Baseline ECH Performance and Configuration For ARIES-CS

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ARIES Project Meeting
October 4, 2006
PPPL, Princeton, NJ

OUTLINE

- ECH scenario studies based on example CS equilibrium
- ECH system configuration
- Conclusions and Discussions

ECH is Attractive for Heating in a CS Reactor

- The ECH system is for plasma initiation and heating to ignition.

ECH is attractive for the following reasons:

- Capable of localized heating and profile control
  - control knobs can be frequency, and wave launch angle
- Requires relatively compact components
  - compatible with complicated coil and vessel geometry in a stellarator
- Minimal neutron irradiation of components as waveguides can be bent with little power loss and launching mirrors can be hidden from direct line of sight of plasma
- Requires no large antenna structure near first wall
- No coupling issue as the EC wave propagates in vacuum
- EC waves do not interact with ions and energetic □’s

Core Accessibility and Strong Single-Pass Absorption

- In the ECRF, the plasma supports the O- and X-modes of propagation.

- The conditions for propagation to core with ω_{pe}, ω_{ce}, where $\omega = n\omega_{ce}$:

  - $(\omega_{pe}/\omega_{ce})^2 < n^2$ for O-mode

  - $(\omega_{pe}/\omega_{ce})^2 < n(n-1)$, $n \geq 2$ for X-mode

  Low density and high B-field are favorable to ECRF core penetration.

- **Strong single-pass absorption** is important, since defocusing and mode exchange can be quite severe from wall reflection,

Perpendicular Launch of ECH Waves

- For plasma heating only, perpendicular EC wave launch, e.g., along equatorial plane on some toroidal locations, may be adequate.

- For **perpendicular launch ($k_{||}$ = 0),** modeling is straightforward, using a 1-D slab model. For example, for the O-mode at fundamental resonance (ω/ω_{ce} =1), the wave number $k_{\perp r}^{O}$ and damping decrement $k_{\perp i}^{O}$ are given by:

$$k_{\perp r}^{O} = \frac{\omega}{c}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2}$$

$$k_{\perp i}^{O} = \frac{2\pi^{1/2}}{60}\frac{\omega_{pe}^2}{\omega_{ce}c}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2}\left(\frac{T_e}{m_e c^2}\right)^{-5/2}\xi_1^5 \exp\left(-\frac{\xi_1^2 m_e c^2}{2T_e}\right)\Theta\left(\xi_1^2\right)$$

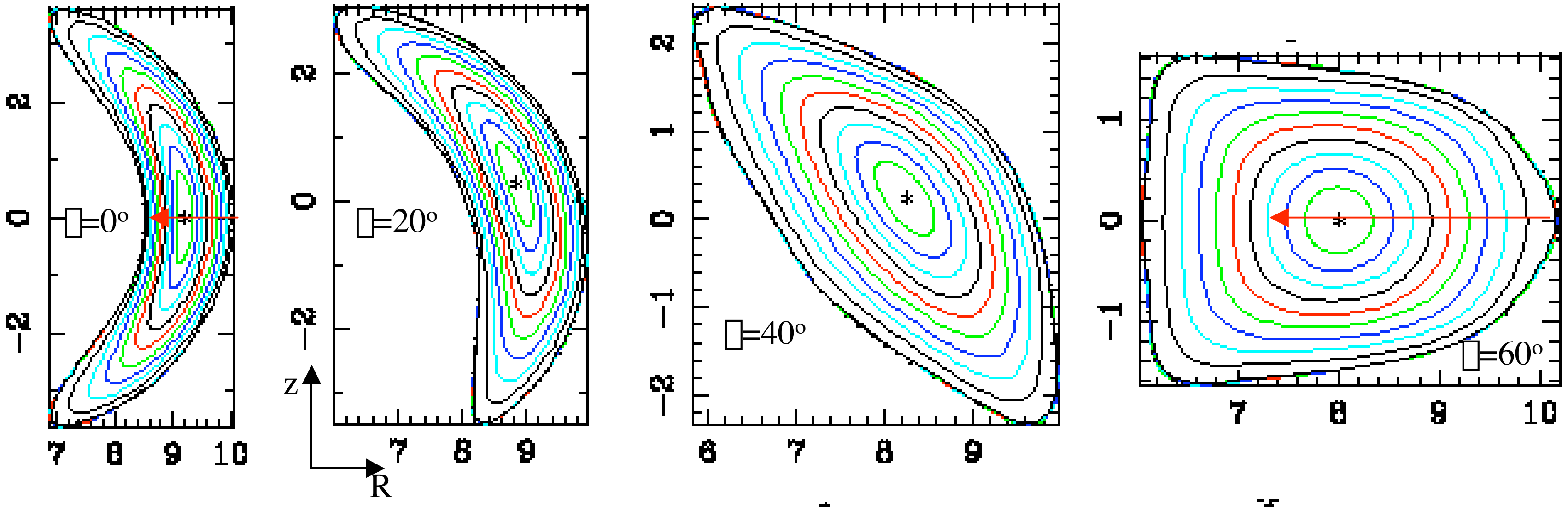
where $\xi_1 \equiv \left(\omega_{ce}^2/\omega^2 - 1\right)^{1/2}$, and Θ(x) = 1, if x≥0, = 0, if x<0.

