Plasma Heating and Current Drive Systems for the Fusion Ignition Research Experiment (FIRE)*

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18th Symposium on Fusion Engineering
Albuquerque, NM
October 25 – 29, 1999

* Research sponsored by the Office of Fusion Energy Science, U.S. Department of Energy, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp., and under contract DE-AC0276-CHO-3073 with Princeton Plasma Physics Laboratory.

Introduction and requirements

FIRE heating and current drive systems:

- Ion cyclotron system
  - Baseline system
  - 30 MW to the plasma
  - Heating only (no current drive requirement)
  - Operate at 10 T
  - Operate for ≥ 10 s
  - Density range <n> ≈ 1 to 5 x 10^{20} m^{-3}

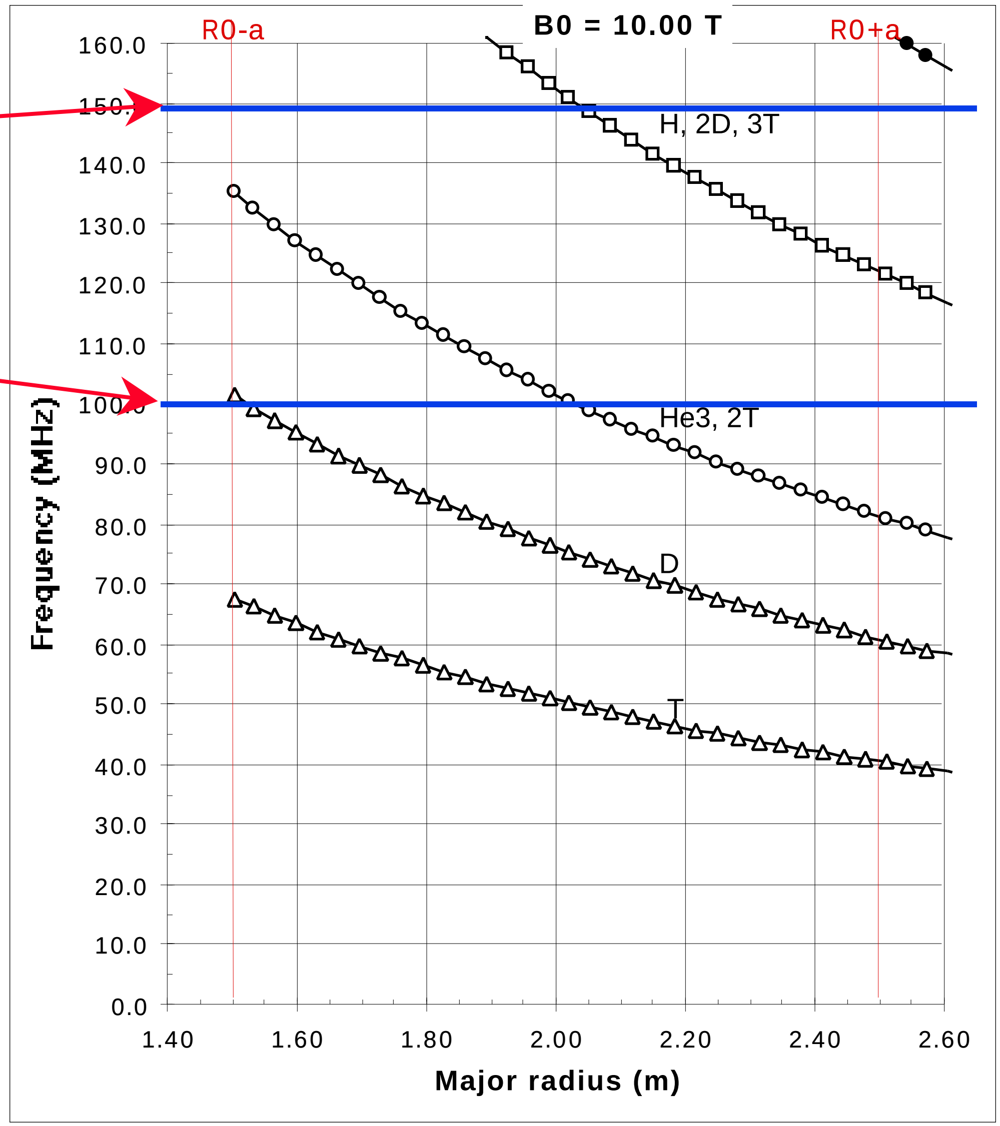
- Lower hybrid system
  - Possible upgrade
  - 25 MW to the plasma
  - Edge current drive (?)
  - Other requirements same as for IC system

Ion cyclotron system: frequencies of operation

For 10 T operation:

- 150 MHz
  - Second harm. D
  - H minority
- 100 MHz
  - Second harm. T
  - He^3 minority (good for D only plasma)
  - Also use at 6.7 T for second harm. D, H minority

