Supported by Office of Science

National Spherical Torus Program

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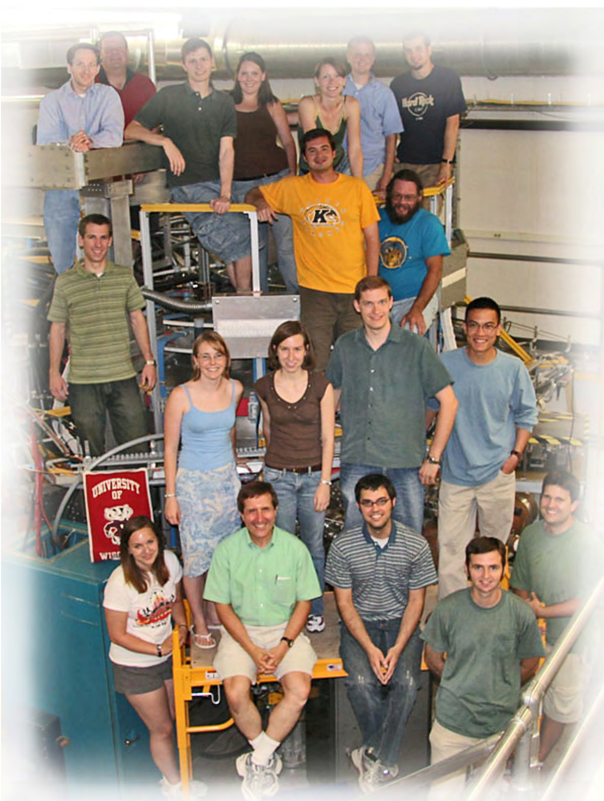
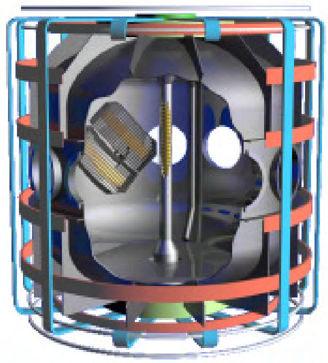
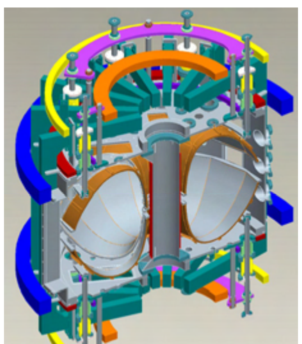


OFES FY09 Budget Planning Meeting
Gaithersburg, Maryland
March 13-14, 2007

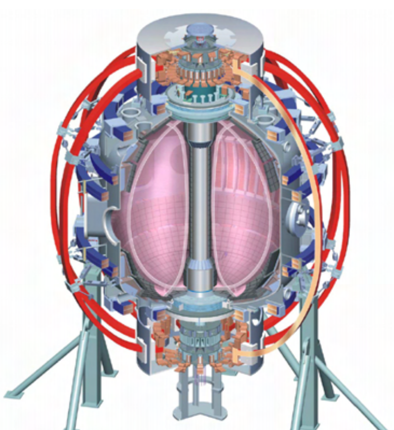
U.S. ST Mission: develop attractive ST fusion applications, support ITER, and address FESAC scientific priorities



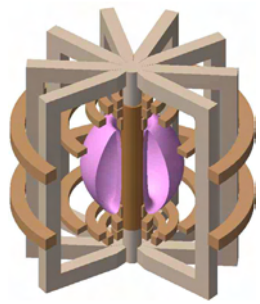
PEGASUS



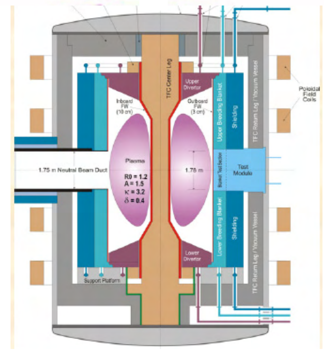
LTX



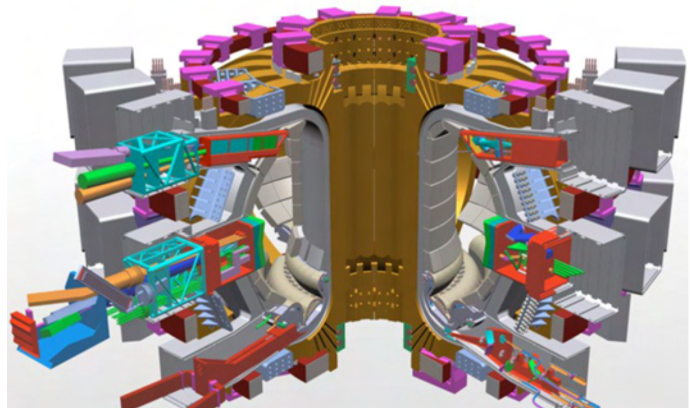
NSTX



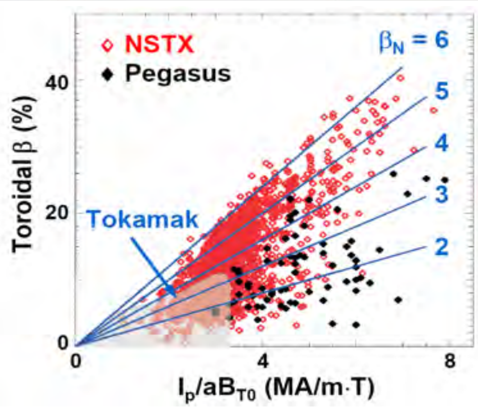
NHTX Concept



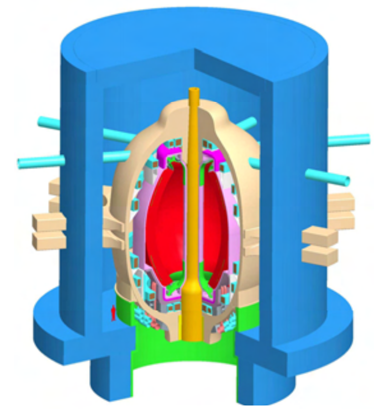
ST-CTF



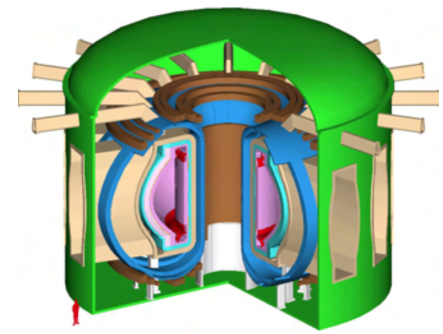
ITER



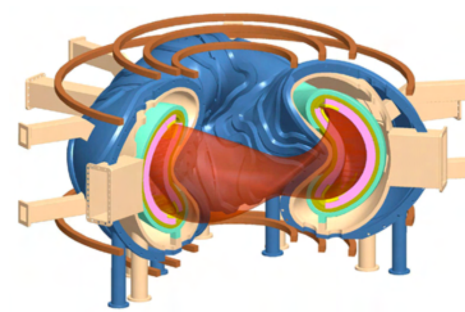
FESAC Scientific Priorities



ARIES-ST



ARIES-AT



ARIES-CS

U.S. ST's support, supplement, and look beyond ITER toward component testing and fusion power

