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An Update of ST-VNS Based on New NSTX Results

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THE U.S.-RUSSIA BILATERAL EXCHANGE I.2: BLANKET AND FUSION CONCEPT FOR THE TRANSMUTATION OF ACTINIDES

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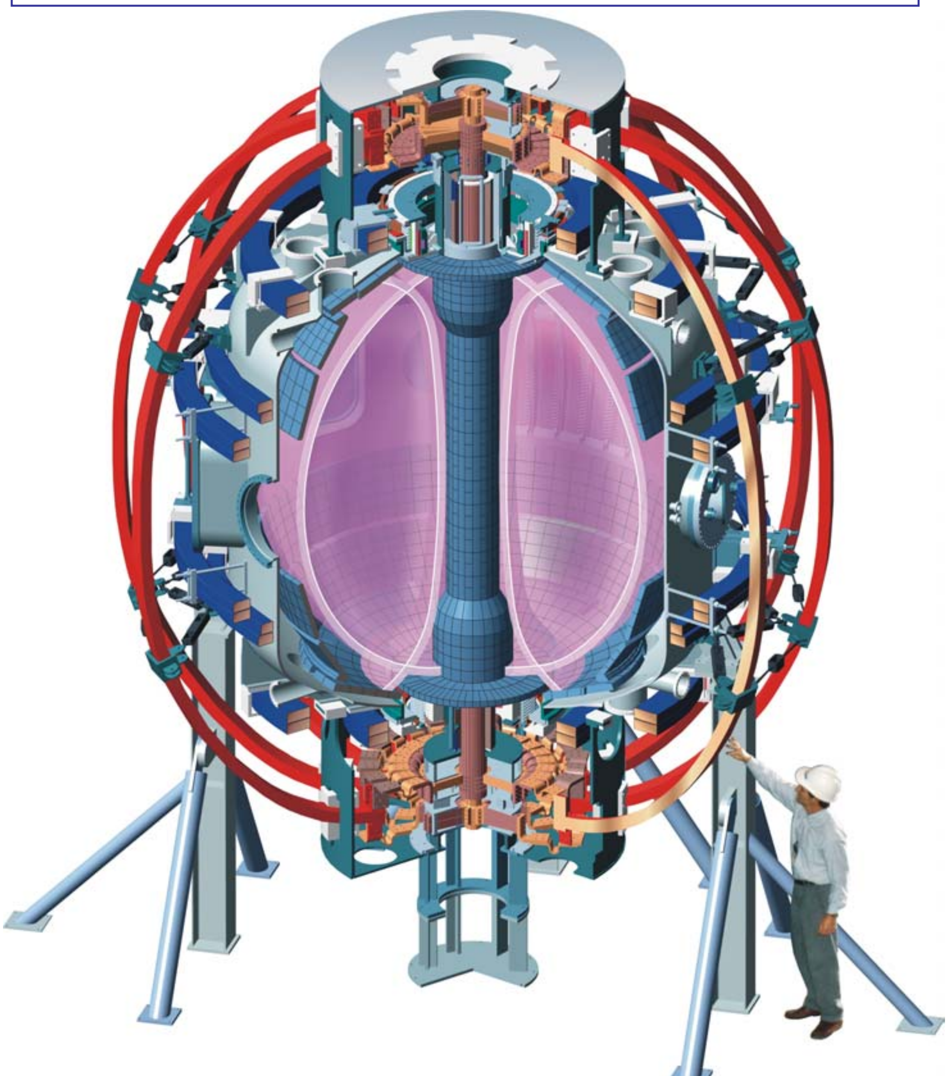
NSTX is a New Magnetic Fusion Energy Sciences Experiment in the U.S.

