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NSTX

Status of World Spherical Torus Research

Martin Peng

NSTX Program Director

ORNL@PPPL

Fusion Power Associates Annual Meeting and Symposium: Fusion and Energy Policy

October 11-12, 2005, Washington, DC

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
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SNL
Think Tank, Inc.
UC Davis
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U Maryland
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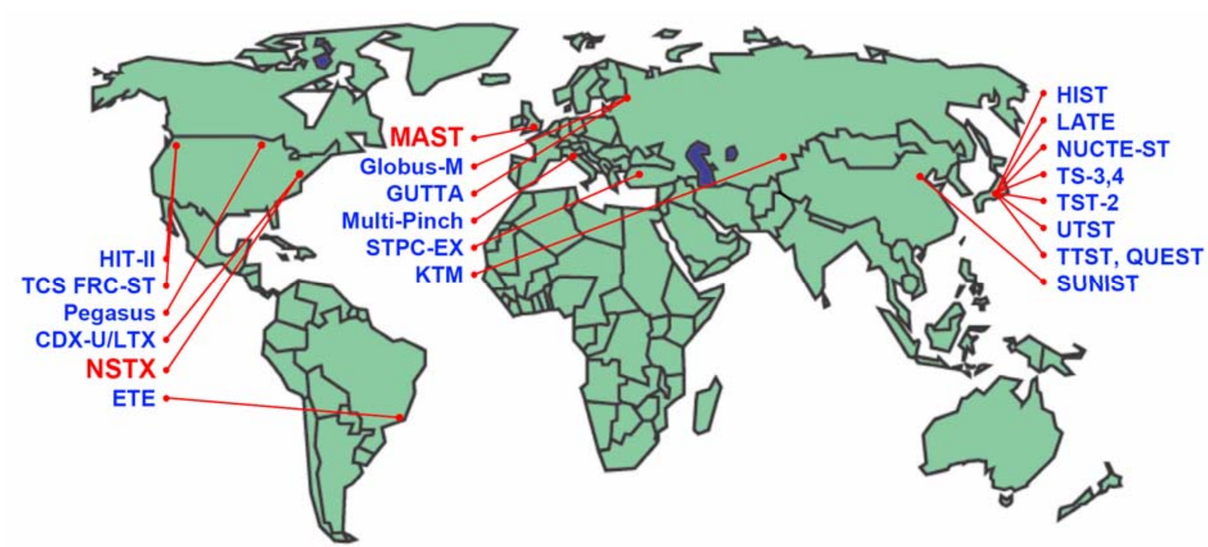
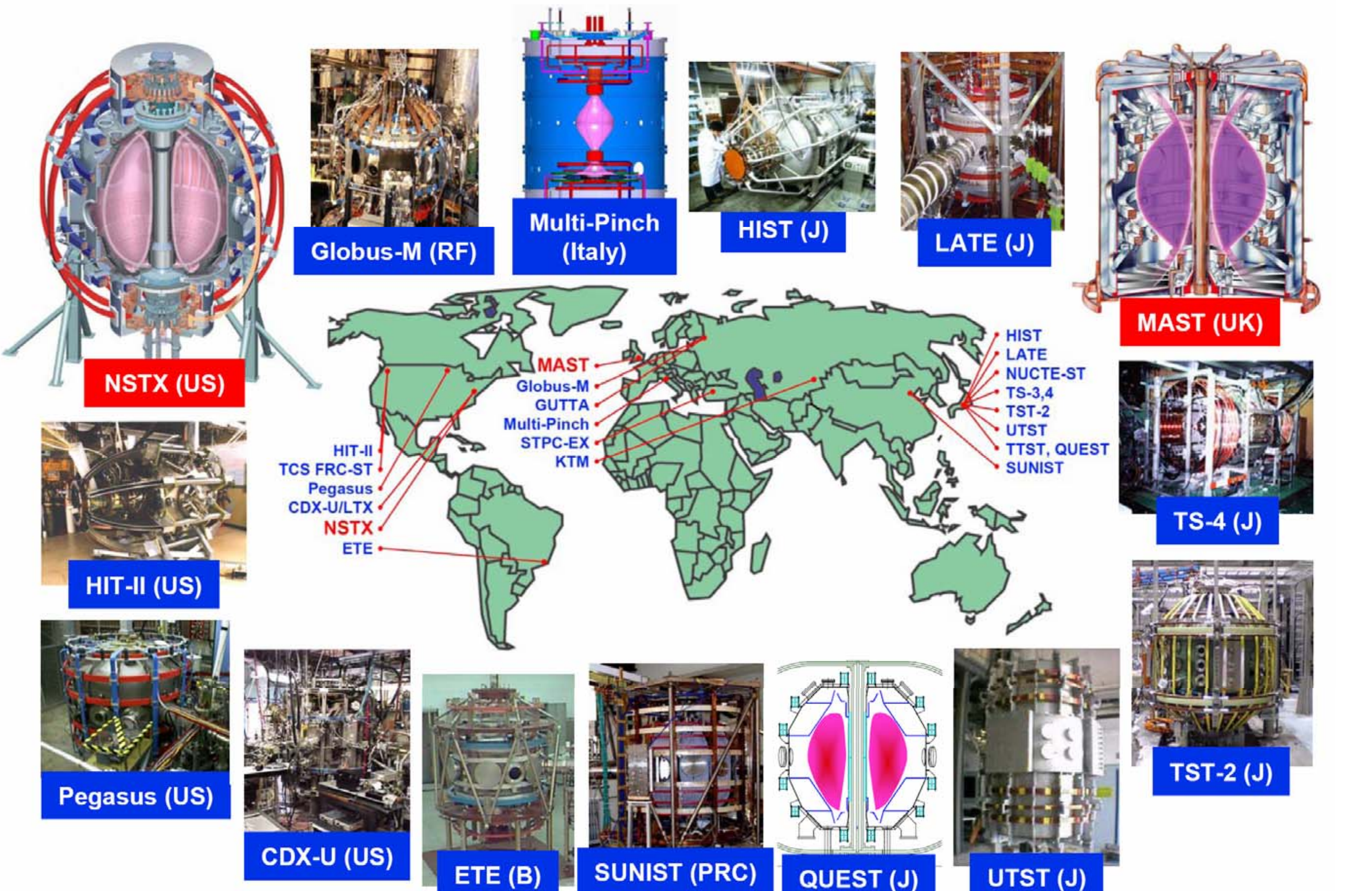
U Washington
U Wisconsin



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

World Spherical Torus Research Is Expanding – 22
"Concept Exploration" and "Proof of Principle" Experiments



World Spherical Torus Research Is Addressing Important Issues in Fusion

- **Active collaboration**
- **“Concept Exploration” STs**
- **“Proof of Principle” STs**
- **Contributions in world fusion programs**

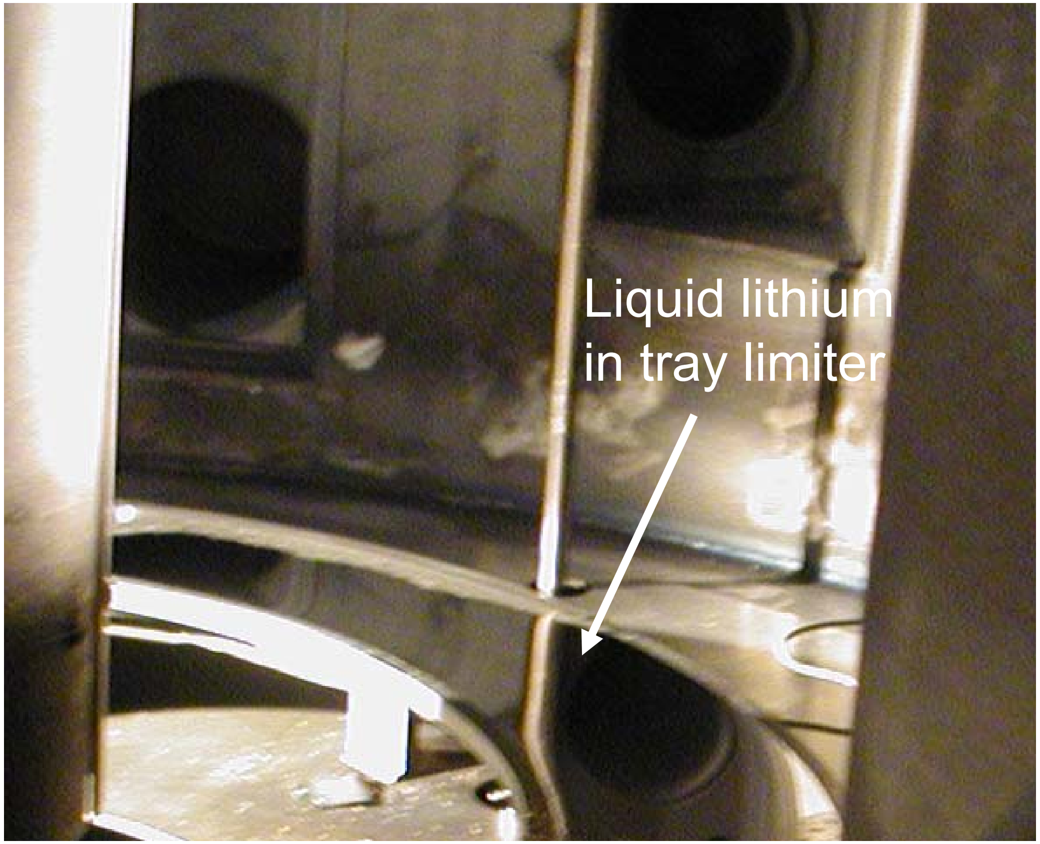
World Spherical Torus Research Has a Tradition of Strong Collaboration

- Active bilateral exchanges
  - UK-US on NSTX and MAST – START collaboration in 1997
  - Japan-US on STs – active exchanges since 2000; contributed to formation of All-Japan ST Program in 2004
  - RF-US on NSTX and Globus-M – since 1997
  - Brazil-US on initiation of ETE – collaboration since 2000
- Annual International ST Workshop since 1994; IAEA TM on ST since 1999
- Special international journal issues on progress of ST research
  - IEEJ jounral issue to appear in November
  - NF issue under preparation
- Progressing toward more coordination in research

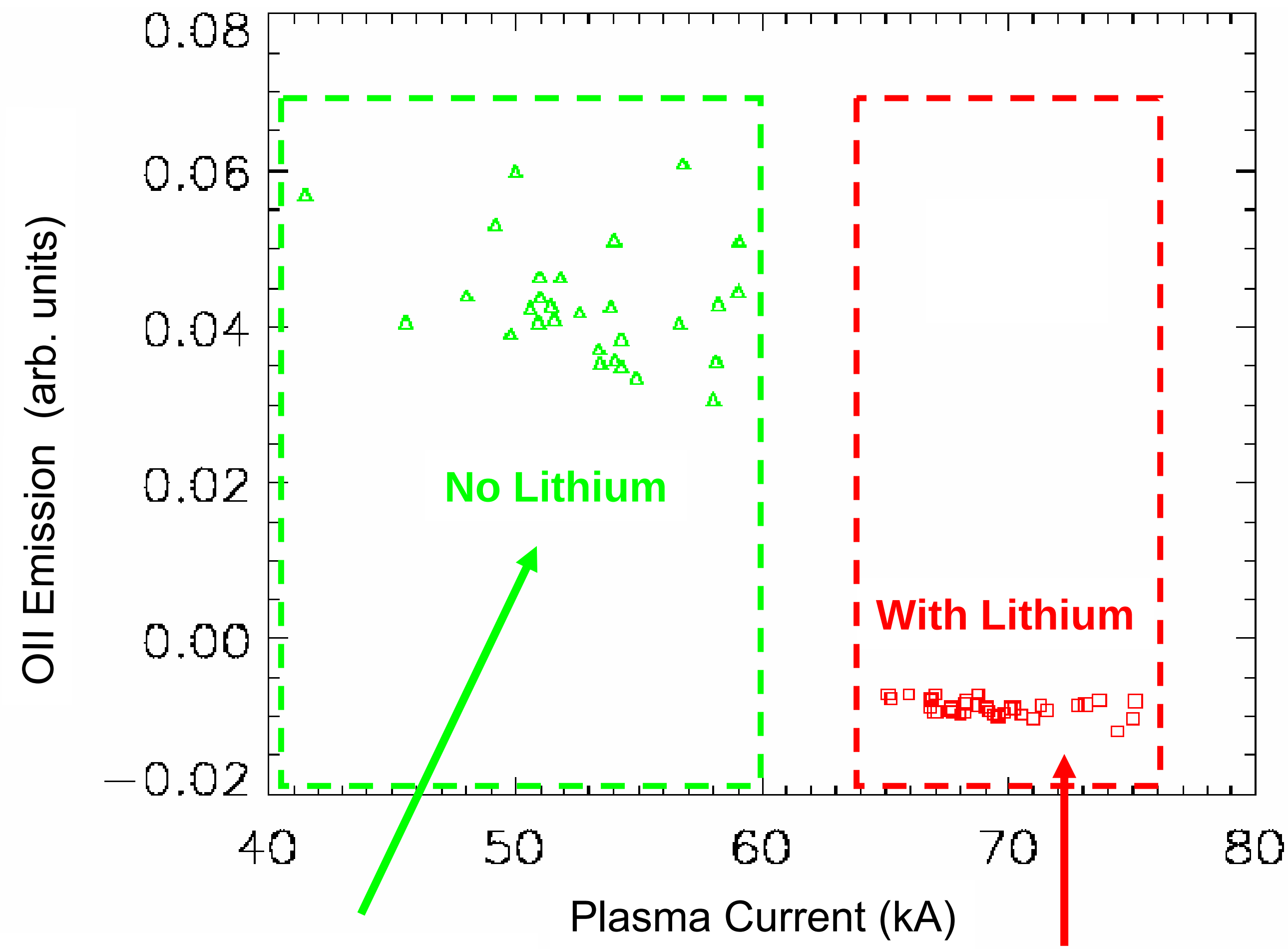
CDX-U Have Carried out Liquid Lithium Tray Limiter Experiments

- 34 cm major radius, 10 cm wide, 0.64 cm deep
- Two halves with toroidal break
- Heaters for T_{max} ≈500^{o}C
- Argon glow discharge cleaning and tray heating removed surface coatings
- Lithium remains in tray with currents to ground ≈100A at B_p≈0.1T for ≈10ms

Liquid lithium in tray after ~40 discharges.



