Synchrotron spectra, images, and polarization measurements from runaway electrons in the Alcator C-Mod tokamak

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Abstract --- In the high-field, compact Alcator C-Mod tokamak, relativistic runaway electrons (REs) generated during flattop plasma discharges emit synchrotron radiation in the visible wavelength range. Thus, spectrometers, cameras, and the Motional Stark Effect diagnostic installed on C-Mod measure absolutely-calibrated spectra, distortion-corrected images, and polarization information, respectively, of REs throughout the plasma. Due to the complex interplay of the RE phase-space distribution, plasma magnetic topology, and detector geometry, the synthetic diagnostic SOFT [1] is used to simulate all three measurements and compare theory with experiment. As inputs, the RE momenta and density distributions are calculated using both a test-particle model [2 – 4] and kinetic solver CODE [5]. In particular, this work explores the following: (1) Synchrotron spectra observed from REs generated at three magnetic fields (B_0 = 2.7, 5.4, and 7.8 T) indicate a decrease in RE energy as synchrotron power loss is enhanced at higher fields [6].
(2) Transport and MHD activity are incorporated into the analysis of synchrotron images to better explain interesting spatiotemporal features.
(3) Profiles of linearly-polarized synchrotron emission intensity and polarization angle are explored as a novel diagnostic of RE dynamics.

References

[1] M. Hoppe, *et al*., Nucl. Fusion 58 (2018).

[2] J.R. Martín-Solís, *et al.*, Phys. Plasmas 5 (1998).

[3] J.W. Connor and R.J. Hastie, Nucl. Fusion 15 (1975).

[4] M.N. Rosenbluth and S.V. Putvinski, Nucl. Fusion 37 (1997).

[5] M. Landreman, *et al*., Comput. Phys. Commun. 185 (2014).

[6] R.A. Tinguely, *et al.*, submitted to Nucl. Fusion (2018).

Acknowledgments

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Outline/Summary

Synchrotron spectra

1. SOFT reproduces experimental spectra better than "traditional" approach
2. Spectra measured are consistent with RE energies *decreasing* as magnetic field *increases*

Synchrotron images

1. SOFT+CODE needed to accurately reproduce experimental images
2. Gain insight into spatiotemporal dynamics and runaway density evolution

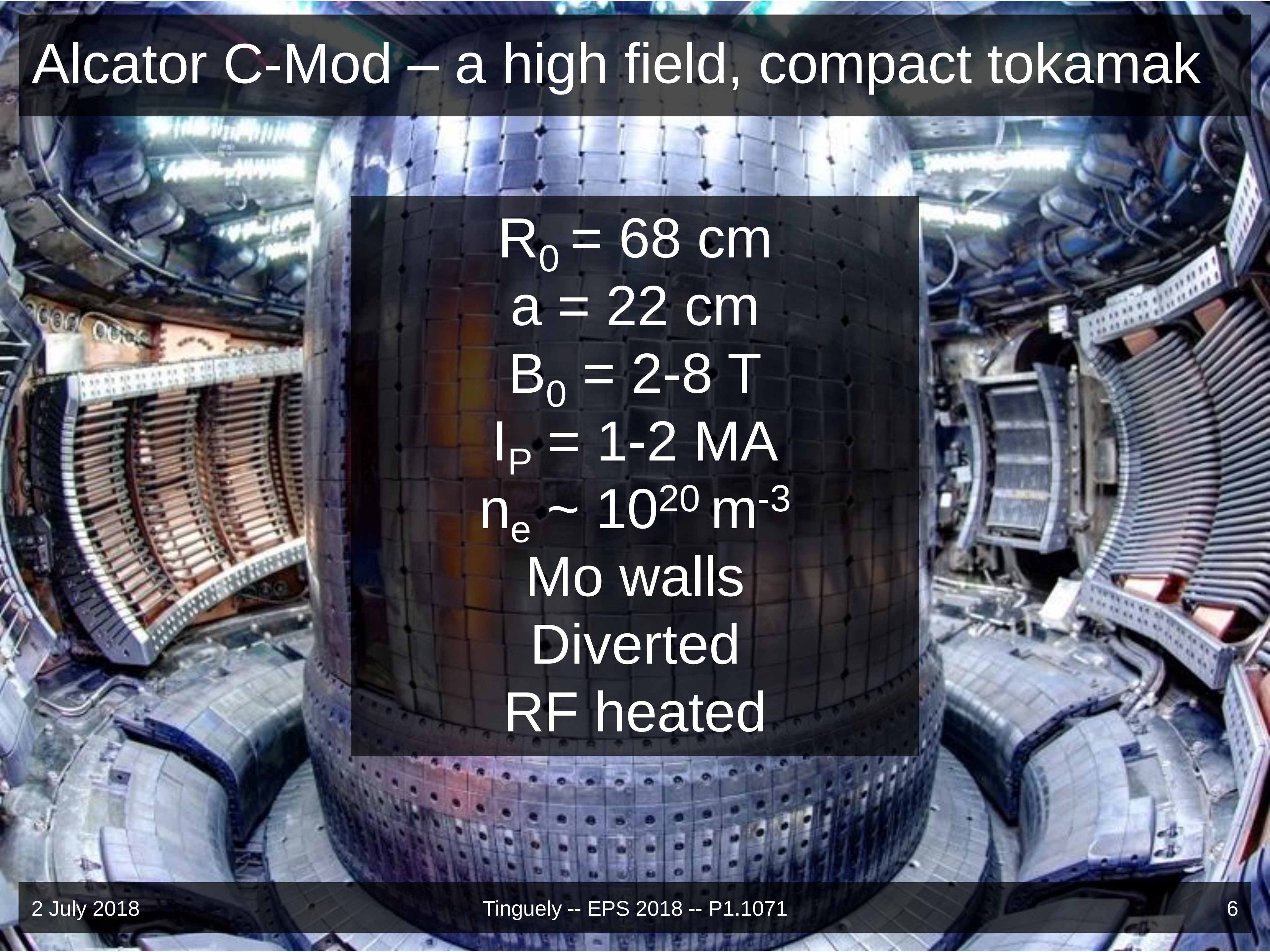
Synchrotron polarization

1. System "implemented" in SOFT (for the first time)
2. Preliminary results are similar to experiment and show promise

Understand the phase space dynamics of runaway electrons (REs) → model, predict, avoid, mitigate

