NSTX

National Spherical Torus Experiment (NSTX)

NSTX Mission, Design & Results

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Outline

- Mission of NSTX
- Engineering Overview
- Research Plan
- Accomplishments

NSTX Mission

- NSTX is an alternate concept *Proof of Principle* experiment whose mission is to demonstrate the ***Physics*** and ***Technology*** of the *Spherical Torus* (ST) plasma

USDOE Fusion Roadmap

Concept Exploration
↓
Proof of Principle
↓
Proof of Performance
↓
Energy Technology
↓
DEMO

Physics Mission: Demonstrate ST Plasma

- Efficient magnetic confinement
  - High beta (e.g. $\beta_T = 2\mu_0 \langle p \rangle / B_0^2 \approx 25 - 40\%$)
  - Reduced toroidal field requirement for confinement
- Natural elongation
  - Reduced poloidal field requirement for shape control
  - Flux expansion in divertor regions, reduced power density on walls
- Enhanced MHD stability
  - Reduced turbulence, improved confinement and transport
- High pressure driven (bootstrap) current $f_{BS} \approx 50 - 90\%$
  - Offsets the fact that an ST reactor cannot rely on inductive current drive using a central solenoid
- Reduced disruption severity

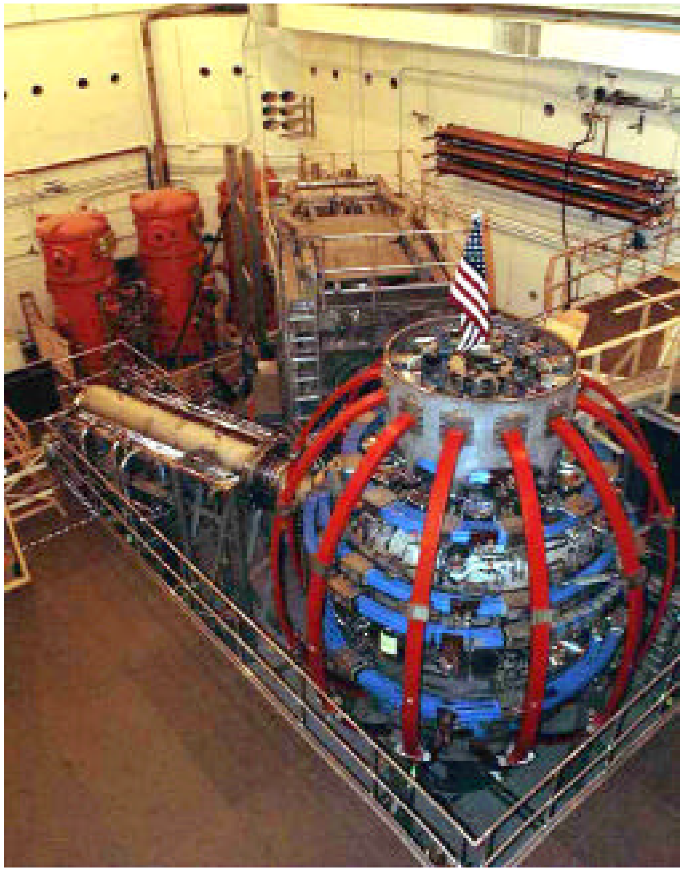
Technology Mission

- Demonstrate Non-Inductive Heating & Current Drive
  - High Harmonic Fast Wave (HHFW) Heating & Current Drive
  - Coaxial Helicity Injection (CHI)
- Construct an ST machine
  - Low aspect ratio, high performance Center Stack
  - Special provision for CHI

Strategy

- Begin with thin, low aspect ratio OH Solenoid
  - Initial experimentation using double swing inductive drive ($T \leq 0.5s$)
  - Single swing plasma with sustainment using HHFW & CHI (T->5 sec)

NSTX Facility and Engineering



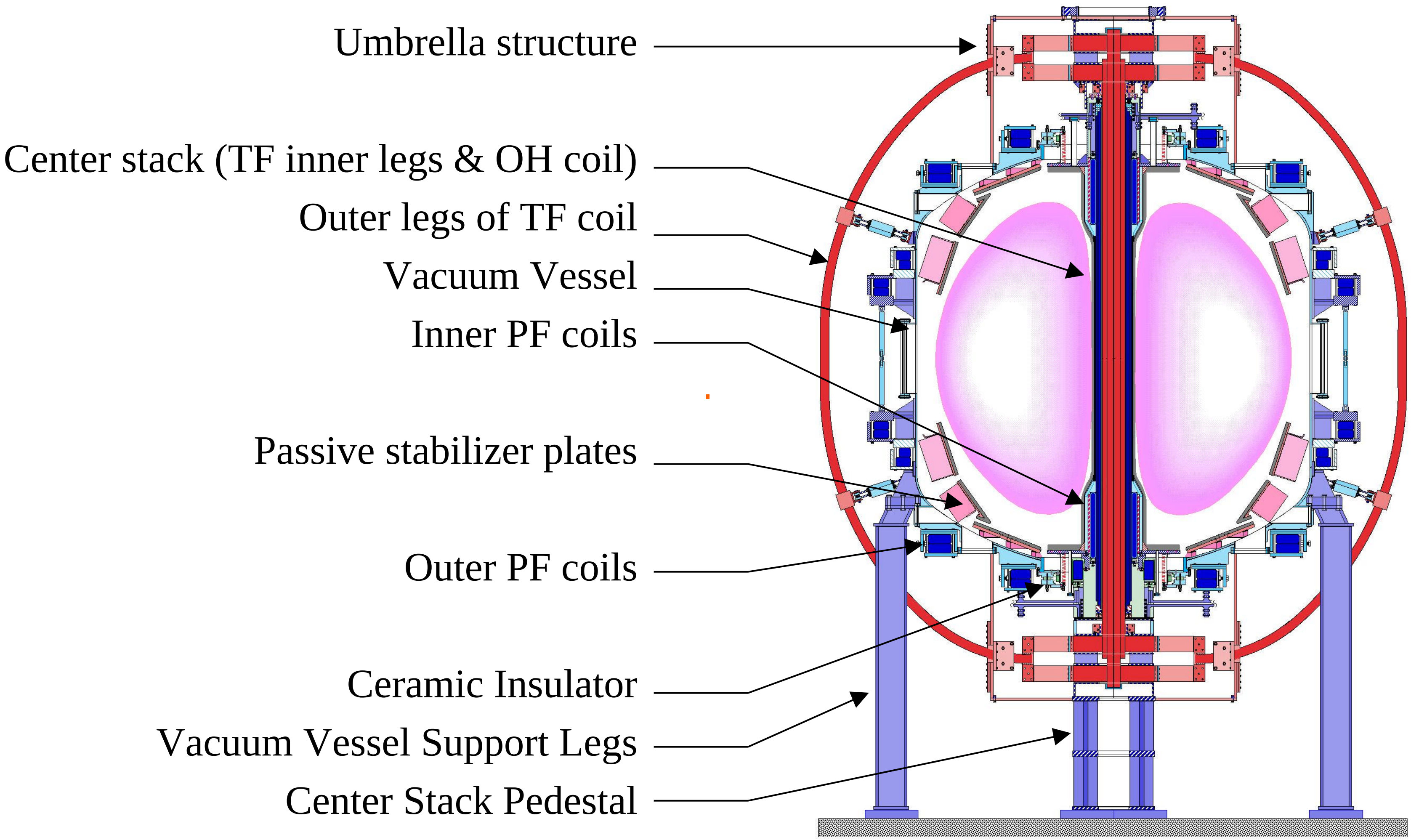
NSTX at 1st Plasma

- Located in the Hot Cell adjacent to the TFTR Test Cell, making extensive use of existing facilities:
  - AC power
  - Magnet power supplies
  - RF systems
  - NBI systems
  - Water systems
  - Buildings and HVAC systems
  - Many components from TFTR
- 1st Plasma in February 1999
- Total Project Cost $23.6M
- Site Credits ≈ $77M

NSTX Ratings and Parameters

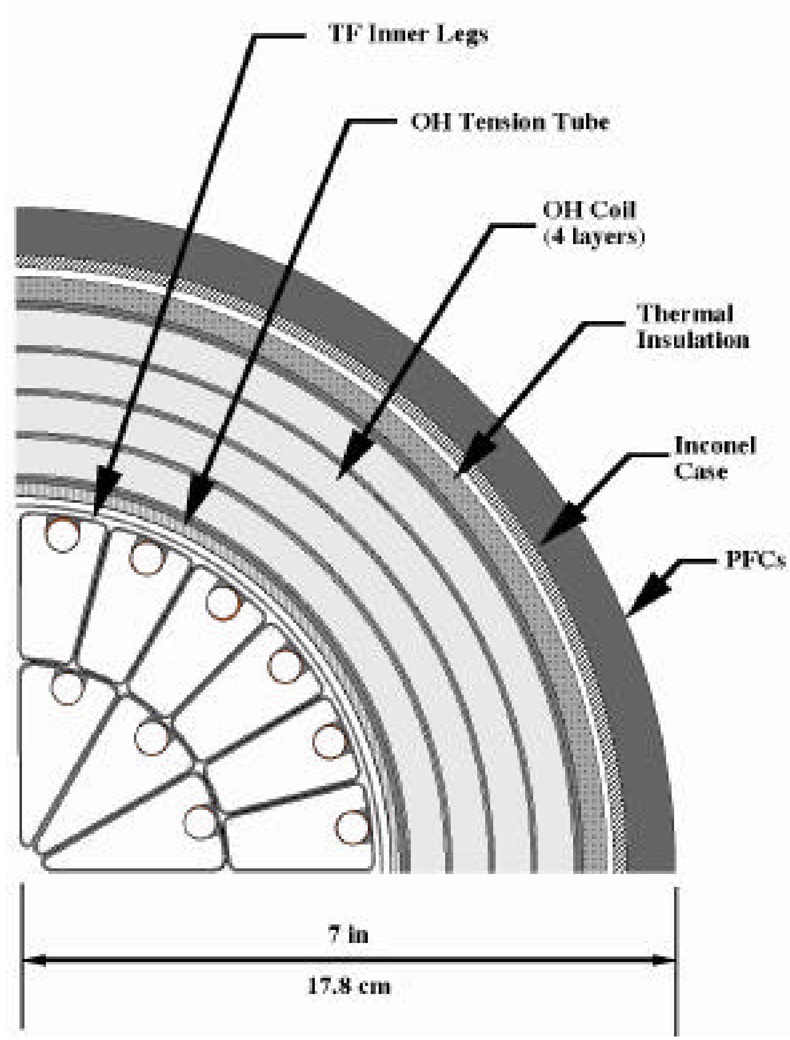
Plasma	Major Radius (R_0)	85.4 cm
	Aspect Ratio (R/a)	1.26
	Volume	$12m^3$
	Elongation	$1.6 \leq \kappa \leq 2.2$
	Triangularity	$0.2 \leq \delta \leq 0.5$
	Current	1.0 MA (1.5MA)
	Ramp Time	0.2 - 0.4 sec
	Flat Top (Inductive)	0.5 sec per 600 sec
	Flat Top (non-Inductive)	5.0 sec per 300 sec
Toroidal Field	Field @ R_0	3.0/6.0 kG
Ohmic Heating	Flux (double swing)	0.9 volt-sec
	Initiation Loop Voltage @ R_0	5.0 volt/turn
Heating/ Current Drive	High Harmonic Fast Wave (HHFW) RF	6.0 MW, 30MHz, 5 sec
	Coaxial Helicity Injection (CHI)	500kA via 50kA injection @ 1kV
	Neutral Beam Injection Upgrade (NBI)	5.0 MW, 80kV, 5 sec
Pre-Ionization	Electron Cyclotron	30kW, 18GHz, 0.1 sec
Bakeout	Bakeout Temperature	350°C PFCs, 150°C VV

