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Progress towards Spherical Torus Physics Basis for Effective Development of Fusion energy

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For NSTX National Team

Current Trends in International Fusion Research: A Review

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Washington, D.C., U.S.A.

Columbia U
Comp-X
GA
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LLNL
Lodestar
MIT
Nova Photonics
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SNL
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UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Wash
U Wisc
UKAEA Fusion
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache

Substantial Progress Is Made Towards Physics Database Needed for Cost-Effective Next-Step STs

- Science and energy missions of NSTX
- Physics metric of cost-effective ST fusion energy development
- Recent NSTX research progress
- FESAC: fusion net electrical output in 35 years
- Near-term research plan

Spherical Torus Offers High β Plasmas with Strong Shaping & Rotational Transform (Safety Factor q ~ 10)

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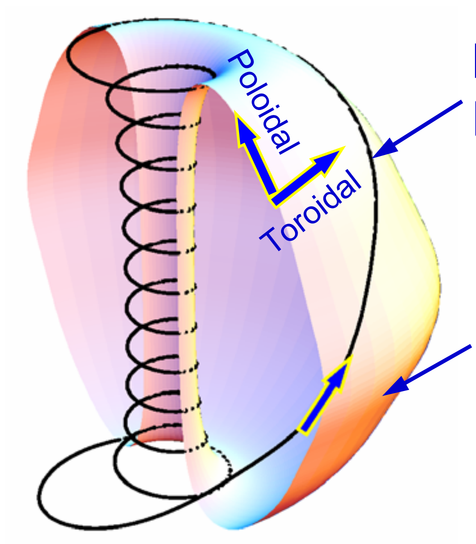
Spherical Torus



Definitions:

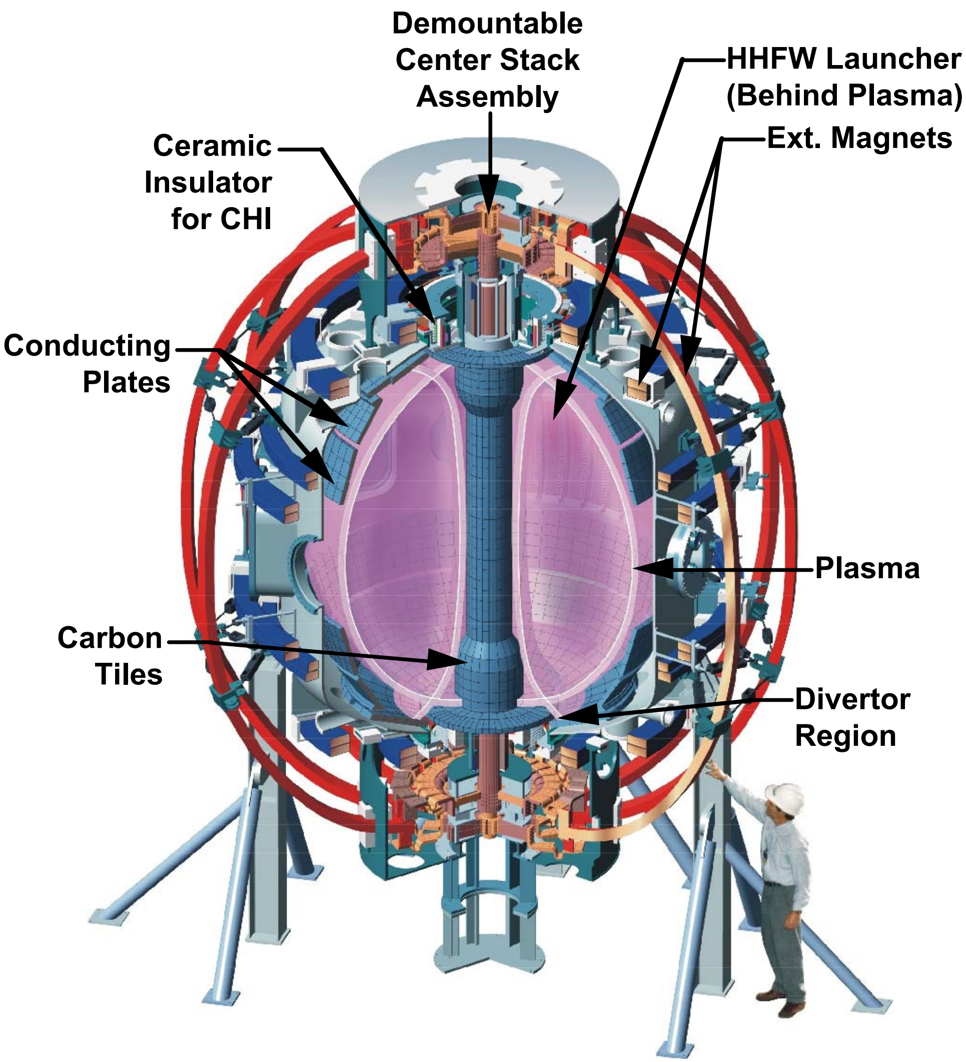
- $A = R/a$ = aspect ratio
- $\beta_T = 2\mu_0\langle p\rangle/B_{T0}^2$
- q = toroidal rotations per poloidal rotation

Expanded plasma parameter space identified for Spherical Torus:

- High β_T (≤ 40%) & central β_0 (~100%)
- Stronger plasma shaping & self fields ($A \geq 1.27$, $\kappa \leq 2.5$, $B_p/B_t \sim 1$, $q_{edge} \sim 10$)
- Reduced internal inductance (ℓ_i) & magnetic stored energy ($\propto \ell_i R I_p^2$)
- Large plasma flow ($V_{rotation}/V_A \sim 0.3$)
- Larger flow shearing rate ($\gamma_{ExB} > 10^5$/s)
- Supra-Alfvénic fast ions ($V_{fast}/V_A \sim 4$–5)
- High dielectric constant ($\varepsilon \sim 30$–100)
- Large B-mirror in edge magnetic field

NSTX Is to Prove Scientific Principle (PoP) of the Extended Toroidal Plasma Parameter Space

National Spherical Torus Experiment



NSTX Mission Contributes to Plasma Physics Understanding

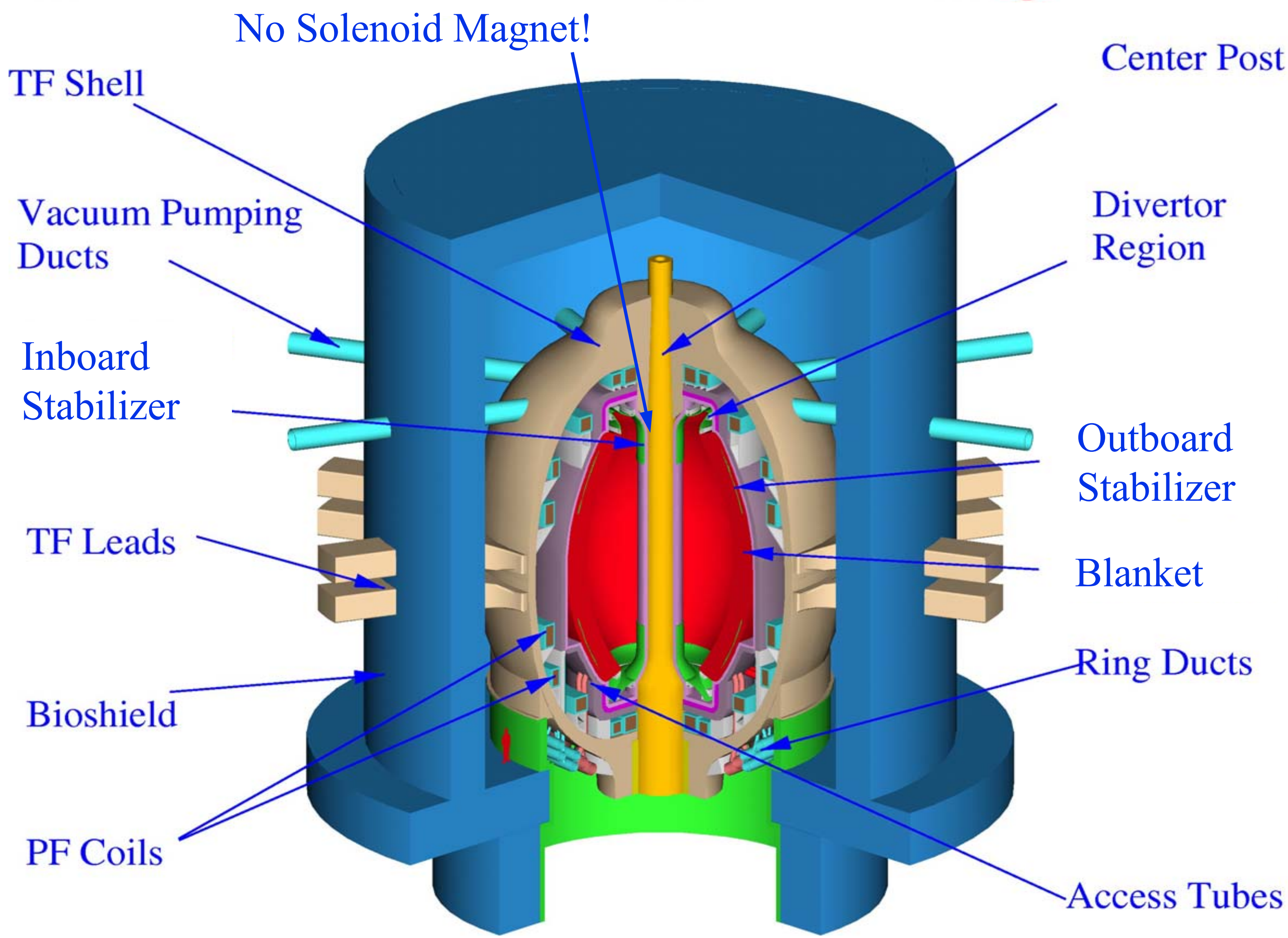
- Solenoid-free startup – **magnetic reconnection**
- Energy confinement - **turbulence**
- Stability at beta (pressure/field^2) $\rightarrow$ order unity - **MHD**
- Heating & current drive - **wave-fast ions-plasma interactions**
- Plasma heat & particle fluxes – **plasma boundary physics**
- Startup & sustainment without induction – **integrated scenarios to achieve all the above conditions**

NSTX Mission Further Utilizes Expanded Physics Basis to Optimize Toroidal Fusion Configurations

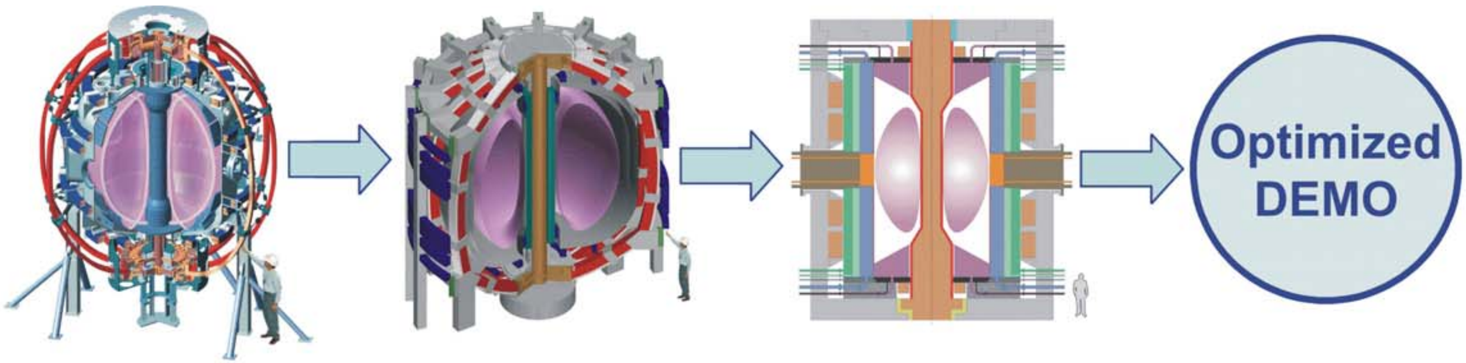
Plasma Science of Expanded Parameter Space	⇒	Optimized Toroidal Fusion Configurations
• Solenoid-free Startup	⇒	Simplified design, reduced operating cost
• Reduced turbulence	⇒	Smaller unit size for sustained fusion burn
• Stable high β_T & β_0	⇒	Lowered magnetic field and device costs
• Effective wave-energetic particle-plasma interaction	⇒	Efficient fusion α particle, neutral beam, & RF heating
• Dispersed plasma fluxes	⇒	Survivable plasma facing components
• Integrated attractive Operations	⇒	Fully sustained operation

ST DEMO & Power Plants Can Have Simplified Modular Designs Using a Demountable Center Post

ARIES-ST



The Benefits of Projected ST Properties Include Potential Cost-Effective PE and CTF Devices



