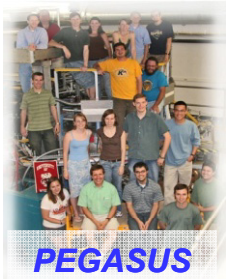
Supported by Office of Science

National Spherical Torus Program, LTX, Pegasus, and Collaboration

NSTX

LTX


PEGASUS

Spherical Torus Coordinating Committee

Martin Peng (Chair, ORNL)
Ray Fonck (Co-Chair, U. Wisconsin)
Jean Paul Allan (Purdue U.)
Larry Baylor (ORNL)
Rob LaHaye (GA)
Fred Levinton (Nova)
Dick Majeski (PPPL)
Jon Menard (PPPL)
Steve Sabbagh (Columbia U)
Kevin Tritz (Columbia U.)
Aaron Sontag (Secretary, ORNL)

Advisors

Ahmed Hassanein (Purdue U.)
Chris Hegna (U. Wisconsin)
Fred Levinton (Nova Photonics)
Brian Lloyd (EURATOM/CCFE, U.K.)
Yuichi Takase (U. Tokyo, Japan)

MAST

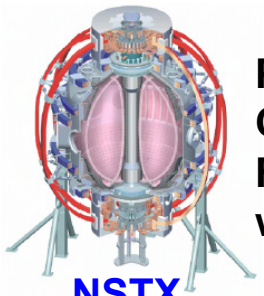
Japan STs

OFES FY10 Budget Planning Meeting

Gaithersburg, Maryland, March 11-12, 2010

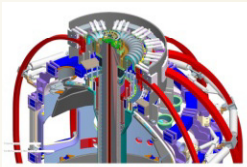
ST research and ST next steps aim to help build the scientific basis for fusion energy, and complement and support ITER

Scientific Basis ⇒ Energy Development



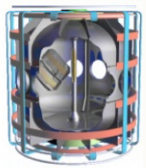
NSTX

PoP; Close-Fitting wall



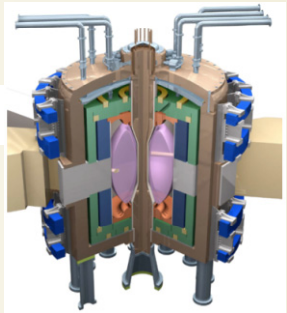
NSTX-U

$2 \times I_p$, B_T, P_{NBI}
$5 \times \tau_{pulse}$
Test Li PFC



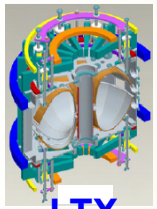
PEGASUS

Start-up; Edge MHD; RF H&CD



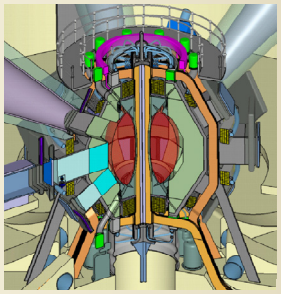
FNSF, Normal A?

Fusion Nuclear Science Q~1



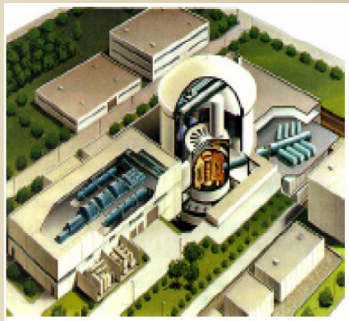
LTX

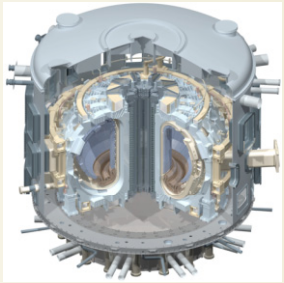
Liquid Li; Low-recycling wall



Upgrade to CTF Q~3

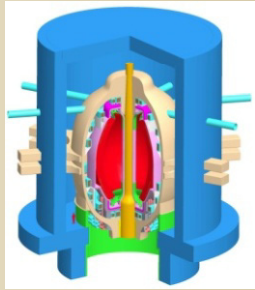
DEMO



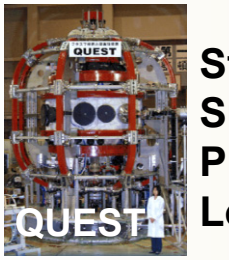


ITER, High-Q ST?

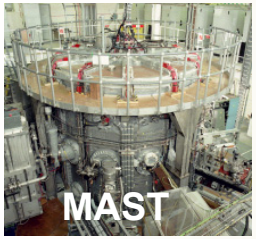
Burning Plasma Science Q~10, & Q~20?



