26th International Workshop on ECR Ion Sources – 17/09/2024

Simulation of Bremsstrahlung emission in ECRIS and its dependence on the magnetic confinement

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Outline

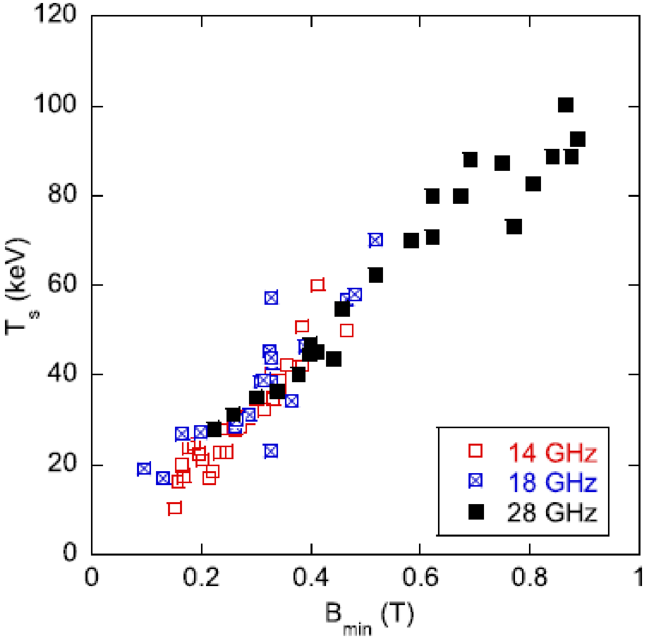
Effect of minimum magnetic field on bremsstrahlung

Dependence of the Bremsstrahlung Spectral Temperature in Minimum-B Electron Cyclotron Resonance Ion Sources

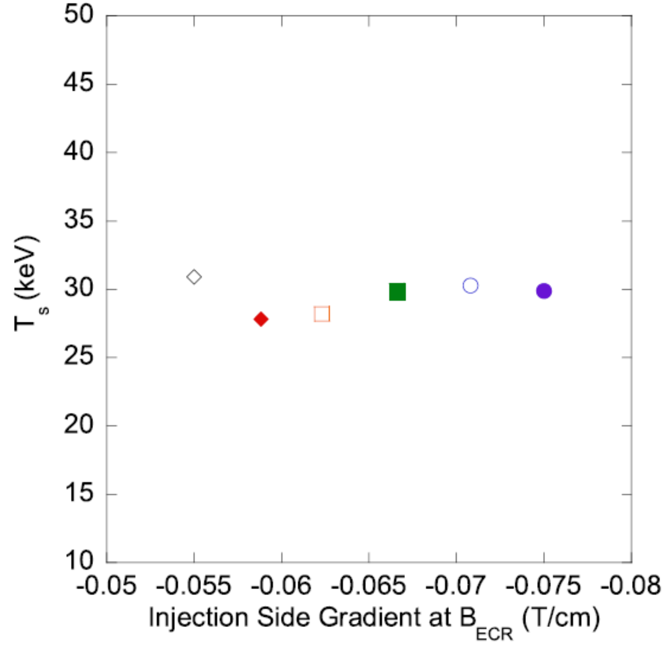
J. Benitez, C. Lyneis, L. Phair, D. Todd, D. Xie

Measured photon spectral temperature in ECRIS is **only** a function of the **minimum magnetic field B_{min}**.

Dependence of **photon spectral temperature** (T_s) on **minimum magnetic field** (B_{min})



Dependence of **photon spectral temperature** (T_s) on **magnetic field gradient at ECR zone**



Benitez et al. (2017), IEEE transaction on Plasma Science.

Anisotropic bremsstrahlung emission

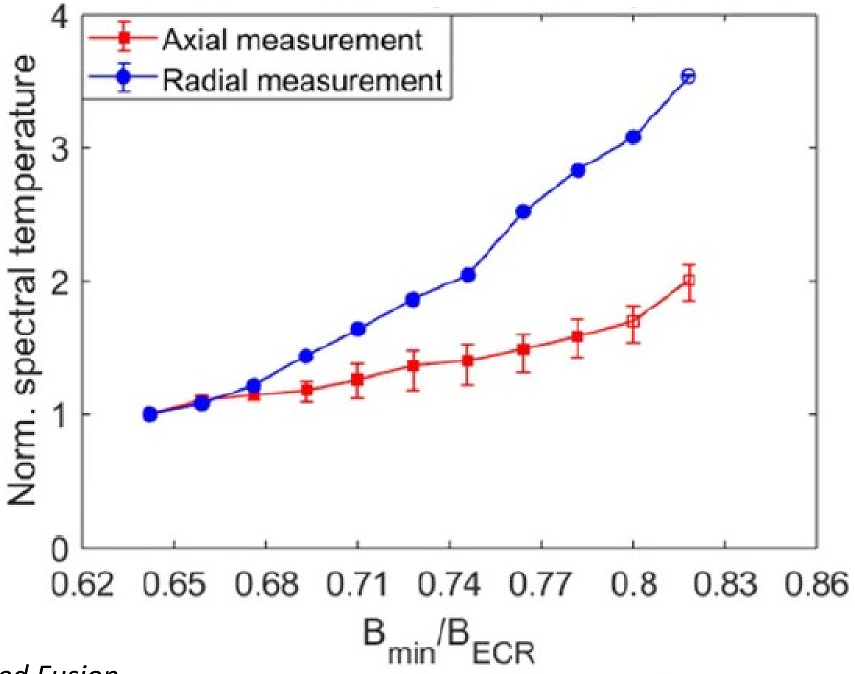
Correlation of bremsstrahlung and energy distribution of escaping electrons to study the dynamics of magnetically confined plasma

B S Bhaskar[1,2,*], H Koivisto[1], O Tarvainen[1,3], T Thuillier[2], V Toivanen[1], T Kalvas[1], I Izotov[4], V Skalyga[4], R Kronholm[1] and M Marttinen[1]

Measured X-ray photon spectral temperature much **higher in radial direction** than axial one at ⇧ E_{ph}.

➢ **Anisotropic** electron energy distribution function (**EEDF**).

B field effect on **spectral temperature**



Bhaskar et al. (2017), Plasma Physics and Controlled Fusion

Recent simulation of ECRIS behavior

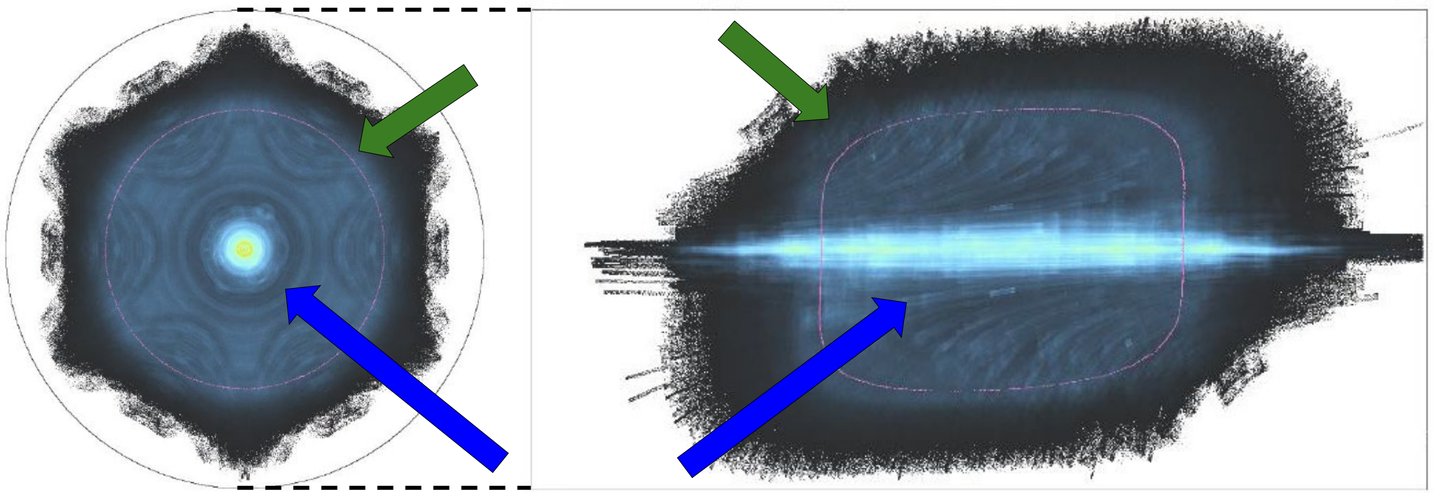
Numerical investigations of the minimum-B effect in Electron Cyclotron Resonance Ion Source

