Synchrotron emission in Alcator C-Mod: Spectra at three B-fields and visible camera images

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Runaway Electron Meeting 2017

Prague, Czech Republic

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Outline

- Runaway electron synchrotron spectra measured at three magnetic fields
- Visible camera images of synchrotron emission and comparison with SOFT
- Radial profiles of synchrotron radiation polarization
- Questions

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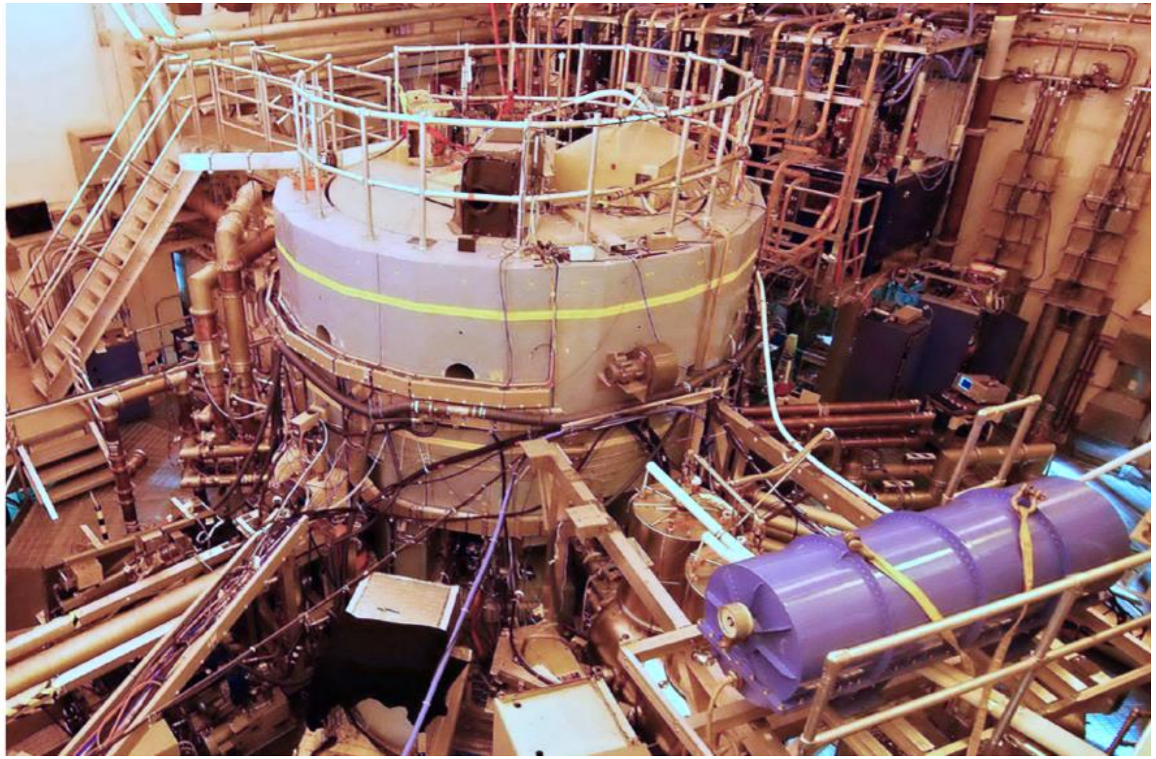
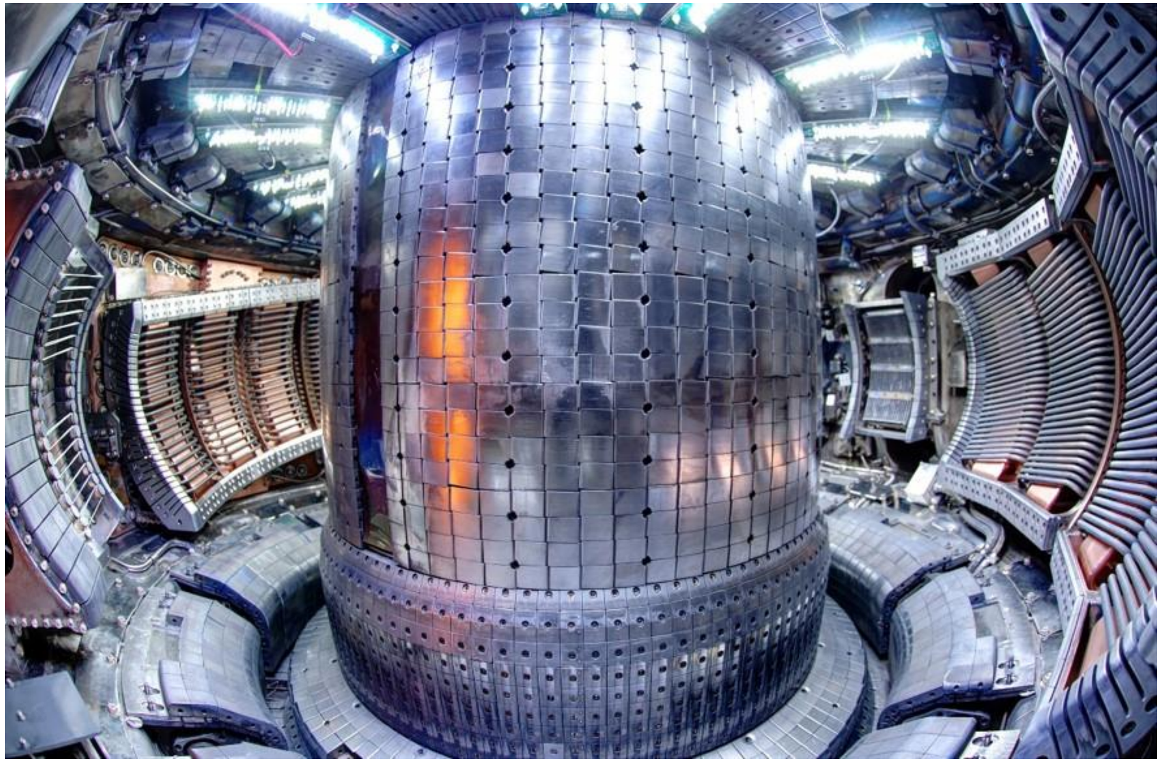
Alcator C-Mod – a high-field, compact tokamak





- $B_0 \leq 8$ T, $I_P \leq 2$ MA, $\langle p \rangle \leq 2$ atm (0.3 MJ/m^3), $R_0 = 0.68$ m, $a = 0.22$ m
- Equipped with extensive disruption-relevant diagnostics
- C-Mod permanently shut down last year

Runaway video

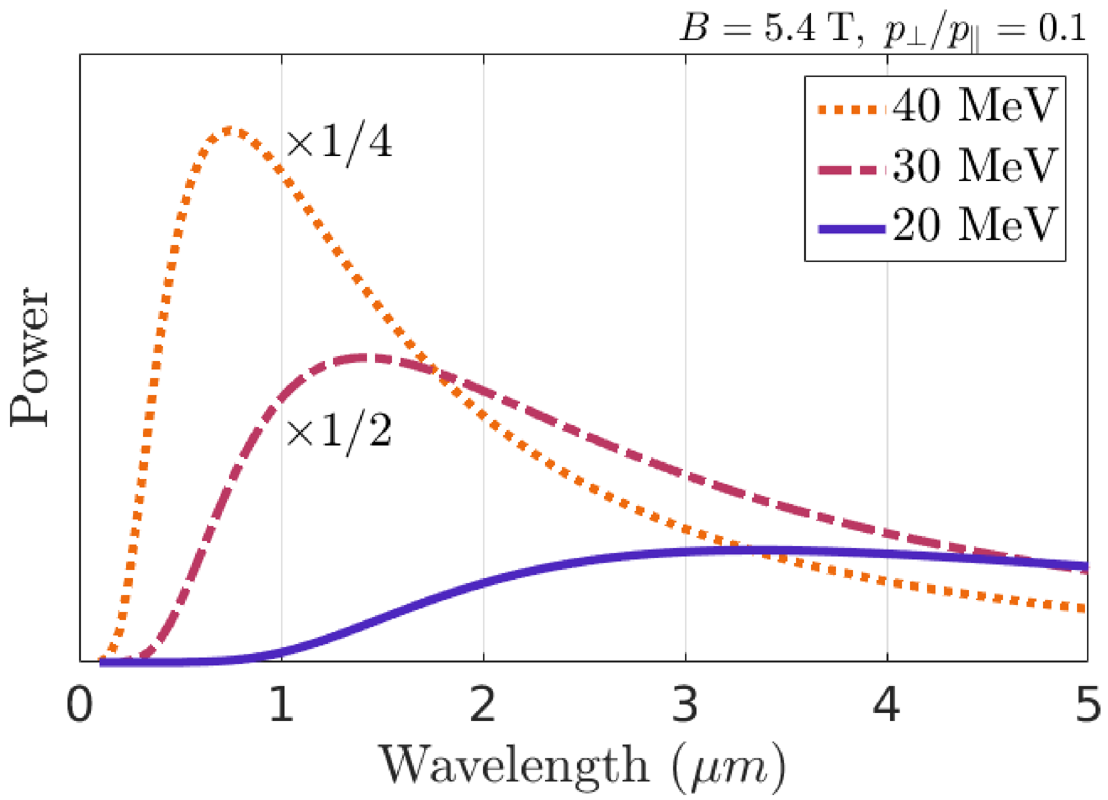
Motivation: Runaways can cause serious damage

Runaway electrons (REs):

- Energies > 10 MeV
- In C-Mod, $I_{RE} << I_P$ during plasma flattop
- Severely damage plasma-facing components

It is necessary to understand the evolution of REs in both momentum space and real space to effectively avoid and mitigate them.

Does synchrotron radiation limit REs maximum energy?



I.M. Pankratov, Plasma Phys. Reports 25 (1999)

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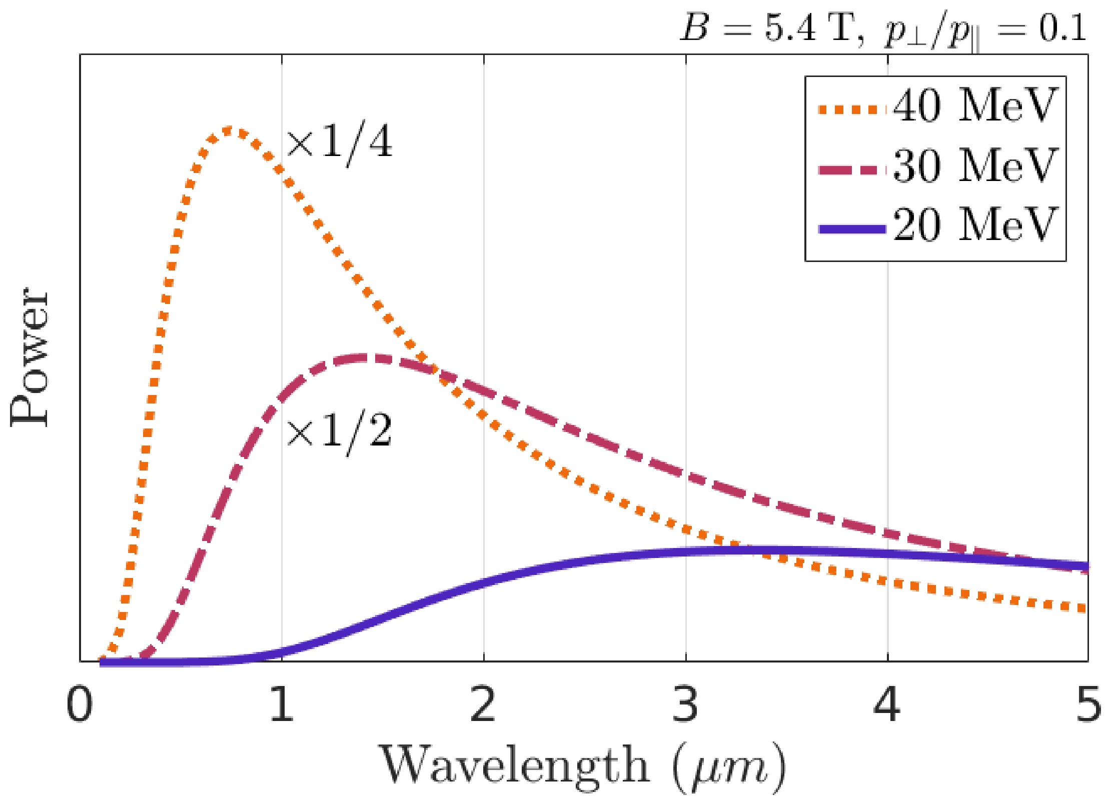

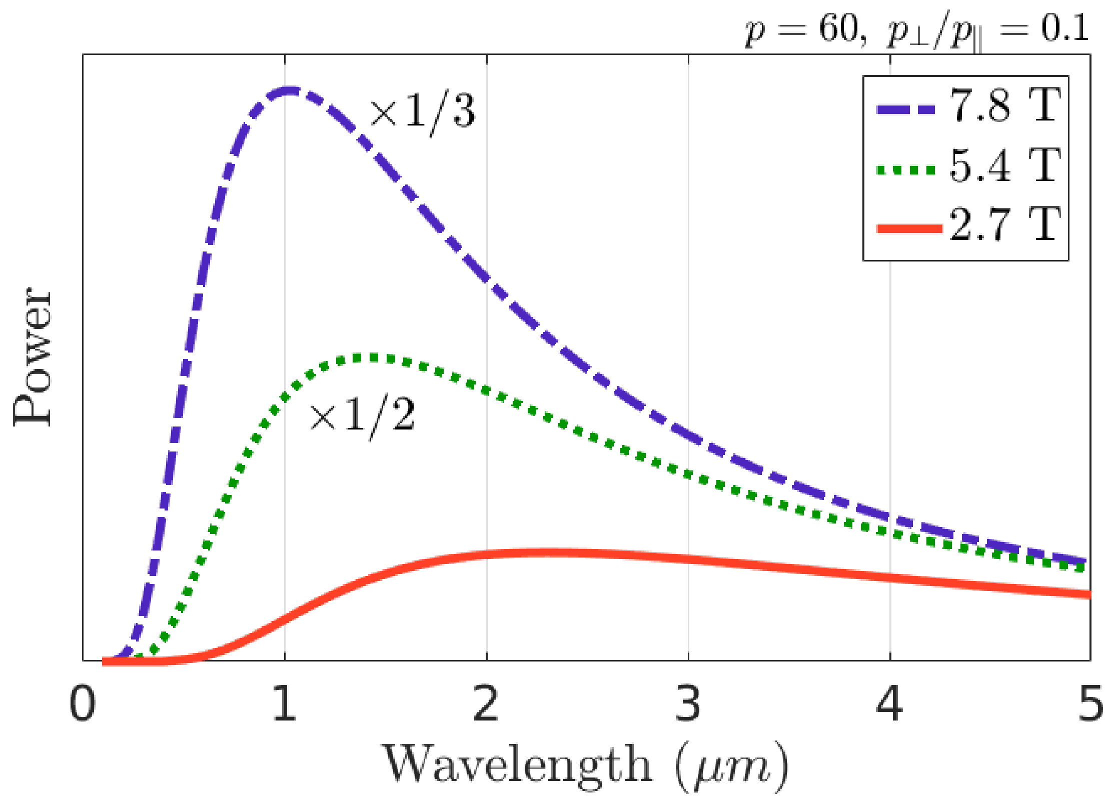

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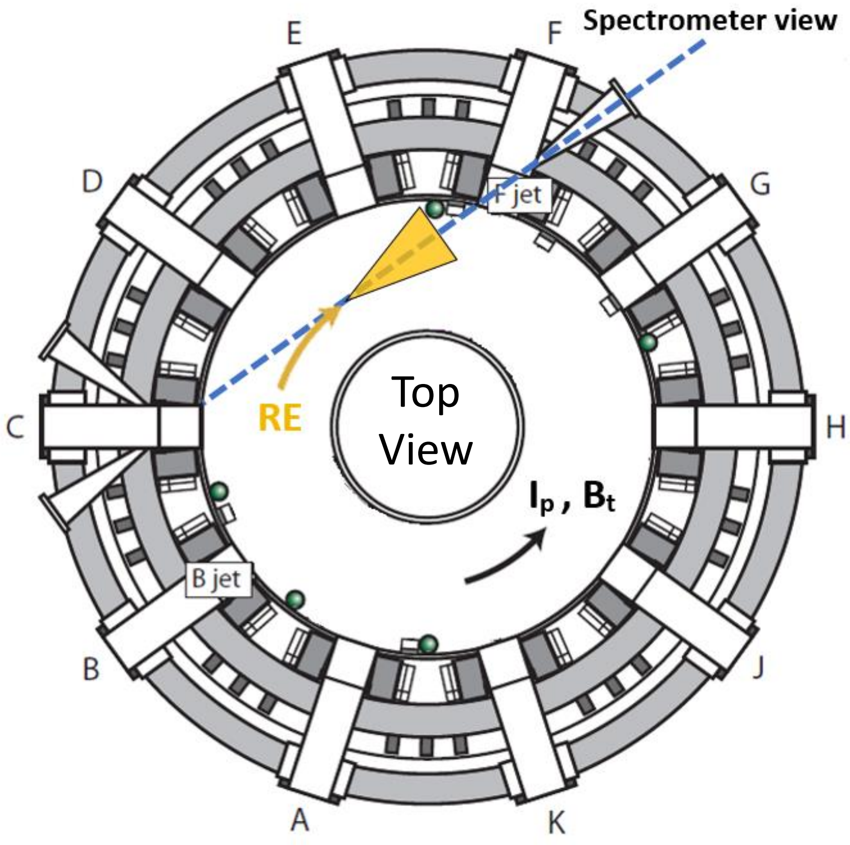
Absolutely-calibrated spectrometers measure emission



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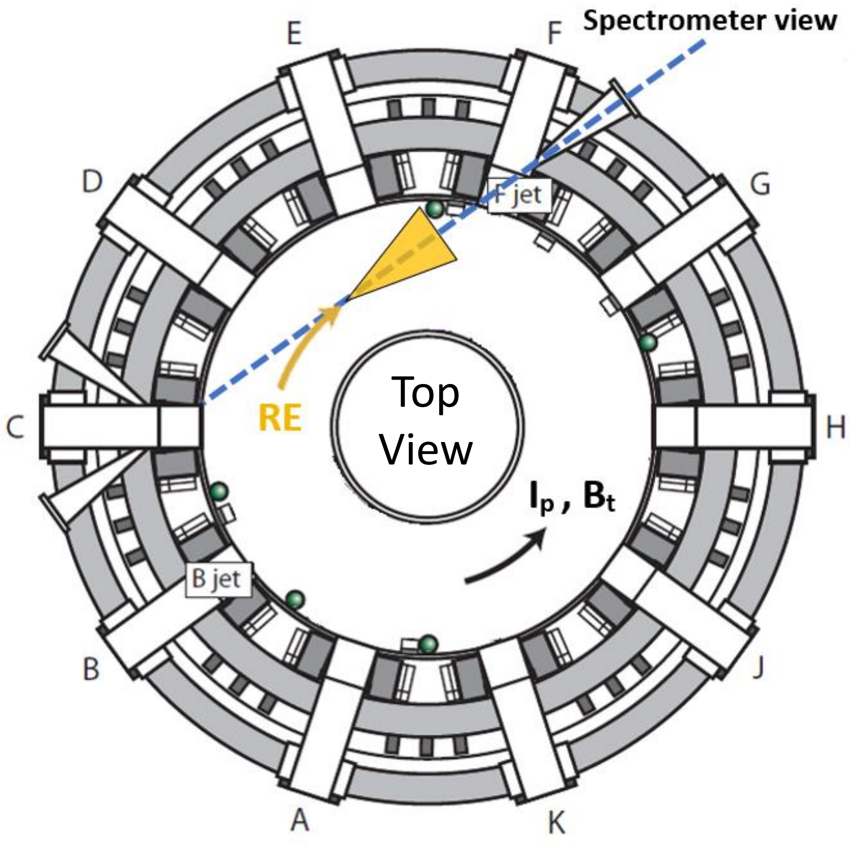

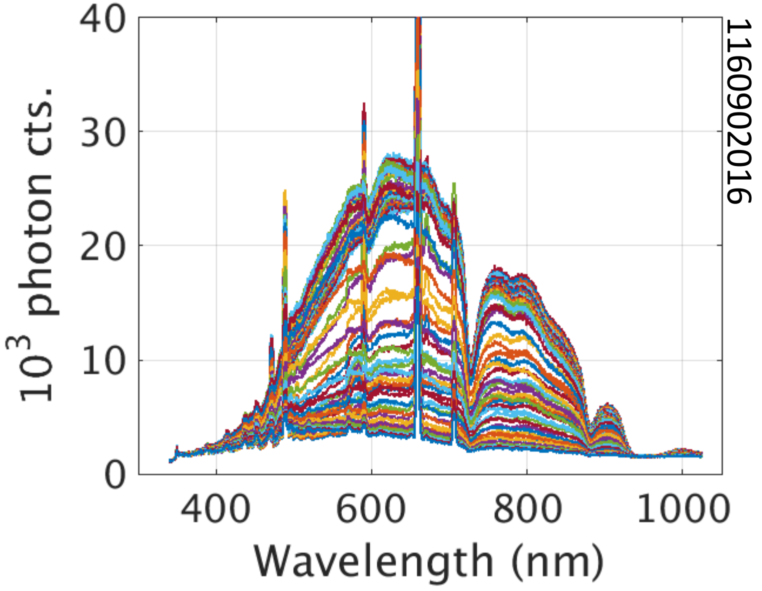

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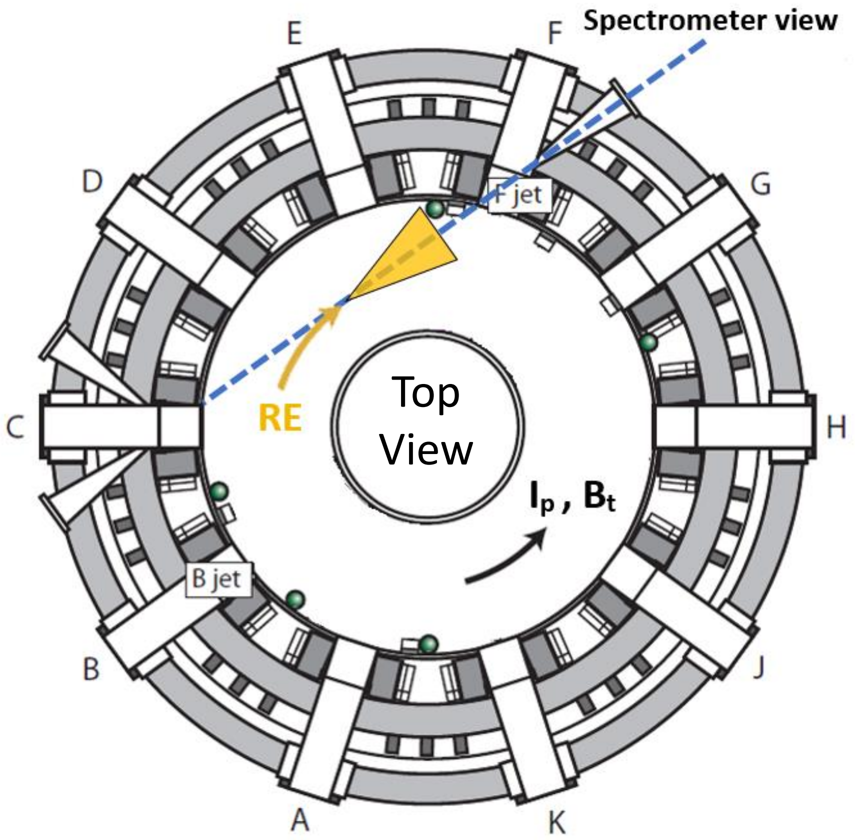
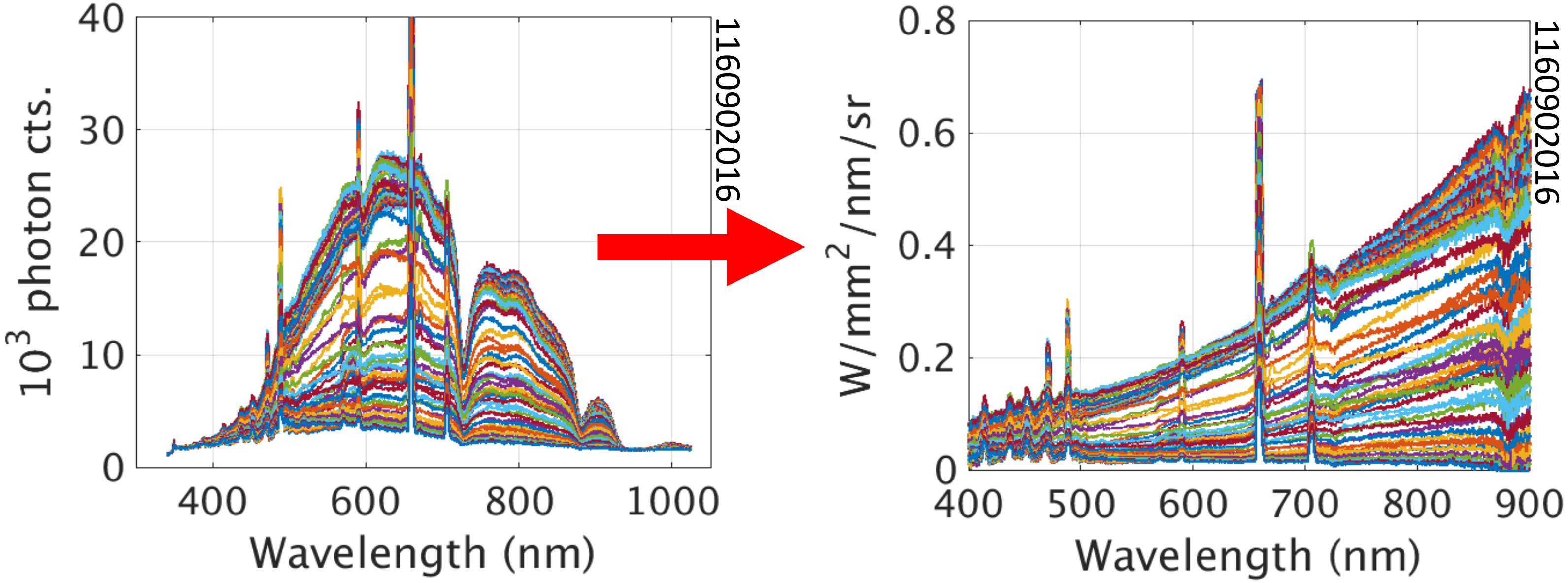
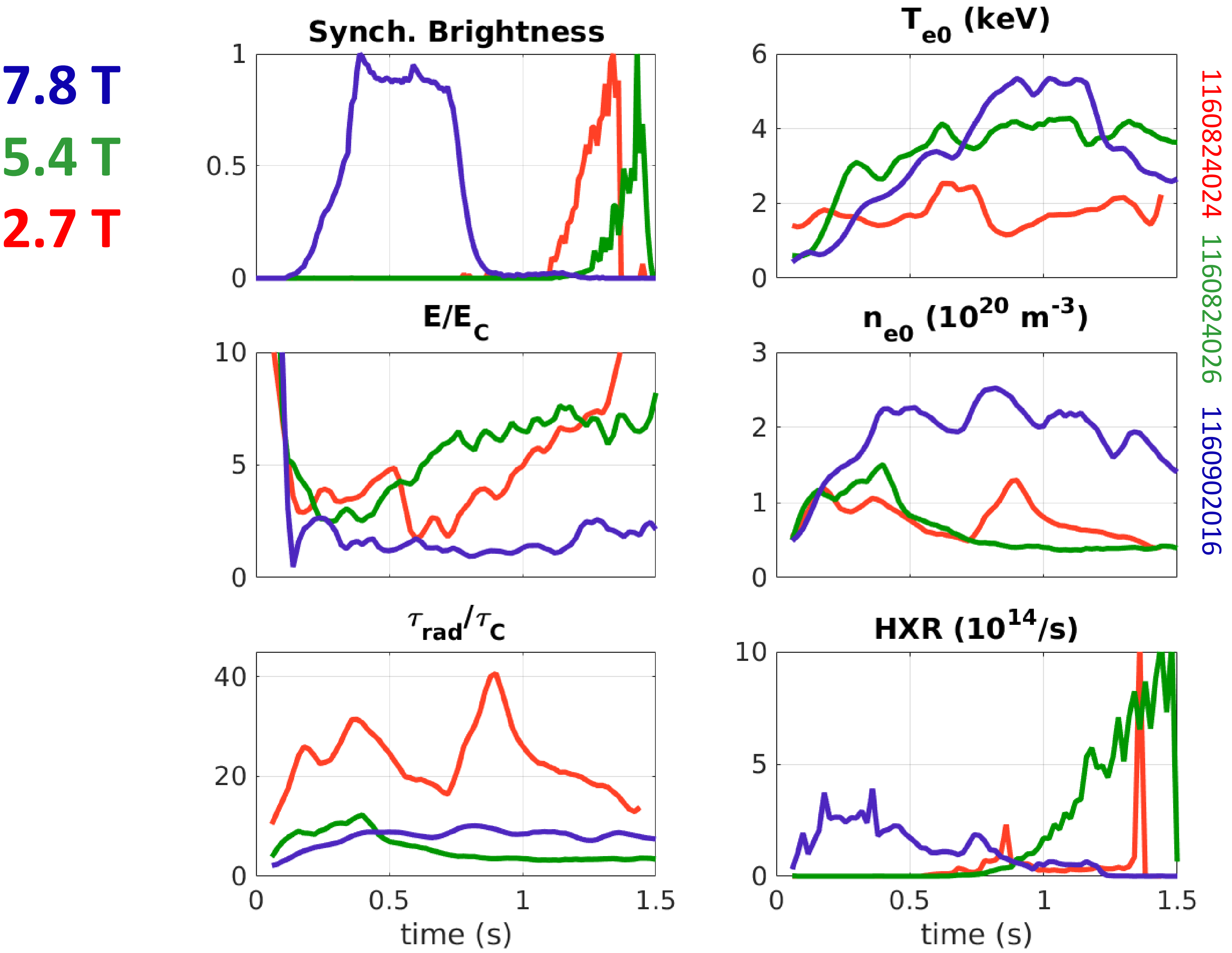


