Exploring ECRF Heating on CS Reactors

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Potential Roles of a Heating System on CS Reactors

- Provide bulk heating during start-up to bring plasma to nominal operating conditions *
- Plasma initiation - gas breakdown and pre-ionization *
- Provide pressure profile control as needed for MHD stability and optimized confinement
- Provide localized current drive to offset bootstrap current for enhanced physics performance

* A CS power plant will most likely be without an OH-solenoid.

ECH is Potentially Attractive for a CS Reactor

- Capable of precise heating localization in plasma
  - dependent on frequency/B-field that are easily controlled
  - dependent on wave launch location and launch angle

- Requires relatively compact components
  - wavelengths in the sub-millimeter range (~100-200 GHz)
  - power handling limit ~ 10’s of MW/m^2

    → Very small hole in reactor first wall
  - small (quasi-optical) waveguides may simplify coil configurations leading to easier maintenance and lower cost

- Strategic bends in the waveguides eliminate direct line-of-sight between plasma and source → Minimize neutron irradiation with shielding

- Requires no large antenna structure near first wall
  - launcher consists of reflecting mirrors in a small “hole in the wall”
  - no coupling issue as the EC wave propagates in vacuum

- EC waves do not interact with ions and energetic α’s

ECH Issues are being Addressed

- EC power source (gyrotrons):
  - Efficiency : 50% obtained using depressed collectors to recover lost heat
  - Pulse length : industry-grade diamond window → 10 s pulse at 1MW in 110-170 GHz
  - High frequency : ~ 300 GHz at ~ 1 MW, short pulses (at MIT)

- Protection and hardening of reflecting mirrors under neutron irradiation environment
  - development of coating material(s)
  - maintenance / replacement

- Density limit for EC wave access to plasma core
  - probably not a serious concern for CS reactors (more later)
  - density limit depends critically on the evolving B-field during startup
  - Mode conversion to electron Bernstein wave at high densities may be considered

There is a Significant ECH/ECCD Experimental Data Base

- Tokamaks : DIII-D (ECH/ECCD)
  JT-60U, Asdex-U, FTU, TCV
  Compass, T-10, WT-2(Kyoto)
  CDX-U, NSTX (EBW)
  ITER-FEAT (planned ECCD)

- Stellarators : W7-AS (ECH/ECCD)
  W7-X (planned)
  HCX
  LHD

- Others : MST (EBW)

Theory and modeling are highly developed, especially for tokamaks.

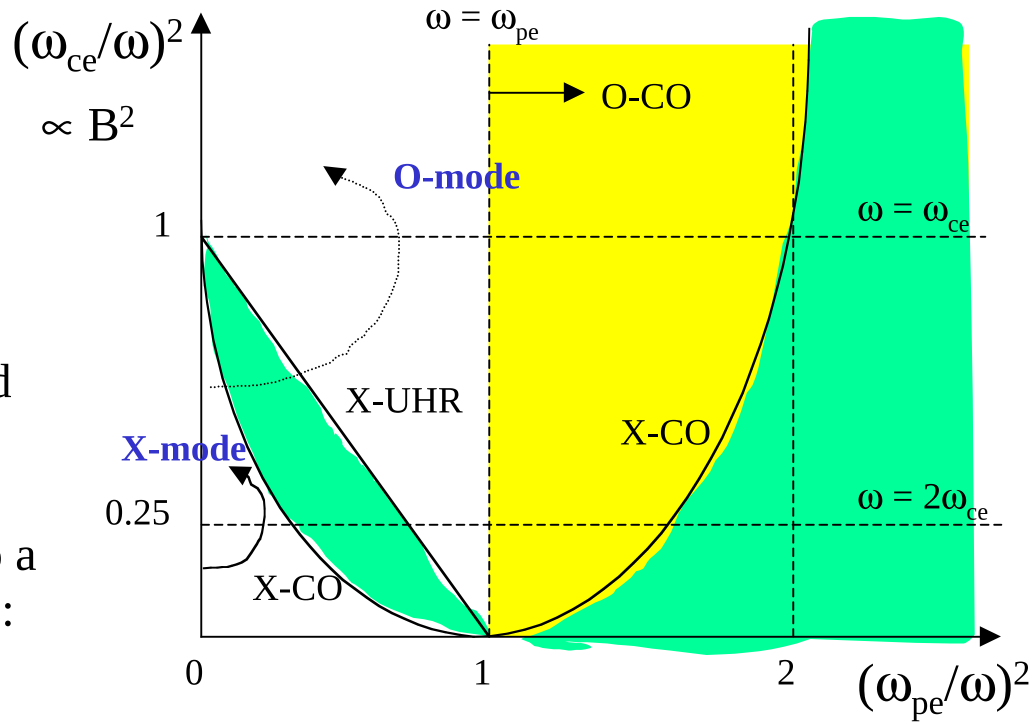
Recent ECCD experiments on DIII-D obtained good agreement between theory and experiment.

