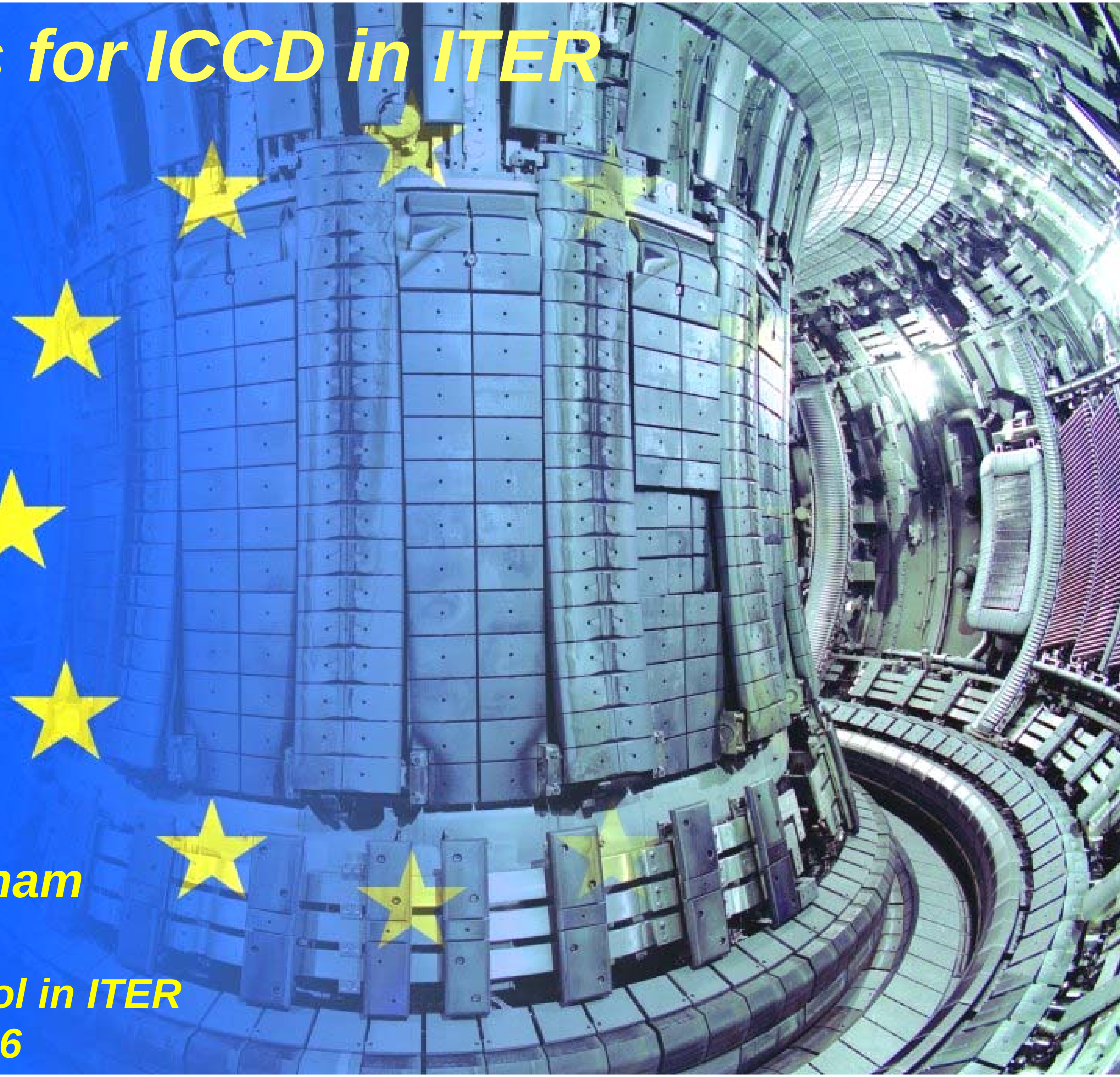
RF Issues for ICCD in ITER



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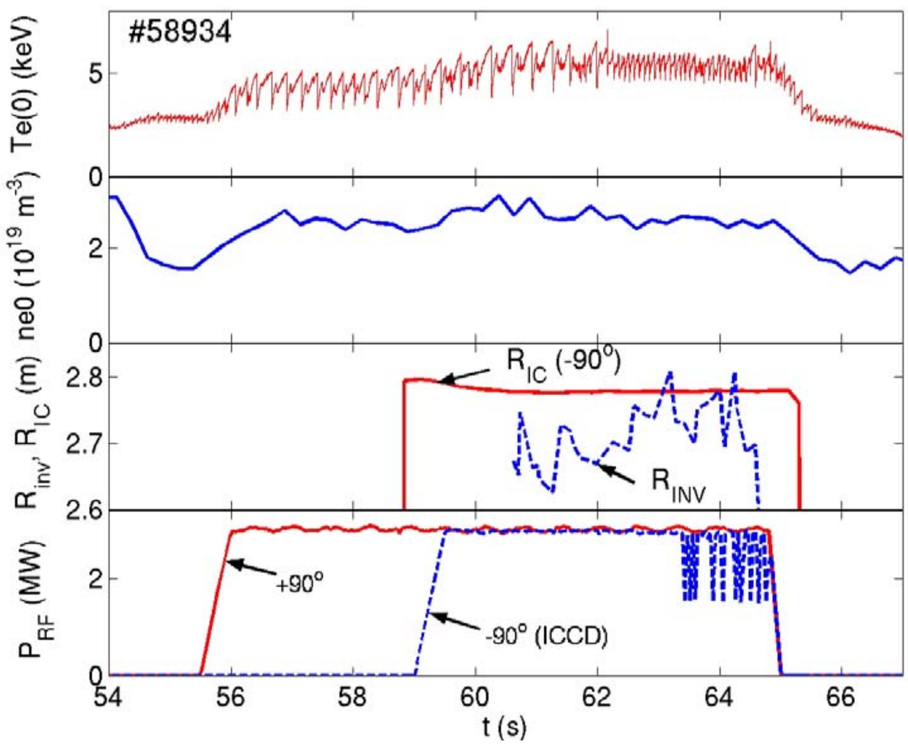
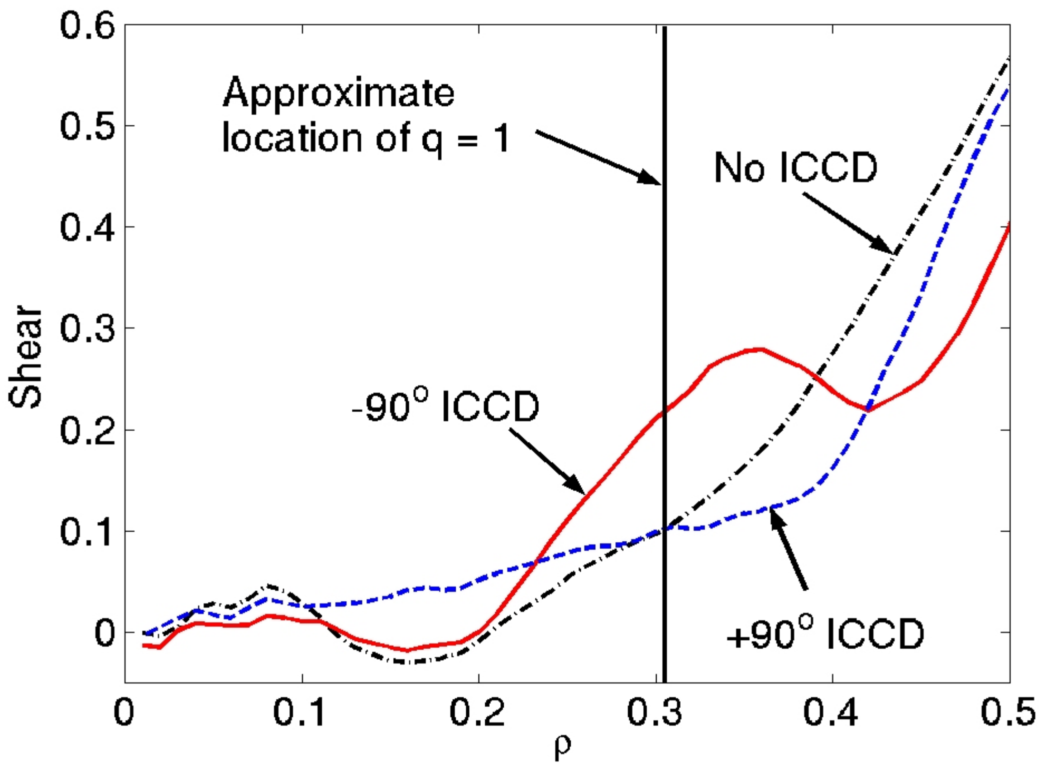
EFDA-CSU Culham