NSTX

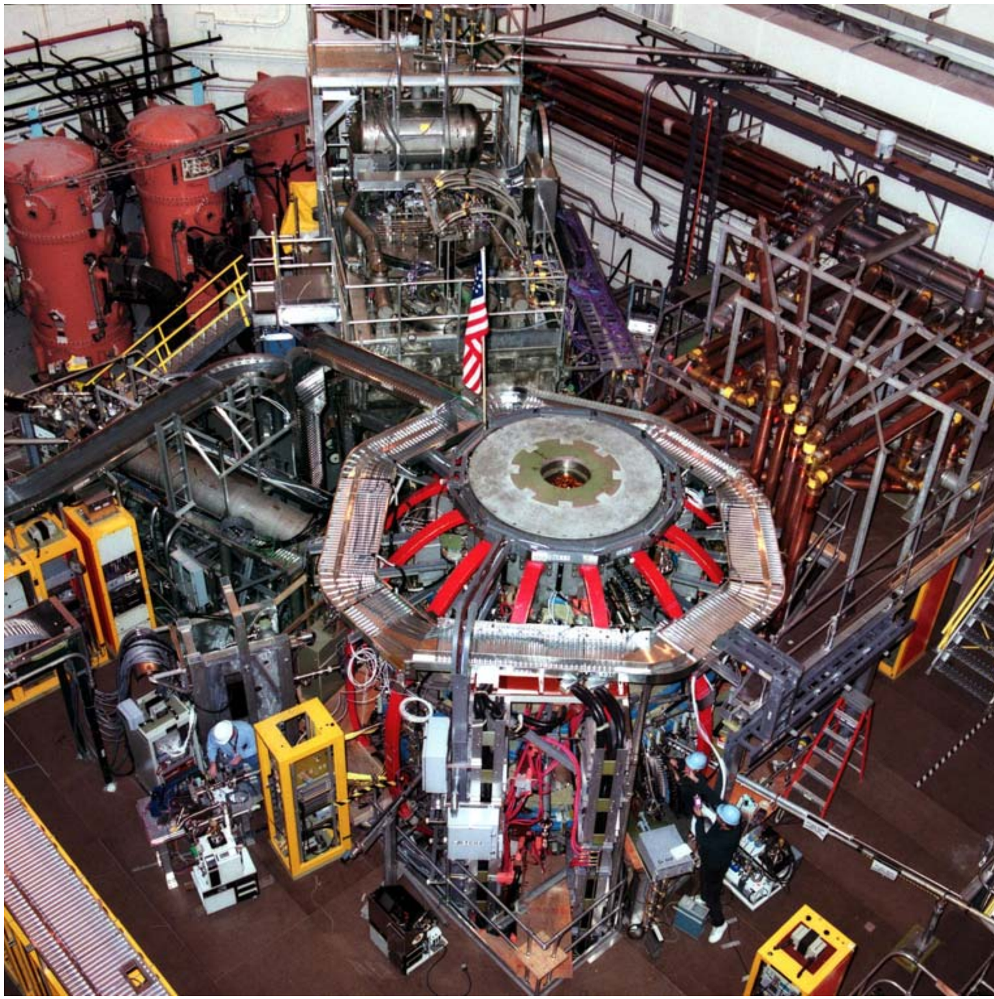
National Spherical Torus Experiment



New results are expanding the parameter space of toroidal plasma science

- Capabilities; research goals in science and fusion energy
- Solenoid-free startup – **magnetic reconnection**
- Energy confinement - **turbulence**
- Stability at beta (pressure/field^2) = order unity - **MHD**
- Heating & current drive - **wave-fast ions-plasma interactions**
- Plasma heat & particle fluxes – **plasma edge physics**
- Future development possibilities

NSTX Facility Has Made Rapid Progress in Capability Since Start of Operation in 9/99

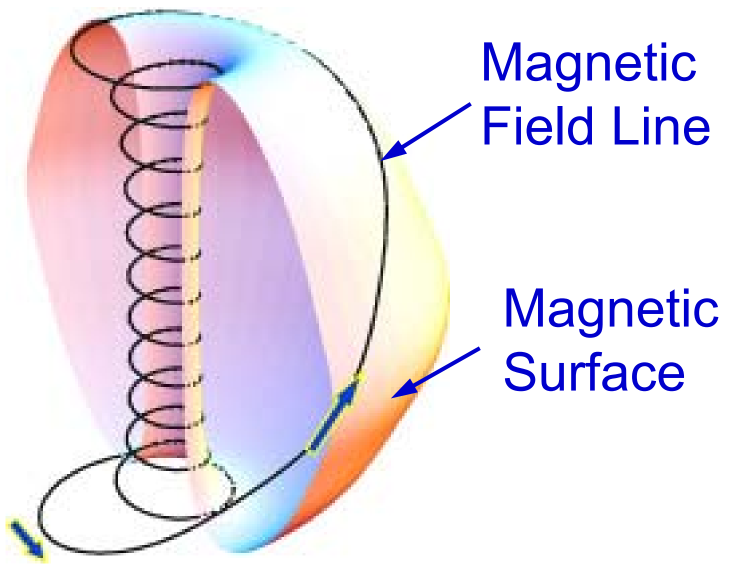


Parameters	Design	Achieved
Major Radius	0.85m	}⇒A≥1.27
Minor Radius	0.68m	
Elongation	≤2.2	2.5
Triangularity	≤0.6	0.8
Plasma Current	1MA	1.5MA
Toroidal Field	0.6T	≤0.6T
Heating and Current Drive		
Induction	0.7Vs	0.7Vs
NBI (90keV)	5MW	7MW
HHFW (30MHz)	6MW	6MW
CHI	0.5MA	0.4MA
Pulse Length	≤5s	1.1s

Spherical Torus Permits Studies of High β Plasmas with Strong Shaping & Rotational Transform ($q \sim 10$)

NSTX

Spherical Torus



- A = aspect ratio
- $\beta_T = 2\mu_0\langle p\rangle/B_{T0}^2$
- q = rotational transform
- ρ_i = ion gyroradius

Expanded plasma parameter space:

- Strong plasma shaping ($A \geq 1.27$, $\kappa \leq 2.5$, $B_p/B_t \sim 1$, $q_{edge} \sim 10$)
- High β_T ($\leq 40\%$) & central β_0 ($\sim 100\%$)
- Large plasma flow ($V_{rotation}/V_A \sim 0.25$)
- Large 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 curvature in edge magnetic field

Expanded Plasma Parameter Space Potentially Also Lead to Attractive Fusion Energy Devices

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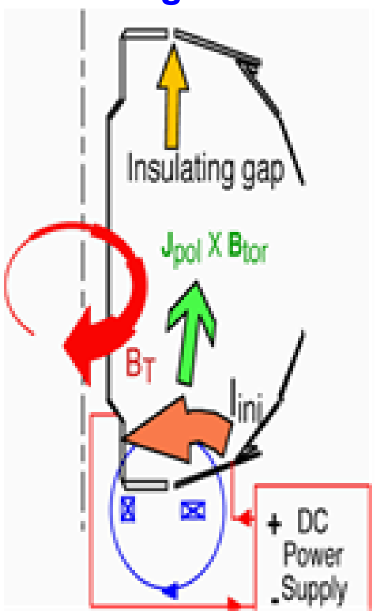
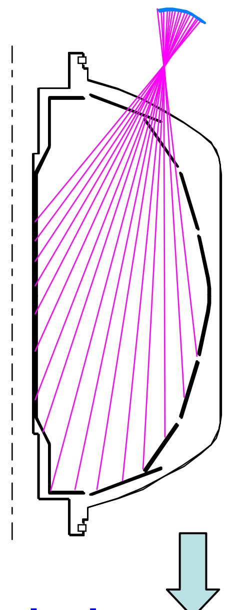
Plasma Science of Expanded Parameter Space	⇒	Attractive Energy Development Steps
• Solenoid-free Startup	⇒	Simplified design, reduced operating cost
• Reduced turbulence	⇒	Smaller unit size for sustained fusion burn
• Stable high β_T & β_0	⇒	Lowered magnetic field and device costs
• Strong wave-energetic particle-plasma interaction	⇒	Efficient fusion α particle, neutral beam, & RF heating
• Dispersed plasma fluxes	⇒	Survivable plasma facing components
• Self organization	⇒	Sustainment without induction