Access of EC Waves to Plasma Core is a Prerequisite

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

- The O-mode is cut off at $\omega < \omega_{pe}$ while the X-mode exhibit low and high density cutoffs.

- The conditions for propagation to a point 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
  - $\omega = \omega_{ce}$ resonance is always not accessible to X-mode from LFS



CO : cut off
UHR : upper hybrid resonance

🟩 : X-mode cut off region
🟨 : O-mode cut off region

- Low density and high B-field are favorable to ECRF core penetration. High B-field(high frequency) may be limited by gyrotron technology.

Strong Single-Pass Absorption is Desirable

- 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 central heating is required.

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

  - $\gamma_{ec} \sim (k_\perp \rho_e)^{2(n-1)}$; $(k_\perp \rho_e)^2 << 1$

- Usually the X-mode exhibits stronger damping than the O-mode since it has the right polarization for interacting with electrons.

- Higher density and higher electron temperature should lead to stronger damping per pass in the plasma (provided it is accessible to the wave). These are conditions present in fusion reactors.

ECH Analysis for CS's is Complex

- Detailed analysis requires 3-D ray tracing in a non-axisymmetric magnetic geometry, coupled with quasilinear Fokker Planck code.
  - US capability : ORNL code for Elmo Bumpy Torus ECH studies.
  - Non-US tools : W7-AS/W7-X group in Germany

- For this exploratory study, a very simple 1-D model is used, which is restricted to a very special launch case:
  - launching the wave from LFS along horizontal midplane, where both flux surfaces and mod-B surfaces are approximately vertical
  - wave propagates perpendicularly to the B-field ($k_{||} = 0$)
  - monotonic decrease of B-field with R (even though there may be local maxima or minima): $B(x) = B_o\,(1+x/R_o)$ with $-a \leq x \leq +a$
  - n_e and T_e profiles are parabolic : $\sim [1-(x/a)^2]^{\alpha}$
  - plasma electrons are weakly relativistic*
    cold plasma dispersion relation*

* Ref. : K.R. Chu et al, *Phys. Fluids* 26 (1983) 69.

A CS/QA Reactor Example

(Taken from Lyons' Talk at Last ARIES Meeting)

- Relevant parameters:

  $R_o = 9$ m, $\langle a \rangle = 2.25$ m, $B_o = 5$ T

  At operating point :

  $\langle n_e \rangle = 9.5 \times 10^{19}\ m^{-3}$; $\langle T_e \rangle_n = 12.4$ keV; $P_{heat} = 0$

  At saddle point (halfway along startup path):

  $\langle n_e \rangle = 4.9 \times 10^{19}\ m^{-3}$; $\langle T_e \rangle_n = 6.1$ keV ; $P_{heat} \geq 12$ MW

- Take $\alpha_N = 0.5$, and $\alpha_T = 1.0$.

  $n_{eo}/\langle n_e \rangle = 1.5$, and $T_{eo}/\langle T_e \rangle_n = 1.67$

  $\longrightarrow (\omega_{peo}/\omega_{ceo})^2 = 0.59$ @ operating point

  0.30 @ saddle point

  This implies both X- and O-modes will penetrate.

