Kinetic study of plasma current start-up under EBW power in tokamak plasmas

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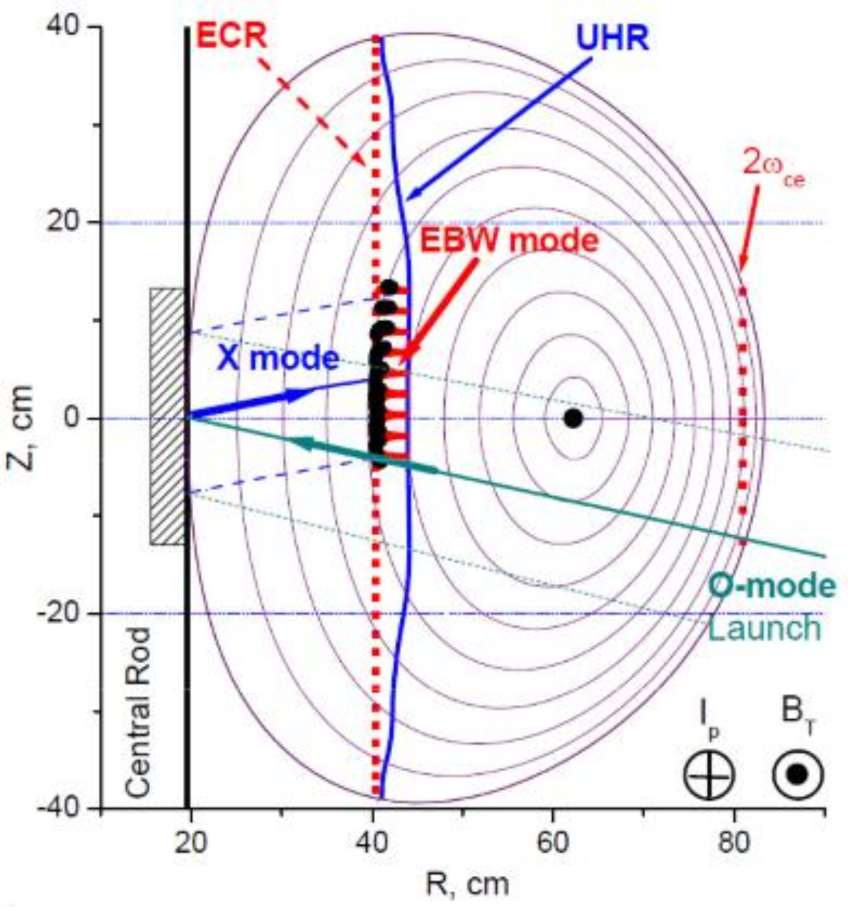
EBW-assisted start-up successfully demonstrated on MAST

- Compact size of STs
  - Limited space for shielded inboard solenoid
  - Need for non-inductive start-up techniques
- Electron Bernstein wave (EBW) start-up demonstrated on MAST
  - Double mode conversion
  - Excitation and absorption of EBWs