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

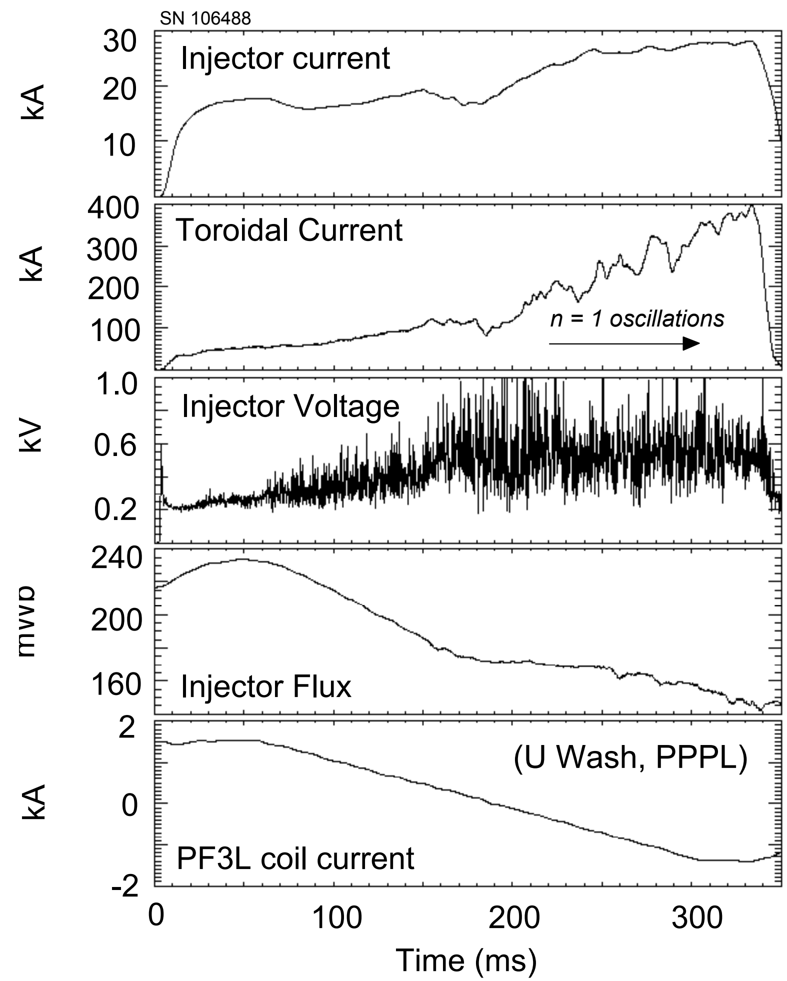
Injection Configuration



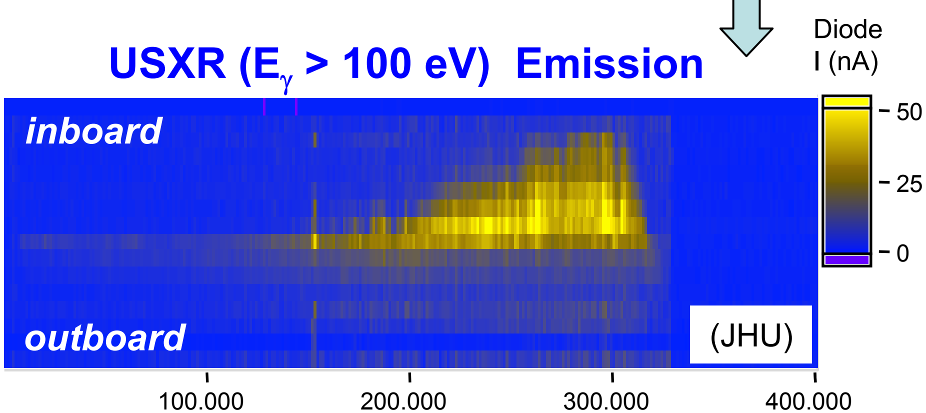
USXR Detectors



n=1 oscillations related to reconnection mechanisms



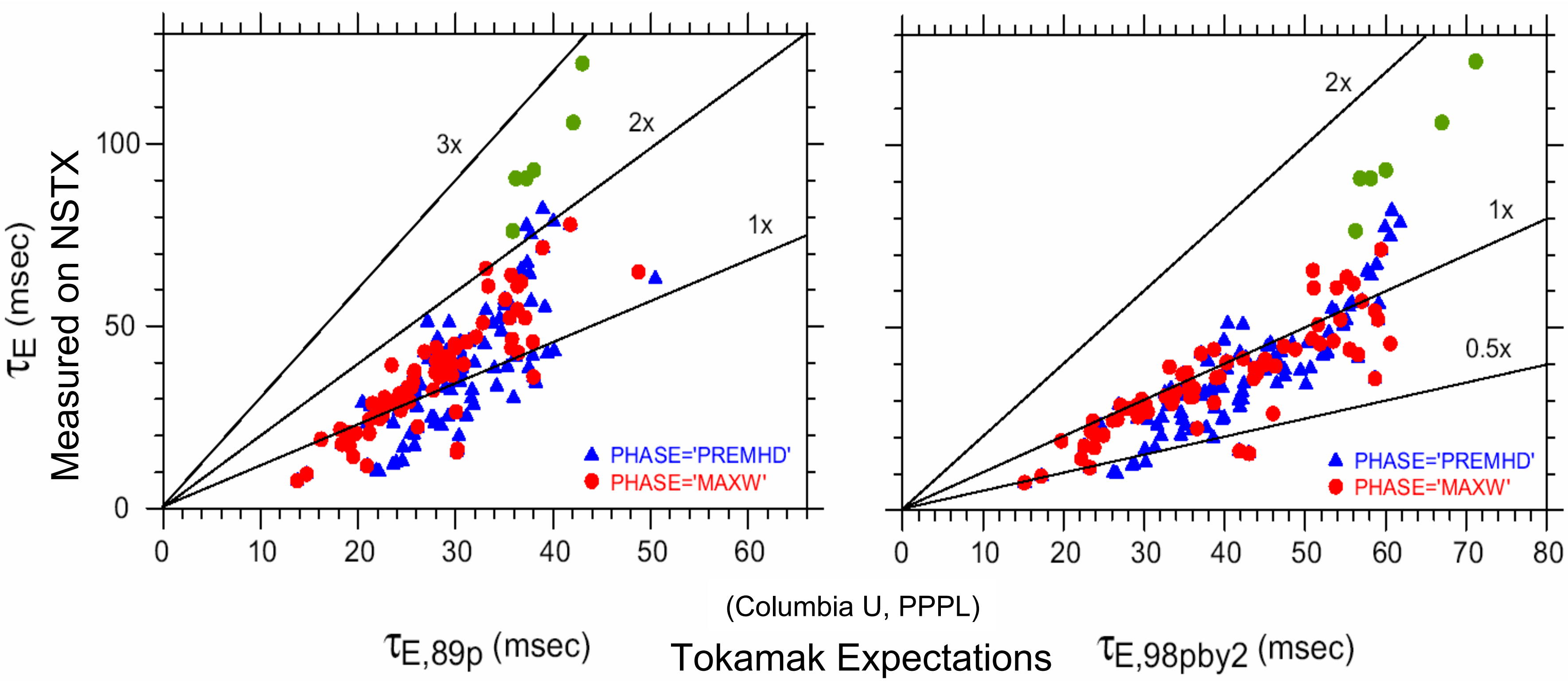
USXR (E_γ > 100 eV) Emission



