A theoretical model of high-B_{min} instabilites and experimental tests of its predictions

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Outline

- Premise: Kinetic instabilities can be trouble for ECR ion sources
- Argument: Axial electron distribution is susceptible to these as B_{min} increases because of small axial magnetic field gradients (not the ones you are thinking of)
- Examples of the effects of these gradients

ECRIS tuning: avoid electron kinetic instabilities

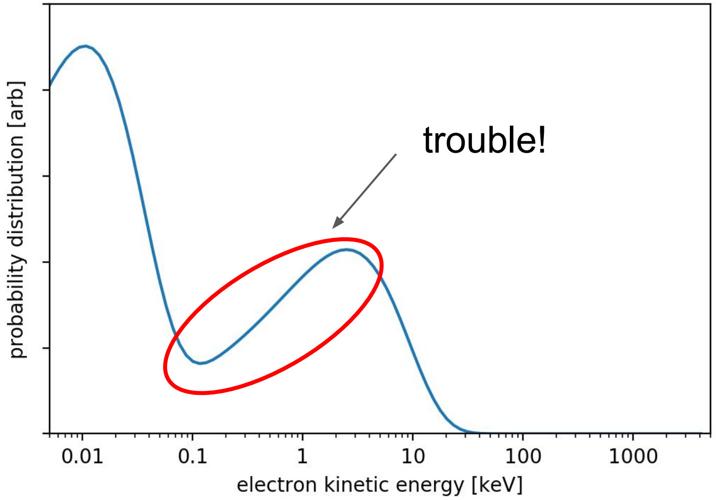
What is kinetic instability?

Kinetic energy (KE) distribution function increases with KE[1]

What works against kinetic instability?

Collisions. However, Spitzer[2] says $\nu_{ei} \propto KE_e^{-3/2}$

→ collisions rare above 10s of keV



[1] O. Tarvainen, Rev. Sci. Instrum. **87**, 02A703 (2016)

[2] L. Spitzer, *Physics of Fully Ionized Gases* (1962)

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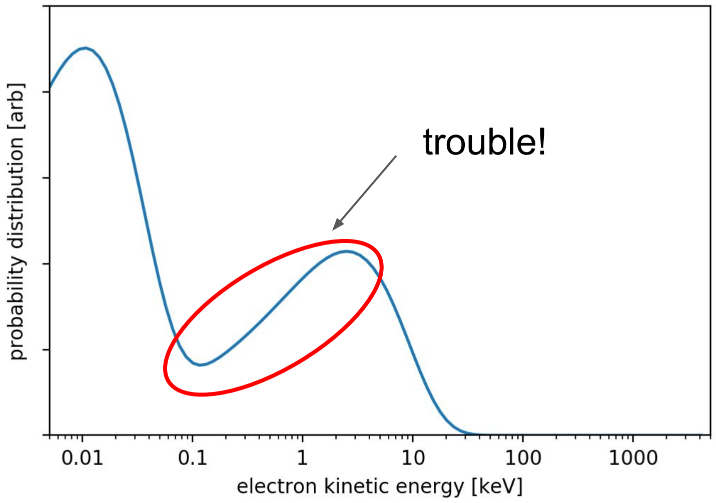
How they can happen in an ECRIS:

If electrons' energies increase much faster than collisions smooth the distribution, plasma is susceptible to kinetic instabilities



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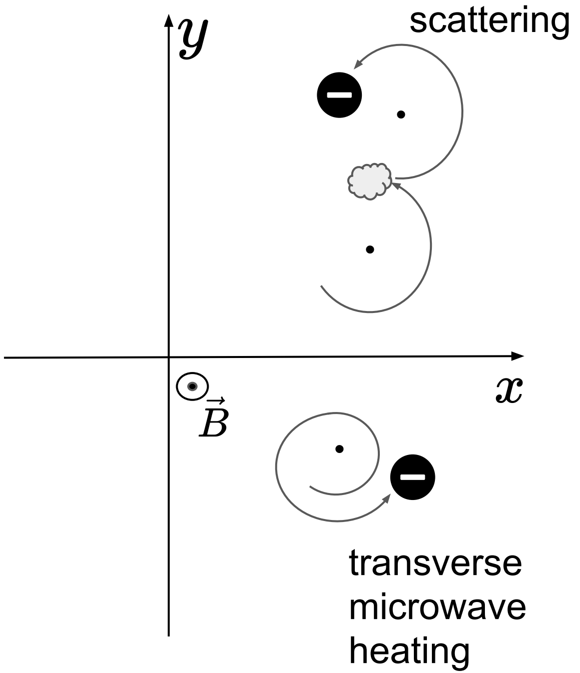
Two electron distributions: axial and halo

- Electrons' relatively low collision rates plus transverse heating leads to slow cross-field diffusion

- Additionally sextupole fields small near axis ($\propto r^2$)

  Result ➞ very slow mixing between populations



Evidence:

- Simulation: Mironov et al[*]
- Experiment: High charge state ions from axis

[*] V. Mironov et al, Plasma Sources Science and Technology, Vol. 29, Num. 6 (2020)

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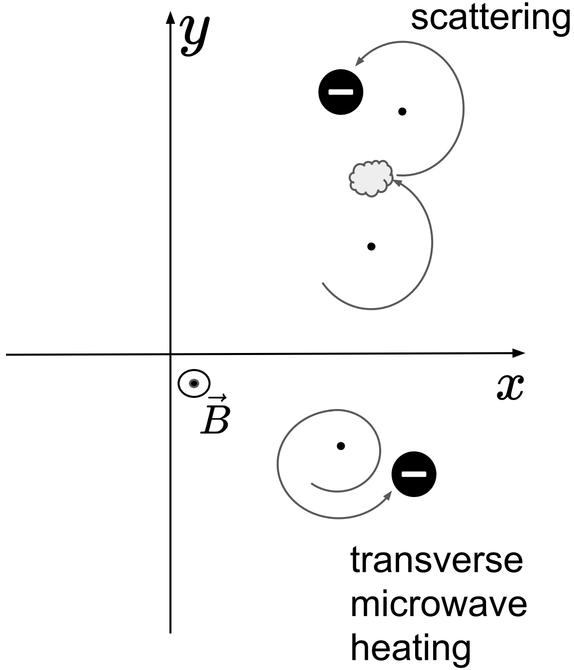
I will only focus on axial electrons here

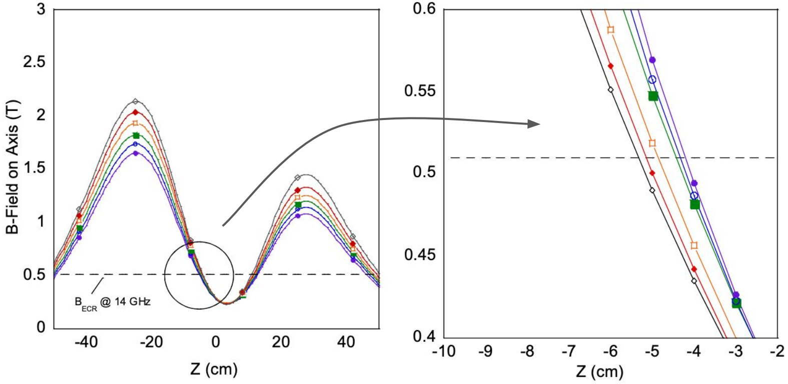


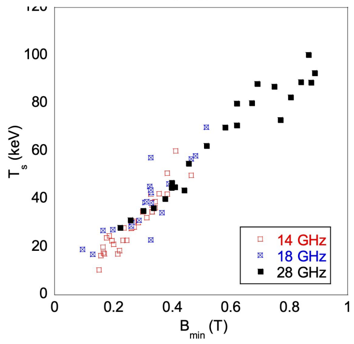
* V. Mironov et al, Plasma Sources Science and Technology, Vol. 29, Num. 6 (2020)

Resonant heating: gradients matter(?)

Common sense and early simulations predict axial $\nabla \cdot \mathbf{B}$ should affect distribution

Bremsstrahlung experiment disagrees[1]:
➔ spectral temperature depends on B_{min}





[1] Benitez, J., et al, ECRIS 2016

Resonant heating: gradients matter(?)