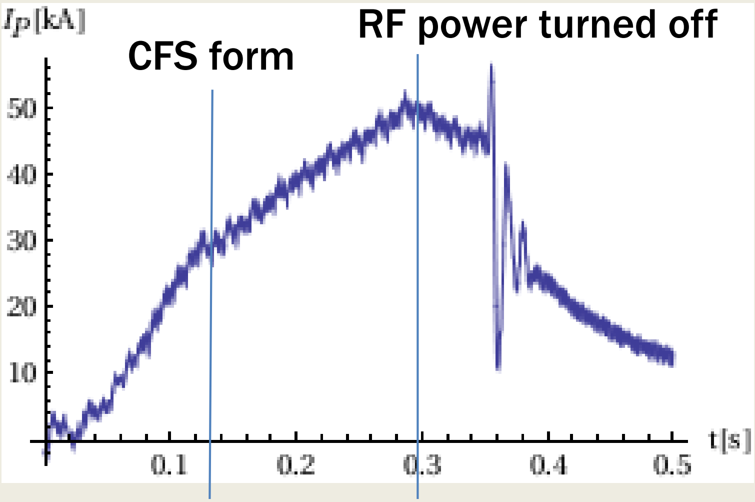


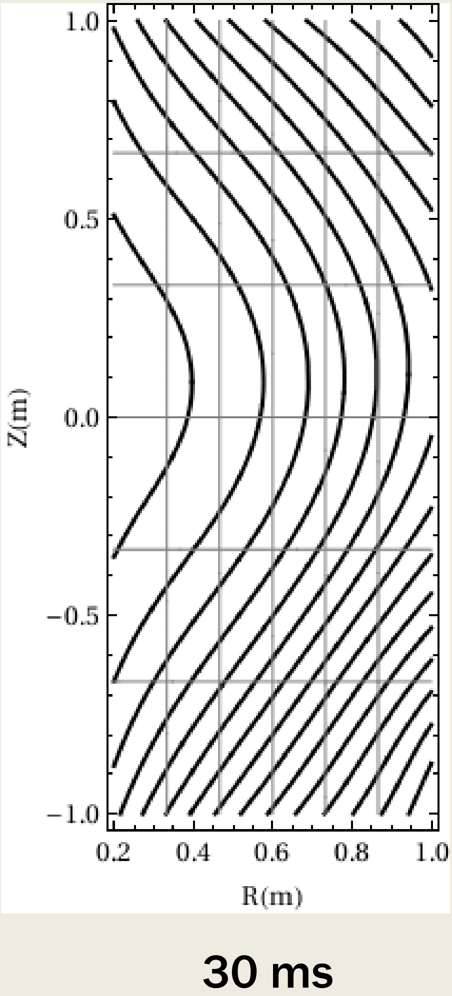
Schematic of EBW start-up in MAST

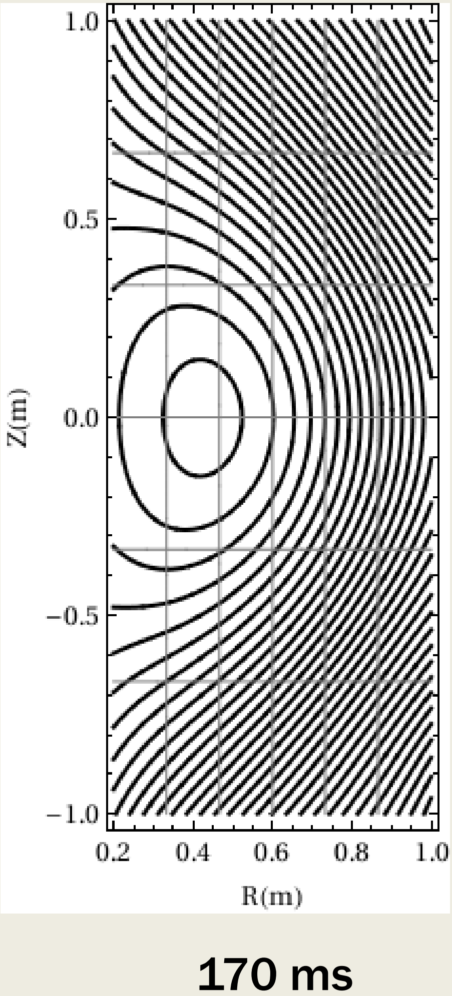
V.F. Shevchenko *et al.*, *Nucl. Fusion* **50**, 022004 (2010).

The generation of a plasma current leads to the formation of CFS

- Plasma current generated under EBW power in MAST
- Crucial for closed flux surfaces (CFS) and improving confinement
- How is the current generated?





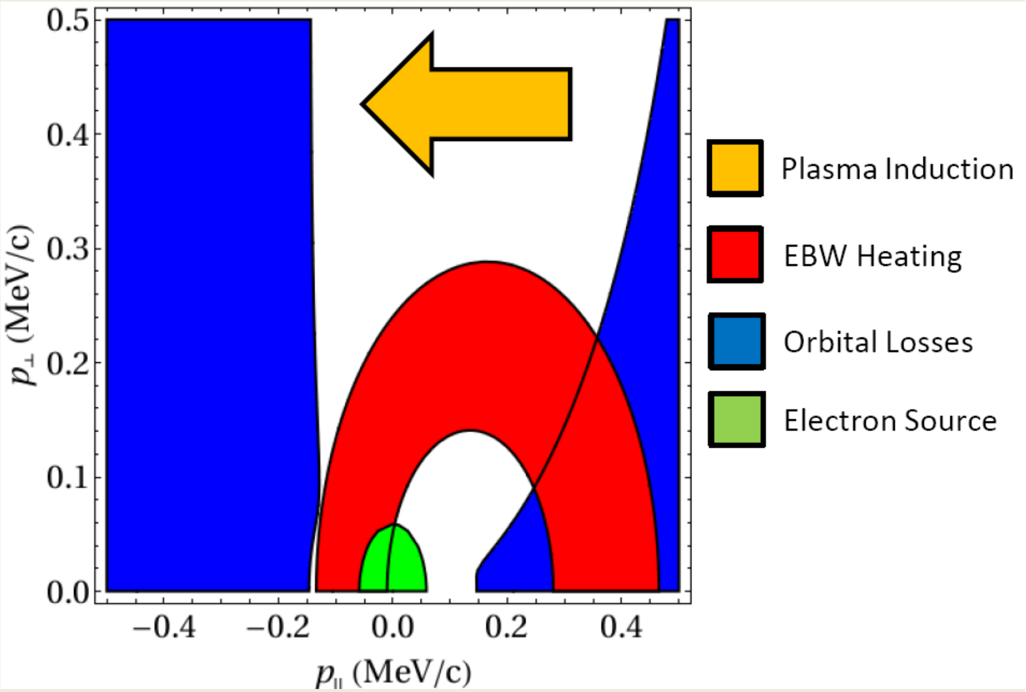


We study the time evolution of the (0D2V) distribution function

- We develop a model that studies the time evolution of the electron distribution function:

$$\frac{\partial f}{\partial t} = \text{source} + \text{loss} + \text{RF Heating} + \text{loop voltage} + \text{collisions}$$

