FUSION ENERGY DIVISION

QPS

ECH, EBW and ICRF for QPS

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Presented by J. F. Lyon

NIFS, October 19, 2001

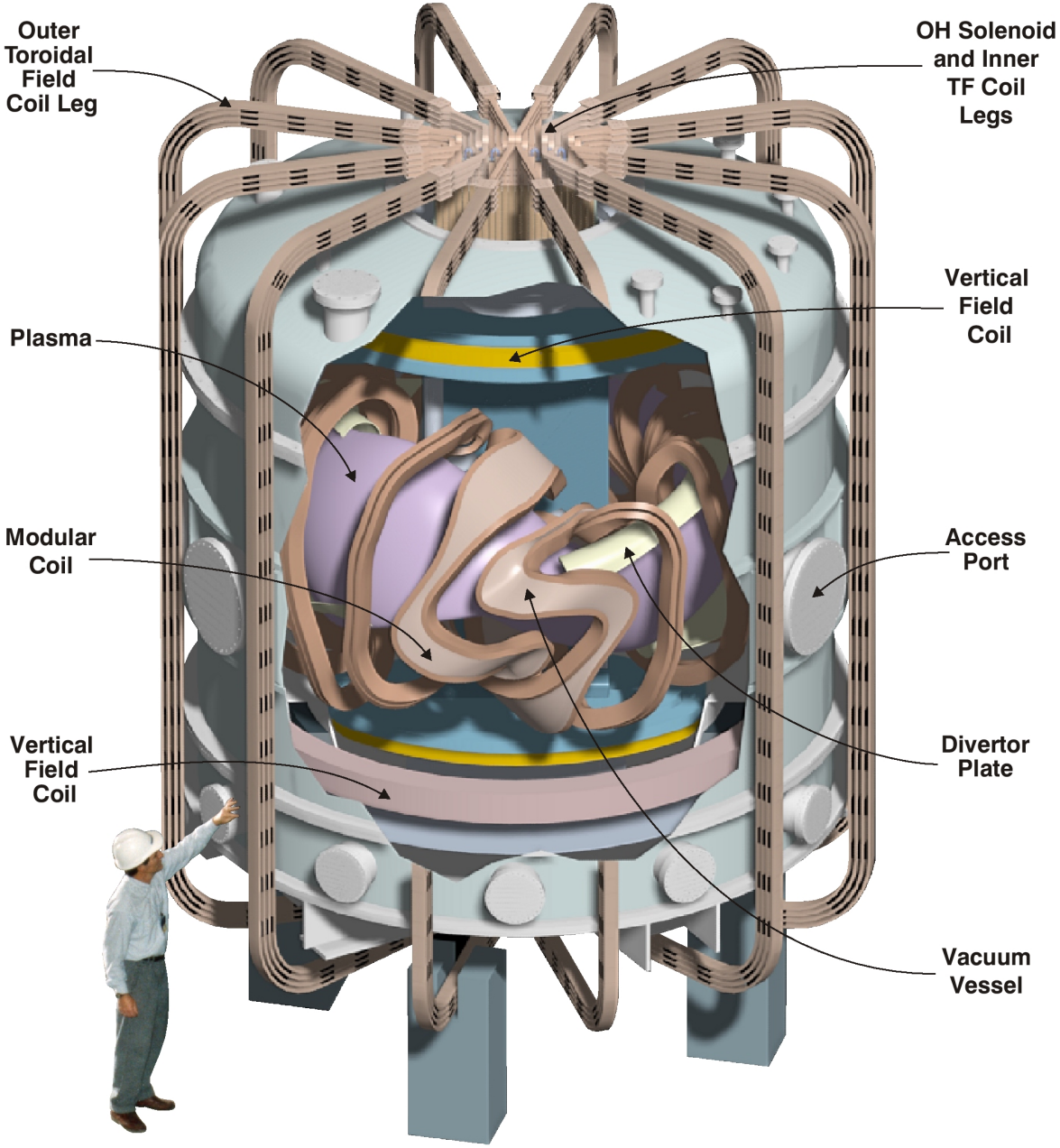
Topics

- QPS vacuum and coil geometry
- QPS magnetic configuration
  - present configuration
  - April configuration for which studies done
- ECH/EBW heating on QPS
- ICRF heating on QPS

U.S. Is Planning Two Compact Stellarators

Feature	NCSX	QPS
R, a, B, $P_{heating}$	1.4 m, 0.33 m, 2 T, 6-12 MW	0.9 m, 0.33 m, 1 T, 1-3 MW
Magnetic Symmetry	Quasi-Axial	Quasi-Poloidal
Aspect Ratio R/a	4.3	2.7
Key physics issue	High-β stability and disruption immunity	Low-$R/\langle a \rangle$: strong toroidal effects on equilibrium, stability & transport
Enhanced Confinement Route	Tokamak-like drift orbits, flow-shear stabilization	Small $B \times \nabla B$ radial drift, reduced poloidal viscosity

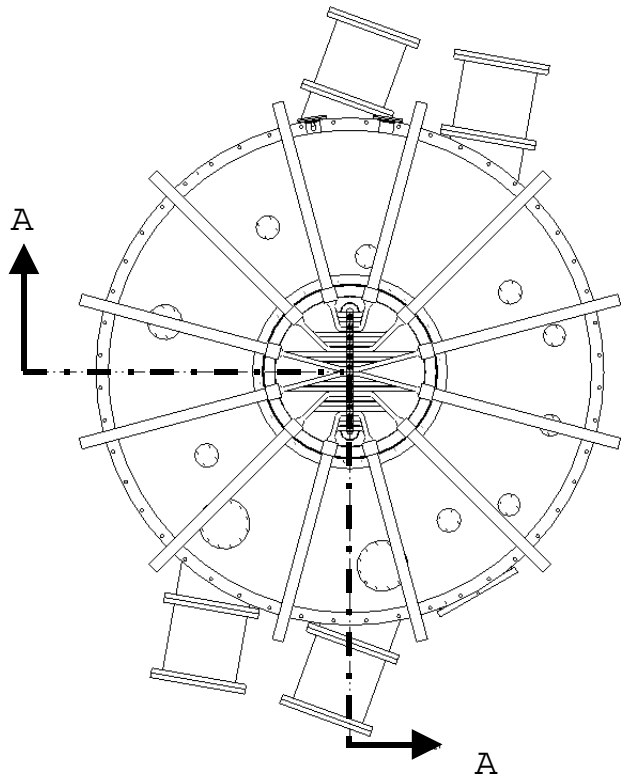
- Both NCSX and QPS have had successful Physics and Project reviews by DOE
- Next step is Conceptual Design, Cost and Schedule Reviews in April and May, 2002
- DOE intends to do both, first plasmas in March 2007

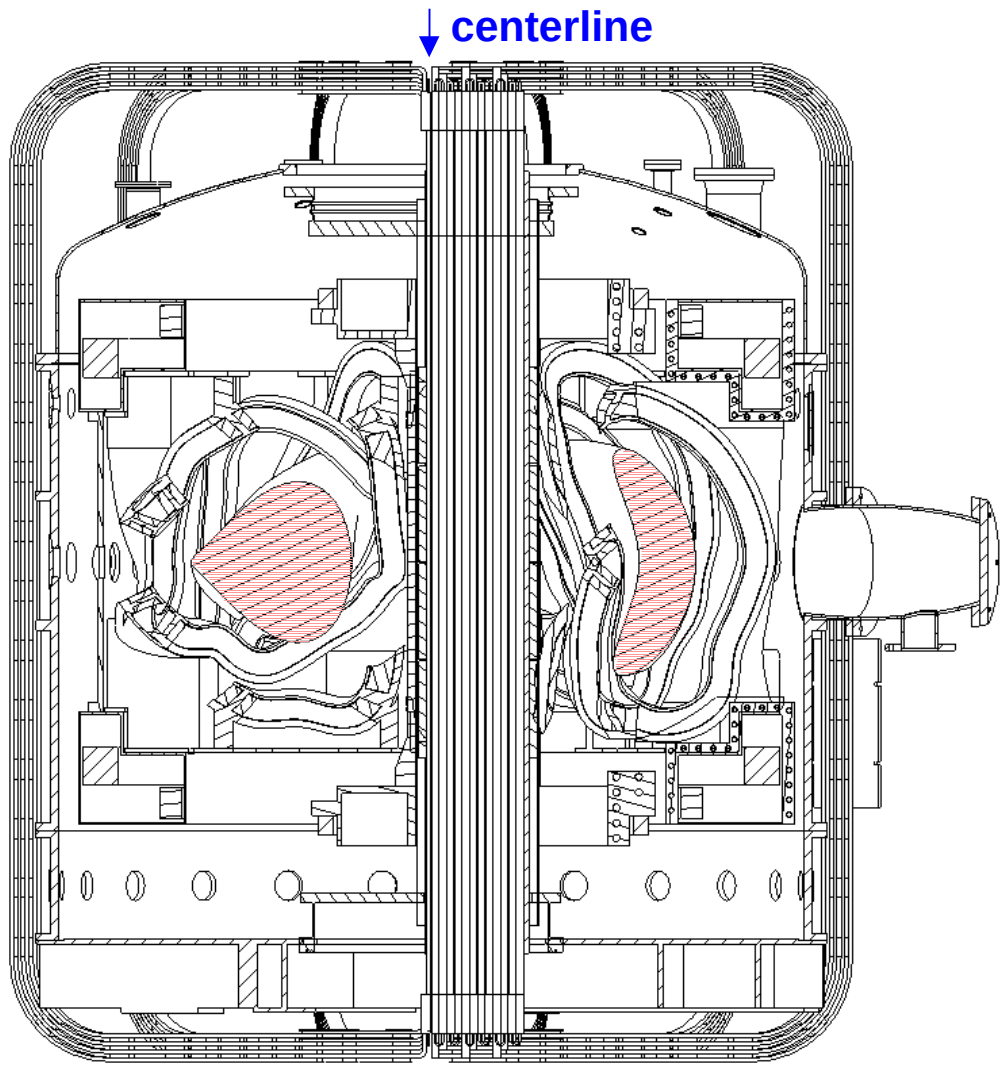


QPS

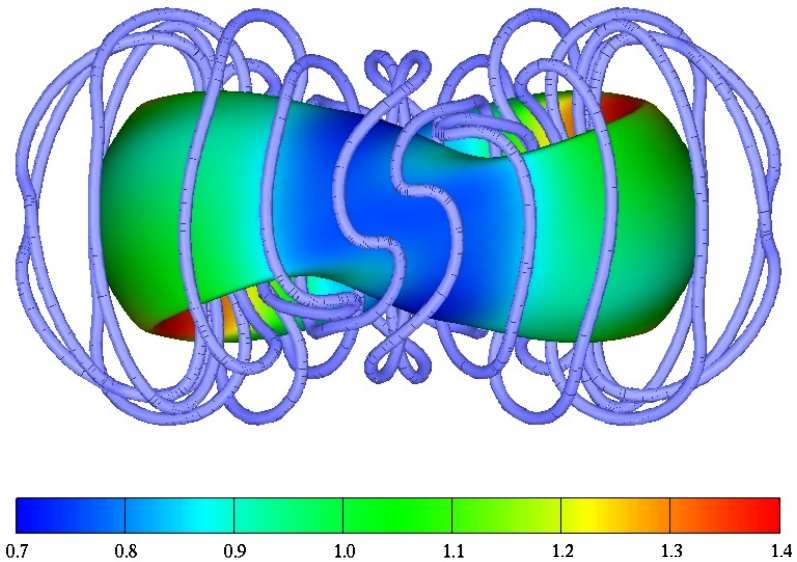
- $\langle R \rangle = 0.9$ m
- $\langle a \rangle = 0.33$ m
- $\langle R \rangle / \langle a \rangle = 2.7$
- $V_{plasma} = 2\ m^3$
- 61-cm dia. Ports
- No interior vacuum vessel
- $\iota_0 = 0.26$, $\iota_a = 0.39$
- $B_{mod} = 1$ T (1 s)
- $B_T = \pm 0.2$ T
- $I_p \leq 150$ kA
- $P_{ECH} = 0.6\text{-}1.2$ MW
- $P_{ICRF} = 1\text{-}3$ MW