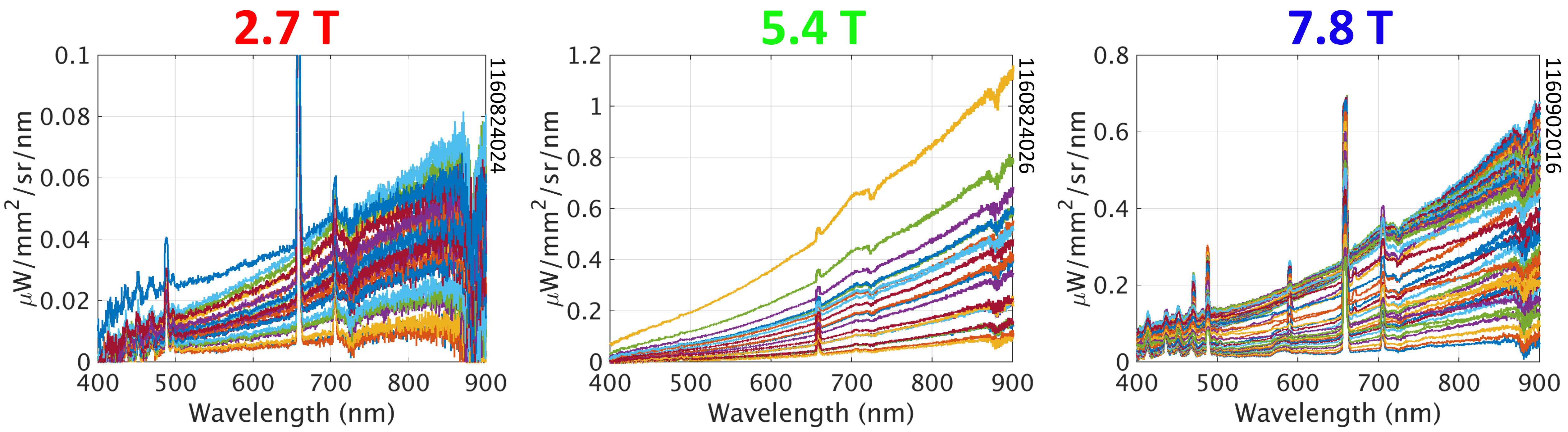




7.8 T
5.4 T
2.7 T
Synch. Brightness
T_{e0} (keV)
E/E_C
n_{e0} (10^{20} m^{-3})
τ_{rad}/τ_C
HXR (10^{14}/s)
time (s)
time (s)
1160824024
1160824026
1160902016

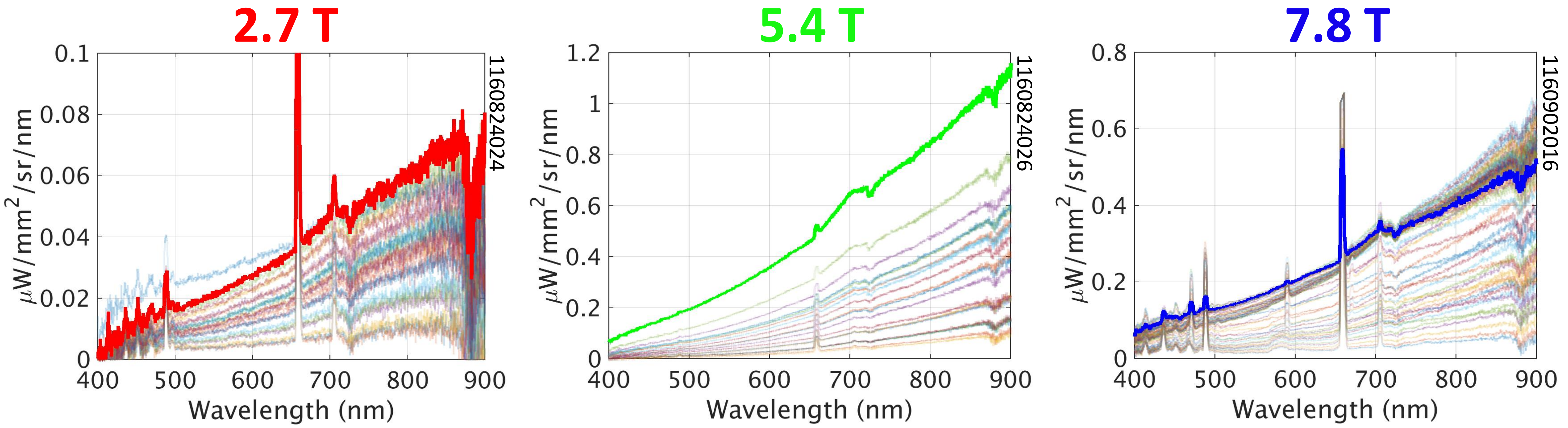
Synchrotron spectra measured at three B-fields

- RE densities are difficult to reproduce, so we are not interested in the absolute amplitude.
- Instead, we are interested in the spectral shape.



Synchrotron spectra measured at three B-fields

- Select one time-slice near maximum emission during steady plasma parameters.
- Take the ratio of two spectra and normalize at one wavelength.



Comparison of spectra

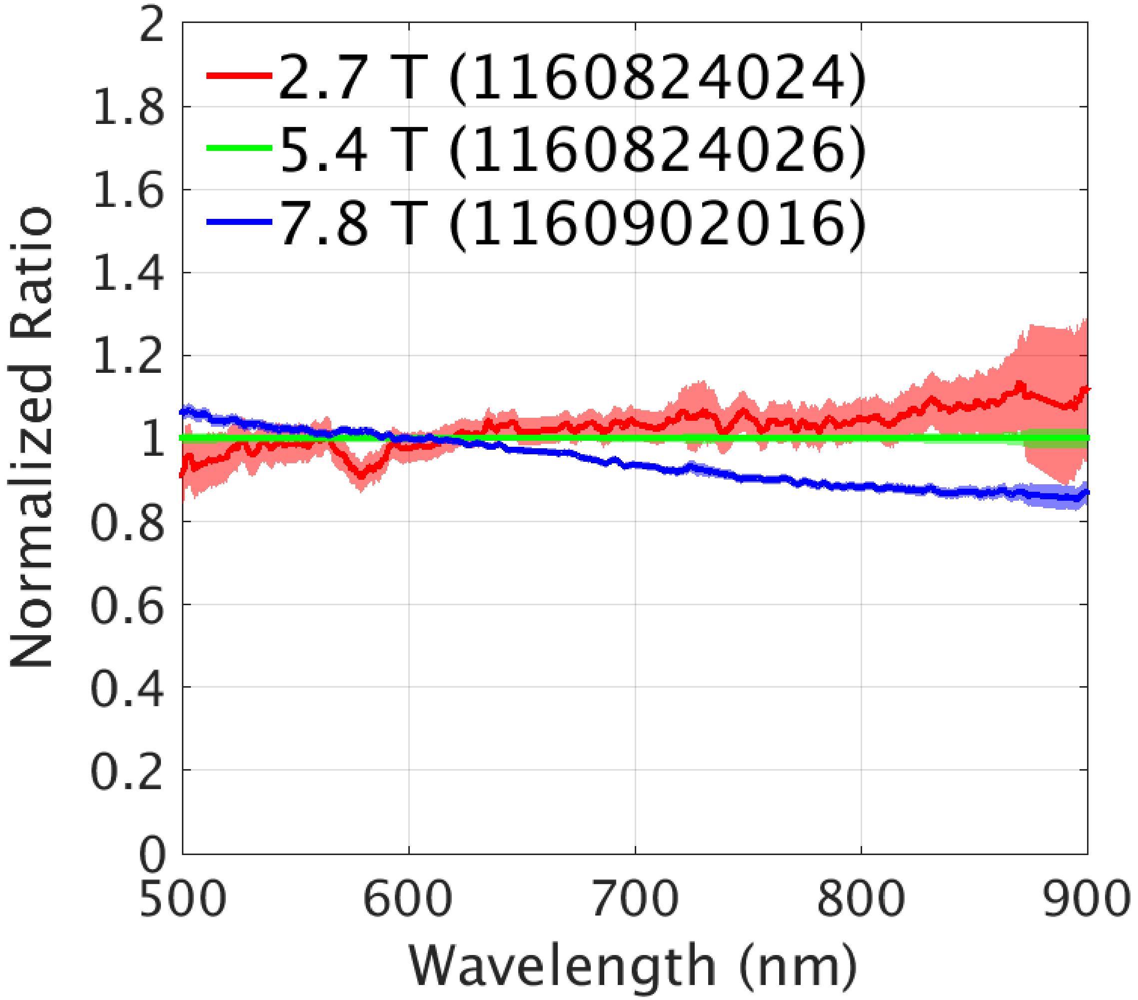
*Relative to the reference spectra

Positive slope

- More brightness at longer wavelengths
- Shifted toward the **red**

Negative slope

- More brightness at shorter wavelengths
- Shifted toward the **blue**



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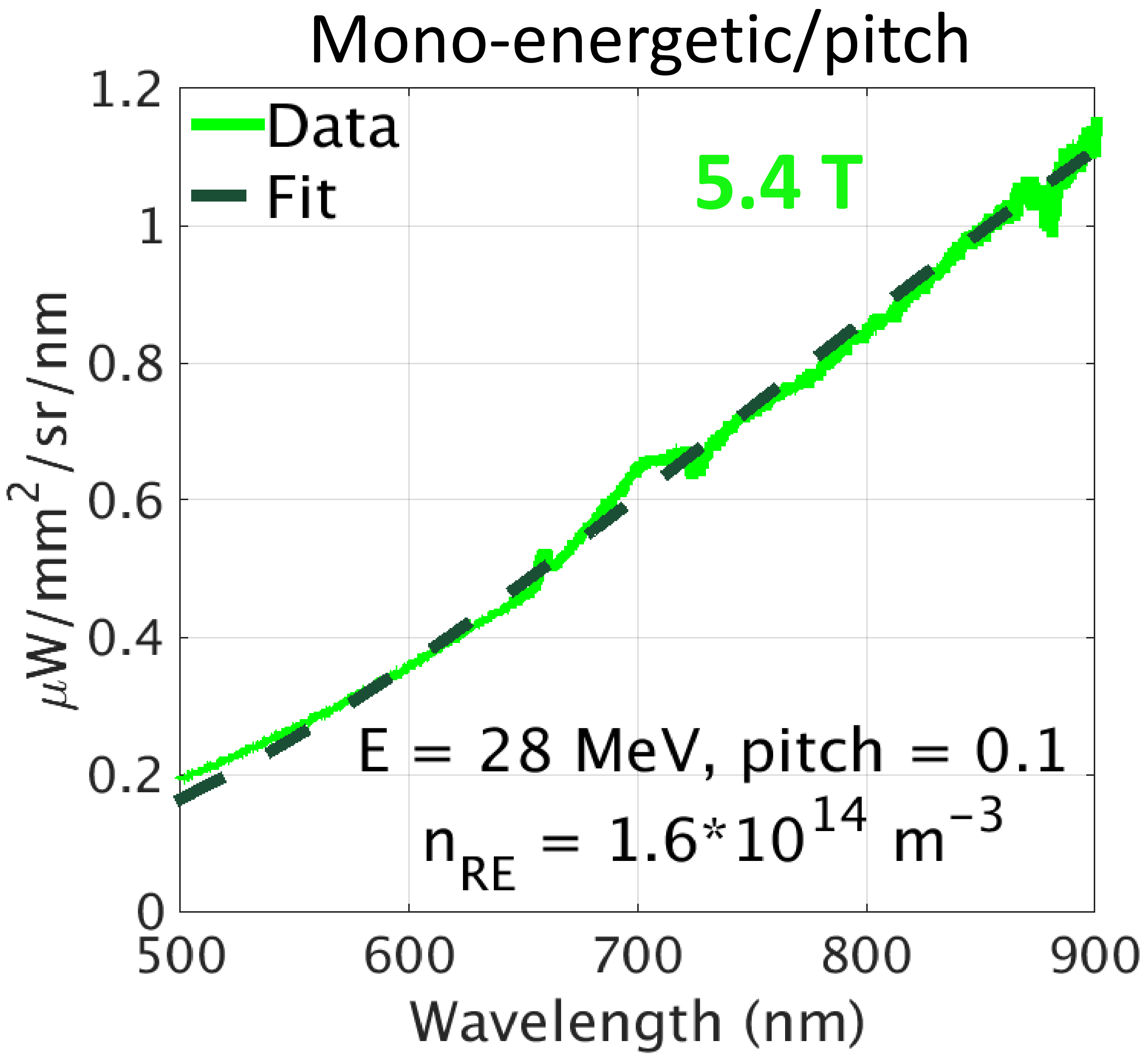

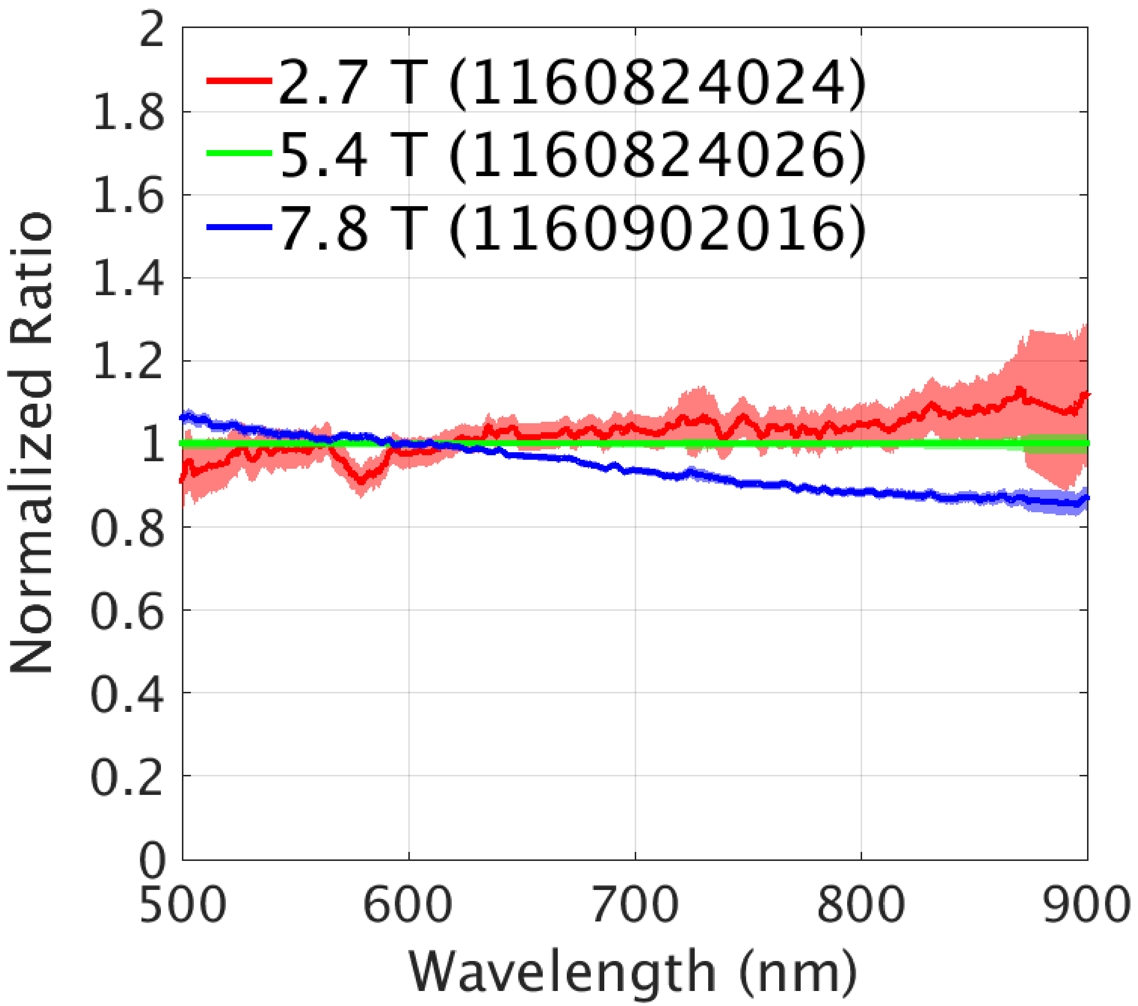

I.M. Pankratov. Plasma Phys. Reports 25 (1999).

J.H. Yu, et al. PoP 20 (2013).

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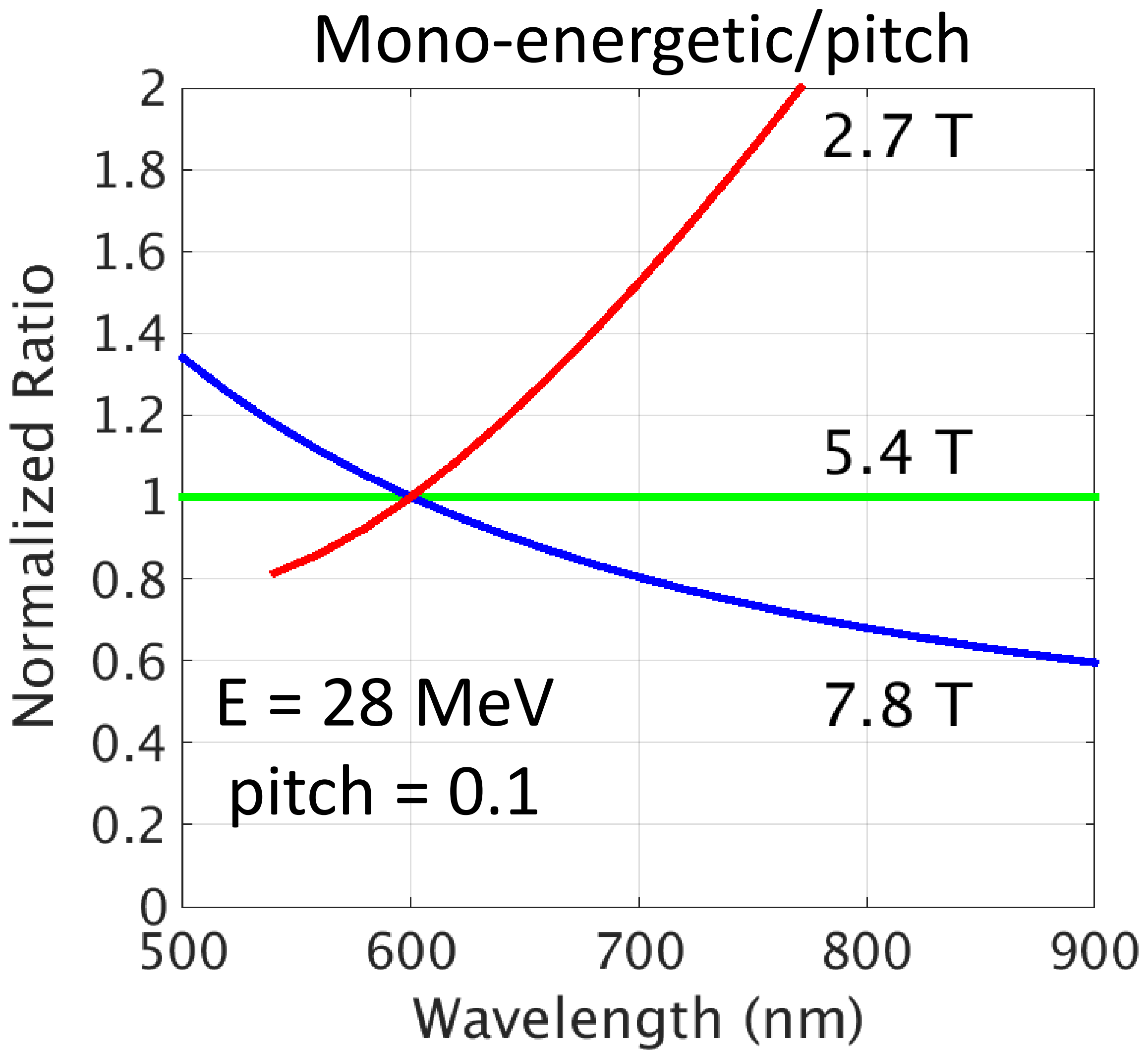