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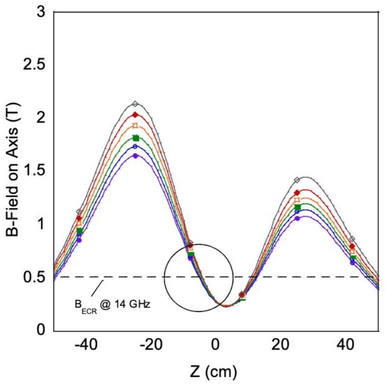
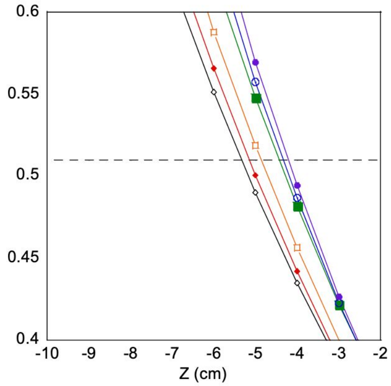
Bremsstrahlung experiment disagrees[1]:

➔ spectral temperature depends on B_{min}

Here we will argue that the axial gradient is very important...just not at the natural resonance field





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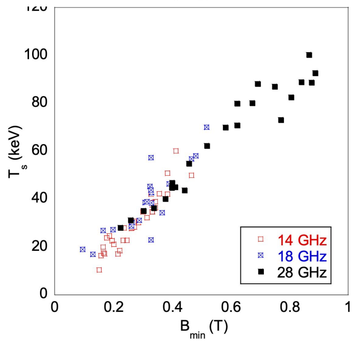


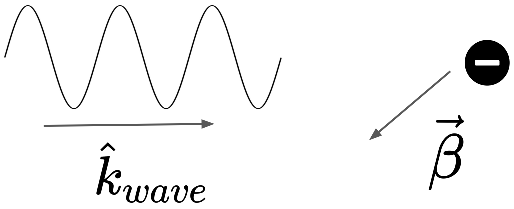
Last ingredient: Doppler shift

For axial RF: $$\frac{B_{res}}{B_{res,\gamma=1}} = \gamma(1 - \hat{k}_{wave} \cdot \vec{\beta})$$

"Toward"

$f_{received} > f_{sent}$

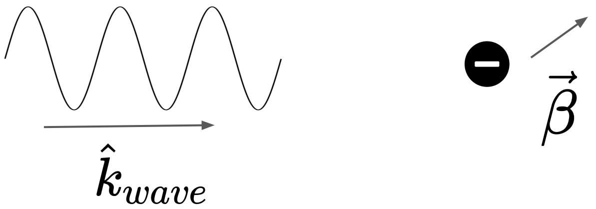
$B_{res} > B_{res,\gamma=1}$



"Away"

$f_{received} < f_{sent}$

$B_{res} < B_{res,\gamma=1}$



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Reflected wave

"Toward"

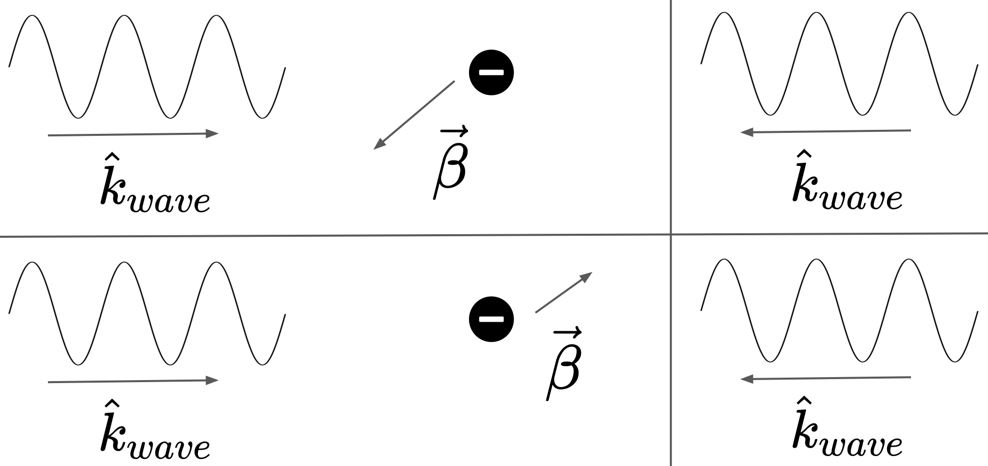
$f_{received} > f_{sent}$

$B_{res} > B_{res,\gamma=1}$

"Away"

$f_{received} < f_{sent}$

$B_{res} < B_{res,\gamma=1}$



"Away"

$f_{received} < f_{sent}$

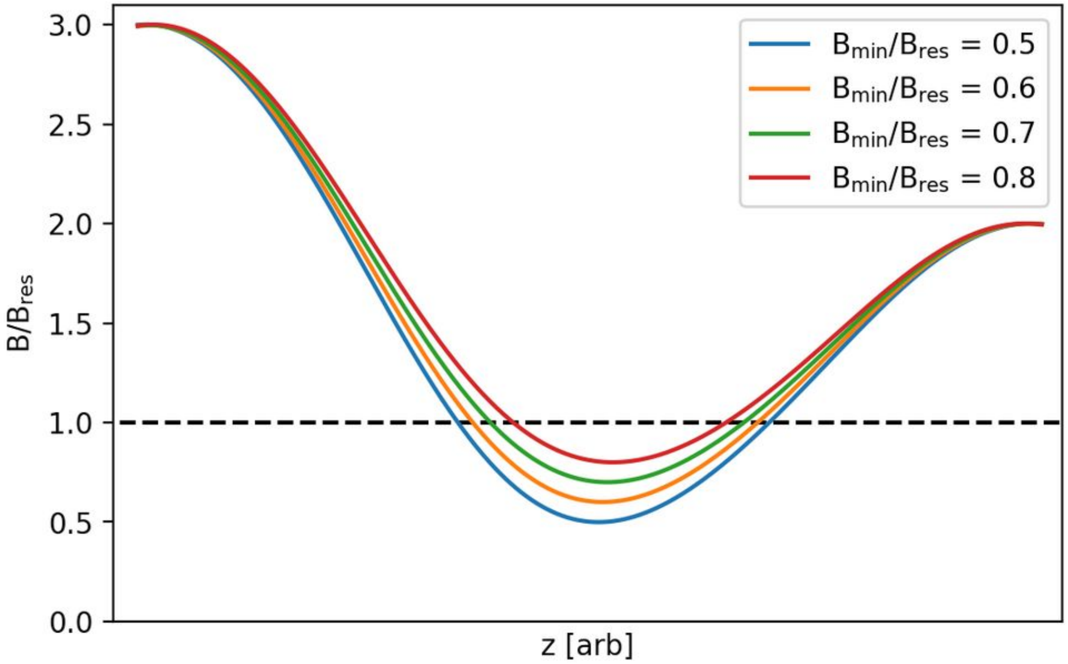
$B_{res} < B_{res,\gamma=1}$

"Toward"

$f_{received} > f_{sent}$

$B_{res} > B_{res,\gamma=1}$

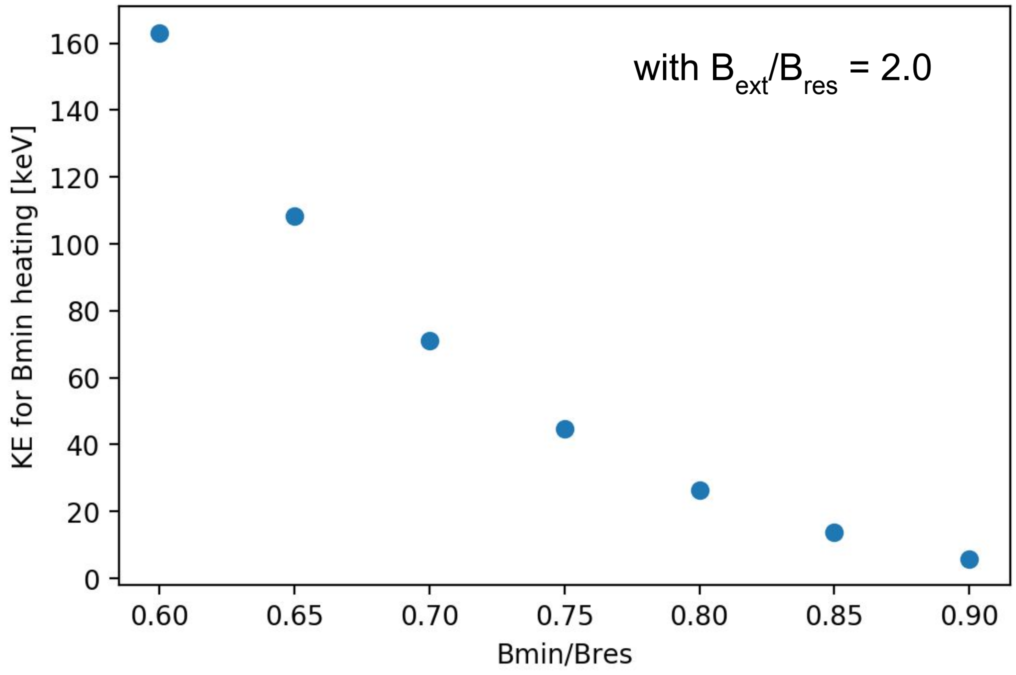
What happens as we increase B_{min}?



