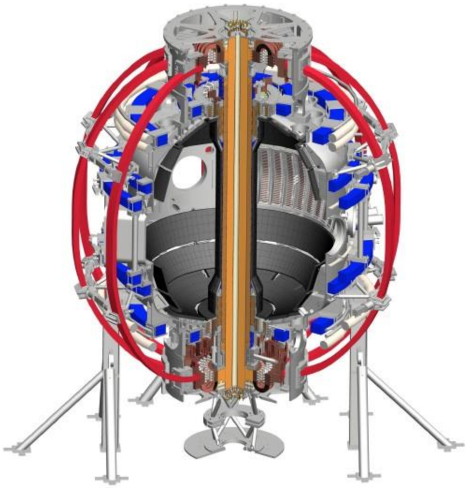
- Steady-state operation by wall temperature control (QUEST)
  - Limitation of plasma duration is estimated by wall saturation time given by modelling.
  - 6h discharge was achieved by cool down of center stack cover.

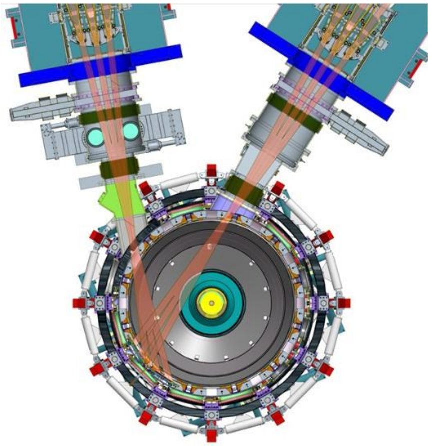




[OV/4-5Rb] NSTX-U research addresses urgent issues for fusion science, ITER and next-step devices

- **NSTX-U mission**: advance low-A physics basis needed to optimize future concepts (J.E. Menard, TECH/2-4); support ITER & critical fusion needs
- Expanded capabilities (1.0 T, 2 MA, 15 MW NBI, 6 MW HHFW) to address key issues, especially at high β
  - Confinement and stability limits at lower collisionality
  - Turbulence changes due to enhanced electromagnetic effects
  - Expanded operating space for 100% non-inductive scenarios
  - Super-Alfvenic NBI fast-ions mimic DT α populations
  - Very high $q_{\perp,PFC}$ to test plasma exhaust & PMI solutions
- NSTX-U Recovery Project in construction & installation - early start now Aug. 2022 following COVID delays (Gerhardt, TECH/P3-17)
- Select highlights of recent NSTX-U research in following slides – see NSTX-U Overview poster for much more (Guttenfelder, OV/4-5Rb)

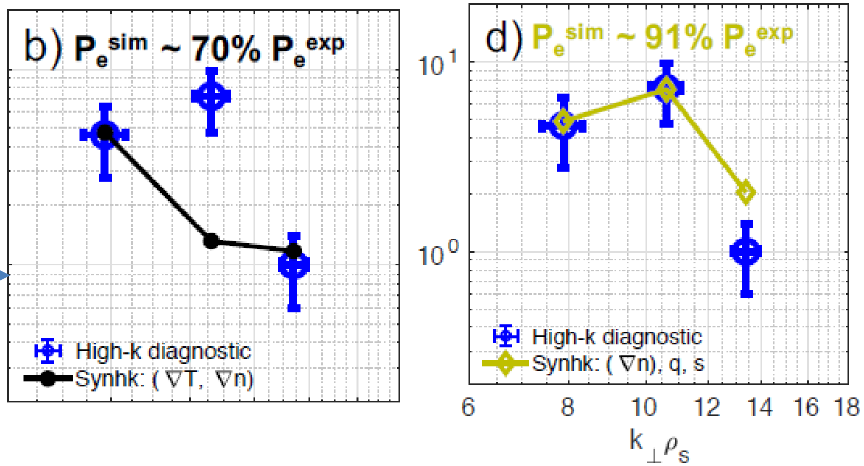




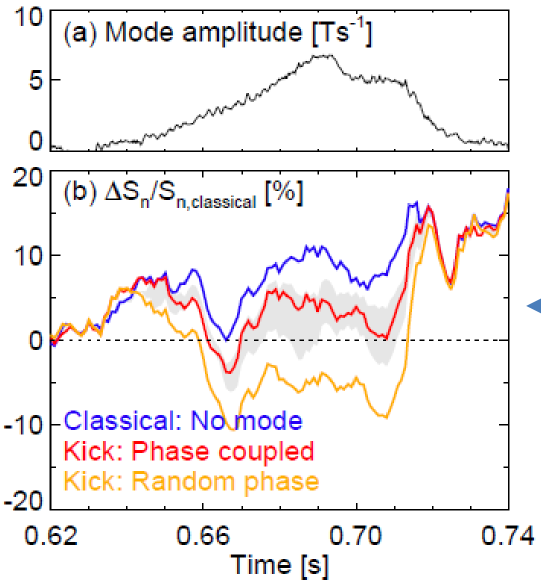
Advances in core transport and energetic particle validation

- Gyrokinetic simulations (GYRO) reproduce electron scale ETG transport & high-$k_\perp$ microwave scattering (J. Ruiz Ruiz, 2019, 2020a, 2020b)
  - Novel synthetic diagnostic used to quantify sensitivity of predicted high-k spectra (along with transport)