Cutaway View of QPS





Section A-A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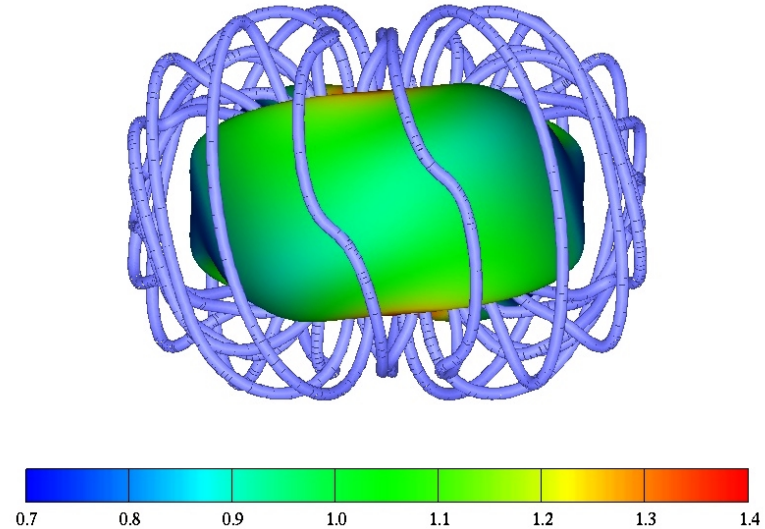
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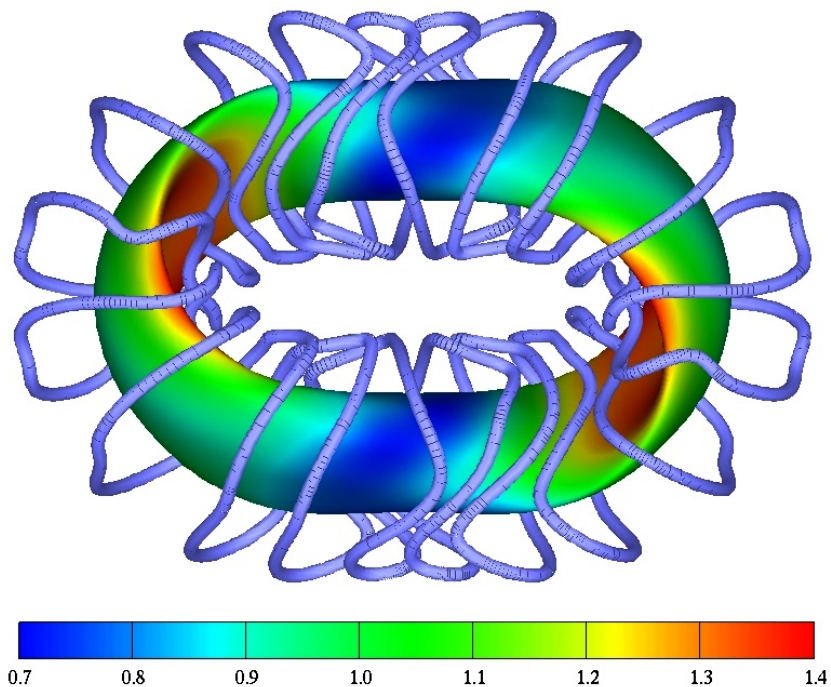
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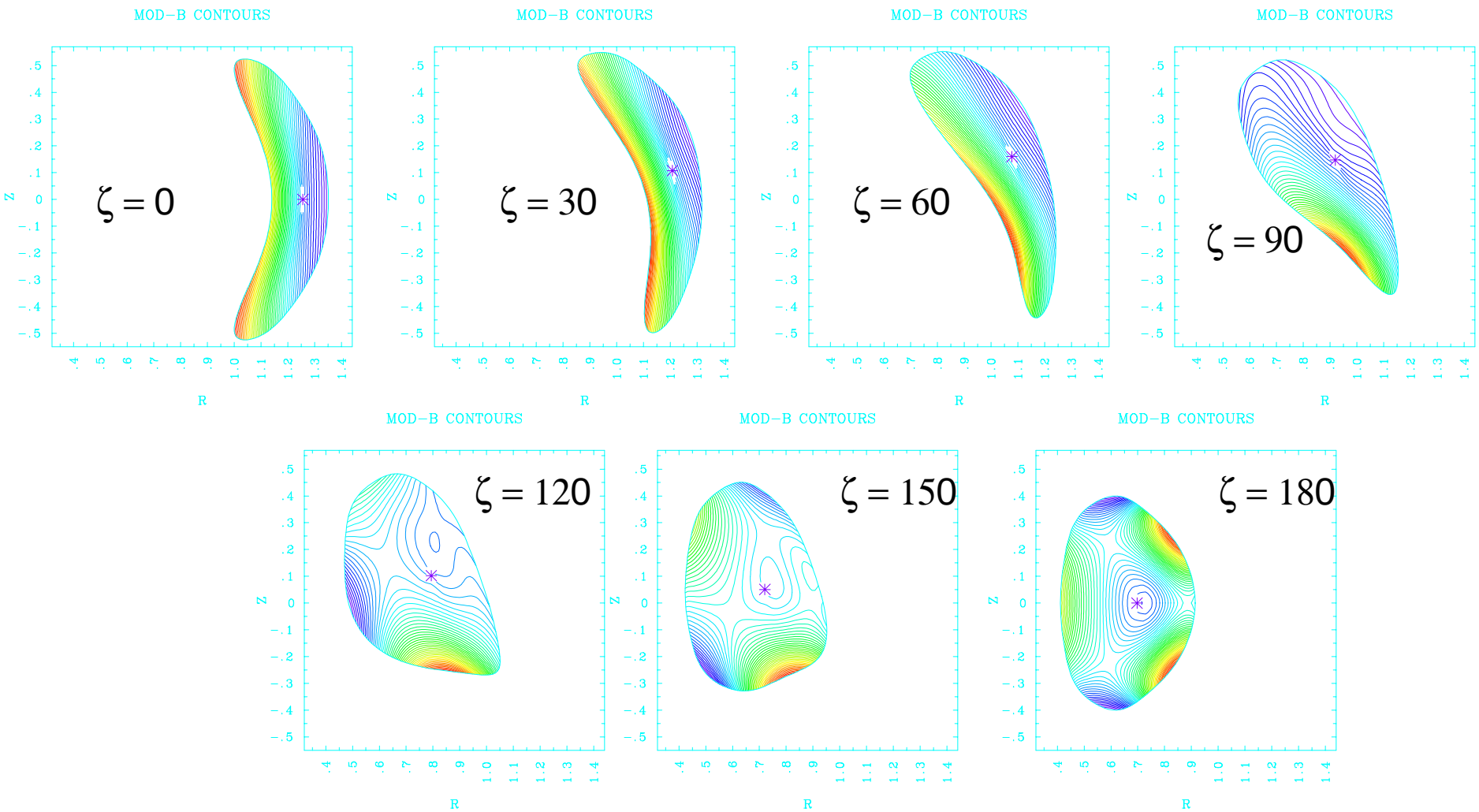
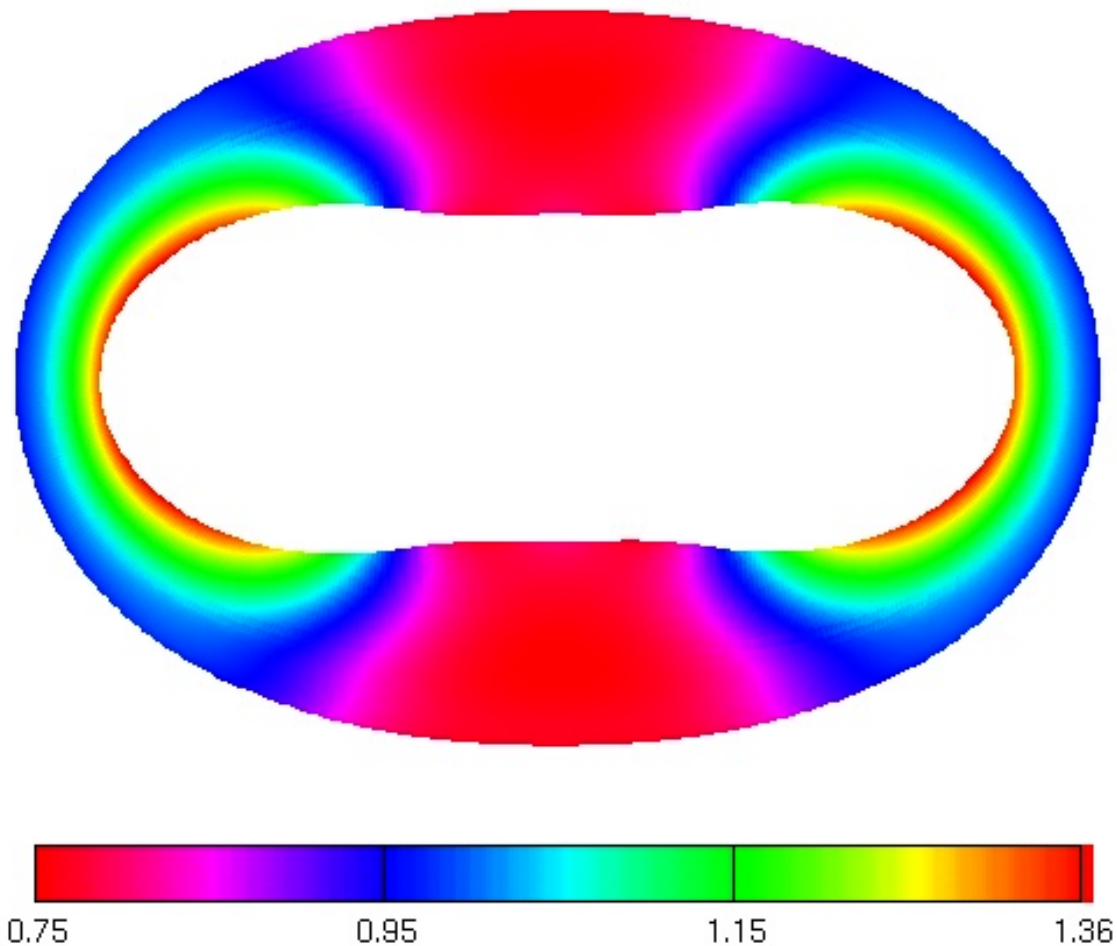
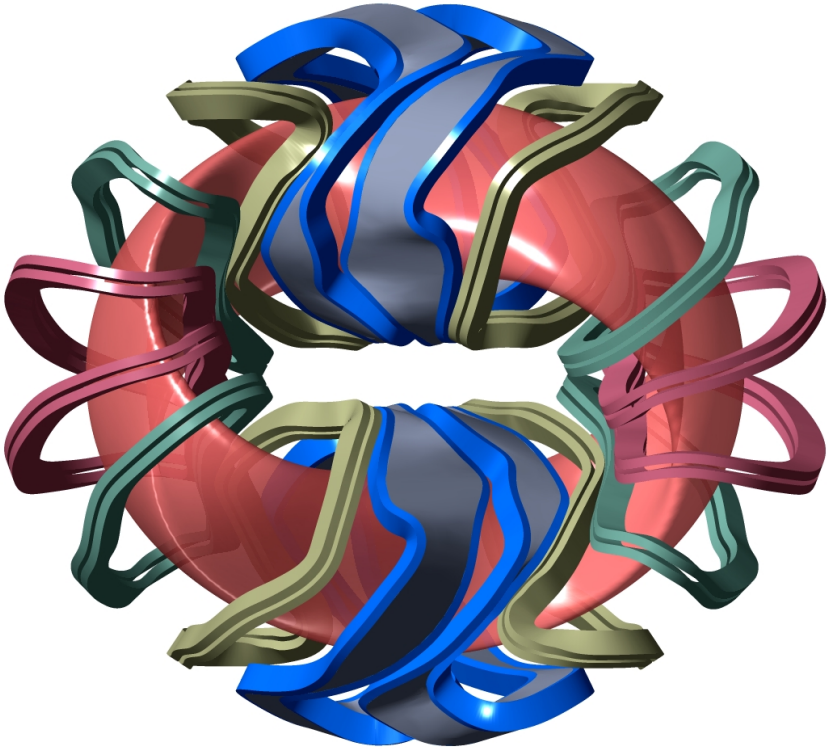
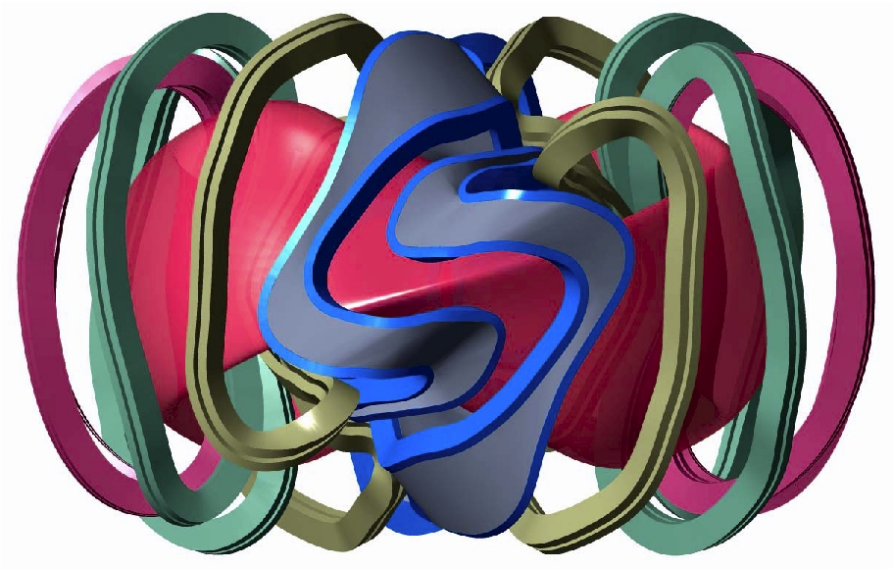
QPS Plasma Cross Sections

