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# RF Heating Scenarios

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Physics Issues for FIRE  
PPPL  
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FIRE Physics Issues 1-3 May 2000



## Introduction and requirements

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FIRE heating and current drive systems:

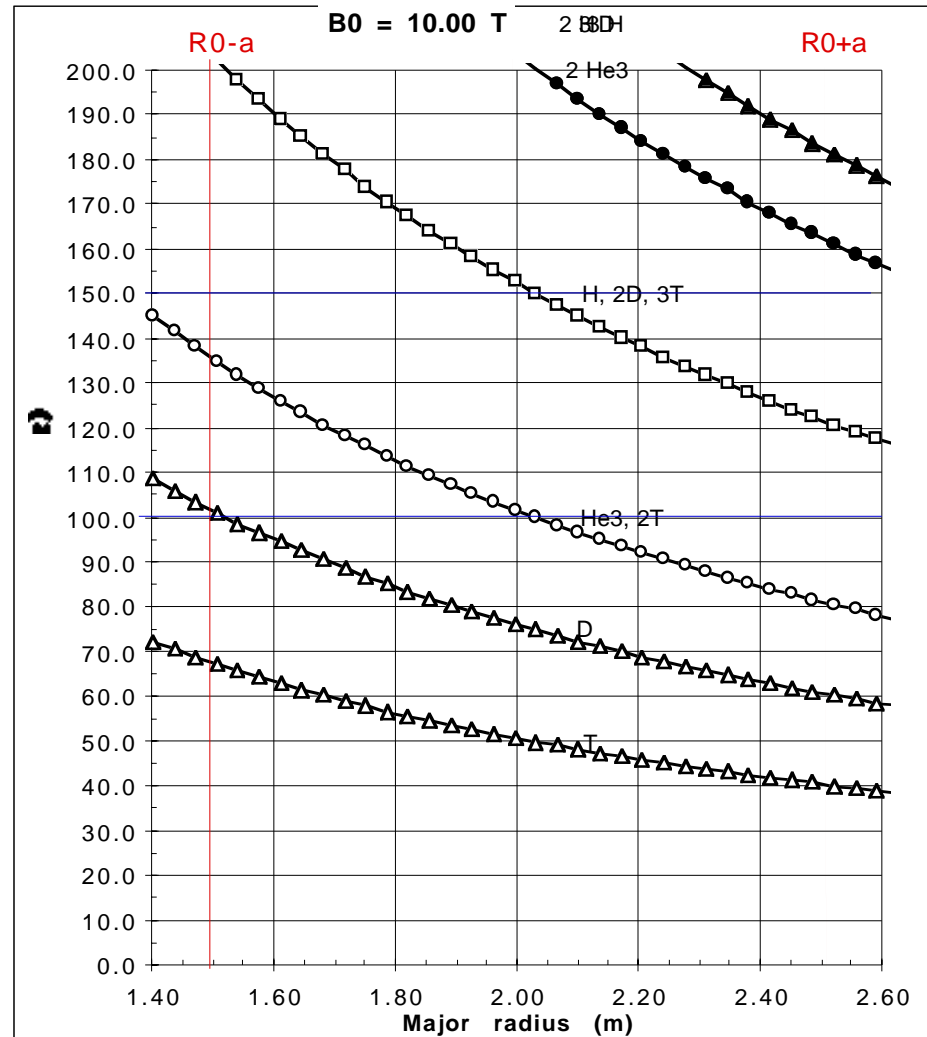
- u Ion Cyclotron system - **ORNL**
  - Baseline system
  - 30 MW to the plasma
  - Heating only (no current drive requirement)
  - Operate at 10 T
  - Operate for  $\geq 10$  s
  - Density range  $\langle n \rangle \approx 1$  to  $5 \times 10^{20} \text{ m}^{-3}$
  
- u High Frequency Fast Wave system - **PPPL**
  - Alternative/partial replacement for ICRH system
  
- u Lower Hybrid system - **ORNL, PPPL**
  - Possible upgrade

## Ion cyclotron system: frequencies of operation

For 10 T operation:

- u 150 MHz
  - $2\Omega_D$
  - H minority
- u 100 MHz
  - $2\Omega_T$
  - He<sup>3</sup> minority (good for D only plasma)
  - Also use at 6.7 T for  $2\Omega_D$ , H minority

