



# Ion Cyclotron Systems for Burning Plasma Experiments\*

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BPP II Workshop  
San Diego  
May 1 – 3, 2001

\* This research was sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract DE-AC05-00OR22725 with Oak Ridge National Laboratory managed by UT-Battelle.

# Introduction

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Ion cyclotron heating and current drive is promising for future burning plasma experiments.

- Low cost
- Flexible capabilities (heating and current drive with rapid time response)
- Scenarios demonstrated in present-day experiments (Talk by Ono on TFTR)
- Launchers can be designed to handle reactor environment (disruptions, neutron & thermal loads)

Summaries of two IC systems will be given as examples:

- ITER (EDA 1998 version)
  - Large, moderate- field (5.7 T) tokamak
  - Long-pulse
  - Large neutron fluence
  - *Extensive* engineering analysis done of IC system design
- FIRE
  - High magnetic field (10 - 12 T), compact device
  - Cu coils
  - Conceptual design; *little* engineering analysis done.

## Main points

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Ion cyclotron systems look promising (but challenging) in burning-plasma experiments.

Two representatives of such experiments (ITER and FIRE) show that

- Heating power can be delivered from a reasonable array of antennas.
- Current drive goals are achievable
- Antenna circuits can respond rapidly to transients and active control requirements
- Antennas can be designed to survive in burning plasma environments.
- Machine parameters and requirements influence design tradeoffs but not basic feasibility

# ITER\*

ITER ion cyclotron system is challenging but doable. Major issues are being resolved by experiments on existing machines, R&D, and design.

Questions: Can the IC system deliver 50 MW to the plasma?

Can the antennas survive in the ITER environment?

Topics:

- Heating and current drive scenarios
- ITER RF system design overview
- Electrical system— delivering the power
- Mechanical issues – survival

\* Most Information in this section is from the ITER Design Description Document for the Ion Cyclotron Heating & Current Drive System, May 29, 1998. Contributions to this document were made by the ITER JCT and the Home Teams from the US , JA, EU, and RU.

Additional information is from US Home Team reports, and *may* not be exactly consistent with the final version of the ITER EDA system report. However, qualitative conclusions are the same.

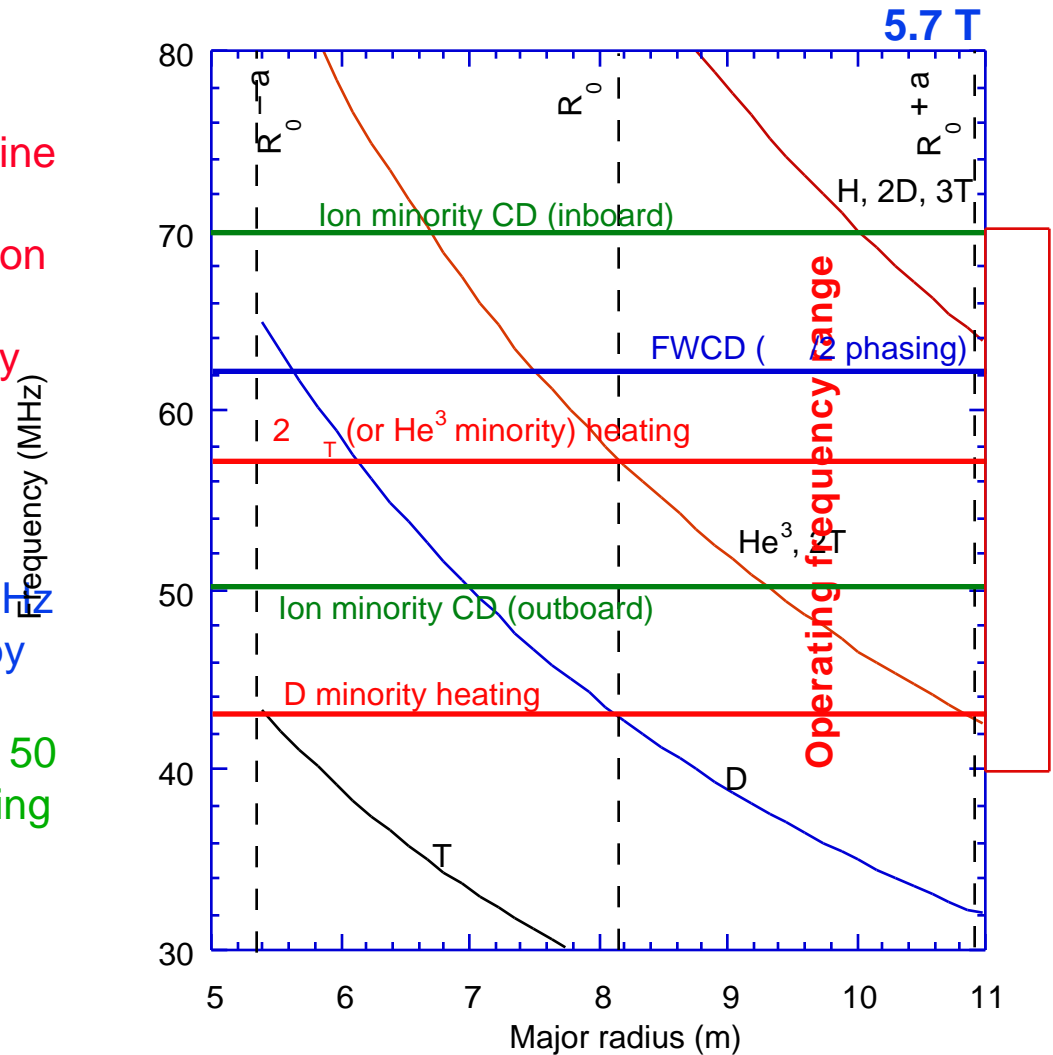
# Fast wave heating and current-drive scenarios

## Heating:

- Second harmonic T (57 MHz): baseline for DT operation.
- D minority (43 MHz): alternative for ion heating, with  $n_D/n_T = 0.3$ .
- He<sup>3</sup> minority (57 MHz): good for early operation without tritium.

## Current drive:

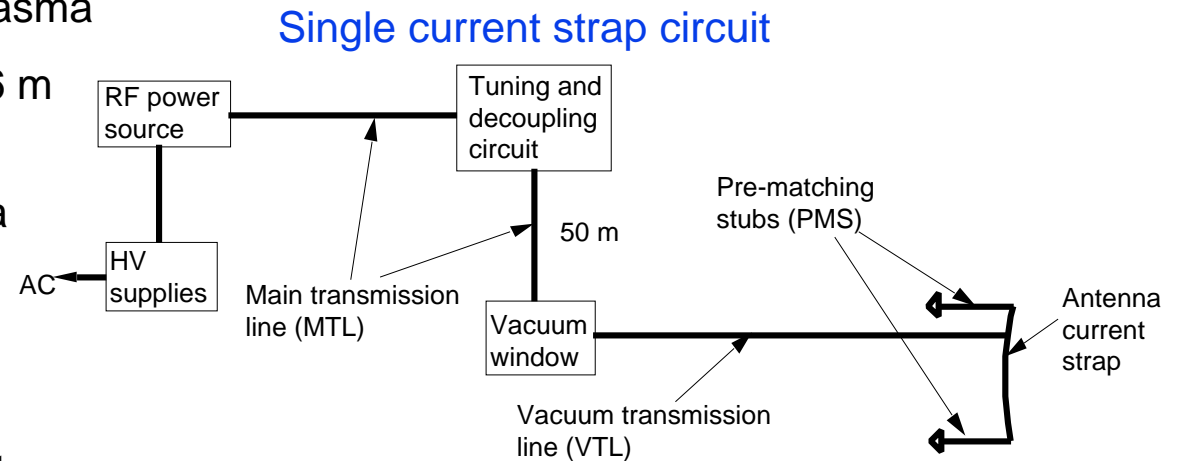
- Fast-wave current drive at 60 - 62 MHz is baseline; competitive absorption by  $2T$  and alphas.
- Inboard (70 MHz) and outboard (50 MHz) He<sup>3</sup> minority ion CD for changing slope of  $q$  at  $q = 1$ .



# ITER RF System Design Overview

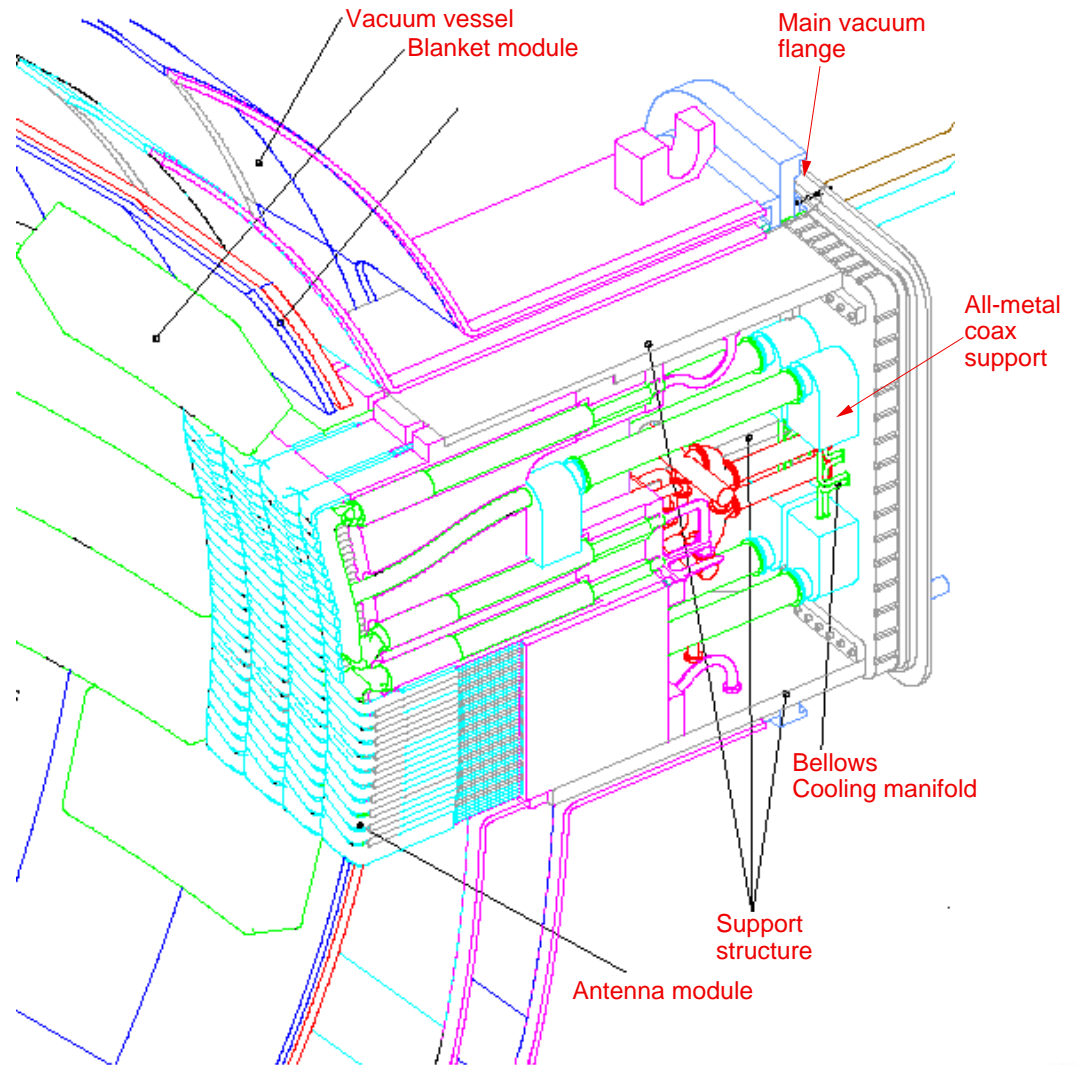
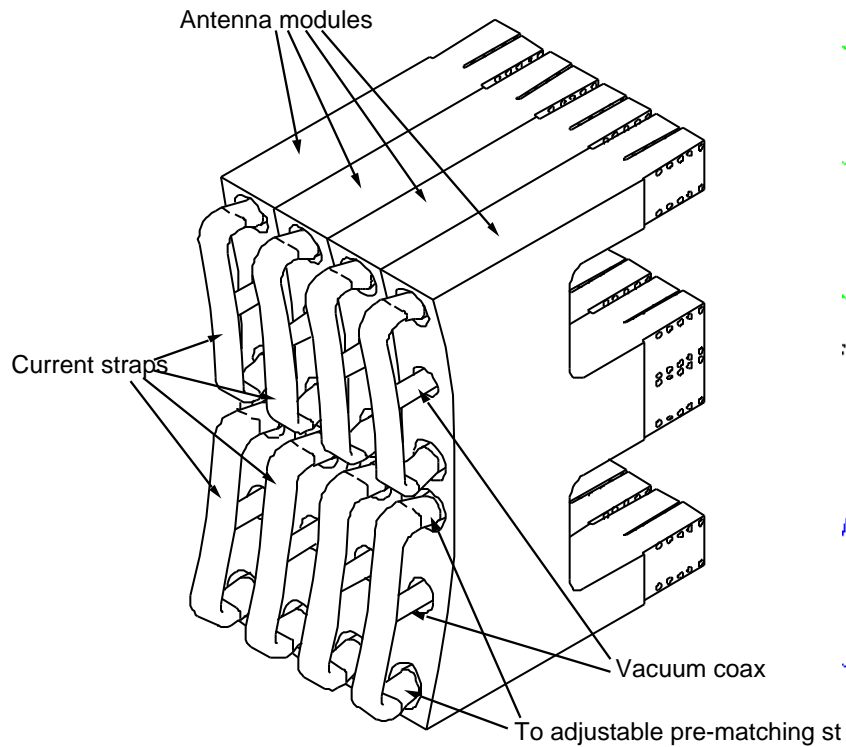
## System parameters:

