Supported by Office of Fusion Energy Sciences — Office of Science

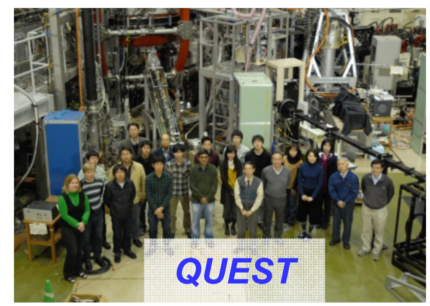
National Spherical Torus Program, Lithium Tokamak Experiment, Pegasus, and International Collaboration

<u>Spherical Torus Coordinating Committee</u>

<u>Martin Peng</u> (Chair, ORNL)
Ray Fonck (Co-Chair, U Wisconsin)
Jean Paul Allan (Purdue U)
Larry Baylor (ORNL)
Rob LaHaye (GA)
Dick Majeski (PPPL)
Jon Menard (PPPL)
Steve Sabbagh (Columbia U)
Kevin Tritz (Johns Hopkins U)
Aaron Sontag (Secretary, ORNL)

<u>Advisors</u>

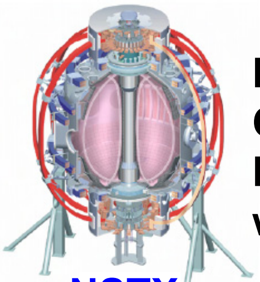
Ahmed Hassanein (Purdue U.)
Chris Hegna (U. Wisconsin)
Fred Levinton (Nova Photonics)
Brian Lloyd (EURATOM/CCFE, U.K.)
Yuichi Takase (U. Tokyo, Japan)



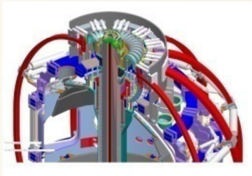
OFES FY10 Budget Planning Meeting
Gaithersburg, Maryland, March 11-12, 2010

ST Research and ST Next Steps Aim to Help Build the Scientific Basis for Fusion Energy; Complement and Support ITER

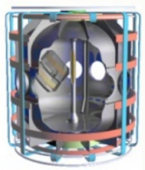
Scientific Basis ⇒ Energy Development


NSTX

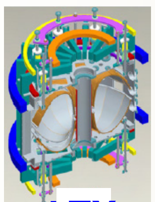
PoP; Close-Fitting wall


NSTX-U

Test & develop Li PFC & XD; CHI-HHFW-BS-NBI startup


PEGASUS

Start-up; Edge MHD; RF H&CD

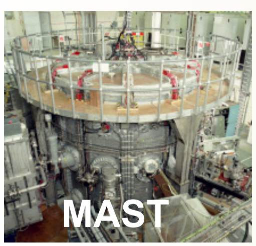

LTX

Liquid Li; Low-recycling wall

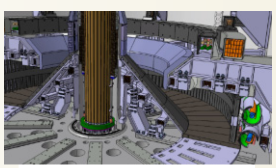
+17 other STs worldwide


QUEST

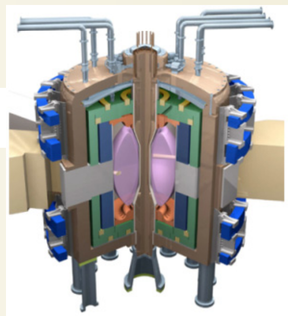
Start-up; Sustainment; PMI; Long-pulse


MAST

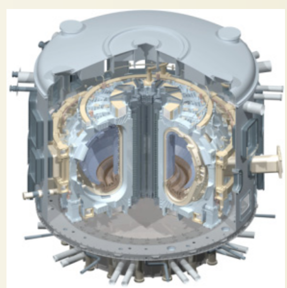
PoP; Far-away Wall


MAST-U

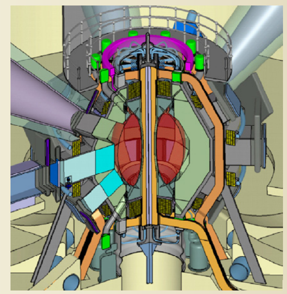
Impl. & test SXD; EBW-BS-NBI startup


FNSF, Normal A?

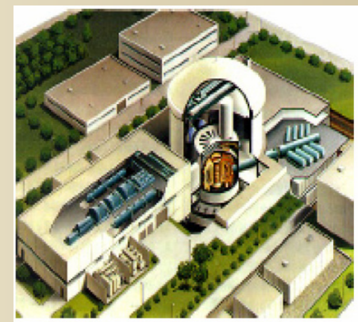
Fusion Nuclear Science Q~1

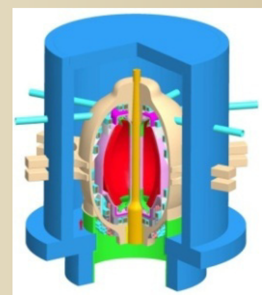

ITER, (High-Q ST?)

Burning Plasma Science Q~10, (Q~20?)


