球型トカマク炉実現への
QUESTが担える役割及び期待

Roles and Opportunities of the QUEST Program for the Spherical Tokamak Reactor Development

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PPPL, Princeton University

QUEST 10th Anniversary Research Meeting
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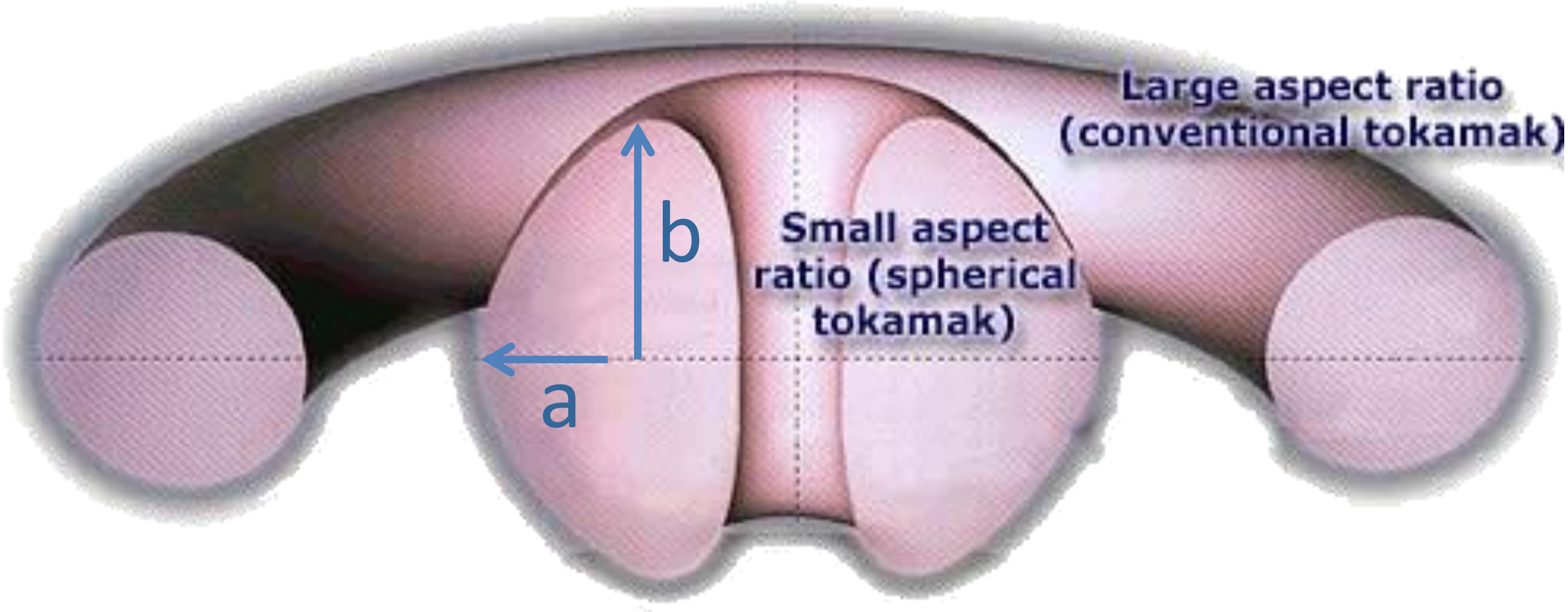
Outline

- Motivation for Spherical Tokamak (ST)
- ST Development Paths
- QUEST in the world ST program
- QUEST/NSTX-U Collaboration
- Summary

STs have higher natural elongation

Elongation $\kappa = b / a$

b = vertical ½ height a = minor radius

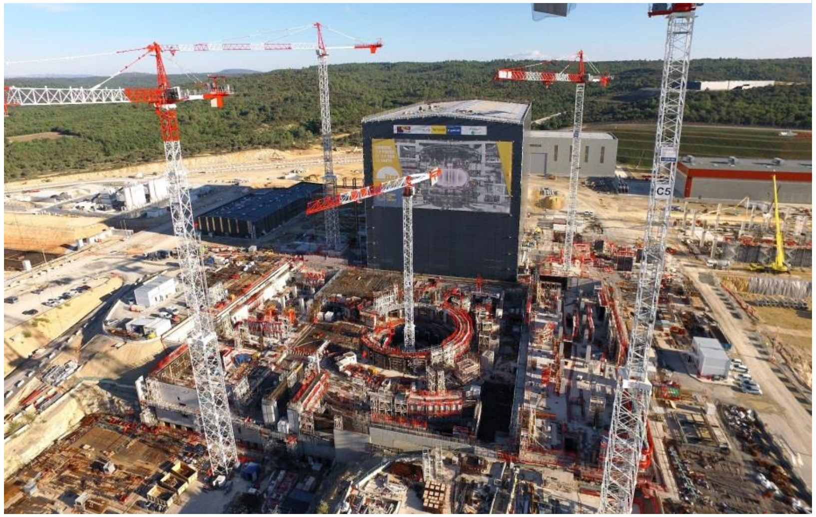


Higher elongation improves stability, confinement

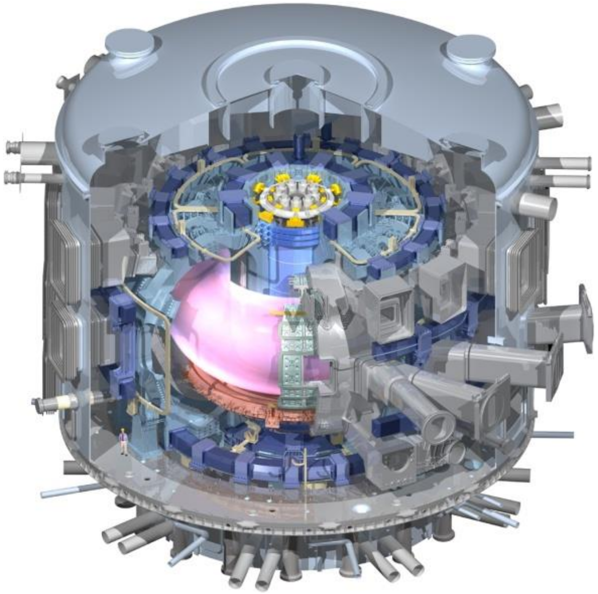
ITER will be first device to access “burning plasma”

- Burning plasma: majority of plasma heating power comes from fusion alpha particles from DT reactions
  - DT reaction energy split: 1/5 in alphas, 4/5 in neutrons
- ITER goal $Q = P_{\text{fusion}} / P_{\text{external heating}} = 10$
- $Q = 10 \rightarrow P_{\text{alpha}} / P_{\text{external}} = 2$
- $P_{\text{alpha}} / P_{\text{alpha + external}} = 2 / 3 > 50\%$

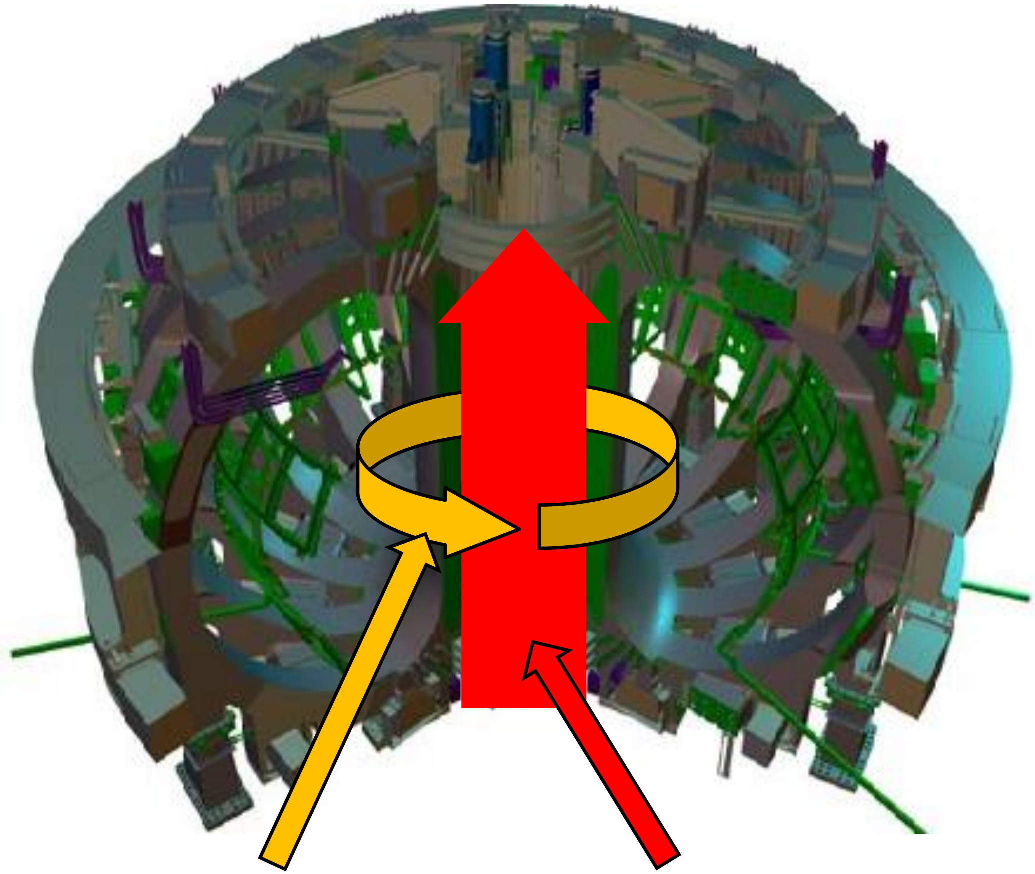
ITER under construction in Cadarache, France