REs striking a limiter in Alcator C-Mod

Alcator C-Mod – a high field, compact tokamak



R_0 = 68 cm

a = 22 cm

B_0 = 2-8 T

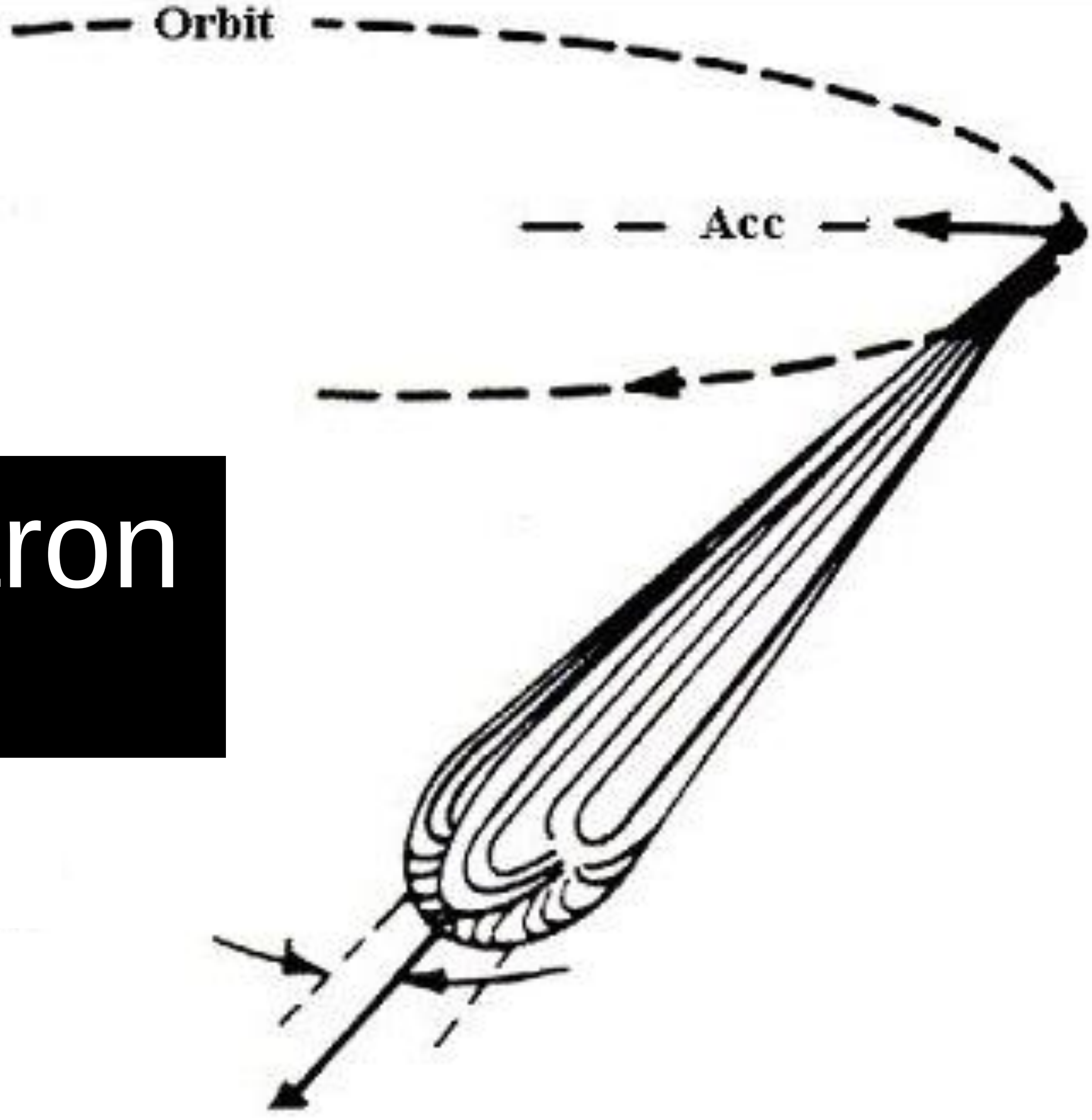
I_P = 1-2 MA

$n_e \sim 10^{20}$ m^{-3}

Mo walls

Diverted

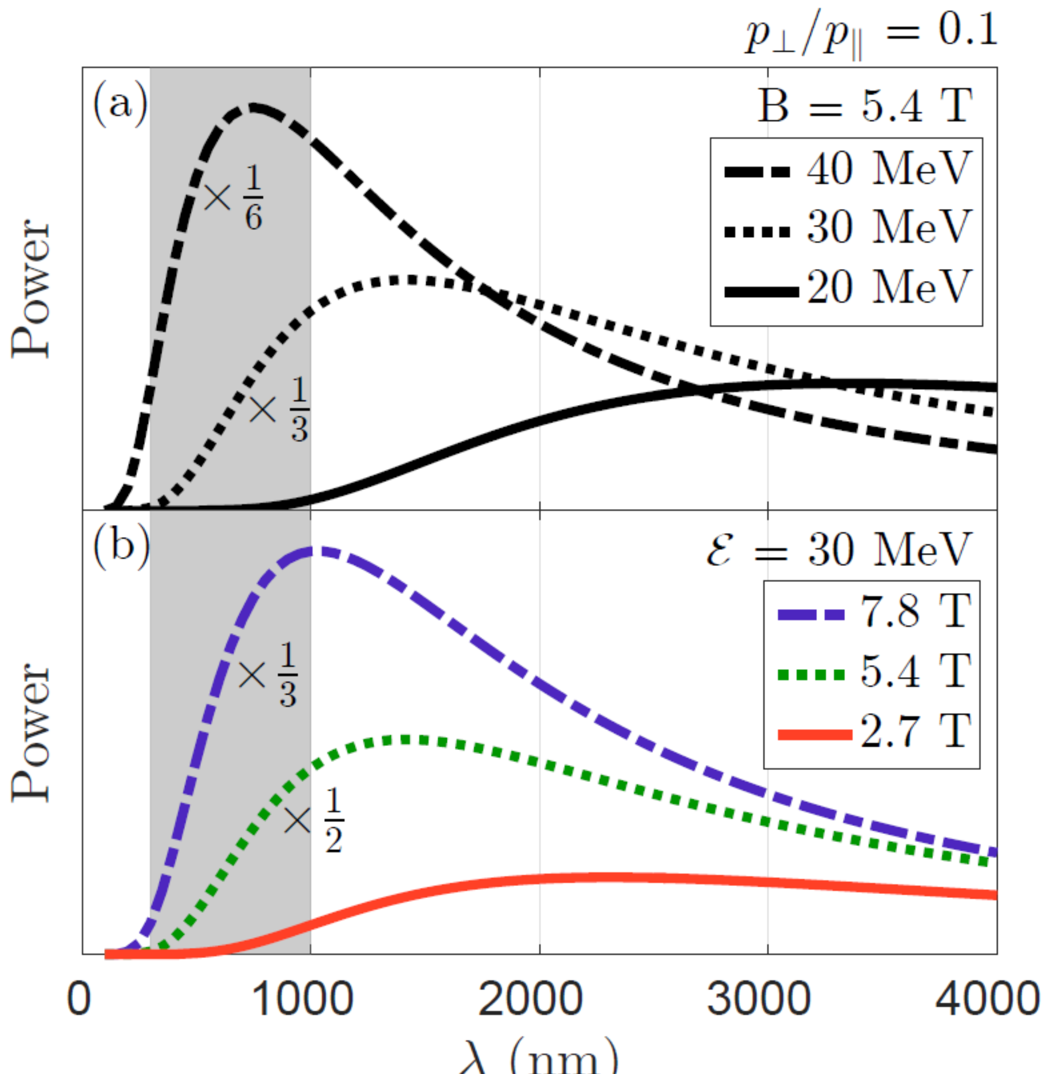
RF heated

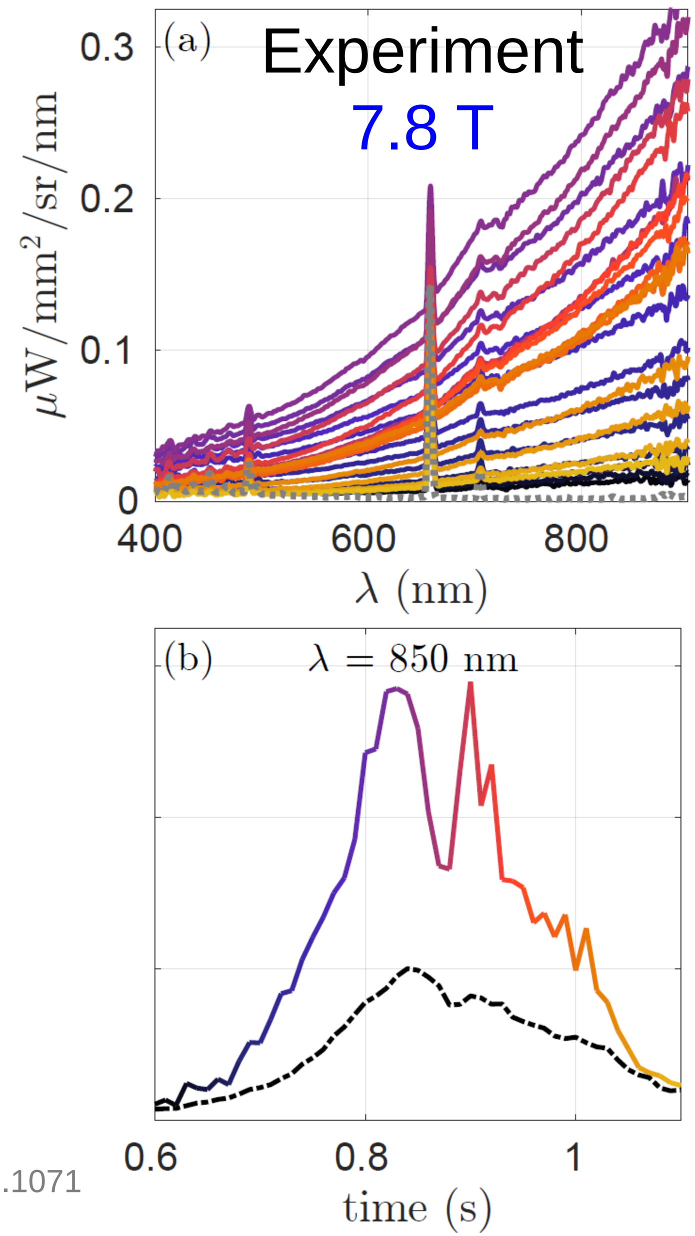


Synchrotron spectra

Synchrotron spectra measured at three magnetic fields

Theoretical spectra [Pankratov 1999]