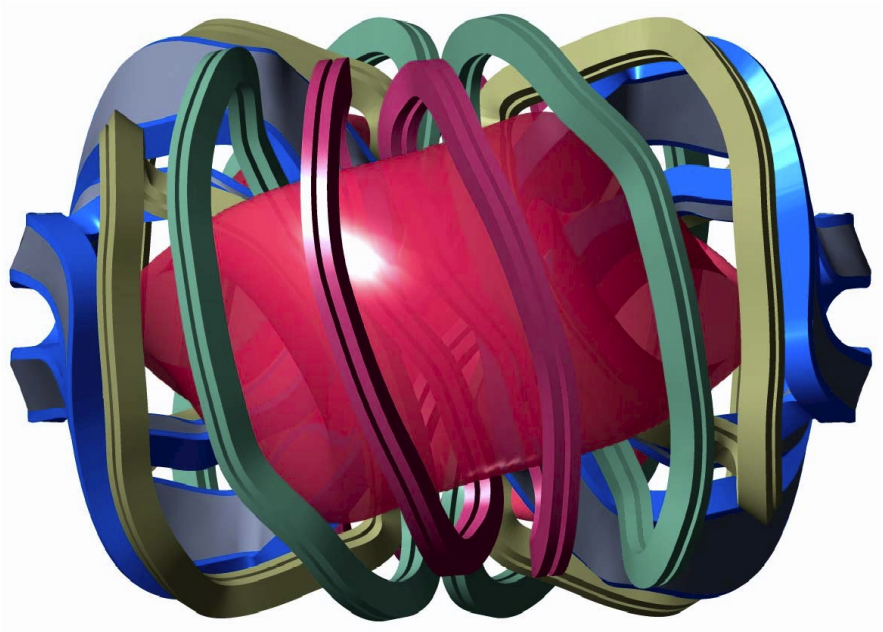


Mod-B Contours in QPS midplane



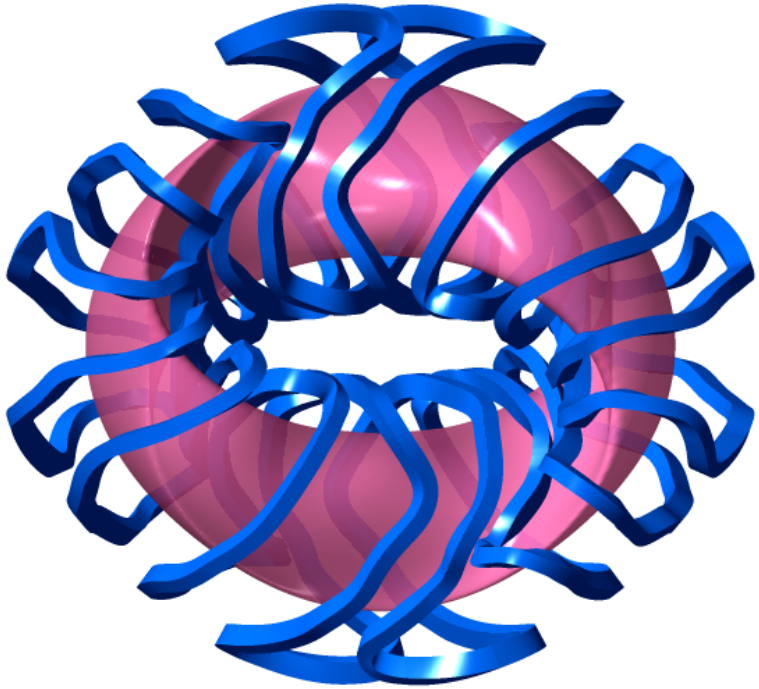


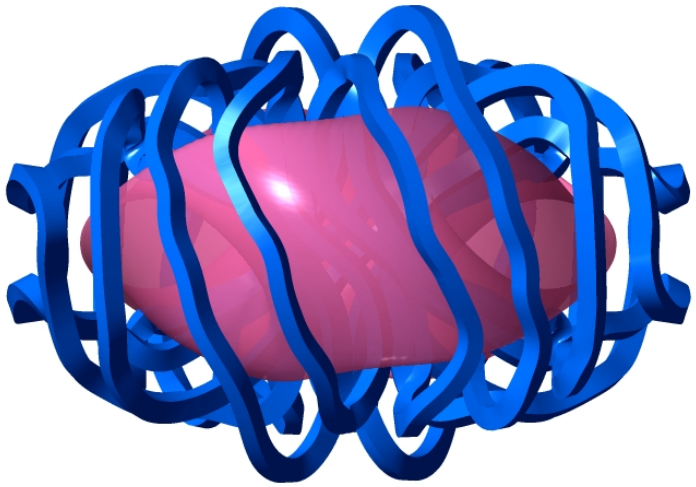


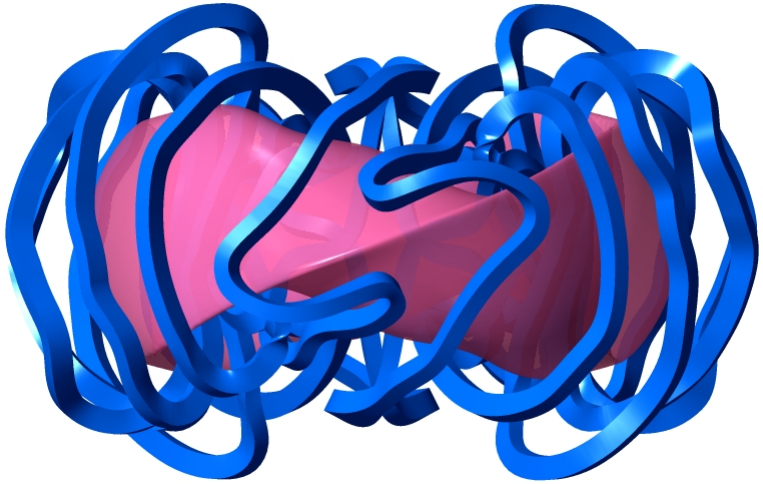


April QPS Coil Set

- Adequate coil-coil spacing, plasma-coil spacing, minimum bend radius
- 16 coils of 4 different types
- Good access between coils for heating and diagnostics
- Less room in center for TF coil legs and OH solenoid

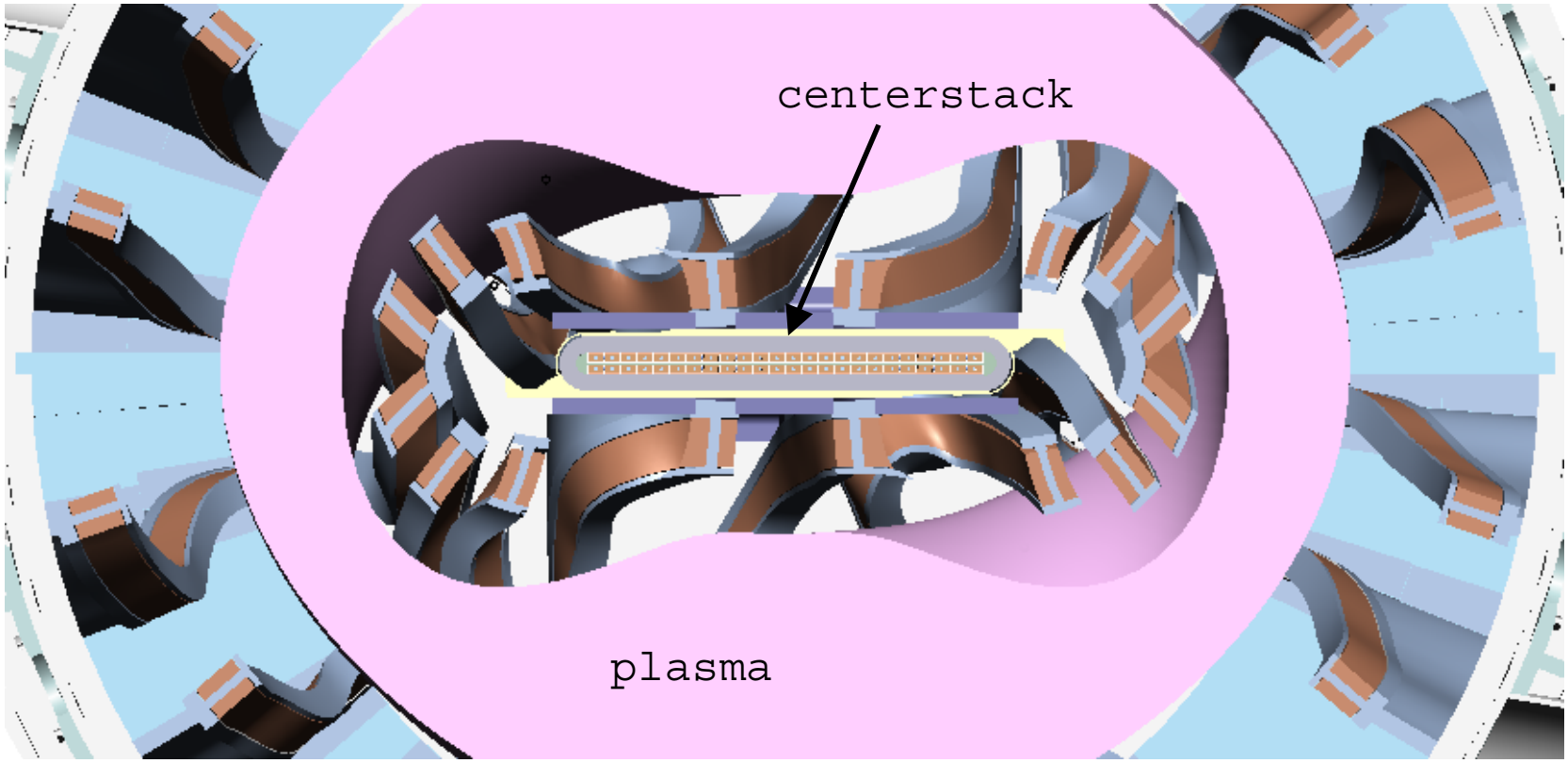


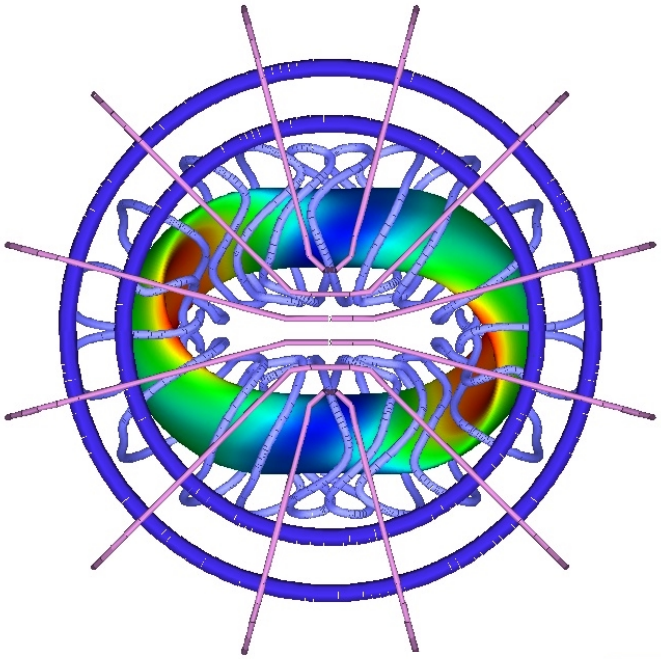


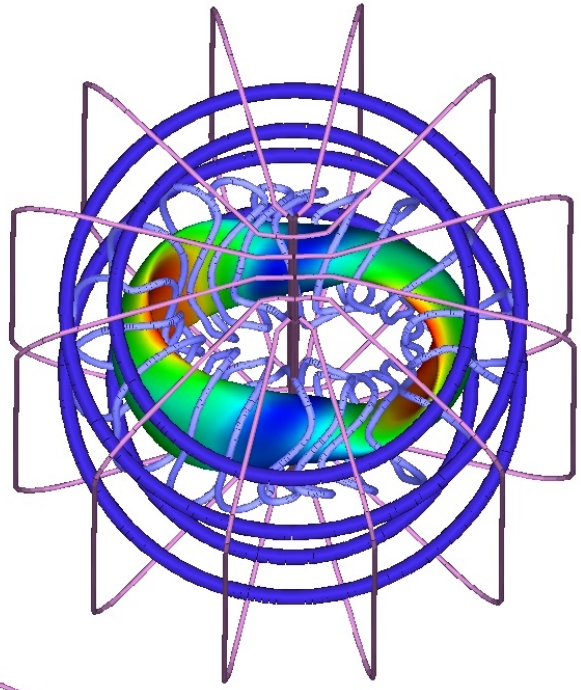


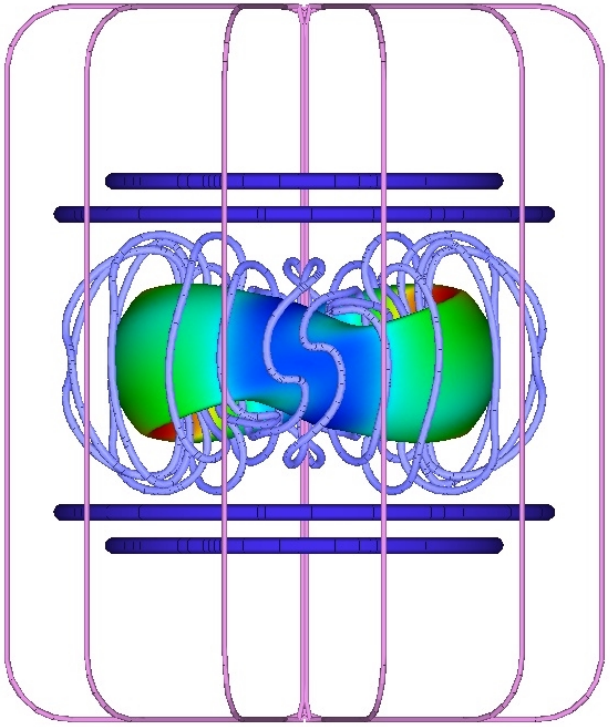
Centerstack occupies center space

- Limited room for TF coils, OH solenoid and vacuum casing
- Available clear vertical bore was ~ 14 x 90 cm