NSTX Machine Cross Section

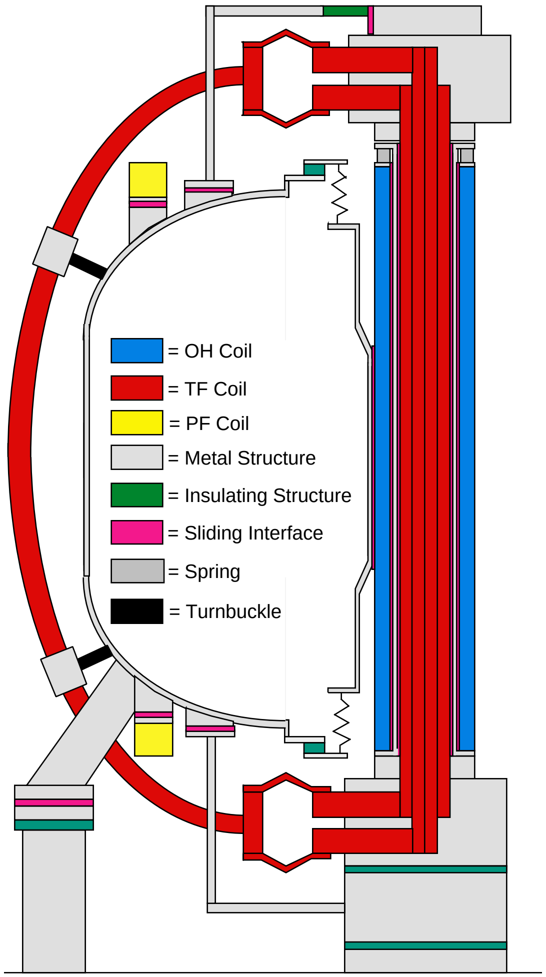


Center Stack Arrangement

- Compact nested TF Inner Legs
  - efficient use of space
  - ease of manufacture
- OH Tension cylinder
  - launching load reaction
  - ease of manufacture
- Four layer, 2-in-hand OH
  - high performance solenoid
  - rapid cool down time
- OH-CS Casing gap
  - ΔR ≈ 10mm, 0.4” for thermal insulation, diagnostics & installation clearance
  - Microtherm insulation ΔT ≈ 500C



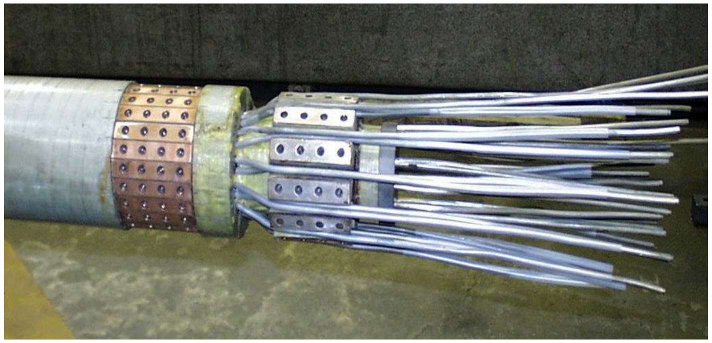
Mechanical Support Scheme

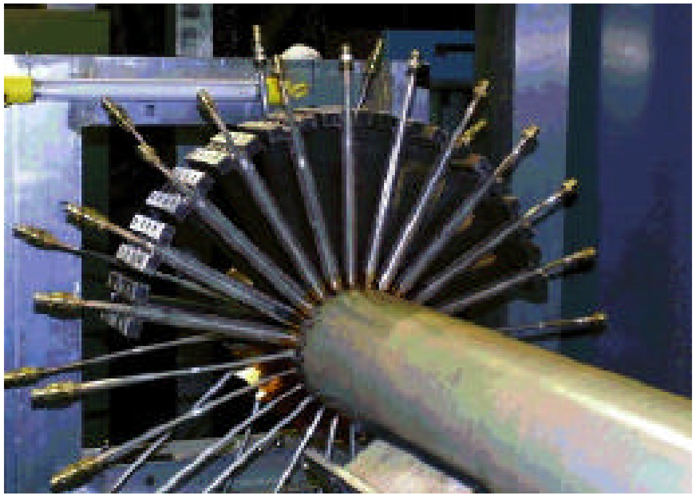


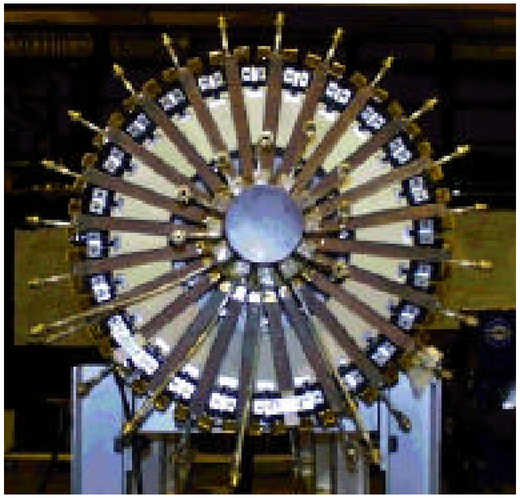
- Center Stack rests on pedestal on floor
- TF Inner Leg assembly thermal growth
  - slides inside OH tension tube
  - connects to outer legs via flex joint
  - connection to top umbrella via sliding spline joint
- TF Inner Leg assembly torsion
  - hub ass'ys transfer load via umbrella to outer VV
- TF Outer Leg dead weight and overturning moment
  - reacted to outer VV via turnbuckles
- OH Thermal Growth
  - slides over tension tube and inside CS casing
  - compresses washer stack at top
- Center Stack Thermal Growth absorbed by bellows
- VV Thermal Growth
  - sliding joints to legs, umbrellas, PF coils, and spline

TF Inner Leg Assembly

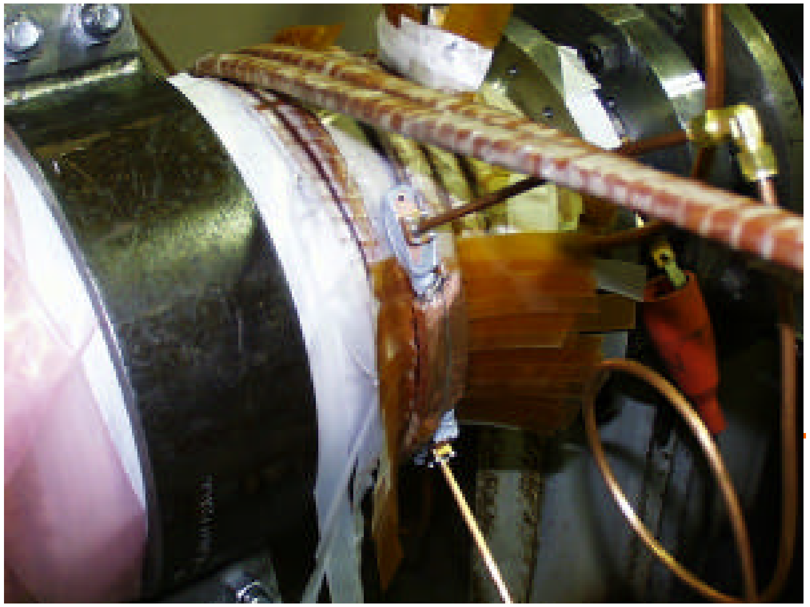
- 12 inner + 24 outer = 36 turns
- Each turn water cooled
- Radial flags secured by wedged hub assembly
- 72kA/turn, 1kV produces 6kG at R_0
- 11.8 MPa (1.7ksi) insulation shear





