Fast wave heating for innovative concepts

Presented by Dick Majeski

with the assistance (unwitting or otherwise) of

S. Bernabei, J. Hosea, J. Menard, T. Munsat, R. Kaita, C. K. Phillips, J. R. Wilson, M. Ono - PPPL

T. Bigelow, M. Carter, D. Batchelor, F. Jaeger, P. Ryan, D. Swain - ORNL

Innovative Confinement Concepts Workshop

Lawrence Berkeley Laboratory

22-25 January 2000

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Introduction

- Recently, radio-frequency heating for a number of alternates has received new attention.
  - High harmonic fast wave (HHFW) heating on NSTX, Pegasus.
  - Lower hybrid current drive for current profile control on MST.
  - Rotamak drive for the UW FRC program.
  - Fast wave heating for NCSX (although ICRH and ECH has been utilized for years in stellarators),
  - Current and rotation drive in the UCLA ET experiment.
- RF heating of high β alternates is one of the most challenging areas.
  - ST, RFP, and FRC.
- HHFW is one of the first forays into RF heating of a high β alternate.
- Here we look at HHFW heating, and new possibilities for the stellarator and FRC.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

High Harmonic Fast Wave Heating and Current Drive Introduction

- HHFW heating as realized on NSTX utilizes a conventional fast wave rf antenna at a "conventional" frequency - 30 MHz.
- However, low magnetic field, high density (=low Alfven velocity) in an Spherical Torus favor fast wave heating at high *normalized* frequency (Ω_{rf}/Ω_i~10 - 20).
  - Modest v_ϕ/v_{Te} for strong electron Landau damping.
  - Very large $k_\perp$ -- for similar parameters, $k_\perp$ for the fast wave is an *order of magnitude* larger in NSTX than was the case in TFTR.
  - Strong per-pass damping, even if the damping decrement *per radial wavelength* is small. Lots of wavelengths!

⇨ Most of the conclusions on HHFW should carry over to other high-beta alternates, notably the RFP.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

High Harmonic Fast Wave Heating and Current Drive

- Some features of HHFW heating in an ST:
  - Power deposition is *generally* not sensitive to Ω_{rf}/Ω_i.
    - » The H fundamental resonance would enter the high field-side edge in NSTX for $B_{TF}(0) > 0.4$ T.
    - » The $2\Omega_H$ resonance at 1T could play a role at 0.6T.
  - Poor focussing (except at very low β and/or low plasma current). Wave trajectory is strongly affected by poloidal field.
    - » Access to the axis requires very low β; very low plasma current.
  - Electron damping is *always* strong.
  - Ion damping is appreciable for $T_i > 1$ keV.
    - » $k_\perp \rho_i \sim 1$ for $T_i \sim 50$ eV, for typical NSTX densities.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

HHFW electron and ion damping

Electron damping is strong for HHFW in an ST.

- (Conventional) fast wave damping decrement due to electrons:

$$\mathrm{Im}(k_\perp) \cong (\omega / v_A)\frac{\sqrt{\pi}}{4}\beta_e \xi e^{-\xi^2}$$

  where $\xi = (\omega/k_{||}v_{Te})$. For constant ξ,

  » $\mathrm{Im}(k_\perp) \sim \omega n_e^{3/2} T_e B^{-3}$.

  – M. Ono has shown that in the high β regime that $\mathrm{Im}(k_\perp) \propto n_e$.

- The density, and electron temperature in NSTX should eventually be similar to L-mode discharges in DIII-D and TFTR.
- The toroidal magnetic field in NSTX is 5 - 10 x (or more) lower than DIII-D, TFTR.
  – Strong electron damping for the HHFW is a consequence of the low Alfven velocity and high beta in an ST.