- The wave power along path is computed along the slab by

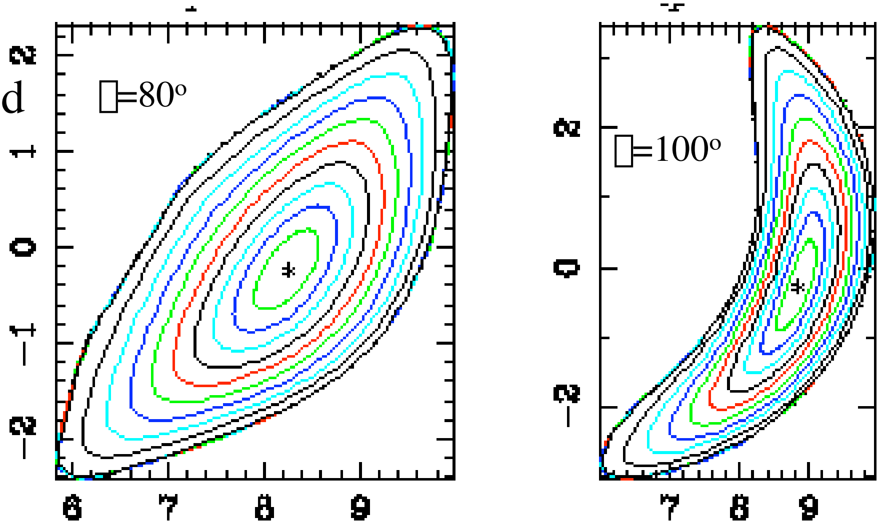
$$P(x) = P_0 \exp\left(-2\int_0^x k_{\perp i}^{O}(x)\,dx\right)$$

Application of 1-D ECH Model to An Example CS/QA Equilibrium

- Shown below are flux surface geometries of an example CS reactor equilibrium provided by L.P. Ku (PPPL), with 3 toroidal field periods (N = 3).



- The 1-D ECH model can be applied to φ=0° and φ=60° locations along the midplane (z=0), on which propagation is parallel to the density gradient.



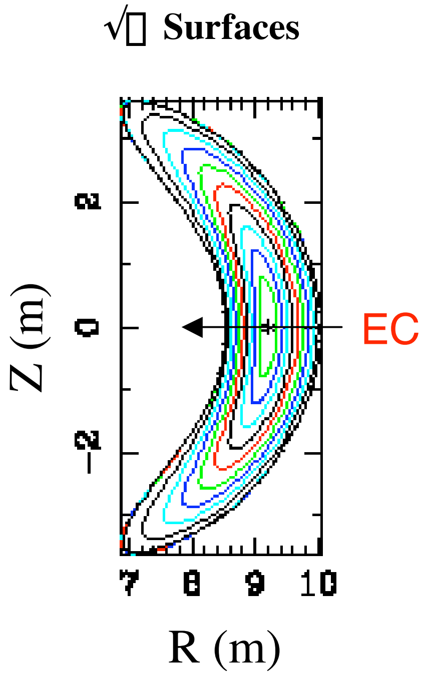
ECH Launch Scenario at □ = 0° Toroidal Location

- For the example equilibrium, $p = p_o\,[1-(r/a)^2]^{1.5}$

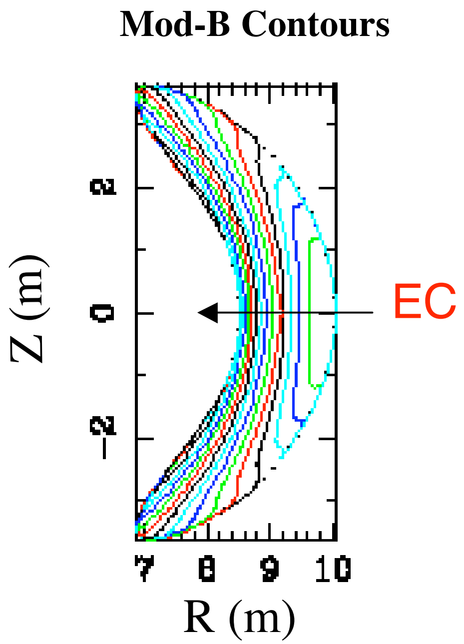
  Assume $n_e \quad (p/p_o)^{0.25}$; $T_e \quad (p/p_o)^{0.75}$

  $n_o/\langle n\rangle = 1.375$; $T_o/\langle T\rangle_n = 1.818$

  $R_{axis} = 9.21$ m; $B_{axis} = 5.24$ T
- Perpendicular Launch from Outboard Side : $k_{\square} = 0$, $k_Z = 0$
- Frequency = (1 - 2) □ f_{ce} (on axis) = 147 - 293 GHz.