High-k microwave scattering (exp & sim)



Neutron deficit from phase-coupled n=1 kink + 2/1 tearing modes



- "Kick" model for fast ion transport updated to model low-frequency non-Alfvenic modes

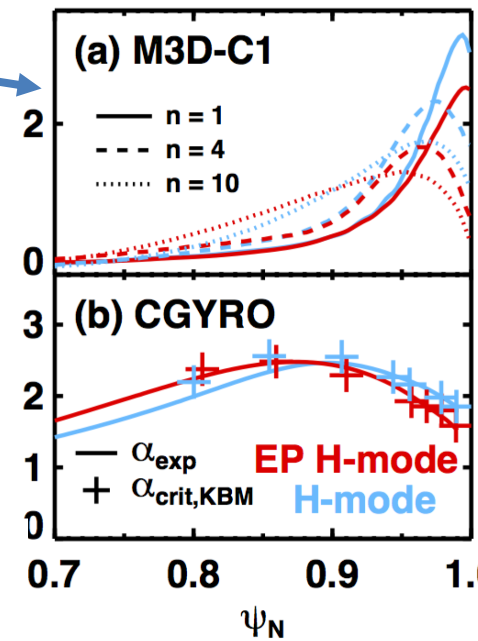
M. Podesta TH/P1-26

  - Predicted neutron rate deficit (ΔS_n) correlates with amplitude of coupled kink (n=1) + tearing (2/1) modes
  - Important to model phase-coupled, as inferred in experiment; different than sum of randomly-phased modes (J. Yang, 2021)

Expanded understanding of transport and stability mechanisms setting pedestal structure in NSTX

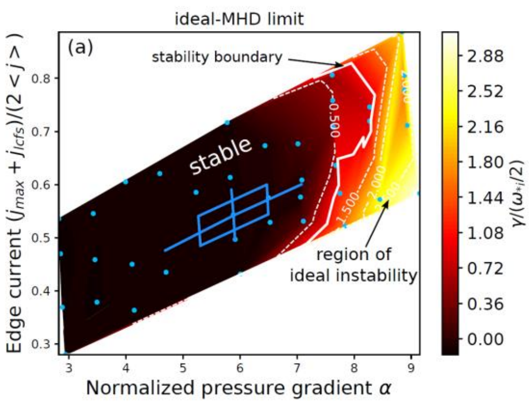
- Enhanced Pedestal H-mode (EPH) is an attractive wide-pedestal, ELM-free scenario: $H_{98}\leq 1.8$, $f_{BS}>0.7$, $f_{GW}>0.7$ (D. Battaglia, 2020)
  - Pedestal unstable to MHD kink/peeling, close to gyrokinetic KBM thresholds → enhanced particle transport enables higher edge $\nabla T_i \approx \nabla T_{i,NC}$ at lower ν_*

Kink/peeling amplitudes (M3D-C1) & KBM thresholds (CGYRO)

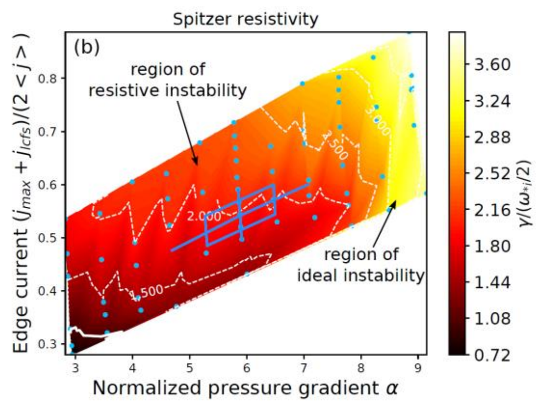


- Resistive MHD simulations (M3D-C1) predict peeling-ballooning (P-B) growth rates larger than ideal P-B (A. Kleiner, 2021)
  - More consistent with experimental results

Peeling-ballooning stability boundary (α_{ped}, j_{ped})