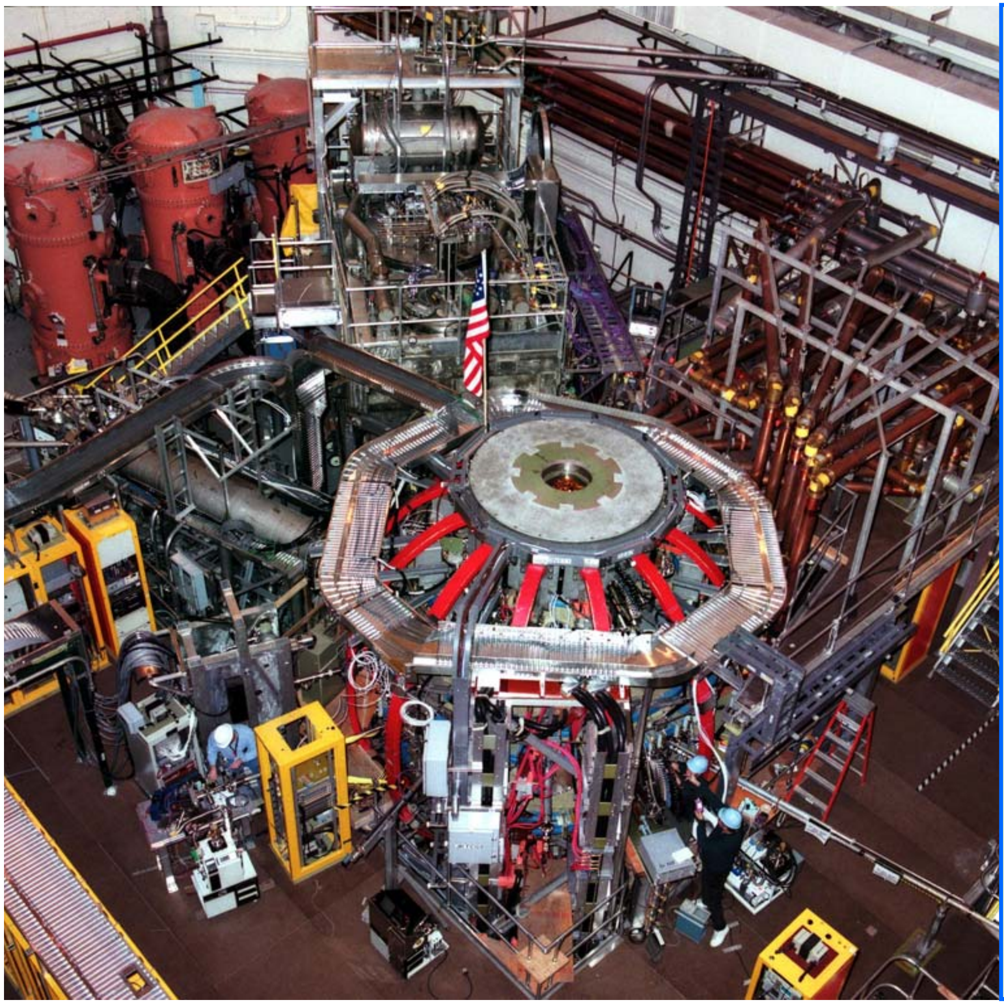
Device	NSTX	NSST	CTF	DEMO
Mission	Proof of Principle	Performance Extension	Energy Development, Component Test	Economy of Fusion Electricity
R (m)	0.85	1.5	1.2	~2.5
a (m)	0.65	0.9	0.8	~1.8
κ, δ	2, 0.8	2.7, 0.6	3, 0.4	~3.4, 0.5
I_p (MA)	1.5	5 – 10	12	~20
B_T (T)	0.3 – 0.6	1.1 – 2.6	2.4	~2
P_{fusion} (MW)	–	10 – 50	≥ 70	~2000
t-pulse (s)	1 – 5	50 – 5	Steady state	Steady state
TF coil	Multi-turn	Multi-turn, LN_2	Single-turn	Single-turn

Metric of Physics Progress Can Be Identified for These Designs & Their Performances

Key ST Plasma Science Parameters	**NSTX (goals)**	**NSST (PE)**	**CTF (FED)**	**DEMO**
• Solenoid-free Startup				
– Internal inductance, ℓ_i	0.25	0.25 – 0.5	0.25	0.13
– Non-inductive energy $\propto \ell_i R I_p^2$ (m-MA²)	0.5	10	40	130
• Reduced turbulence				
– Thermal ion radius, a/ρ_i	40	80 – 120	100	150
– $M_A = V_{flow}/V_{Alfvén}$	0.3	0.5	0.5	0.3
– Flow shear rate (10^5 /s)	3	10	10	3
• Stable high β's				
– Toroidal beta, β_T	0.25 – 0.40	0.4 – 0.2	0.2 – 0.4	0.5
– Normalized beta, β_N	8	8 – 4	4 – 8	9
• Effective heating & sustainment				
– $\omega_{pe}^2/\omega_{ce}^2$	50	50 – 20	20	20
– Bootstrap current fraction	0.7	0.8 – 0.2	0.5 – 0.8	0.9
• Dispersed plasma fluxes				
– Normalized flux, P/R (MW/m)	12	30	40	160
• Integrated attractive Operations				
– Sustained duration, $\tau_{flattop}/\tau_{skin}$	3	10	∞	∞

NSTX Facility Has Since 9/99 Made Rapid Progress in Capability to Support PoP Mission

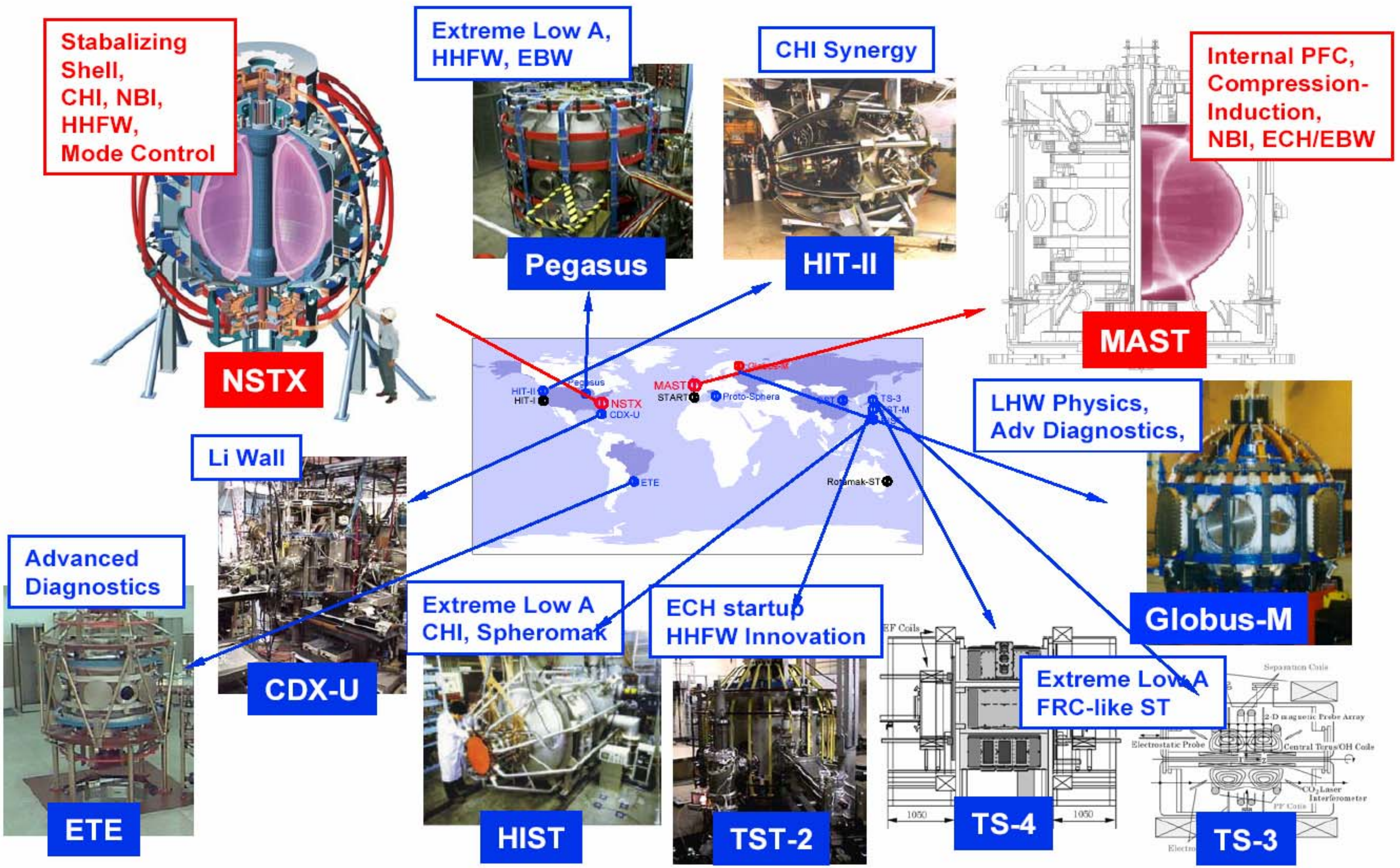
NSTX



Parameters	Design	Achieved
Major Radius	0.85m	}⇒A≥1.27
Minor Radius	0.68m	
Elongation	≤2.2	2.5
Triangularity	≤0.6	0.8
Plasma Current	1MA	1.5MA
Toroidal Field	0.6T	≤0.6T
Heating and Current Drive		
Induction	0.7Vs	0.7Vs
NBI (90keV)	5MW	7MW
HHFW (30MHz)	6MW	6MW
CHI	0.5MA	0.4MA
Pulse Length	≤5s	1.1s

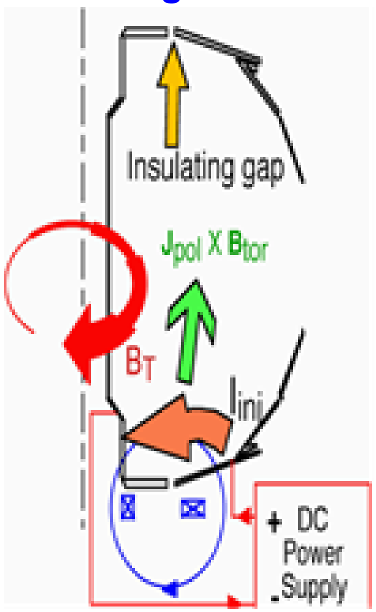
NSTX is Part of U.S. and Worldwide ST Research

Concept Exploration (~0.3 MA) | Proof of Principle (~MA)

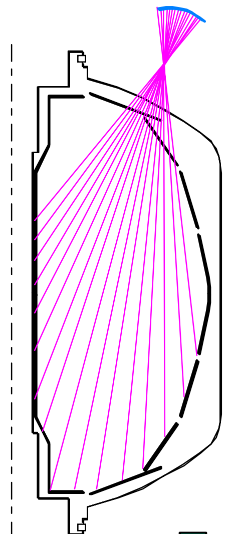


Obtained 390 kA Toroidal Current by Coaxial Helicity Injection (Helicity =ÚA∑B dV)

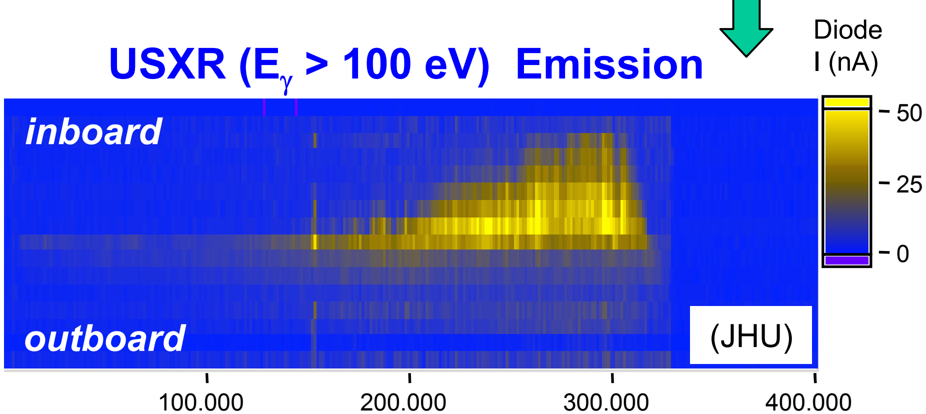
Injection Configuration



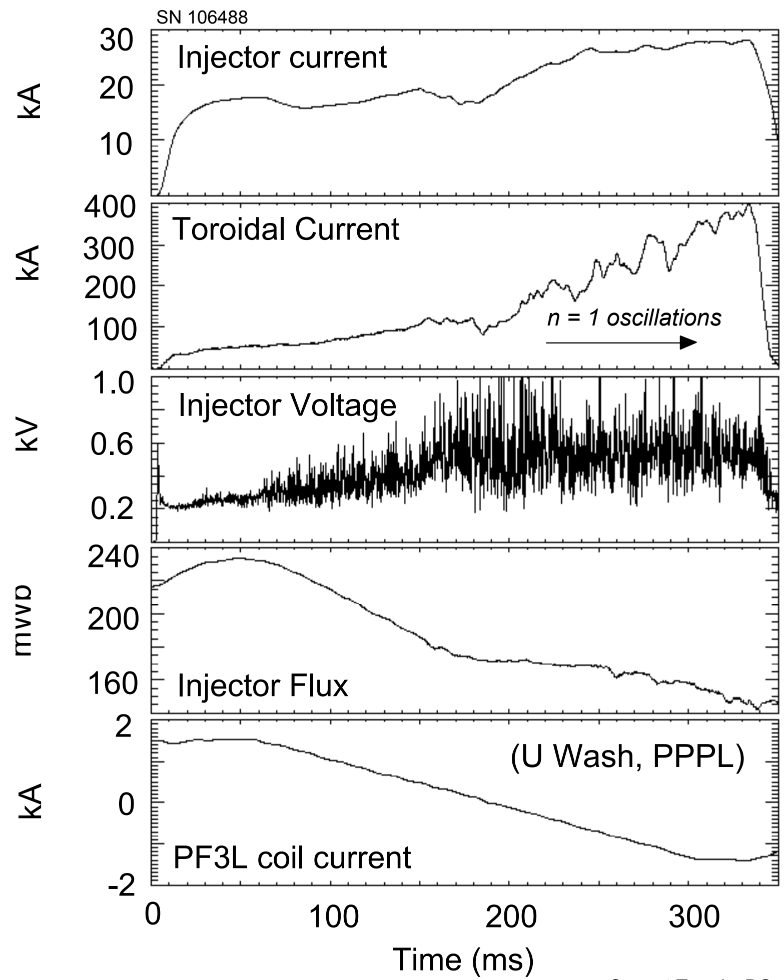
USXR Detectors



USXR (E_γ > 100 eV) Emission



n=1 oscillations related to reconnection mechanisms



This Enables Studies of Reconnection Needed to Form Nearly Closed Magnetic Surfaces