	Pegasus	LTX	NSTX
Supports ITER			
• Develops tools to increase plasma pressure by stabilization.			√
• Studies of super-Alfvénic ions anticipated in ITER.			√
• Detailed studies of transport of electron heat.			√
• Techniques to reduce divertor heat flux.			√
Supplements ITER			
• Operates at high I_N(MA/m-T) due to low A.	~20		~7
• Operates at high plasma β(%).	√		√
• Studies transport at high β and I_N.		√	√
• Study effects of minimized particle recycling from wall.		~10%	~90%
• Study wave-plasma interactions in high (ω_{pe}/ω_{ce}).	~20		~7
• Study energetic particle physics with mode overlap.			√
Looks beyond ITER toward CTF and Demo			
• Addresses plasma startup with small central induction.	guns		CHI
• Test innovative divertor physics solutions using liquid Li.		all-wall	div
• Establish Tokamak-ST phys commonality for CTF and Demo.	√	√	√

U.S. ST's also broadly support the FESAC scientific priorities

		Pegasus	LTX	NSTX
T1:	How does magnetic field structure impact fusion plasma confinement?	√	√	√
T2:	What limits the maximum pressure that can be achieved in laboratory plasmas?	√		√
T3:	How can external control and plasma self-organization be used to improve plasma performance?	√	√	√
T4:	How does turbulence cause heat, particle, and momentum to escape from plasma?		√	√
T5:	How are electromagnetic field and mass flows generated in plasmas?	√		√
T6:	How do magnetic fields in plasmas reconnect and dissipate their energy?	√		√
T10:	How can a 100-million °C burning plasma be interfaced to its room temperature surroundings?	√	√	√
T11:	How do electromagnetic waves interact with plasma?	√*		√
T12:	How do high energy particles interact with plasma?			√
T13:	How does the challenging fusion environment affect plasma chamber systems?		√	√
T15:	How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?		√	√

(*incremental)

Pegasus Mission Supports Many FESAC Priorties and Research Thrusts

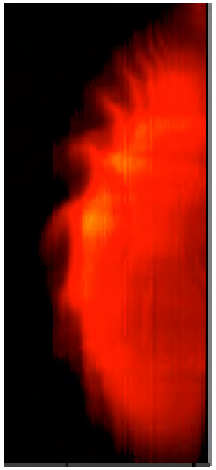
Pegasus is an extremely low-aspect ratio experiment
- Explore quasi-spherical, high-pressure plasmas;
- Develop plasma formation & control techniques for future ST/Tokamak applications.

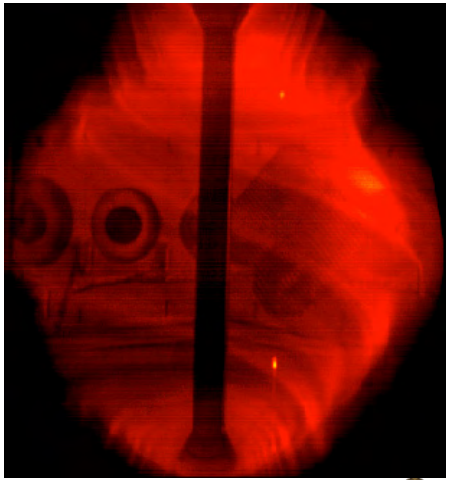
Experimental Parameters

	Achieved	Goal
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.45	0.2-0.45
I_p (MA)	$\leq$ 0.18	$\leq$ 0.30
I_N (MA/m·T)	6-12	6-20
RB_T (m·T)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4-3.7	1.4-3.7
τ_{shot} (s)	$\leq$ 0.02	$\leq$ 0.05
β_T (%)	$\leq$ 25	> 40
P_{HHFW} (MW)	0.2	1.0

<u>Contributions to FESAC Research Thrusts:</u>

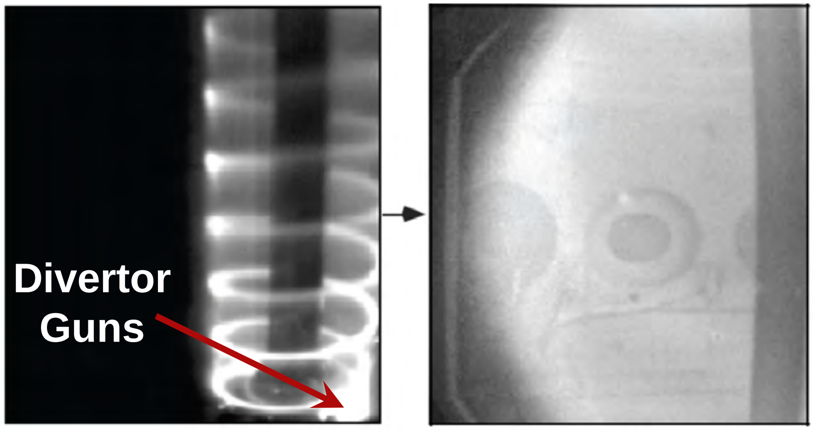
- *Plasma confinement at the limit of extreme toroidicity.* **(T1)**
- *Nature of the kink and beta limits as $A \rightarrow 1$.* **(T2)**
- *Relaxation of an injected current filament into a tokamak configuration.* **(T3,T6)**
- *Potential relaxation of a plasma in the tokamak-spheromak overlap regime.* **(T5)**
- *Stability of high j_{edge} and low toroidal field. (i.e., high edge $j_{||}/B$) – Peeling/Ballooning modes?* **(T10)**
- RF interactions in over-dense plasmas. **(T11)**