A=3.1, R=6.2m, B_T=5.3T, I_P=15MA



ITER magnets will be largest ever built



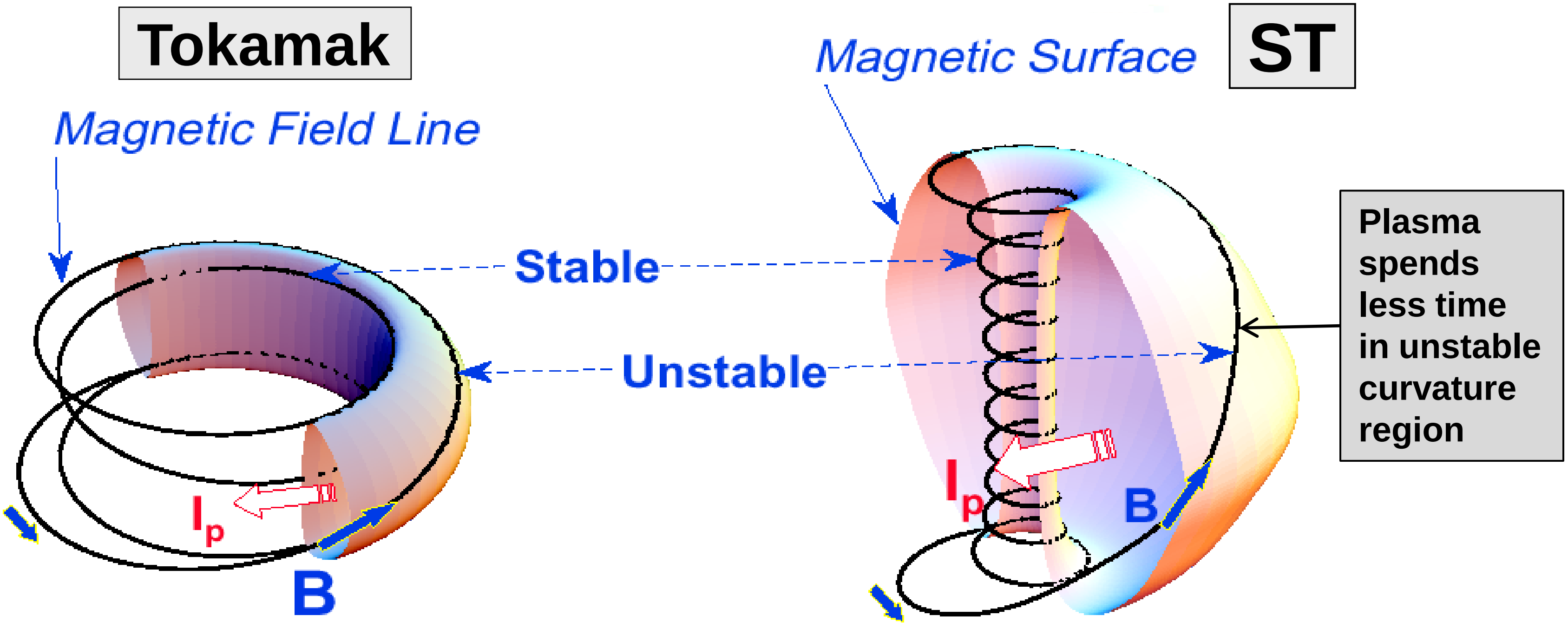
Plasma current:
15 million amps

Toroidal field current
165 million amps

- 18 toroidal field magnets
- 12 Tesla at coil
- Weight: 6500 tons
- 80,000 km of Nb3Sn superconducting strand in total length

These are large numbers

Favorable average curvature improves stability



Plasma spends less time in unstable curvature region

Tokamak

$A \sim 2.5\text{-}4$

$\kappa = 1.5\text{-}2$

$\beta_T = 3\text{-}10\%$

ST

$A \sim 1.3\text{-}2$

$\kappa = 2\text{-}3$

$\beta_T = 10\text{-}40\%$

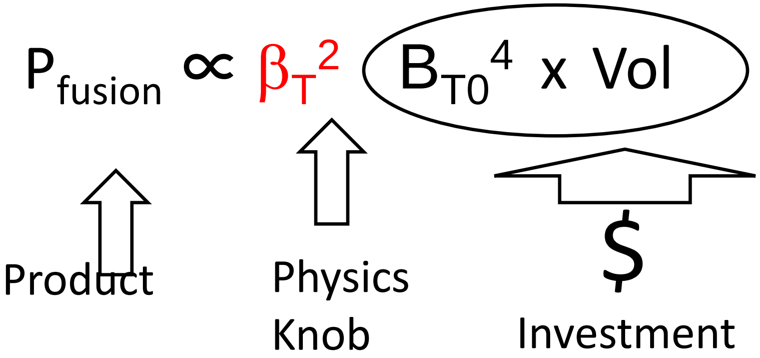
Aspect Ratio $A = R/a$

Elongation $\kappa = b/a$

Toroidal beta $\beta_T = \langle p \rangle / (B_{T0}^2/2\mu_0)$

Higher β_T enables higher fusion power and compact FNSF for required neutron wall loading

$$P_{\mathrm{fusion}} \propto \uparrow p \Uparrow^{2} \ \mathrm{x\ Vol}$$



$$P_{\mathrm{fusion}} \propto \beta_T^{2} \ B_{T0}^{4} \ \mathrm{x\ Vol}$$

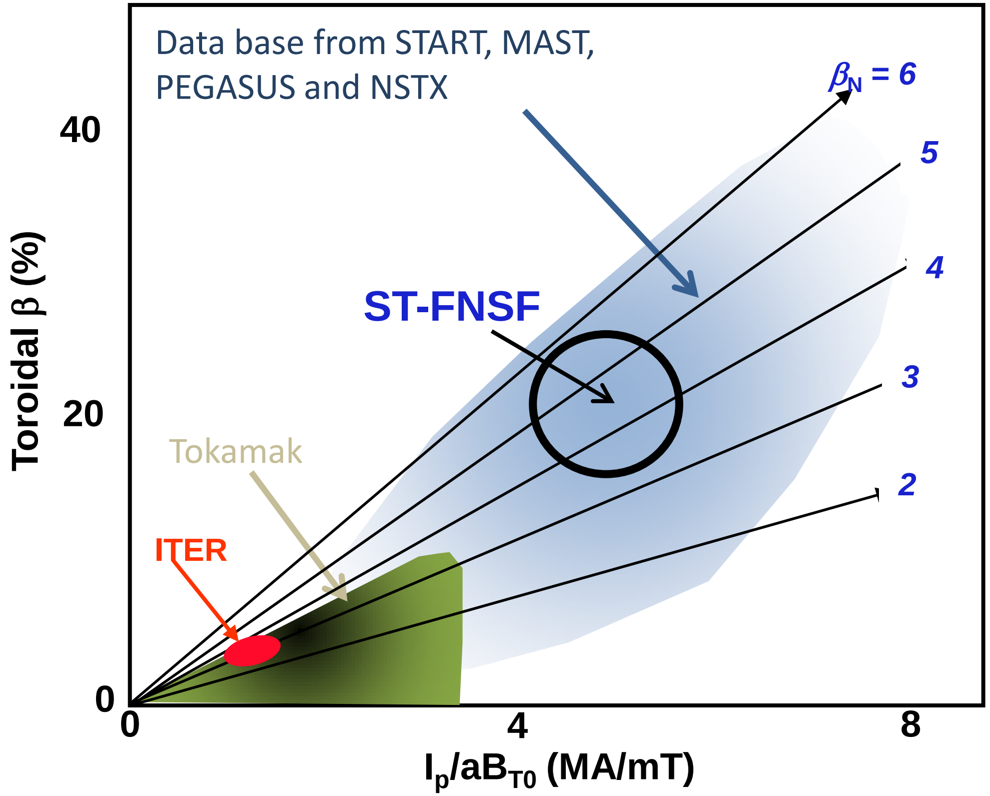
Product

Physics Knob

$

Investment

High neutron wall loading W_n possible in a compact ST



$$W_n \propto P_{\mathrm{fusion}} / \mathrm{Area}$$

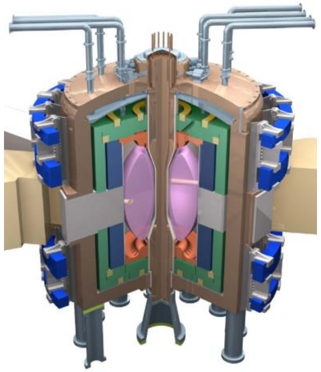
$W_n \propto \beta_T^{2} B_{T0}^{4}\ a$ (not strongly size dependent)

⇨ W_n ~ 1 MW/m^2 with R ~ 1 m FNSF feasible!

ST Development Paths

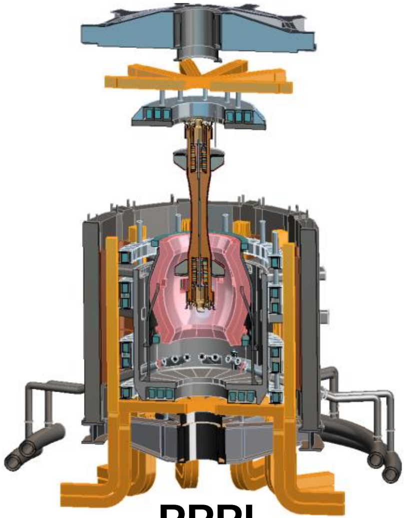
Fusion Power Can Be Generated in Diverse Range of STs

ST-FNSFs



ORNL

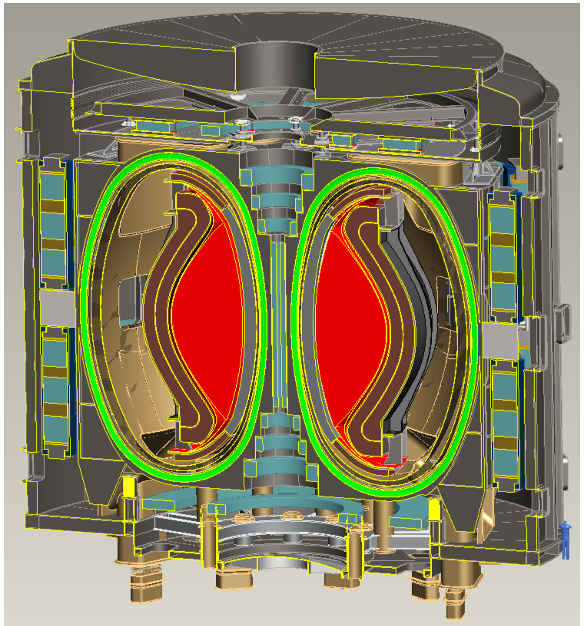
R=1.0m: **TBR < 1 (≈ 0.9)**



PPPL

R=1.7m: **TBR ≥ 1**

A=2, R_0 = 3m HTS-TF
FNSF / Pilot Plant

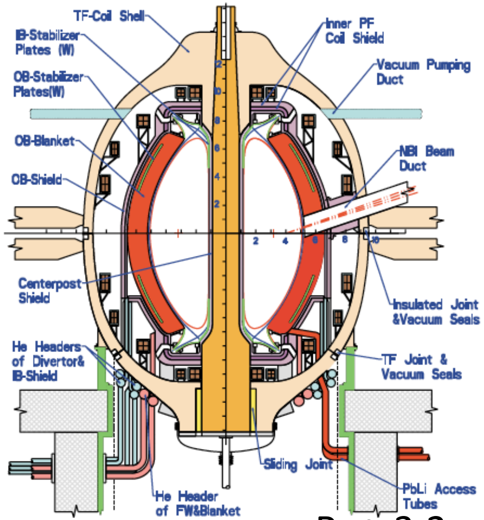


PPPL

Cryostat volume and I_{TF} ~ 1/3 of ITER

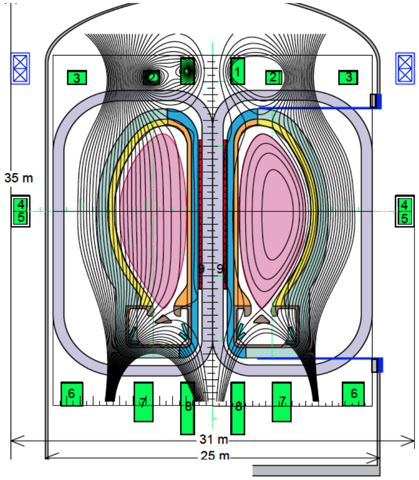
P_{fusion} = 520 MW
Q_{eng} = 1.35
P_{net} = 73 MW