- 50 MW to plasma
- Four antennas mounted in horiz. ports, each delivering 12.5 MW to the plasma
- Antenna size 1.6 m (toroidal) x 2.6 m (poloidal)
- 15-cm separation between plasma separatrix and antenna
- Tuning and decoupling circuits to respond to
  - fast plasma loading transients (ELMS)
  - Changing antenna phase to go from heating to current drive
- 32 rf sources, 2 MW each



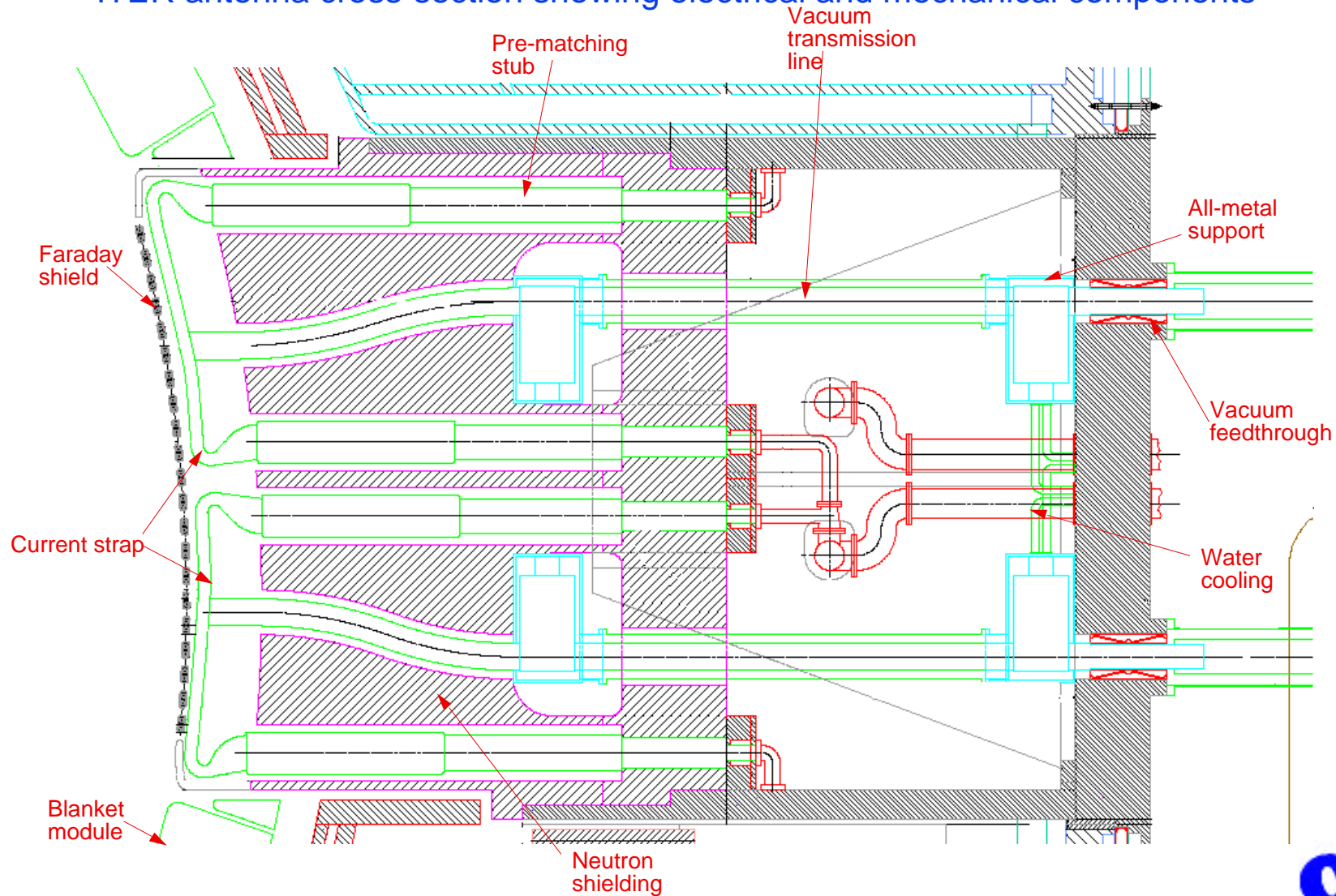
# The ITER antenna design

- 8 current straps in each port in 4 (toroidal) x 2 (poloidal) array
- Resonant-double-loop (RDL) strap configuration, with internal pre-matching stubs (PMS)