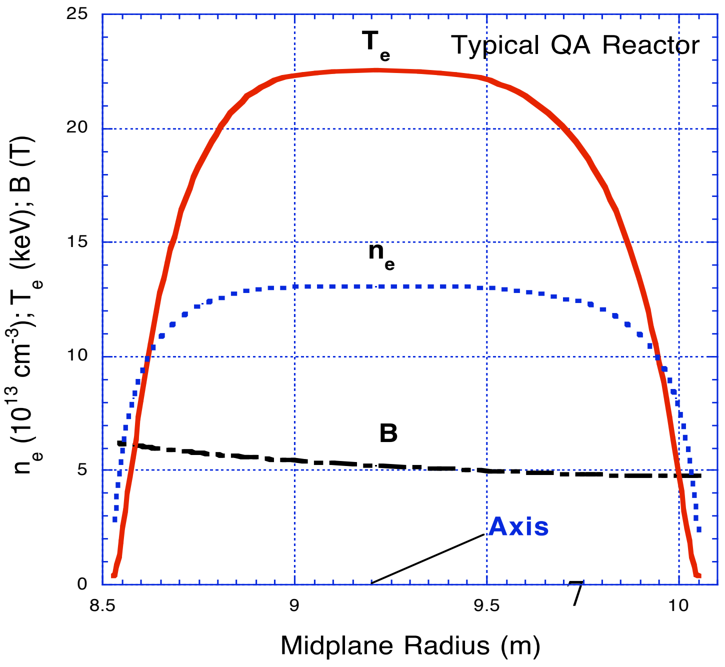


√□ Surfaces



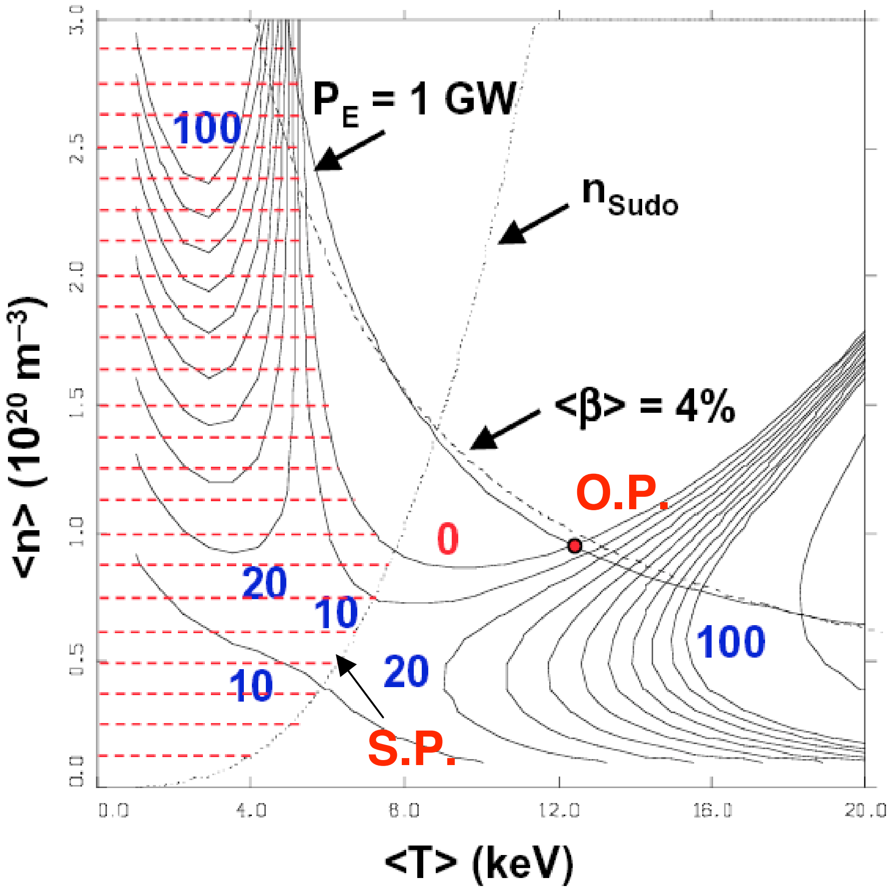
Mod-B Contours

Plasma Profiles along Midplane



<n>, <T> Operating Range for a Typical QA Reactor

(J. Lyon, Oct. 02 ARIES Meeting)