ARIES-ST Cu Power Plant



R_0 ~ 3.2 m

JUST SC ST Power Plant



VECTOR, Slim CS

R_0 ~ 4.5m

Spherical Tokamaks have the potential attractiveness for fusion development paths

Attractiveness of Spherical Tokamaks for Fusion Energy Development:

- Projected to access high neutron wall loading for fusion material and engineering development at moderate R_0, P_{fusion}

  W_n ~ 1-2 MW/m^2 , P_{fus} ~ 50-200MW, R_0 ~ 0.8-1.8m

- Modular, simplified maintenance
- Tritium breeding ratio (TBR) near 1 in a compact size (R ~ 1.7m)

  Requires sufficiently large R_0, careful design

- Net electricity possible for an ST with R = 3m

R&D Needs for Fusion Energy Development:

- Non-inductive start-up, ramp-up, sustainment

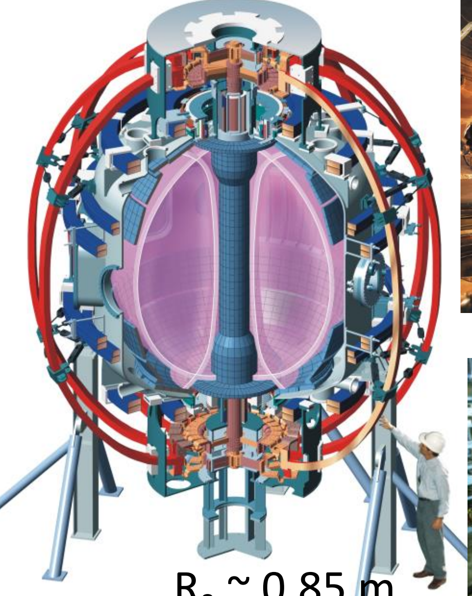
  Low-A → minimal inboard shield → no/small transformer

- Divertor solutions for high heat flux
- Confinement scaling (especially electrons)
- Stability and steady-state control
- Radiation-tolerant magnets, design

Operating ST Research Facilities Since 2000

NSTX and MAST: MA-class STs, other STs addressing topical issues

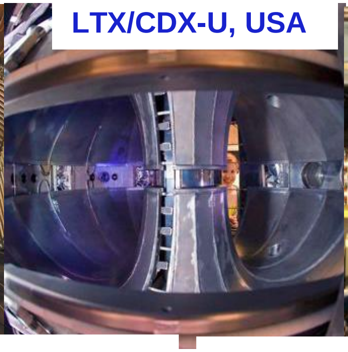
NSTX, USA



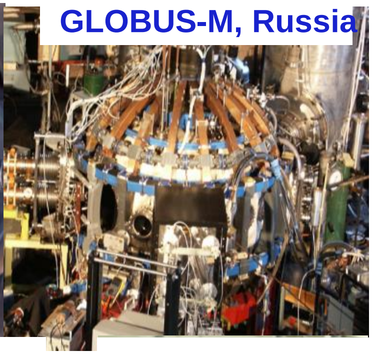
R_0 ~ 0.85 m

PEGASUS, USA

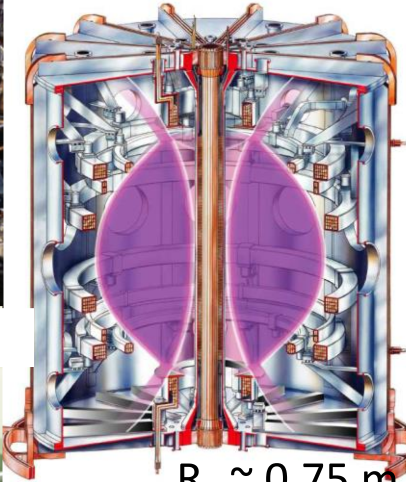
LTX/CDX-U, USA



GLOBUS-M, Russia



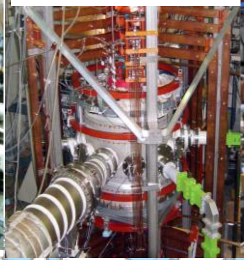
MAST, *UK*



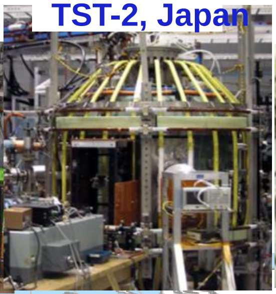
R_0 ~ 0.75 m

HIST, Japan

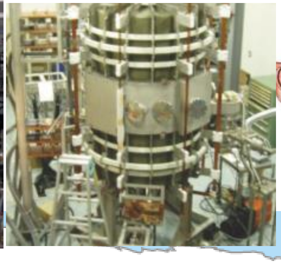
LATE, Japan



TST-2, Japan



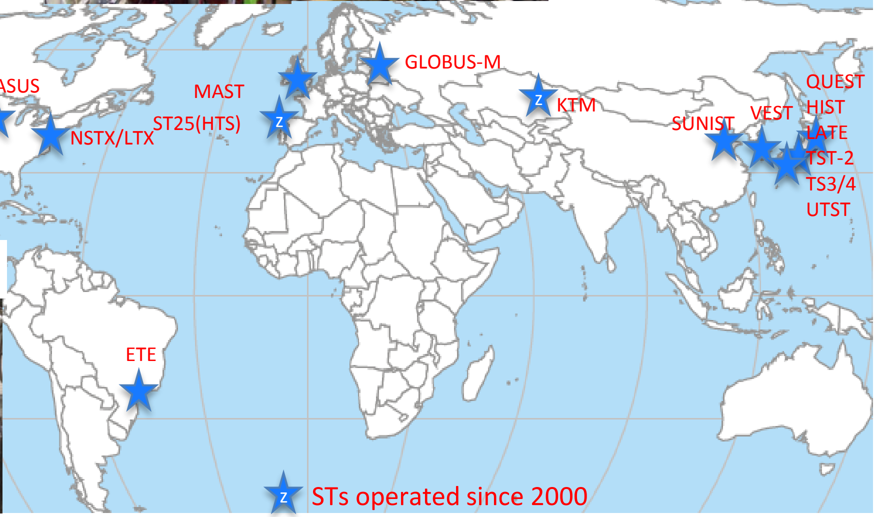
UTST, Japan



QUEST/CPD, Japan

VEST,

HIT-II, USA



SUNIST, China

ETE, Brazil

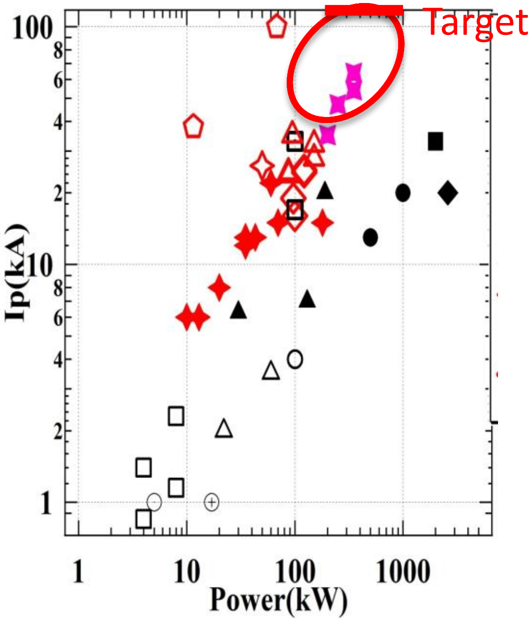
ST25, UK

TS3/4, Japan

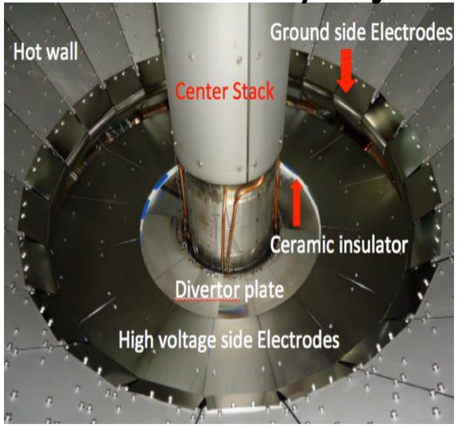
QUEST is the only ST which can operate long-pulse

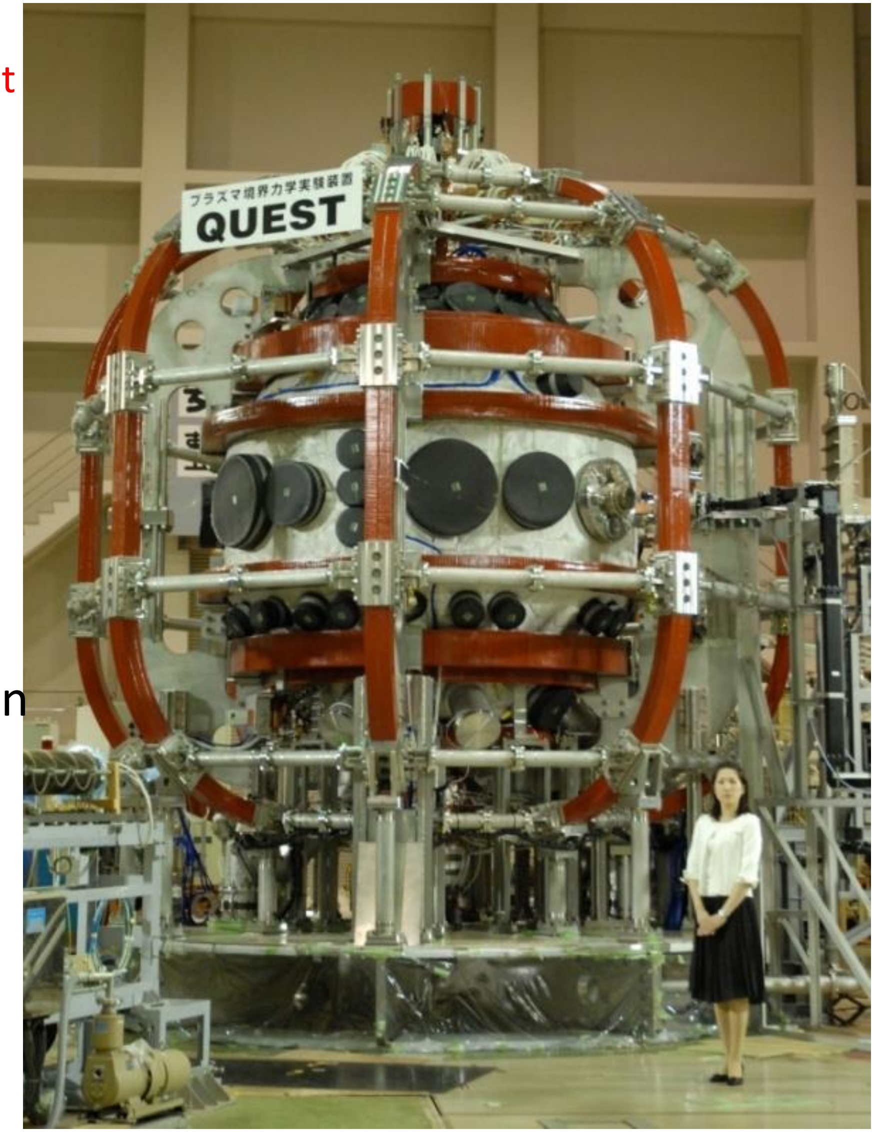
QUEST is also unique in hot-wall, high power ECH, and CHI