Active MHD Control in ITER
PPPL, 6-8 Nov 2006

ICCD for MHD Control

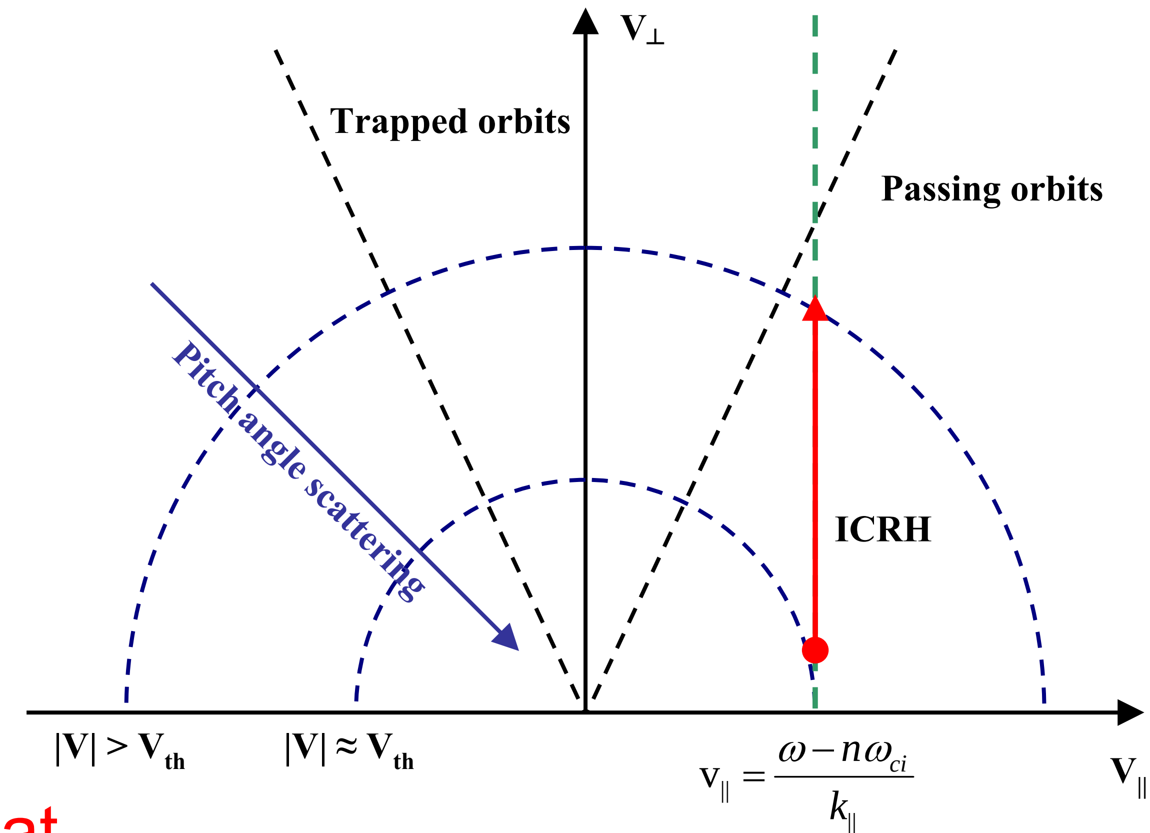
- NTM avoidance by sawtooth destabilisation
  - Important in high-β plasmas with large α-populations
  - Increase magnetic shear at q = 1
  - Successfully tested at JET, e.g. Eriksson, NF 2006





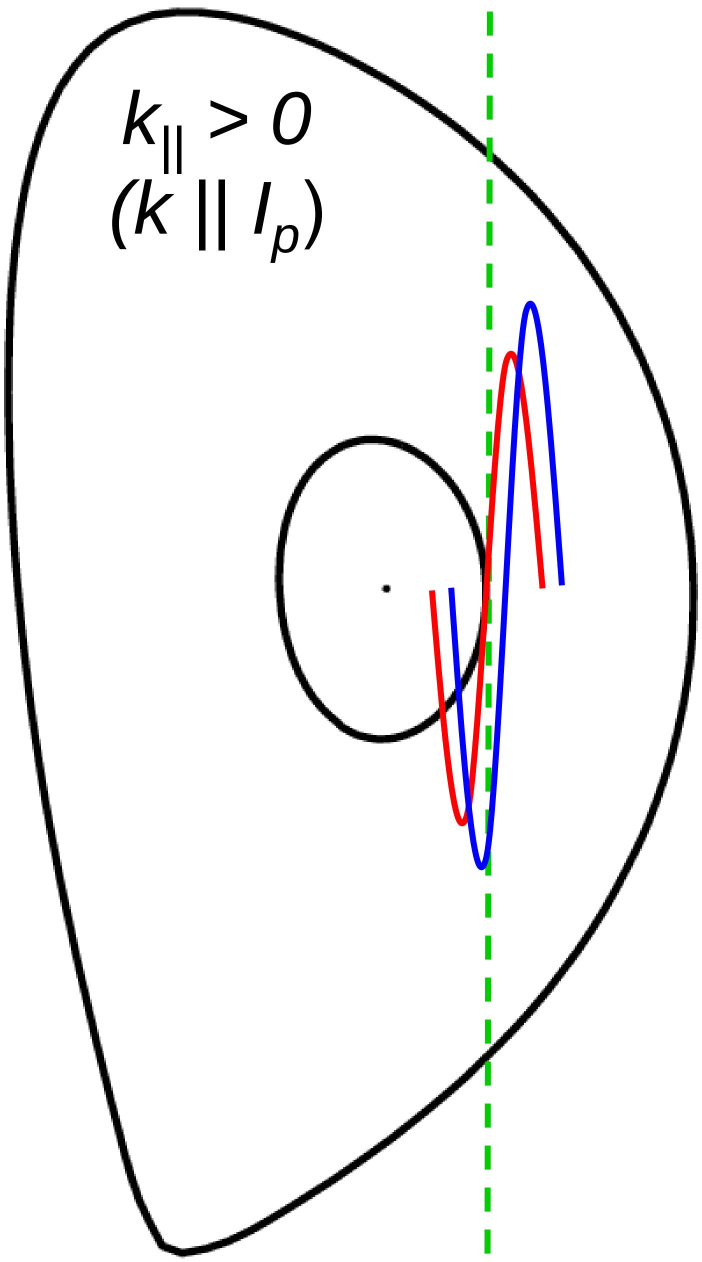
Physics of ICCD

- Fisch, NF 1981
  - Current driven by Doppler-resonant passing ions
- Hellsten, PRL 1995
  Carlsson, PoP 1998
  - Orbit effects important at modest power densities
    - Orbit trapping
    - Broad orbit current drive



Detailed modelling required!