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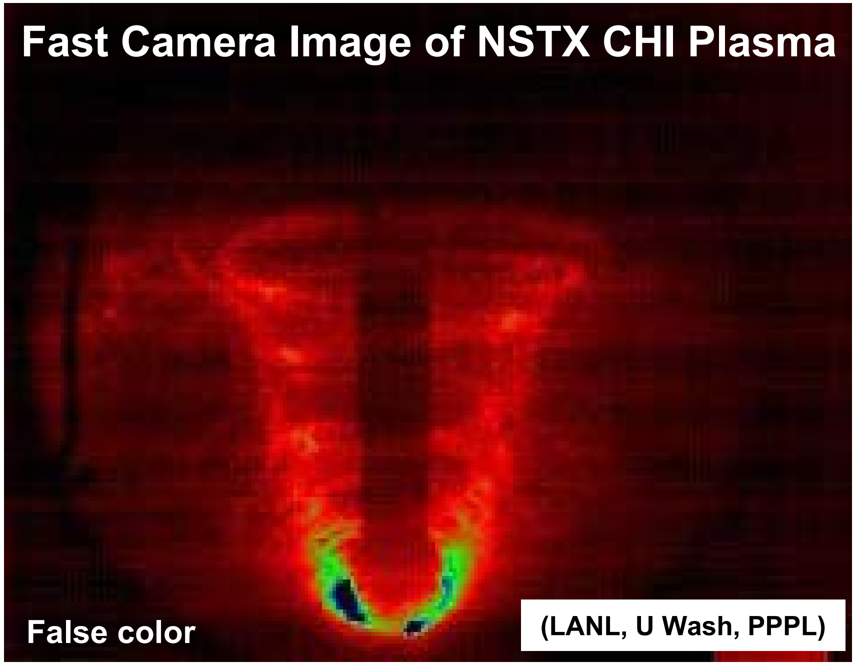
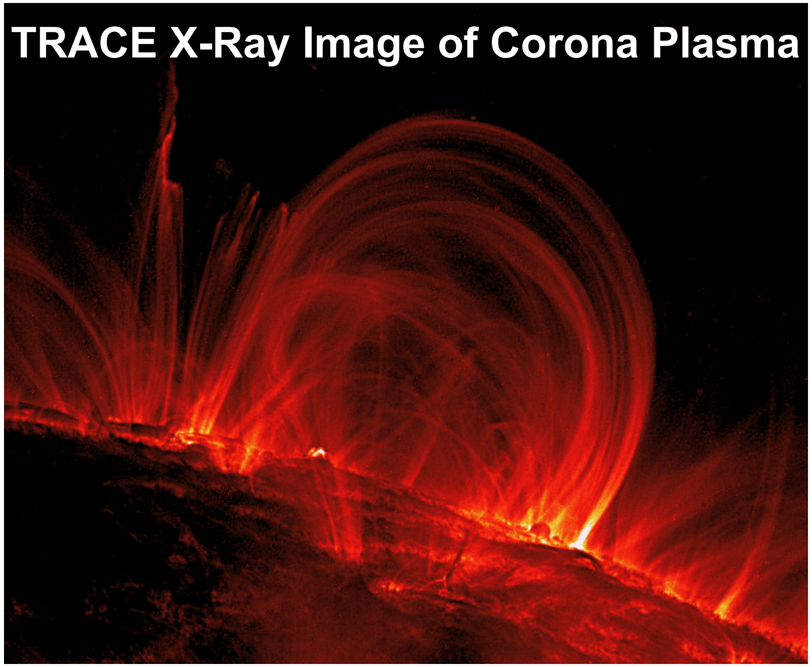
- Flux surface closure important to solenoid-free startup
- Need effective coupling to solenoid induction and RF heating
- Lundquist No. S(CHI) ~ $10^4 - 10^6$ vs. S(corona) ~ $10^{10} - 10^{12}$
- Laboratory investigation of interest to space plasma studies



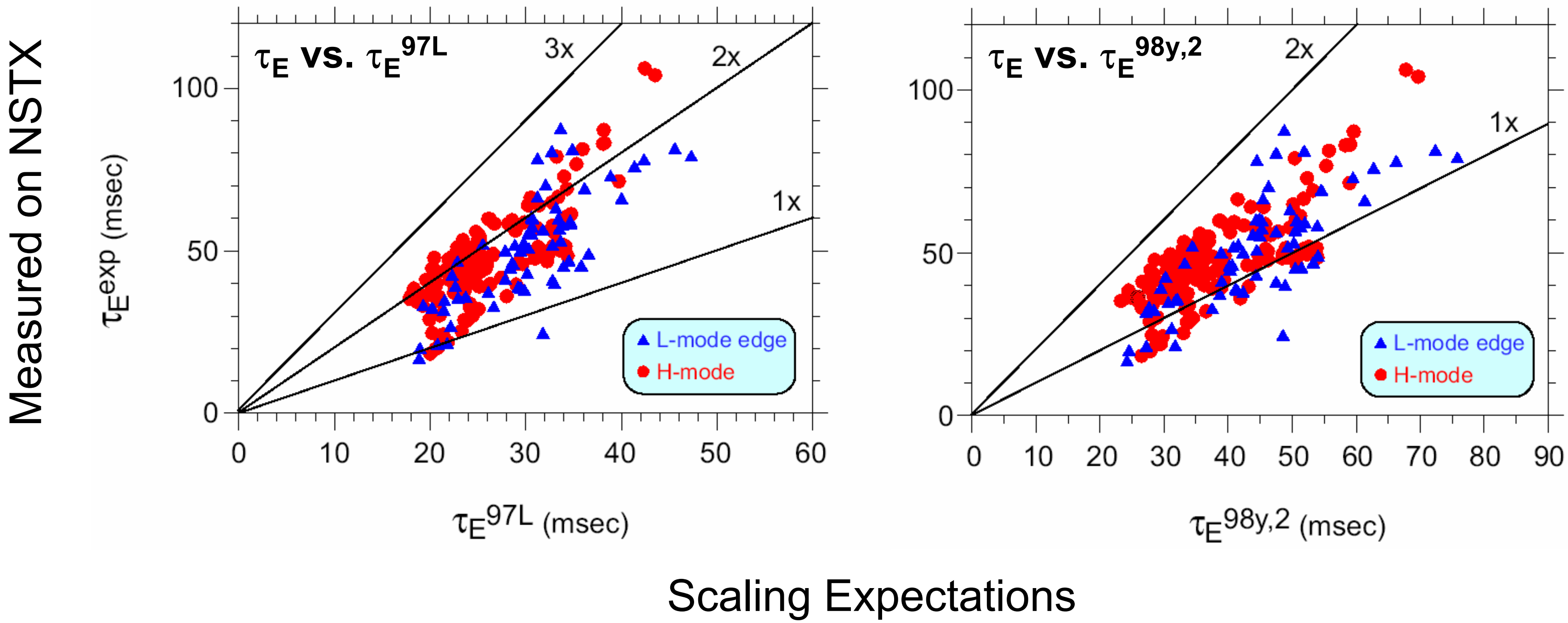
2 m



$3x10^7$ m

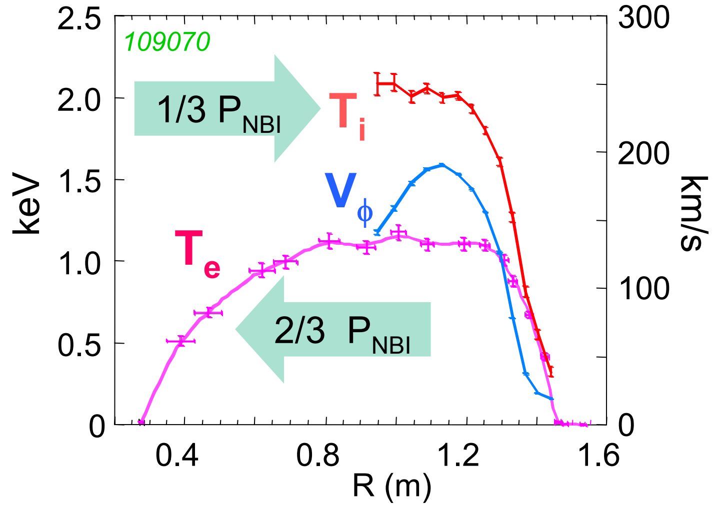
Plasmas with Beam Heating Show Favorable Energy Confinement Compared to Scaling Predictions

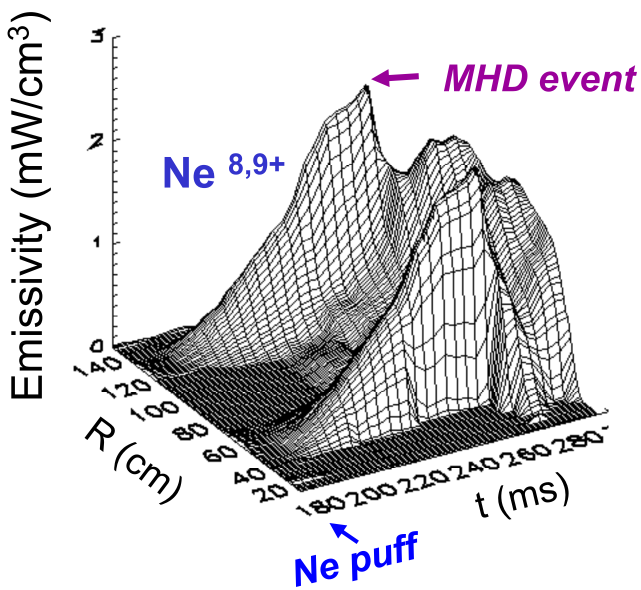
- True with (H-mode) or without (L-mode) edge confinement barriers
- Encouraging indications for future small fusion energy devices
- Important to understand why



Under Intense Neutral Beam Heating, Ion Energy and Particle Diffusivities are Very Low

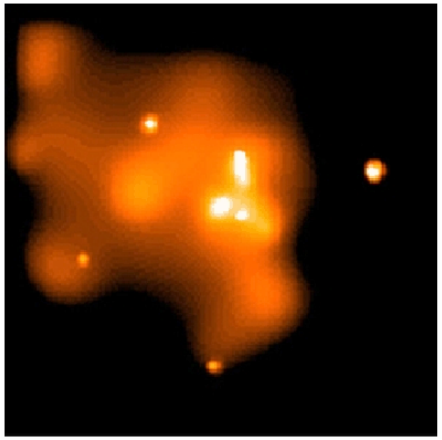
Core Transport Physics	NSTX Results
Thermal Conductivity	• $\chi_{ion} \sim \chi_{neoclassical}$ • $\chi_{elec} >> \chi_{ion}$
Impurity Diffusivity	• $D_{imp} \sim D_{neoclassical}$
Micro-instability turbulence theory	• Driven by T and n gradients • $k_\theta \rho_i < 1$ (ion gyro-scale) stable or suppressed by V_ϕ shear • $k_\theta \rho_i >> 1$ (electron gyro-scale) strongly unstable





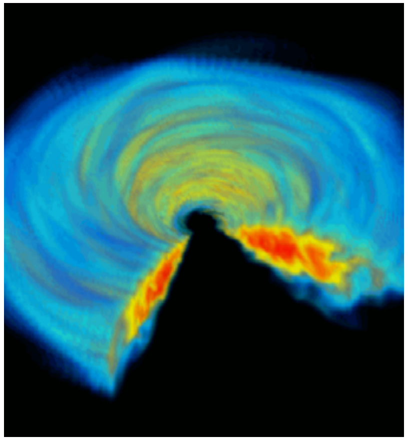
Laboratory High-β (~1) Turbulence Has Broad Scientific Relevance Including Astrophysics

Milky Way center
10^5 times "too dim?"