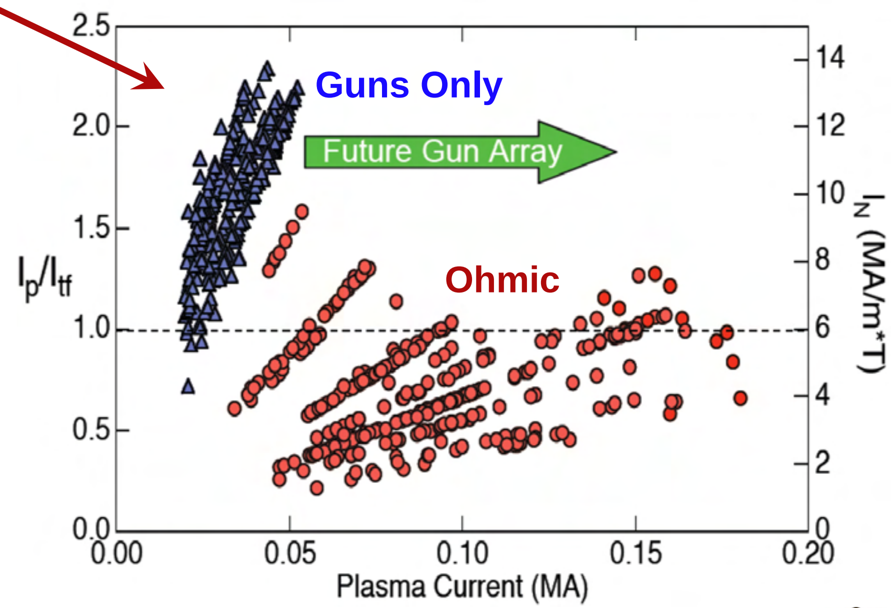


FY07-09: High-I_N Access Studies; Helicity-Assisted Startup and J(R) Mod

- **Research Plans**
  - **Non-solenoid startup w/ local current sources**
    - FY07: Test added anode plate ⇒ ~50KA
    - FY08-09: Test added bias coil ⇒ 0.1-0.3 MA
    - FY08-09: Test outboard gun/collector array – more scalable to larger devices
  - **Plasma stability & confinement as A ➠1**
    - OH plasmas with active control
    - j profile variations w/OH and gun helicity
    - HHFW heating to β-limit
- **Major Pegasus Facility Upgrades**
  - Mid-plane plasma gun injector systems, supplies & bias coil
  - Divertor coil for H-mode and edge stability
  - Diagnostics: multipoint Thomson Scatt; SXR imaging for j(r,t)



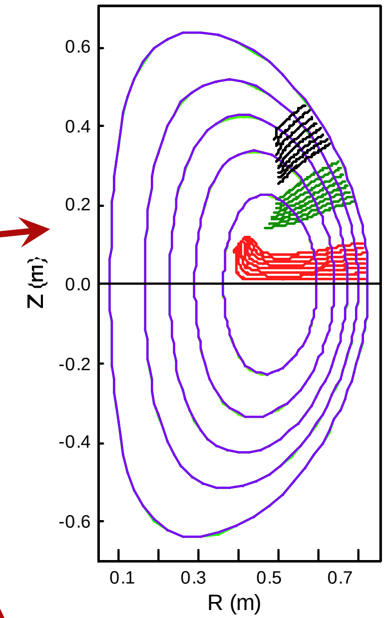
Field-line following current filament relaxes spontaneously to tokamak plasma



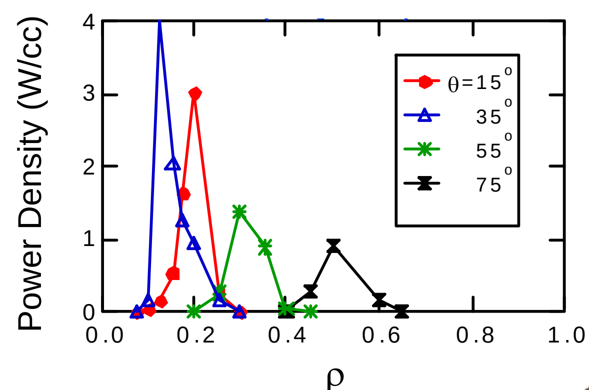
Full-Use Budget Supports Critical EBW Tests for Future ST Applications

- **Full-Use: +$300K/yr**
  - Maintain science and technical staff (**7 graduate student**, 2 scientists, 1 engineer, 2 technician)
  - **EBW: 1 MW heating and current drive tests in an ST**
    - 2.45 GHz sources from PLT
    - Research collaboration with PPPL/NSTX
- **Baseline = $903k,$930k for FY07,08**
  - Lost 1/2 technician, stop equipment support (FY07)
  - Lose 3 grad students and 1/2 technician (FY08)
- **Reduced case: -10%**
  - Further personnel reduction: 1 staff or 1-3 grad students
  - Slow down or eliminate major systems:
    - Downgrade or eliminate one of the High-I_p test gun arrays
    - Drop multipoint Thomson Scattering

Injection Angles (GENRAY)



Power Deposition vs. Injection Angles (CQL3D)



LTX program addresses many of the FESAC priorities

The Lithium Tokamak eXperiment (LTX) is the world's first device to study confinement with full liquid lithium, low-recycling walls

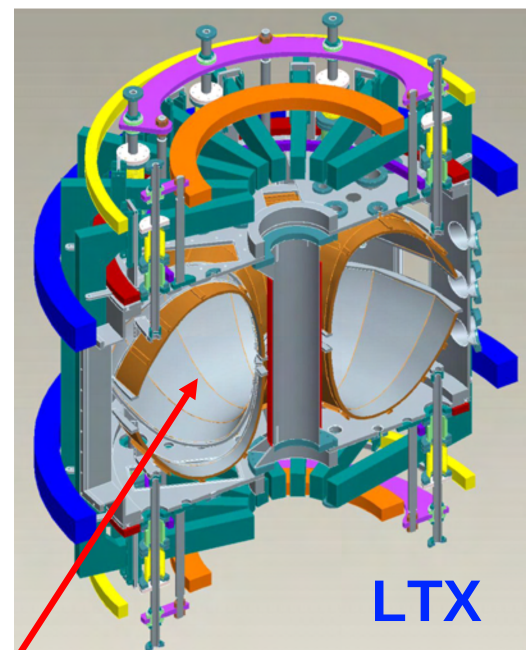
LTX

Relevance to FESAC research priorities:

- Study confinement with a close-fitting, conducting, stabilizing, and limiting wall – no vacuum gap **(T1)**
  - Does lithium limiting surface permit high temperature plasmas?
- Study control of the pressure profile with fueling profile **(T3)**
  - via SSGI, molecular cluster injector, and gas puff
- Study heat and particle transport with *much reduced* ∇T_e and edge particle source **(T4)**
- Using full liquid metal wall, study
  - Very low recycling plasma-wall interface **(T10)**
  - Plasma impact on liquid wall **(T13)**
  - Fueling and pumping in presence of liquid wall **(T15)**

LTX Design Parameters

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



***Liquid* lithium coated shell**

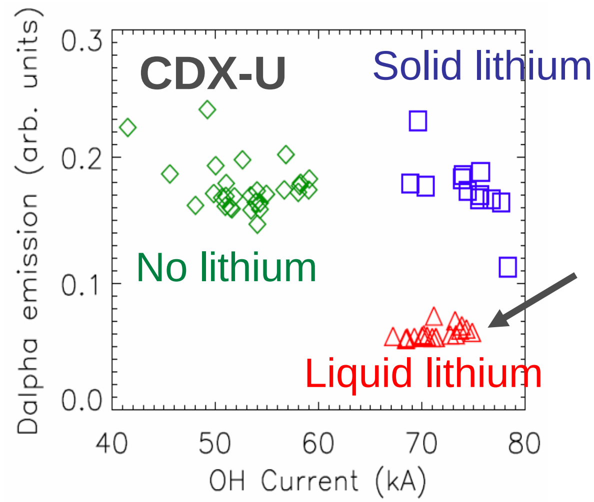
Education: 3 graduate students, 2 post-docs

Aims for first plasma & liquid lithium research in FY08-09

- **FY07:** Complete construction and pumpdown

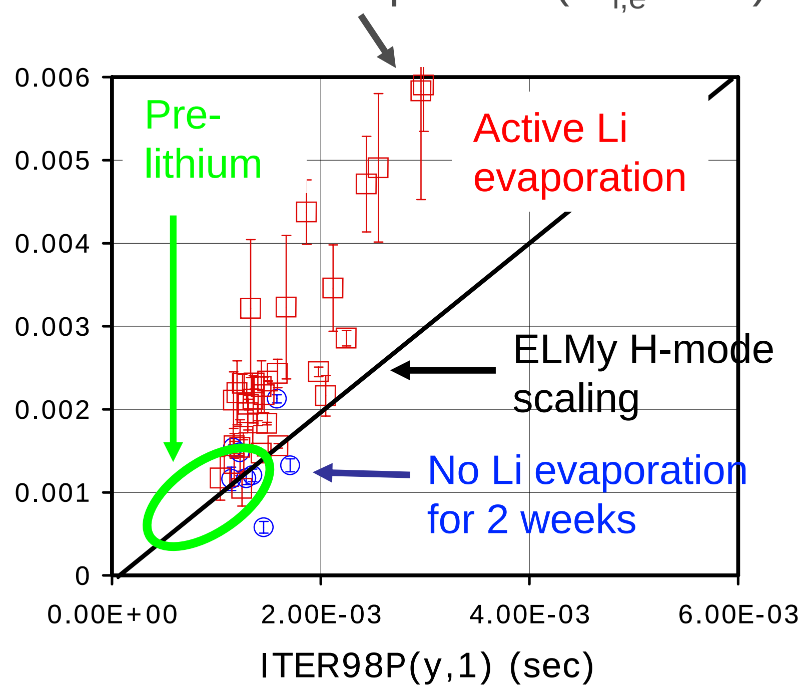
- **FY08-09:** Investigate plasma science and technology of full liquid lithium walls
  - Evaporative coating of first wall
  - Rapid fueling turn-off to transiently eliminate edge neutrals
  - Diagnose T_e with Thomson scattering

- **FY09:**
  - Prepare NBI (collaboration with UW-Pegasus)
  - Investigate lithium-filled porous molybdenum wall technology (directly relevant to NSTX liquid lithium divertor)



Record low recycling for magnetically confined plasma

Record confinement enhancement factor for Ohmic plasma ($\nu^*_{i,e}$~ 0.1)



Full use of LTX: enable core fueling and heating via NBI for confinement studies with low recycling walls

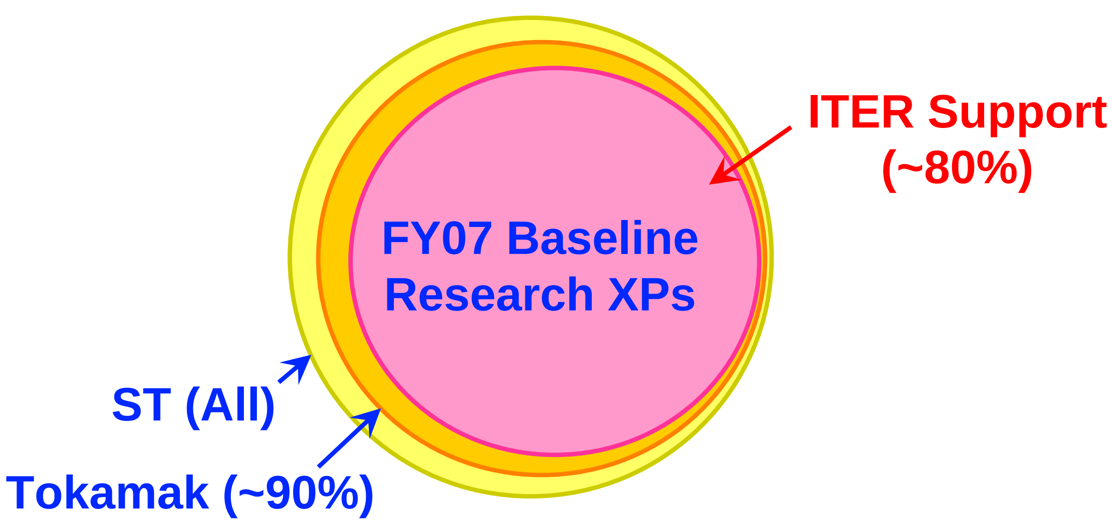
- **Full use case: +400k/year**
  - **FY08:** Implement OH supply upgrade to design capability & feedback control
  - **FY09:** Install NBI for core fueling and heating in very low recycling regime (collaboration with UW-Pegasus)