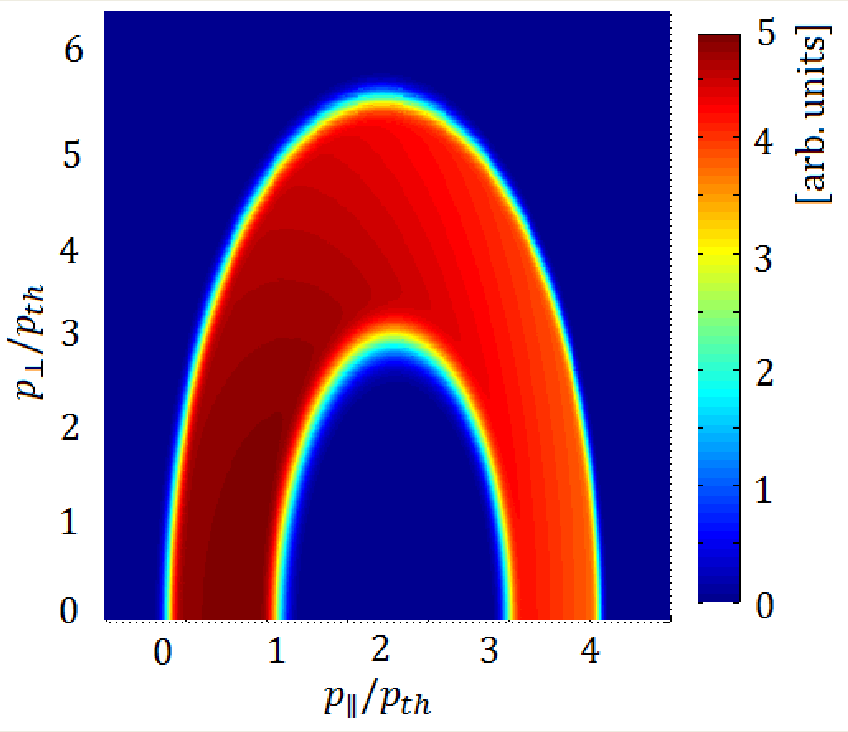
- To ensure the model is tractable it is 0D in space
  $$f = f(p_{\parallel}, p_{\perp}, t)$$
- Assume the important physics can be captured in a number of terms
- Appropriate volume averages and approximations account for spatial dependences



RF heating increases the energy of resonant electrons

$$\left(\frac{\partial \mathrm{f}}{\partial \mathrm{t}}\right)_{\mathrm{RF\ Heating}} = D_0 \frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}\, p_\perp \left\langle \exp\left[-\left(\frac{\omega - k_\parallel v_\parallel - n\omega_c}{\Delta\omega}\right)^2\right]\right\rangle_{\mathrm{volume}} \frac{\partial f}{\partial p_\perp}$$

- RF heating increases the perpendicular energy of electrons
- A volume average is taken over the region of absorption to obtain a spatially independent term
- The value of D_0 is iterated over to ensure the correct power is absorbed



Example of the diffusion operator

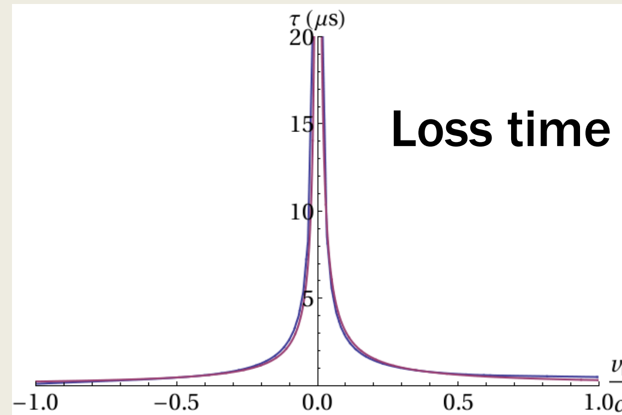
Open magnetic field lines lead to losses of most electrons

- Electrons can freely stream along the open magnetic field lines out of the plasma
- Electrons are subjected to a ∇B and curvature drift,

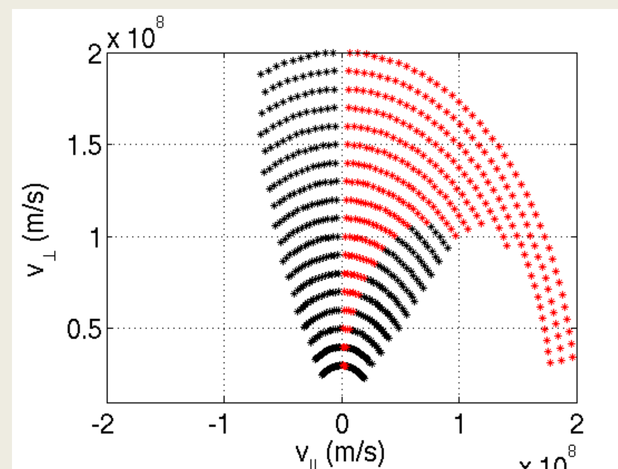
$$V_Z = \frac{B_Z}{B} v_\parallel - \frac{m_e}{eBR}\left(v_\parallel^2 + \frac{v_\perp^2}{2}\right)$$

- Electrons with $V_Z = 0$ will be confined
- Leads to a loss term,

$$\left(\frac{\partial f}{\partial t}\right)_{\text{loss}} = -\frac{f}{\tau_{\text{loss}}} P_{\text{loss}}(p_\parallel, p_\perp)$$



