Modeling the anisotropic radiation of runaway electrons

Mathias Hoppe[1]

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

- How to measure the runaway distribution?
- Runaways emit bremsstrahlung & synchrotron
- Measured in most larger tokamaks
  - **Bremsstrahlung:** hard X-rays ($\sim$ MeV range)
  - **Synchrotron:** visible & IR
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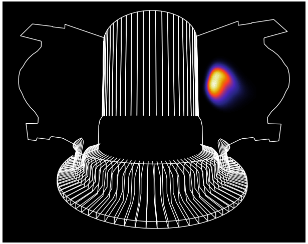
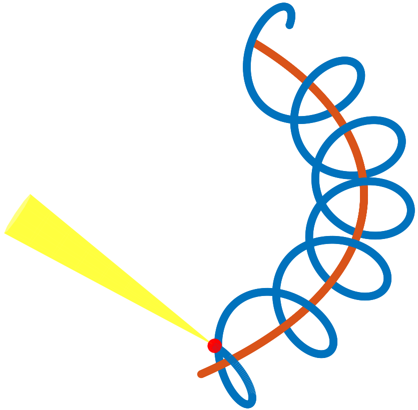


Continuous acceleration
+ relativistic energy

$\Longrightarrow$ **Radiation directed along velocity vector**



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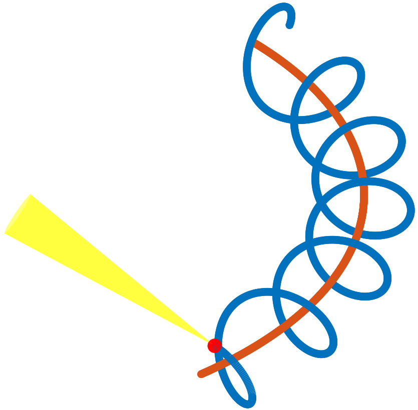

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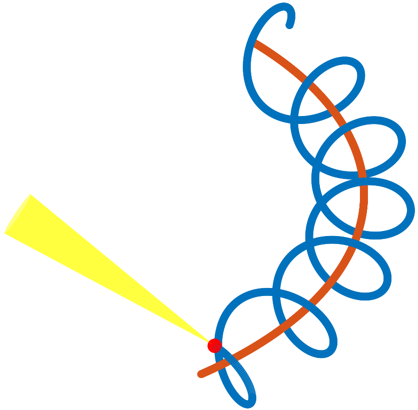

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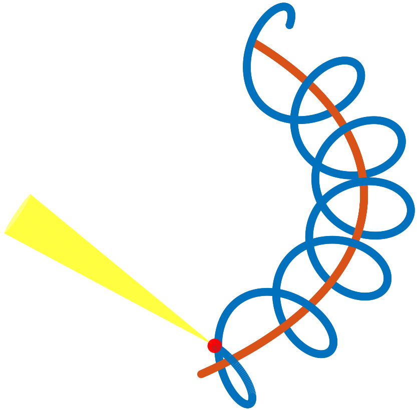
$\Longrightarrow$ **Radiation directed along velocity vector**

$\Longrightarrow$ **Radiation depends on pitch angle ($\theta_{\rm p}$)**



Continuous acceleration
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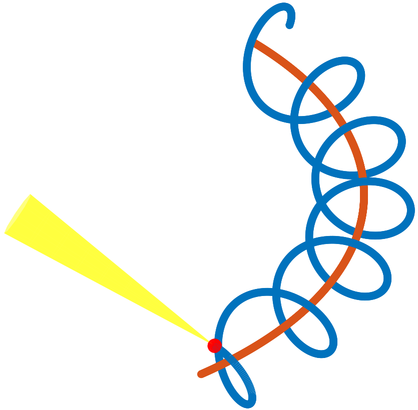
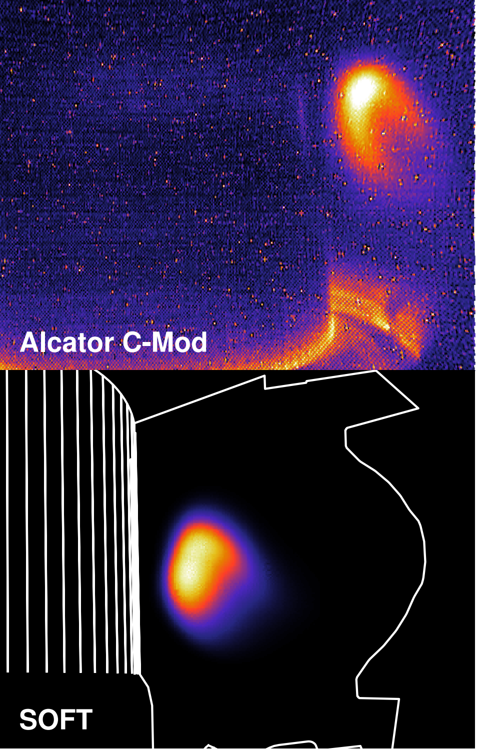
$\Longrightarrow$ **Radiation directed along velocity vector**