Gradients decrease near resonance

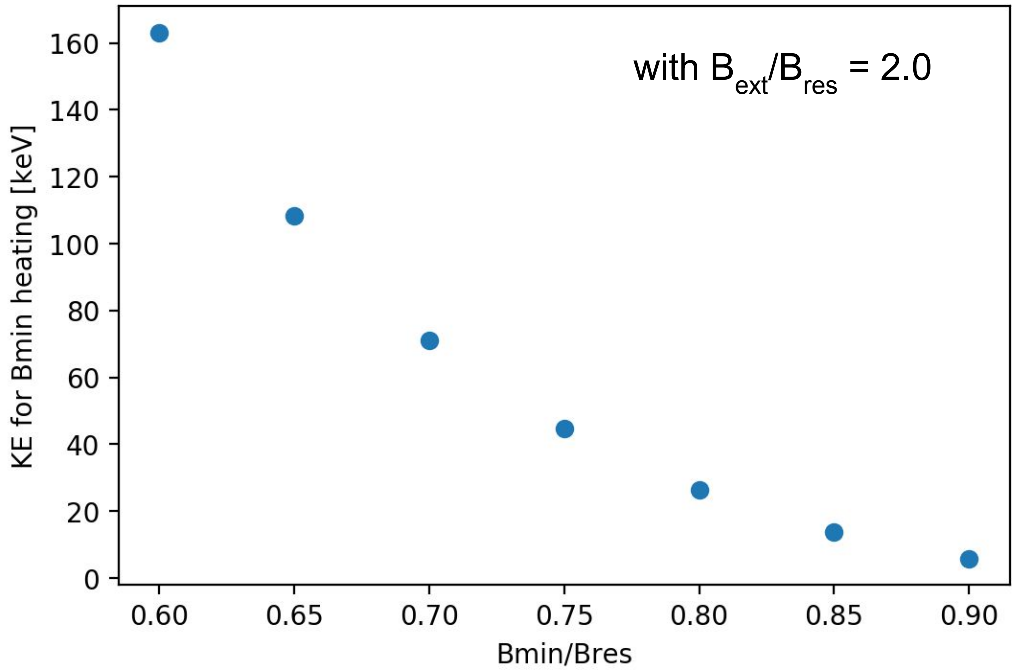
More importantly, a region of zero-gradient becomes accessible to lower-energy electrons

Minimum KE for resonant heating at B_{min}



- For $B_{min}/B_{res} \approx 0.8$ zero-gradient resonance can be reached by ~20 keV electrons
- True for all sources!

Minimum KE for resonant heating at B_{min}



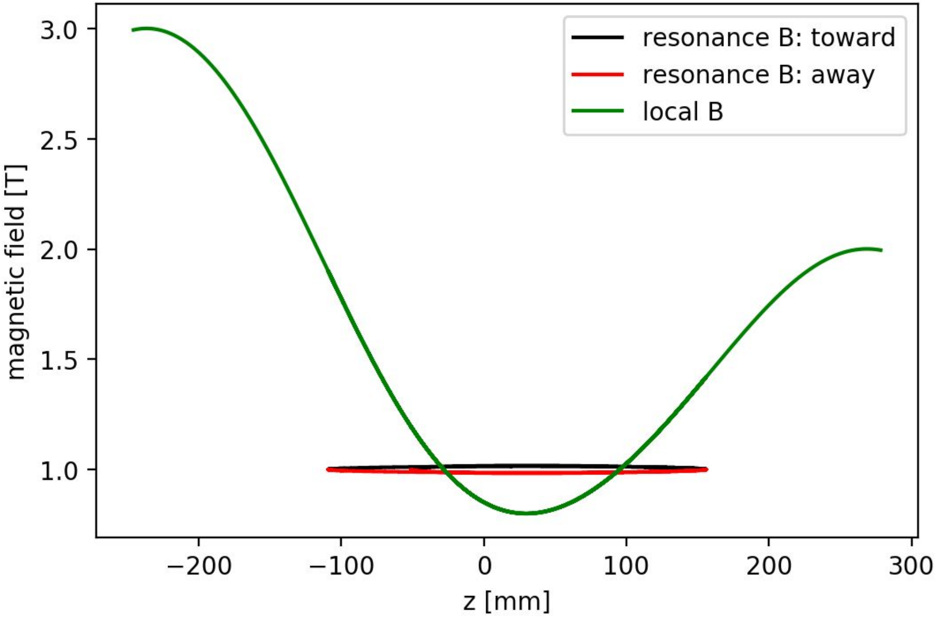
- For $B_{min}/B_{res} \approx 0.8$ zero-gradient resonance can be reached by ~20 keV electrons
- True for all sources!

What are the ramifications?

Resonant heating

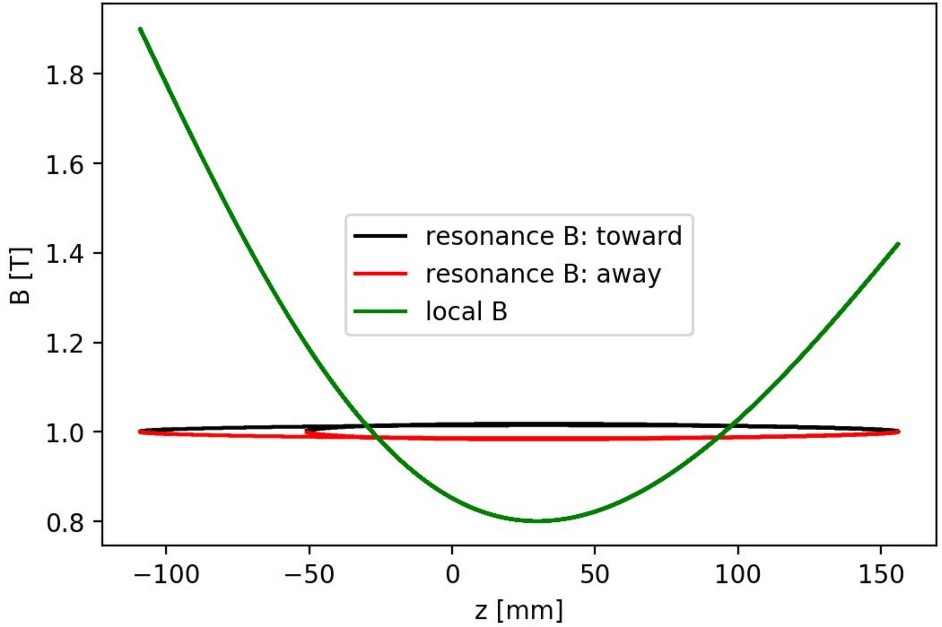
Simulation:

- VENUS (28 GHz)
- Single electron at a time
- E_{rf}=10 kV/m

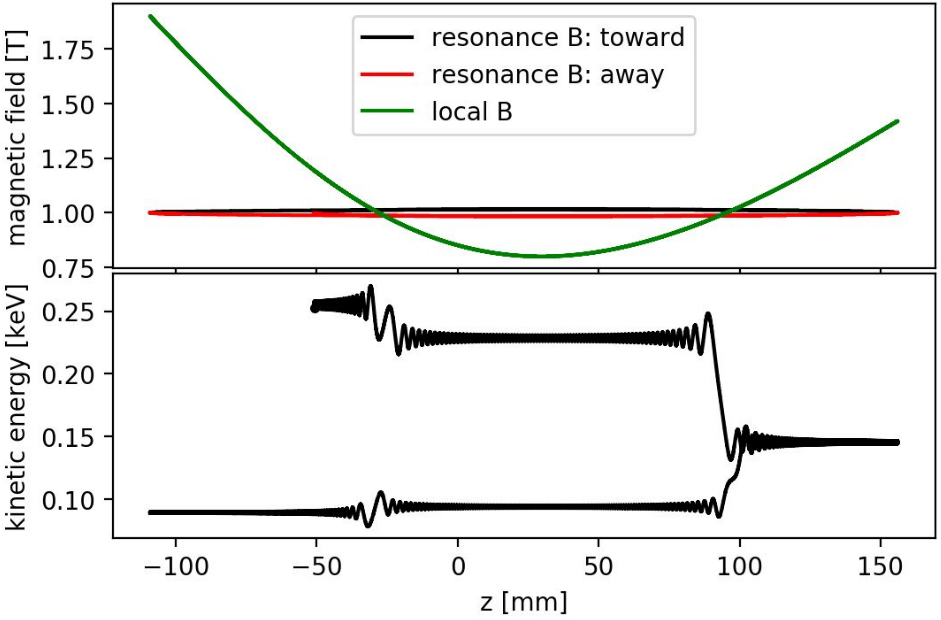


Calculate resonance fields B_{toward} and B_{away} at each step

Resonant heating, zoomed

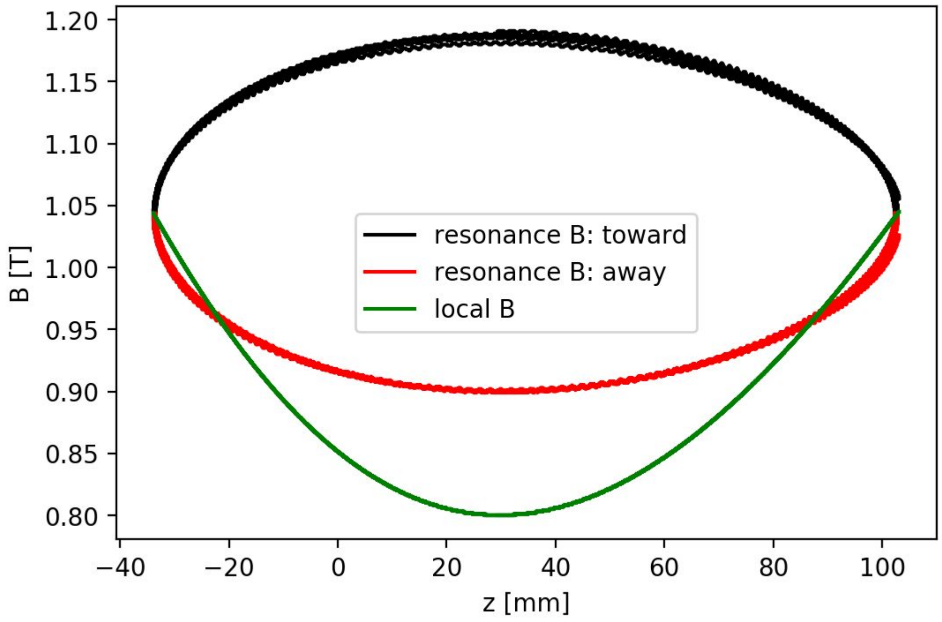


Resonant heating and energy change

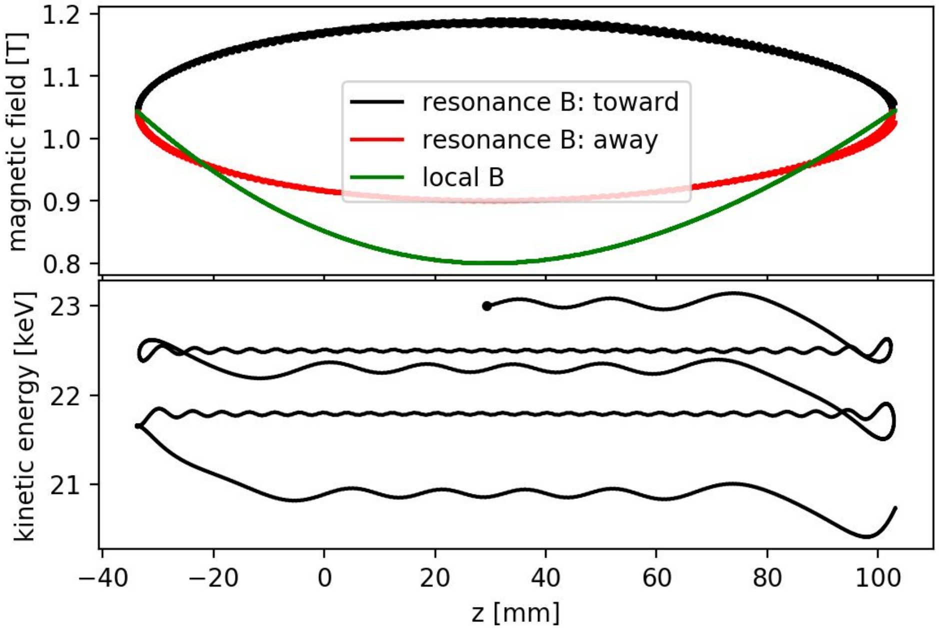


- Energy changes when resonance field equals local field
- Changes in energy on crossing typically 10s to 100s of eV

Modes of heating: two crossings, away and toward

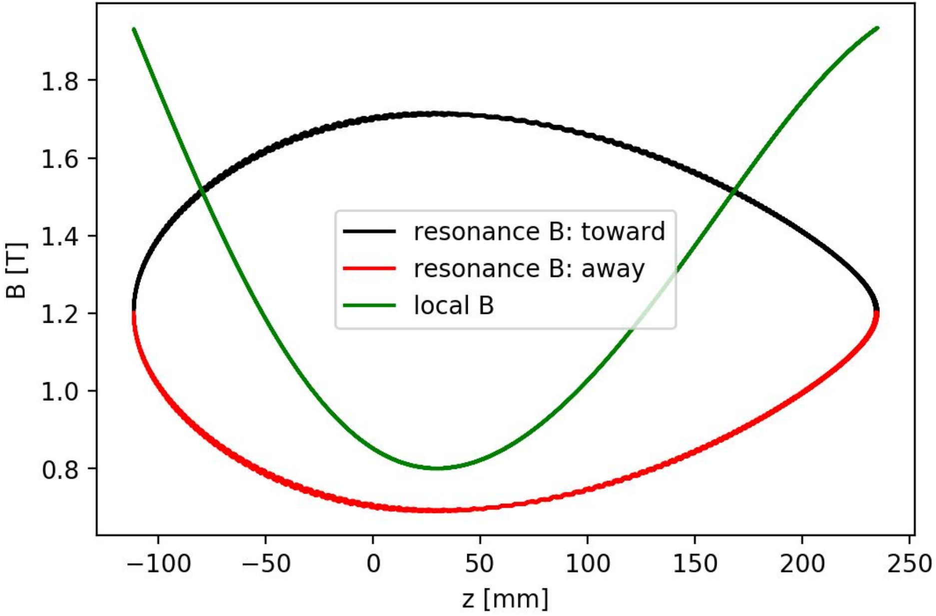


Modes of heating: two crossings, away and toward

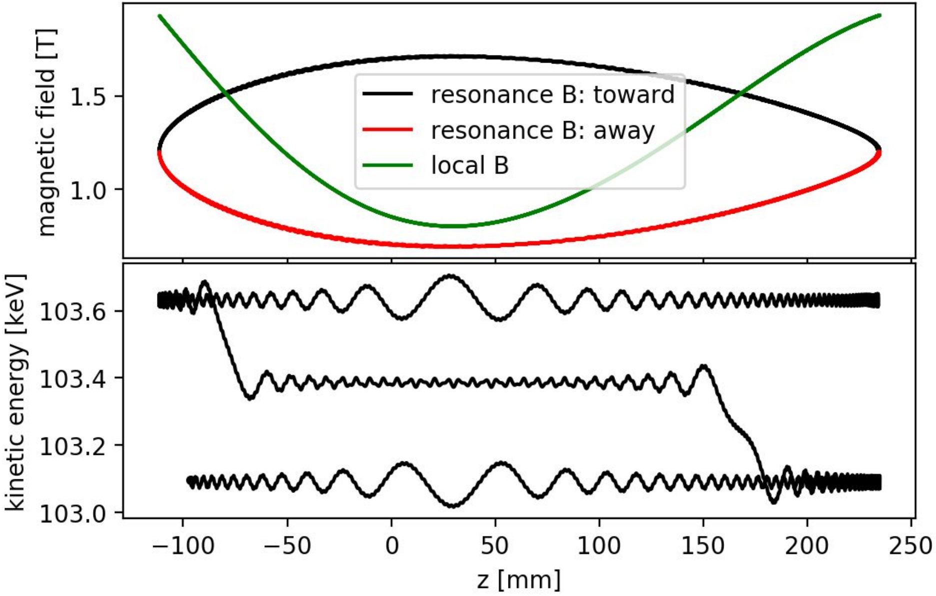


- Two crossings on each side
- One crossing with near-zero axial velocity so large ΔKE of keV possible
- Doesn't require high B_{min}

Modes of heating: one crossing, toward

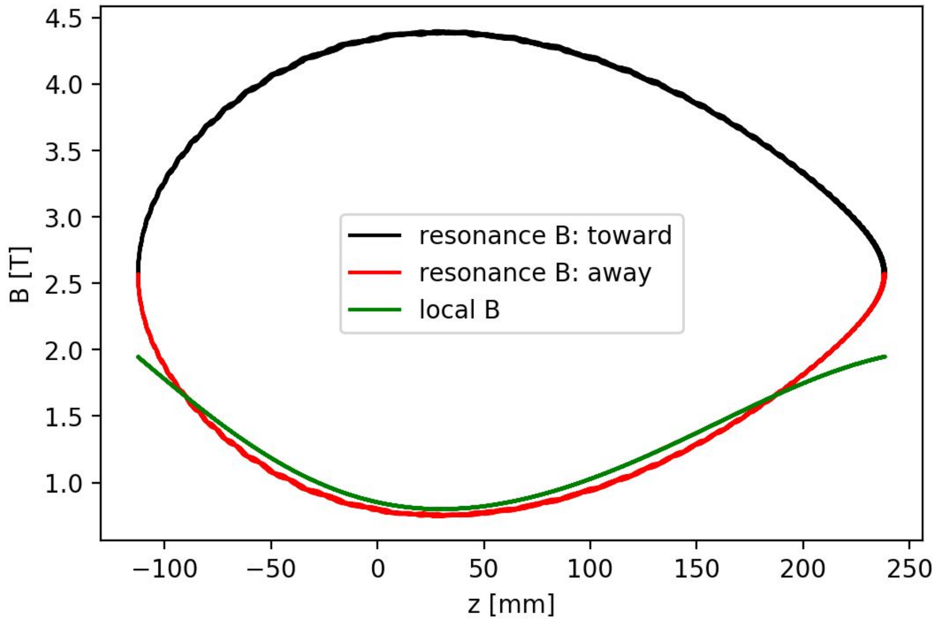


Modes of heating: one crossing, toward

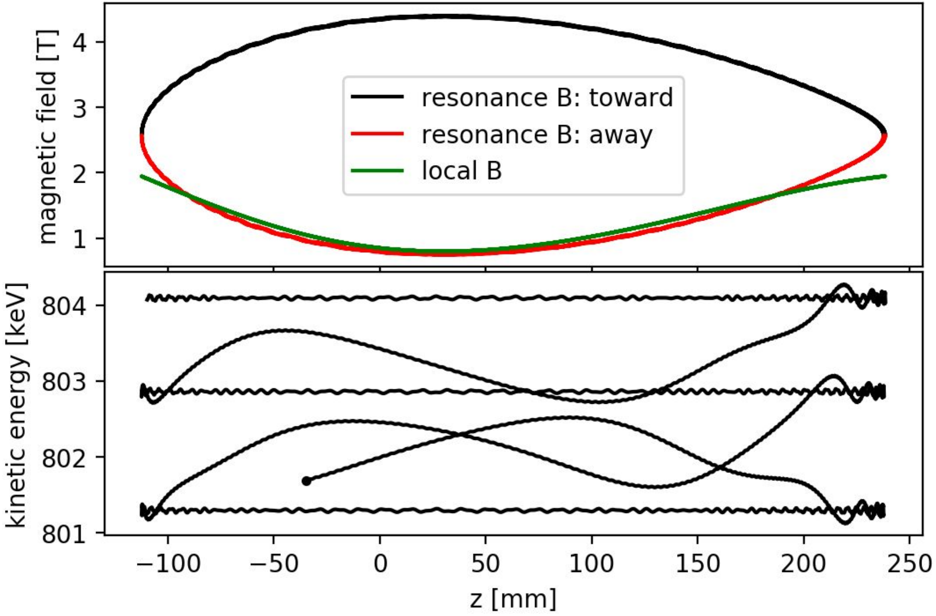


- Axial velocity large enough for no away resonance
- Single-pass energy changes remain relatively small