# ITER antenna design was carried to a fairly detailed level

ITER antenna cross-section showing electrical and mechanical components

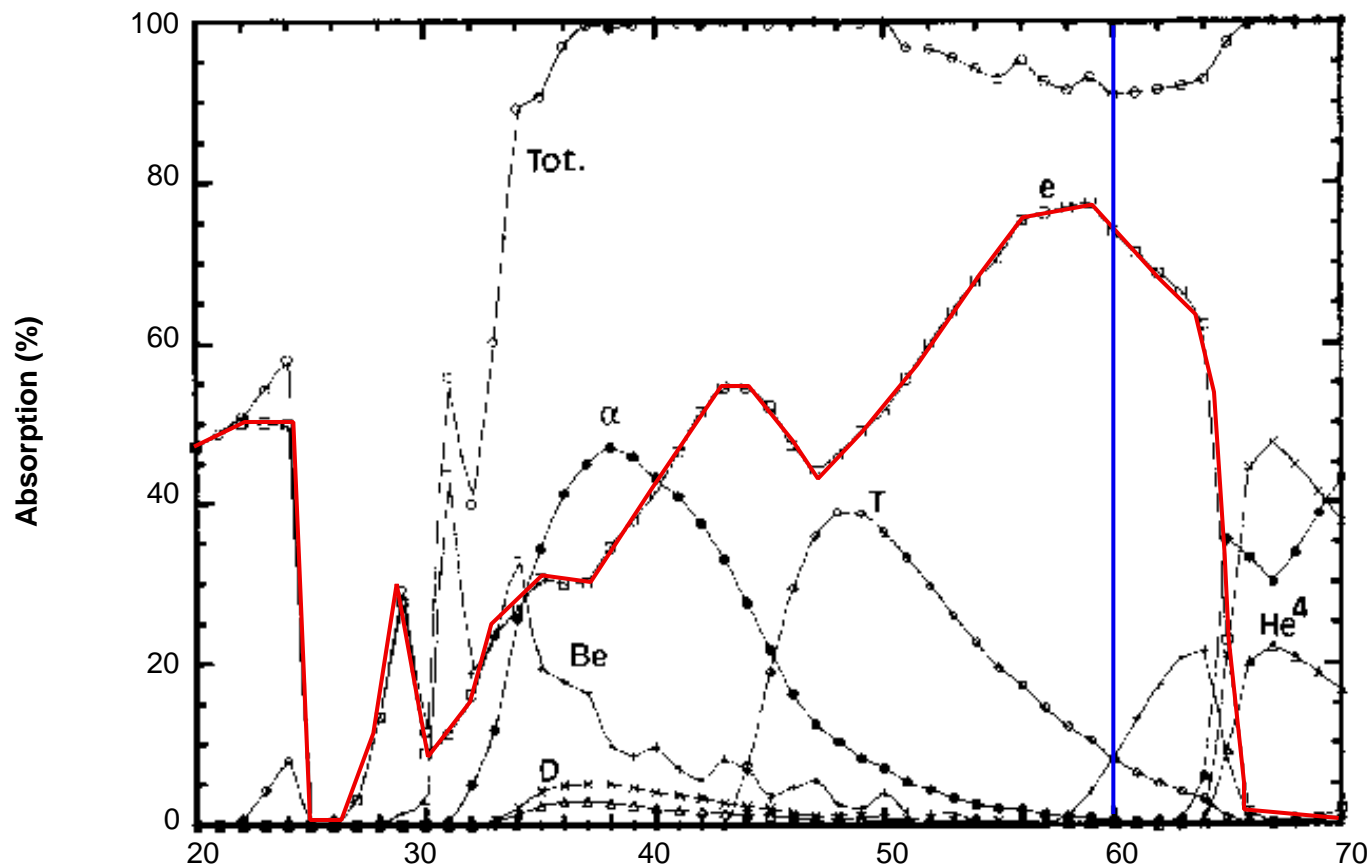




## ITER current drive frequency

Red – Fraction of launched power absorbed by electrons

Blue – FWCD frequency 60 MHz gives > 75% electron absorption

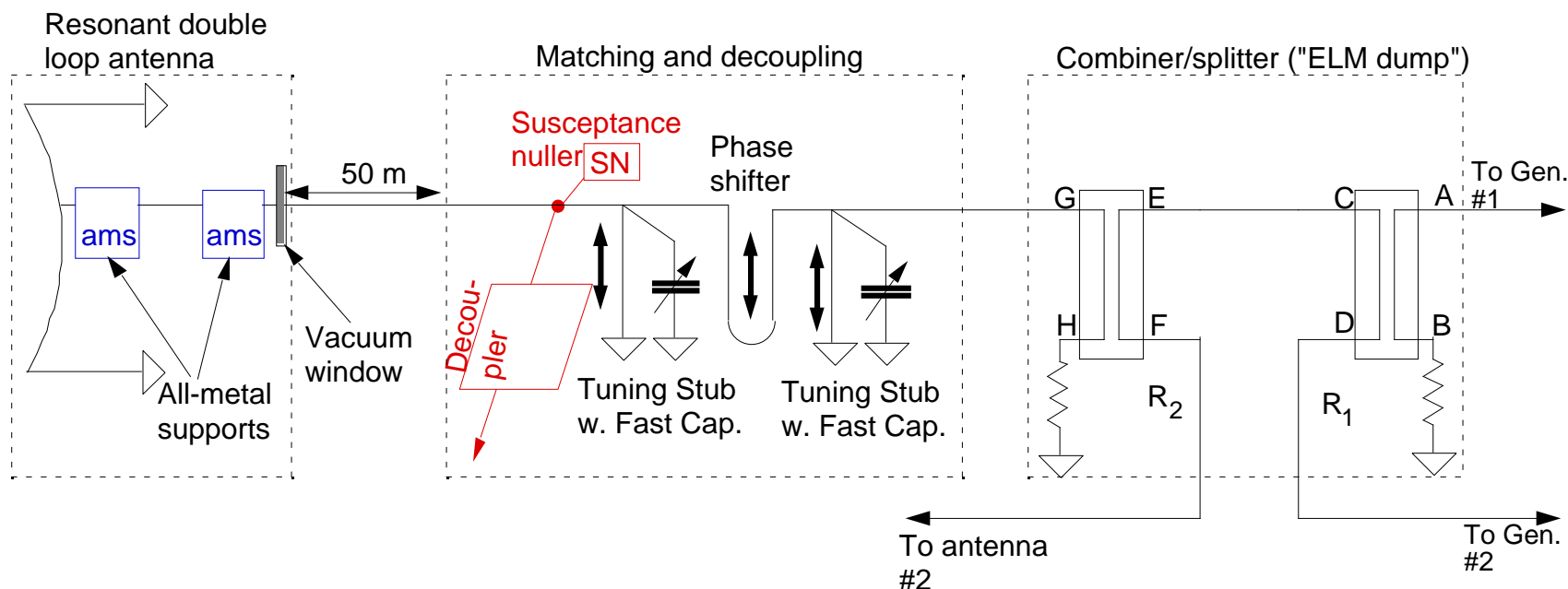


From Van Eester, Physics Lett A 227,97 (1997)

## Matching and decoupling circuits – almost “off the shelf”

### Proposed tuning and decoupling circuit

- All-metal supports in antenna provide mechanical strength, cooling
- Matching and decoupling circuit 50 m from machine
- Decouplers between lines
- Fast capacitors (per TEXTOR) for fast matching (Durodie, ERM/KMS)
  - Can match for 3:1 VSWR
  - Can get to 1.4 VSWR in 20 ms at 65 MHz
- Combiner/splitter (“ELM dump”)



## Fast capacitor tuning can match to ELMs quickly

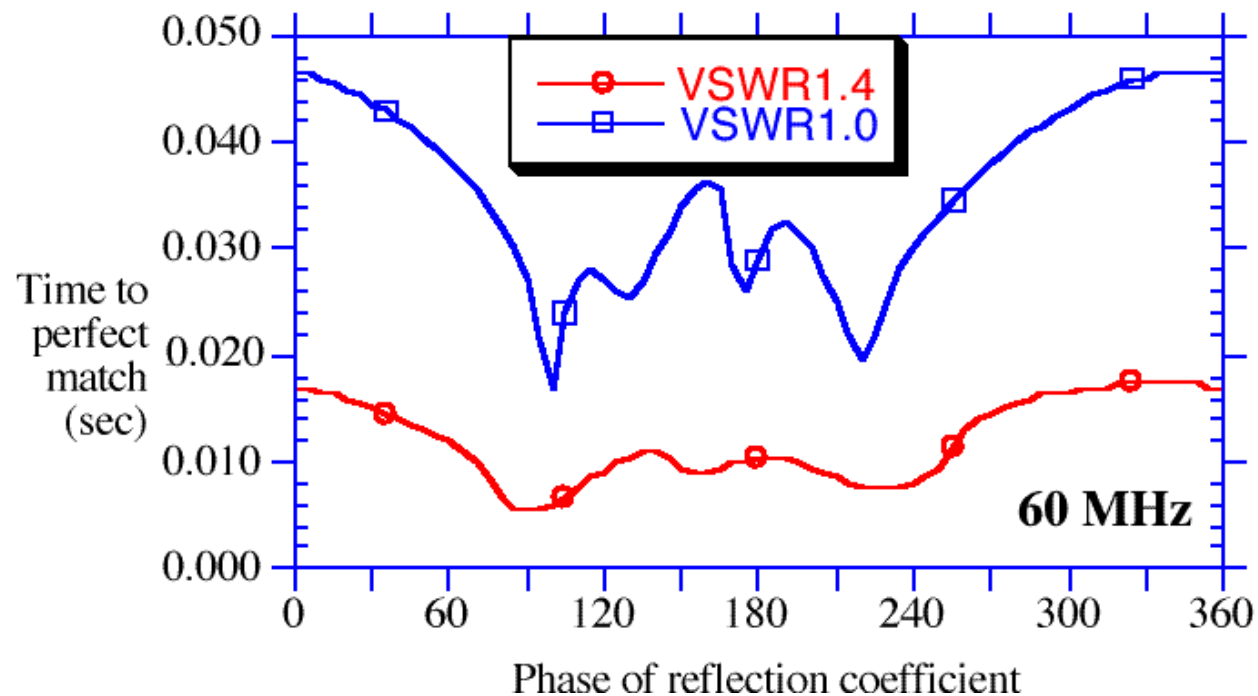
Design of fast-capacitor matching system has been done.

- Modeled on system tested on TEXTOR.

Fast transient assumed to change VSWR in antenna transmission line to 3 (corresponds to approximate doubling of plasma loading).

Fast-capacitor tuning system can bring VSWR down

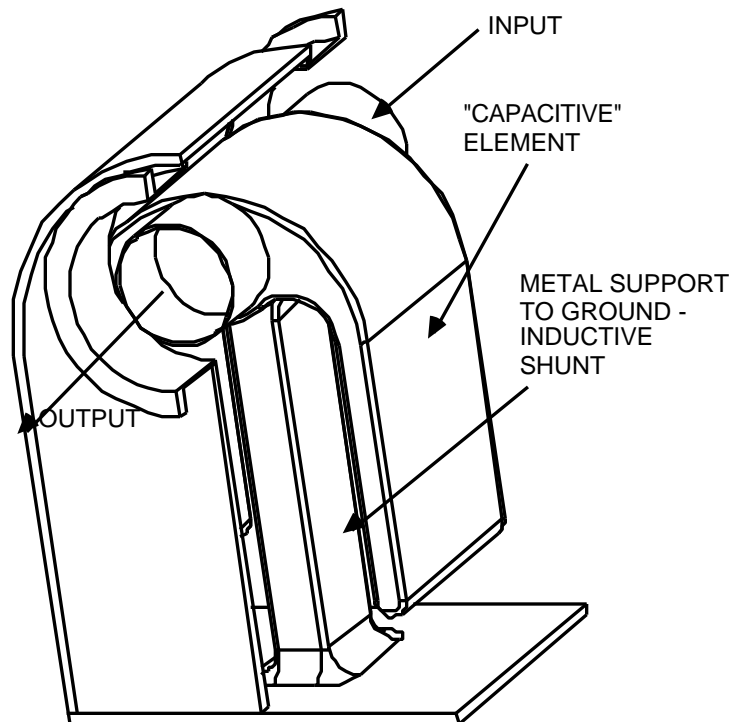
- to 1.4 within 20 ms
- to 1.0 within 50 ms



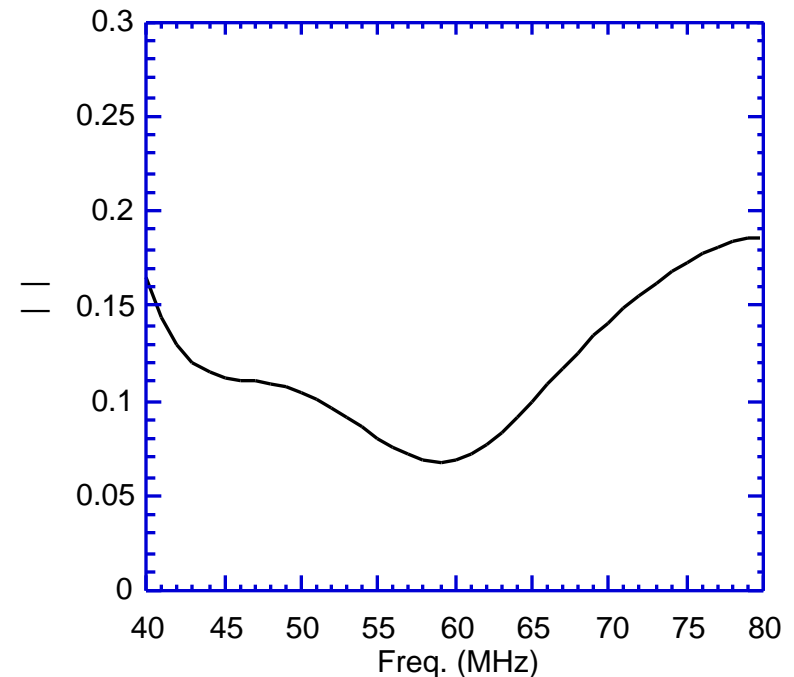
# All-metal support provides mechanical support for vacuum transmission line with no ceramics



All-metal support (AMS) has metal “inductive” support to ground and “capacitive” wings. Choose effective L and C so that structure is parallel-resonant (i.e.,  $Z_{shunt} \gg Z_{line}$ ) at frequency of interest.



By proper choice of AMS resonant frequencies, can get  $| \Gamma | < 0.2$  for two AMS's in ITER VTL.

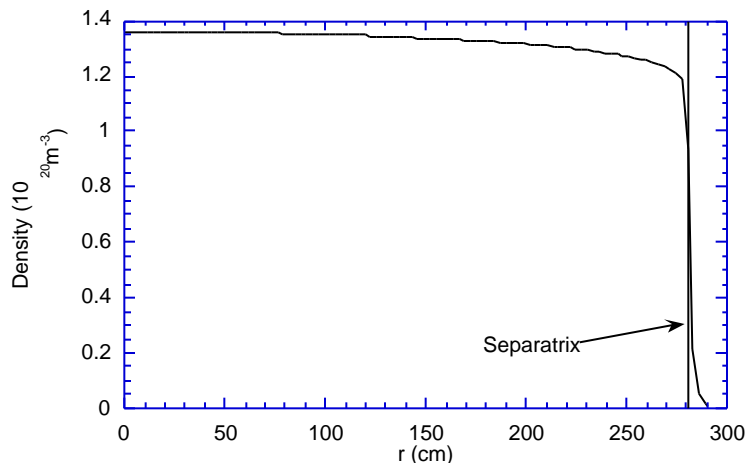


AMS concept from Kimura et al., JAERI  
Tested in high-voltage system for satisfactory electrical operation