$\Longrightarrow$ Probes

- Radial position
- Pitch angle
- Energy



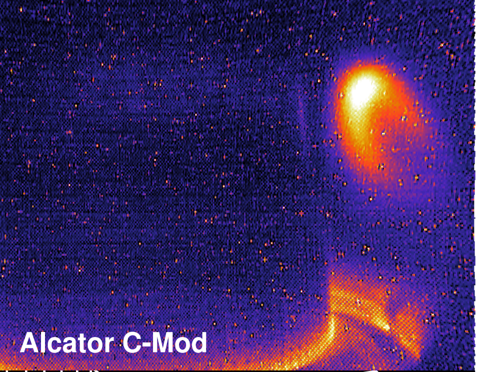


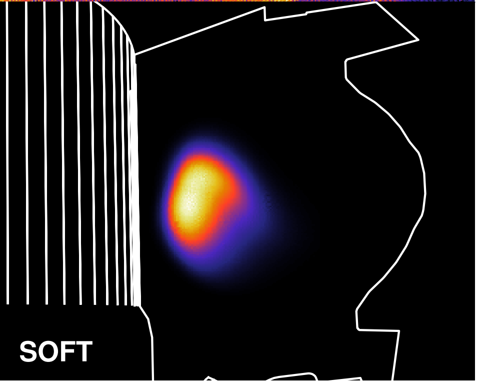
SOFT

Synchrotron-detecting Orbit Following Toolkit

- Synthetic diagnostic for radiation from runaways
- Real(istic) magnetic geometry
- Includes RE distribution
- Image/spectrum/Green's function

$$\text{Image/spectrum} = \int W(\boldsymbol{x}, \boldsymbol{p}) f(\boldsymbol{x}, \boldsymbol{p}) \mathrm{d}\boldsymbol{x} \mathrm{d}\boldsymbol{p}$$





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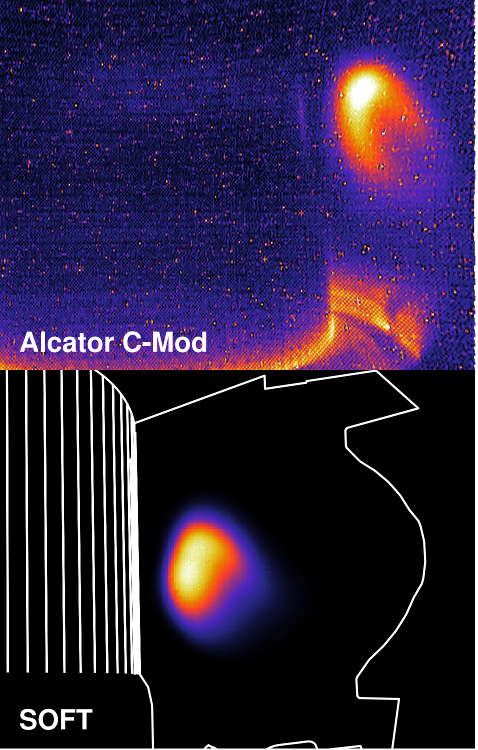

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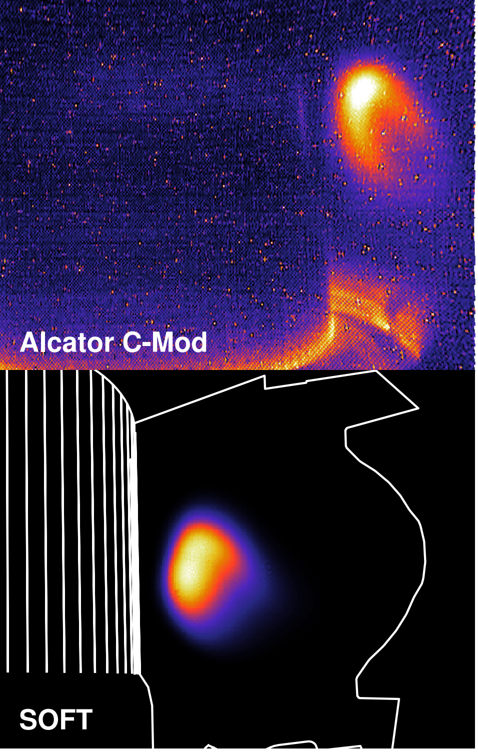

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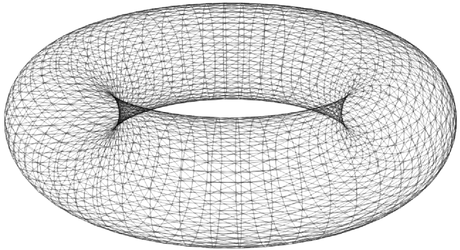

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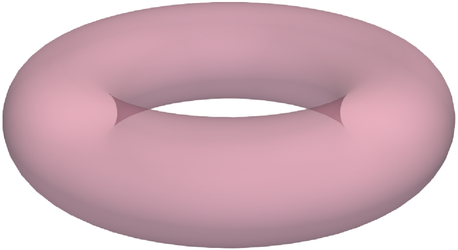