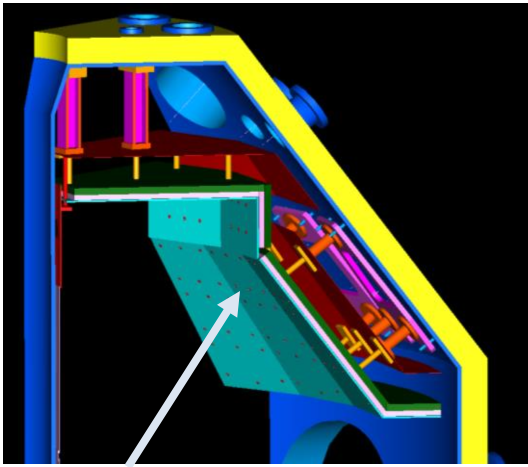
Record ECH Start-Up



Coaxial Helicity Injection

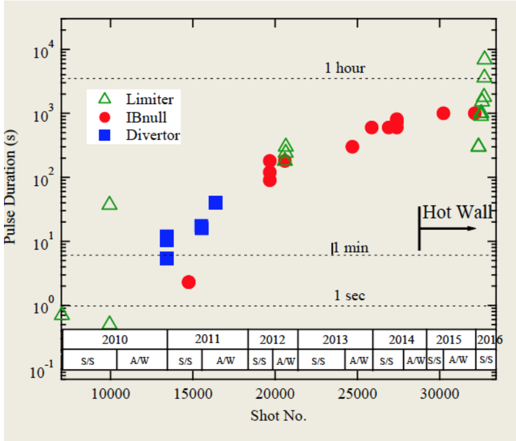




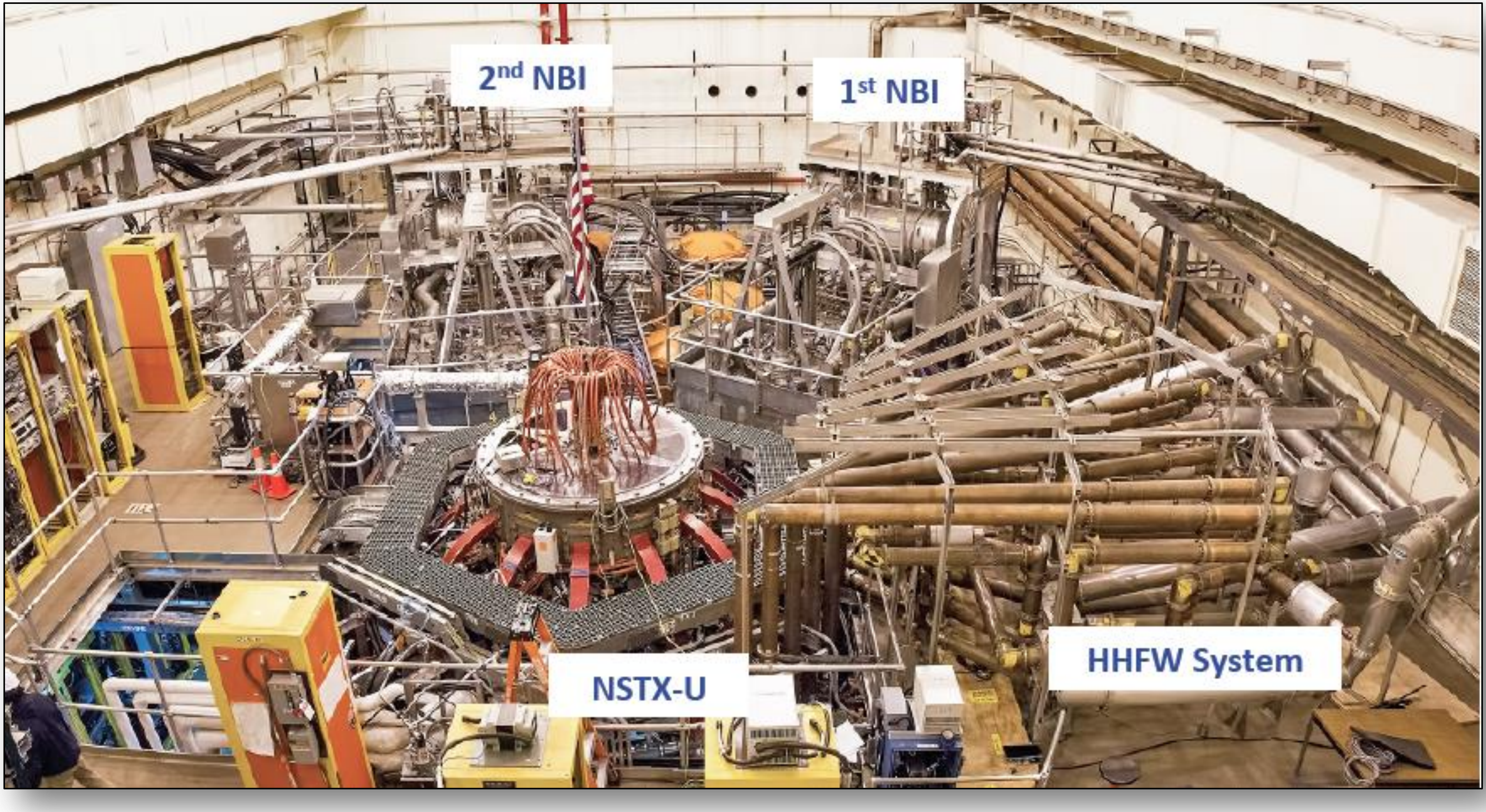


Hot wall

Long-Pulse Plasmas

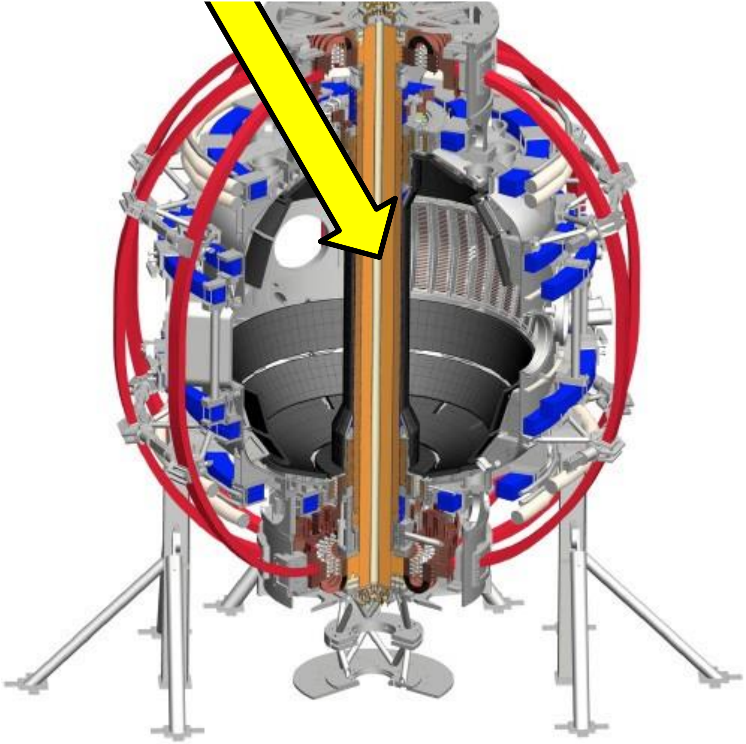


NSTX Upgrade Device and Test Cell – Aerial View

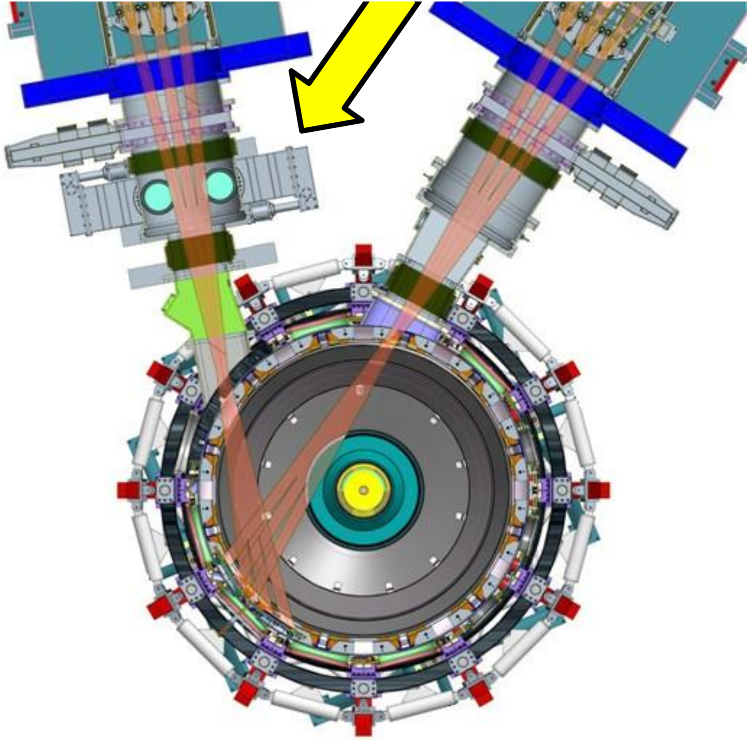


NSTX Upgrade will access new physics with 2 major new tools:

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Higher T, low ν* from low to high β

