ECRF Heating on CS Reactors

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ARIES Project Meeting
May 6-7, 2003
Livermore, California

OUTLINE

- ECH scenario studies based on example CS equilibrium
- Development of ECH analysis capability for CS geometries
- Preliminary assessment of ECH system
- Conclusions and Discussions

ECH is Attractive for Heating in a CS Reactor

- A plasma heating system is essential for heating to ignition, plasma initiation, and pressure and current profile control for MHD stability and confinement optimization.

ECH is attractive for the following reasons:

- Capable of localized heating and profile control
  - control knobs are frequency, wave launch location and launch angle
- Requires relatively compact components
  - potentially compatible with complicated coil and vessel geometry
- Minimal neutron irradiation of components as only launching mirrors are in 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 α's

Core Accessibility and Strong Single-Pass Absorption Are Desirable

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

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

  - $(\omega_{pe}/\omega_{ce})^2 < n^2$ 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.

- Since defocusing and mode exchange can be quite severe from wall reflection, it is important to have the wave energy absorbed in its initial pass through the plasma, particularly when efficient central heating is required.

- Damping is stronger at the lower harmonic resonances (n = 1,2), and weakens considerably as the harmonic number n is raised.

  - Damping decrement $\propto (k_\perp \rho_e)^{2(n-1)}$; $(k_\perp \rho_e)^2 << 1$

1-D Slab Model Facilitates ECH Scoping Analysis

- A 3-D ray tracing code for non-axisymmetric systems is required for comprehensive scoping of ECH scenarios on stellarators.

- However, a restricted class of ECRF launch scenarios can be studied using a 1-D slab model, e.g., along equatorial plane on some toroidal locations.

- For perpendicular launch ($k_{||} = 0$), the dispersion relation due to Chu and Hui is used. For example, for the O-mode at fundamental resonance ($\omega/\omega_{ce} = 1$), the wavenuumber $k_{\perp r}^{O}$ and damping decrement $k_{\perp i}^{O}$ are given by:

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

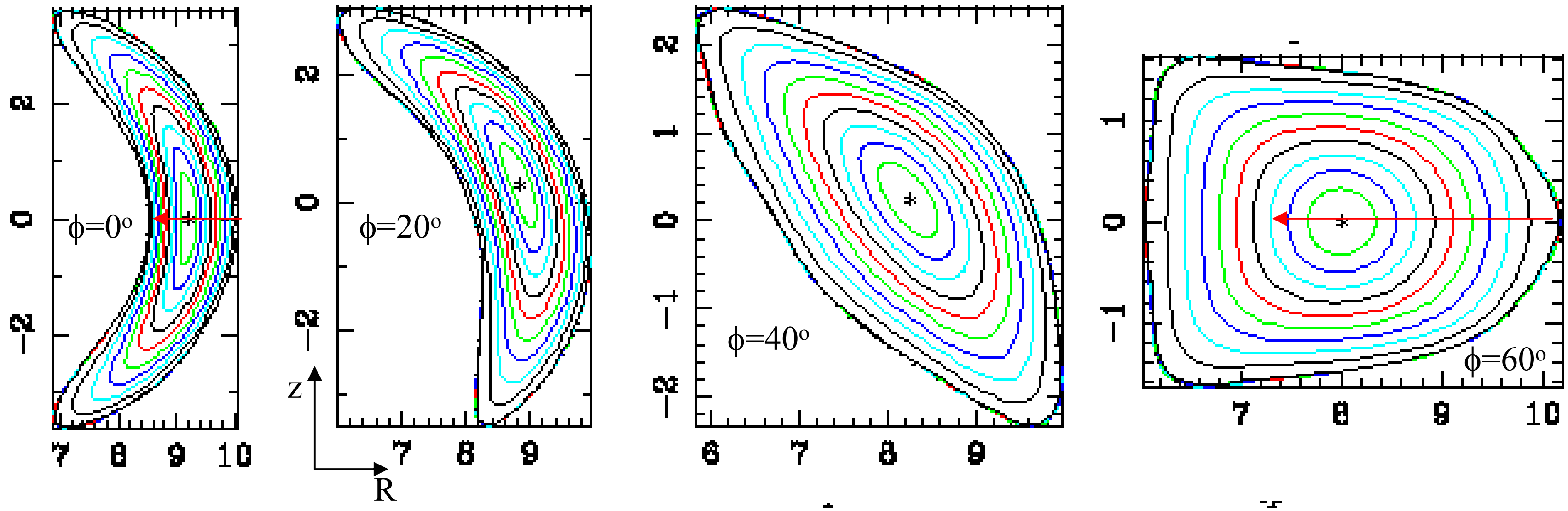
$$k_{\perp i}^{O} \cong \frac{2\pi^{1/2}}{60}\frac{\omega_{pe}^{2}}{\omega_{ce}c}\left(1-\frac{\omega_{pe}^{2}}{\omega^{2}}\right)^{1/2}\left(\frac{T_e}{m_e c}\right)^{-5/2}\Delta_1^5 \exp\left(-\frac{\Delta_1^2 m_e c^2}{2T_e}\right)\Theta\left(\Delta_1^2\right)$$

where $\Delta_1 \equiv \left(\omega_{ce}^{2}/\omega^{2} - 1\right)^{1/2}$, and $\Theta(x) = 1$, if $x \geq 0$, $= 0$, if $x < 0$.

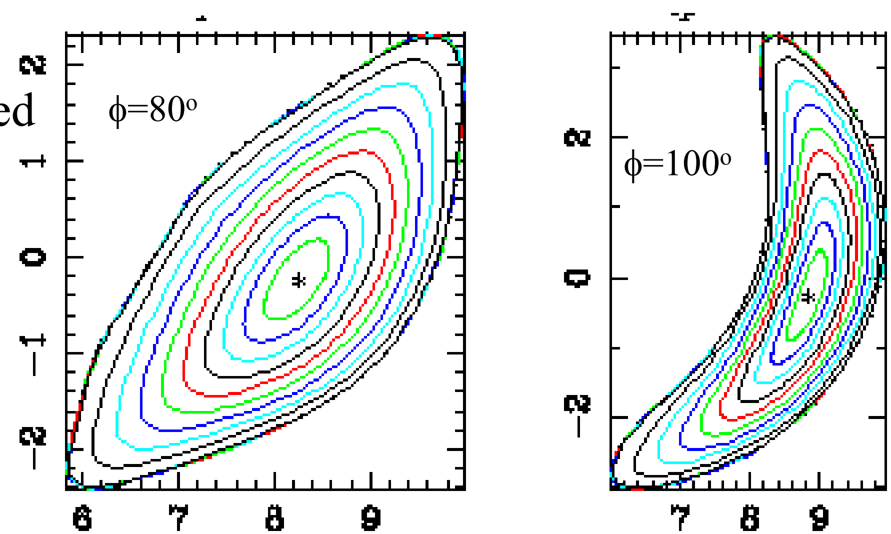
- The wave power along path is $P(x) = P_0 \exp\left(-2\int_0^x k_{\perp i}^{O}(x)\,dx\right)$