Upgrade to CTF Q~3

DEMO




ARIES-ST

U.S. STCC Selected Three Mission Options, Taking Advantage of Attractive ST Features

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 synergistic effects in science of fusion plasma and neutron material interactions, fuel cycle & power extraction in full fusion nuclear environment up to 1 MW-yr/m^2.

- **Plasma Material Interface (PMI)**

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

[STCC Report, 12/12/09, "Shared Documents" @ https://info.ornl.gov/sites/us_stcc/default.aspx]

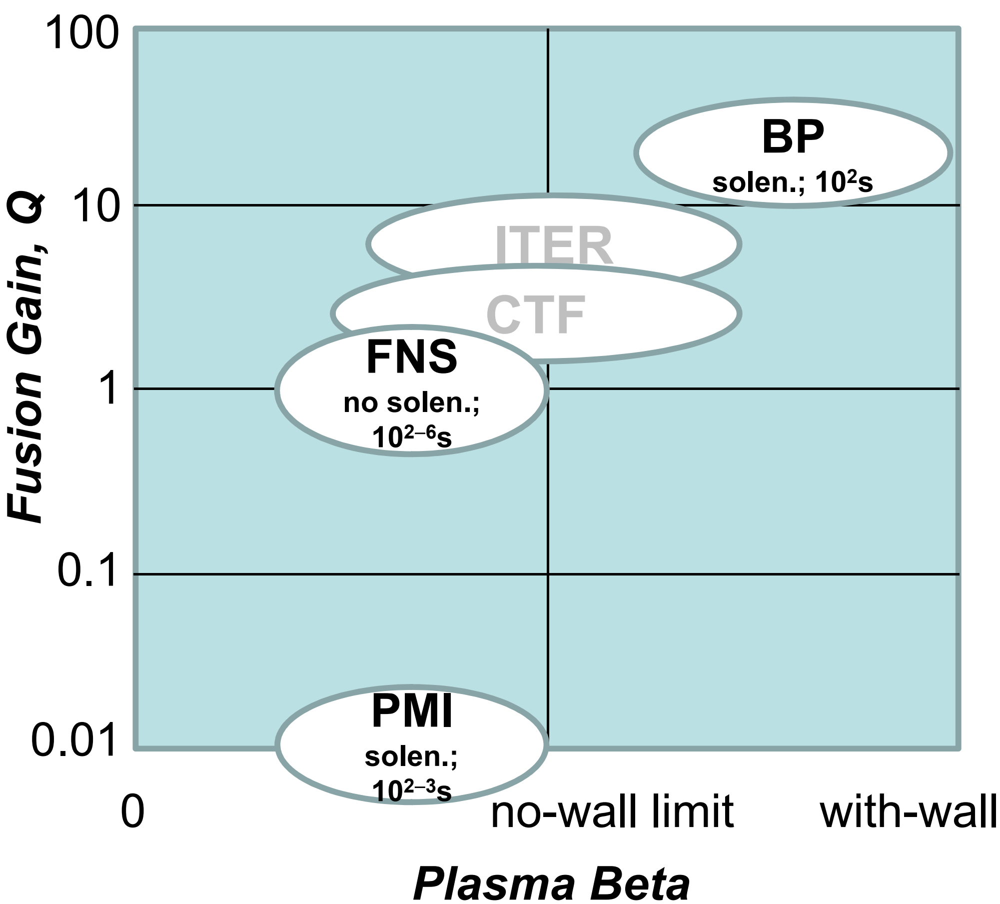
Attractive Features

- **Plasma**: high β_T limits, τ_{Ei} (>>τ_{Ee}), q_{CYL}
- **Device**: small (size × field × P_{FUS} × P_{aux}); high Φ_{DIV}, W_L
- **Discovery**: extend toroidal plasma regime and enhance understanding

	PMI	FNS	BP
Q	0.01	0.8-1.5	10-20
P_{FUS} (MW)	0.2	19-75	300
R (m)	1.2	1.3	1.5
I_p (MA)	3-4	4-7	9-17
q_{CYL}	3	4-6	3
β_N	≤3	2-3.3	5-7
W_L (MW/m^2)	-	0.3-1.0	3
Φ_{DIV} (MW/m^2)	varied	≤10	varied

Research Priorities Established for a Coherent, Integrated Plan to inform DOE's Decisions on Research Strategies

ST Mission/Parameter Space



Research Priorities for Different Missions

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

TBD: *need exploratory R&D*

LTX focus in FY10-12: Effects of low recycling, liquid metal walls (T-II, III)

- **Global electron transport with low recycling walls**
  - Confirm CDX-U Ohmic confinement enhancement
  - Response of edge electron temperature to reduced recycling
- **Particle transport without edge fueling source**
  - Code validation: particle transport
  - Density profile evolution with pulsed fueling
    - ⇒ Partial neutral beam core fueling