Illustration, ICCD on LFS

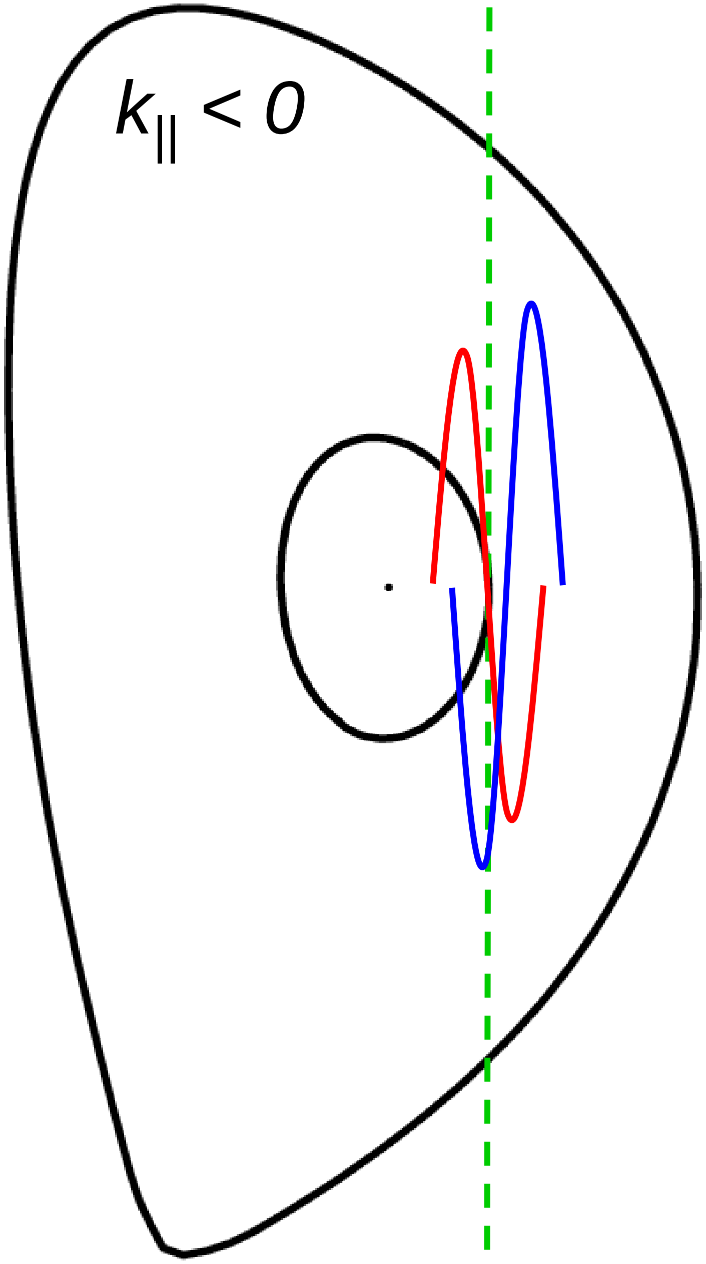


$$v_{||} = \frac{\omega - n\omega_{ci}}{k_{||}}$$

$$\omega_{ci} \sim B \sim 1/R$$

Passing current

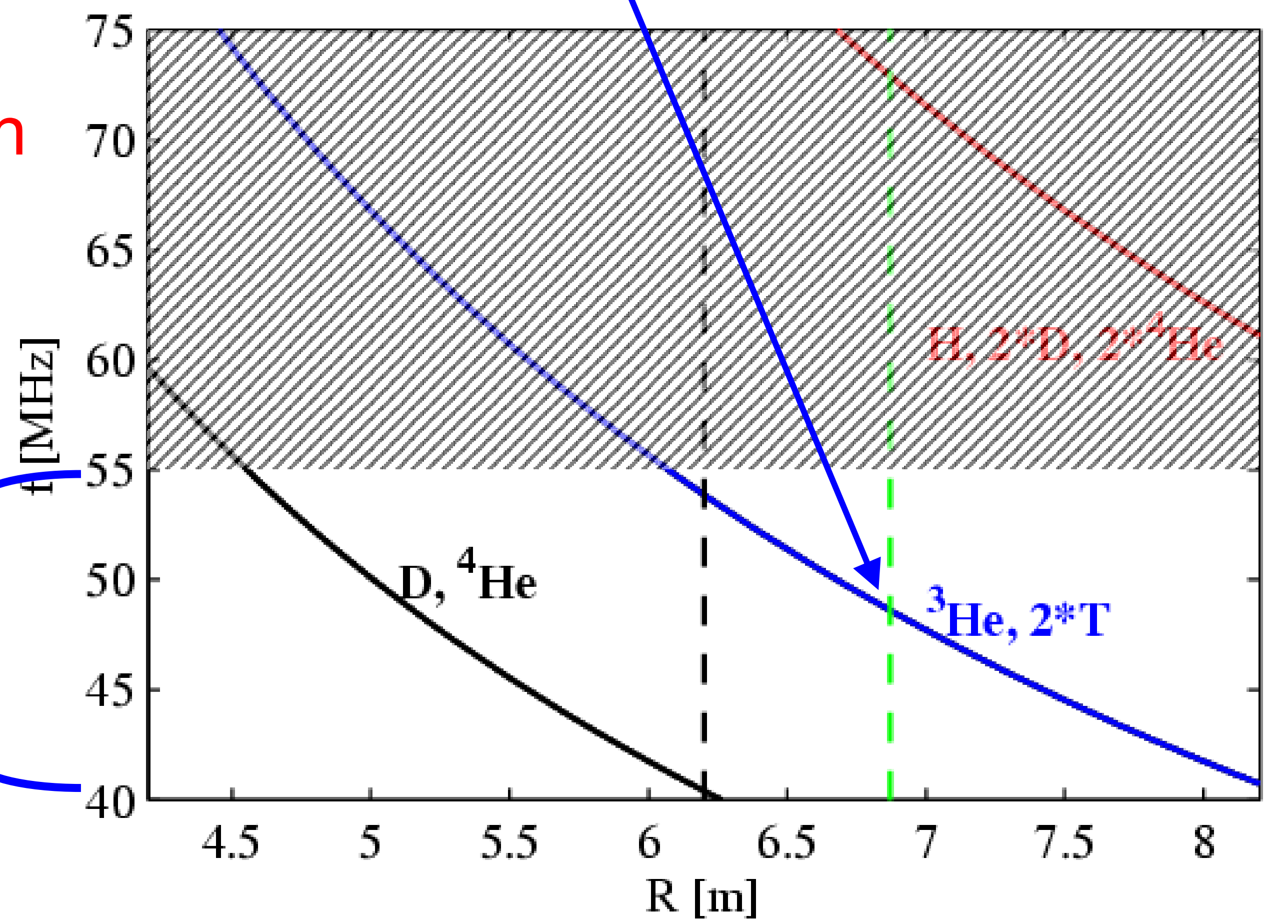
Trapped current



ITER H&CD Systems

- NBI:
  - 33 MW
  - 1 MeV
  - Co-current injection
- ECRH / ECCD
  - 20 MW
  - 170 GHz
- ICRH / ICCD
  - 20 MW
  - 40 - 55 MHz

^{3}He the only resonant minority!

