Supported by

Facility Status and Plans

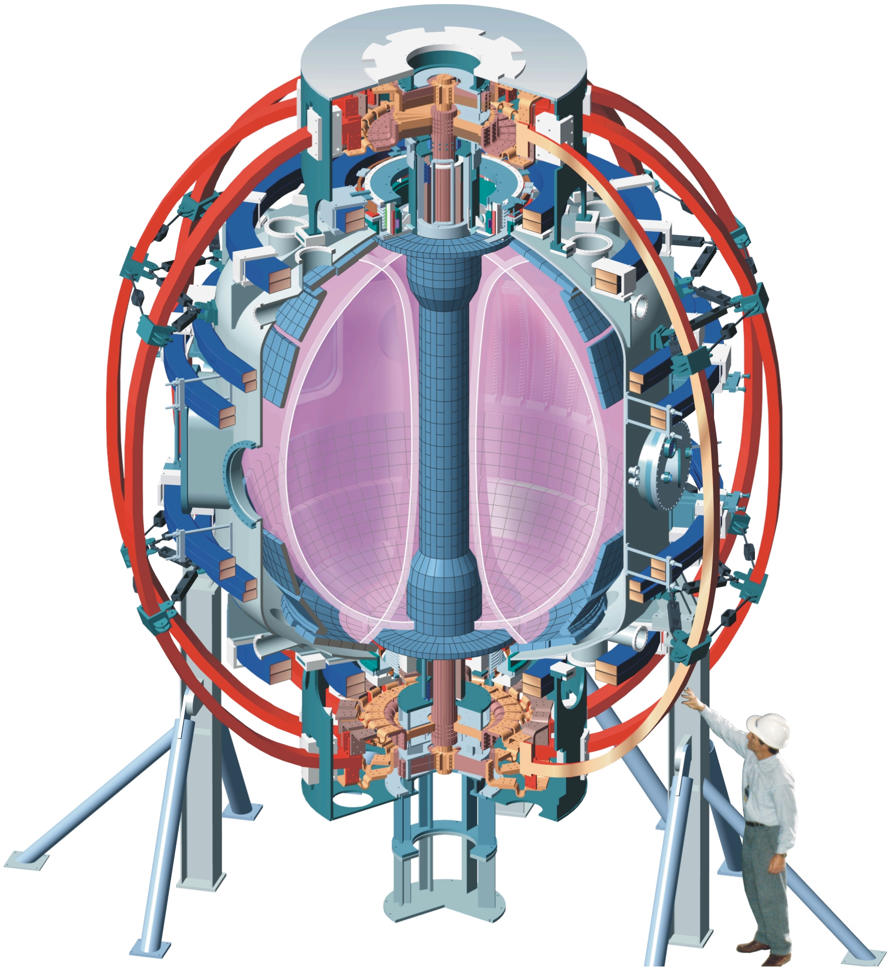
M.G. Bell
PPPL

For the NSTX National Team

DOE Review of
NSTX Five-Year Research Program Proposal
June 30 – July 2, 2003

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



Experiments started in Sep. 99

Achieved Parameters	
Aspect ratio A	1.27
Elongation κ	2.2
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6T
Solenoid flux	0.7Vs
Auxiliary heating & current drive:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
CHI	0.4MA
Pulse Length	1.1s