10 light years

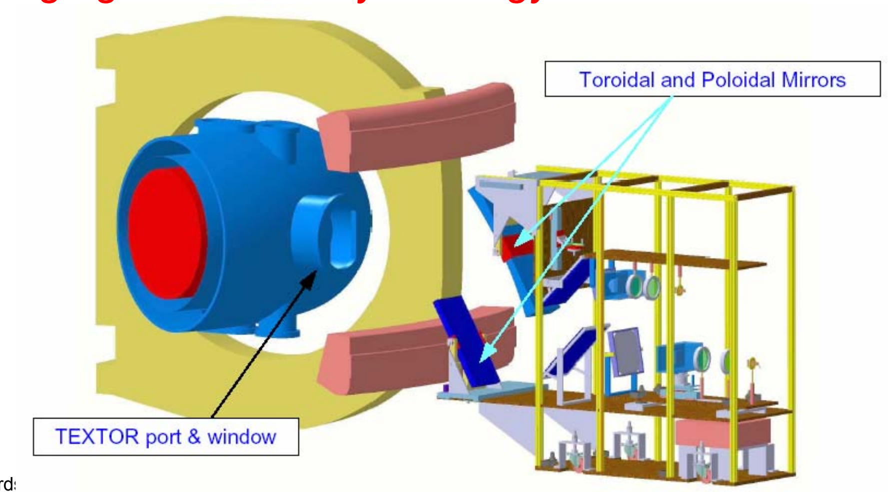
Accretion Disk Simulation ($\beta \geq 1$)



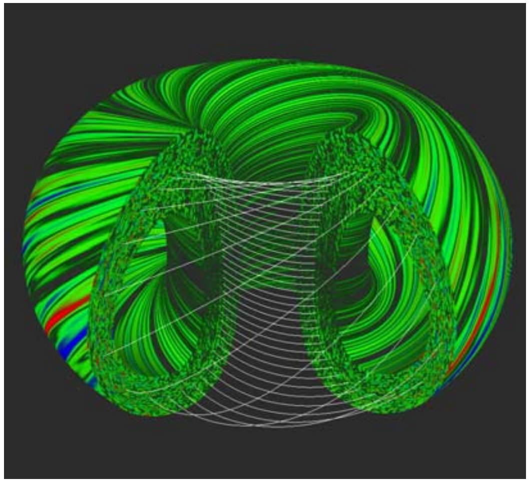
(Hawley, Balbus, Univ. Virginia)

- Accretion disk: cascading of MHD turbulence to ion gyro-scales could explain observations
- Fusion's gyrokinetic models appropriate for turbulence of high β astrophysical systems
- Astrophysicists interested in benchmarked codes

Imaging reflectometry of ion gyro-scale turbulence



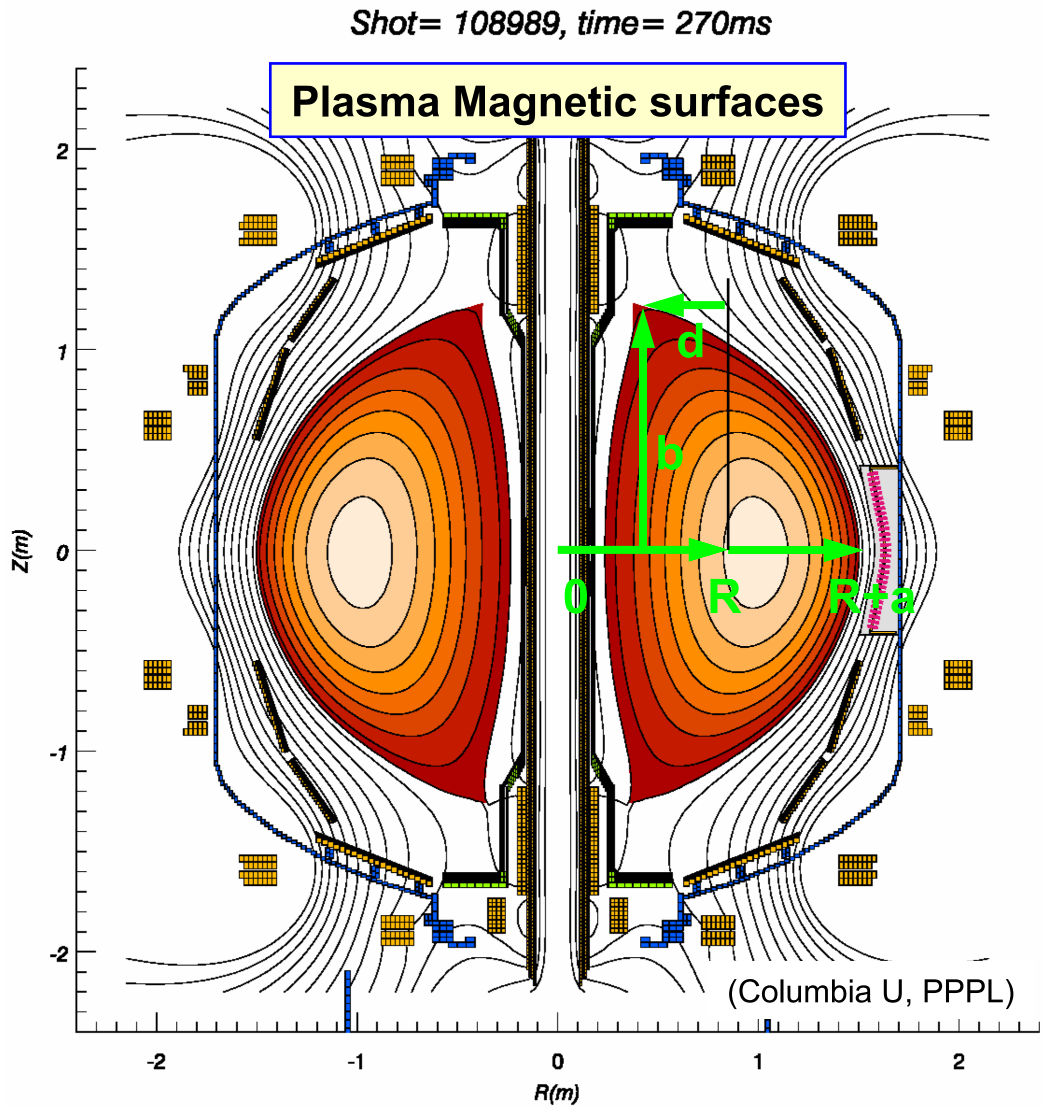
Toroidal Simulation



(GA, LLNL)

Strong Plasma Shaping Increases Stable β

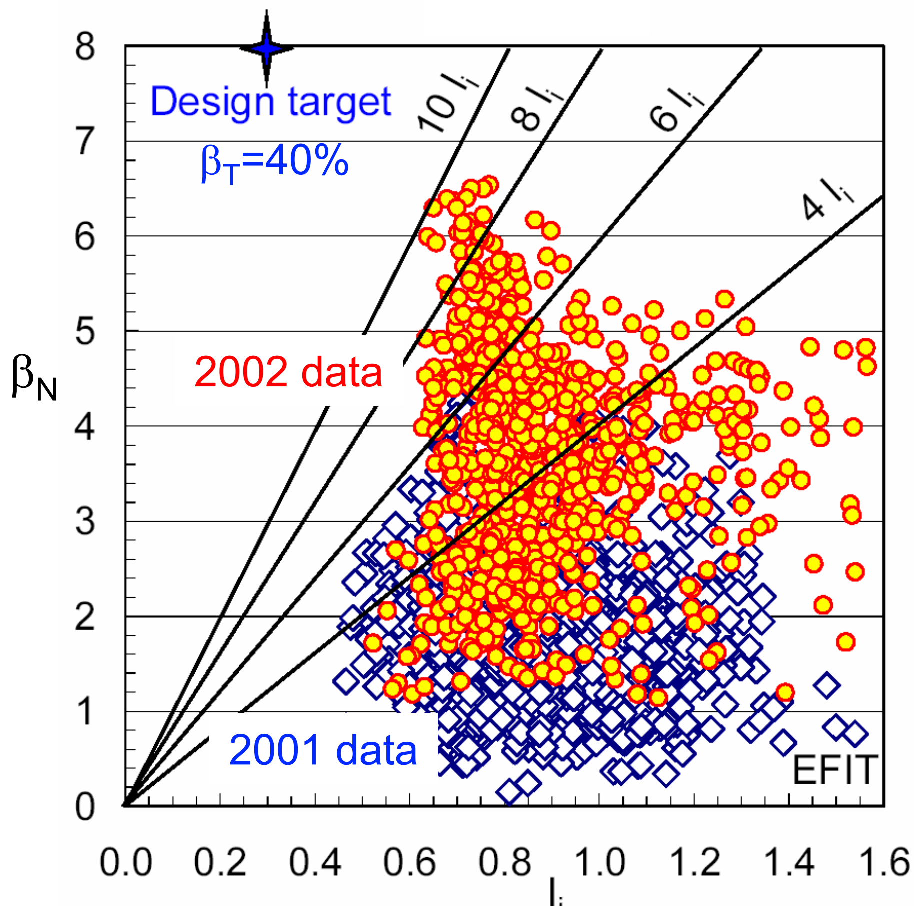
- **Strong shaping:**
  - Small $A = R/a \sim 1.4$
  - Large $\kappa = b/a \sim 2.0$
  - Large $\delta = d/a \sim 0.8$
- **Raises edge q** for fixed plasma current and toroidal field
- **Higher I_p/aB_{t0}**: utilization of size and applied field:
- **Increased stability** during fast I_p ramp up



High β_N (6.5) & β_T (35%) Attained With Low Internal Inductance ℓ_i, as Suggested by Theory

- Progress benefited from 10x reduction of field errors
- Positive effects of nearby conducting wall & plasma rotation on pressure driven MHD modes
- "Tearing," locked, and fast ion driven modes may also limit pressure
- In-vessel sensors and active mode control planned to test target
- Effects of shaping important

Rapid Progress toward high β_N & low ℓ_i



Evidence for Wall Stabilization Is Under Examination

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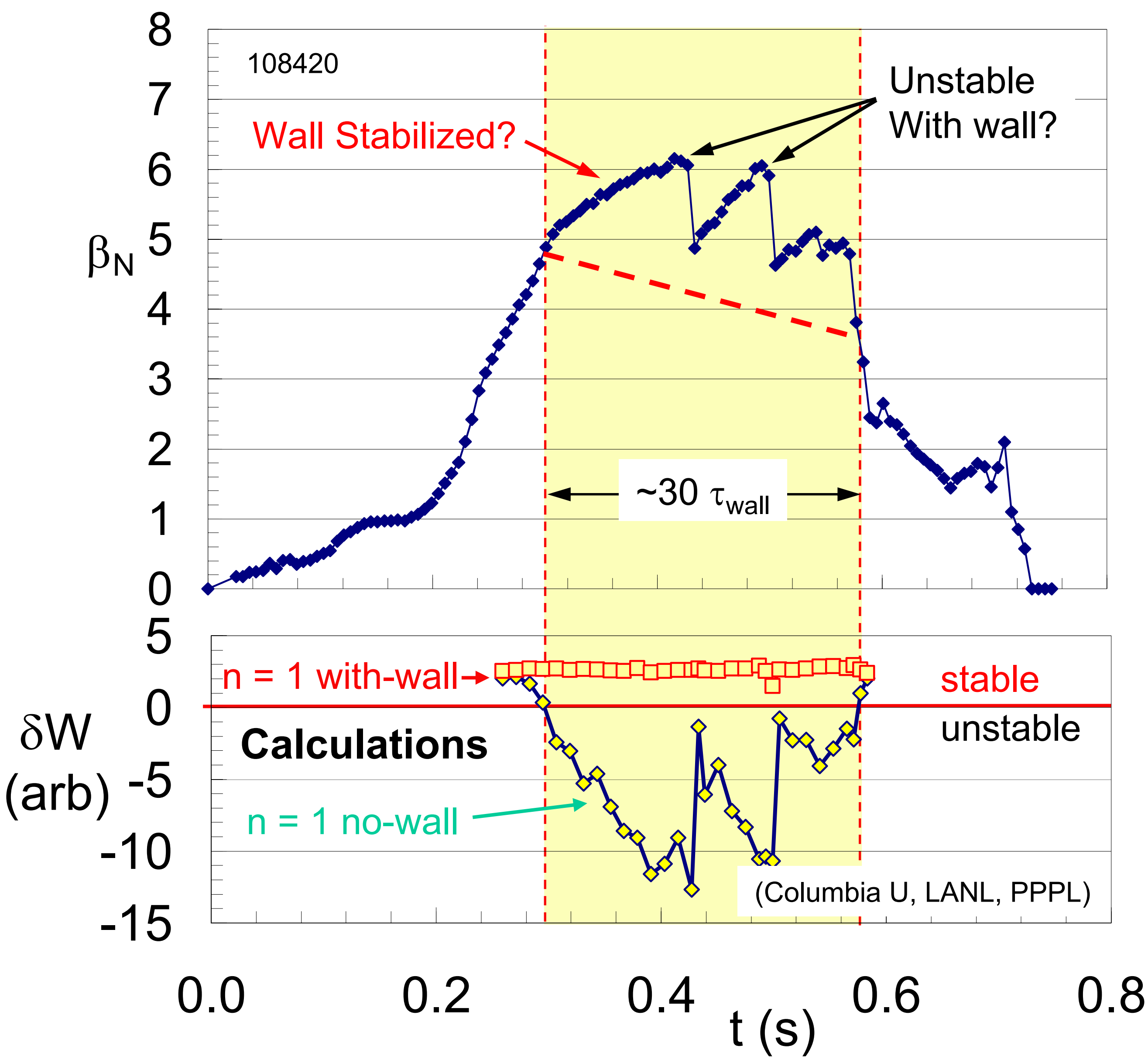


- Suggested by theory
- Strong experimental evidence from DIII-D tokamak (GA, U.S.)
- Ideal no-wall limit exceeded for many τ_{wall}
- Plasma rotation stabilizing
- Subject to mode, field error, & rotation control
- Active mode control
- Crucial to $\beta_T \rightarrow 40\%$

High Harmonic Fast Wave Utilizes High ε (~100) in ST for Efficient Heating and Current Drive

