Analysis of Runaway Electron Synchrotron Emission in Alcator C-Mod

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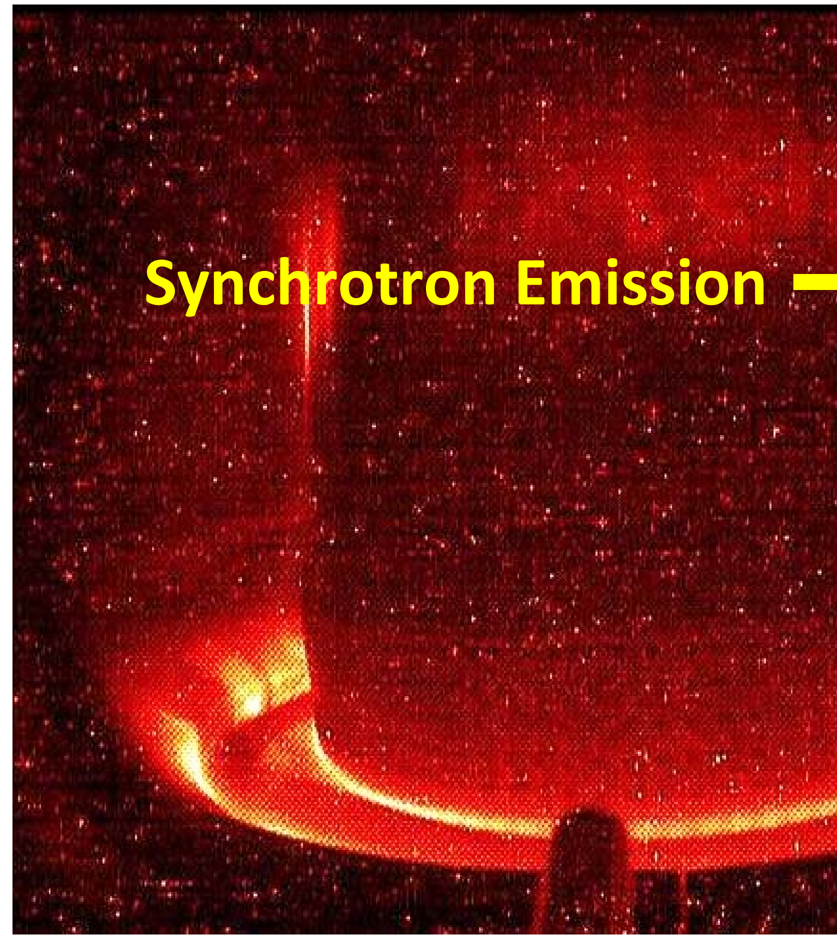
Runaway electrons

- In plasmas, the Coulomb collision frequency between particles varies as (*density*)/(*velocity*)^3.
- This can lead to a cascade of relativistic "runaway" electrons (REs) with energies of tens of MeV.
- Relativistic charged particles emit a cone of synchrotron radiation (SR) in their direction of motion.



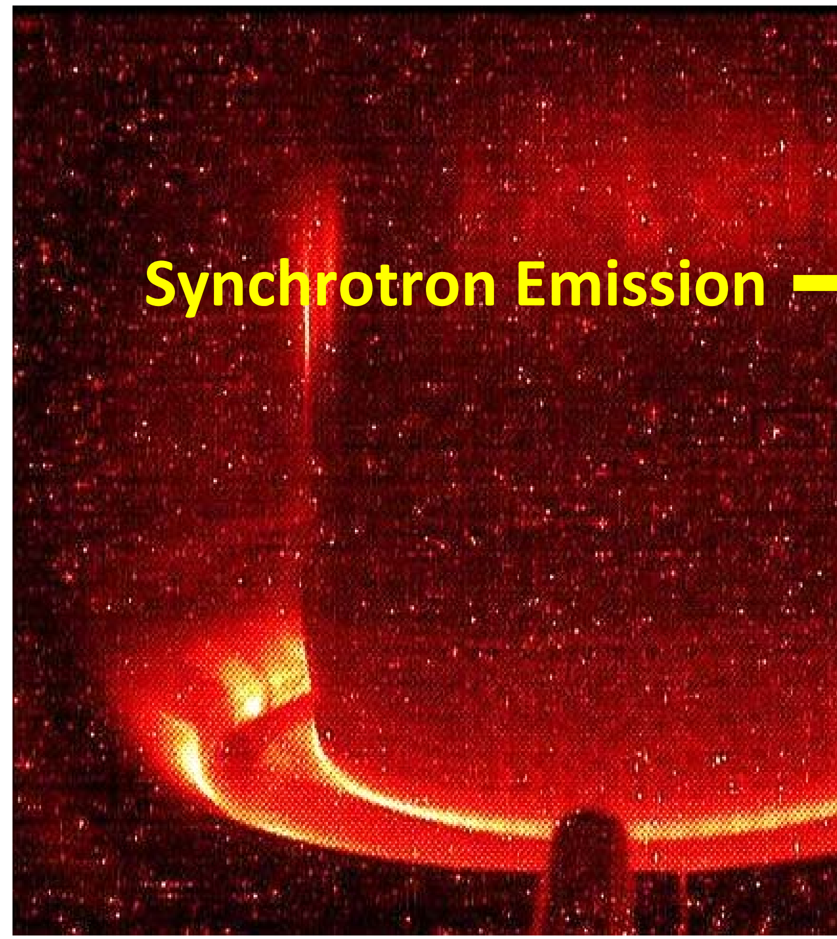
Camera view inside Alcator C

Runaway electrons in C-Mod

Plasma Parameters	Alcator C-Mod	ITER
B_{tor} (T)	5.4 (2 – 8)	5.3
I_p (MA)	1 (0.5 – 2)	15
	1 (0.2 – 4)	1.0
T_{e0} (keV)	1 – 8	8.8
R (m)	0.68	6.2
a (m)	0.22	2.0

Synchrotron radiation (SR) can be in the visible/near-infrared range (300-1000 nm).

http://wiki.fusenet.eu/fusionwiki/index.php/ITER



Camera view inside Alcator C

Motivation

Q: From SR, can we distinguish a **mono-energetic** (and mono-p

distribution from a **continuum distribution** of energies and p

- Recent studies [1-3] have predicted that REs will accelerate to a maximu which the radiative force and collisional friction balances the electric for a "bump" on the tail of the energy distribution function.
- Others [4,5] suggest that a broader distribution contributes to the SR sp
- Knowing the maximum energy of REs, as well as current and density, ca important implications for RE mitigation in fusion devices.