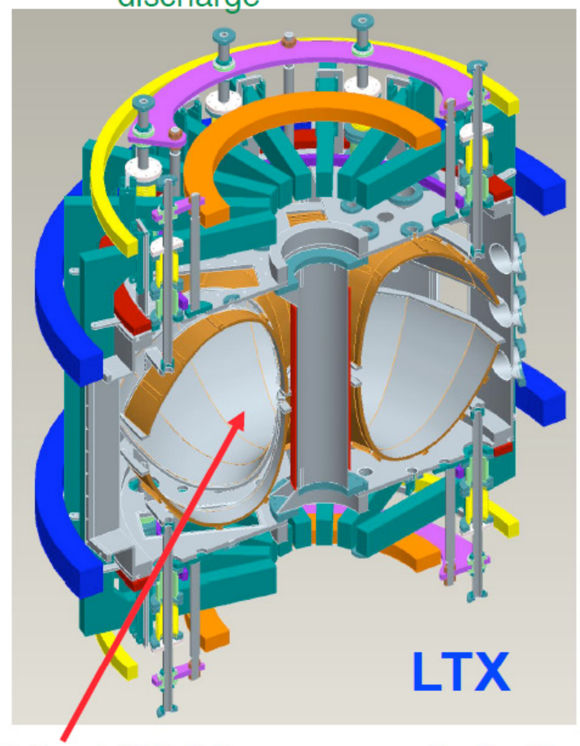
⇒ LTX liquid metal wall development addresses PFC development needs highlighted in ReNeW

⇒LTX liquid lithium wall development supports LLD implementation in NSTX

4 graduate student theses in progress

LTX design parameters:

$R_0 = 0.4$ m
$a = 0.26$ m
$\kappa < 1.6$
$B_T < 3.2$ kG
$I_p < 400$ kA
$\tau_{discharge} < 0.25$ s

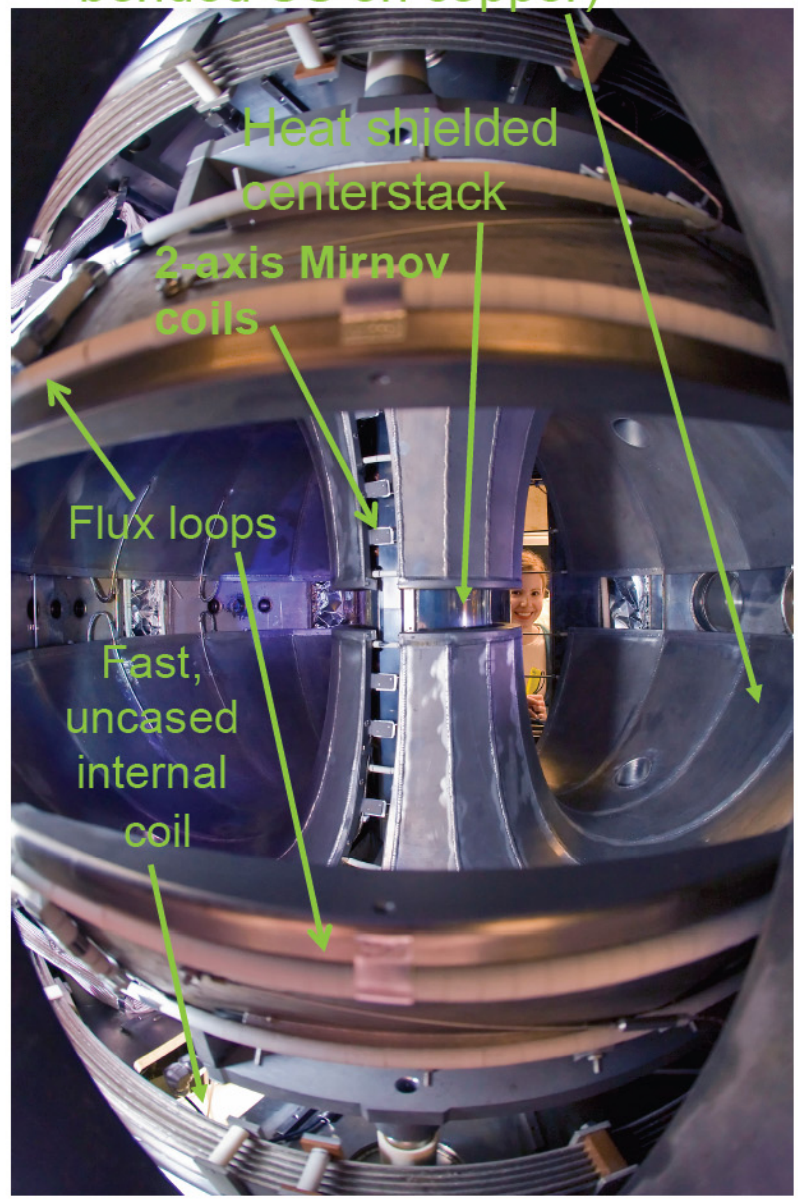


Liquid **lithium coated shell**

LTX timeline for 2009 - 2012

- FY09 - First plasma
  - Discharge development
  - 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 – 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
  - NBI