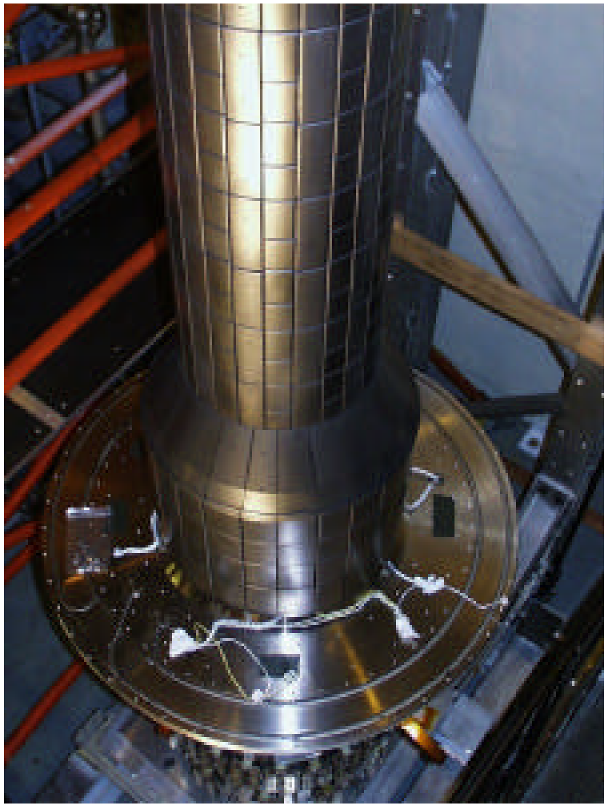


OH Solenoid



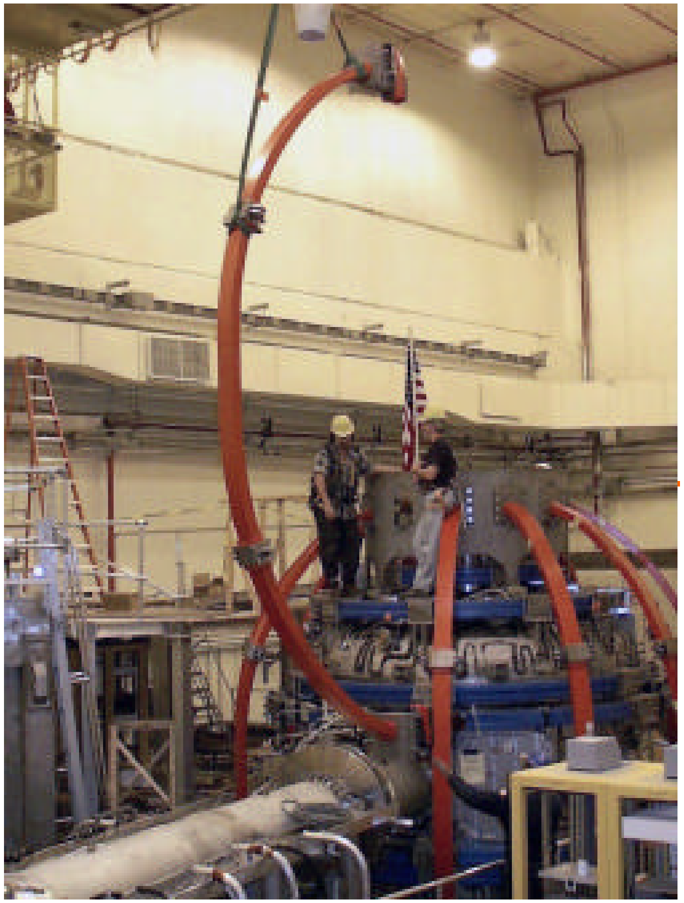
- approx. 1000 turns in 4 layers wound 2-in-hand
- 8 parallel cooling paths, 600 second cool down
- +/- 24kA/turn, 6kV produces 0.6 volt-sec flux swing
- Central B approx. 8T, 138 MPa (20ksi) Cu stress

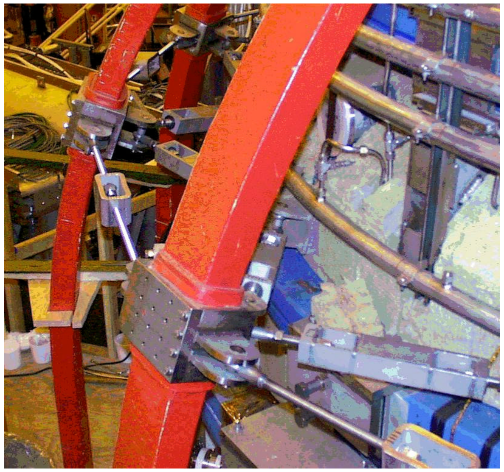
Center Stack Assembly

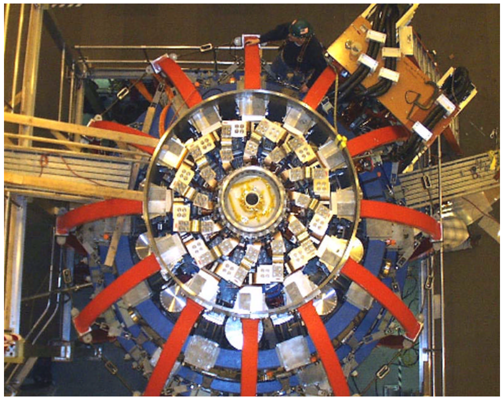


- Compact interlocking CFC tiles on Inner Wall (ΔR=14mm, 0.55”)
- Center Stack Assembly is completely removable

TF Outer Legs

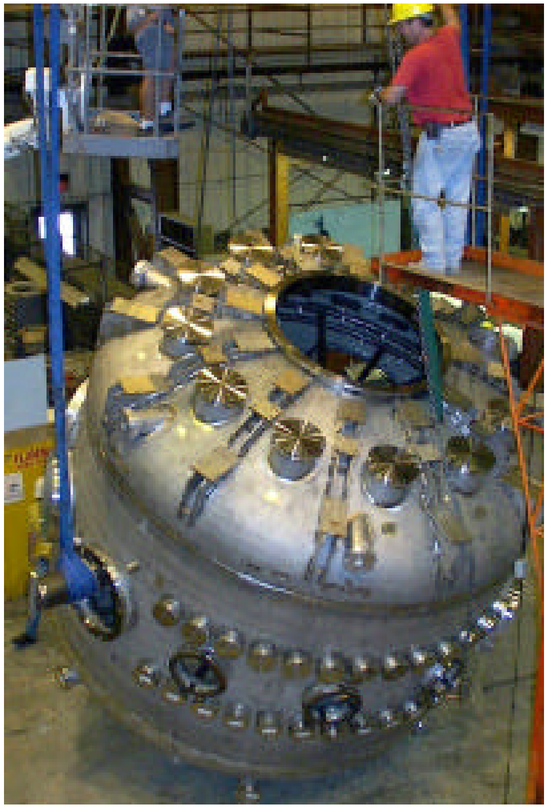


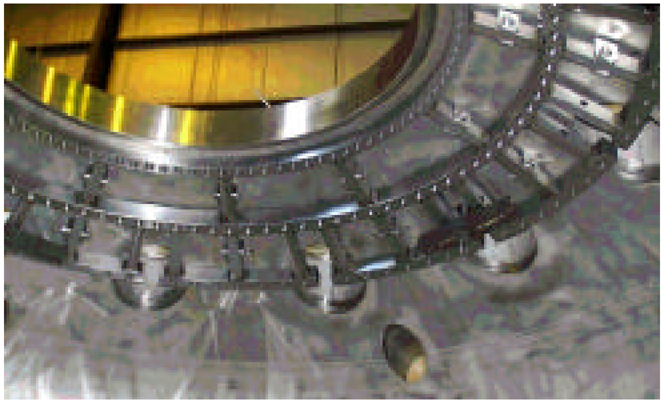




• Demountable bow shaped outer legs with turnbuckle supports

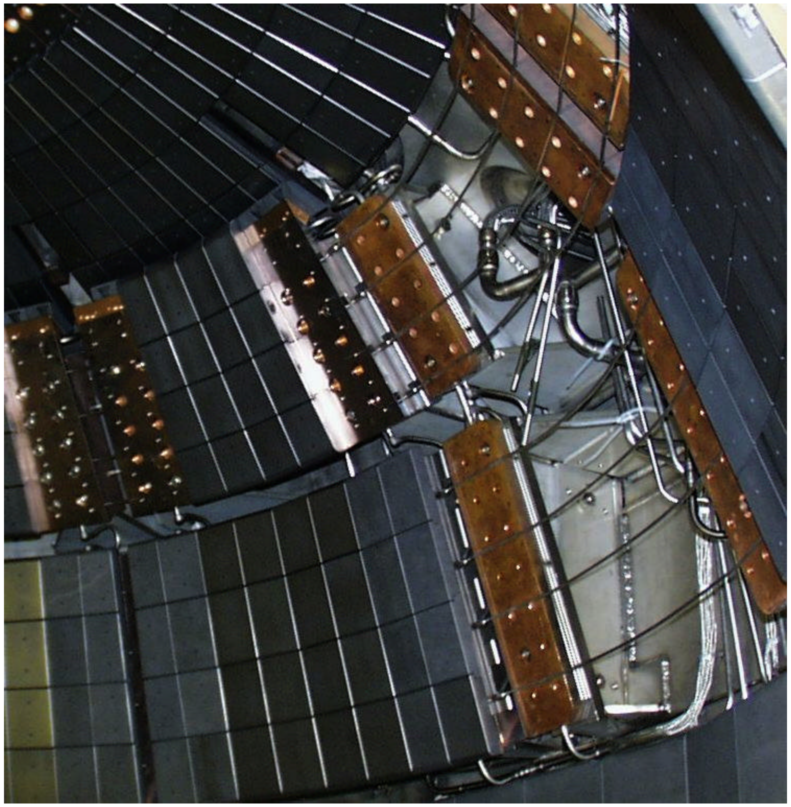
Vacuum Vessel

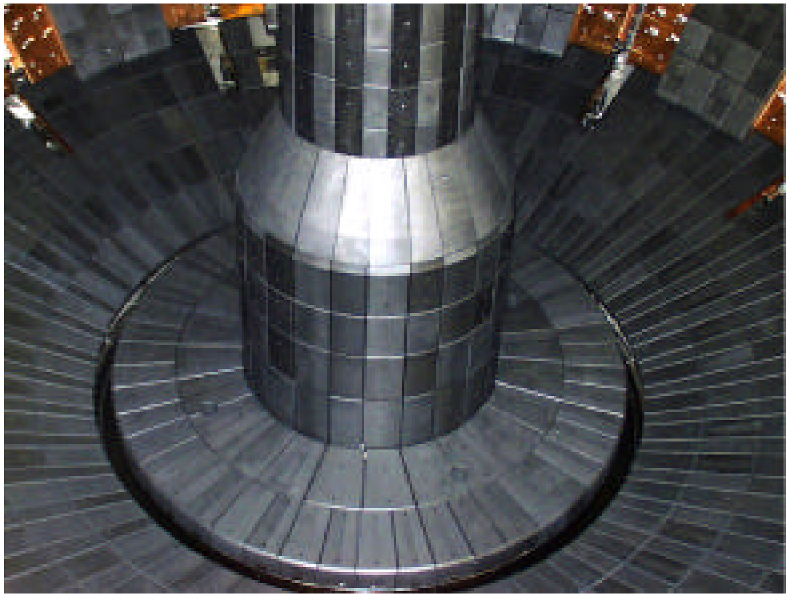




- Continuous 304 Stainless Steel VV (thickness = 16mm, 5/8")
- Sliding supports for outer PF coils and internal hardware

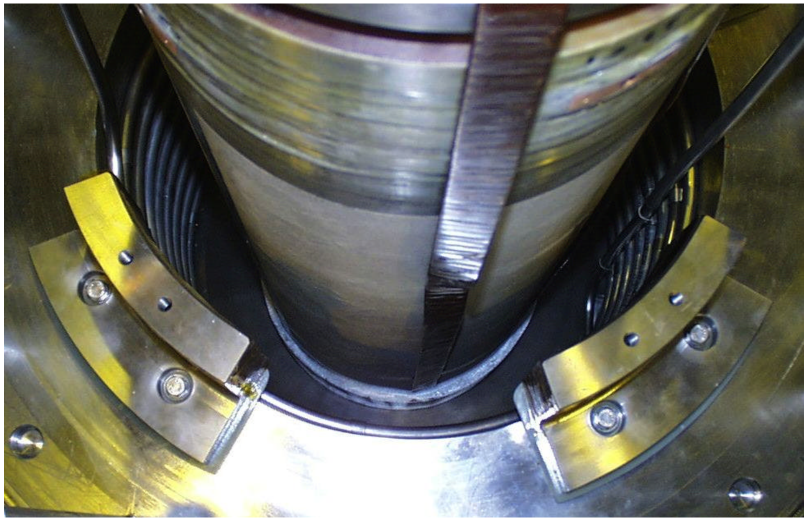
Internal Hardware & Plasma Facing Components