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 $\phi = 0^o$ Toroidal Location

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

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

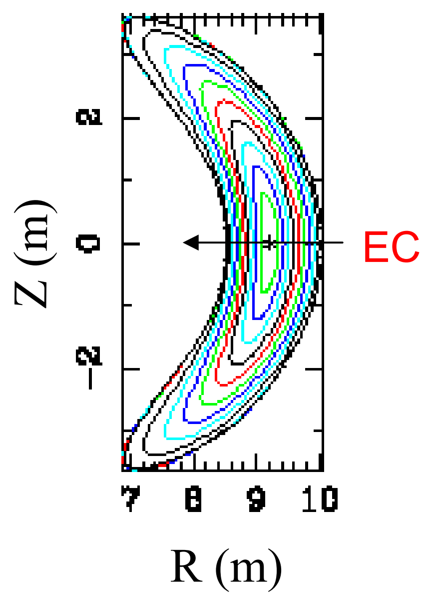
  $n_o/\langle n \rangle = 1.375$; $T_o/\langle T \rangle_n = 1.818$

  $R_{axis} = 9.21$ m; $B_{axis} = 5.24$ T

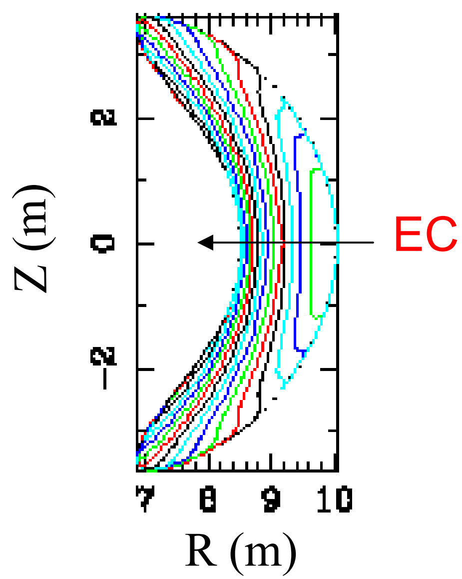
- Perpendicular Launch from Outboard Side : $k_\phi = 0$, $k_Z = 0$

- Frequency = (1 - 2) × f_{ce} (on axis) = 147 - 293 GHz.