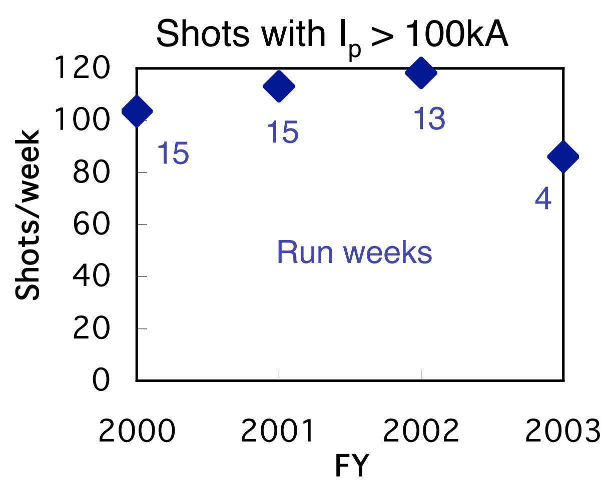
Operational Periods Are Very Productive

NSTX

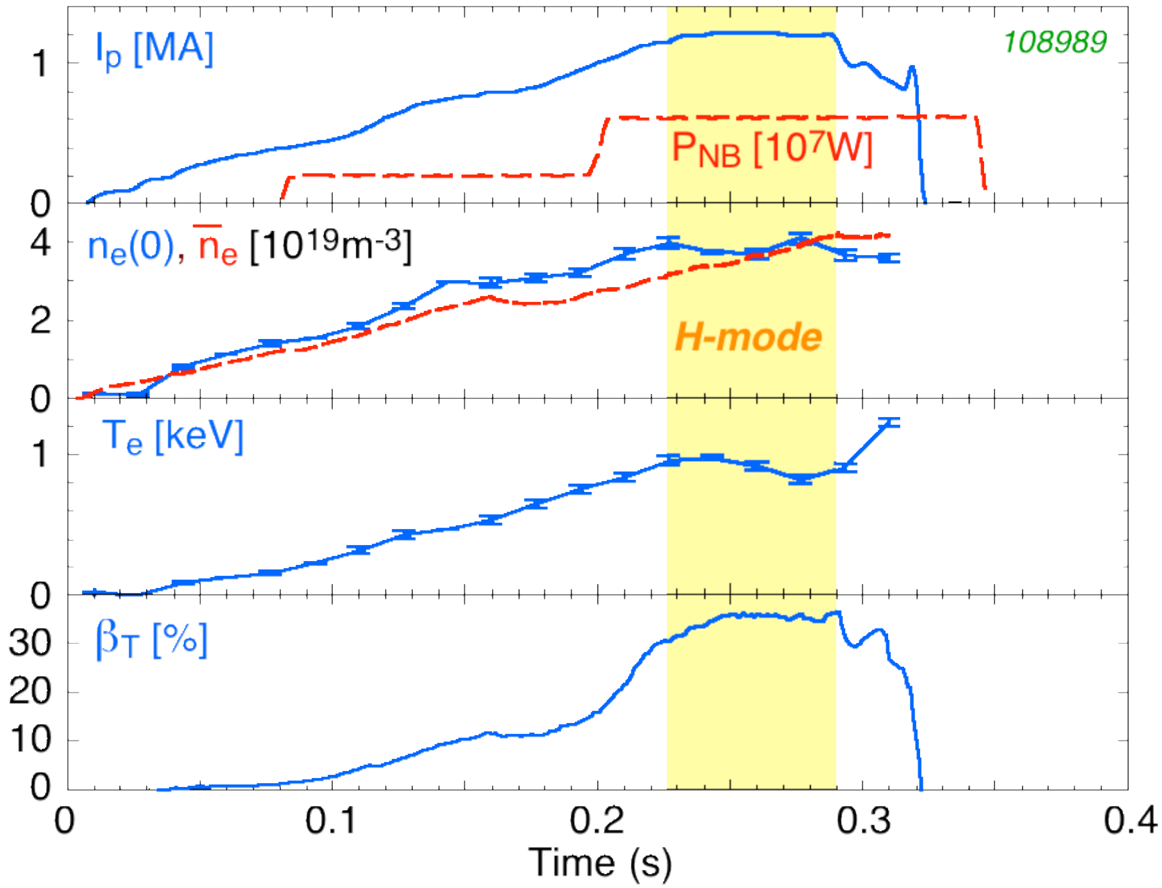
Operational log of last 5 weeks of FY'02 run

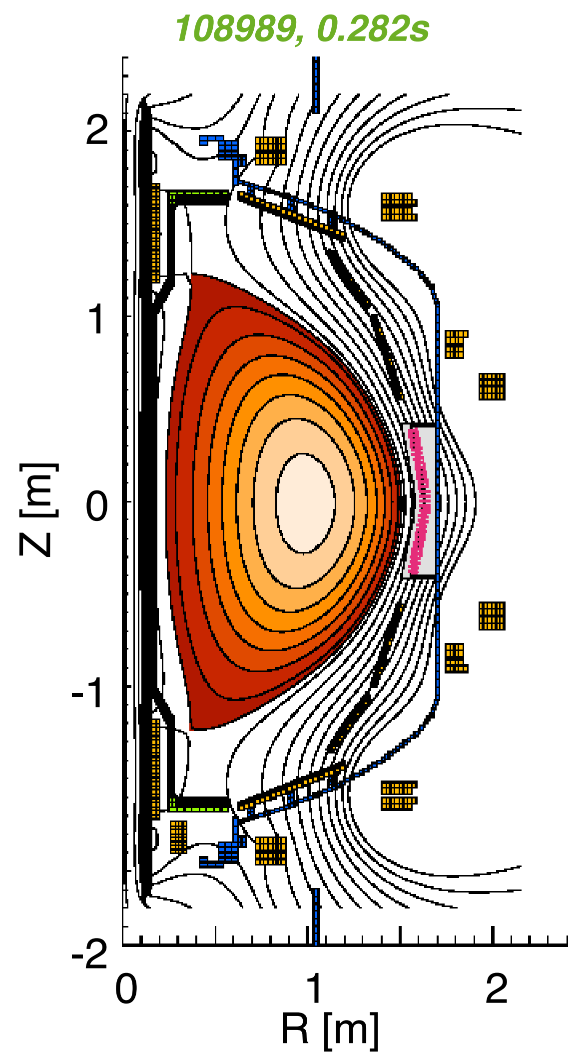
Week	Monday	Tuesday	Wednesday	Thursday	Friday
May 6 – 10	**XP-38** *31* Triangularity scan **β_T = 31%**	**XP-216** *40* External Kink	**XP-202** *33* RWM **XP-209** *5* IW gas H-mode	**XP-223** *33* Effect of ρ* & rotation	**XP-214** *36* HHFW-Fast Ion Interactions
May 13 – 17	**XP- 224** *38* Edge turbulence	**XP-204** *38* Effect of T_e on NBI heating	**XP-218** *43* HHFW current drive	**XP-221** *22* Stability at low l_i **XP-209** *16* IW gas H-mode (extended shift)	**XP-227** *40* ELM study
May 20 – 24	**XP-226** *36* Bootstrap current	**XP-218** *36* HHFW current drive	**XP-223** *38* Effect of ρ* & rotation	**MP-24** *7* rt-EFIT commissioning	**MP-24** *16* rt-EFIT commissioning
May 27 – 31	Holiday	Maintenance	Maintenance	**Ne glow calib'n** **Boronization 15**	
June 3 – 7	**XP-228** *36* Long pulse high I_p	**ISTP** *11* **0.6T TF comm.** **100kV NBI** **XP-229** *19* Long pulseH-mode (extended shift)	**XP-218** *41* HHFW current drive	**XP-223** *18* Effect of ρ* & rotation **XP-220** *12* High stored energy **W = 390kJ**	**XP-208** *27* CAE stability **XP-215** *17* H-mode threshold (extended shift)
June 10 – 14	**XP-220** *14* High stored energy **XP-218** *24* HHFW current drive **Boronization 16**	**XP-223** *46* Effect of ρ* & rotation **MP-24** *3* rt-EFIT comm. **rt-EFIT control demonstrated** (extended shift)	**XP-217** *14* Edge charact'n **XP-220** *18* High stored energy **β_T = 35%**	**XP- 210** *23* Wall Mode Study **XP-217** *13* Edge charact'n (extended shift) **MP** *8* Gauge calib'n	**XP-217** *11* Edge charact'n **XP-229** *17* Long pulse Hmode **1s, 0.8MA pulse**
June17 – Sep 30	Outage				