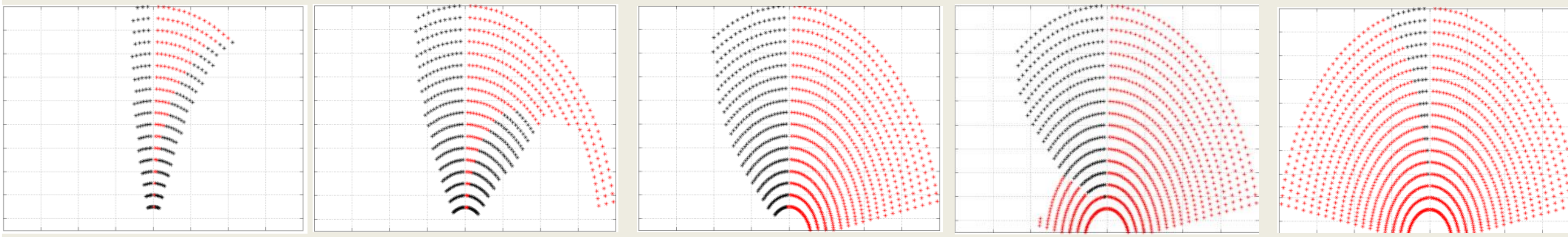
Loss time τ_{loss}



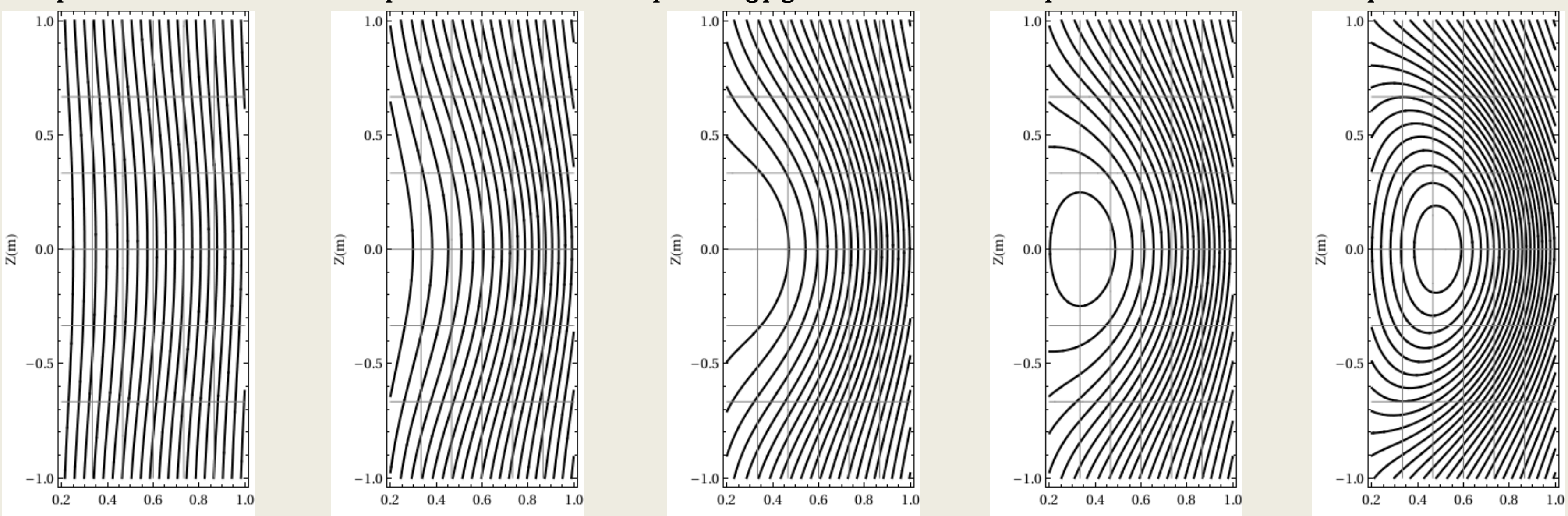
Electron confinement $P_{\text{loss}}(p_\parallel, p_\perp)$ before CFS formation passing (red) and trapped (black)

Increase in plasma current leads to improved confinement

Confinement of energetic electrons (up to $100\ \mathrm{keV}$) for increasing plasma current
Passing orbits (red) and trapped orbits (black)

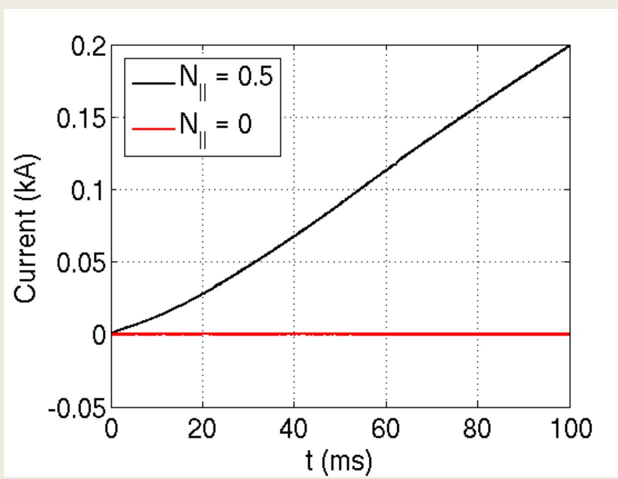


$I_P = 3\ \mathrm{kA}$ | $I_P = 9\ \mathrm{kA}$ | $I_P = I_{CFS} = 15\ \mathrm{kA}$ | $I_P = 18\ \mathrm{kA}$ | $I_P = 30\ \mathrm{kA}$