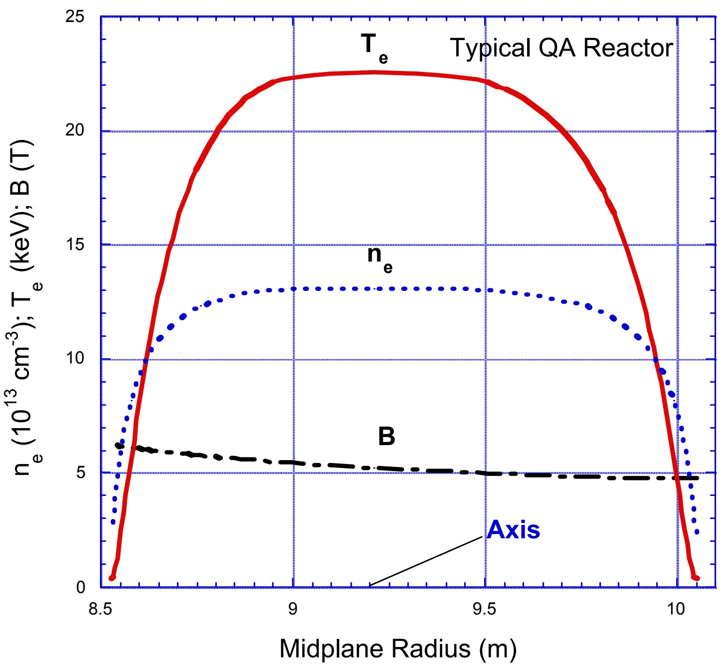
√Φ Surfaces



Mod-B Contours

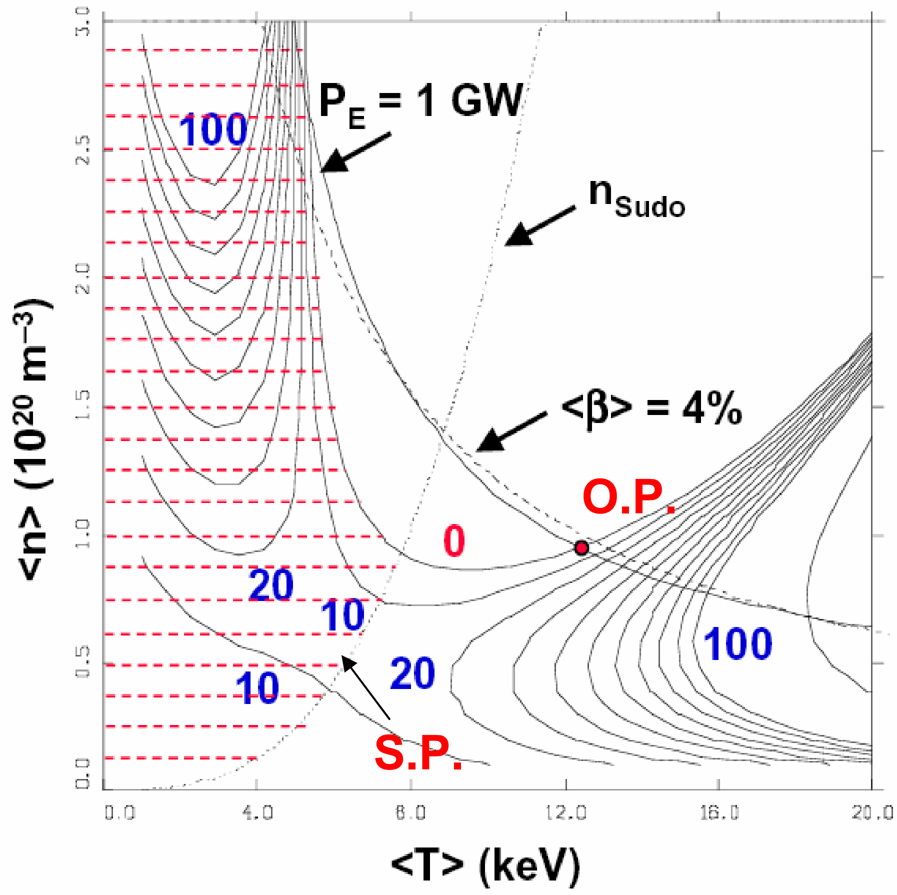


Plasma Profiles along Midplane



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

(J. Lyon, Oct. 02 ARIES Meeting)



Operating Point

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

$\langle T \rangle = 12.4$ keV

$\langle \beta \rangle = 3.6$ %

$P_{fus} = 1.73$ GW

Saddle Point

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

$\langle T \rangle = 6.1$ keV

$\langle \beta \rangle = 0.9$ %

$P_{aux} = 12$ MW

Ignition minimum

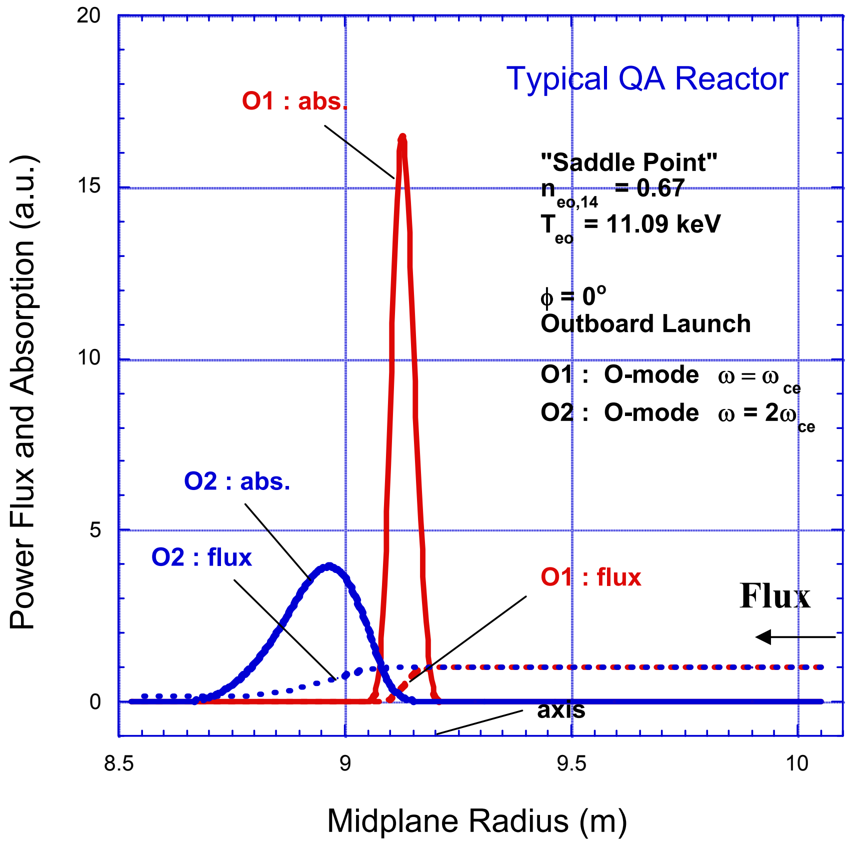
$\langle \beta \rangle = 2.2$ %

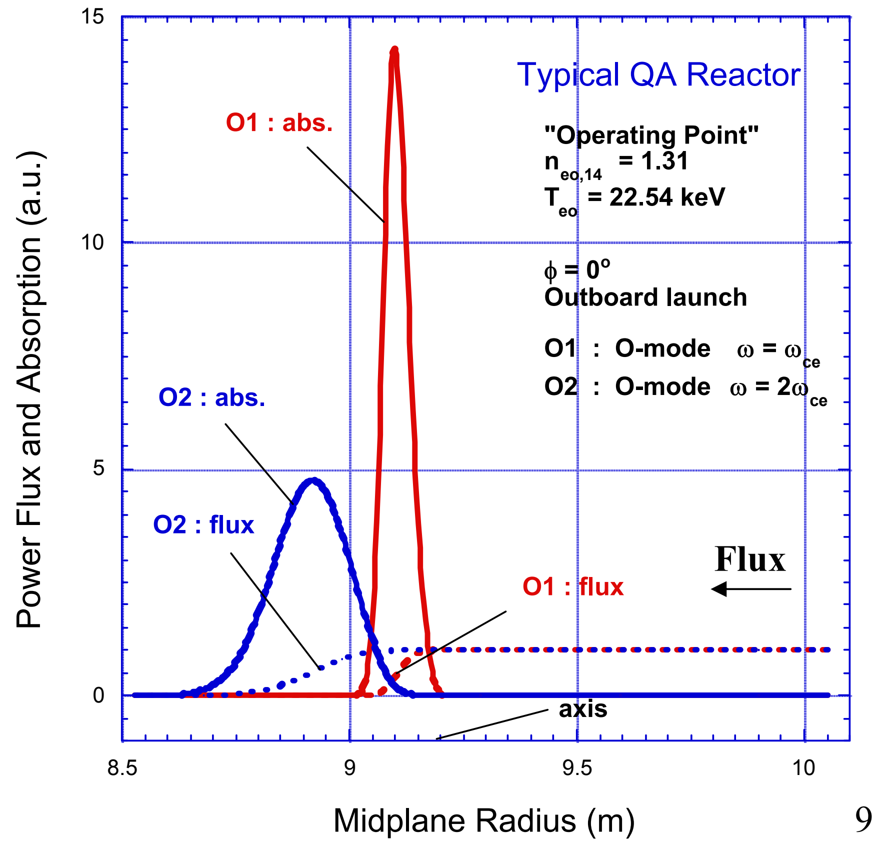
$P_{fus} = 0.6$ GW

- $R = 9$ m, $B_0 = 5$ T ($B_{coil} = 12.7$ T), 2.5 x ISS-95, 5% α loss
  $\tau_{He}/\tau_E = 6$ $\Rightarrow$ 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.
- Results are similar to those obtained previously with an approximate plasma model.