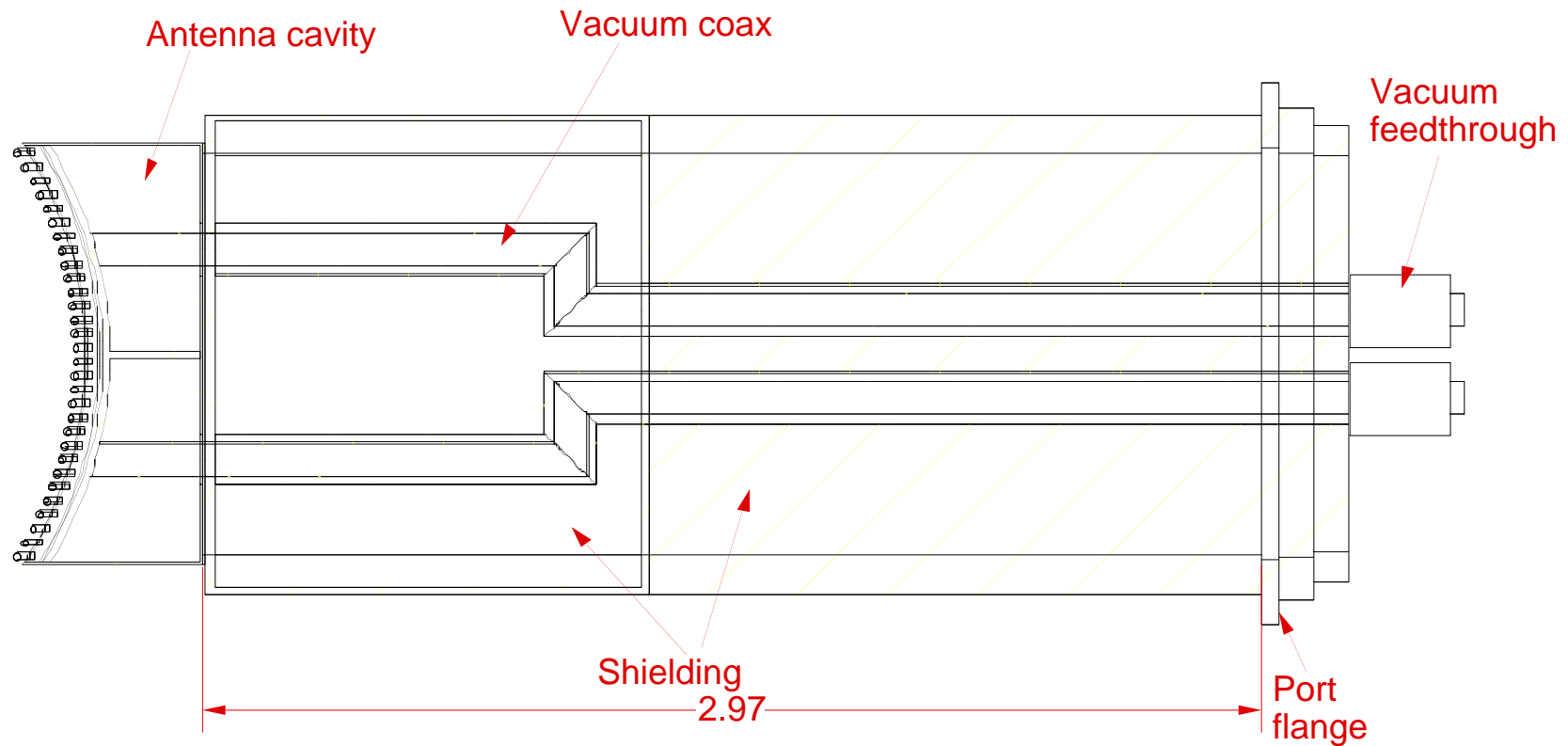
⇒ Design system that can operate in 100- 150 MHz frequency range.