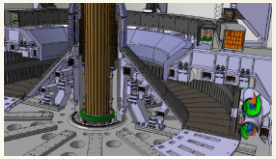
ARIES-ST



Start-up
Sustainment
PMI
Long-pulse



PoP; Far-away Wall



MAST-U

$2 \times I_p$, B_T, P_{NBI}
$5 \times \tau_{pulse}$
Operate SXD

U.S. STCC Report: ST Mission Options & 5-Year Research Priorities, Accounting for World ST Capabilities & Opportunities

Three ST missions to advance fusion energy science during the ITER Era (~20 years)

- **High-Q Burning Plasma (BP)**

  Explore strongly coupled nonlinear plasma conditions ($f_{BS} \rightarrow 1$, $\beta \rightarrow$ ideal wall limit, etc.) prototypical of DEMO.

- **Fusion Nuclear Science (FNS)**

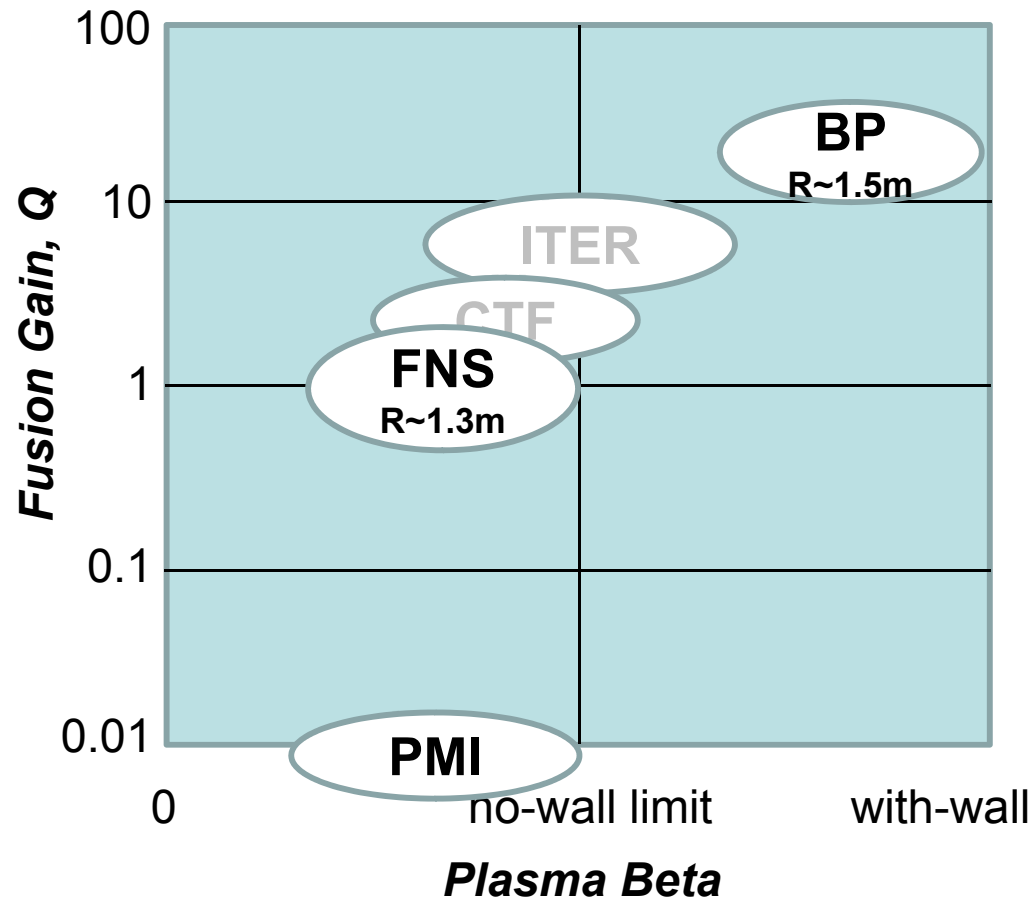
  Elucidate and resolve strong synergistic effects in science of fusion plasma material interactions, fuel cycle & power extraction in full fusion nuclear environment.

- **Plasma Material Interface (PMI)**

  Qualify candidate PFCs in long-pulse DD facility approaching conditions of a fusion nuclear device.