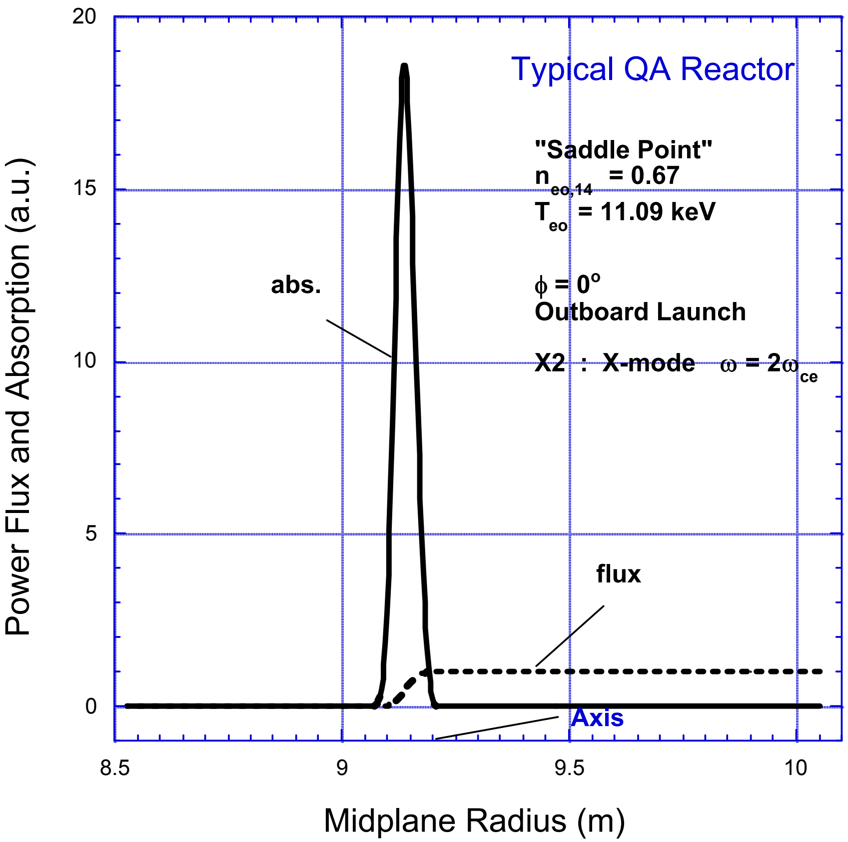


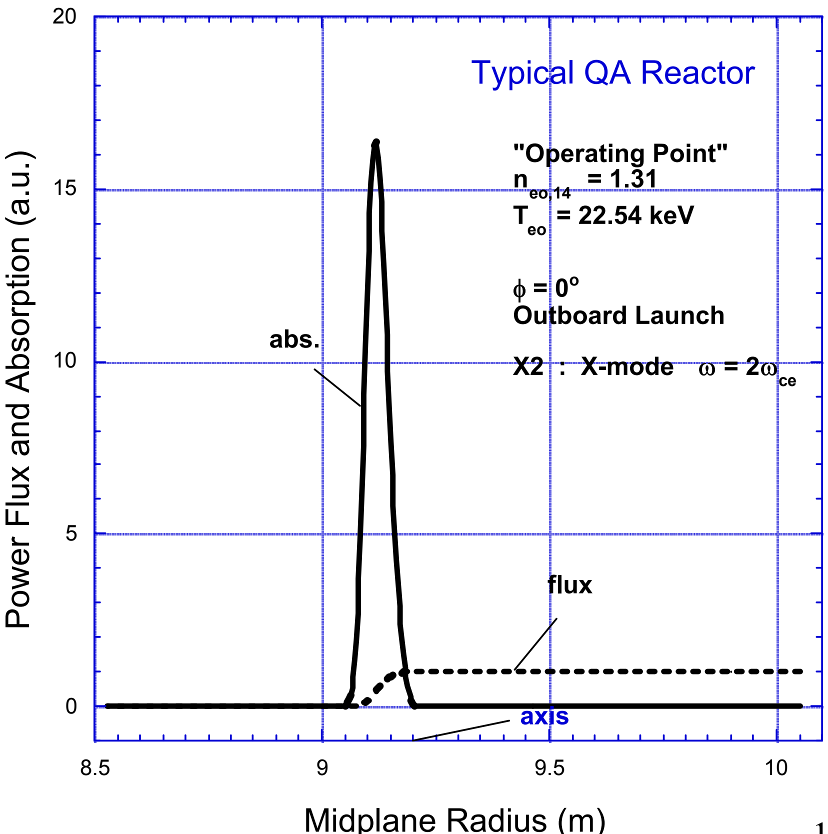


Even Stronger Absorption of the X-Mode

- The on-axis $\omega = \omega_{ce}$ resonance is inaccessible to the X-mode when launched when launched from the outboard edge.

- However, with the $\omega = 2\omega_{ce}$ resonance on axis, the X-mode is strongly damped in one radial transit, even stronger than the O-mode at $\omega = \omega_{ce}$ on axis. This is because the X-mode has the correct polarization to interact with electrons.