Plasmas with Beam Heating Can Surpass "High-Confinement Mode" Level Without Edge Barrier

NSTX

- Trend of confinement time data better than expectations based on Tokamak data
- Encouraging indications for future small fusion energy devices

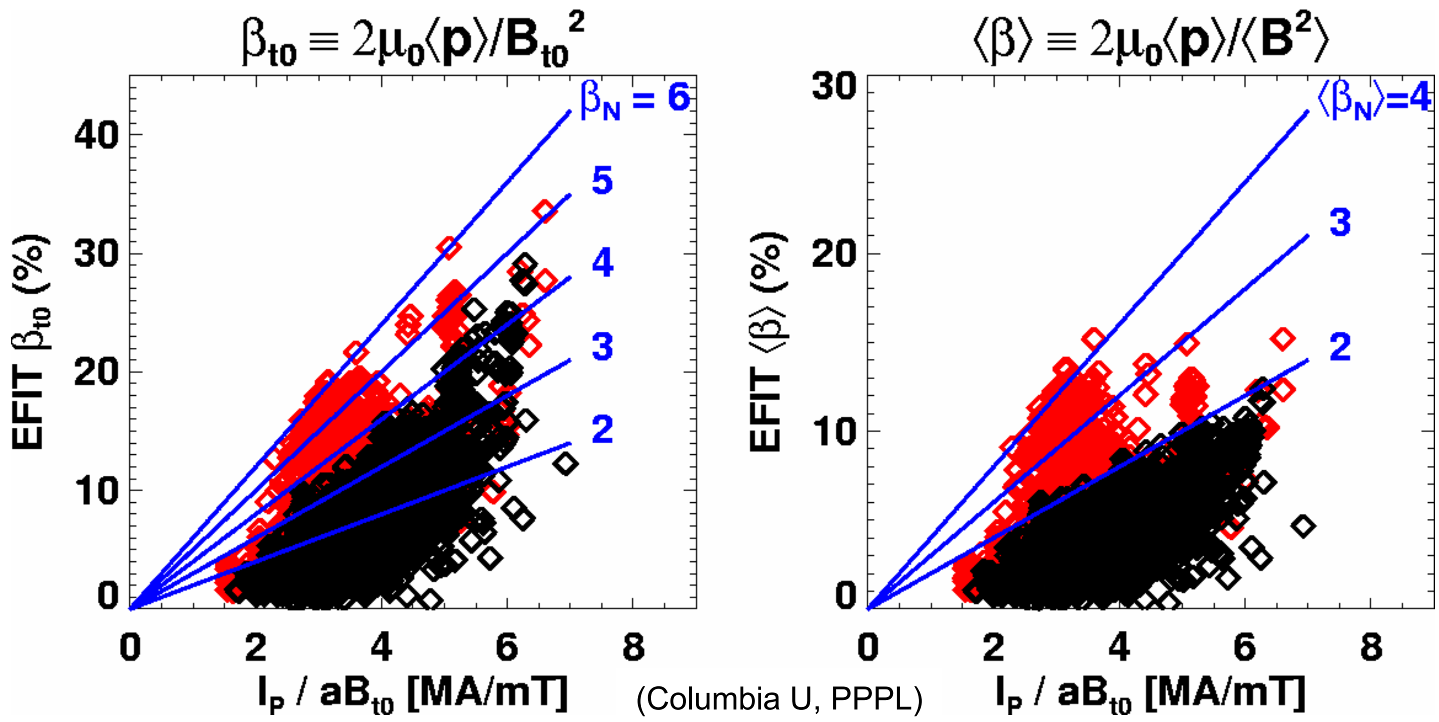


(Columbia U, PPPL)