Operating Point

$\langle n \rangle = 9.5\ 10^{19}\ \mathrm{m}^{-3}$

$\langle T \rangle = 12.4$ keV

$\langle \beta \rangle = 3.6$ %

$P_{fus} = 1.73$ GW

Saddle Point

$\langle n \rangle = 4.9\ 10^{19}\ \mathrm{m}^{-3}$

$\langle T \rangle = 6.1$ keV

$\langle \beta \rangle = 0.9$ %

$P_{aux} = 12$ MW

Ignition minimum

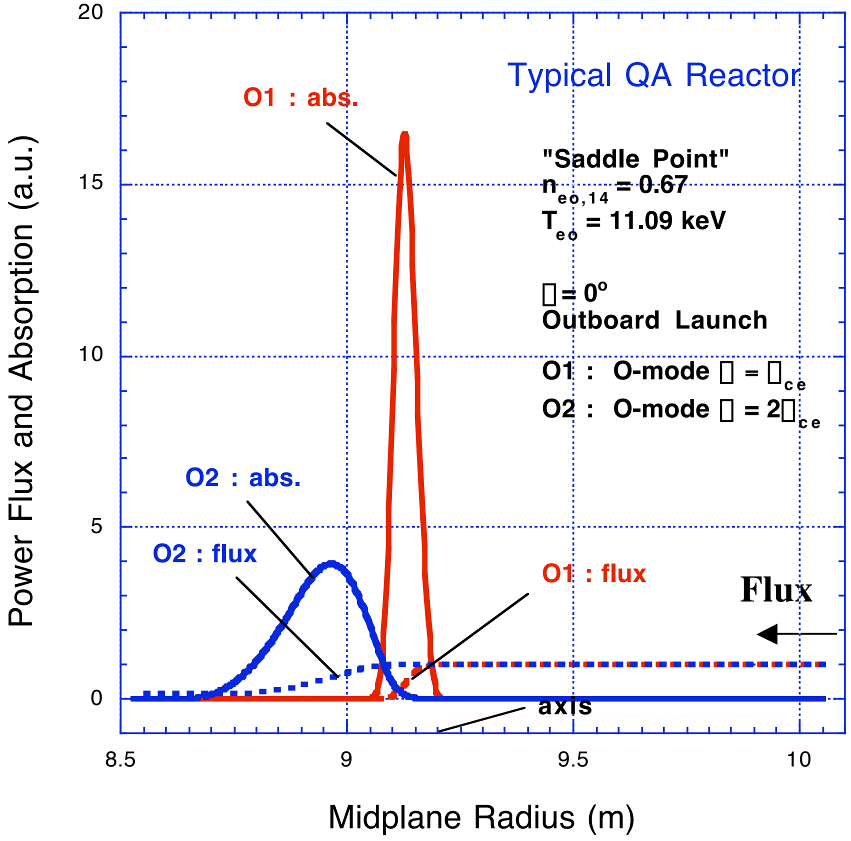
$\langle \beta \rangle = 2.2$ %

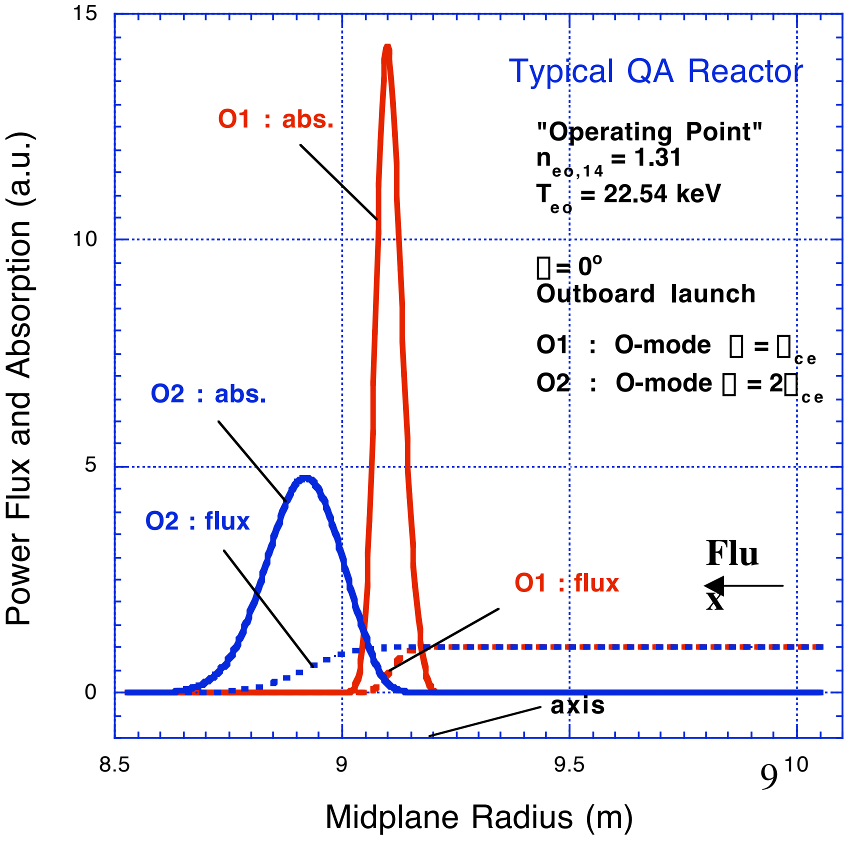
$P_{fus} = 0.6$ GW

- $R = 9$ m, $B_0 = 5$ T ($B_{coil} = 12.7$ T), 2.5 x ISS-95, 5% α loss
  $\tau_{He}/\tau_E = 6$ ⇒ 5.3% He, $n_{DT}/n_e = 0.83$, $Z_{eff} = 1.5$

Strong Single-Pass EC Absorption of the O-Mode

- O-mode at $f = f_{ceo}$ [O1] shows complete absorption in one radial pass for both the operating point and the saddle point.
  At $f = 2f_{ceo}$, [O2] absorption is weaker, with broader deposition profile on HFS of axis.
- Broader absorption profile is obtained at higher T_e due to relativistic effect.