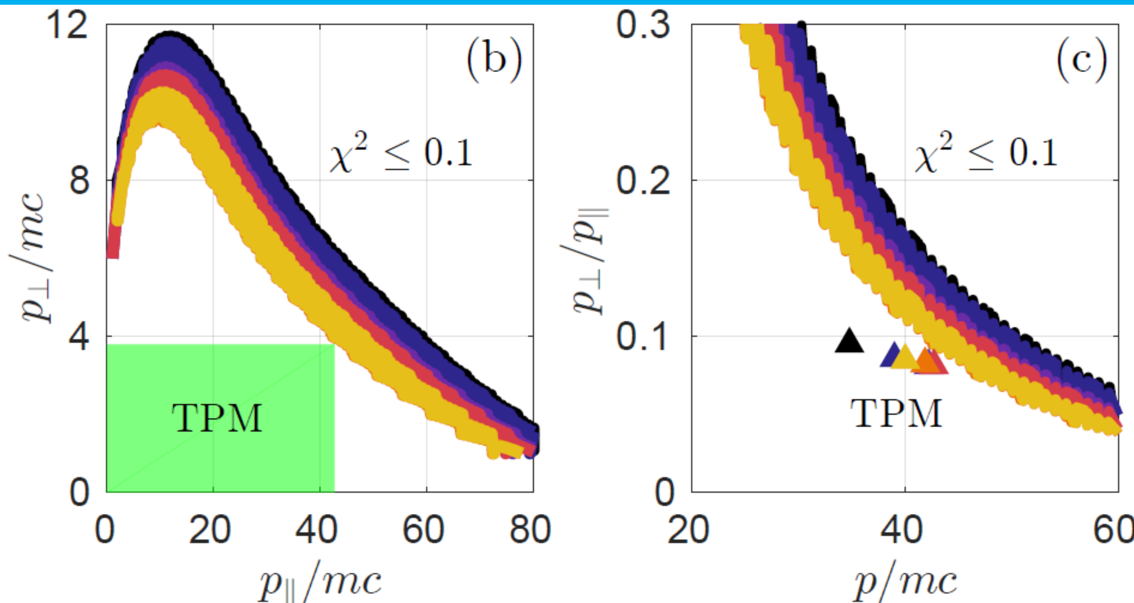


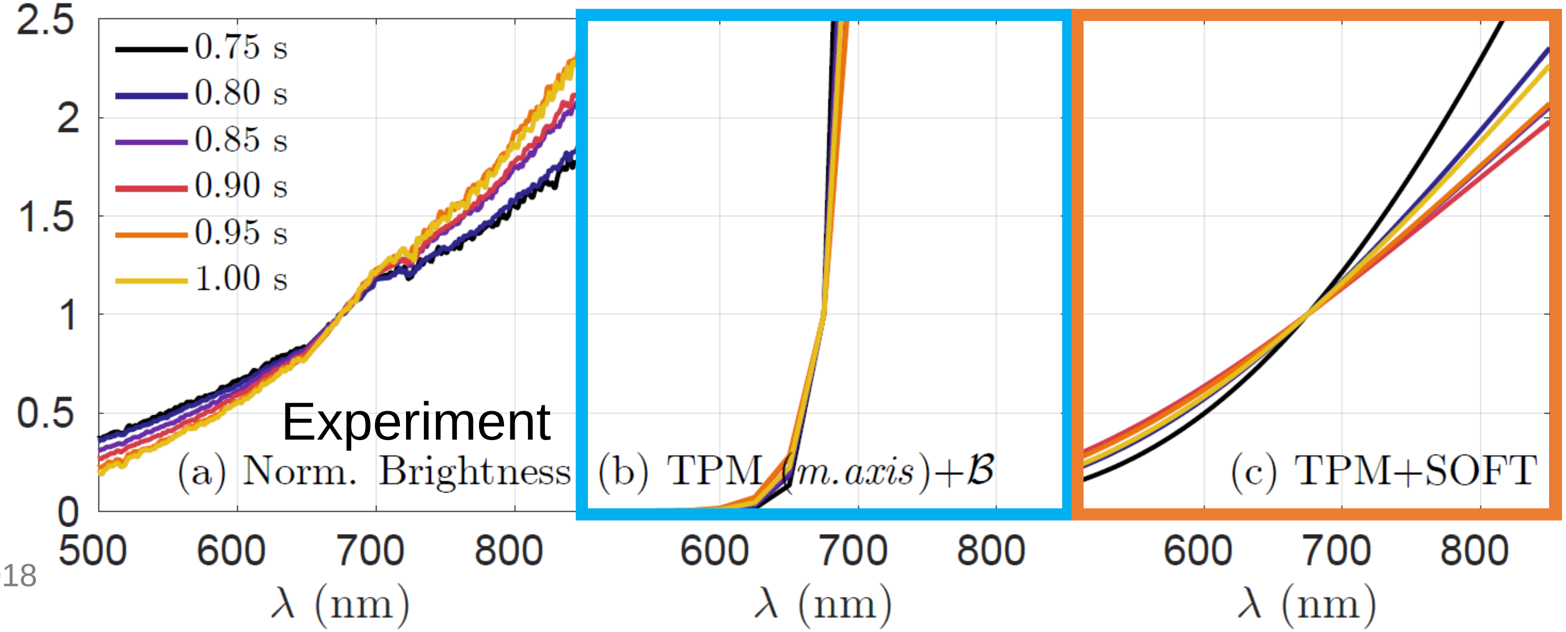


Need SOFT to reproduce experimental spectra

“Traditional” approach:

- Fit to brightness $\mathcal{B}$
- No unique solution →
- Unphysical interpretation





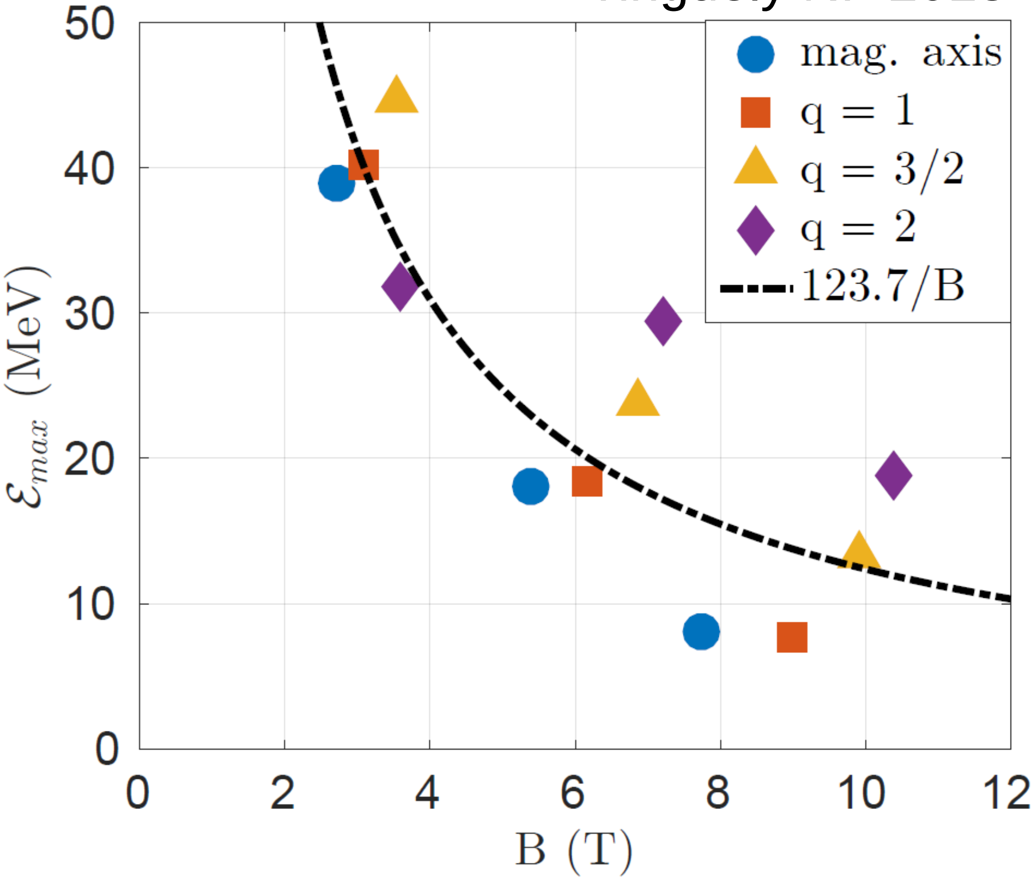
RE energies *decrease* as B *increases*

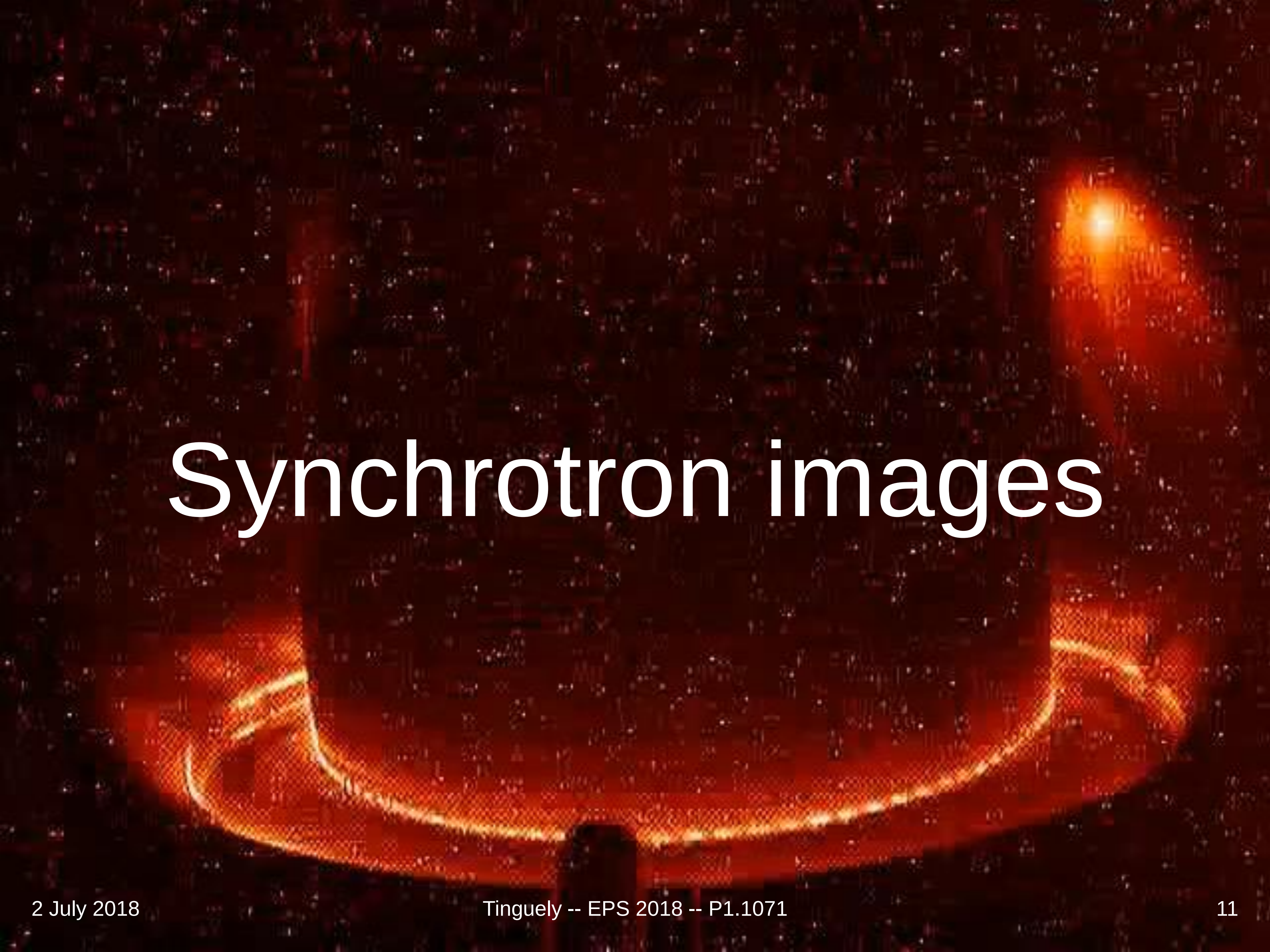
- Predicted energies are typically highest on outer flux surfaces…
- Unless particle drifts lead to loss of confinement