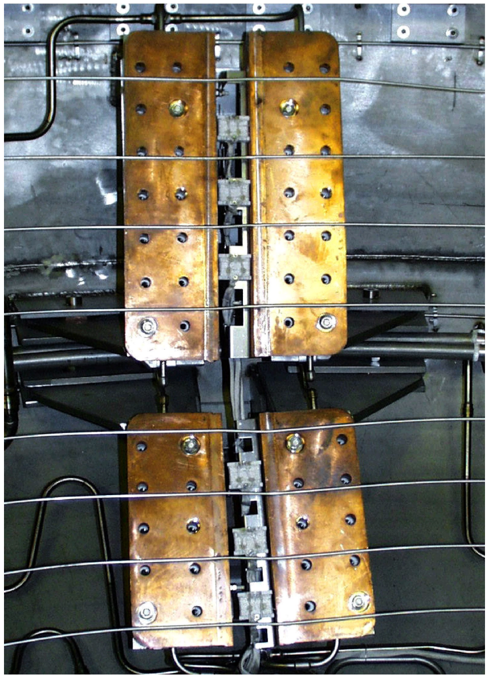




- CuCrZr passive stabilizer plates with heating/cooling system
- approx. 3000 tiles (design provided by ORNL)

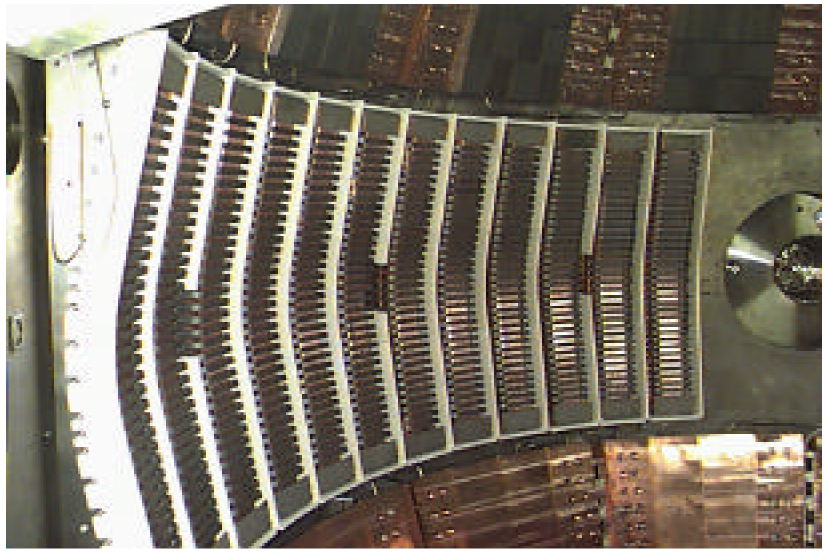
Diagnostic Sensors





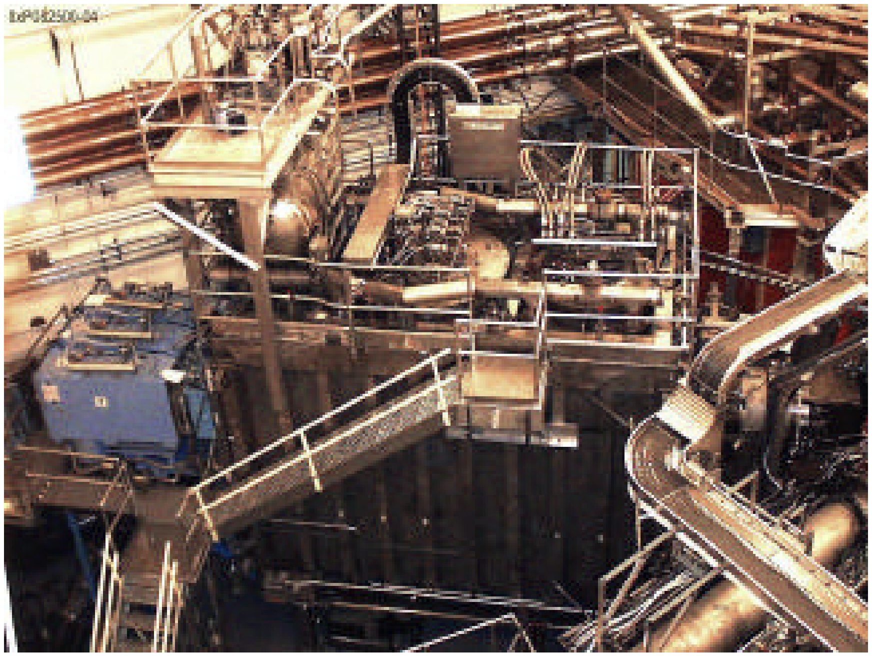
- Compact Ip Rogowski's in center stack (ΔR=3.5mm, 0.135")
- High temp (up to 600C) in-vessel sensors
- 17 Rogowskis, 105 flux loops, 135 Mirnovs, 24 Langmuirs, 128 TCs

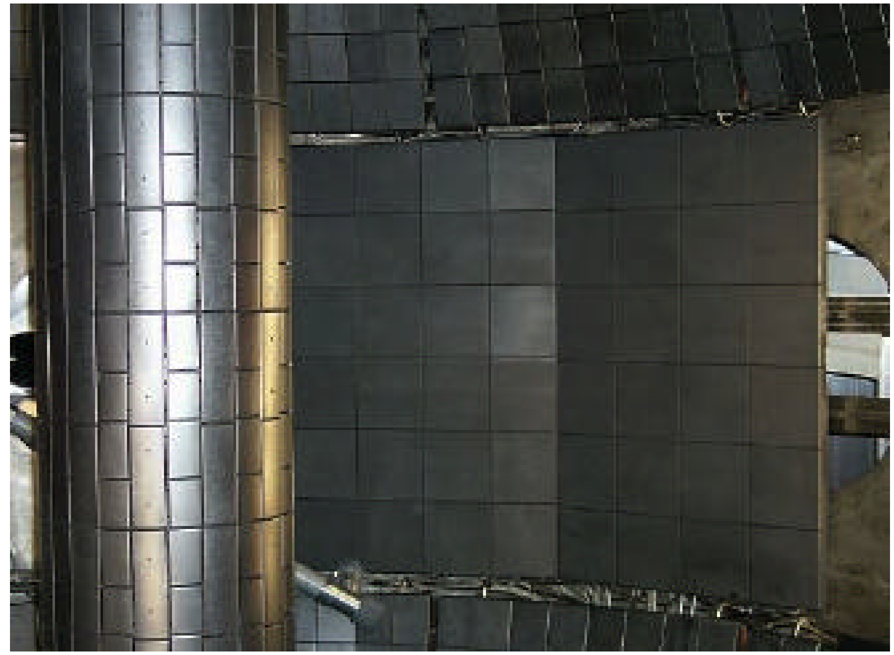
RF Systems



- High Harmonic Fast Wave (HHFW) RF
  - 6MW @ 30MHz, absorbtion mainly by electrons
  - Six PPPL sources, TFTR xmission lines, new 12 strap antenna
  - Tuning and matching network designed by ORNL
- Electron Cyclotron (EC) Pre-ionization system provided by ORNL

Neutral Beam Injection (NBI)

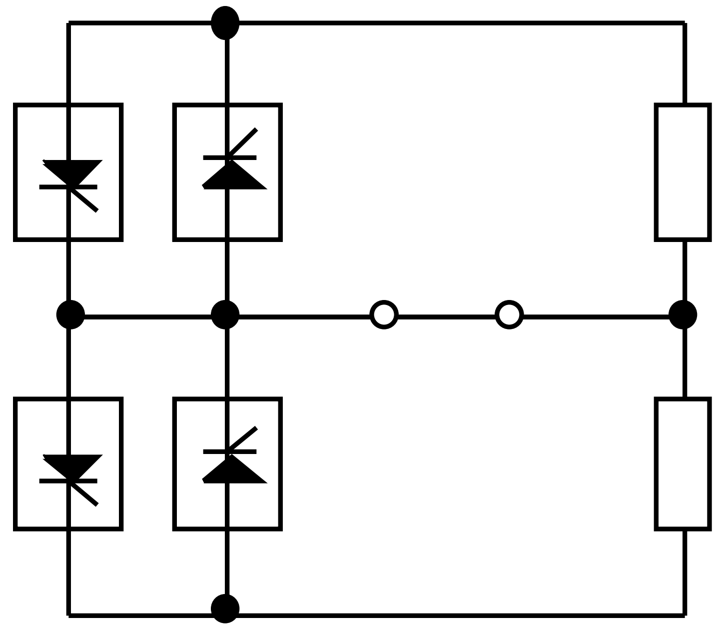




- One TFTR Beam Line @ 5MW, 80kV, 5 seconds

Magnet Power Supplies

- Extensive use of existing facilities
- One MG set to buffer load from grid
  - Smax ≈ 200MVA, Wmax ≈ 170MJ
- Modular TFTR rectifier design
  - 74 six-pulse bridges available
  - Direct digital control from central computer
- Advanced 3-wire, antiparallel configuration
  - 4-quadrant operation
  - separate control of upper and lower PF coil pairs



Key Engineering Features

- Compact, removable Center Stack
  - Nested two-tier TF inner leg conductors
  - Four layer, two-in-hand high performance OH solenoid
  - Tight tolerances and precise assembly
  - Compact inner wall PFC tile design
  - Miniature diagnostic sensors
  - Microtherm insulation
- Unique support schemes and mechanical load paths
- Extensive use of TFTR facility and components

Research Plan

TOPICS →	• Ohmic studies • Initial CHI • Initial HHFW	• Transport • Full HHFW • Macro-stability • Full CHI • Plasma-wall • β-τ_E integration	• Turbulence • Active Stabil. • Edge control • Noninductive • Integration >> τ_E
(FY99)	**(FY00)** **(14 weeks)**	**(FY01-FY03)** **(40weeks)**	**(FY04-FY06)** **(40weeks)**