V. Mironov, S. Bogomolov, A. Bondarchenko, A. Efremov, V. Loginov, D. Pugachev

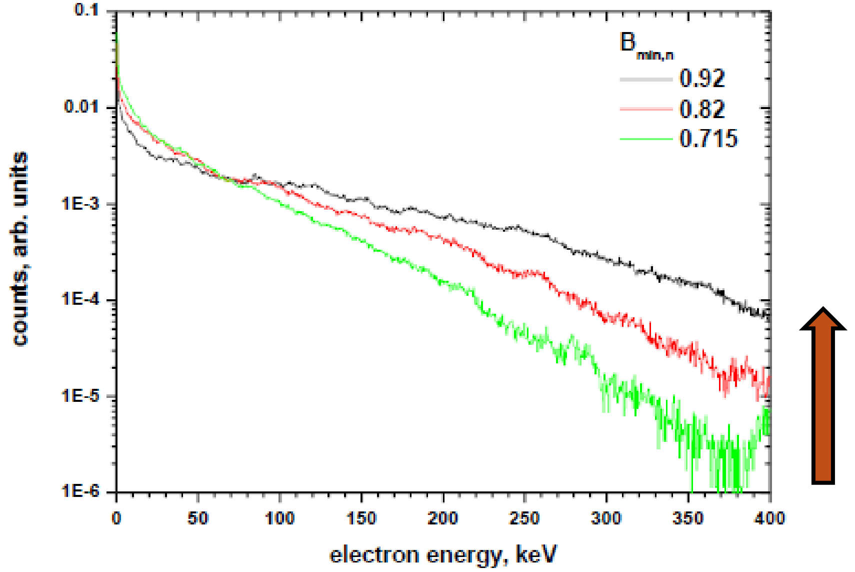
NAM-ECRIS: 2 iterative 3D code to **separately simulate** electrons (***e***$^-$) and ion dynamics.

- ***e***$^-$ **distribution** → Colder dense core + Hotter dilute halo.
- ⇧ $\boldsymbol{B_{min}}$ → ⇧ *e*$^-$ temperature (T_e), more compact plasma in longitudinal direction.

Transversal and longitudinal cross-sections of the ***e***$^-$ **distribution**



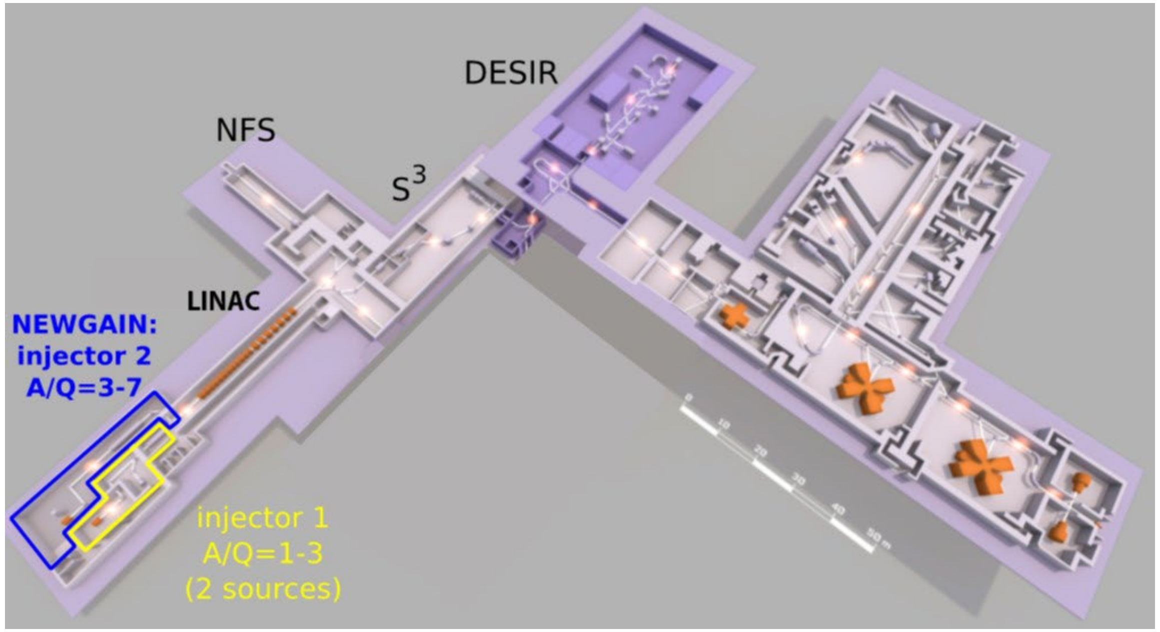
$\boldsymbol{T_e}$ **spectrum** of trapped e$^-$ for ≠ B_{min}

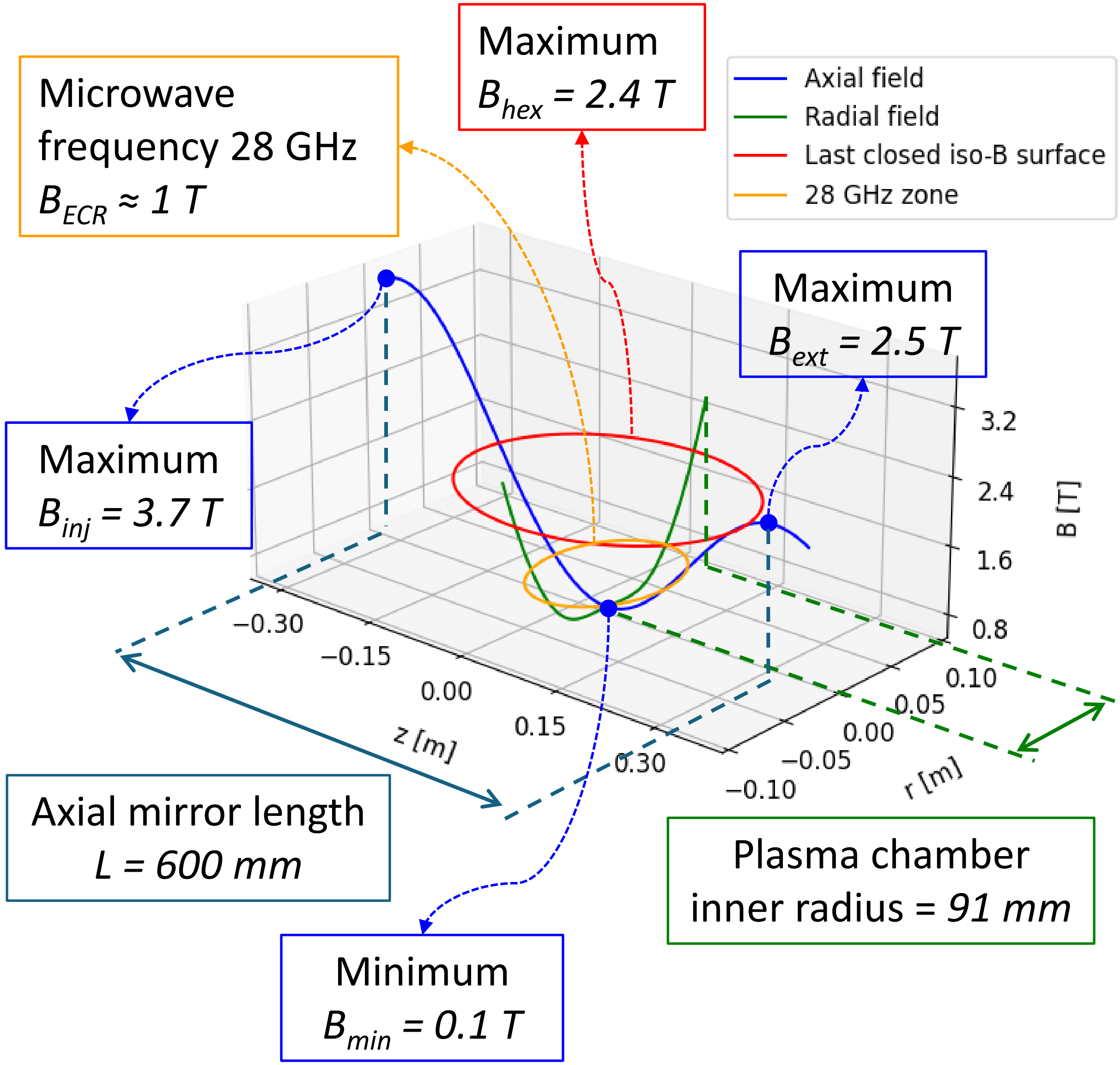


Mironov et al. (2021), Journal of Instrumentation.