[1] P. Aleynikov, et al. Phys. Rev. Lett. 114, 155001 (2015).
[2] J. Decker, et al. Plasma Phys. Contr. Fusion 58, 025016 (2016).
[3] E. Hirvijoki, et al. J. Plasma Phys., vol. 81, 47810502 (2015).
[4] A. Stahl, et al. Phys. Plasmas 20, 093302 (2013).
[5] M. Landreman, et al. Computer Physics Communications 1

Motivation

Q: From SR, can we distinguish a **mono-energetic** (and mono-p
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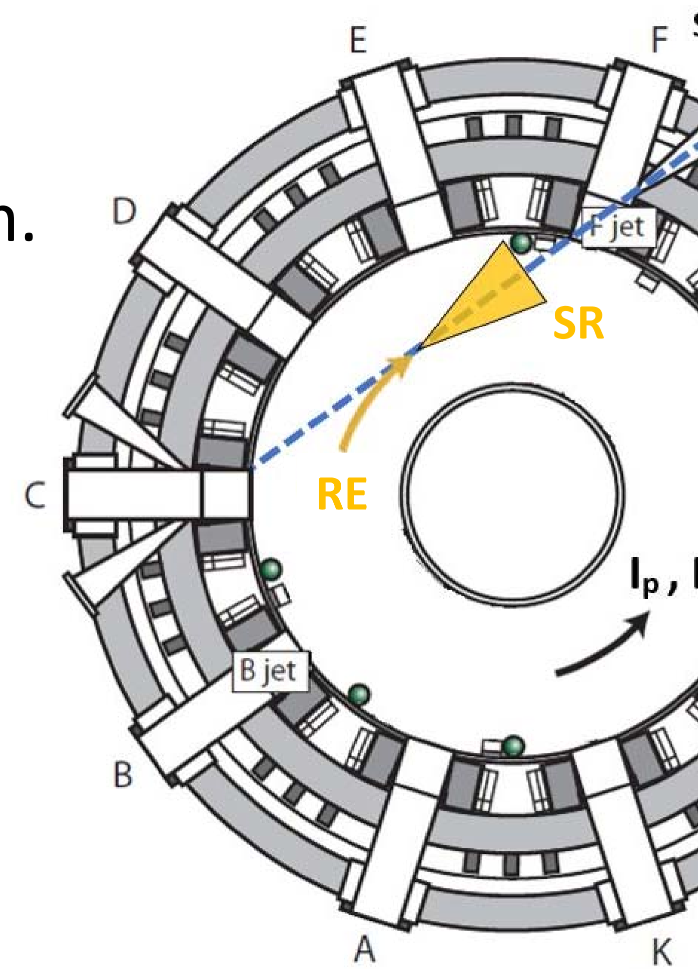
A: Not yet…

Experimental setup

Data is collected using an absolutely-calibrated spectrometer installed on C-Mod, with spectral range of ~350-1020 nm.



Toroidal cross section of C

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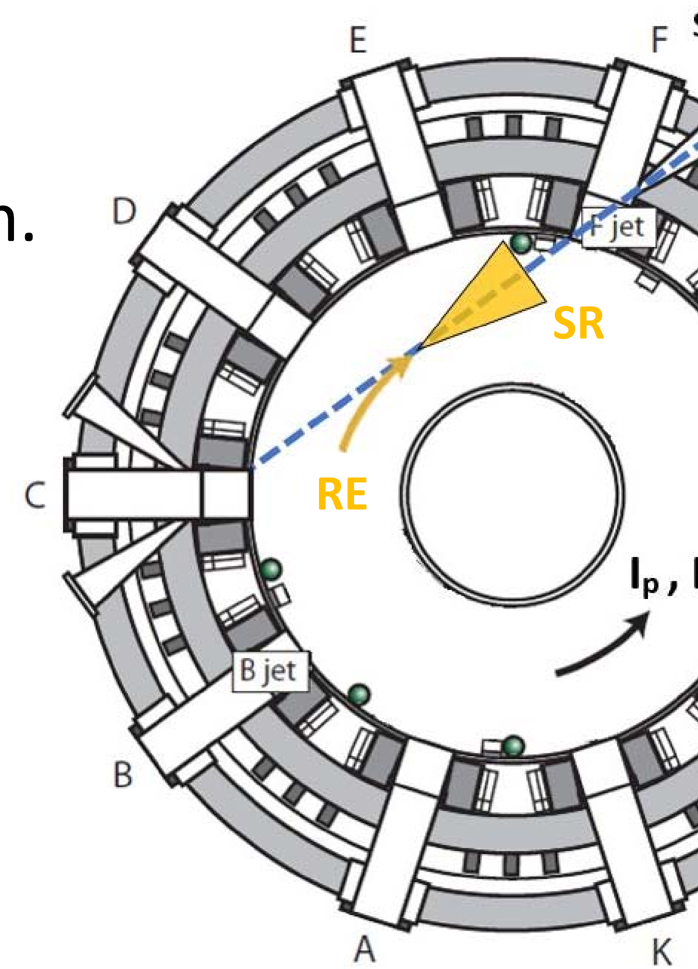
View outside vessel

View inside vessel



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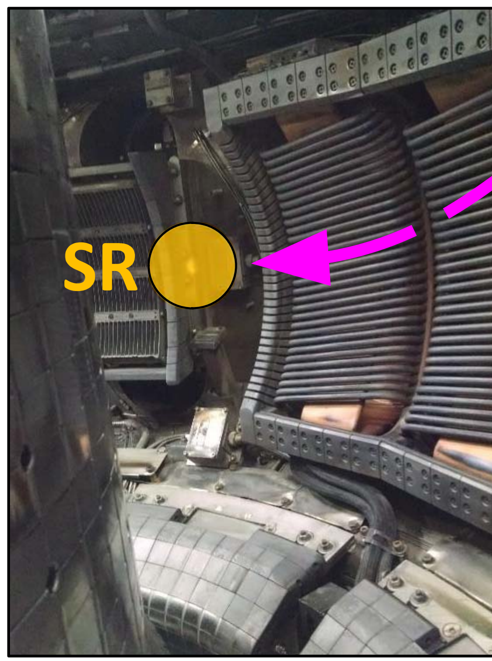