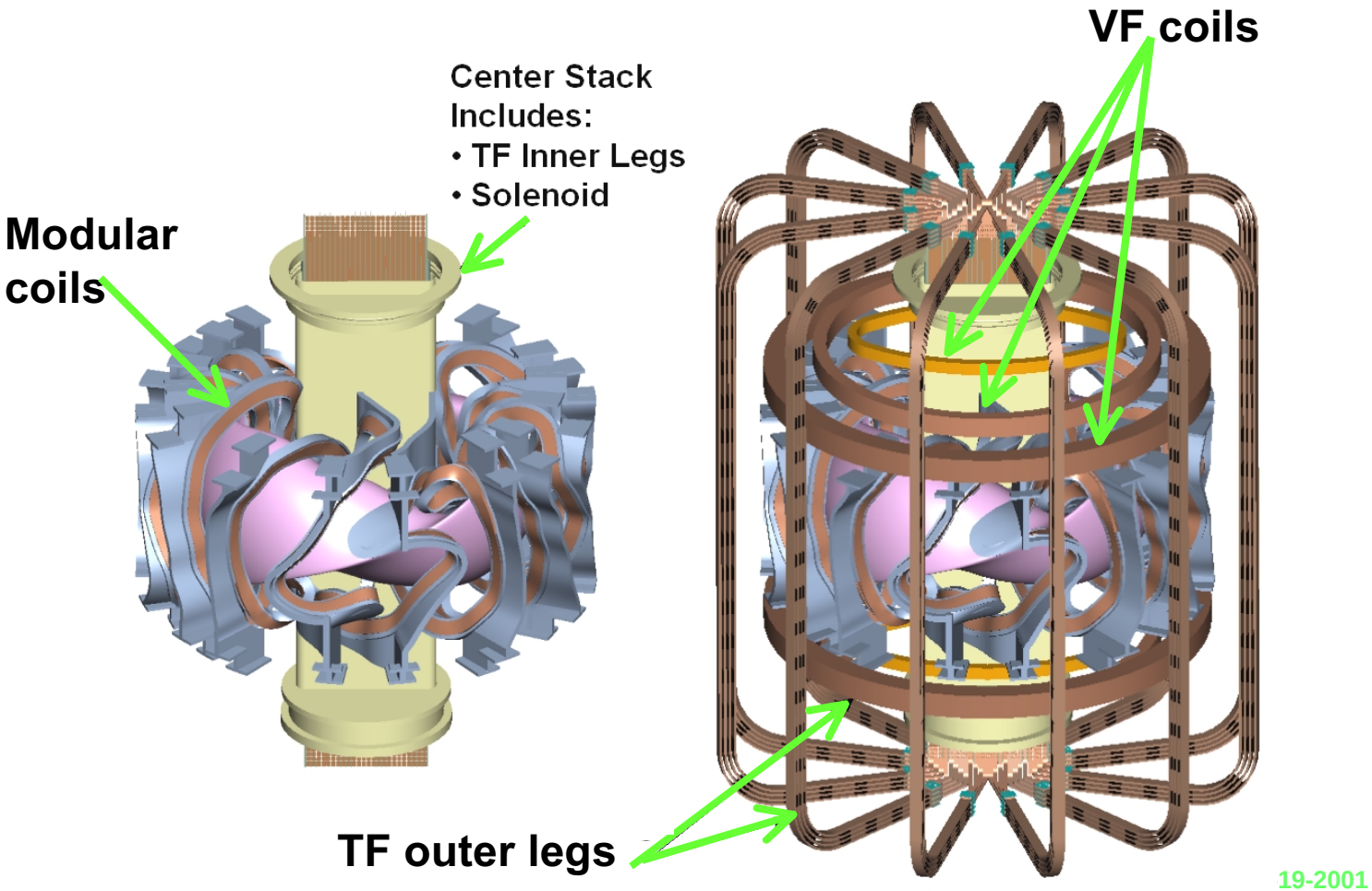




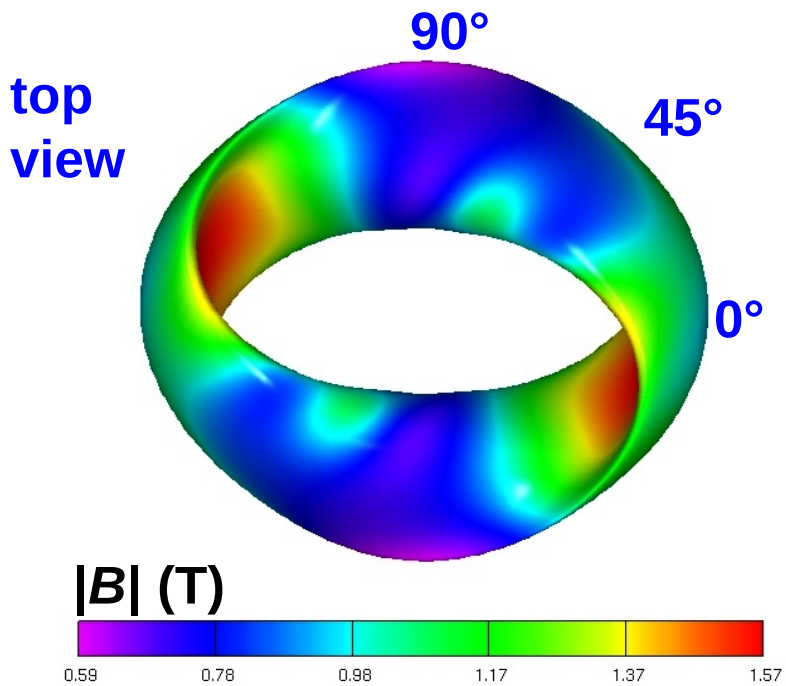


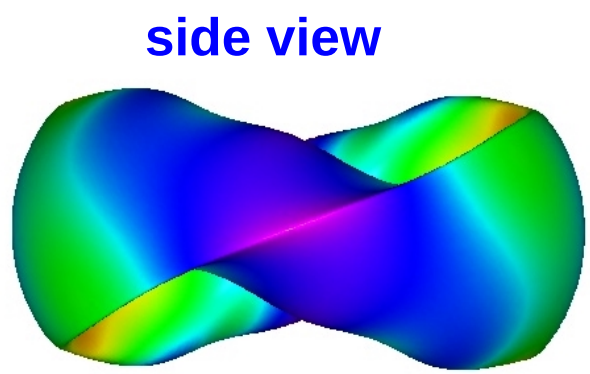
Auxiliary Coils Allow Changing Transform, Shear, and Magnetic Configuration for Physics Studies

- $\Delta B_T = \pm 0.2$ T, PF coils for shifting and shaping the plasma
- ±150 kA Ohmic current allows changing transform and shear

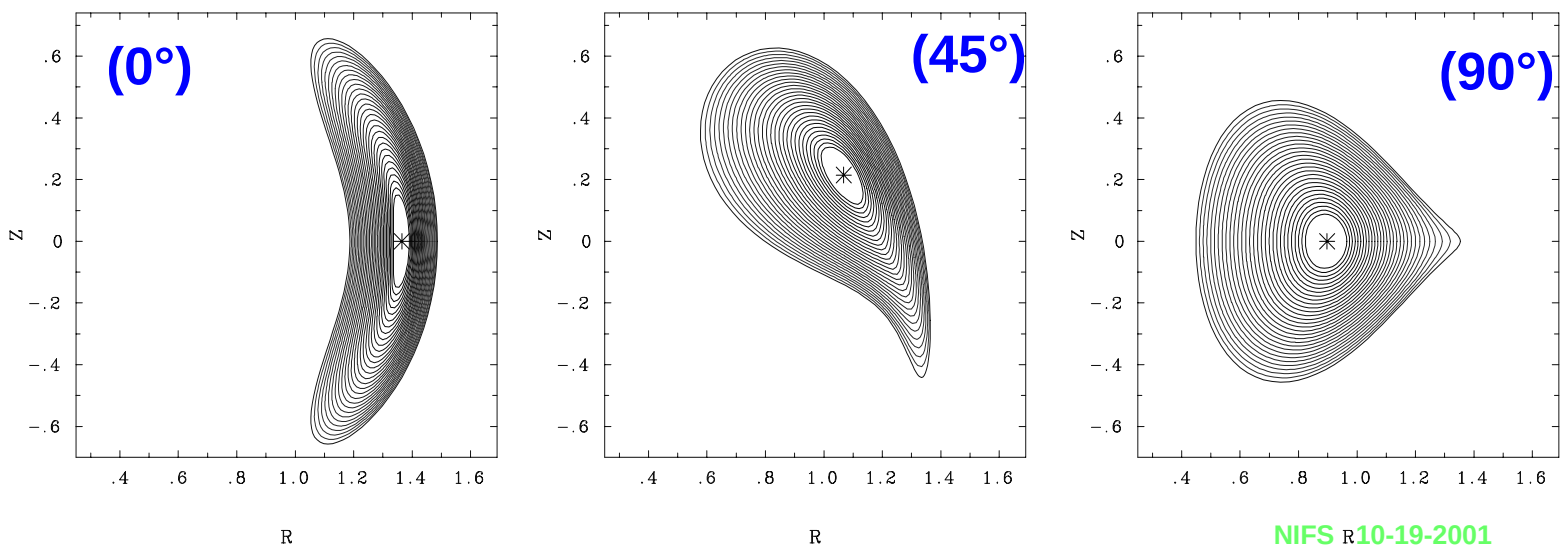


April QPS Magnetic Configuration

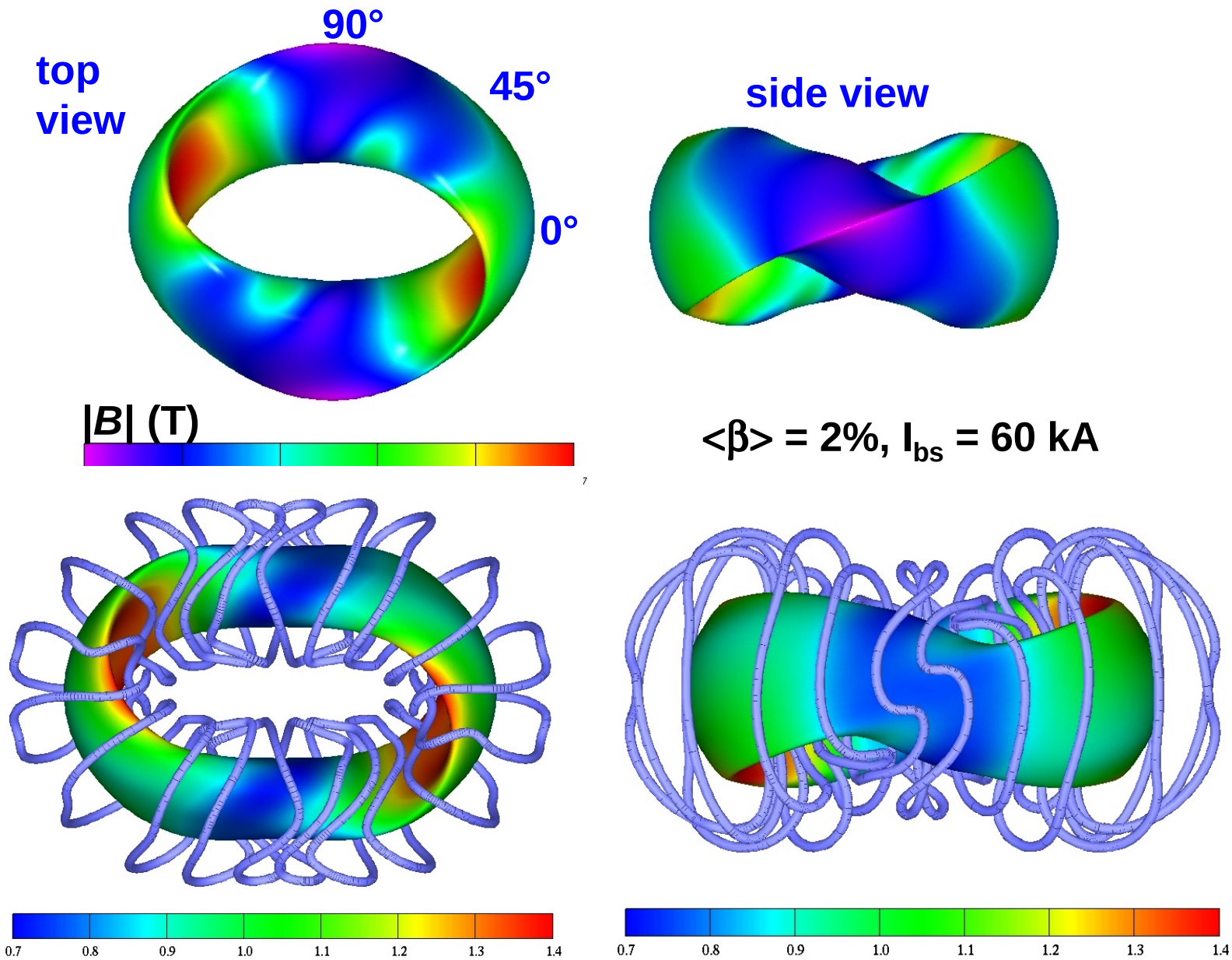




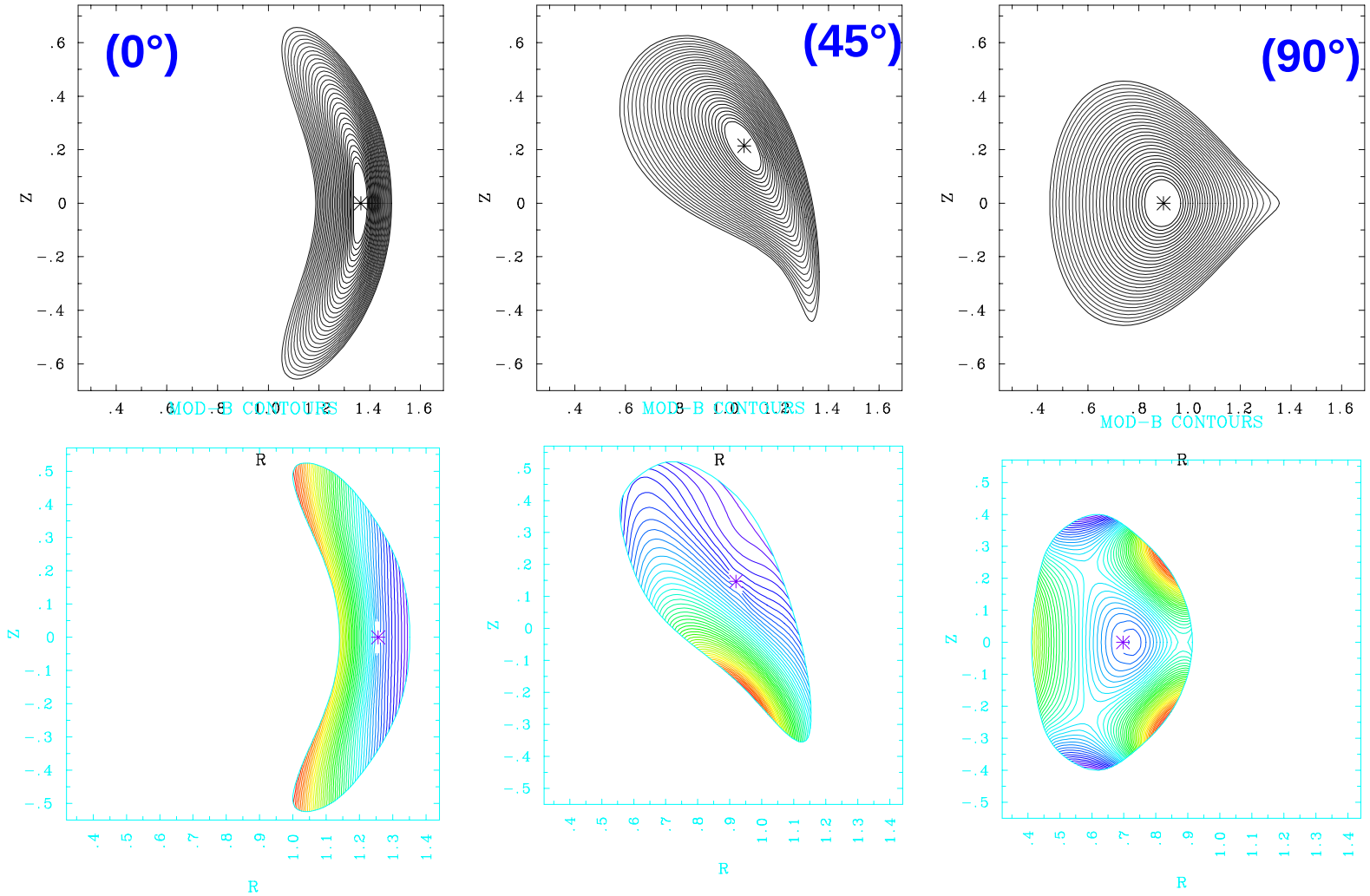
$\langle\beta\rangle = 2\%$, $I_{bs} = 60$ kA