[Dec. 12, 2009]

ST Mission Space and Options



Research priorities differ for PMI, FNS, and high-Q BP Missions

Research Priorities Established for ST Mission Options as Input to DOE's Decisions on Research Strategies

Preliminary Concepts

	PMI	FNS	BP
R (m)	1.2	1.3	1.5
Q	0.01	0.8-1.5	10-20
I_p (MA)	3-4	4-7	9-17
q_{CYL}	3	4-6	3
β_N	≤3	2-3.3	5-7
P_{FUS} (MW)	0.2	20-75	300
W_L (MW/m^2)	-	0.3-1.0	3
Φ_{DIV} (MW/m^2)	varied	≤10	varied
Solenoid	Yes	No	Yes
τ_{PULSE} (s)	10^2-10^3	10^3-10^6	10^2

Research Priorities

ReNeW Thrust-16 Topics	PMI	FNS	BP
I) Start-up & Ramp-up: Initiation; Ramp-up	L	H	M
II) Divertor, First Wall: XD	H	H	H
Liquid-Metal	H	*	H
Hot-Walls	H	H	M
III) Confinement: Scaling	M	M	H
Energetic particles	L	M	H
IV) Disruption-Free: Control 3D Field Errors	M	H	H
V) Current & Profiles: Tools	M	M	H
S-U, R-U Mod/Sim	M	H	H
VI) Radiation-tolerant coils	Did not address		
VII) Extend Tok. Mod/Sim	M	M	H

***Unknown at present, need exploratory R&D**

LTX focus in FY10-12: First exploration of the effects of very low recycling, liquid metal walls **(T-II, III)**

- Characterize global electron transport with very low recycling walls, in an Ohmic discharge
  - Confirm CDX-U confinement results
    - ⇒ Evaluate global confinement with equilibrium diagnostics, Thomson scattering
  - Document response of the edge electron temperature to reduced recycling
- Characterize particle transport in the absence of an edge fueling source
  - Compare predicted, observed response of density profile to pulsed fueling
  - Employ partial neutral beam core fueling

LTX liquid metal wall development addresses PFC development needs highlighted in ReNeW

LTX liquid lithium wall development supports LLD implementation in NSTX

4 graduate student theses in progress

Design parameters for LTX:

R_0 = 0.4 m

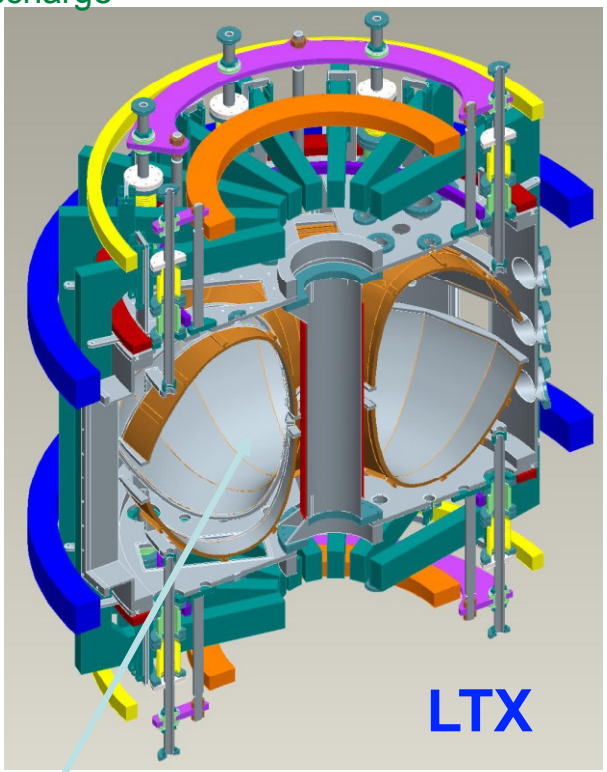
a = 0.26 m

$\kappa < 1.6$

$B_T < 3.2$ kG

$I_p < 400$ kA

$\tau_{discharge} < 0.25$ s



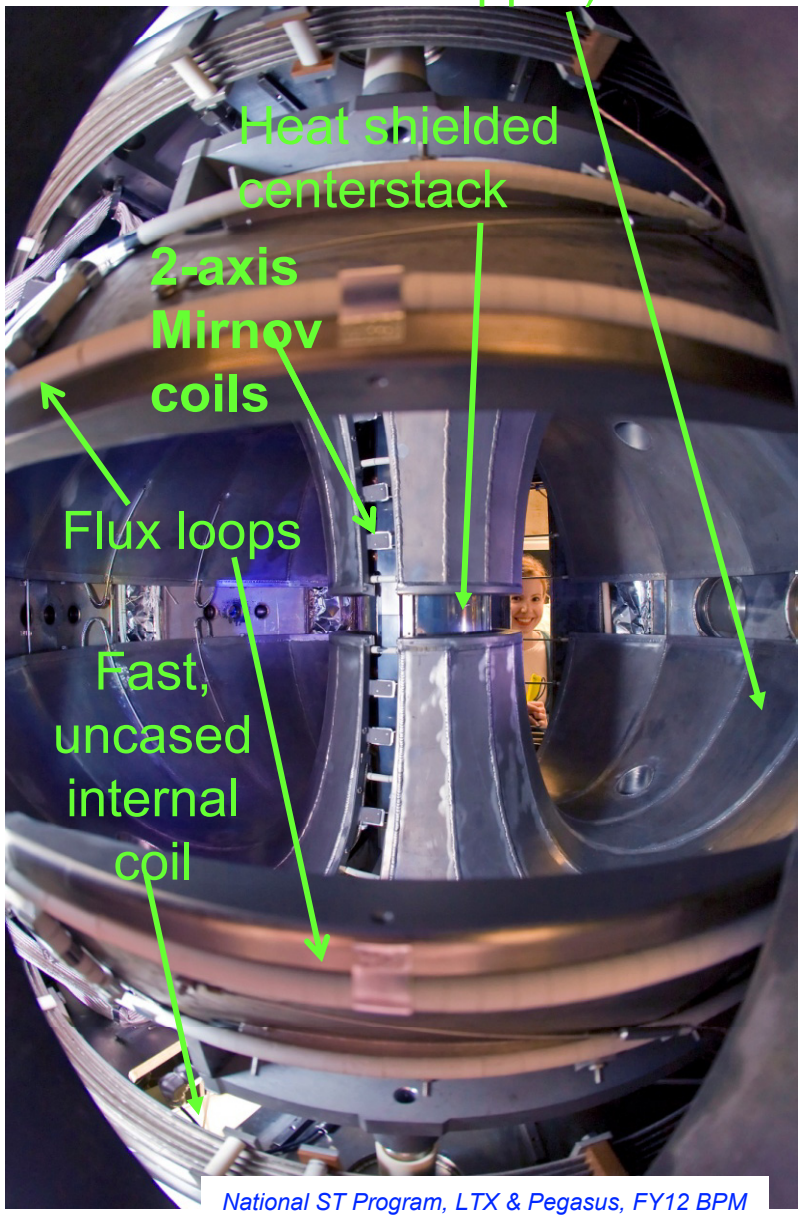
***Liquid* lithium coated shell**

National ST Program, LTX & Pegasus, FY12 BPM

PPPL PRINCETON PLASMA PHYSICS LABORATORY

LTX timeline for 2009 - 2012

- FY09 - First plasma
  - Discharge development
  - Vented for final in-vessel installations
- FY10 – LTX operating
  - Lithium wall operations to begin
  - $T_e(r)$ as a function of recycling
    - Thomson scattering for core T_e
    - Lyman-α + DEGAS 2
- FY11 – Improve plasma control
  - Evolution of confinement, $T_e(r)$ during fast pulsed gas fueling
  - Begin particle transport studies
- FY12 – ARRA projects implemented
  - Full OH supply
  - Edge Thomson scattering
    - Improved recycling determinations



LTX program and budget

- Baseline budget ($957k/year + $952k ARRA)
  - Verify prediction of high edge electron temperature with low recycling
    - Power flux is carried by particles at the edge
    - Poor fueling efficiency (~10%) for recycled particles = high particle density at the wall
    - High recycling = low power/particle (low edge temperature)
    - Low recycling = high power/particle (high edge temperature)
  - Edge Thomson scattering (noncontact T_e, n_e+ DEGAS2 for recycling estimates)
  - 400 kA, 100 – 200 msec OH supply for current scaling
  - 3.2 kG TF for toroidal field scaling
  - Add services for 5A, 20 keV, 1 sec neutral beam (NCSX diagnostic beam)
- Incremental funding allows full utilization of ARRA-funded upgrades (+$492k/year)
  - Complete installation of neutral beam
  - Add ion temperature diagnostics
  - Add beam-emission spectroscopy for density fluctuations, particle transport
  - Initiate plasma-material interaction studies
  - Post-doctoral research associate

(to update) Pegasus Research Program has 3 Thrusts Addressing Critical Issues for the ST & AT (T-I, III, V)

Non-solenoidal startup, ramp-up
(Theme C)