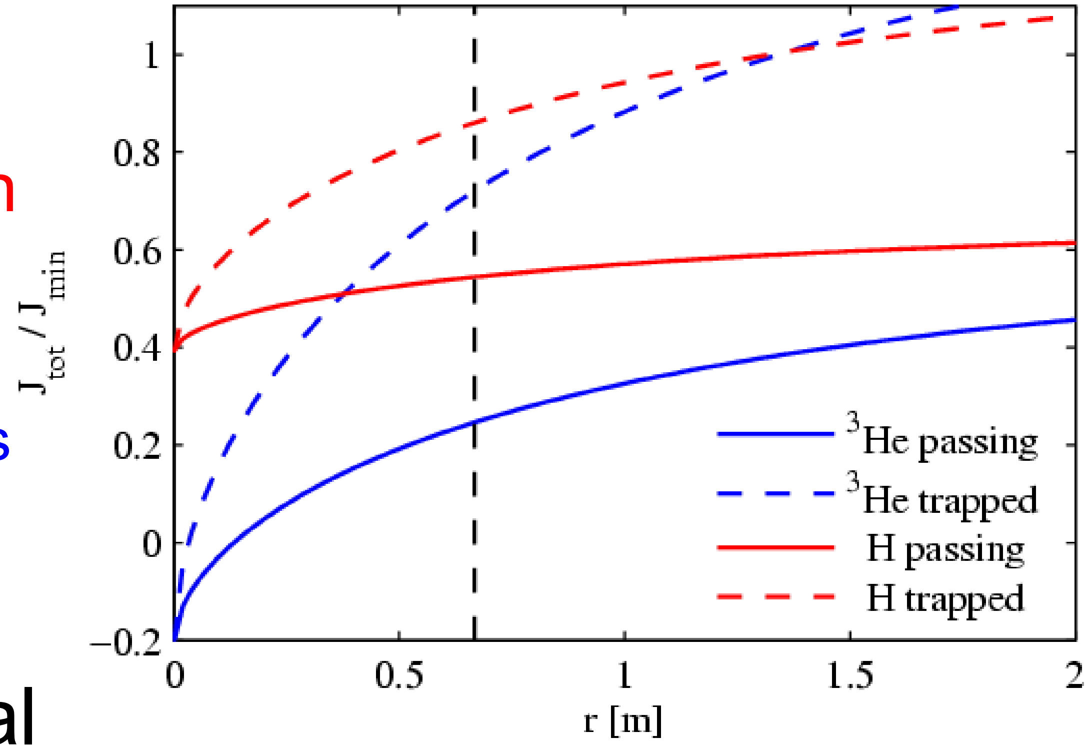


ICCD Back Current

- Back current from
  - Momentum conservation
    - Passing ions (Fisch CD)
  - Dragged electrons
    - Passing and trapped ions

  [Bhatnagar, NF 1994]

- High-Z ICCD not optimal



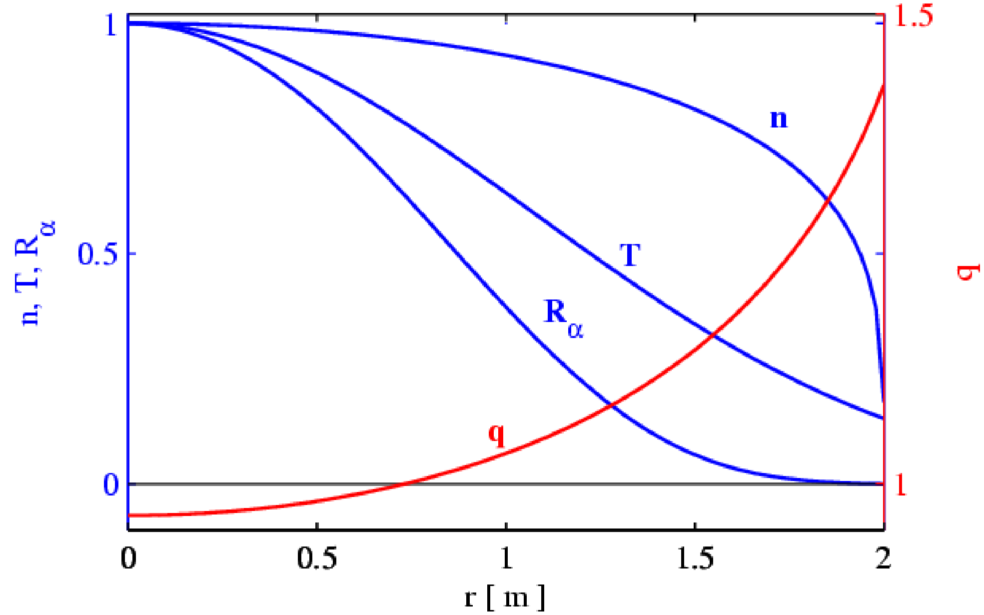
$$J_{tot} = J_{min}\left(\left(1-\frac{Z_{min}}{Z_{eff}}\right) - \frac{\lambda m_{min}\sum_i Z_i n_i\left(1-\frac{Z_i}{Z_{eff}}\right)}{Z_{min}\sum_i n_i m_i} + f_t A(Z_{eff})\left(\frac{Z_{min}}{Z_{eff}} - \frac{\lambda m_{min}\sum_i n_i Z_i^2}{Z_{min} Z_{eff}\sum_i n_i m_i}\right)\right)$$

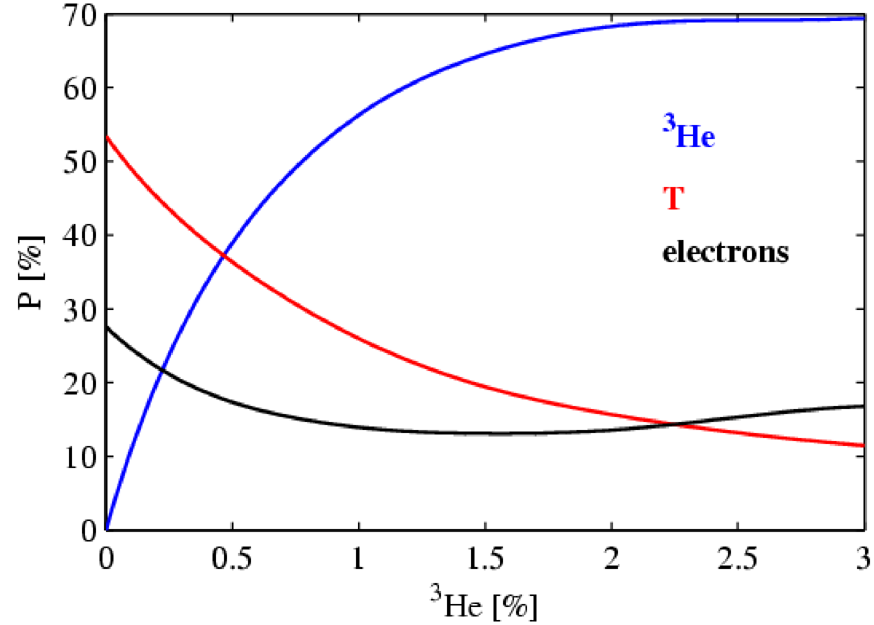
< 0 $\quad$ < 0 $\quad$ $\sim\varepsilon^{1/2}$ $\quad$ > 0

Evaluated ITER Scenario

- Inductive H-mode
  - 5.3 T / 15 MA
  - $T_i = T_e = 20$ keV
  - $n_e = 1.25E20\ m^{-3}$
  - $Z_{eff} = 1.66$
  - $P_{fus} = 400$ MW
  - $P_{\alpha} = 80$ MW
  - $P_{NBI} = 33$ MW