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

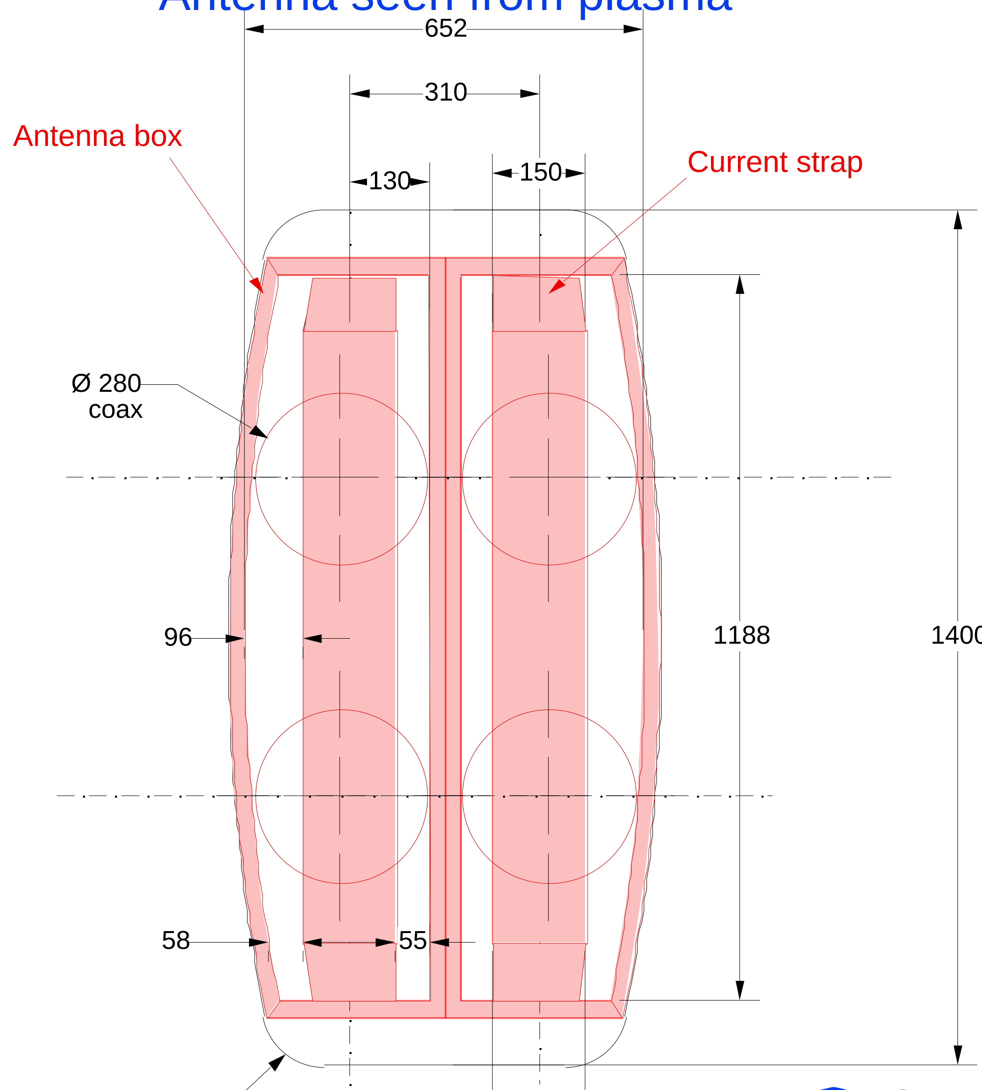


Antennas have been designed to fit in main ports

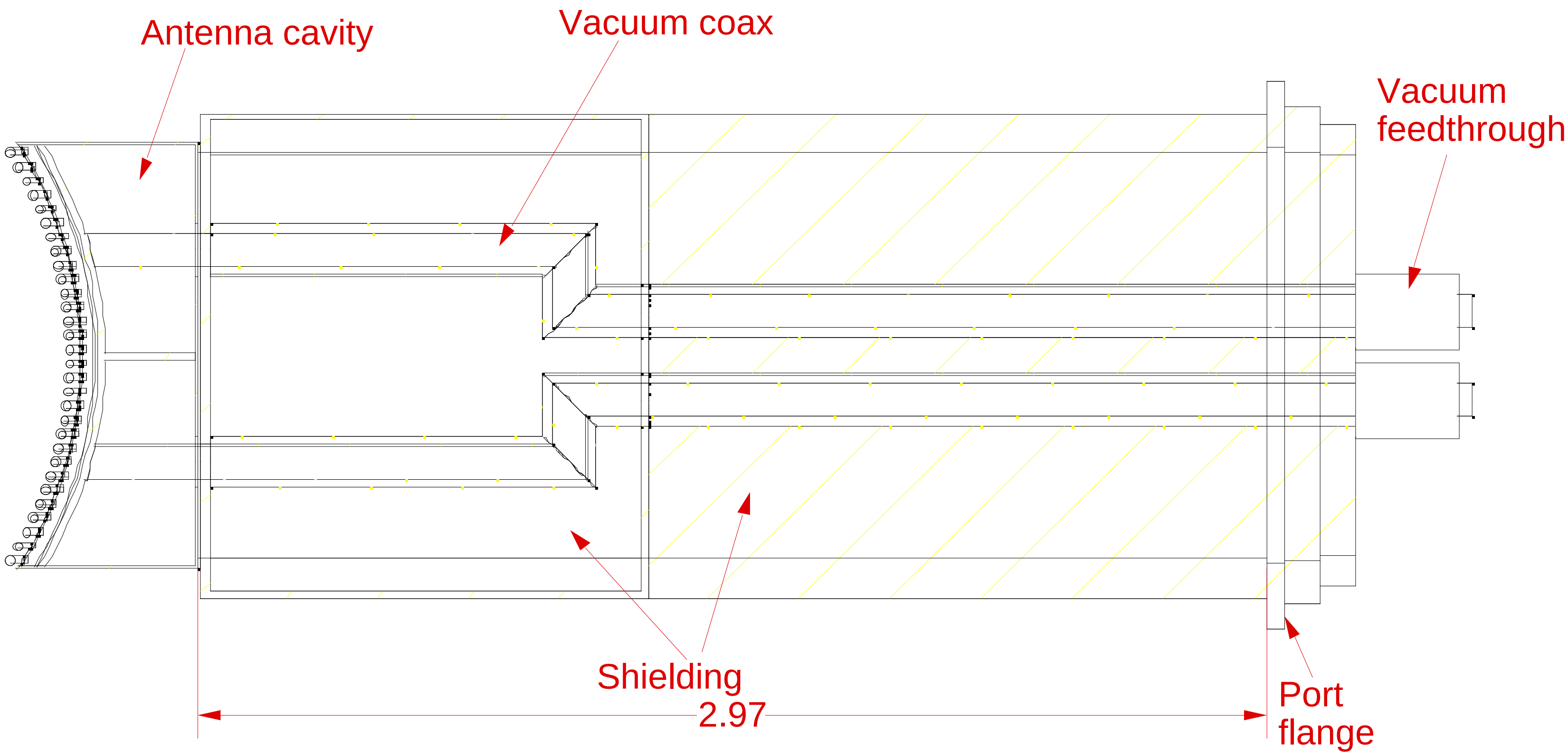
Antenna characteristics:

- 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 may be required during a shot (particularly on FS tubes).