Ideal → Resistive

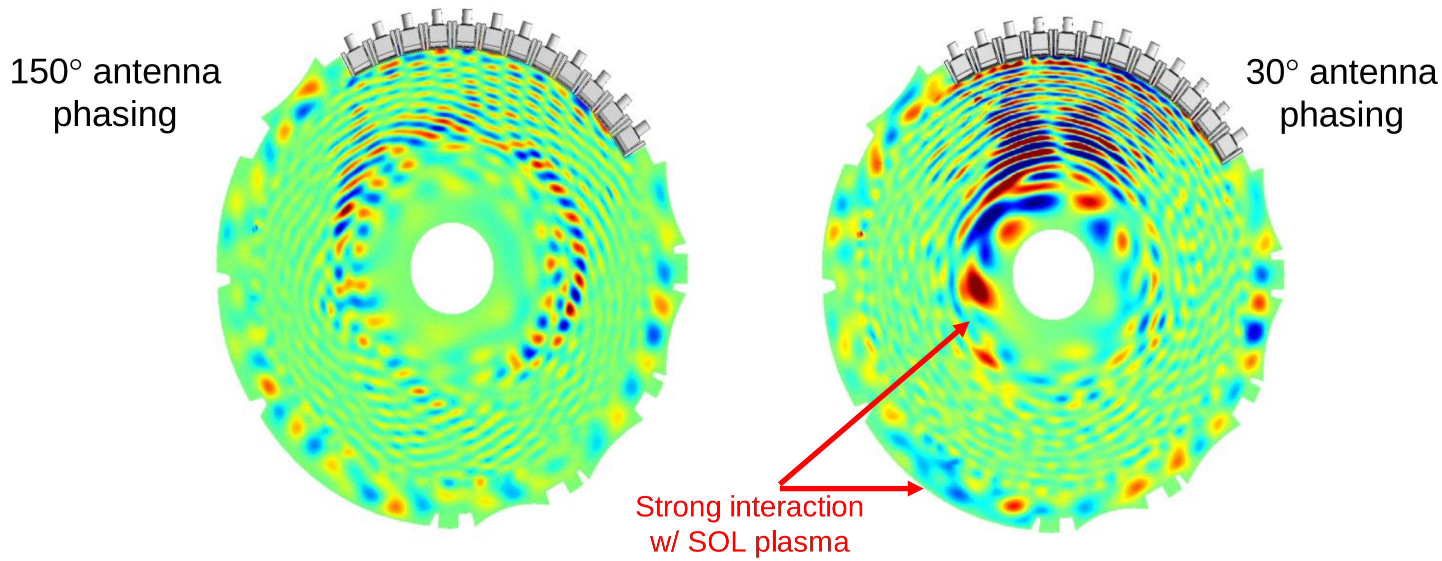


Moving towards generalized pedestal structure model

Realistic 3D RF simulations (Petra-M) applied to study NSTX-U HHFW heating and SOL losses

- Significant HHFW power often lost to SOL in NSTX, especially at low phasing
  - Cavity modes predicted by 2D full wave simulations (FW2D, AORSA) (E.H. Kim, 2019; N. Bertelli, 2019)
- Petra-M developed for consistent 3D simulations including SOL (3D CAD, EFIT equilibrium)
  - Predicts stronger SOL interaction and loss with lower antenna phasing, consistent with experiment

Ez component of wave field (3D Petra-M)



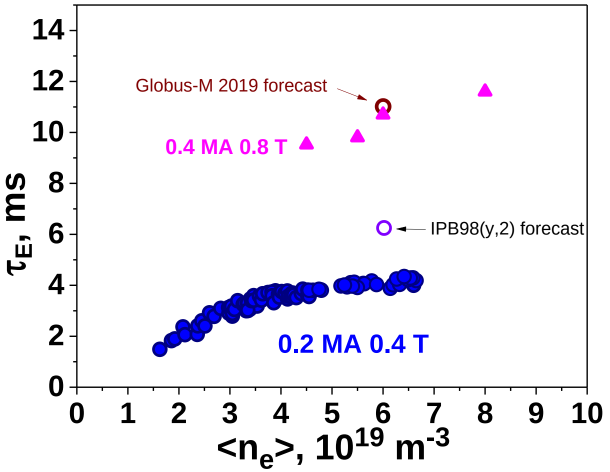
S. Shiraiwa, TH/7-2; N. Bertelli, TH/P2-16 (FEC2021)

Energy confinement in Globus-M2

Ioffe Institute

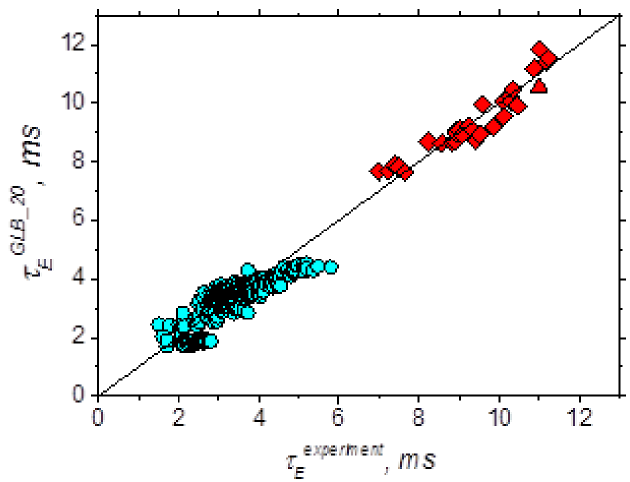
- Globus-M2 (a=0.36 m, R=0.24) has reached **B_T = 0.8 T** and **I_P = 400 kA** (80% of the design values).
- Regimes with T_e and T_i in the keV range, <n_e> ~ 10^{20} m^{-3} and with low collisionality were obtained.

τ_E increase in Globus-M2 in comparison with Globus-M



3 fold increase of τ_E at 2 fold increase of B_T – significantly more, than predicted by IPB98(y,2) scaling

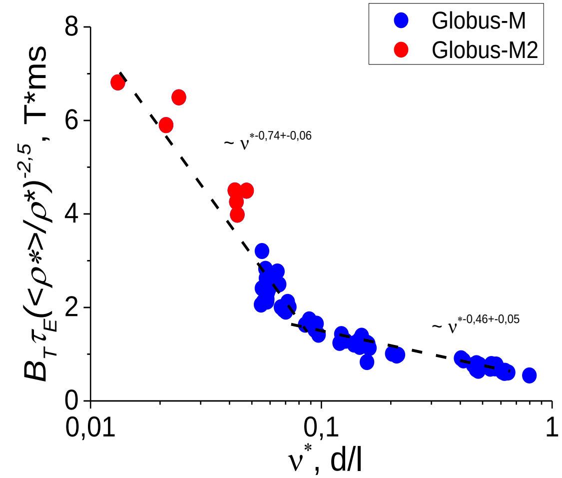
τ_E scaling in the range of 0.25 T<B_T< 0.8 T 0.1 MA< Ip < 0.4 MA