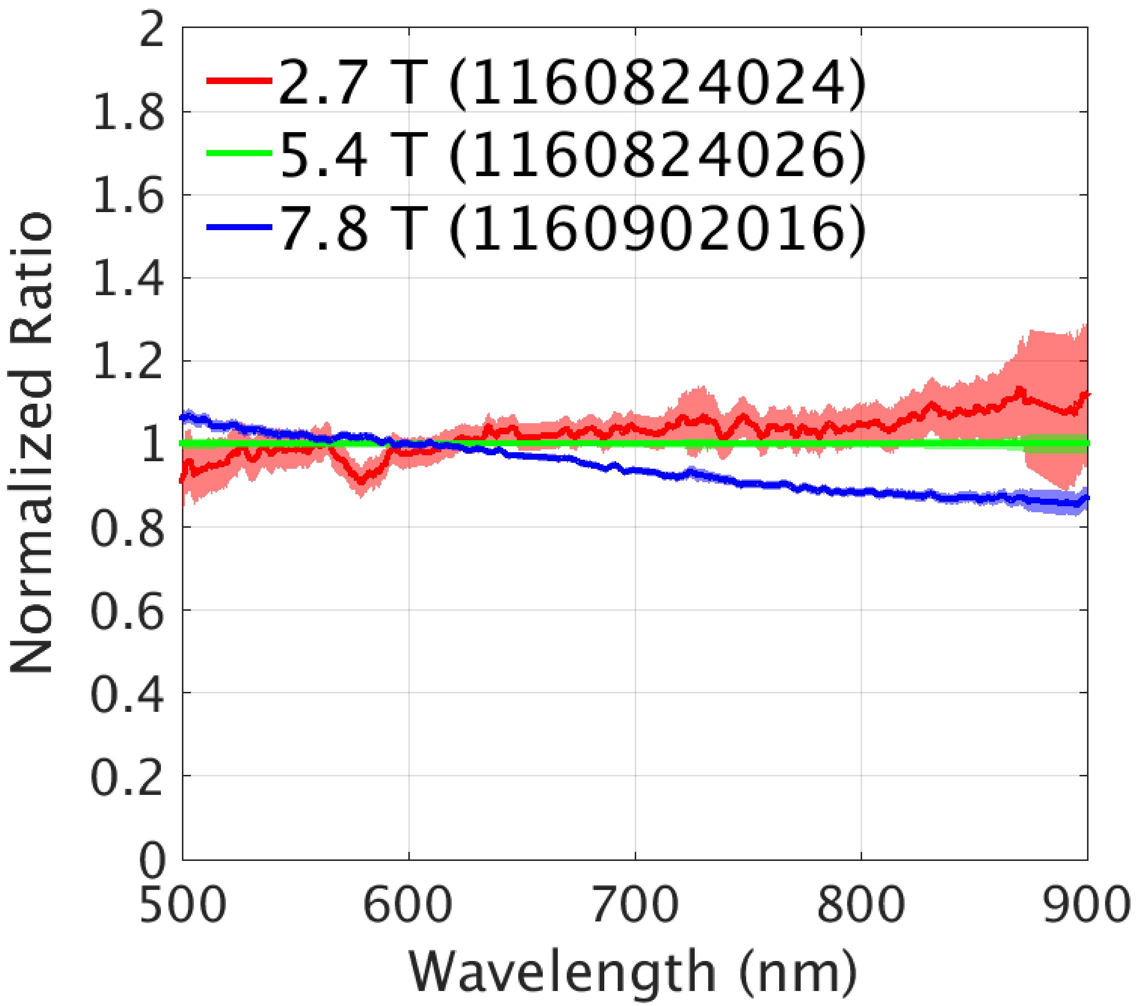

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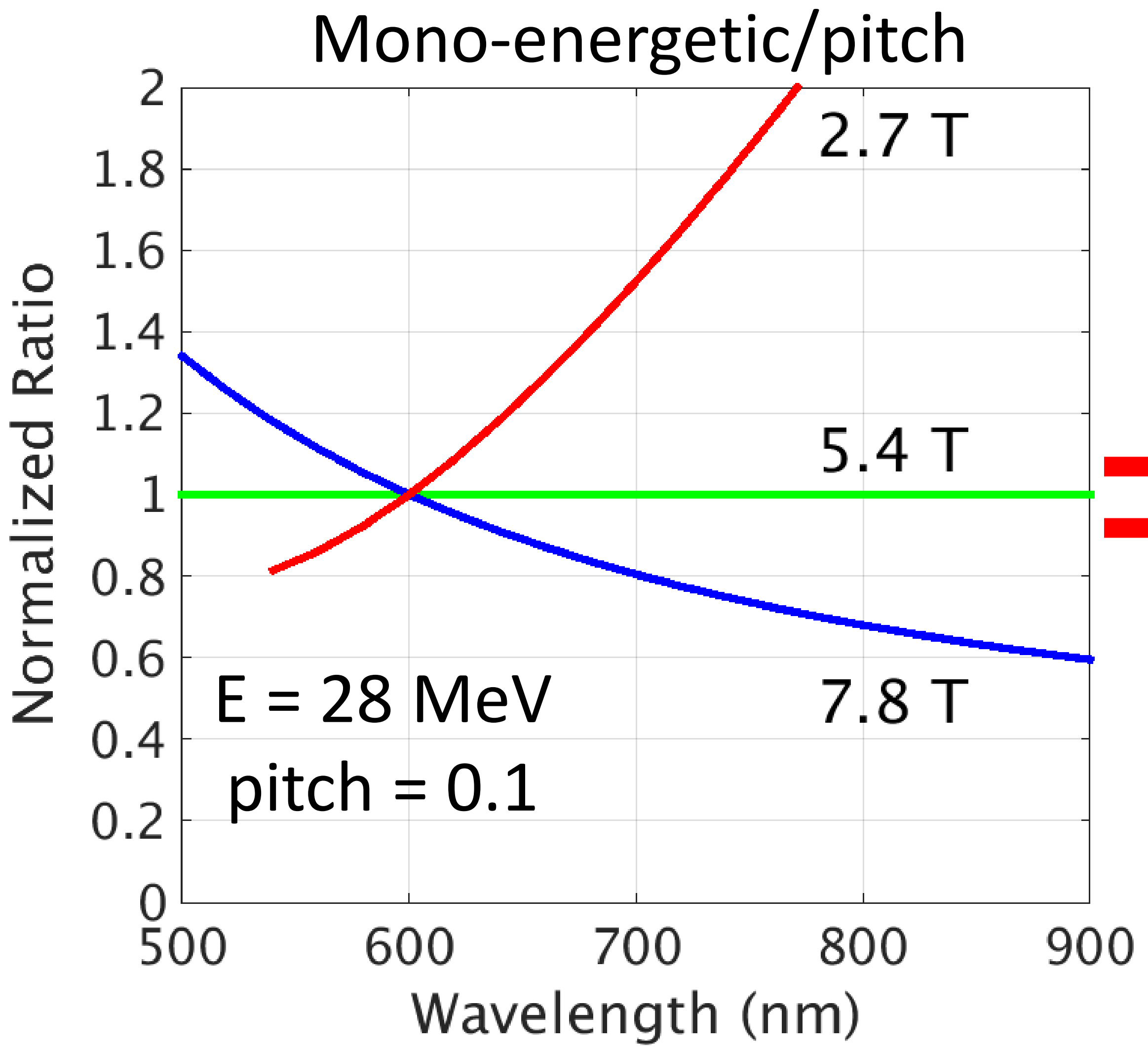

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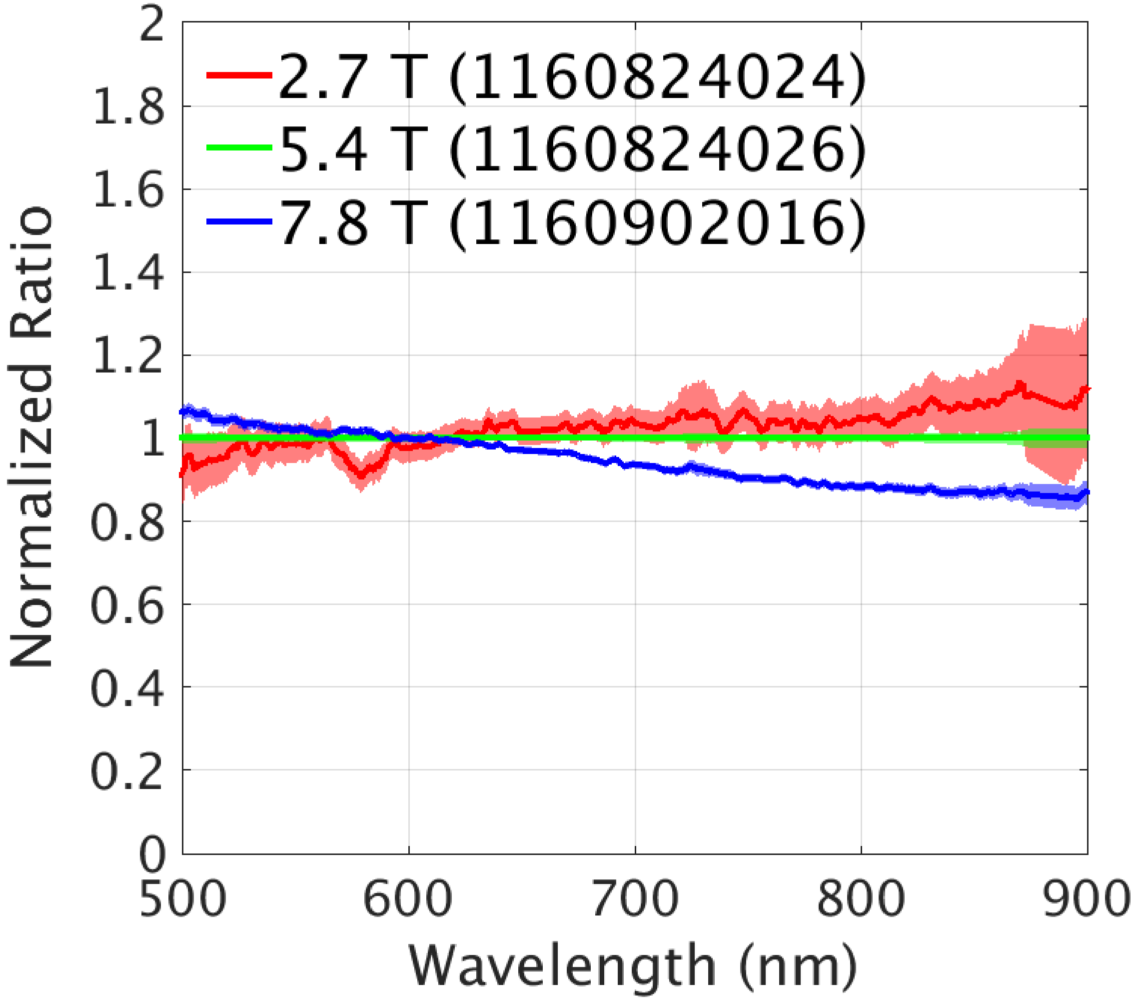

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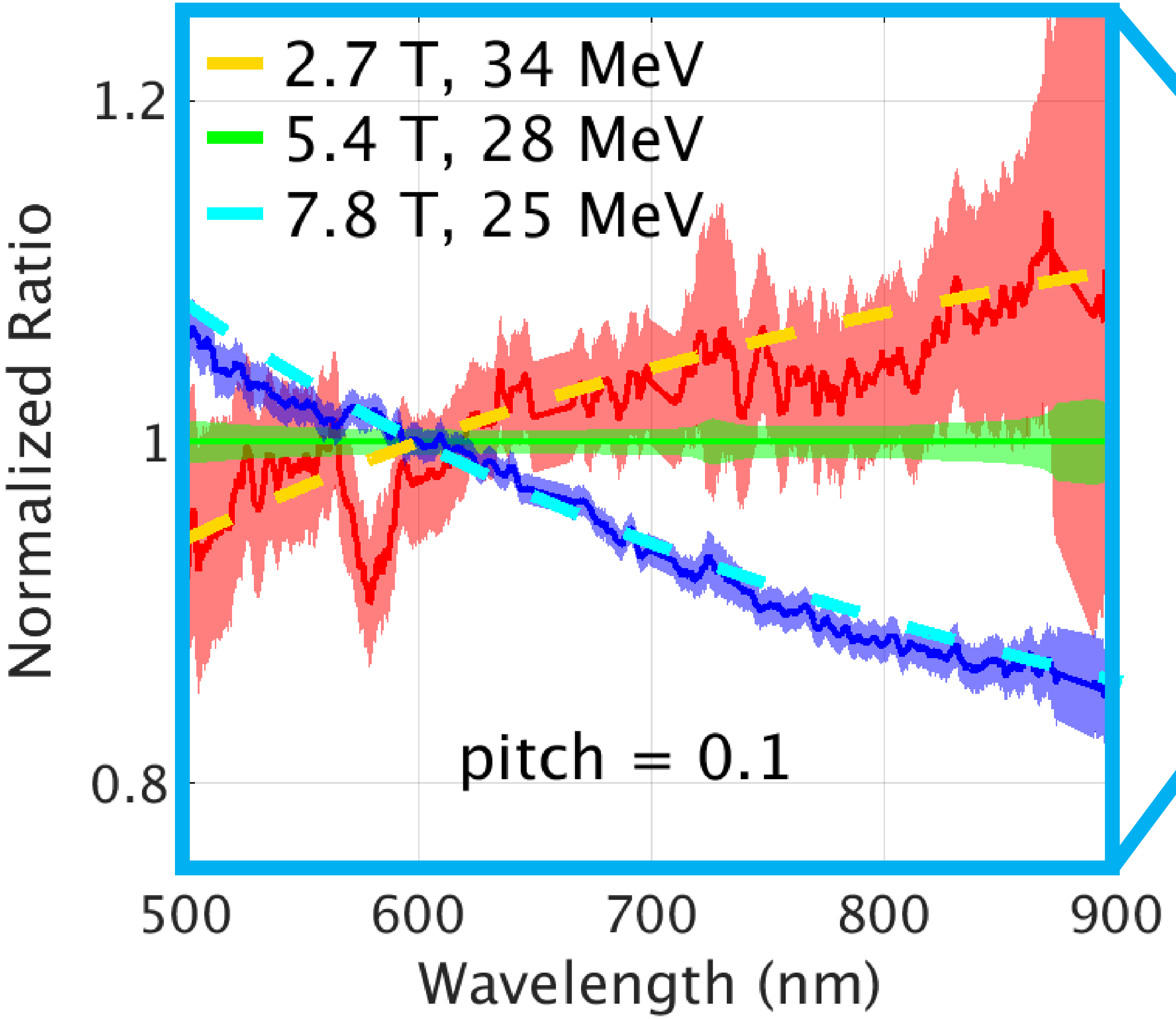
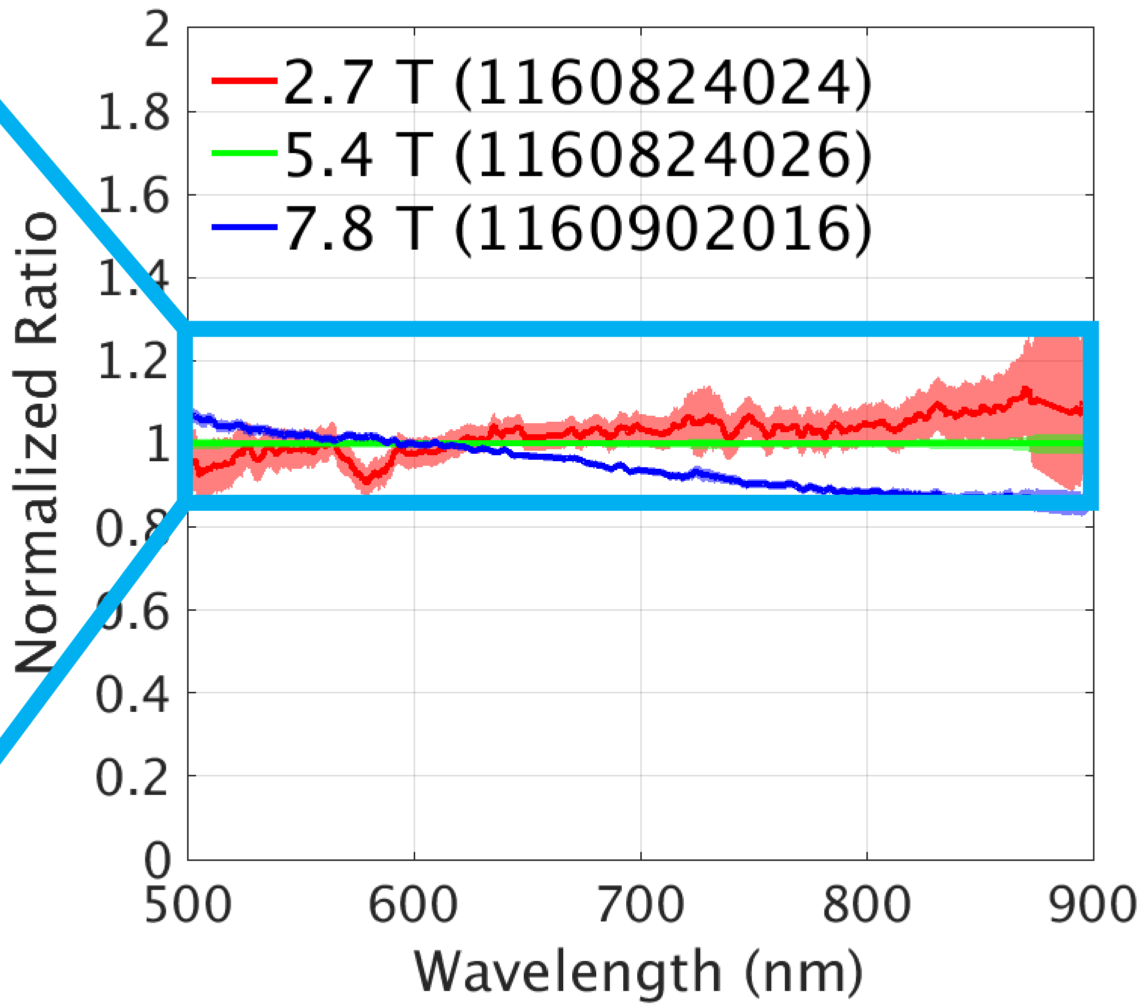
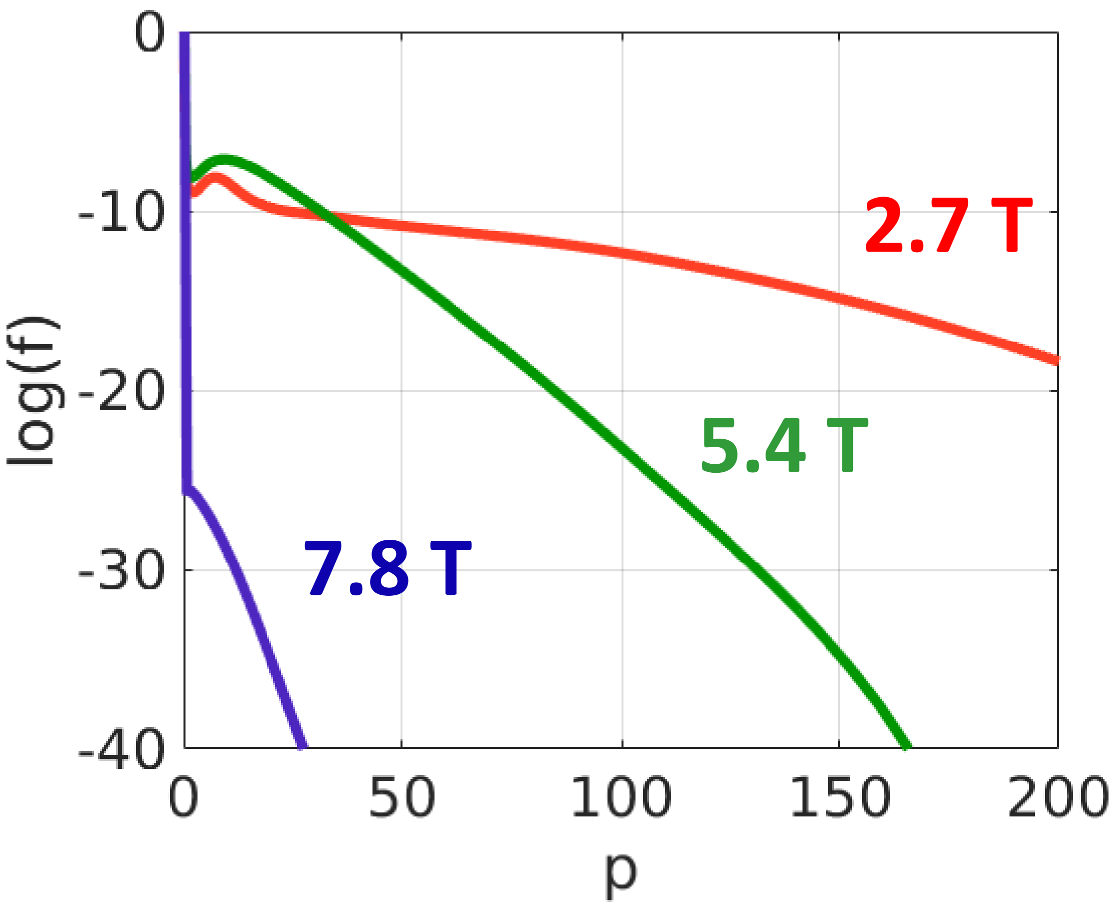
Synchrotron emission limits the mono-energetic RE energy





Very preliminary modeling shows the same trend

- Used experimental parameters for RE evolution in time
- Emphasize that this is not the full physical picture
- In fact, simulation predicted REs at times when none were observed experimentally



From correspondence with Pavel Aleynikov.

Summary, part 1

- Per particle, synchrotron emission increases and shifts toward shorter wavelengths with increasing magnetic field and energy (for fixed pitch).

- Measured synchrotron brightnesses at three magnetic fields (2.7, 5.4, and 7.8 T) have similar spectral shapes.

- Assuming a mono-energetic RE beam at a fixed pitch, an increase in synchrotron emission per particle (from an increase in magnetic field) reduces the energy.

  → Synchrotron emission is limiting the energy of REs.

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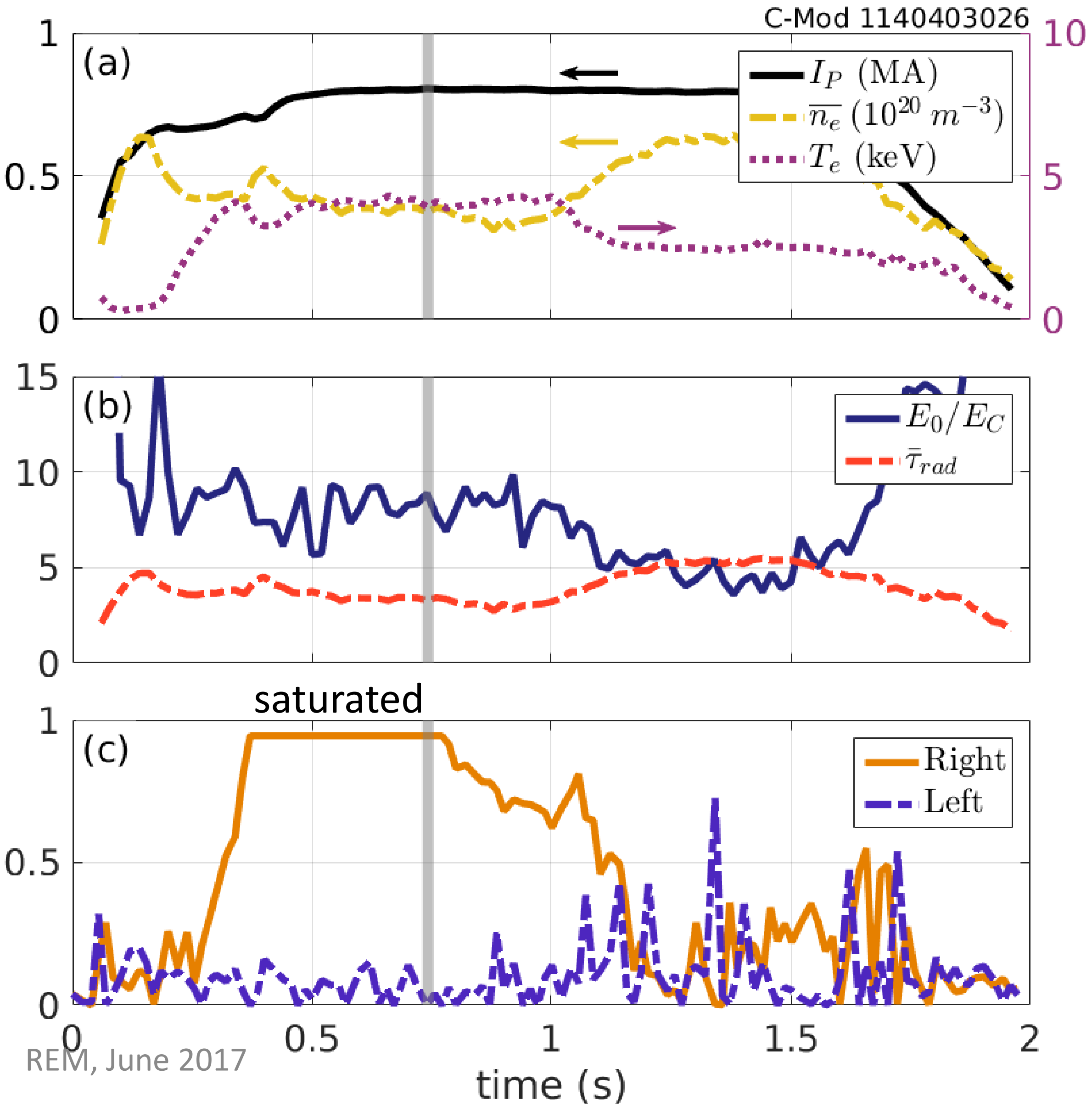
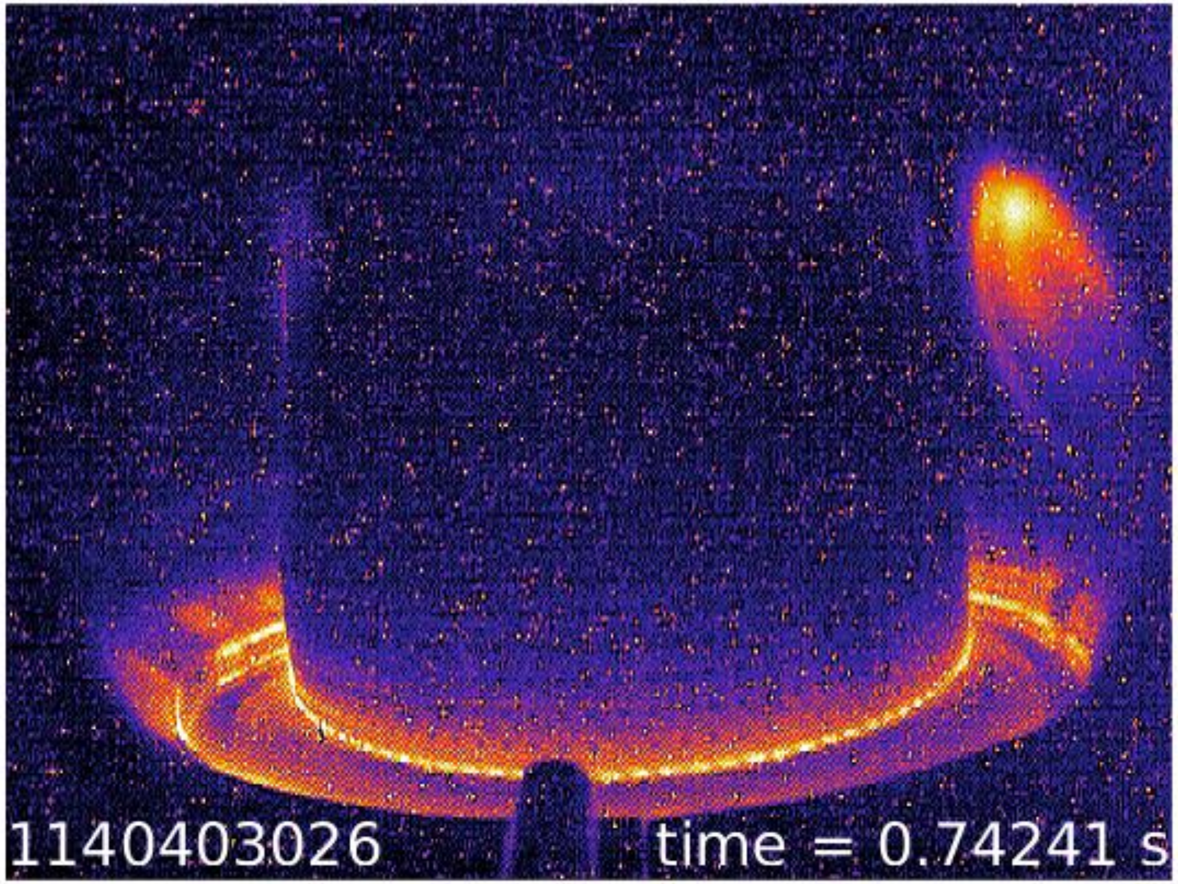
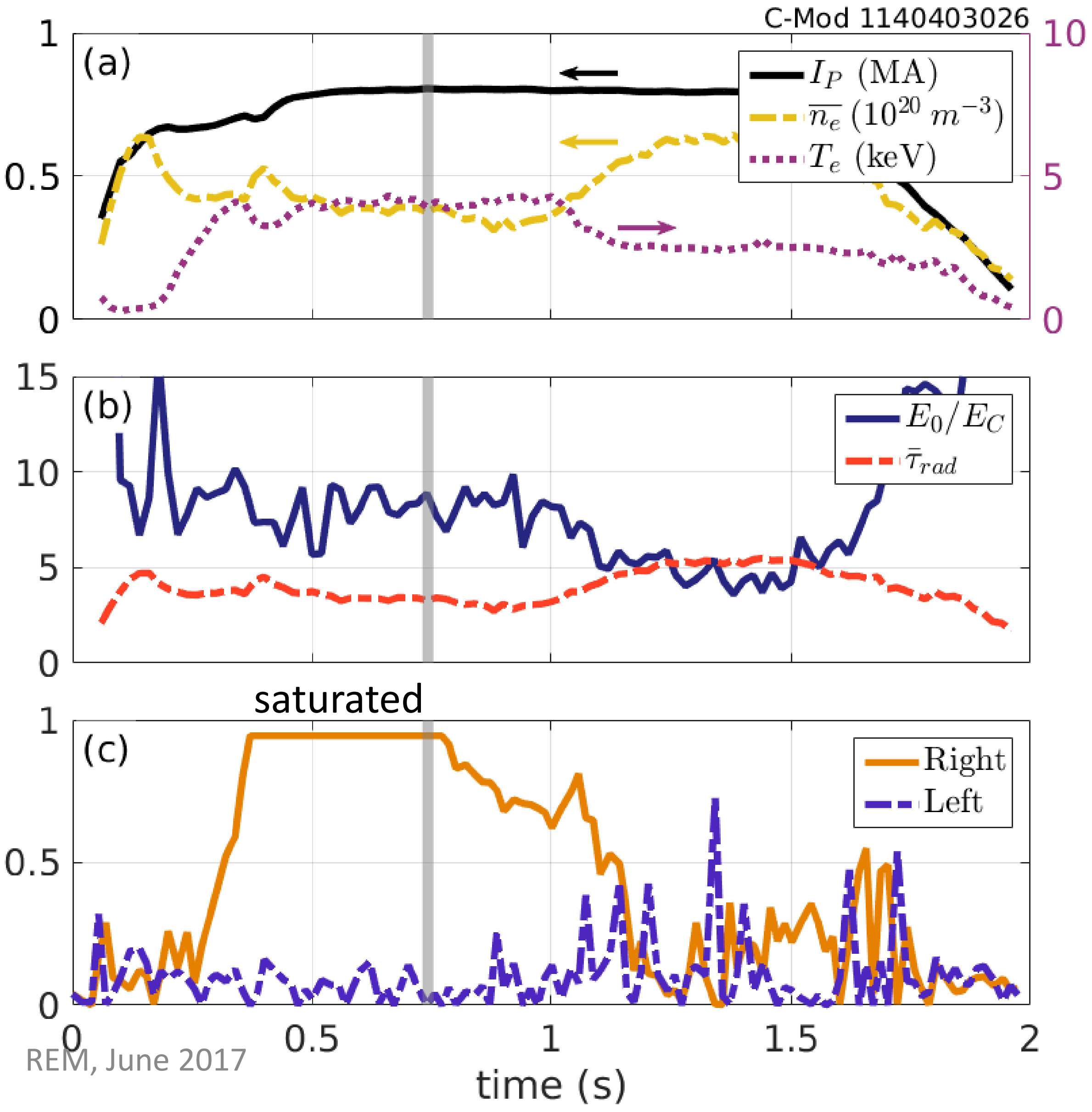
Synchrotron video