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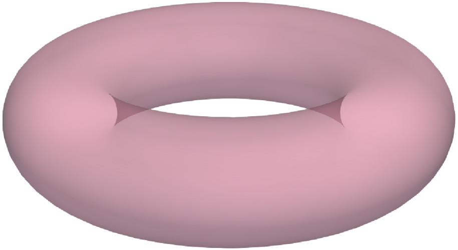

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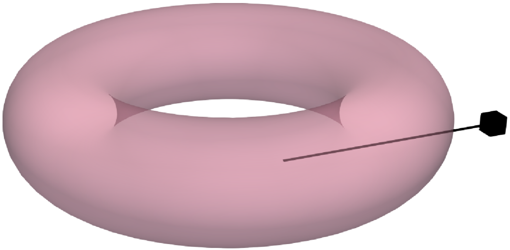

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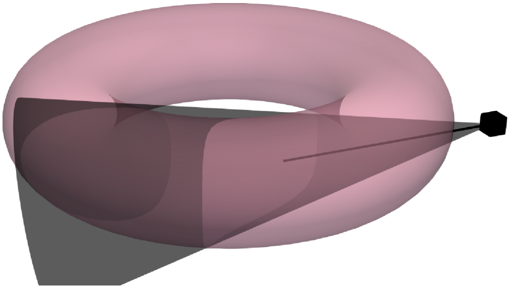

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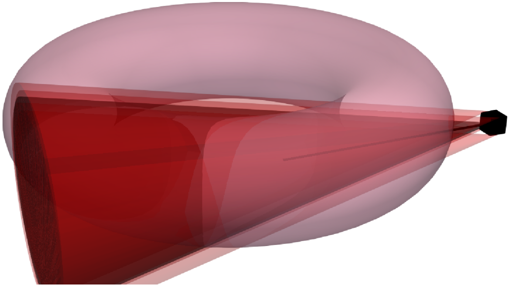
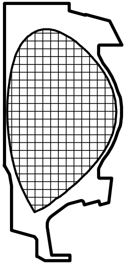


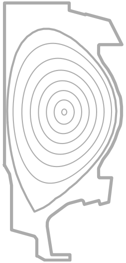
Trick in SOFT: Use other coordinates for $\int \ldots \mathrm{d}\boldsymbol{x}\mathrm{d}\boldsymbol{p}$

Parametrize using guiding-center orbits (μ conservation)

$$\boldsymbol{x} \to \begin{cases} \rho, & \textbf{Initial} \text{ major radius (outer midplane)} \\ \tau, & \text{Time parameter along orbit} \\ \phi, & \textbf{Initial} \text{ toroidal angle} \end{cases}$$

$$\boldsymbol{p} \to \begin{cases} p_{\parallel}^{(0)}, & \textbf{Initial} \text{ parallel momentum} \\ p_{\perp}^{(0)}, & \textbf{Initial} \text{ perpendicular momentum} \\ \zeta, & \text{Gyro-angle (averaged out)} \end{cases}$$





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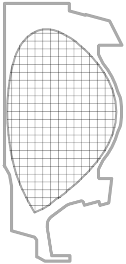

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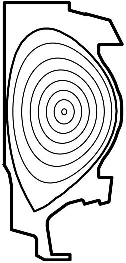

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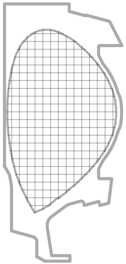

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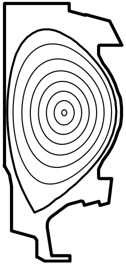

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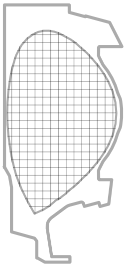

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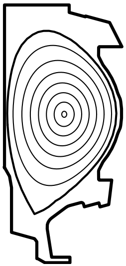

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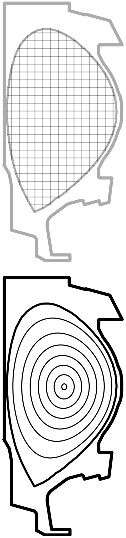

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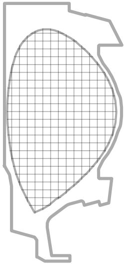

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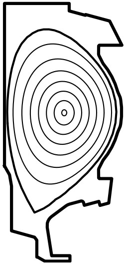

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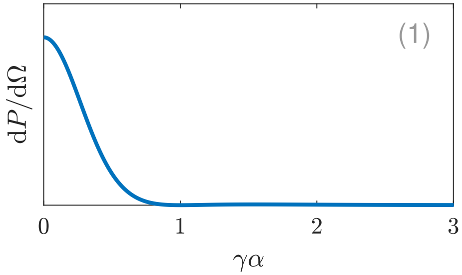
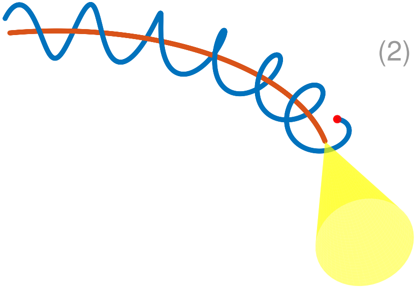
$$\text{Angular distribution:} \quad \frac{\mathrm{d}^2 P}{\mathrm{d}\lambda\mathrm{d}\Omega} = \ldots \textit{from e.g. Jackson}, \tag{1}$$

$$\text{Cone model:} \quad \frac{\mathrm{d}^2 P}{\mathrm{d}\lambda\mathrm{d}\Omega} = \frac{1}{2\pi}\frac{\mathrm{d}P}{\mathrm{d}\lambda}\delta\left(\cos\mu - \cos\theta_{\mathrm{p}}\right) \tag{2}$$