1st Plasma February 99 — ***1 MA*** — ***200kA CHI*** — ***NBI, 4MW HHFW***

Capabilities	Inductive	Assisted Non-Inductive	Full Non-Inductive
Plasma Current	• → 0.5 MA	• → 1 MA	• ~ 1 MA
Pulse	• → 0.5 s	• → 1 s	• → 5 s
HHFW Power	• → 4 MW	• ~ 6 MW	• ~ 6 MW
NBI Power		• → 5 MW	• ~ 5 MW
CHI Startup	• → 0.2 MA	• → 0.5 MA	• ~ 0.5 MA
Toroidal Beta		• → 25%	• → 40%
Bootstrap		• → 40%	• → 90%
Control	• current, R, shape	• heating, density	• profiles, modes
Measure	• $T_e(r)$, $n_e(r)$	• $j(r)$, $T_i(r)$, flow, edge	• turbulence

NSTX 2001

Parameters
Baseline and (Achieved)

Elongation ≤ **2.2** (2.5)

Triangularity ≤ **0.6** (0.5)

Plasma Current
1 MA (1.07 MA)

Toroidal Field
0.3 to 0.6 T (≤0.45 T)

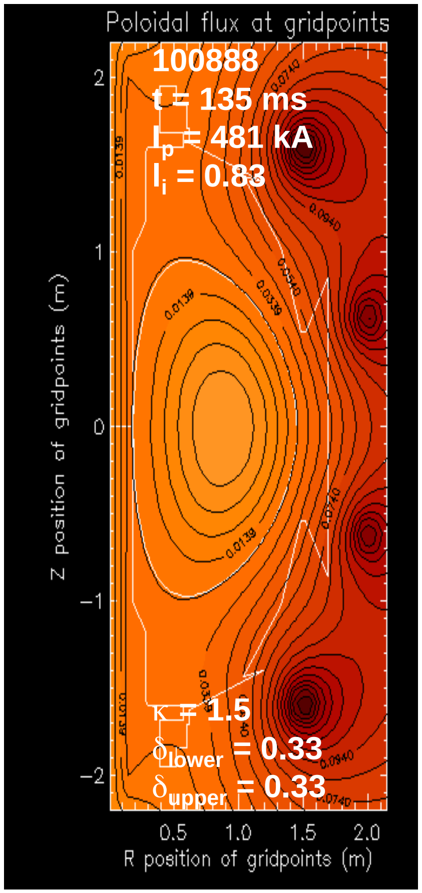
Heating and CD
5 MW NBI (3.2 MW)
6 MW HHFW (4.2 MW)
0.5 MA CHI (0.26 MA)
Pulse Length
≤ **5 sec** (0.5 sec)

Objectives of Initial Phase of Research Have Been Accomplished and Exceeded

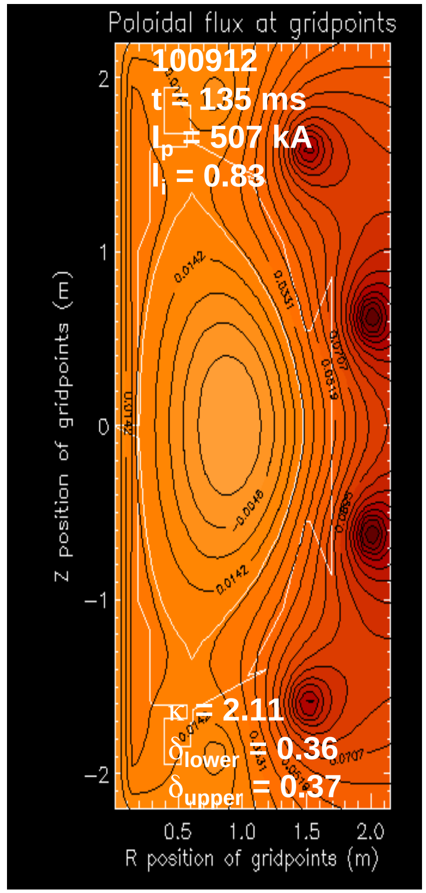
- Explored Inductive (OH) Operating Regime
  - Established target equilibria
  - Studied confinement trends, operating limits, and limiting mechanisms up to 1 MA
- Achieved <βt>=22% with Neutral Beam Injection (NBI)
  - Confinement looks very good
- High Harmonic Fast Waves (HHFW) used for electron heating
  - Significant increase in Te(0)
- Non-inductive startup using Coaxial Helicity Injection (CHI)
  - Significant toroidal currents generated
- H-mode has been observed