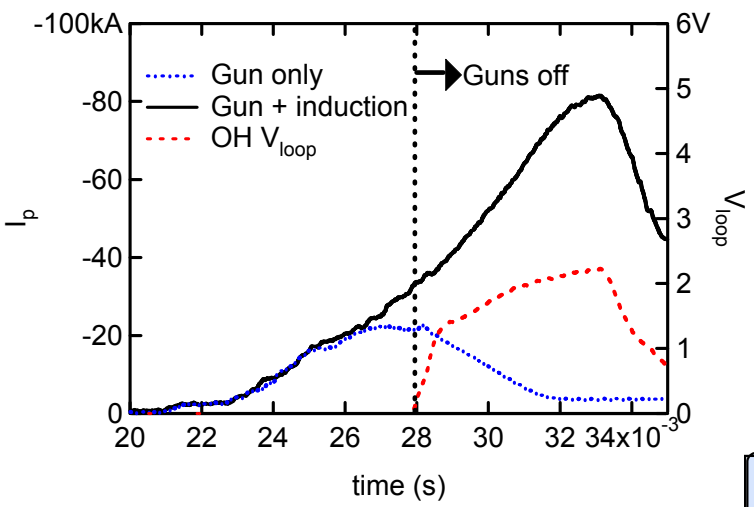
- Develop scalable plasma gun arrays
  - *demonstrate high I_p with high TF*
  - *0.1 - 0.3 MA in FY08-10*
- Ramp-up via HHFW
  - *FY 09-11*
- Ramp-up via EBW
  - *collab. w/PPPL & ORNL?*

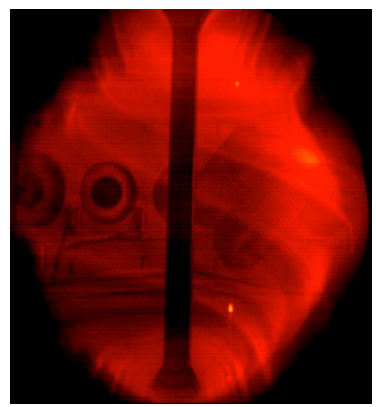
Edge stability at high $(j_{||}/B)_{edge}$
(Theme B)

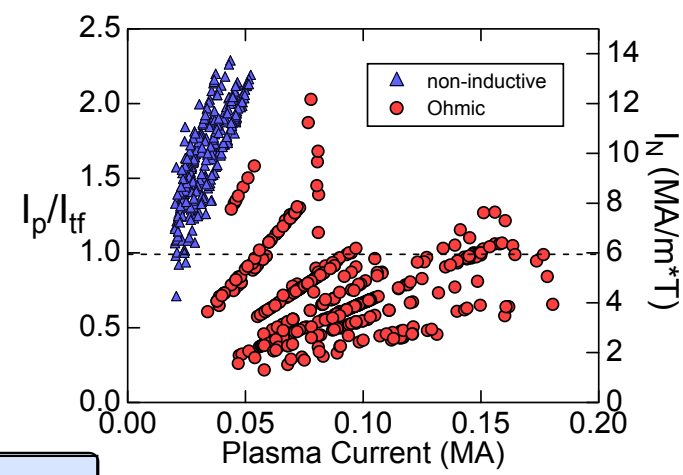
- High density magnetic probe arrays
  - *determine m & n in FY08-09*
- Edge probes: directly measure $j_{||}/B$, p(R)
  - *FY 08-10*
- Divertor coils for edge stability mod.

j(R) mod. for high-I_N, β_t
(Theme C)

- Edge current drive via guns
  - *broad j(R)*
  - *0.1 - 0.3 MA in FY08-10*
- New centerstack
  - *access high I_p, β_t*
  - *FY 10-12*







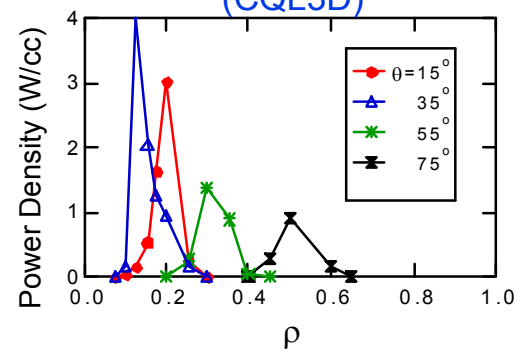
Experimental Parameters

Parameter	Achieved	Goals
A	1.15-1.3	1.12-1.3
I_p (MA)	≤0.18	≤0.30
I_N (MA/m-T)	6-12	6-20
$I_{non\text{-}inductive}$ (MA)	0.05	0.3
β_t (%)	≤25	>40
τ_{shot}	≤0.02	≤0.1

(to update) Full-Use Budget Supports Upgrades for Addressing 3 Main Thrusts of Program

- Full-Use: +~$500K/yr
  - Optimize centerstack upgrade (+$75 K/year for FY09-10)
  - Refurbish HHFW to 1 MW (+$25 K/year for FY09-10)
  - Post-doc for Thomson Scattering (+$100 K/year)
  - **EBW: 1 MW current ramp-up tests in an ST** (+$300 K/year)
    - Collaboration with PPPL/ORNL?