April (top) and Present (bottom) QPS Magnetic Configurations

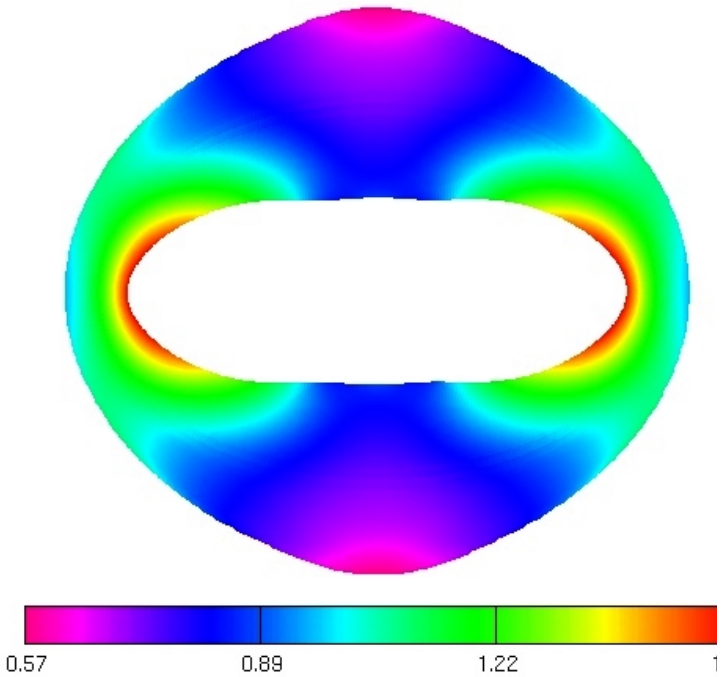


April (top) and Present (bottom) QPS Magnetic Configurations

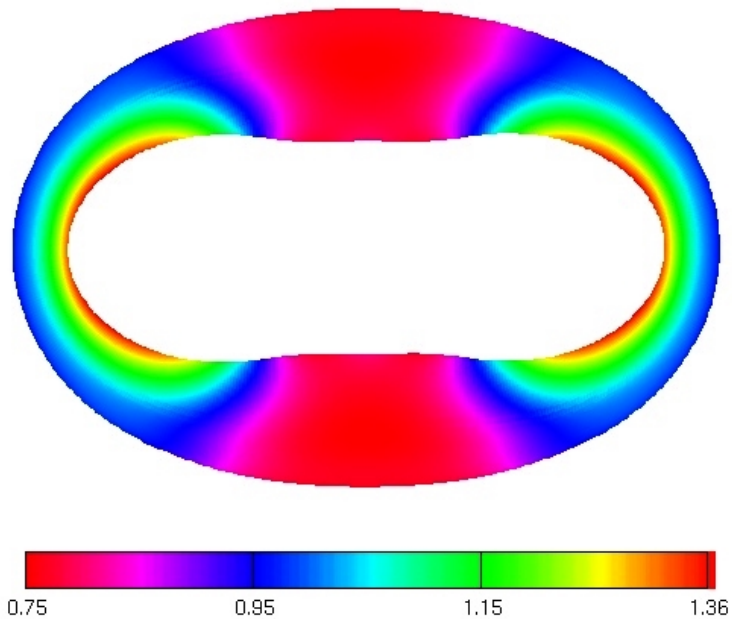


Mod-B Contours in QPS midplane

April 2002



Present



Plans

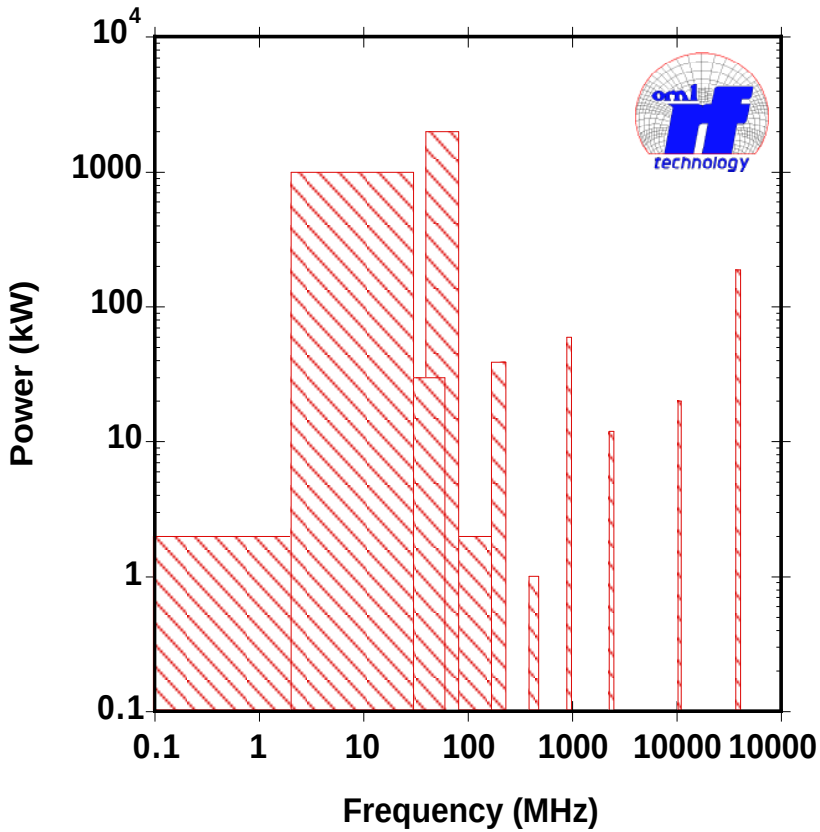
- Further improve the plasma and coil configuration
- Complete assessment of QPS physics properties
- Assess flexibility obtained with VF, TF, and OH solenoid
- Improve engineering design and cost/schedule estimates
- April 2002: Design, Cost & Schedule Review
- 2003-2006: R&D, design and construction
- March 2007: first plasma

Plasma heating on QPS

- QPS offer new opportunities in ICRF, ECH/EBW
- Worldwide ICRF and ECH experience on stellarators can be applied to QPS
- QPS has the access and conditions for ICRF, ECH and EBW
- Heating of bulk electrons and ions at high beta is achievable
- We have developed a staged approach for heating electrons and ions (Baseline with backup options)

ICRF, ECH/EBW and LH Assets

Type of RF Heating	Power and Frequency Range
ECH/EBW	1.2 MW at 28 GHz, 0.3 MW at 27.7 GHz, 0.2 MW at 35 GHz, 0.6 MW at 53.2 GHz, 0.2 MW at 56 GHz
ICRF	1.5 MW at 40-80 MHz, 2 MW at 6-20 MHz
Lower Hybrid	1 MW at 2.45 GHz, 0.1 MW at 800 and 915 MHz



Heating strategy - Staged approach with backup options

- Heat electrons at modest density - ECH only
- Heat electrons at high density
  - High Harmonic Fast Wave into an ECH target
  - Low field, outside antenna

Baseline

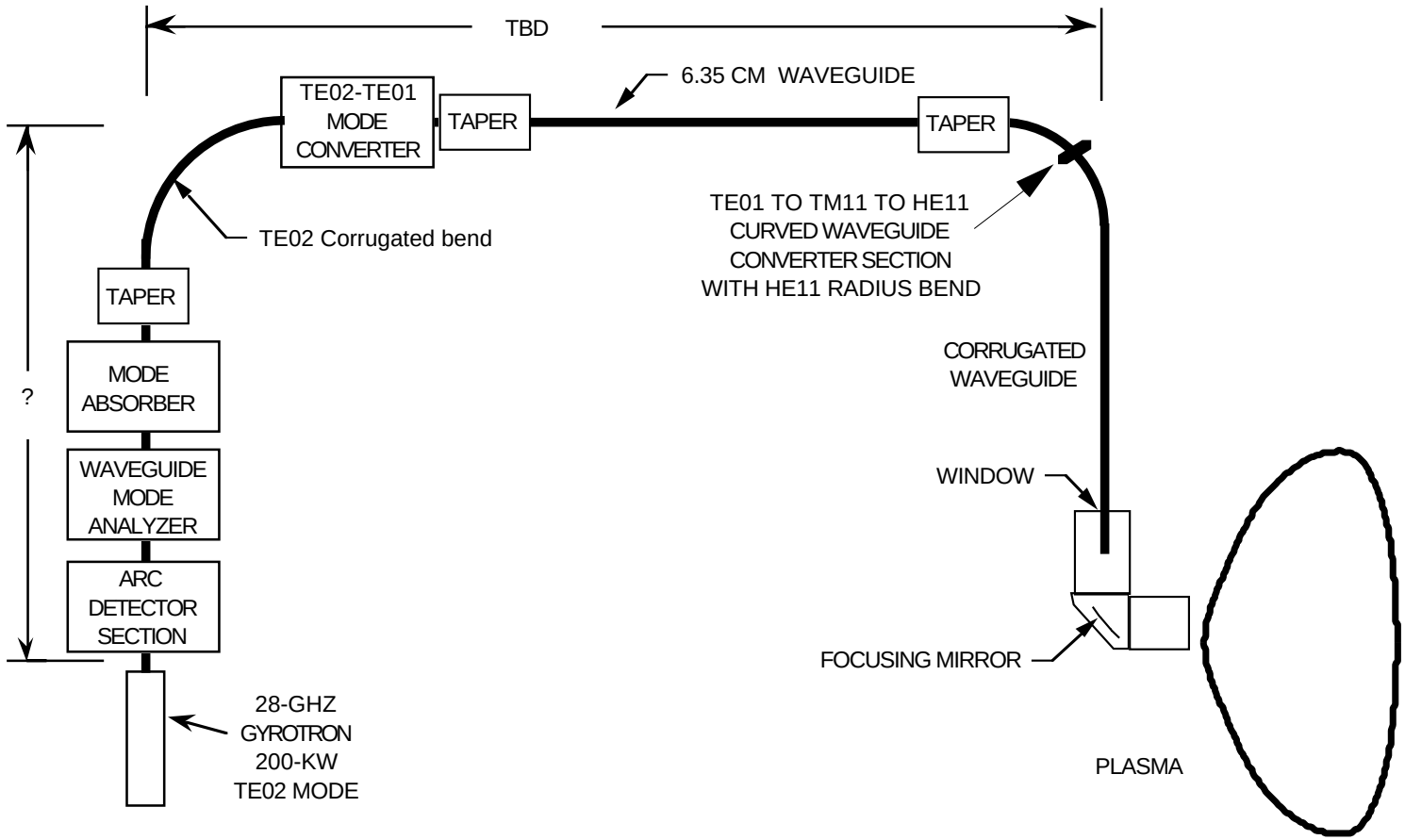
- Heat ions and electrons at high density
  - Mode conversion into an ECH target or ICRF only
  - High field, inside antenna
- Heat bulk ions at high density
  - Beach heating, ECH an target or ICRF only
  - High field, inside antenna
- Heat electrons at high density/beta - EBW

Backup options

- Heat tail ions to study orbit losses
  - Minority heating
  - Low field, outside antenna
- Current drive and flow control
  - Fast wave, EBW or LH current drive

Physics Opportunities

Existing QPS 28-GHz ECH/EBW waveguide hardware



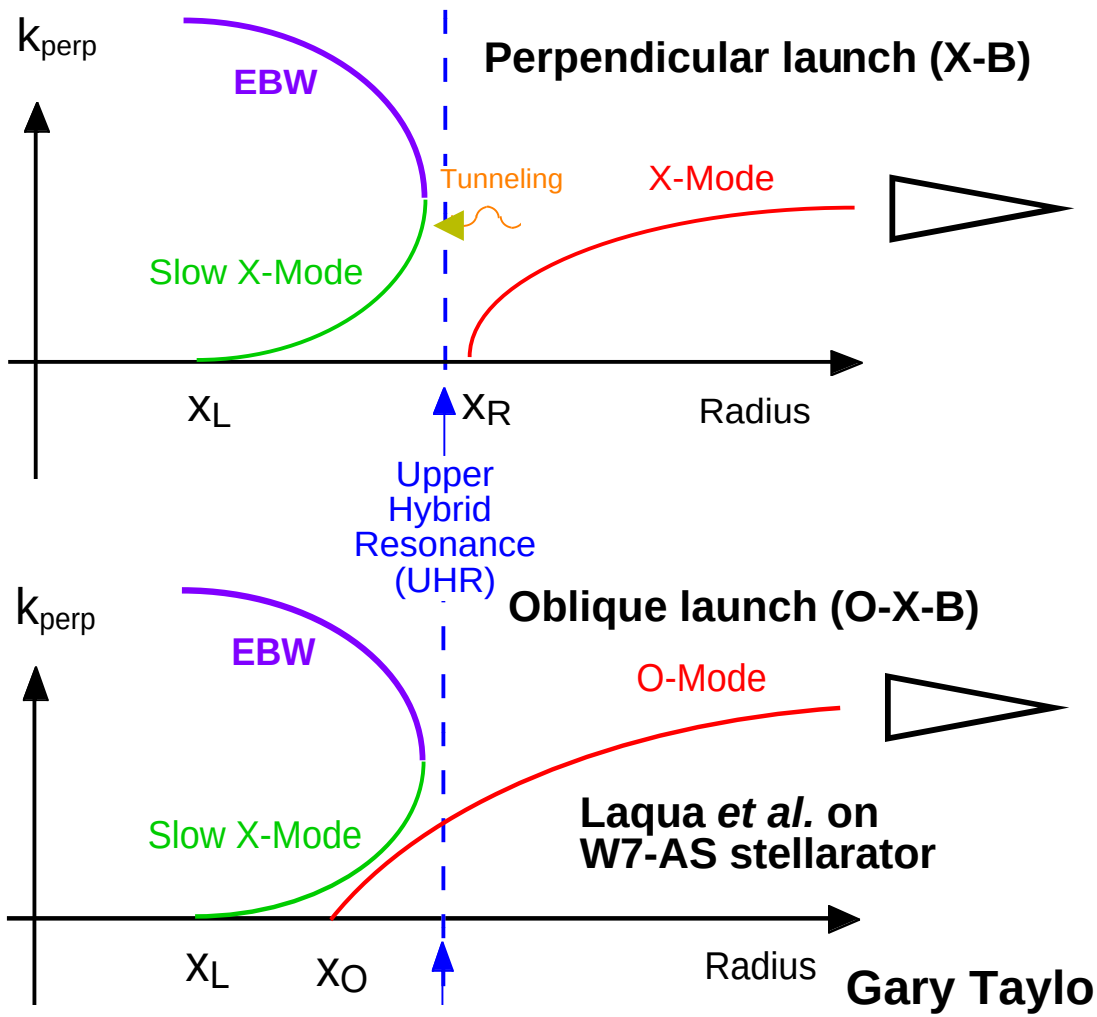
Motivation for Electron Bernstein Wave emission studies and heating & current drive