ASTERICS ion source

ECRIS for the new GANIL injector (**NEWGAIN**) for ***A/Q ≤ 7*** to the existing **SPIRAL2** linear accelerator at the Grand Accelerateur National d'Ions Lourds (**GANIL**) facility.





Objectives and methodologies

Investigate **electron dynamics** inside ASTERICS ion source:

- Effect of magnetic field on **density, energy and velocity distributions**.
- Effect of magnetic field on volume **bremsstrahlung** emission.
- Study of the **anisotropic photon emission** inside ECRIS.

- Large cavity (*15.6 dm^3*).
- Long timescale (*1 ms*).
- **Hot non-collisional** plasma ($T_e \approx 5\text{-}10\ keV$).

3D Monte-Carlo (MC) electron simulation.

Monte-Carlo code

E **and** ***B*** **fields evaluation at** e^- **position** → Particle pusher (relativistic Boris algorithm) → Collision phenomena (n_e = 15% n_{crit}) → Bremsstrahlung emission

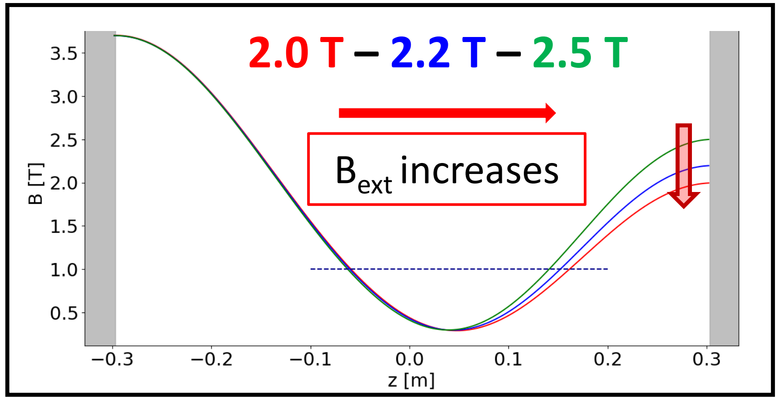
- 2D hexapolar magnetic field map + fringe field model.
- Axisymmetric 2D axial magnetic field map. → Profiles:
- *28 GHz* microwave providing *7 kW* (planar wave approx.).

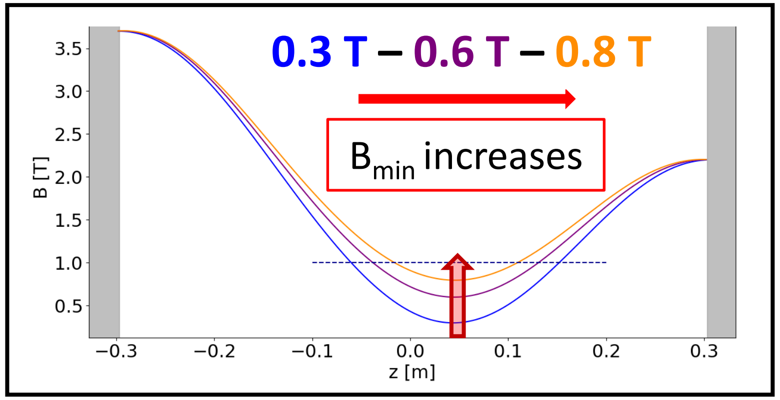
B_{ext} increases

2.0 T – 2.2 T – 2.5 T

B_{min} increases

0.3 T – 0.6 T – 0.8 T





Results on electron behaviour

Electron dynamics

E and ***B*** fields evaluation at e^- position

Particle pusher (relativistic Boris algorithm)

Collision phenomena

(n_e = 15% n_{crit})

Add visual

Bremsstrahlung emission

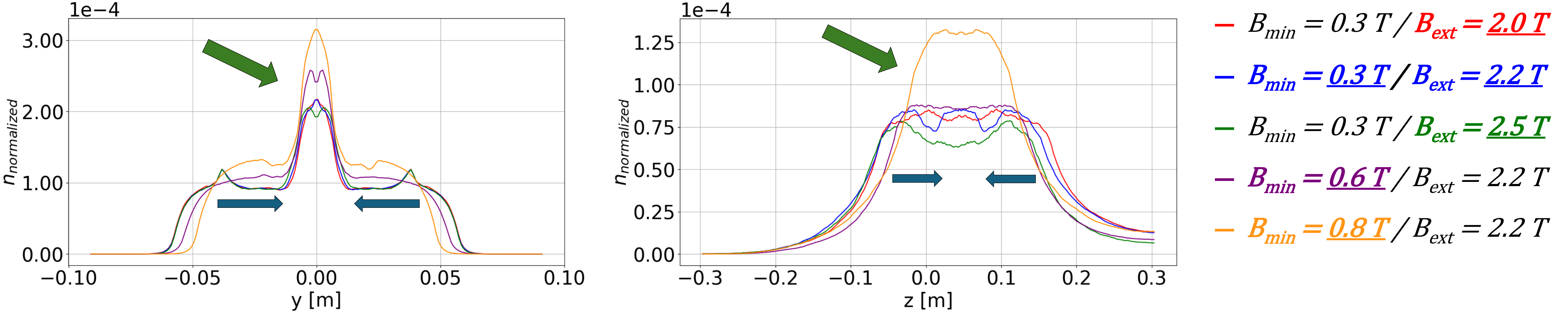
Electron density

Same results as complex simulations: **Dense** electron **core**, ⇧ B_{min} → Plasma **compression**.

- Hot electrons in ECRIS **marginally affected** by plasma.
- Dense plasma core volume scales with plasma chamber volumes.

XY plane at z_{min} along y-axis with $x=0$

XZ plane along z-axis at $y=0$

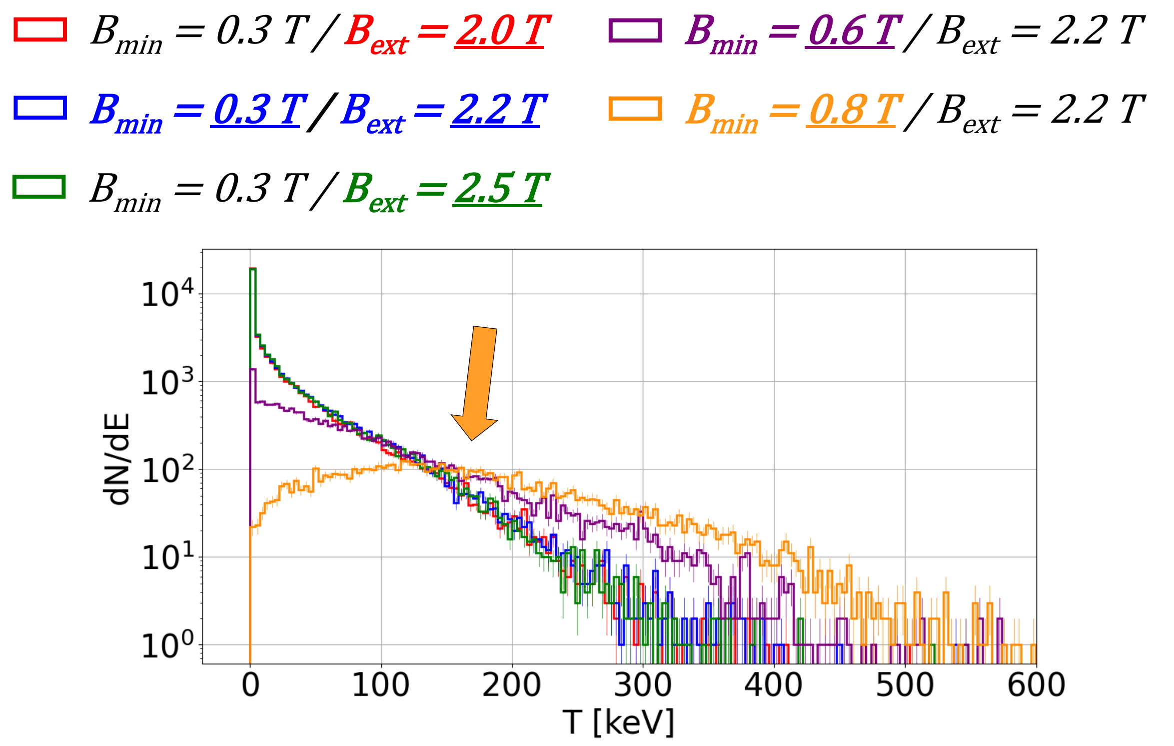


Electron energy distribution (EED)