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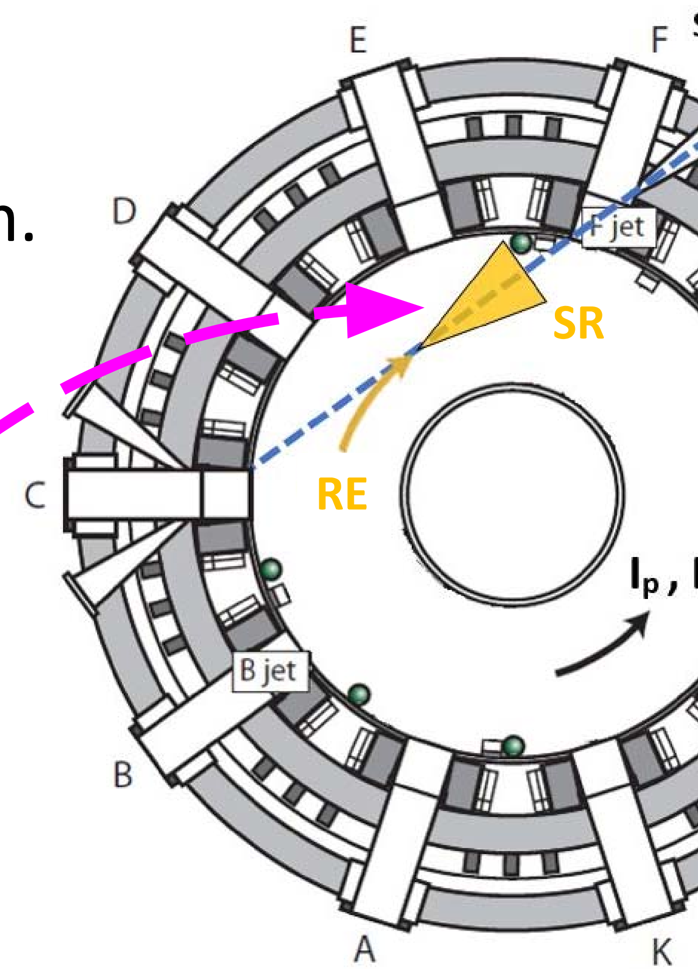