B_T = 1 T for 5 sec,

Ip = 2 MA

Full non-inductive current drive

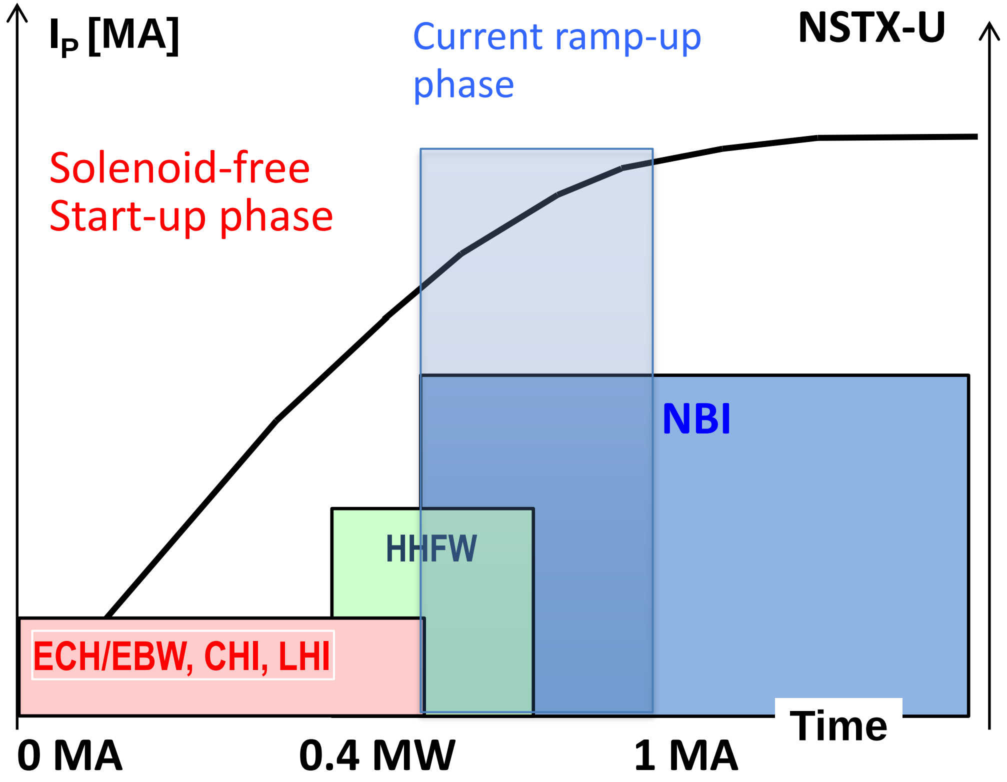
P_{NBI} = 10 MW

P_{HHFW} = 5 MW

Solenoid-free Start-up and Ramp-up are Critical Issues for Compact ST and Tokamak-based Reactors

- ST has been addressing critical issue of solenoid-free start-up
  - A compact ST has little space for a central solenoid
  - Solenoid-free start-up is also attractive for tokamak designs
- Maximizing solenoid-free start-up currents reduces reliance on less developed non inductive current ramp-up scenarios
- Few MA start-up current is projected for reactors
  - Higher currents may be feasible

NSTX-U will not conduct solenoid-free start-up / ramp-up experiments near term



ECH / EBW – Utilize 1 – 2 MW, 28 GHZ gyrotron

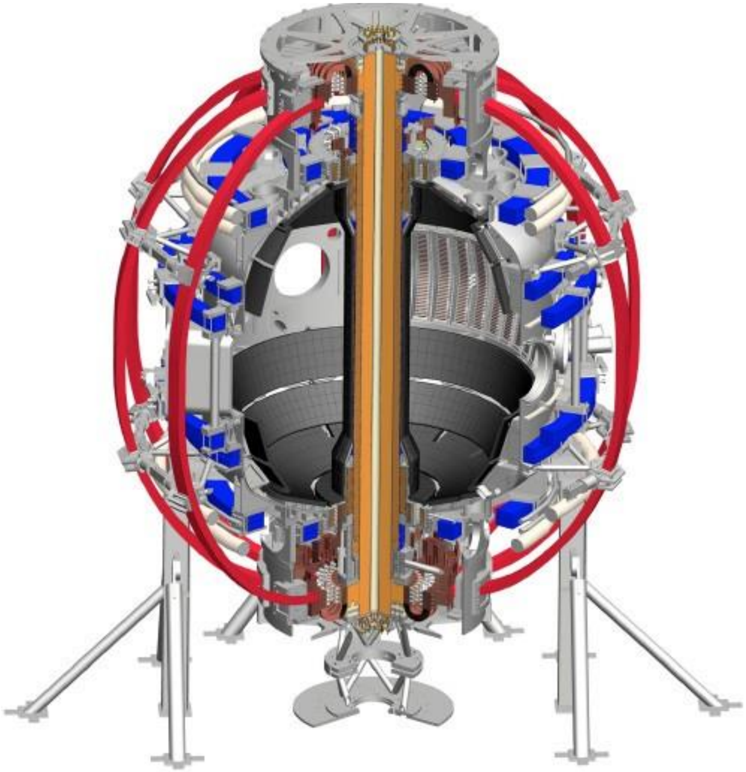
CHI, LHI – Coaxial Helicity Injection and local helicity injection up to ~ 400 kA

HHFW ~ 4 MW 30 MHZ High Harmonic Fast Wave

NBI ~ 10 MW NBI

NSTX-U and QUEST are complementary
Short-pulse vs. Long-pulse

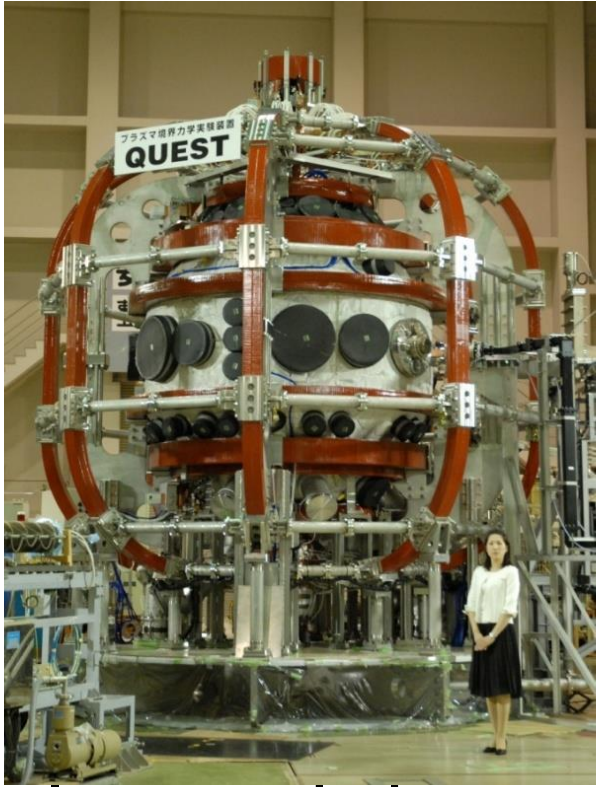
NSTX-U



High field – high power for a few sec

All carbon wall without hot wall,
no ECH and CHI in near term

QUEST



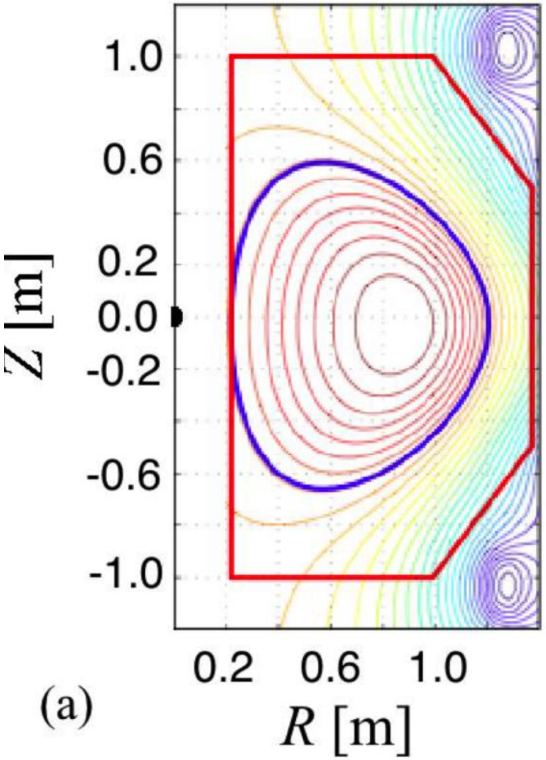
Long-pulse non-inductive operations

CHI and high power ECH,
all metal hot wall, steady-state

NSTX-U would like to collaborate with QUEST to pursue ECH, CHI, long-pulse, all metal hot wall

QUEST Has an Active World-Class Program on ECH Start-Up NSTX-U Plans to Contribute via. Theory and Diagnostic Support

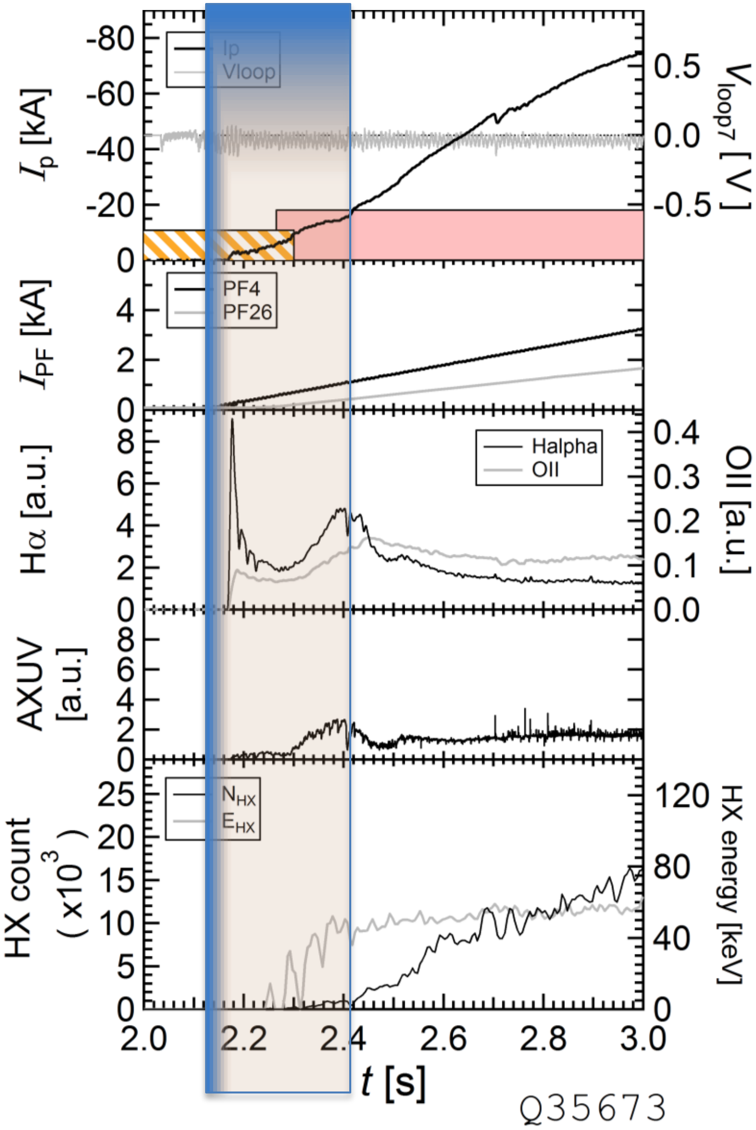
- QUEST and its high power ECH system has an impressive physics capability:
  - Focusing and steering capability to control the ECH deposition profiles.
  - Capable of scanning in $N_{||}$ and polarization for wave physics.
  - B_T scanning to explore the resonance layer position dependence.