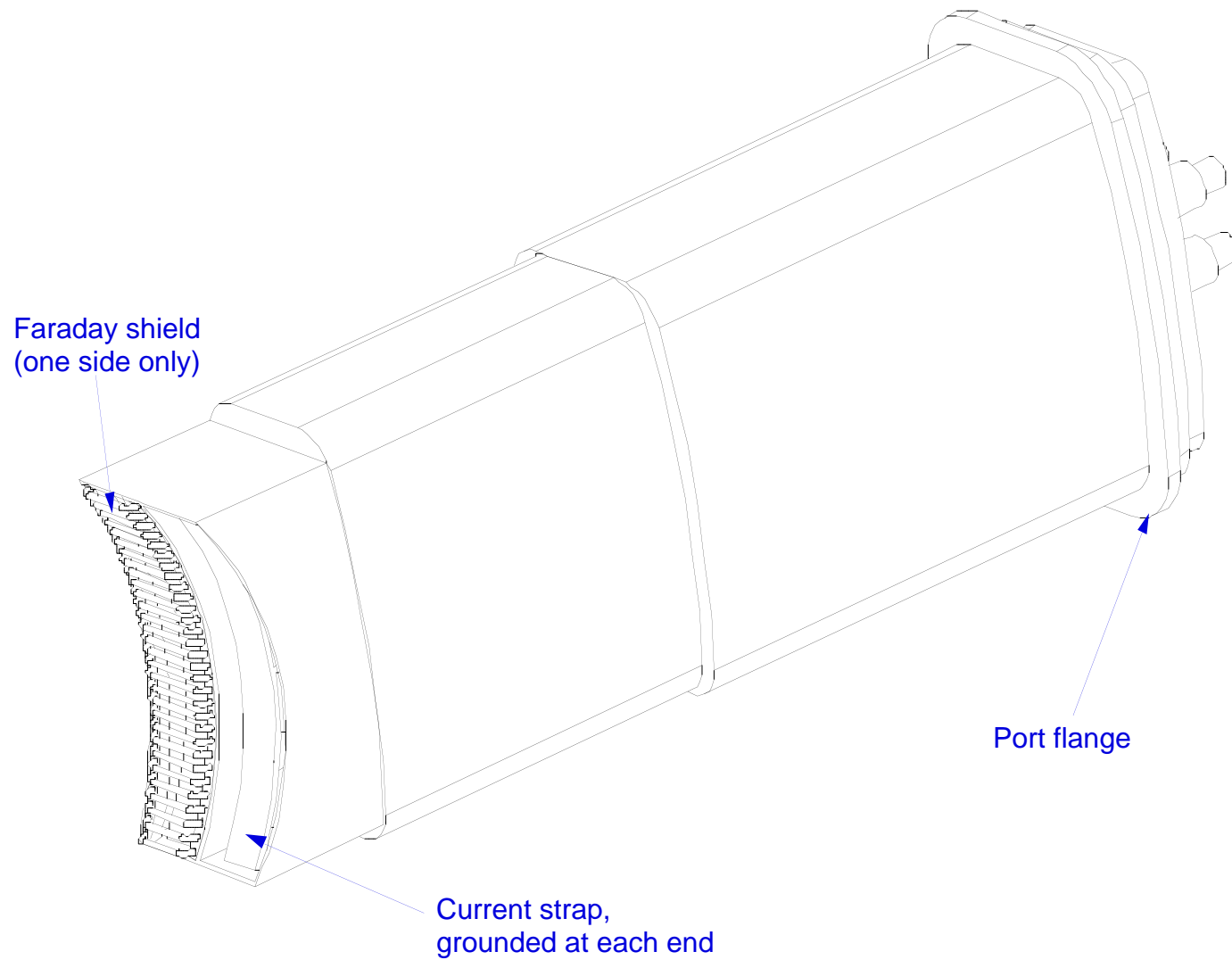
Each antenna contains shielding to reduce radiation at outside flange so that hands-on maintenance can be done

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# Modular construction of antenna facilitates installation in radiation environment

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

RANT - 3D modeling for:

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

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

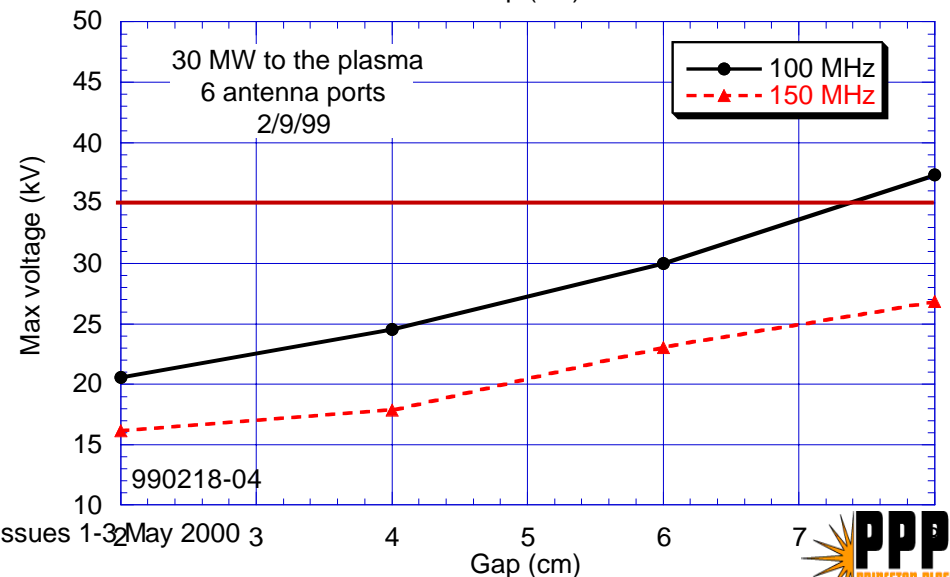
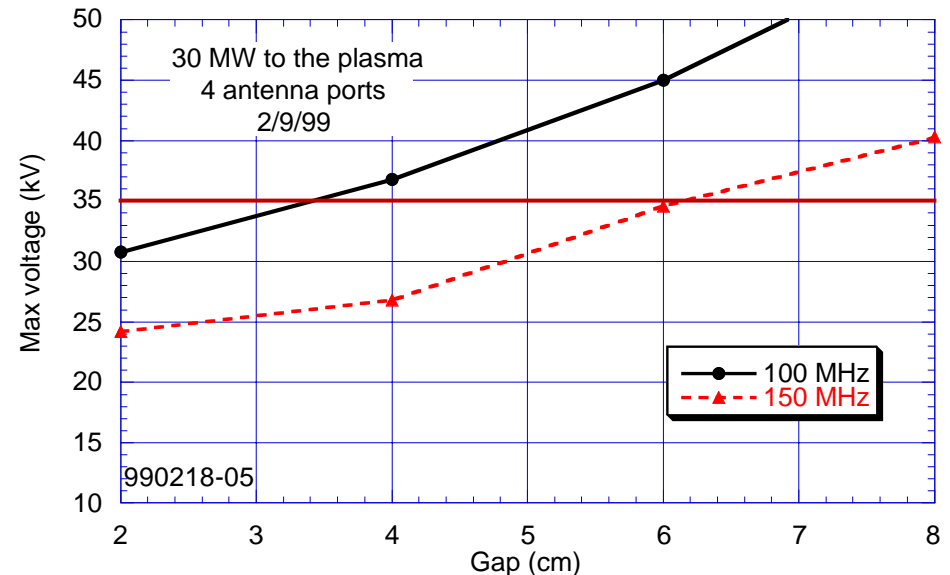
- u **Four** ports for gap  $\leq 3.5 \text{ cm}$  @ 100 MHz,  $\leq 6 \text{ cm}$  @ 150 MHz
- u **Six** ports for gap  $\leq 7.5 \text{ cm}$  @ 100 MHz, more at 150 MHz.

For  $V_{\text{max}} = 30 \text{ kV}$

- u **Four** ports for gap  $\leq 2 \text{ cm}$  @ 100 MHz,  $\leq 5 \text{ cm}$  @ 150 MHz
- u **Six** ports for gap  $\leq 6 \text{ cm}$  @ 100 MHz, more at 150 MHz.

*Decision made to tentatively allocate four ports*

- u Gap  $\leq 3.5 \text{ cm}$



## RF sources are an issue

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Requirements and constraints:

- u 30 MW to plasma
- u Four ports, each with two current straps
- u Two rf feeds per current strap.

30 MW through 16 rf feeds means  $\approx 2$  MW per feedthrough.

How to get 2 MW at 150 MHz?

- u Present tubes can deliver  $\approx 2$  MW into matched load at  $\leq 100$  MHz, but power decreases with frequency.
- u Probably will require TWO output tubes for 2 MW at 150 MHz.
- u Derating to 80% would imply 18 tubes for 100 MHz, 36 tubes for 150 MHz.



## High frequency fast wave (HFFW) heating for FIRE

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Similar to the DIII-D FWCD regime in harmonic number.

- u But: several hundred MHz at FIRE toroidal field.

High  $\beta$  not a necessity for effective direct electron heating.

- u Major factor is the short radial wavelength (integrated damping decrement) at high harmonic number.
- u Aided by high density.

Maximum frequency set by need to avoid a significant lower hybrid resonance in the edge.

Minimum frequency set by ion resonances.