(2)

α = Angle between particle velocity & line-of-sight

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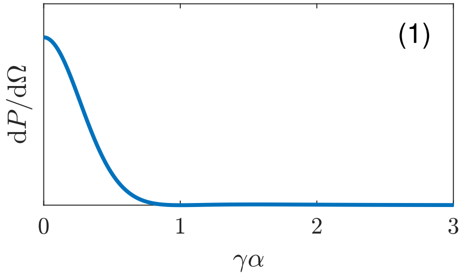

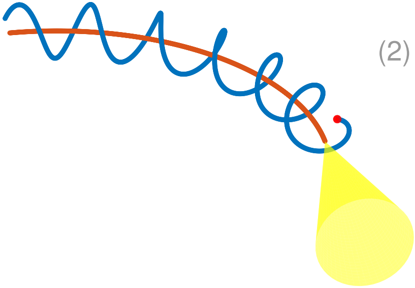

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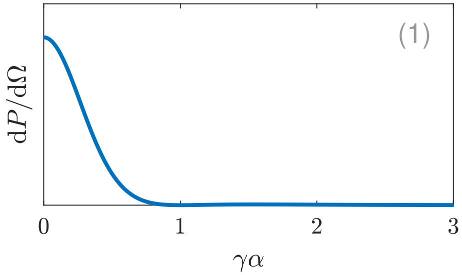

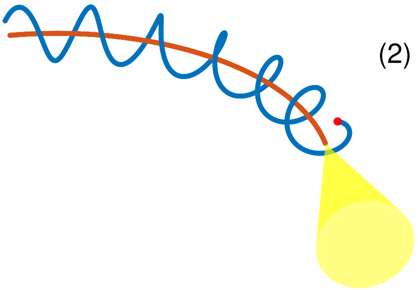

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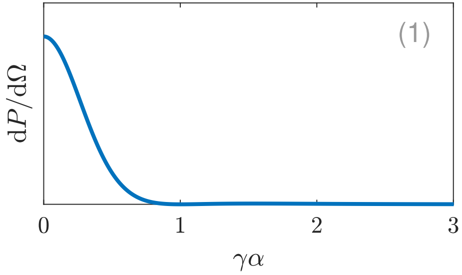
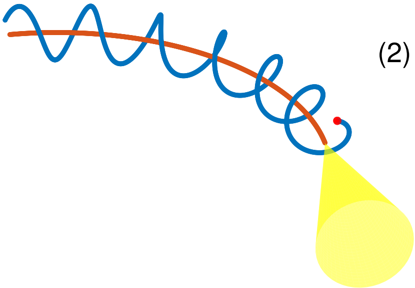
($\sim$ 10-100 times faster)





α = Angle between particle velocity & line-of-sight

Elements of a RE radiation image

Specify momentum

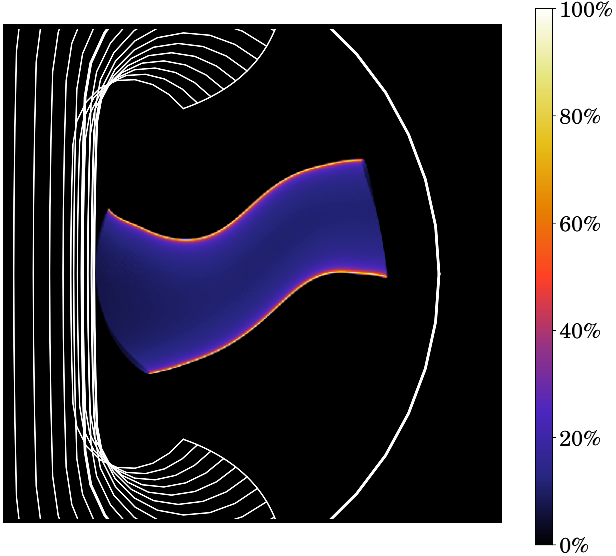
$$(p, \theta_{\mathrm{p}}) = (p_0, \theta_0)$$

What does the corresponding image look like?

Specify momentum

$$(p, \theta_{\mathrm{p}}) = (p_0, \theta_0)$$

What does the corresponding image look like?