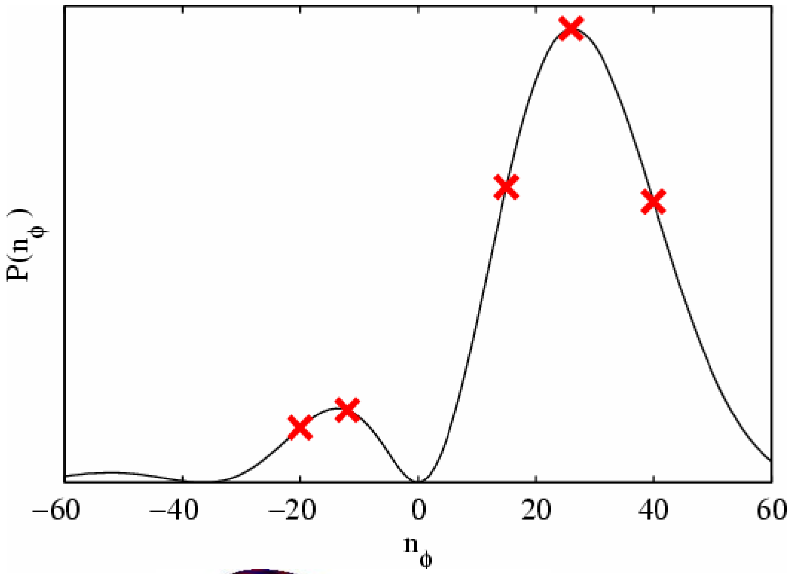
  - $P_{ICCD} = 20$ MW (Full power)
  - R_{res} tangential to LFS q = 1
  - 2% ^{3}He