Tokamak Expectations

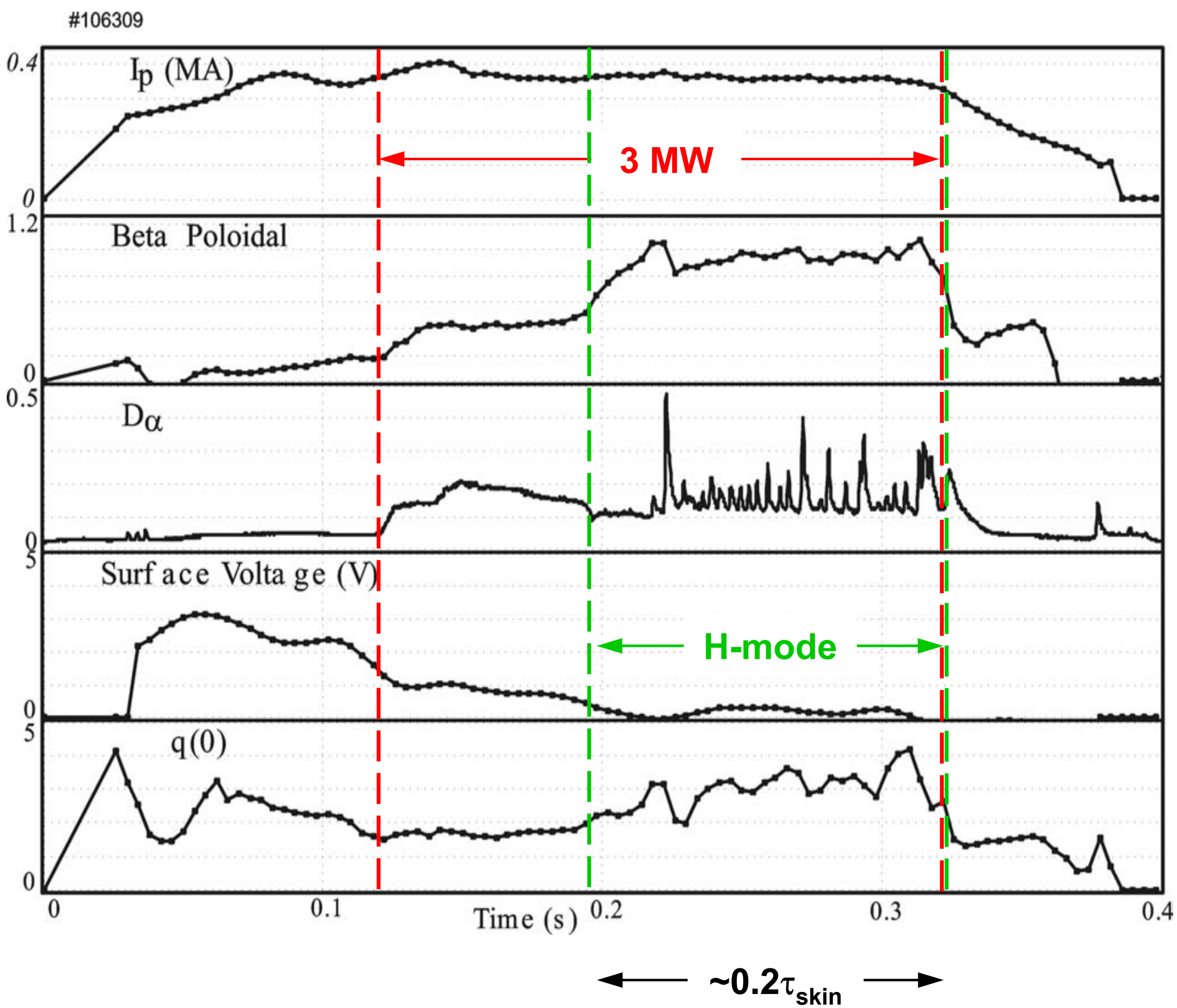
Troyon Scaling ($\beta_{t0} = \beta_N I_p/aB_{t0}$) Continues to be Obeyed

- $\beta_{N,max}$ ~ 6.3, W_{MAX} ~ 390kJ
- $\beta_P \leq 1.5 \Rightarrow$ first indication of diamagnetic current that lowers B_t
- Improved field axisymmetry and wall cleanliness $\Rightarrow$ higher β



(Black $\Rightarrow$ 2001 data   Red $\Rightarrow$ 2002 data, coil alignment + bake to 300 °C)

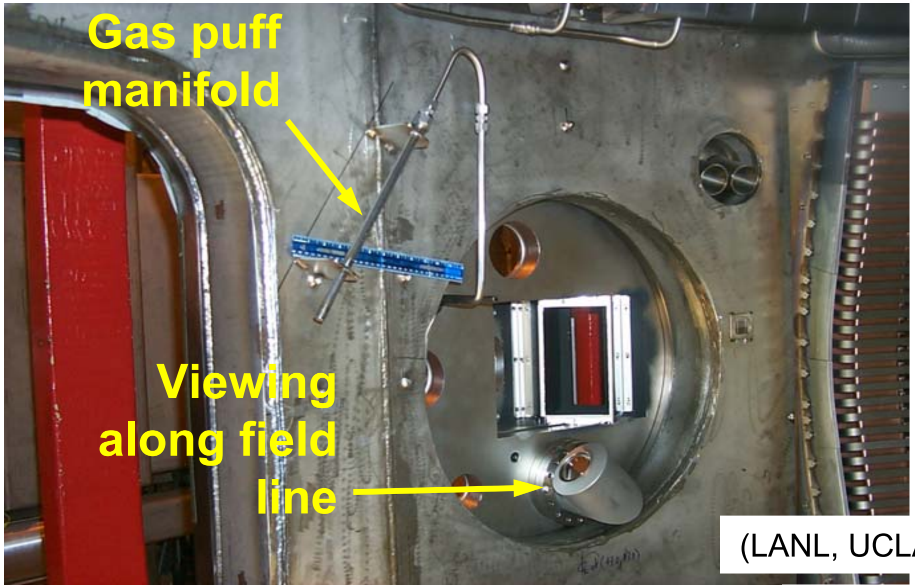
First Indications of HHFW-Heated Plasmas with Reduced Inductive Requirements