Modes of heating: one crossing, away

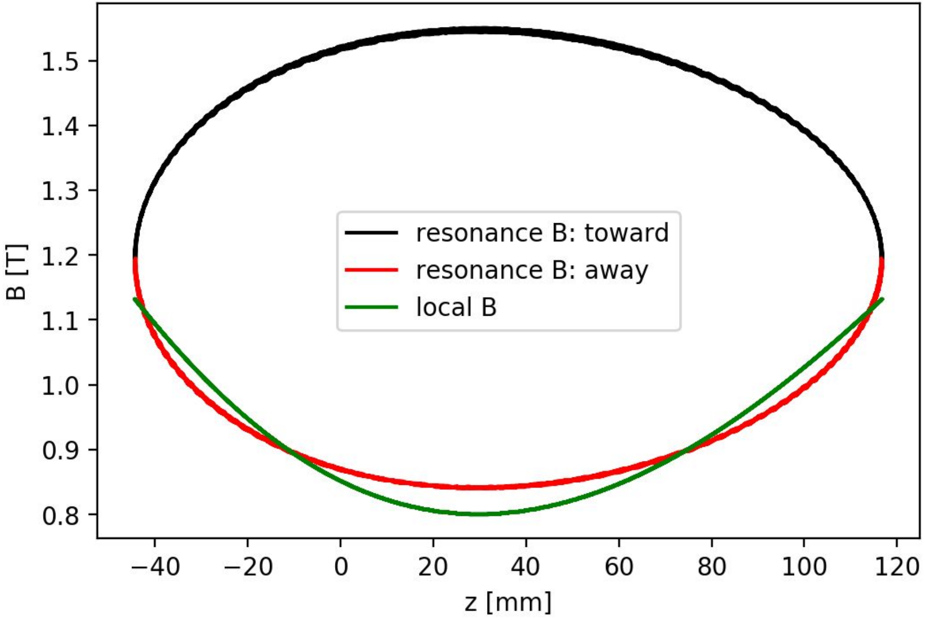


Modes of heating: one crossing, away

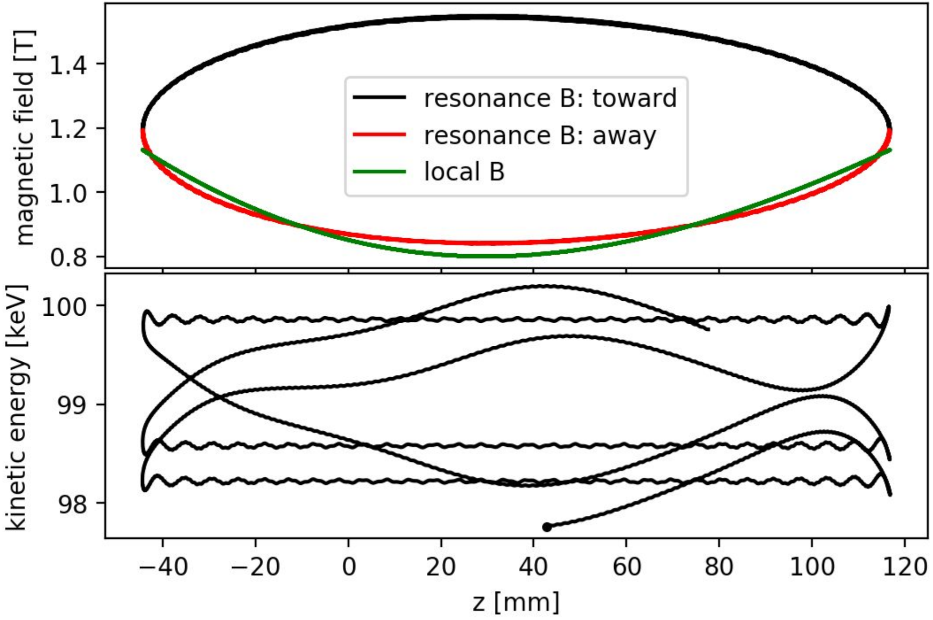


- Axial velocity large enough for no toward resonance
- End-to-end energy changes larger (keV range)---near resonance most of the time
- Only possible for energies where B_{min} is accessible

Modes of heating: two crossings, away

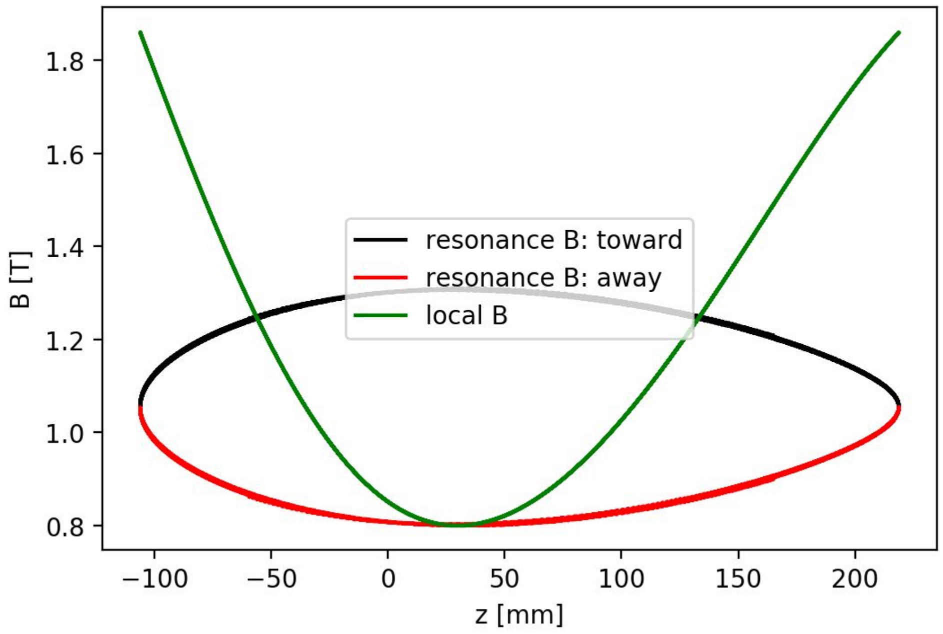


Modes of heating: two crossings, away

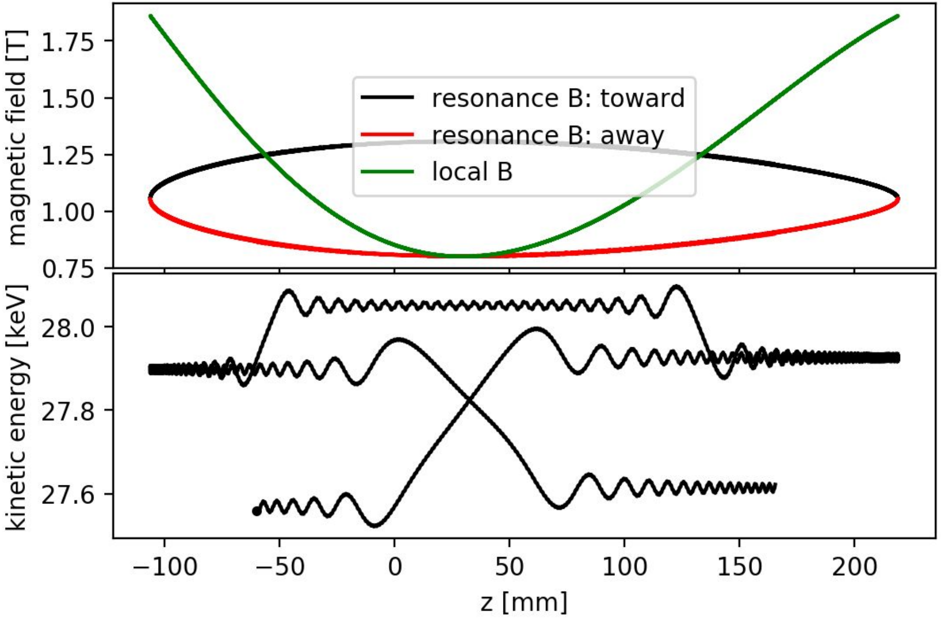


- End-to-end energy changes larger (~keV) as there can be near resonances along entire
- Requires B_{min} be accessible