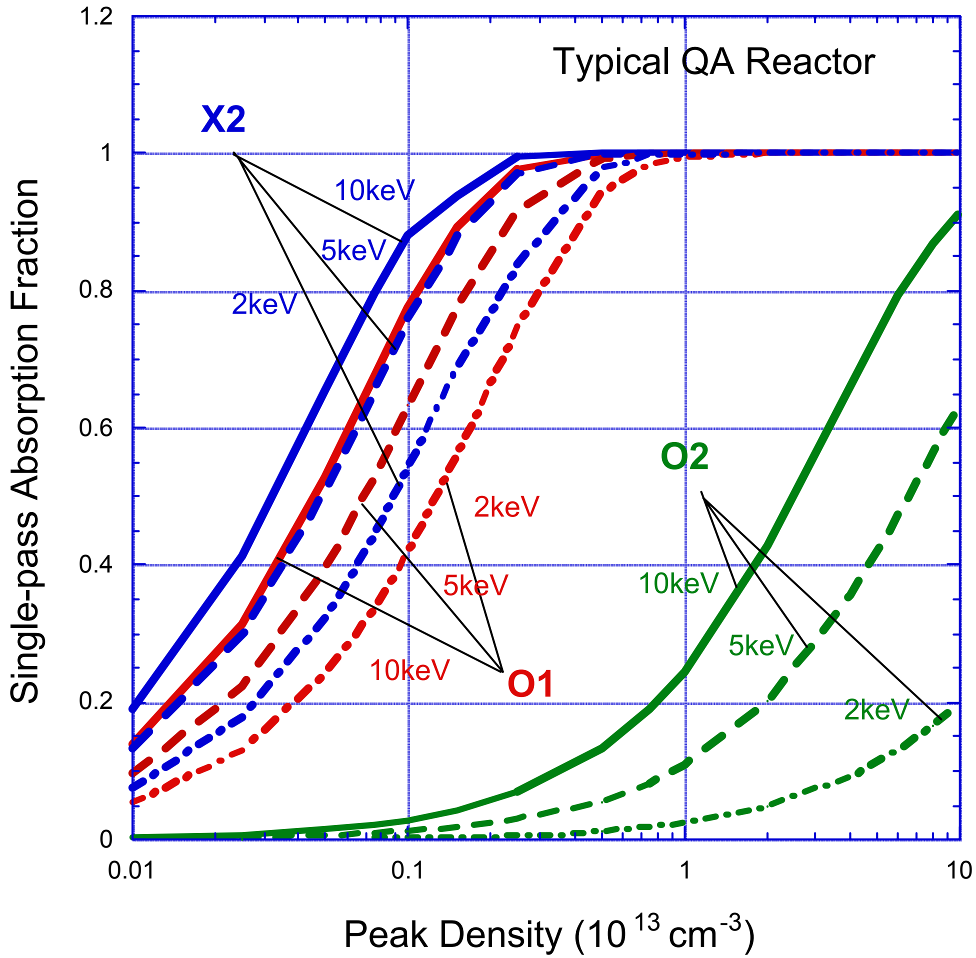
O-mode (n=1) is the Most Attractive for Heating

- 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 restricted launch scheme.

Strength of absorption increases with n_e and T_e.



Absorption Location and Profile Can be Controlled by Frequency and Launch Angle

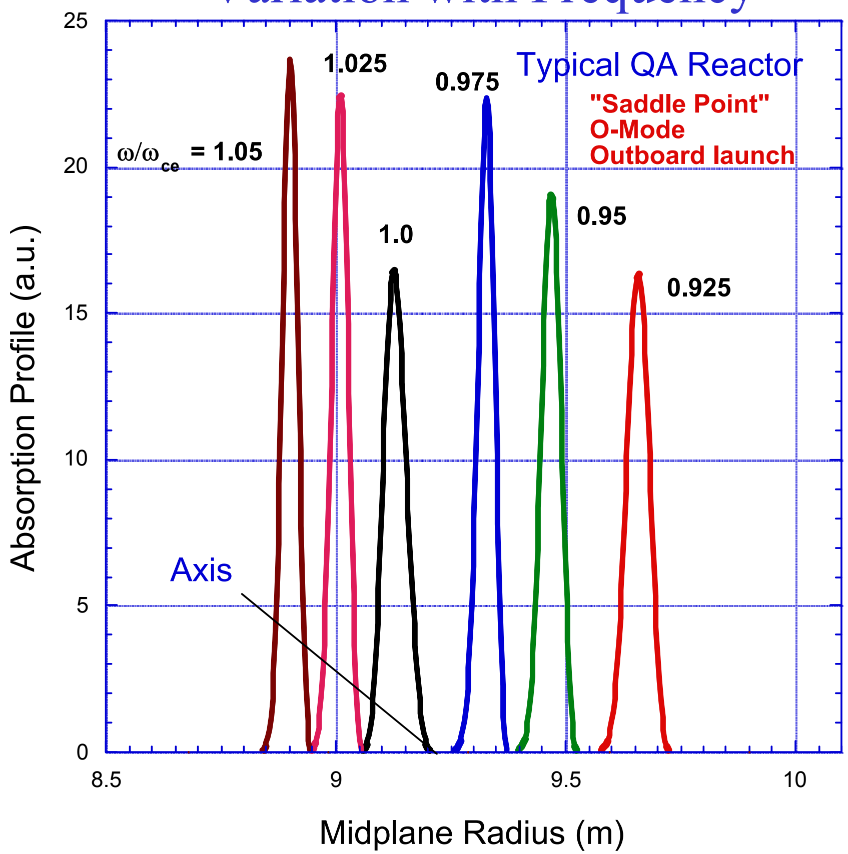
- The capability to control the wave absorption profile is a desirable feature especially for local profile (pressure and current) control for improved stability and transport.

- Varying the frequency shifts the radial location of main power deposition and current drive, as shown for O-mode.

- Varying the launch angle (w.r.t. surface normal) or $k_{||}$, and the launch position (poloidal) changes the deposition location,profile broadness and the current drive efficiency.

- $k_{||}$ is a comprehensive control knob. [but the tool to analyze this is being developed for 3-D geometries.]

Variation with Frequency



Development of Ray Tracing Tool for a Non-Axisymmetric Geometry

- A complete analysis of ECH scenarios on CS reactors requires a ray tracing tool for a non-axisymmetric toroidal geometry, to account for finite beam width, dependence on beam launch angle and on launch location, and for maximizing CD efficiency if needed.

- Most tokamak ray tracing codes (TORAY, CURRAY) solves the ray equations by neglecting terms proportional to $\partial/\partial\phi$.

- The GENRAY code (developed at CompX, Del Mar) appears suitable for our purpose, since the terms containing $\partial/\partial\phi$ are retained. It also contains an adequate EC dispersion relation and is coupled to an RF quasilinear Fokker Planck code which is useful for in-depth analysis.

- To make GENRAY useful, we need to develop an interface to a 3-D equilibrium generated by the VMEC code.

- Depending on the funding situation, an alternative may need to be found.