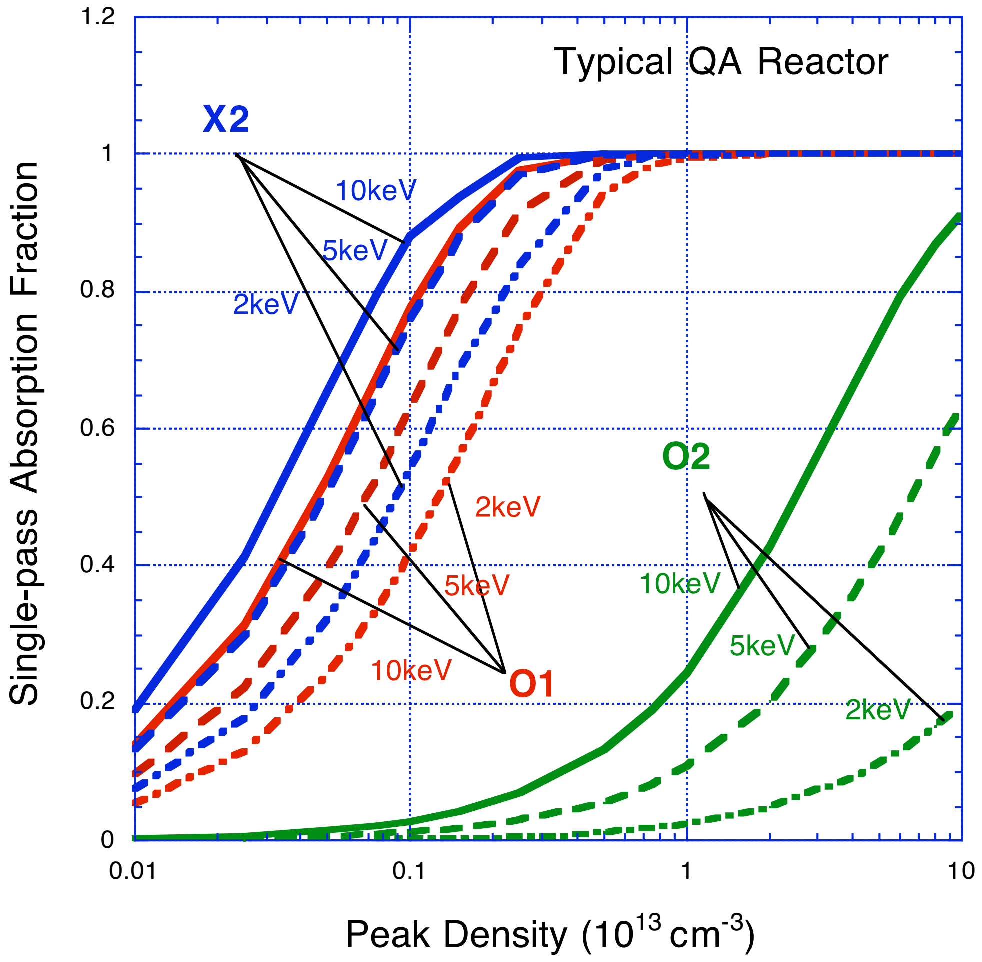
O-mode (n=1) is the Most Attractive for Heating

- O-1 and X-2 modes are attractive for heating purposes as they provide strong single-pass damping over the start-up range of plasma parameters.

- A drawback for the X-2 mode is the high frequency of ~293 GHz which requires substantial gyrotron development, or operation at lower B.

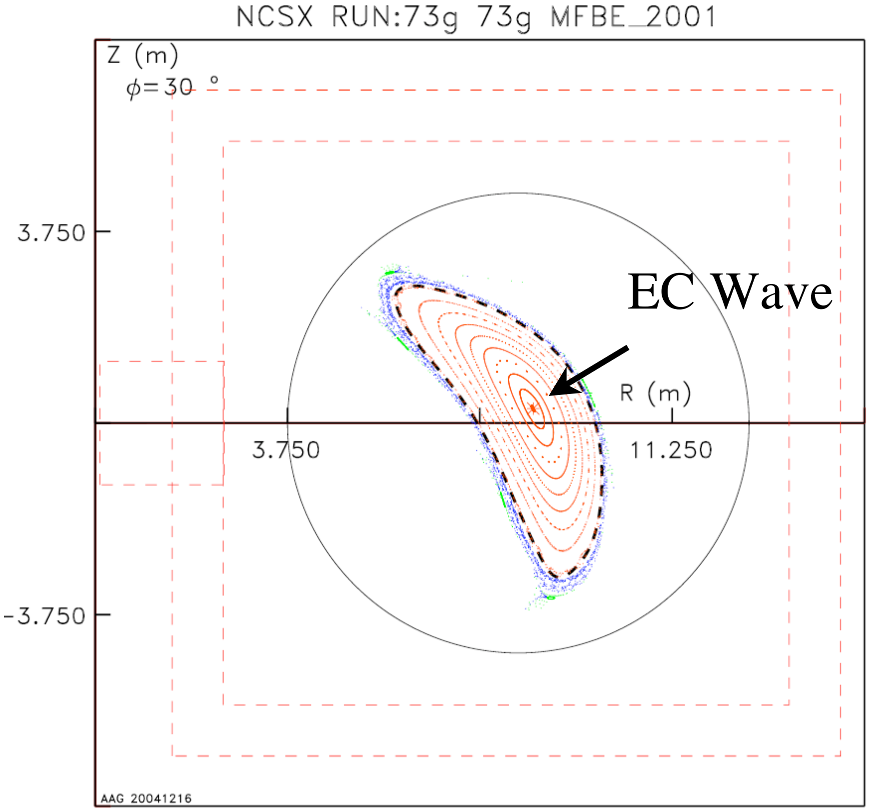
- Note these results are based on a perpendicular launch scheme.

Strength of absorption increases with n_e and T_e.



Application of Perpendicular ECH Launch To Non-Symmetric Cross Section at 35^o

- Necessitated by engineering, space, and maintenance constraints.
- Probably a very narrow range of launch angle that can be modeled by a 1-D slab code.
- Should be verified by a 3D-ray tracing analysis.



EC Wave

A Remote Steering Mirror System

[Kasparek et al., Nucl. Fus. 43 (2003) 1505.]