Impurity Control with Liquid Lithium Indicated by Reduction of Oxygen Emission



Many conditioning shots required without Li to achieve currents ≈ 60kA

No conditioning shots required with Li to achieve currents > 60kA

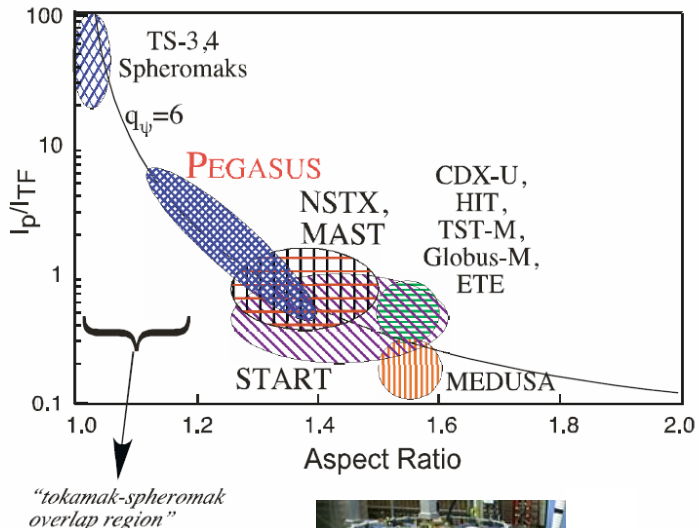
Pegasus Is an Innovative ST to Explore Plasma Limits as A → 1

Pegasus is an extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability

Original Goals:

- Stability and confinement at high I_p/I_{tf}
  - *Extension of tokamak studies*
- Limits on β_t and I_p/I_{tf} (kink) as $A \rightarrow 1$
  - *Overlap between the tokamak and the spheromak*

I_p/I_{tf} = figure of merit for access to low-A physics



Future Emphases:

- Support ST program movement to next stages
  - *EBW tests for heating & CD (w/PPPL)* } *Discussed in this talk*
  - *Noninductive startup & CD tests* }
  - *Diagnostic development*
  - *High-pressure gas puff for deep fueling*

Pegasus (US)

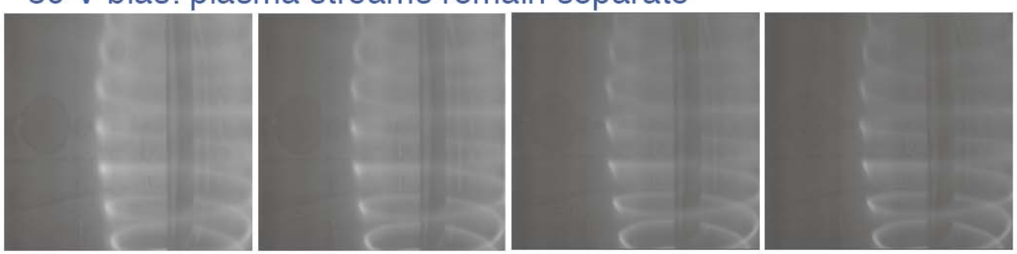
Pegasus Is Exploring Innovative Startup via Electron Beam Injection

- Nature of produced plasma changes as bias increased:
  - Low bias voltage:
    - = $I_{toroidal}$ = (I_{gun}) x (geometric windup)
    - = *plasma appears as separate streams*
  - High bias voltage:
    - = $I_{toroidal}$ = (I_{gun}) x (geometric windup) x (additional multiplication)
    - = *streams merge into uniform-appearing plasma*

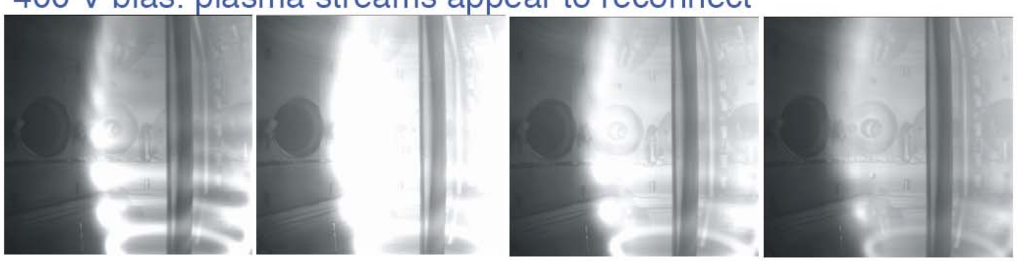
- No evidence yet of closed flux surfaces

- Two guns found to add to $I_{toroidal}$ linearly

50 V bias: plasma streams remain separate

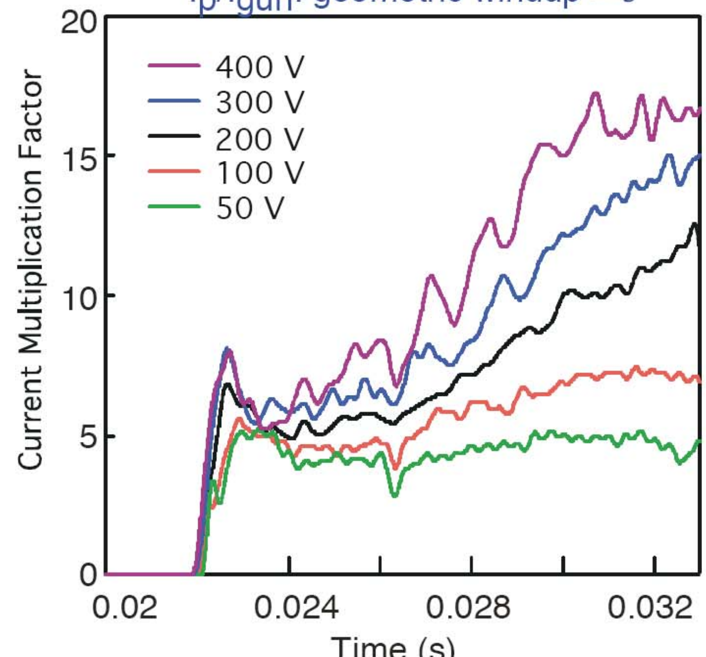


400 V bias: plasma streams appear to reconnect



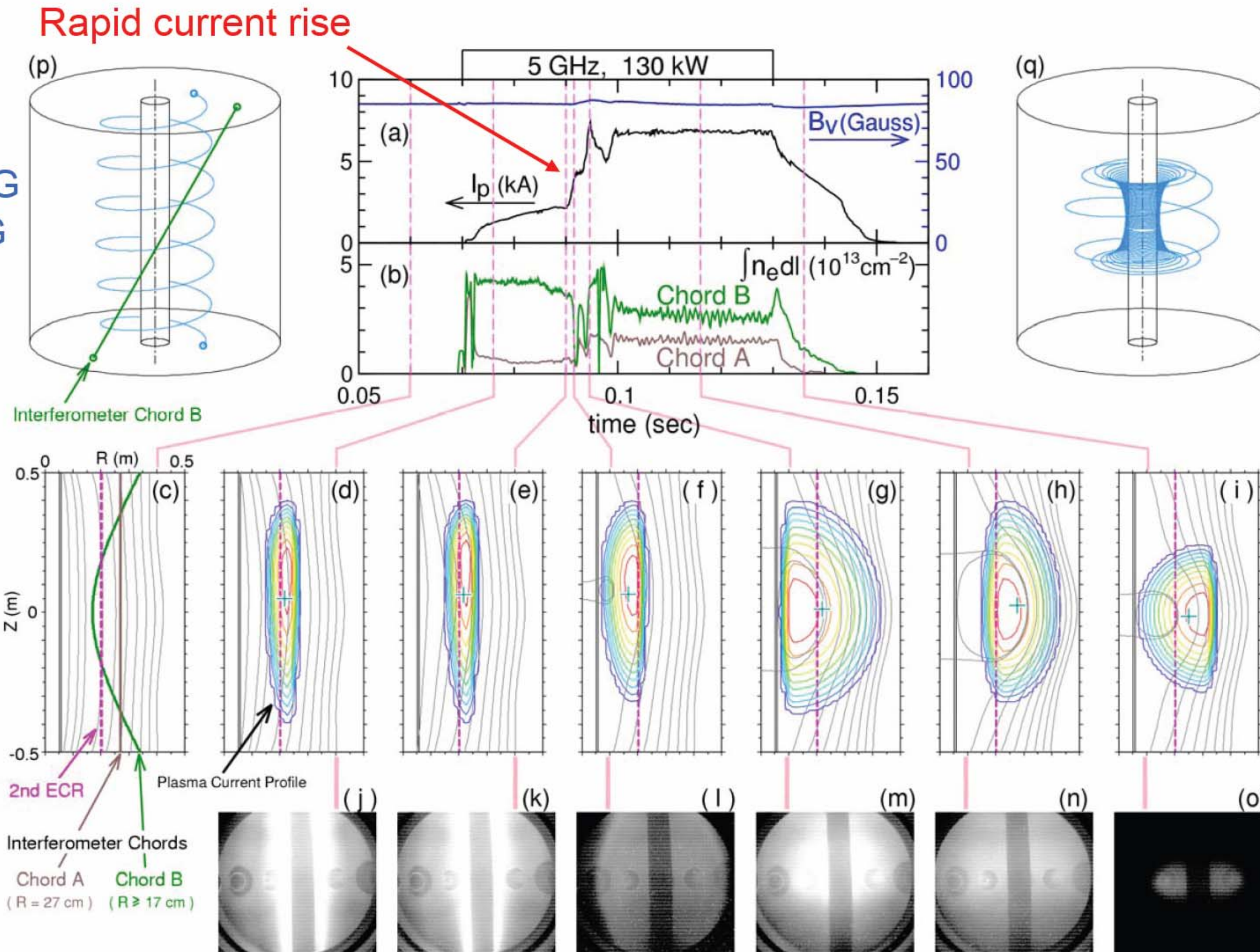
1 ms per frame

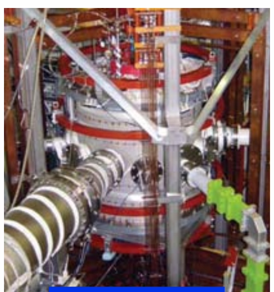
I_p/I_{gun}: geometric windup ≈ 5



Spontaneous formation of closed field equilibrium via rapid current rise under steady Bv field

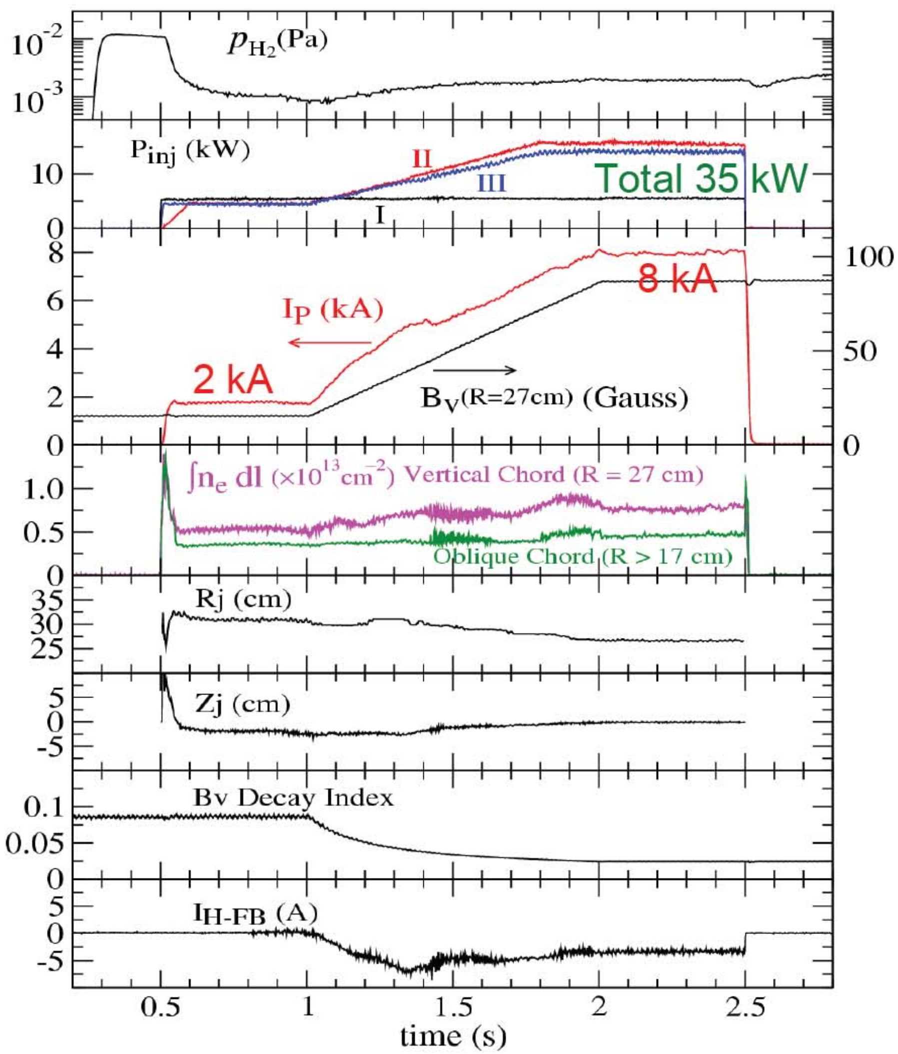
Bt=720 G
Bv=85 G

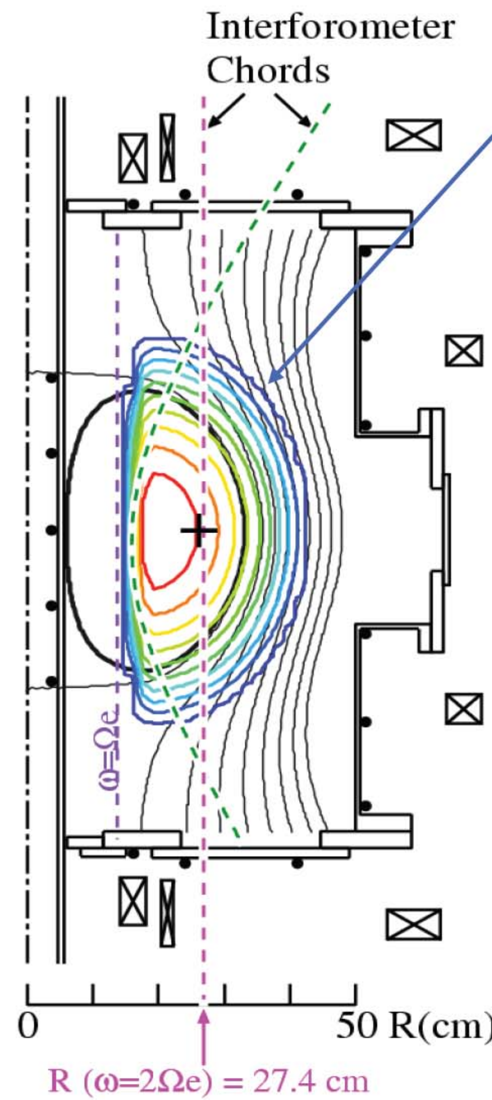




LATE (J)