For each flux surface:

- Plotting max energy *during discharge* versus max B-field experienced
- Energy monotonically decreases with B

Tinguely NF 2018





Synchrotron images

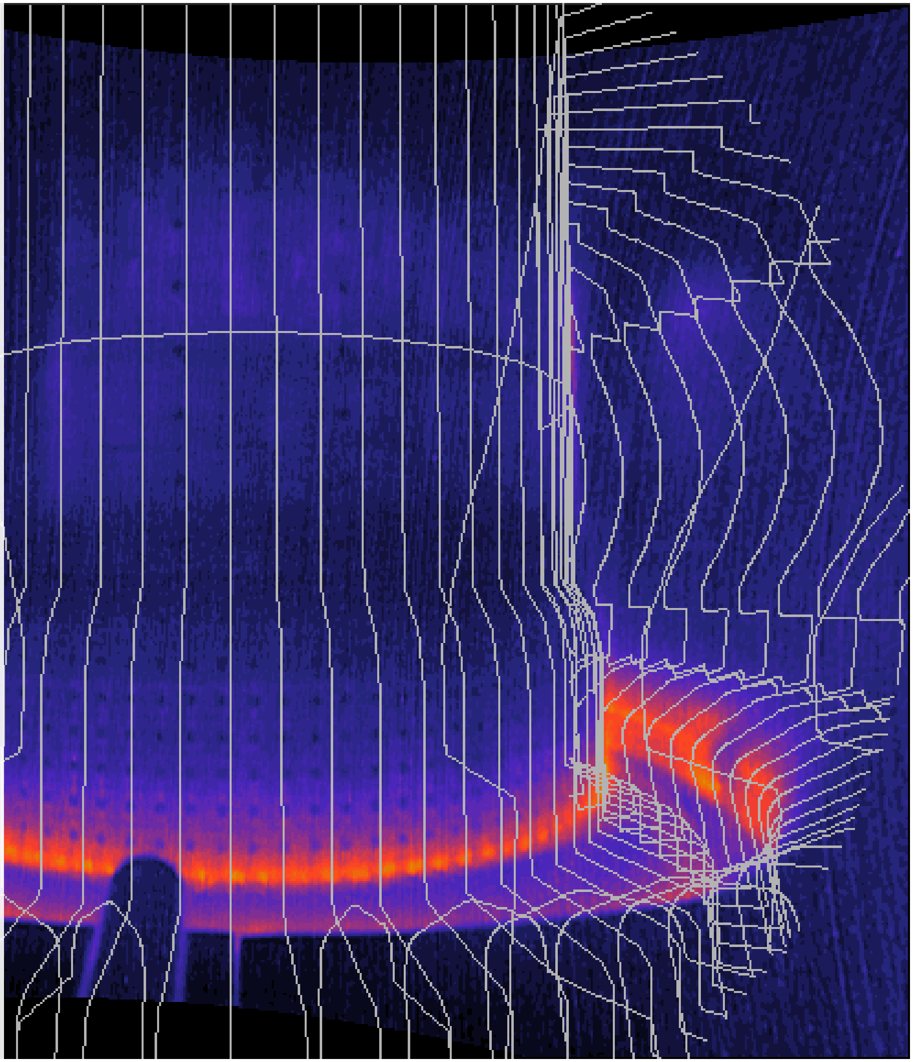
Wide-angle camera captures RE dynamics

Camera specifications:

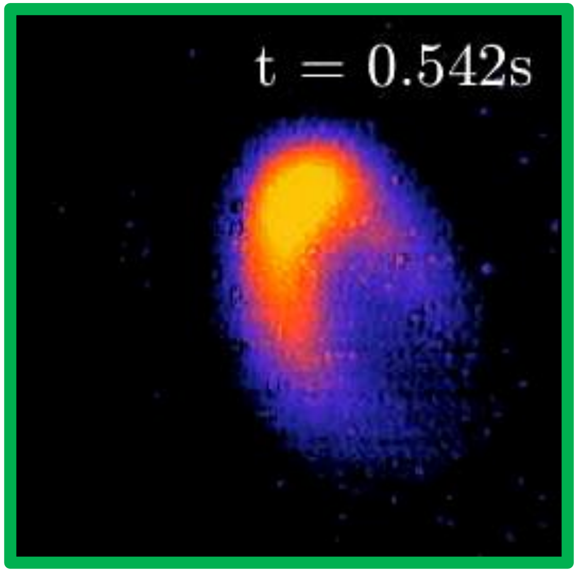
- Z ~ -21 cm
- ~60 fps
- Visible/NIR (B&W)
- No auto-gain → saturation

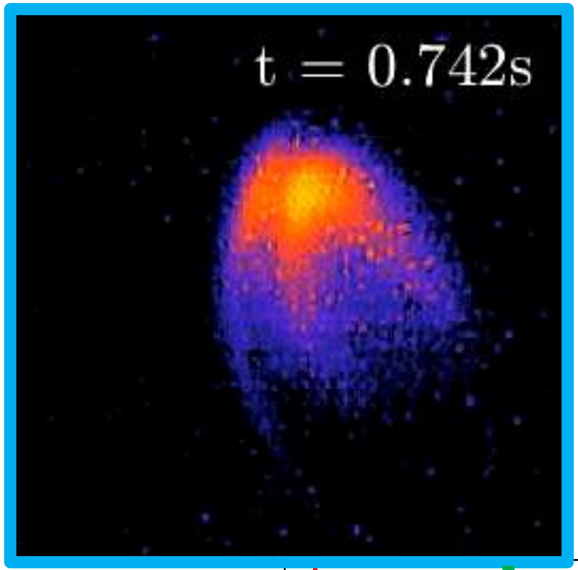
Image details:

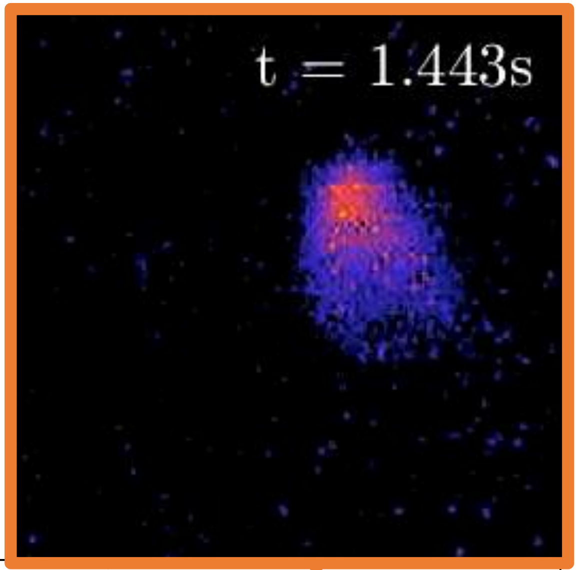
- NOT absolutely-calibrated
- Distortion-corrected
- Background-subtracted
- HXRs ‘removed’



Can we explain/reproduce RE dynamics?



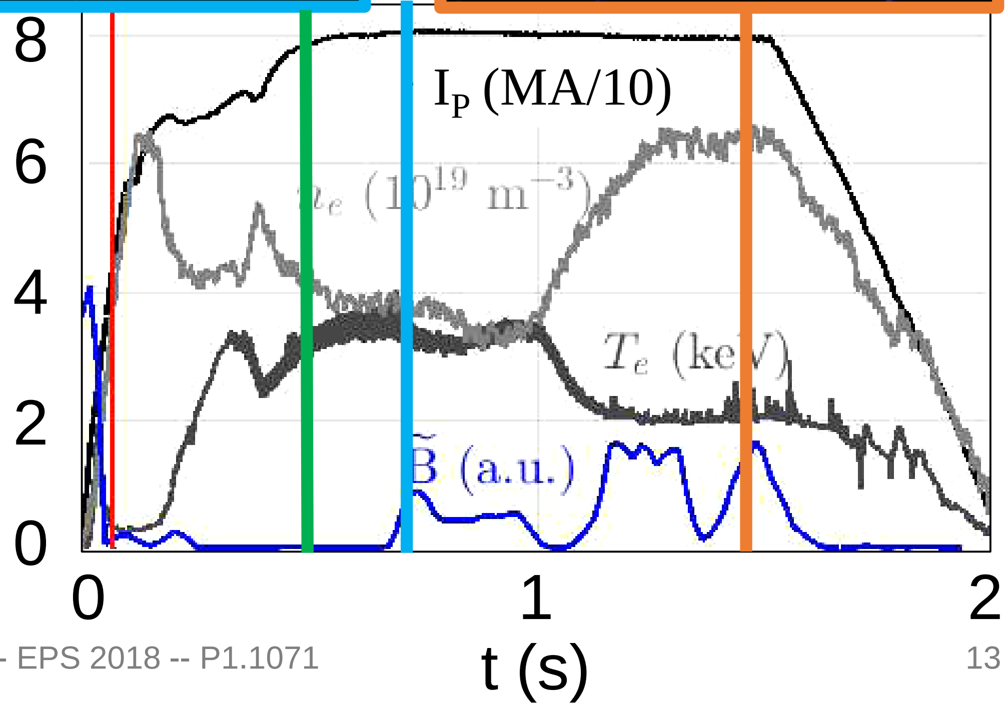




Beam increases in size and intensity as n_e decreases

Interesting spatial structure observed (‘third leg’) during locked mode ($\tilde{B}$)