- Places mirror outside cryostat and behind shield.
- Corrugated square waveguide of half beat wavelength, $L = 4a^2/$□, generates anti-symmetric image of input field. [Talbot effect]
- Angular scanning range is $-10^o <$ □ $< +10^o$
- Scanning in one plane only.

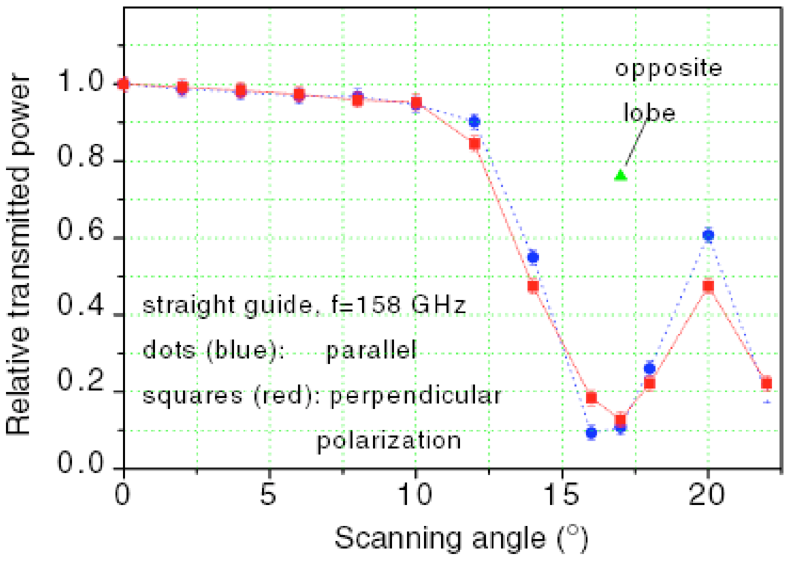


Figure 5. Dependence of the transmitted power in the main beam as a function of the scanning angle for the straight waveguide.

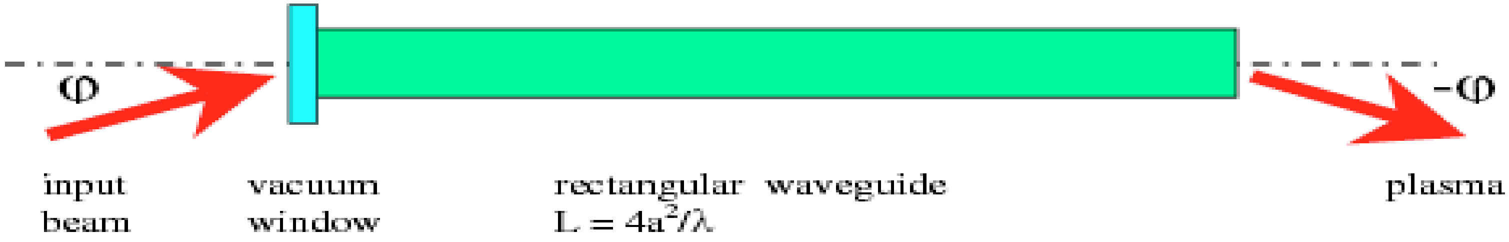


Figure 1. Principle of a remote steering antenna based on a corrugated square waveguide.

Addition of Miter Bends will Result in ~9% Loss at □ = 10 º

- A pair of miter bends can be used to reduce neutron flux to windows.
- The steering plane has to be □ to the plane of the bends.
- Loss in the bends can be reduced by replacing the corrugation with an isotropic impedance wall or by suitably rotating the corrugation.

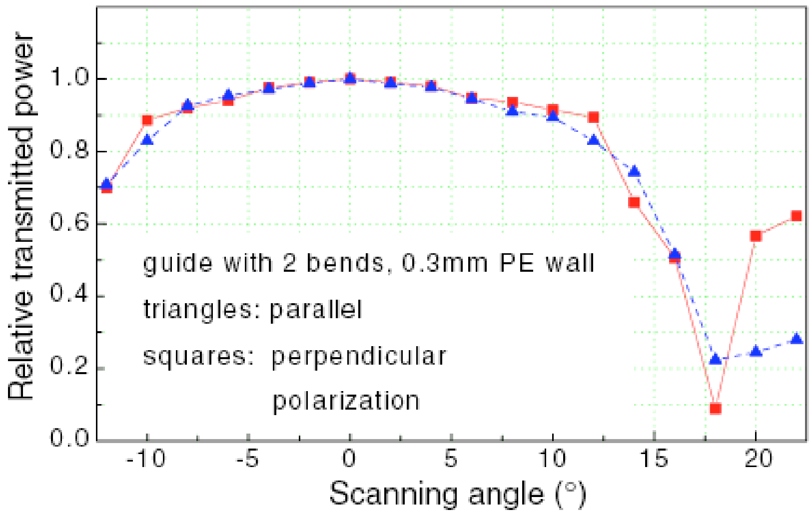


Figure 9. Dependence of the transmitted power in the main beam as a function of the scanning angle for the square waveguide antenna with two mitre bends equipped with a PE wall coating with 0.3 mm thickness. Polarizations are parallel (blue triangles) and perpendicular (red squares) with respect to the scanning plane.