- ~800 shots in 25 days
  - 20 experiments
  - B_T = 0.6T
  - P_{NBI} = 7MW
  - W_{tot} = 0.39MJ
  - β_T = 35%
  - 1s pulse
  - rtEFIT control



Neutral Beam Injection System Has Been Workhorse of High-β Research





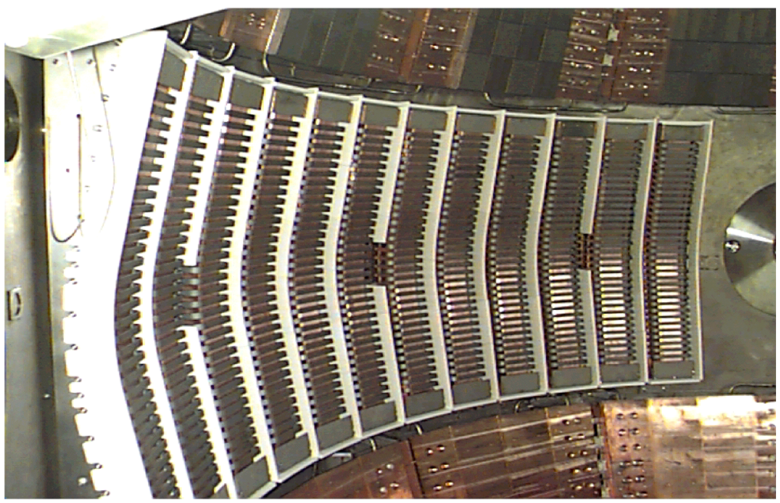
- β_T (= $2\mu_0\langle p\rangle/B_{T0}^2$) = 35% for P_{NB} = 6.2MW
- Maximum P_{NB} = 6.9MW ($V_{NB} \approx$ 100kV)

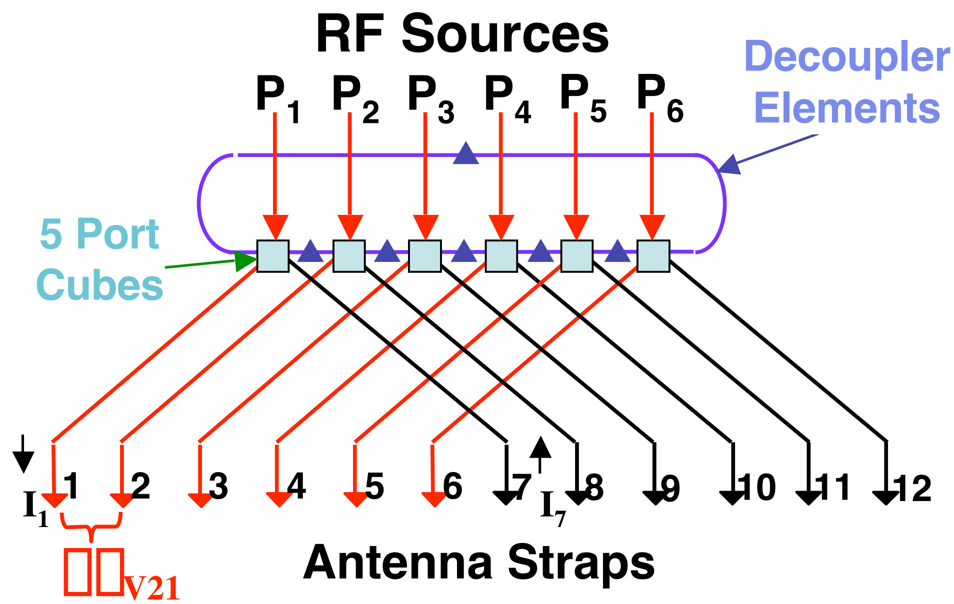
Feedback Control of NB Power

- Upgrade NB control system for pulse-width modulation of sources (FY'04)
- Data links to/from Plasma Control System computer
  - Source status to PCS
  - Source permissive signal from PCS
- Feedback control of □
  - □ obtained from rt-EFIT analysis of magnetic data
- Provide NB "notching" for diagnostics, *e.g.* CHERS

HHFW System Provides Flexible Auxiliary Power for Heating and Current Drive

- 12-element antenna for 6MW coupled power at 30MHz
  - Well within capability of the 6 RF sources
- Real-time phase control of straps demonstrated
  - $\mathbf{k}_{tor} = \pm(4 - 14)\ m^{-1}$





- Observed effective electron heating in FY'00 and first indications of current drive in FY'02