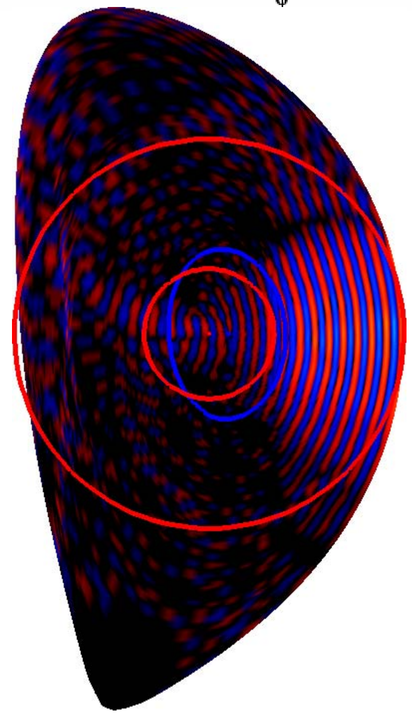




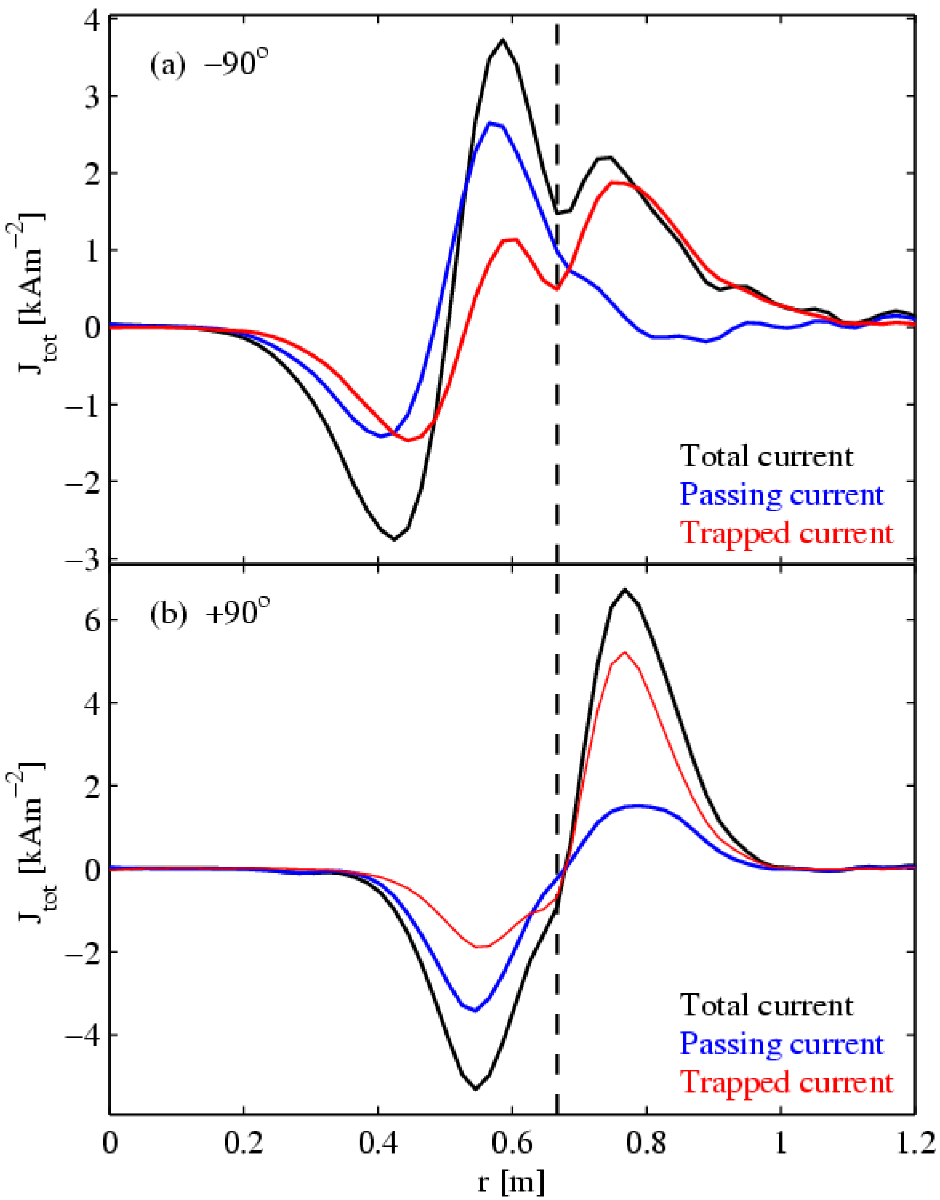
The SELFO Code

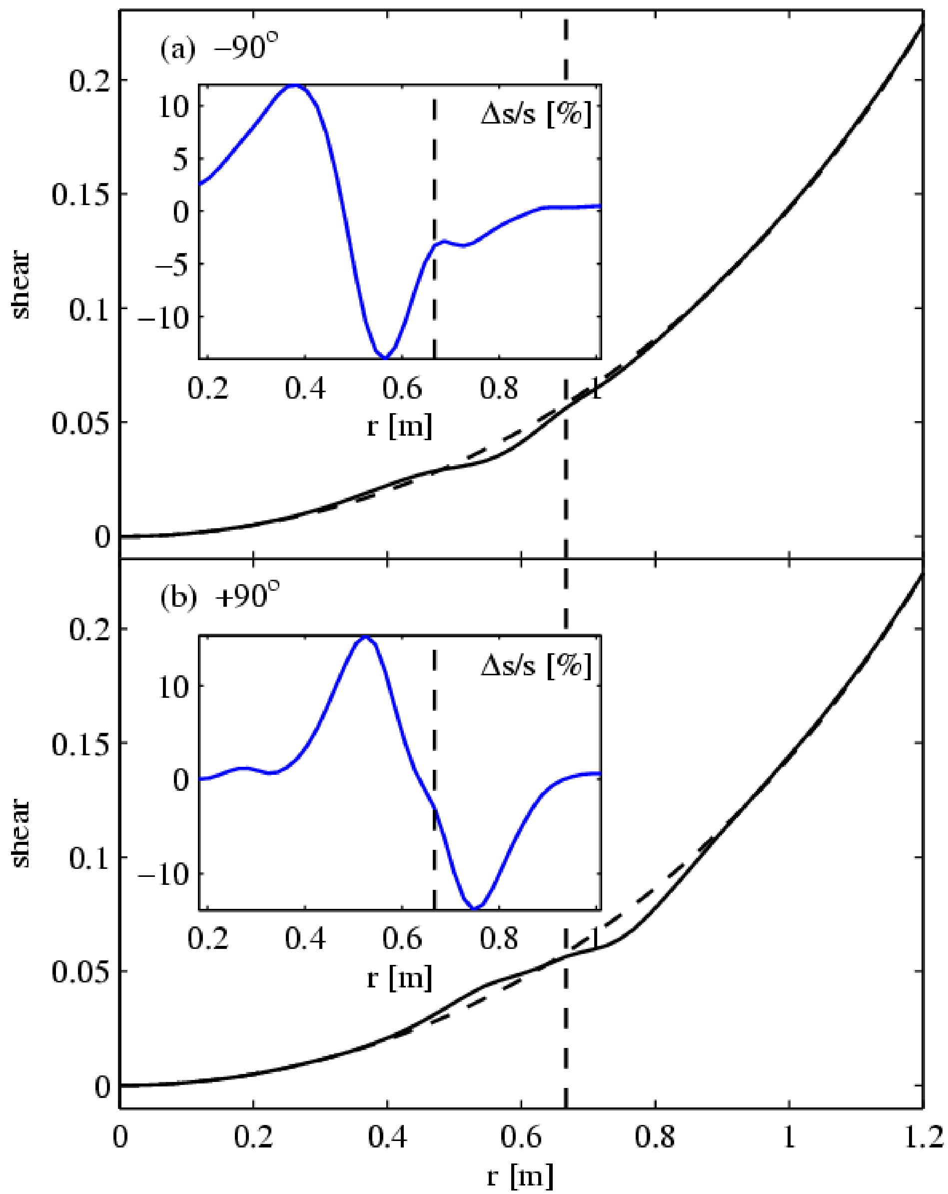
- Self-consistent ICRH simulations
  - FIDO: MC Fokker-Planck solver
    - Complete drift orbit topology
    - NBI and α-particle sources
    - Dielectric susceptibility calculations
  - LION: 2D Full wave solver
    - E-fields and $k_{\perp}$ from calculated hot susceptibilities
  - Arbitrary # resonant species and fields
  - Full Bessel functions in dielectric tensor
- Circular equilibrium
  - Power and current reduced by 20% to match ITER power and current densities