State of the Art of ECH Source Technology

- Required performance of a gyrotron includes higher unit power (>1 MW), high efficiency (>50%) and long pulse length (→ CW).
  Desired properties: Higher frequency (→ 300 GHz) and frequency tunability (?)
- The projected frequency range for CS reactor applications : 140 - 300 GHz
- The prospect for EC source technology is encouraging [M. Thumm, FZK report ,03]

Institution	Frequency [GHz]	Power [MW]	Efficiency [%]	Pulse Length [s]
CPI, Palo Alto	140	0.9	38	0.005
	140	0.52	38	0.5
FZK, Karlsruhe	140.5	0.46	51	0.2
	140.1	1.6	60	0.007
GYCOM-N	140	0.88	50.5	1.0
	140	0.99	47	0.5
GYCOM-M	170	0.85	48	5.0
	170	0.5	36	80
JAERI, TOSHIBA	170.2	0.9	43.4	9.2
	170.2	0.3	40	60

The advances are attributable to the use of single-stage depressed collectors and advanced water cooled windows made of sapphire, diamond or Au-doped silicon.

Advances in Window Technology are Promising

- Windows are used in two places in an ECH system:

  - As an output window for the gyrotron

  - As a vacuum seal inside the waveguide to the launching mirror near the first wall

- Maximizing the energy through-put leads to high power per tube and high power transmission per waveguide, lowering the number of subsystems

- Active cooling is required for CW operation.

PARAMETERS FOR LONG PULSE, HIGH POWER OPERATION ACHIEVED FOR ALTERNATIVE WINDOW CONCEPTS [1]

[Heidinger et al.,IEEE/PS 30 (02) 800]

Material / Concept	Power [kW]	Pulse length [s]	Fre-queny [GHz]	Institution
CVD Diamond water edge cooled	470	180	140	FZK/THALES + Euratom partners
	640	140	140	
	1000	10	140	
	500	20	170	JAERI/ TOSHIBA
	900	9.2	110	
	340	50	118	FZK/CEA/ THALES
	260	111	118	
	1000	5	110	CPI-GA
	1000	1.5	170	GYCOM/ FZK
Sapphire FC75 face cooled	350	5	110	JAERI/ TOSHIBA
	200	CW	140	CPI
Sapphire LN2 edge cooled	350	100	118	CEA/CRPP/ FZK/TTE
Boron Nitride	1030	1	170	GYCOM-M
	1000	*≈5*	*170*	*estimated extreme limit*

Using the Latest ITER-FEAT ECH Design as a Model

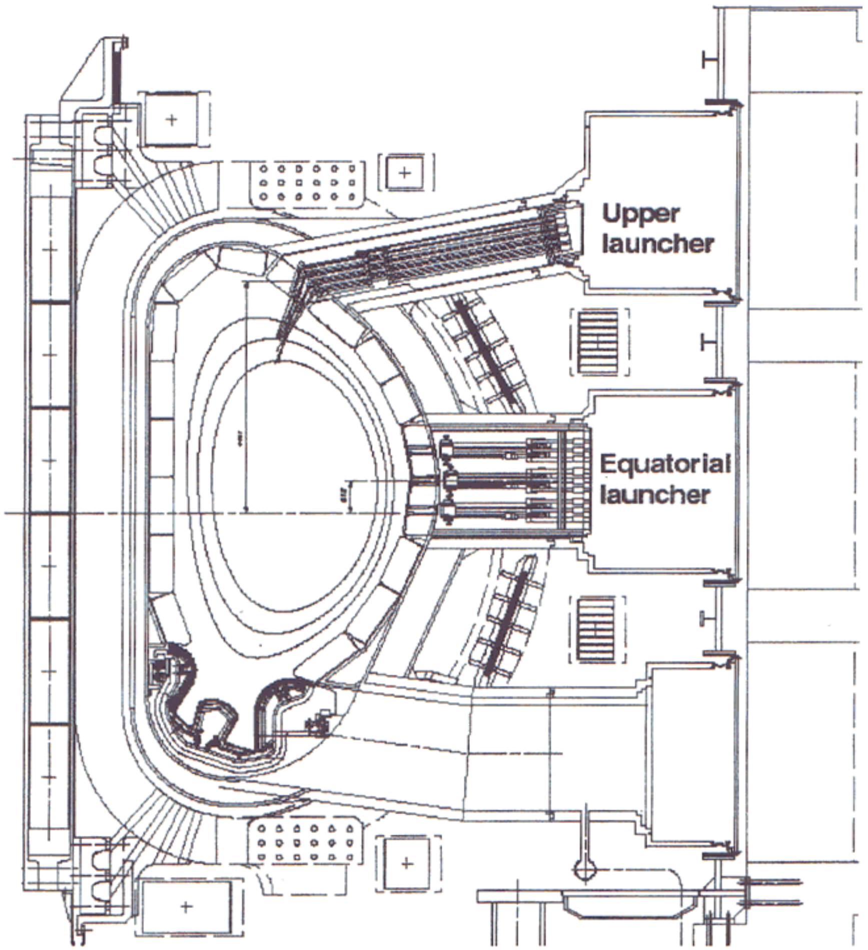
- There are two types of launchers:

  - Equatorial launcher:
    - # 20 MW @ 170 GHz for heating and CD; Has toroidal beam steering capability (±12.5°)
    - # 2 MW @ 120 GHz mainly for plasma initiation

  - Upper launcher:
    - # 20 MW @ 170 GHz for stabilizing NTM with precise CD located at q = 2, 3/2; Has poloidal beam steering capability (±5°)