Modes of heating: two crossings with B_{min}

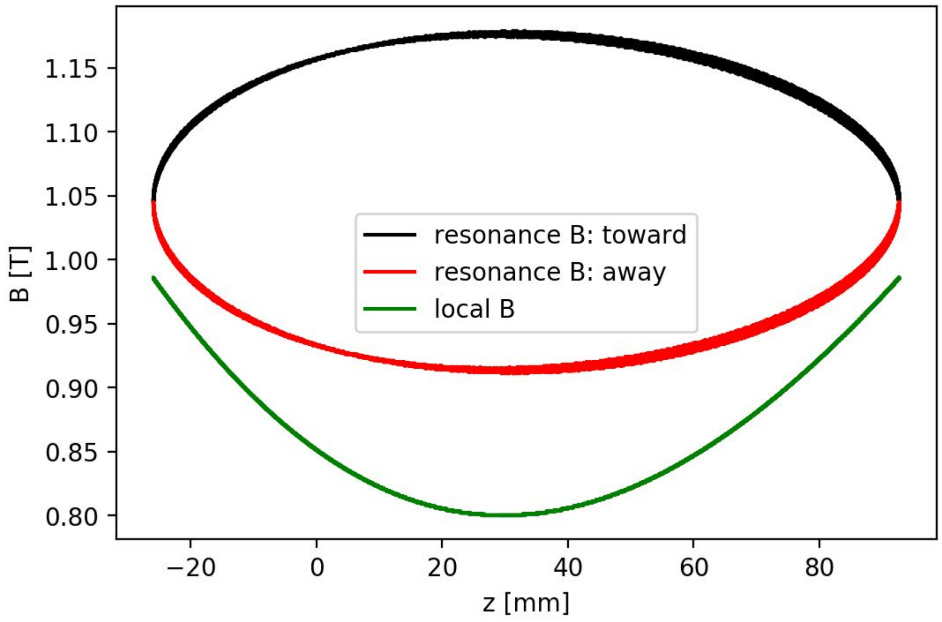


Modes of heating: two crossings with B_{min}

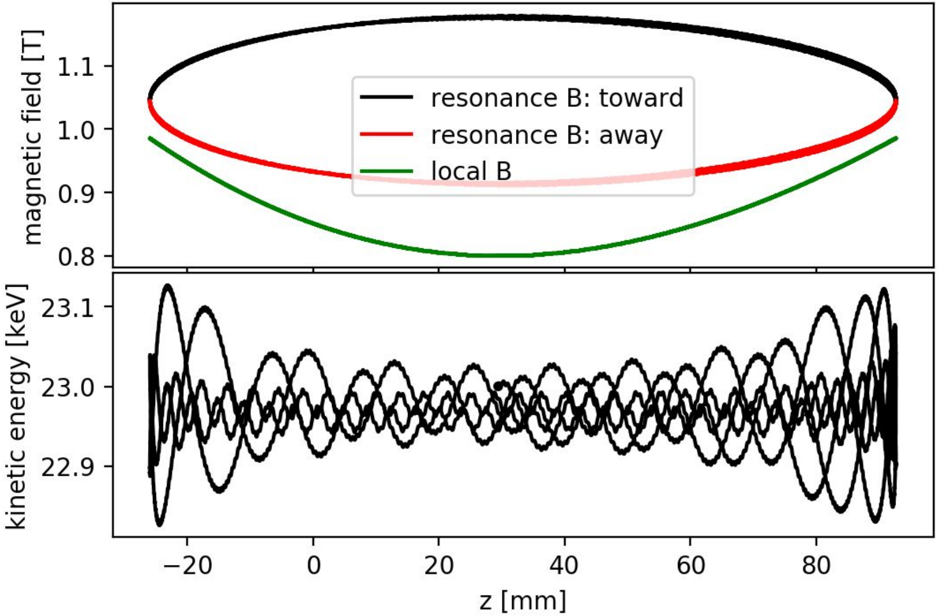


- Includes B_{min} resonant heating, so requires accessible B_{min}
- Zero-gradient heating so large ΔKE possible

Modes of heating: no resonant heating

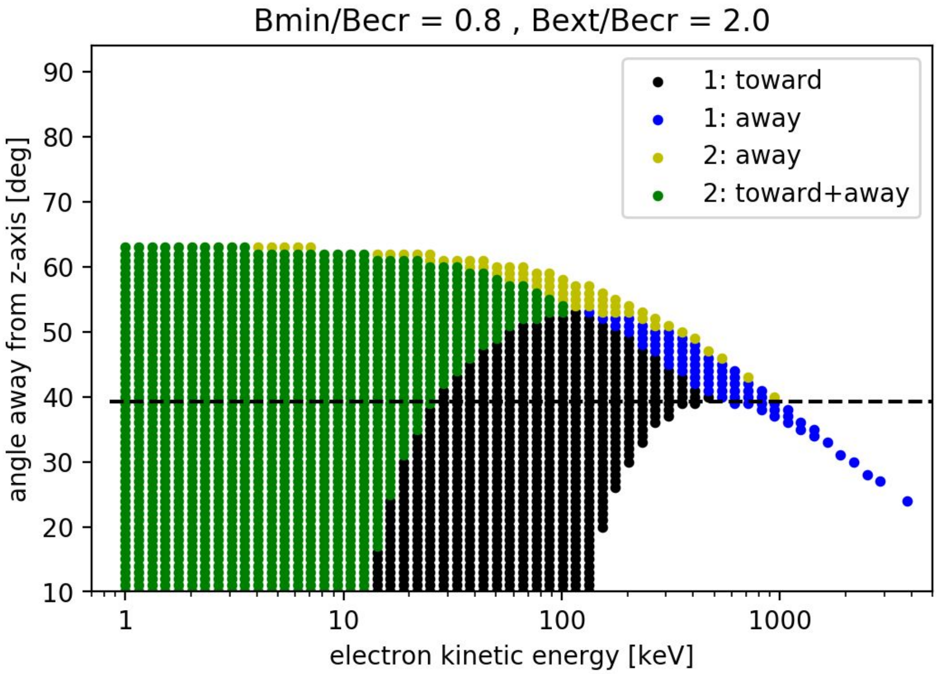


Modes of heating: no resonant heating

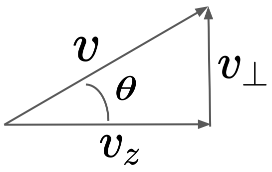


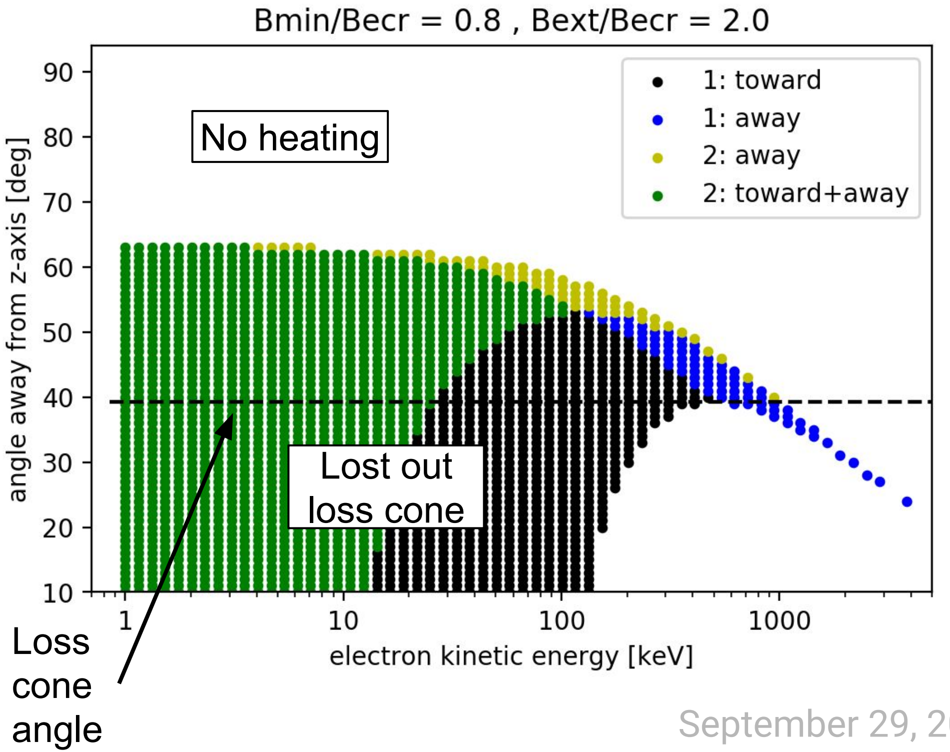
- Axial angle too large so resonance isn't reached