After spontaneous formation Ip can be ramped-up by a slow ramp of Bv for equilibrium at larger plasma current (2.45GHz Experiment).





t = 2.37 s
Ip = 8.1 kA
(70% inside LCFS)
Rj = 26.5 cm
Zj = 0 cm

R_0 = 20 cm
a = 14 cm
b = 24 cm

A ~ 1.4
κ~ 1.7

$\bar{n}_e \sim 2 \quad 10^{11} cm^{-3}$

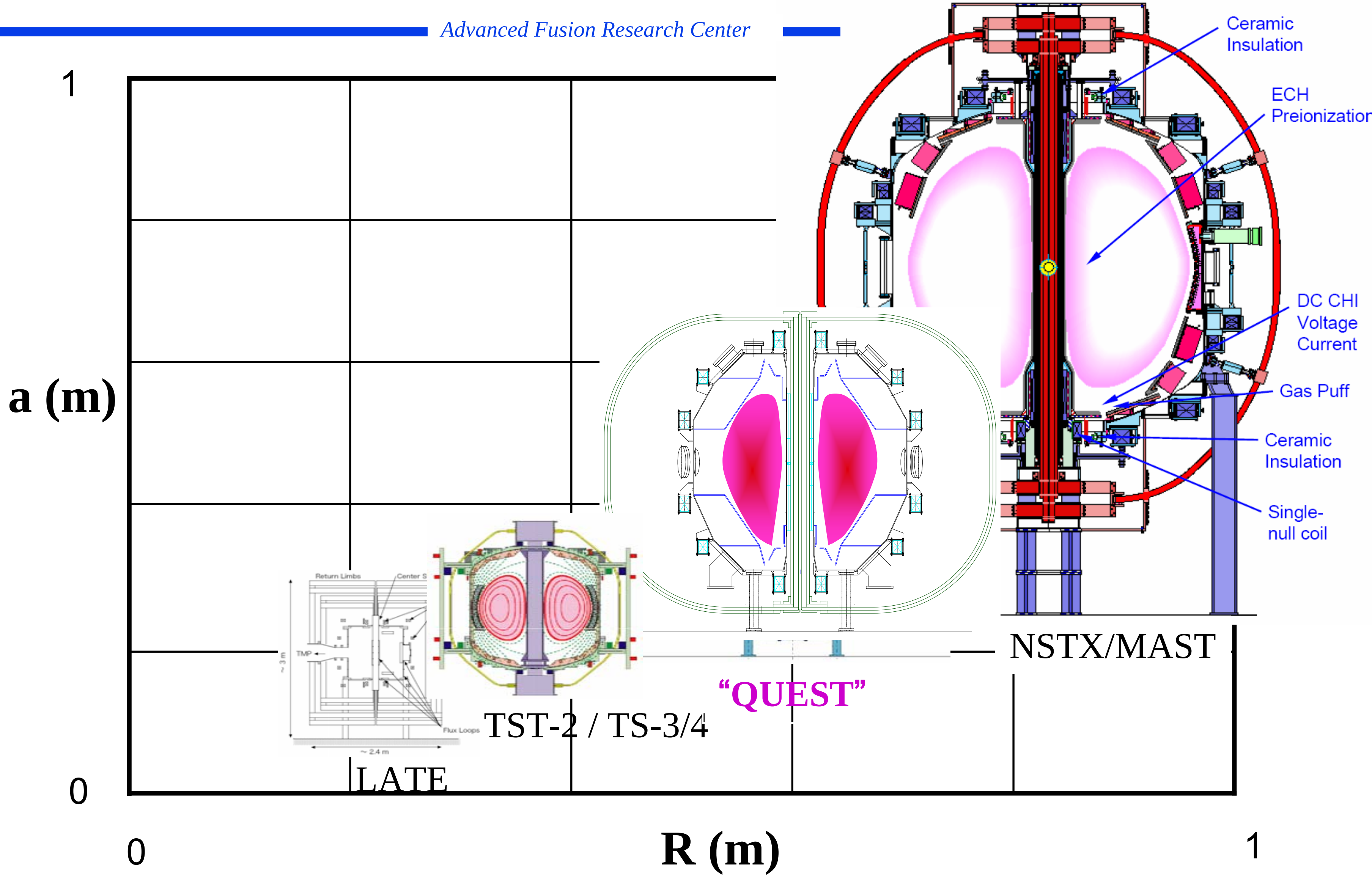
3 times of cutoff density

2nd ECH by EBW

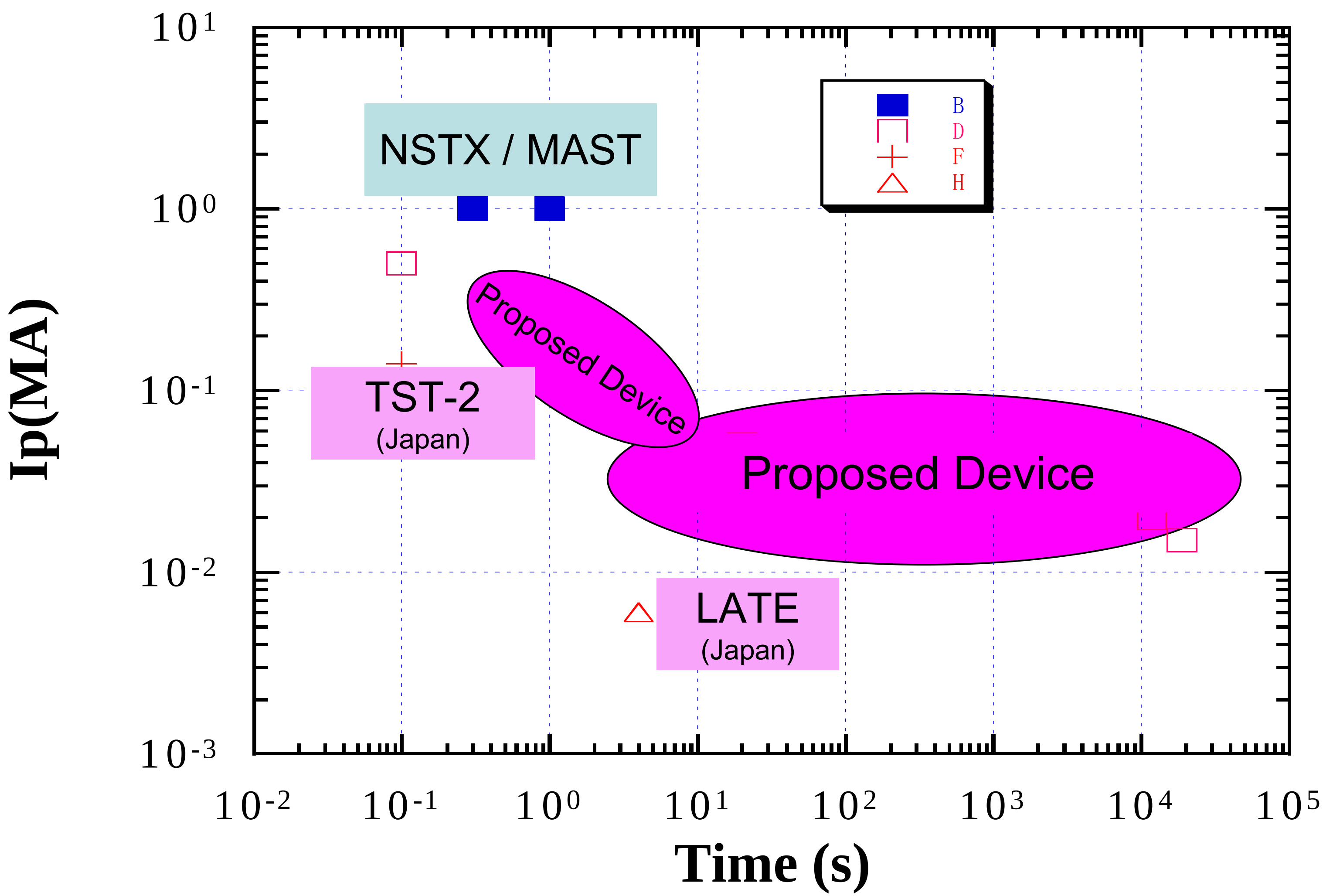
QUEST

QUEST : Q-shu University Experiment on Steady State Spherical Tokamak

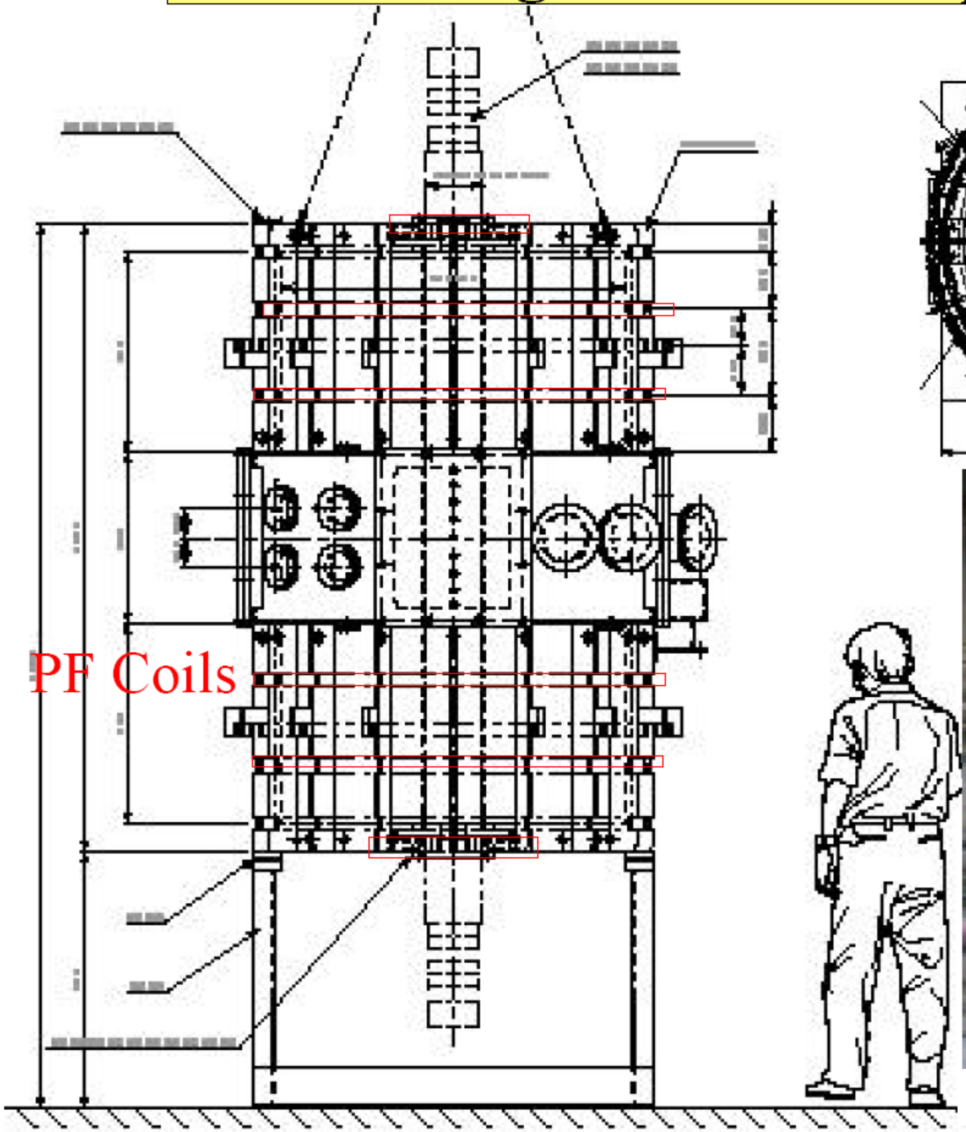
Advanced Fusion Research Center

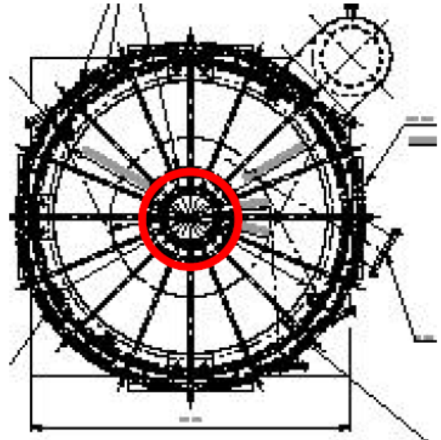


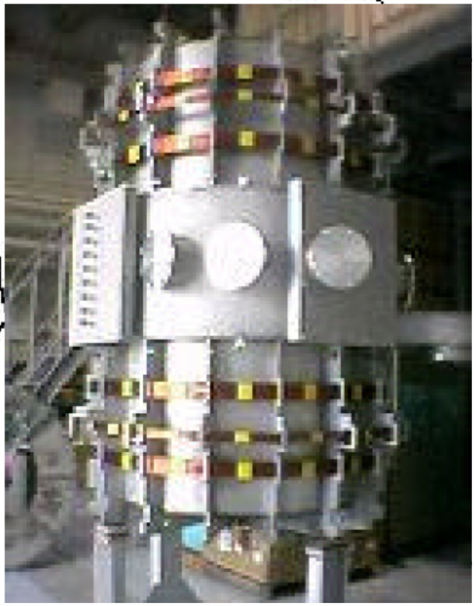