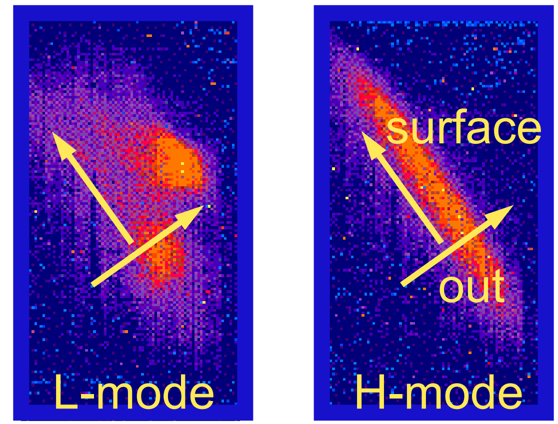
- Moderate plasma current
- High β_p ~ 1
- H-mode with Edge-Localized Modes
- Induction voltage reduced to <0.5 V
- Low internal inductance l_i ~ 0.9

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

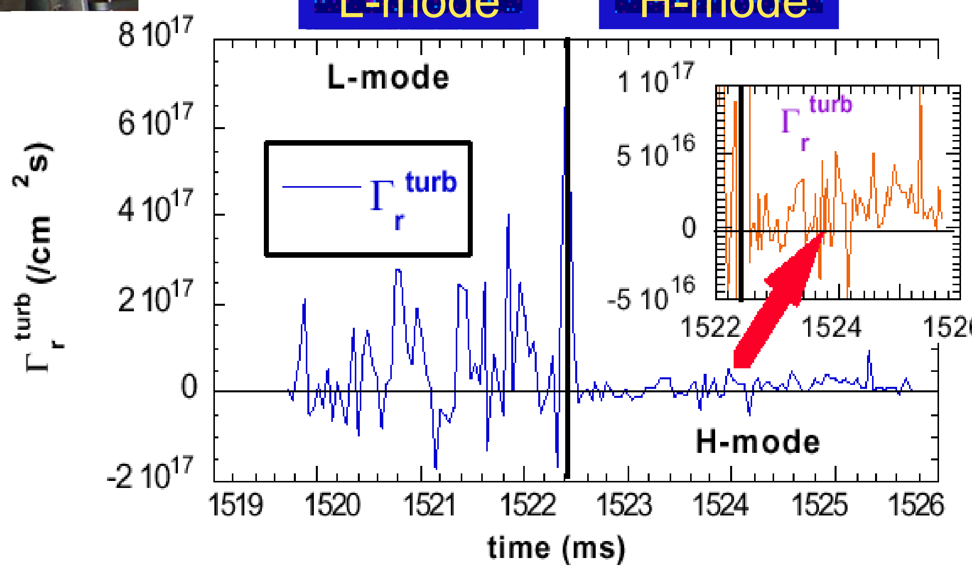
NSTX



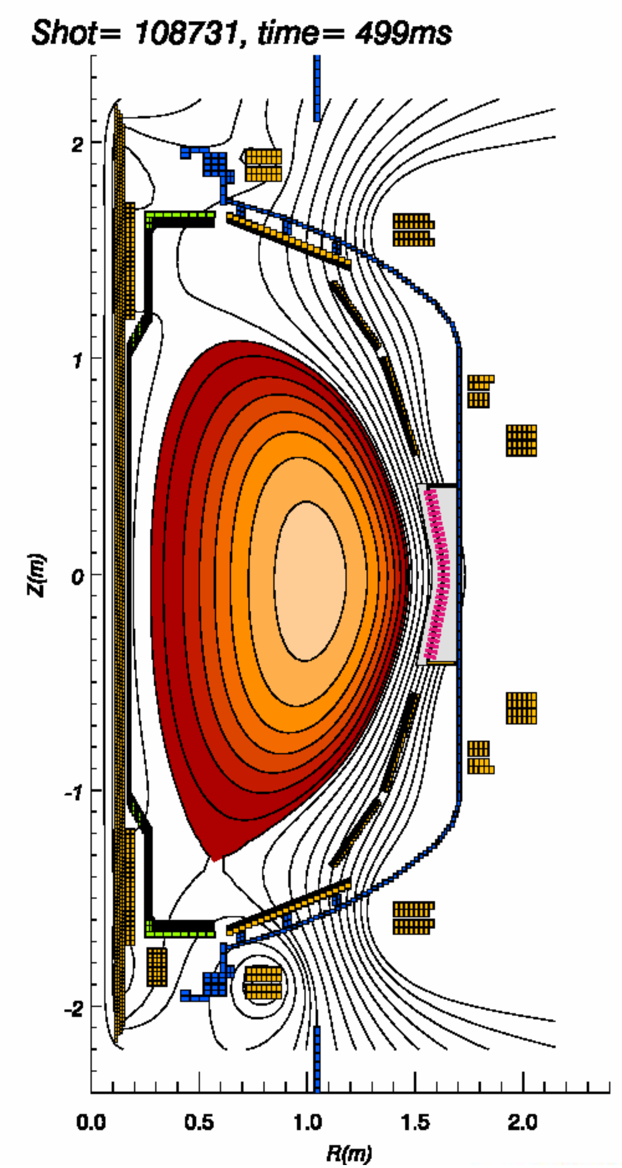
(LANL, UCLA, PPPL)