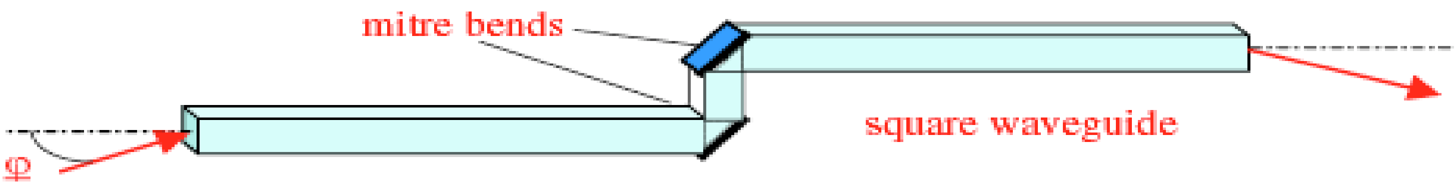


Figure 6. Geometry of the remote steering antenna with two mitre bends included.

Description of Entire ECH System

Nominal required power for heating is **20 MW**, delivered by **24 gyrotron sources each delivering 1 MW CW of power at a frequency of 158 GHz**, which corresponds to absorption of the O-mode at the fundamental resonance on-axis where B = 5.64 T.

From each gyrotron, the wave power is coupled to a **corrugated waveguide of circular cross-section** of 0.0635 m inner diameter, 0.0756 m outer diameter, and wall thickness of 0.013 m. The waveguide is practically loss-free and its length can be in ~100 m, if desired.

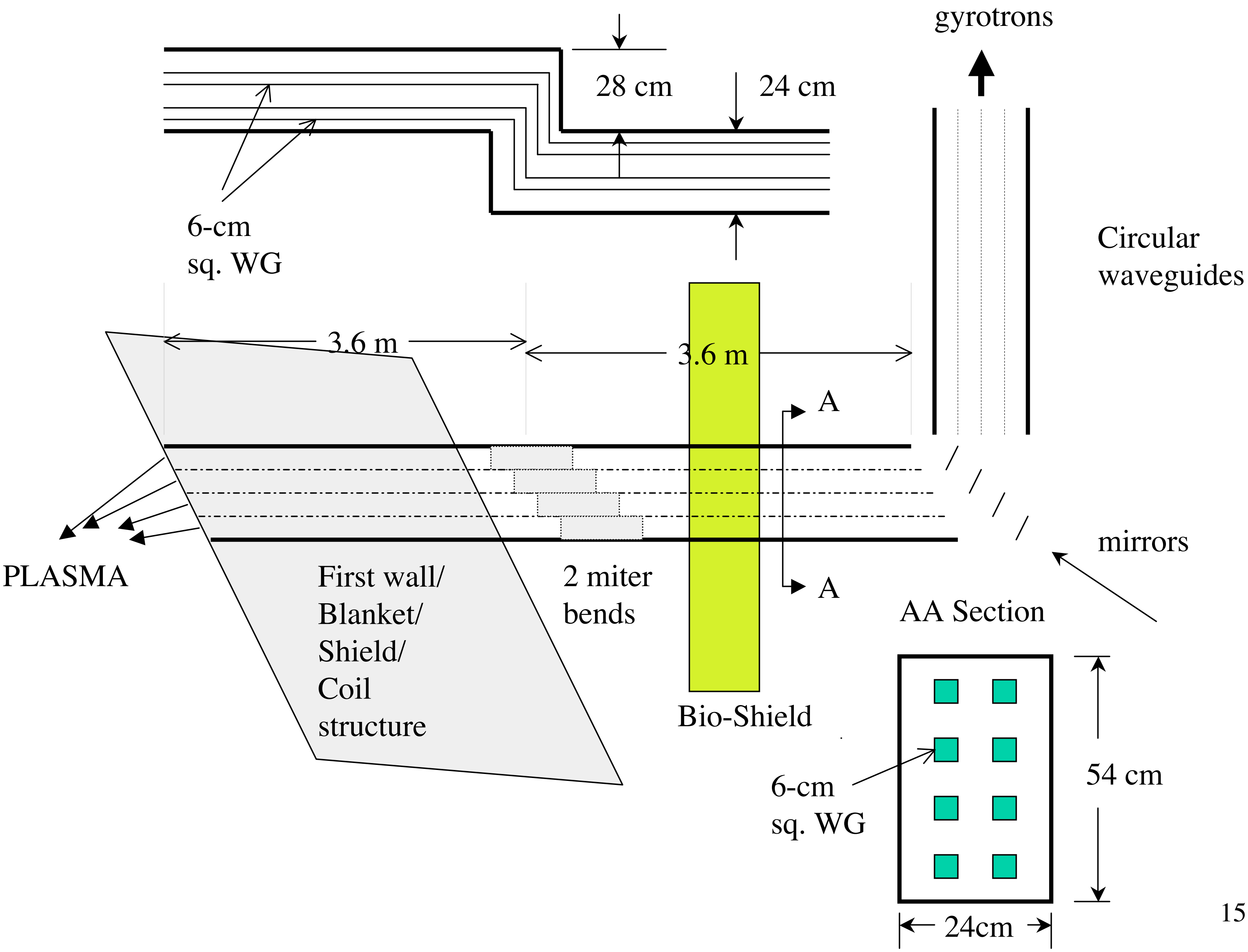
Close to the coil structure, the wave is coupled via **a steering mirror into a waveguide of square cross-section with width = 0.06 m and 7.5 m long**. The steering mirror can remotely steer the rf beam in the range (-10,+10) degrees from the horizontal.