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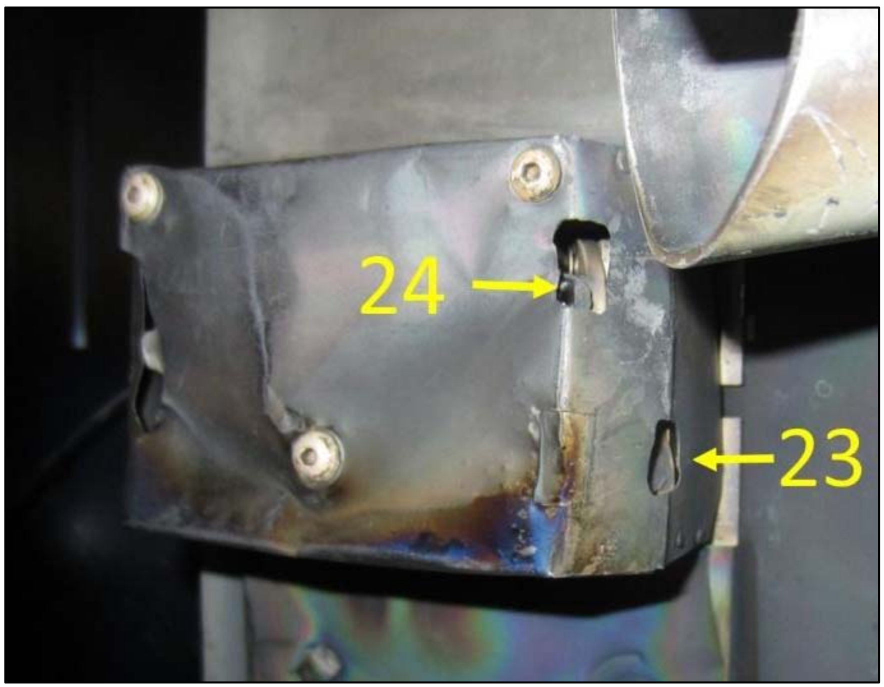
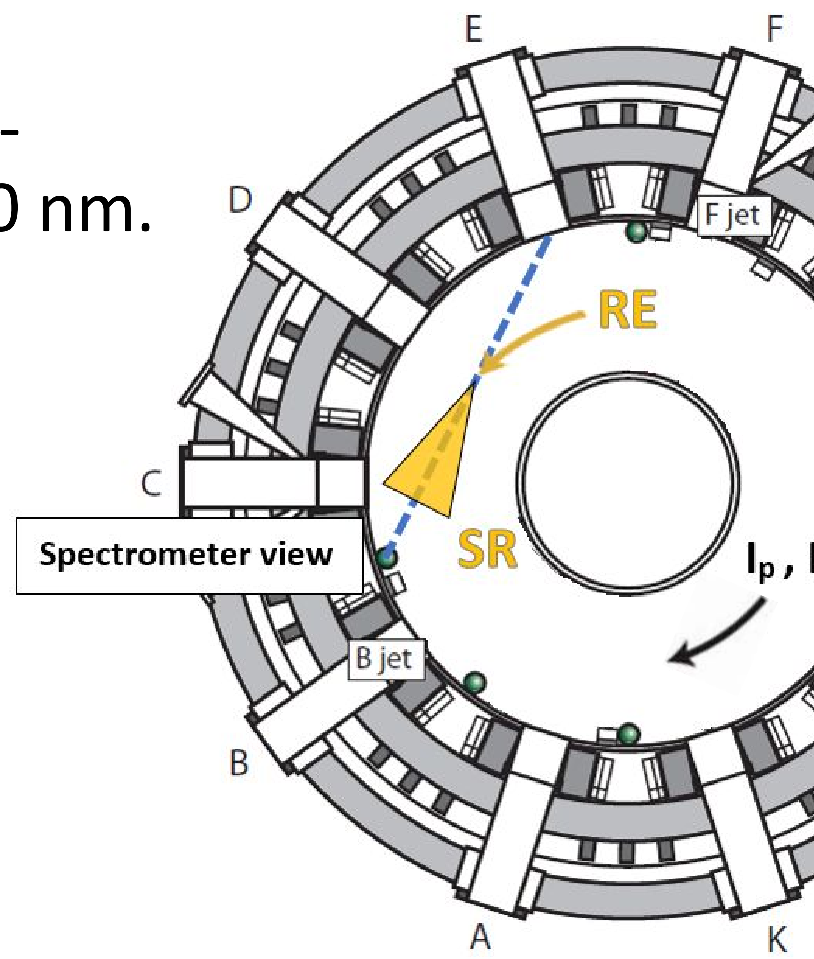
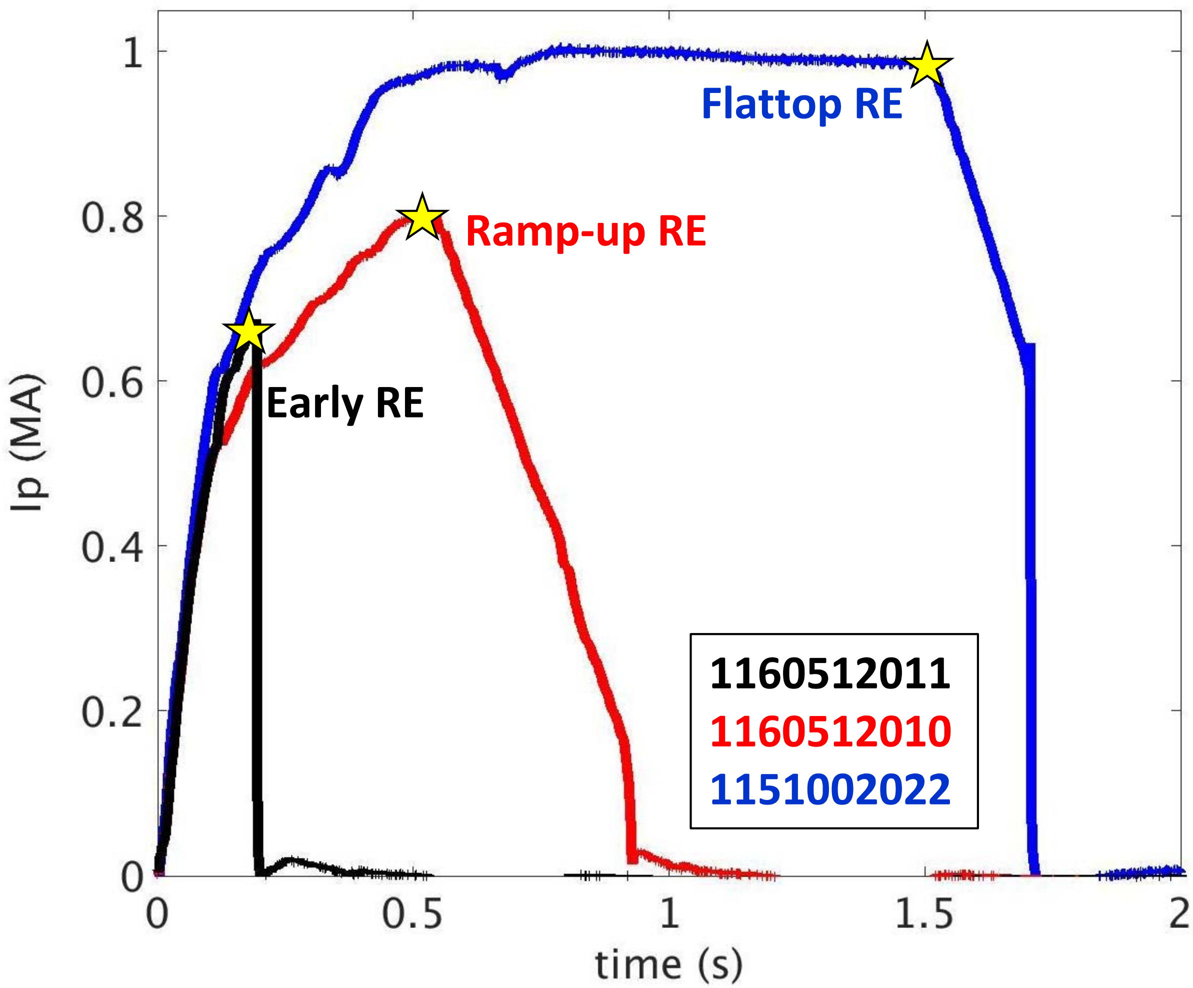
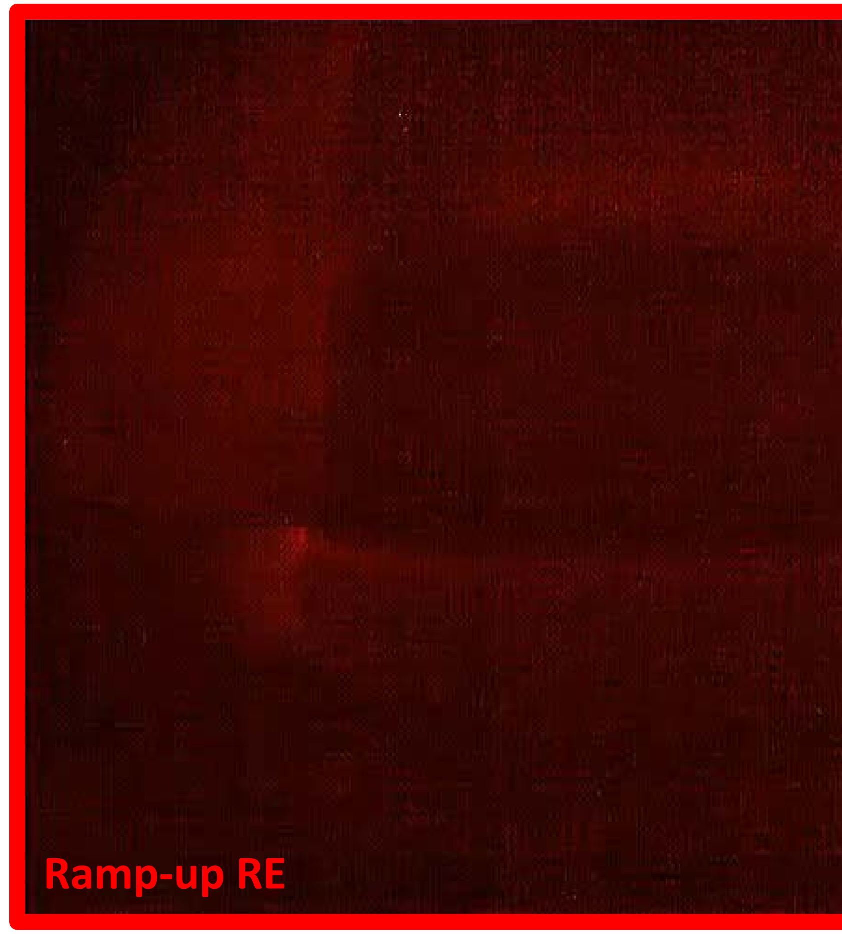