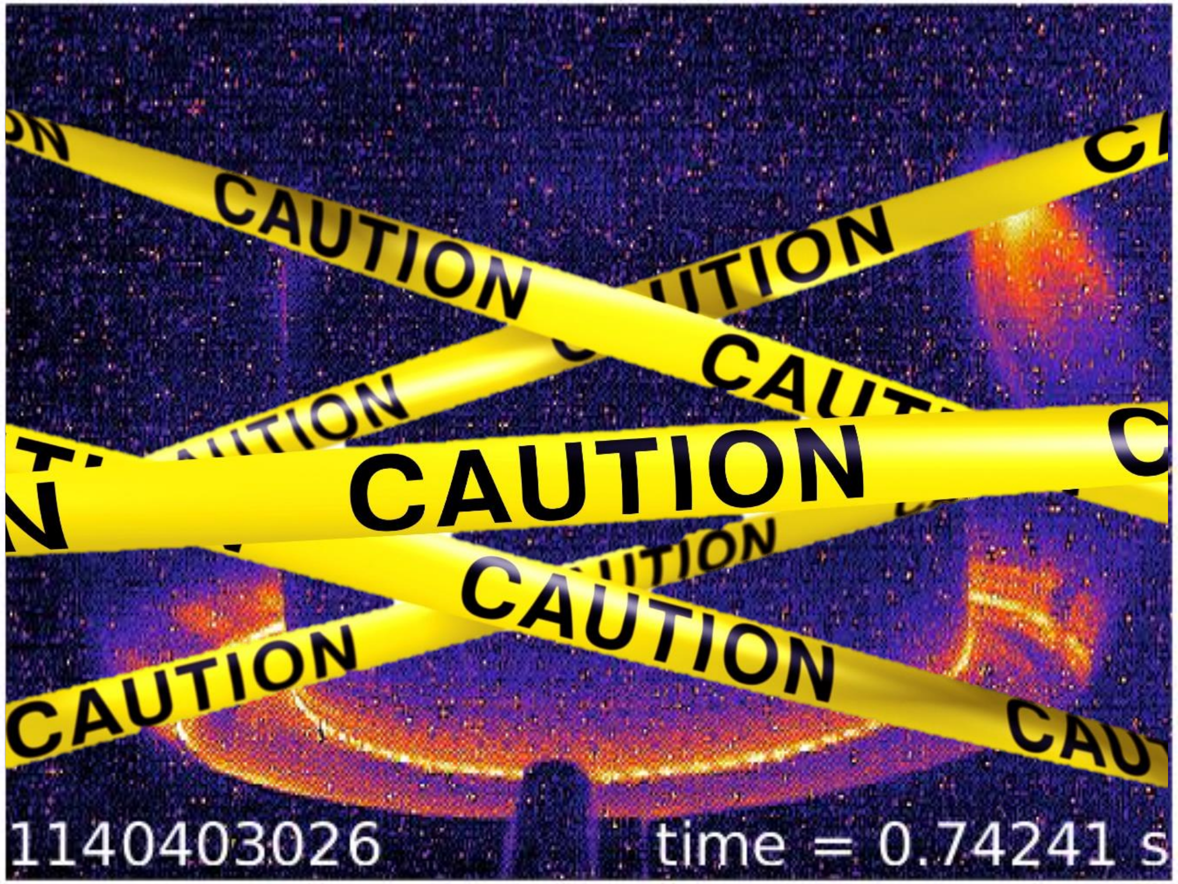
Synchrotron emission captured



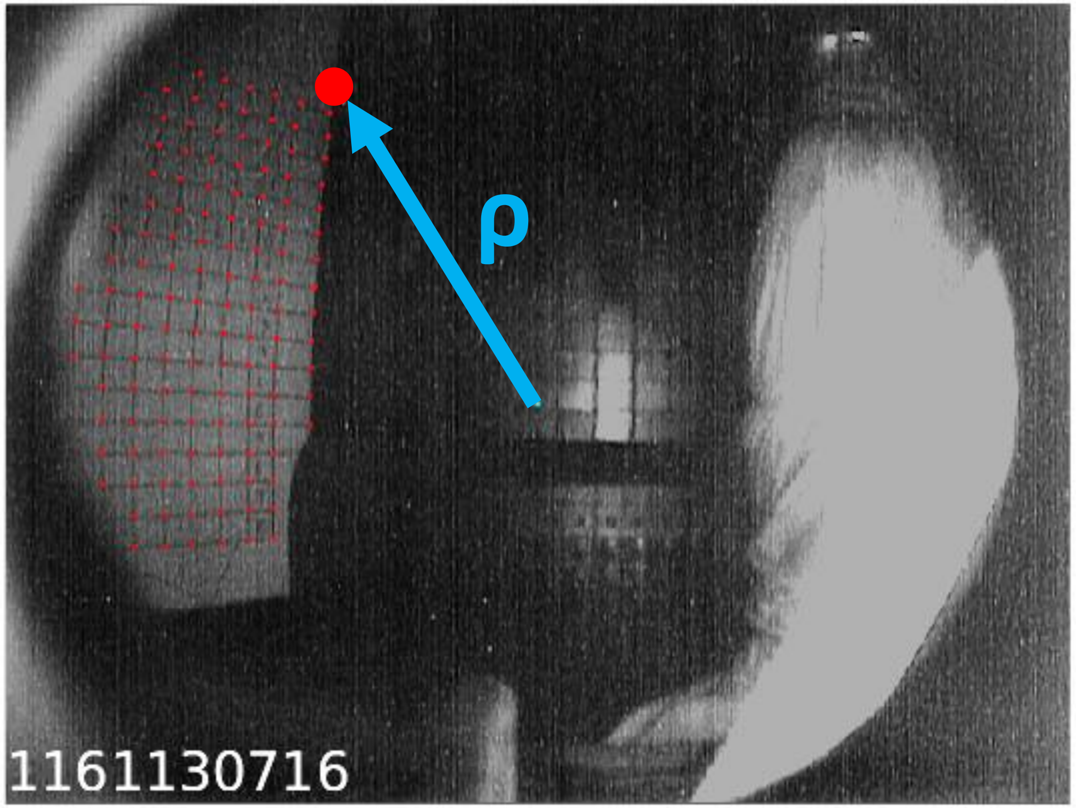


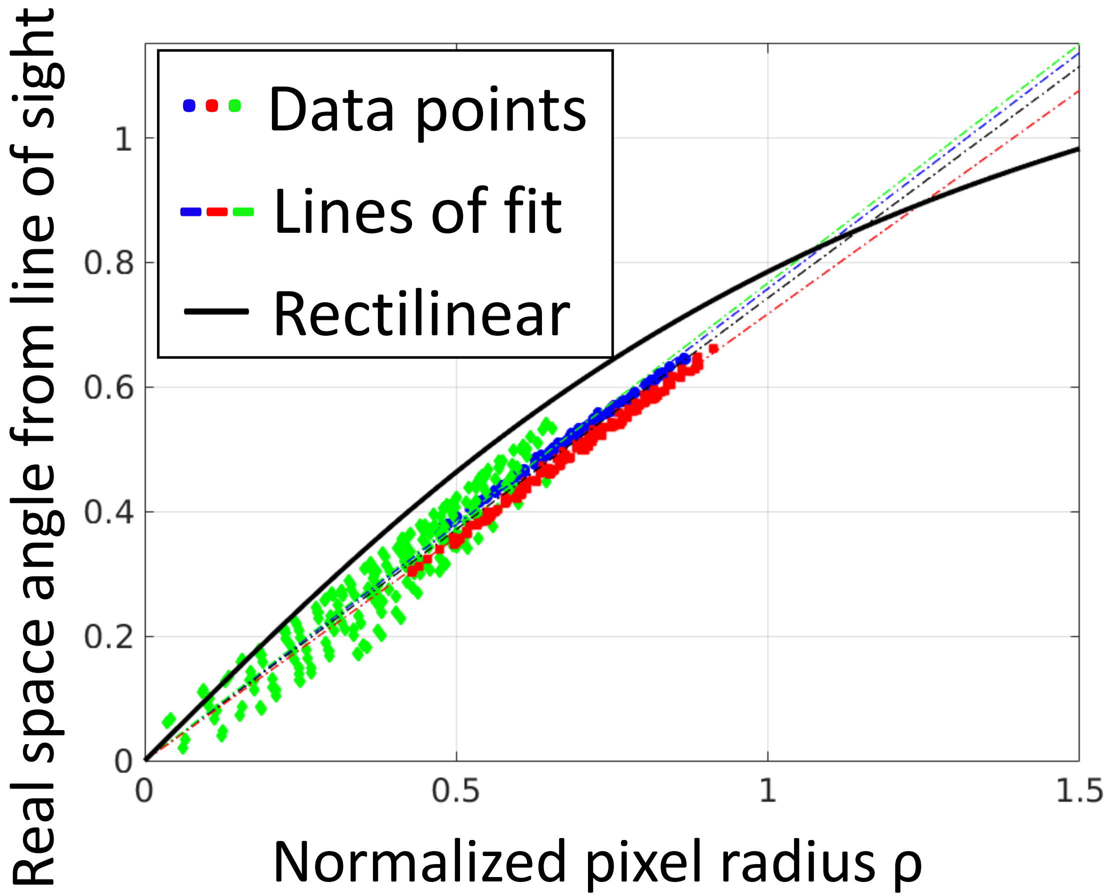
Synchrotron emission captured





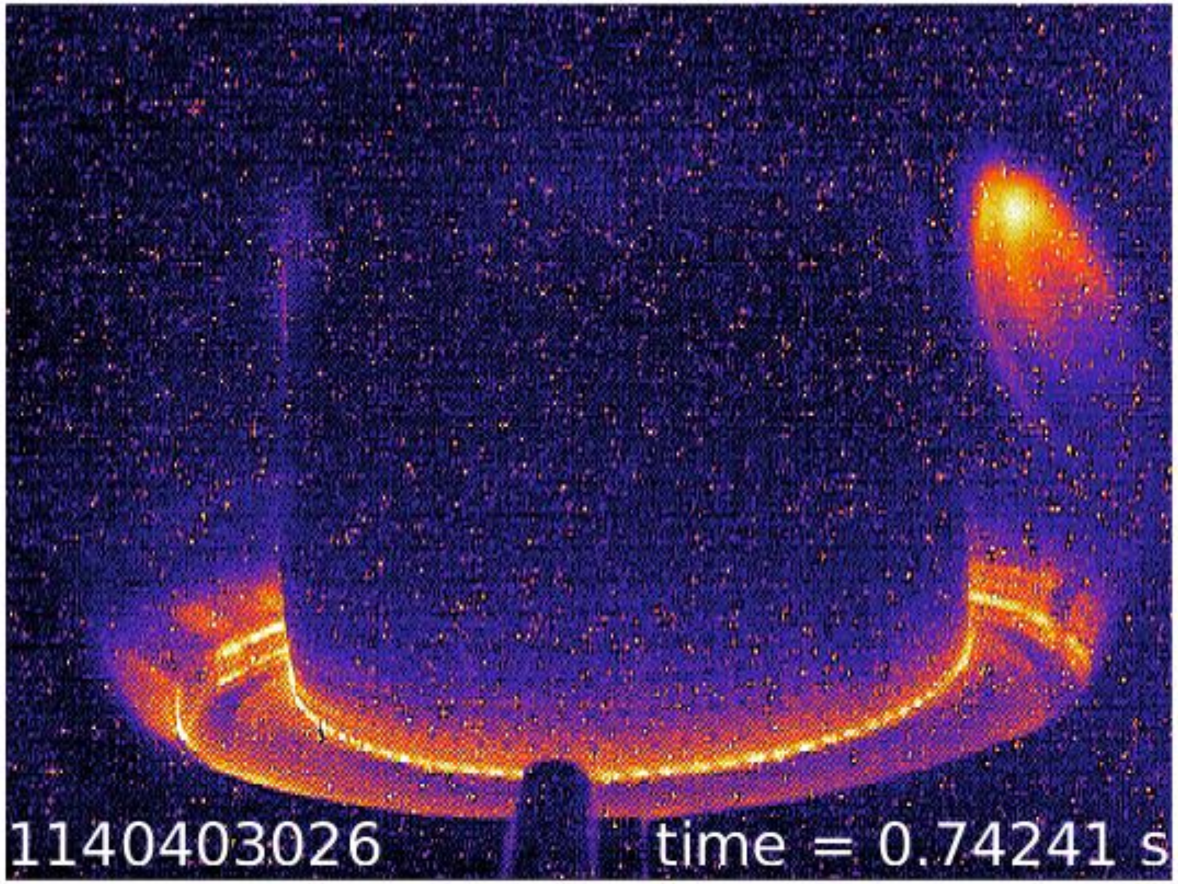
Distortion correction



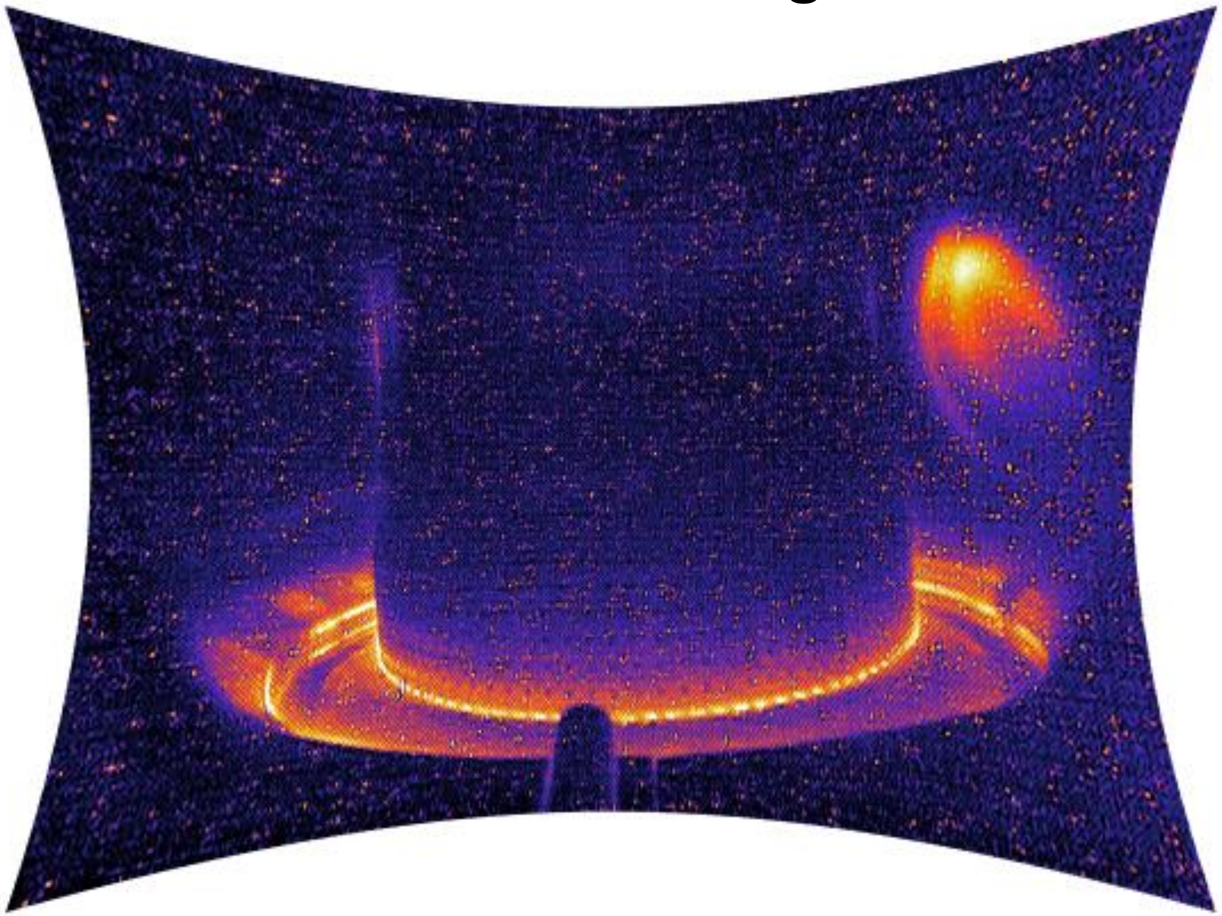


Distortion corrected

Original image

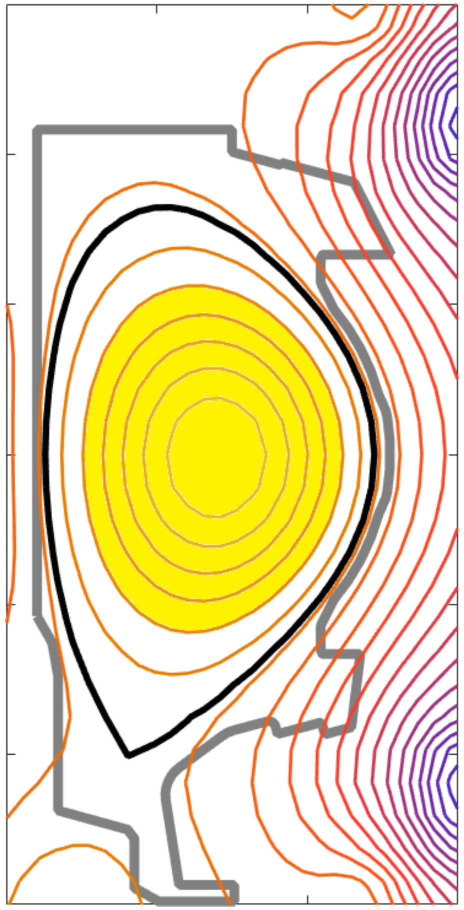


Corrected image



SOFT applied to experiment for the first time

Uniform radial distribution



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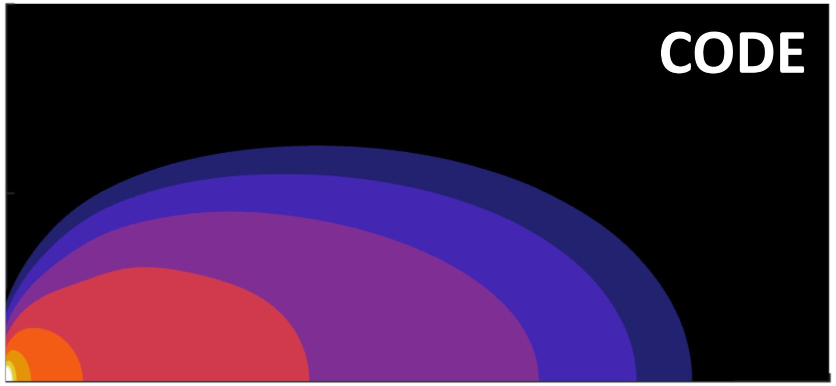