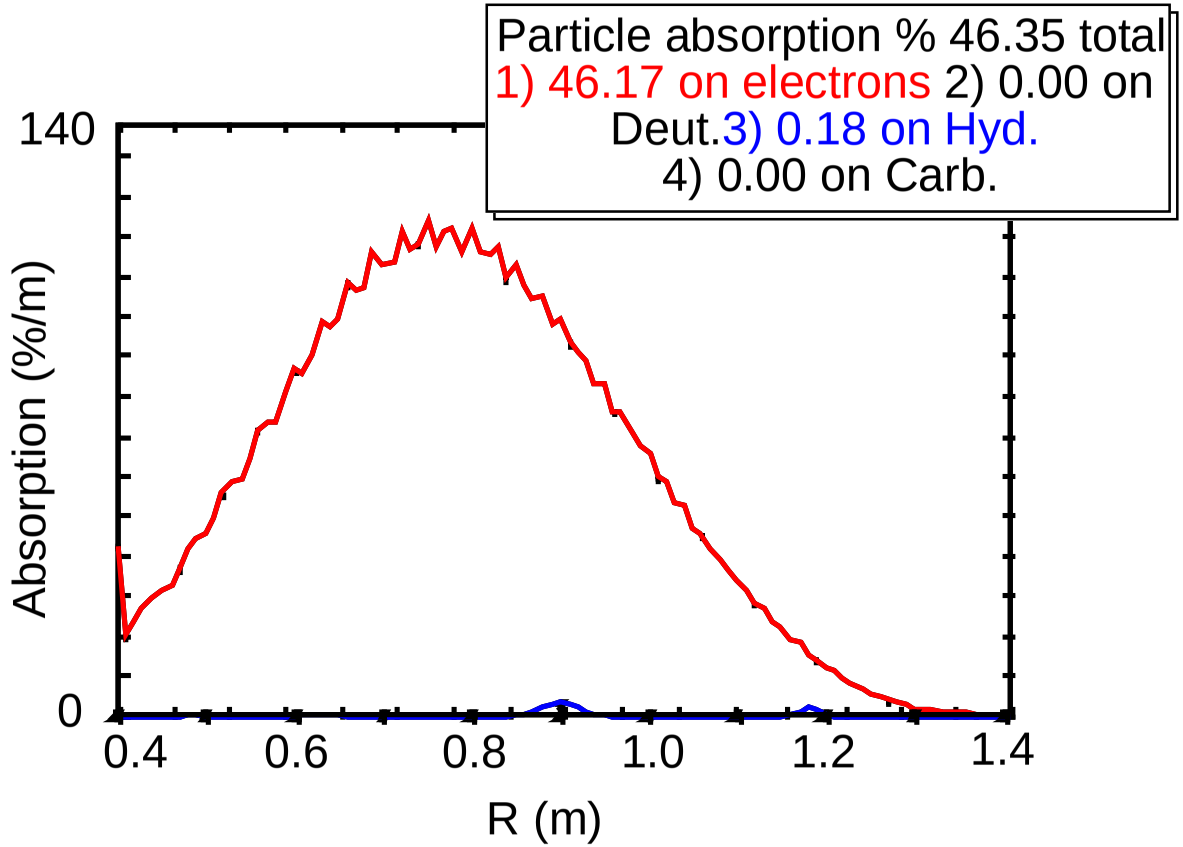
PPPL PRINCETON PLASMA PHYSICS LABORATORY

High per-pass damping in NSTX even for startup plasmas

$T_e(0)$ = 350 eV, $T_i(0)$ = 300 eV, $n_e(0) = 3.0 \times 10^{19}\ m^{-3}$. $\beta \sim 3\%$

92% deuterium, 2% hydrogen, 1% carbon.

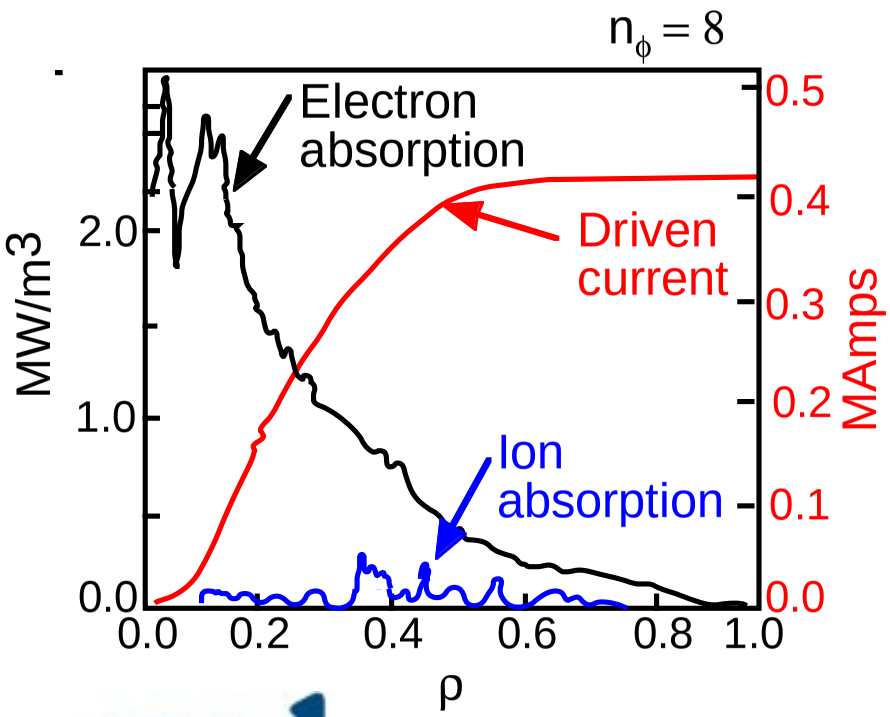
Launched $k_{||} = 8\ m^{-1}$ at 30 MHz ($N_{||} = 12.5$).