# For nominal operating conditions, required IC power can be delivered - delivering the power

## Results of power analysis:

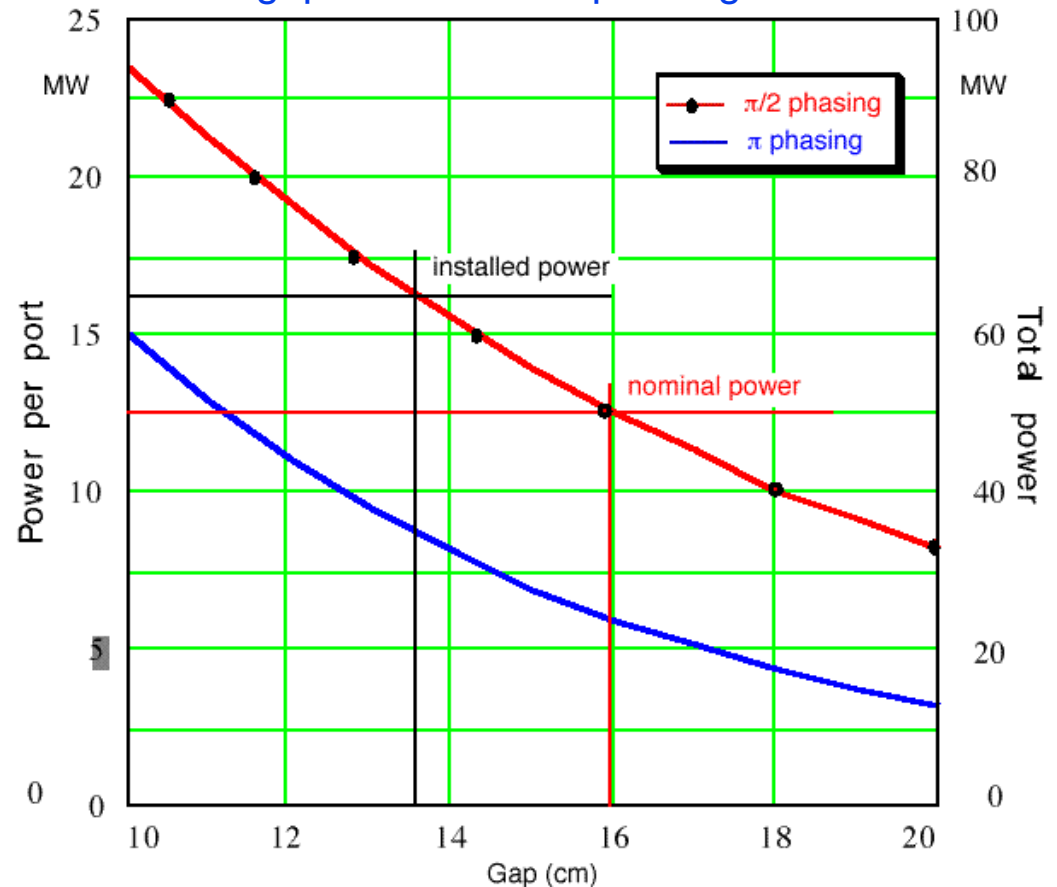
- 50 MW at 40 kV (12.5 MW/antenna) for 16-cm gap with interstrap-phasing  $\pi/2$
- 64 MW at  $\pi/2$  phasing for 13.5 cm gap
- 100 MW (!), if available, could be delivered at  $\pi/2$  with a 9.5 cm gap



Density profile used for ITER density calculations

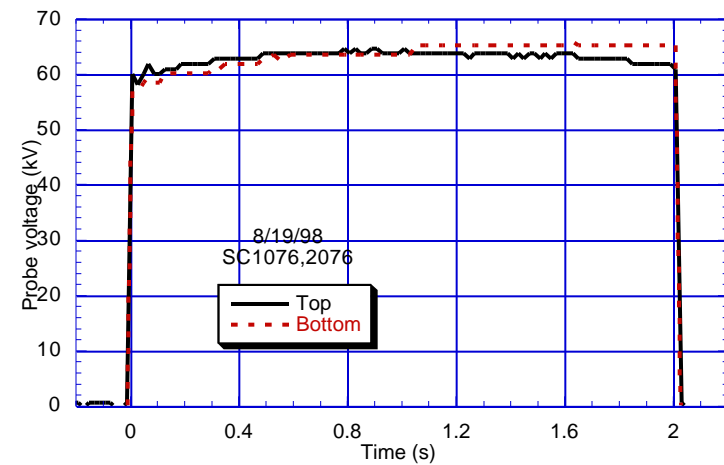
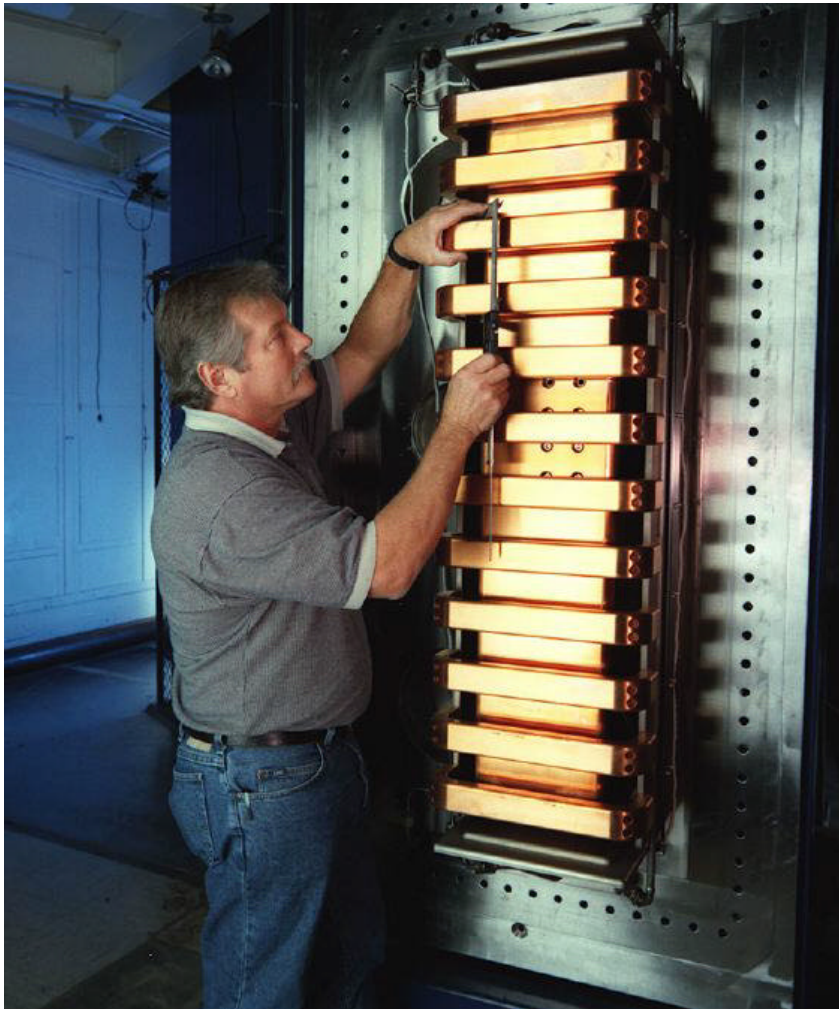
From "The ITER Ion Cyclotron System" ITER Document ITER/US/96/IV-RF-05

## Value of power delivered vs. gap for $\pi/2$ and $\pi$ phasing



Peak voltage depends on antenna-plasma gap and interstrap phasing.

A prototype antenna has been operated at  $> 60$  kV  
for 2 seconds - delivering the power



# Mechanical issues – survival

## Critical issue!

*Extensive* thermal and stress analysis done of ITER antenna:

- Thermal analysis during normal operation, w. plasma radiated power, RF losses, neutron heating of antenna volume
- Thermal and stress analysis of antenna components during disruptions.

## Example- Faraday shield thermal analysis

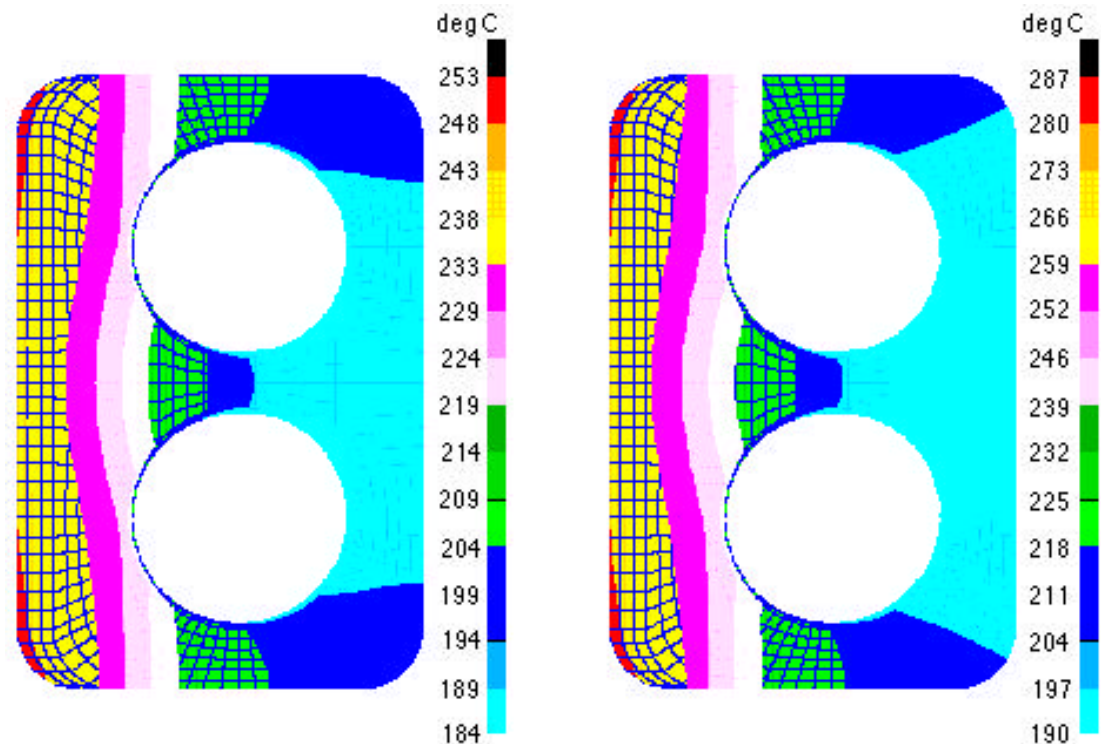
Normal heat loads (left):

- 15 MW/m<sup>3</sup> neutron heating at surface
- 0.25 MW/m<sup>2</sup> radiated power incident on front of FS

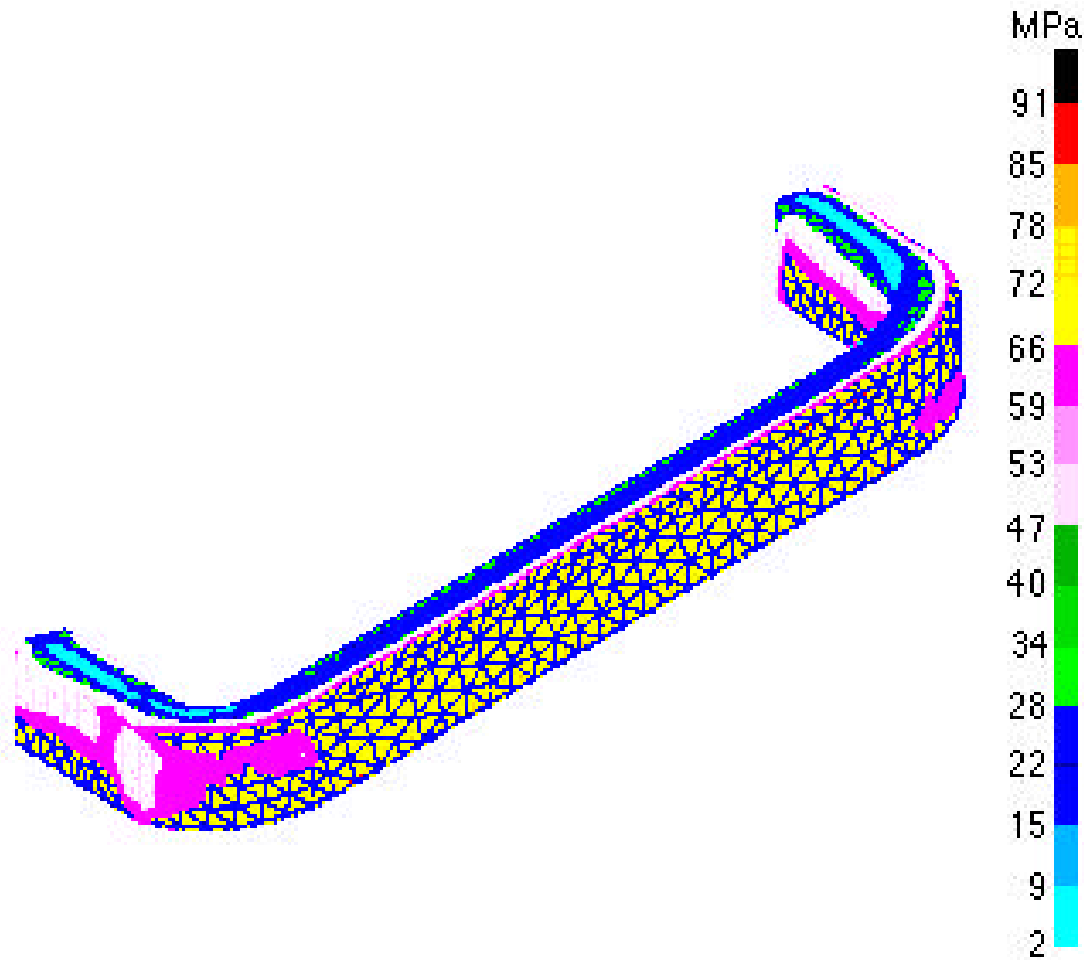
Transient heat loads (right):