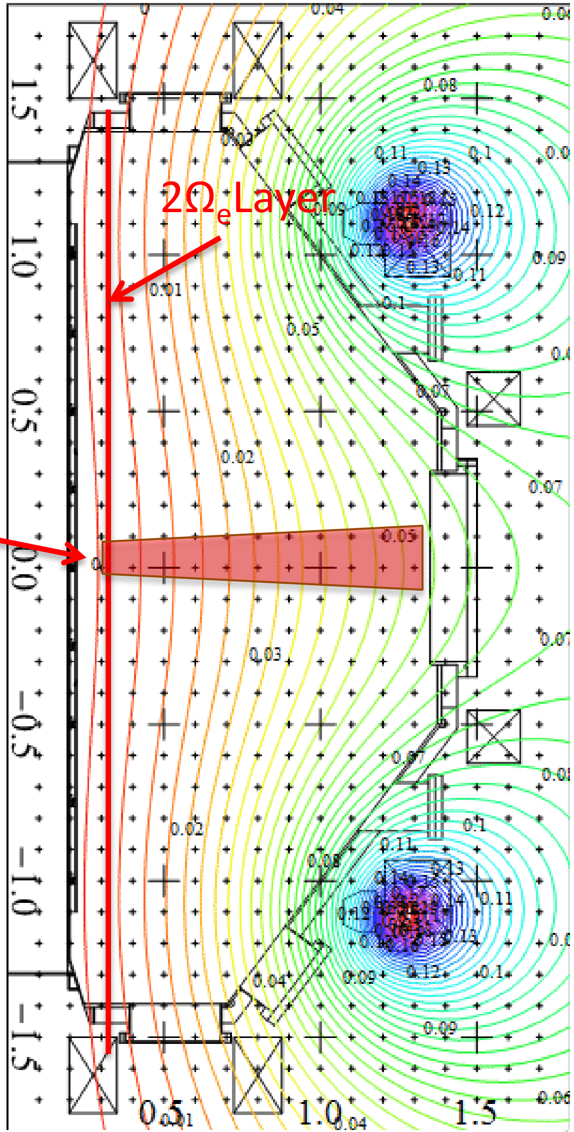
Develop comprehensive picture of QUEST ECCD:

- Provide fast electron generation with GENRAY and CQL-3D for ECH fast electron generations. (N. Bertelli, R. Harvey)
- Measure time and spatially resolved soft x-ray profiles using NSTX-U multi-energy soft x-ray Pilatus camera together with other x-ray detectors on QUQEST. (L. Delgado-Aparicio, M. Ono)
- Developing a new synthetic diagnostic tool for multi-energy soft x-ray camera with UT/TST-2 to obtain fast electron evolutions. (L. Delgado-Aparicio with H. Yamazaki)
- Aim to develop a comprehensive predictive modeling including the ECH generated fast electron transport and confinement. (M. Ono, N. Bertelli, G.J. Kramer)

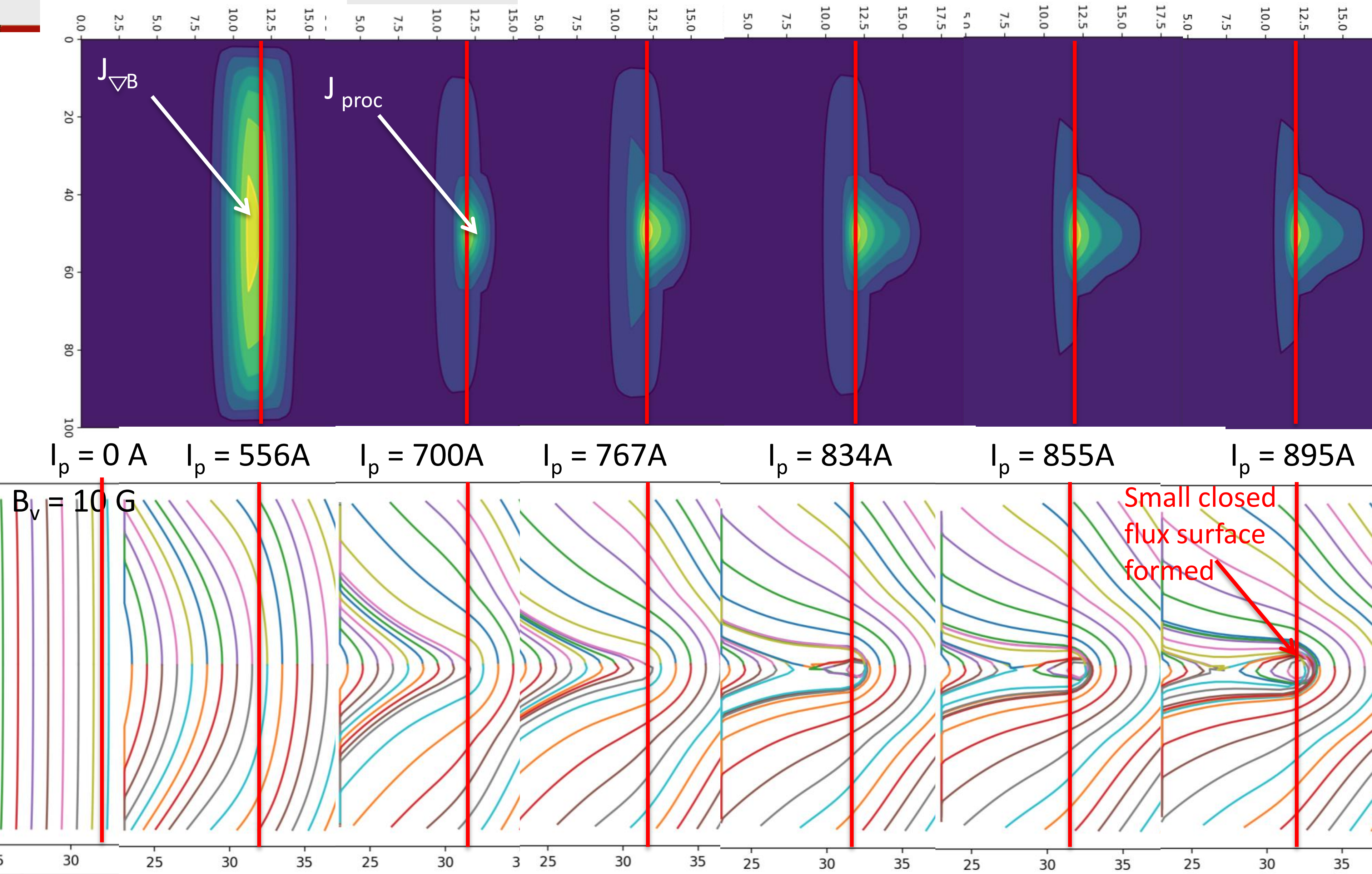
A Tokamak Start-up Modeling being Developed Initially Multi-pass Non-Phased Electron Cyclotron Heating



Strong ECH focusing for single pass absorption



Grad-B and Processional Currents can lead to closed flux configuration
ECH without directionality – low absorption – multi-pass expected

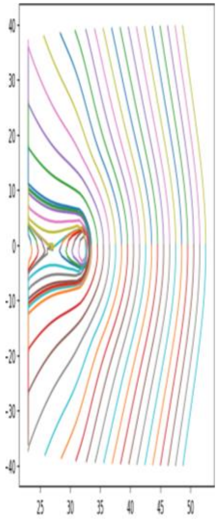


Bootstrap Currents Can Enhance Closed Flux Surfaces

Bootstrap current can rapidly increase the plasma current

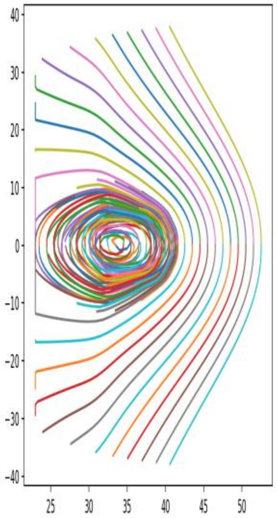
P_{ECH} = 100 kW
B_v = 10 G
$n_e = 10^{12} cm^{-3}$