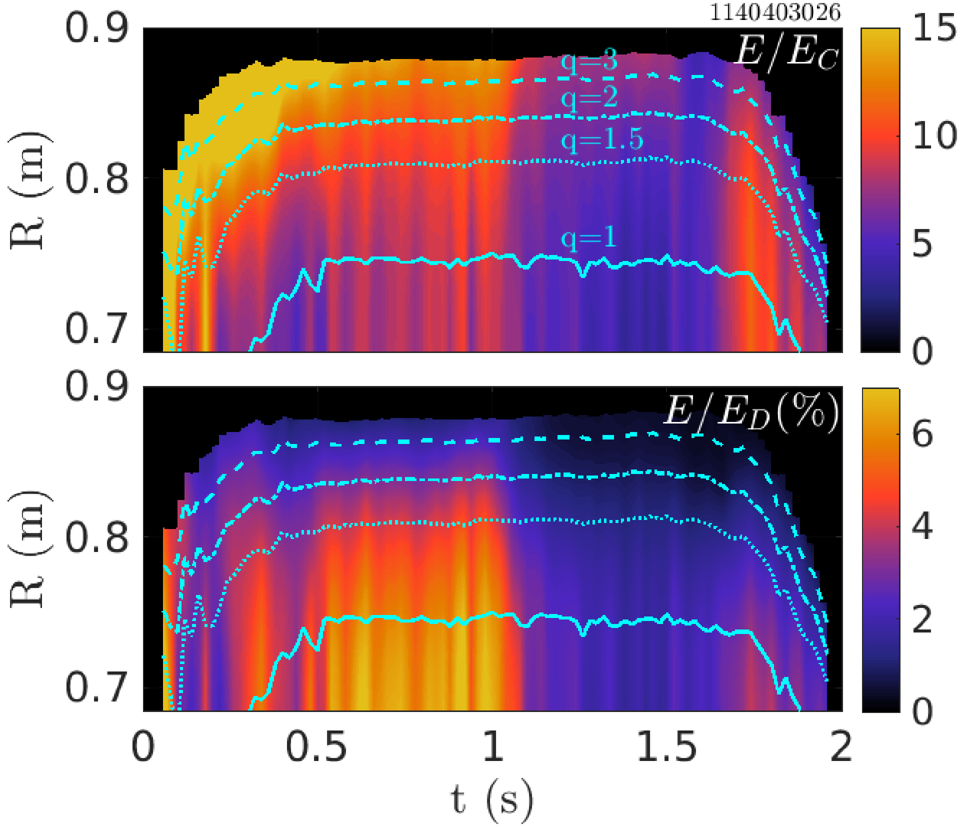
Beam decreases in size and intensity as n_e increases



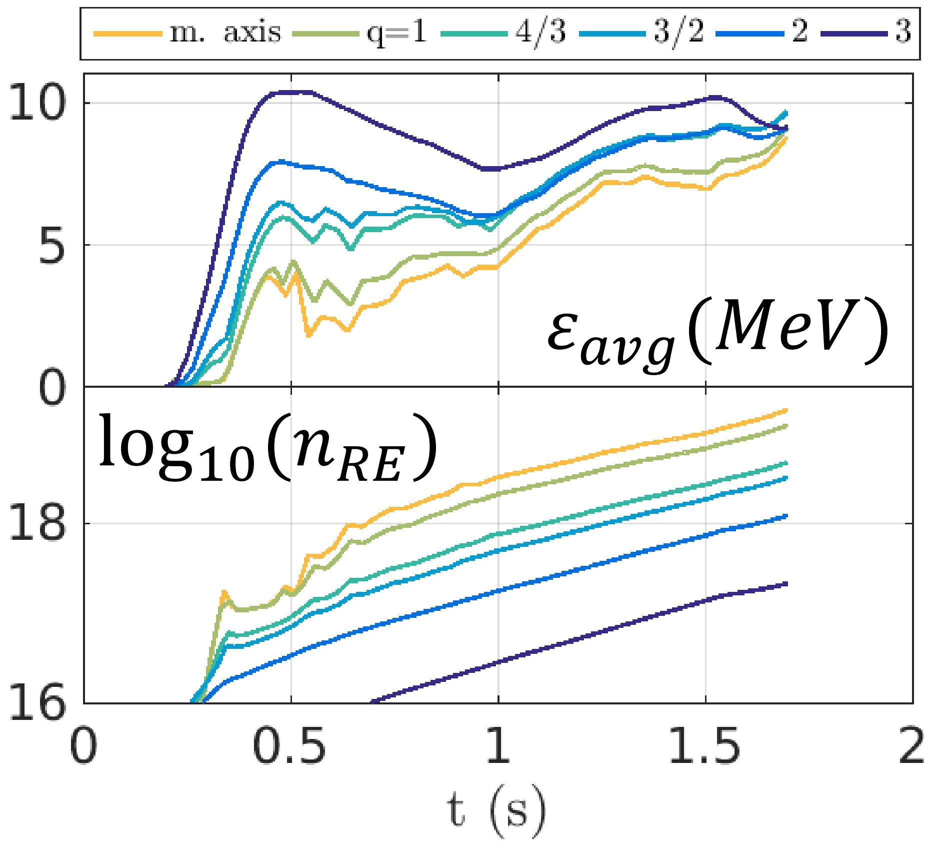
COllisional Distribution of Electrons (~300 CPU hrs)

Landreman CPC 2014, Stahl NF 2016

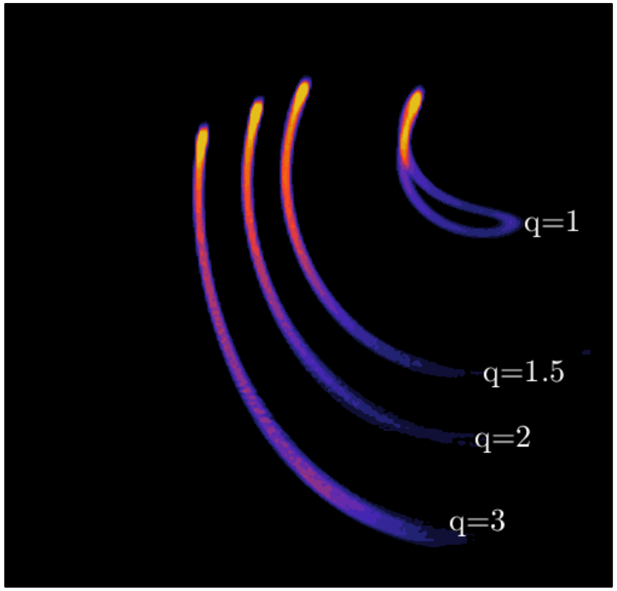
Inputs



Outputs

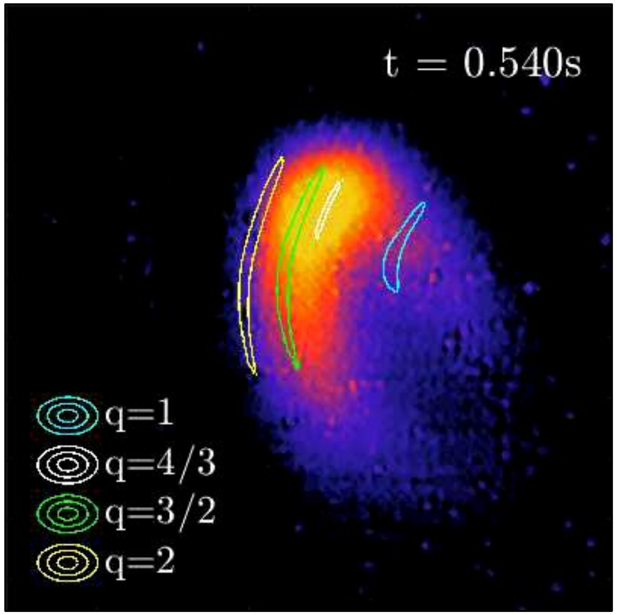


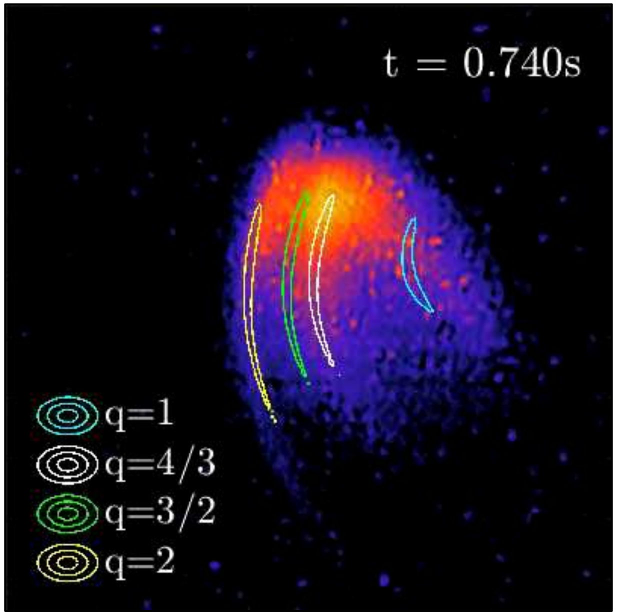
‘Build’ image from q-surfaces like basis functions