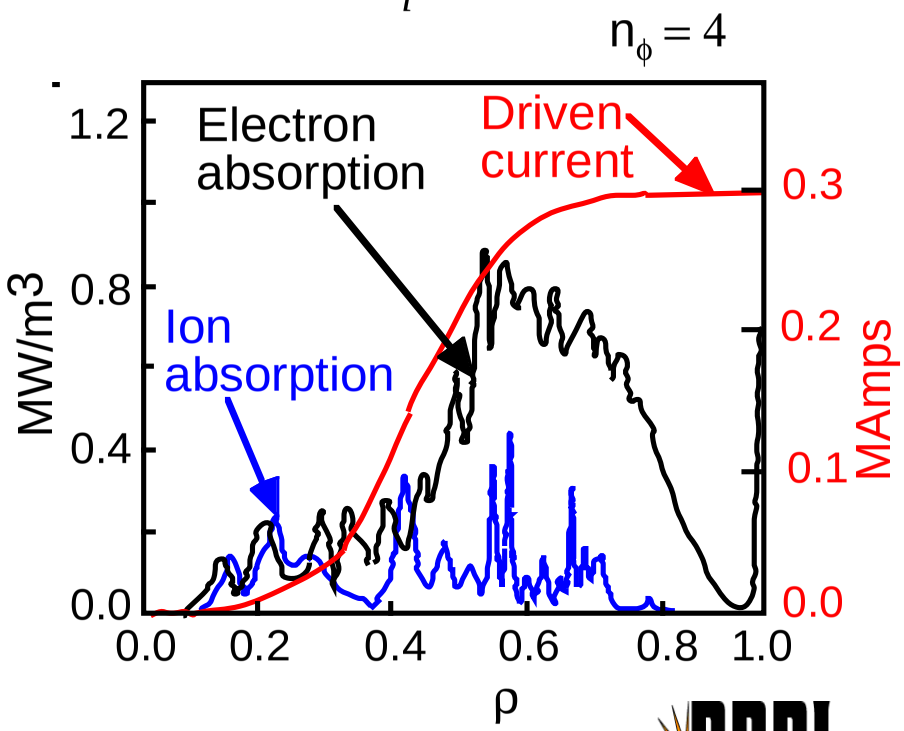
For higher β plasmas stronger electron absorption is expected to result in off axis power deposition and current drive

Predictions from PICES

- At 5% plasma β the waves penetrate into the plasma core.
- Driven current will be peaked on-axis.

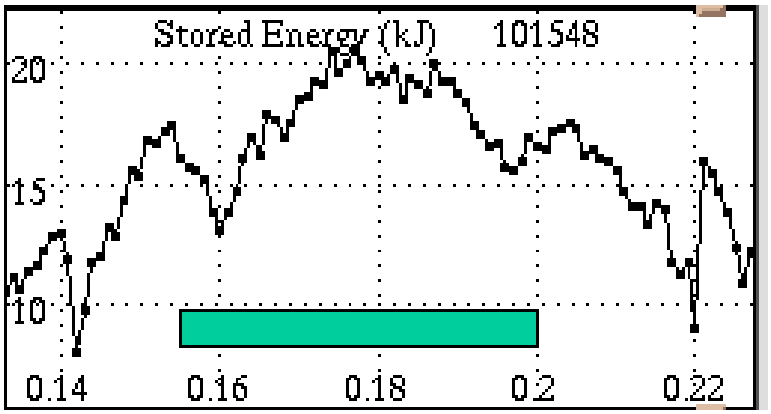


- At 25% plasma β the waves are absorbed at r/a > 0.5.
- Driven current profile will be hollow - low ℓ_i