$\tau_E^{GLB\_20} \sim I_p^{0.43} B_T^{1.19}$

the ST scaling is valid for a wide parameter range

$B_T\tau_E$ increases with collisionality decrease



Globus-M/M2 scaling:

$B_T\tau_E \sim \nu^{*-0,74}$

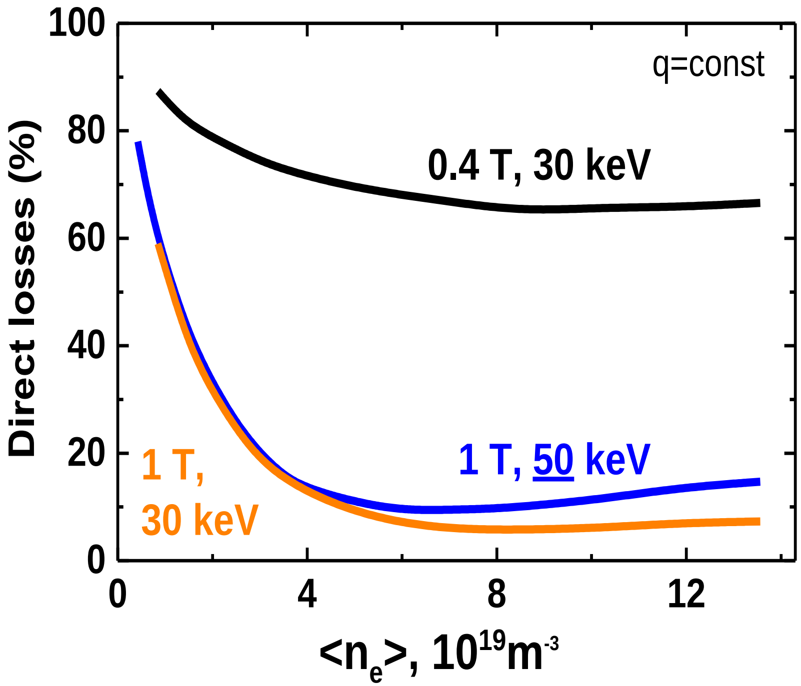
IPB98(y2) scaling:

$B_T\tau_E \sim \nu^{*-0,01}$

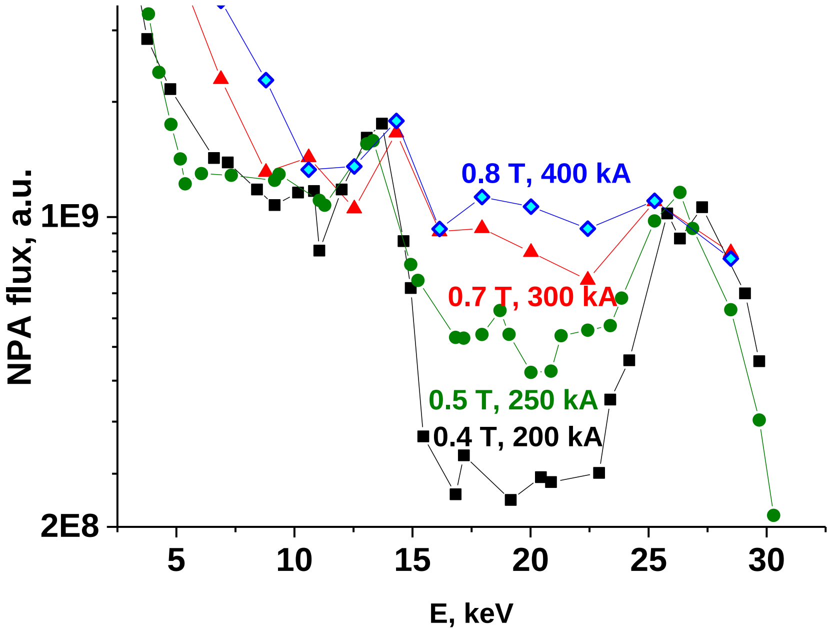
Fast particle confinement

Ioffe Institute

Full orbit modeling of fast particle direct losses in Globus-M2



CX particle spectra, measured with a tangentially directed NPA at 28 keV 0.8 MW NBI



- I_p and B_T rise improve fast ion confinement
- Ions with energies of 50 keV are confined in Globus-M2