- The wave frequency is set at f = 140 GHz for n = 1

  280 GHz for n = 2

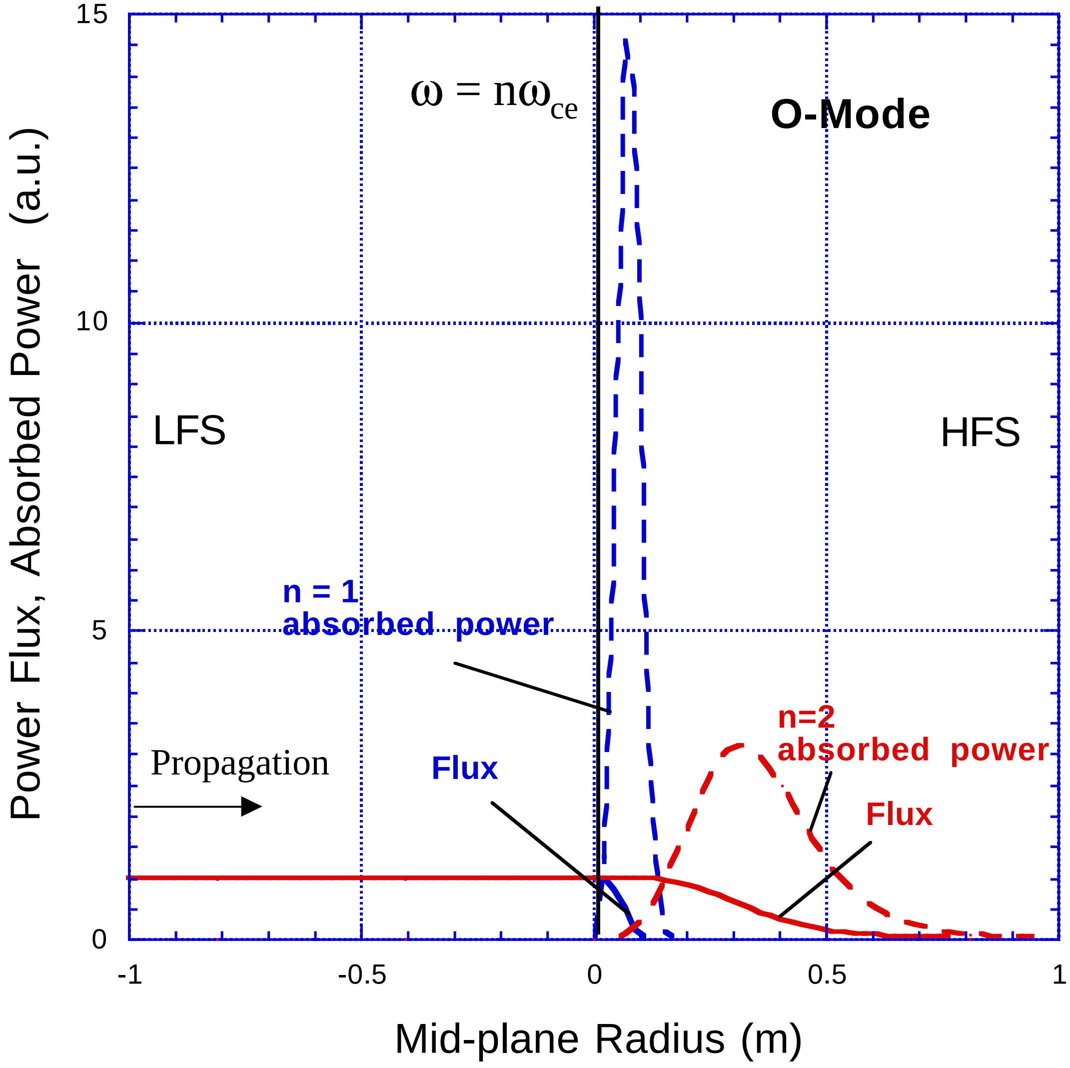
O-Mode is StronglyAbsorbed at Saddle Point

- Strong single-pass absorption for both cases:

  f_{abs} = 1.0 n =1
  0.99 n = 2

- More peaked absorption profile for n=1 indicates stronger damping.