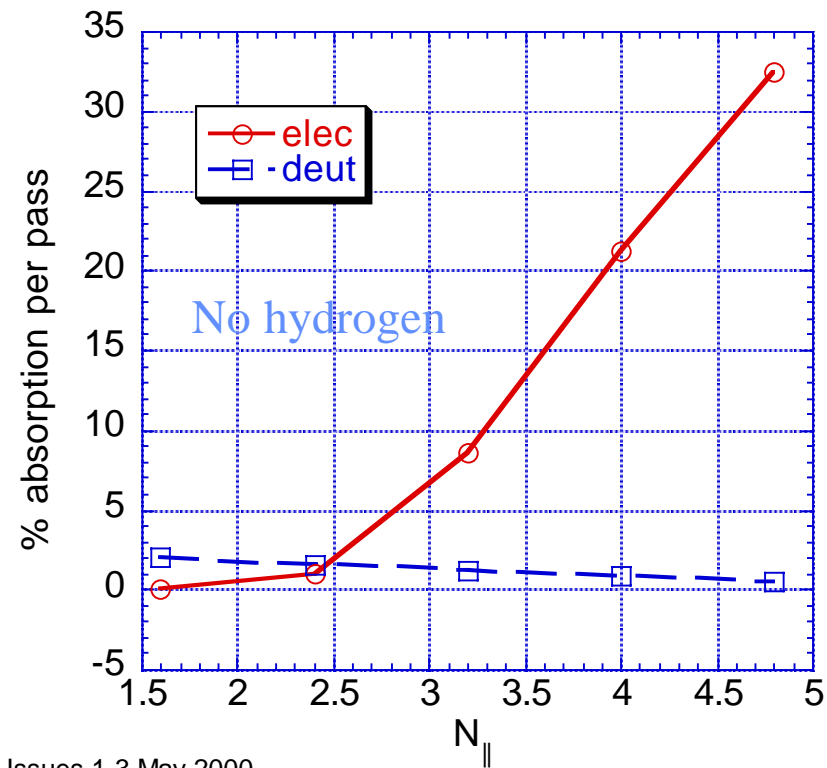
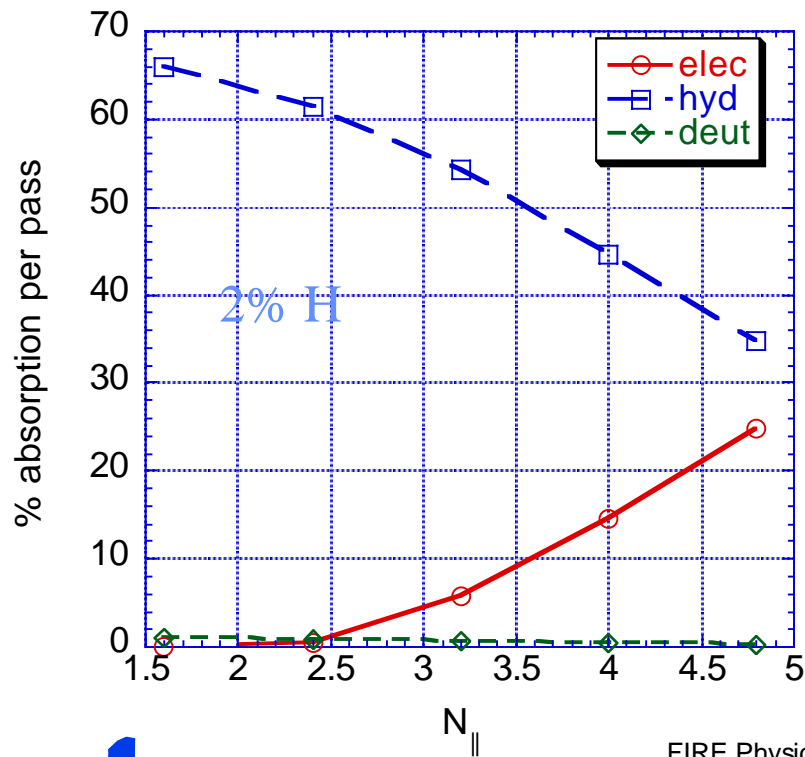
For FIRE, look at 300 MHz fixed-frequency system.

- u Lower hybrid resonance at  $4 \times 10^{18} \text{ m}^{-3}$ .
- u  $2\Omega_{\text{H}}$  on axis for 10T.