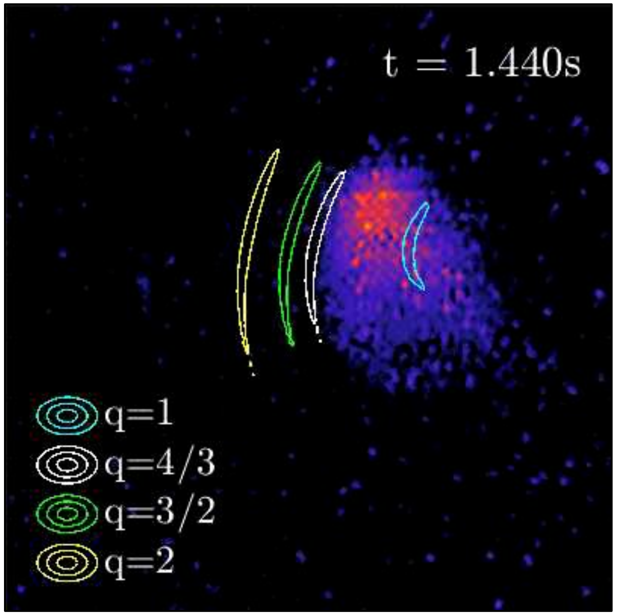


← SOFT [Hoppe NF 2018]
← Camera does not see REs on the magnetic axis

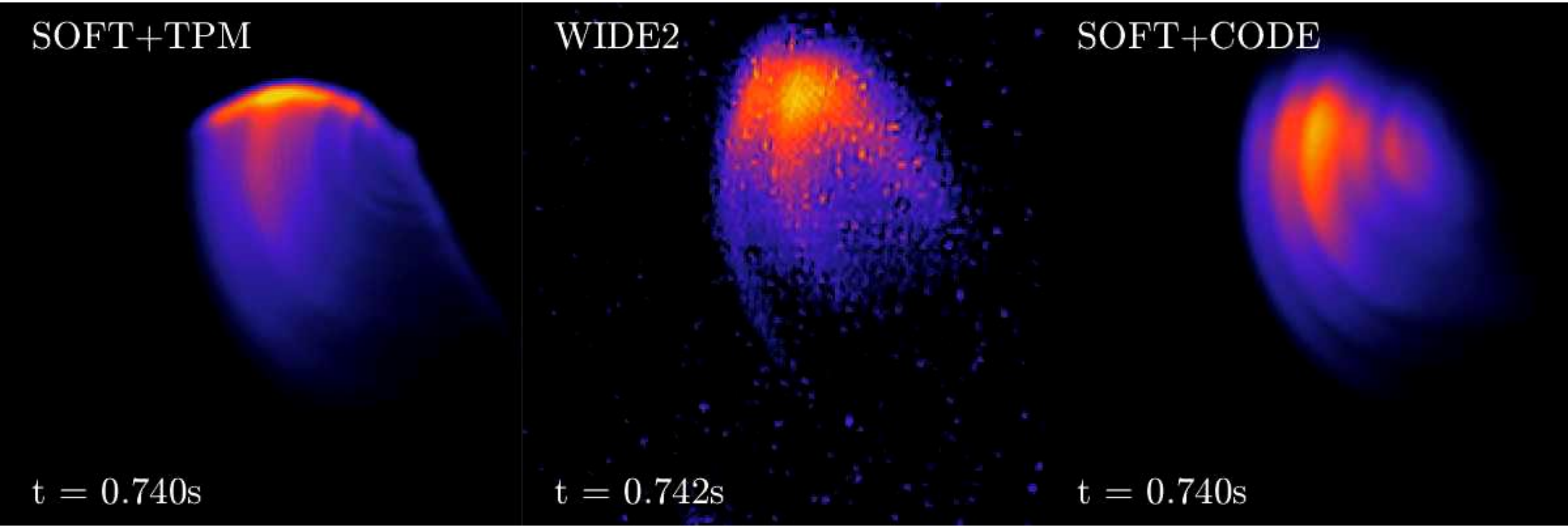
- Most applicable during flattop
- Structure/edges at rational q?







Comparing test-particle model to CODE

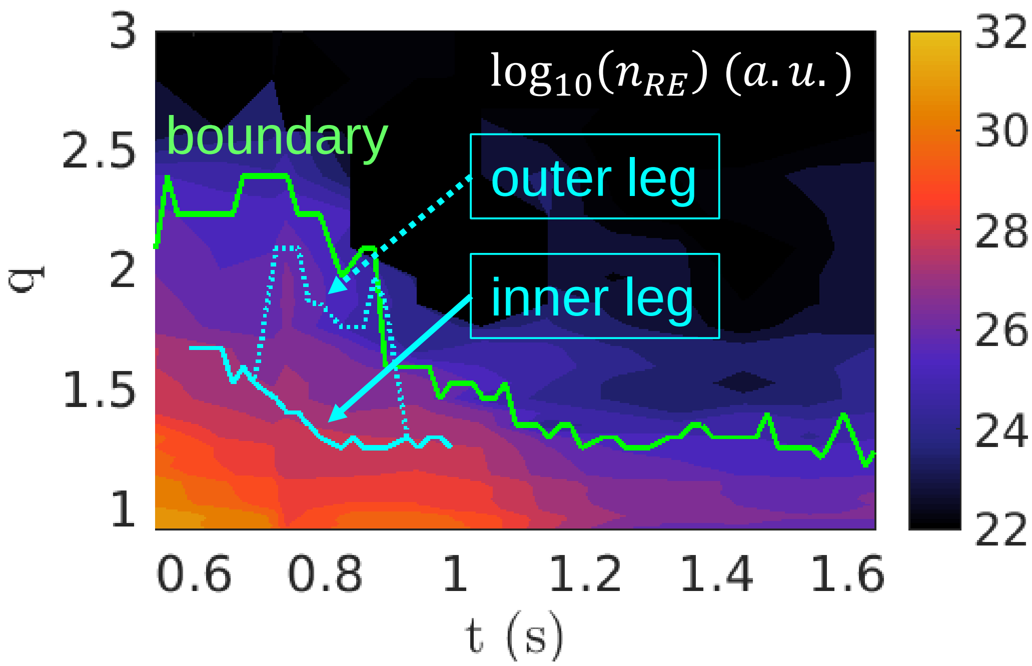


Full momentum-space distribution functions from CODE

- Capture full vertical extent of image
- Pose a challenge during early times (during I_p ramp)
- Most accurately reproduce spatial features (later)

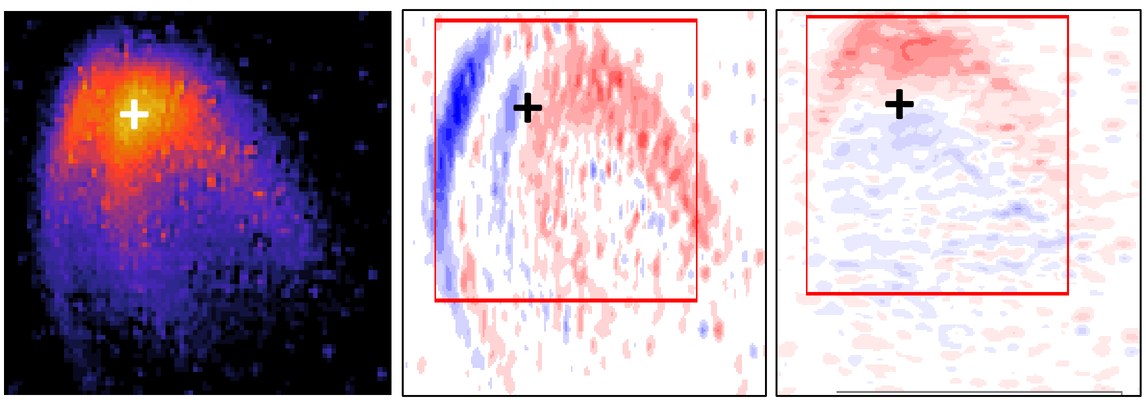
Gain insight into spatiotemporal evolution

- Beam shrinks in size, starting at locked mode
- Runaway density decreases as n_e increases