Inner heated shell (explosively bonded SS on copper)



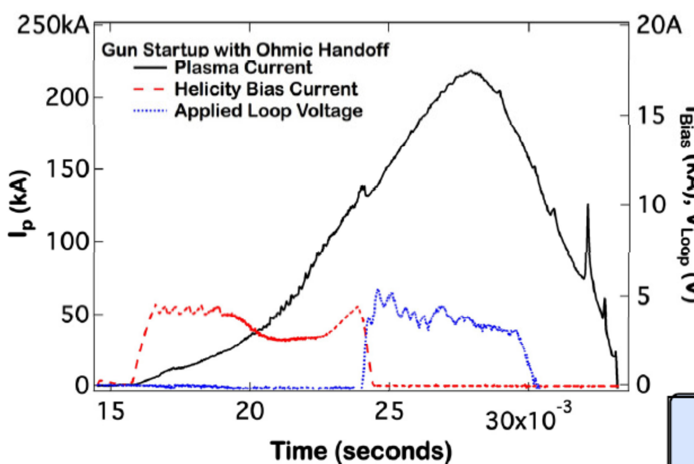
Program and budget

- Baseline budget ($957k/year + $952k ARRA)
  - Verify prediction of high edge electron temperature with low recycling
  - 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)
  - Cannot operate for full year; ~4 month shutdown
- Impact of 10% reduction: further reduction in operations
  - Additional ~1-2 month shutdown
- 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

Pegasus Research in FY10-12: Exploring and Exploiting Near-Unity Aspect Ratio Science (T-I, IV)

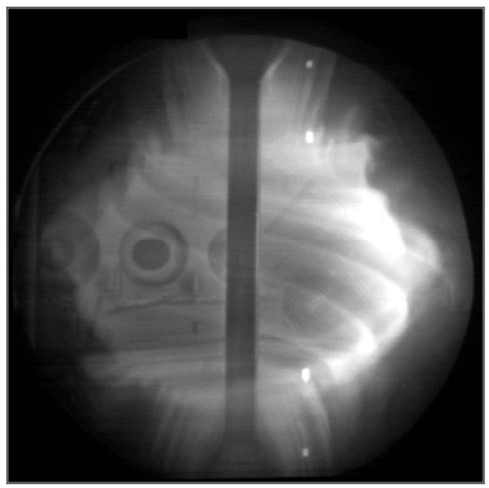
Non-solenoidal startup, growth

- Develop scalable local plasma gun concept
  - *Demonstrate high $I_p \sim 0.2$ - 0.3 MA*
  - *Test predictive understanding of point-source helicity injection*
- Startup, Ramp-up via EBW, HHFW
  - *Synergy with helicity injection*
  - *Unique high-power EBW H&CD*
  - *Collaboration w/ORNL*



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

- A ~ 1 naturally gives high peeling drive
- Directly measure $j_{||}/B$, p(R)
  - *Peeling-Ballooning model tests*
- Divertor/Separatrix for edge stability modifications

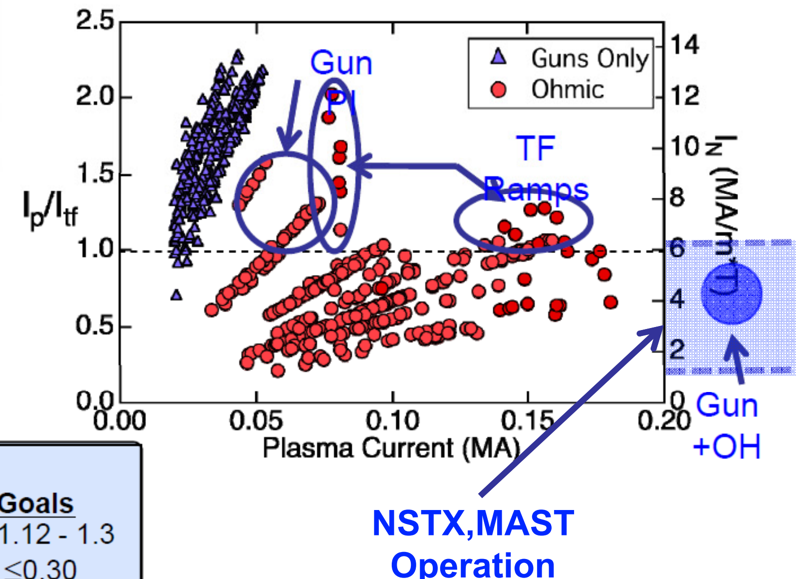


Experimental Parameters

Parameter	Achieved	Goals
A	1.13 - 1.3	1.12 - 1.3
I_p (MA)	≤ 0.22	≤ 0.30
I_N (MA/m-T)	6-14	6-20
$I_{non\text{-}inductive}$ (MA)	0.16	0.3
β_t (%)	≤ 25	>40
τ_{shot}	≤ 0.02	≤ 0.1