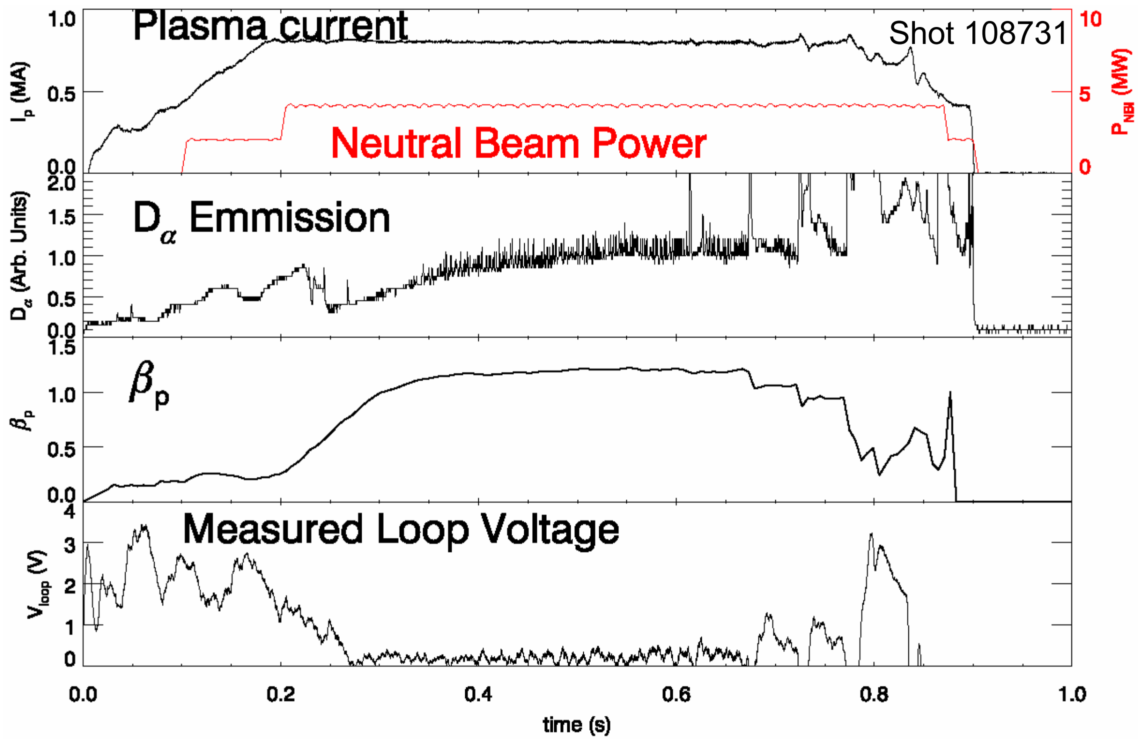
- Also in C-Mod Tokamak (MIT)
- He puff in D_2 discharge
- 10 μs exposures @ 100 kHz
- Several cm in cross section
- Moves at a few hundred m/s
- Coincidental with "Low-Mode"
- Absent or rare in "High-Mode"