- Same as normal, +
- Additional 0.25 MW/m<sup>2</sup> radiated power incident on front of FS, for up to 10 s

Temperature distribution in Cu alloy Faraday shield with 3 mm of Be on front



Peak thermal stress well within operating limits,  
90 MPa - 400 MPa allowable

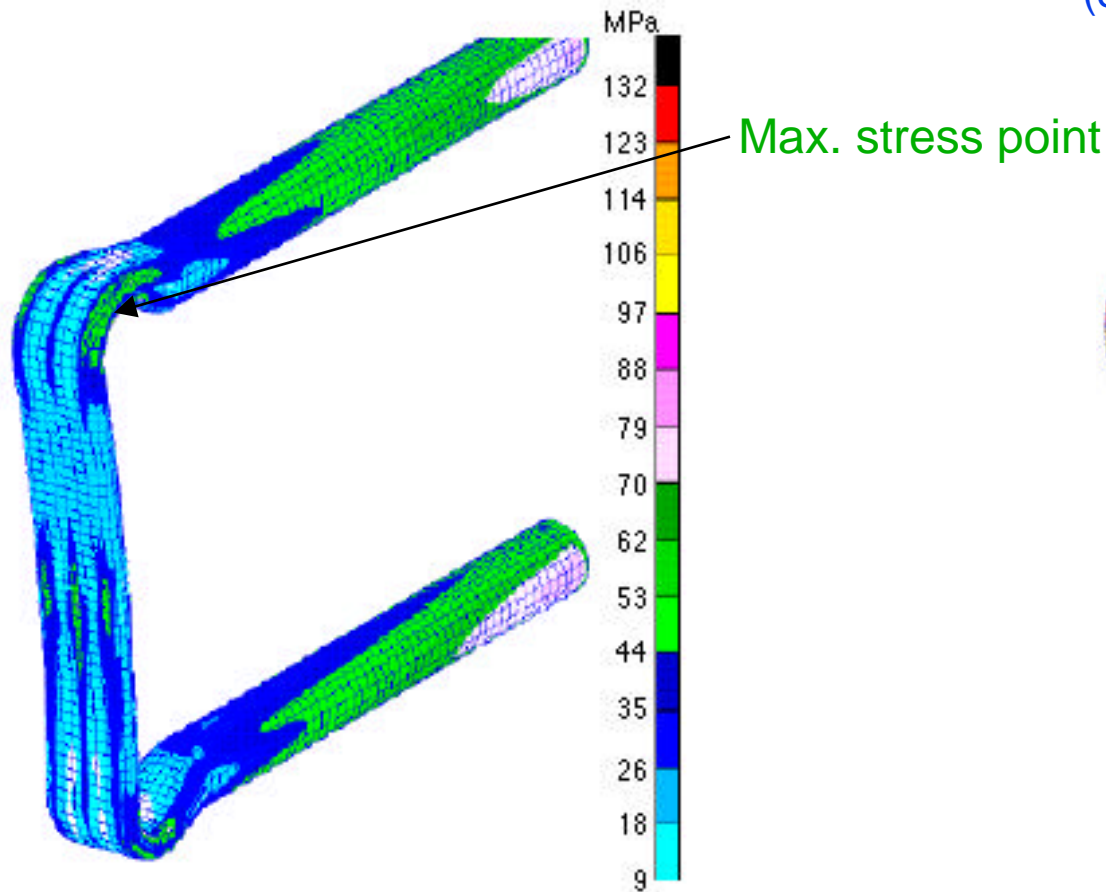


3D stress contours at end of thermal transient



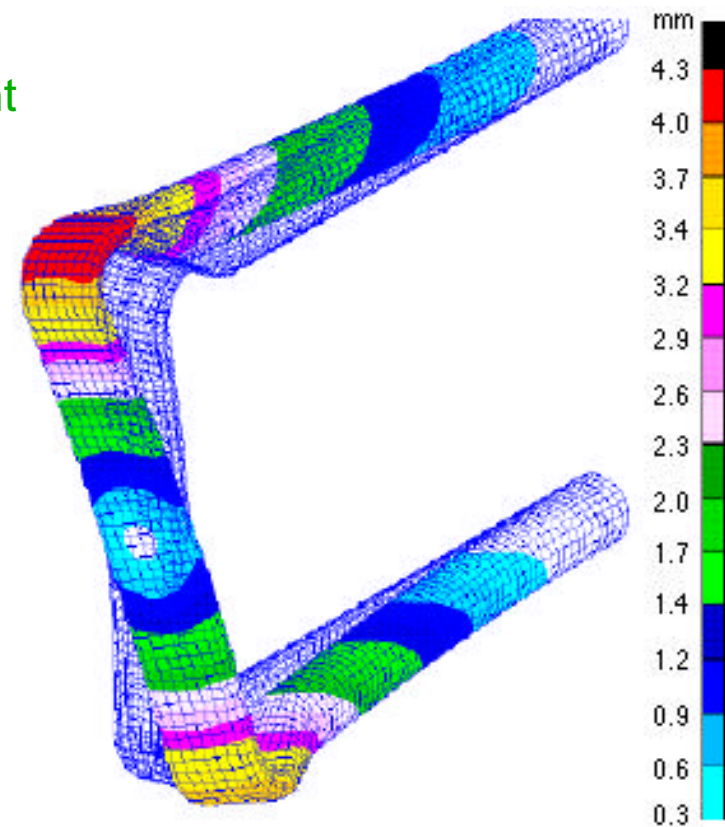
# Stress analysis during disruptions was done

## Stress levels in strap



Disruption stresses in current strap 130 MPa.  
High, but tolerable.

## Peak strap displacement (exaggerated displacement scale)



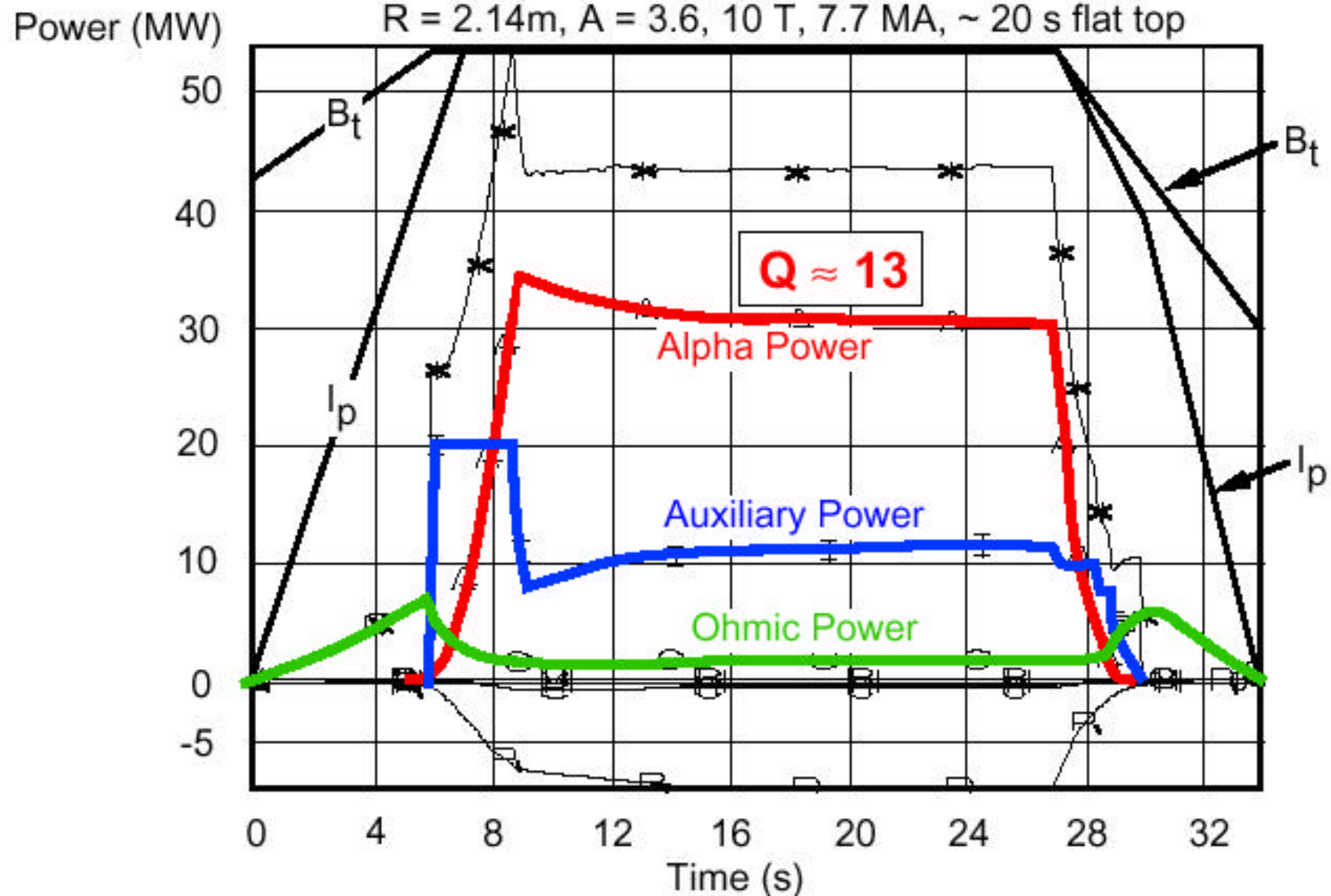
## Summary: Stress calculations indicate ITER antenna **will survive**

### Comparison of calculated vs. allowable stresses in the antenna

Component	Condition	Stress type	Stress MPa	Allowable MPa
Faraday shield	Normal ops.	Thermal	90	400
	Disruption	Electromagnetic	130	400
	Disruption	Combined	190	400
Current strap (all ss)	Normal ops.	Thermal	260	420
	Disruption	Electromagnetic	130	420
	Disruption	Combined	330	420