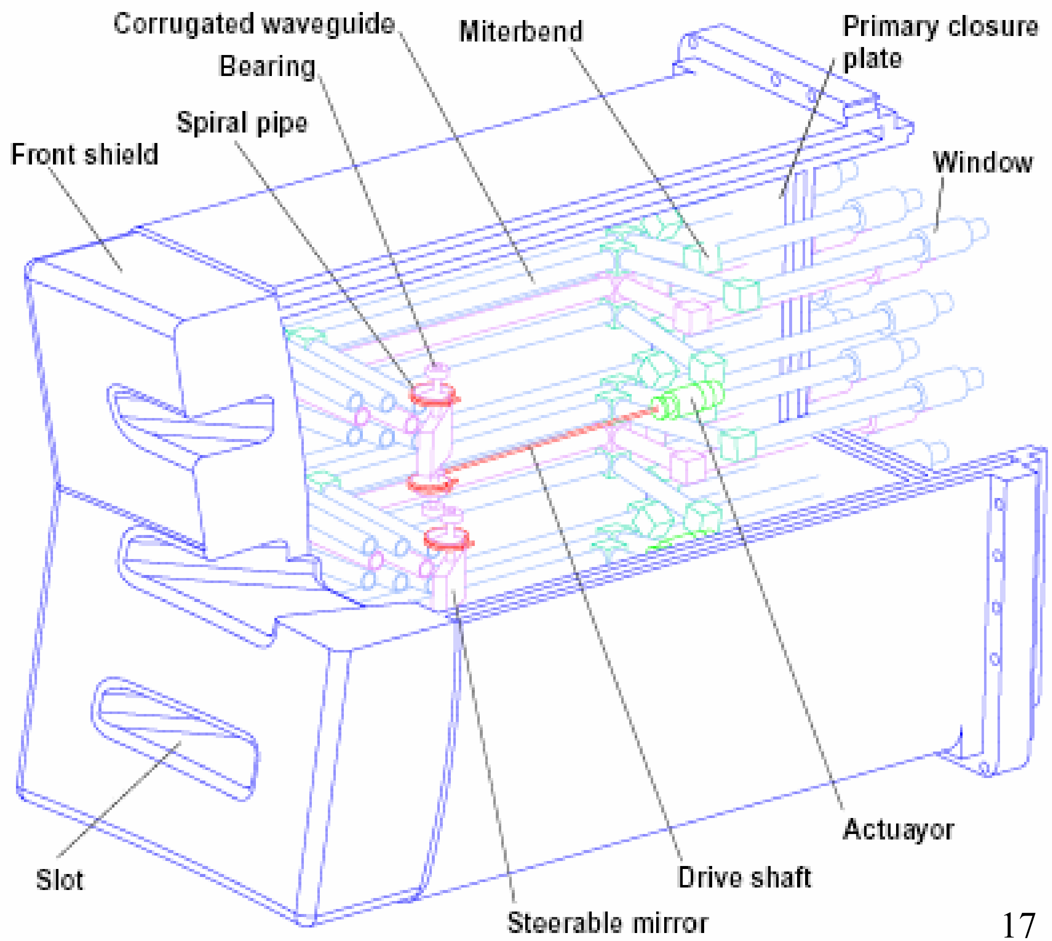
- 20 MW of power is switched between the two launcher modules

R = 6.2 m; a = 2.0 m



The ITER Equatorial Launcher As a Design Basis for CS

- Launcher module consists of
  - plasma facing neutron and radiation shield; 3 horizontal slots for beam aiming each transmitting 6.7 MW
  - 3 sets of steerable mirrors, each collecting 8 beams; mirrors made of GlidCop, supported by pivot mounted on bearings; water-cooled for ~60 kW/mirror heat; pneumatic actuator drives pivot that rotates mirror
  - 24 circular corrugated wg's; evacuated; dog leg helps avoid excessive neutron streaming
  - Miter bend: electrically insulated; needs water cooling
  - Window: CVD diamond disc serves as primary vacuum window; simple edge water cooling; 1 MPa pressure



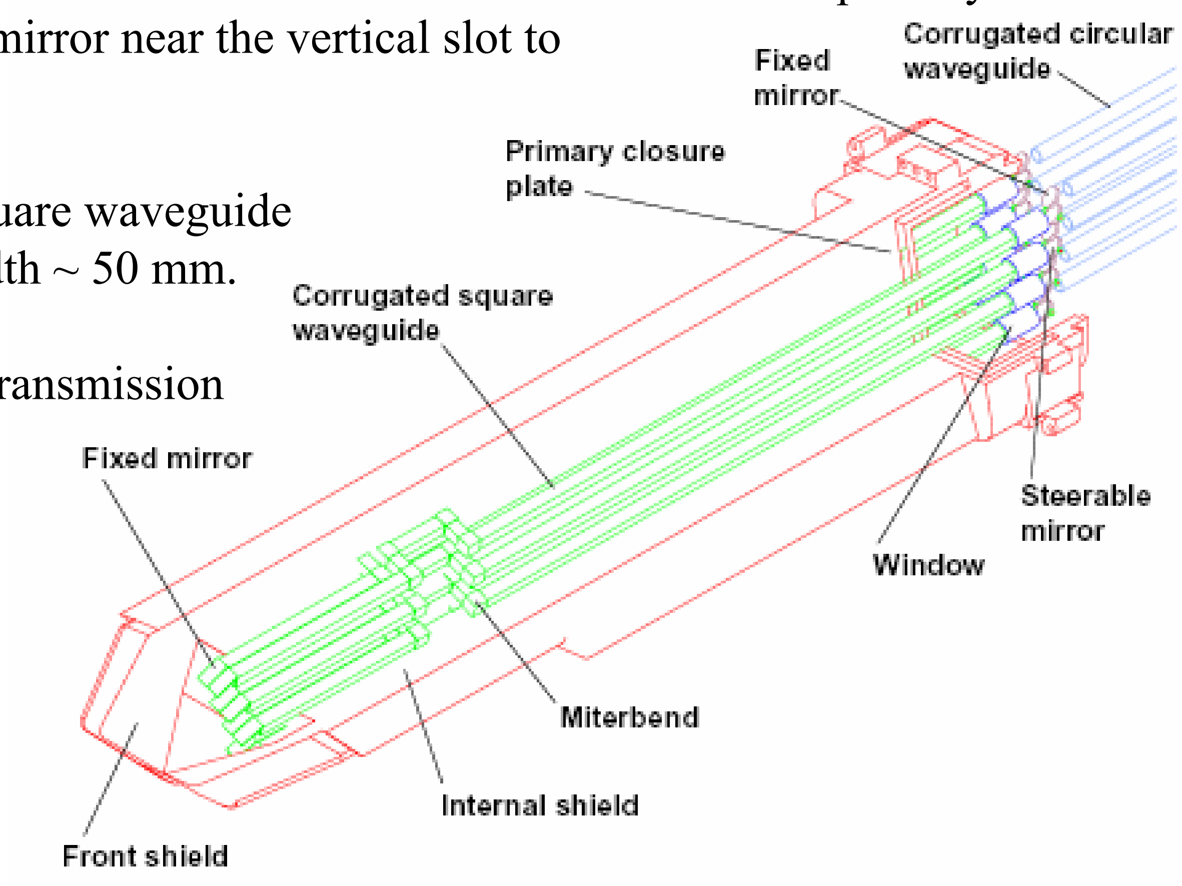
The ITER Upper Launcher as an Alternative for CS

- This is an option for more precise power deposition (perhaps off-axis) for detailed profile control of current and pressure.