- High β plasmas with $w_{pe} >> W_{ce}$ (NSTX) cannot use ECH, ECCD or ECE $T_e(R,t)$ diagnostics
- Electron Bernstein waves (EBWs) can propagate in these "overdense" plasmas
- EBWs have high optical thickness at ECE resonances; $\tau \sim 1000$ for QPS
- Potential for local heating, current drive and $T_e(R,t)$ diagnostic
- EBW emission yields information about viability of EBW heating and current drive
- Recent demonstration of EBW HEATING on W 7-AS

Motivation for Electron Bernstein Wave emission studies and heating & current drive

- **Uses existing gyrotron assets**
  - First generation Gyrotrons (28-56 GHz) get a new lease on life
  - Low density experiments can break the density barrier
- **New community effort to establish EBW heating**
  - PPPL, ORNL, GA, MIT, Wisconsin
  - NSTX, CDX-U, MST, Pegasus, NCSX, QPS
  - Promising EBW emission results on MST, NSTX
  - Recent heating results from W 7-AS

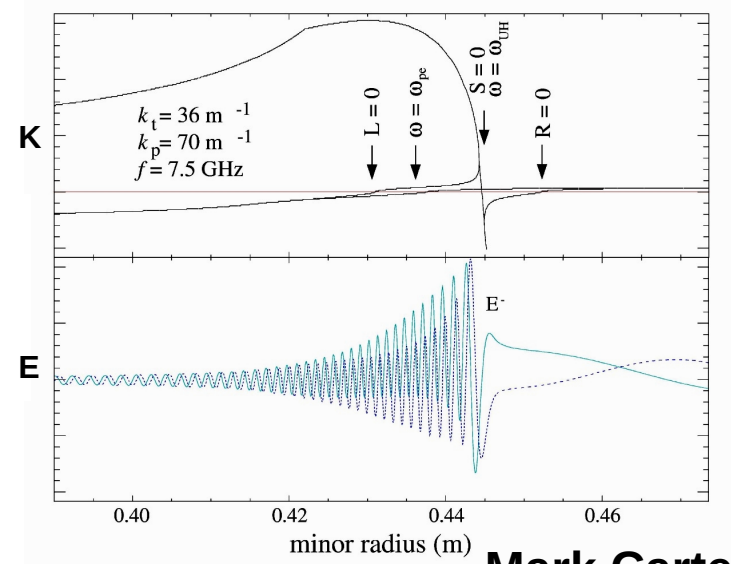
Mode Conversion to EBW at the Upper Hybrid Resonance



Gary Taylor

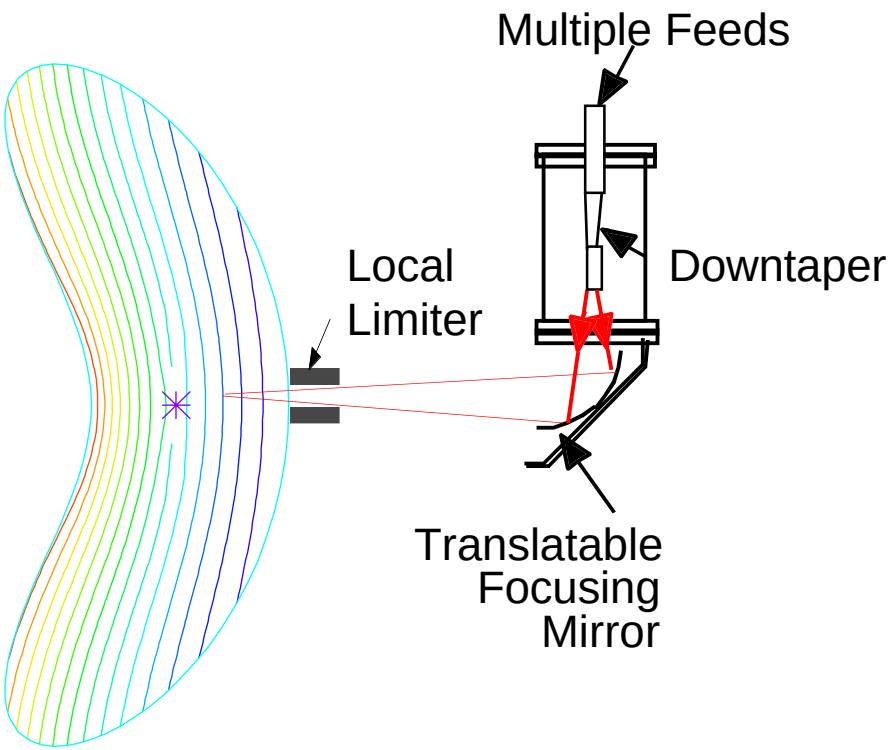
With a locally steepened density profile at the Upper Hybrid Resonance, the X-mode can tunnel through to the EBW mode

Heating is the reciprocal of the emission (MST, CDX-U, NSTX)



Mark Carter

Conceptual layout of 28 GHz $n_{//} = 0$ Launch EBW antenna located on QPS midplane

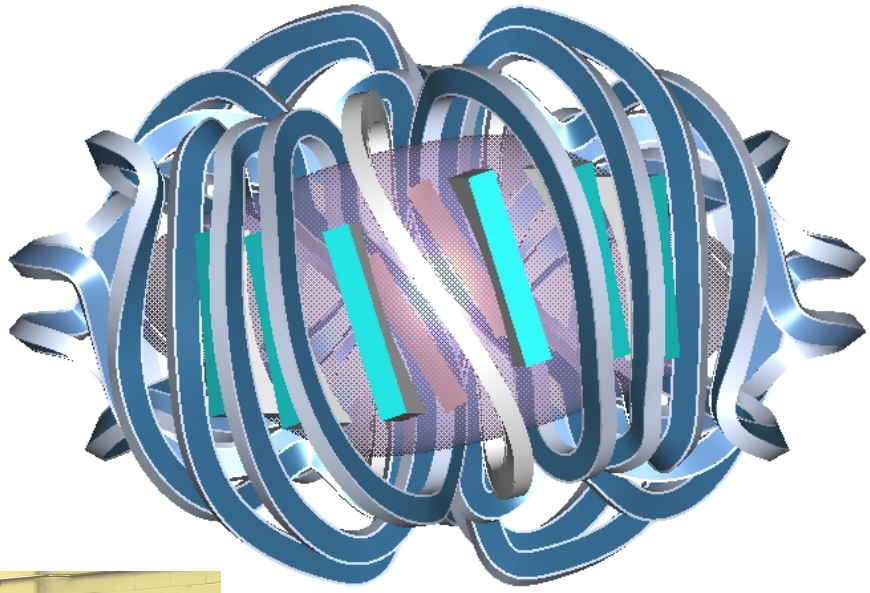


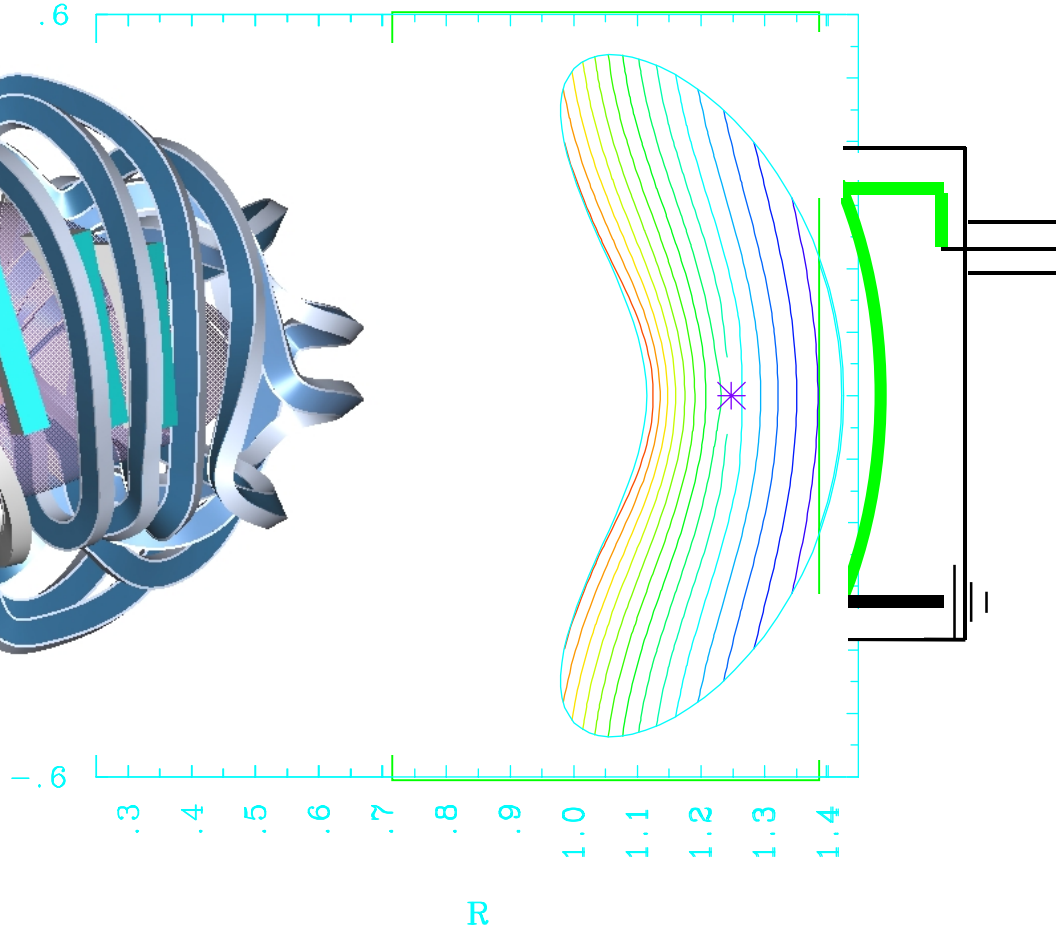
- **Focusing mirror translated poloidally to vary $n_{//}$ at EBW resonance location**
- **Local limiter to control the scrape off density profile for maximum X-EBW mode conversion**

ICRF options in priority order

- Direct electron or high harmonic heating (≥20 MHz)
  - FW and HHFW bulk electron heating
- Mode conversion heating (~ 15 MHz at 1.0 T)
  - IBW mode conversion at two-ion hybrid resonance layer
  - bulk electron heating
- Magnetic beach heating (< 14 MHz at 1.0 T)
  - bulk ion heating
- Minority heating (~ 14 MHz at 1.0 T ; He majority, H minority)
  - ~ 5 % minority (tail heating)
  - ~ 30 % minority (bulk ion heating)
- Current drive and flow control)
  - FWCD (≥20 MHz)
  - EBW CD (28 GHz)
  - LHCD (2.45 GHz, 915 MHz, 800 MHz)

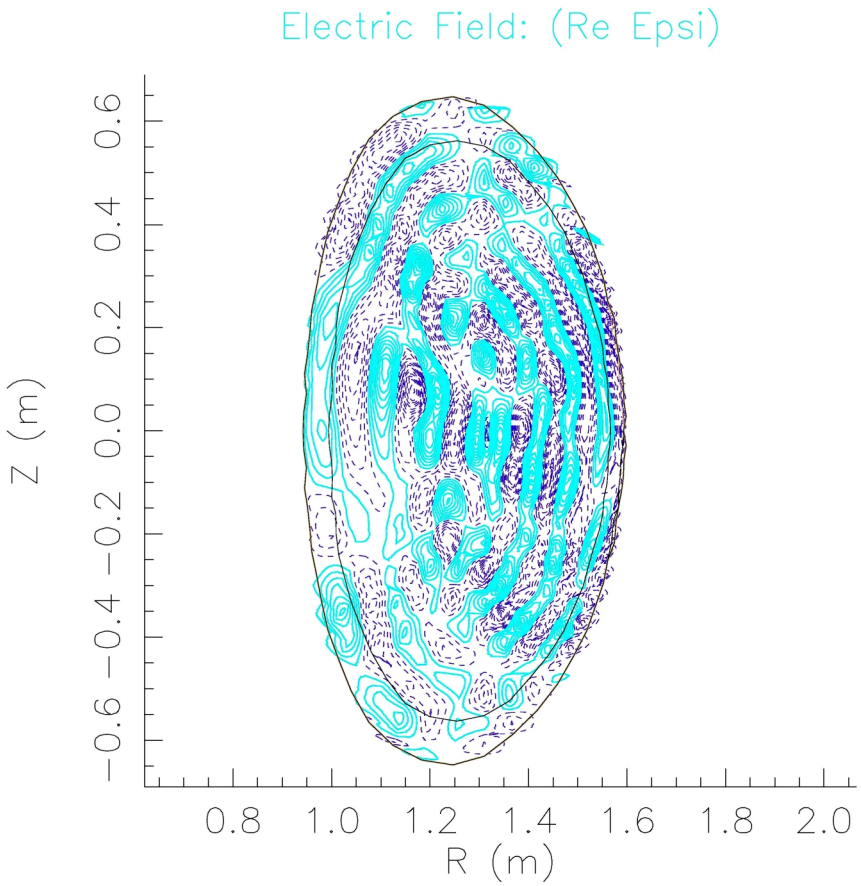
FW & High Harmonic FW and Minority heating