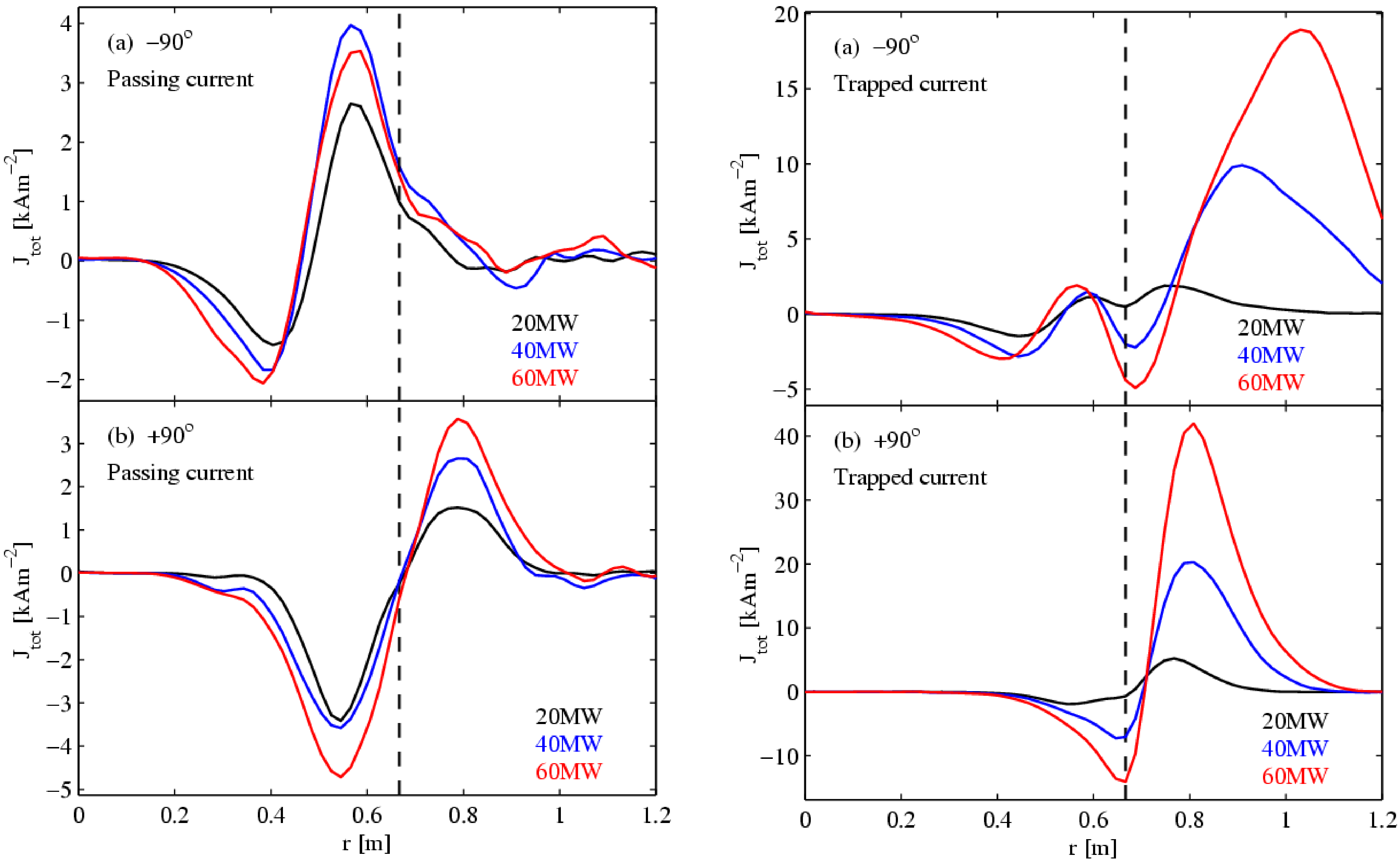


^{3}He ICCD at Full Power

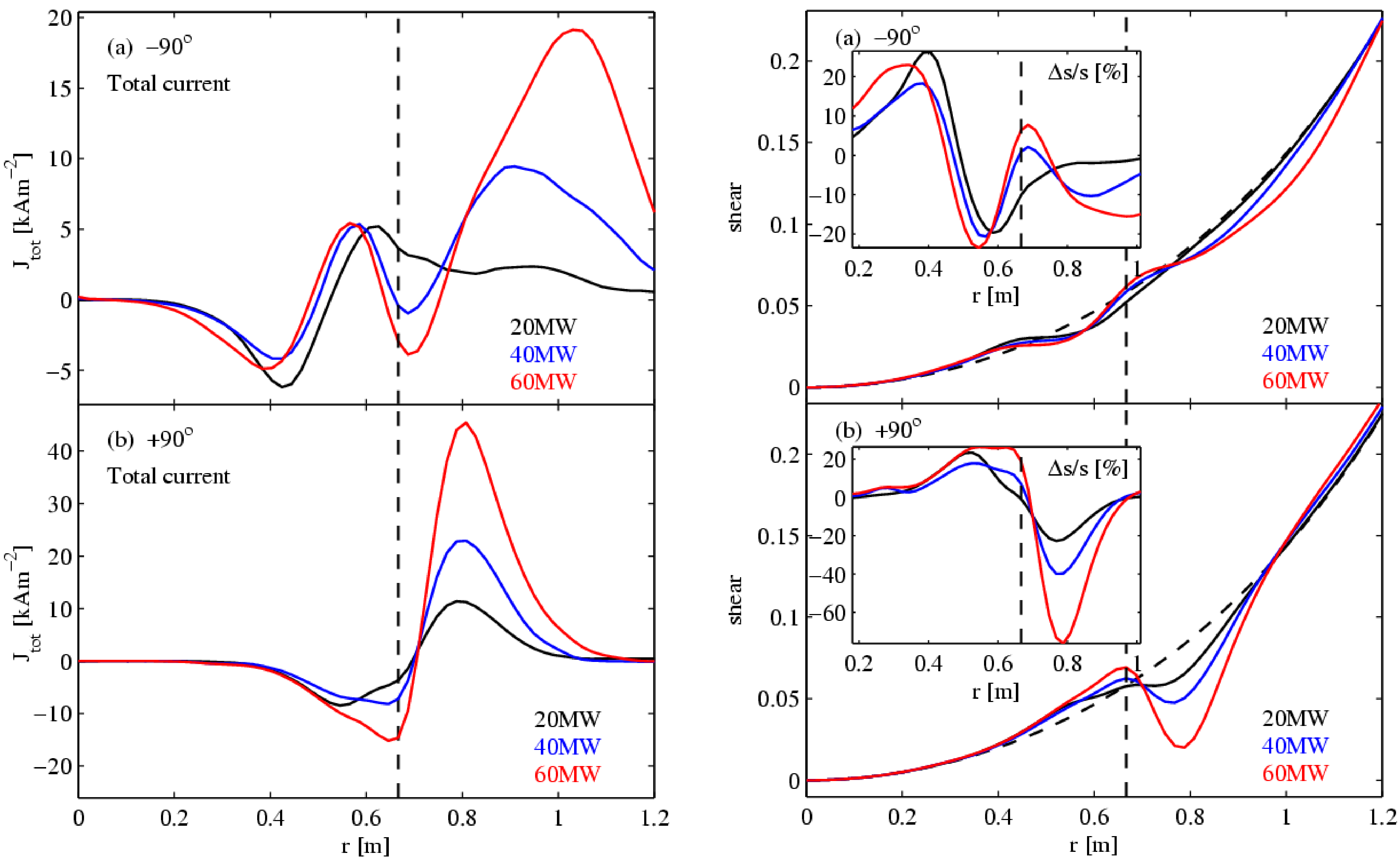




Brute Force – More Power! (1)



Brute Force – More Power! (2)