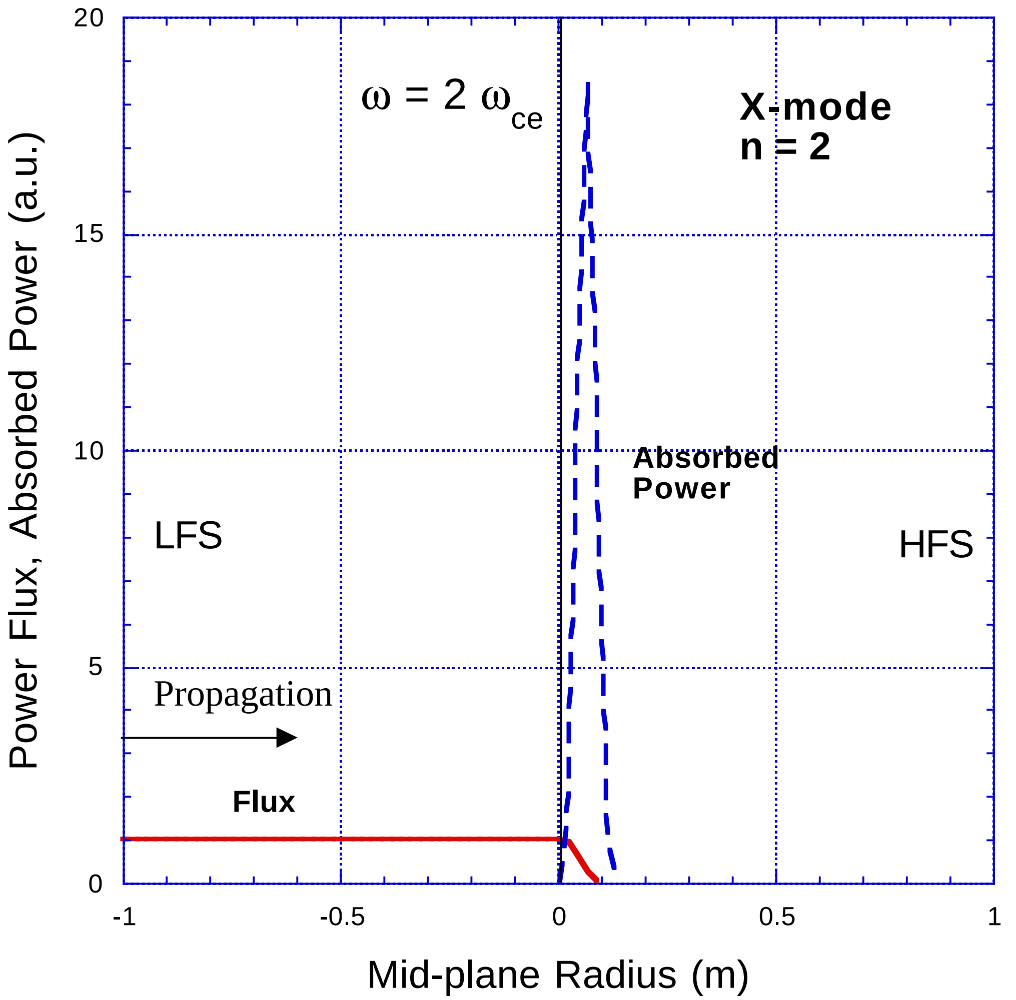
- Absorption takes place on HFS of resonance indicating relativistic effect.



The X-Mode is Strongly Absorbed at Saddle Point

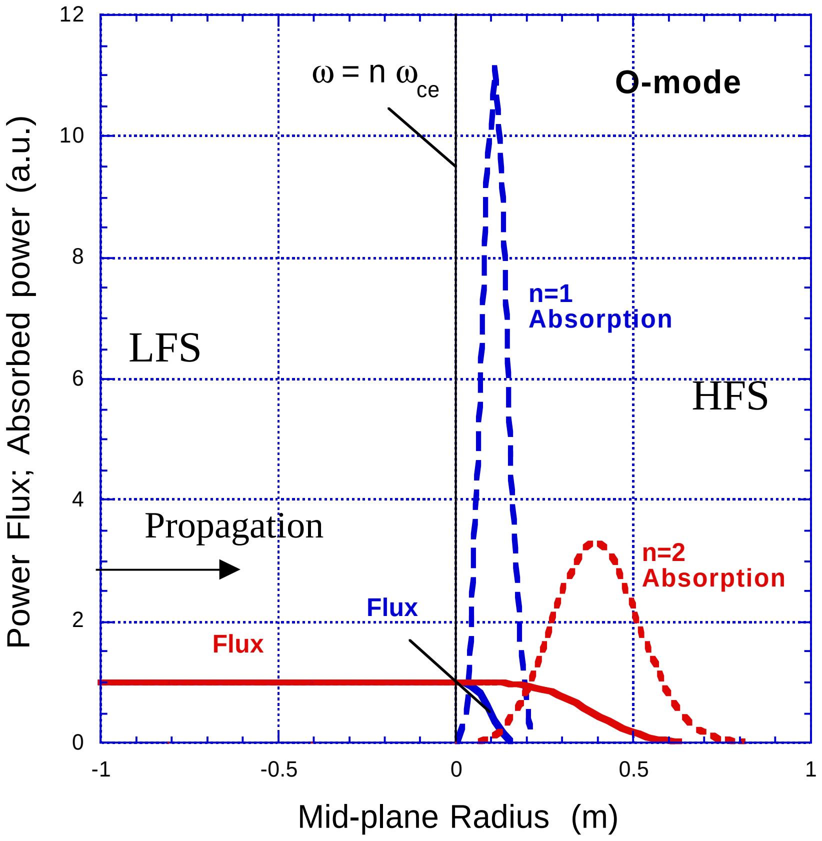
- There is total single-pass absorption for the X-mode.
  $f_{abs} = 1$