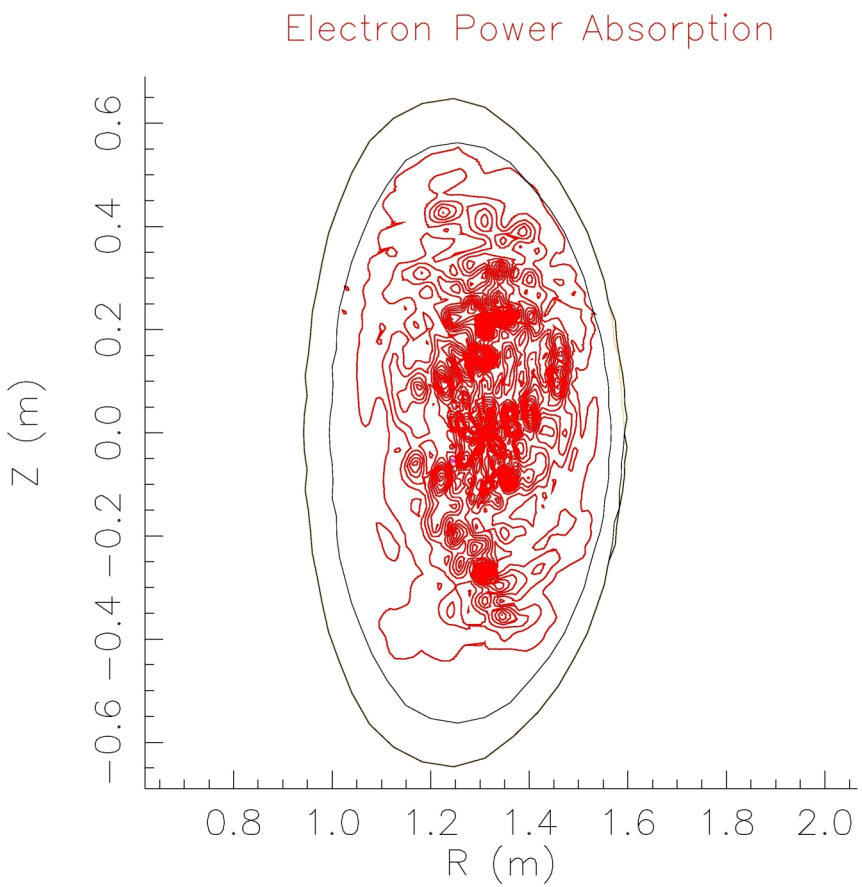




Low Field Side Antenna (NSTX style)

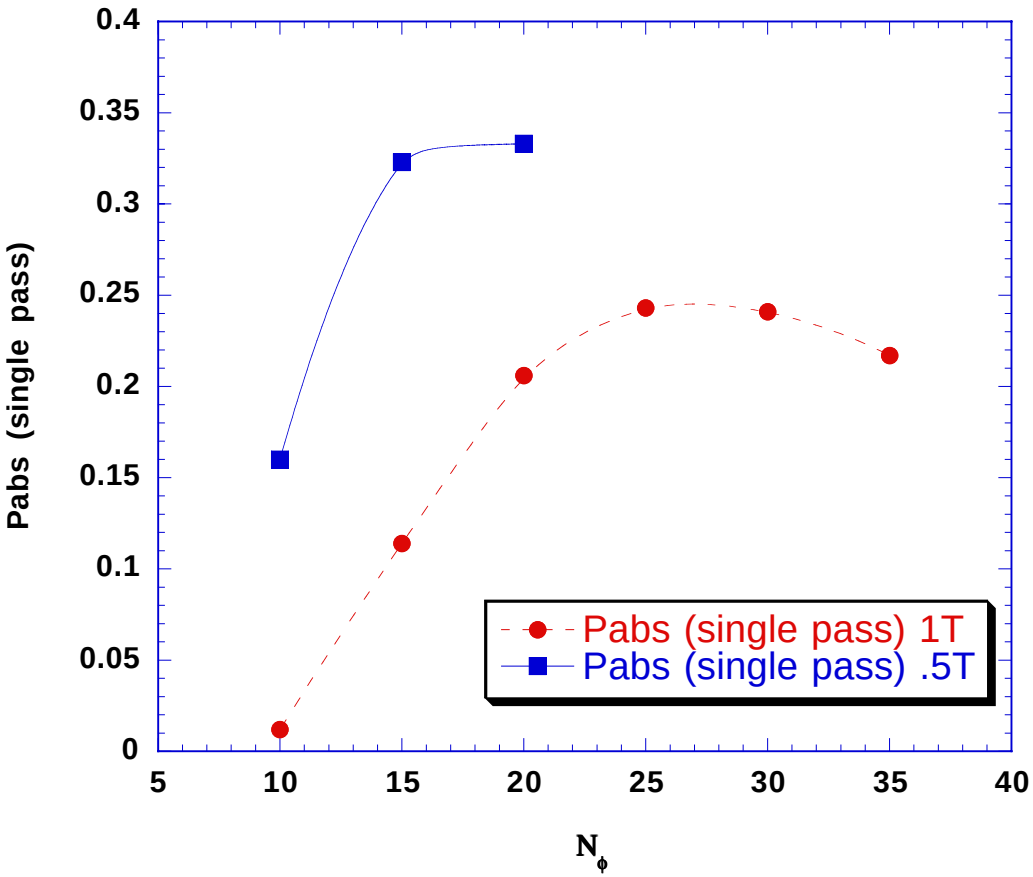
High Harmonic FW Absorption 1T 1% beta 60 MHz





Fred Jaeger

Single pass absorption calculations for HHFW look promising

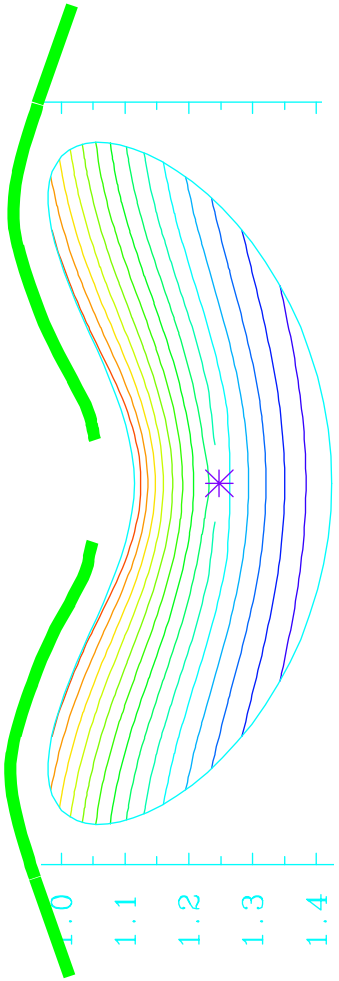


ECH Target Plasma

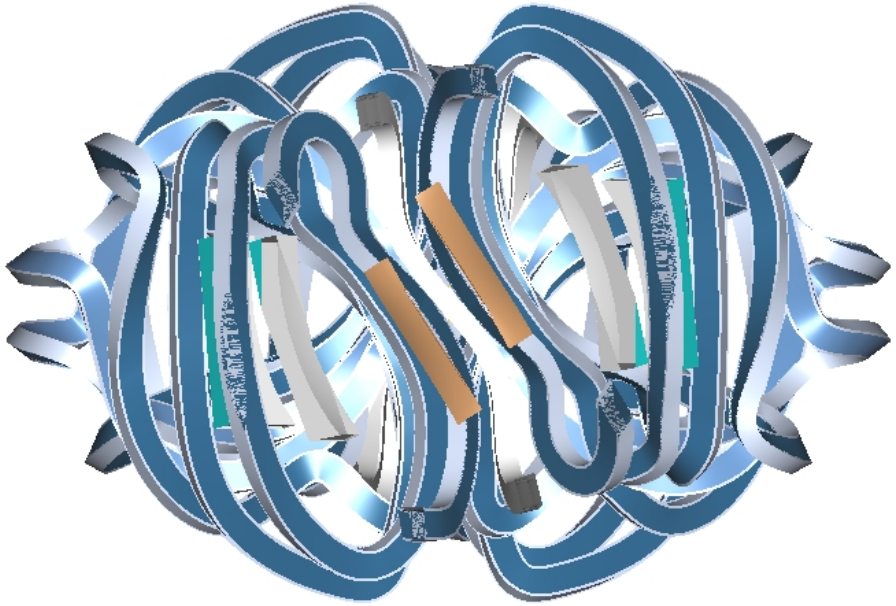
ECH power perpendicular electron heating	28 GHz 4 @ 300KW ea. 2nd 28	53 & 56 GHz 4 @ 200KW ea. 2nd 53
Parameter	**low**	**high**
B (T)	0.5	1.0
R (m)	0.83	0.83
a (m)	0.35	0.35
V_p (m^3)	1.78	1.78
P (MW)	1.0	0.5
n (10^{19} m^{-3})	0.45	1.8
$\langle\beta\rangle$ (%)	1.5	1.02
τ_E (ms)	2.25	12.1
T_{e0} (keV)	3.1	2.1
T_{i0} (keV)	0.30	0.23

Fred Jaeger

Mode Conversion, Minority heating



Upper and lower single strap antennas



High Field Side Antenna (LHD/CHS Style)

Mode conversion heating of electrons and ions on CHS

NIFS/ORNL collaboration

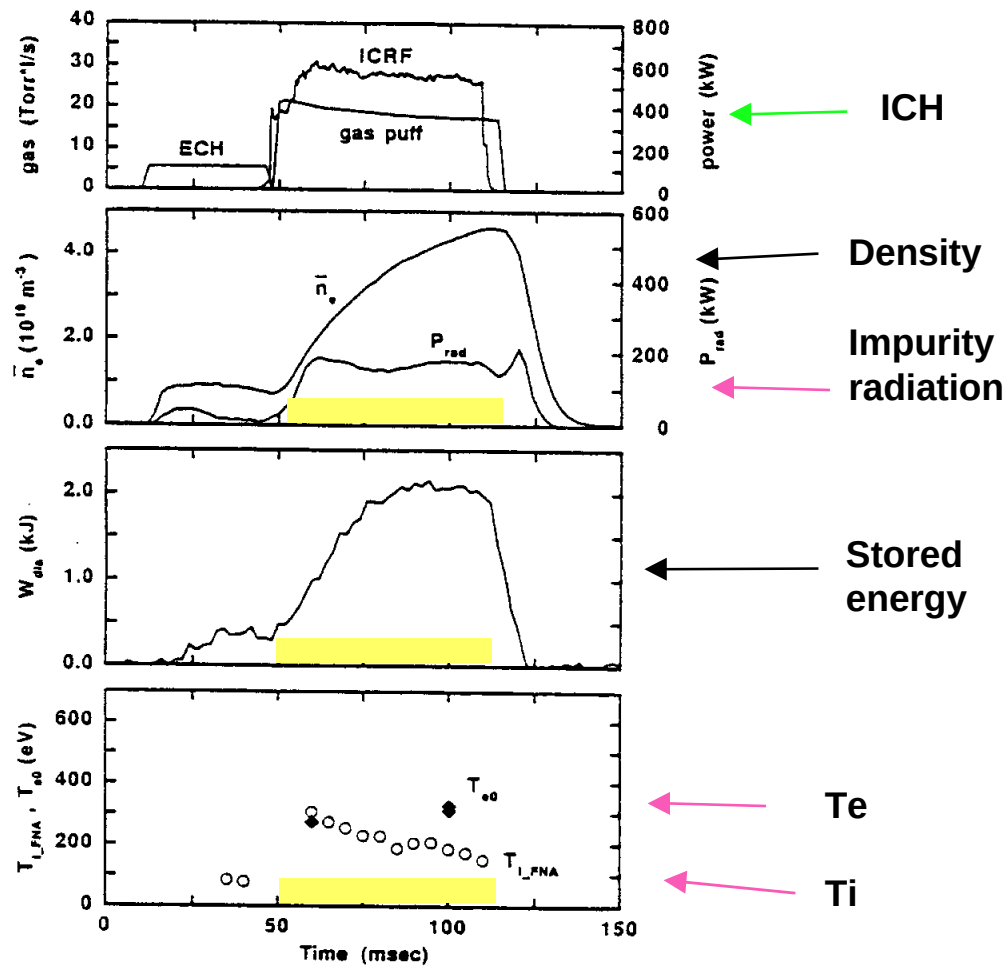
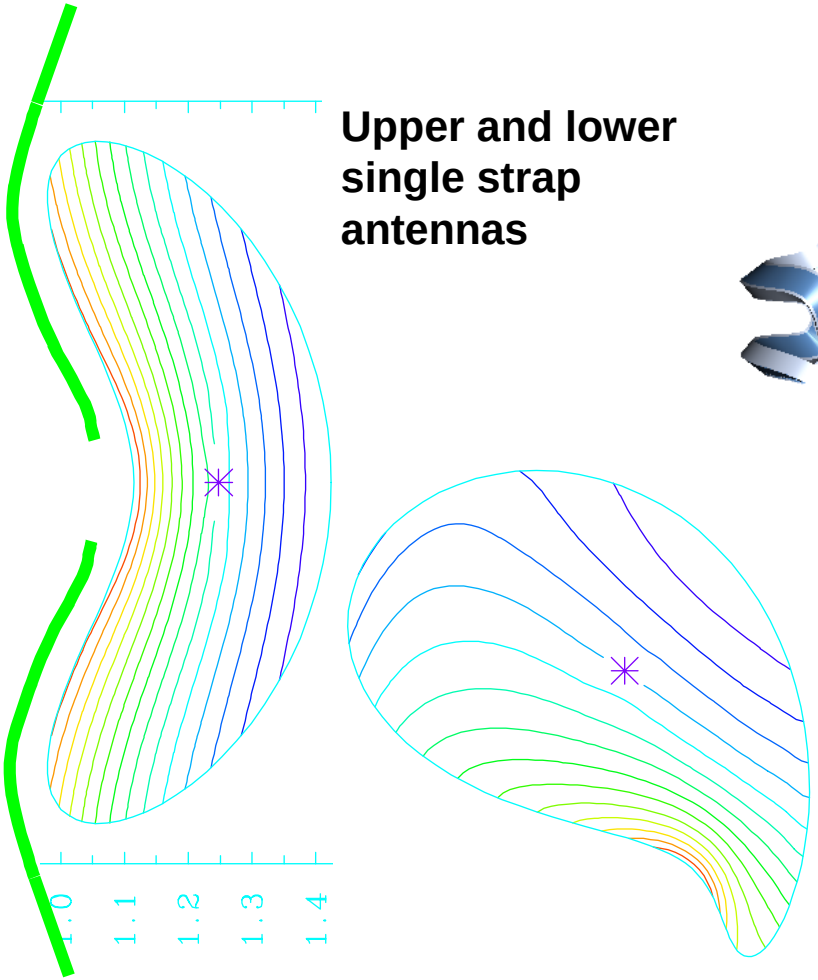
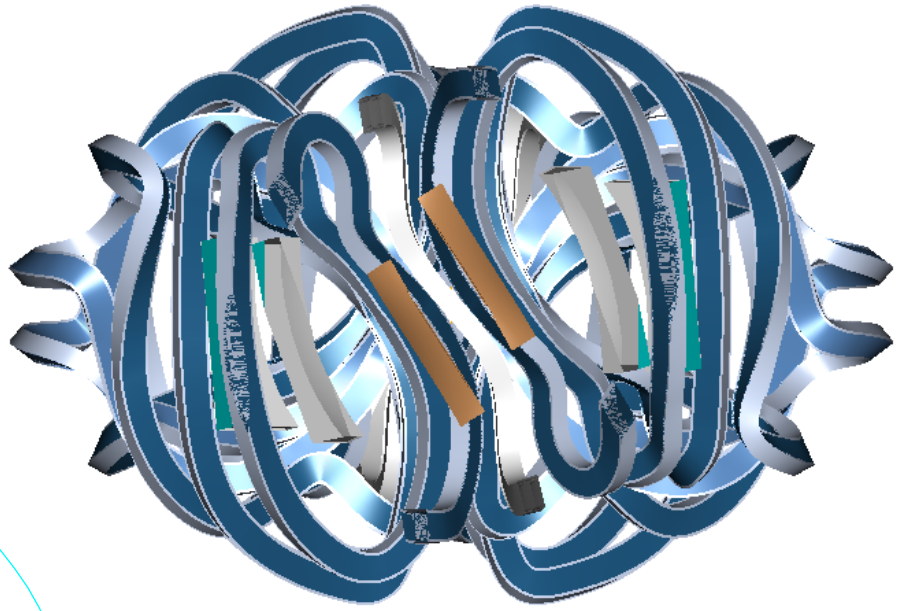