Can be reduced by making the strap partially of Cu alloy

# 1 1/2-D Simulation of Burn Control in FIRE\* (TSC)



- ITER98(y,2) scaling with  $H(y,2) = 1.1$ ,  $n(0)/\langle n \rangle = 1.2$ , and  $n/n_{GW} = 0.67$
- Burn Time  $\approx 18$  s  $\approx 21 \tau_E \approx 4 \tau_{He} \approx 2 \tau_{skin}$

# FIRE IC system: frequencies of operation

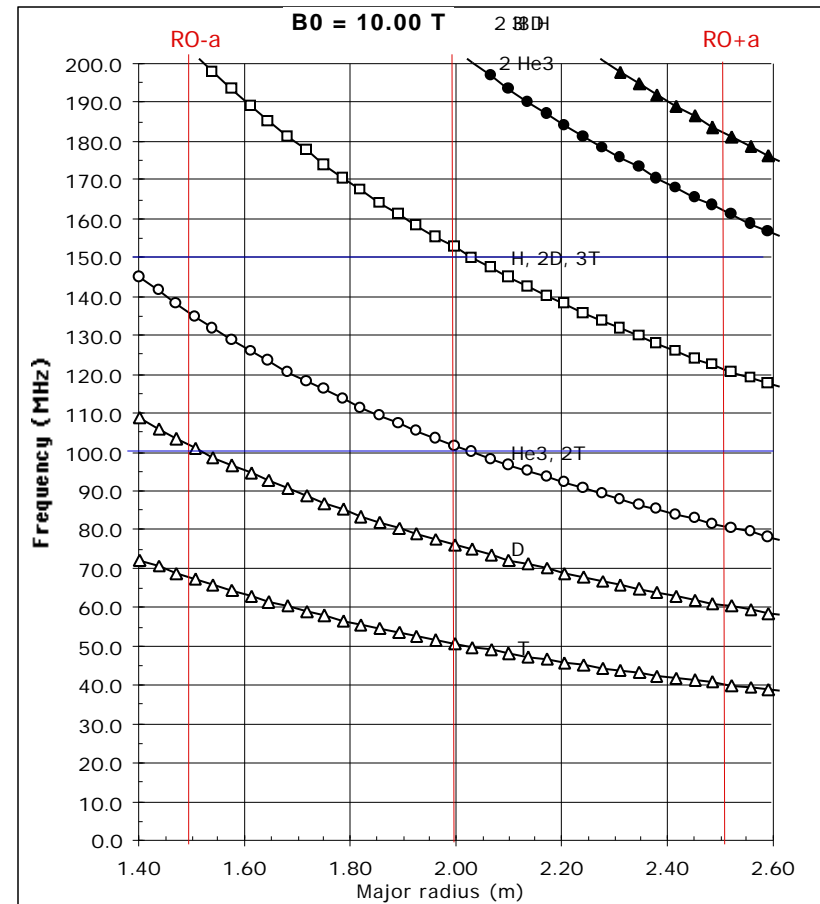
## 10.0/8.5 T - scenarios

### Heating:

- Second harmonic T (100 MHz): baseline for DT operation.
- Second harmonic D (150/127 MHz):
- H minority (150/127 MHz): no activation.
- He<sup>3</sup> minority (100 MHz): good for early operation without tritium.
- 6.7 T Second harmonic D and H minority (100 MHz)
- 4.0 T HHFW:

### Current drive:

- Fast-wave current drive at 115/100 MHz is baseline; competitive absorption by 2 $\tau$  and alphas.



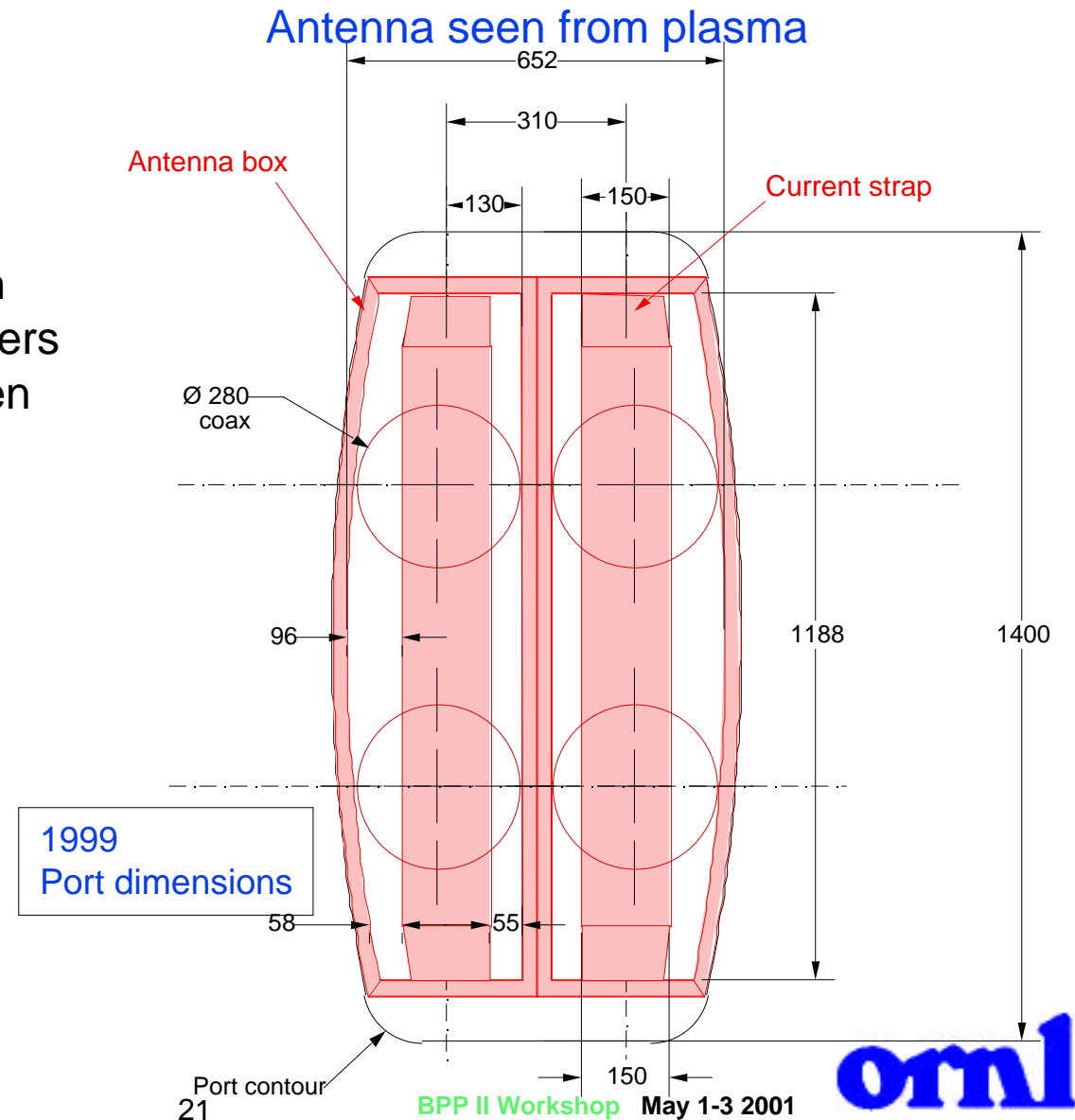
Design system that can operate in **100 - 150 MHz** frequency range.  
Can also be used for higher or lower field operation.

# Antennas have been designed to fit in main ports

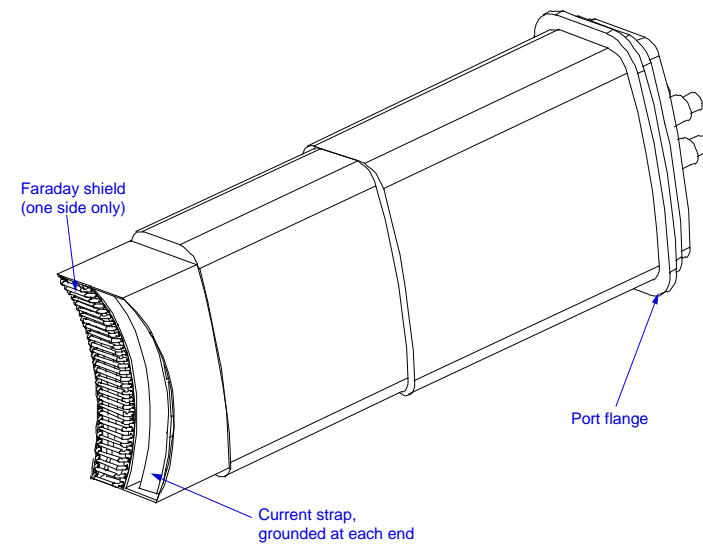
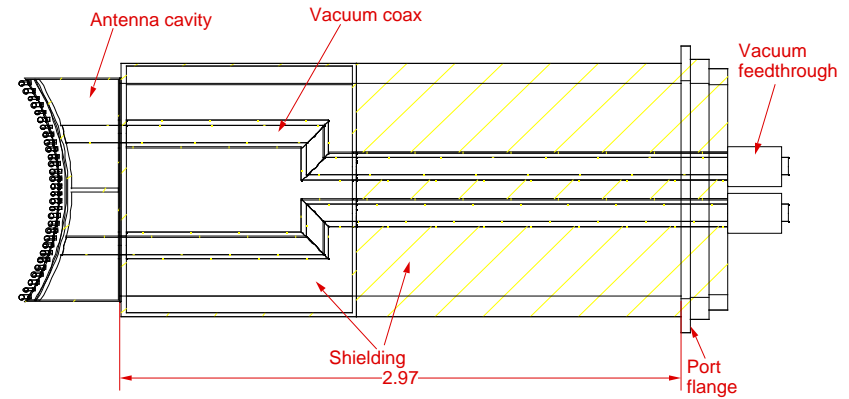
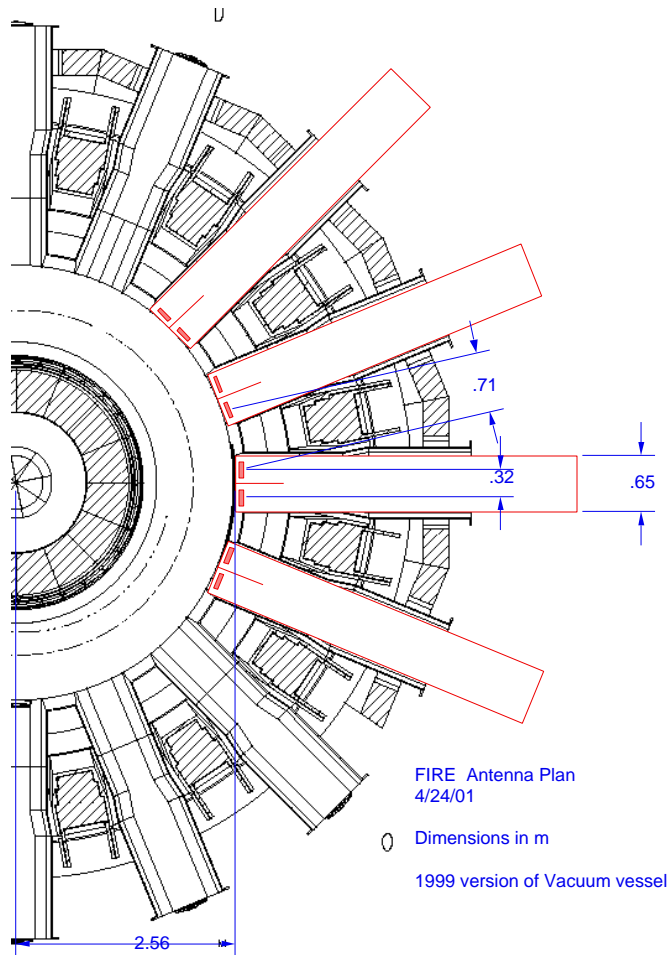
## Design Overview

### Antenna characteristics:

- Two current straps
- Straps grounded at each end
  - also in center if desired
  - good mechanical strength
- Each strap fed by 2 coax feeders
  - Feeds at midpoint between center and ends
  - Driven out of phase
- Antenna covered by Faraday shield (not shown)
  - Single-layer tubes
  - Probably connected to frame at center
- Active water cooling will be required during discharges 10 s ( FS tubes and strap).