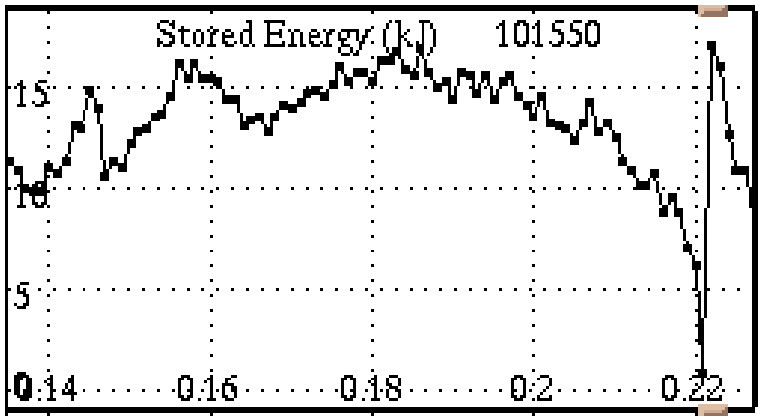


Evidence of HHFW heating in NSTX has now been observed

900 kW rf



No rf

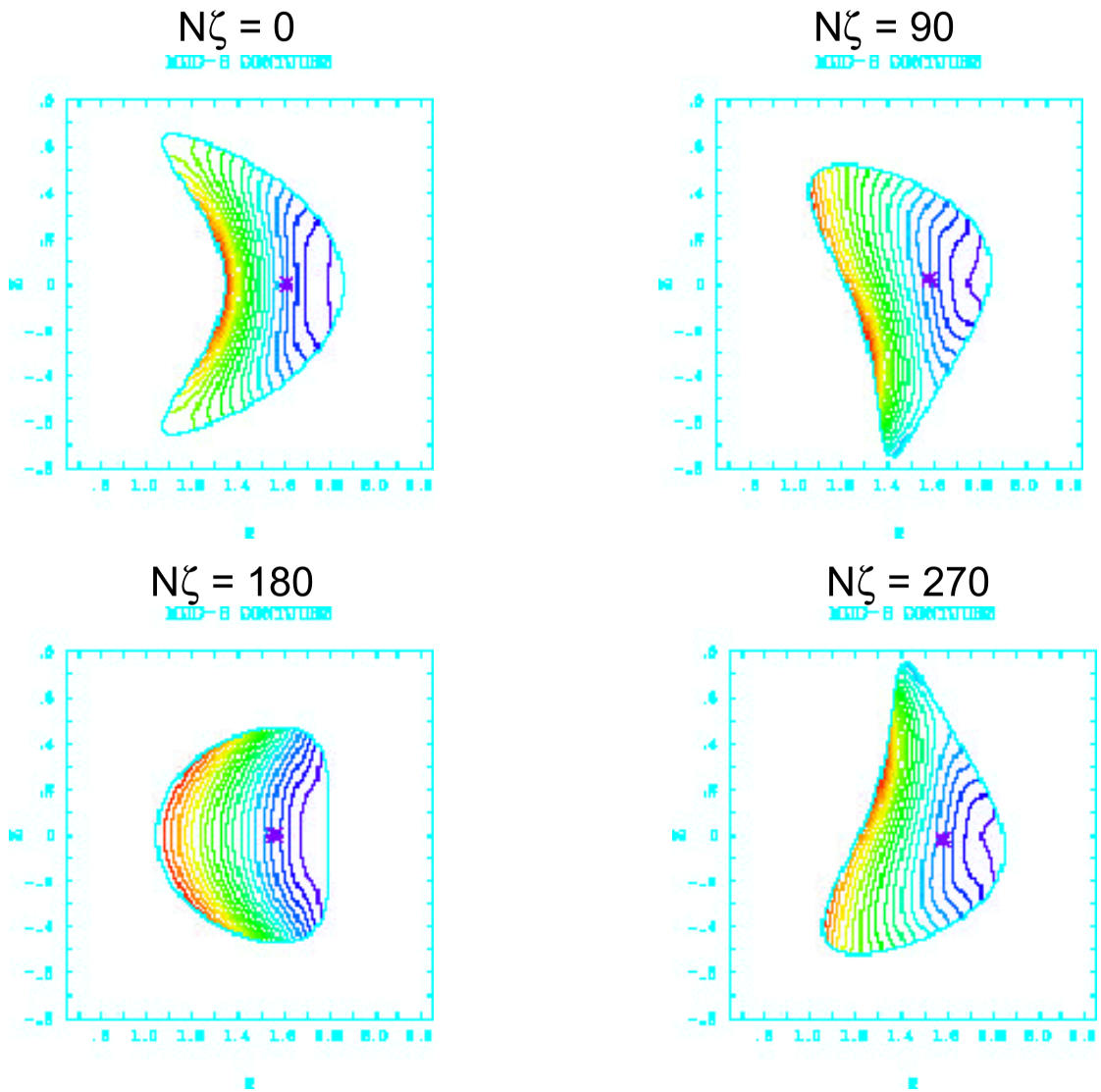


High *frequency* fast wave heating for NCSX

- Long history of RF heating in stellarators.
- But - heating requirements for NCSX are somewhat different than for conventional stellarators
  - Startup not an issue: ohmic system will be available
  - Modest current drive capability is a plus
- QAS design provides for a more tokamak-like geometry
- Field coil design favors rf launchers on the outboard equatorial plane
  - Net result: rf heating scenarios are similar to low-field side launch tokamak scenarios
- Toroidal field range: 1 - 2 T
- Hydrogen majority plasmas
- Hydrogen NBI
  - Deposition on beam ions would enhance losses
- Direct electron heating desirable

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Outboard equatorial plane wave launch in NCSX resembles a low field side launch in a tokamak



Illustrative mod-B surfaces

C10 configuration

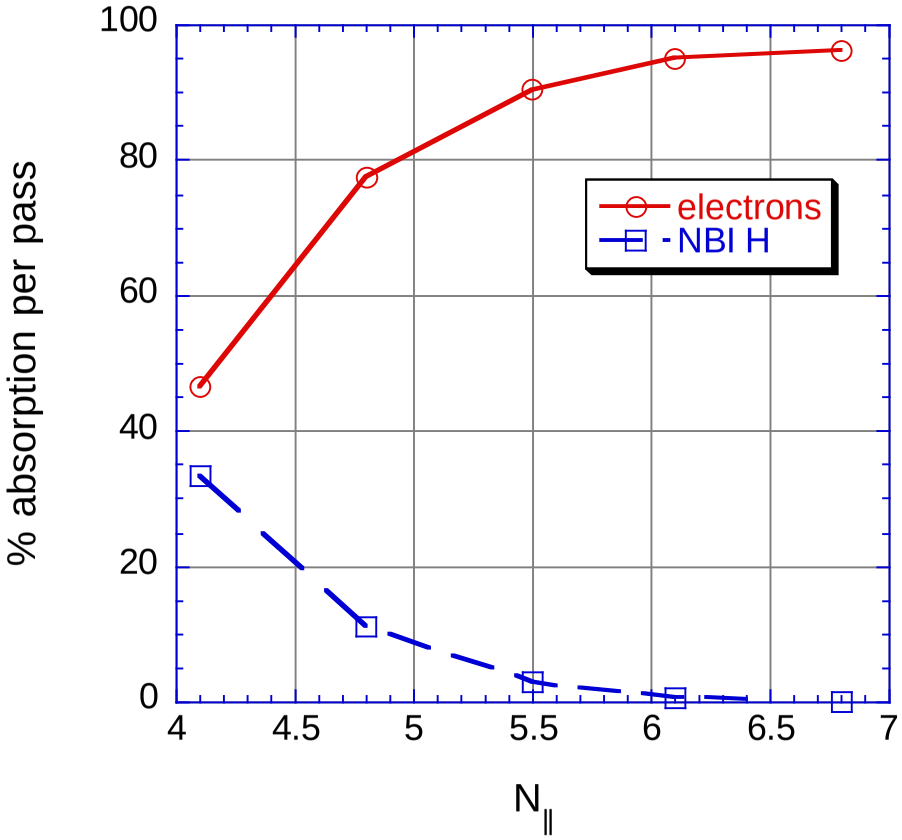
High frequency fast wave (HFFW) heating for NCSX