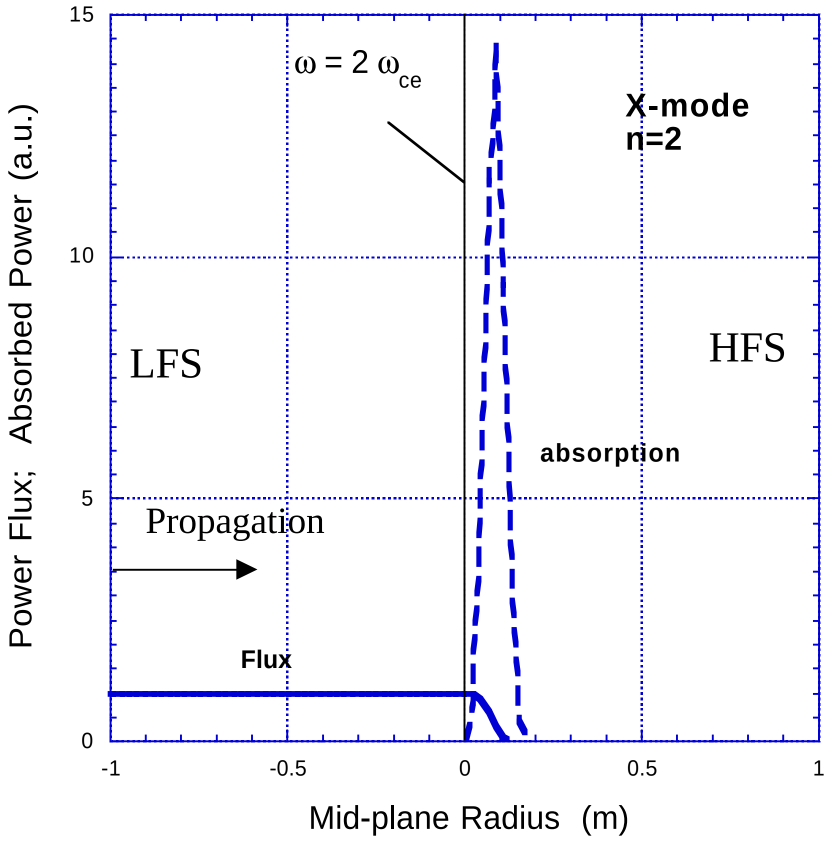
- Comparison of the absorption peaks indicate that the X-mode at n=2 damps more strongly than the O-mode at n=1.