Toroidal cross section of C

Look at 3 different runaway shots





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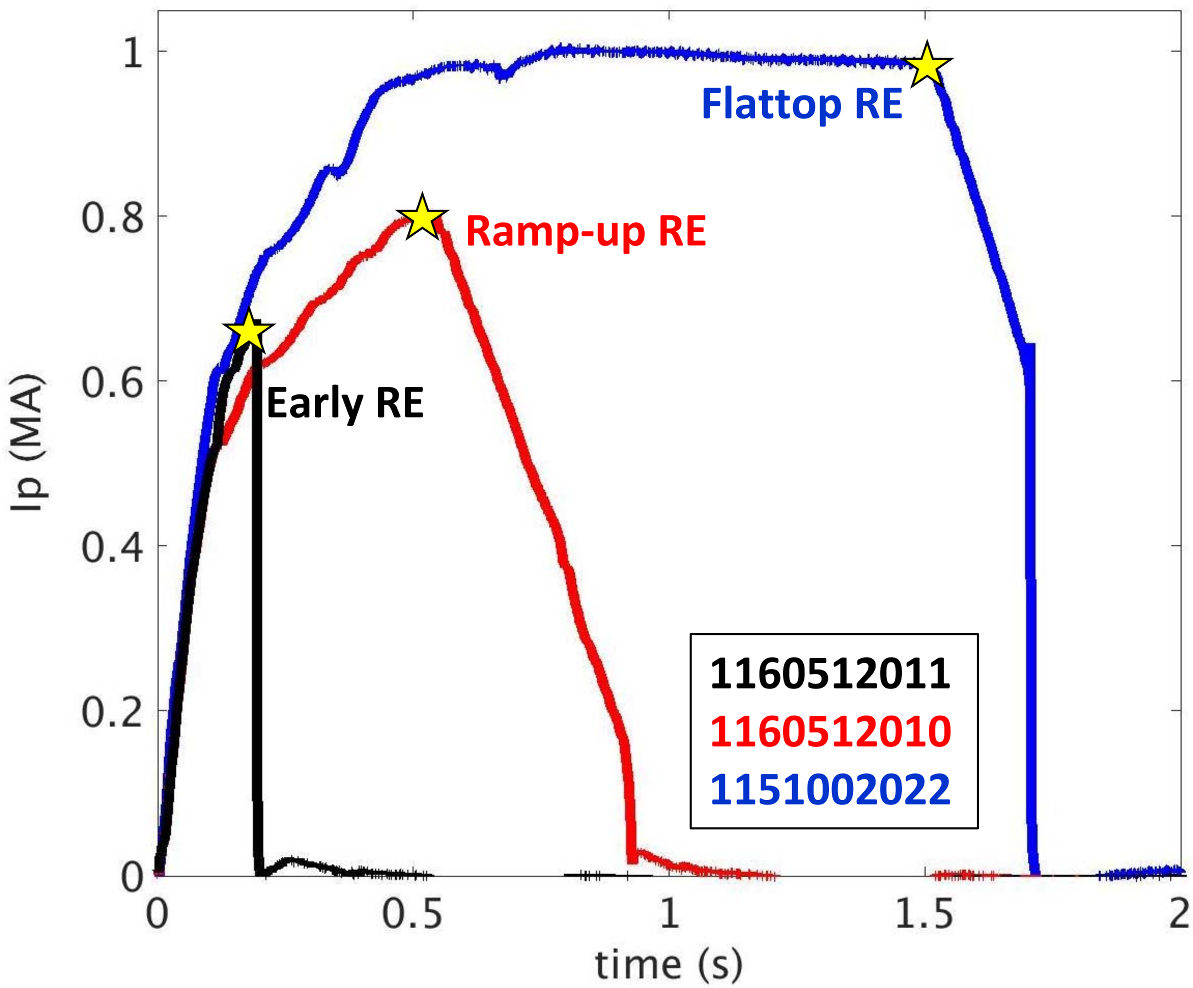