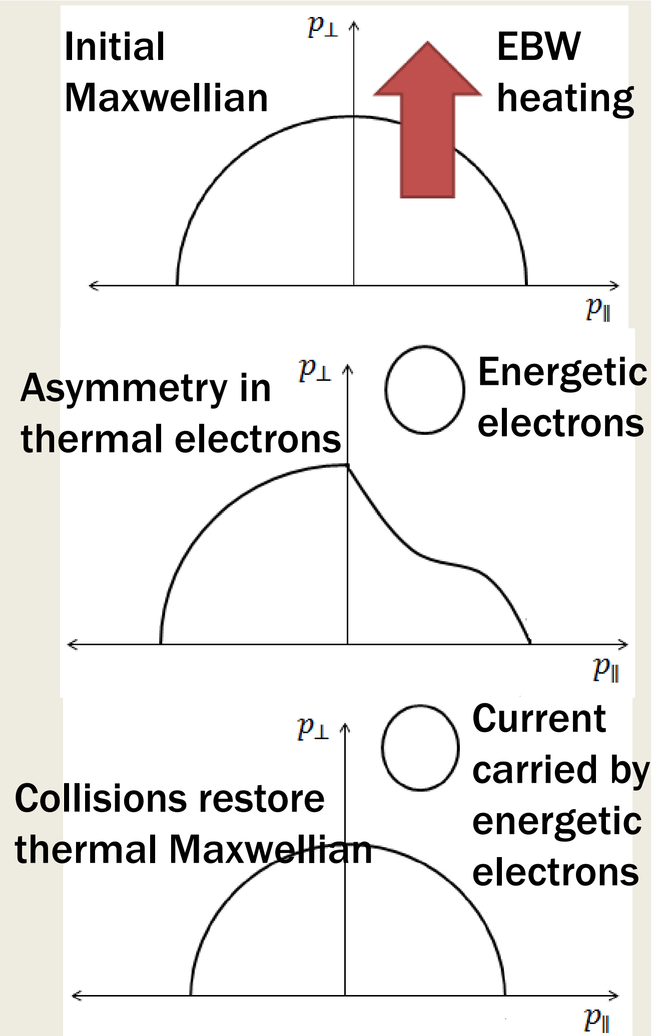


Collisions generate a current carried by energetic electrons under EBW heating

- Fisch-Boozer mechanism: Preferential heating of electrons creates anisotropic plasma resistivity which generates a current
- Large population of energetic electrons are created by the EBW