EED of electrons confined in the plasma volume.

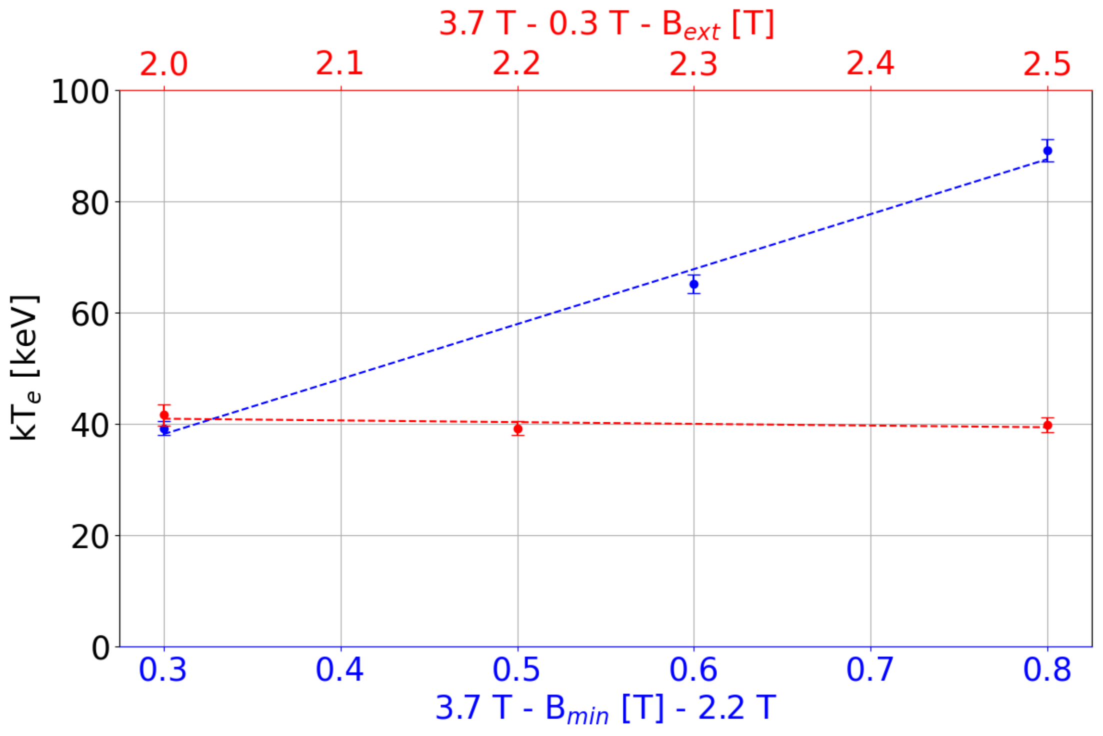
- ⇧ B_{ext} → No visible effect.
- ⇧ B_{min} → ⇧ T_e (quasi-linear).

➢ Change of slope in $B_{min} = 0.8\ T$ → Possibly related to plasma **instabilities**.



Hot electron tail (*T > 100/200 keV*) interpolation with **Maxwell-Boltzmann** distribution.

Temperature fit: $$f(E) \propto \sqrt{\frac{E}{(kT_e)^3}}\, e^{-E/kT_e}$$

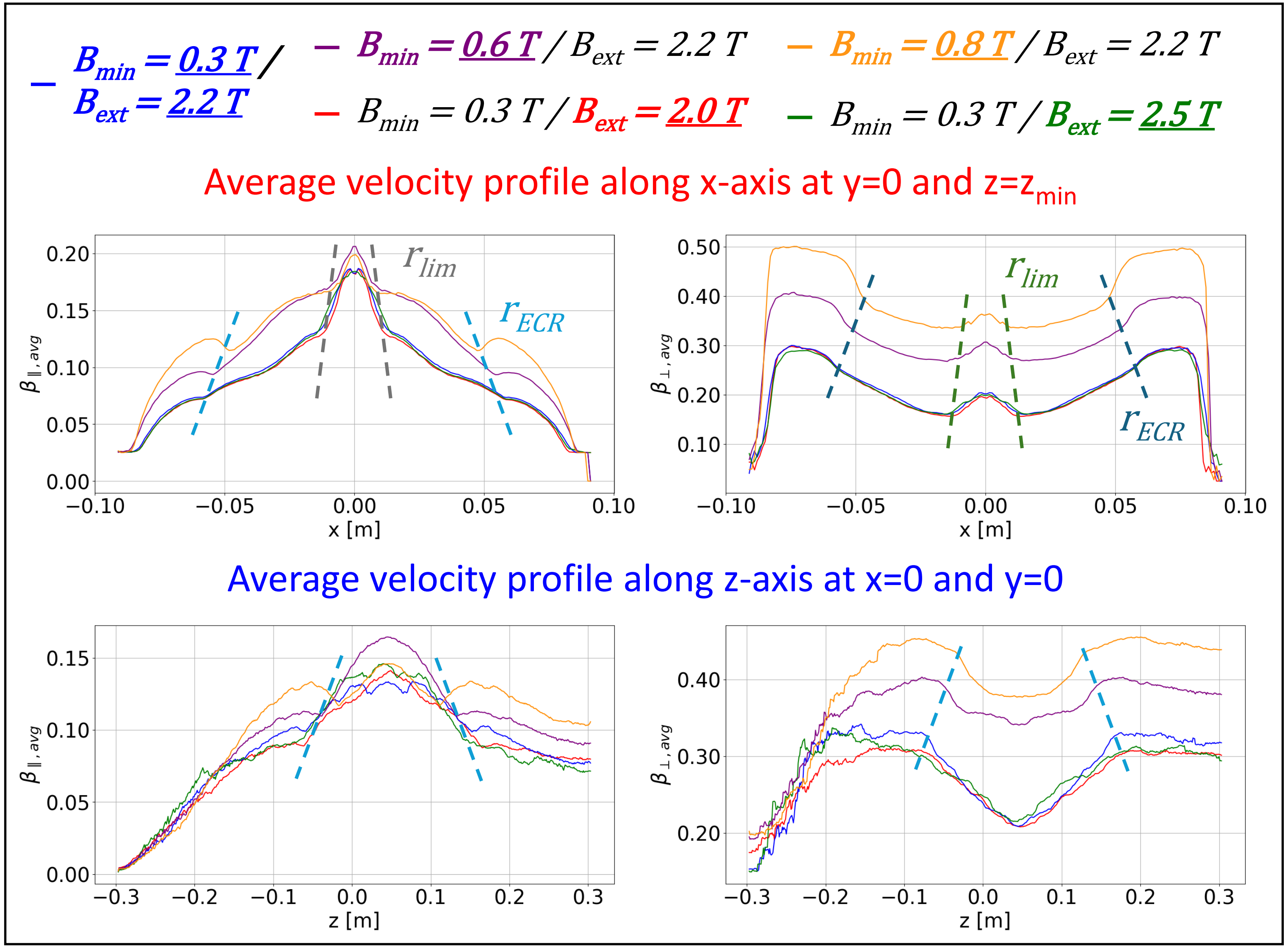


Electron velocity spatial distribution (EVSD)

Transversal profile → **3** main **regions**:
- $\boldsymbol{r} \leq r_{lim}$: e^- trapped in **axial trajectories**.
- $r_{lim} \leq \boldsymbol{r} \leq \boldsymbol{r_{ECR}}$: ⇧ $\boldsymbol{\beta_\perp}$ with ⇧ $\boldsymbol{r}$ due to $\mu_{av} \approx const.$
- $\boldsymbol{r} \geq \boldsymbol{r_{ECR}}$: **Larger** region for ⇧ $\boldsymbol{B_{min}}$.