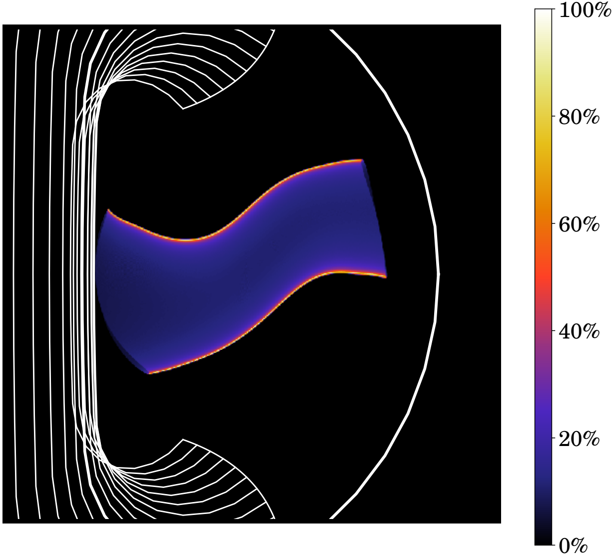


Specify momentum

$$(p, \theta_p) = (p_0, \theta_0)$$

What does the corresponding image look like?

Edges much brighter than body



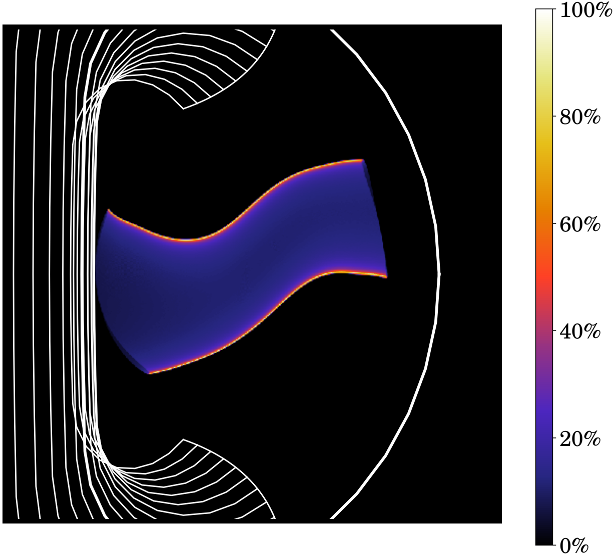
Specify momentum

$$(p, \theta_{\mathrm{p}}) = (p_0, \theta_0)$$

What does the corresponding image look like?

Edges much brighter than body

Radiation emitted on “surface” (with thickness)!

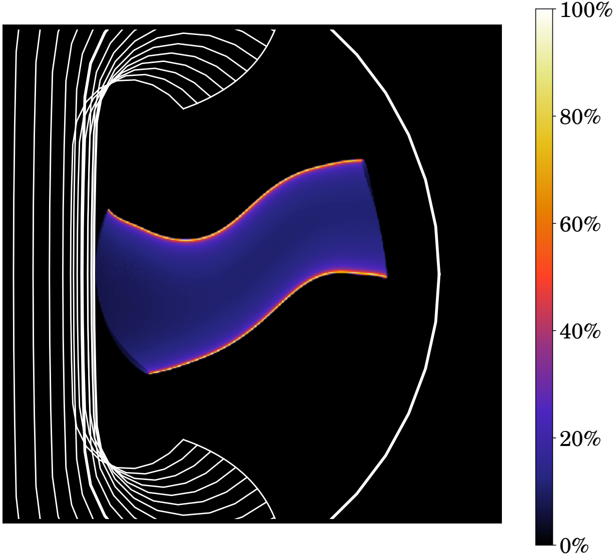


Specify momentum

$$(p, \theta_{\mathrm{p}}) = (p_0, \theta_0)$$

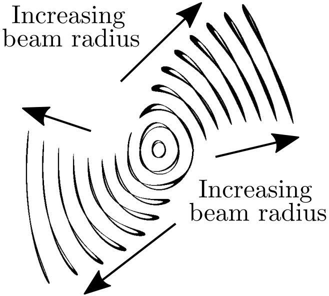
What does the corresponding image look like?

Edges much brighter than body

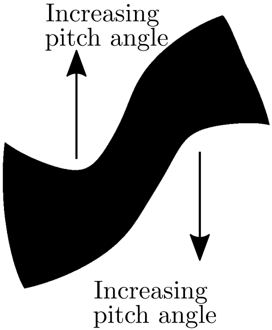


Radiation emitted on "surface" (with thickness)!
$\Longrightarrow$ Line integration effect