# Heating the ohmic FIRE plasma with 300 MHz rf power requires a small hydrogen impurity

Second harmonic hydrogen heating is predicted to be effective in FIRE  
 Direct electron heating requires somewhat higher  $N_{||}$ .

$$n_e(0) = 5 \times 10^{20} \text{ m}^{-3} \text{ (parabolic}^{0.25}), T_e(0)=T_i(0)=5 \text{ keV (parabolic), } 10T, \text{ equal fractions of D, T.}$$

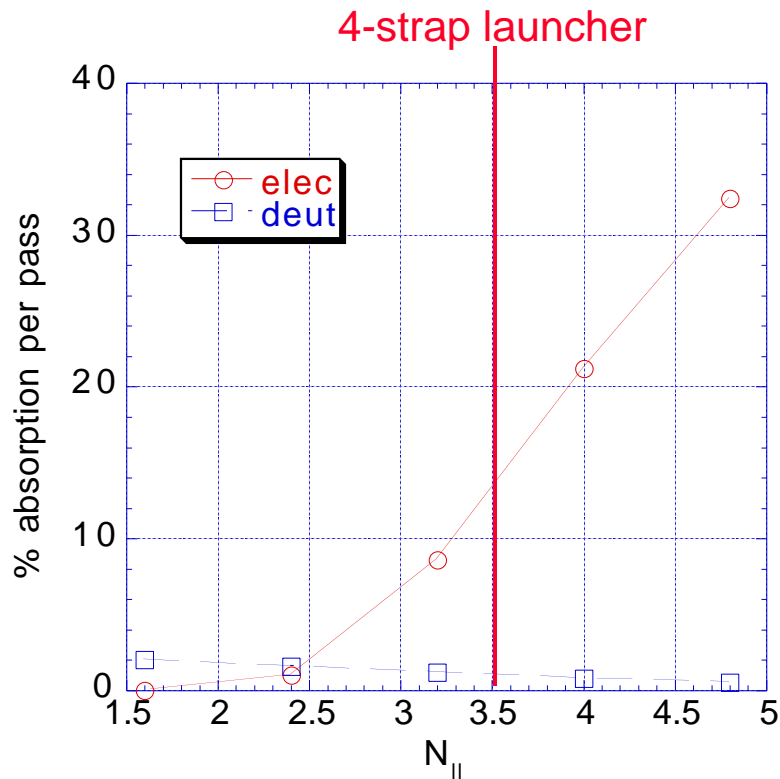


# Use of 4-element array (toroidally) launches spectrum w. $N_{||} \approx 3.5$ , allowing adequate single-pass absorption

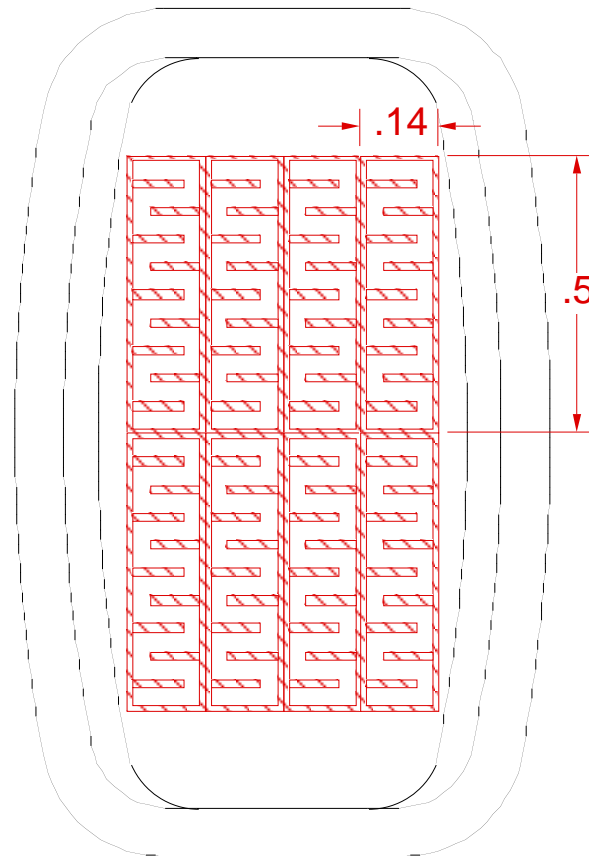
Possible launchers:

- u 4 x 2 array of current straps
- u 4 x 2 array of folded waveguides

4 x 2 folded waveguide array for 300 MHz operation,  $\pi$  phasing.  
 Narrower waveguide required for directed launch.