- **Baseline funding: $947k (FY07), $973k (FY08), $993k (FY09)**
  - **FY08:** OH power supply at 1/4 design, no feedback (first plasma & lithium operation)
  - **FY09:** New porous molybdenum shell in FY09 (SBIR)
  - Test of NBI core fueling and heating in FY10 at earliest

- **Reduced case: -10%**
  - **FY08:** No upgrades to diagnostics
  - **FY09:** No new porous molybdenum shell installation
  - No preparation for NBI

NSTX addresses key issues for ST fusion energy development, ITER burning plasma, and plasma science

- **Enable attractive CTF and fusion power plants, by addressing unique ST development issues and benefiting from common ST-Tokamak database for burning plasma.**
- **Support and benefit from USBPO-ITPA activities, using the physics breadth provided by ST in preparation for burning plasma research in ITER.**
- **Complement and extend toroidal plasma science, by maximizing synergy in investigating key scientific issues of toroidal fusion plasmas.**

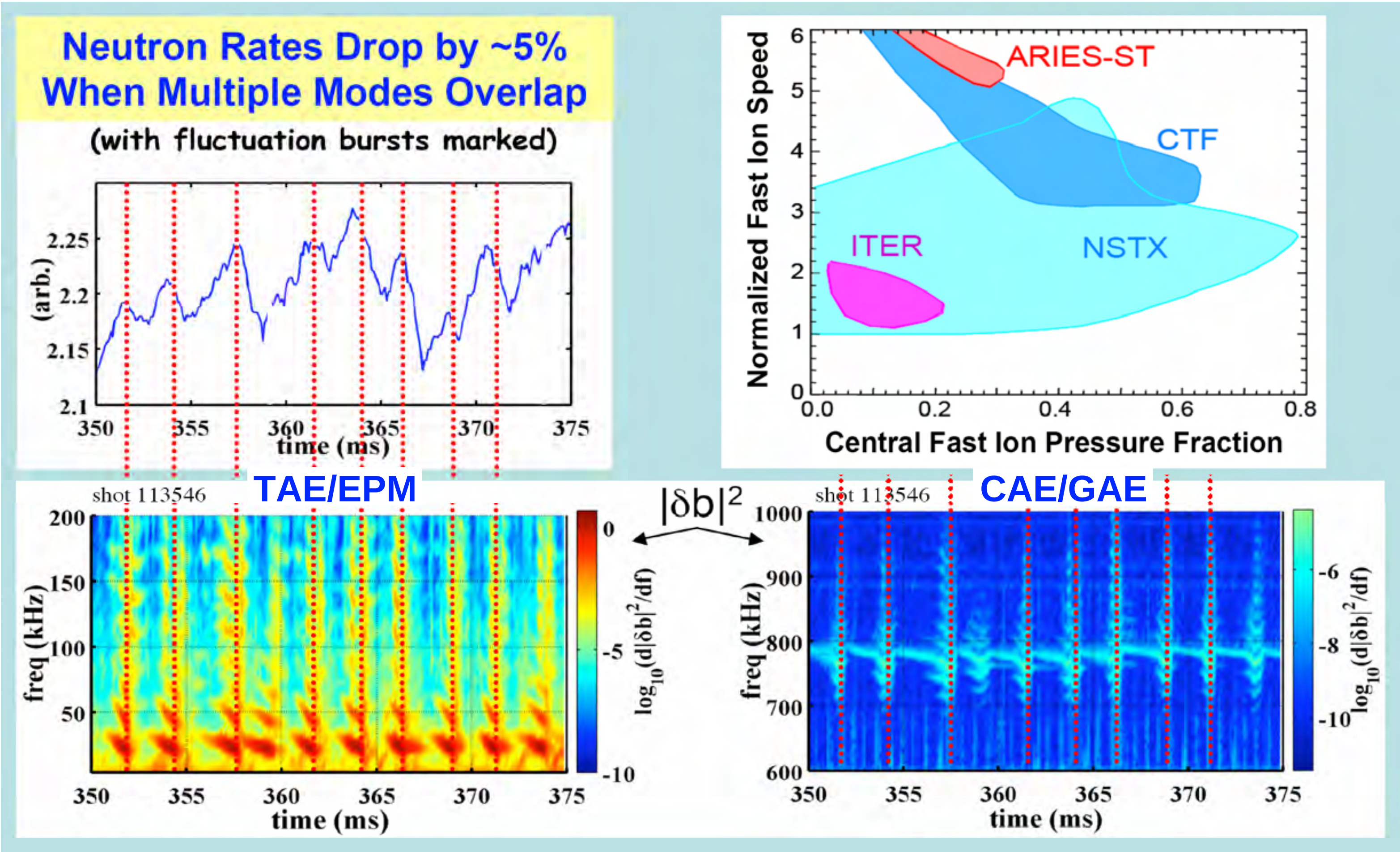


NSTX provides very high β_T, collisionless plasmas

Delivered Experimental Parameters

R_0 (m)	0.85 - 0.95
A	1.3 - 1.6
κ	3.0
δ	0.8
I_p (MA)	1.5
B_T (T)	0.55
I_N (MA/m-T)	7.2
P_{NBI} (MW)	7
P_{HHFW} (MW)	3
τ_{shot} (s)	1.5
$\beta_{T,tot}$ (%)	***40***
ν*	***0.1***
ρ*	***0.03***
I_{CHI} (MA)	***0.16***

NSTX provides unique laboratory plasmas for studying super-Alfvénic ion physics, with full MSE capability



- Establish basis to extrapolate to CTF, and in turn, to ST reactors
- Contribute unique data to ITER – overlapping modes drive fusion α loss
- Address how high-energy particles interact with plasma **(T12)**