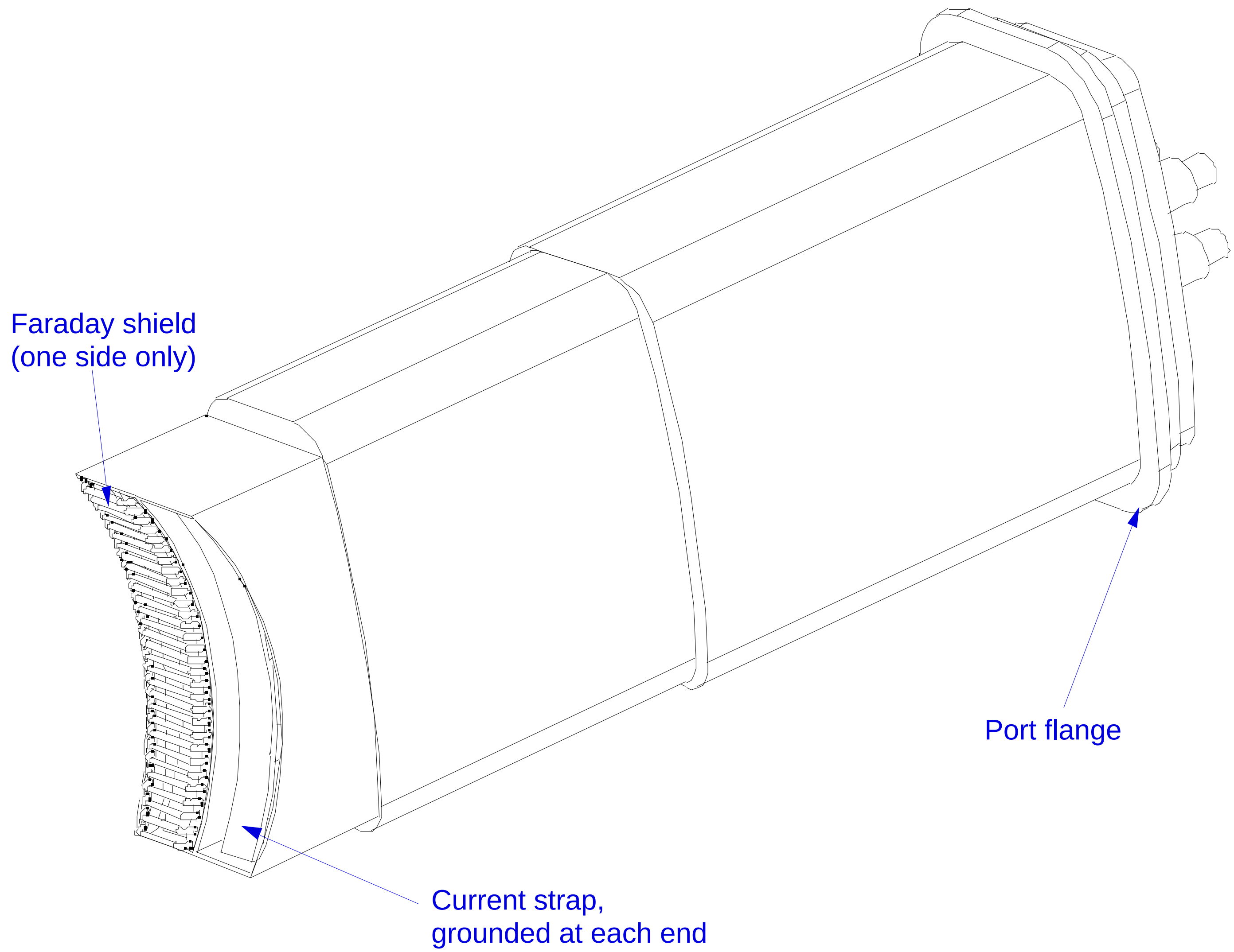
Antenna seen from plasma



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



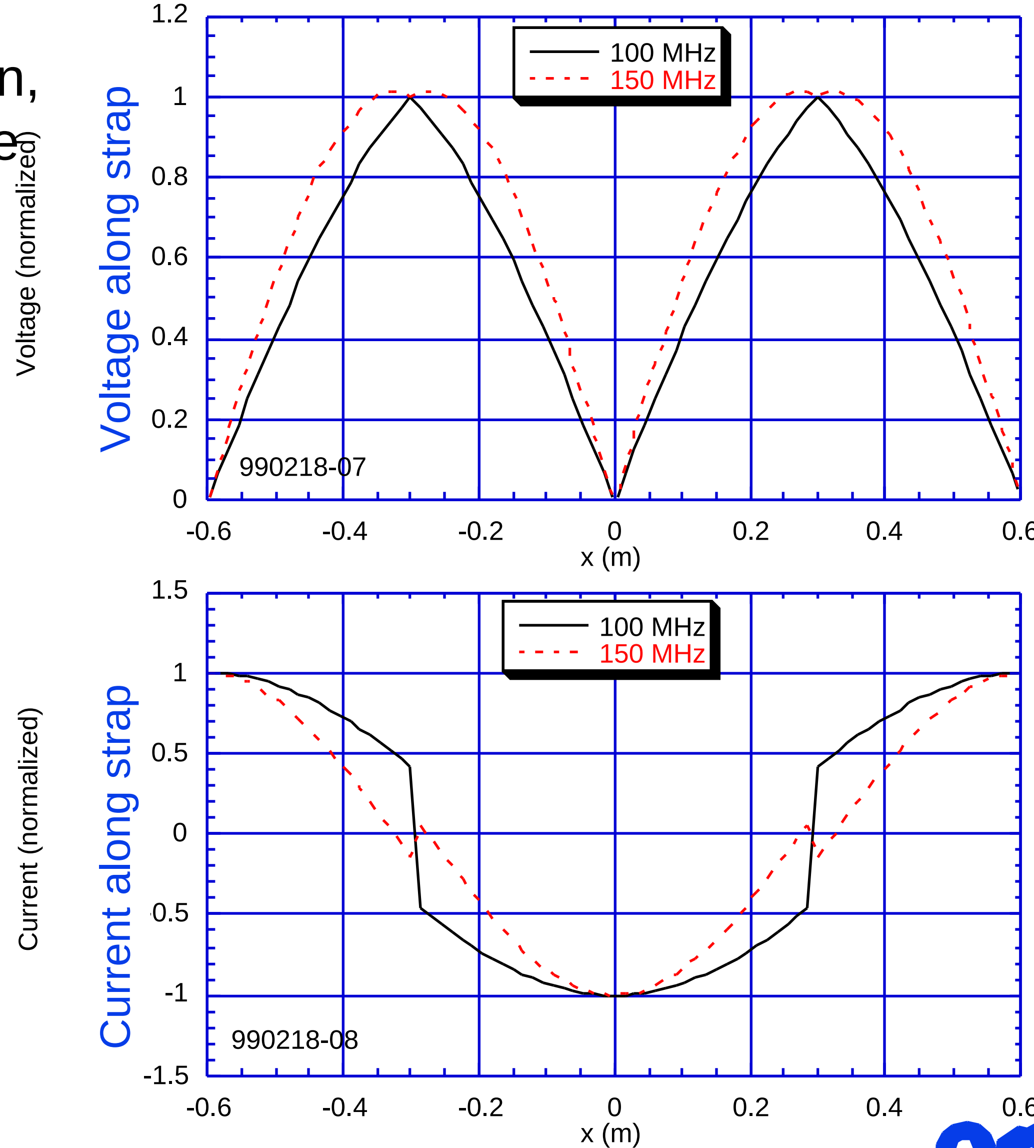
Modular construction of antenna facilitates installation in radiation environment



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)