High-I_N, β_t via j(R) manipulation

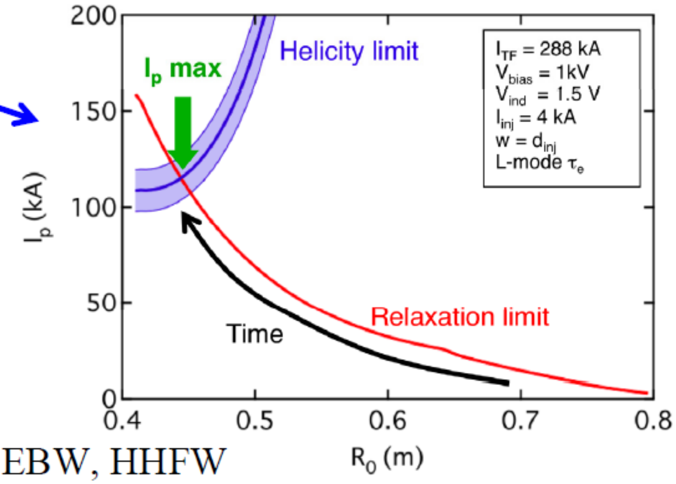
- Edge current drive via guns
  - *Broad j(R) [$l_i \leq 0.4$]*
  - *$I_N \geq 10$; $\beta_t \leq 25\%$ (to date)*
- Maintain stable plasmas via CD
  - *OH, HHFW, EBW, TF-ramp*



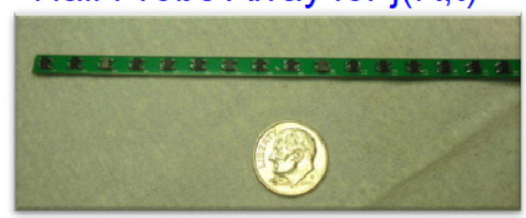
Pegasus Program Activities in FY10-12

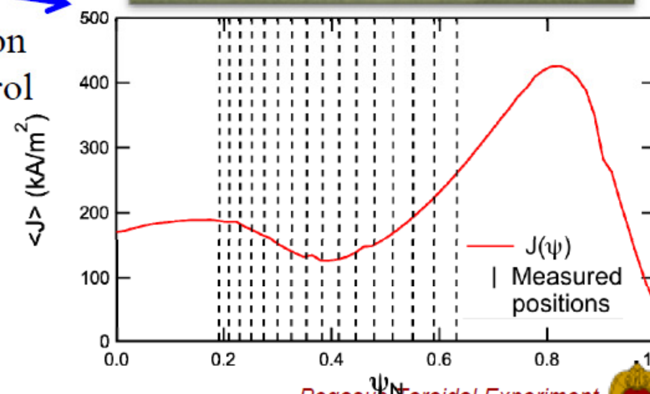
- Predictive understanding of point-source helicity injection
  - Verify relaxation model scaling of I_p limit to ~ 0.3 MA
  - Determine physical processes governing critical properties
    - Edge current scale length; Source impedance
    - Helicity dissipation rates and Confinement
- Non-solenoidal startup and plasma growth
  - Using HI, HHFW, and EBW and synergistic combinations thereof
    - Confinement and transport; Impurity properties
  - High-power, edge and central EBW H&CD tests
  - Ion channel dynamics with strong reconnection processes during HI + EBW, HHFW
    - Flows and flow shears resulting from strong edge biasing.
  - Scalable, high-power point-source HI development for NSTX deployment
    - Verify predictive models for integrated startup in larger experiments.
- Tests of Peeling-Ballooning stability theory at high j_{edge}/B
  - Edge stability, precursors with j(r) and P_e(r) profiles in edge plasma region
  - Effects of magnetic shear, separatrix, flow shears, and possible j_{edge} control
- Stability boundaries at high I_N, high β_t, low l_i as A → 1
  - Current channel control and evolution during formation
  - j(r) manipulation via HI and OH formation schemes, and RFCD
  - Auxiliary heating: challenge β_t limits → unity using RF heating

Point Helicity Injection
+ Poloidal Induction Model



Hall Probe Array for j(R,t)