Research Region of QUEST



U. Tokyo UTST-(TS&TST) Experiment for High-ß ST Startup and RF Sustainment



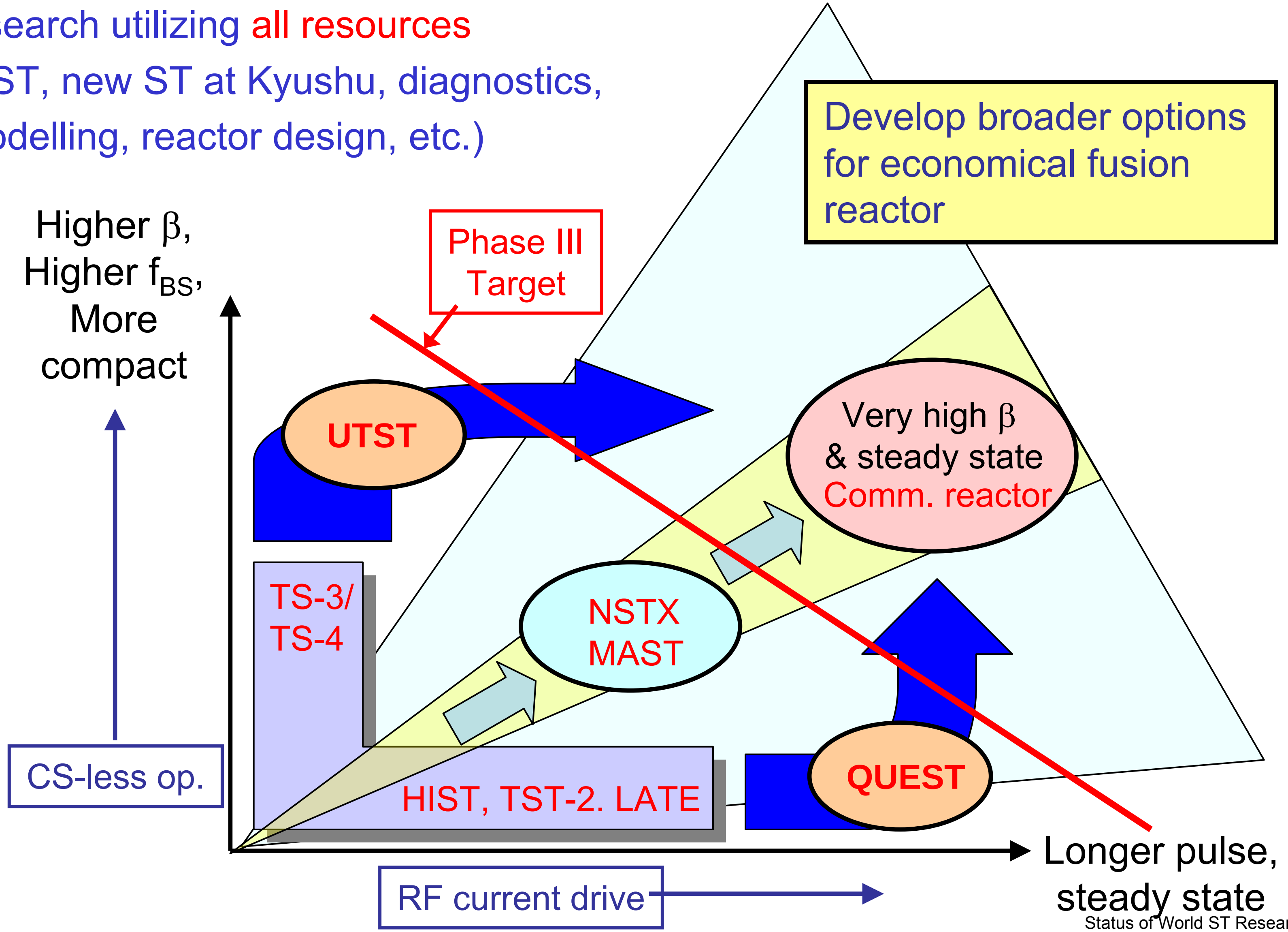




Strategy of the All-Japan ST Research Program

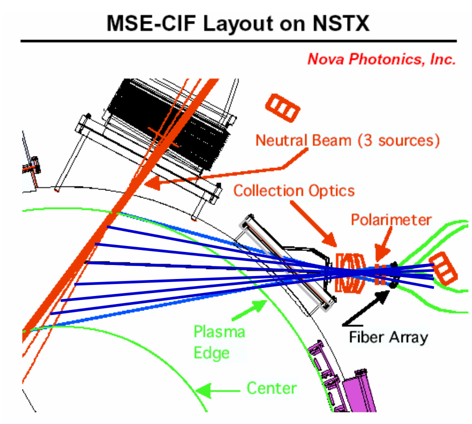
(Prof. Yuichi Takase, June 2005)

Broad research utilizing all resources (existing ST, new ST at Kyushu, diagnostics, theory/modelling, reactor design, etc.)

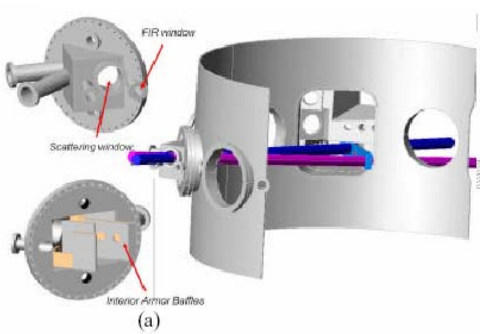


New Capabilities in NSTX

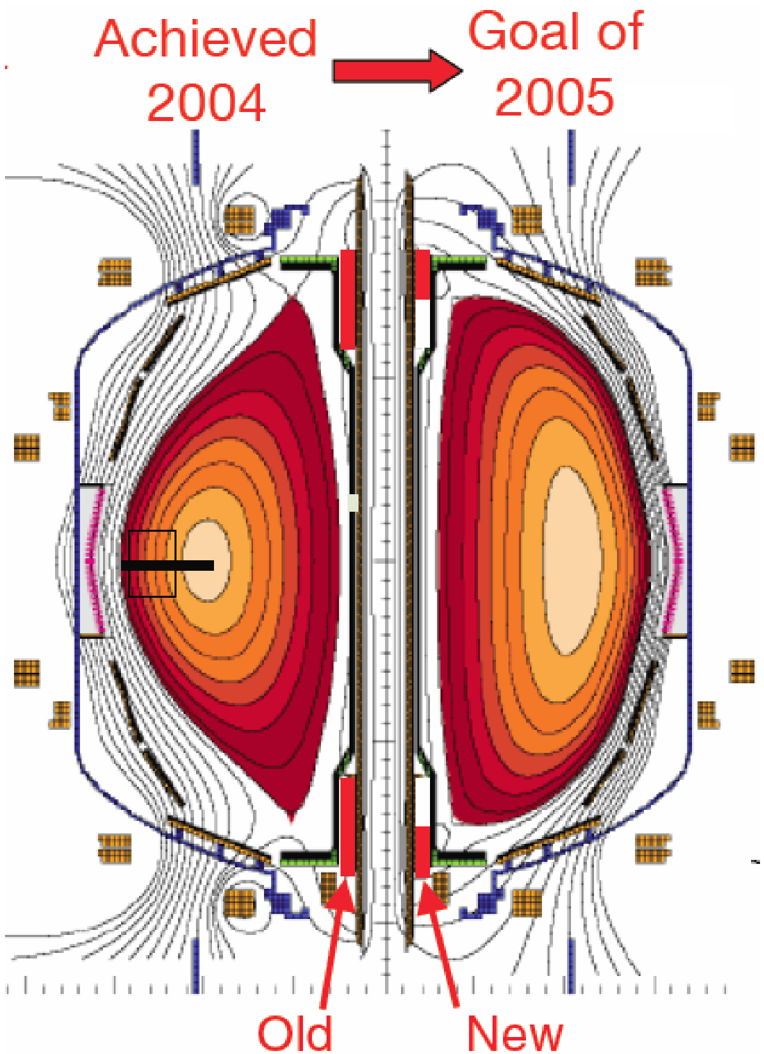
Novel j(r) diagnostics for Advanced physics



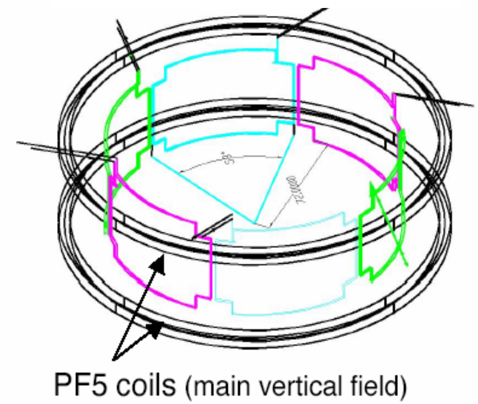
Direct Measurement of Electron Turbulence