I_p = 835A



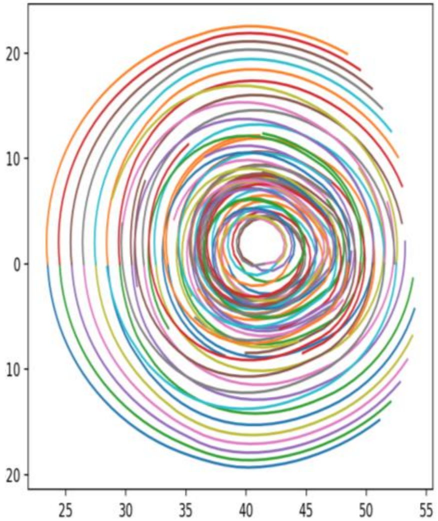
P_{ECH} = 3.35 kW

I_p = 1706 A



P_{ECH} = 30 kW

I_p = 3769 A

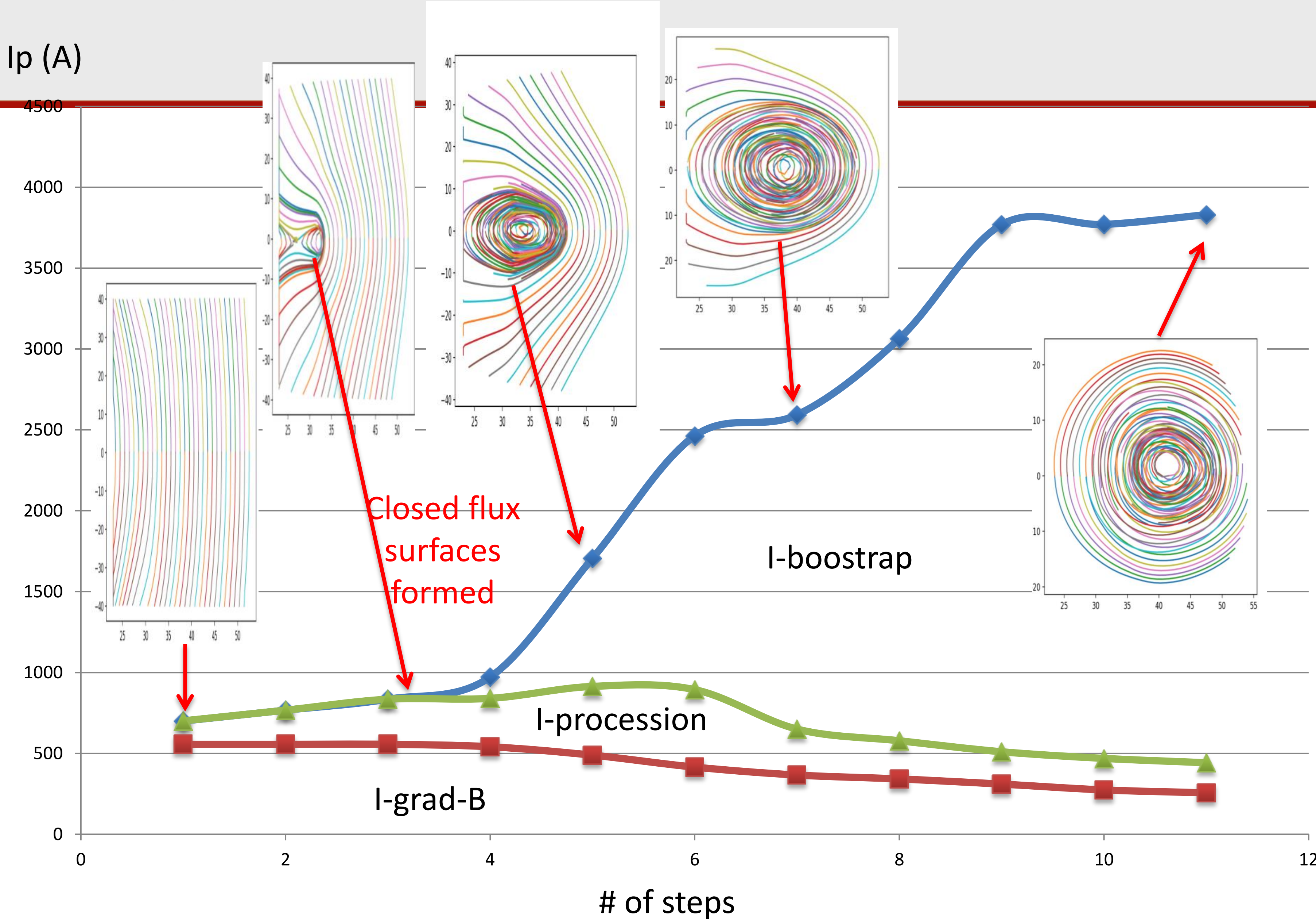


P_{ECH} = 61 kW

- ECH generated bootstrap currents were investigated in CDX-U and DIII-D.*
- Scaling using ITER 89P confinement scaling was developed which scaling was used here.
- Boostrap current increases cofinement which in term generate more currents.
- More current increases the closed flux surface volume increasing the P_{ECH} within the closed flux surface volume.
- Eventuall reaches saturation since the increasing current increases poloidal fields which tends to reduce poloidal beta.

*Y.S. Hwang, et al., PRL 1996, C.B. Forest, et al., *PoP 1994*

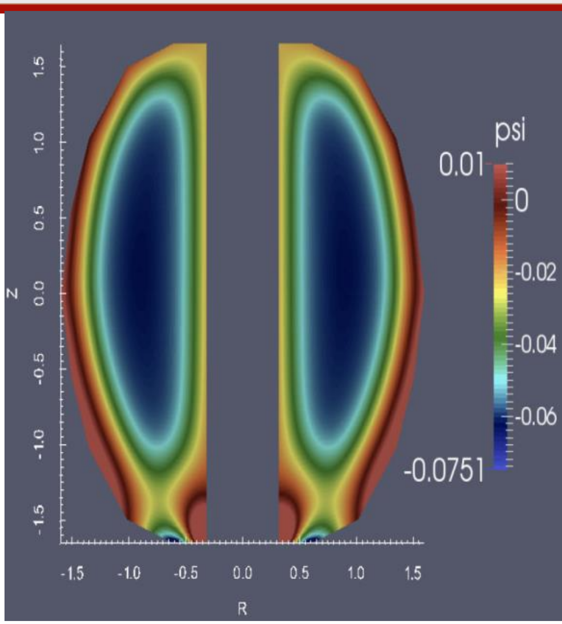
Formation of Flux Surface Formation With Pressure-Driven Currents

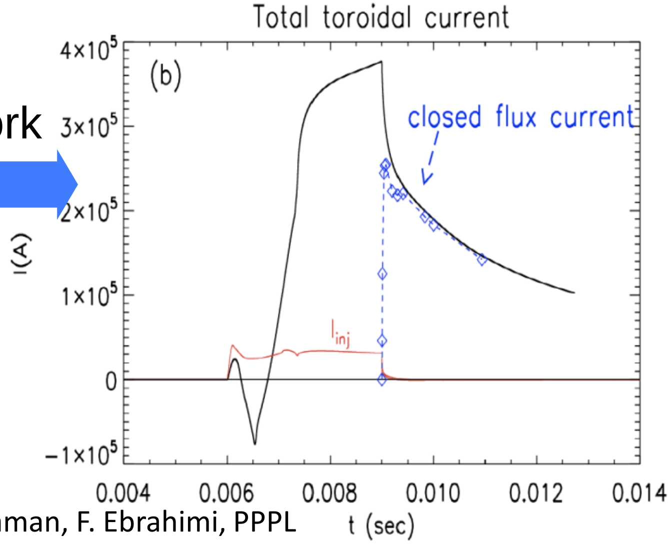


Closed flux surfaces formed

Transient CHI: It is advantageous to achieve ~ few MA and reduce demand on non-inductive current ramp-up

- NSTX Transient CHI injects poloidal magnetic flux from divertor area into vessel on a 1-3ms time scale
  - Injector flux shaping and injector current ramp-down causes open flux to form closed flux surfaces (like in a soap bubble)
- Obtained ~ 200 kA close flux discharge and aiming to achieve ~ 500 kA in NSTX-U
- Significantly ramped up computational modeling work to understand CHI scaling
- Theory and NSTX-U/HIT-II Experimental work has resulted in simple scaling relation for transient CHI to project to reactor scale devices (Ip Injected flux)
- QUEST is testing reactor-relevant CHI capability – localized electrodes.

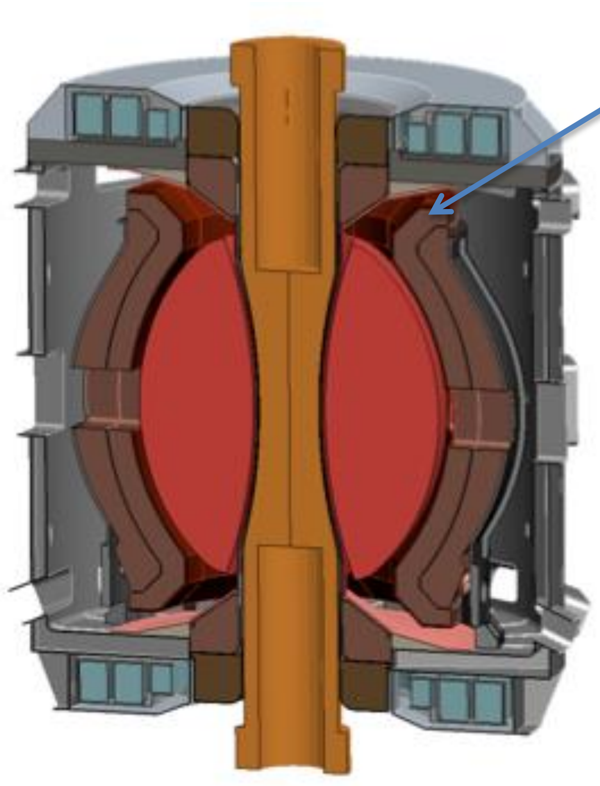




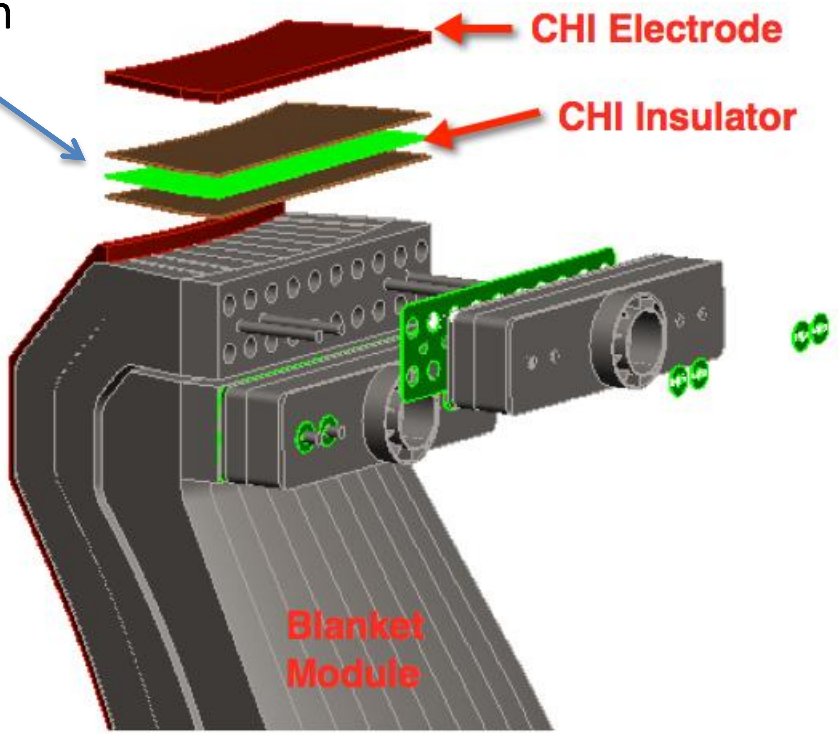
R. Raman, F. Ebrahimi, PPPL

Biased Electrode Concept to protect CHI insulator from Neutron damage for life of Reactor