NSTX accesses very high beta, low collisionality regimes

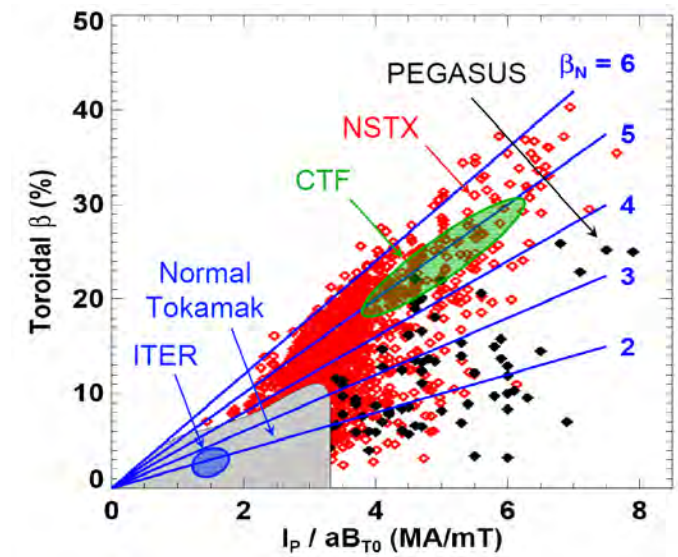
NSTX

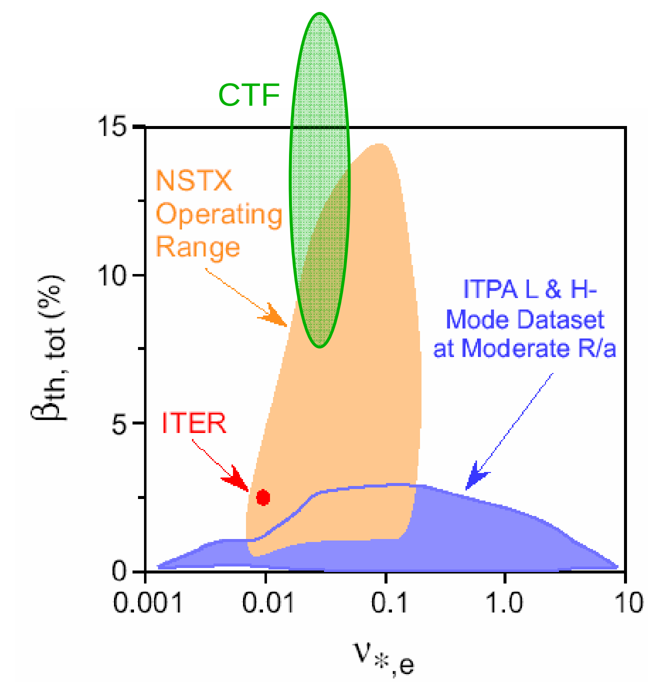
Macroscopic Plasma Physics

- Establish CTF stability regime; study power plant basis
- Study RWM feedback control using ITER-like coils
- Clarify underlying science of V/V_A and V/V_s, in comparison with DIII-D and JT-60U **(T1, T2, T3)**

Multi-scale Transport Physics

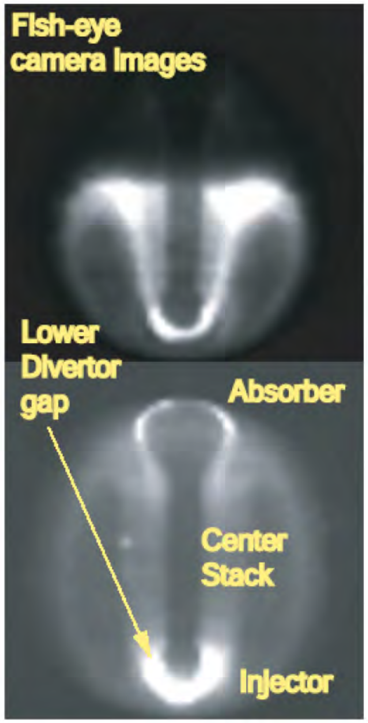
- Confirm confinement scaling favorable to future ST's
- Provide strong test of β scaling for ITER
- Study electron turbulence with suppressed ion turbulence in H-mode ITB plasmas **(T4, T5)**

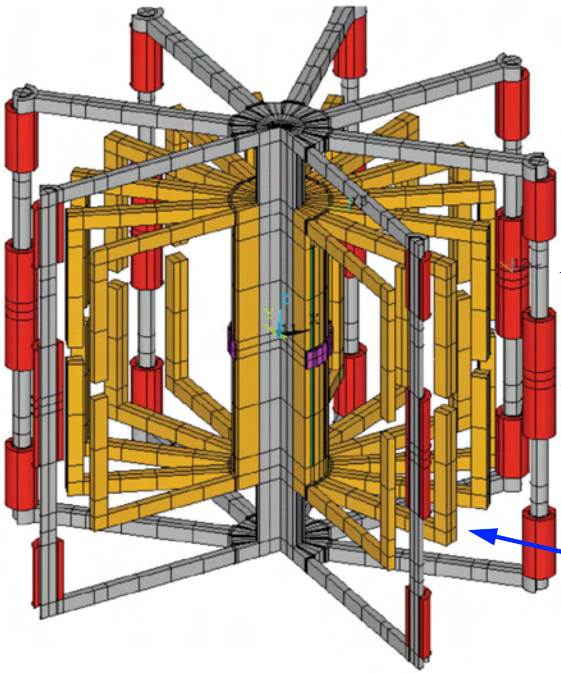




NSTX has unique capability and focus on start-up and ramp-up testing

HIT-II + NSTX (U Wash) CHI achieved record 160 kA current in closed flux surfaces in NSTX



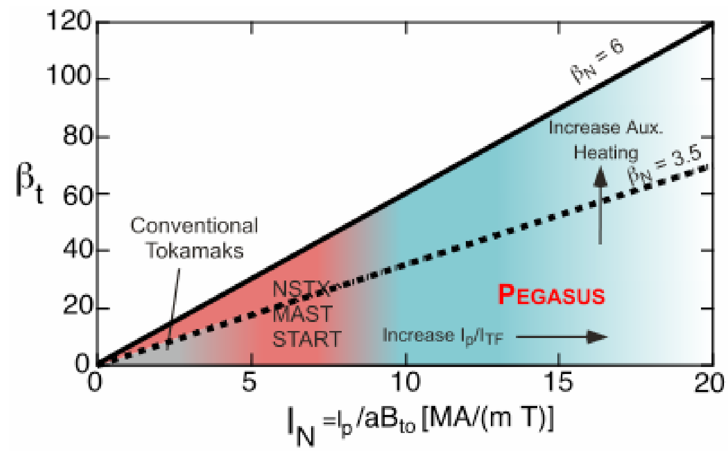


Iron core in all-metal TF center post (Dave Gates)