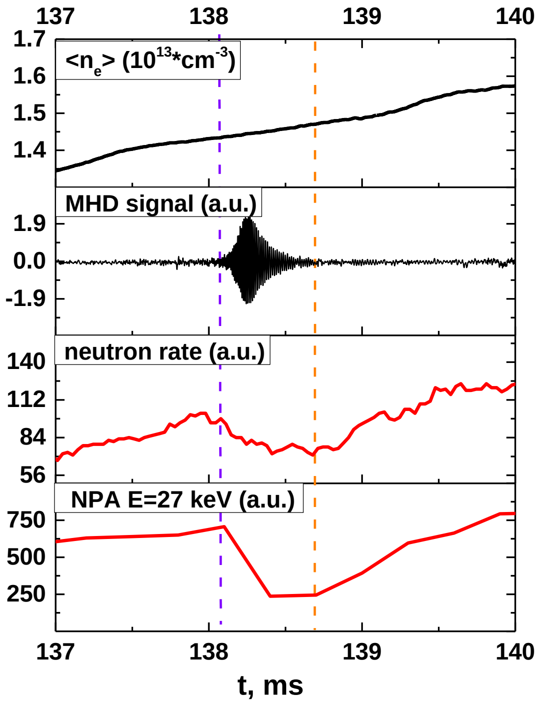
Strong drop of the NPA fluxes practically disappears at high values of currents and fields

Experiments prove modeling predictions

Toroidal Alfvén eigenmodes and fast ion losses

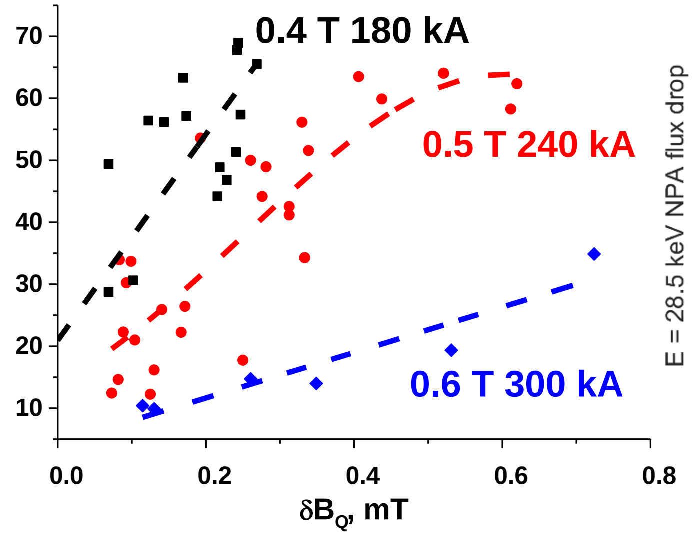
Ioffe Institute

Waveforms of a shot with bursting TAE



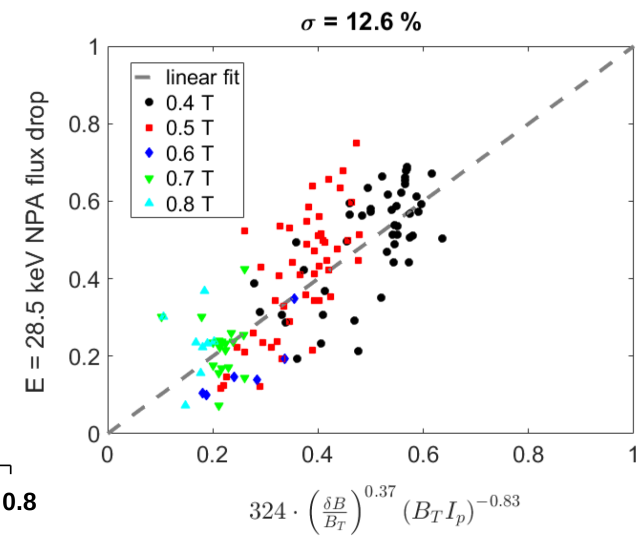
TAE bursts result in the neutron rate and CX flux drop due to fast ion losses

28.5 keV CX flux drop (%)



Fast ion losses grow with an increase in the TAE amplitude **but** decrease with an increase in B_t and I_p.

Regression fit for relative fast particle losses



The scaling:

$$\Delta N/N \sim \left(\frac{\delta B}{B_T}\right)^{0.37} (B_t * I_p)^{-0.83}$$

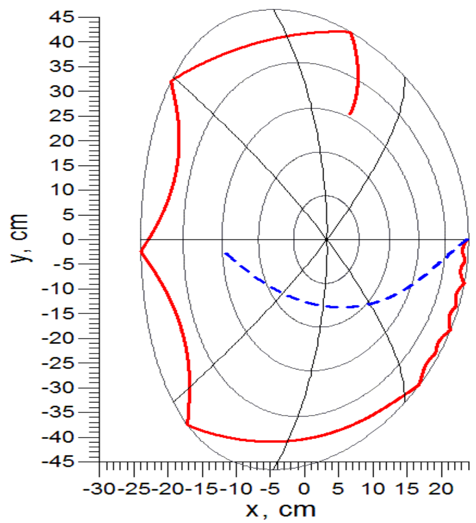
gives optimistic forecast for future STs.

Lower Hybrid Current Drive in Globus-M2

Ioffe Institute

Globus-M2 is the only ST with LHCD system.