- An attractive, flexible heating scenario for NCSX is a close cousin of HHFW heating.
- NCSX will typically operate at moderately susceptibility ($\omega_{pe}^2/\Omega_{ce}^2 \sim 5$)
- Very high frequency fast waves can be strongly damped
- High power, reliable, CW sources are available for frequencies > 300 MHz
- Here we look at 350 MHz HHFW heating for NCSX
  - Compact launchers, probably folded waveguide
  - Isolators can be implemented at this frequency
    - » Reduces sensitivity of the system to changes in the plasma edge
  - Current drive capability is significant
  - Sources are typically CW, > 1 MW per tube

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

350 MHz HHFW strongly absorbed in NCSX

350 MHz, $n_e(0) = 6 \times 10^{19}\ m^{-3}$ (parabolic$^{0.5}$), $T_e(0) = T_i(0) = 2$ keV, $B_0 = 1.2T$, 2%NBI H

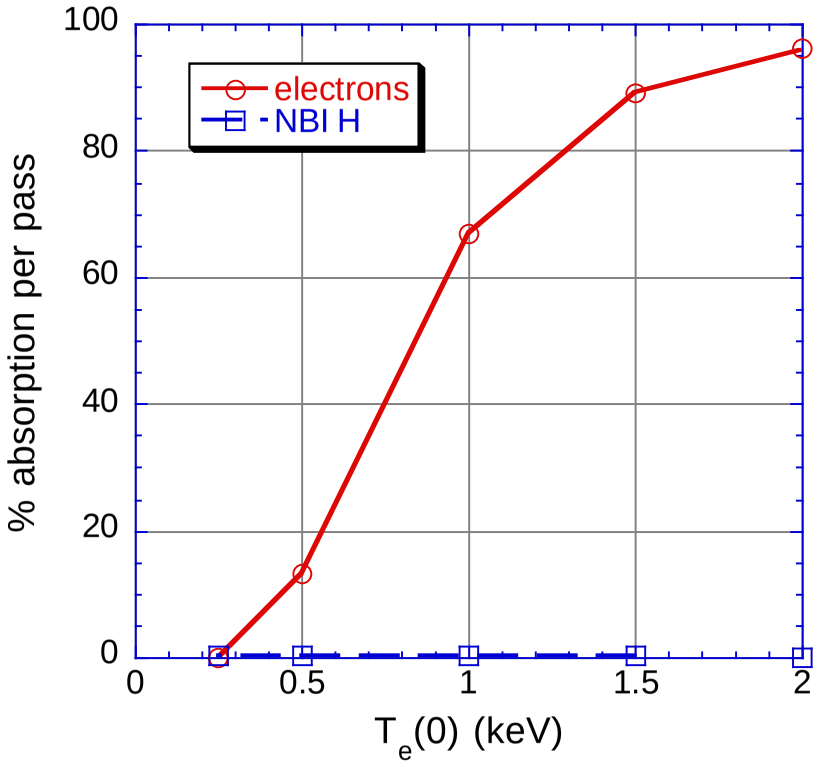


- High $N_{||}$ <u>not</u> required for strong absorption
- Significant noninductive current drive capability
  - ~0.03 - 0.05 A/W (TORIC)
  - Accurate estimate requires detailed geometry