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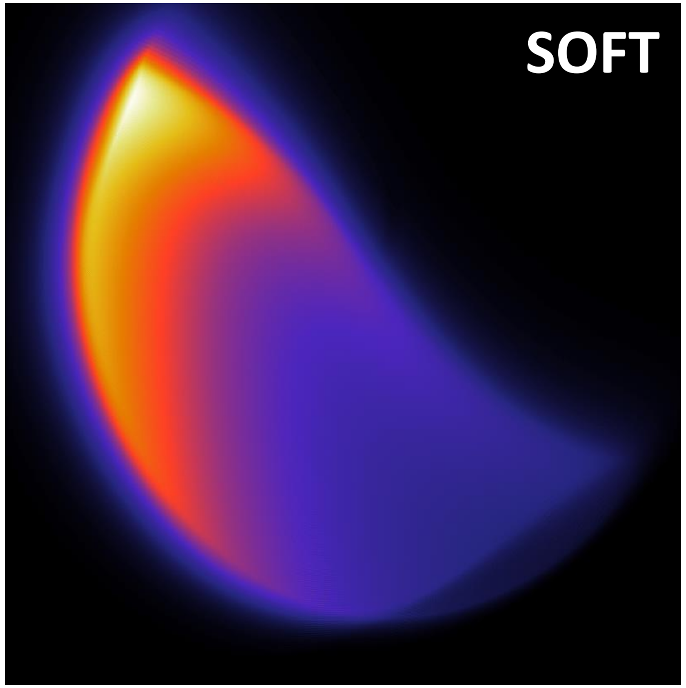
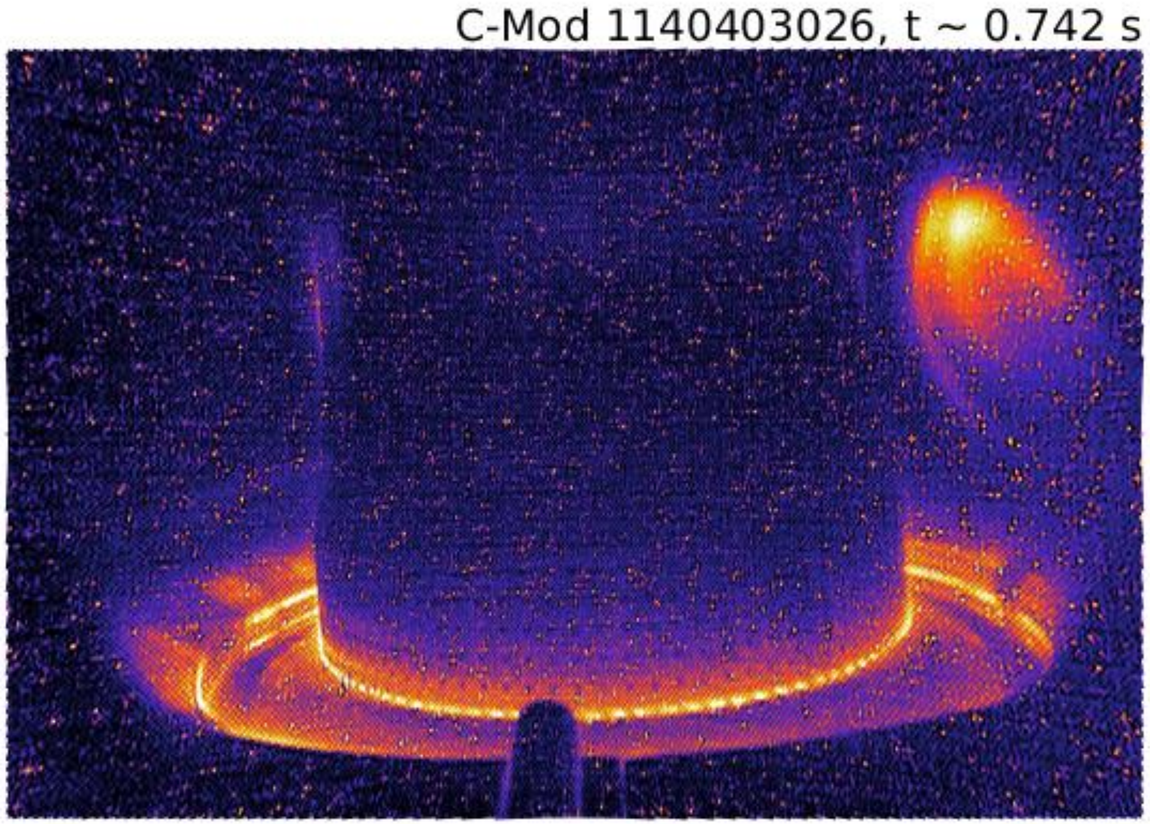
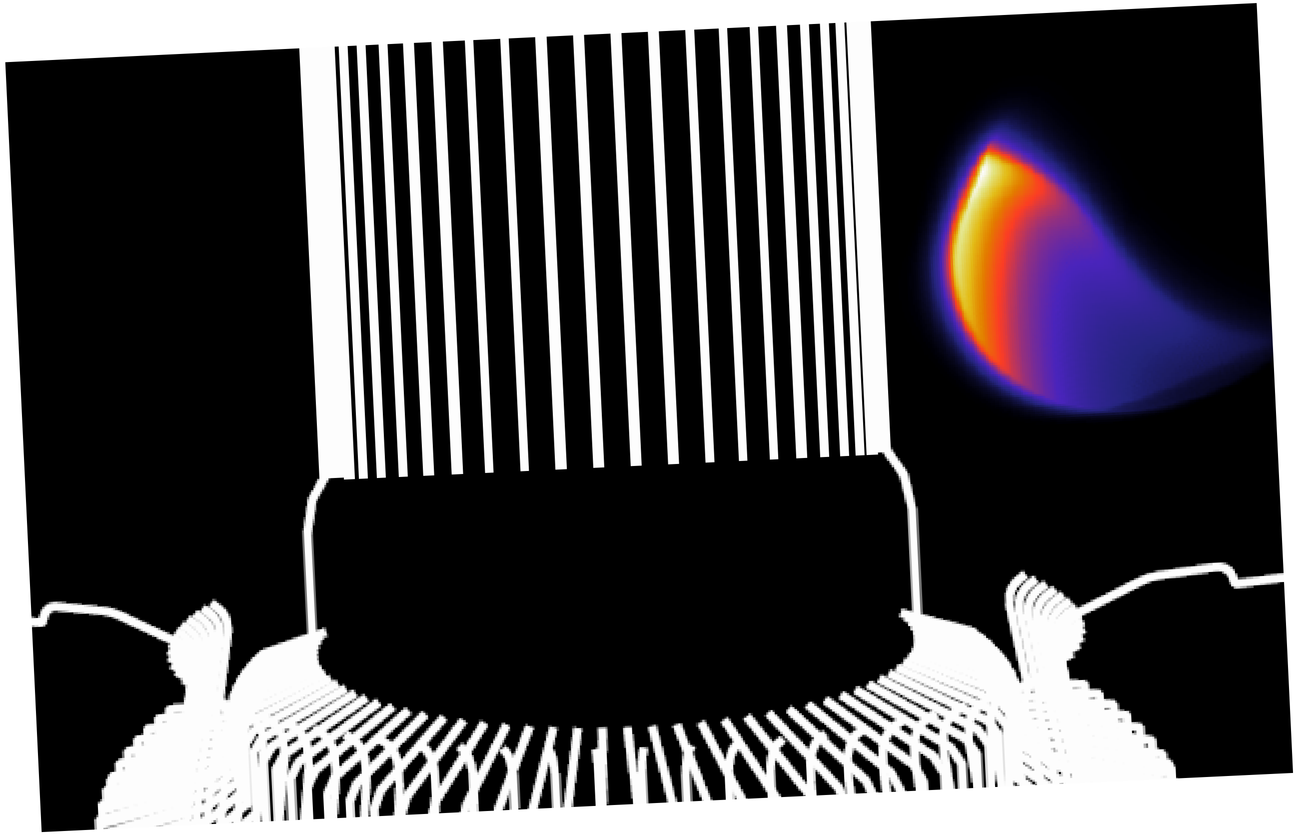


M. Hoppe, et al. Synthetic synchrotron diagnostic for runaway electrons in tokamaks. In progress.

M. Landreman, et al. CPC (2014) A. Stahl, et al. NF (2016)

Good agreement between experiment and SOFT





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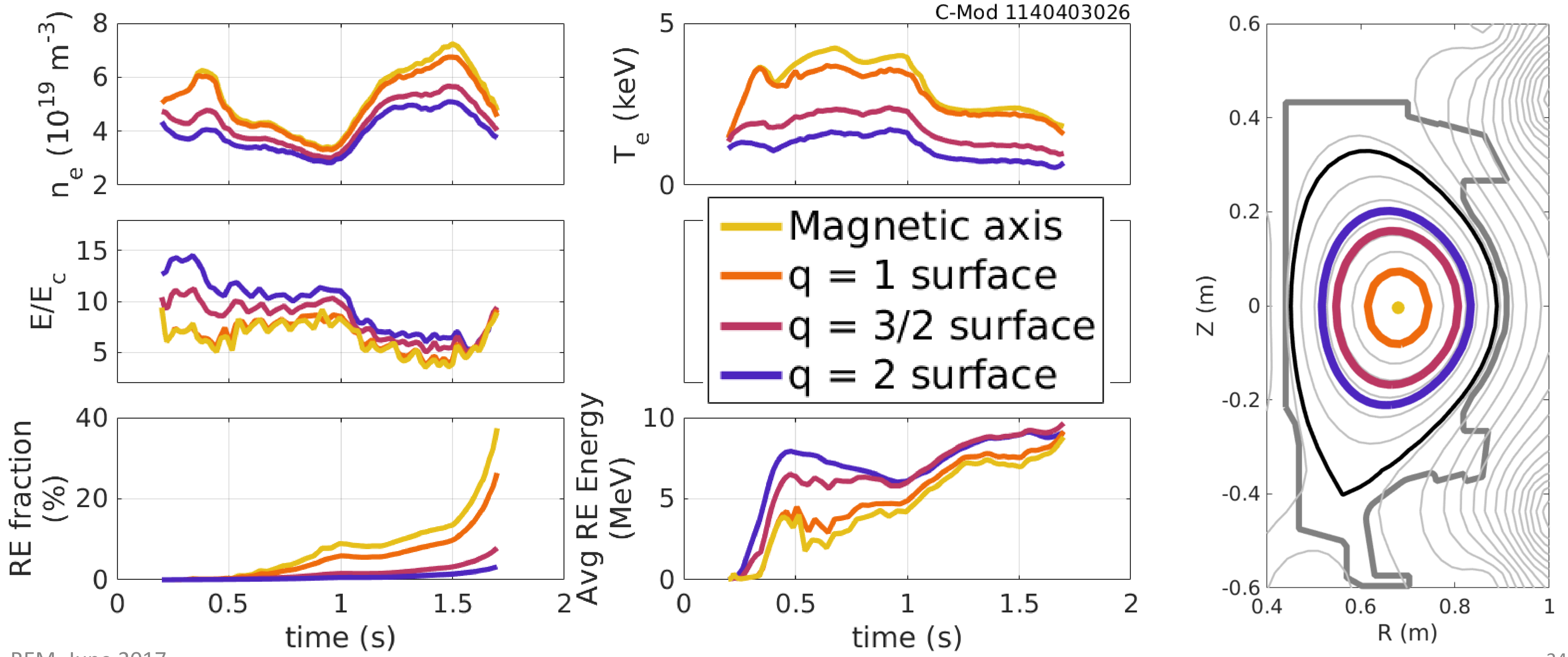
M. Landreman, et al. CPC (2014)   A. Stahl, et al. NF (2016)

RE energy evolution will also vary in space

Consider rational surfaces – there exists a trade-off in RE **energy** and **density**



Summary, part 2

- New synthetic camera diagnostic SOFT (with inputs from momentum space solver CODE) shows promise in reproducing experimental synchrotron images

- However, the apparent lack of a unique solution makes it difficult to solve the inverse problem and requires us to solve the forward problem (simulations)

- Momentum and real space evolutions of REs are coupled as plasma parameters vary in space, so a coupled solver will likely be needed

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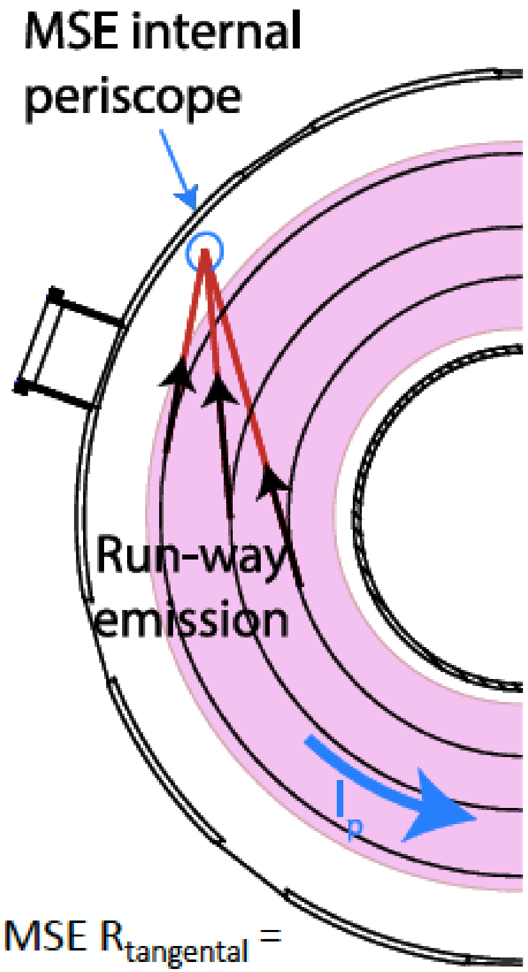
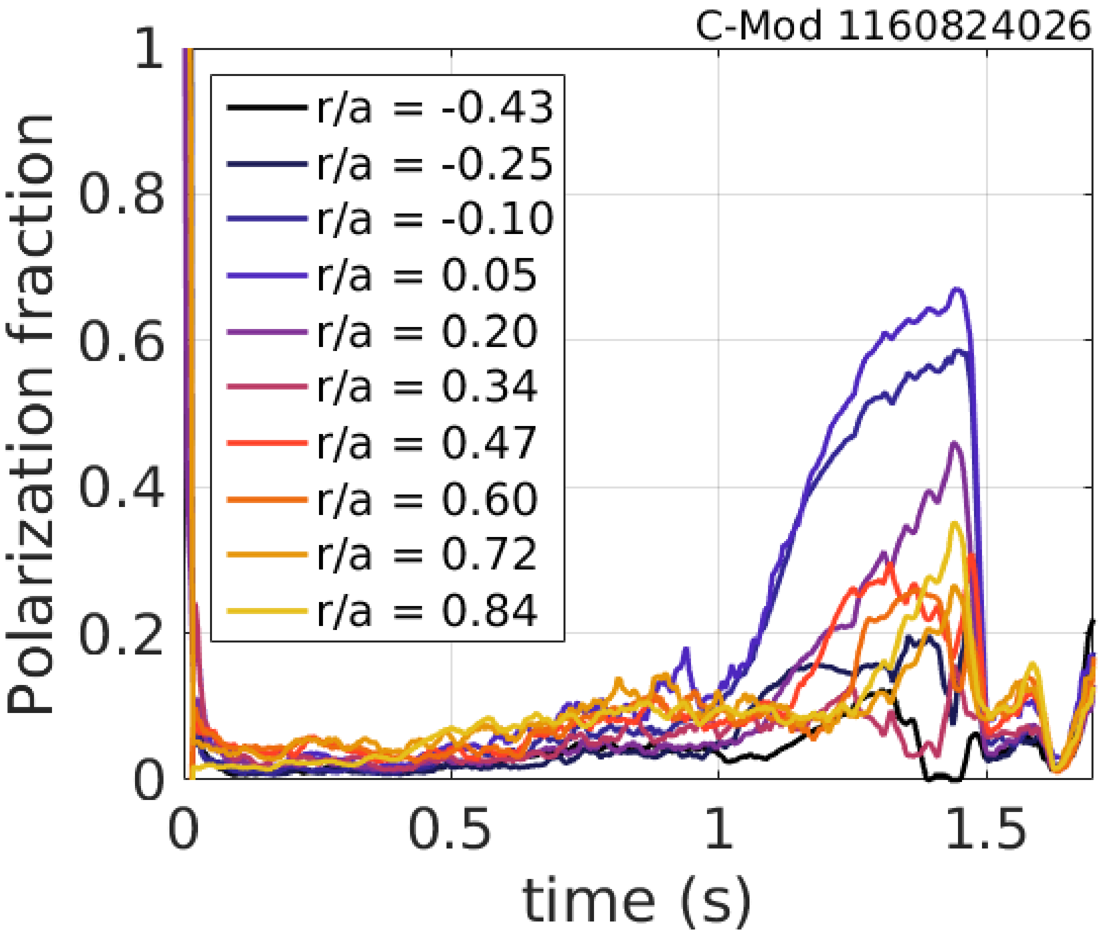
MSE measures polarization at 10 midplane locations

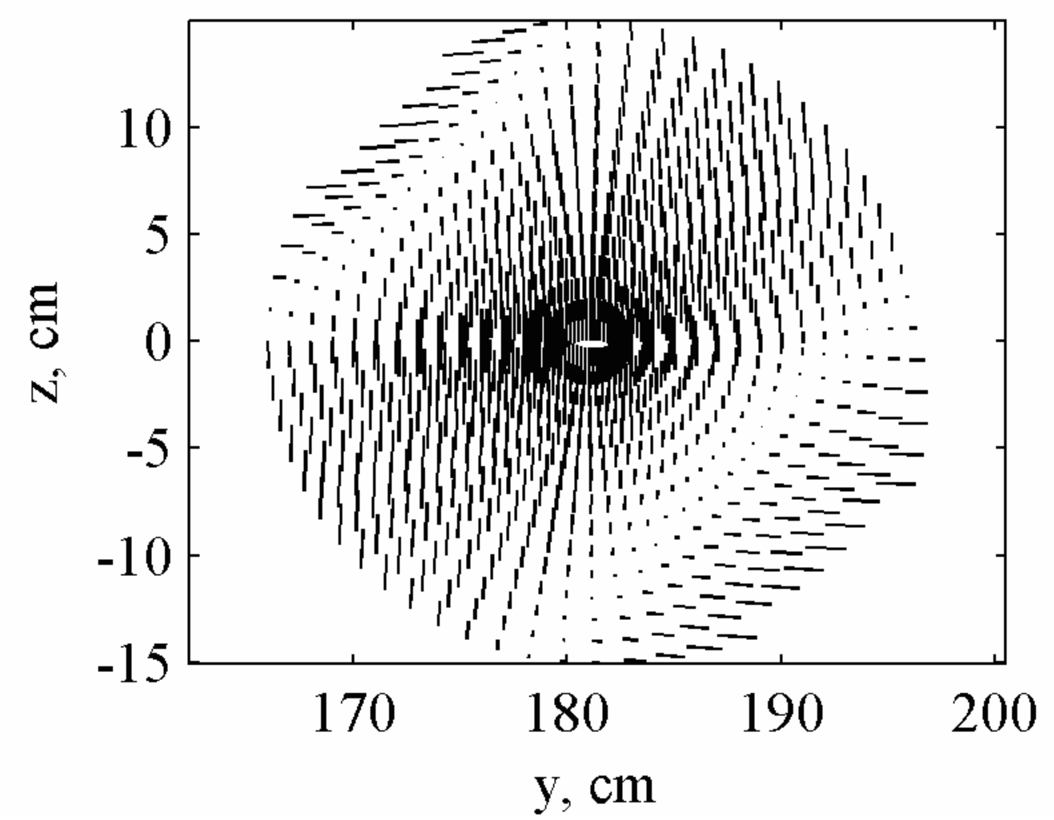


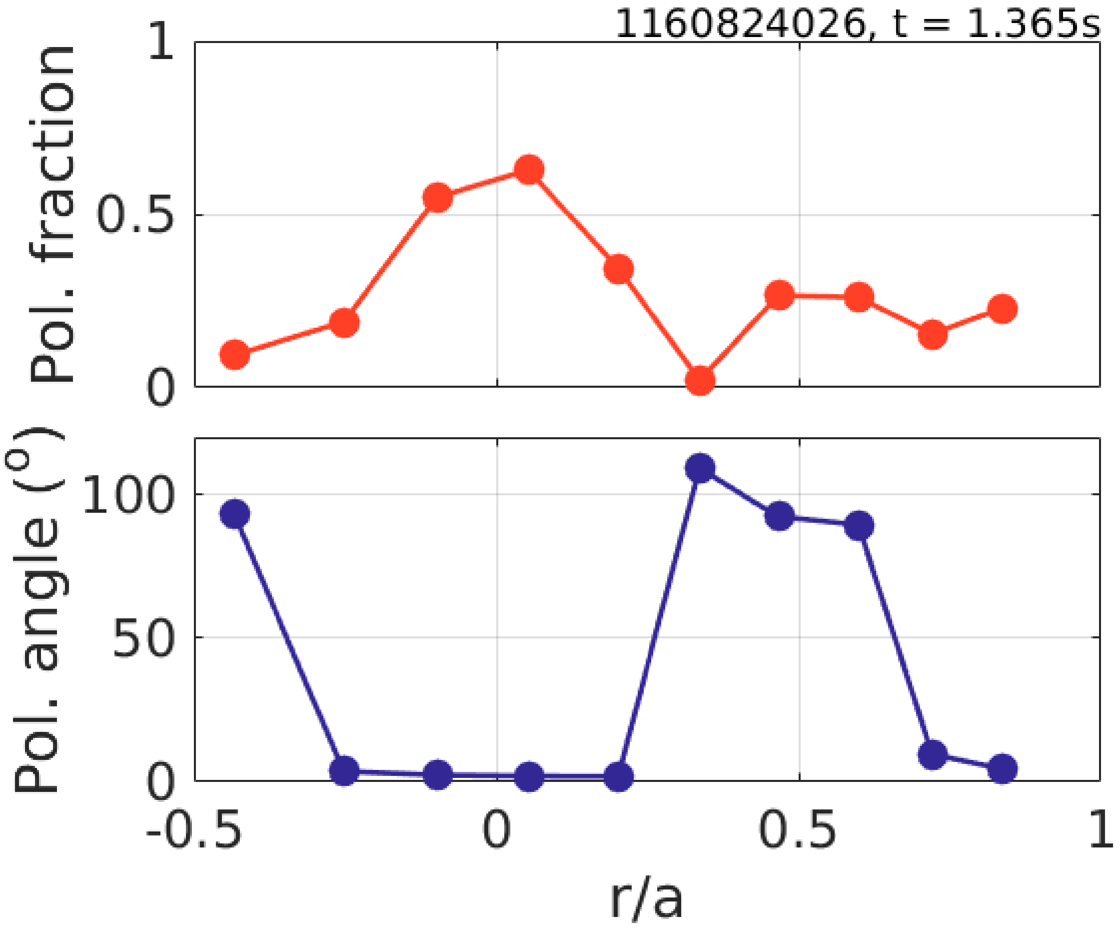
MSE $R_{tangental}$ =
60cm – 85cm, 10chs
Time resolution = 2ms



Radial polarization data similar to theory

Synchrotron polarization (poloidal projection).
B_0 = 3 T, R_0 = 1.75 m, a = 0.4 m, q_0 = 1,
r_b = 0.15 m, γ = 50, θ = 0.1





Ya.M. Sobolev, ISSN 1562-6016, BAHT (2013)

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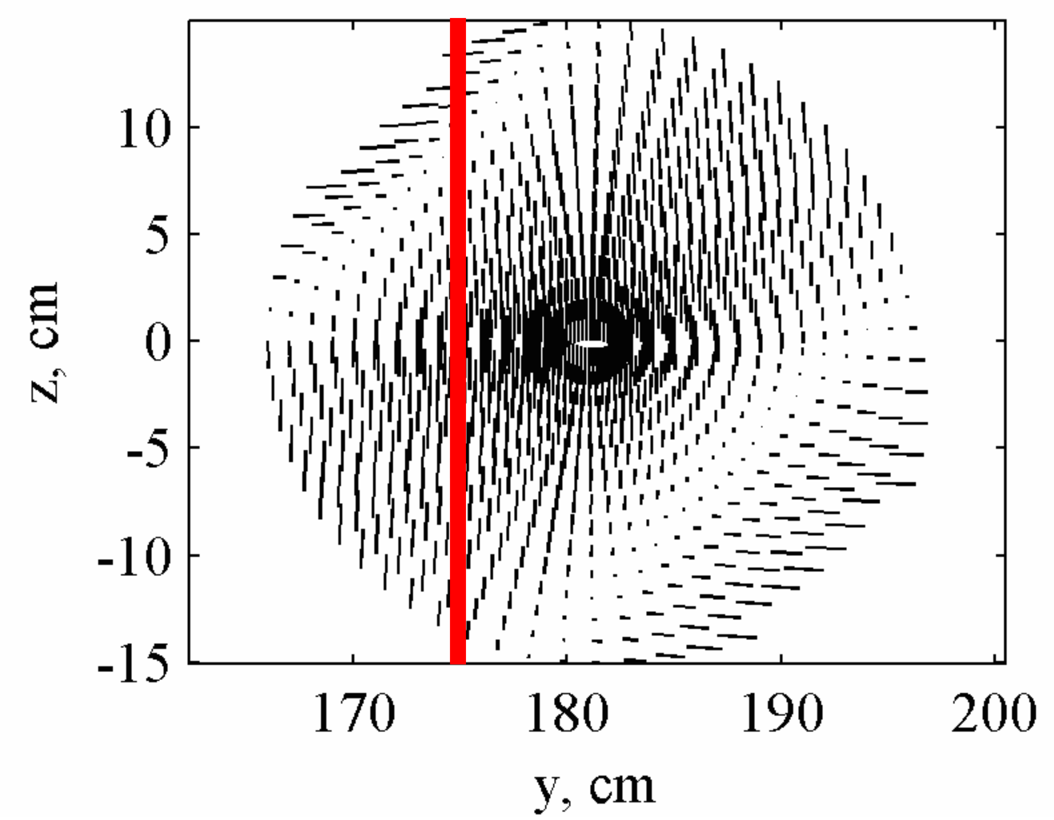