Longitudinal profile:
- e^- velocity at **extraction** much **higher** than at **injection**.
- Inside ECR volume average **adiabatic** evolution of $\boldsymbol{\beta_\perp}$ and $\boldsymbol{\beta_{//}}$.

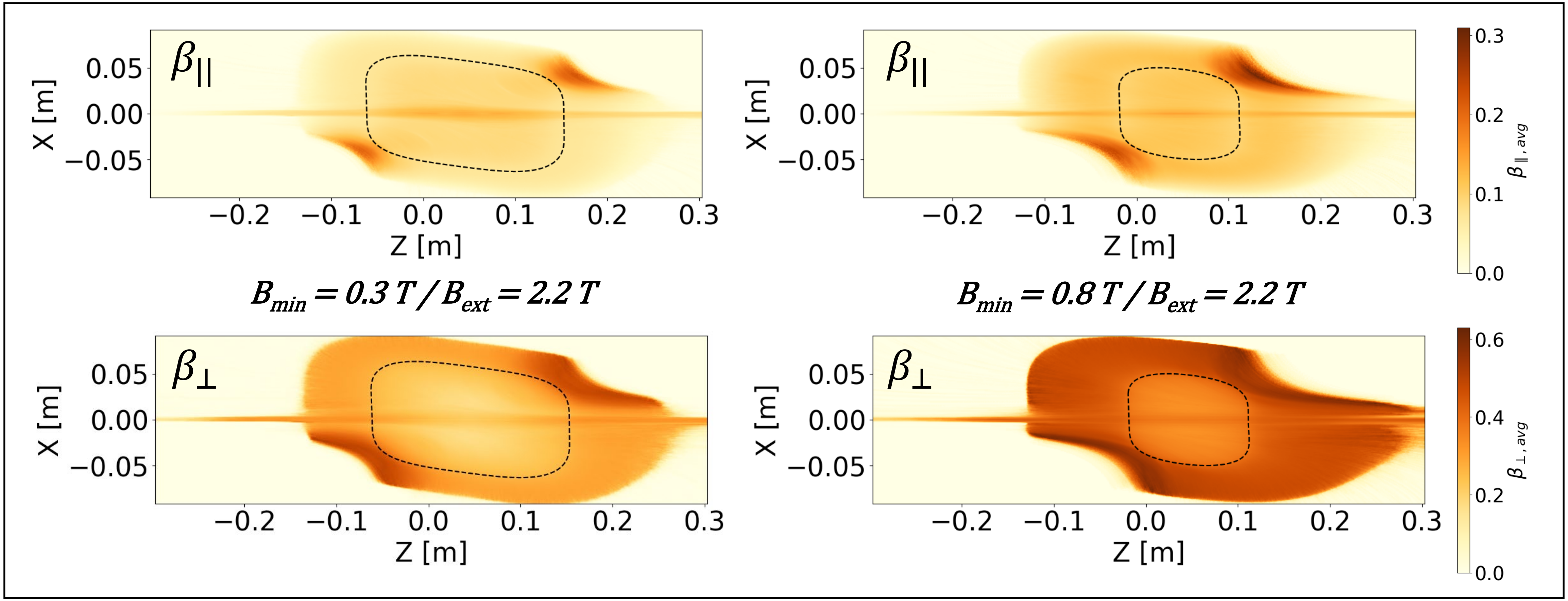
General considerations:
- ⇧ $\boldsymbol{B_{ext}}$ → No significant effect.
- ⇧ $\boldsymbol{B_{min}}$ → ⇧ **velocities** and profile modifications.



Electron velocity spatial distribution (EVSD, XZ plane)

⇧ B_{min} → ⇧ $\beta_\perp$ **in the whole plasma volume.**

➢ ⇩ ***ECR radius*** with ⇧ B_{min} → ⇧ **volume** available for relativistic ECR heating.



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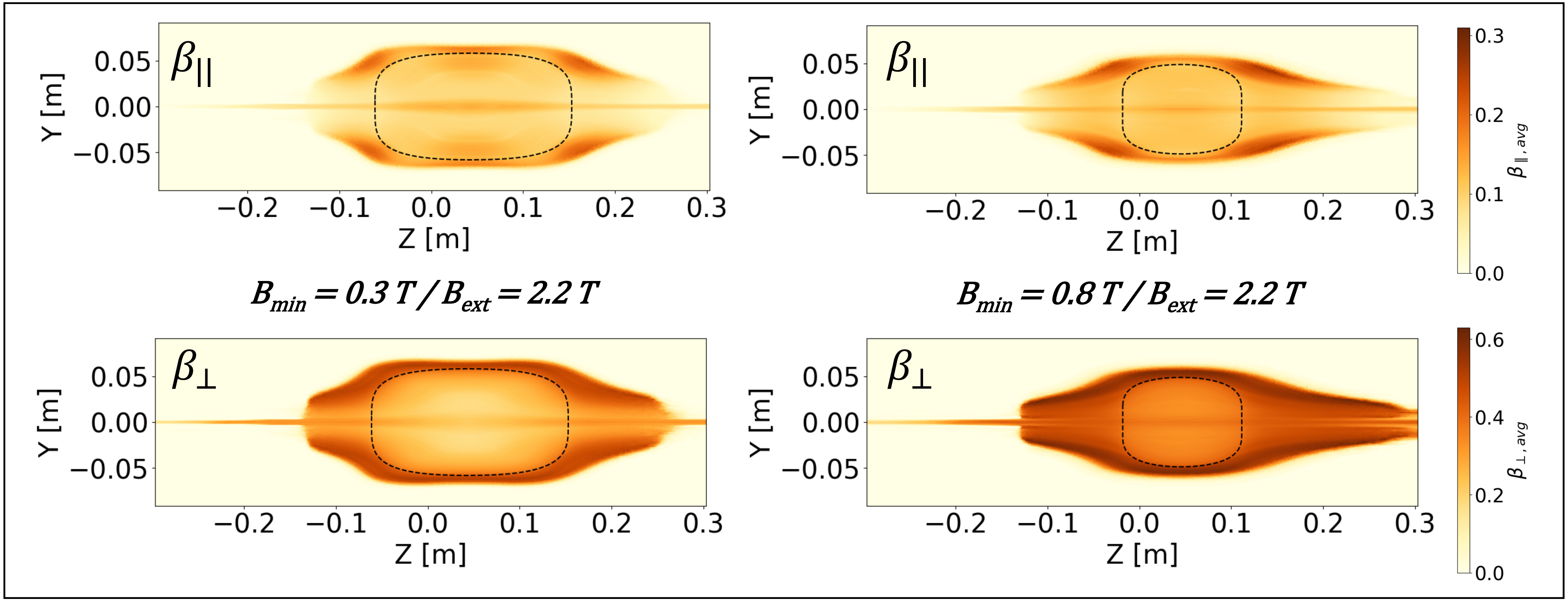
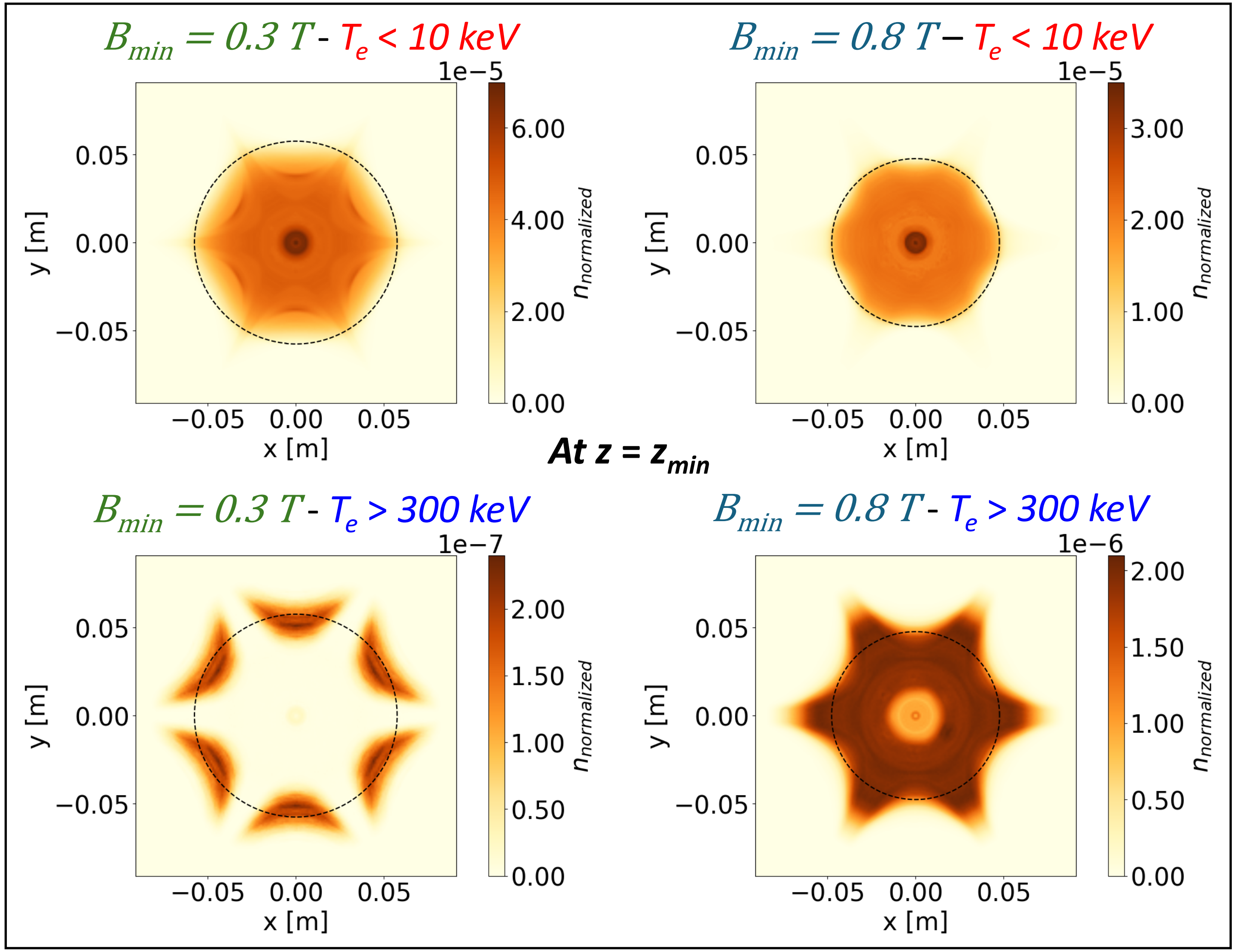