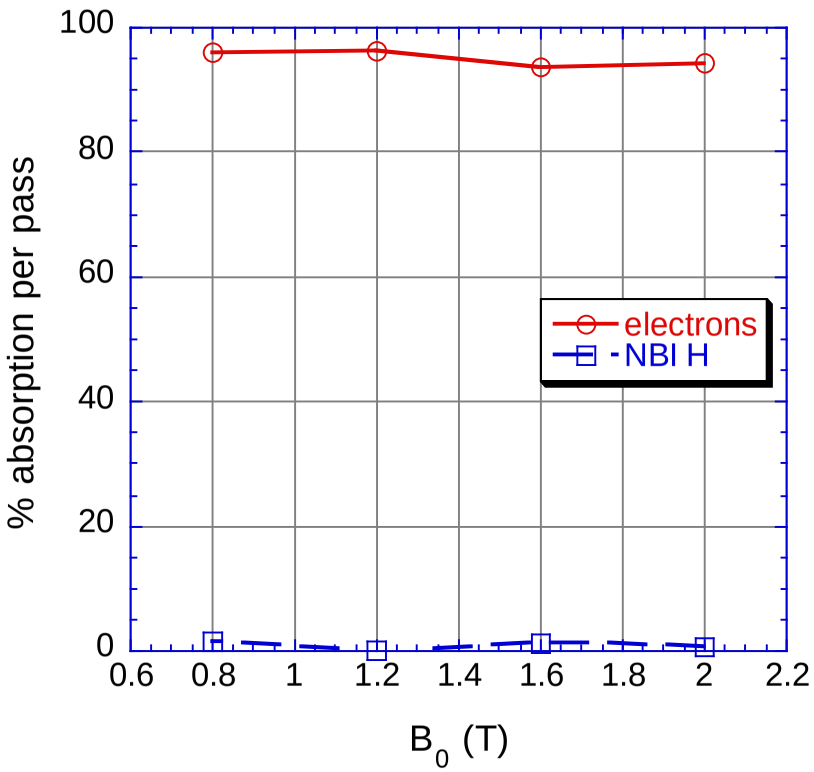
1-D results from METS

HHFW absorption is strong over a wide range in T_e, B_0

350 MHz, $n_e(0) = 6 \times 10^{19}\ m^{-3}$ (parabolic$^{0.5}$), $T_e(0) = T_i(0)$, $N_{||} = 6.8$, $B_0 = 1.2T$, 2%NBI H



350 MHz, constant β, $N_{||} = 6.8$, 2%NBI H

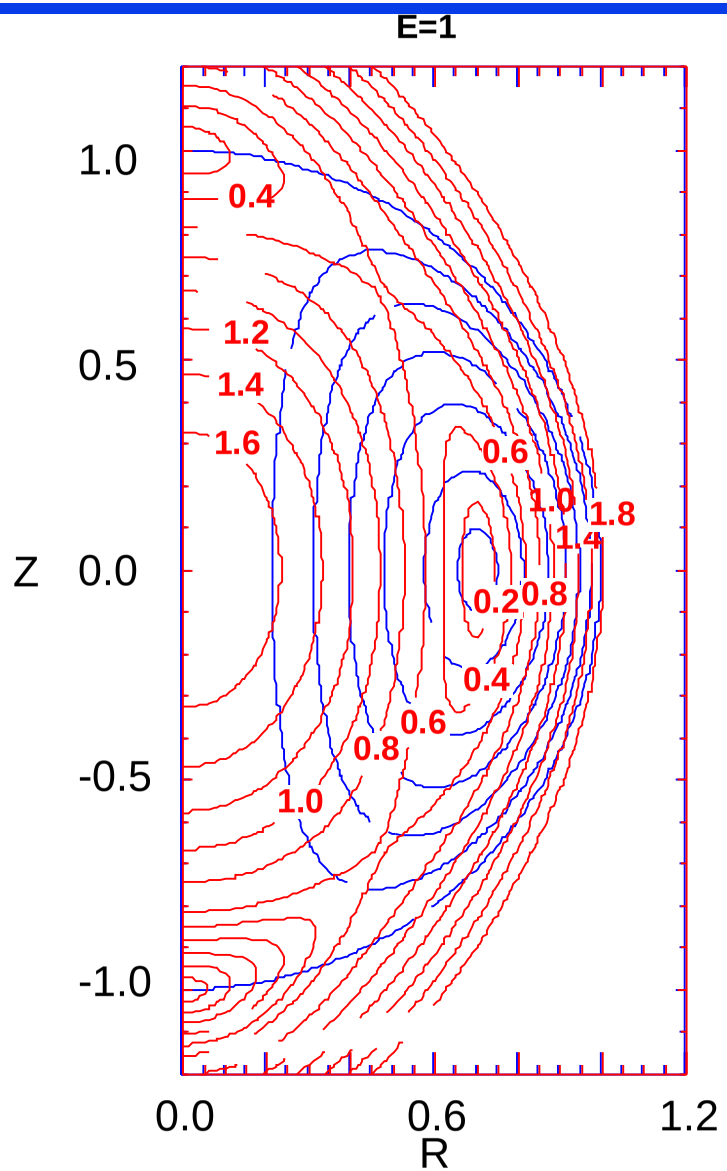


RF heating for the FRC

- There has long been “RF” research into the FRC - the rotamak!
- Extension of rotamak current drive to a large FRC introduces new physics:
  - Cyclotron resonance. For a rotamak driven at $\omega_{rotating} < \Omega_{ci(equilibrium)}$, there will be a cyclotron resonance for the rotating field between the separatrix and the field null.
    - » For a small rotamak driven at $\omega_{rotating} > \Omega_{ci(equilibrium)}$, harmonics of the ion cyclotron frequency may produce ion heating at high β.
- Ion heating is desirable for an FRC.
  - Axis encircling ion orbits may have a stabilizing effect on the tilt mode.
  - Fast ions on loss orbits would produce a radial electric field.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

FRC heating scenarios with fast and slow waves are possible



- Fast waves would propagate cross-field, into the core plasma.
  - Encounter multiple harmonics of the bulk ion cyclotron resonance.
  - Strong damping at high ion beta.
  - Ion Bernstein wave generation.
  - *Minority* ion heating is also feasible.
- Slow waves would propagate along the magnetic field, into a low field region.
  - Magnetic beach.
- Either wave could be used to effectively heat ions.