Similar Absorption Pictures at Operating Point

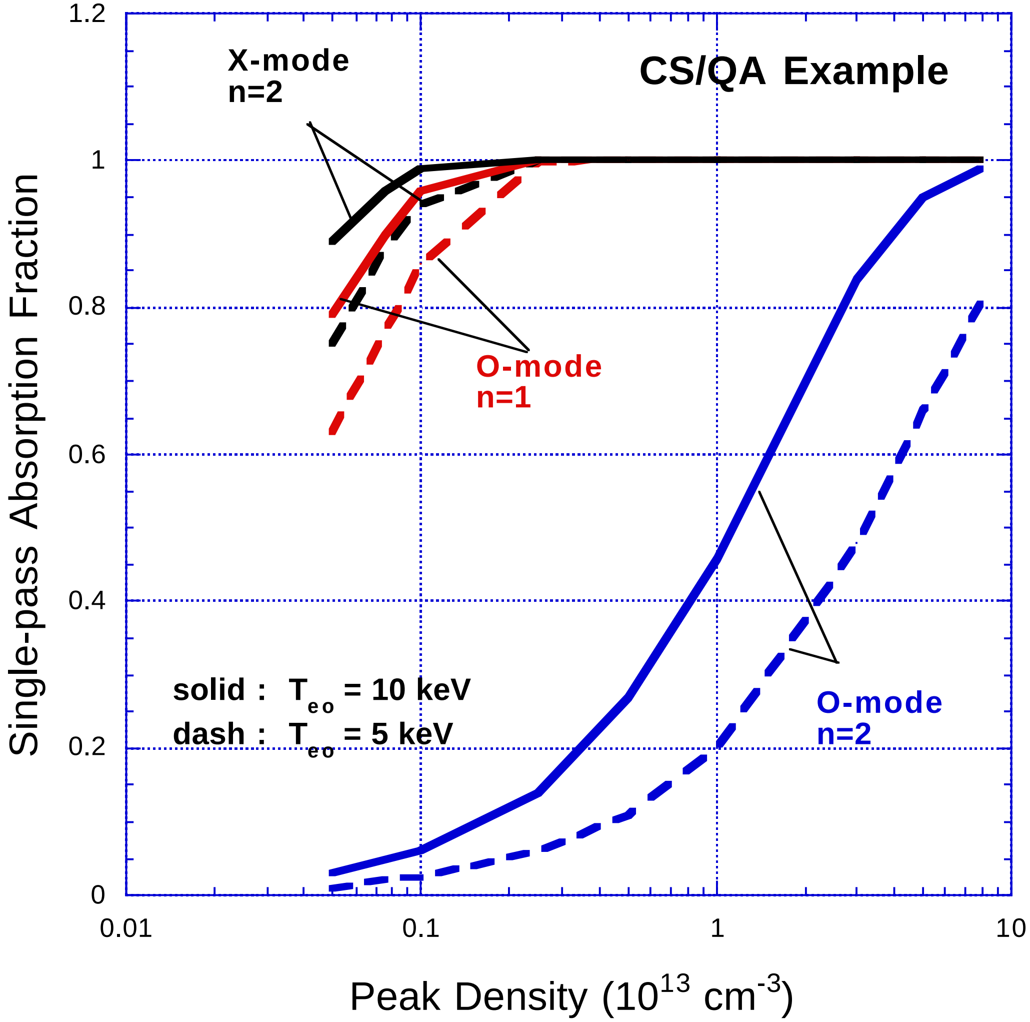
- At the operating point, all wave power is damped in one pass.
- The absorption profiles are very similar to those at the saddle point.





X-mode (n=2) and O-mode (n=1) are Attractive

- X-2 and O-1 modes are attractive for heating purposes as they provide strong single-pass damping over the start-up range of plasma parameters.
- X-2 mode @280 GHz may require gyrotron development effort.
  - Use lower B-field
- Note these results are obtained assuming LFS launch along the horizontal midplane.



Conclusions and Discussions

- EC wave is an attractive RF heating scheme for the CS Reactor, because of physics (localized heating and control) and engineering (compact components) advantages.
- For a typical CS/QA reactor, EC wave penetration to the plasma core should not be an issue, provided the B-field is sufficiently high.
- Based on a simple model, strong single-pass absorption can be obtained over a wide range of startup plasma parameters.
- The X-mode (n=2) and O-mode (n=1) appear to be attractive candidates. (May require high-frequency gyrotron development.)

- *The simple model should be extended to include the effect of a finite* $k_{||}$.
- *Need detailed magnetic and flux surface information for a CS reactor to carry out realistic analysis.*
- *However, the ultimate analysis tool will be a 3-D ray tracing code on a non-axisymmetric toroidal magnetic geometry.*
  - *Modify existing axisymmetric ray code ? TORAY? CURRAY?*
  - *Make use of existing numerical tools? W7-X Group? Others?*
- *HFFW and MC/IBW are proposed for heating and control on NCSX. Will examine their applicability on a CS reactor.*