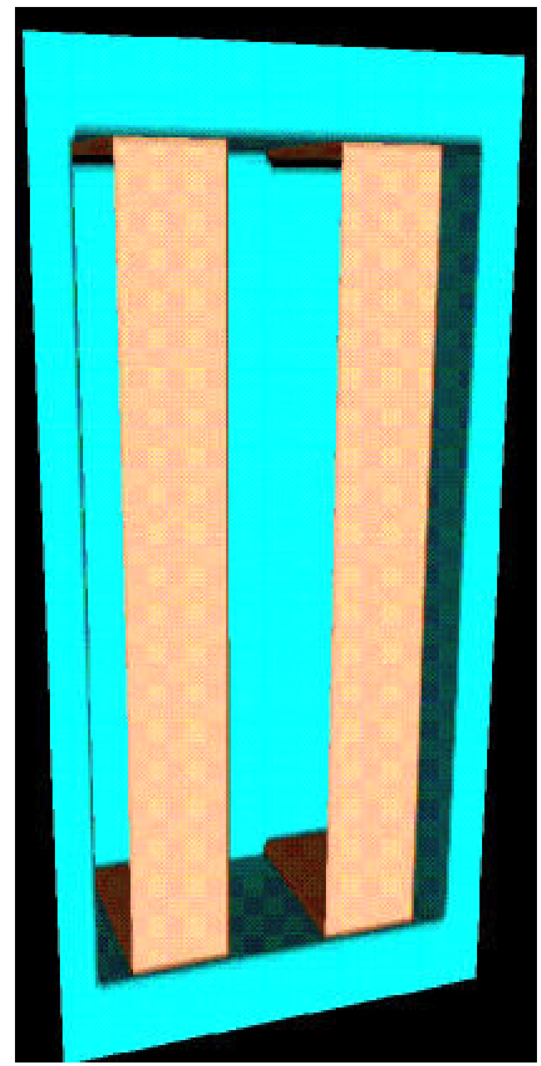
Antenna assumptions in RANT3D:

- Antenna flush with first wall
- π phasing between current straps

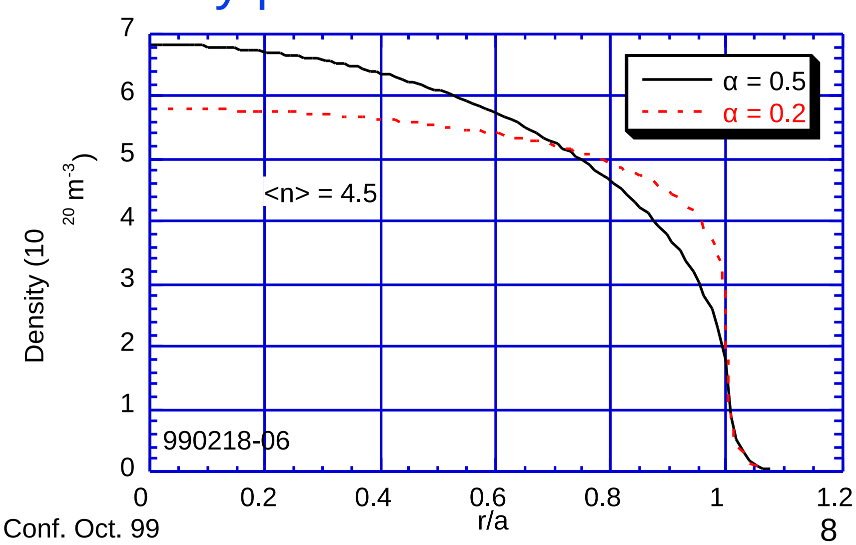
Plasma assumptions:

- parabolic-to-a-power density (α = 0.2 and 0.5)
- $n_{sep}/n_0 = 0.2$
- $\lambda_{scrapeoff} = 1$ cm
- <n> = 4.5 x 10^{20} m^{-3} (also did scan on <n>)

Antenna geometry (RANT3D)



Density profiles used in R' calculations

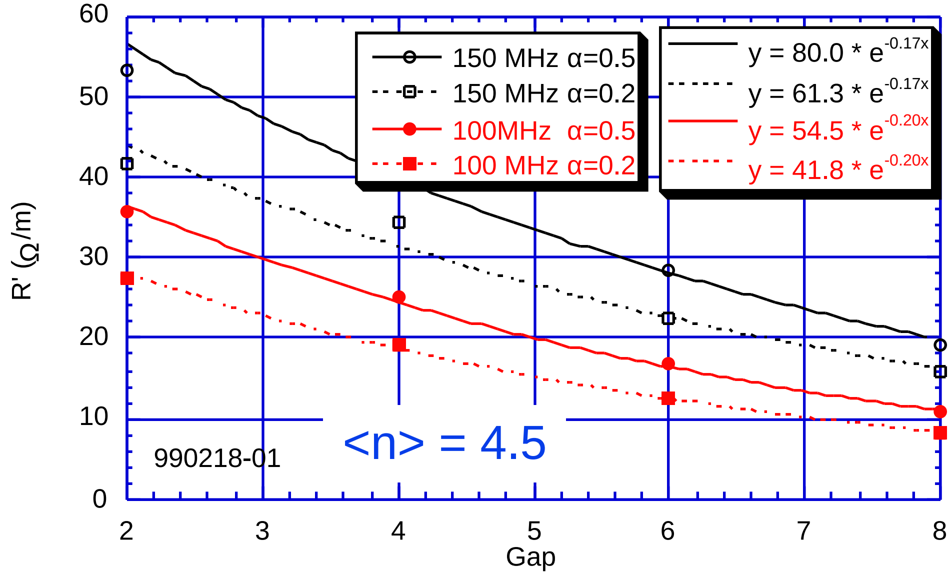


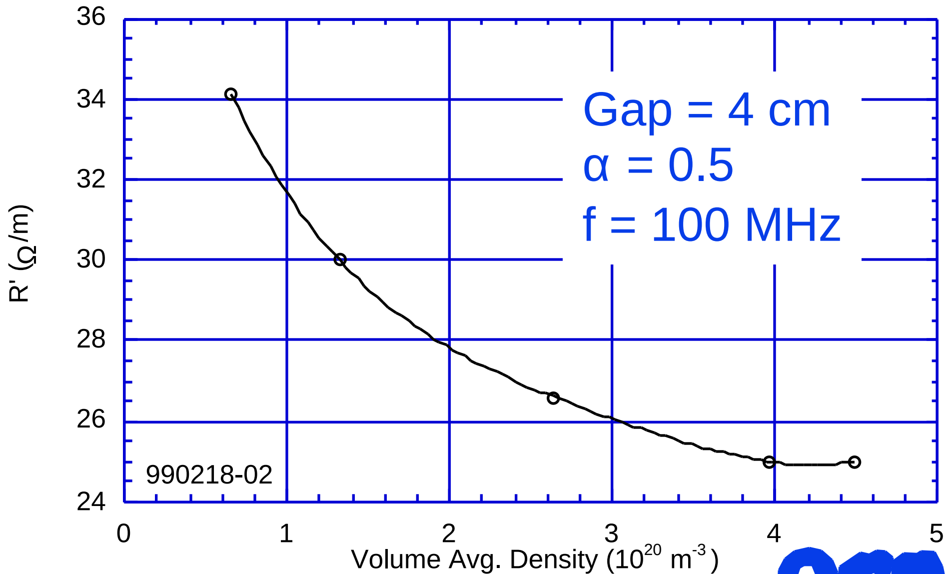
R’ calculated vs. “gap” and <n>

$P_{plasma} \sim R' \, V_{max}{}^2 \, N_{antennas}$,
where V_{max} is the maximum operating rf voltage for the system (for given antenna geometry and frequency).