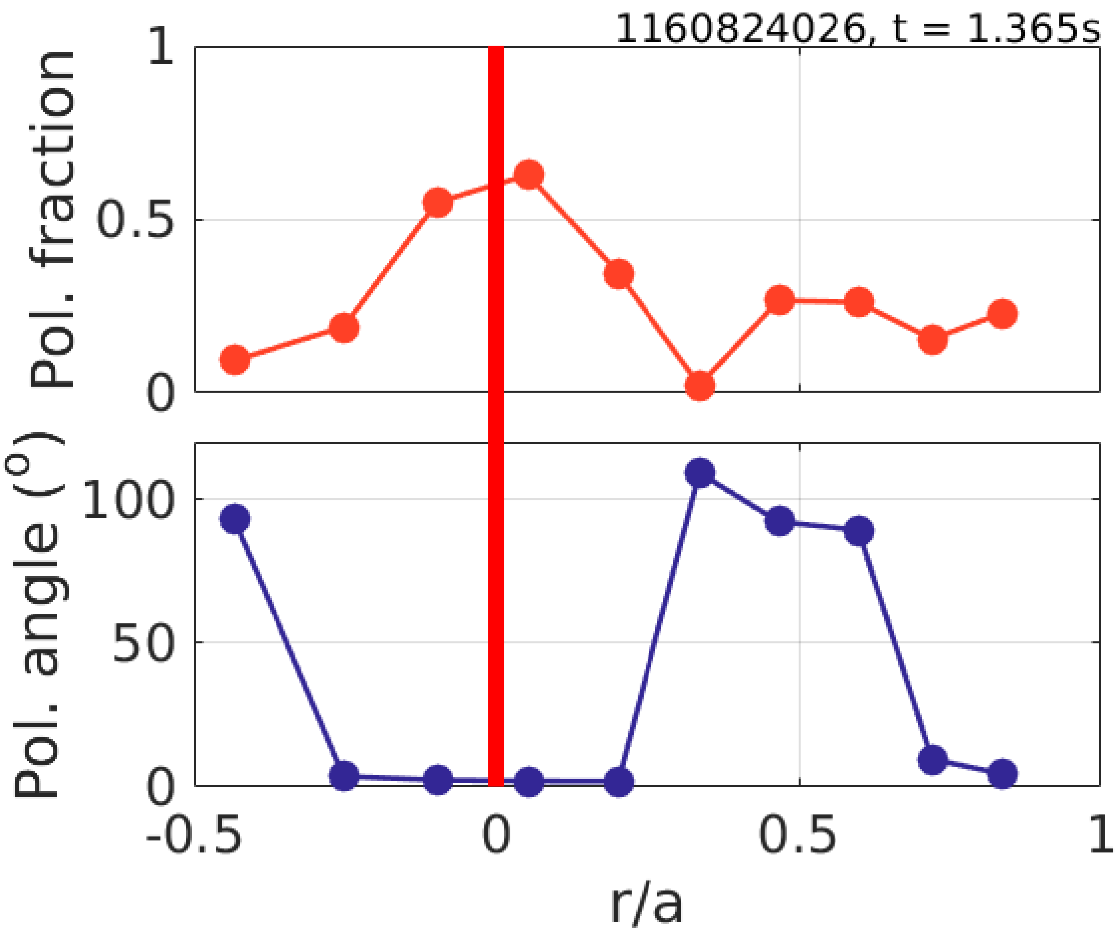

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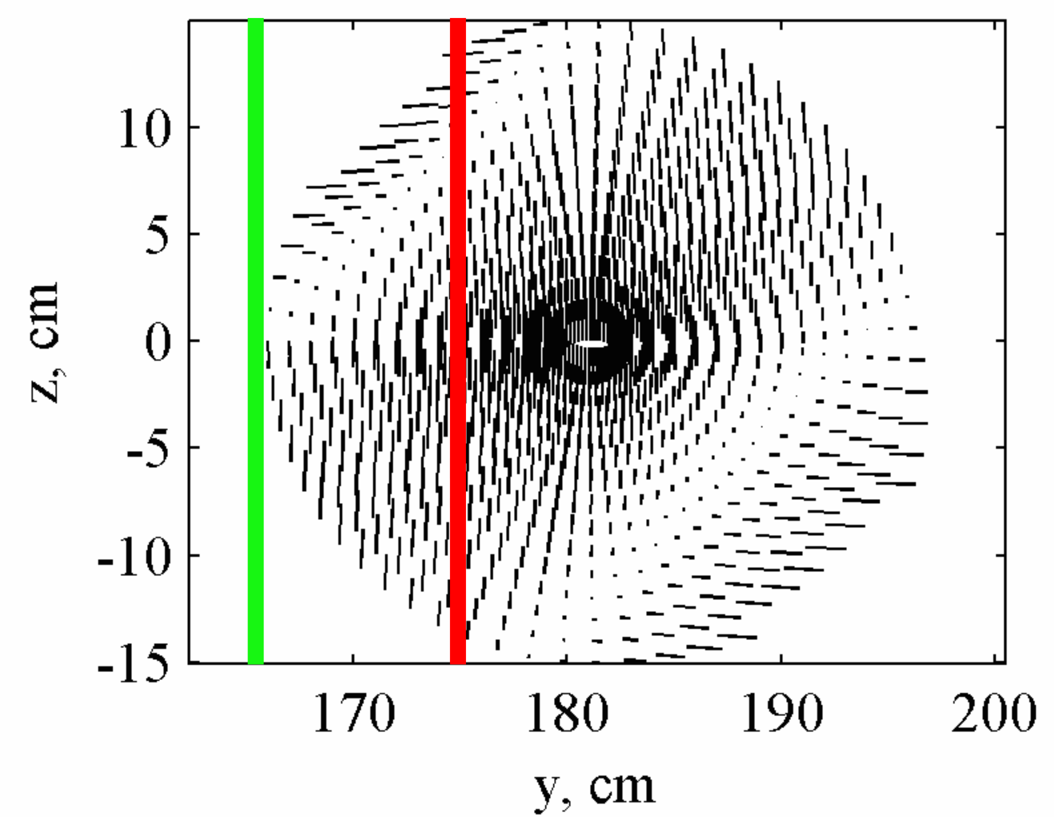

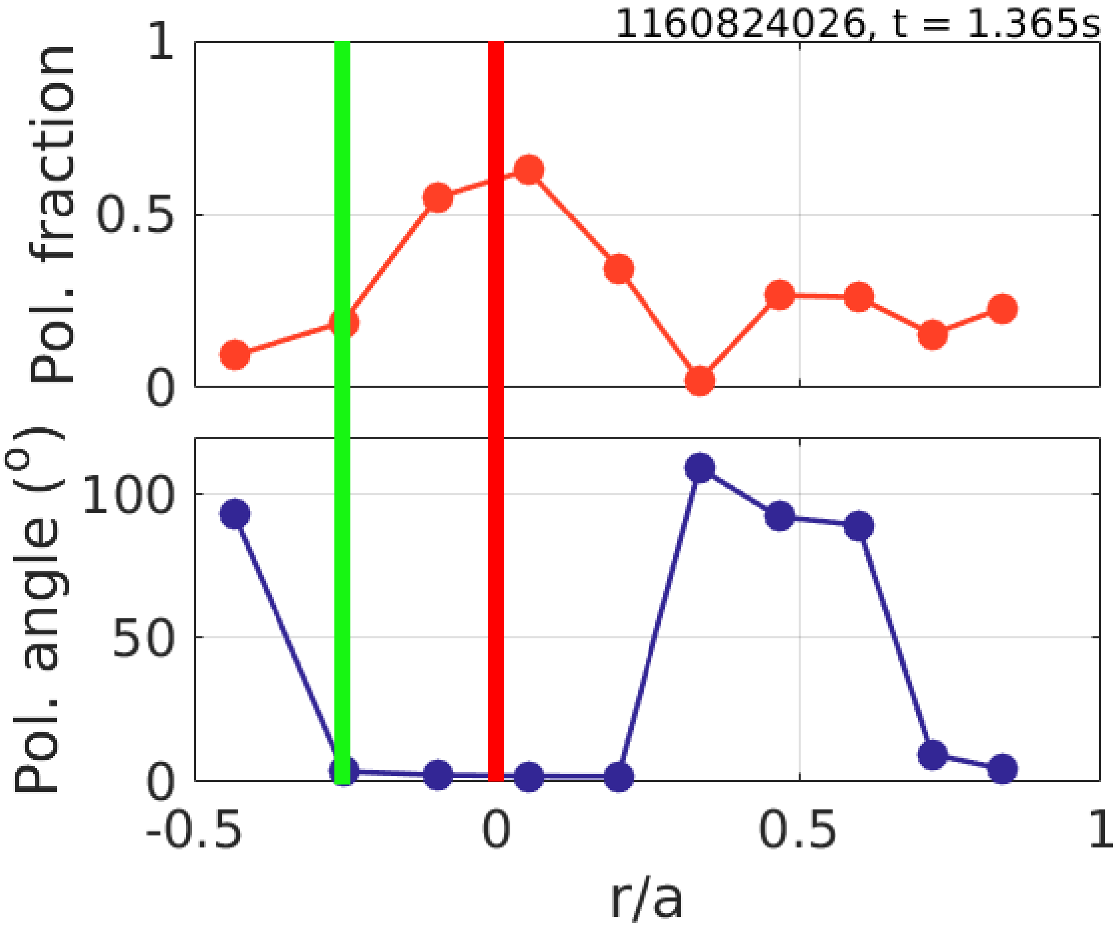

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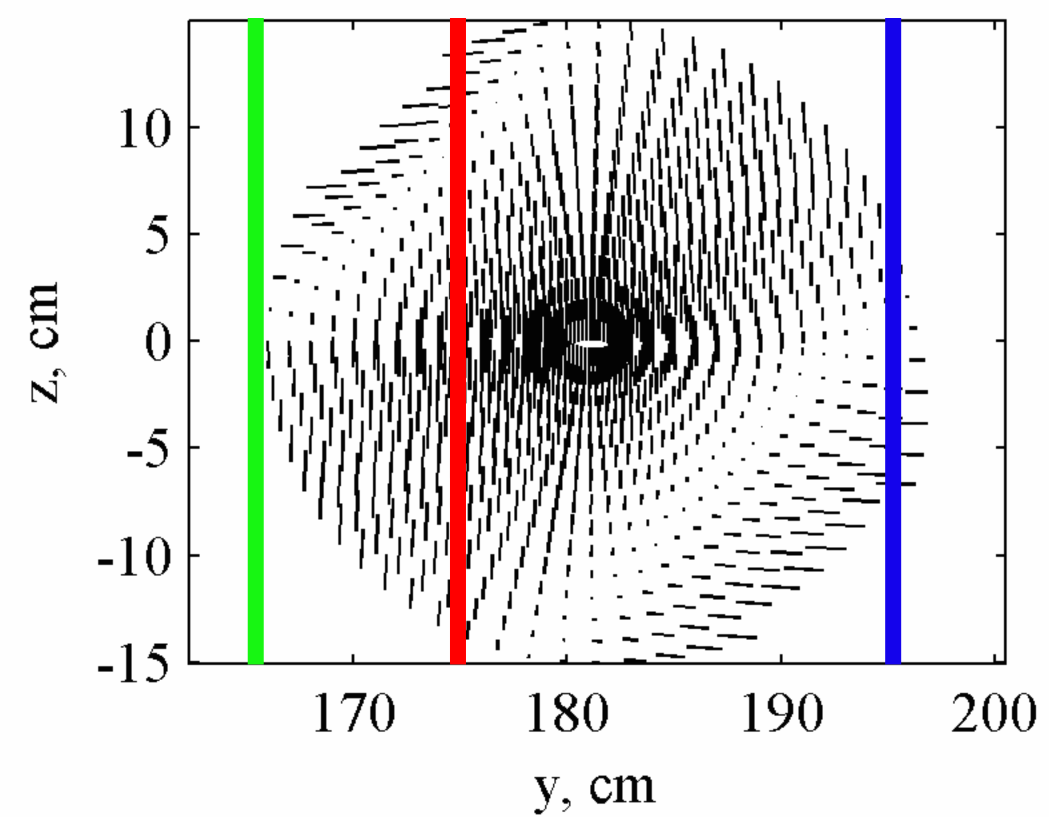

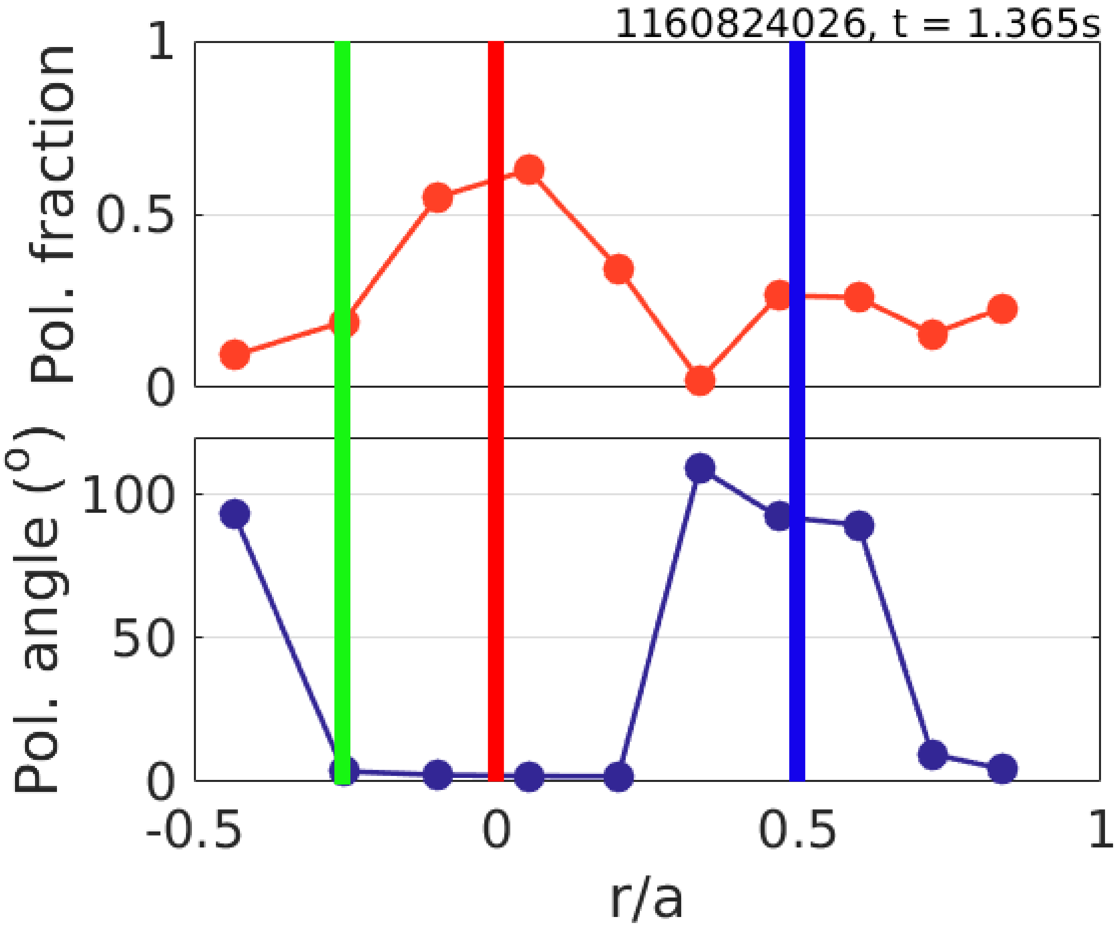

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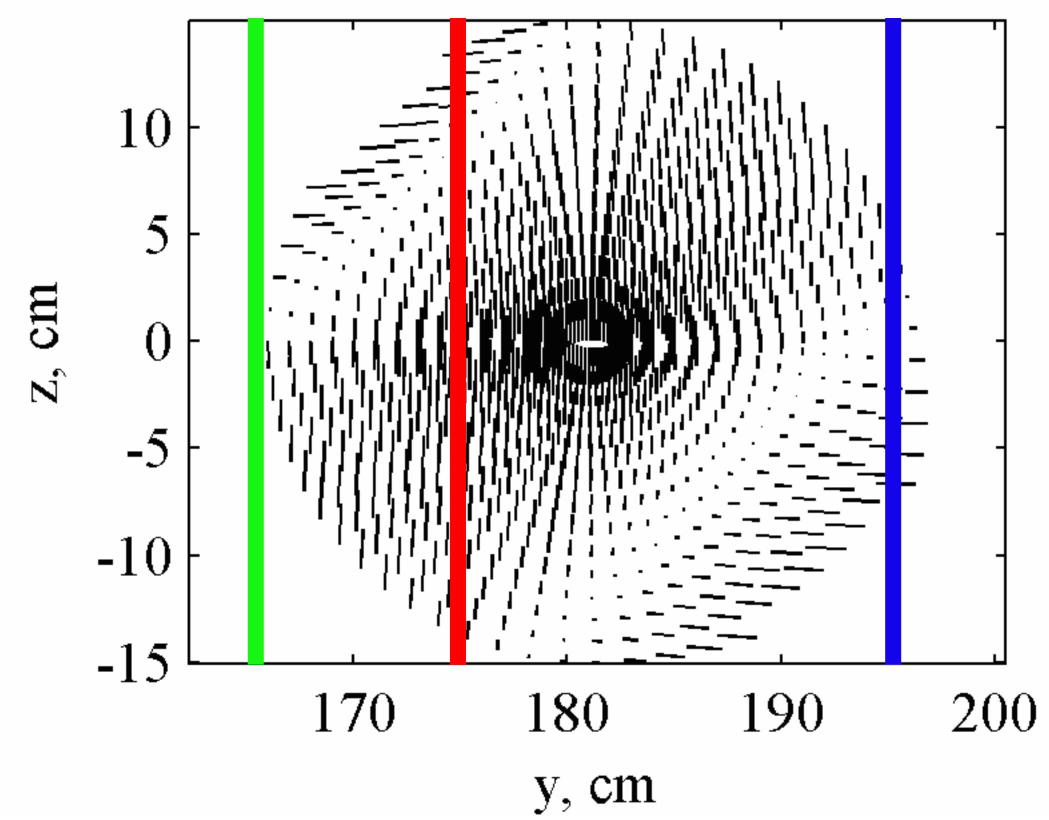

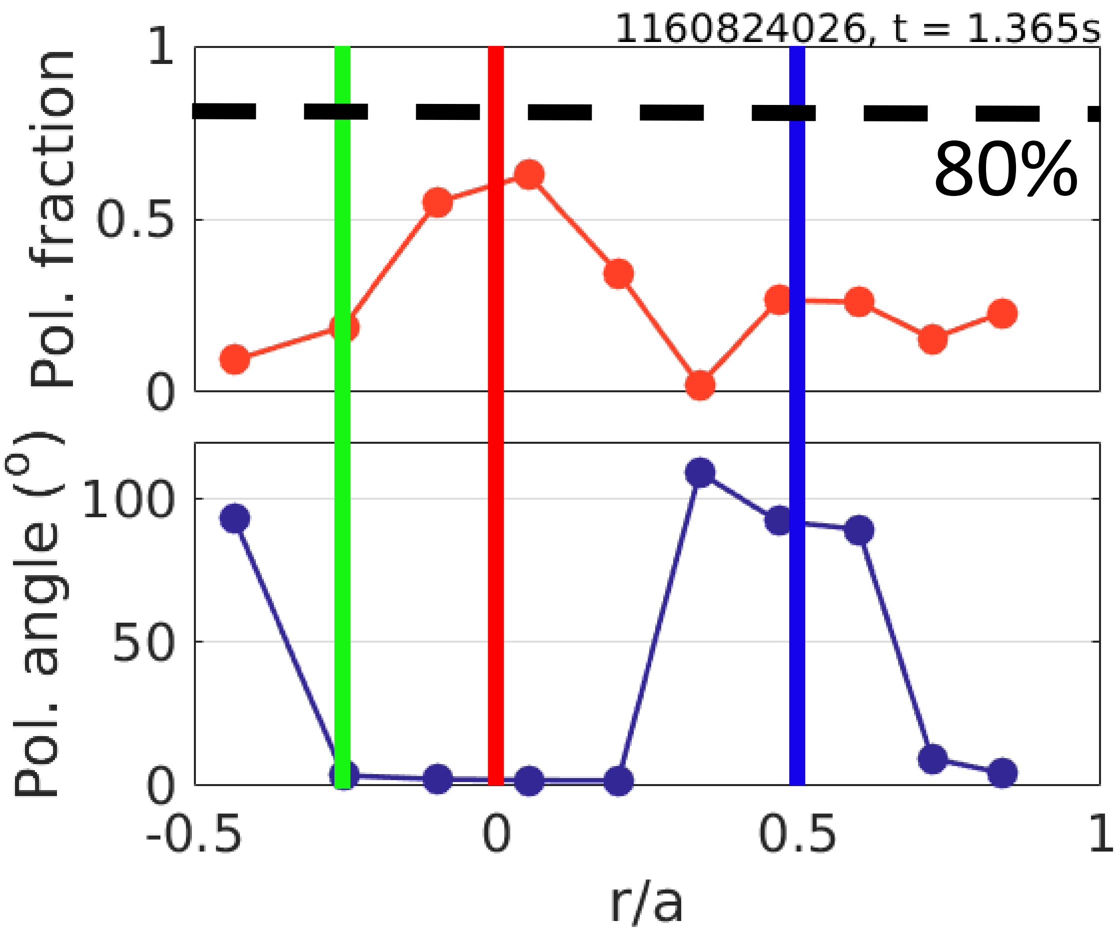

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- *SOFT images*: Are flux-surface-averaged quantities good enough? Should we move on to coupled solvers like LUKE?

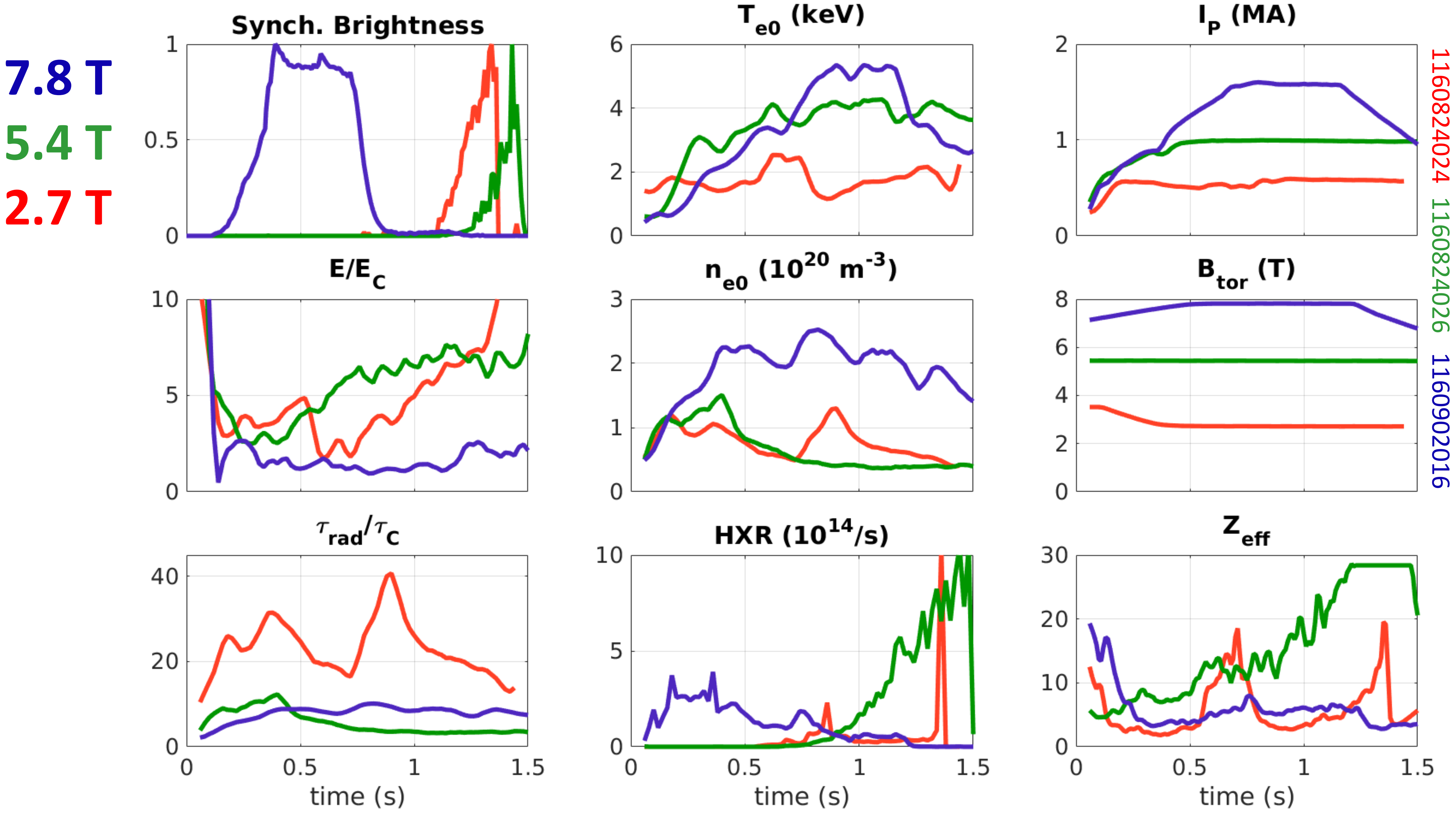
- *Polarization data*: Do any codes currently calculate synchrotron polarization? If not, would this be easy to implement?

Extra

Abstract

Alcator C-Mod's high magnetic field allows runaway electron synchrotron emission to be observed in the visible wavelength range. Visible spectrometers were used to measure synchrotron spectra at three magnetic fields: 2.7, 5.4, and 7.8 T. Assuming fixed energy and pitch, the spectral shape is expected to shift toward shorter wavelengths with increasing magnetic field. However, the similarities among measured spectra indicate that runaway electron energies decrease with increased field and are thus limited by synchrotron radiation. Additionally, distortion-corrected visible camera images show the spatial distribution and evolution of runaways in C-Mod. Initial results show good agreement between experiment and the new synthetic diagnostic SOFT (Synchrotron-detecting Orbit-Following Toolkit) [1].

[1] M. Hoppe, et al. Synthetic synchrotron diagnostic for runaway electrons in tokamaks. In progress.