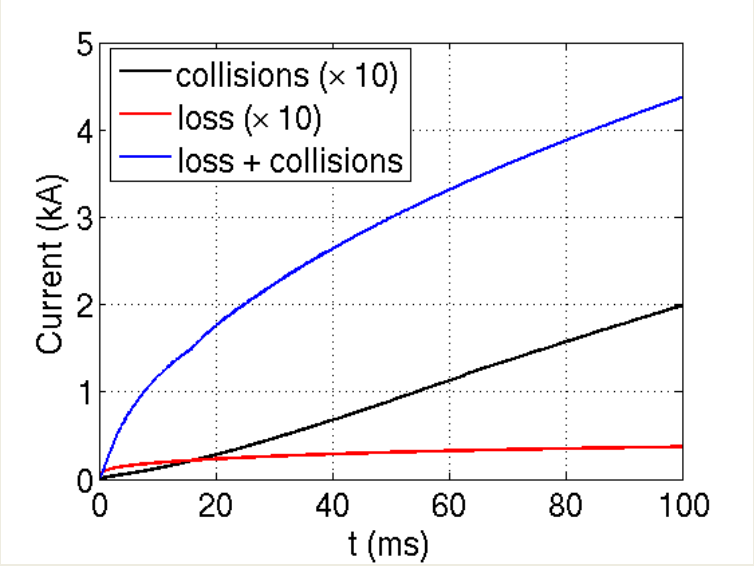


Simulated plasma current

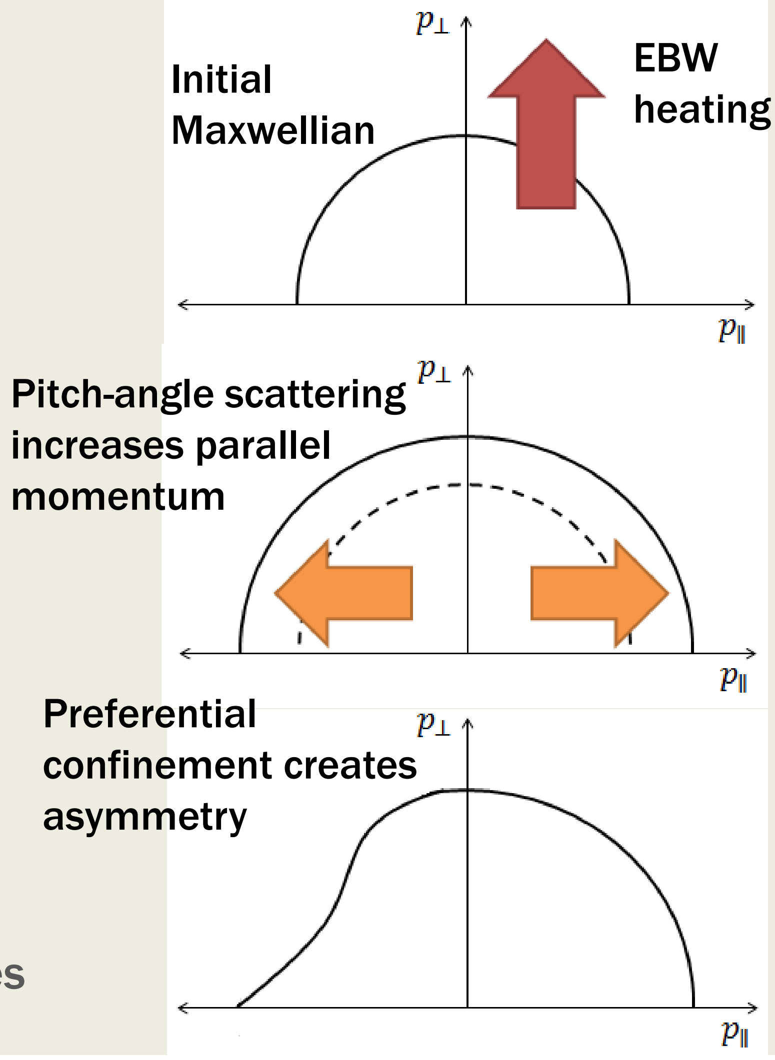


Preferential confinement of electrons generates a larger current

- Pitch-angle scattering increase temperature ⇒ greater losses ⇒ preferential confinement creates asymmetry and increase in current



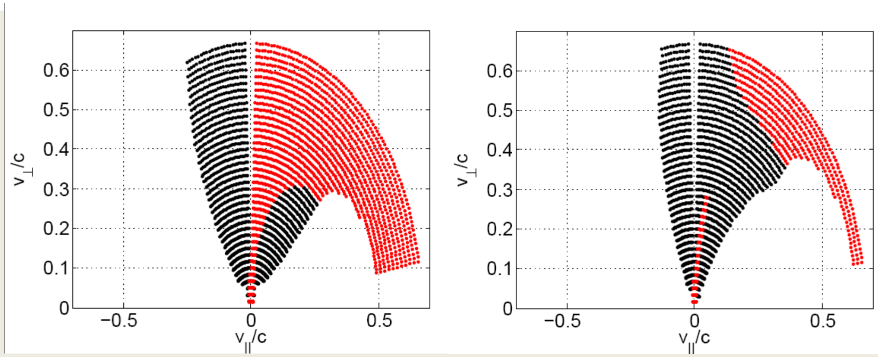
Simulated plasma current for three different cases



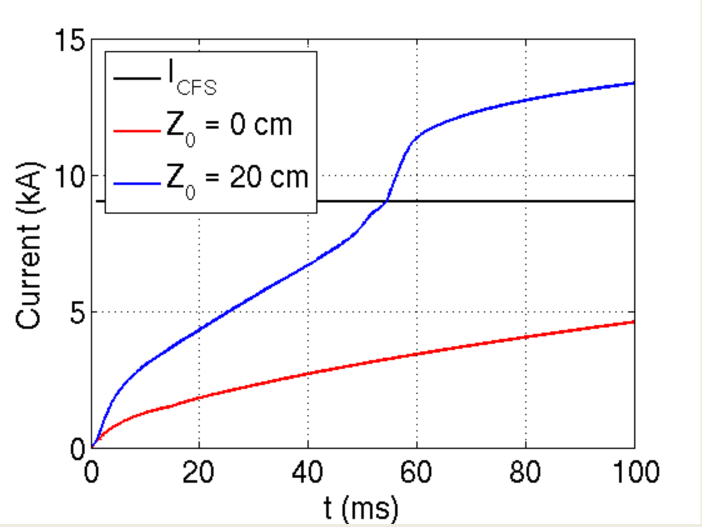
Vertical shift of the plasma increases the plasma current for two reasons

- Experiments: A vertical shift of the plasma helps the formation of CFS – increases I_P
- Two reasons:

1. A vertical shift enhances the asymmetry of electron confinement ⇒ increase in I_P
2. Creates favourable $N_{\parallel}$ in absorption area
   - In MAST, $B_V < 0$
   - $N_{\parallel} < 0$ above and $N_{\parallel} > 0$ below midplane
   - Vertical shift ensure $N_{\parallel} > 0$