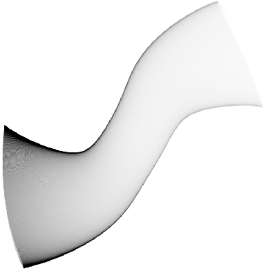
Radial location



Pitch angle

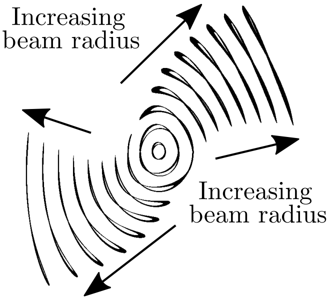


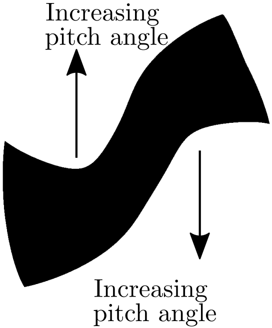
Energy

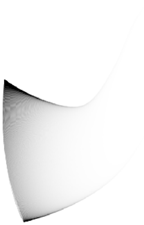


High energy:
$P(\lambda) \propto \sqrt{B}$

Radial location Pitch angle Energy

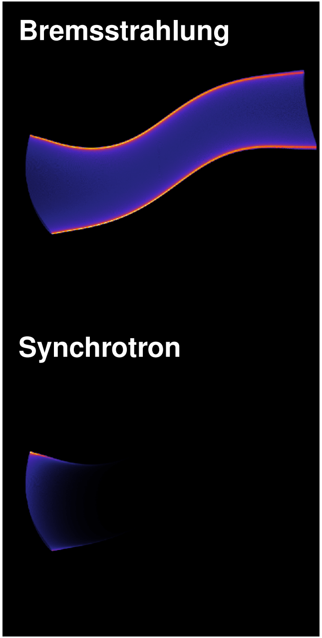


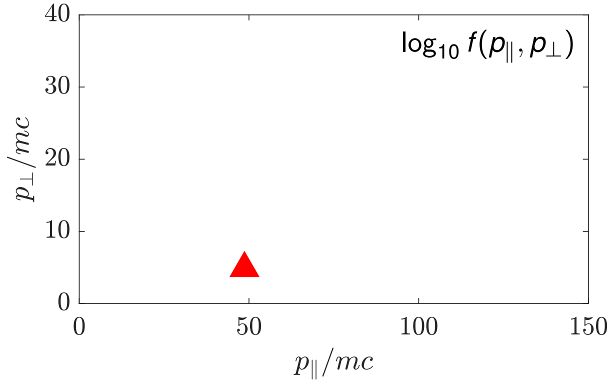




Low energy:

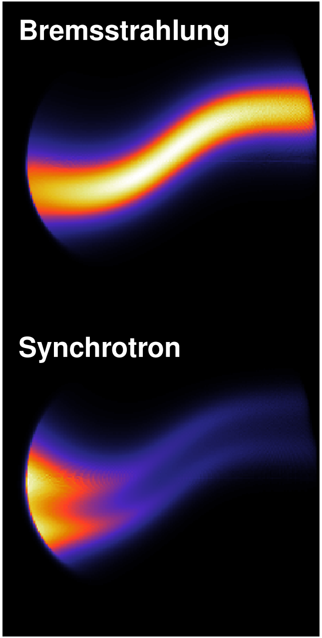
$$P(\lambda) \propto \exp\left[-\left(B_{\mathrm{c}}/B\right)^{1/3}\right]$$

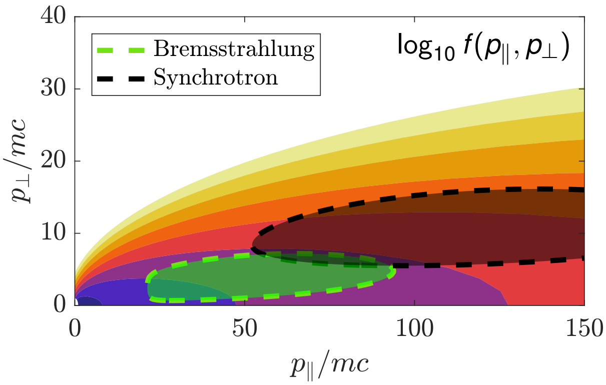




- Different generation mechanisms
  - Bremsstrahlung: Collisions
  - Synchrotron: Gyration
- Different windows into distribution

Distribution function





- Different generation mechanisms
  - Bremsstrahlung: Collisions
  - Synchrotron: Gyration
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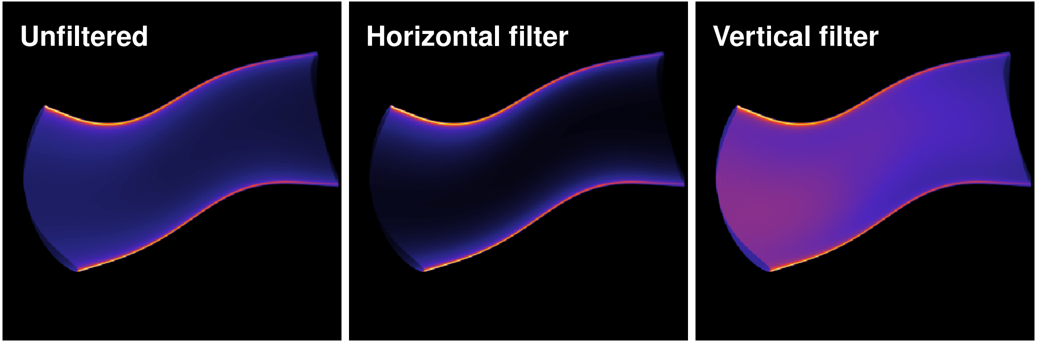
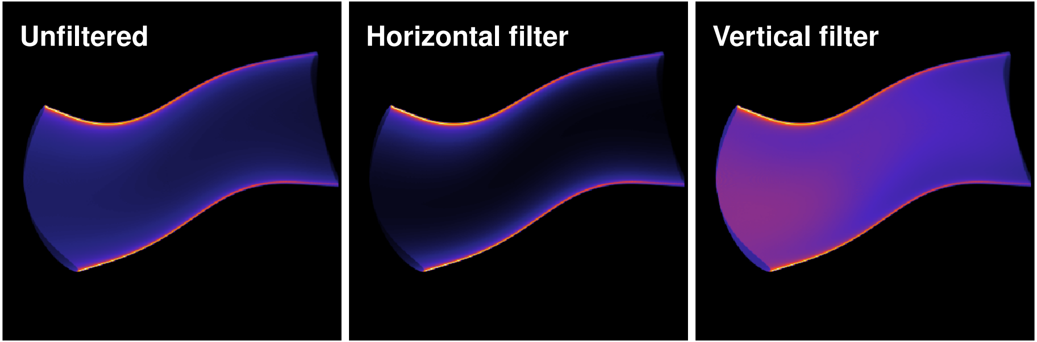