7.8 T
5.4 T
2.7 T
Synch. Brightness
T_{e0} (keV)
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E/E_C
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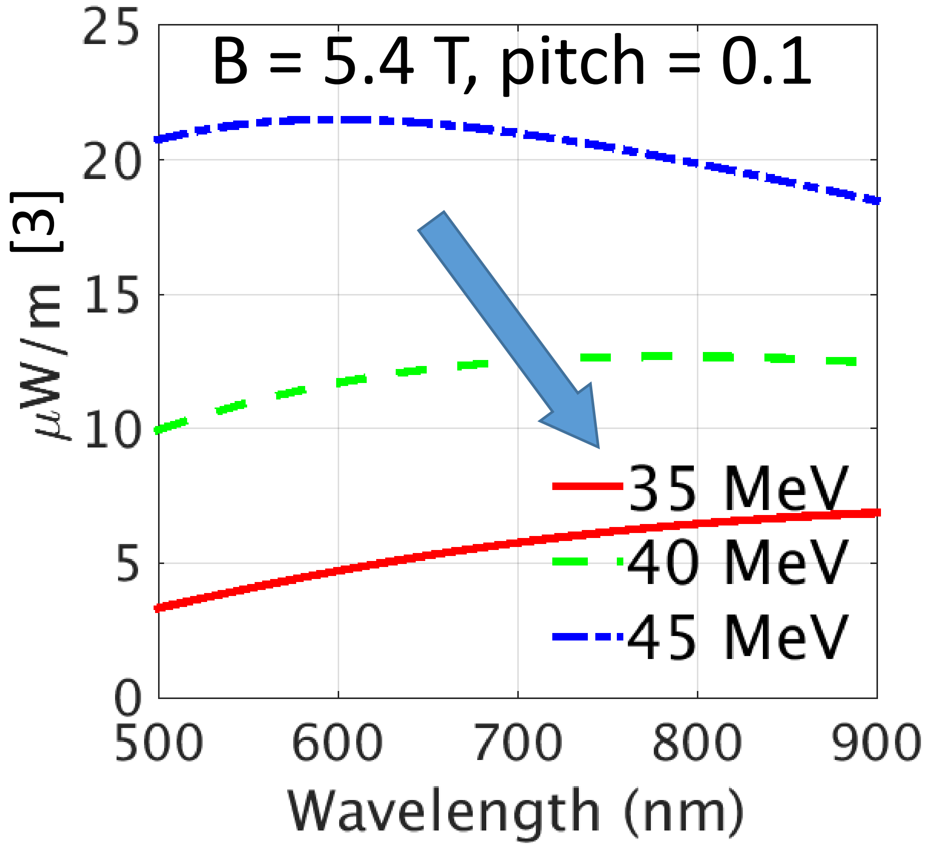
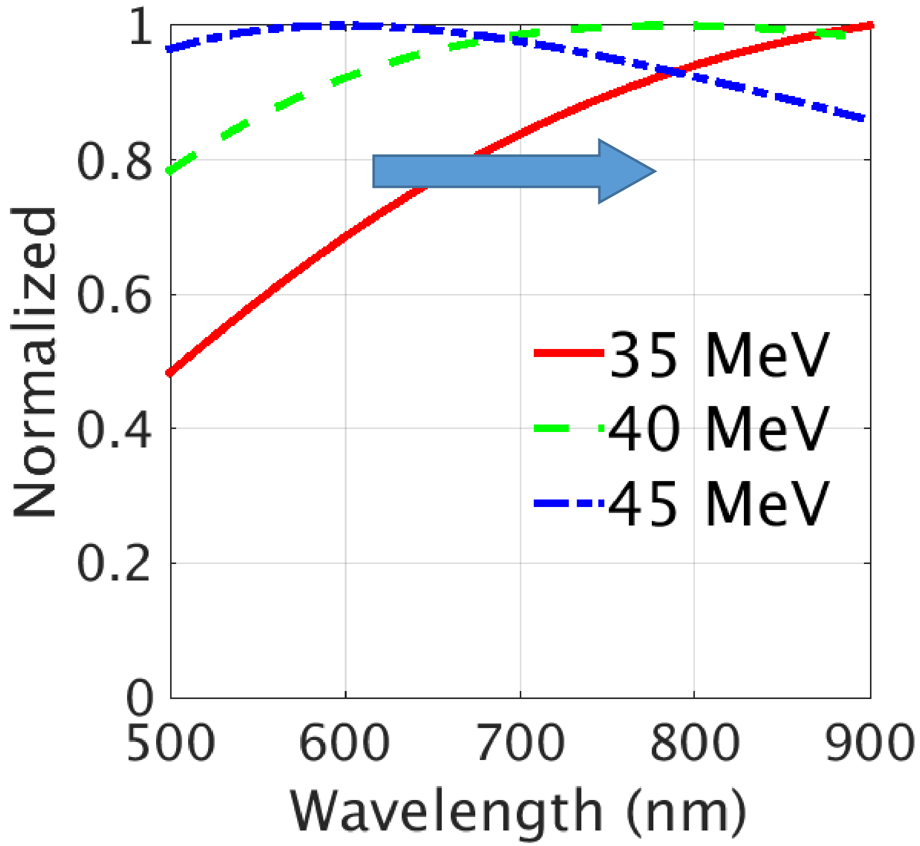
τ_{rad}/τ_C
HXR (10^{14}/s)
Z_{eff}
time (s)
1160824024
1160824026
1160902016

Decreasing RE **energy** decreases amplitude, shifts toward red

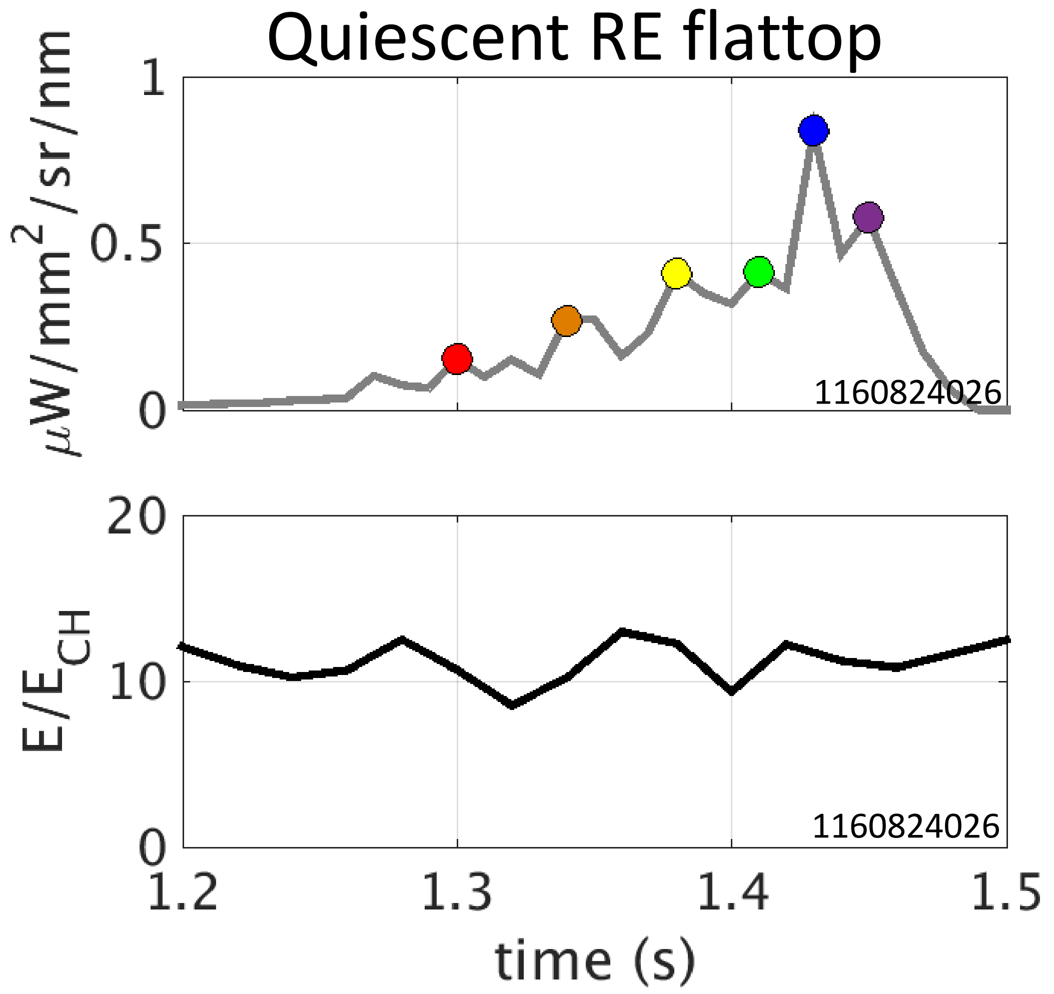


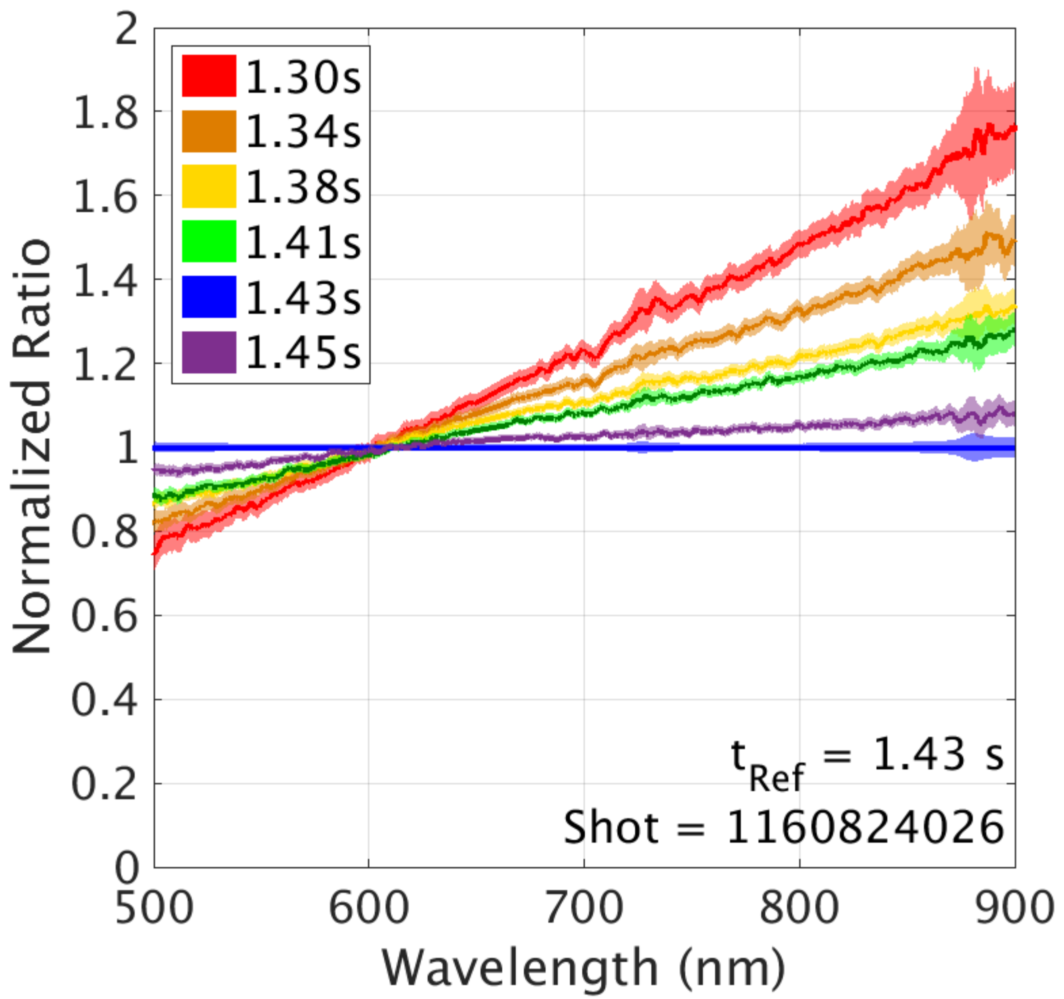


→ To keep the brightness the same, an increase in magnetic field requires a decrease in energy.

I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).

Evolving RE energy distribution is observed in spectra





Runaway electrons – unique plasma phenomena

- In a plasma, the Coulomb collision frequency varies as *density/velocity*^{3}

$$\frac{dp}{dt} = -eE - F_c\left(\frac{n}{v^2}\right)$$

- There exists a critical electric field [4],

$$E_c \approx 0.08\, n_{20}$$

  such that for $E \geq E_c$, some electrons will be **continuously accelerated**

- If $E \geq E_D = 2E_c \frac{c^2}{v_{th}^2}$ [5], all electrons will **runaway** to relativistic speeds

- Collisions between high energy and thermal electrons causes an **avalanche** of runaway particles

- However, accelerating charges **radiate**:
  - Magnetic fields → Cyclotron
  - Collisions → Bremsstrahlung

$$\frac{dp}{dt} = -eE - F_c - \mathbf{F_{rad}}(\vec{\mathbf{p}}, \mathbf{B}, \mathbf{Z_{eff}}, \dots)$$

→ Radiation serves as both a **power loss mechanism** and useful **diagnostic** tool

Motivation: Runaway electrons may severely damage ITER

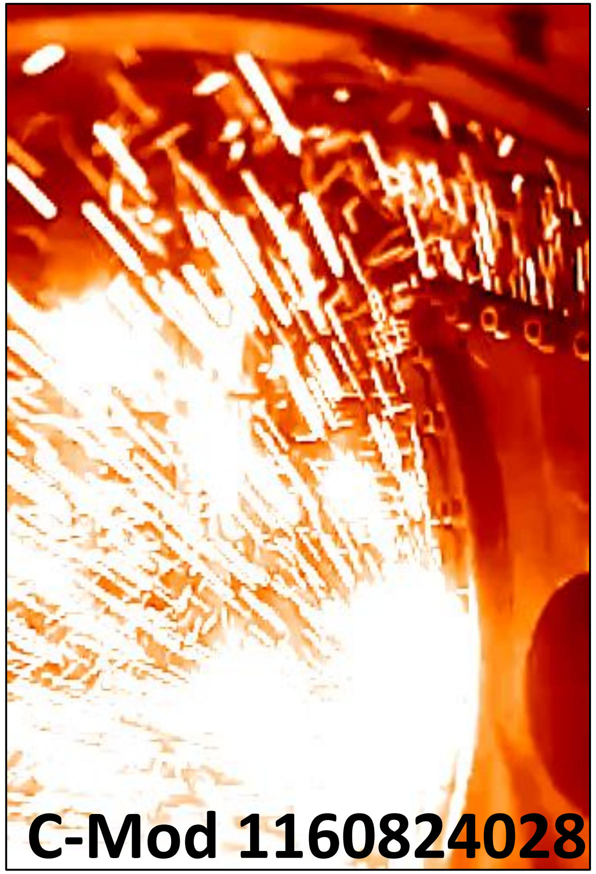
Relativistic "Runaway" Electrons (REs):

- Energies > 10 MeV
- Current ≲ 60% of I_P [6]
- In ITER, RE beams of **9 MA**!

REs can cause significant damage to plasma-facing components →

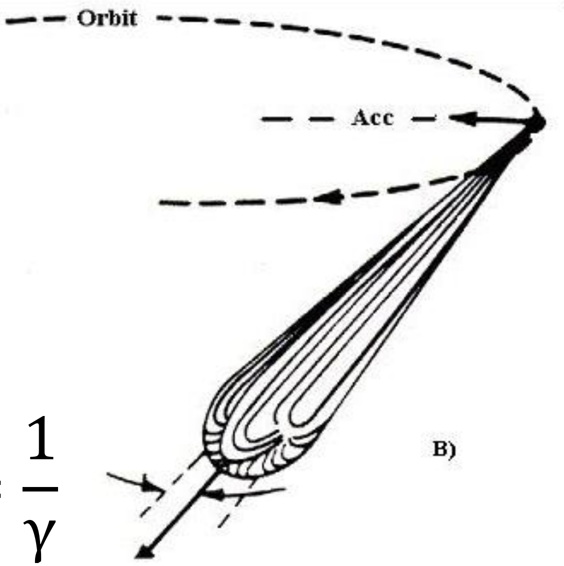
It is necessary to understand both the **momentum** and **real space** distribution and time evolution to effectively avoid and mitigate REs

RE beam collides with limiter



SOFT, Synchrotron-detecting Orbit-Following Toolkit [1]

- Synthetic diagnostic simulating a camera inside a tokamak
- REs emit highly forward-peaked cone of synchrotron radiation in their direction of motion
- SOFT captures light hitting the detector



$$\Delta\theta = \frac{1}{\gamma}$$

Lots of flexibility:

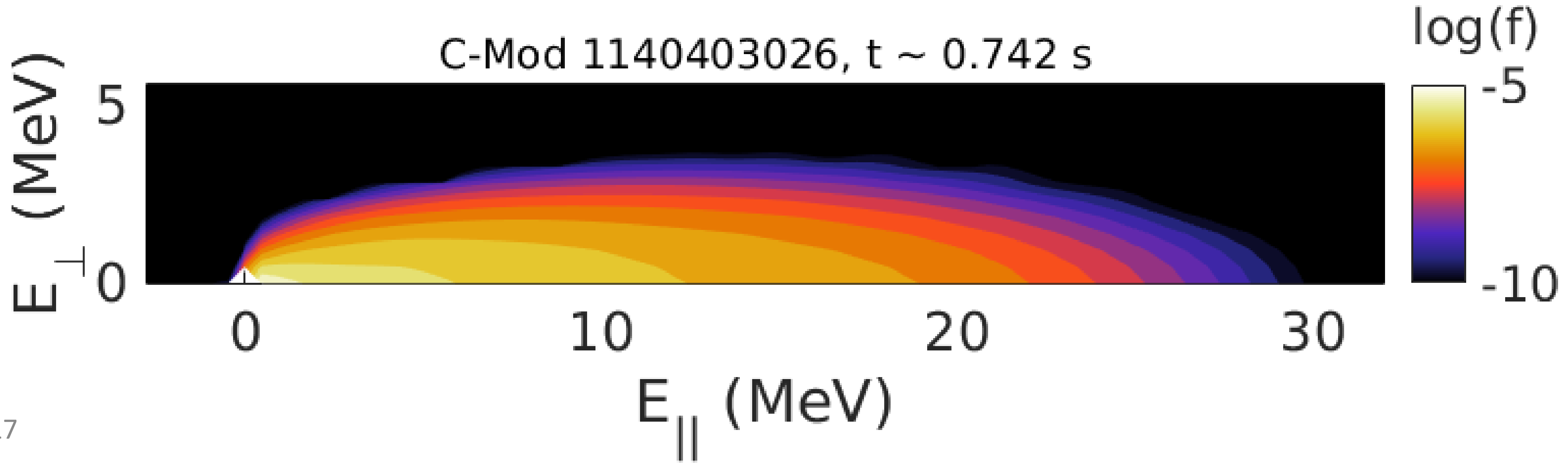
- Camera viewing geometry (position, angle, aperture size, etc.)
- Camera sensitivity (wavelength range)
- Magnetic field geometry
- Momentum space distributions (energy and pitch) – can also couple to CODE [2,3]
- Spatial distributions (radial profiles)

CODE, COllisional Distribution of Electrons [2,3]

- Solves the linearized kinetic equation for RE evolution in **momentum** space
- Includes secondary avalanching mechanisms

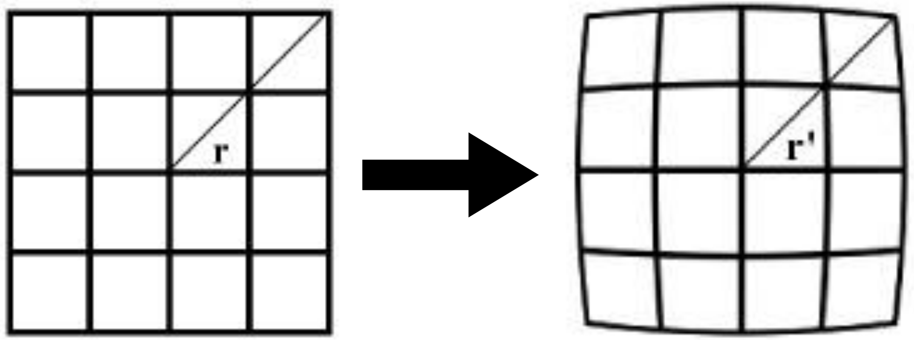
Plasma parameters vary in time:

- Loop voltage → Driving force
- Density, temperature, and Z_{eff} → Friction
- Magnetic field → Synchrotron power loss

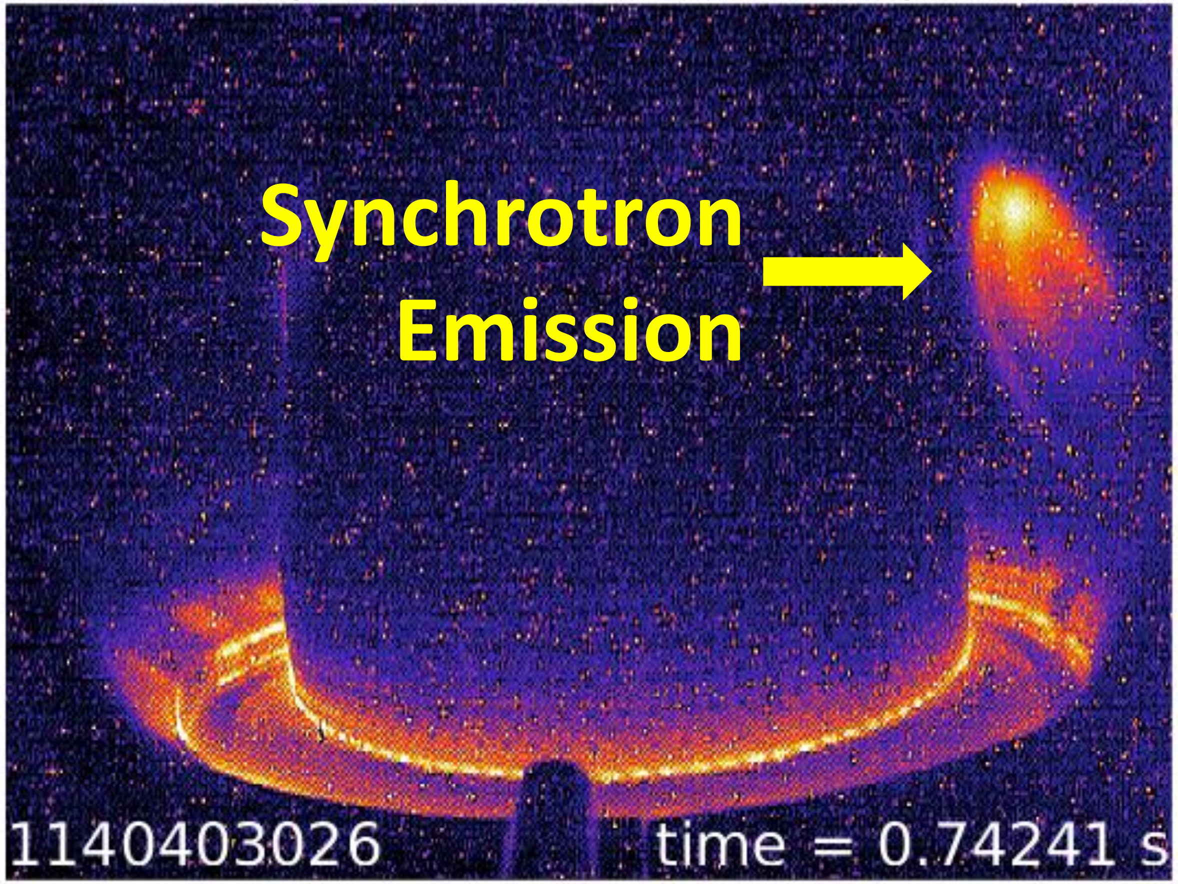


Cameras inside C-Mod capture RE spatial evolution

- Due to Alcator C-Mod's high magnetic field (2-8 T), synchrotron radiation is emitted in the **visible** wavelength range
- Note that ITER (~5 T) will also have visible synchrotron emission
- Cameras are affected by fisheye-lens/barrel distortion

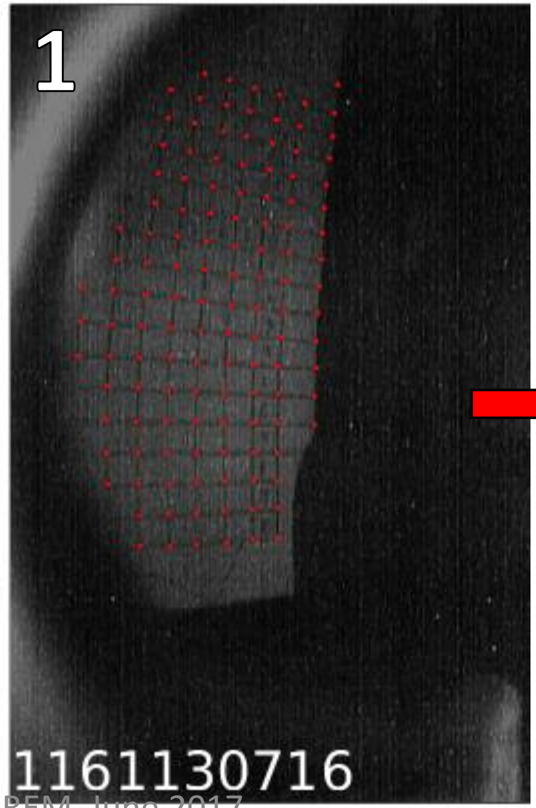


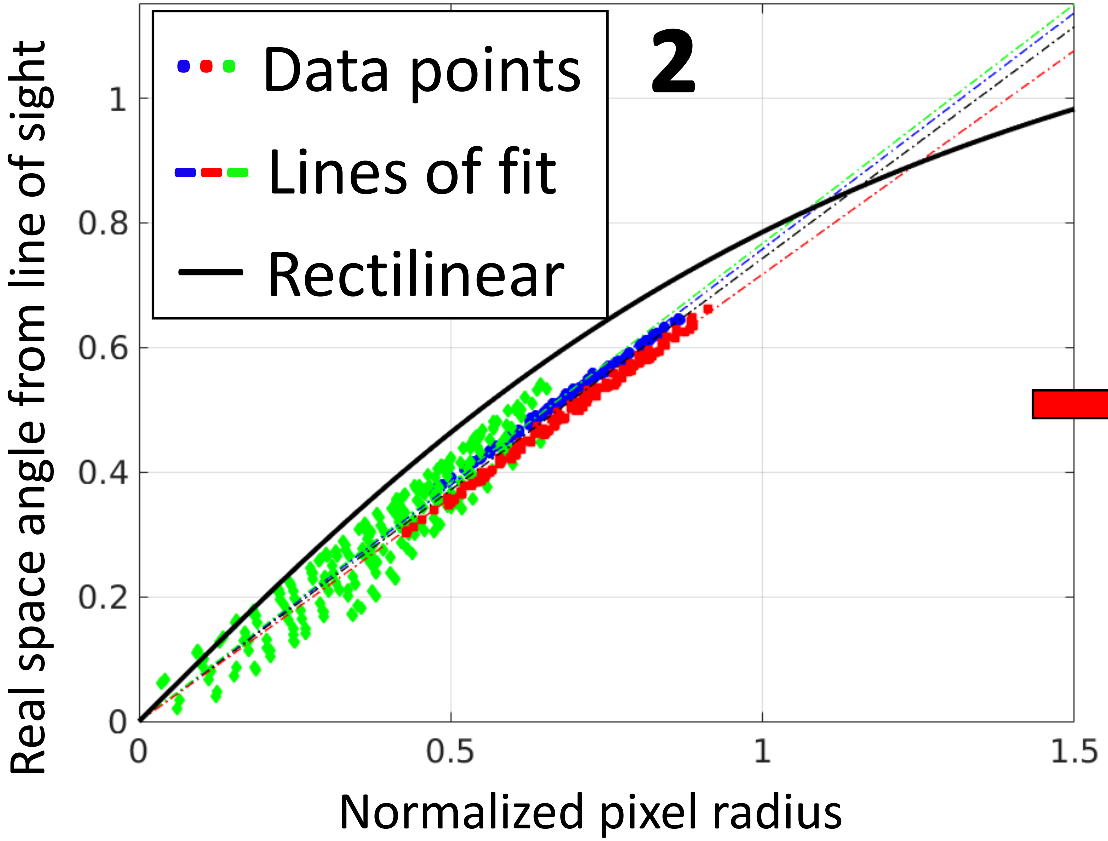
Original (distorted) image

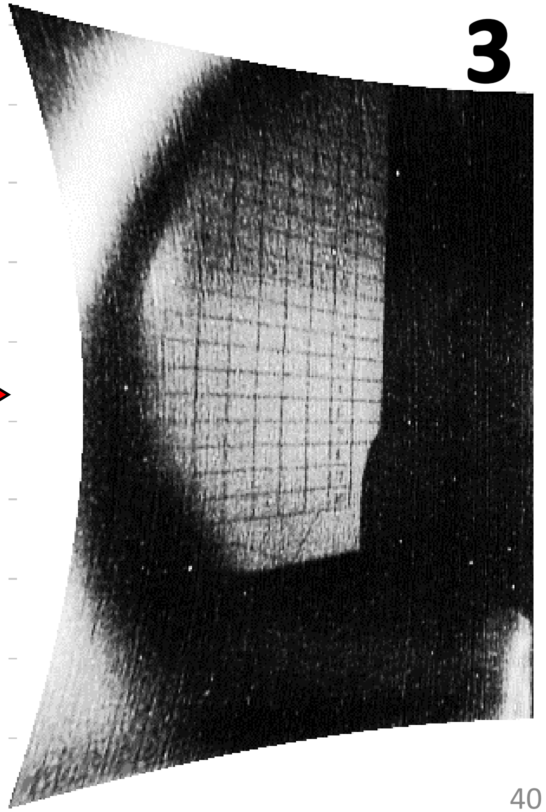


In-vessel calibration corrects for camera distortion

1. Take photos of gridded vacuum vessel cross-section
2. Map pixel location (radius) to real space position (angle)
3. Transform to rectilinear image