Direct electron absorption makes heating *insensitive* to value of toroidal field



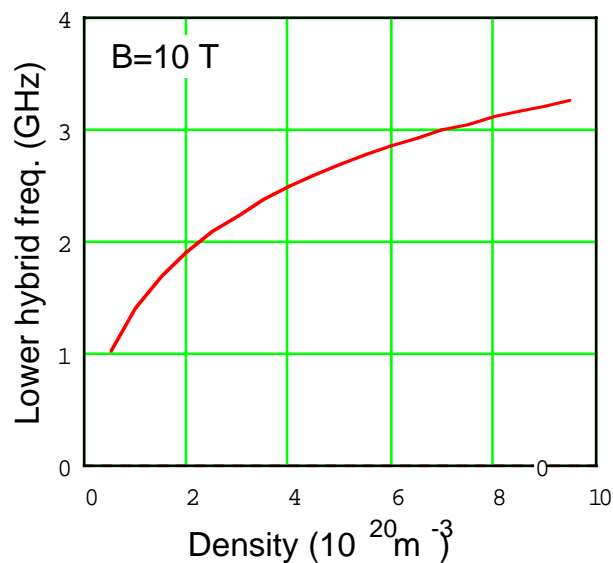
## RF sources for this frequency range exist

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- u Klystrons in the 1 MW (CW), 300 - 400 MHz range have been developed by EEV, CPI. In wide usage for particle accelerators.
- u Power transmission could use waveguide.
- u Matching system could use conventional waveguide isolators, providing good decoupling between klystron and load.
- u Primary advantage of HFFW over conventional system is *flexibility*
  - Toroidal field ramps
  - Very low  $N_{\parallel}$  operation (with 1-2% H) for operation with large gaps
  - Directed spectra for CD assist in AT scenarios
- u Primary disadvantage: untested. No significant experience with this system, compared to conventional ICRH.

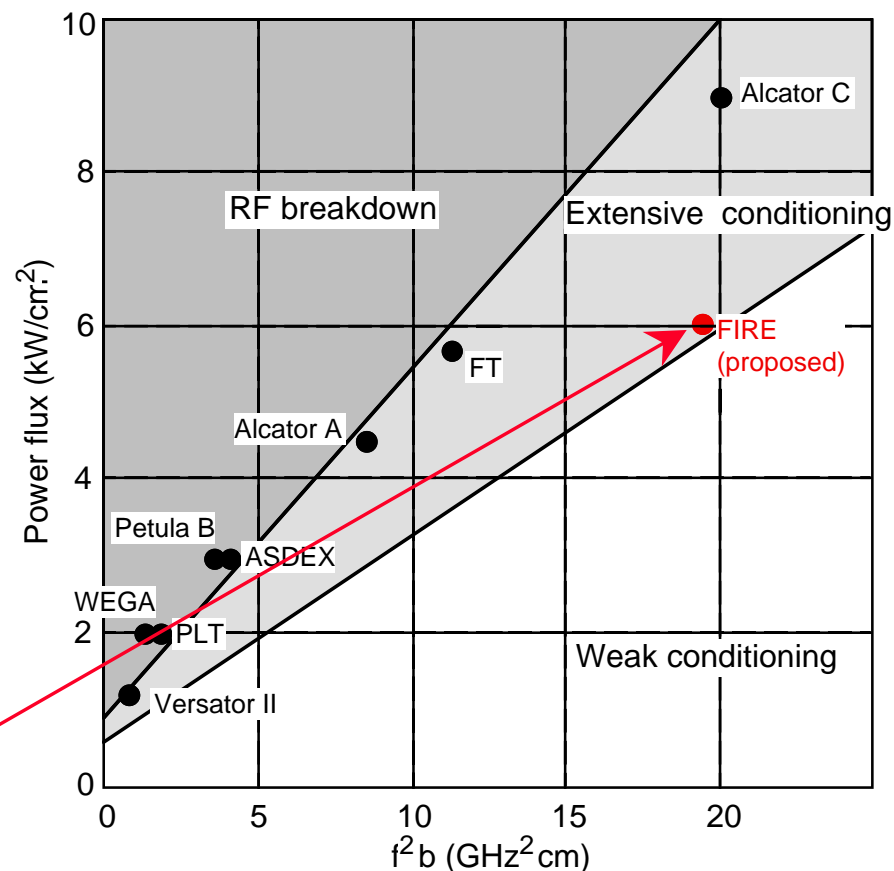
## Lower hybrid system- upgrade option

~ 8 GHz needed to drive current  
(must keep  $f > 2 f_{LH}$ ).