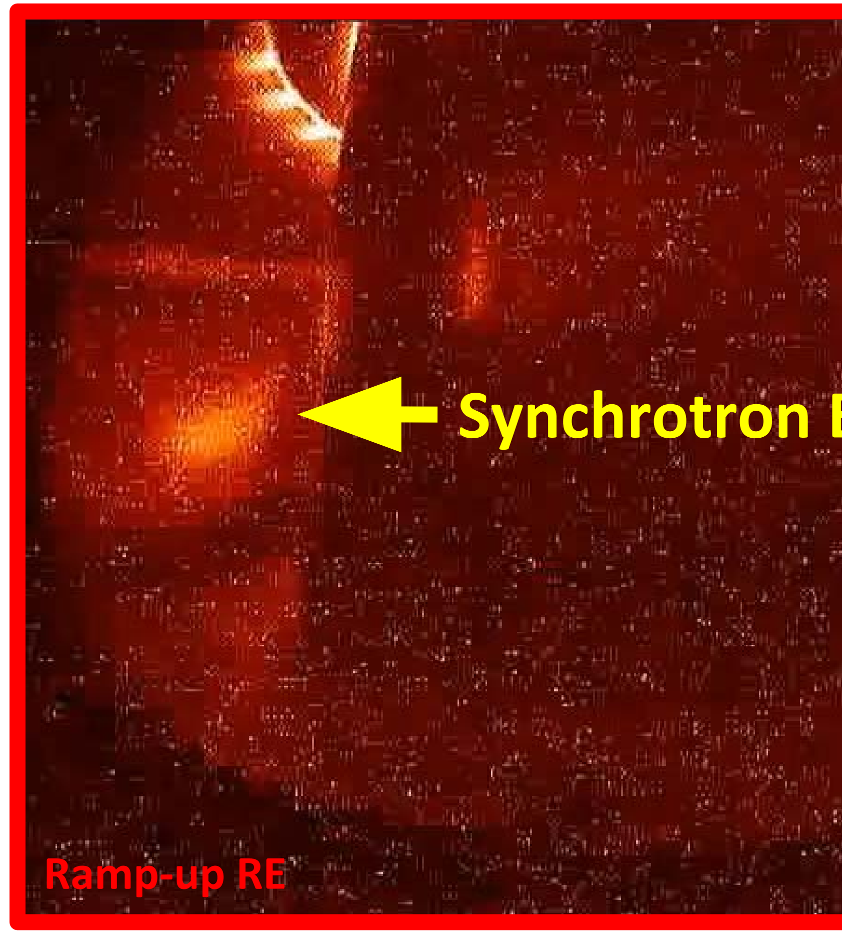

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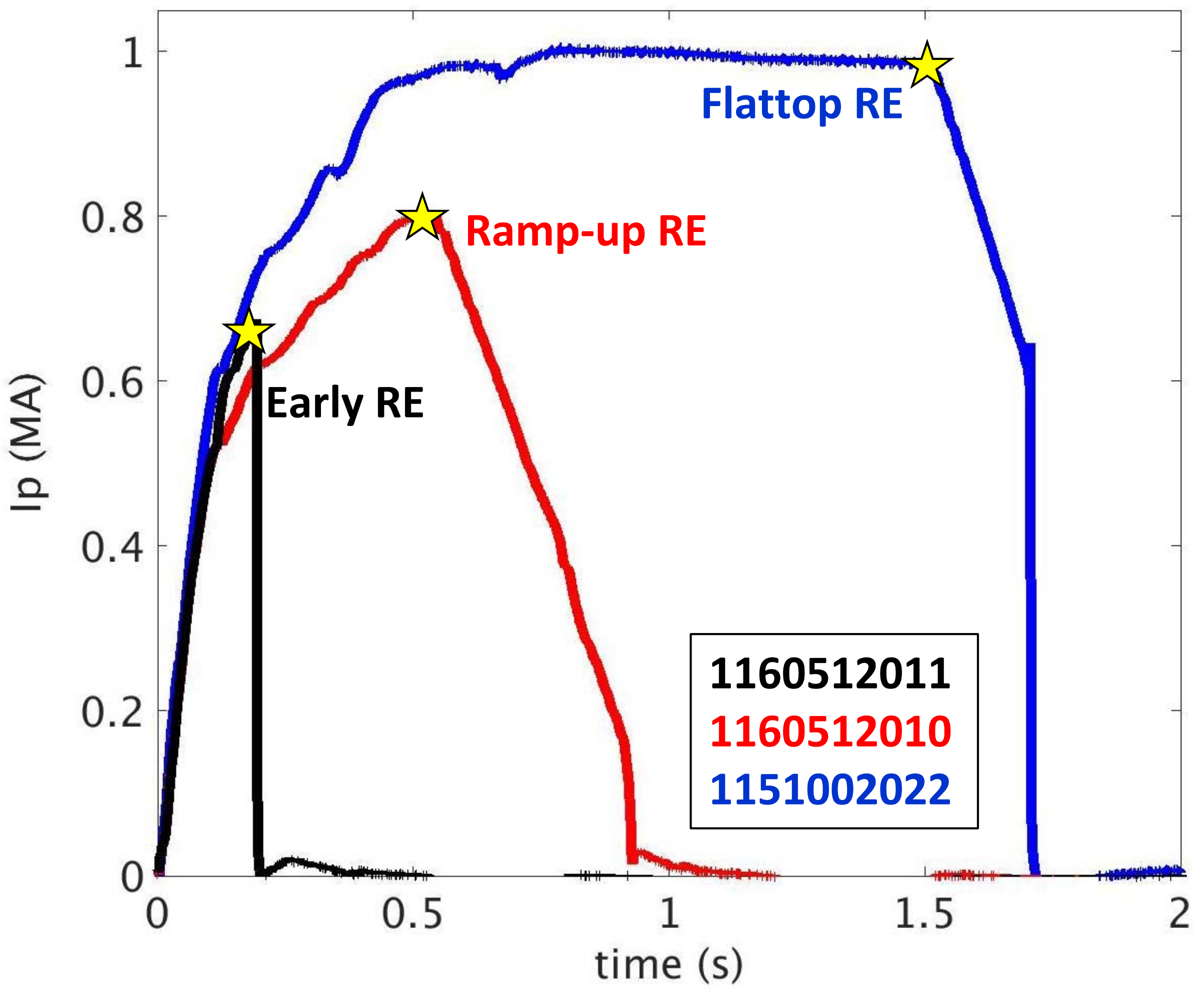
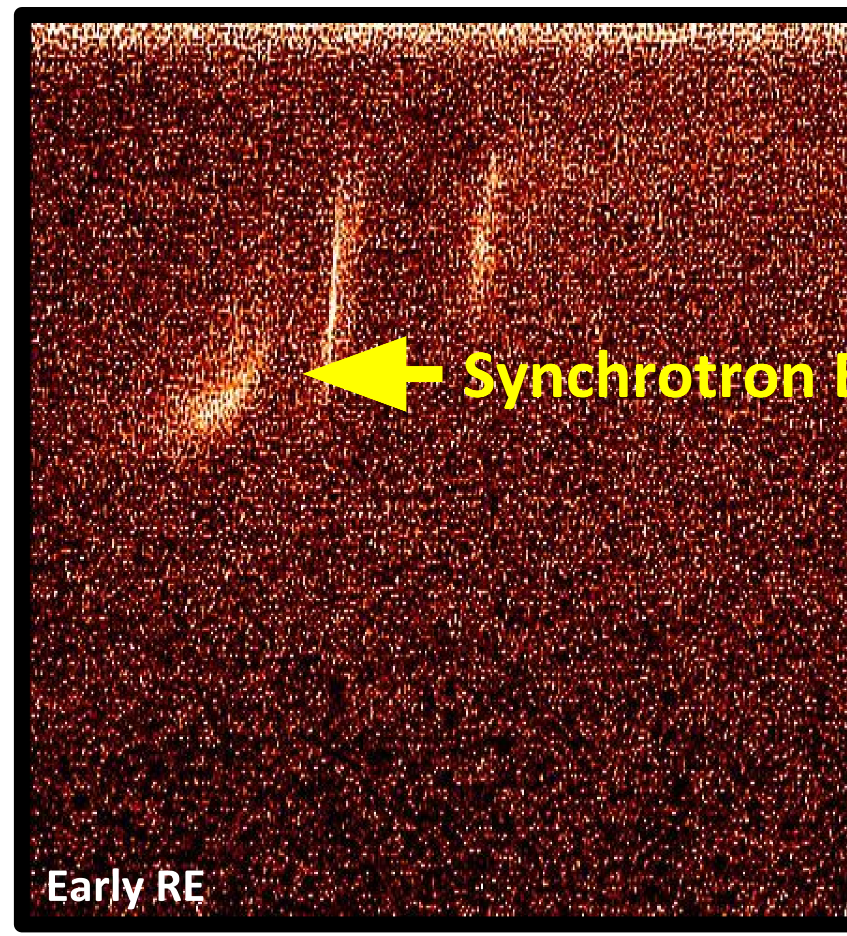
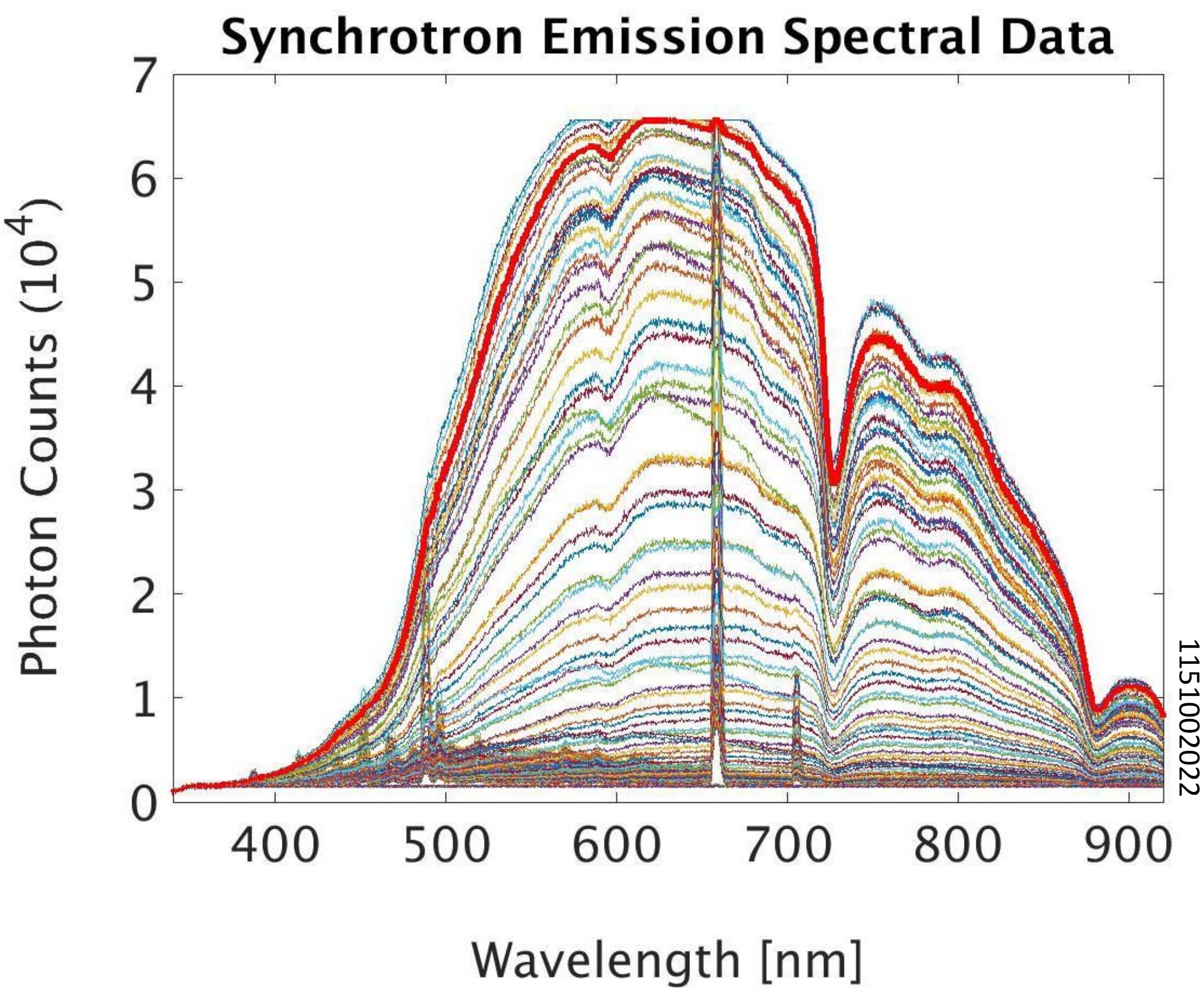