Variety of Ohmic Plasmas Have Been Produced

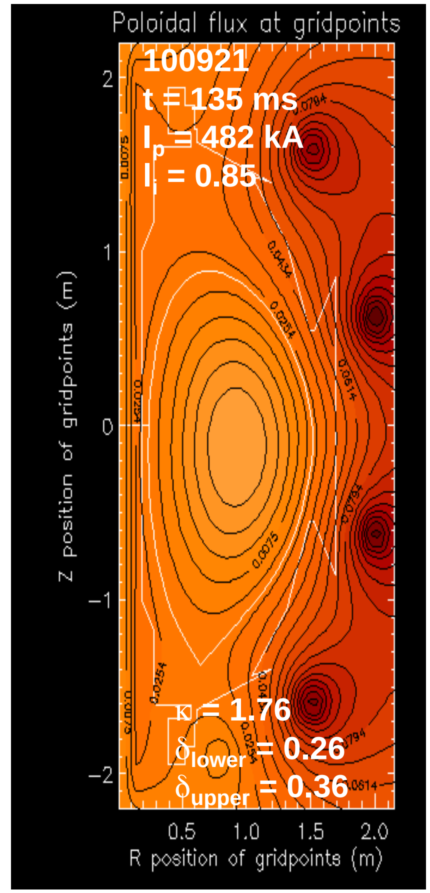
Wall Limited



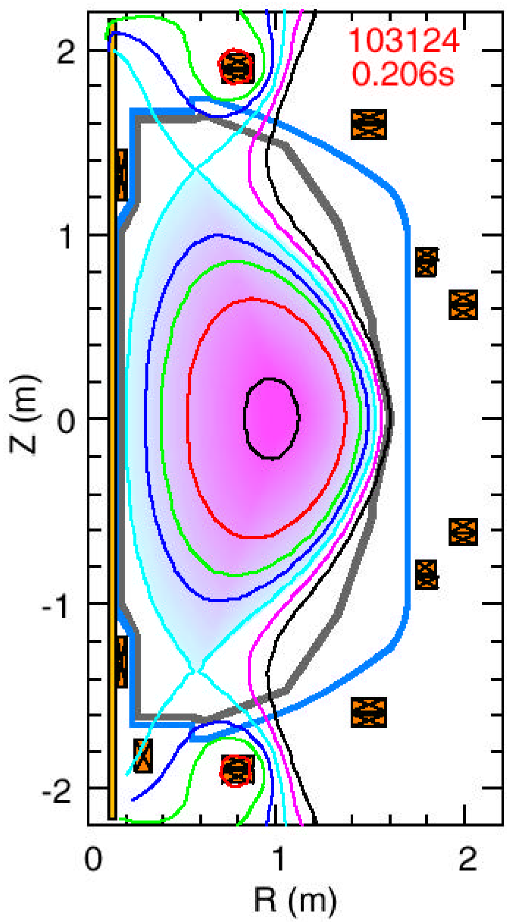
Double-Null

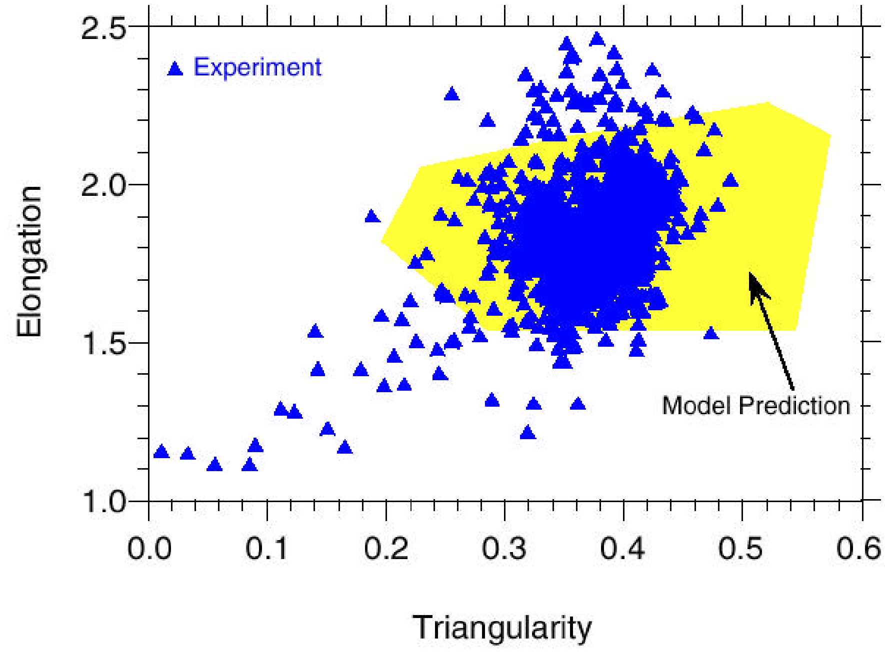


Single-Null

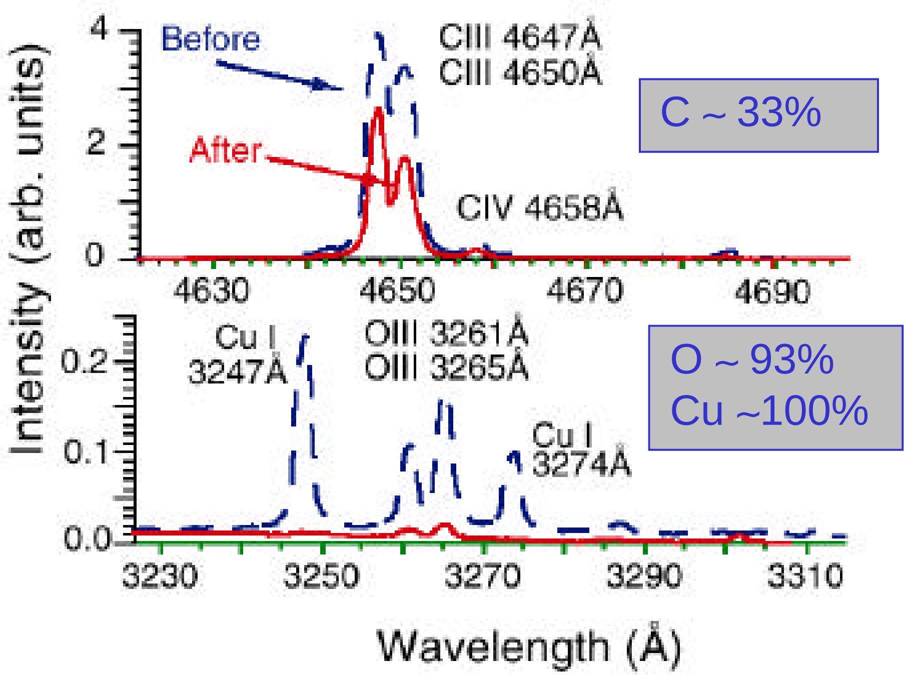


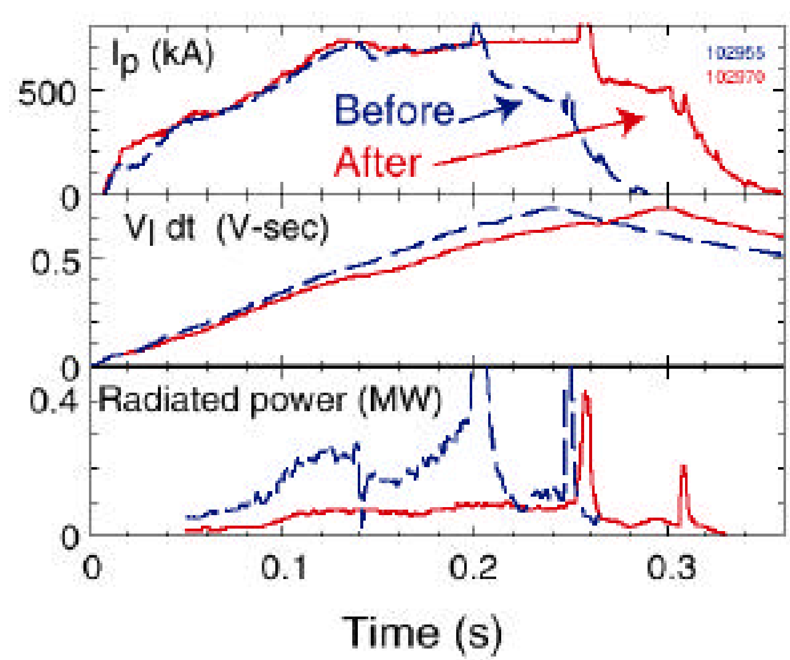
Range of Plasma Shapes Has Been Explored





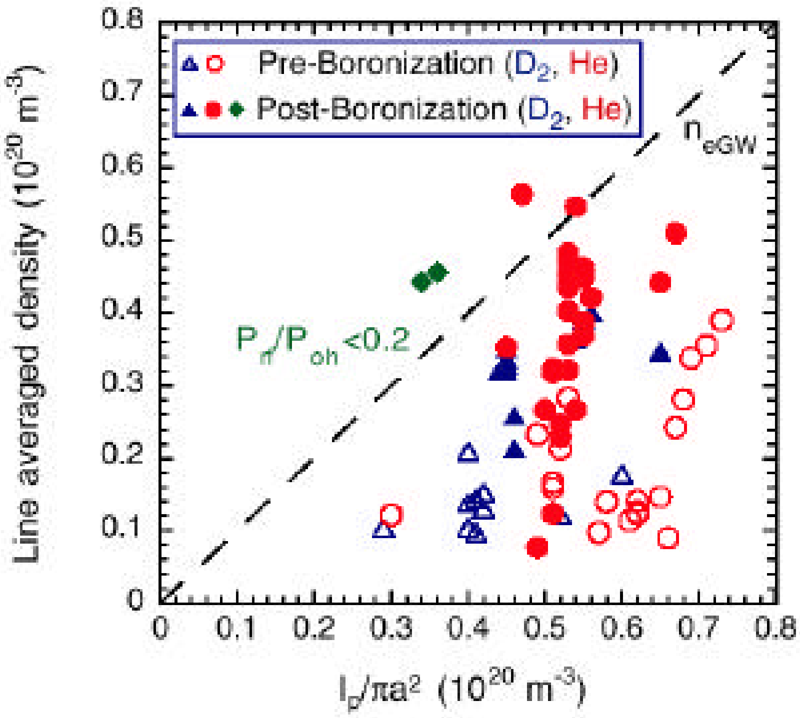
Boronization Used To Reduce Impurities and Flux Consumption



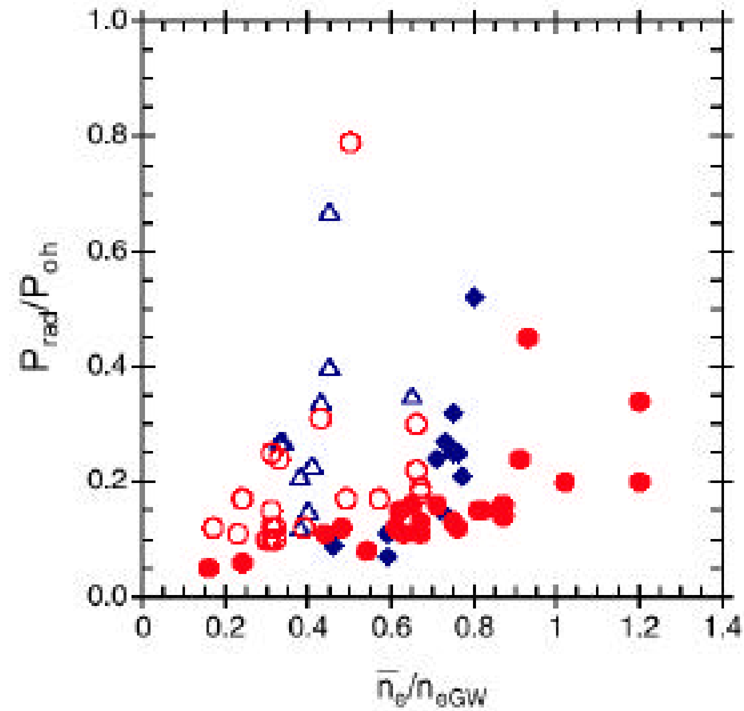


Achieved Densities Above Greenwald Limit

Boronization extends accessible n_e range



P_{rad}/P_{oh} increases, but still low (≤0.40) at high density

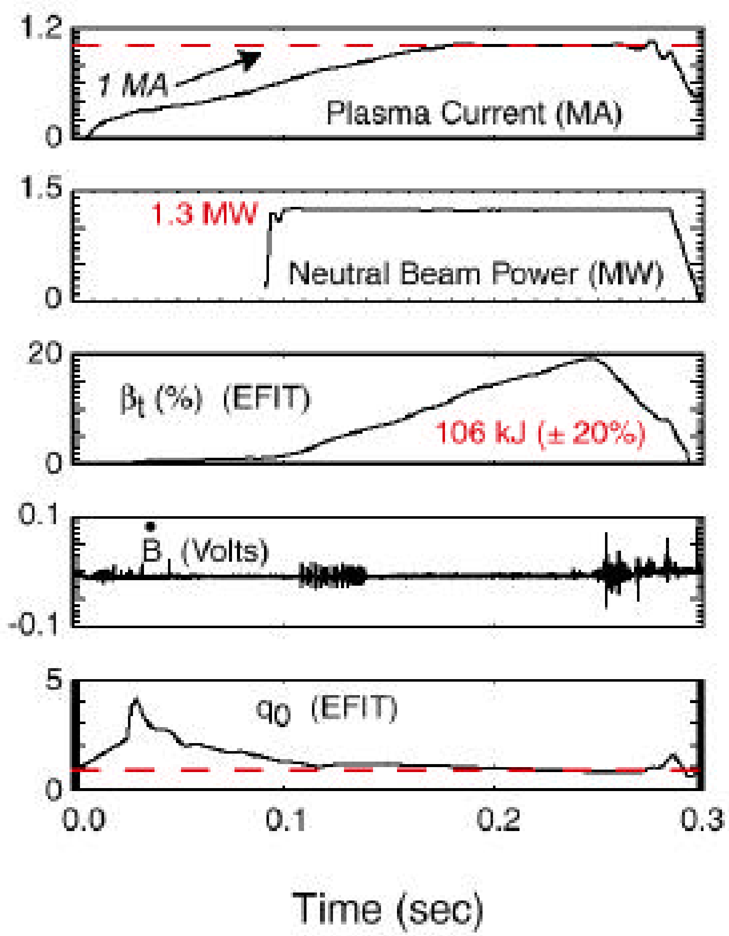


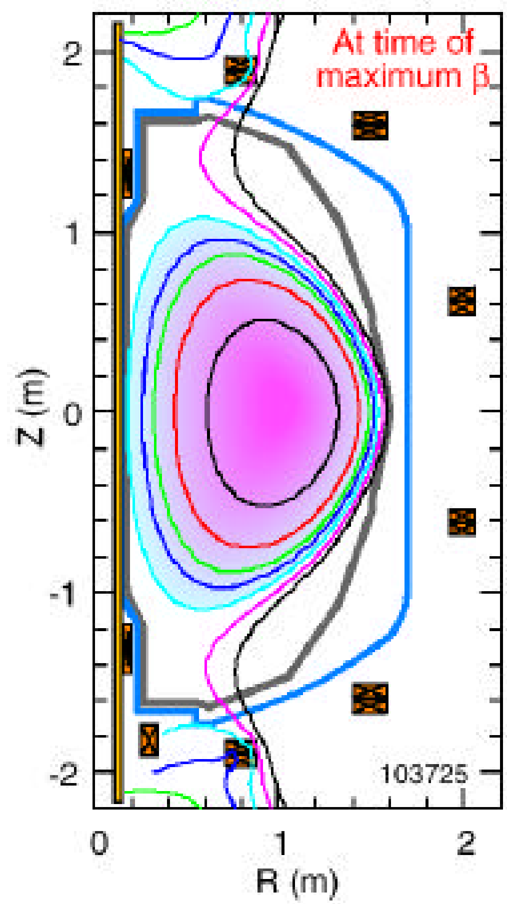
Density appears to be set by fueling limitations

NSTX

High-β_t With Good Confinement Obtained

$\beta_t=2\mu_0\langle p\rangle/B_0^2=19.7\%$, $\beta_n=3.9$, $B_0=0.3$ T, $q_\psi=7.5$