Tangential scattering UCD

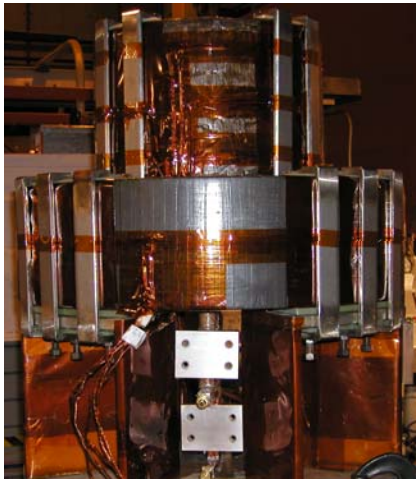


EF/RWM coils to extend β limits

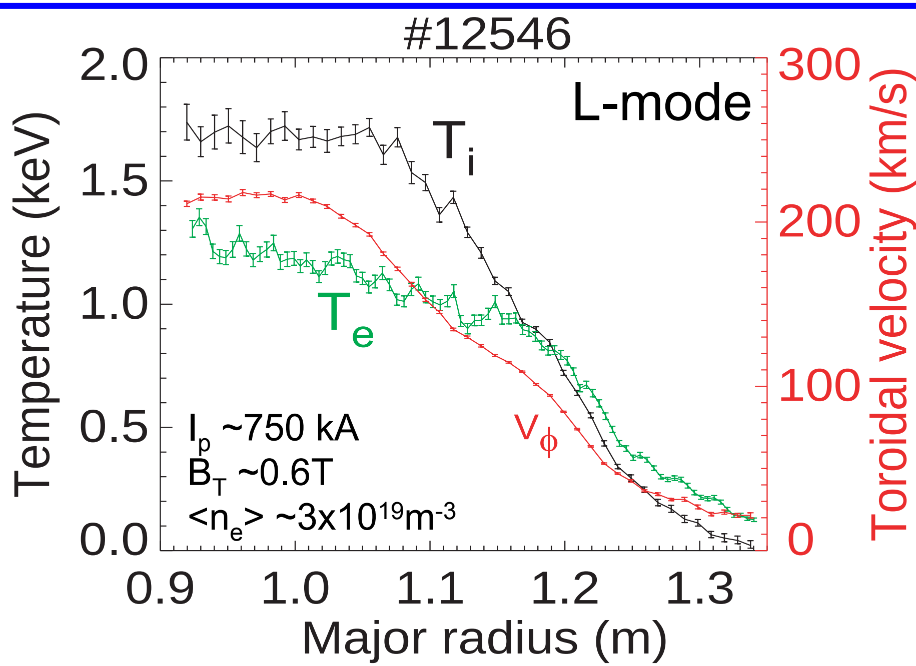


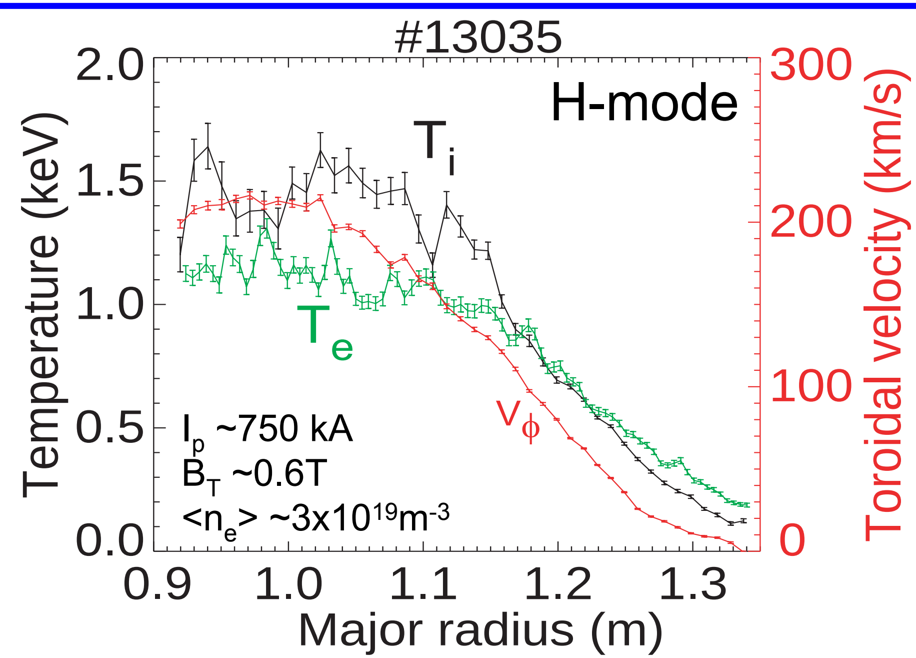
Columbia

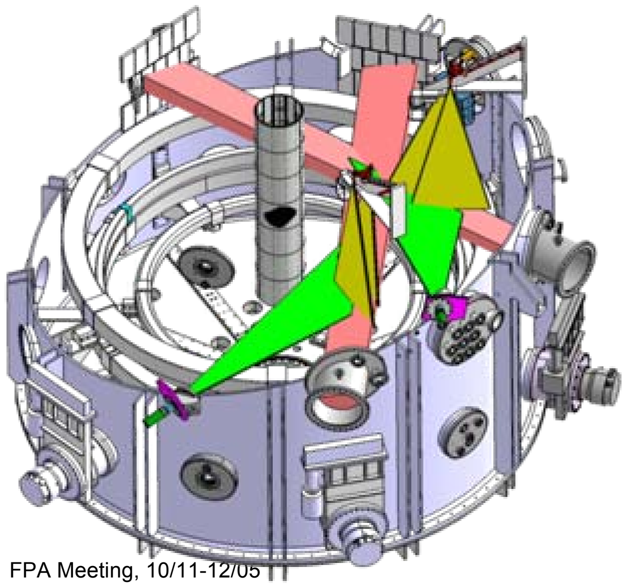
New PF1A coil for advanced shaping



Enhanced CXRS ($\Delta_R \sim \rho_{Li}$) in MAST





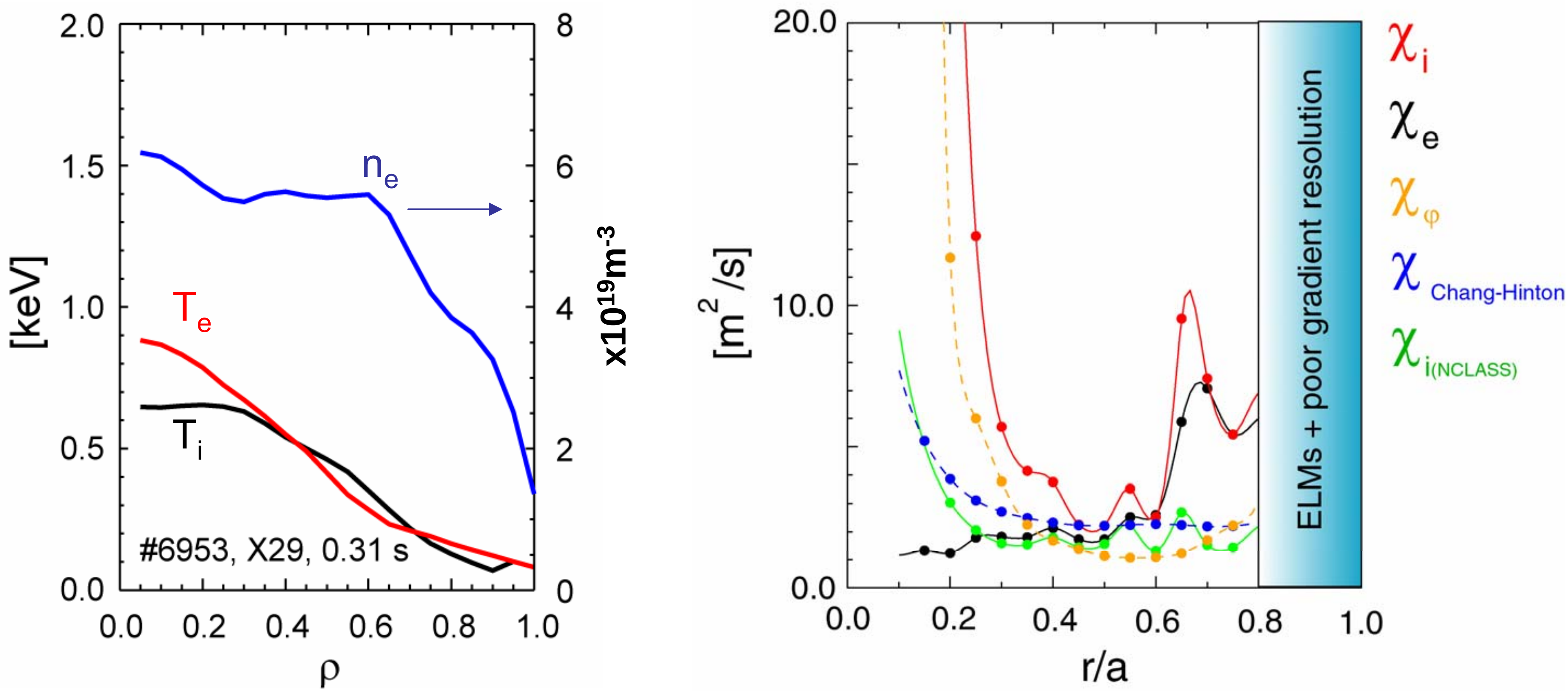


- ❑ Spectrometer coupled to 224 chords
- ❑ 64 toroidal chords on each NBI
- ❑ 32 passive toroidal chords
- ❑ 64 poloidal chords (32 32 on/off-beam) being commissioned

UKAEA Fusion Working in Europe

H-mode Transport Coefficients Can Be Close to Ion Neoclassical

$\chi_e \sim \chi_i$ around mid-radius & close to $\chi_i^{Z\text{-}CH}$ [Chang & Hinton]

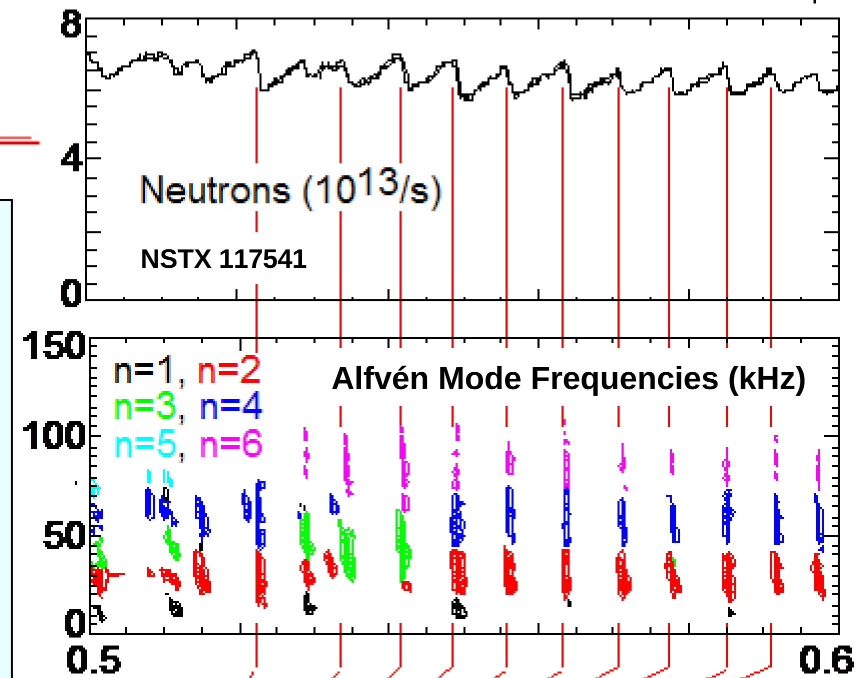


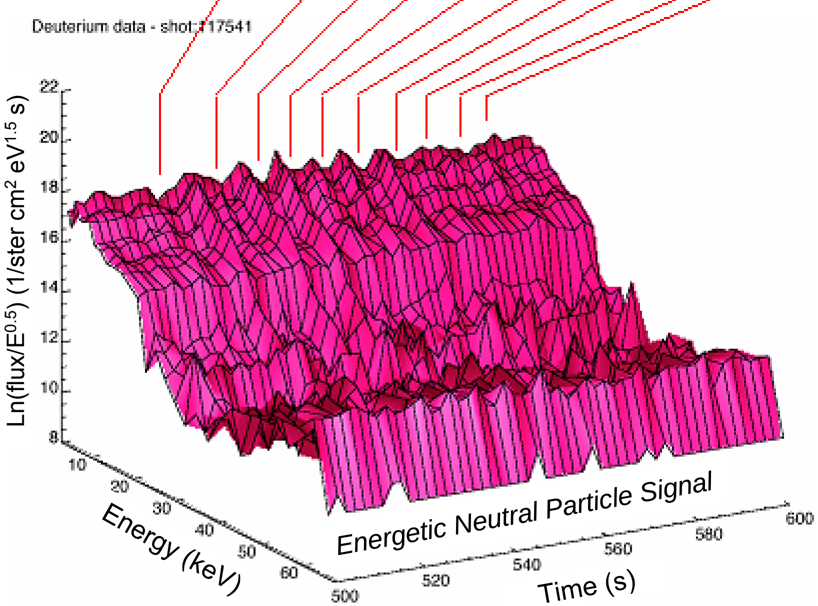
TRANSP modelling

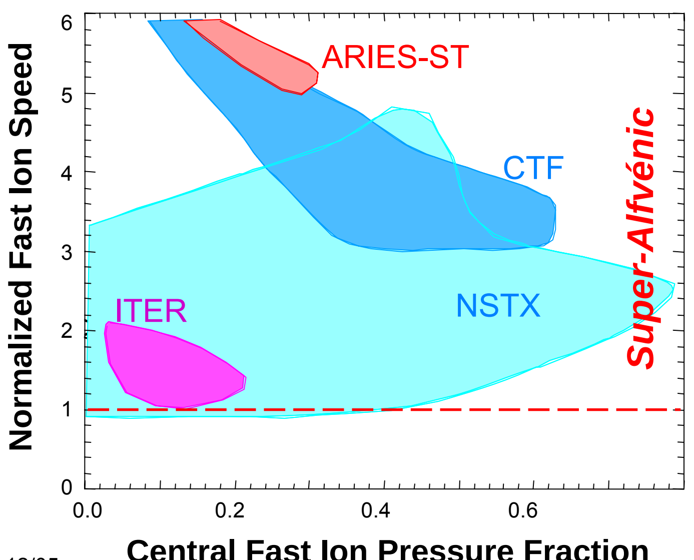
UKAEA Fusion Working in Europe

STs Are Studying Super-Alfvénic Ion Heating for ITER and CTF

- **NSTX has Super-Alfvénic ions (NBI), as in ITER (fusion α's)**
- **Measured instabilities driven by such fast ions & coincidental fast ion losses**
- **Interactions driven by small ρ_{fast}^* (ITER), copious fast ions (both), and Doppler shifted resonance with Alfvén instabilities (both)**
- **Will fusion α's in ITER & CTF suffer similar losses?**





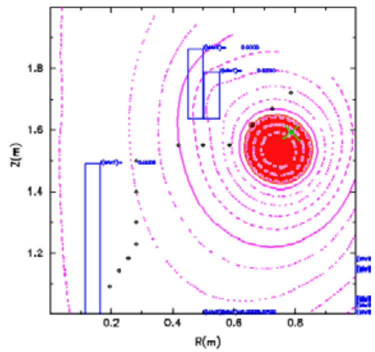


[E Fredrickson, S Medley]

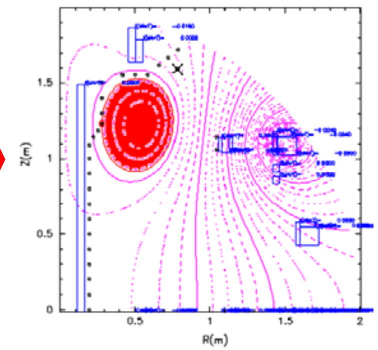
Start-up Schemes – Double-Null Merging

- compatible with future ST design
- Double-null merging (DNM) involves **breakdown at a quadrupole null** between pairs of poloidal coils in upper and lower divertor
- Modelling predicts **merging of plasma rings** as current in coils ramped to zero