Technical Aspects and Upgrades of HHFW

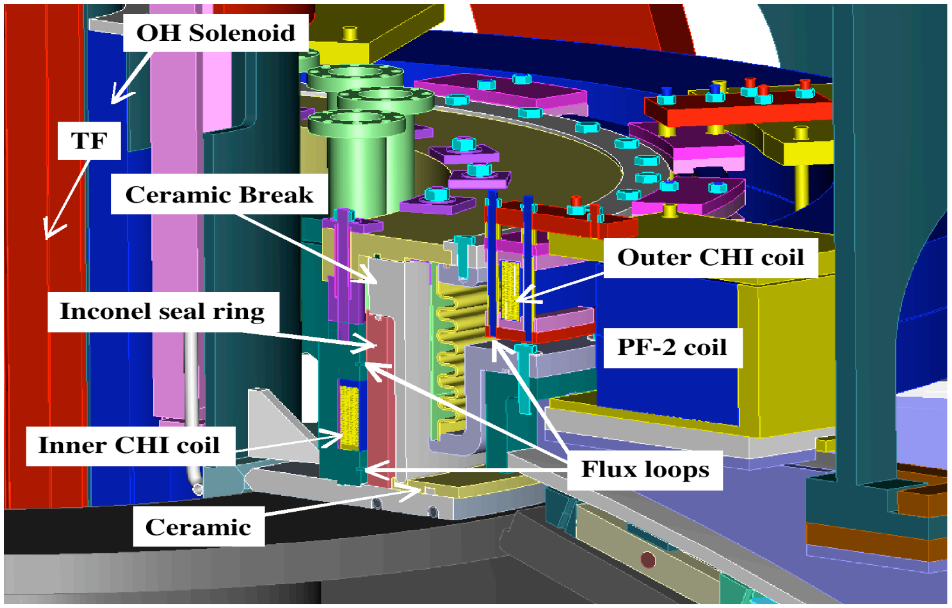
- Phase feedback system works well
  - Phases set to arbitrary waveforms between shots
  - Now developing algorithms for real-time feedback
- Power limited to < 3MW through FY'02 run
  - Found evidence of arcing in feedthroughs
  - Modified center conductors to reduce electrical stress
- Better performance in brief FY'03 experiments
- Feedback to maintain antenna coupling planned for FY'04
- Upgrade to symmetric end-fed design in FY'05, if needed
  - Increase power by factor 4 at constant voltage

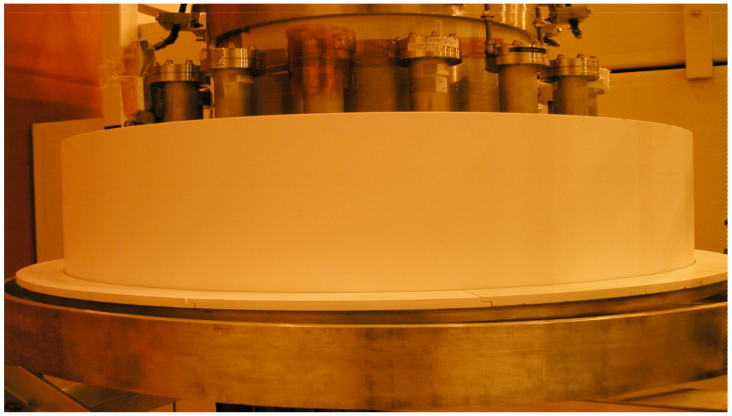
Improvements Have Been Made to Address Technical Problems for CHI Experiments

- Arcs across absorber insulator limited pulse length
  - Installed new absorber insulator and coils after FY'02 run
- Flashovers in external circuit due to large dI_{CHI}/dt
  - Moved transient suppressors closer to injector gap
- Noise pick-up in magnetic diagnostics prevented adding CHI to inductive plasmas
  - Have now improved shielding, grounding and signal processing for magnetic sensors

New CHI Absorber Insulator Designed to Resist Arcing Installed in FY'02

NSTX



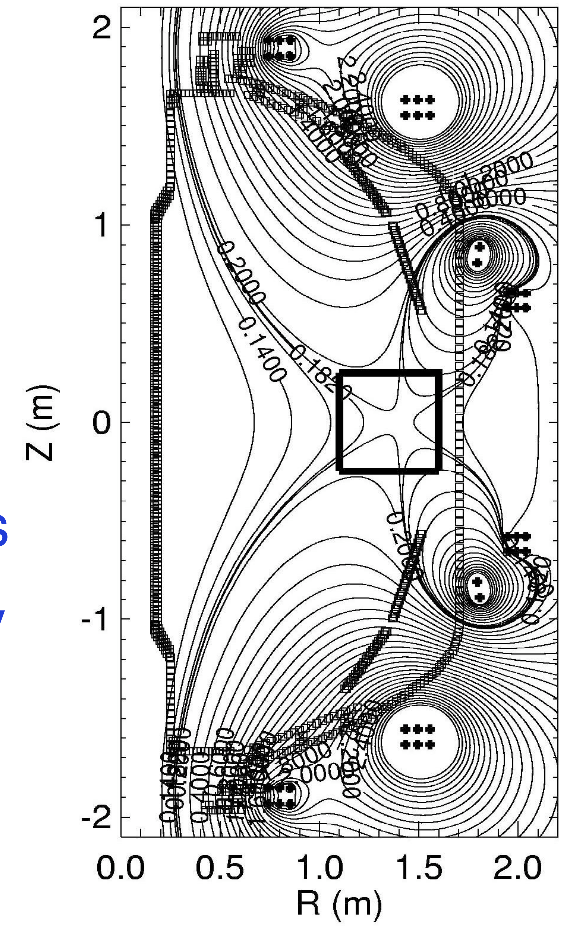


- Insulator on high-field side
  - Plasma entering absorber flows towards lower field
- Arc path longer and more tortuous
- Indications from FY'03 that arcs are suppressed
- Added coils to null poloidal field across absorber gap
  - UWash developing a power supply for these
  - Install in FY'04 if needed