Observations:

- R’ decreases as the distance from the separatrix to the antenna (the “gap”) is increased. (~ 5 cm e-fold)
- R’ higher at lower density values (for <n> = 0.6 to 4.5 x 10^{20} m^{-3})
- R’ higher at 150 MHz than 100 MHz
- R’ lower for steeper n profile (α = 0.2)





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

For

- $\alpha = 0.5$
- $<n> = 4.5 \times 10^{20}$ m^{-3}

For V_{max} = 35 kV

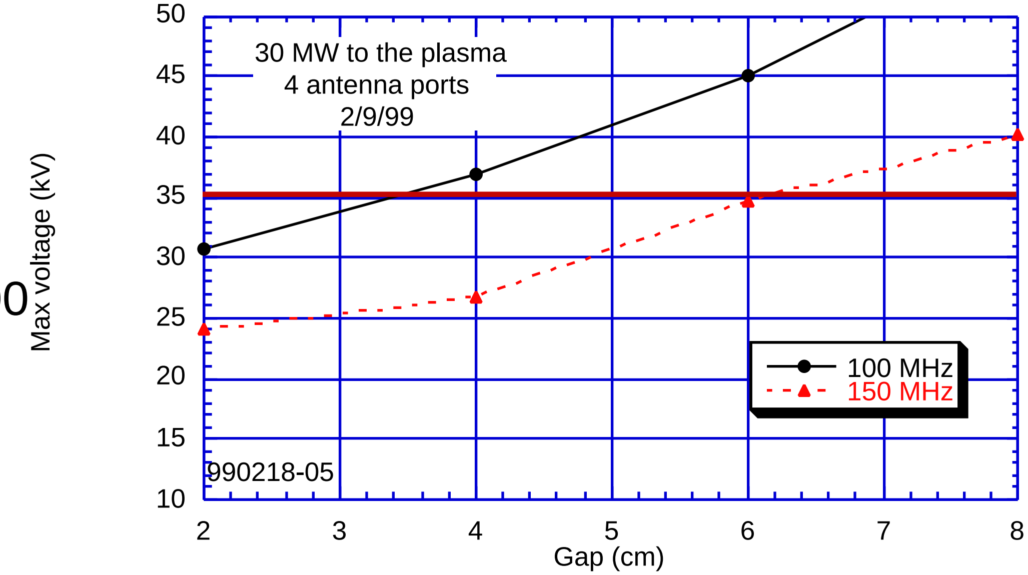
- Four ports for gap ≤ 3.5 cm @ 100 MHz, ≤ 6 cm @ 150 MHz
- Six ports for gap ≤ 7.5 cm @ 100 MHz, more at 150 MHz.

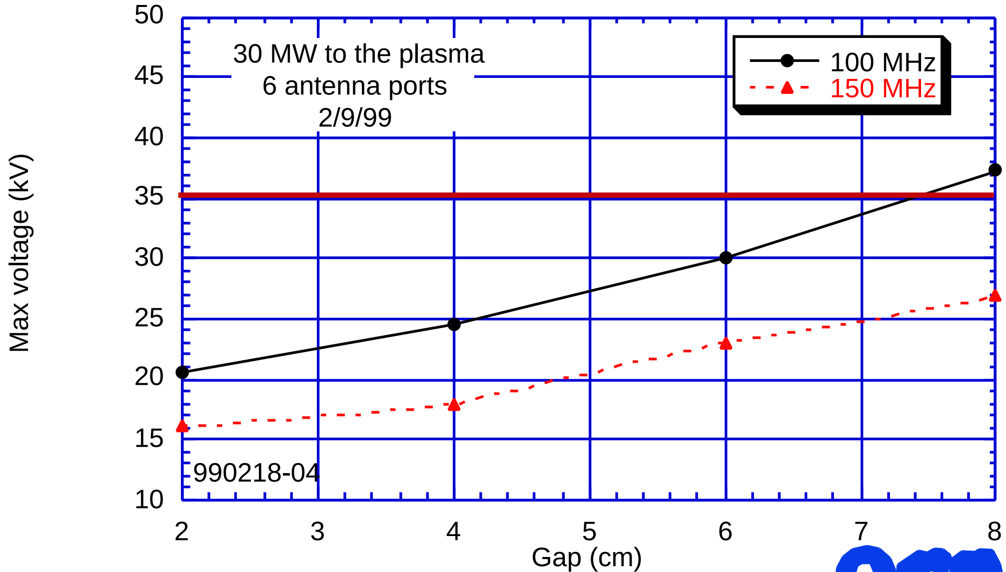
For V_{max} = 30 kV

- Four ports for gap ≤ 2 cm @ 100 MHz, ≤ 5 cm @ 150 MHz
- Six ports for gap ≤ 6 cm @ 100 MHz, more at 150 MHz.

Decision made to tentatively allocate four ports

- Gap ≤ 3.5 cm
- Lower density improves loading





RF sources are an issue

Requirements and constraints:

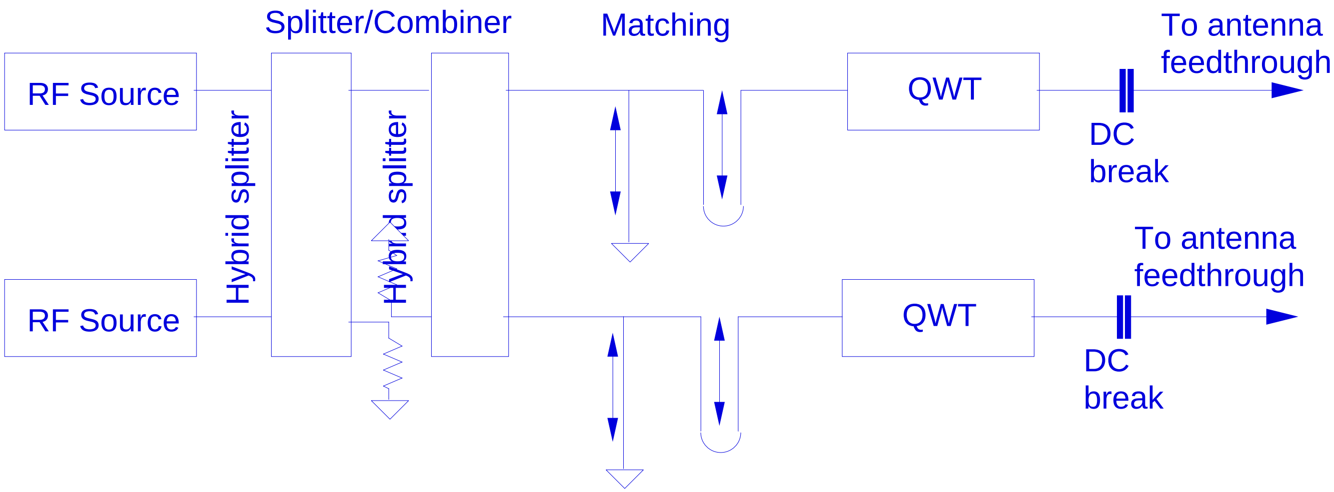
- 30 MW to plasma
- Four ports, each with two current straps
- Two rf feeds per current strap.