Non-inductive current ~50% in high β_p discharges

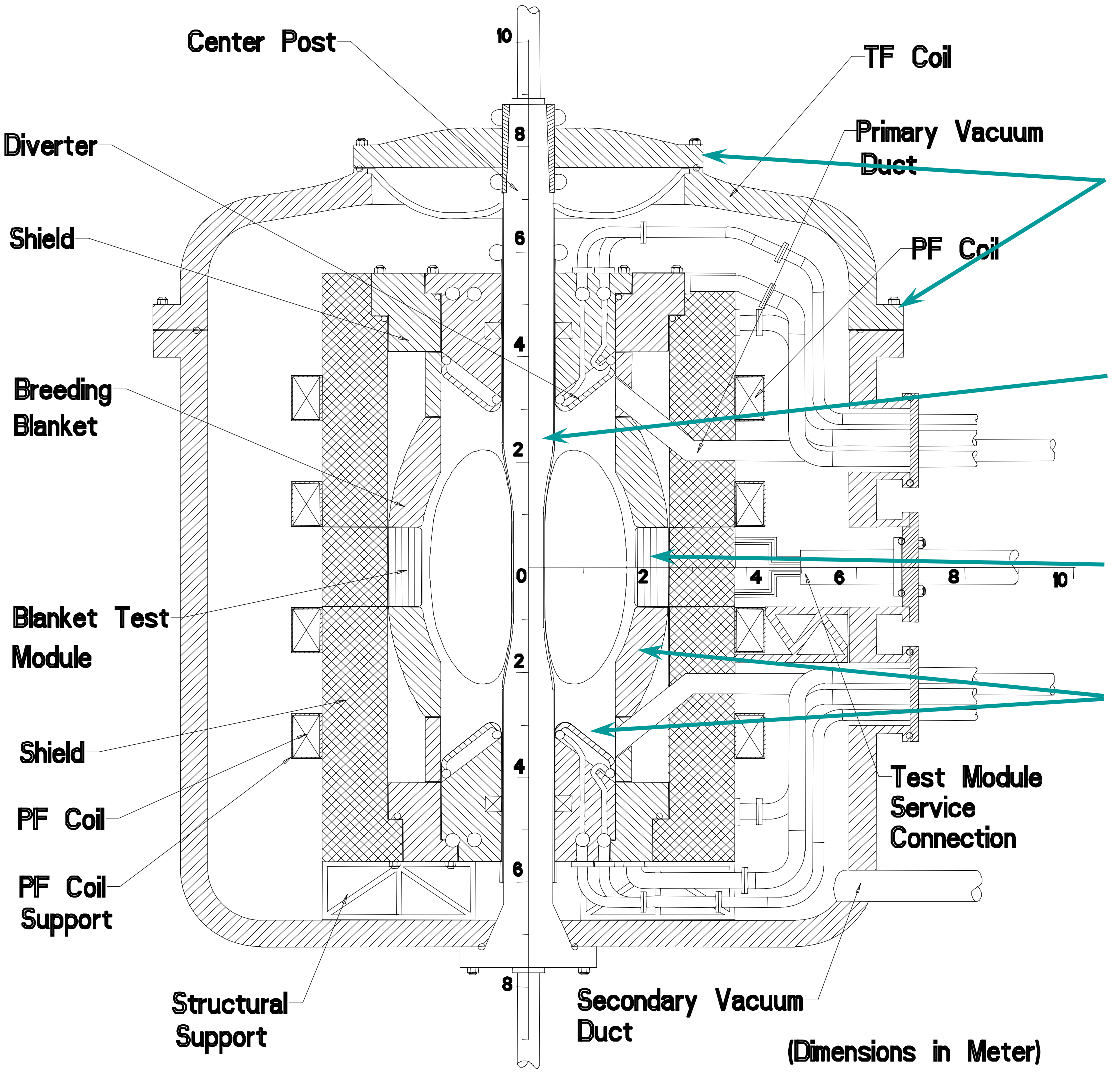


- Bootstrap current crucial to the ST concept
- Loop voltage < 200mV for > 0.4s
- Single null offers easier H-mode access
- Plasma pulse > 1 s also achieved



ST Could Enable a Small Volume Neutron Source (VNS) with Desirable Maintenance and Testing Features

VNS



Features

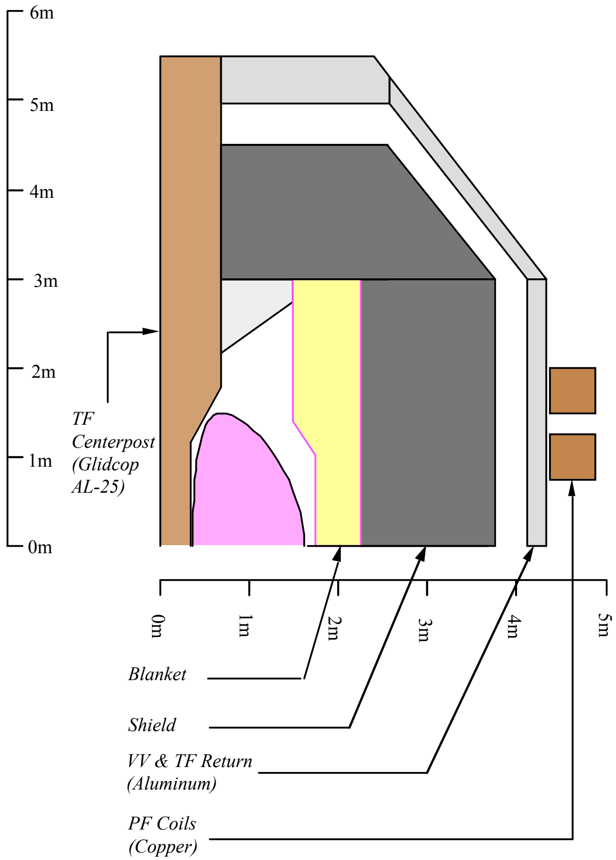
- **Remote maintenance** for activated first-wall, divertor, blankets
- **Demountable single-turn** toroidal field magnet center leg
- **Full access** to test blanket modules
- **Modular** design
- Core components could use ITER EDA

New Technology

Single-turn TF center leg

VNS Update

Prototype Transmutation ST (P-TST) & full scale *Transmutation ST* (TST)



	P-TST	TST	VNS
R0 (m)	1.000	1.000	1.070
A	1.400	1.400	1.400
κ	2.521	2.521	2.300
δ	0.400	0.400	0.400
q_{95}	7.000	7.000	8.443
B_T (T)	1.500	1.500	1.900
Ip (MA)	10.144	10.144	9.700
β_N (%)	3.48%	5.37%	3.59%
β_T(%)	32.9%	50.8%	24.0%
β_P(%)	34.0%	52.4%	42.5%
f_{GW} (%)	16.4%	31.6%	25.8%
f_{BS} (%)	22.3%	34.3%	36.8%
$\langle T_e \rangle$ (keV)	12.2	9.75	13.0
HH	1.6	1.6	1.8
Q	0.92	1.41	1.60
P_{Fusion} (MW)	20.0	50.0	32.1
$\sum P_{Electric\ Input}$ (MW)	154.5	188.7	192.7
Average N_{wall} (MW/m^2)	0.43	1.07	0.619

- PPPL System Code includes engineering algorithms for steady state TF and PF coils
  - -TF uses water cooled Glidcop AL-25 inner leg @ 4.3kA/cm^2, 15% coolant fraction
  - -TF return current through Al vacuum vessel @ 150A/cm^2
  - -PF coils are water cooled copper @ 1kA/ cm^2, 20% coolant fraction

The Basic Design Concept for VNS Has Remained Consistent with the Latest NSTX Data

- Recent NSTX data has been encouraging:

  Ip = 0.8 MA, A ~ 1.4, κ ~ 2, q_{95} ~ 8, β_N ~ 6, β_p ~ 1.2, β_T ~ 16%, ℓ_i ~ 0.7, Induction ~ 0.1-0.2 V, H_{98pby2} ~ 1.5, constant for ~ 0.4 s.
- Data under analysis; extrapolate to VNS: $\kappa \geq 2.5$, $\beta_T \geq 25\%$, ℓ_i ~ 0.4 at R ~ 1.1 m and current ~10MA?
- Physics issues:
  - Ti ~ 2 Te?
  - NBI current drive efficiency vs. beam energy in ST?
  - H-mode plasma with inboard limited natural divertor?
- Data needs:
  - Proof of Principle data for durations >> τ_{skin}
  - Performance Extension data at ~ 5MA level