Fig. 3 Temporal evolution of plasma parameters for an ICRF heating experiment (#40991). Top column : gas puffing rate and input power. Second column : line averaged electron density and radiation loss. Third column : stored energy measured by a diamagnetic loop. Bottom column : electron and ion temperature measured by Thomson scattering and NPA, respectively.

Beach heating - similar to W7-AS



Upper and lower single strap antennas

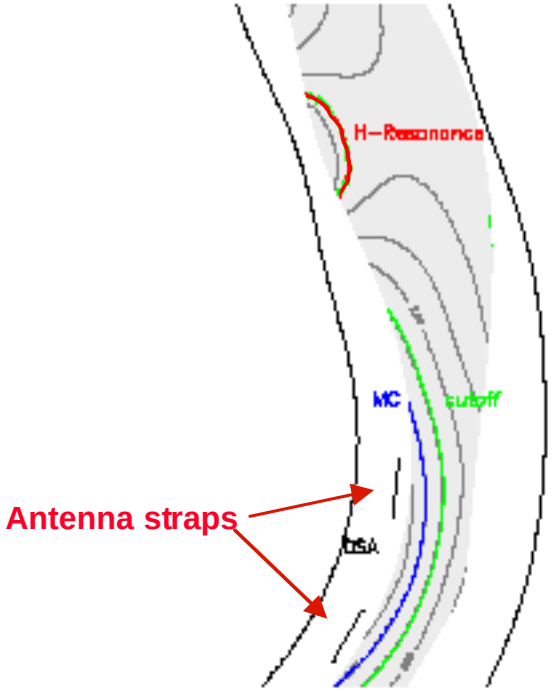


ICRF propagates to lower field “beach” region

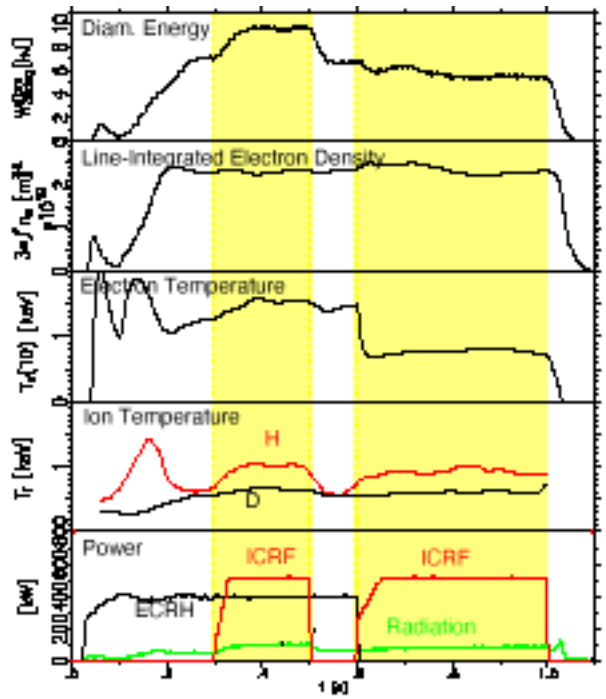
High Field Side Antenna (LHD/CHS or W7-AS Style)

Magnetic Beach heating on W7-AS

Similar to Model-C, mirror machines



Magnetic field lines for W7-AS showing MC resonance, cutoff layer and H-resonance

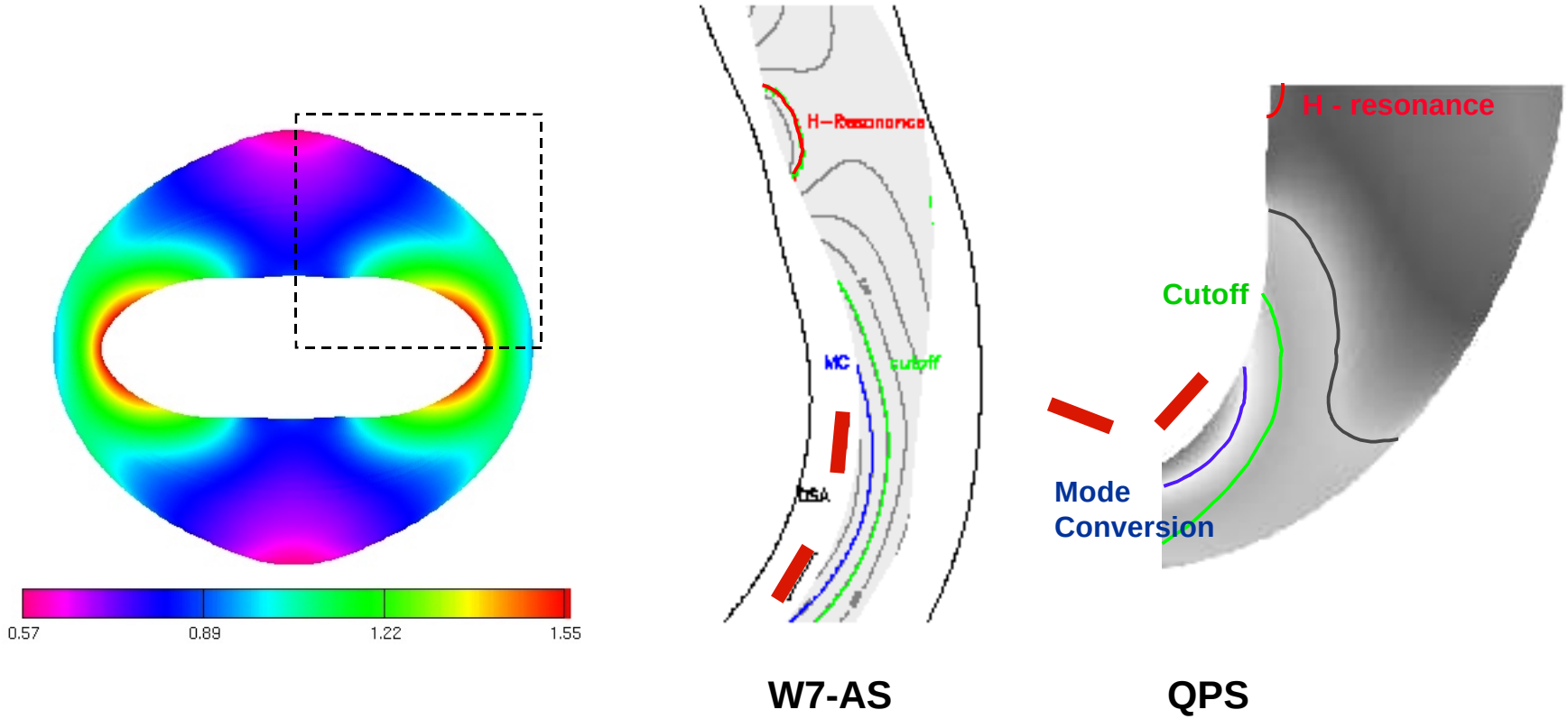


Example shot for magnetic beach heating

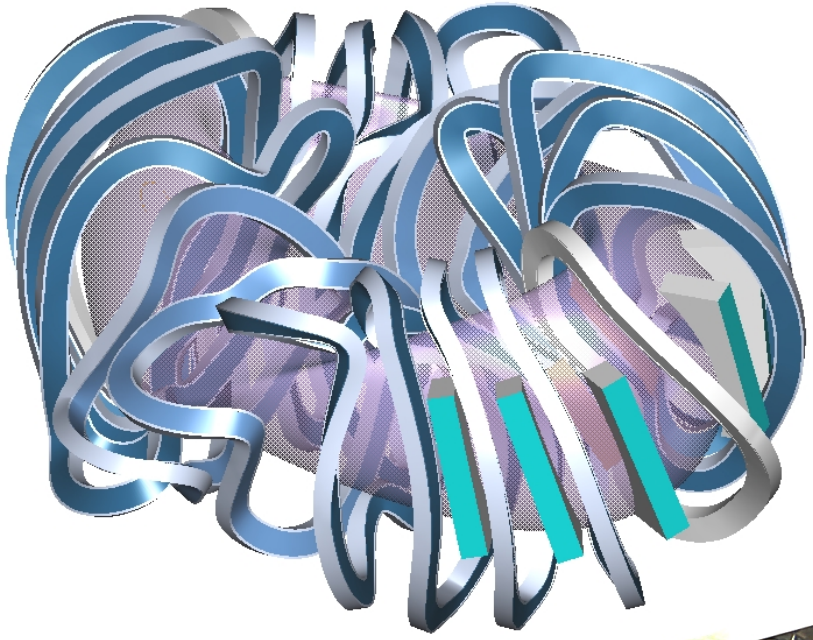
Hartmann, et al (1999)

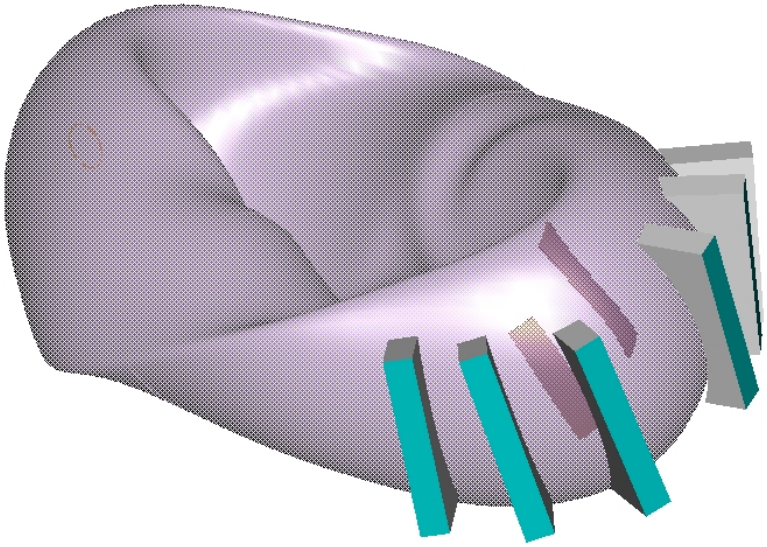
R. W. Palladino, T. H. Stix (1958)

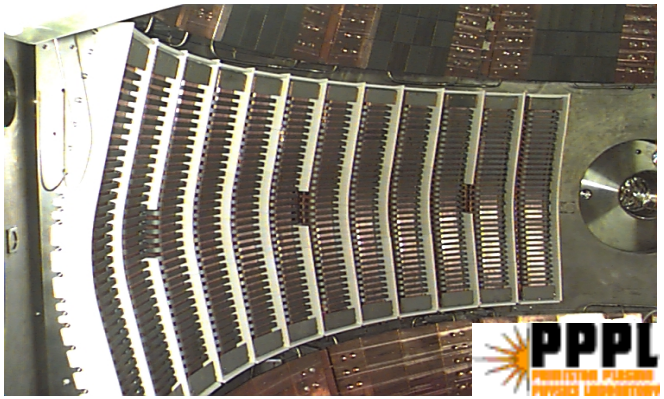
Mod-B Contours QPS midplane



FW and HHFW array for current drive and flow control (NSTX style)







FUSION ENERGY DIVISION

ICRF and ECH/EBW summary

- QAS & QPS offer exciting opportunities in ICRF, ECH/EBW
- ECH will be a mainstay, EBW is a good high beta option
- ICRF is successful on similar sized stellarators
- Access and conditions for ICRF look favorable
  - Several possible ICRF antenna designs
    - Low field side antennas similar to NSTX
    - High field side antennas may be possible similar to LHD/CHS, W7-AS
  - HHFW, Mode conversion & magnetic beach heating also feasible
- Questions to ponder as we go forward
  - ICRF antenna - Outside, inside or both?
  - FWCD antenna size and directivity?
  - EBW emission/heating optimization?
  - LH frequency and port size?