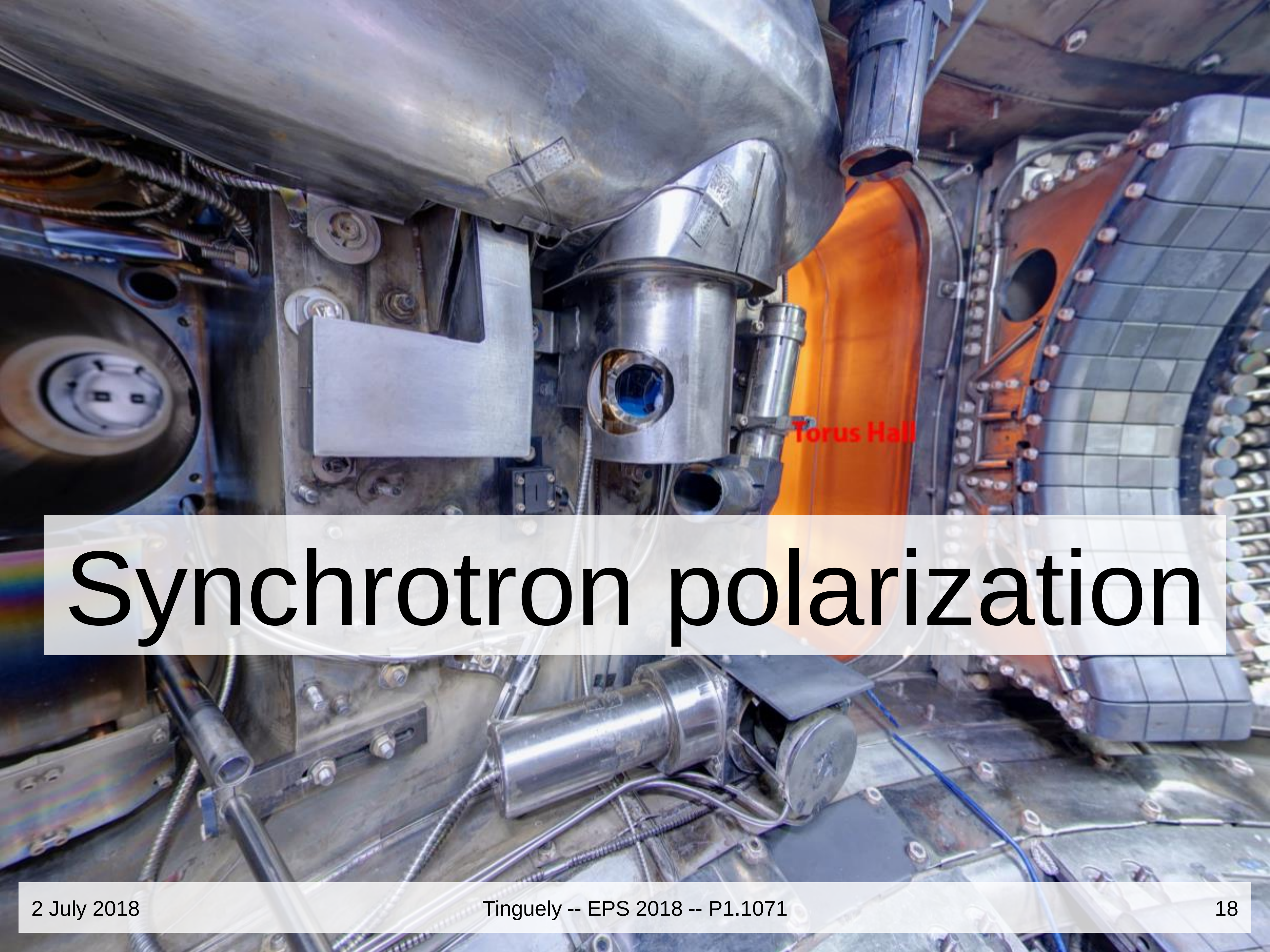


Use edge detection to track spatial features

Sobel gradient →
blue/red = +/-



Horizontal Vertical

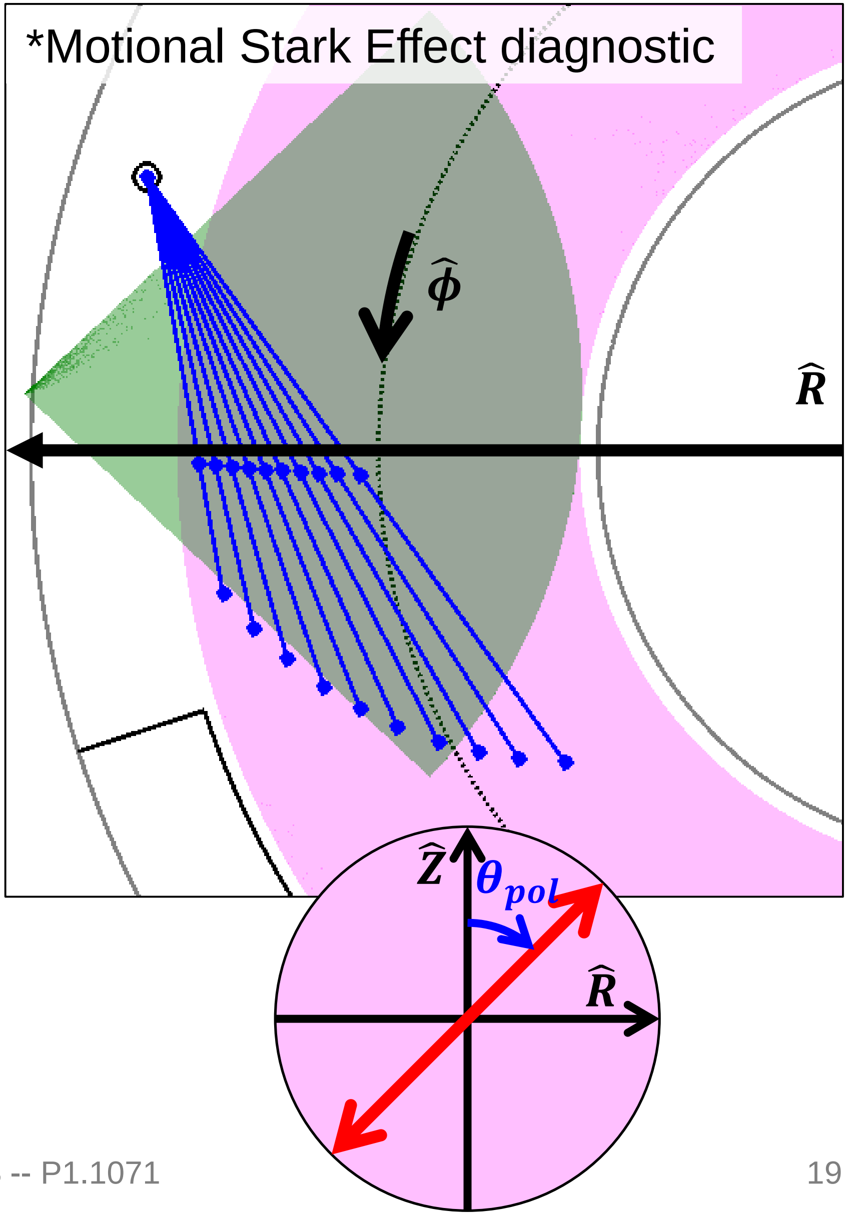


Synchrotron polarization

10 channel system* measures polarization info

- Stokes vector $[I, Q, U, V]$
- Intensity of polarized light
  $$L = \sqrt{Q^2 + U^2 + V^2}$$
- Fraction of linearly-polarized light
  $$DOLP = \frac{\sqrt{Q^2 + U^2}}{I}$$
- Linear polarization angle
  $$\theta_{pol} = \frac{1}{2}\text{atan}\left(\frac{U}{Q}\right)$$