- Filters out **body** (horizontal) and **edges** (vertical)
- Views same parts of momentum-space
- Closely coupled to magnetic geometry



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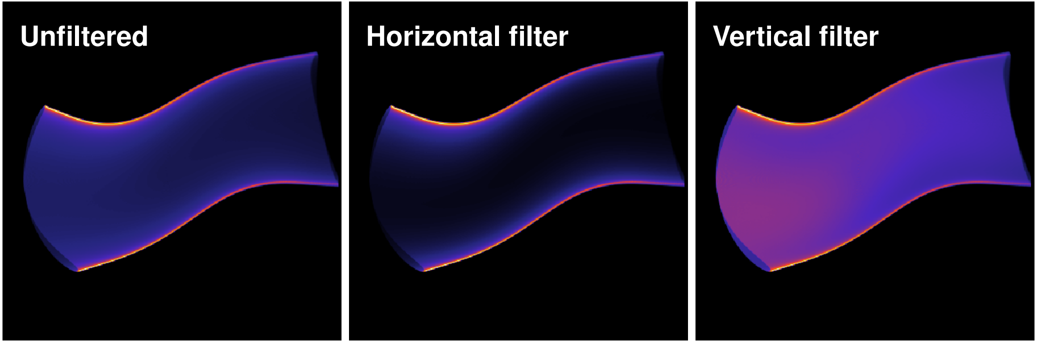

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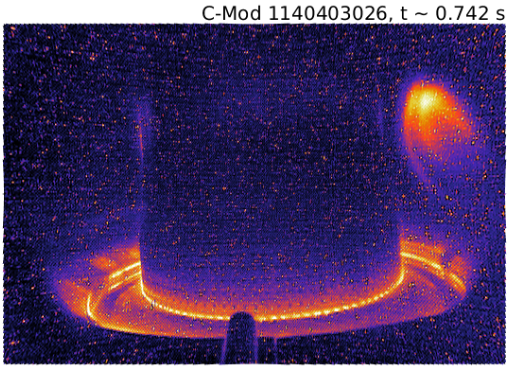
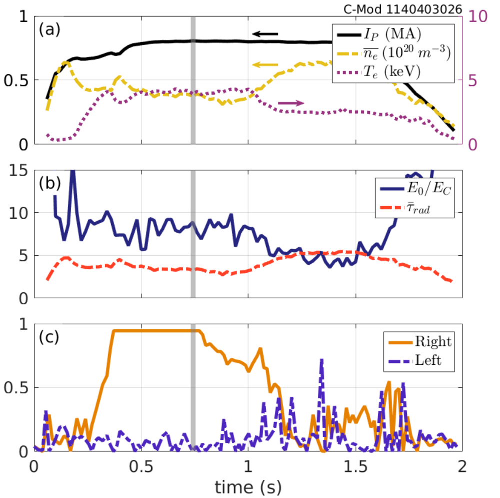
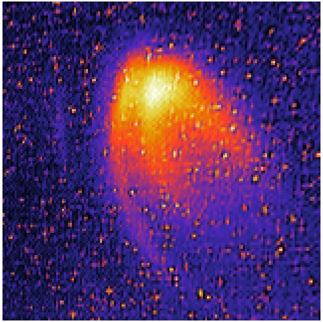
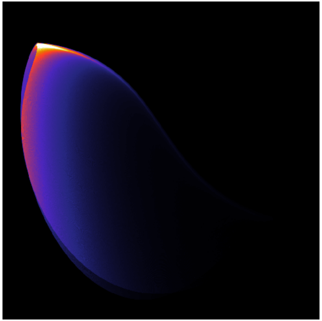




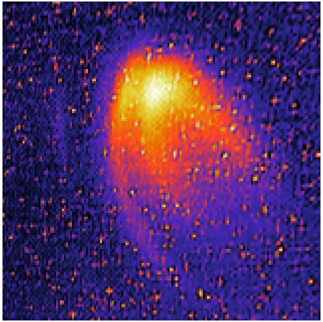
- Low-density QRE in C-Mod
- $B = 5.4\,\mathrm{T}$ on-axis
- Much synchrotron in visible range