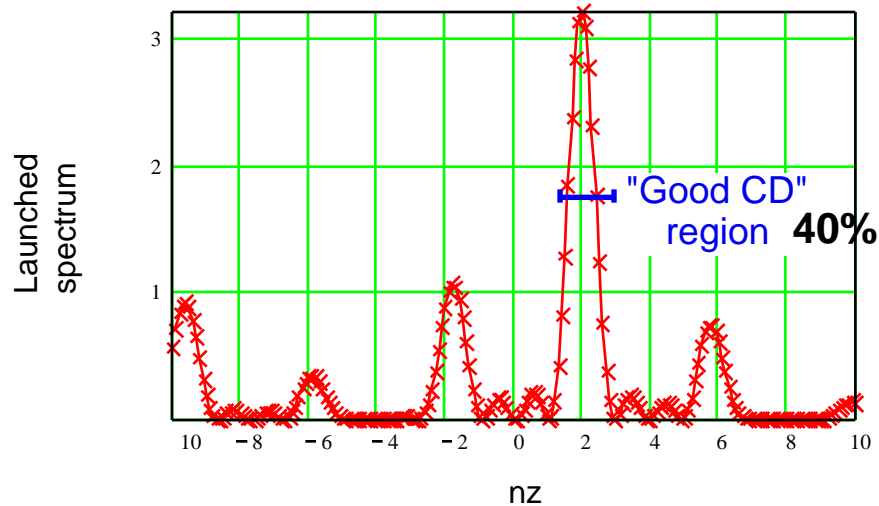


# Modular construction and internal shielding facilitates installation and maintenance in radiation environment



# Antenna array provides a spectrum with adequate current drive efficiency and low parasitic heating at 115 MHz

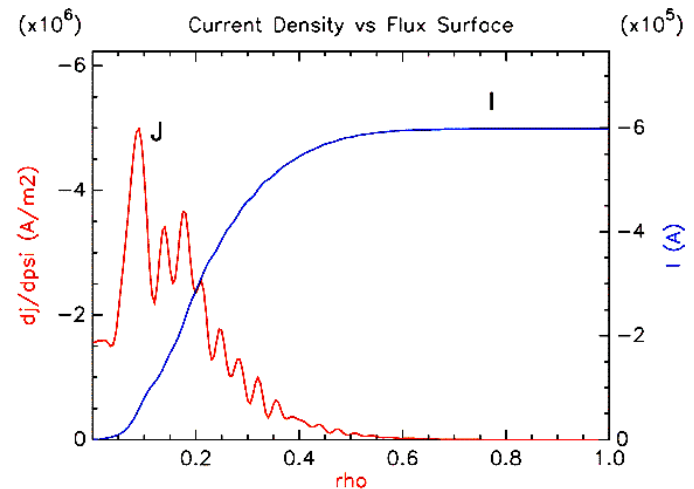
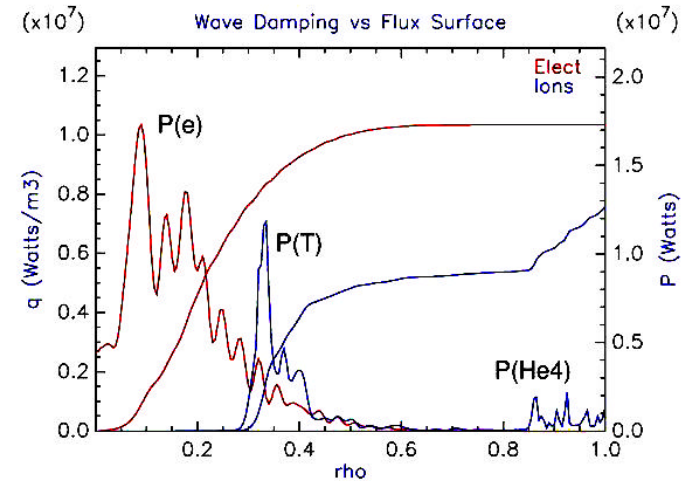
### Antenna spectrum



$T_e$  14 keV    $N_0$   $5 \times 10^{20}$     $N_z$  2

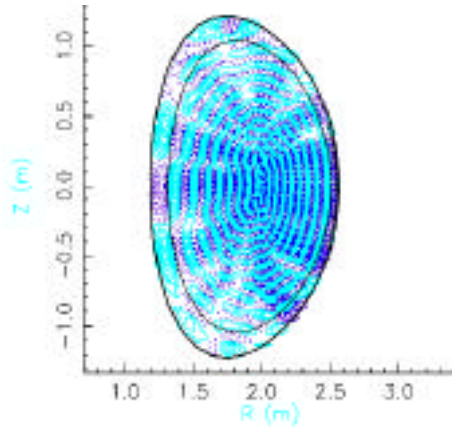
	115 MHz	75 MHz
electrons	58 %	13
majority D	6.5 %	73
minority T	2.9 %	15
alphas	6.6 %	14
CD/W	- 0.02 A/W	- 0.0045 A/W
CD eff	- 0.12 A/W/m <sup>2</sup>	- 0.021 A/W/m <sup>2</sup>
FWCD	- 0.4*598 kA	- 0.4*135 kA