We assume there will be an **ECH port** in each field period, so each port with have 8 waveguides, arranged in 4 rows of 2 wg's. Assume each waveguide with take 0.12 m x 0.12 m of space (for wg wall, coolant, support, and/or shield), each port will have dimensions 0.24 m x 0.48 m.

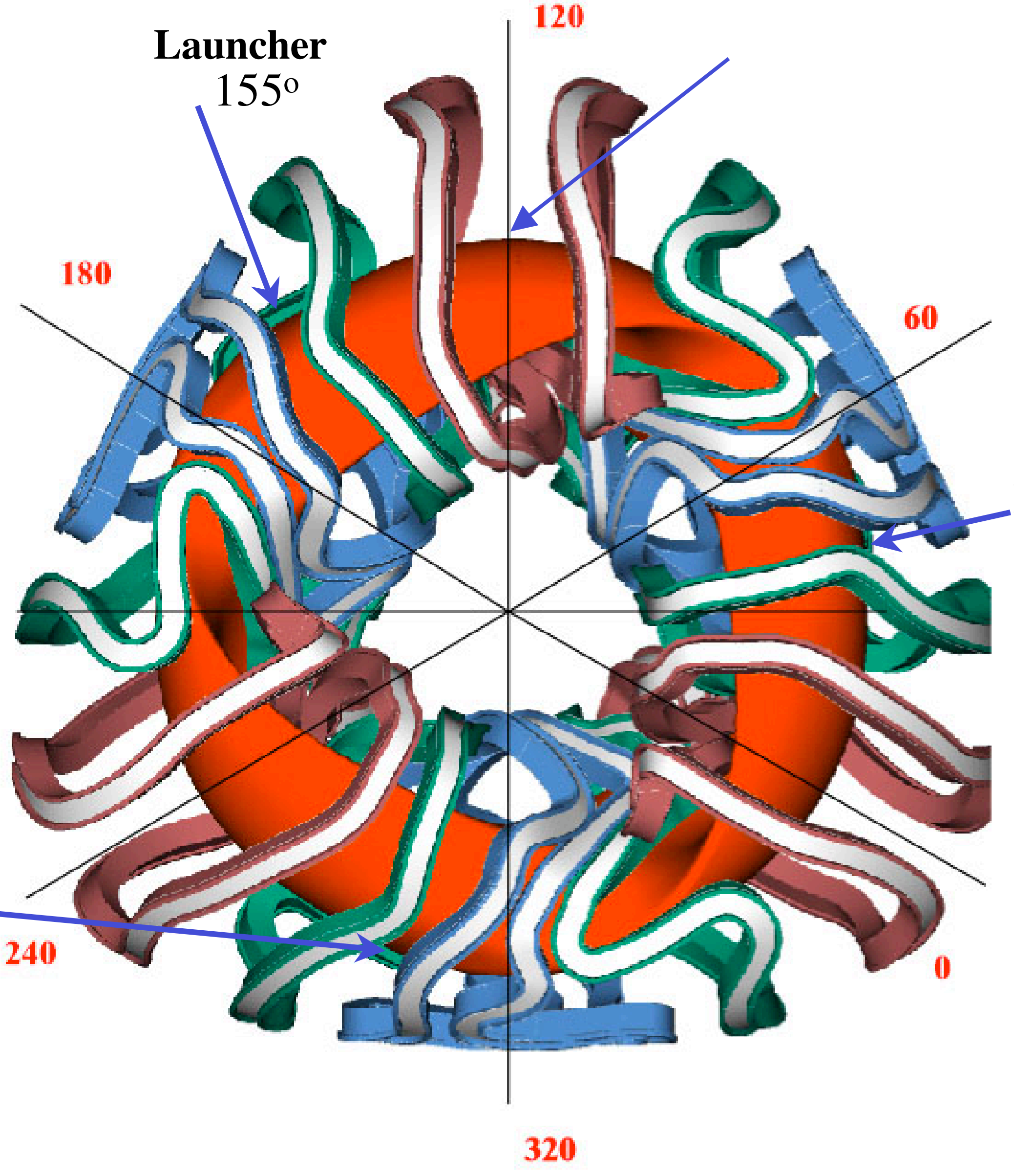
To minimize neutron streaming, the square waveguide will have **two miter bends** outside the coil structure at suitable locations. The first bend is 3.6 m from the first wall and the second 3.6 m from the input (and mirror) side.

The square waveguide and the mirror region should be evacuated to prevent breakdown at high power. The circular waveguide can be pressured and sealed with windows.

Top View of Miter Bends



Locations of ECH Launchers



Launcher 155°

Launcher 35°

Launcher 275°

Conclusions and Discussions

- Based on simple 1-D analysis, strong single-pass damping of the EC waves is obtained for an example CS reactor over most of the startup path.

- The O-mode fundamental resonance heating should be workable with above-midplane outboard launch at the □ = 35 °, 155 °, and 275 ° locations.

- A conceptual design of an ECH system for ARIES-CS has been carried out, using the circular-cross-section corrugated waveguide as the main transmission line. The concept of a remote steering launcher with a square-cross-section waveguide section is deployed to focus the microwave beam onto the plasma center.

- For a 20 MW heating power requirement, each field period will be equipped with an ECH port that accommodates 8 launcher units each delivering ~0.9 MW of power to the plasma.