Ray tracing at toroidal launch

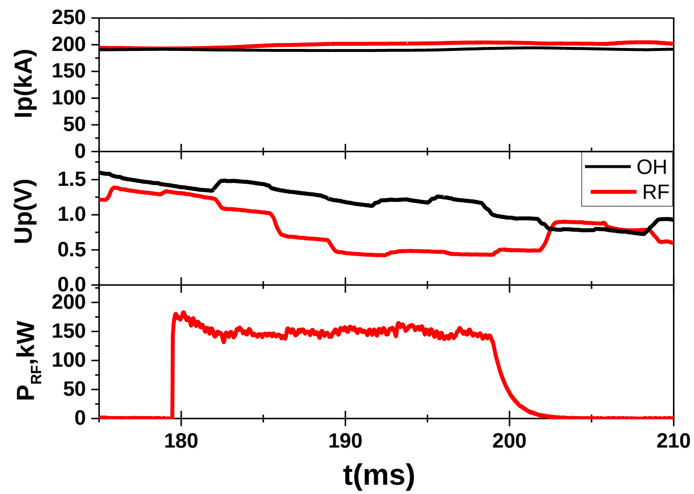


$N_{\parallel} = -3.0$,

$B_T = 0.6$ T

$B_T = 1.0$ T

Drop in loop voltage during RF pulse $B_T = 0.8$ T,



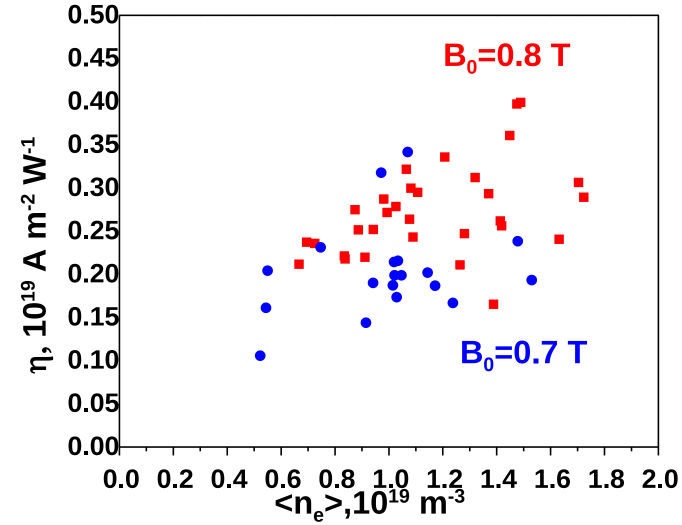
Toroidal grill orientation

2.45 GHz, 150 kW, $N_{||} = -3$,

$I_p = 200$ kA, $\langle n_e \rangle = 1\times10^{19} m^{-3}$,

$T_e(0) = 500$ eV,

LHCD efficiency

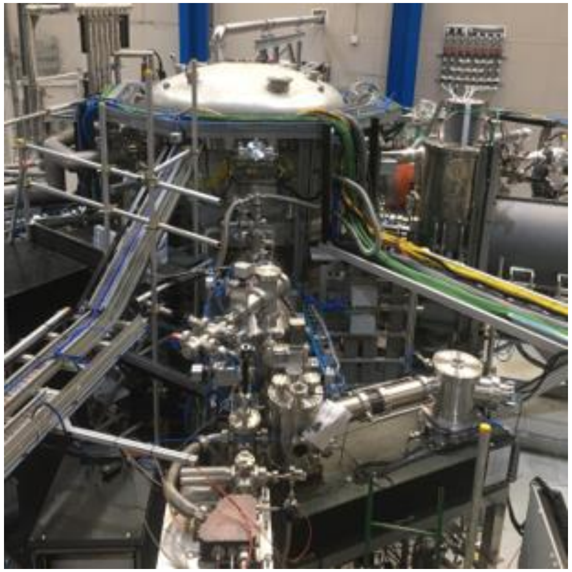


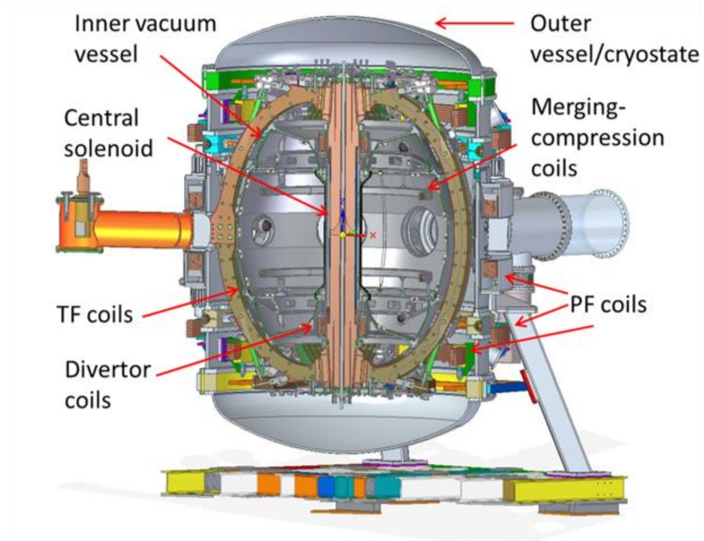
The achieved efficiency :