### AORSA results @ 115 MHz

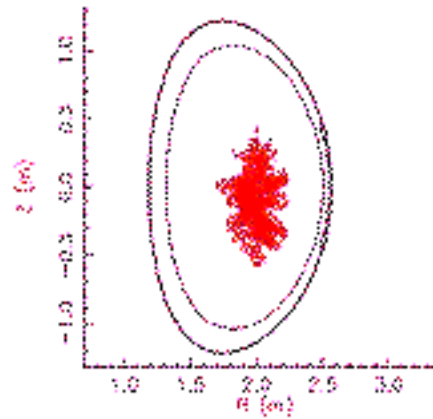


# AORSA full wave code results at 115 MHz

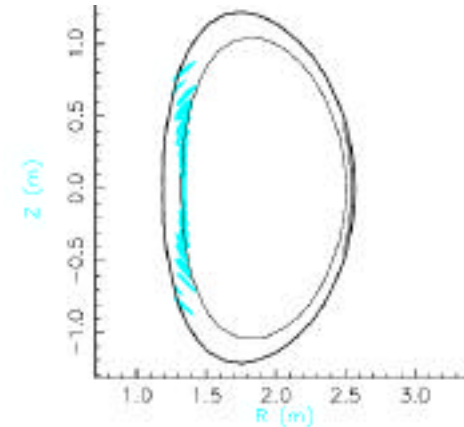
Electric field <sup>a)</sup>



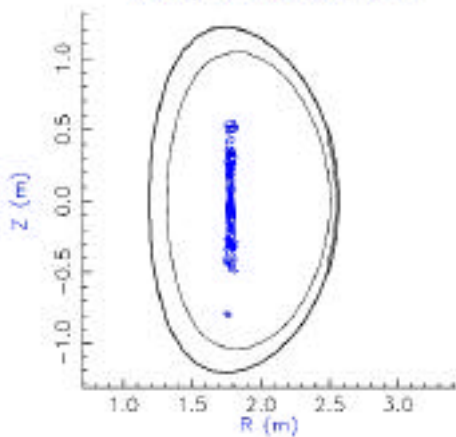
Electron absorption



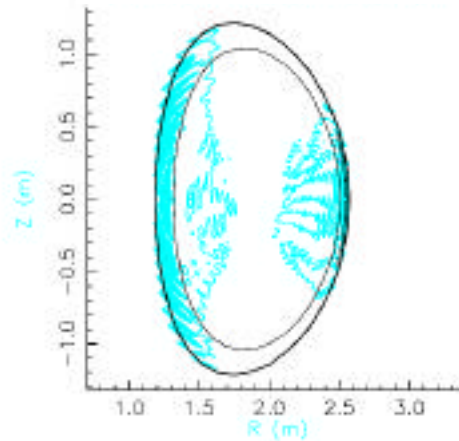
Majority D absorption



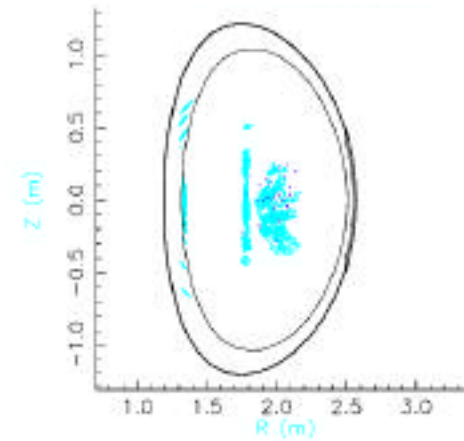
Minority T absorption



Alpha absorption

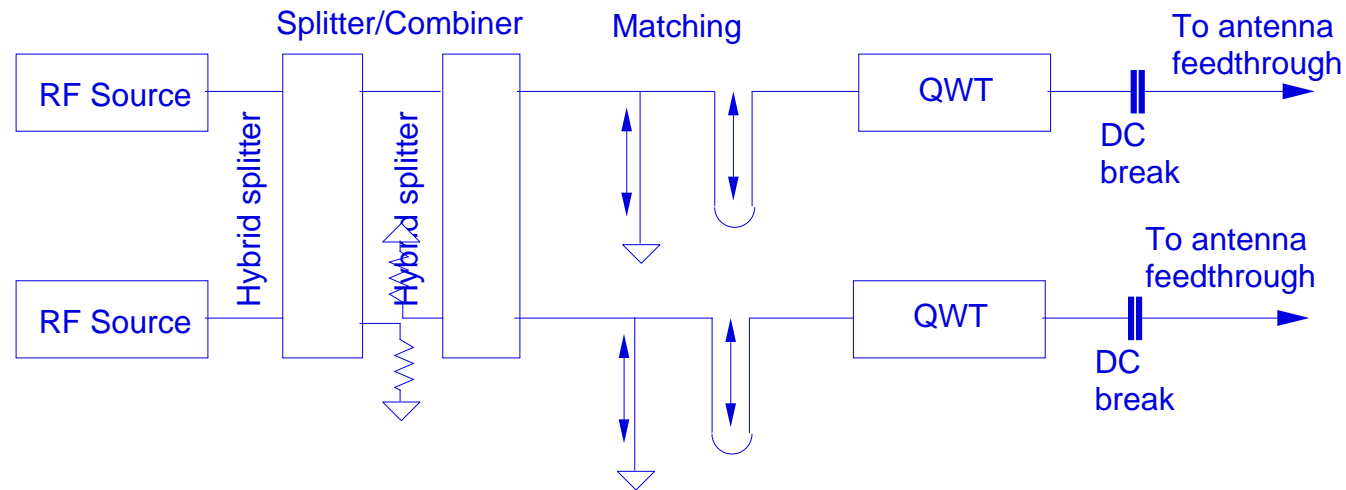


Total absorption





## Tuning and matching



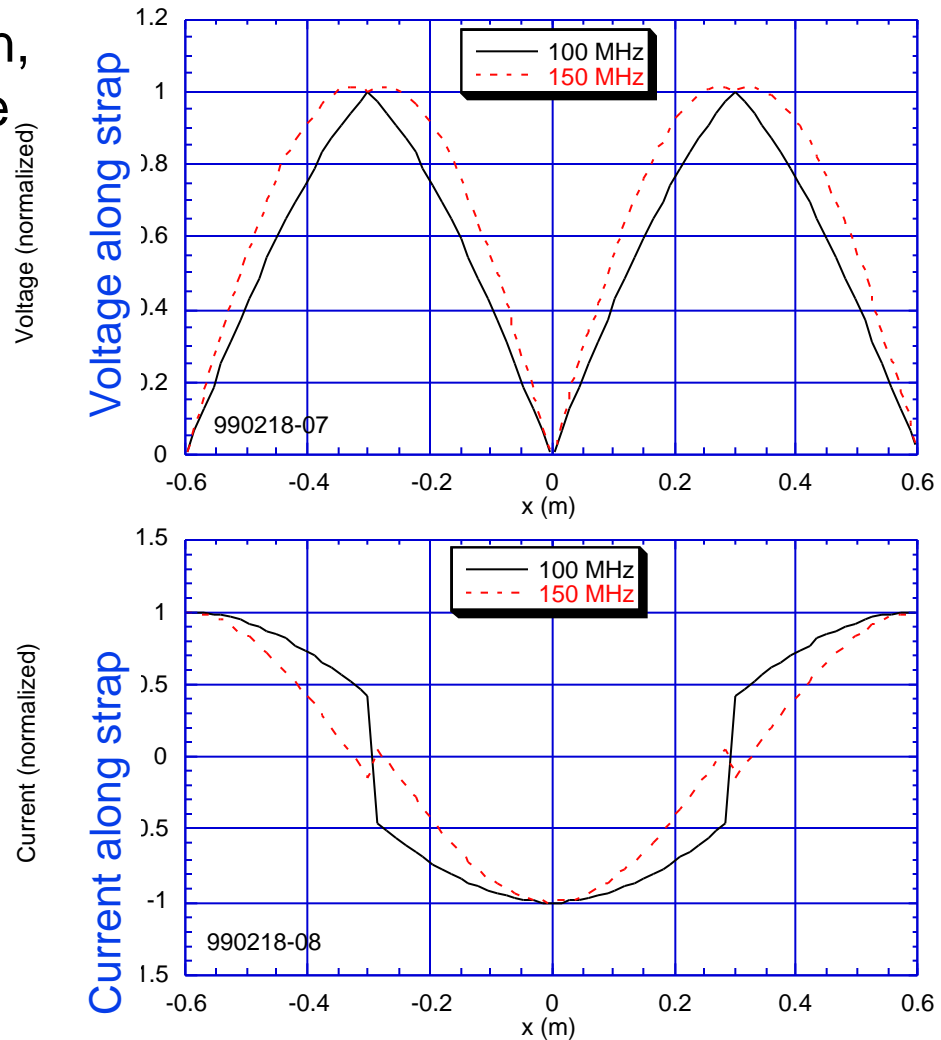
Relatively conventional design for tuning and matching:

- Two sources (90° relative phasing) feed hybrid combiner/splitter (“ELM dump”).
- Split power goes through standard stub/phase shifter matching circuit.
- Quarter-wave transformer for pre-matching.
- “ELM dump” – any power reflected from antennas due to transient changes in plasma conditions (e.g., an ELM) wind up in load resistors and aren’t seen by rf sources.
- Result is that sources can operate at near full power throughout shot.

## V and I along strap over 100 – 150 MHz range OK

For antenna dimensions shown, antenna electrical length is one wavelength at  $f = 140$  MHz.

Antenna will operate over the 100 to 150 MHz range



# Power to the plasma - calculation of $R'$ (plasma loading of antenna)

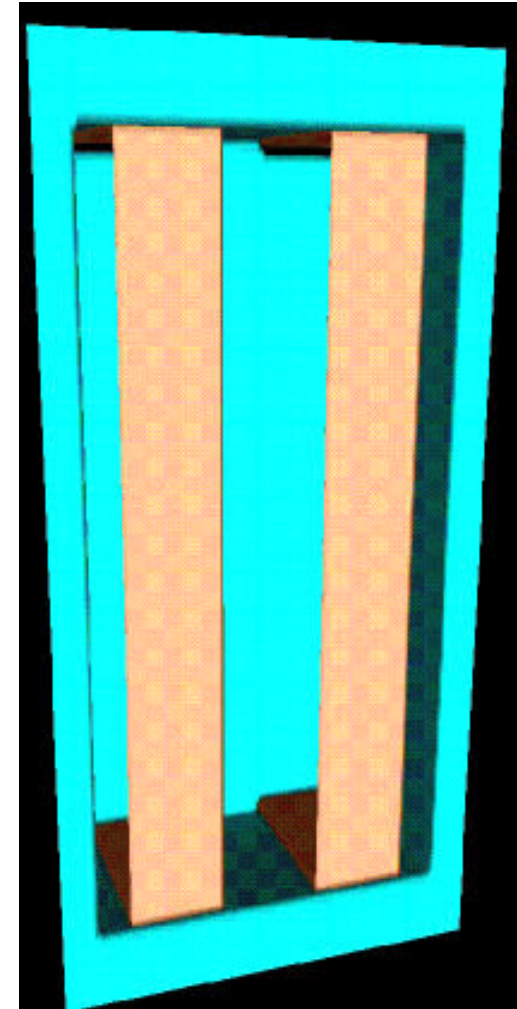
## Antenna assumptions in RANT3D:

- Antenna flush with first wall
- phasing between current straps

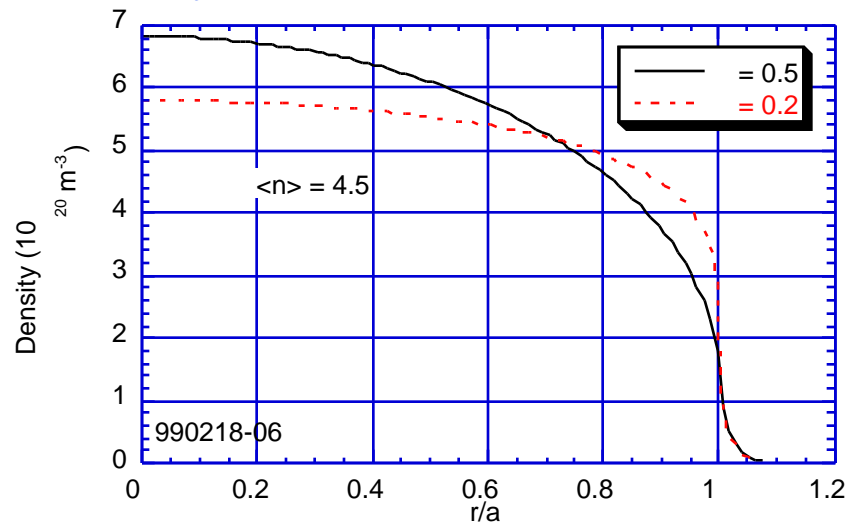
## Plasma assumptions:

- parabolic-to-a-power density ( $\beta = 0.2$  and  $0.5$ )
- $n_{\text{sep}}/n_0 = 0.2$
- $r_{\text{scrapeoff}} = 1$  cm
- $\langle n \rangle = 4.5 \times 10^{20} \text{ m}^{-3}$  (also did scan on  $\langle n \rangle$ )

## Antenna geometry (RANT3D)



## Density profiles used in $R'$ calculations



# How many ports are needed to deliver 30 MW to the plasma?

For

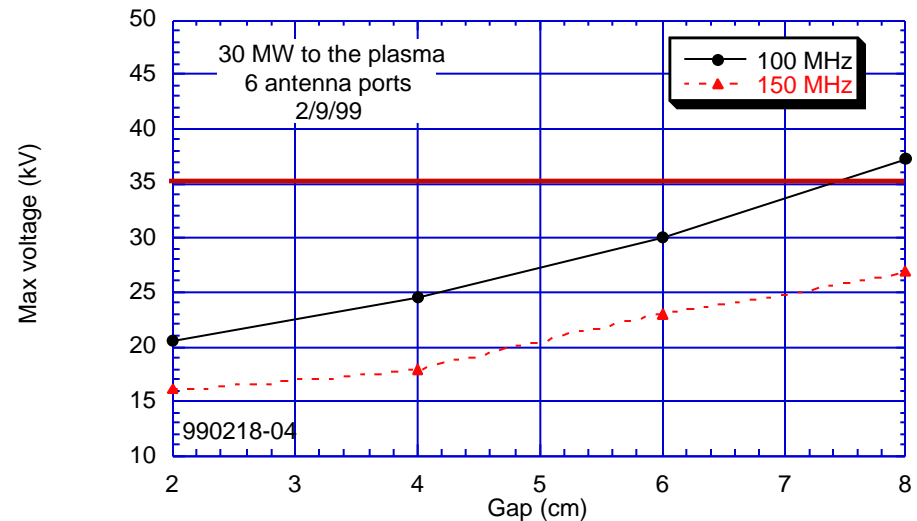
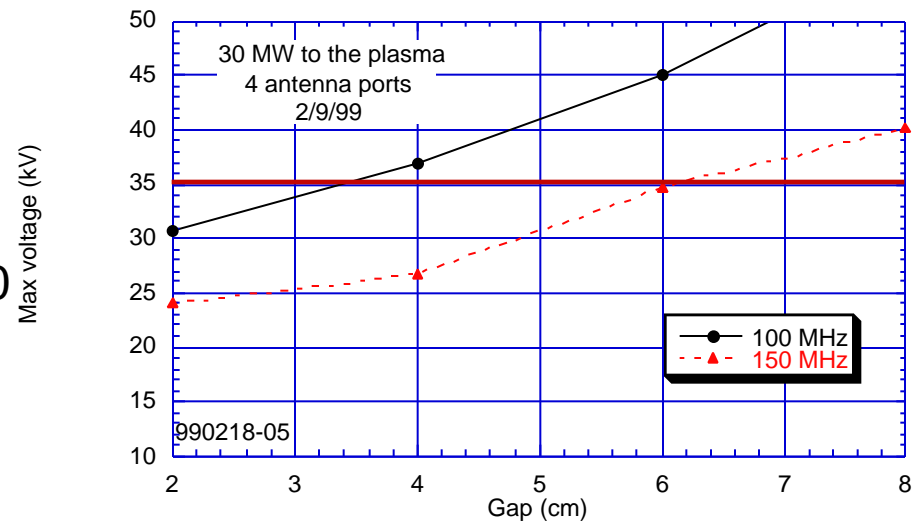
- $\tau = 0.5$
- $\langle n \rangle = 4.5 \times 10^{20} \text{ m}^{-3}$

For  $V_{\text{max}} = 35 \text{ kV}$

- **Four** ports for gap 3.5 cm @ 100 MHz, 6 cm @ 150 MHz

*Decision made to allocate four ports*

- Gap 3.5 cm
- Lower density **improves** loading



## Conclusions - Ion cyclotron heating and/or current drive enables access to burning and advanced-tokamak operating modes.

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Ion cyclotron systems look promising (but challenging) in burning-plasma experiments. Two representative experiments (ITER and FIRE) show that

- Heating power can be delivered from a reasonable array of antennas.
- Current drive goals are achievable
- Antenna circuits can respond rapidly to transients and active control requirements
- Antennas can be designed to survive in burning plasma environments.
- Machine parameters and requirements influence design tradeoffs but not basic feasibility

RF Development is working to improve the ion cyclotron system capability over the next several years.

- Improve voltage limits
- Improve system response to transients
- Improve reliability

A burning plasma experiment would further test RF performance:

- High thermal and neutron loads
- Potential for high disruption loads
- Remote handling environment
- Test competition between electron and alpha RF power absorption