30 MW through 16 rf feeds means ≈ 2 MW per feedthrough.

How to get 2 MW at 150 MHz?

- Present tubes can deliver ≈ 2 MW into matched load at ≤ 100 MHz, but power decreases with frequency.
- Probably will require TWO output tubes for 2 MW at 150 MHz.
- Design of these rf sources may be tricky; will definitely require some R&D

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.

IC system cost estimated at ~ $3.70 per watt

Cost (in $M) for rf systems, based on past estimates and actuals for DIII-D

	TPX			DIII-D			ITER		
	Cost	%	$/W	Cost	%	$/W	Cost	%	$/W
Antenna	9.85	51	1.23	2.46	26	0.82	51.6	30	1.03
T&M	4.57	24	0.57	2.13	22	0.71	14.8	8	0.30
Trans. lines	0.8	4	0.10	inc. above			8.5	5	0.17
Source	0.77*	4	0.09	4.52	47	1.50	73.8	42	1.48
HV supp	1.46*	7.5	0.18	inc. above			26.6	15	0.53
I&C	2.03	10	0.25	0.43	5	0.14			
Total	**19.5**		**2.43**	**9.54**		**3.17**	**175.3**		**3.50**

– * Includes modification of existing rf sources and supplies only. TPX also takes some credit for transmission lines, etc.

Costs are for systems operating at or below 100 MHz. For 150 MHz and above, cost of *source* is higher.

Based on extrapolation from past costs, with some R&D costs for sources, estimate is ≈$110 M for 30 MW or about $3.70/W to the plasma.

Possible alternative: "Moderate-harmonic" fast-wave heating (MHFW)

We have looked at MHFW for FIRE, with f = 300 MHz.

Pros:

- Deposition profile not significantly affected by TF ramps if absorbed on electrons
- *May* have good loading so fewer ports needed (calculation not done yet)

Cons:

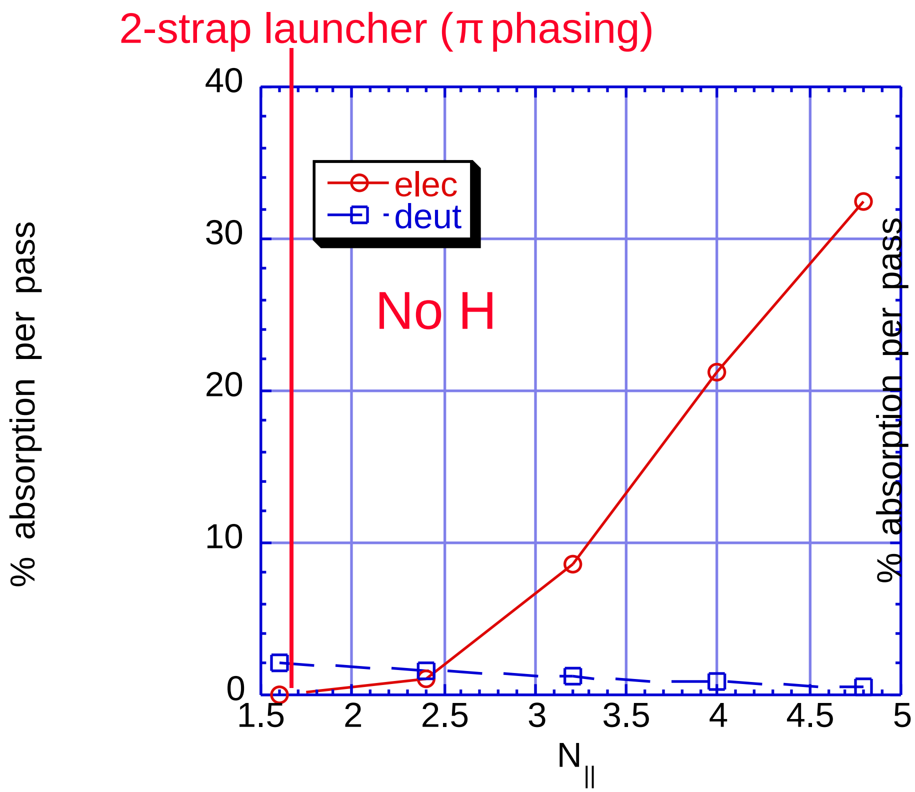
- Cost may be higher, but klystrons @300 - 400 MHz available.
- Database on IC at this frequency is sparse.

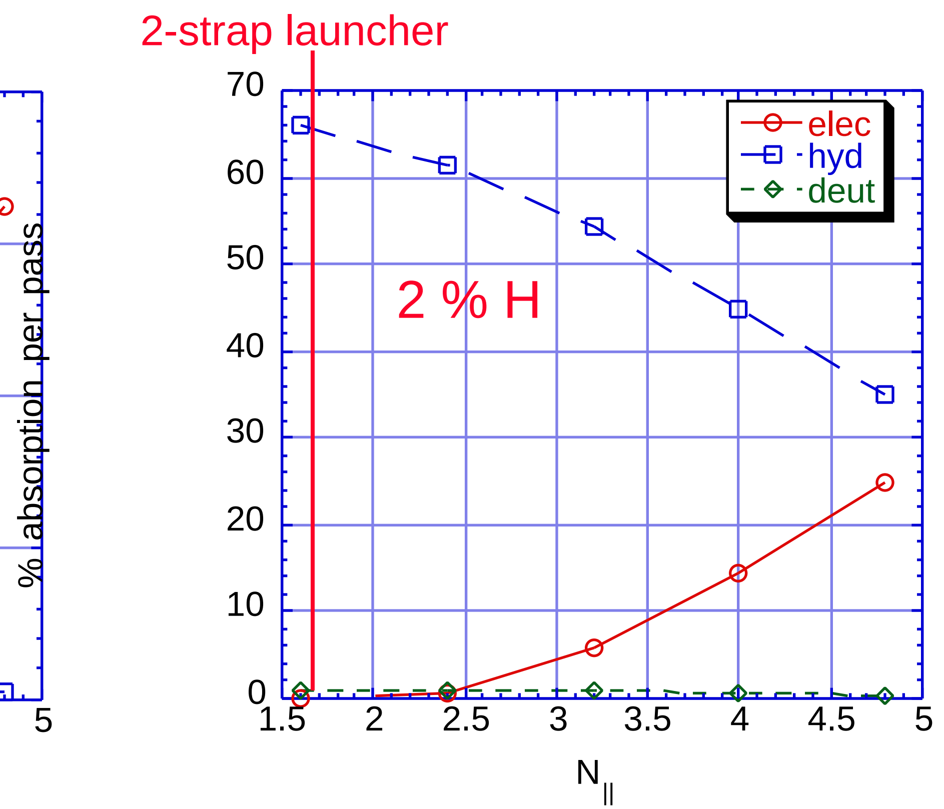
No system design done for this option. Antennas could be folded- or ridged waveguides (may have higher power density, but relatively untested at this freq. range).