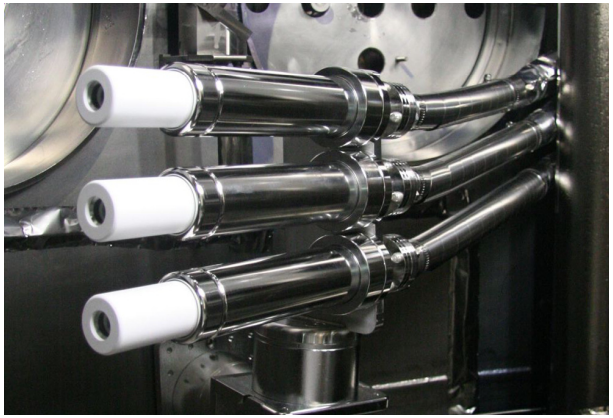
Power Deposition from Injection Angle Scan (CQL3D)



- FY08 baseline = $954K
  - Support staff and students
  - Scalable, high-power gun array development

- Reduced case: -10%
  - Personnel reduction: staff or grad students
  - Downgrade or eliminate one of the High-I_p test gun arrays

- Major Facility Activities - baseline funding
  - **Plasma gun injector systems development and testing**
    - Power supplies; Scalable high-current midplane arrays
  - Divertor coil upgrade for edge stability
  - SXR imaging for j(r,t)
  - Upgrade centerstack for high TF and $I_{non\text{-}inductive} \geq 0.2$ MA

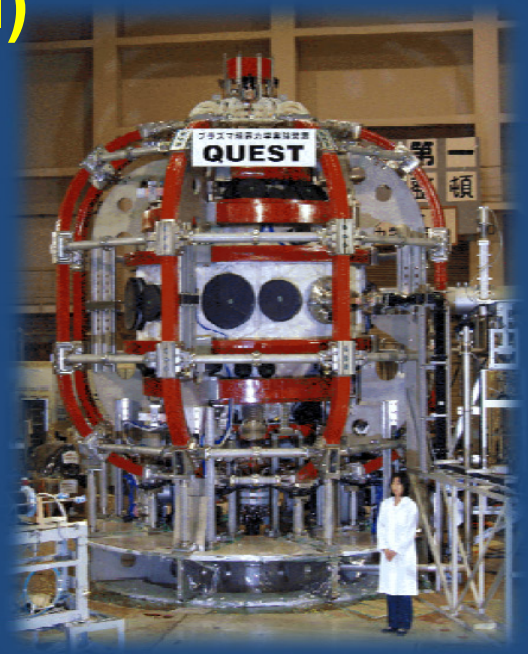


QUEST Experiment

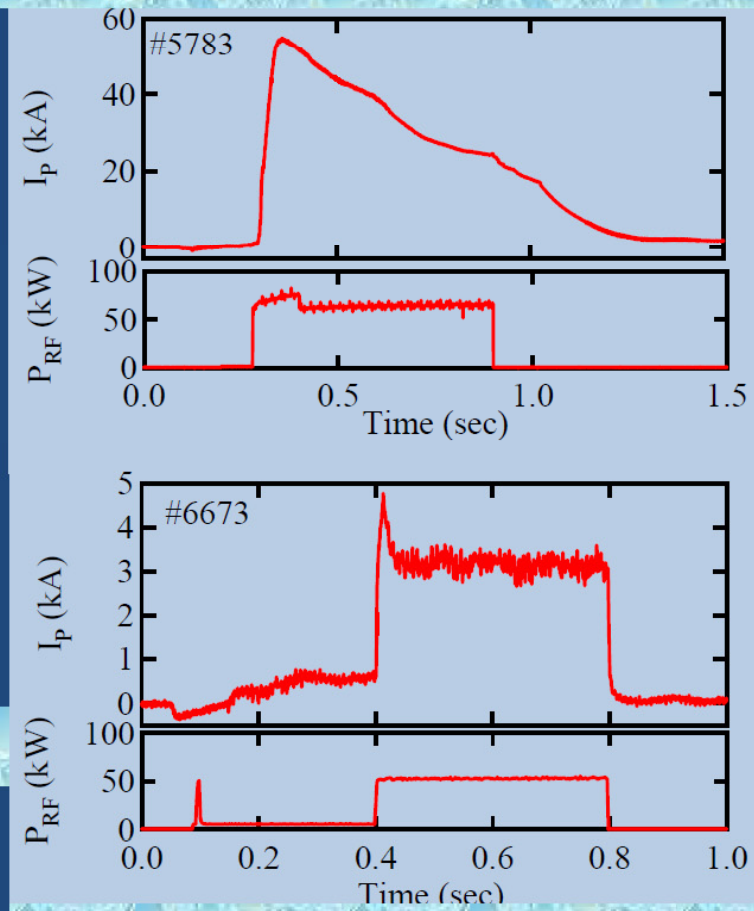
(T-V, VII)