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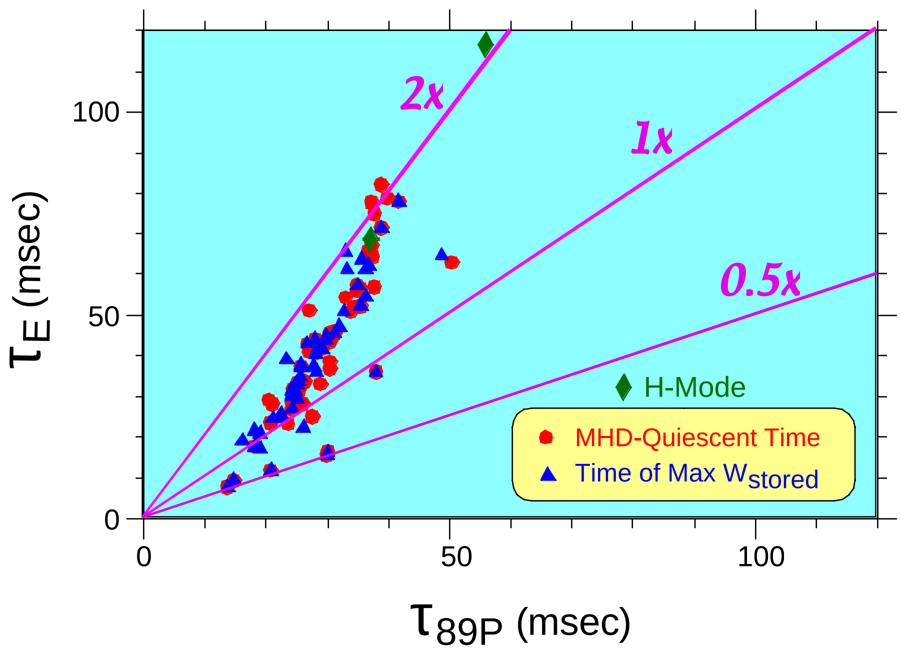
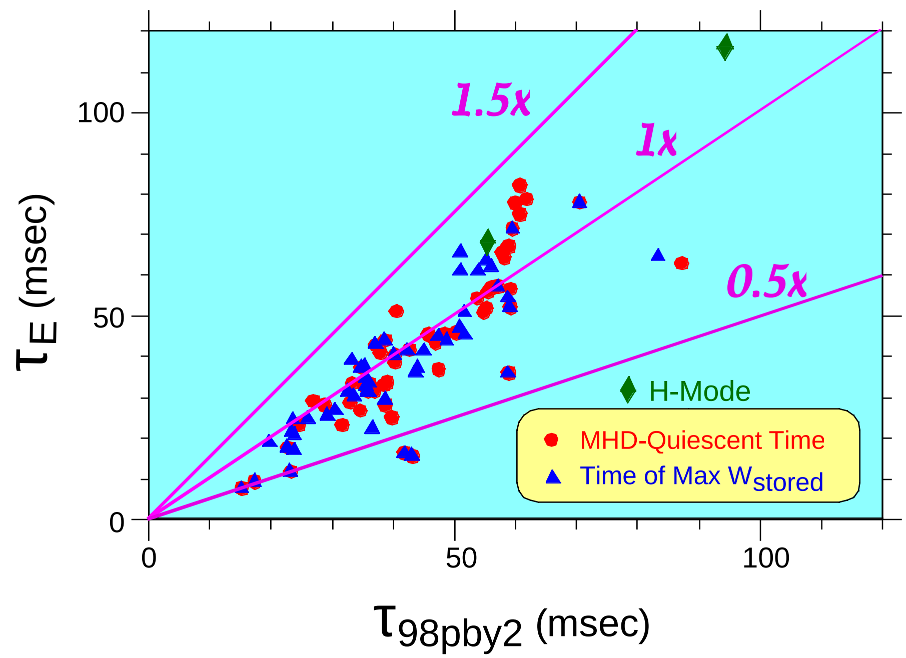
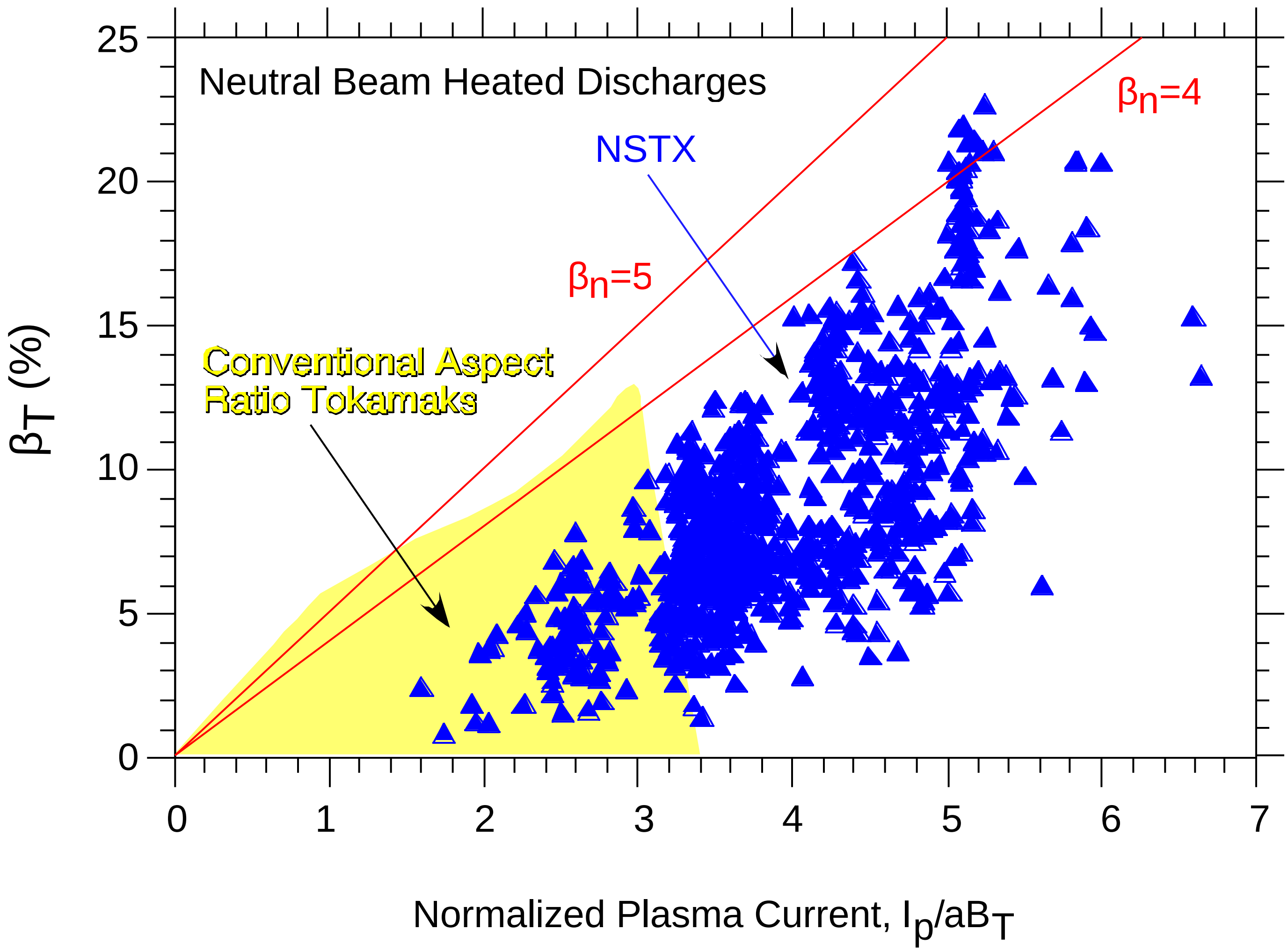
Energy Confinement Enhanced Over Both L- and H-mode Predictions