Flattop synchrotron emission dat



Plasma parameters at **t =**

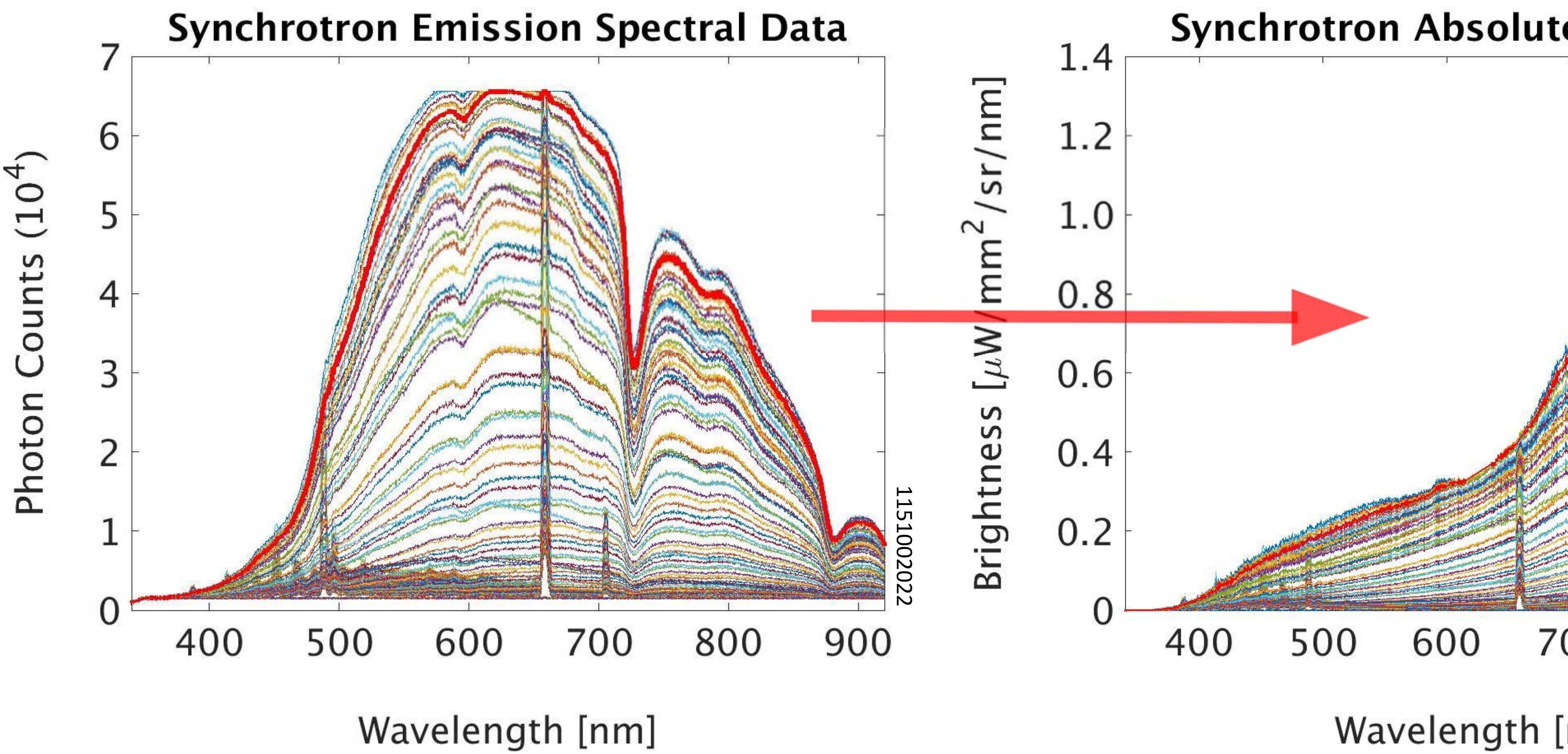
- B_t = 5.35 T
- $I_p \approx$ 1 MA (end of flat-to
- $\bar{n}_e = 2.5 \cdot 10^{19}$ m^{-3}
- T_{e0} = 4.25 keV
- $a_{beam} \approx$ 5 cm (as seen by
- V_{loop} = 1.05 V