R=0.68m
a=0.4m
A=1.78
B_T=0.25T @ 0.64m
P_{RF}=0.2MWX2
8.2GHz

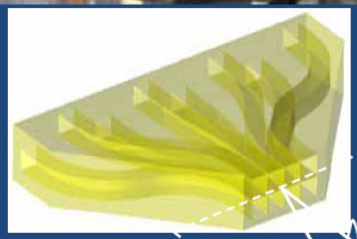
Started experiments in Oct. 2008.

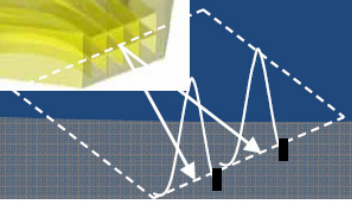


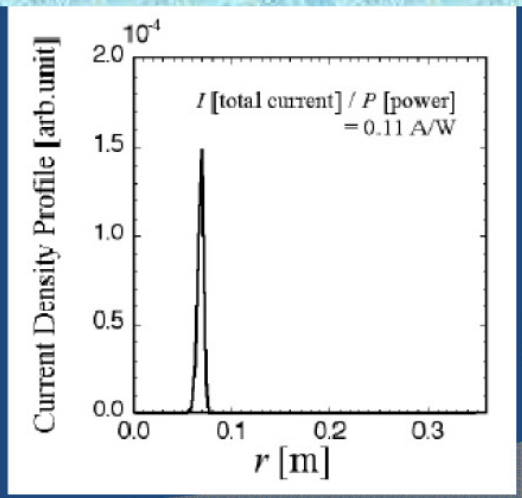
OH plasma and RF maintained plasma



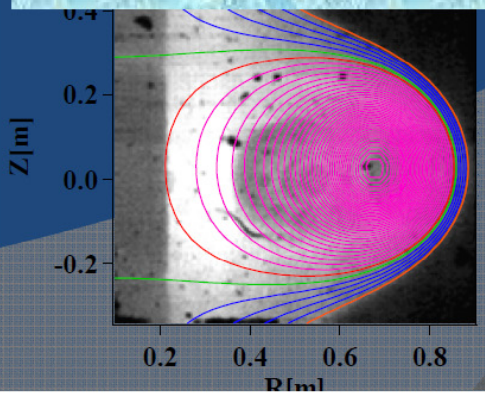
New EBW Antenna expected driven current profile







Flux surfaces of OH + RF plasma



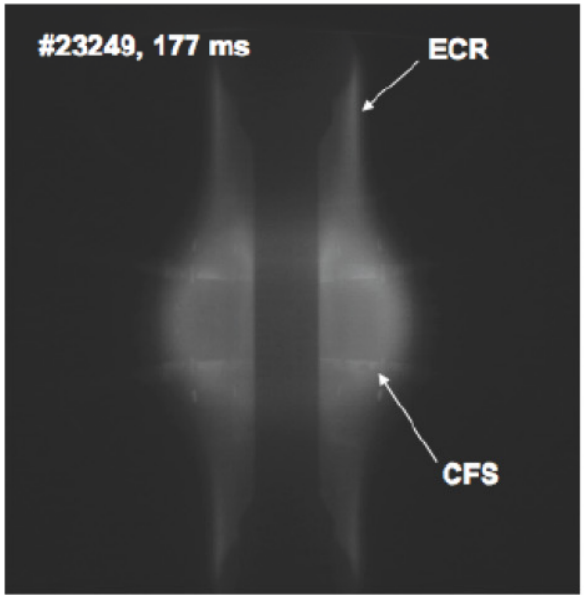
R=0.55m
a=0.3m
A=1.83
I_P=40kA
B_T=0.15T
P_{RF}=0.06MW

EBW-assisted start-up (T-I)