- The module transmits 20 MW @ 170 GHz via four mirror subsystems: each contains one steerable mirror and one fixed mirror outside the primary vacuum, and one fixed mirror near the vertical slot to the plasma.

- Length of corrugated square waveguide is ~6.5 m, with w.g. width ~ 50 mm.

- Beam optics and power transmission efficiency are insensitive to corrugation depth and w.g. alignment.



Power Transmission System After ITER-FEAT

- Transmission lines are commercial products, and consist of

  - an RF conditioning unit
  - straight sections of circular or square X-section corrugated waveguides
  - a number of miter bends [d ~ 63.5 mm or 50 mm]
  - auxiliary equipment such as DC breaks, expansion segments, vacuum pumping sections, damping segments, isolation valves, etc.

- All sections of the transmission line is evacuated to 10-3 Pa and water cooled. Pumping is provided by the RF conditioning unit.

- The mm-wave beam from gyrotron is converted TEM_{00} to HE_{11} circular waveguide mode for long distance transmission. This involves matching optics and a number of polarizers.

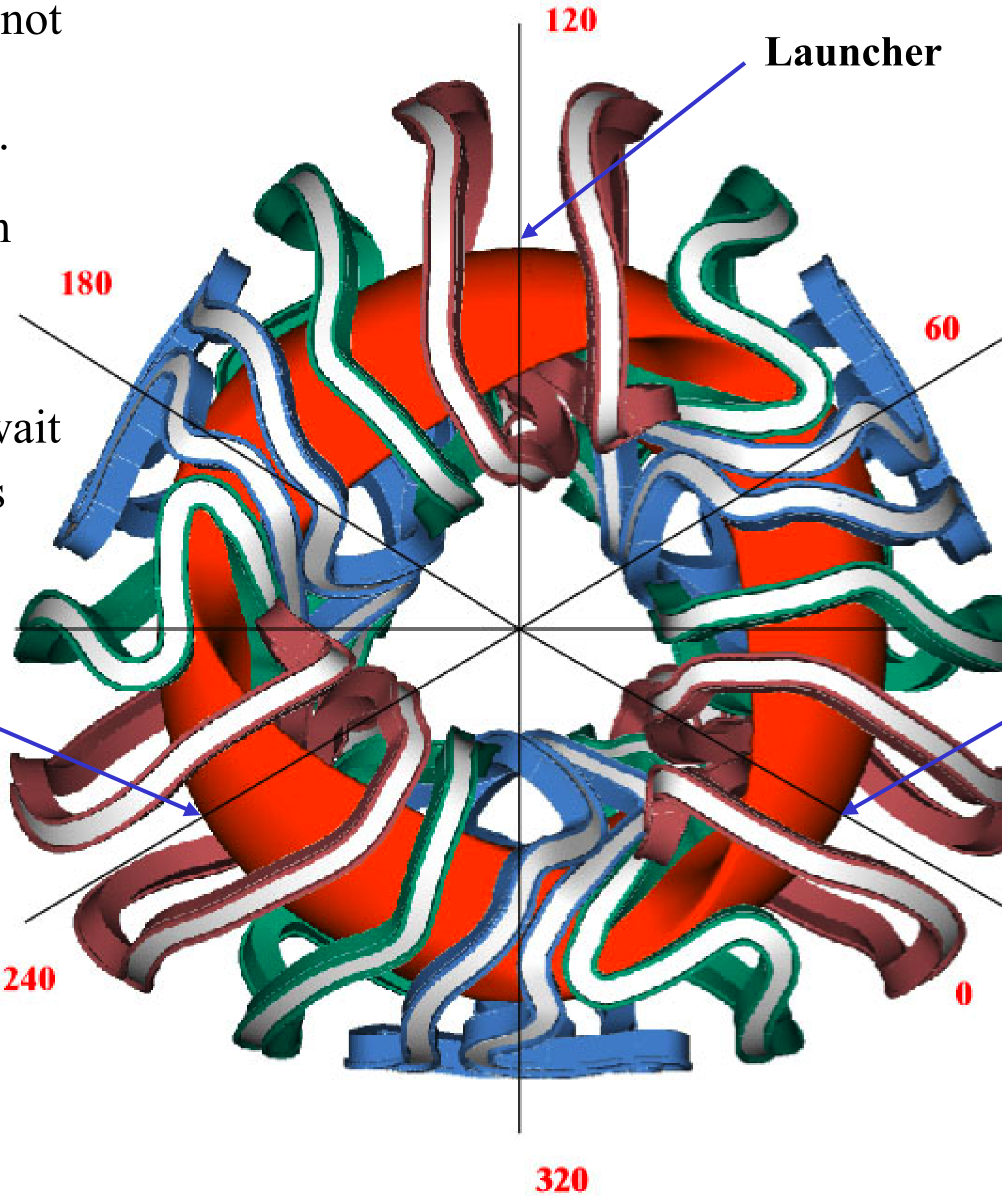
- The overall power transmission efficiency from gyrotron to injection point, over a transmission line length of 70-100 m., is ~ 80% for both launchers.

Possible Locations of ECH Launchers

The launcher locations are not in conflict with perceived maintenance port locations.

There appears to be enough local space for launcher modules.

Precise locations should await more detailed requirements and EC analysis



Assuming an EC power requirement of 20 MW, a single launcher module may be necessary, perhaps requiring only one special blanket sector.

Conclusions and Discussions

- Based on simple 1-D analysis, strong single-pass damping of the EC waves is obtained for a typical CS reactor over most of the startup path. The O-mode fundamental resonance with outboard launch appears most attractive at the $\phi = 0^{o}$, 120^{o}, or 240^{o} locations.

- A more comprehensive look at ECH scenarios including beam width, launch angle effects will be undertaken to address all requirements for the EC system, e.g., plasma initiation, heating, stability, confinement.

- A 3-D ray tracing capability is being developed for CS geometries.

- A preliminary assessment for ECH system for CS has been carried out, using the latest ITER-FEAT design as a start.

- For a 20 MW power requirement, a single-module ECH system embedded in one specialized blanket sector appears feasible.

- More detailed design for the ECH system will be carried out as an optimized CS reactor design evolves.