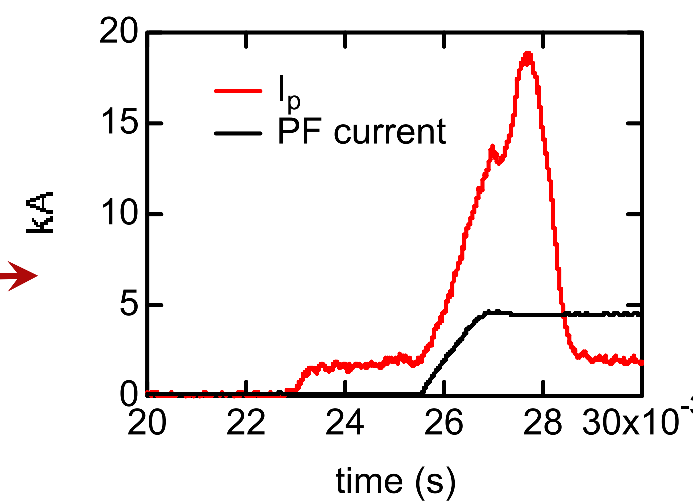
- Carry out studies critical to ST development
  - Small iron core can provide significant flux, mimic by reduced solenoid induction
  - Collaborate with ORNL (ECH, EBW), C-Mod (LHW), MAST, LATE, TST-2, JT-60U
  - Consider option of plasma gun start-up under investigation by Pegasus
- Clarify ARIES-AT requirements for solenoid-free start-up and ramp-up
- Address basic science of reconnection **(T6)**

Pegasus makes unique contributions to national ST program

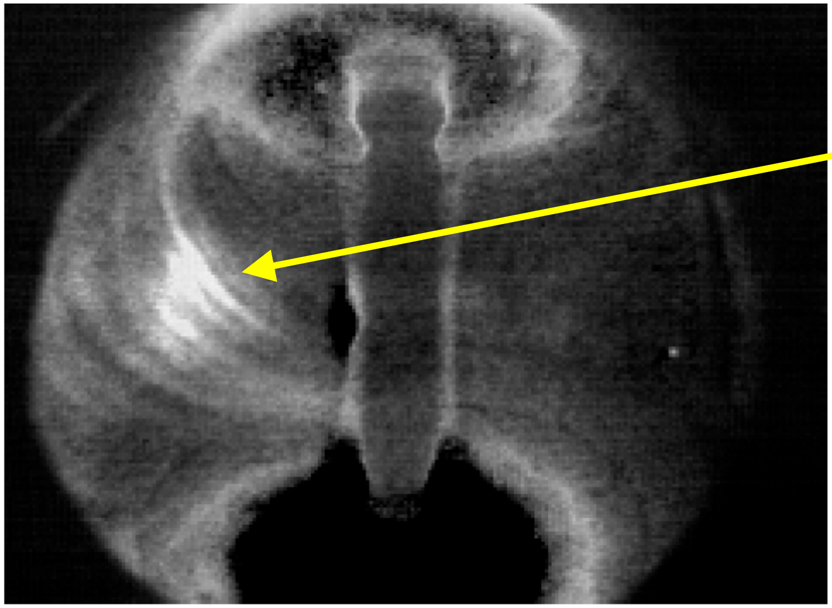
- **Equilibrium and stability at near-unity aspect ratio**
  - $A < 1.2$ regime inaccessible to other STs
    - Very high I_p/I_{tf}, I_N operation space
  - Allows stable high-β_t without stabilizing wall



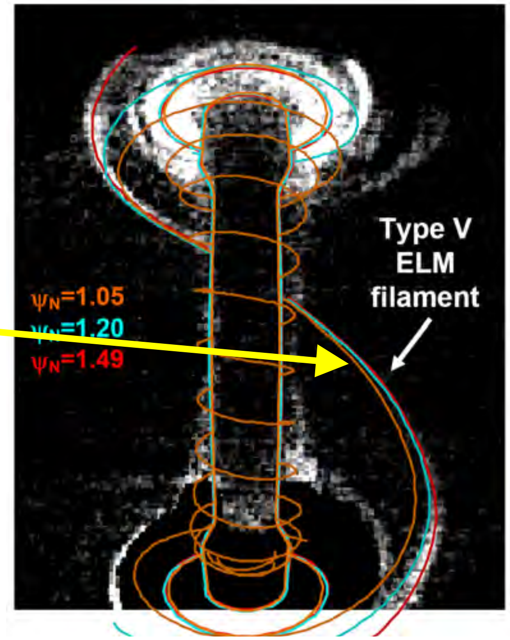
- **Non- solenoidal startup**
  - Plasma guns provide point helicity sources
  - 2 guns in divertor region: 50 kA toroidal plasma current
  - Gun-anode system on outer midplane + PF induction may scale to NSTX and beyond
    - Initial tests with ~1 kA seed current: >10x current amplification achieved
    - Upgraded system for $I_{seed} \geq 5$ kA with closed flux surfaces in construction
    - Hardware attached to midplane port: *Requires no modification of vessel*



NSTX provides unique Boundary Physics data

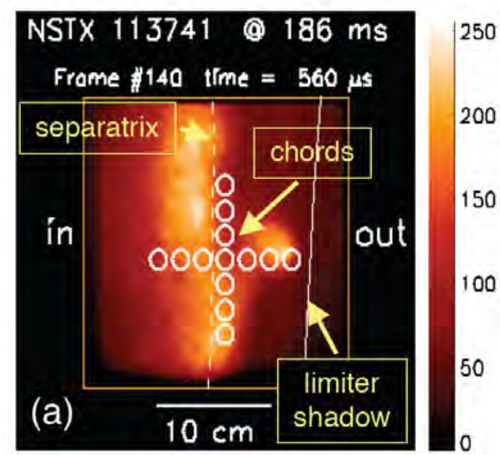


Large ELM (multiple filaments) vs. Small ELM (single filament)