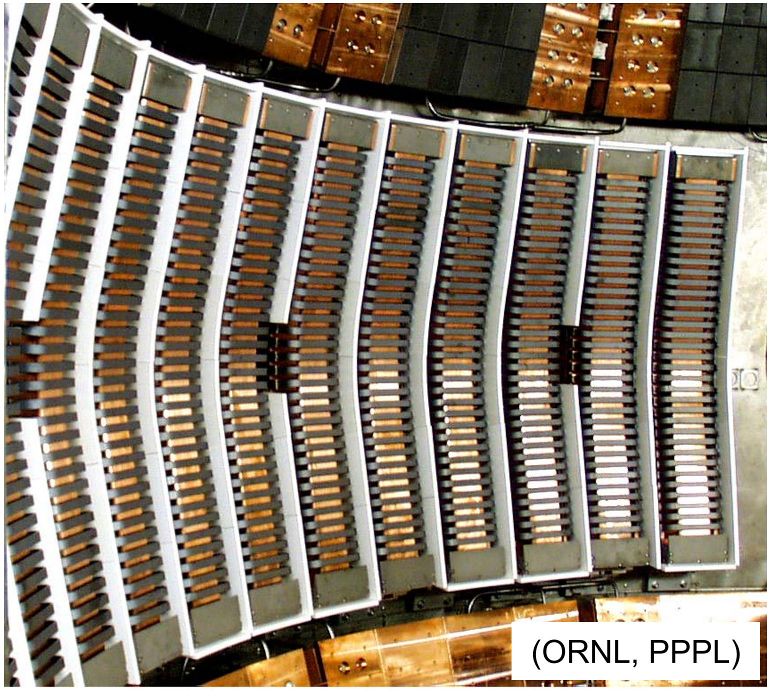
NSTX

M. Ono (1995): Fast wave decay (absorption) rate:

$$k_{\perp im} \sim n_e / B^3 \sim \varepsilon / B,$$

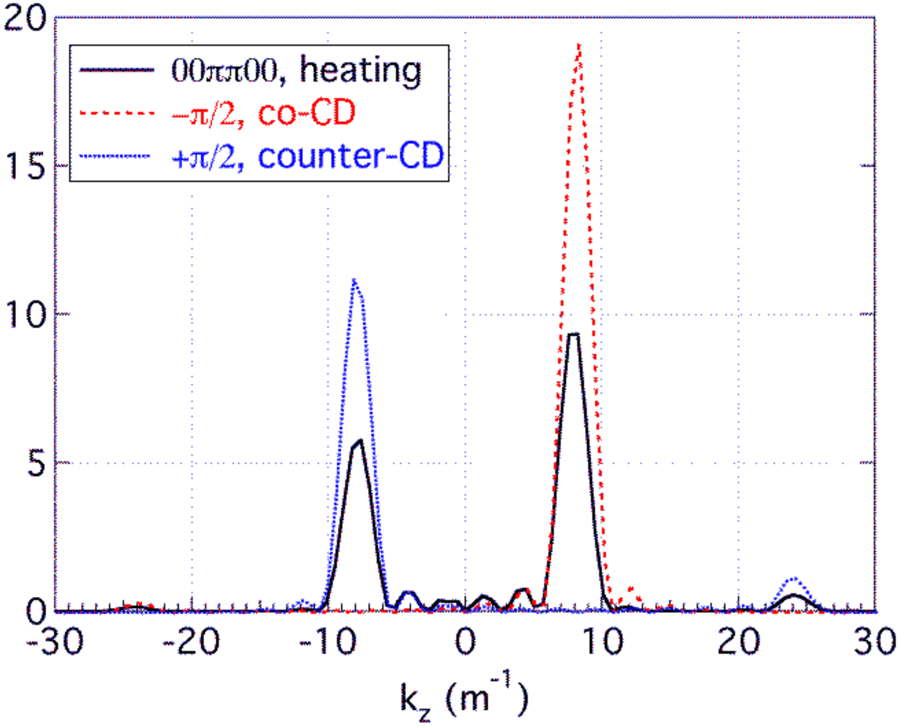
$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$

- 6 transmitters and phase controls
- Flexible spectrum

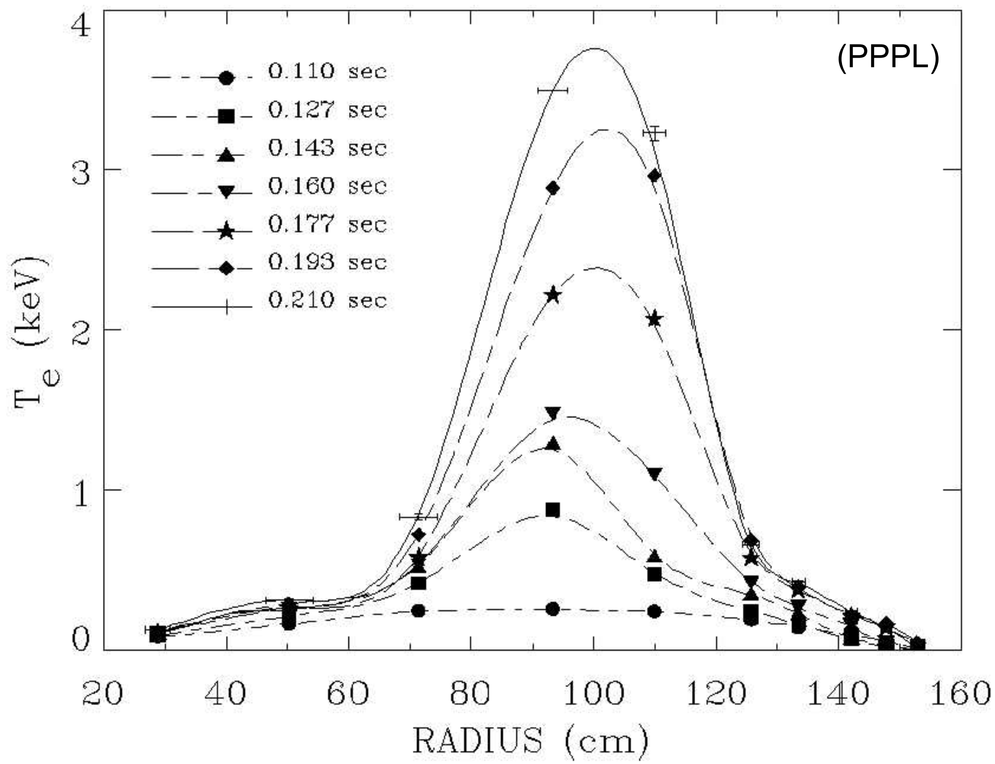


12 HHFW ANTENNA

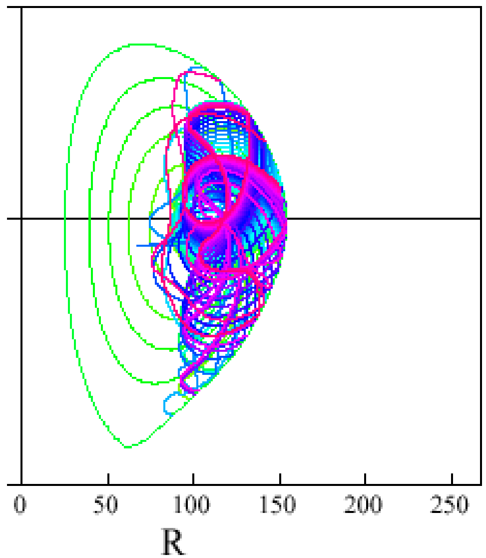
GLOSI/RANT3D calculations



HHFW (A Magnetosonic Wave at High Harmonics) Can Interact Strongly with Electrons



Laser Thomson Scattering



GENRAY Code

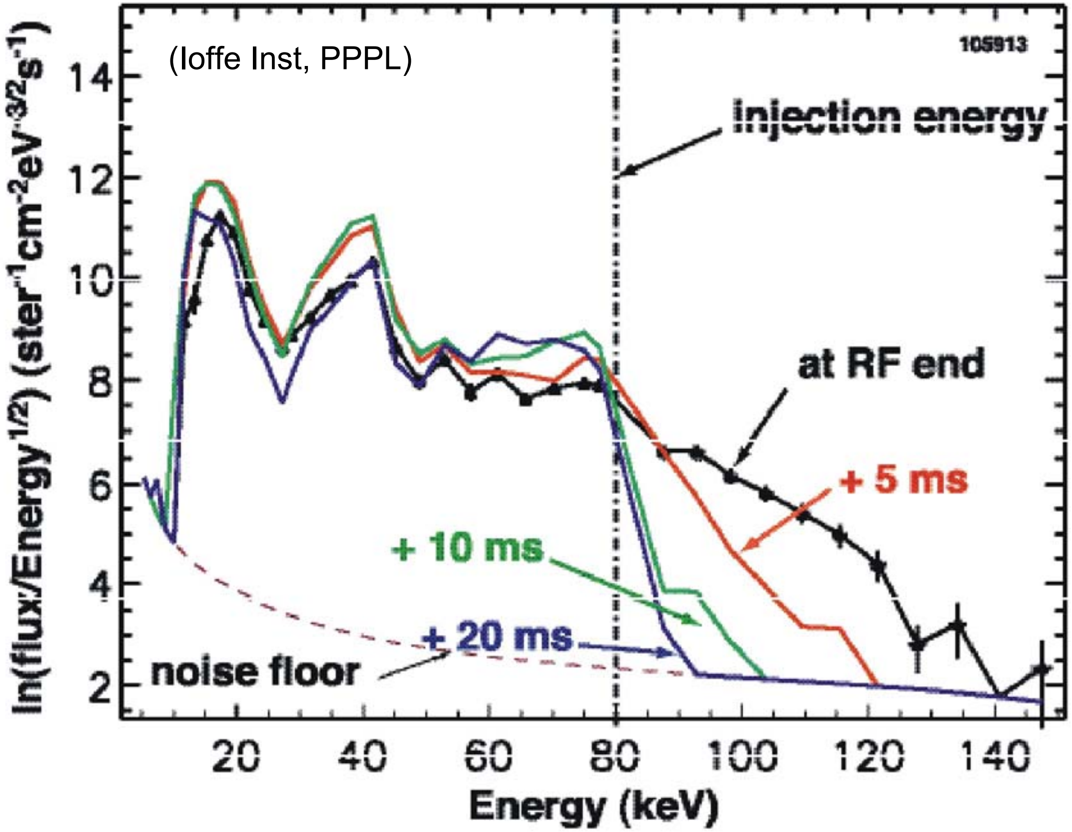
(CompX)

- Deuterium, 0.8 MA, 0.45 T, $n_e(0) \sim 2x10^{13}/cm^3$
- P_{HHFW} = 2.5 MW; $\mathbf{k}_{||}$ = 14 m^{-1} (heating phasing)

HHFW Also Interacts Readily with Supra-Alfvénic Neutral Beam Injected Ions

NSTX

- Data from Neutral Particle Analyzer
- P_{RF} = 3 MW
  P_{NBI} = 1.5 MW
  $T_e(0)$ = 1.0 - 0.4 keV
  $n_e(0) \approx 3 \times 10^{19} m^{-3}$
- Ions accelerated to higher multiples of $V_{Alfvén}$



New Bursting Modes Observed in the Toroidal Alfvén Eigenmode (TAE) Frequency Ranges

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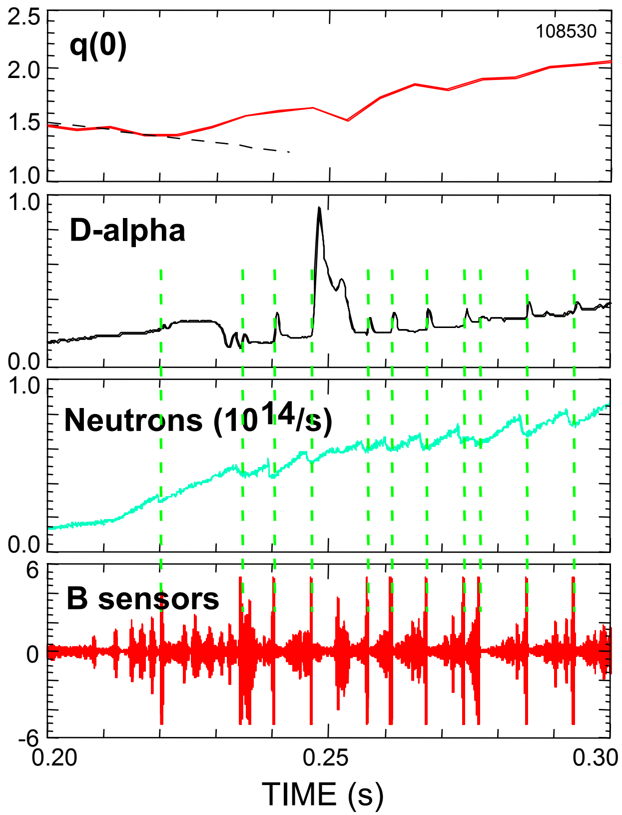
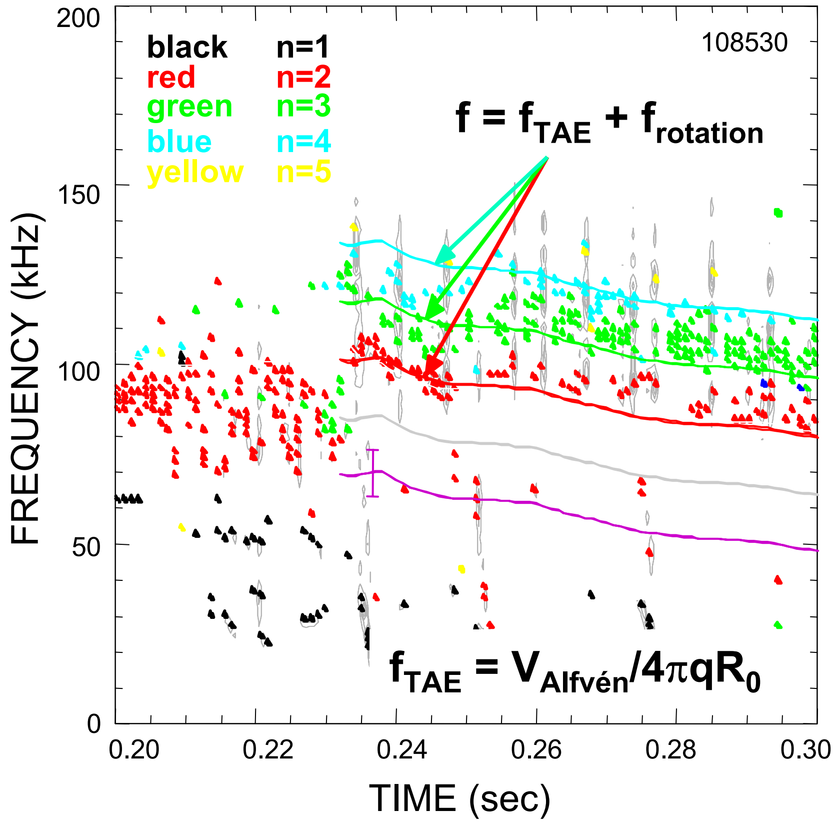
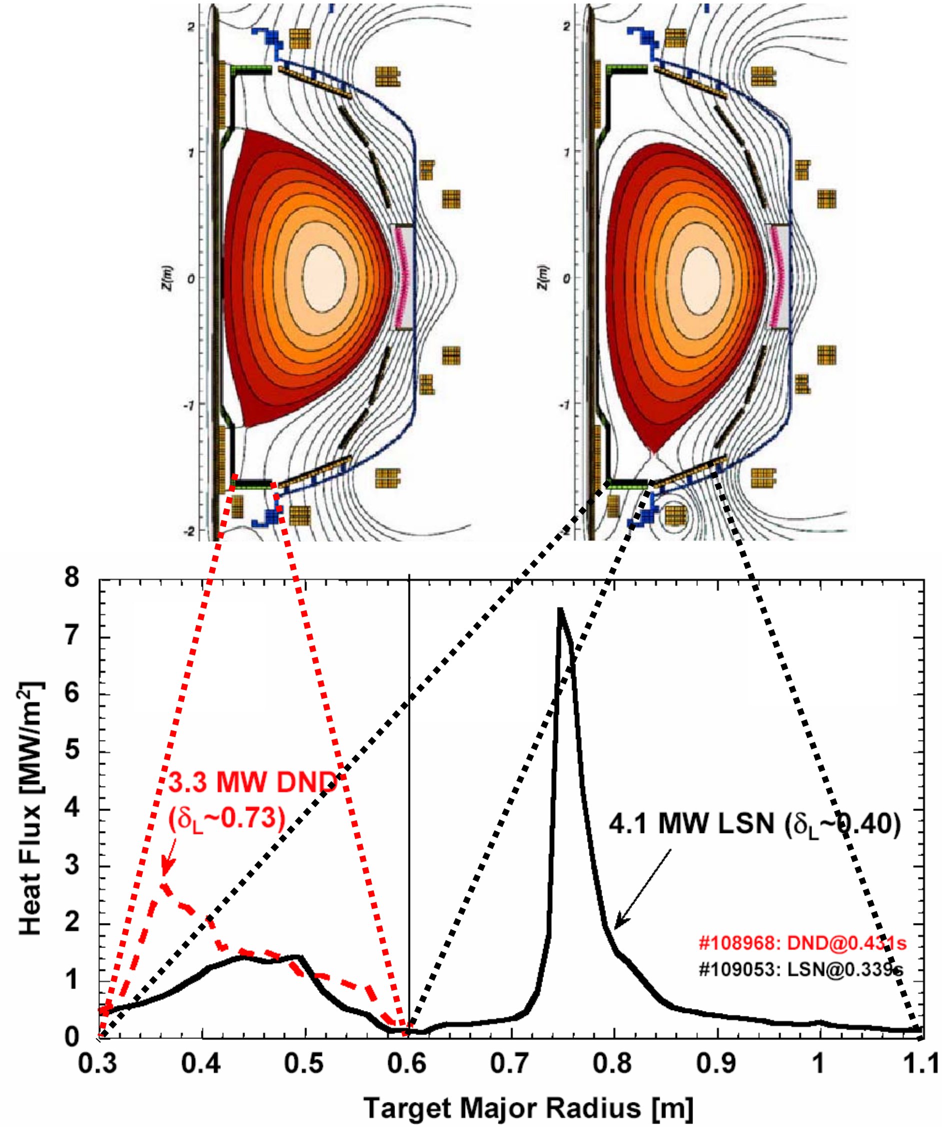
- Most evident in H-mode plasmas with q(0) > 1
- Multiple modes burst simultaneously, with concomitant effects
- Impact on fast ion confinement, D-D neutrons