Heating the ohmic FIRE plasma with *2-strap* antenna at 300 MHz requires a small hydrogen impurity

$N_{||}$ too low for direct electron absorption with $T_e(0)$ = 5 keV. (need ≥ 10 % single-pass abs.)

Addition of small H impurity makes good absorption at 2 Ω_H





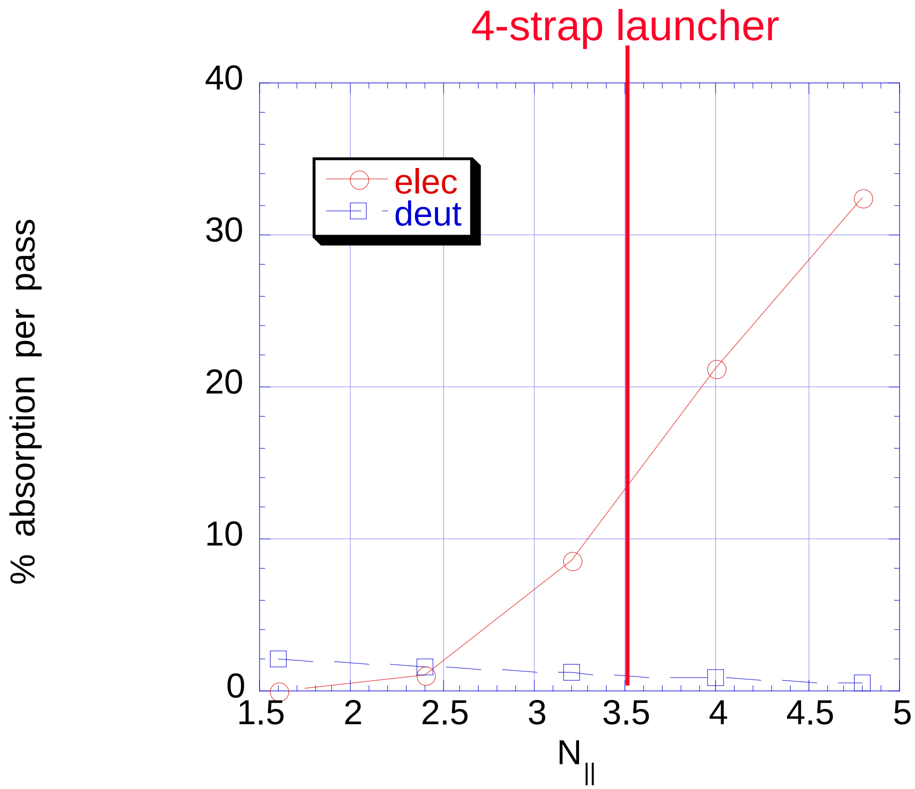
calc. using METS code, courtesy D. Smithe (MRC)

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

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

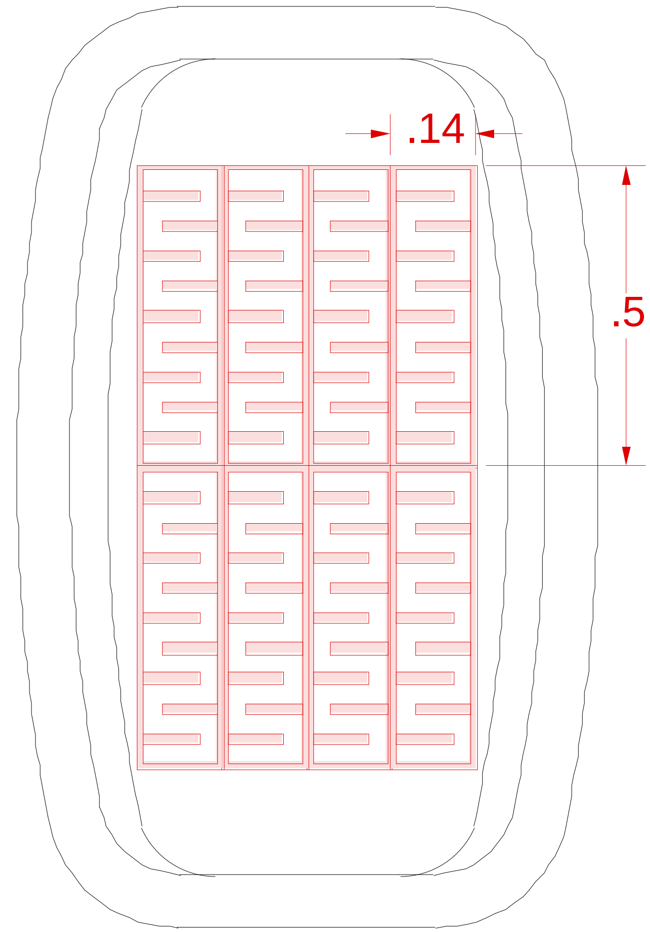
Possible launchers:

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



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

4 x 2 folded waveguide array for 300 MHz operation



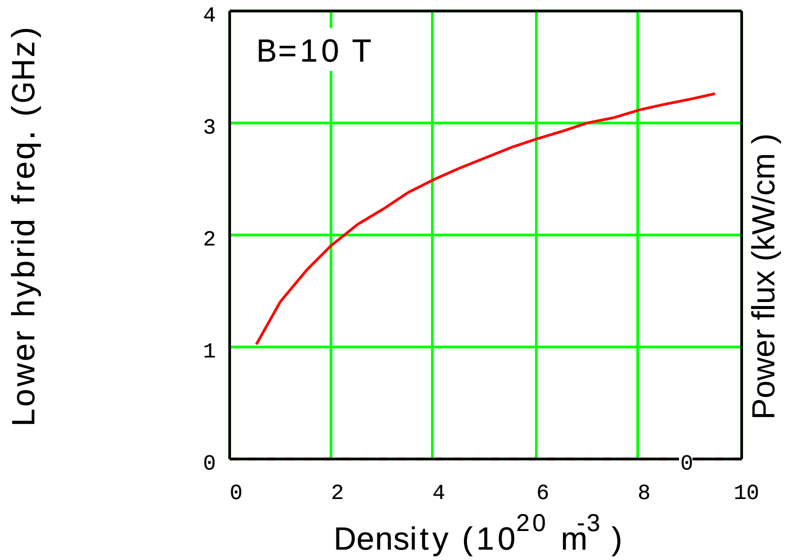
ornl

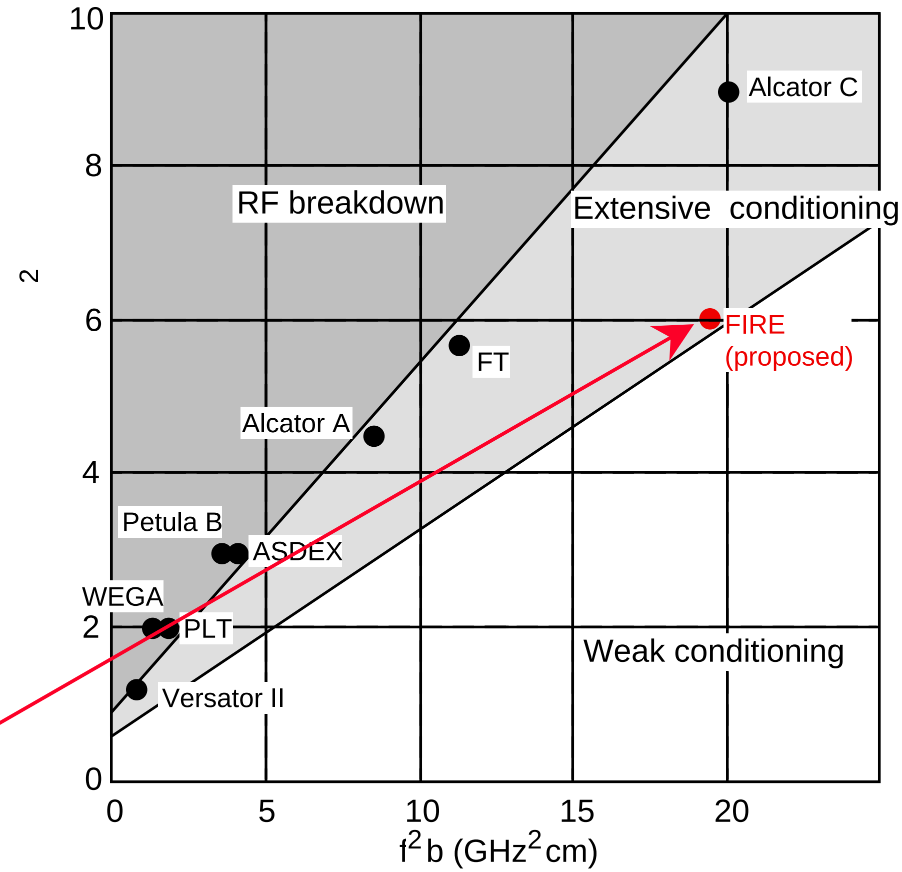
RF sources for this frequency range exist

- Klystrons in the 1 MW (CW), 300 - 400 MHz range have been developed by EEV, CPI.
- Power transmission could use waveguide.
- Matching system could use conventional waveguide isolators, providing good decoupling between klystron and load.
- Primary advantage of MHFW over conventional system is *flexibility*
  - Toroidal field ramps
  - Very low $N_{||}$ operation (with 1-2%H) for operation with large gaps
  - Directed spectra for CD assist in AT scenarios
- 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

- Each waveguide 3.6 cm high x 0.3 cm toroidally
- RF power flux ≈ 60 MW/m^2, so need ~ 0.4 m^2 of radiating area
- Need ~ 3,800 waveguide elements

Thanks for help from Stefano Bernabei

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

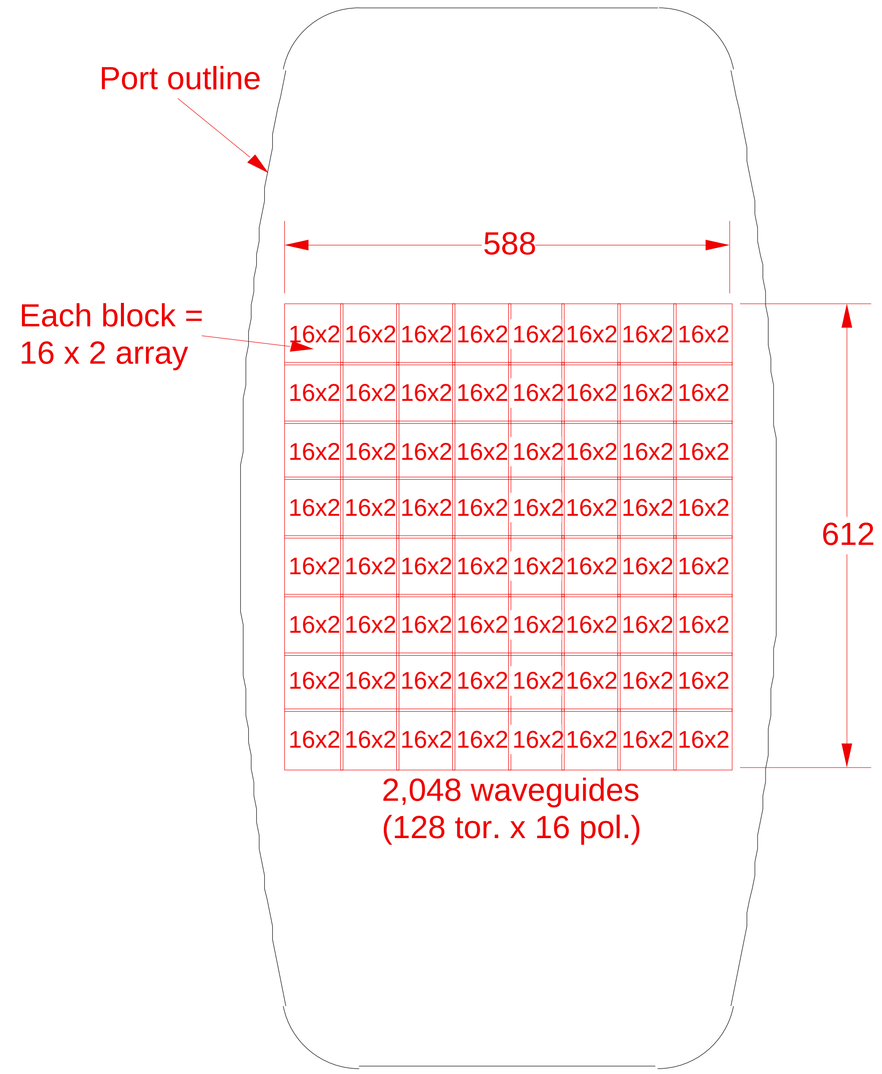
For one port, put array as shown.

- Array area ≈ 0.33 m^2, so
- P_{LH} ≈ 12.8 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?



Conclusions

Ion cyclotron and lower hybrid heating and current drive are feasible for FIRE.

- Four ports for IC system to deliver 30 MW
- Two ports for LH system to deliver 25 MW

Need more information before continuing with design

- Operating scenarios
  - Pulse length and heat loads vs. time?
  - First wall-separatrix distance (and plasma shape) vs. time?
  - Need heating while toroidal field is increasing?
- Info on disruptions
  - dI_p/dt during disruption?
  - Heat loads during disruption?
- What materials are allowable
  - as plasma facing components?
  - in vacuum?

Design work will continue, in parallel with IGNITOR IC collaboration (similar issues).