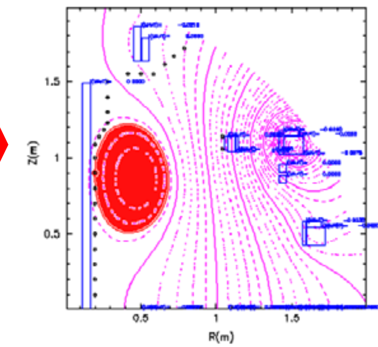
t=15ms I_p = 150 kA

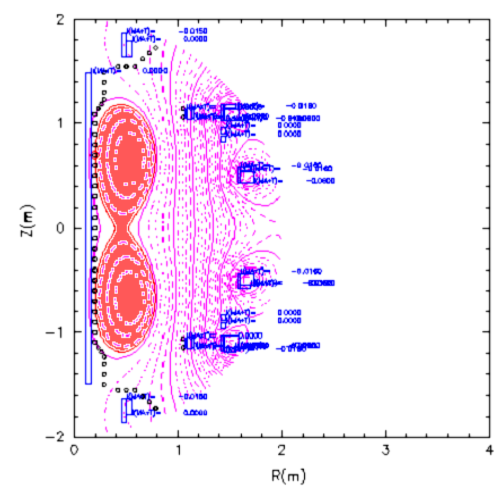


t=21ms I_p = 250 kA

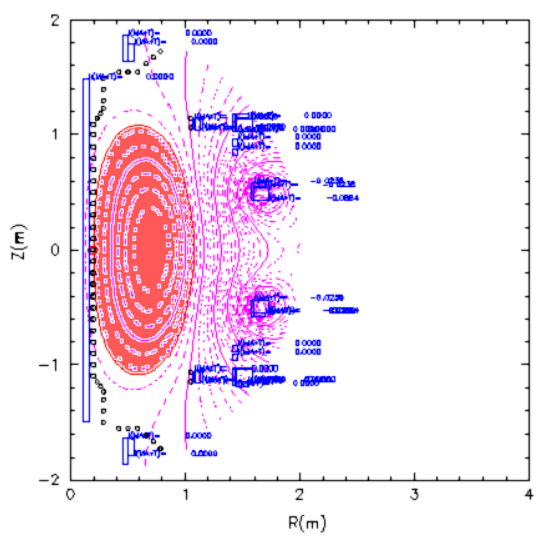


t=45ms I_p = 450 kA





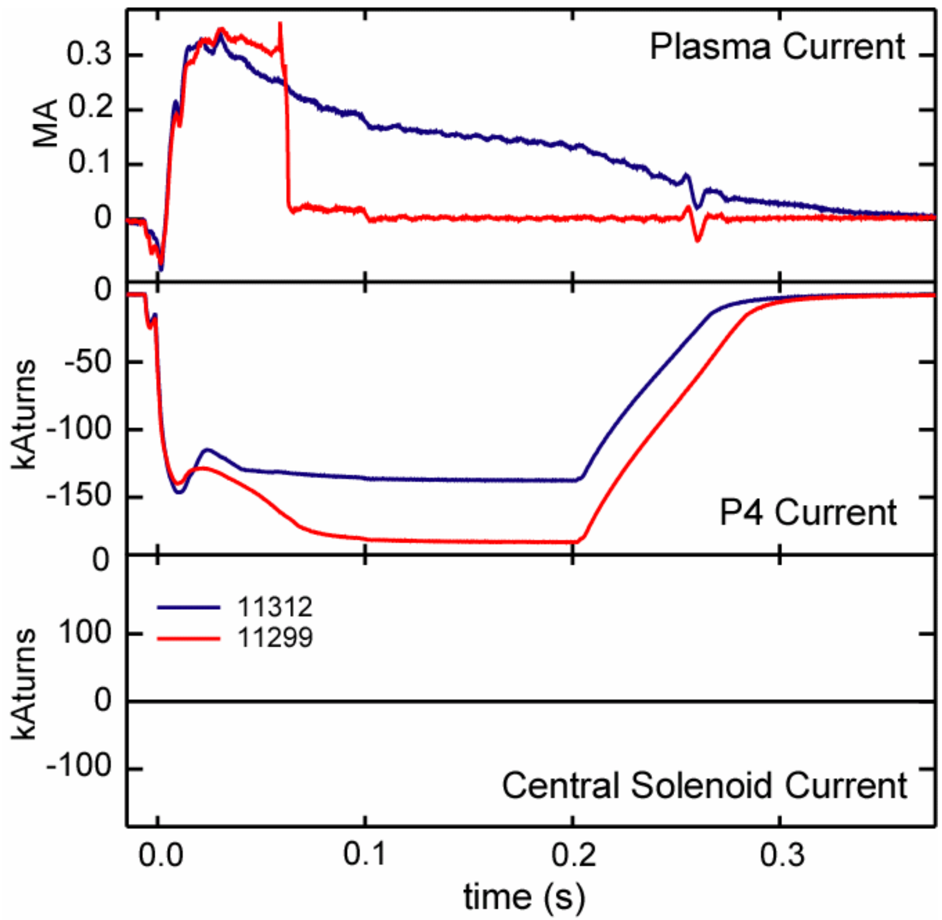
t=60ms I_p = 600 kA

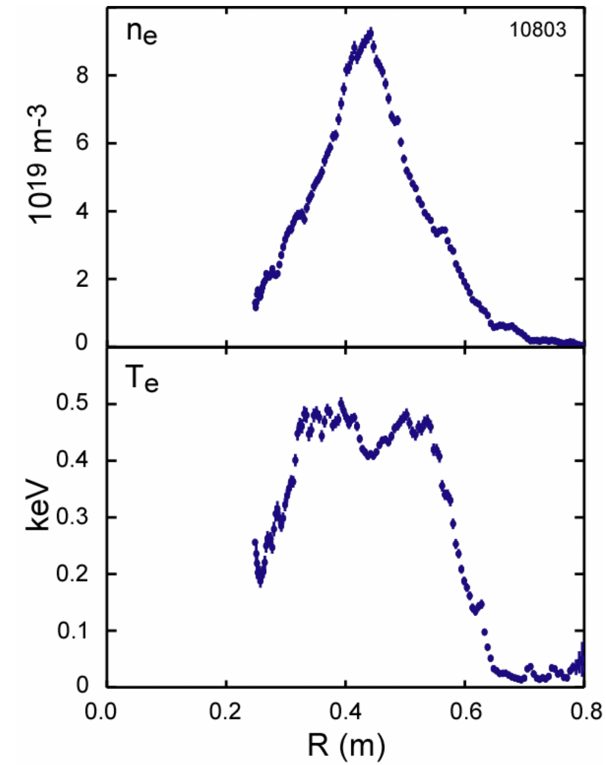


t=75ms I_p = 600 kA

Double-Null Merging Formation Demonstrated

After some optimisation, plasma current up to 340kA formed and plasma sustained for 0.3sec with zero current in central solenoid



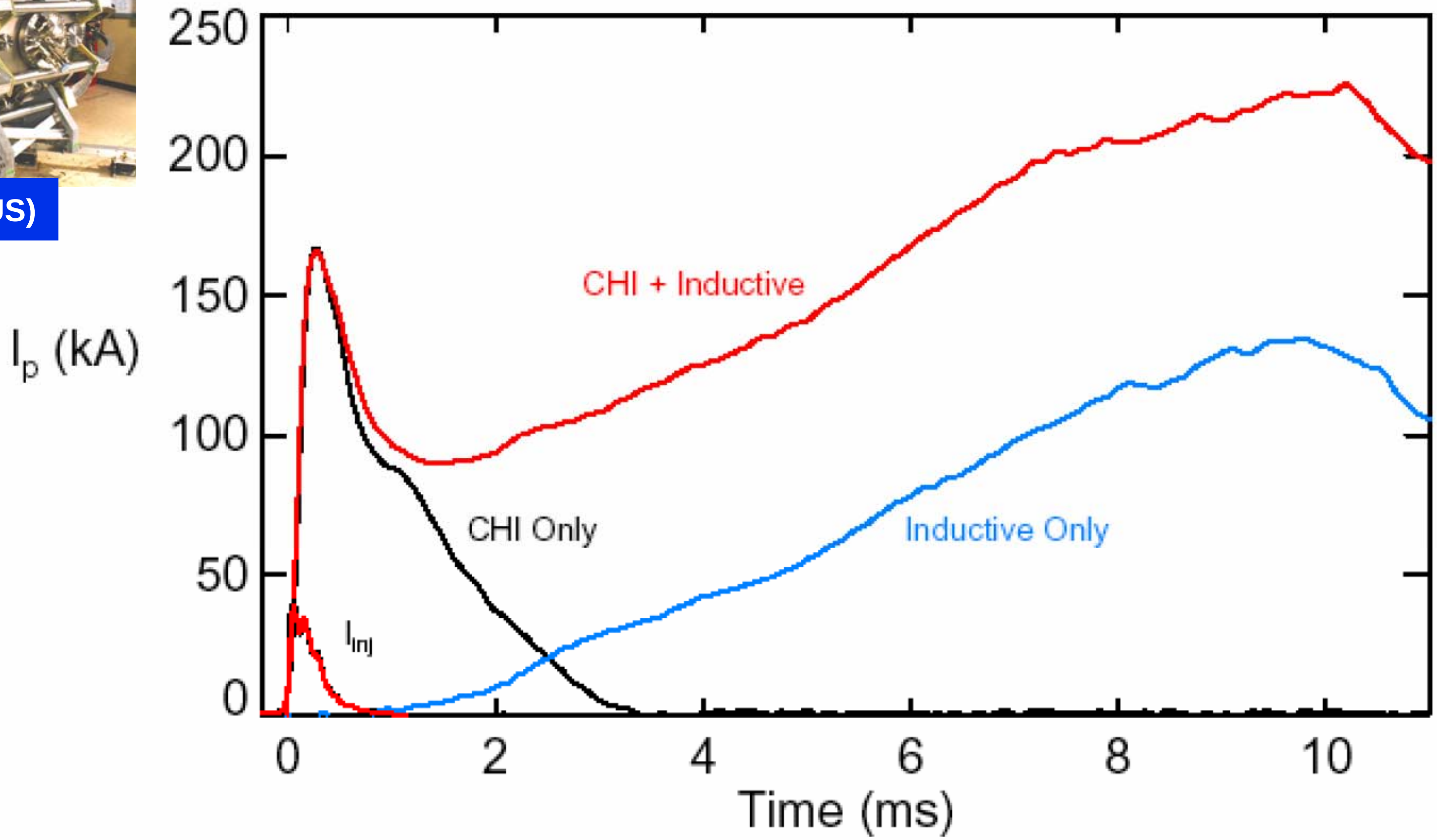


$T_e \sim 0.5$keV and $n_e \sim 9\times10^{19}m^{-3}$

In HIT-II, nearly all Transient CHI produced closed flux current couples to the subsequent inductive drive

HIT-II

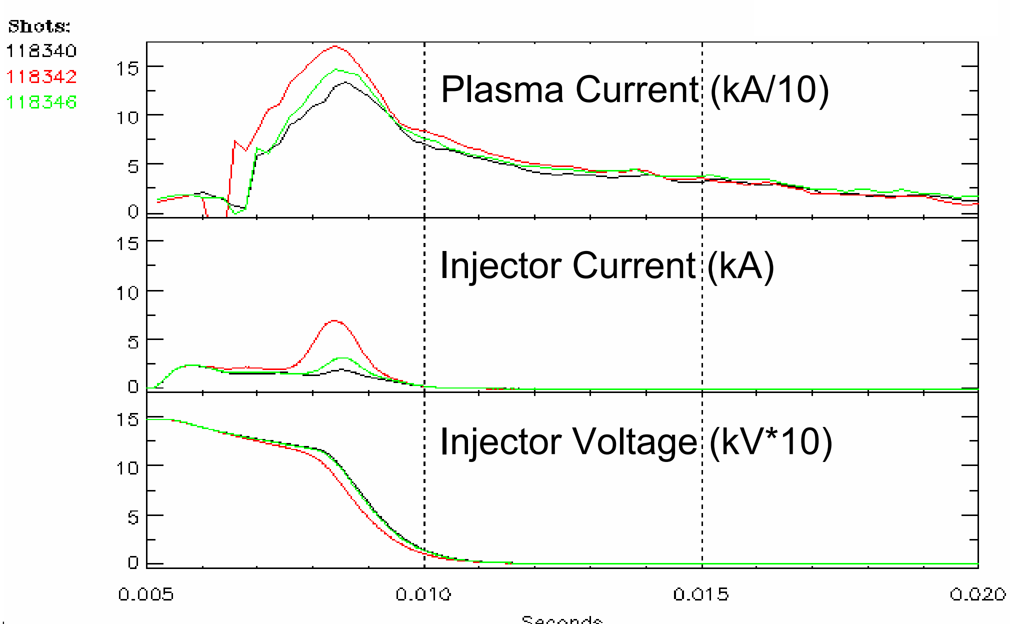
HIT-II (US)

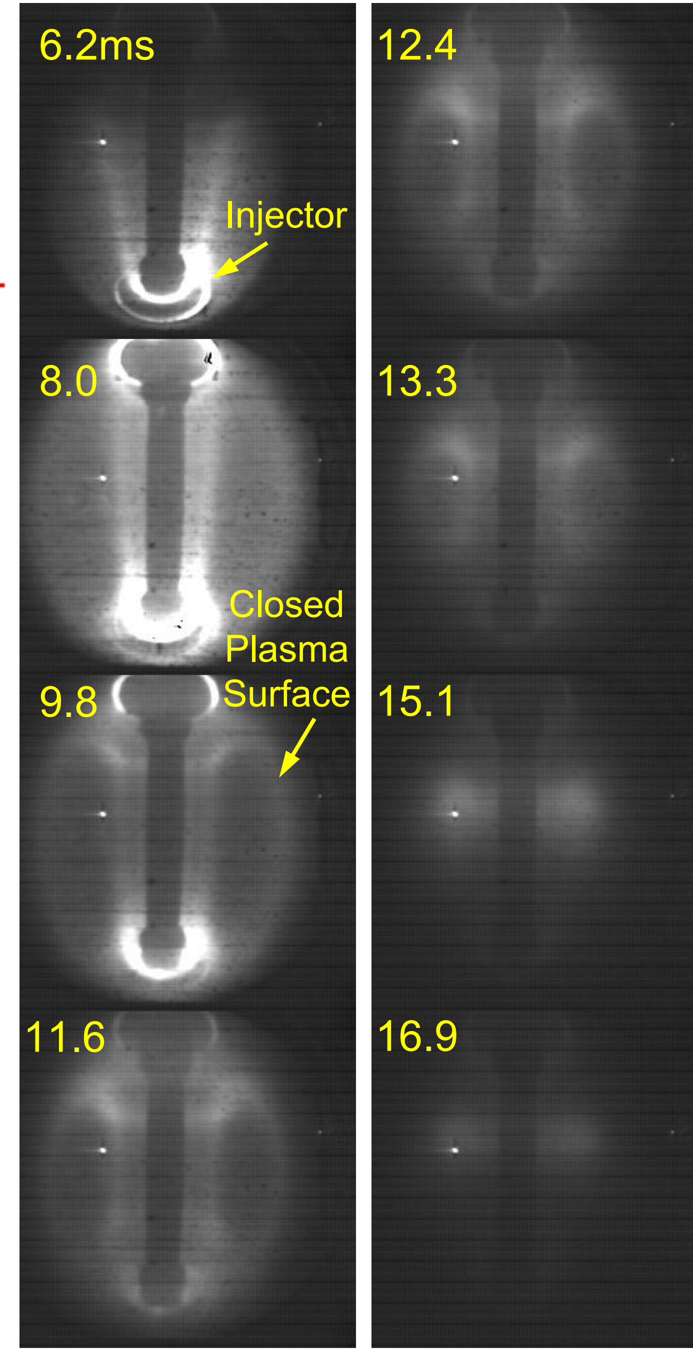


Both discharges have identical loop voltage programming

NSTX Produced Sustained ST Plasmas via Coaxial Helicity Injection (Introduced by HIT-II)