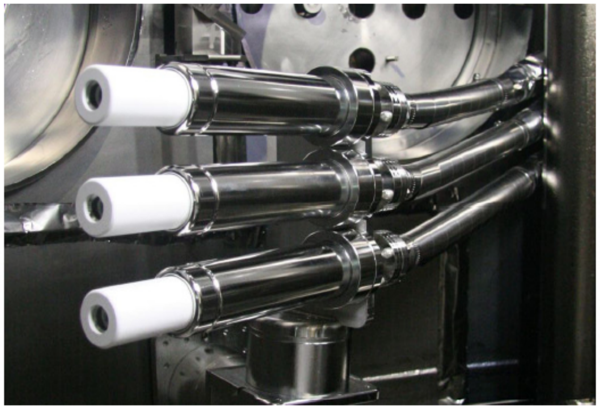


Pegasus Program and Budget

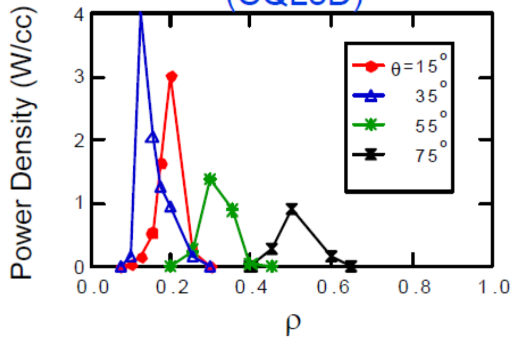
- FY10 baseline = $914K; ARRA = $485K
  - Reduced staff and students from FY08
  - Scalable, high-power gun array development
  - ARRA provides
    - 1) TF doubling; 2) Thomson Scattering; 3) EBW power supply

- FY11-12 Request: staff reinstatement, EBW program
  - Recover losses of staff (1) and graduate students (1-2)
  - **Baseline proposal = $1.05M**
    - Post-doc for Thomson Scattering
    - Plasma gun injector systems development and testing
      - Power supplies; Scalable high-current system; NSTX prototype
    - Divertor coil power supply for edge stability
    - Internal $R_o(t)$ control coils
  - **Increment: ~ 1MW EBW tests in an ST (+$350 K/year)**
    - Unique opportunity to develop EBW for radially flexible H & CD
    - Collaboration with ORNL; increases faculty involvement
  - **One-time increment: DNB for ion dynamics ($150K)**

- Reduced case: -10% from Proposed Baseline
  - Personnel reduction: staff and graduate students
  - Drop: 1) EBW prep; 2) Peeling-Ballooning stability program
  - Slow down helicity startup development activities



Power Deposition from Injection Angle Scan (CQL3D)

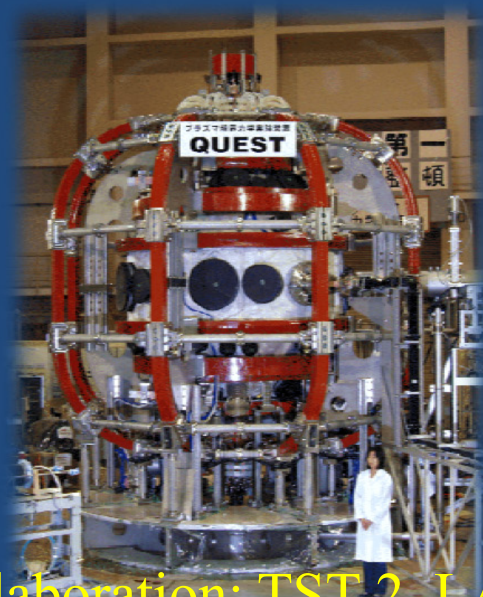


Kyushu U. ST Started RF-Sustained Plasma Experiments (T-V, VII)

QUEST Experiment

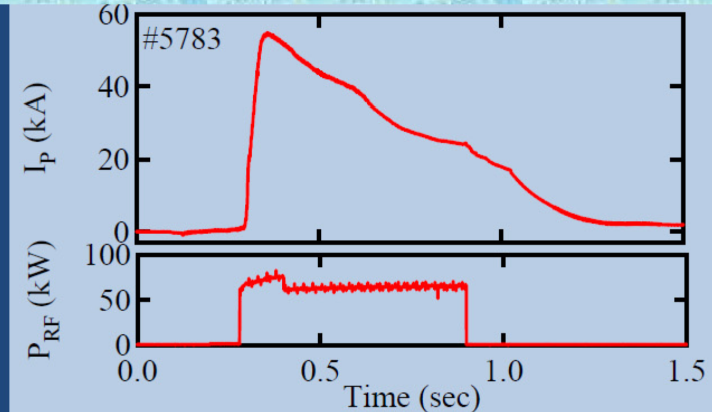
R=0.68m
a=0.4m
A=1.78
B_T=0.25T @ 0.64m
P_{RF}=0.2MWX2
8.2GHz

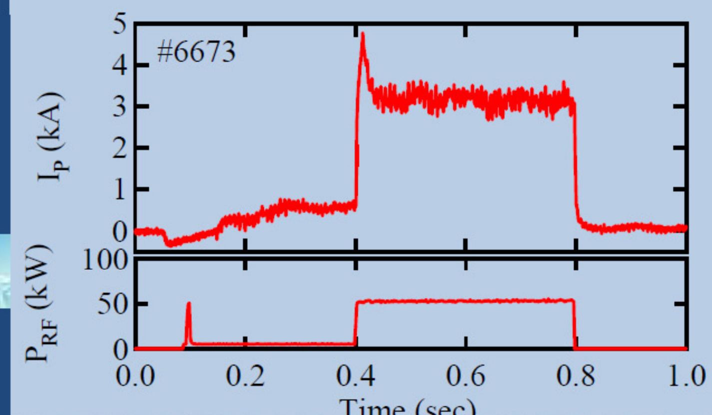
Started experiments in Oct. 2008.