Electron energy spatial distribution (EESD)

Warm and **Hot** electrons

- Very **similar** density **distribution**.
- ⇧ normalized **density** for ⇩ B_{min}.



Very hot electrons

- ⇩ B_{min} → e^- mostly around **ECR zone.**
- ⇧ B_{min} → e^- distributed at $r_{lim} \leq r \leq r_{ECR}$ and ⇧⇧ normalized **density**.

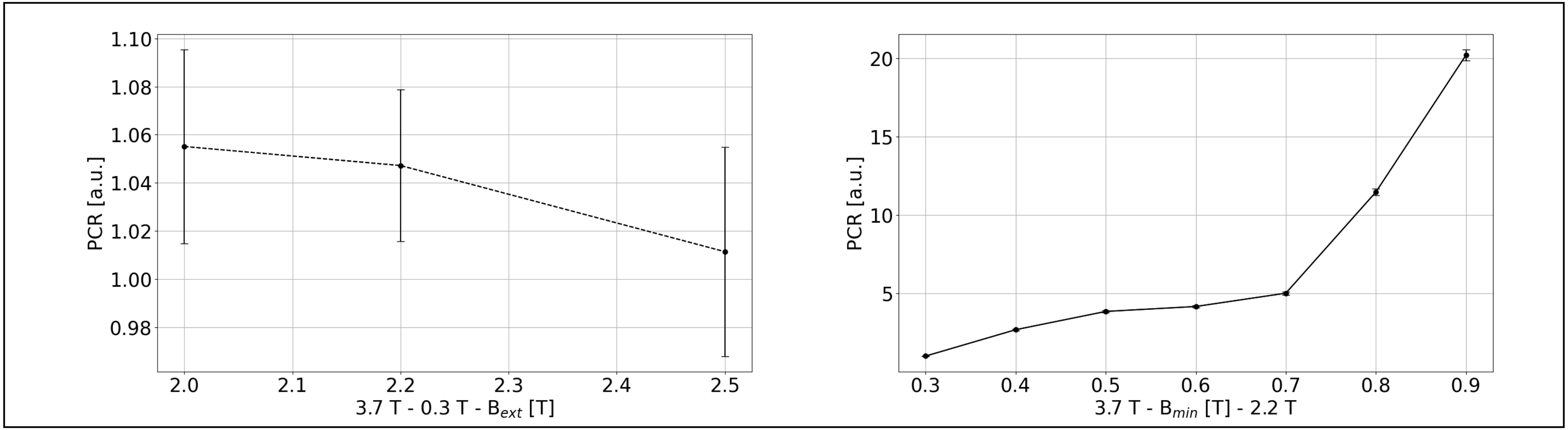
Results on bremsstrahlung emission

Electron dynamics

E and *B* fields evaluation at e^- position → Particle pusher (relativistic Boris algorithm) → Collision phenomena (n_e = 15% n_{crit}) Add visual → Bremsstrahlung emission

Bremsstrahlung emission – Photon count rate (PCR)

- ⇧ B_{ext} → No significant effect.
- ⇧ B_{min}: ⇧ **PCR** → Strong increase from $B_{min} = 0.7\ T$.

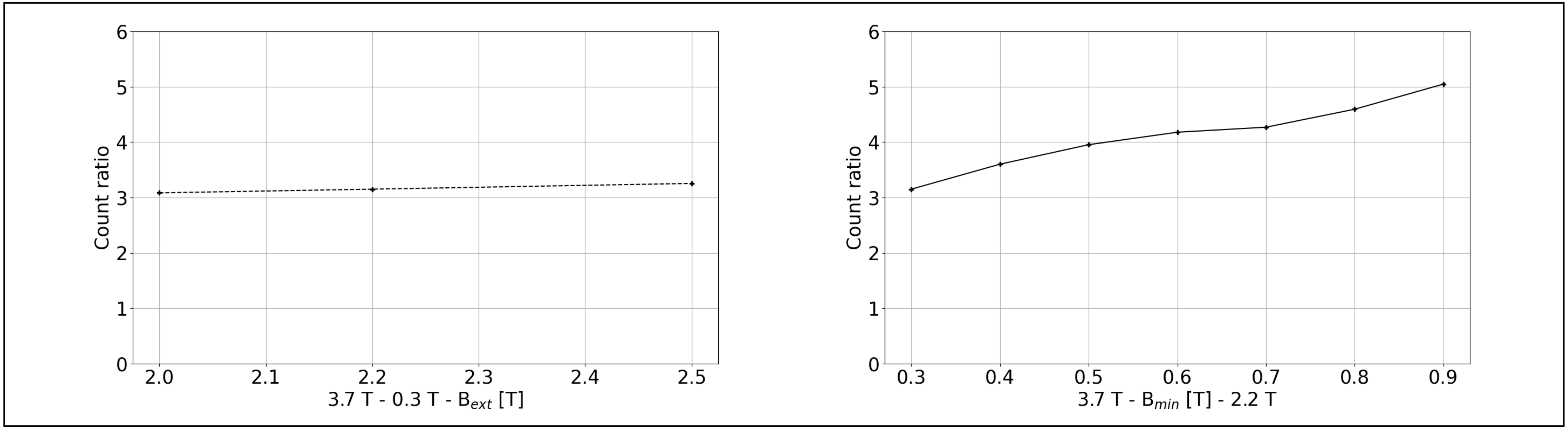


Bremsstrahlung emission – Photon count rate (PCR)

- ⇧ B_{ext} → No significant effect.
- ⇧ B_{min}: More **anisotropic** photon count in **radial** direction.