- **Rapid turn-off of injector current → closure of plasma surface → 60 kA, ~2 m² volume**
- **First demonstrated on HIT-II (U Wash)**
- **Important progress for attractive ST and Tokamak fusion systems**

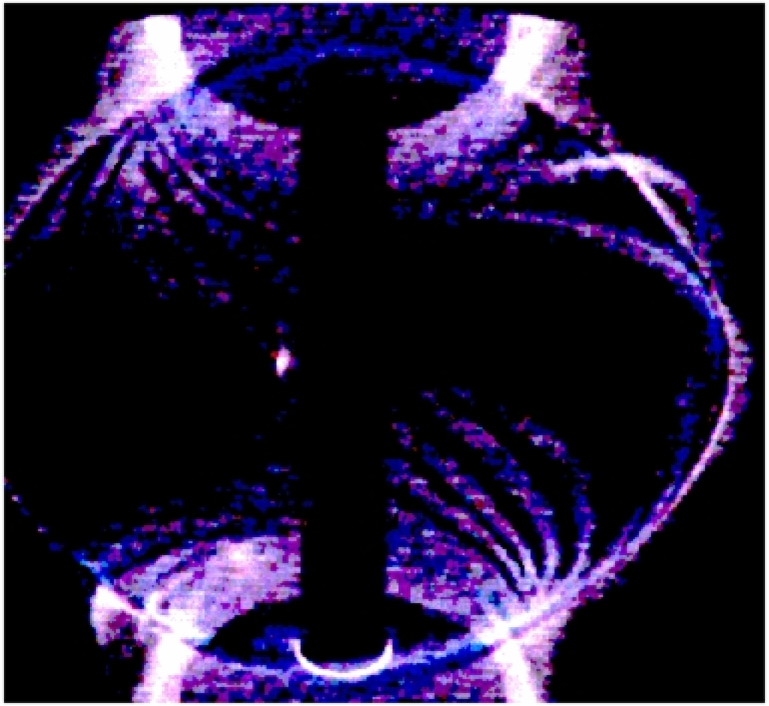


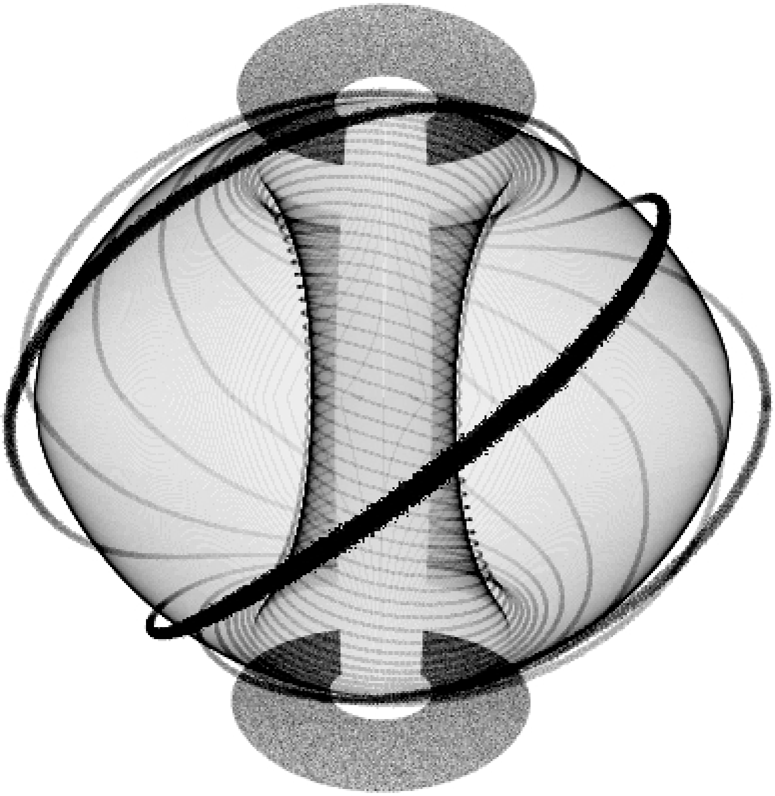


Univ. of Hiroshima camera: N. Nishino; R. Kaita

ELM Spatial Structure (Experiment + Theory)

Image simulation of the expected structure with q_{95}=4 and n=10



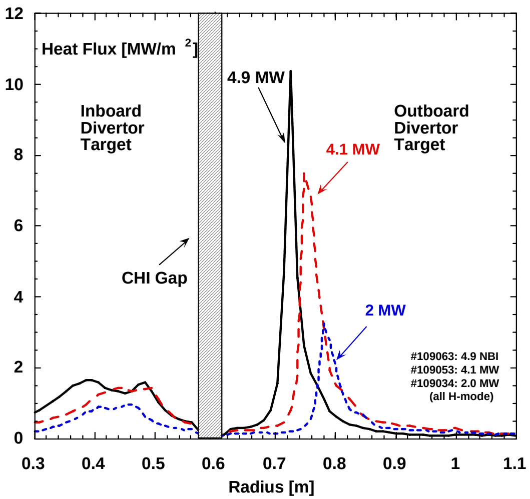


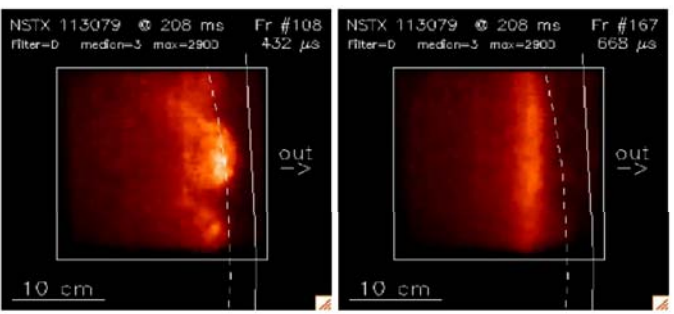
Filaments are consistent with the structures expected from the theory of the non-linear evolution of ballooning modes [Wilson and Cowley]

Unique ST Properties and Approaches Advance Boundary Physics

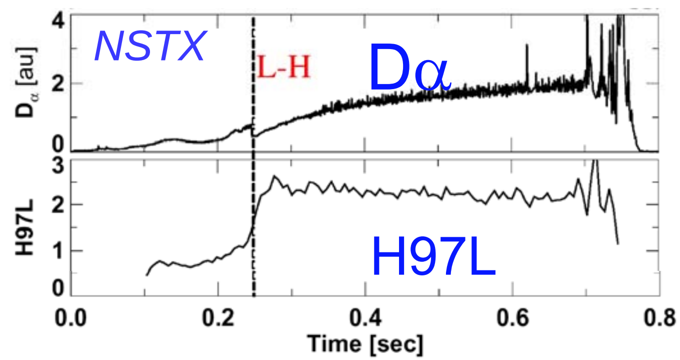
NSTX

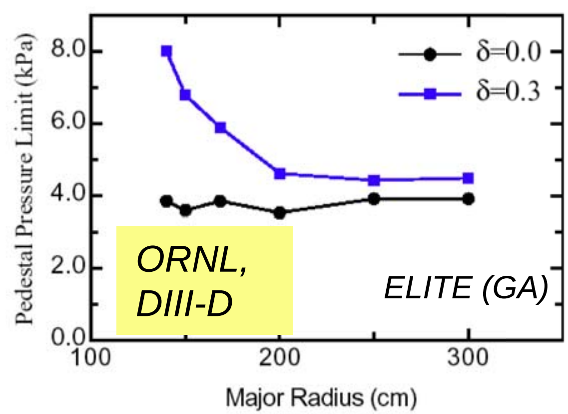
ITER-relevant heat fluxes (10 MW/m[2]).
Shaping & flux expansion



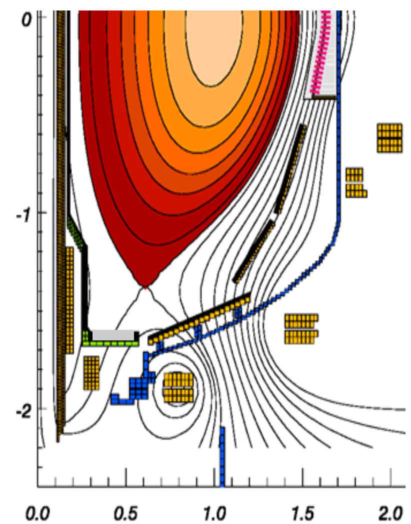


Turbulence imaging: large ρ_i slow dynamics enable good resolution



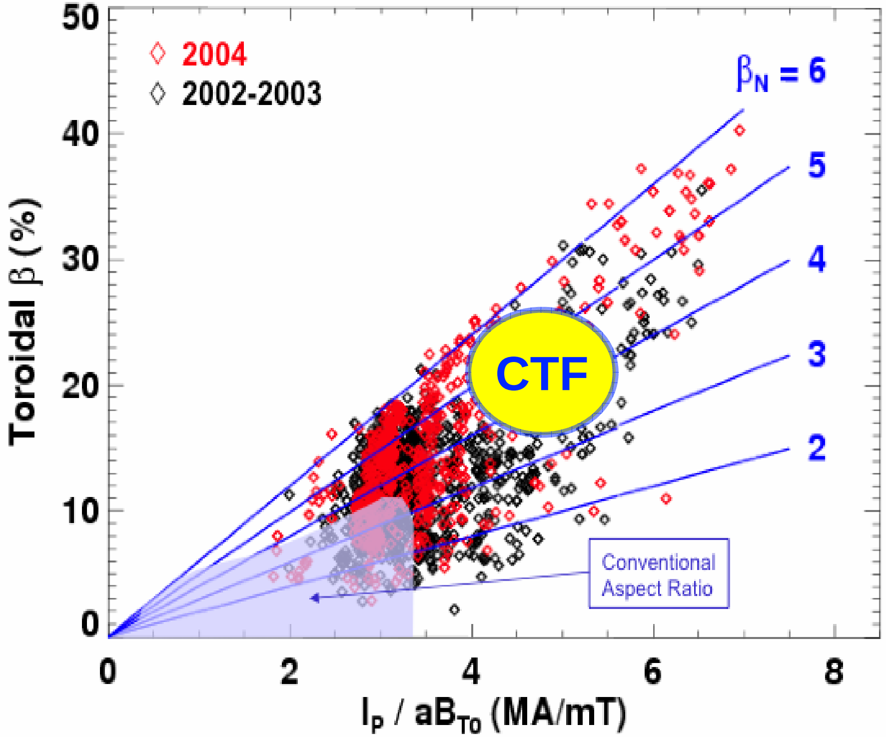


Pedestal stability: strong shaping, low A: magnetic geometry pedestal stability & SOL transport

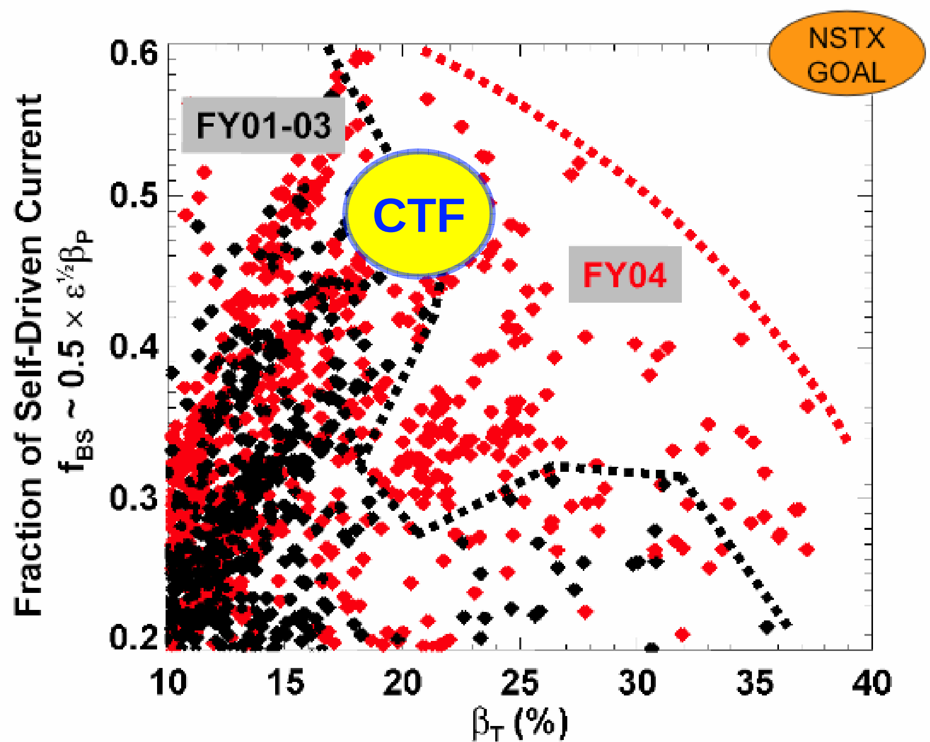


Heat, particle fluxes: Detached regimes, lithium coatings & liquid targets

NSTX Accesses High β, High Bootstrap Plasmas



Fusion Requires
High Beta
Steady State



NSTX

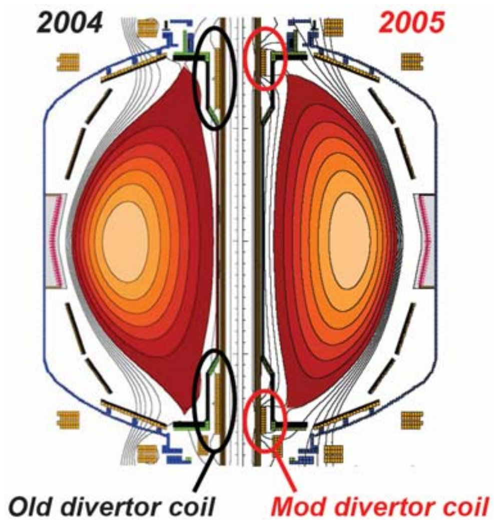
⇒ Toroidal Physics (ITER)