Additional Power Supplies Will Provide Alternative Non-Solenoid Startup

- Use PF5, PF4, PF3, PF2 to get poloidal flux *and* poloidal field null
  - ~0.15Wb available at ~1m radius
    - Possibility for > 100kA
  - Meets requirements for breakdown with adequate preionization
  - Provide power supply for PF4 coils (FY'04)
  - Reverse unipolar PF5 supply for initial tests
  - If successful, provide PF5 bipolar capability
- Also investigate JT-60U non-solenoid scheme
  - Proposal from U. Tokyo collaborators

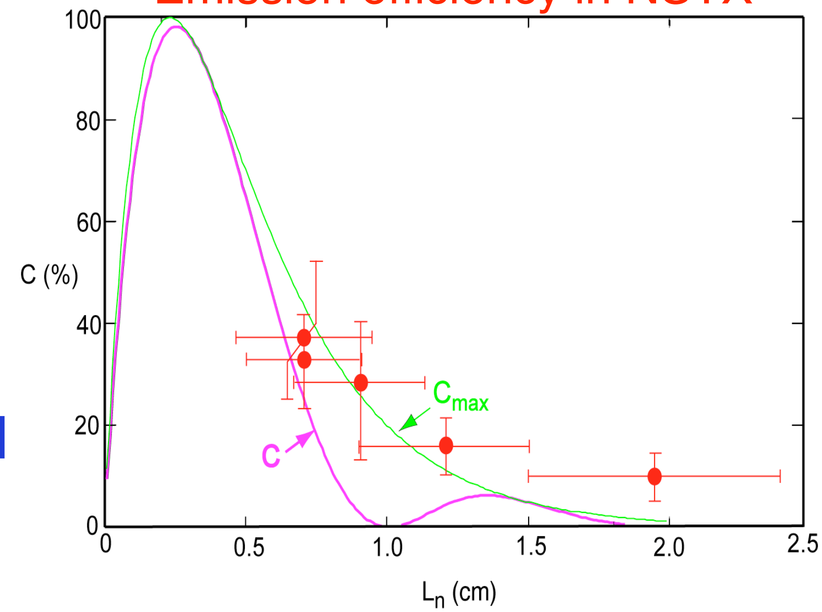
Poloidal flux contours at time of breakdown



Electron Bernstein Waves Can Provide Localized Current Drive in Advanced Scenarios

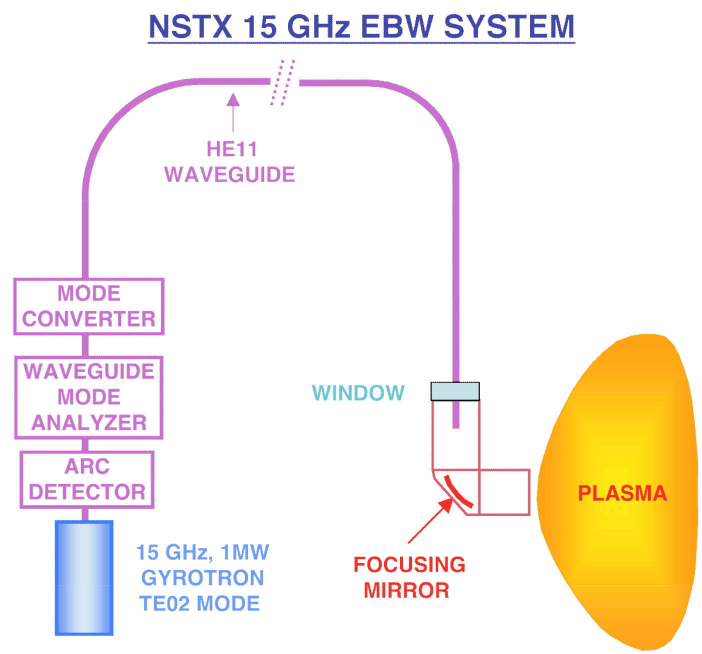
- EBW can drive localized current in “overdense” plasmas
  - Supplement bootstrap current and stabilize NTMs
- Requires mode-conversion of coupled EM wave to EBW
  - Characteristics of edge plasma are critical
    - Small L_n at conversion layer
  - Investigating with emission measurements in NSTX
    - Including local edge profile modification
  - Valuable input from CDX-U and MAST EBW programs

Emission efficiency in NSTX



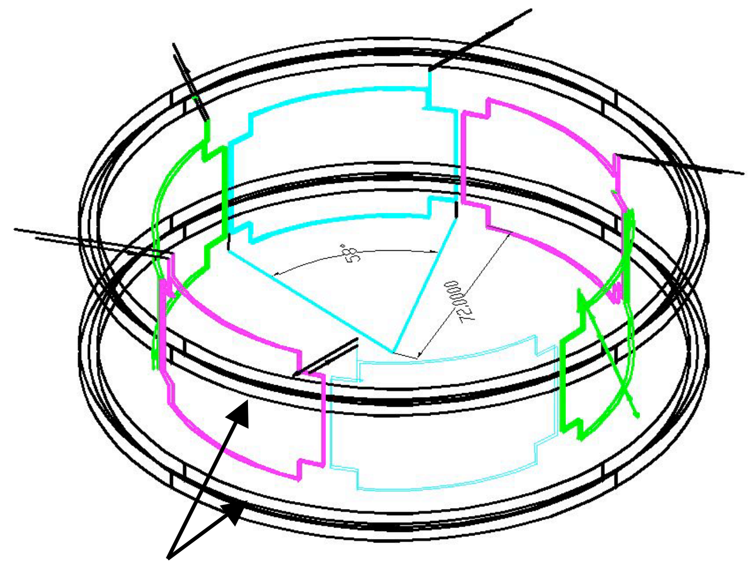
3MW EBW System Proposed

- Calculations show ~3MW (delivered) EBW power can provide control needed for advanced scenarios in NSTX
- ~15GHz for f_{ce} and Doppler-shifted $2f_{ce}$ absorption
- Develop ~1MW gyrotron sources (FY'04 – 05)
  - Collaboration with MIT, VLT
    - Possible vendor CPI
  - Adaptation of existing technology
- Steerable mirror launcher and low-loss waveguide
- Up to 1MW (1 tube) in FY'06
  3MW (4 tubes) in FY'07