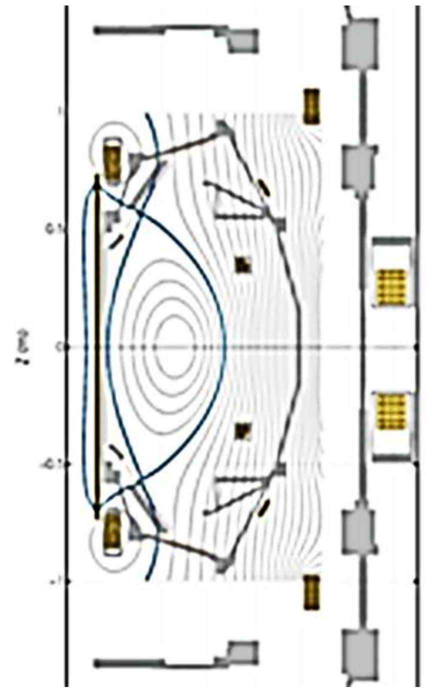
$\eta = (0.1 - 0.4)\ 10^{19}\ Am^{-2}W^{-1}$

is comparable with the conventional tokamak one

ST40 status April 2021





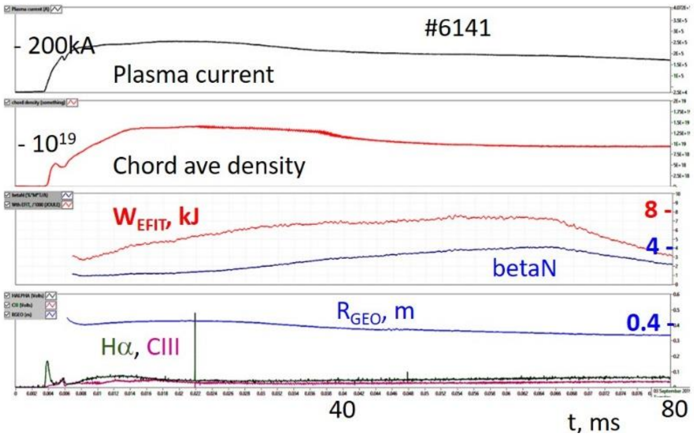


- ***B_t* = 3T (highest in STs)**, I_p = 2MA, R_0 =0.4-0.6m, R/a=1.6-1.8, κ=2.5
- **2 MW** (up to 5) of **auxiliary heating** (NBI / ECRH, 1MW 25kV and 1MW 50kV **operational**, 3rd NBI ordered, 1 MW gyrotron ordered). Pellet Injector ordered.
- Pulse flat-top 1 sec at nominal 3T, longer for lower TF.
- LN2 cooling of **Cu magnets** commissioned.
- Bioshield installation completed.
- Experimental campaign 2.2 has started with 10 keV range temperatures as a goal.

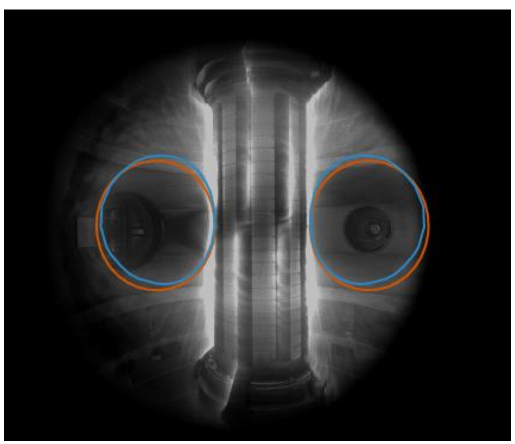
- DND operations possible, HFS Cu passive plates and divertor (Mo) installed

Results from 2019 – 2020 experiments

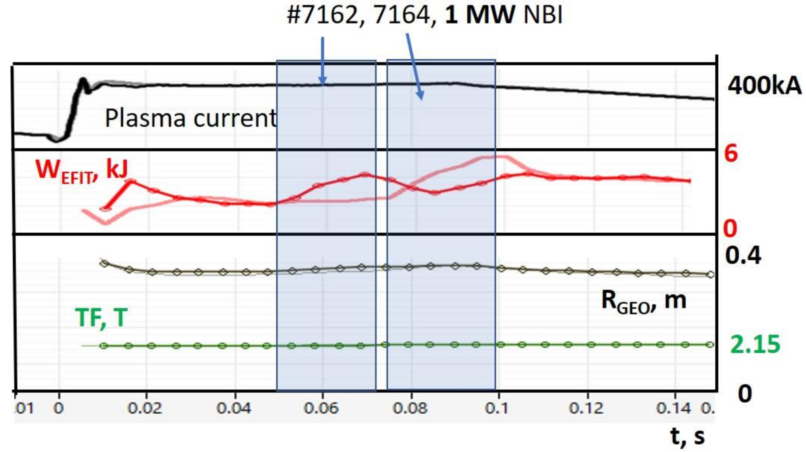
tokamak energy
a faster way to fusion

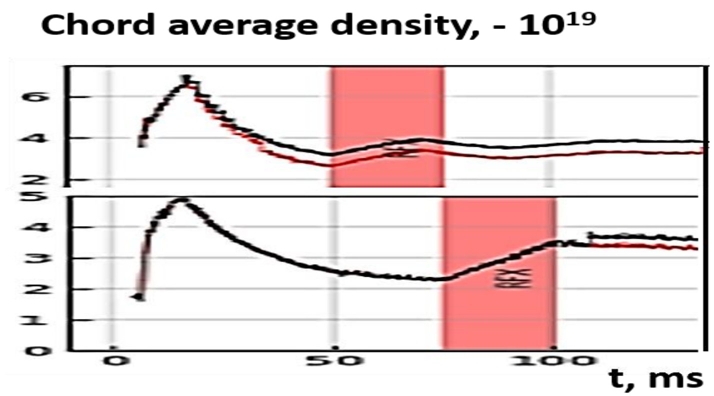


- **OH:** Highest β_N (EFIT) above 4, W_{EFIT} ~ 20 kJ – confirmed by diamagnetic loop data