Waveguide array

- u Each waveguide 3.6 cm high x 0.3 cm toroidally
- u RF power flux  $\approx 60 \text{ MW/m}^2$ , so need  $\sim 0.4 \text{ m}^2$  of radiating area
- u Need  $\sim 3,800$  waveguide elements



*Thanks for help from Stefano Bernabei*

## LH will probably need launchers in 2 ports to deliver 25 MW

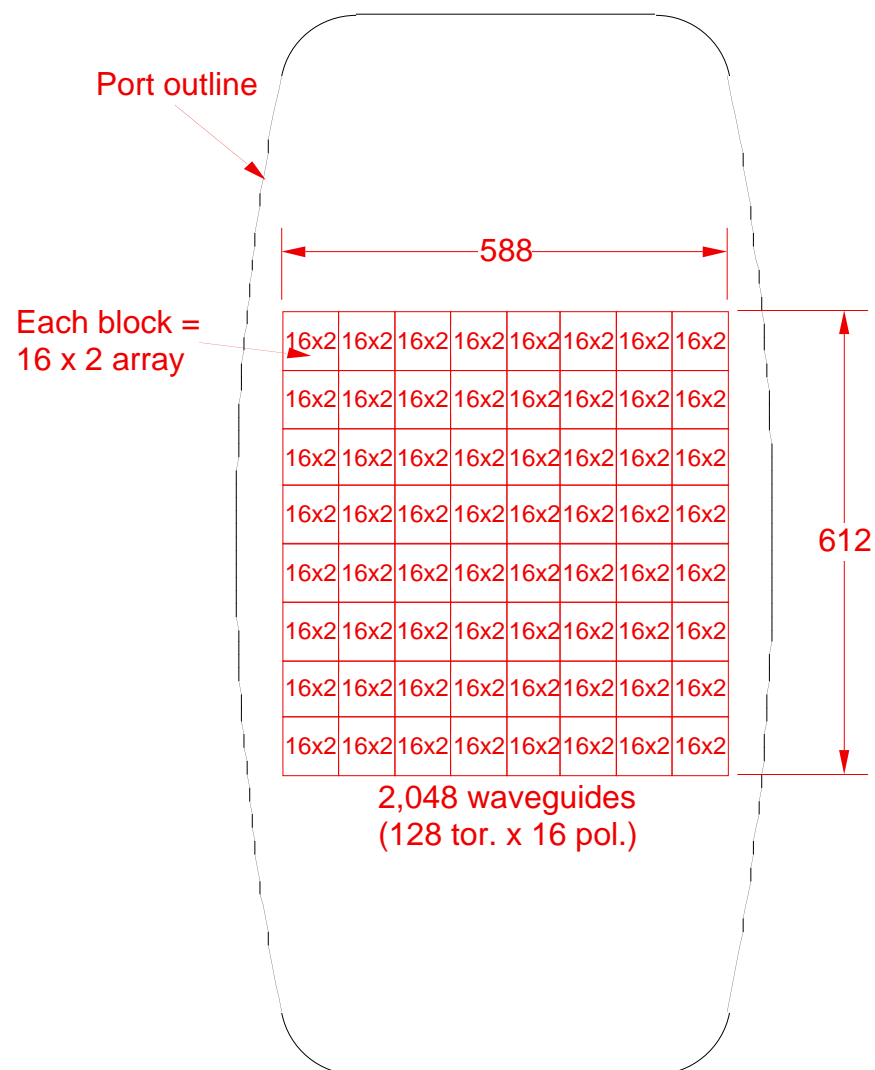
For one port, put array as shown.

- u Array area  $\approx 0.33 \text{ m}^2$ , so
- u  $P_{\text{LH}} \approx 12.8 \text{ MW/port}$ .

-> Need two LH ports to deliver 25 MW.

LH launcher contour must conform very closely to the plasma contour for good coupling. The higher the coupler, the greater the constraint on the plasma outer separatrix.

Issue: How much change will there be in the plasma shape during a shot, or under different experimental conditions?



## Summary

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- u Ion cyclotron heating is feasible for FIRE at 100 - 150 MHz.
  - Four to possibly six ports required for 30 MW.
  - System would require 15-18 tubes for 100 MHz, probably 30-36 tubes for 150 MHz.
  - Heating only.
- u High frequency fast wave heating may be an alternative (partial or full).
  - FWG tests at ORNL suggest higher power densities may be feasible.
  - System would require 30 tubes for 30 MW delivered (80% rated output).
  - Direct electron heating/central current drive is possible.
  - *BUT* a test of this concept is needed. C-mod?
- u LH at 8 GHz would require 2 ports for 25 MW delivered.