Count ratio:

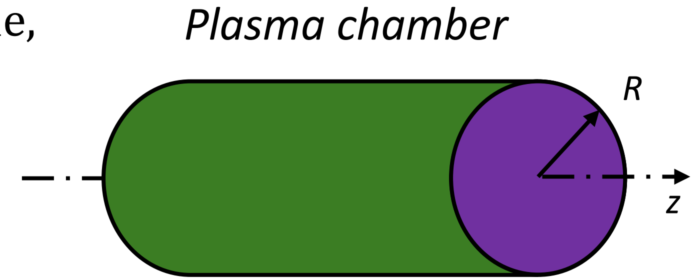
$$\frac{PCR\ at\ radial\ wall\ per\ unit\ surface}{PCR\ at\ extraction\ wall\ per\ unit\ surface}$$



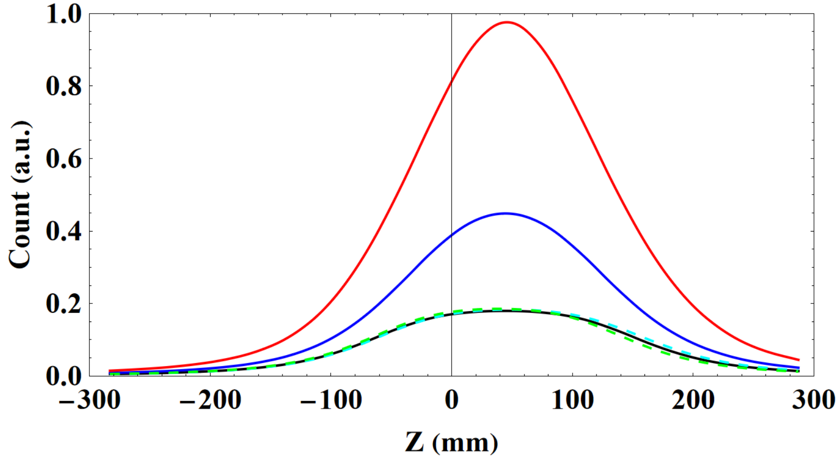
Bremsstrahlung emission – Photon directionality

- **Radial wall** → X-ray emission inside ECR zone, peaking at $z = z_{min}$.
  → Narrower emission for ⇧ B_{min}.
- **Extraction wall** → ~ Flat x-ray emission.

Plasma chamber

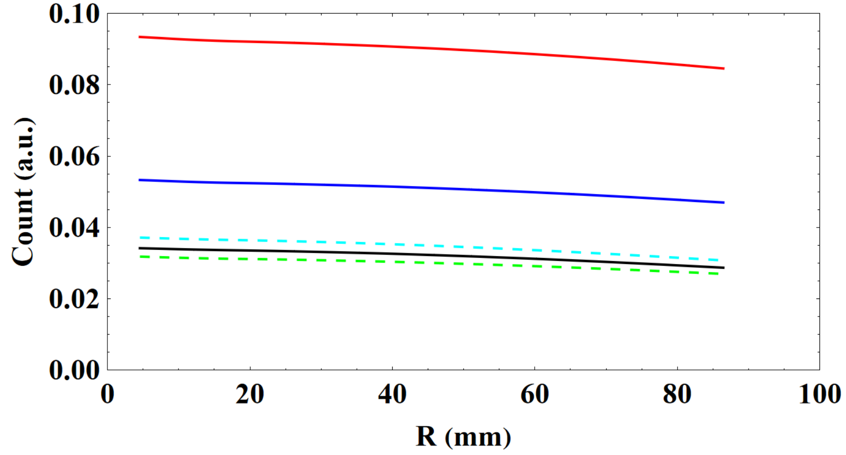


PCR at radial wall per unit surface



- - $B_{min} = 0.3\ T\ /\ B_{ext} = 2.0\ T$
— $B_{min} = 0.3\ T\ /\ B_{ext} = 2.2\ T$
- - $B_{min} = 0.3\ T\ /\ B_{ext} = 2.5\ T$
— $B_{min} = 0.6\ T\ /\ B_{ext} = 2.2\ T$
— $B_{min} = 0.9\ T\ /\ B_{ext} = 2.2\ T$

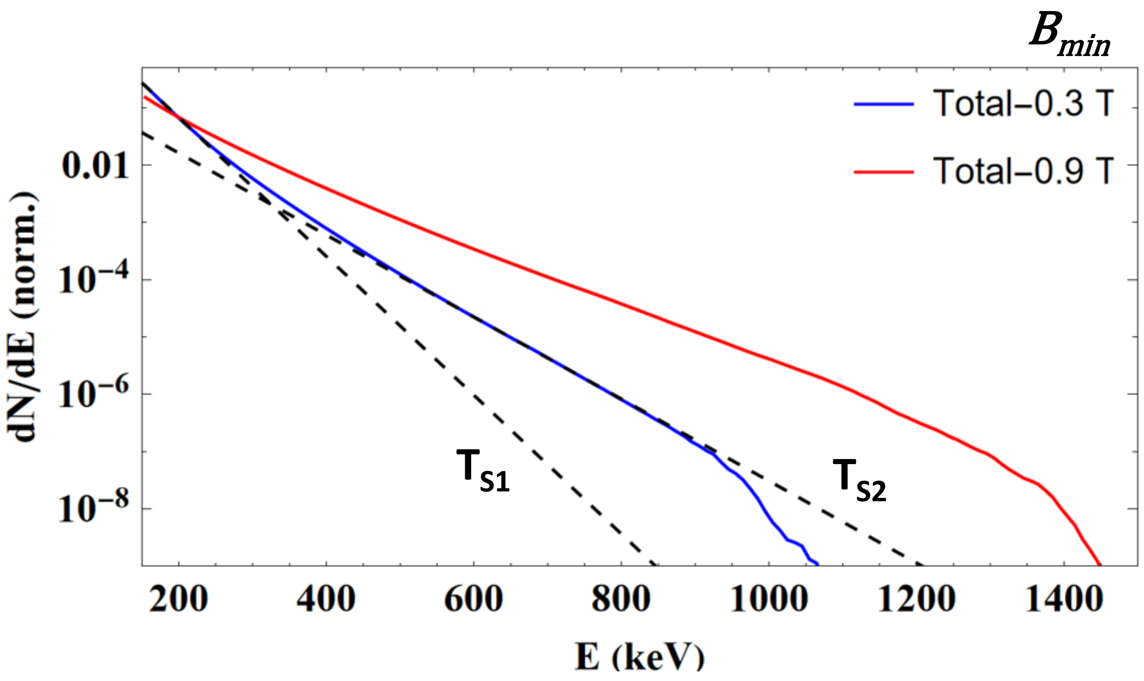
PCR at extraction wall per unit surface



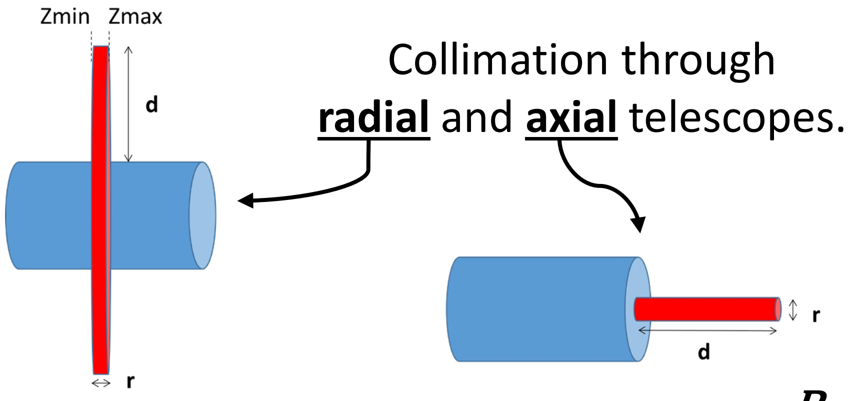
Bremsstrahlung emission – Photon energy spectrum