Active Control of Resistive Wall Modes

- RWM identified in plasmas above the wall-stabilized β-limit
  - Amplifies non-axisymmetric field errors
    - Field errors greatly reduced by PF5 realignment in FY'02
- Install 6 external "picture frame" correction coils in FY'04
  - Operate as 3 opposing pairs with Switching Power Amplifiers
- Experiments to counteract error field amplification in FY'04
  - Planned in 21-week run
- Active RWM feedback in FY'05
- Assess need for installing internal control coils in FY'06

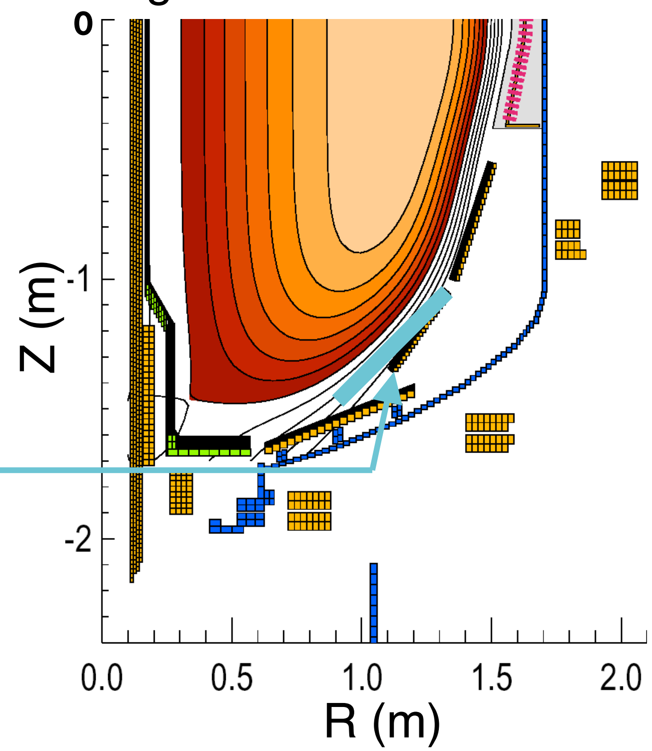


PF5 coils (main vertical field)

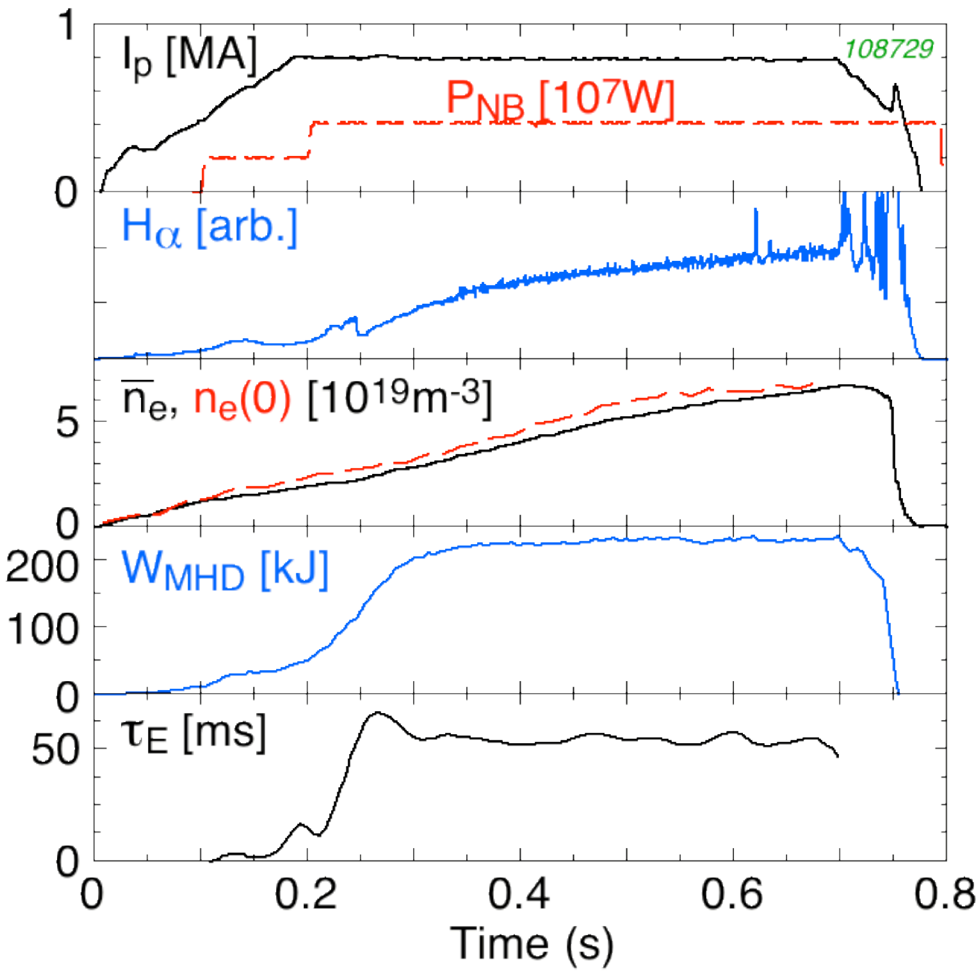
Modifying PF1A Coils Can Produce Higher Triangularity at Higher Elongation