CCD image in visible light overlapped with EFIT reconstruction



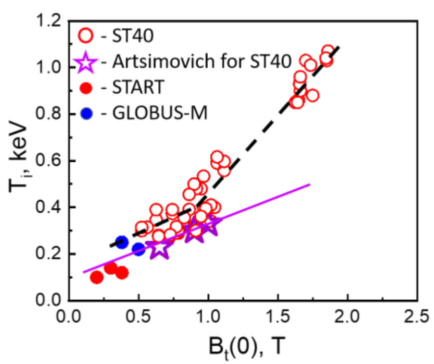


- First results with **NBI**
- 25 keV 1.0 MW NBI: visible increase in plasma density and stored energy
- Increase in T_i from ~ 0.6 keV to ~ 1.2 keV in these shots (NPA data)

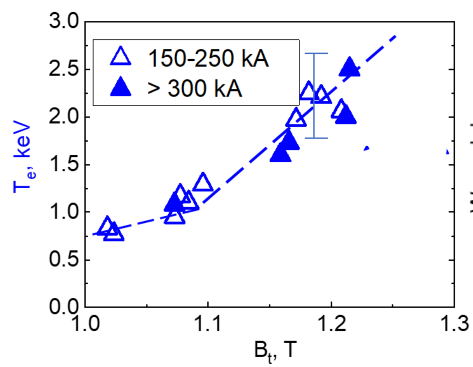
Improvement in performance with increased TF

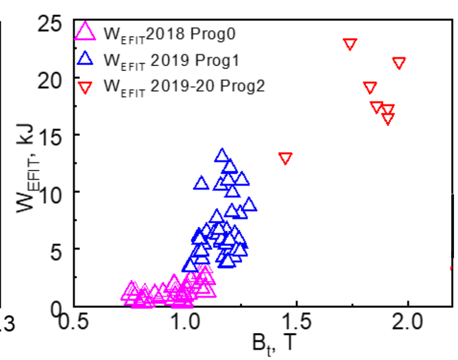
- Increase in T_e , T_i and W_{therm} with TF has been observed for TF up to ~ 2 - 3 T.
- Sharp improvements in performance with increased toroidal field **above 1 T**.

- **Below 1 T TF**, OH experiments show similar trends as in NeoAlcator scaling.
- At average densities above *2 - 6* $10^{19} m^{-3}$ **ohmic saturated mode** has been observed with critical density depending on I_{pl} rather than on TF.

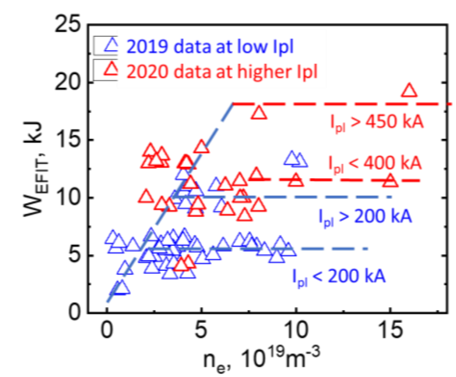


Ion temperature measured on *ST40, START and Globus-M against toroidal field, along with* T_i *predicted by* ***Artsimovich*** *formula*





Electron temperature (SXR spectrometer) *and* ***thermal energy*** W_{EFIT} *show sharp increase at TF > 1 T*



Saturated Ohmic Mode: W_{EFIT} *saturates at critical density*

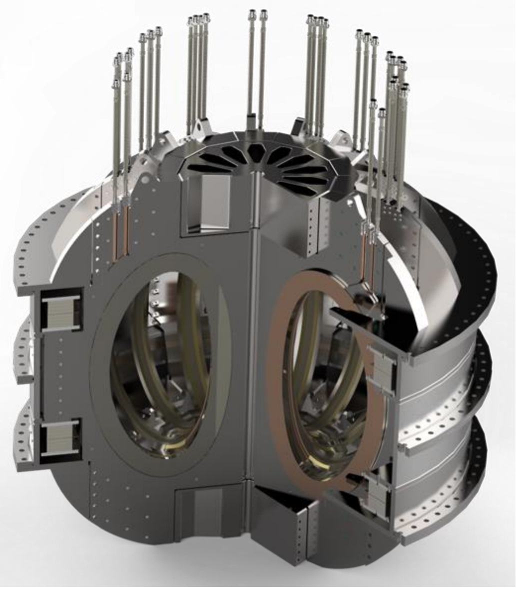
HTS Development

2015: ST25-HTS
First full-HTS tokamak
Achieved **0.1 T** @ R 0.25 m
Plasma pulse duration 29 h

DEMO3, 2019:
Record field in all-HTS magnet
24.4 T @ 21 K

DEMO4, 2021:

- Exceed **24 T** on centre column @ temperature ~20 K
- TF: ~40 km tape, PF: ~20 km tape
- **16 MJ** stored energy
- Demonstrate scalable quench protection
- Test PF / TF interaction (DC & AC)
- Simulate fusion heating



DEMO4, ST25-10T
Target **10 T** @ R 0.25 m
Under construction