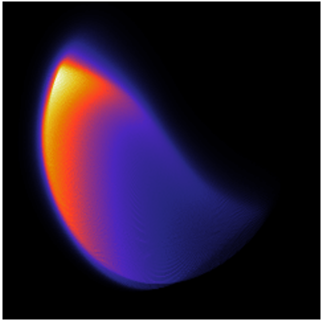




Understanding the synchrotron spot

1. Single energy (15 MeV), single pitch angle (0.15 rad)
2. CODE distribution function from plasma parameters
3. + simple radial distribution
4. Radial distribution fit





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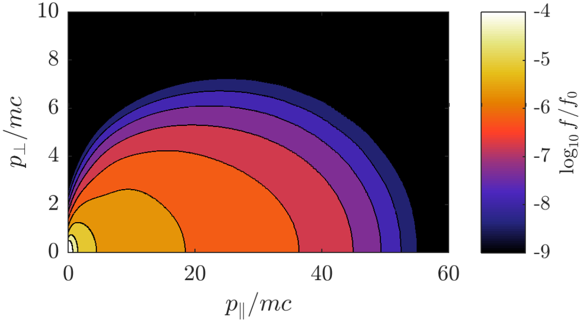
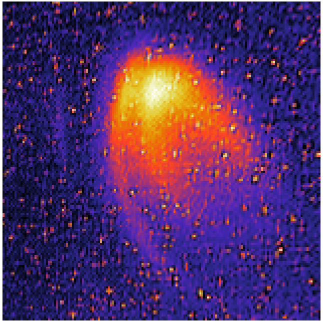
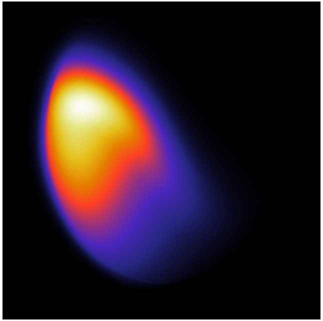
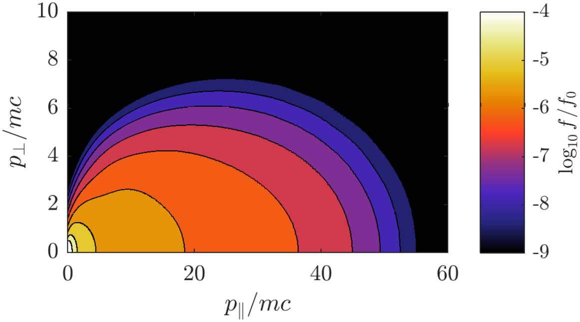


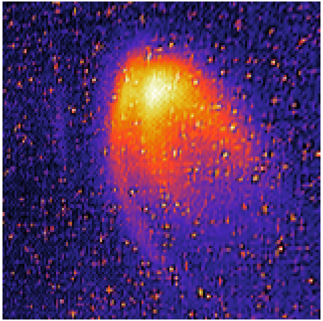


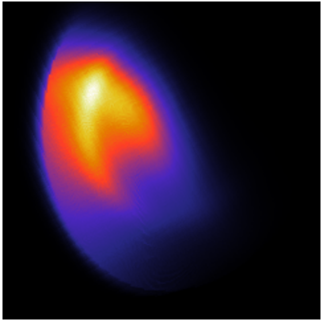


Understanding the synchrotron spot

1. Single energy (15 MeV), single pitch angle (0.15 rad)
2. CODE distribution function from plasma parameters
3. + simple radial distribution
4. Radial distribution fit







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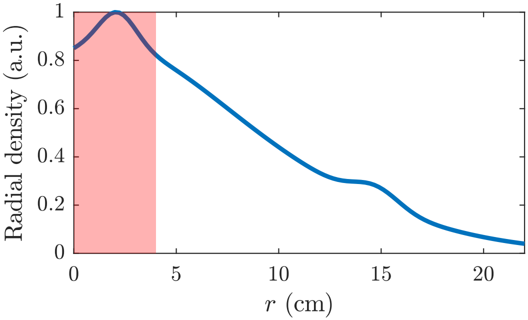

- SOFT simulates runaway **bremsstrahlung** & **synchrotron** radiation
- Radiation highly sensitive to both spatial & velocity parts of runaway **distribution**
- Linearly polarized SR views **same part** part of distribution as unfiltered SR
- Non-uniform radial density needed to explain C-Mod image

Further reading:

[1] Hoppe M. et al., *SOFT: a synthetic synchrotron diagnostic*, Nucl. Fusion **58** 026032 2018

[2] Hoppe M. et al., *Interpretation of runaway electron synchrotron and bremsstrahlung images*, Nucl. Fusion **58** 082001 2018

[3] Tinguely R. A. et al., *Measurements of runaway electron synchrotron spectra at high magnetic fields in Alcator C-Mod*, Nucl. Fusion **58** 076019 2018

SOFT and other runaway electron tools are freely available at `http://ft.nephy.chalmers.se/retools`