- Higher triangularity ~ 0.8 at elongation > 2 desirable
  - MHD benefit mainly through higher toroidal current for fixed q
- Moving PF1A coils further from midplane or splitting coils gives greater shaping capability
  - Moving coils simpler but range of shapes limited
  - Split coils give more flexibility
- Increase benefit to stability by realigning secondary passive stabilizers closer to boundary
- Assess trade-offs, design in FY'04
- Install in FY' 05 opening

Using outer half of PF1A coils



High-Field-Side Gas Injection Improved Both Reproducibility and Longevity of H-mode



- HFS injector gives large initial flow then continuing lower flow
  - contributes to density rise
- Later, less reliable transition with same flow from LFS
- More controllable HFS injector installed on CS upper shoulder for FY'03
- Injectors planned for other poloidal locations in FY'04

- *New fueling methods may provide means to advance physics*

Solid Pellets and Supersonic Gas Injection Will Enhance Fueling Capabilities

- Injector for room-temperature solids now in development for installation this year
  - Lithium, boron, carbon as pellets or micro-pellet ensembles
  - 20 – 400 m/s with up to 8 pellets/shot
- Supersonic gas injector being developed with CDX-U and M&AE Dept. for installation this year
  - Up to 6×10^{21} D in 300ms at ~1.8km/s
- Deuterium pellet injector proposed for installation in FY'05 in collaboration with ORNL
  - Multiple pellets/shot capability
  - Initially outside mid-plane launch through pump duct
  - Upgrade to guided *inside* launch in FY'06

Investigate Both Fueling and Momentum Effects with Compact Toroid Injector

- CT injector used on Tokamak de Varennes available to NSTX
  - Collaboration with University of Washington
- High field gradient of ST well suited to CT injection
  - Variable fuel mass and deposition location
- Provide momentum injection (≡50ms of 1MW NBI)
  - Induce H-modes (STOR-M, TdeV) or ITBs
  - Transport studies by isotopic impurity tailoring
  - Prompt density injection to avoid locked modes
- Conduct off-line testing (FY’05–6)
  - UWash to investigate development of multi-shot capability
- Install on NSTX in FY’07

Improved Treatment of Plasma Facing Components Benefited Physics Studies

- Boronizaton routinely applied since Sep. '00
  - Glow discharge (~2 hr) in mixture of deuterated trimethyl boron $(CD_3)_3B$ ("TMB") [10g], He [90% by vol.]
  - After bakeout & every 2 weeks of operation (19 times)
- Full bakeout capability introduced in Mar. '02
  - Center column to 350C
  - Outer PFCs to 320C (heated by high-pressure helium)
- Immediate benefits in terms of
  - reduced flux consumption
  - lower impurities
  - improved H-mode access
  - reduced MHD activity
- Investigate boronization *during* bakeout and daily, or between-shots, boronization in FY'04

Propose Two Methods for Coating Plasma Facing Components with Lithium

- Demonstrated benefit of coating carbon limiter in TFTR
  - Strong edge pumping (reduction of recycling)
  - Improvement of energy confinement (2)

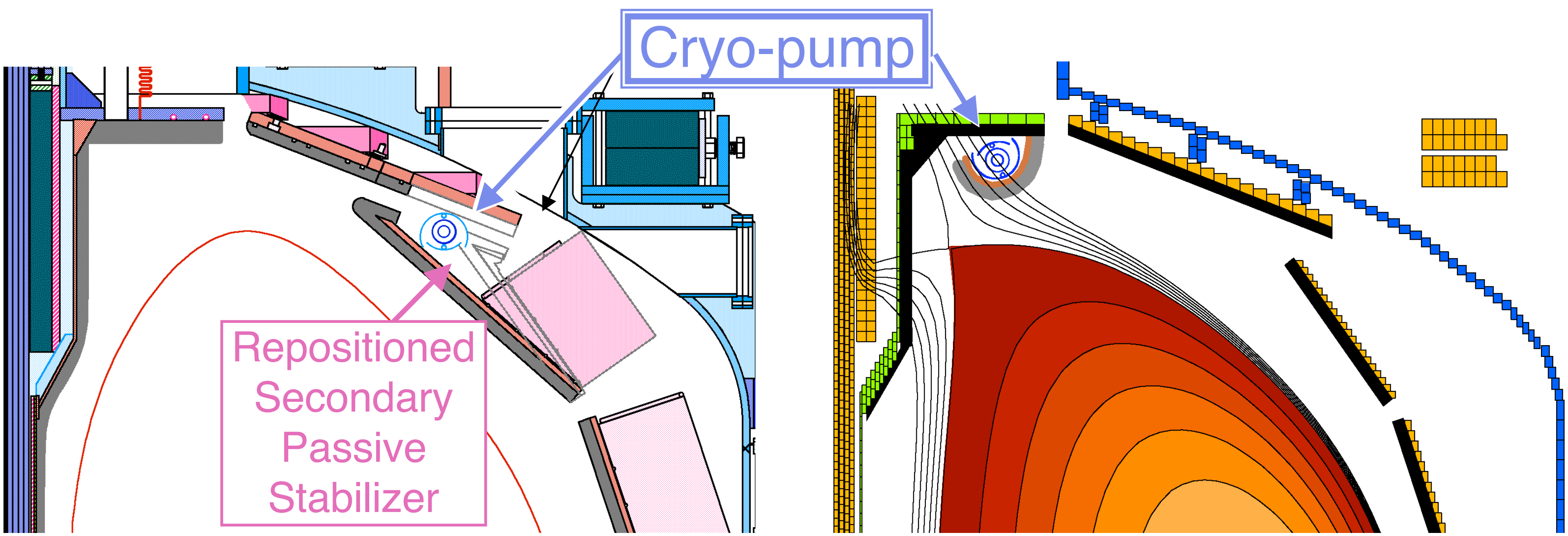
1. Lithium pellet injection (FY'04)
   - Use multiple pellet capability
   - Could also investigate other materials (*e.g.* B)
2. Lithium evaporator (FY'05)
   - CDX-U developing modular e-beam evaporator
   - Use several evaporators to cover NSTX divertor
   - Benefit from CDX-U research to optimize substrate material
     - Possible change from carbon PFCs in FY'07