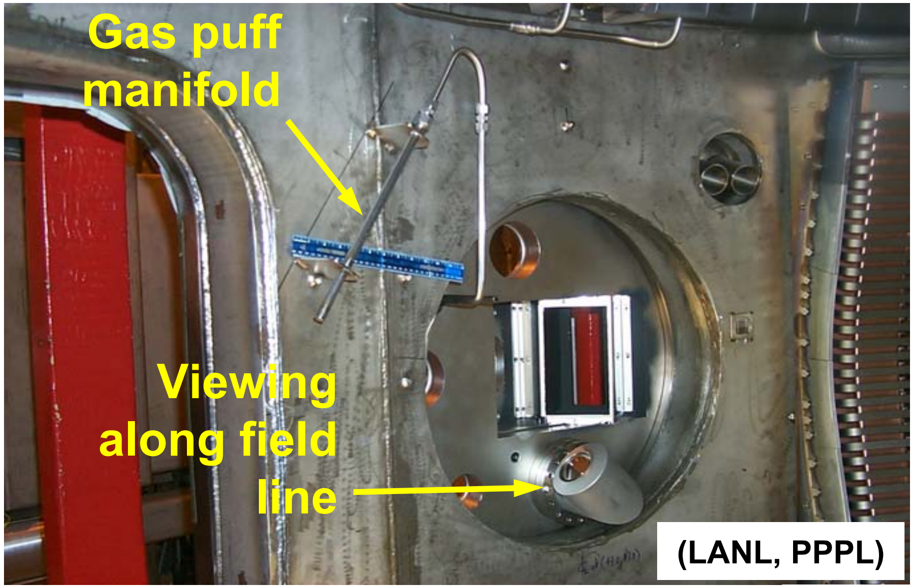


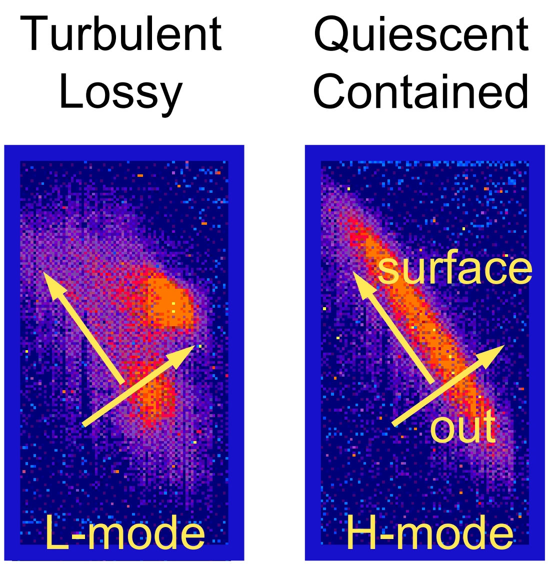
Very Low Aspect Ratio Enables Enhanced Spread of Divertor Heat Fluxes

- **Low A effects on SOL observed**
  - Large R_{out}/R_{div} increases flux-tube expansion
  - H-mode – quiescent SOL with intermittent bursts
  - L-mode – turbulent SOL
- **Important physics issues identified**
  - Scaling of SOL divertor flux
  - Bursts vs. Edge Localized Modes (ELM's)
  - Large magnetic mirror ratio → impacts SOL stability
  - H-mode for inboard-limited ST plasmas (MAST)

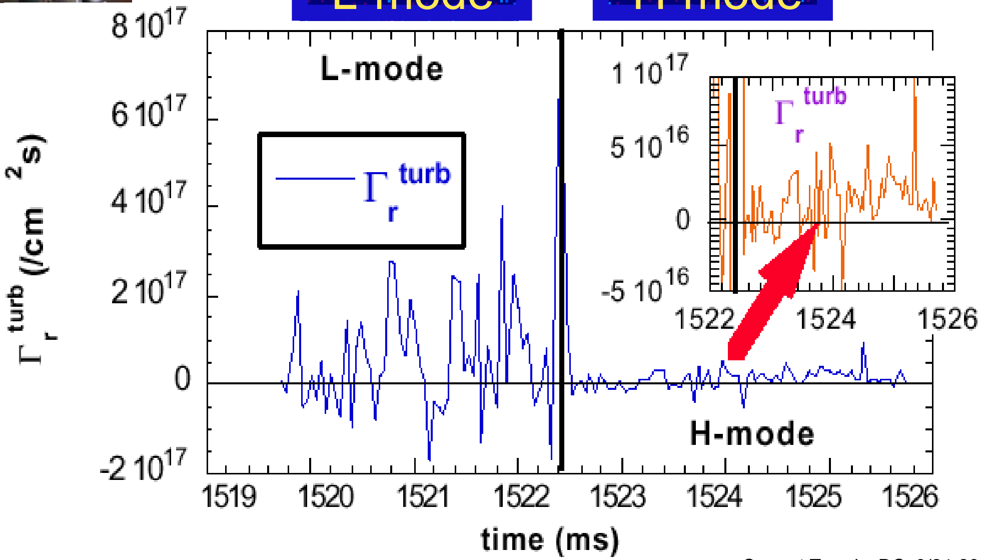


Emission from Gas Puff Imaging Reveals Ejected "Filaments" Leading to Large Edge Plasma Loss

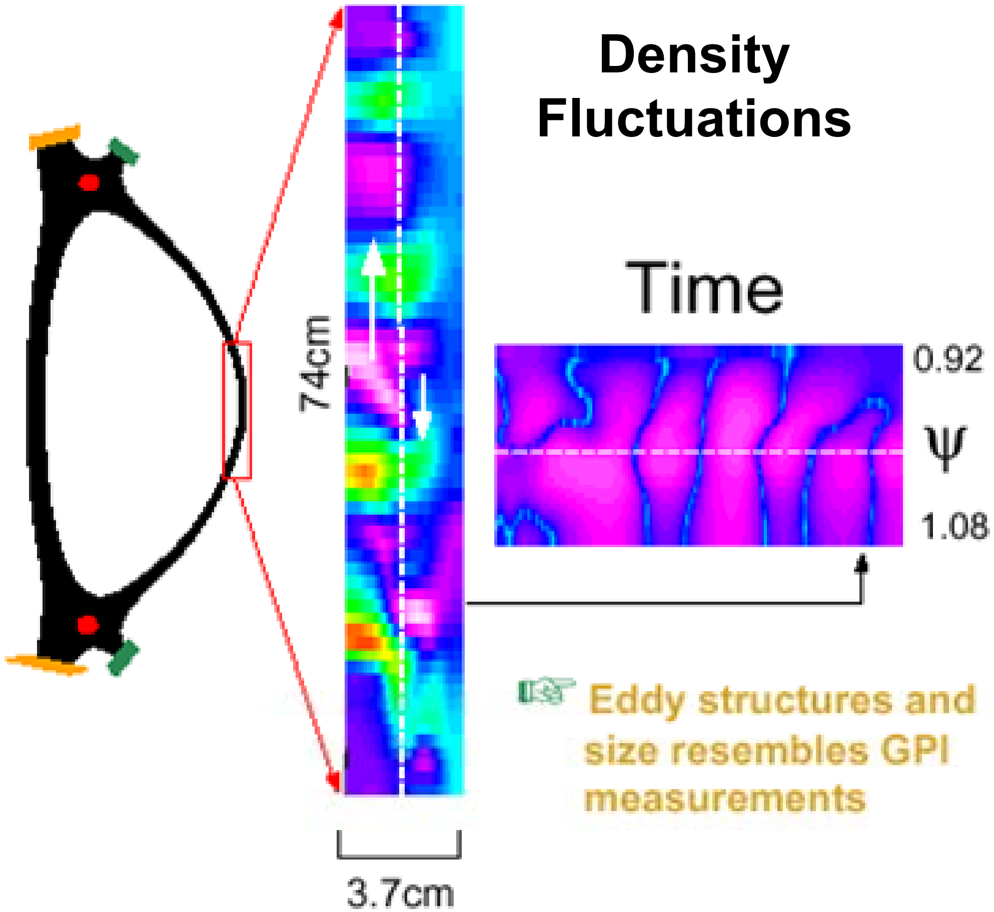




- Also in C-Mod Tokamak (MIT)
- He puff in D_2 discharge
- 10 μs exposures @ 100 kHz
- Several cm in cross section
- Moves at a few hundred m/s
- Coincidental with "Low-Mode"
- Absent or rare in "High-Mode"