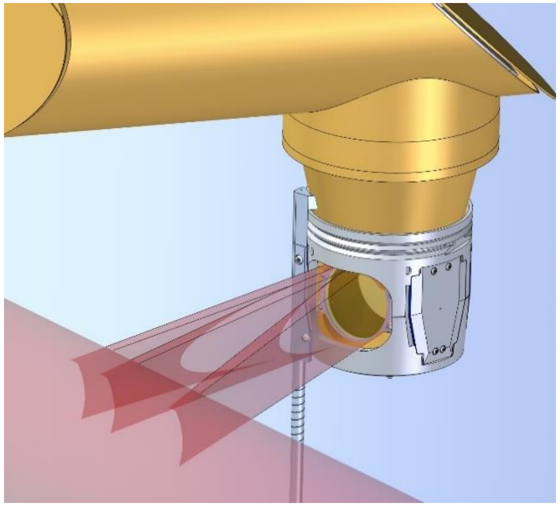
*Motional Stark Effect diagnostic



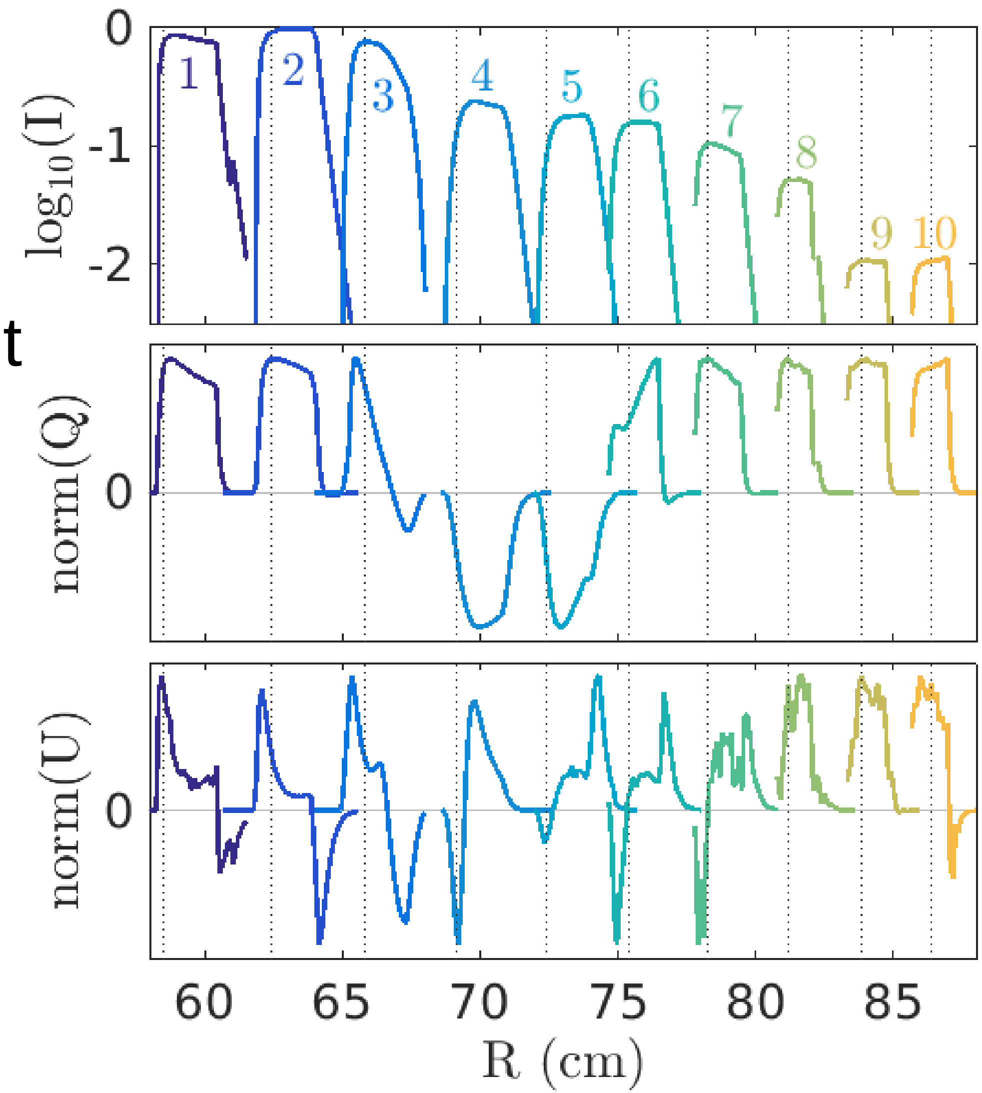
10 channel system has been modeled in SOFT

Hoppe NF 2018

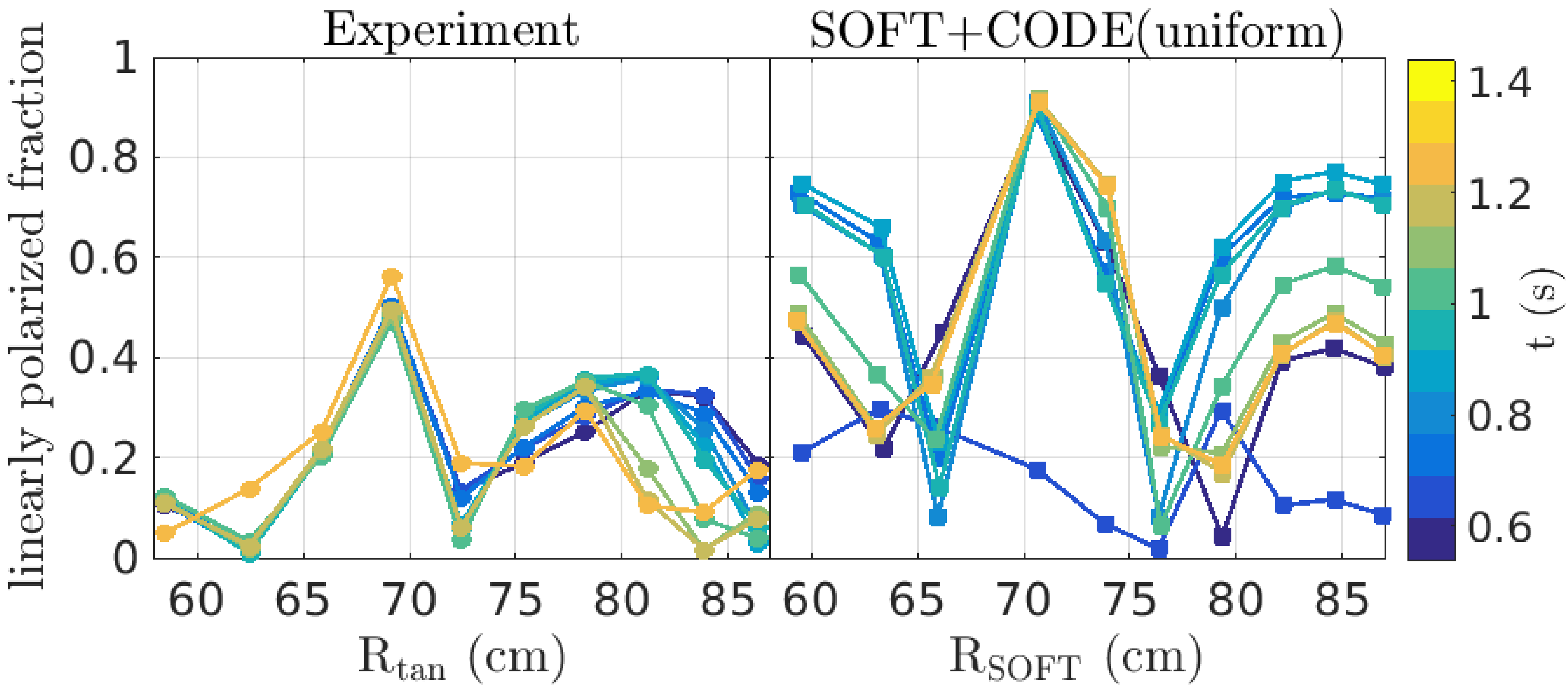
- Localized measurements of synchrotron emission
- Some measurements (DOLP, θ_{pol}) ~independent of local intensity



Courtesy of R. Mumgaard

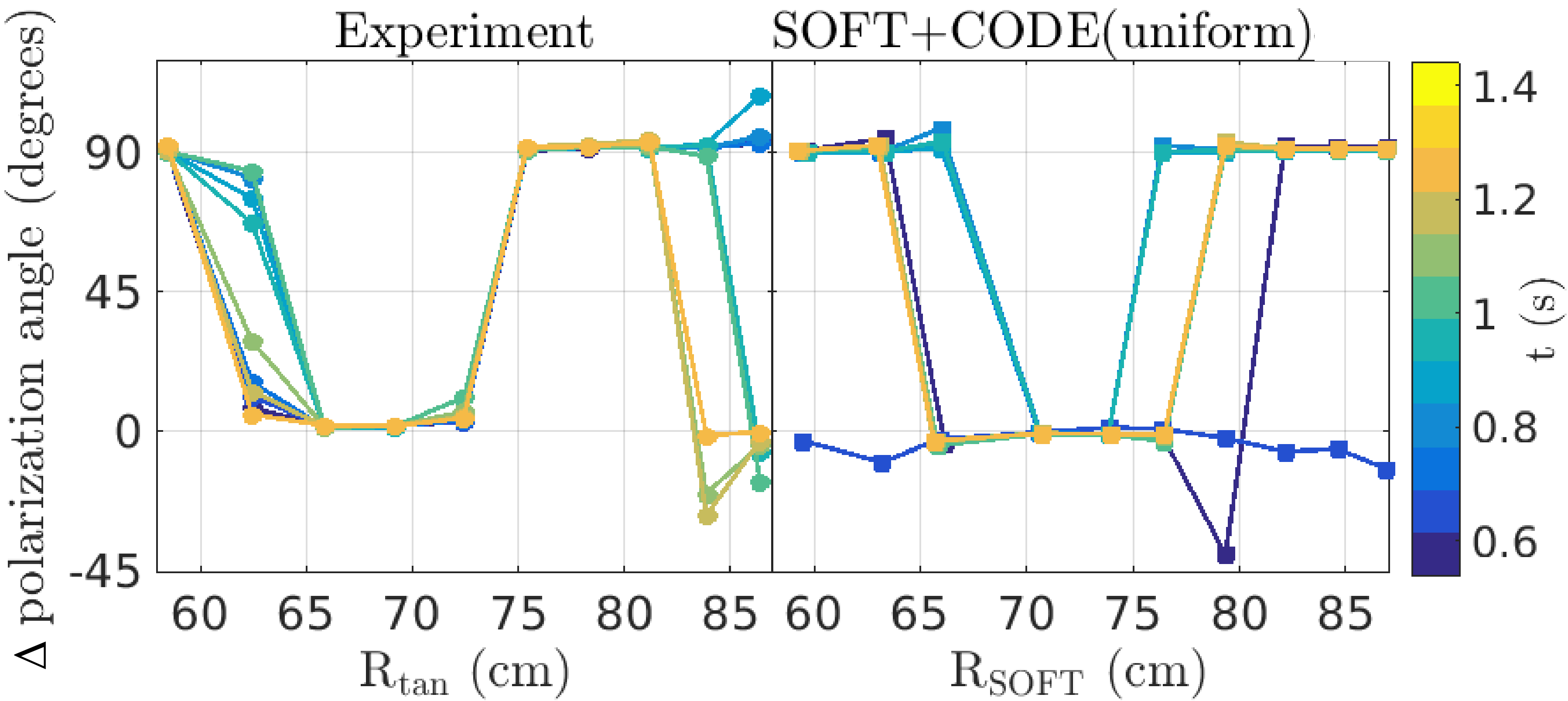


First simulations of DOLP show similar features



- Experimental data is shifted toward smaller R compared to SOFT – perhaps due to drifts?
- Amplitude difference could result from background light?

First look at polarization angle shows promise



- Again, experimental data is shifted toward smaller R…
- Working to clarify experimental and SOFT geometries for appropriate comparison of angles