Mapping the heating phase space



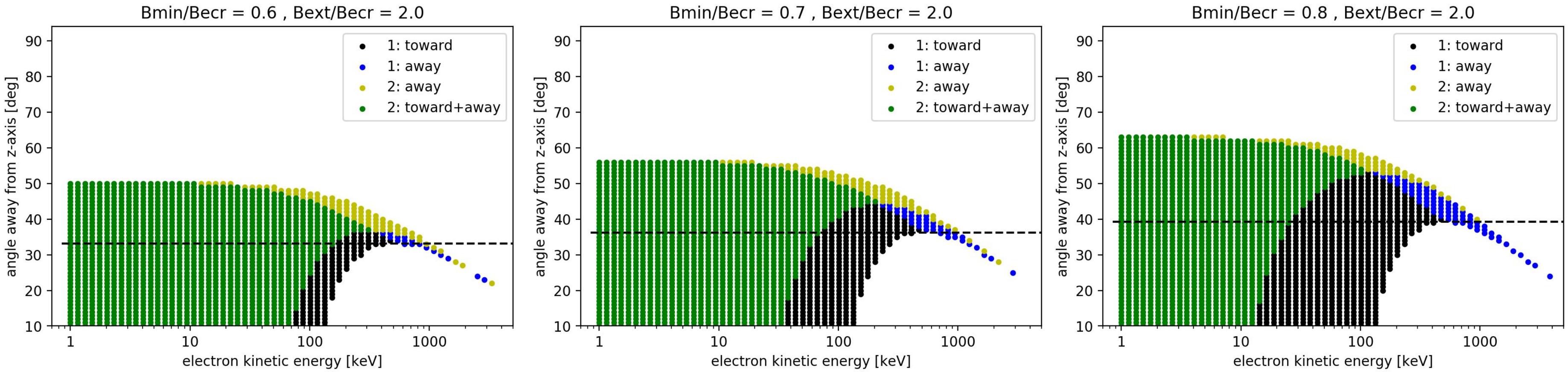
Mapping the heating phase space





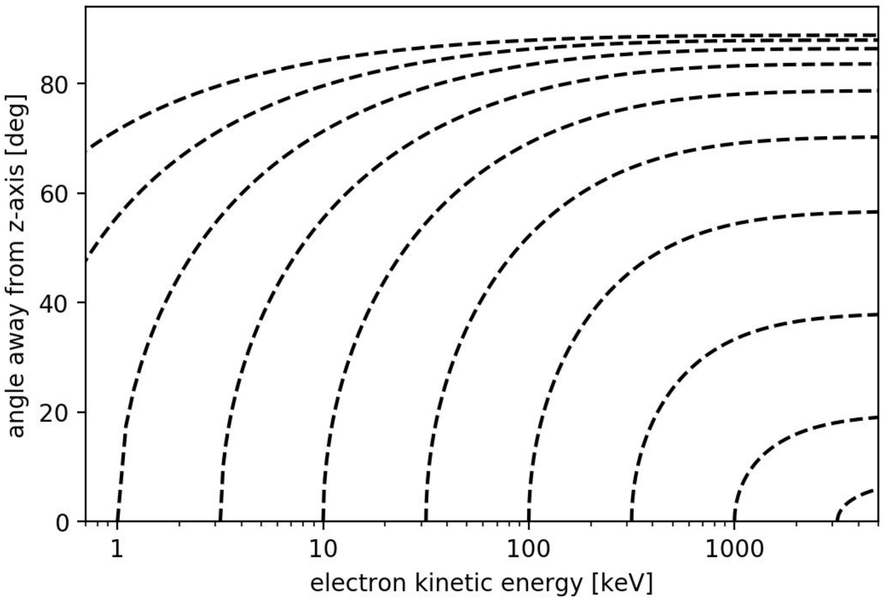
- $B_{res} = B_{min}$ heating along green/black border
- Defines phase space area where resonant heating may occur
- True for all ECRIS

Heating phase space comparison

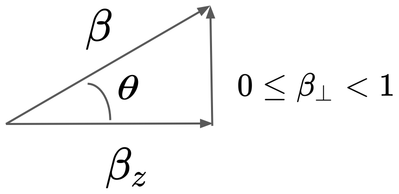


- $B_{res} = B_{min}$ moves to higher energies
- Resonant heating phase space area increases

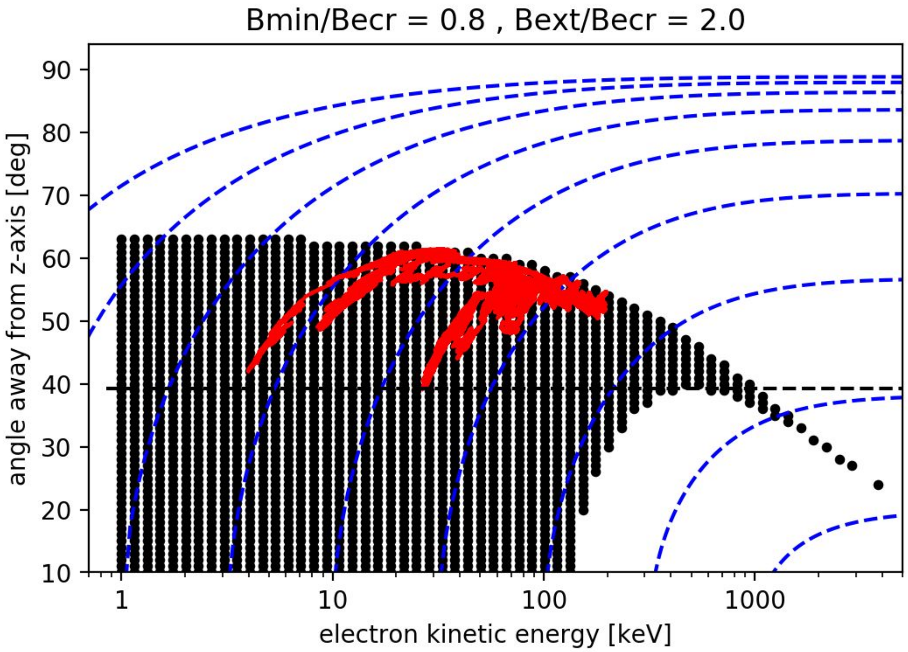
Transverse heating lines



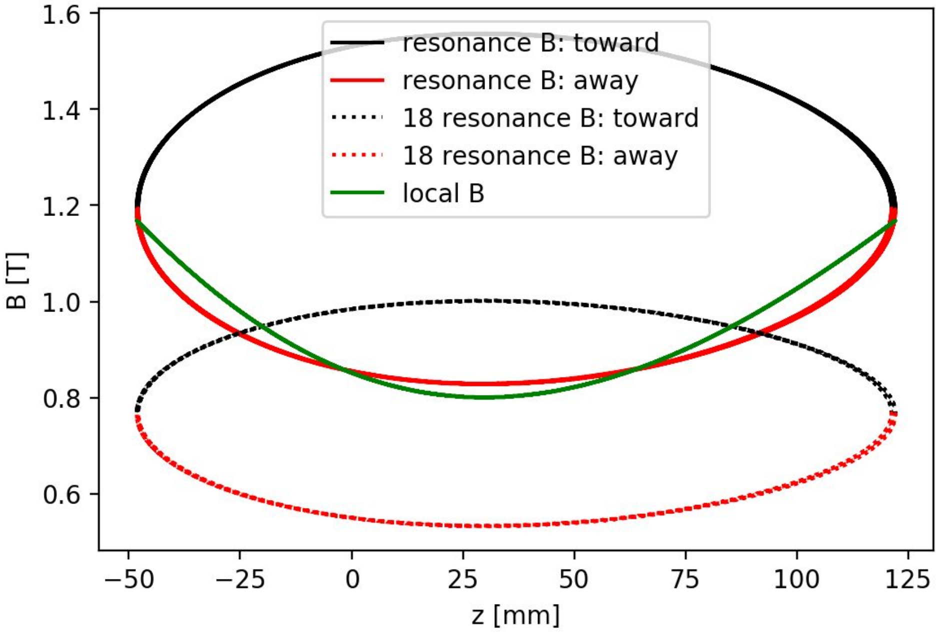
Dashed lines are curves where all energy changes only alter transverse velocity



Transverse heating lines with electrons

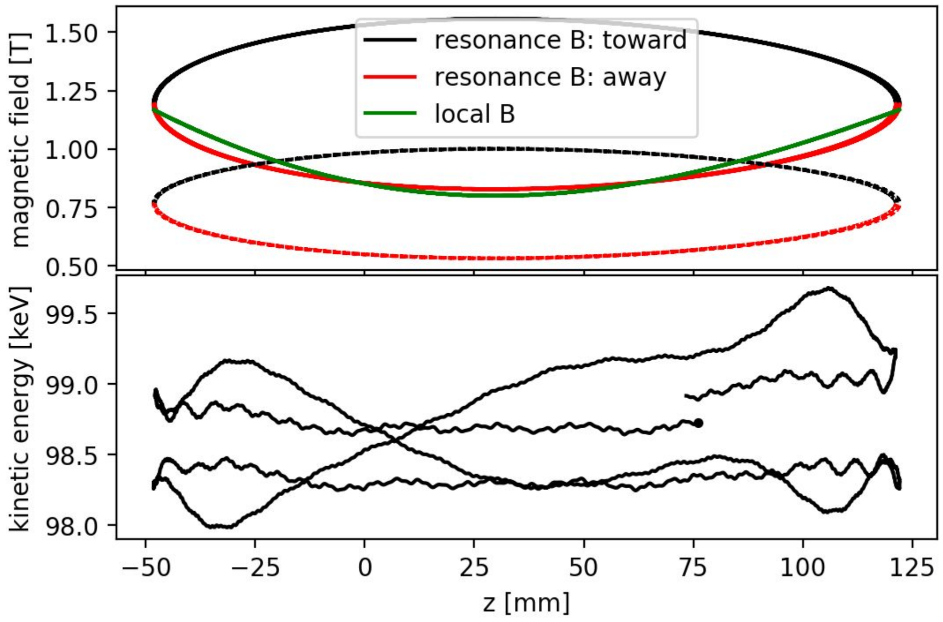


What happens when you add a second frequency?