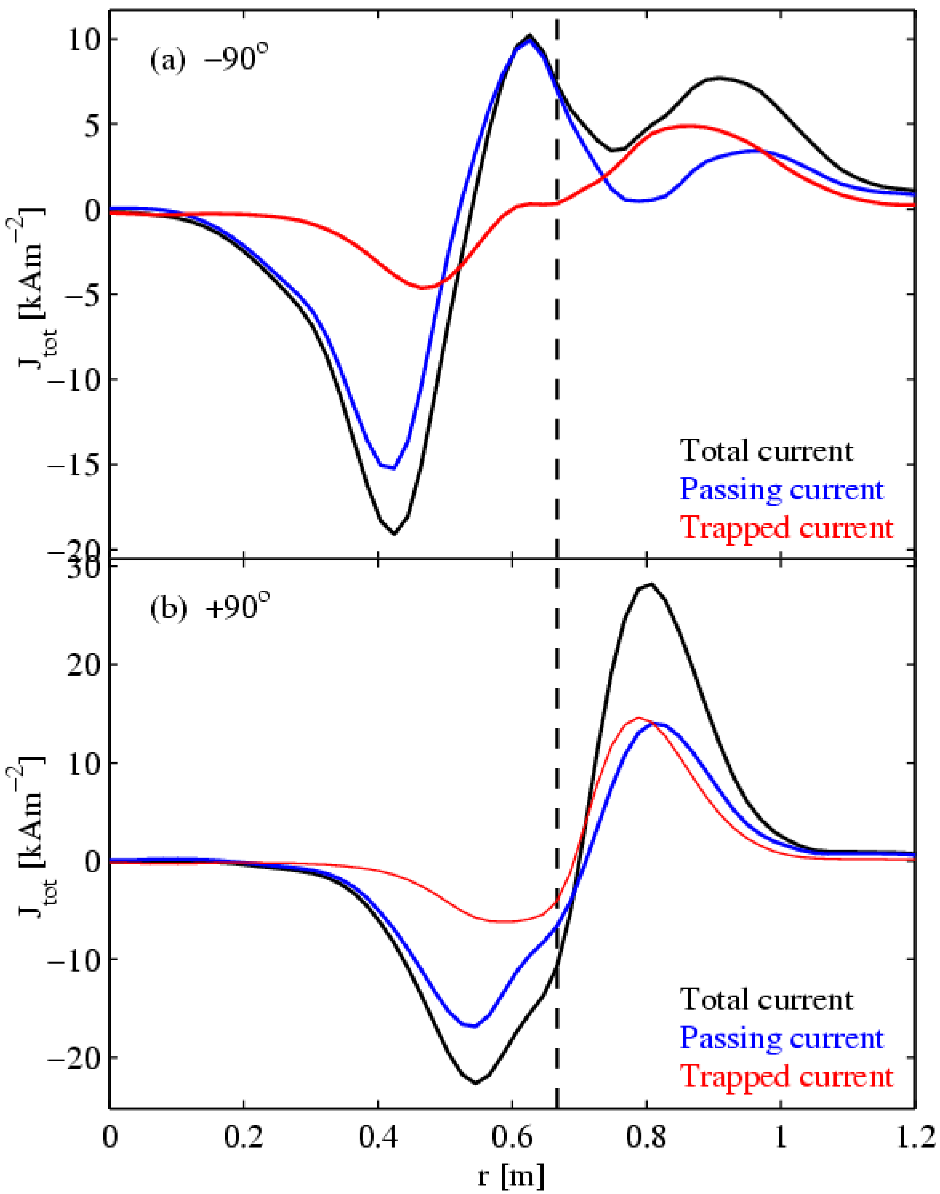


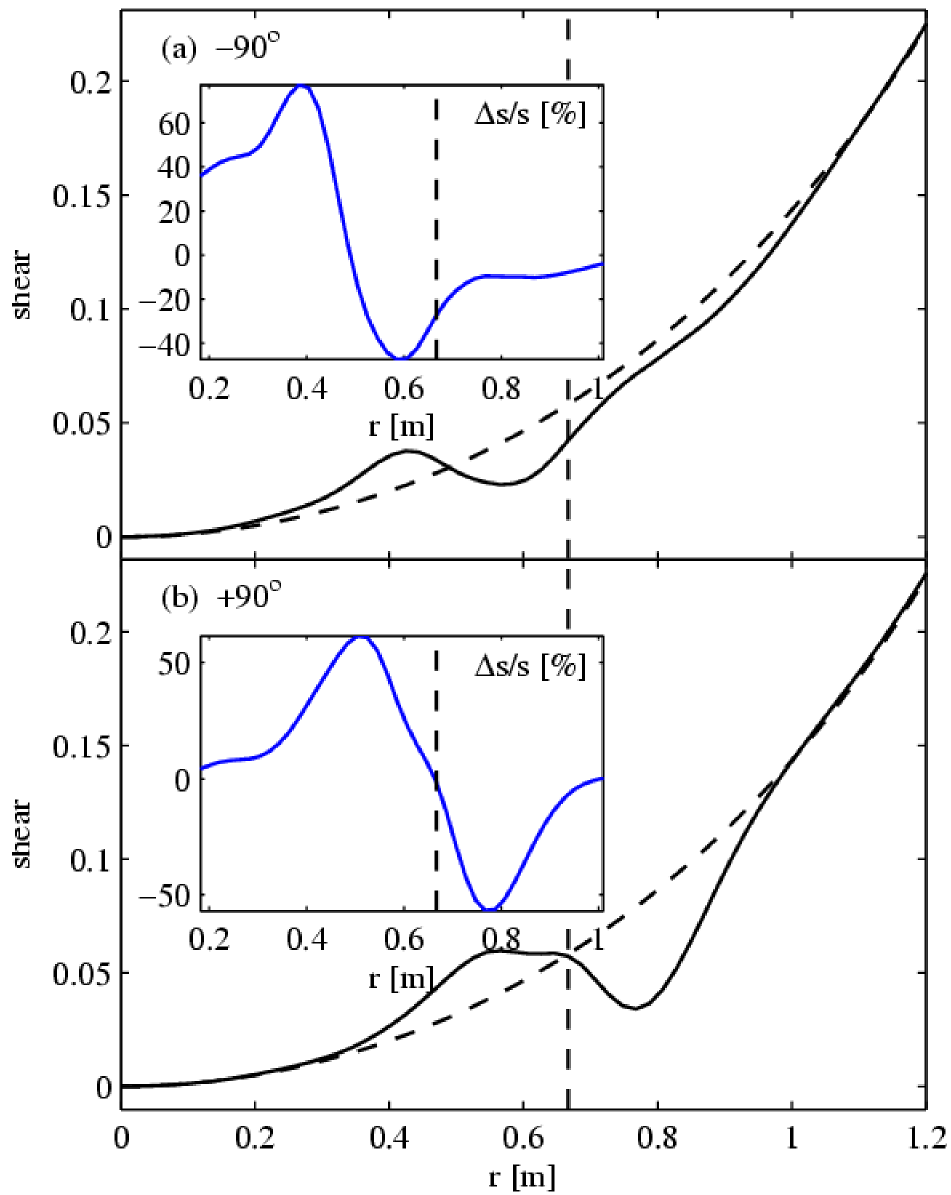
Changing ^{3}He Concentration

- Increased ^{3}He concentration
  - Mode conversion regime - Direct electron damping
    - Lower total power absorbed by ^{3}He minority
    - Lower absolute minority currents

    (But perhaps mode conversion current drive?)
- Decreased ^{3}He concentration
  - Higher power per minority ion
    - Increased trapping as in 40 & 60MW case
  - Lower total power absorbed by ^{3}He minority
    - Lower absolute currents
- No ^{3}He
  - Majority T ICCD
    - 2nd harmonic RF damping – FLR effect
    - Primarily trapped currents

Alternative - H ICCD



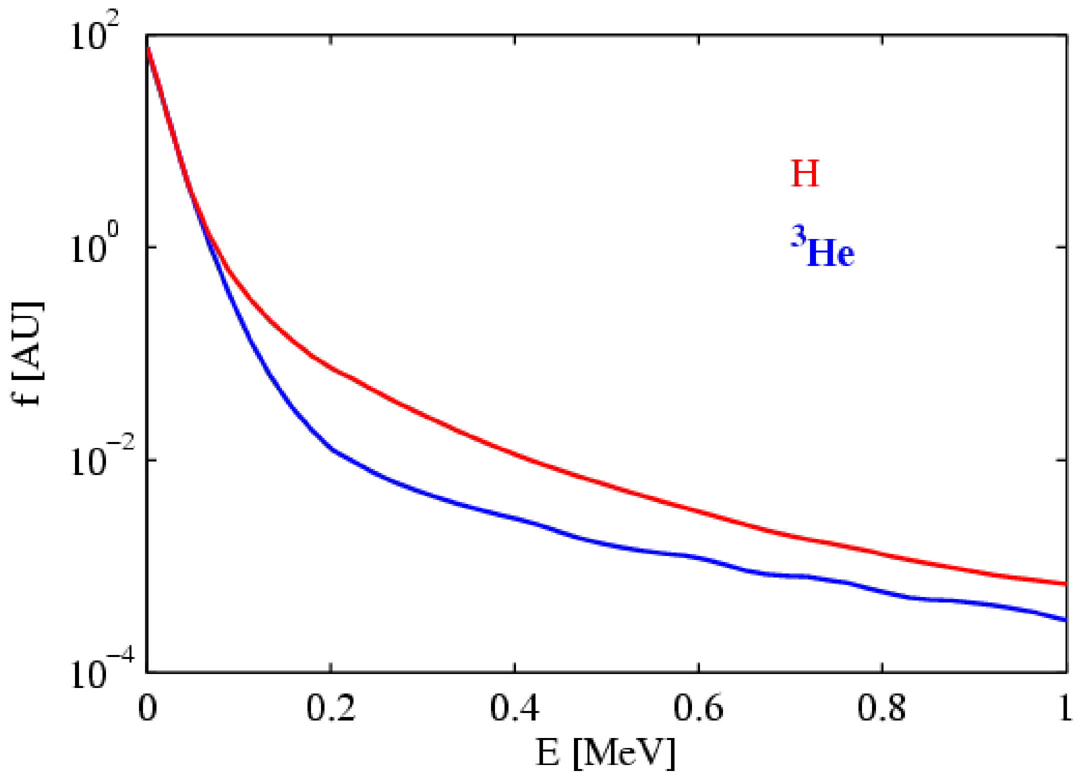


Compared to ICCD in JET

- Similarities
  - Power density: 20 MW / 840 m^3 vs 2.5 MW / 80 m^3
  - Fast ion slowing down time: 0.6s vs 0.7s
- Differences
  - Higher density
    - ¼ of the power per minority ion
  - LFS instead of HFS resonance
    - More trapped ions, closer to trapped-passing boundary
  - ^{3}He instead of H minority
    - Larger back current
    - Higher ion collisionality - weaker ^{3}He tail formation (E_{crit} for decreasing ion collisions 420 keV vs 140 keV)

Drawbacks of H instead of ^{3}He

- H resonance degenerate with 2nd harmonic ^{4}He
  - 12% parasitic α absorption (2% on thermal ^{4}He)
- W_{fast}
  - 1.8 MJ for H
  - 0.8 MJ for ^{3}He
- Lower bulk ion heating
  - 8 MW for H
  - 12 MW for ^{3}He
- Possible optimisation
  - H concentration
  - Antenna spectrum



Conclusions

- H ICCD significantly more efficient than ^{3}He ICCD, but not covered in present ICRH system design
  - Extend frequency range?
    - Implications on technical performance?
  - Move frequency range?
    - Implications on bulk ion heating?
    - Implications on parasitic absorption by α-particles?

  (Neither solutions likely to be accepted)
- ^{3}He ICCD should be tested experimentally
  - Preliminary tests at JET were “inconclusive”
- Bottom line: ICCD scales poorly to ITER
  - ECCD or MCCD likely to be more suitable for shear control