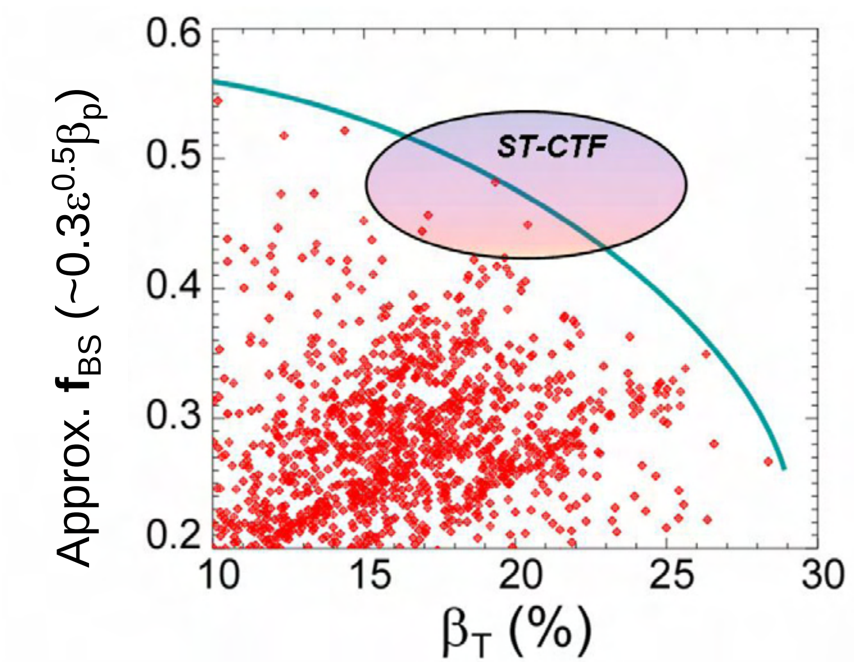


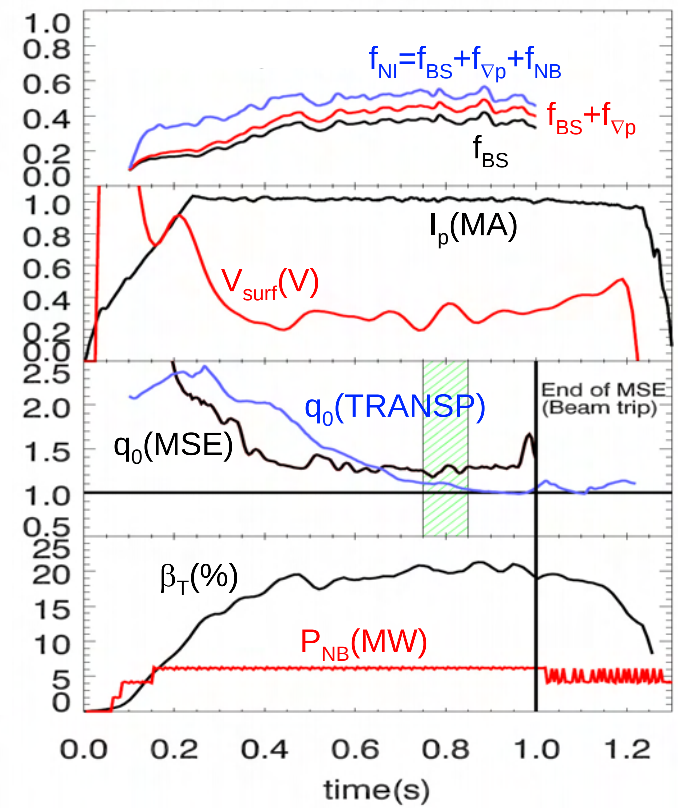
- Explore high divertor heat flux solutions for ST-CTF, ARIES-AT and ARIES-ST, e.g., liquid lithium & SOL flux expansion
- Contribute to ITER in pedestal, ELM, and RMP physics
- Elucidate basic science of edge & divertor heat flux via strong changes in key parameters: β, ε, local shear **(T10)**
- Test liquid lithium as alternate PFC **(T13)**
  - Collaboration with SNL; strong synergy with LTX

Small (Type-V) ELM dynamics being studied

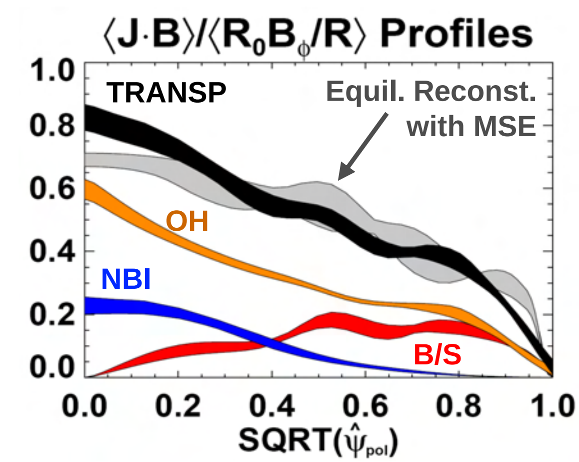


NSTX high performance plasmas operates for up to 5 current relaxation times





- Study 50% bootstrap fraction conditions ~ ST-CTF level
- Investigate sustained high q_0 (=1.3) vs. time using extensive fast ion diagnostics – similar to ITER Hybrid mode
- Understand external control vs. self-organization in sustaining elevated q_0 **(T3)**



Collaboration has been instrumental to the success of Pegasus, LTX, and NSTX research

- **Pegasus & LTX research collaborations**
  - **Pegasus:** Bruker AXS, GA, MST, NHMFL, PPPL
  - **LTX:** ANL, JHU, LLNL, UCSD, ORNL, SNL, UCLA, U Wisc
  - **With NSTX:** potentially plasma gun startup, lithium PFC, EBW
- **NSTX plans in FY07 to carry out ~50% of the 23 requested ITPA-USBPO 2007 joint experiments**
- **NSTX national collaboration renewed in 3-year cycles**
  - 29 domestic institutions; 25 foreign institutions
  - **2004; 2007:** University and industry grants
  - **2005; 2008:** Major diagnostic collaborations
  - **2006; 2009:** Laboratory collaborations
- **2008 proposals will begin NSTX-NCSX joint planning, as NCSX plans to start full research program in 2011**
  - **Collaboration options:** NSTX only, NCSX only, or both
  - **NSTX five-year plan** (2009-2013)

U.S. STs develop attractive ST fusion applications, support ITER, and address FESAC priorities

- **Pegasus uses very low A and high I_N to explore order-unity β_T, and develops plasma gun formation and control with high potential for testing at larger scales including NSTX**
- **LTX to study full liquid-lithium, very low-recycling walls, informing preparation on NSTX**
- **NSTX, Pegasus, and LTX are world-class experiments**
  - **Address key issues for ST fusion energy applications (CTF & Demo)**
  - **Support, supplement ITER with various unique capabilities**
  - **Contribute broadly to FESAC scientific priorities**
- **National and worldwide collaboration is instrumental to success**

The national ST program is making important and timely contributions to the U.S. and world fusion programs