⇒ Component Test Facility (CTF)

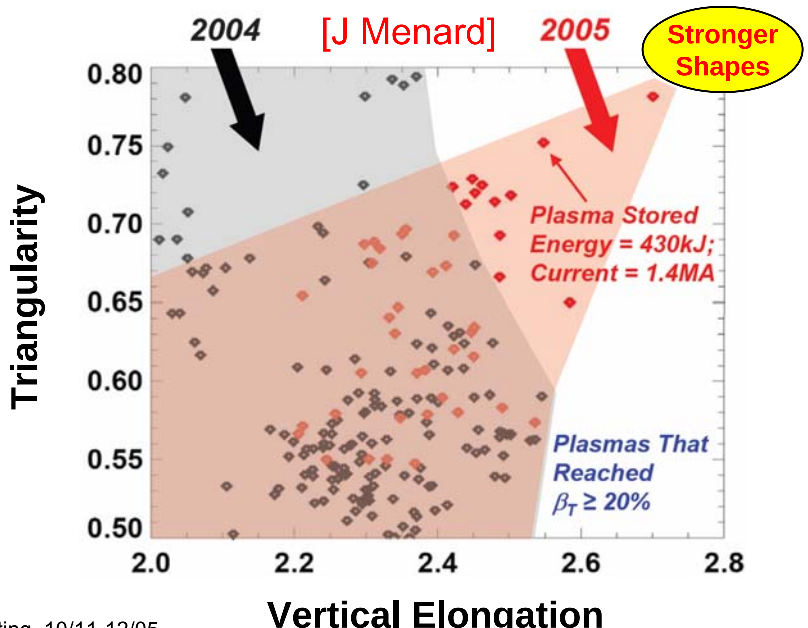
⇒ Power Plant

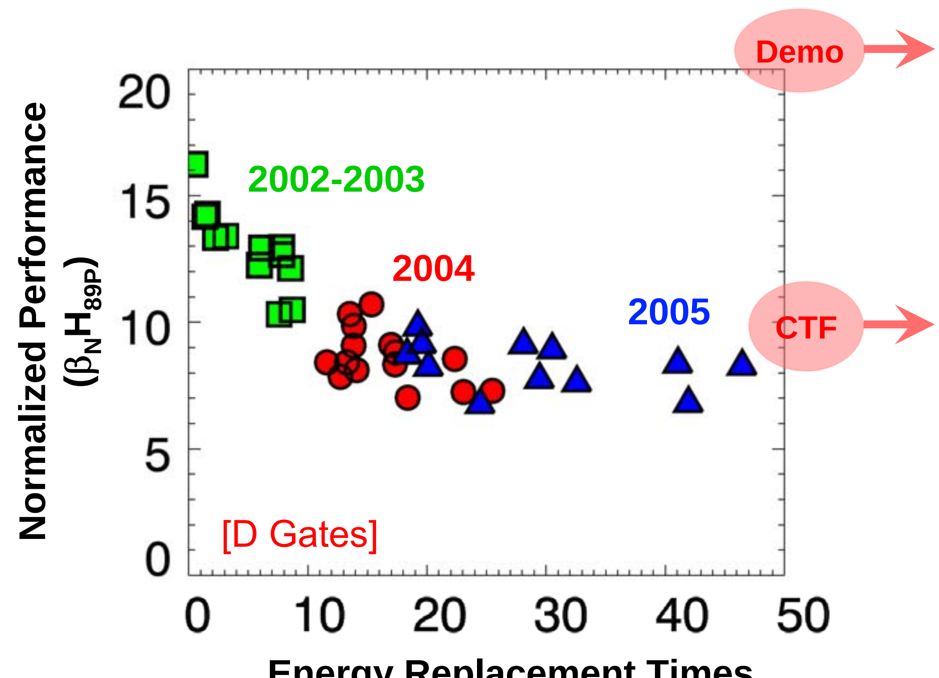
Substantially Expanded the Spherical Torus Operating Space to Clarify Future ST Options

NSTX



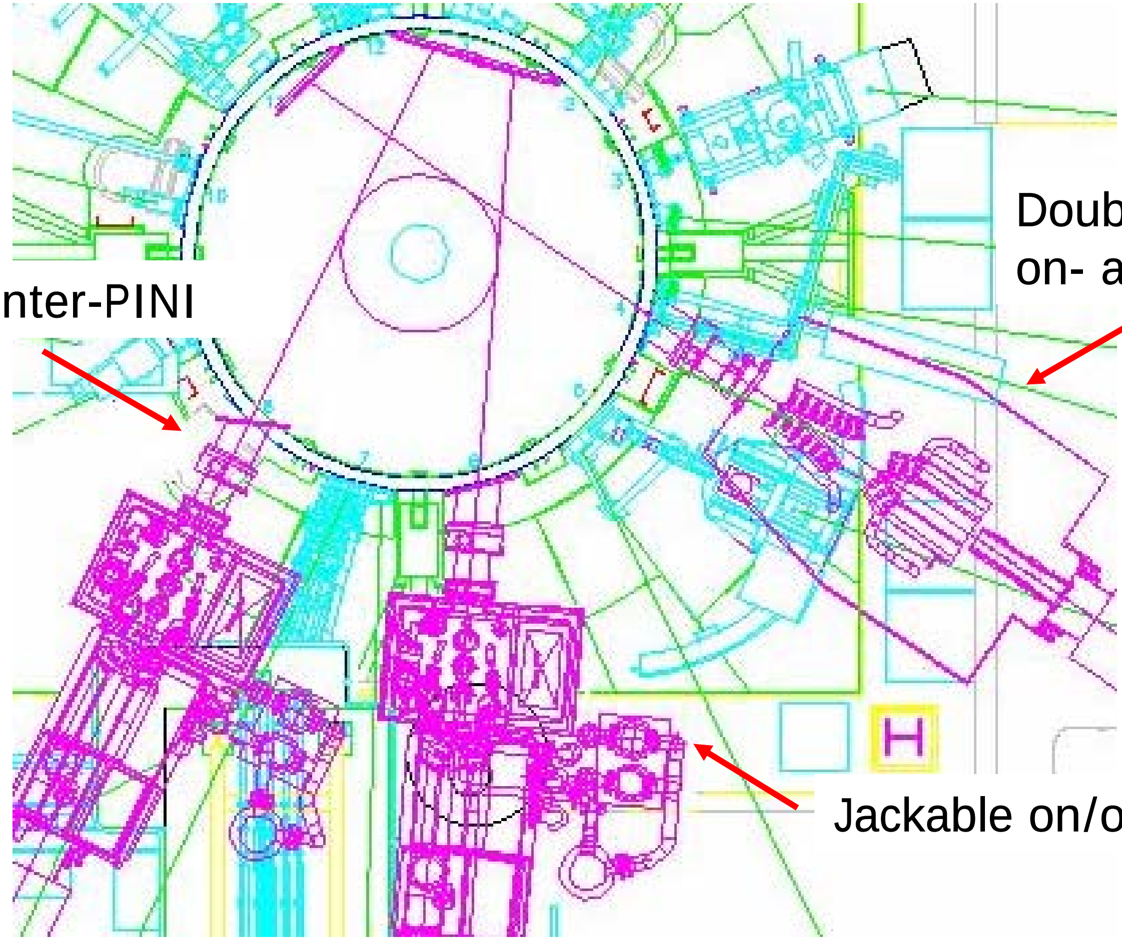
- **Improved divertor coils**
- **Extended plasma to stronger shapes**
- **High triangularity at high elongation leads to quiescent core and edge conditions**





MAST Upgrades: Proposed NBI Systems

- Investigating bold options for NBI current profile control
- Flexible system 4 PINIs, up to 10 MW (1 counter- and 3 co-current)
- Off-axis NBCD optimised with 2 off-axis co- and 2 on-axis co/counter PINIs



BUTTRESSES ⇒ Reduce Risk/Acceleration

(Sir. Chris Llewellyn Smith, FPA meeting 2005)

- **Multi-beam** material test facility - study damage from irradiation with heavy ions to material samples with implanted Helium (+ hydrogen?)
- **Satellite tokamak** - to be operated in parallel with ITER, as part of ITER programme, to test new modes of operation, plasma technologies,...
- **Component Test Facility (CTF)** - to test engineering structures (joints, …) in neutron fluences typical of fusion power stations

We assume that a 'fast track CTF' (possibly a small spherical tokamak that would not need to breed tritium?) **could be operating with D-T in 2026**

Assuming successful development, it would speed up the advent of fusion power significantly ***and*** reduce risks (note that in 'Pillars only' model DEMO phase 1 is effectively a very expensive and large CTF)

UKAEA Fusion Working in Europe

ST Research Contributes to Major Components of Office of Science 20-Year Strategic Plan for Fusion

*Strategic Timeline—Fusion Energy Sciences**

2003 2005 2007 2009 2011 2013 2015 2017 2019 2021 2023 2025

The Science

Burning Plasma Demonstration

- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation in IFE-relevant fuel pellets (2012)
- Complete ITER experiments to determine plasma confinement in parameter range required for an energy-producing plasma (2017)
- Complete experiments on NIF to advance the science of ignition and burn propagation needed to design optimized fuel pellets for an Inertial Fusion Energy plant (2020)
- Complete experiments on ITER to determine the impact of the fusion process on the stability of energy-producing plasmas (2020)
- Achieve high fusion power for long durations on ITER to define engineering requirements for fusion power plants (2025)

Fundamentals of Plasma Behavior

ITER Performance Enhancement

- Achieve a fundamental understanding of tokamak transport and stability in pre-ITER plasma experiments (2009)
- Major aspects relevant to burning plasma behavior observed in experiments prior to full operation of ITER are predicted with high accuracy and are understood (2015)
- Determine the physics limits that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high-energy density physics (2015)
- Deliver a complete integrated simulation of a power-producing plasma, validated with ITER results, that enables the design of fusion power plants (2020)

Plasma Confinement

Performance Extension Test

- Evaluate the ability of the compact stellarator configuration to confine a high-temperature plasma (2012)
- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to design and build fusion-power-producing Next-Step Spherical Torus (2008)
- Demonstrate use of active plasma controls and self-generated plasma current to achieve high-pressure/well-confined steady-state operation for ITER (2008)
- Evaluate the feasibility/attractiveness of potential drivers, including heavy ion beams, dense plasma beams, and lasers for fusion approaches involving high-energy density (2009)
- Resolve key scientific issues and determine the confinement characteristics of a range of attractive confinement configurations (2015)
- Determine the potential of one or more of the promising plasma configurations (for example a spherical torus) for use as a component test facility or a fusion power source (2020)

Materials, Components, and Technologies

- Start production of superconducting wire needed for ITER magnets (2006)
- Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sufficient fuel cycle (2013)
- Complete first phase of testing in ITER of blanket technologies needed in power-producing fusion plants capable of extracting high-temperature heat from burning plasmas and having a self-sufficient fuel cycle (2024)

Component Test Facility

- Complete first round of testing in a component test facility to validate the performance of chamber technologies needed for a power-producing fusion plant (2025)

*Future Facilities***

ITER: ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma."

Next-Step Spherical Torus (NSST) Experiment: The NSST will be designed to test the spherical torus, an innovative concept for magnetically confining a fusion reaction.

Fusion Energy Contingency: If ITER construction and operation goes forward as planned, additional facilities to develop and test power plant components and materials will be needed to complete the process of making fusion energy a viable commercial energy resource by mid-century.

Integrated Beam Experiment (IBX): The IBX will be an intermediate-scale experiment to understand how to generate and transmit the focused, high-energy ion beam needed to power an IFE reaction.

*These strategic milestones are illustrative and depend on funds made available through the Federal budget process.
**For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.*

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World Spherical Torus Research Is Expanding and Addressing Important Issues in Fusion

- Growing in breadth and depth – 22 experiments in active collaboration
- “Concept Exploration” STs push the ST scientific envelope
  - Explore high leverage innovations
  - Establish basis for “Proof of Principle” testing
- “Proof of Principle” STs
  - Contribute to resolve issues important to ITER burning plasma performance
  - Establish scientific feasibility for ST “performance extension,” CTF volume neutron source, & Demo Optimization
- STs are part of plans in world fusion programs