Toroidal electrode on top of blanket structure, analogous to CHI ring electrode



Upper portion of blanket



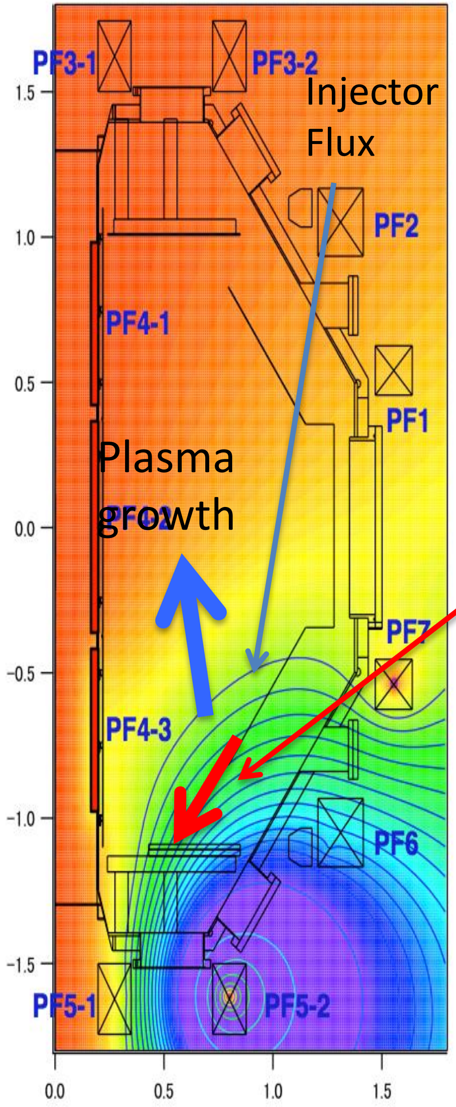
Injector flux connects upper portion of vessel to the electrode plate on the upper portion of the blanket assembly

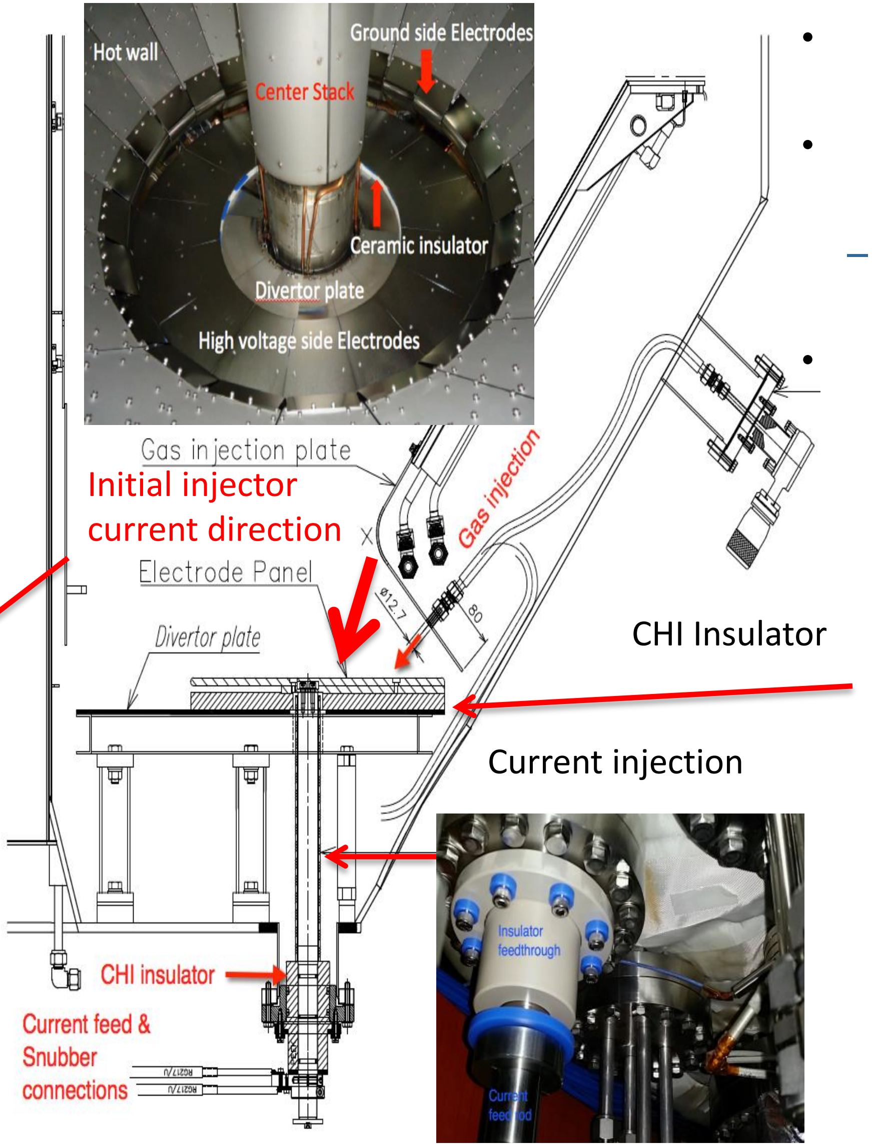
R. Raman, T. Brown, L.A. El-Guebaly, et al., Fusion Science & Technology (2015)

*Insulator dose:
~6×10^9 Gy @ 6FPY < 10^{11} Gy limit

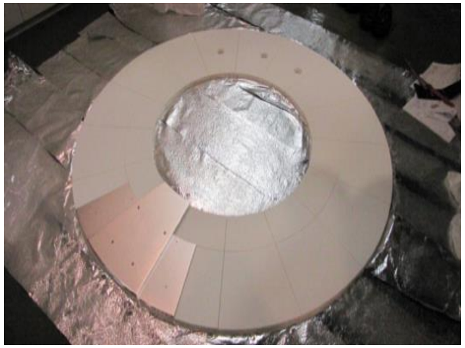
*** L. El-Guebaly, et al., MCNP Neutronics**

QUEST (in Japan) is Developing Reactor-Relevant CHI Configuration & Will Test ECH Heating of a Transient CHI Plasma



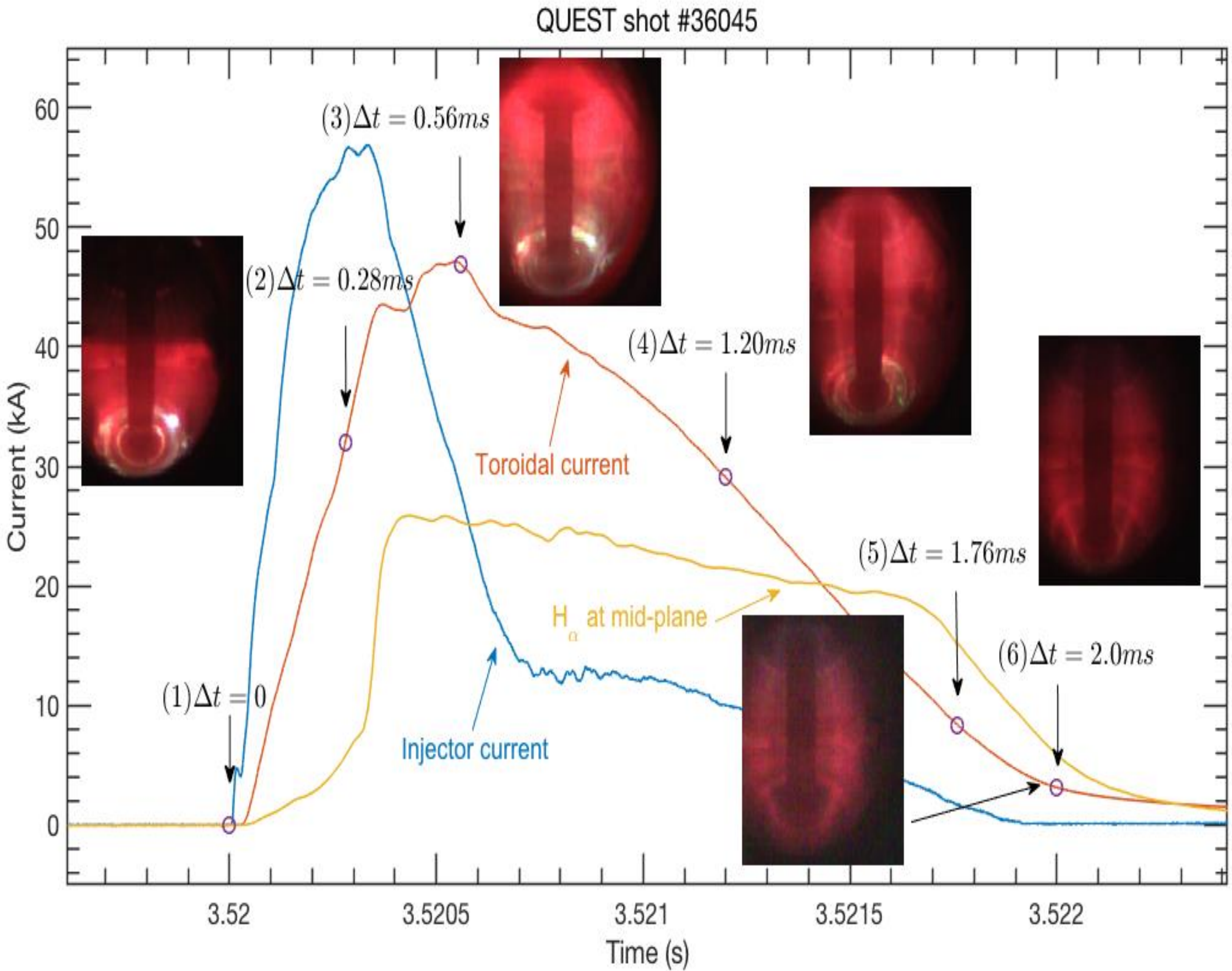


- In reactor concept insulator can be shielded from neutrons
- Insulator not part of vacuum boundary as on NSTX
  - Needs experimental test / verification
- CHI system on QUEST is similar in concept to the one planned for NSTX-U



University of Washington, PPPL

Transient CHI Discharges Successfully Established in QUEST PPPL fast camera used to capture CHI discharges



K. Kuroda, et al., sumitted to PP&CF

NSTX-U and QUEST Are Complementary Looking forward for the long-term collaboration!

- QUEST is unique among the ST worldwide which can operate long-pulse.
- QUEST is very complementary to NSTX-U and MAST-U. It is addressing a long term ST reactor problems such as start-up, long-pulse, high temperature all metal wall not being addressed by NSTX-U and MAST-U in the near term. This motivates our strong collaborations with QUEST.
- NSTX-U wishes to collaborate with QUEST to address physics areas not covered by NSTX-U in the near term:
  - Support ECH / EBW start-up studies through modeling and diagnostics.
  - Support CHI work through physics support, modeling and diagnostics.
  - Support Long-pulse operations through physics support.