Divertor Cryo-Pump Can Provide Needed Density Control

- Proven technique
- Requires adequate conductance from neutralization region
- Two schemes being evaluated for FY’05 installation

1. Behind secondary plates
- Suitable for ≤ 0.5
- Requires plate relocation

2. Shield on inner divertor
- Suitable for ~ 0.8
- Installation on center stack

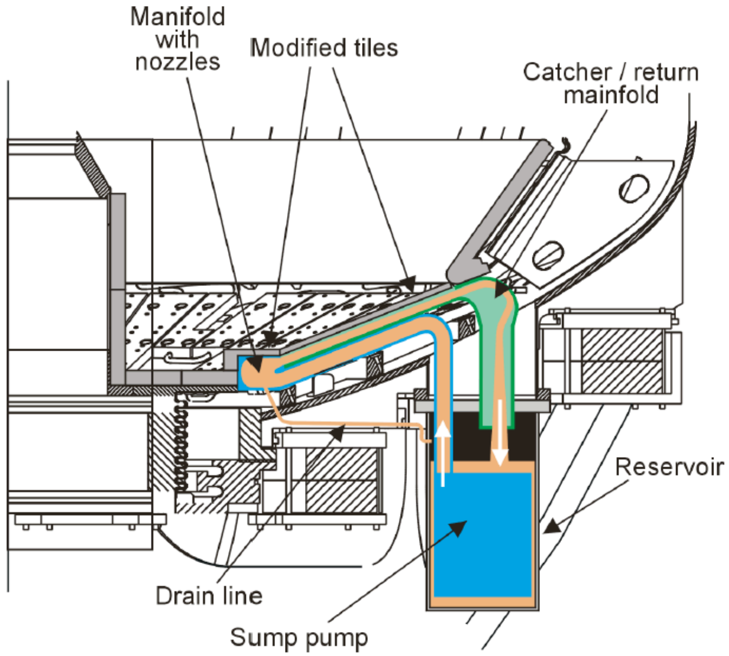


Upgrade of Divertor Tiles May Be Needed for Long-Pulse Operation at High Power

- Present divertor tiles of ATJ graphite
- Limit surface to 1200C to avoid radiation-enhanced sublimation “carbon blooms”
- Measurements indicate tiles adequate for 3s at full NB + HHFW power
- Investigate heat-flux mitigation techniques in FY’04-5
  - Strike-point sweeping
  - Enhanced divertor radiation
- Assess need for material upgrade to be installed FY’07
  - Options include CFC, refractory metals, possibly combined with lithium coating
  - Decision will benefit from accumulated experience of CDX (Li), C-Mod (Mo) and ASDEX (W)

Liquid Lithium Surface Module Will Address Important Reactor Issues

- Development under aegis of ALIST group of VLT
- A potential solution for *both* power and particle handling
  - Tantalizing possibilities for advanced regimes
  - Liquid Li tray in CDX-U dramatically reduced recycling



- Modules ~1m^2 close to plasma
- Flow liquid Li at 7 – 12 m/s to avoid evaporation at full power
- Installation in FY'08

Proposed Upgrades Build Steadily on Solid Research to Create a Vibrant Program

NSTX

Upgrade	Research Areas of Interest							Development/Installation					
	MHD	Transport	HHFW	EBW	CHI	Boundary	Integration	FY03	FY04	FY05	FY06	FY07	FY08
Auxiliary Systems													
Absorber field null control					√			▒	■				
NB power modulation	√	√					√		■				
PF power supply upgrade	√		√				√		■				
HHFW antenna end-feed			√						▒	■			
EBW system, 1MW	√	√		√					▒	▒	■		
EBW system, 3MW	√	√		√			√					■	
MHD/Error Field Control													
RWM sensors & detection	√						√	■					
Active mode-control	√						√		■		■		
PF1A coil modification	√					√	√		▒	■			
Passive stabilizer relocation	√						√		▒	■			
Fueling, Power and Particle Control													
Li/B pellet injector		√				√	√	■					
Supersonic gas injector		√				√	√	■					
Lithium wall coating	√	√	√	√	√	√	√		▒	■			
Divertor cryo-pump		√	√	√	√	√	√		▒	■			
D pellet injector (LFS)		√				√	√			■			
D pellet injector (HFS)		√				√	√			▒	■		
CT injector		√				√	√			▒	▒	■	
Divertor long-pulse upgrade						√	√				▒	■	
Liquid Li surface module	√	√	√	√		√	√					▒	■