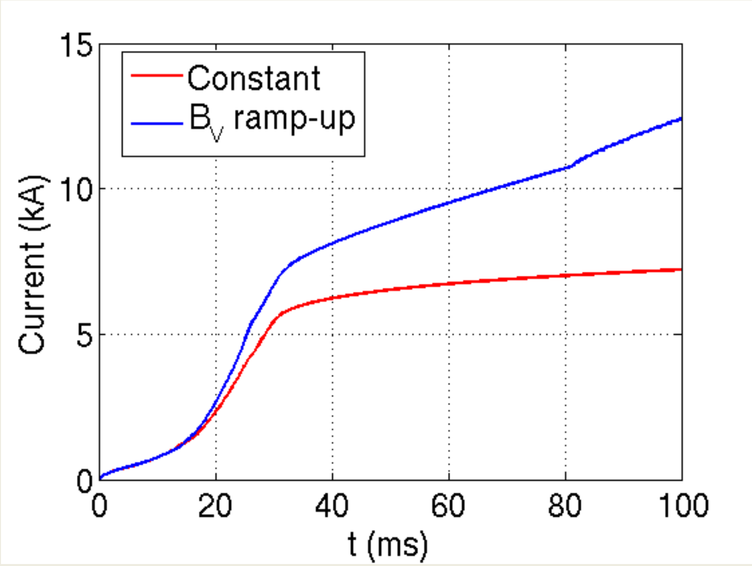
$Z_0 = 0$ cm $Z_0 = 40$ cm



Simulated plasma current with and without a vertical shift

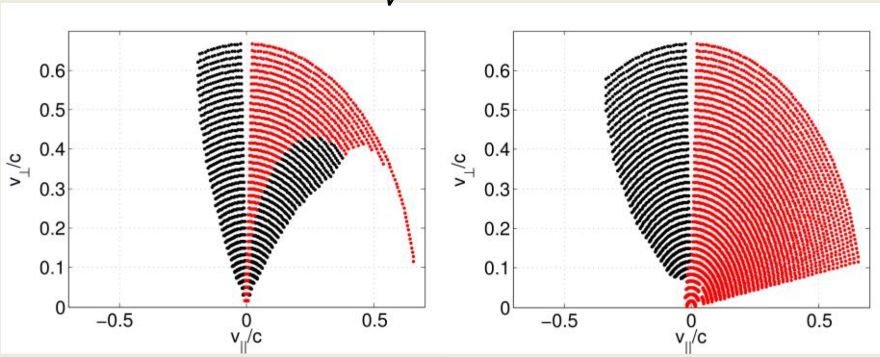
Increasing the vacuum poloidal field B_V leads to larger plasma current

- Experiments: larger currents can be generated by increasing B_V
- Increasing B_V allows for larger I_P while keeping the preferential confinement intact



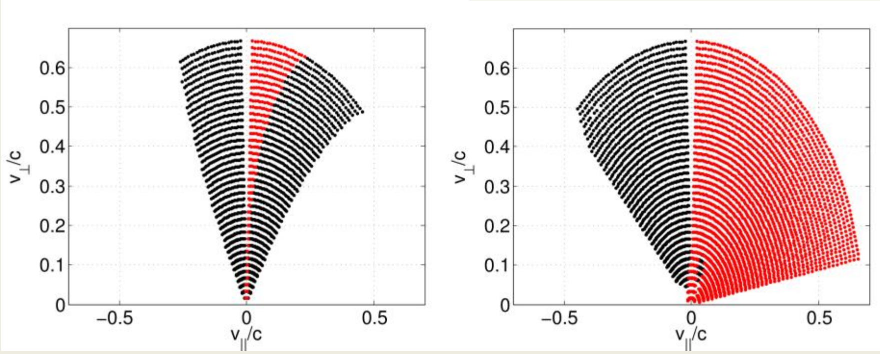
Simulated plasma current for a constant and linearly increasing B_V

$B_V = 10$ mT



$I_P/I_{CFS} = 1/2$ $I_P/I_{CFS} = 1$

$B_V = 20$ mT

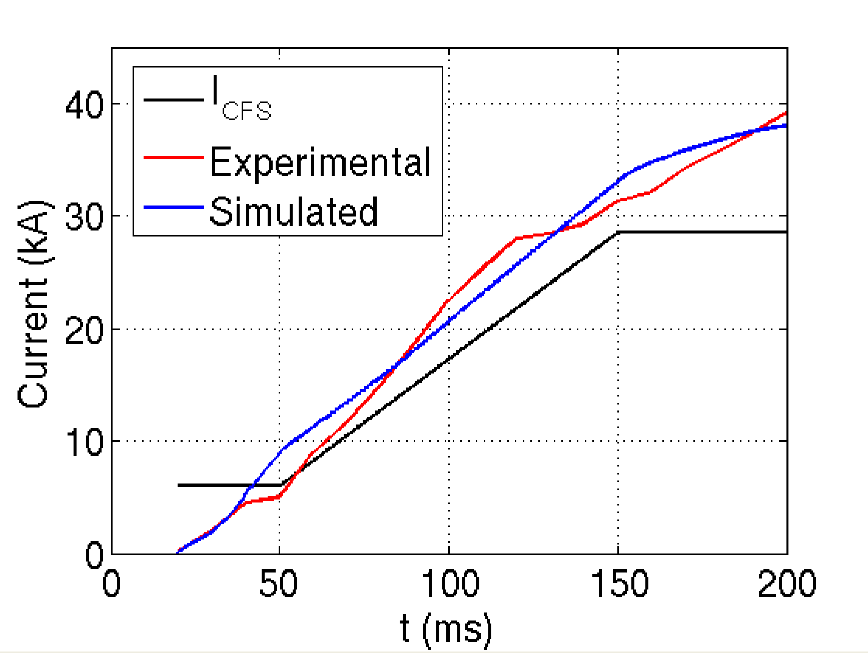


$I_P/I_{CFS} = 1/2$ $I_P/I_{CFS} = 1$

Experiments use combination of vertical kick and B_V ramp-up

- Experiments use a combination of vertical shift (to ensure optimal $N_{\|}$) and B_V ramp-up to achieve higher I_P