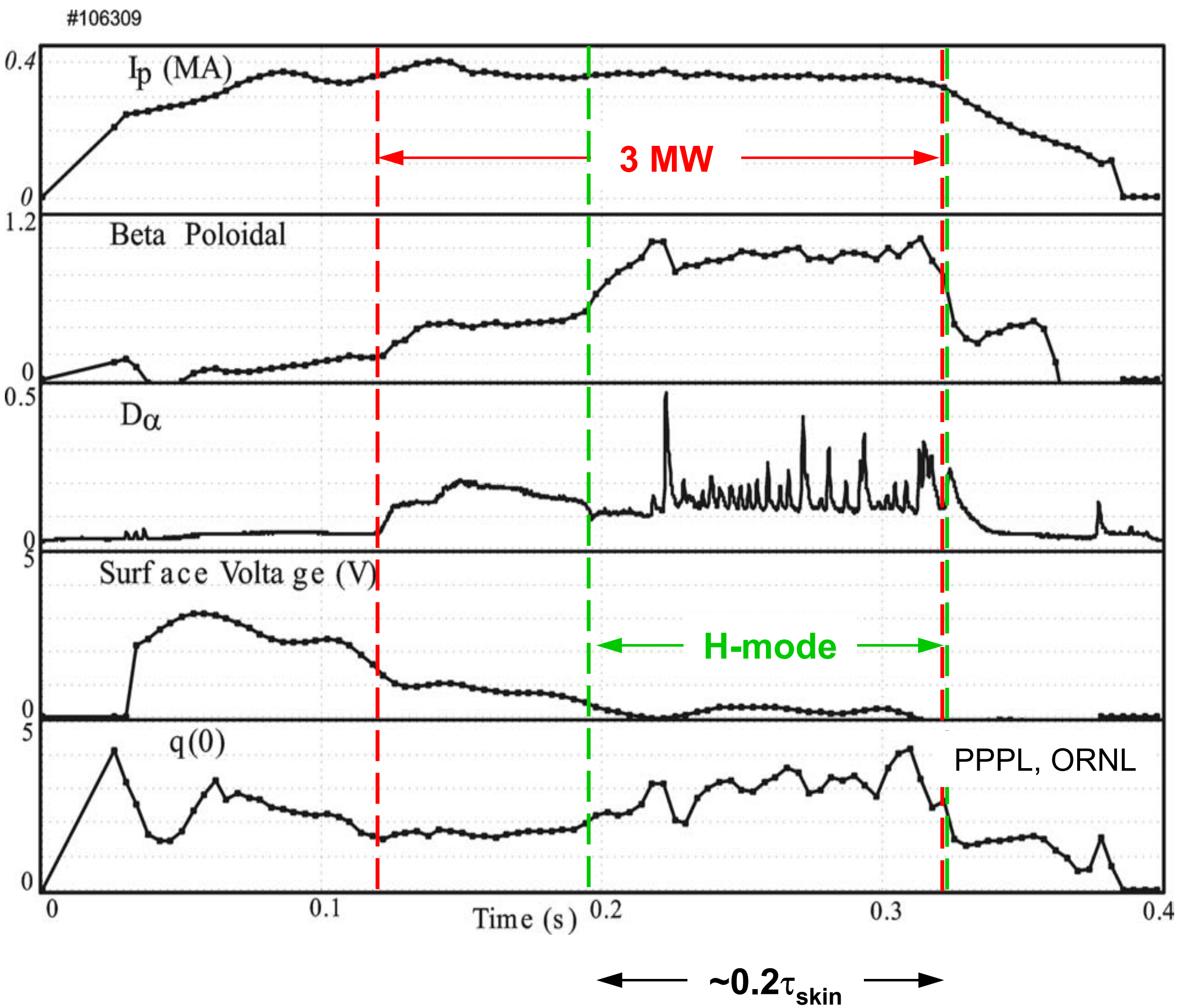
Simulations Confirms Theory: Sheared Flow Reduces Fluctuations & Improves Edge Confinement



BOUT Fluid Simulation code (LLNL)

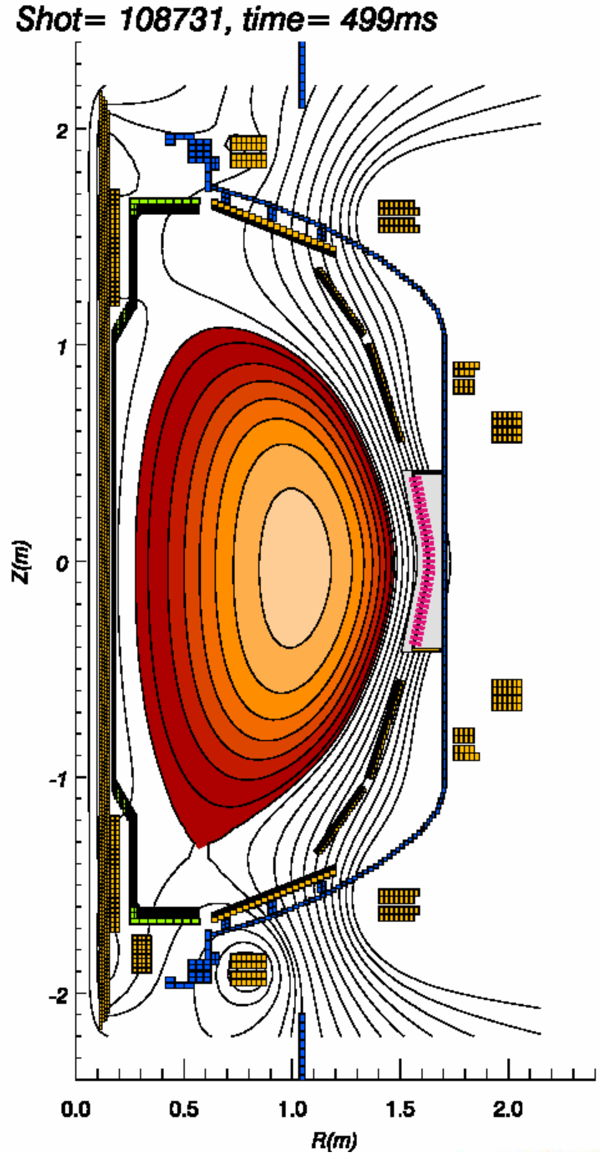
- EFIT equilibrium for 104312, at 250 ms.
- Edge: $T_i = T_e = 26$ eV, $n_i = 2.3\times10^{18}$ m^{-3}
- ψ=0.9: $T_i = T_e = 51$ eV, $n_i = 4.4\times10^{18}$ m^{-3}
- Driven by edge pressure gradient in bad field line curvature, but reduced by sheared flow
- Kinetic and boundary effects important
- **Impacts plasma flux dispersion**

First Indications of HHFW-Heated Plasmas with Reduced Inductive Requirements

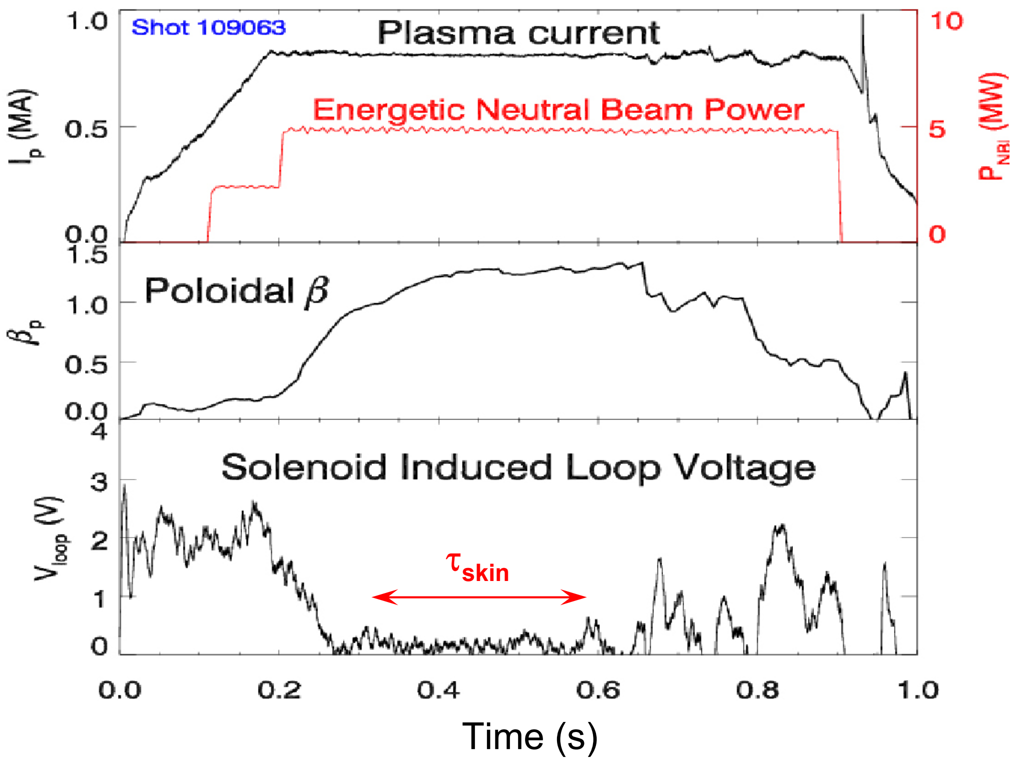


- **Moderate plasma current**
- **High β_p ~ 1**
- **H-mode with Edge-Localized Modes**
- **Induction voltage reduced to <0.5 V**
- **Low internal inductance l_i ~ 0.9**

Stronger Indications of NBI-Heated High-β_p Plasma Nearly Sustained without Induction

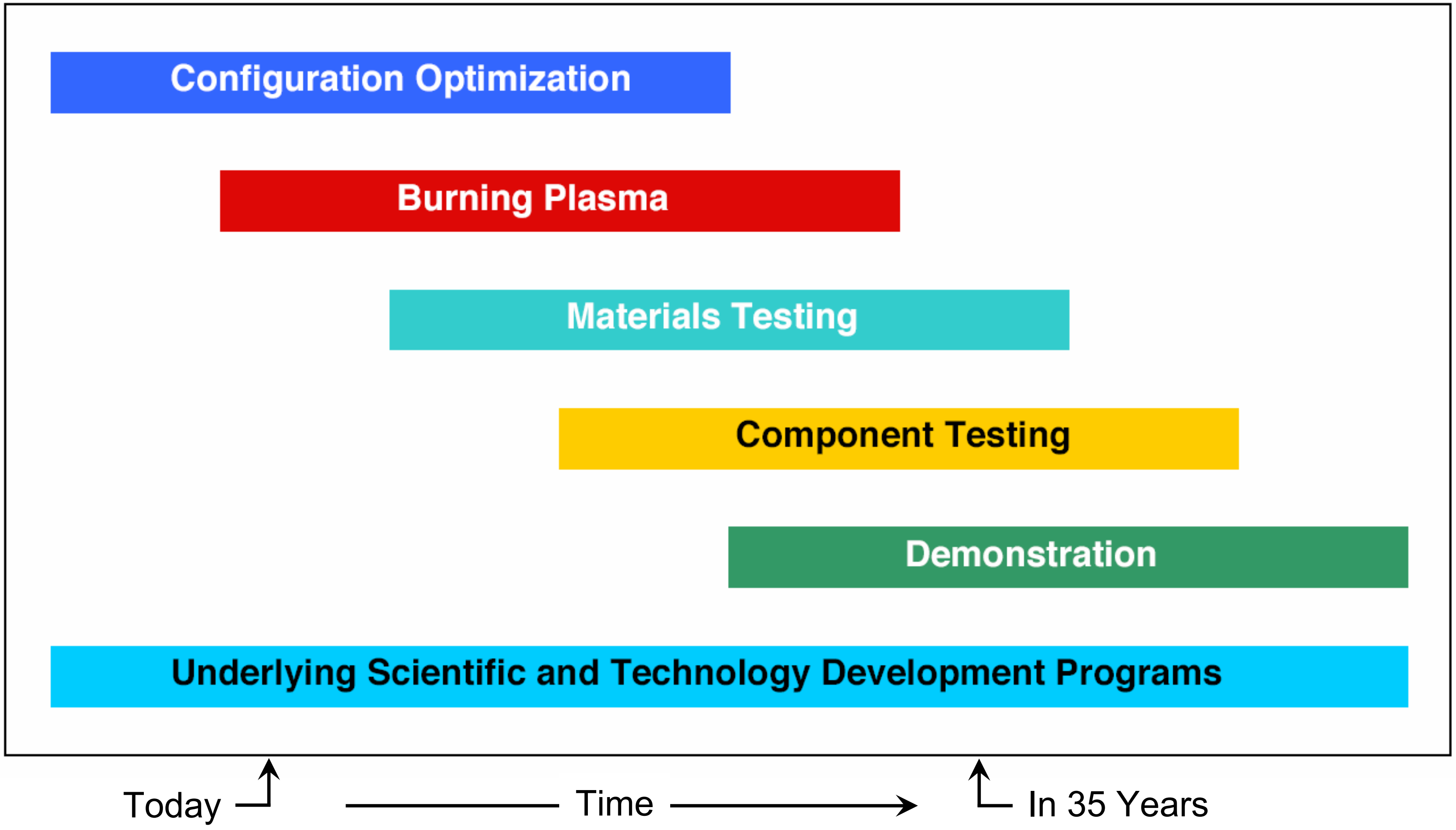


- Edge turbulence largely quieted – H-mode
- β_p ($\propto$ pressure/I_p^2) ~ 1.2 $\Rightarrow$ high bootstrap current fraction (~0.5)
- Neutral beam also drives substantial current
- Inductive voltage reduced ~10-fold for > 0.4s

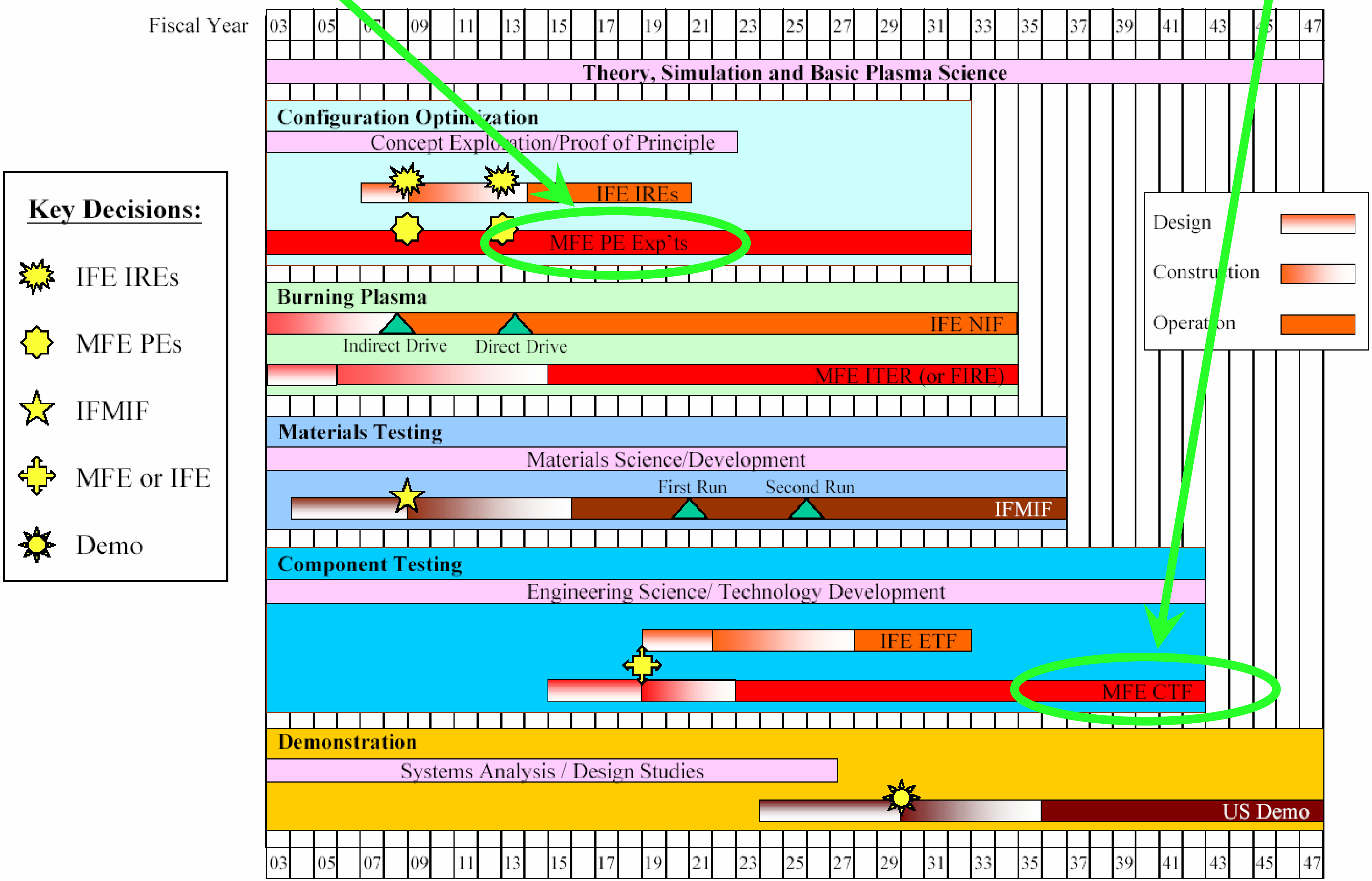


FESAC Panel Recently Articulates Key Components Needed for Developing Net Fusion Electricity in 35 Years