- Add 18 GHz
- E_{18}= 4 kV/m
- E_{28}=10 kV/m

Second frequency addition



Needs going forward

- Statistics:
  - what percentage of electrons find fast-heating modes?
  - energy distribution (not average!) vs. time

- Better microwave model (distribution and magnitude)
  - progress has been made elsewhere (Mironov, for example) showing higher fields outside resonance zones
  - question: are lower second frequencies (especially without a natural resonance such as VENUS 18GHz at B_{min}=0.8 T) less attenuated so lower power is needed to disturb fast, fundamental heating??

In Summary

1. A plasma distribution that gains kinetic energy faster than its distribution can be equilibrated via scattering will be more prone to kinetic instabilities

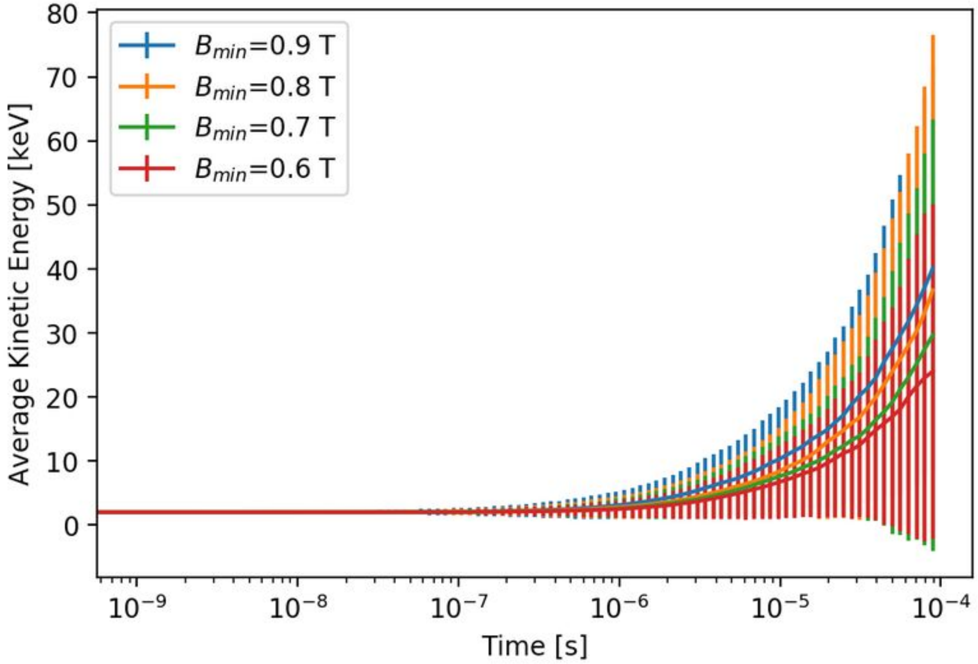
2. Resonantly heating near low magnetic field gradients means potentially greater changes in electron energy

3. Raising B_{min}/B_{res} to ~0.8 makes zero-gradient, axial heating accessible ~20 keV electrons...for all sources

4. The ability to access very-low-gradient regions allows for keV energy changes in a single end-to-end pass (up from 10s to 100s of eV)

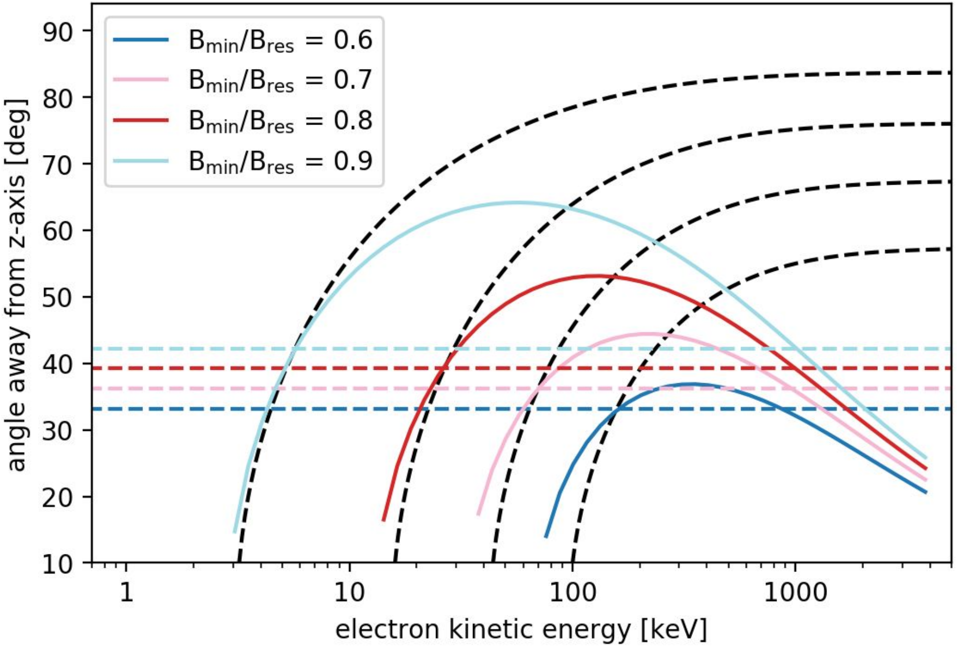
5. Adding a second frequency acts provides a “scattering event” to disturb fast kinetic-energy-gain paths

Need statistics...



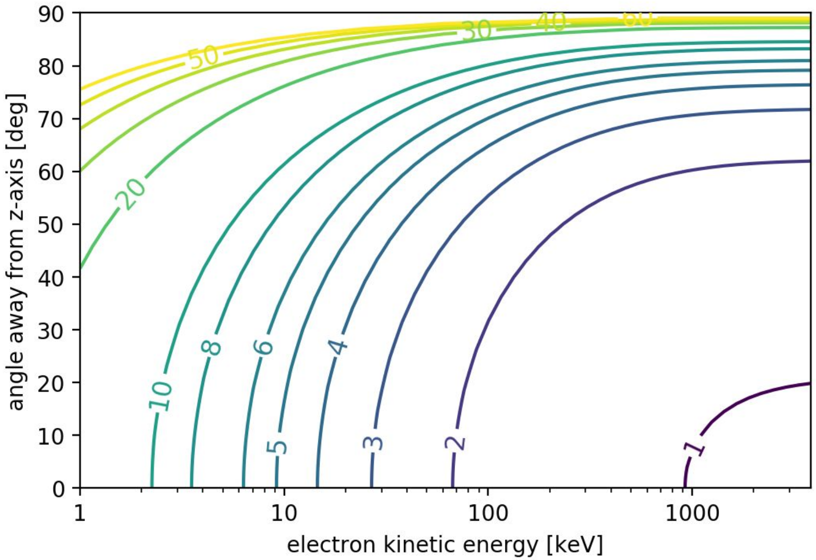
- Axial angle too large so resonance isn't reached

Heating lines, Bmin lines

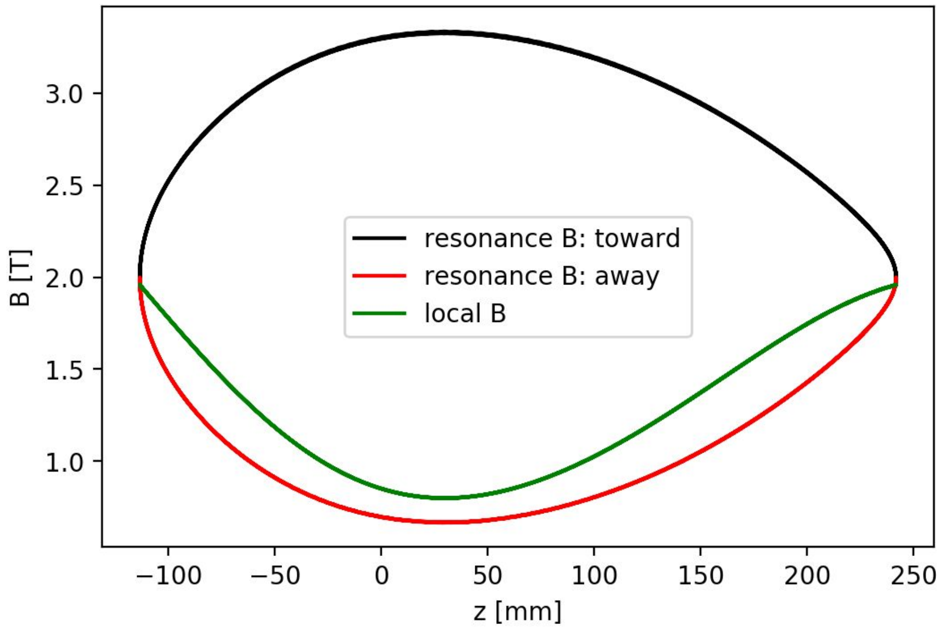


Revolutions per mm at 1 tesla

Cyclotron revolutions per mm as a function of kinetic energy and angle



The notch


3.0
2.5
2.0
1.5
1.0
B [T]
resonance B: toward
resonance B: away
local B
−100
−50
0
50
100
150
200
250
z [mm]

Distribution function troubles