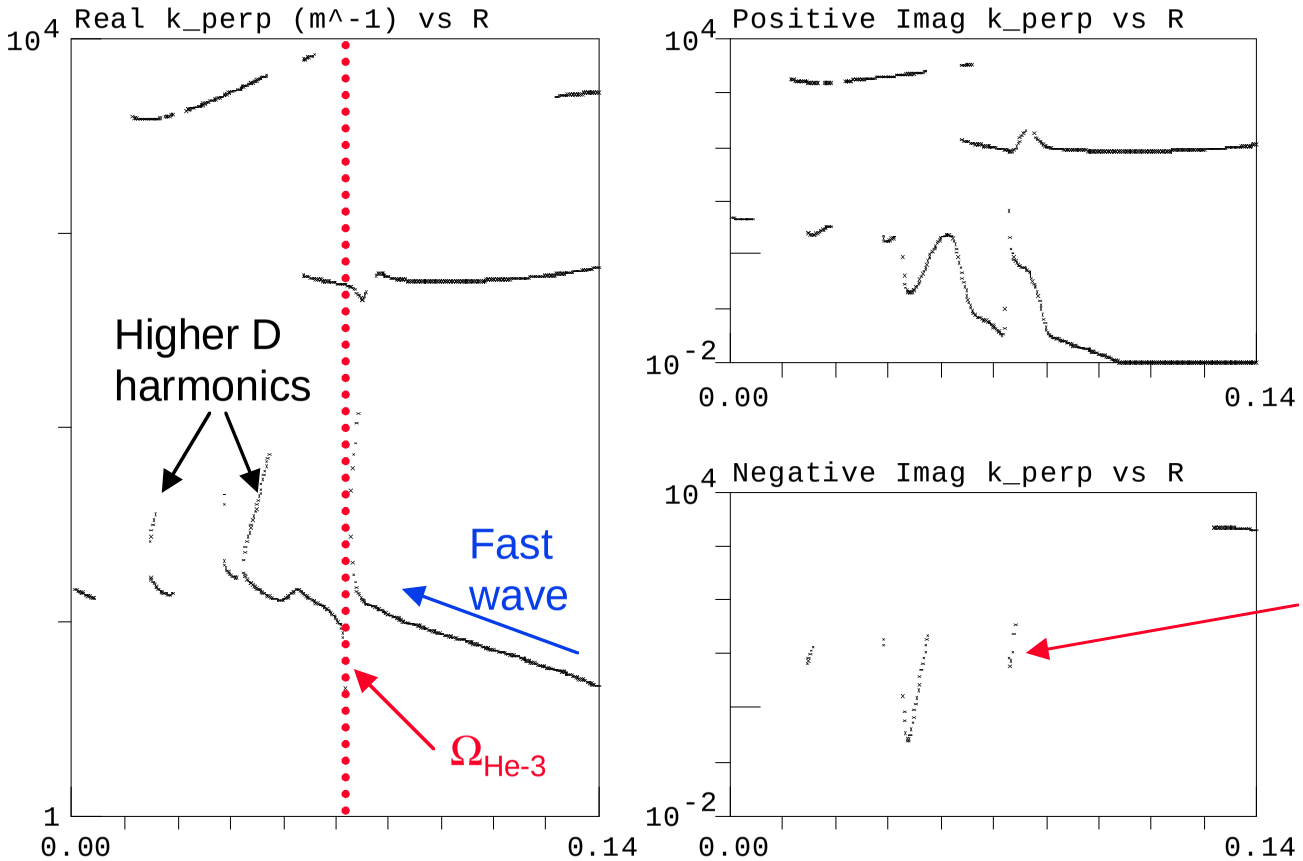
Minority ion heating

- Minority ion heating has long been used in tokamaks to create fast ion populations.
- Fast wave heating of a minority ion is a promising scenario for an FRC.
- FRC magnetic geometry $\Rightarrow$ high field side launch in a tokamak.
  - Fast wave will mode convert to a slow wave.
  - Strong heating of the minority ions, for a wide concentration range.
  - Minority concentration controls fast ion temperature, density.
- Intent is to form a hot, possibly axis encircling ion population.
  - Target plasma requirements are modest compared to NBI.
- A promising heating scenario is a heavy ion minority (^{3}He) in a light ion (H) majority plasma.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Hot plasma dispersion relation for 10% ^{3}He in H