("A Plan for the Development of Fusion Energy," final report to FESAC, March 5, 2003)



Spherical Torus Is Strong Candidate for MFE Performance Extension (PE) Experiment and Component Test Facility (CTF)



Simulations of J_{NI} = 100% Plasmas Identify Scenarios and Motivate Important NSTX Research Topics

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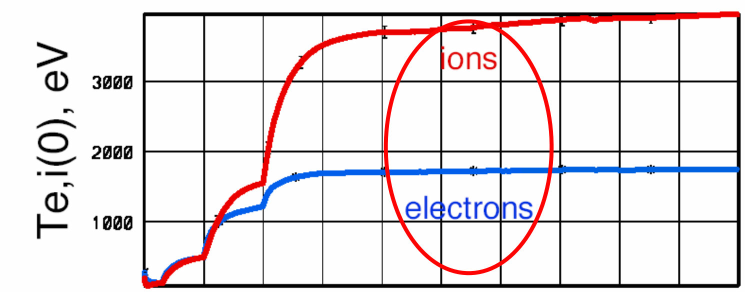
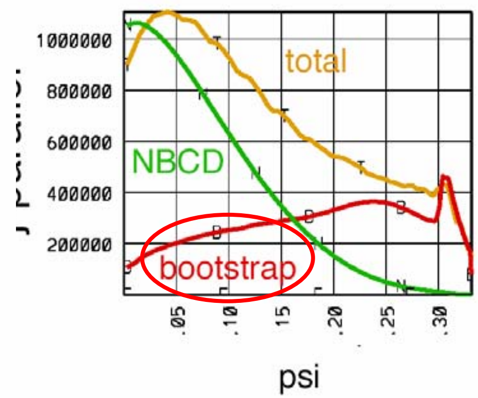
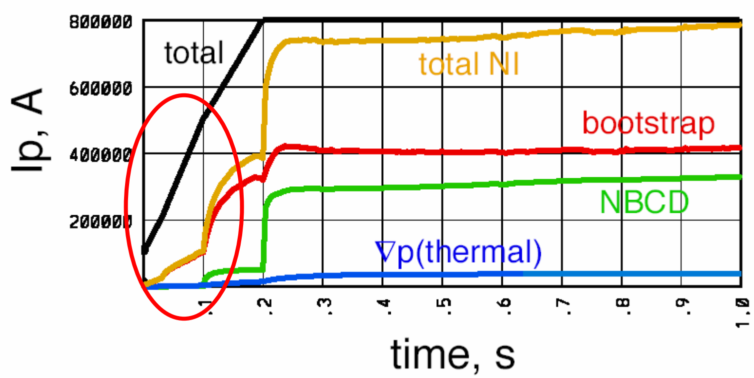
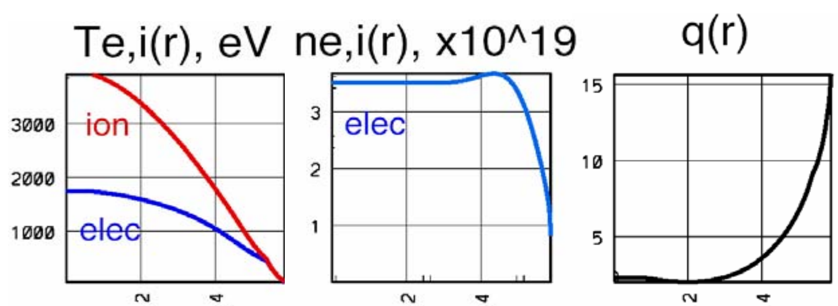
Identified Scenarios to Achieve Long Pulse Sustainment





Assume #109070 plus χ_e, $\chi_i \propto P^{-0.5}$:
κ = 2.6, $H_{98(y,2)}$ = 1.1,
β_N = 7.0, β_T = 20%,
Stable to n = 1 & ∞

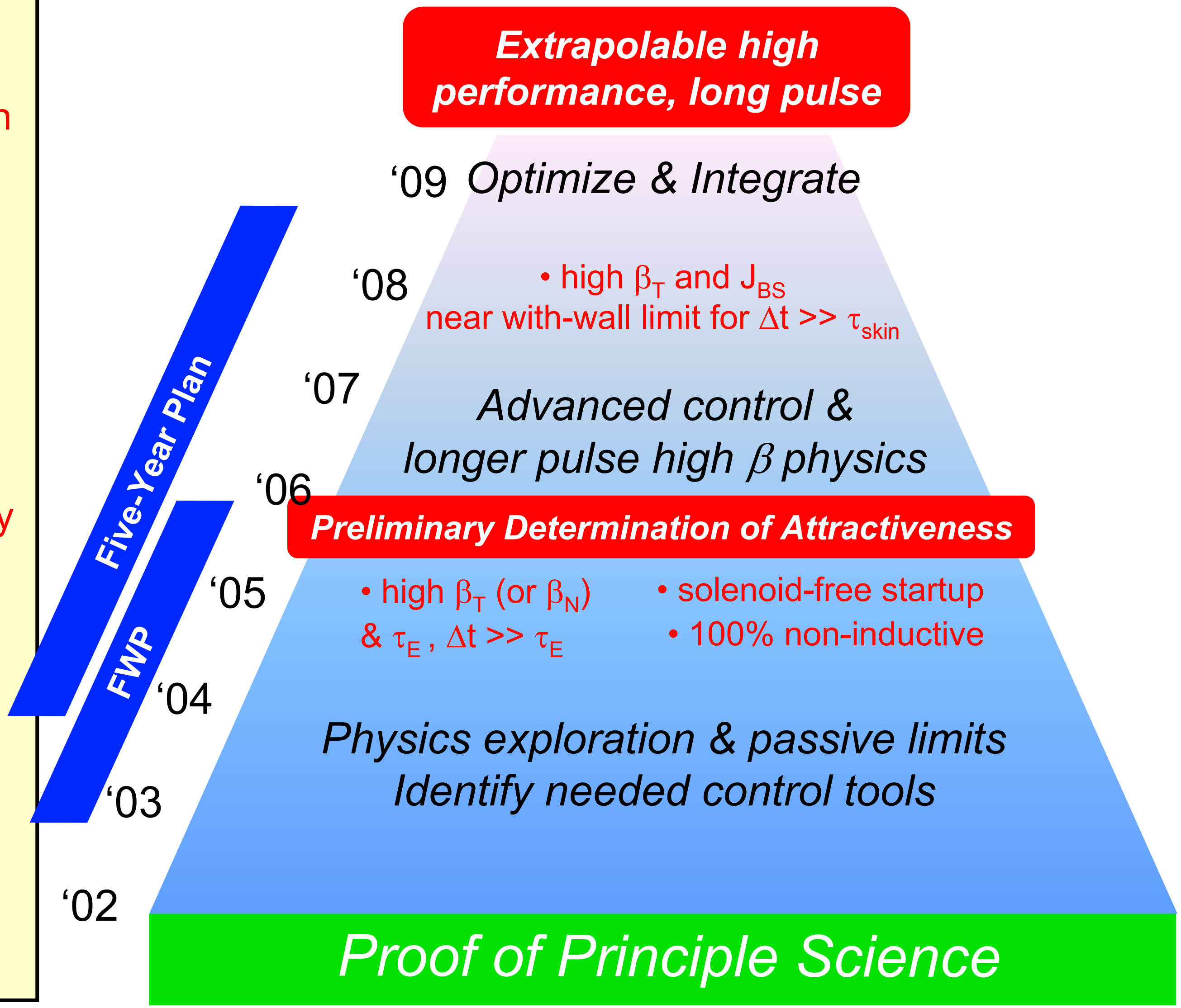




- **ST research topics**
  - Bootstrap J at low A
  - HHFW heating in presence of NBI
  - Scaling of χ_e, χ_i with $T_i >> T_e$
  - Effects of large V_ϕ and V_ϕ shear on stability & transport
- **Scenario elements**
  - CHI or EBW I_p initiation
  - Non-inductive I_p ramp-up
  - Active particle control
- **Relevance: CTF plasmas**

Research Planned for FY03-05 Aims to Achieve the Initial Goals of the NSTX 5-Year Plan

- **5-year plan (FY04-08)**
  - Establish physics basis for optimization and integration of extrapolable high performance & long pulse
  - Database for next step (NSST)
- **FY03-05 plan**
  - Complete preliminary determination of ST attractiveness
- **Both**
  - Advance control tools
  - Implement key measurements
  - Carry out supporting analyses

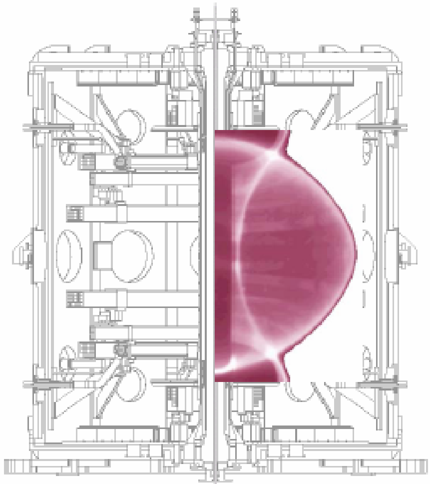


ST Physics Mission in Fusion Energy Science Has Led to Broadened Collaborations

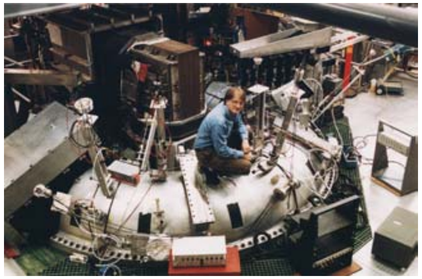
NSTX

- **Merging database with MAST, U.K.**
  - NBI H-mode, transport, τ_E
  - EBW H&CD (1 MW, 60 GHz), FY03
  - Divertor heat flux studies, FY03-04
  - NTM, ELM characterization
- **Exploratory ST's in Japan**
  - **TST-2**: ECW-EBW initiation
  - **TS-3,4**: FRC-like β~1 ST plasmas
  - **HIST**: helicity injection physics
  - **LATE**: solenoid-free physics
- **MST:** electromagnetic turbulence, EBW
- **Began participation in ITPA (ITER)**
  - A and β effects: H-mode, ITB, ELM's & pedestal, SOL, RWM, and NTM
- **DIII-D & C-Mod collaboration**
  - Joint experiments on RWM, Fast ion MHD, pedestal, core confinement, edge turbulence

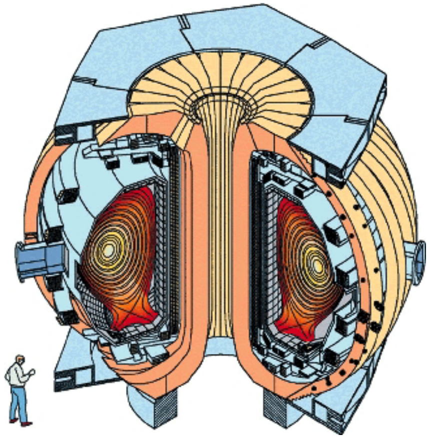
MAST (U.K.)



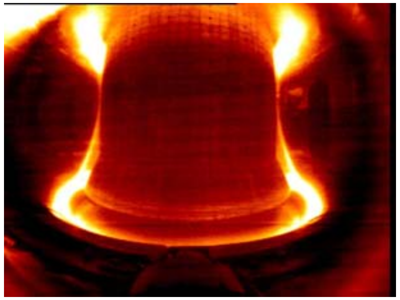
MST (U.S.)



DIII-D (U.S.)



C-Mod (U.S.)



Substantial Progress Is Made Towards Physics Database Needed for Cost-Effective Next-Step STs

NSTX

- Mission expands toroidal science basis for cost-effective fusion energy
- Identified physics metric for PoP, PE, and CTF
- Made rapid progress towards physics basis
- FESAC recommends strong ST roles in achieving net electrical output in 35 years
- Establish in 5 years physics basis for next step