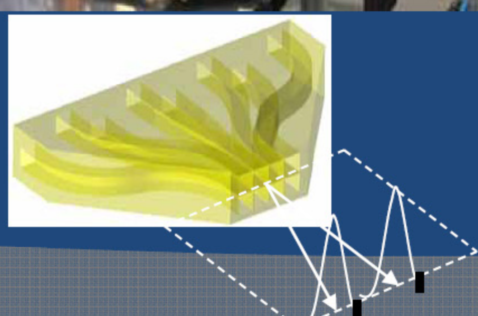
Bi-Directional Collaboration: TST-2, LATE

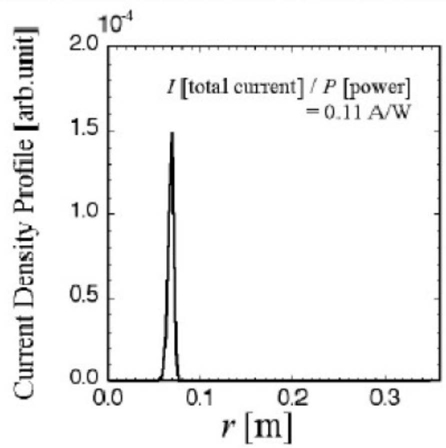
OH plasma and RF maintained plasma



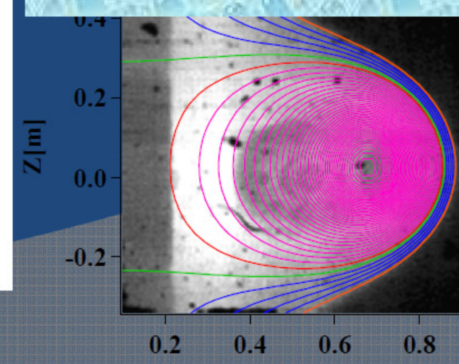


New EBW Antenna expected driven current profile





Flux surfaces of OH + RF plasma

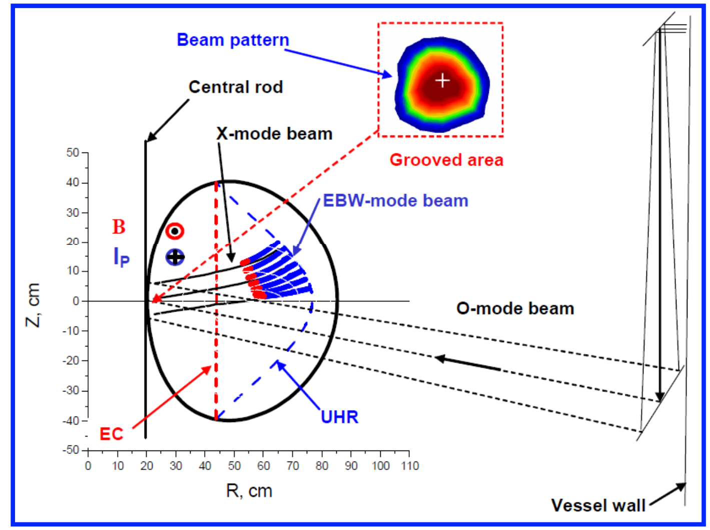


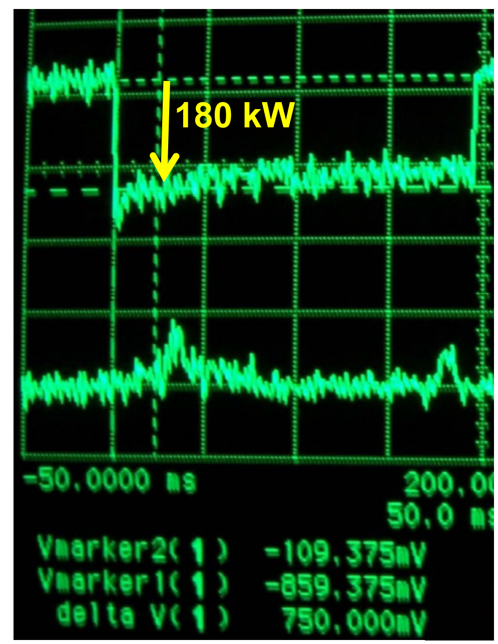
R=0.55m
a=0.3m
A=1.83
I_P=40kA
B_T=0.15T
P_{RF}=0.06MW

EBW Start-Up Collaboration on MAST – Progressing toward Tests at ~300 kW, ~300 ms (T-I)