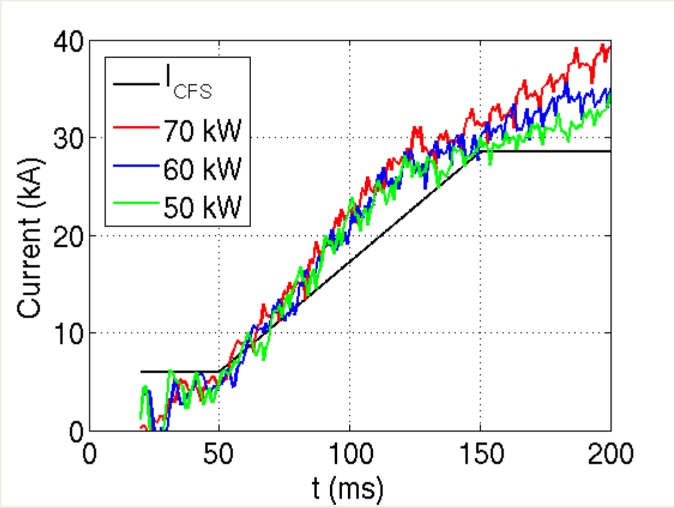
- Simulations compare favourably to experiments

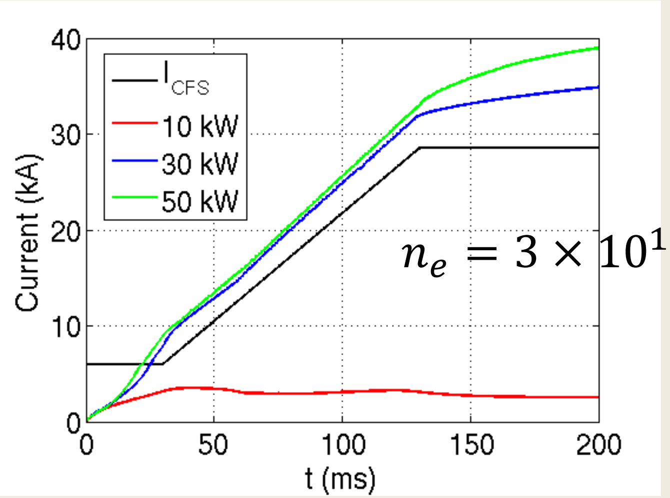


Comparison between simulation and experiment for shot 28941 for a 50 kW input

The generated current is independent of input power during B_V ramp-up

- Experiments showed a linear relationship between I_P and P_0
- This is only true after CFS have formed, and the collisions dominate the CD! (Fisch-Boozer mechanism)
- The time evolution of I_{CFS} determines the current generation, provided the power is high enough

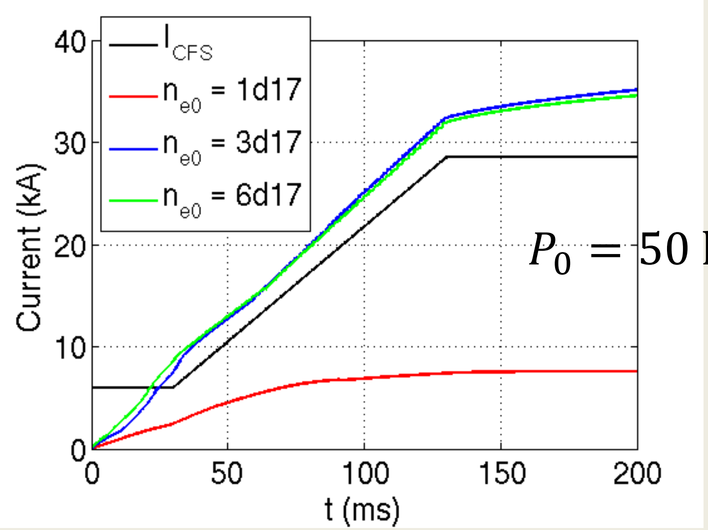




$n_e = 3 \times 10^{17}\ \mathrm{m}^{-3}$

The relationship between density and power is needed for further study

- Experiments suggests that density decreases for increasing power
- Similar as before, the time evolution of I_{CFS} determines the current generation, provided the density is high enough
- The relationship between power and density is needed for further study, but this is beyond the scope of this work



$P_0 = 50$ kW

Increase $P_0 \Rightarrow$ Increase I_P (constant n_e)

Increase $n_e \Rightarrow$ Increase I_P (constant P_0)

Increase $P_0 \Rightarrow$ Decrease $n_e \Rightarrow I_P$?

Conclusion

- The preferential confinement of electrons, due to the open magnetic field line configuration, is responsible for the majority of the generated current until CFS forms
- Collisions only act to "feed" the loss term by increasing the parallel momentum of electrons and therefore the rate at which they are lost
- Two effects are used to generate larger currents:
  - A vertical shift ensures a favourable $N_{\parallel}$
  - A vacuum field ramp-up allows for an increase in the plasma current while maintaining the asymmetry in the loss term
- Simulations compare well to experiments, but for further predictions, the relationship between density and power is needed