Fast wave is strongly absorbed on the He-3 minority



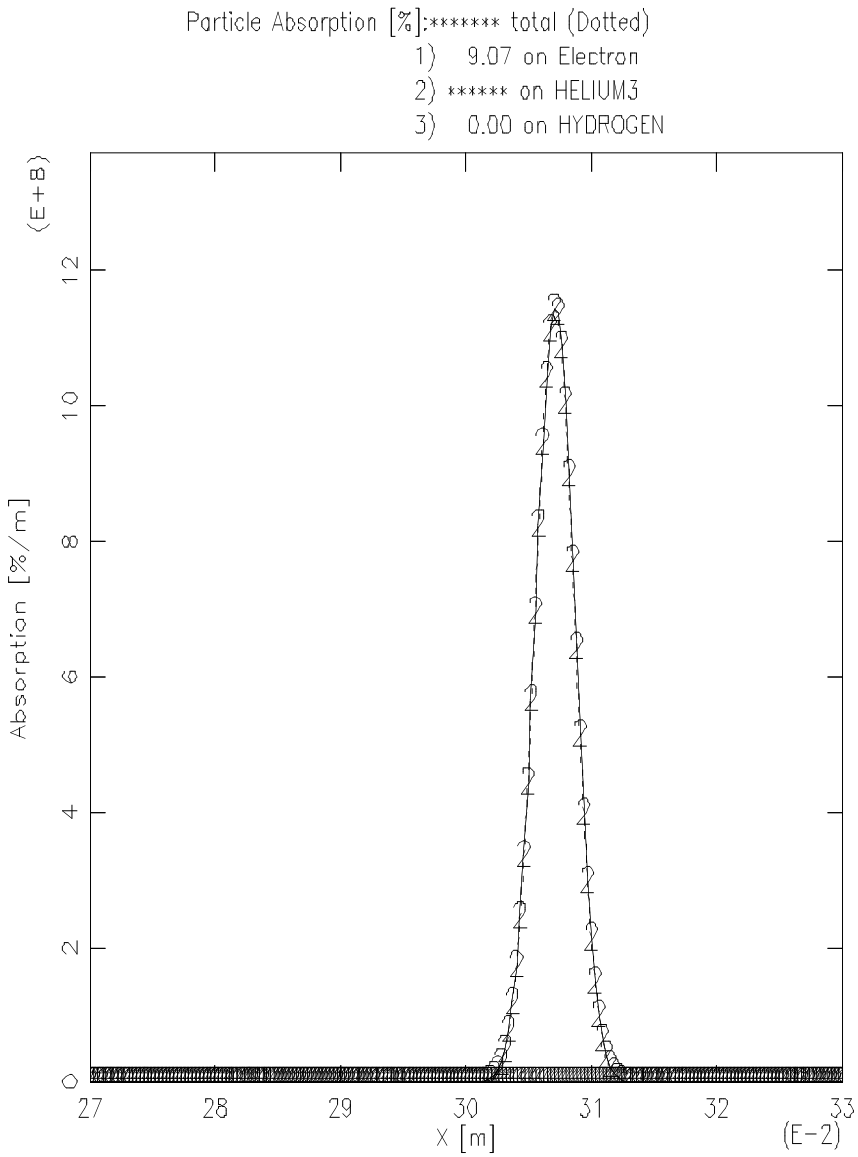
100 eV ions
cold electrons
2 x 10^{19} m^{-3}
800G external field
400 kHz

Mode converts to ion Bernstein wave

Field "null"

Wave is incident from the right (separatrix region)

RF modeling of an FRC will benefit from the ST effort



- But it still ain't easy.
- Shown is an incompletely converged result from METS.
  - 1-D integral code (D. Smithe, MRC).
- H(He3) case for an FRC
- Power deposition is >90% on the He3, with a FWHM of *<1 cm.*
  - Calculation performed for an FRC with r_s=22 cm

Induced plasma rotation

- Hot, nonthermal ^{3}He ion population would probably be subject to significant losses.
  - Fast ion orbits large even in comparison to the ST.
- Fast ions on orbits which intersect walls, flux conservers, or are otherwise unconfined will produce a loss current.
  - Would result in generation of a radial electric field.
  - For $\phi \sim kT_{i(thermal)}$ the electric field would produce plasma rotation in the FRC at $M \sim 1$.
- Induced rotation via this mechanism observed in tokamaks.
  - Proposed as rotation drive for the UCLA ET experiment.
- ICRH could therefore result in *combined* hot ion + rotational stabilization.
  - Ponderomotive stabilization may also be effective in an FRC.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Summary

- New techniques for RF heating of alternates are now under investigation or implementation.
  - Physics is often distinct from tokamak rf heating.
- One of these techniques (HFFW), although it may be tested first in an alternate (NCSX), could be attractive for large tokamaks.
  - Under consideration for Ignitor.
- Other techniques (slow wave heating, ponderomotive stabilization) which have not been experimentally investigated since the mirror program may find application in the FRC.

➨Innovation in confinement concepts has led to innovation in RF heating techniques

PPPL
PRINCETON PLASMA PHYSICS LABORATORY