- **Motivated by 2007 results on MAST**
  - *Started 56 kA using 100 kW source, 90 ms, 28 GHz*
  - *Obtained > 0.5 A/W and T_e > 500 eV (TS)*
- **EU-US-JA collaboration (IEA ST Agreement)**
  - *Complementary, high leverage, cost-effective*
  - *ORNL commissioned and shipped in 2008-2009 a 350-kW, 300-ms gyrotron*
  - *Gyrotron delivered 160-180 kW for 200 ms on site*
  - *4 U.S., 2 Japan researchers, 7 run-days (9/09)*
- **Experiments in 2010 (< $150k/yr)**
  - *Investigating arcing in waveguide & launcher*
  - *Next exp. in April 2010*
  - *To measure dependence on EBW power*
- **FY 2011-2012 goals**
  - *Increase gyrotron power toward 300 kW*
  - *Improve transmission and launcher*
  - *Carry out higher-power experiments*
  - *Modeling to compare & enable predictions*
- **Incremental: to $250k/yr to enable full commissioning and research participation (14 run-days/yr)**

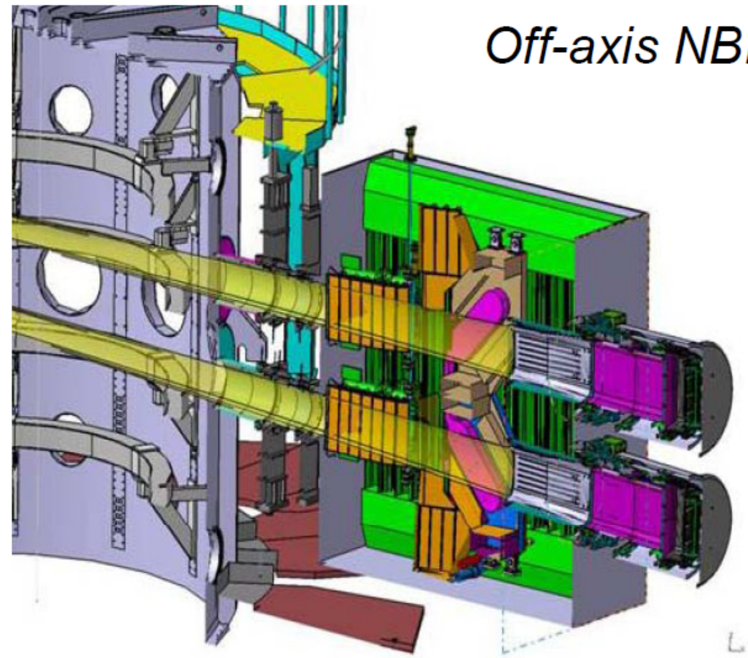
HFS X-Mode via Central Reflection

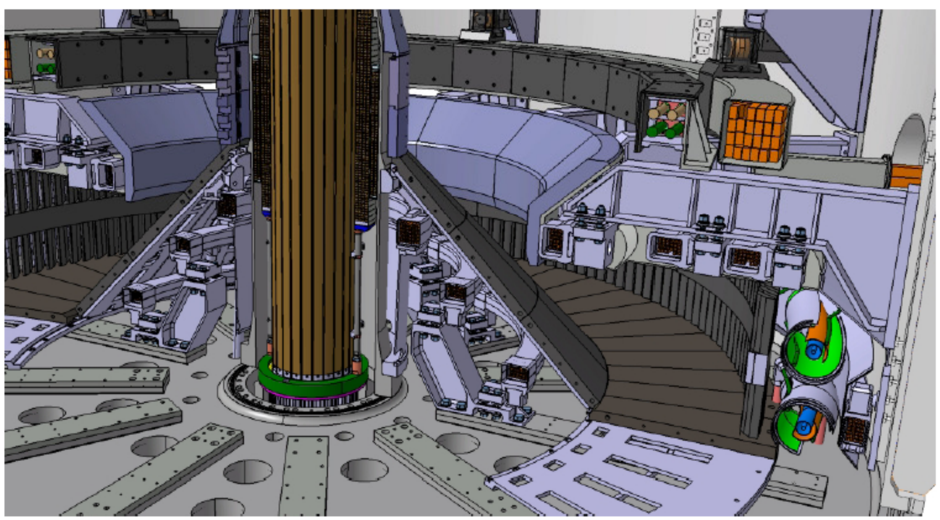




MAST-U Proceeding with Increased NBI Power, TF, Flux, and NSTX-U Complementary Super-X Divertor (T-II)

- 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 Program Helps Build the Scientific Basis for Fusion Energy, while Complementing and Supporting ITER

- STCC Selected PMI, FNS, and High-Q BP Missions for the ITER Era
- Identified respective research priorities among ReNeW Thrust-16 ST topics, in a coherent integrated ST research plan
- LTX exploring science for liquid metal, low recycling wall → opportunity: confinement improvements
- Pegasus making progress in non-solenoidal startup and boundary stability → opportunities: EBW heating & current drive of plasma gun started plasma and $\langle\beta_T\rangle \rightarrow 1$
- Launched leveraged ST research collaboration in EBW startup on MAST (IEA: EU-US-JA) → opportunity: verify ~0.5 A/W efficiency up to 300 kW
- MAST-U with SXD operation – highly complementary to NSTX-U liquid lithium PFC exploration → opportunity: SXD research collaboration
- STCC coordinated research planning in US and worldwide – enhance progress and efficiency

Next: NSTX Research Program, Facility, and Upgrade plans