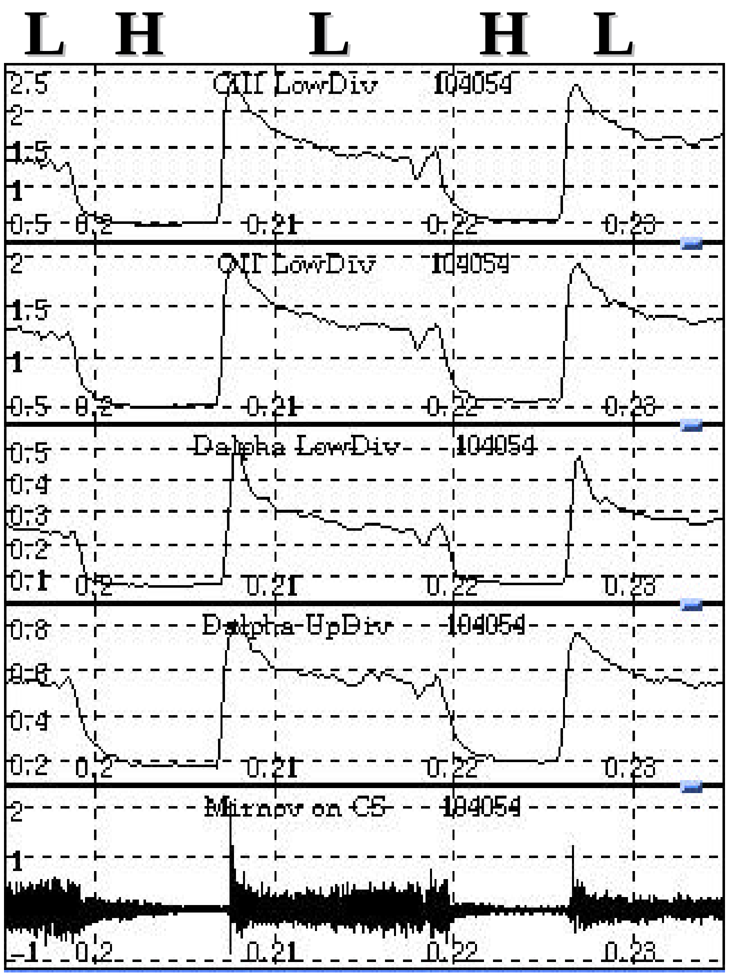




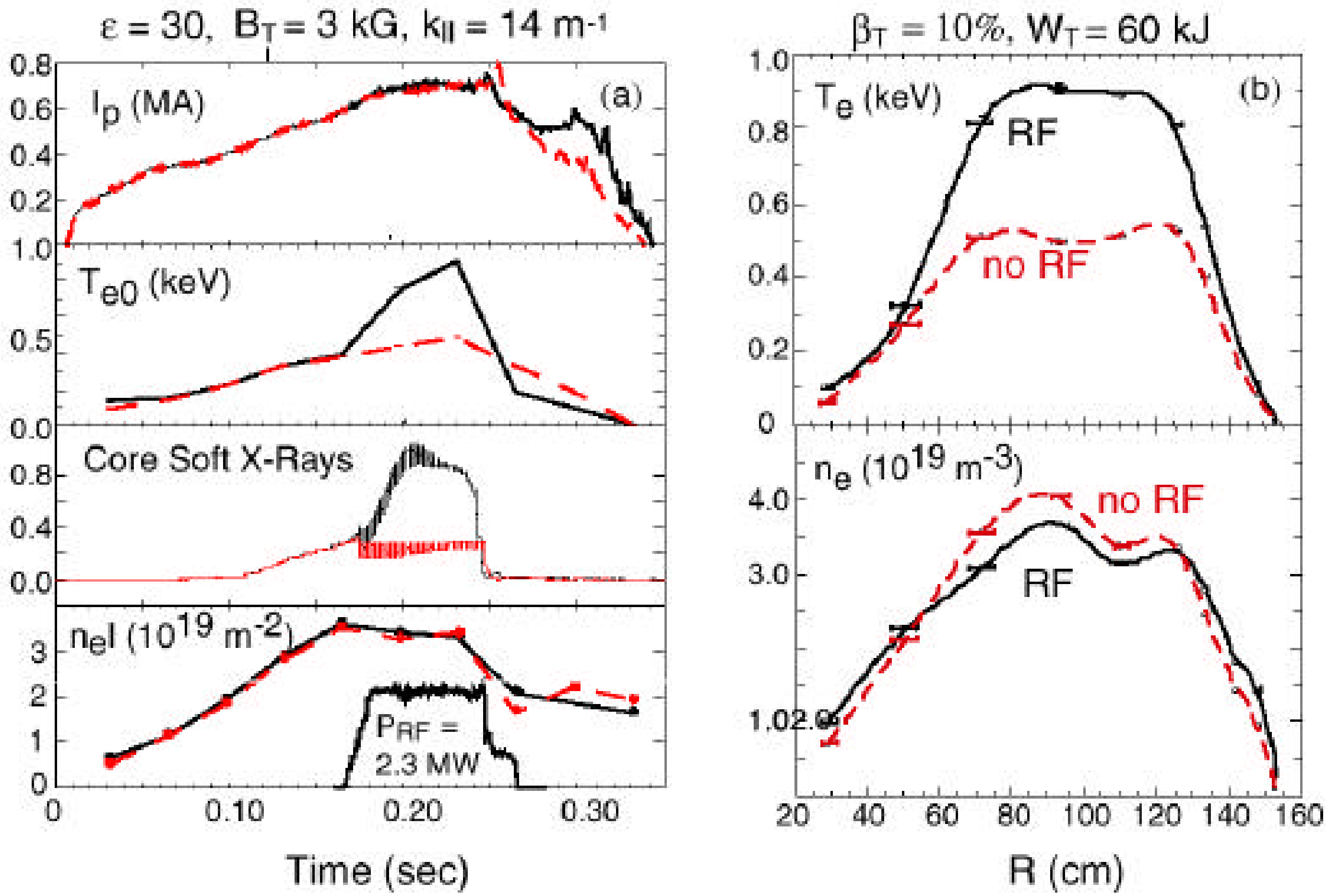
High-β_t Achieved



Brief H-mode Observed in NSTX



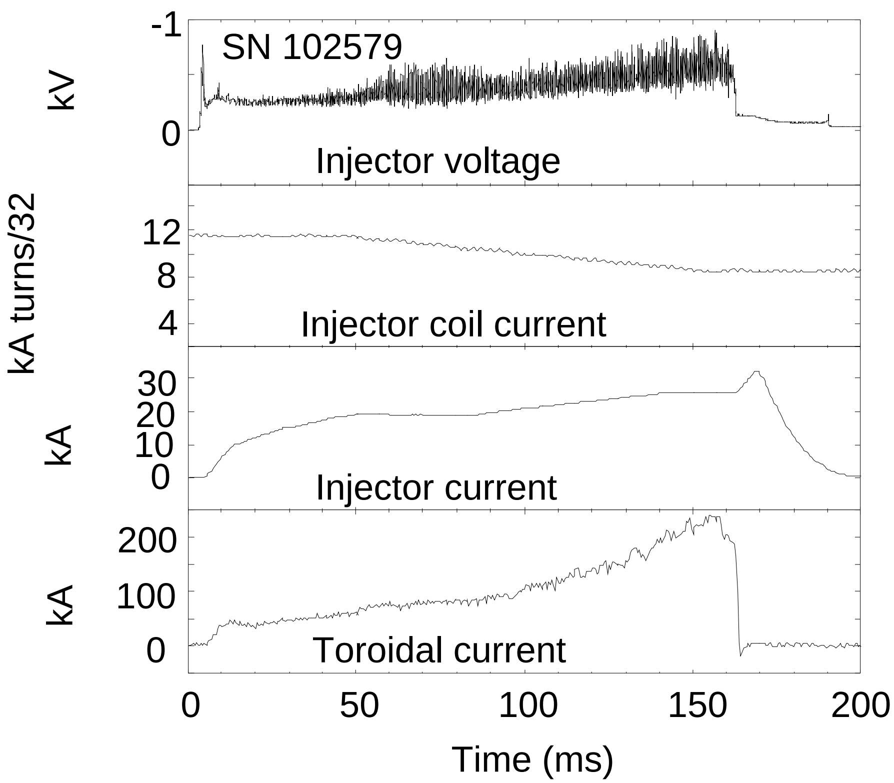
HHFW Electron Heating On- and Off-Axis

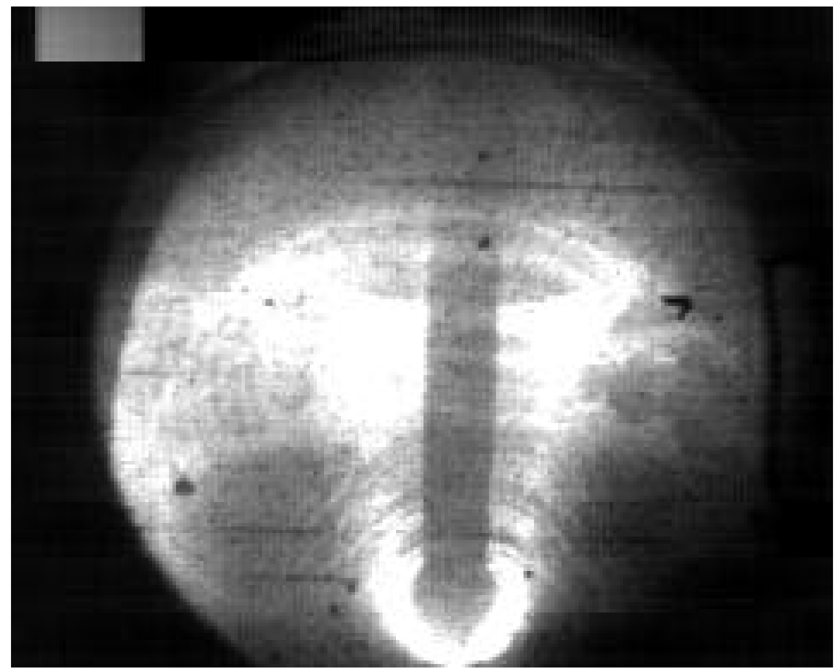


Coaxial Helicity Injection (CHI)

- Discharge initiated across inboard and outboard divertors in lower half plane
- JxB forces lead to toroidal current transported upwards from injector region
- Toroidal current ≈ 10 to 20 times injected current
- Reconnection leads to closed flux surfaces
- Ip ≈ 270kA has been produced with multiplication factor ≈ 10
- Issues
  - understanding reconnection physics, confirming flux closure
  - feedback control and absorber arc avoidance
  - impurity influx
  - eventual coupling with RF current drive

240kA CHI Discharge





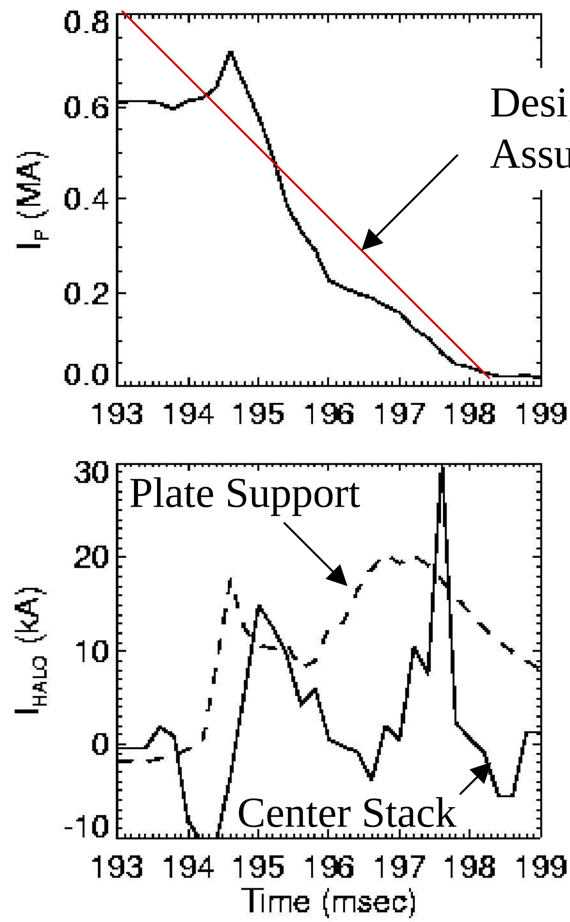
T = 150ms

Summary of Performance (best non-simultanous)

Plasma Current I_p	$\leq$ 1.0 MA
I_p Flat Top @ 1MA	$\leq$ 250 ms
dI_p/dt	~ 5.5 MA/s
Ejima Coefficient = $\int V_{res} dt / \mu_0 R_0 I_p$	~ 0.35
Stored Energy W	~ 164 kJ
Confinement time τ_E	~ 120 mS
$\beta_{T} = 2\mu_0 <p> / B_0^2$	~ 21%
T_e	~ 1.5keV
T_i	~ 2keV
n_e	1 ~ 6 x 10^{-19} m^{-3}
$n_e / n_{greenwald}$	~ 1
P_{nbi}	$\leq$ 3.2MW
P_{hhfw}	$\leq$ 4.2MW
I_p CHI	$\leq$ 270kA
Z_{eff}	~ 3

Plasma Disruptions

- Disruption / halo current j x B forces were a major design concern
- Vertical Displacement Events (VDEs) result in fast disruptions $dI_p/dt \approx 166$ MA/sec as predicted
- Observed halo-currents are modest, ≤ 5 % of I_p (10% was design requirement)



Summary

- First phase operations have been highly successful
- RF and NBI heating experiments are underway
- β_T (≤ 21%) and confinement (≤ $2\tau_E^{89P}$, $1.6\tau_E^{ELMy}$) very good
- Challenging current sustainment phase comes next