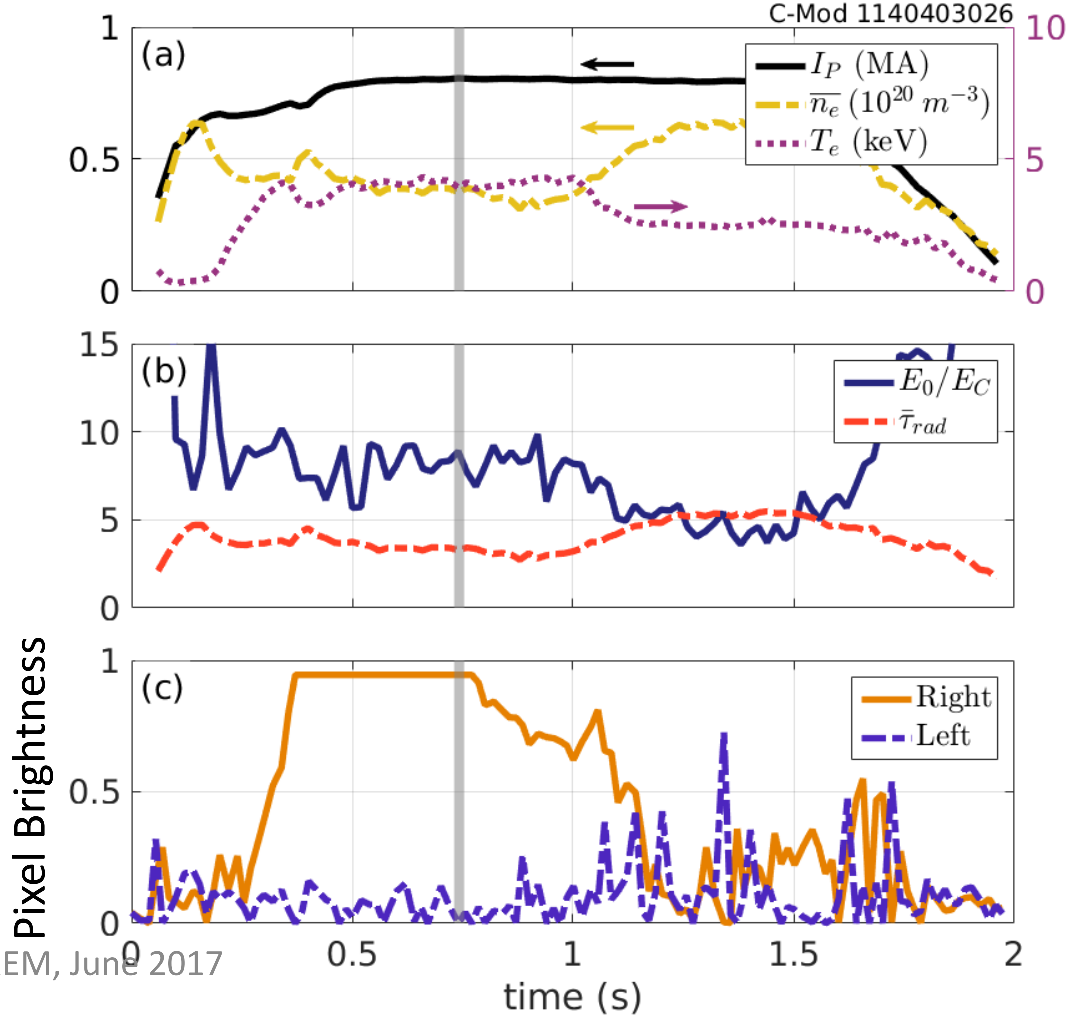




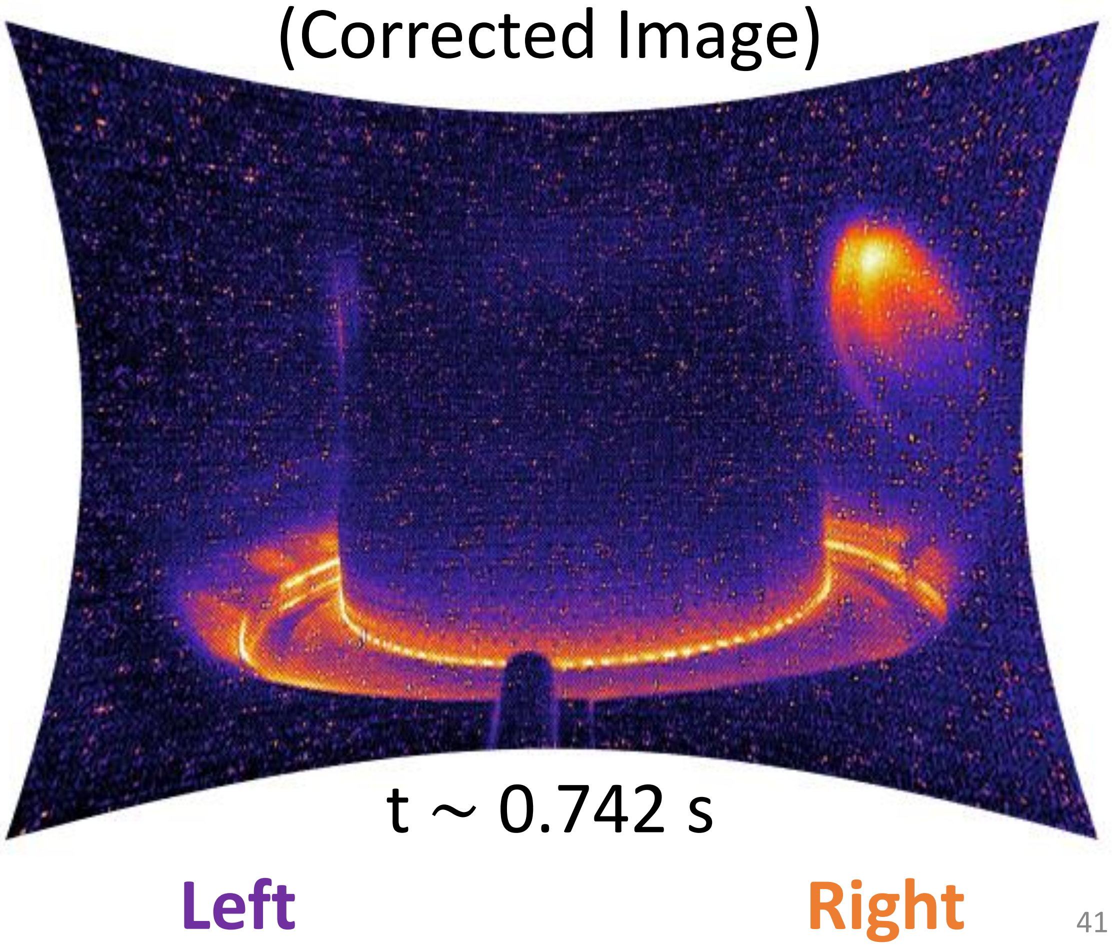


Interesting RE spatial distributions are observed

- REs are generated as density (and collisional friction) decreases



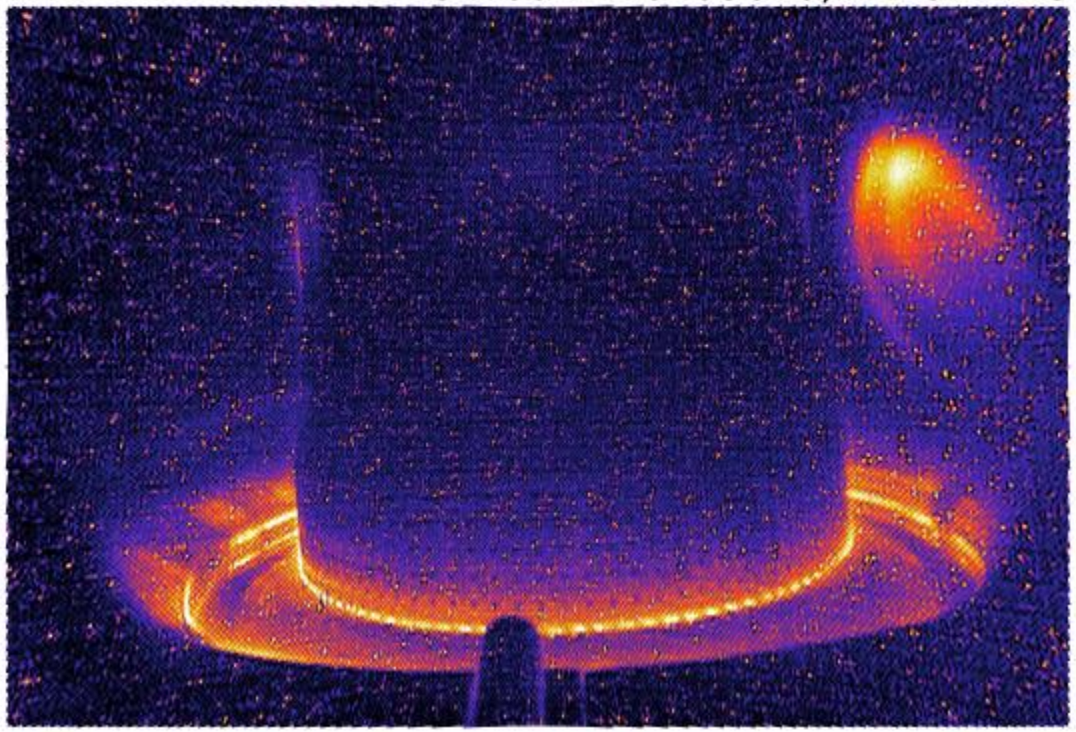
- Double-parabolic feature forms, grows, and moves in time



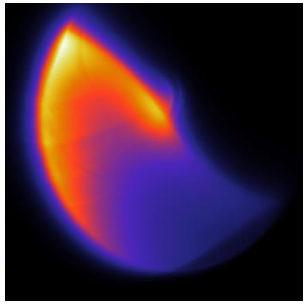
Good agreement between SOFT and experiment

- Uses uniform spatial/radial profile (shaded)
- Produces very similar parabolic structure
- Does not yet capture double feature

C-Mod 1140403026, t ~ 0.742 s



SOFT

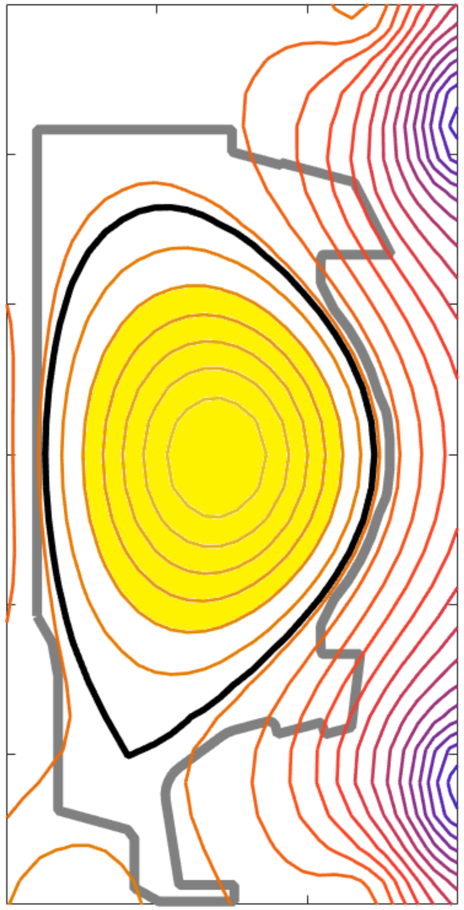


←

CODE

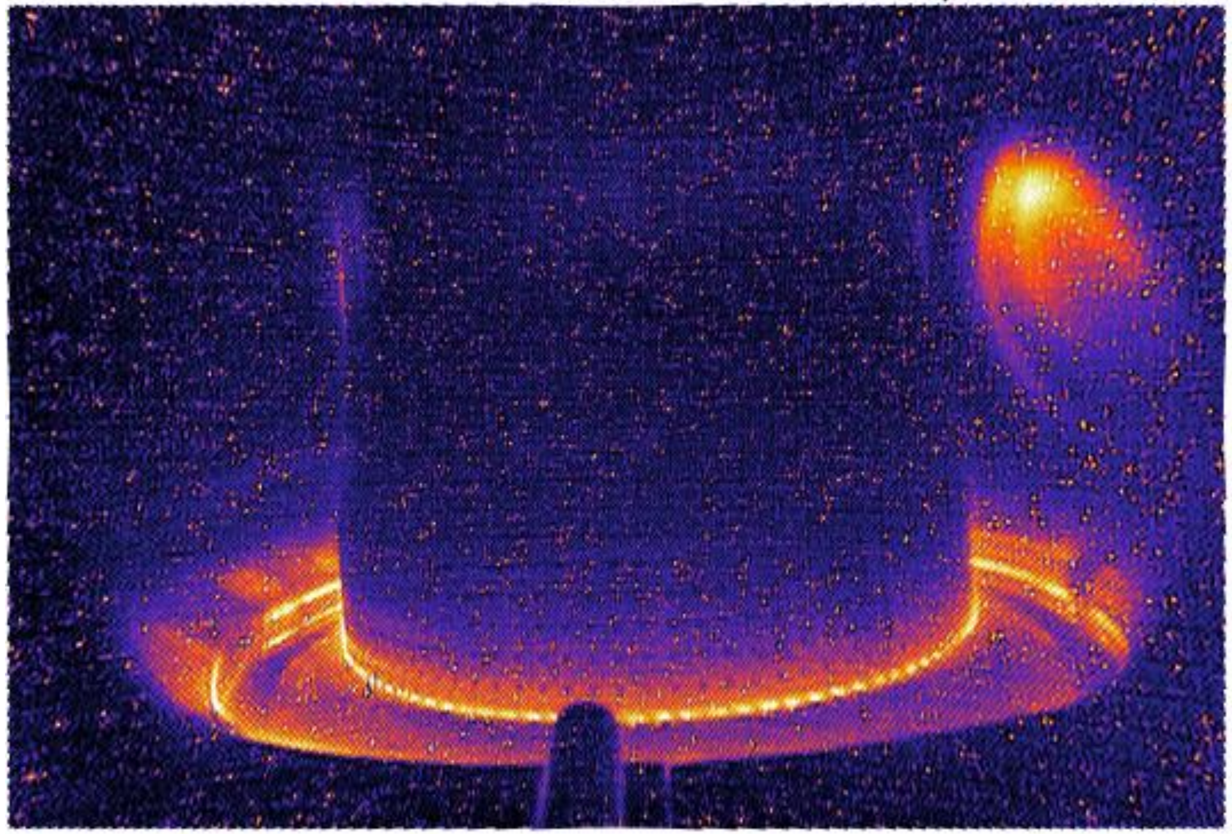
+

Magnetic Geometry

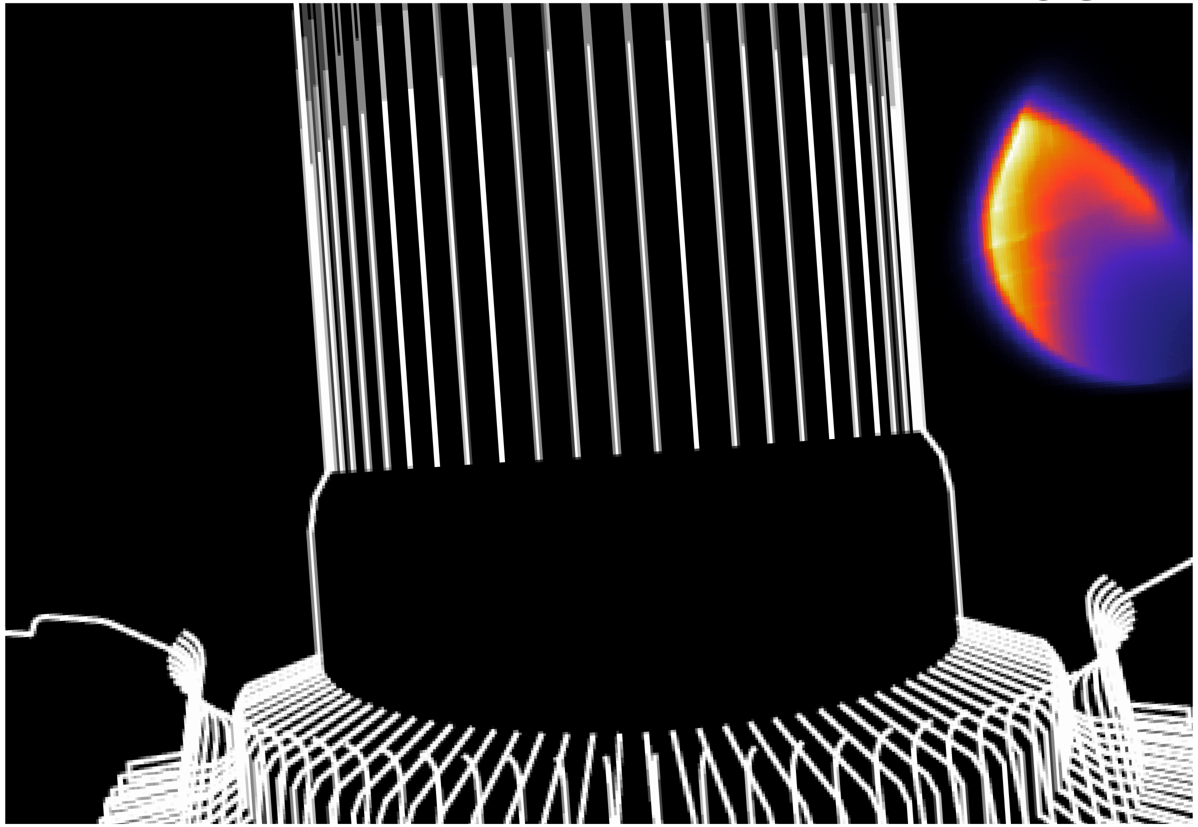


Good agreement between SOFT and experiment

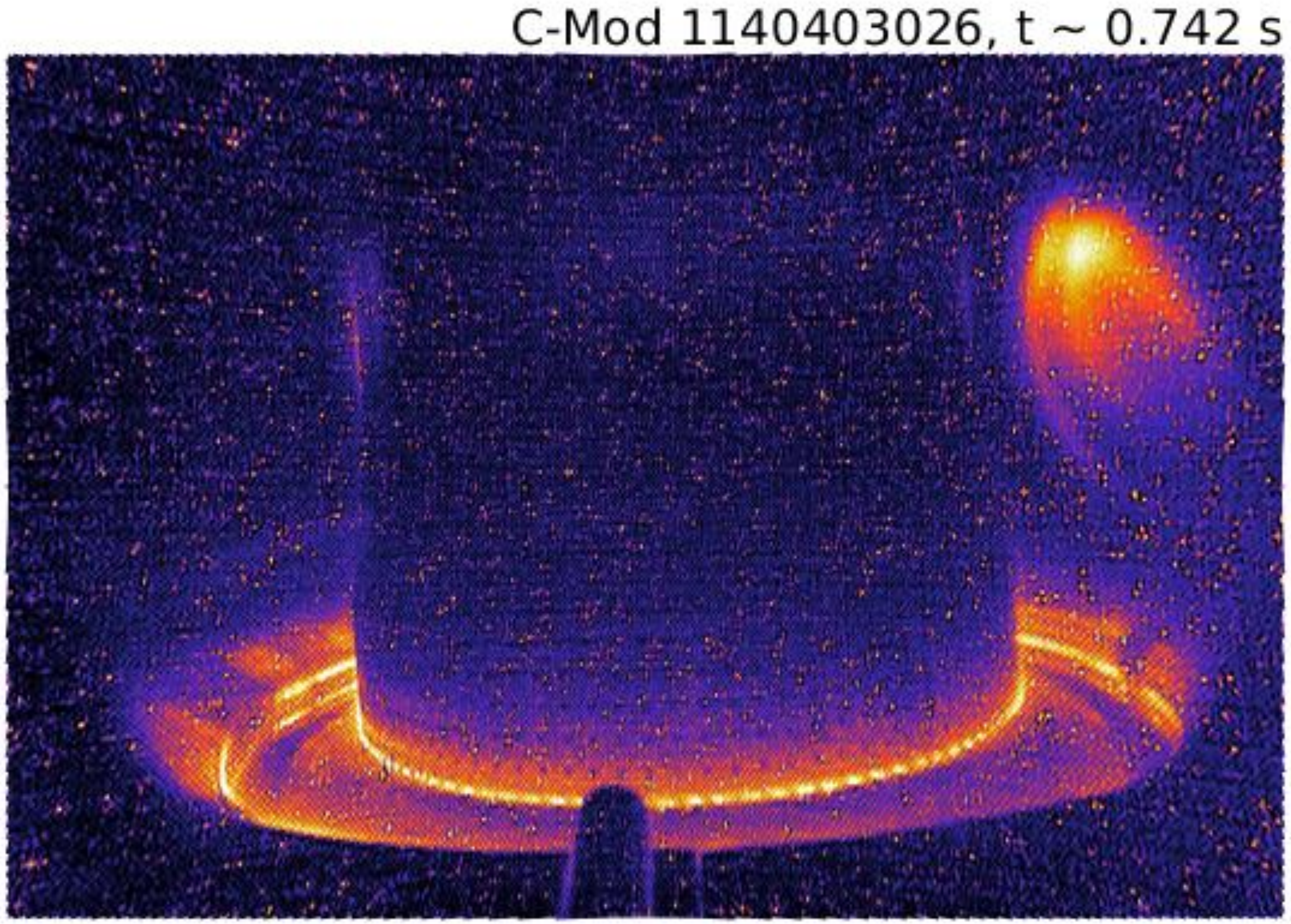
C-Mod 1140403026, t ~ 0.742 s

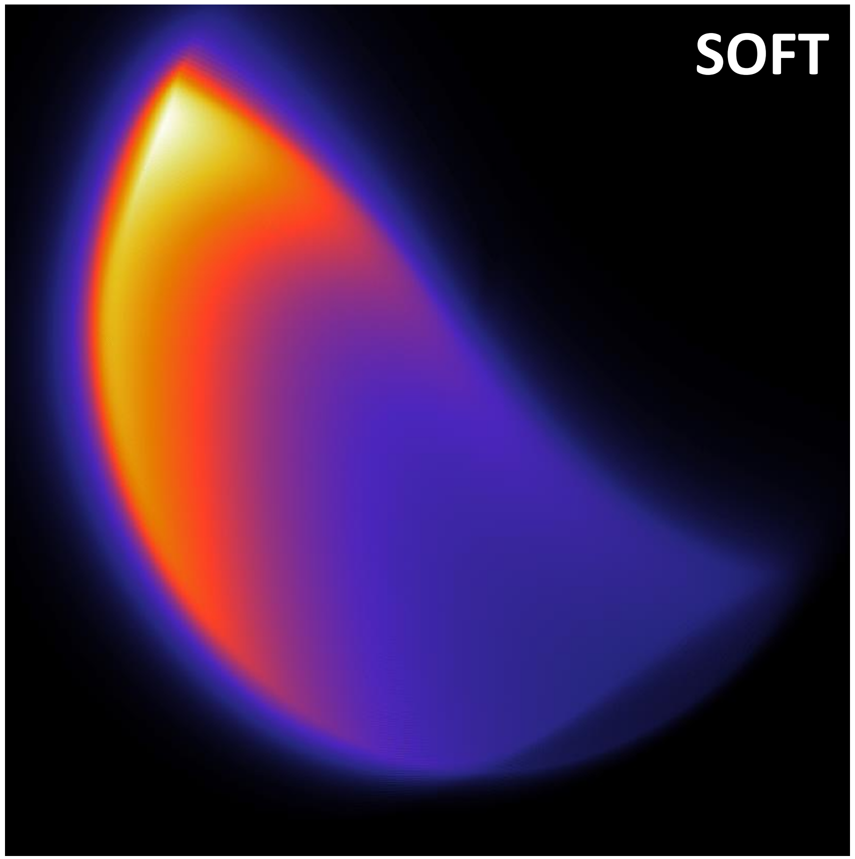


SOFT



Good agreement between experiment and SOFT





Entry video

Summary, part 2

- Visible images of synchrotron emission can provide useful information of the spatial distribution and evolution of REs
- New synthetic camera diagnostic SOFT (with inputs from momentum space solver CODE) shows promise in reproducing experimental synchrotron images
- However, the apparent lack of a unique solution makes it difficult to solve the inverse problem and requires us to solve the forward problem (simulations)
- Momentum and real space evolutions of REs are coupled as plasma parameters vary in space, so a coupled solver will likely be needed
- Future work will utilize SOFT's capability to include varying spatial profiles of different RE energy distributions