EU-US-JA collaboration

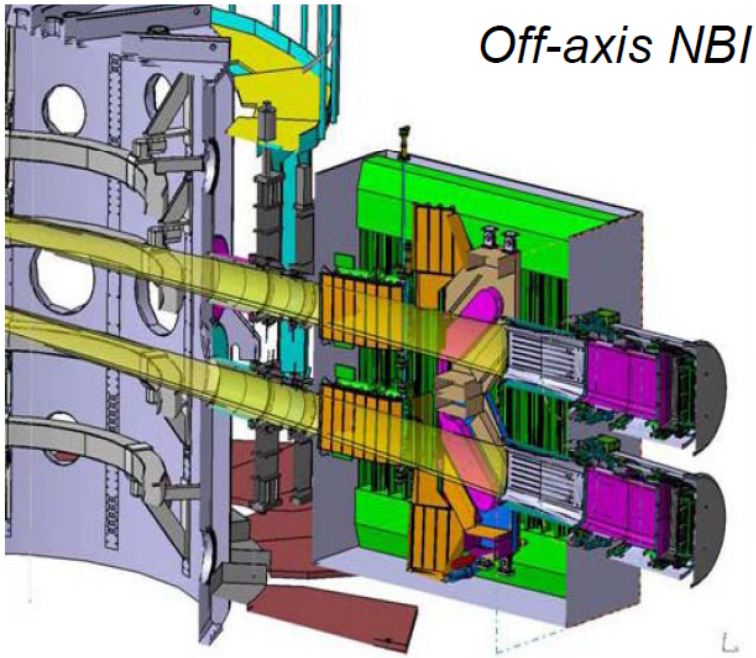
- High power, long pulse28GHz gyrotron, on loan from ORNL, for electron Bernstein wave assisted start-up studies
  - *first experiments carried out Sep 2009*
  - *further experiments planned after transmission line improvements*

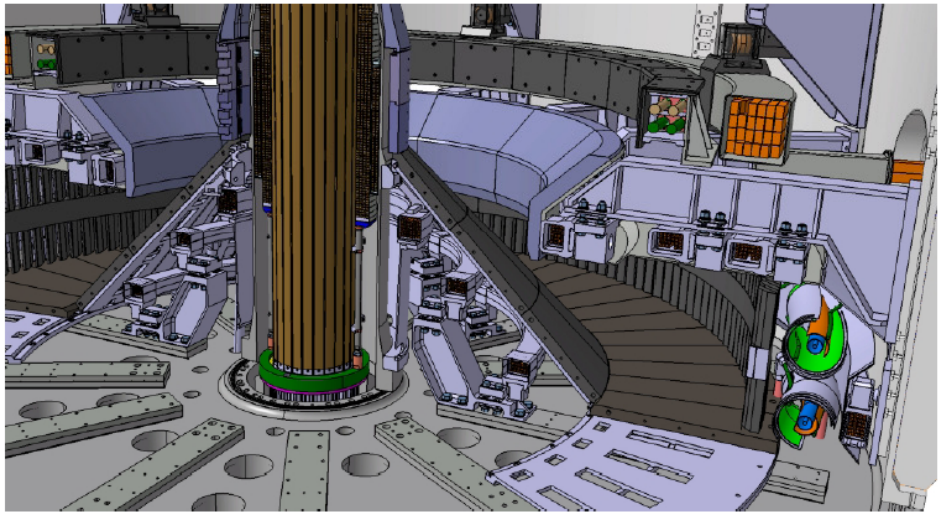
- 4 US scientists/engineers + 2 Japanese scientists visited Culham to participate in experiments and gyrotron commissioning



MAST Upgrade (T-II)

- Increased heating power
  - more adaptable system for control of j(r), p(r), v(r)
- Increased TF, increased solenoid flux
  - higher current, longer pulse
- Relaxed current profile
  - fully non-inductive operation possible
- Improved exhaust and density control
  - cryopumped 'Super-X' divertor





Following a review of the UK Fusion programme, EPSRC has recently announced its support for an upgrade to MAST (implementation by 2015 on present plans)

ST Community in Position to Make Important Contributions to Fusion Energy Sciences Program

- **Help build the scientific basis for fusion energy, and complement and support ITER**
- **PMI, FNS, and High-Q BP Missions selected for the ITER Era; Identified respective, varied research priorities among ReNeW Thrust-16 ST topics**
- **LTX exploring science for liquid metal, low recycling wall → opportunity in confinement improvements**
- **Pegasus making large progress in non-solenoidal startup and boundary stability → opportunities in EBW heating & current drive, $\langle\beta_T\rangle \sim 1$**
- **Started high leverage ST research collaboration on MAST EBW startup (IEA: U.K., U.S., Japan)**
- **New STs in Japan with complementary goals started operation: QUEST (long pulse RF sustainment), UTST (merging plasma → $\langle\beta_T\rangle \sim 1$)**
- **MAST-U with SXD operation – highly complementary to NSTX-U liquid lithium PFC exploration**

Next: NSTX Research Program, Facility, and Upgrade plans