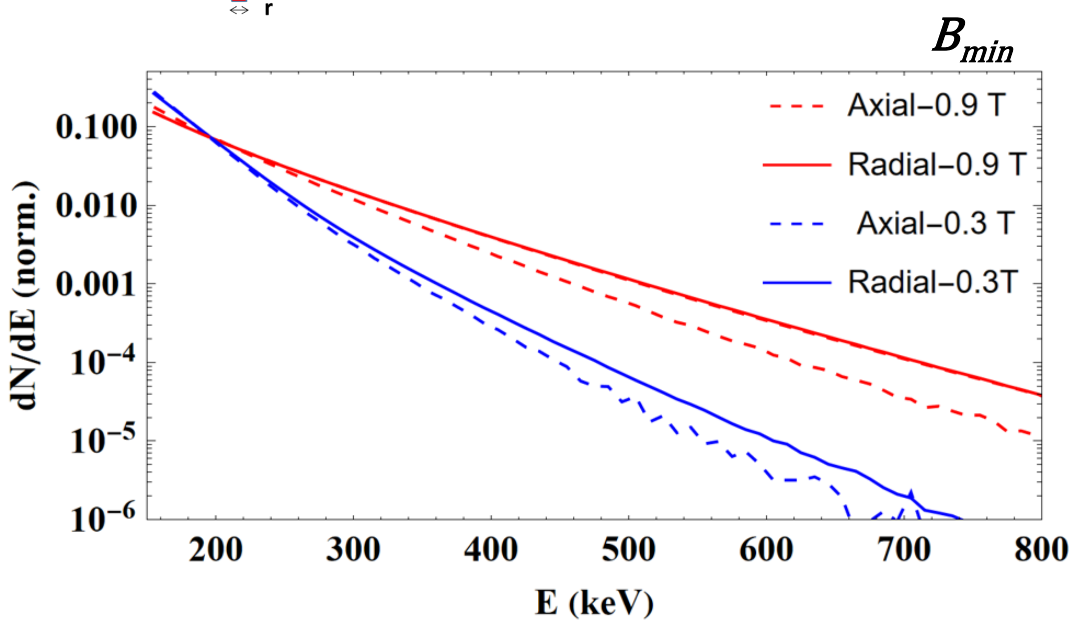
Interpolation of photon energy spectra with a **double exponential decay model** (**T_{S1}** and **T_{S2}**) due to **non-Maxwellian** EEDF.

Population fit: $f(E) \propto e^{-E/kT_s}$



Collimation through **radial** and **axial** telescopes.

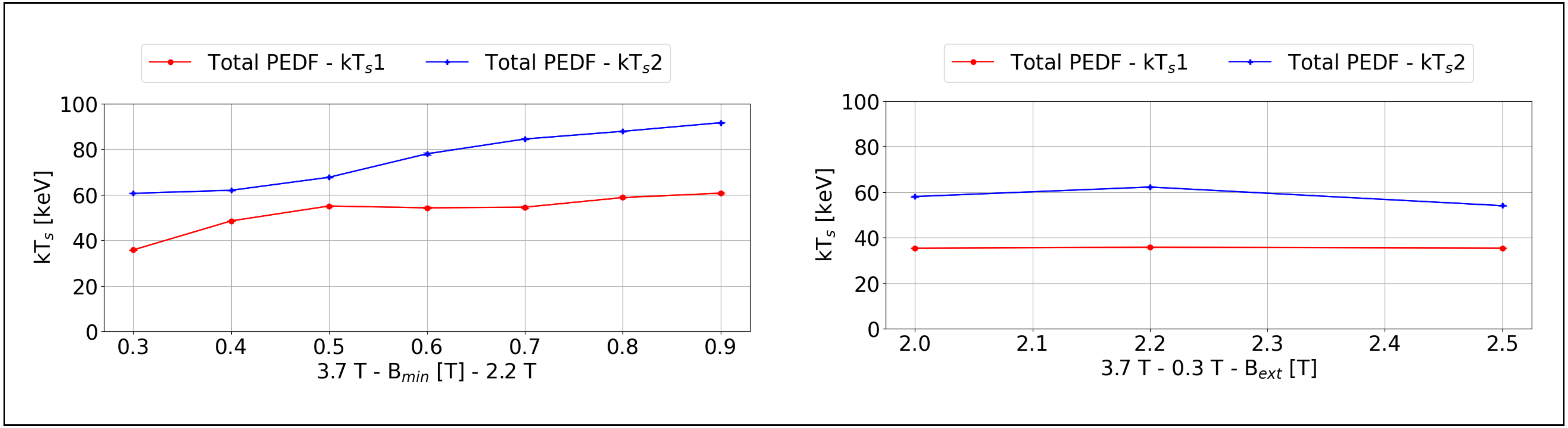




Bremsstrahlung emission – Photon energy spectrum

Photon energy spectrum change **only** with ⇧ B_{min}:

- **⇧ Photon spectral temperature** T_s.

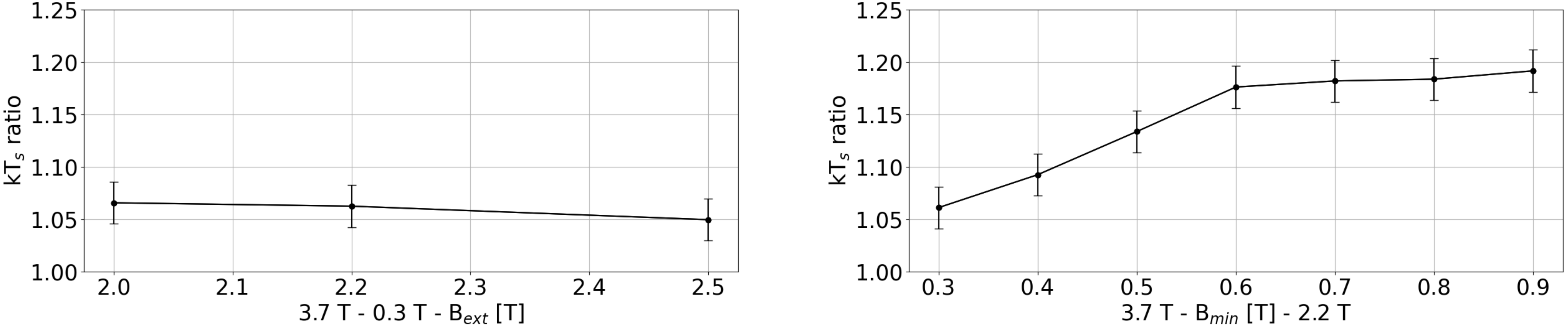


Bremsstrahlung emission – Photon energy spectrum

Photon energy spectrum change **only** with ⇧ B_{min}:

- More **anisotropic** photon spectral temperature in **radial** direction at ⇧ E_{ph}.

$$kT_s\ ratio = \frac{T_{s,RADIAL}}{T_{s,AXIAL}}$$



Conclusions

☑ Experimentally verified

MC code

- **Reproduce** results from more **complex simulation** with much **higher statistics**.
  - ➢ **Hot** electrons behaviour **marginally** affected by plasma.
- Useful tool to **investigate electron** behaviour in the future **ASTERICS** ion source.

Bremsstrahlung emission simulations simulated for the first time directly inside MC

- ➢ ⇧ B_{min} → ⇧ T_s and ⇧ photon count. ☑
- ➢ ⇧ B_{ext} → No influence. ☑
- ➢ ⇧ E_{photon} → **Anisotropic** x-ray emission (⇧ T_s and ⇧ *photon count* in radial collimator). ☑
  - o Weaker anisotropy than experimental observations.

Possible explanation for dependence of hot electrons only on B_{min}

- ➢ ⇩ ***ECR radius*** with ⇧ B_{min} → ⇧ **volume** available for relativistic ECR heating.
- $\mu_{av} \approx const$ inside ECR volume → ⇧ $\beta_\perp$ with ⇧ **radius.**

Thanks for the attention!

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