→ E = 0.25 V/m

→ **E/E_c = 12**

The red highlighted data is at t = 1.5 s and is used in this

Flattop synchrotron emission dat



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Two models for the RE distributio

For a **mono-energetic** and mono-pitch RE beam, the brightness (W/m^3/sr) is [6]:

$$B_{mono}(\lambda, \boldsymbol{\theta}, \boldsymbol{p}) = \frac{2\,R\,\boldsymbol{n_r}}{\pi\,\theta_{eff}(\boldsymbol{p}, \boldsymbol{\theta})} P(\lambda, \theta_{eff}, \boldsymbol{p})$$

where $\boldsymbol{n_r}$ is the density of REs emitting SR, $\boldsymbol{\theta} = \boldsymbol{v}_\perp/\boldsymbol{v}_\parallel = \boldsymbol{p}_\perp/\boldsymbol{p}_\parallel$ is the pitch, and $\boldsymbol{p} = \sqrt{\boldsymbol{E}^2/\boldsymbol{m}^2\boldsymbol{c}^4 - \mathbf{1}}$ is the normalized momentum.

[6] J.H. Yu, et al. Phys. Plasmas 20, 042113 (2013).

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- For a **distribution**, f_{RE}, of energies

$$f_{RE}(\boldsymbol{p}_\parallel, \boldsymbol{p}_\perp) = \frac{\boldsymbol{n_r}\,\hat{E}}{2\pi c_Z\,\boldsymbol{p}_\parallel\,ln\Lambda} \exp\Big(-$$

the brightness (W/m^3/sr) is [4]:

$$B_{dist}(\lambda) = 4R \int\int \frac{1}{\theta_{eff}(\boldsymbol{p}_\parallel, \boldsymbol{p}_\perp)} P(\lambda, \theta_{eff}, \boldsymbol{p})$$

[4] A. Stahl, et al. Phys. Plasmas 20, 093302 (2013). [6] J.H. Yu, et al. Phys. Plasmas 20, 042113 (2013). [7] T. Fülöp, et al. Phys.

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The RE density, $\boldsymbol{n_r}$, is estimated [4,6] using the plasma current carried by the REs , $\boldsymbol{I_r}$, a
cross-sectional area, A_r, of the beam (as seen by our cameras):

$$\boldsymbol{n_r} = \boldsymbol{I_r}/(ecA_r)$$

During the discharge, we do not know $\boldsymbol{I_r}$, so we have to fit the data by varying the RE cu
the mono-energetic and continuum distributions.

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Mono-energetic fit matches **flattop** c

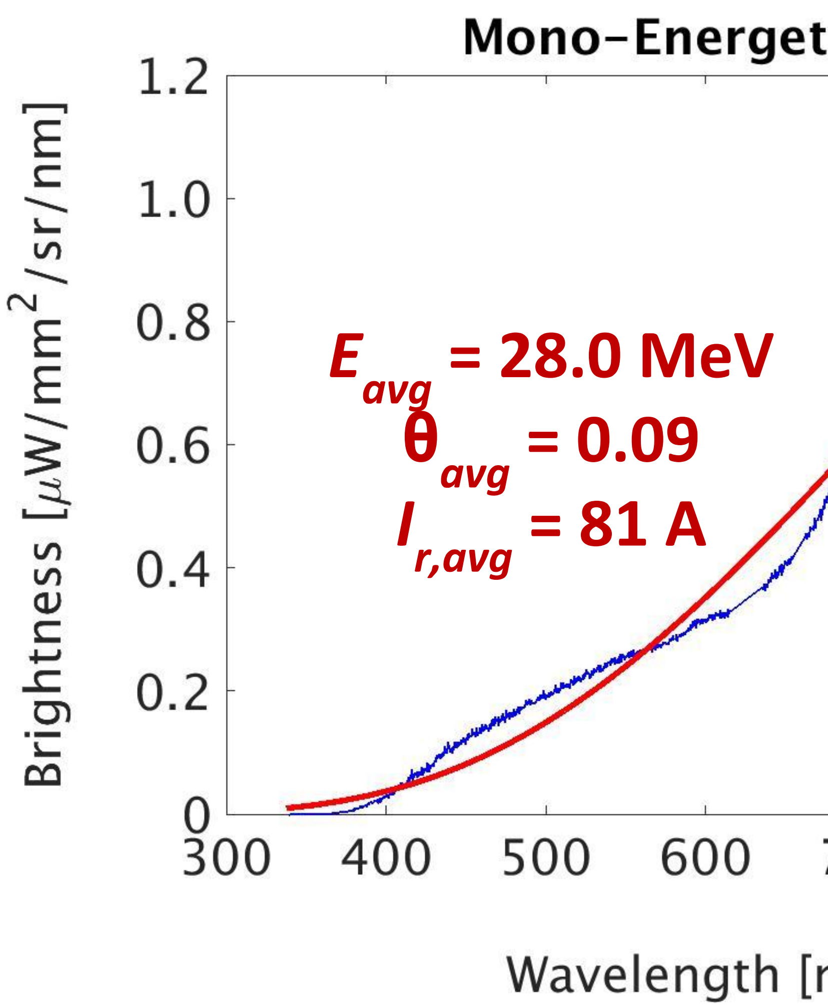
- This data can be well-fit for a range of RE energies, pitches, and currents:

$$24.8 \text{ MeV} \leq E_{mono} \leq 30.6 \text{ MeV}$$

$$0.070 \leq \theta = \frac{v_\perp}{v_\parallel} \leq 0.125$$

$$77 \text{ A} \leq I_{r,mono} \leq 82 \text{ A}$$

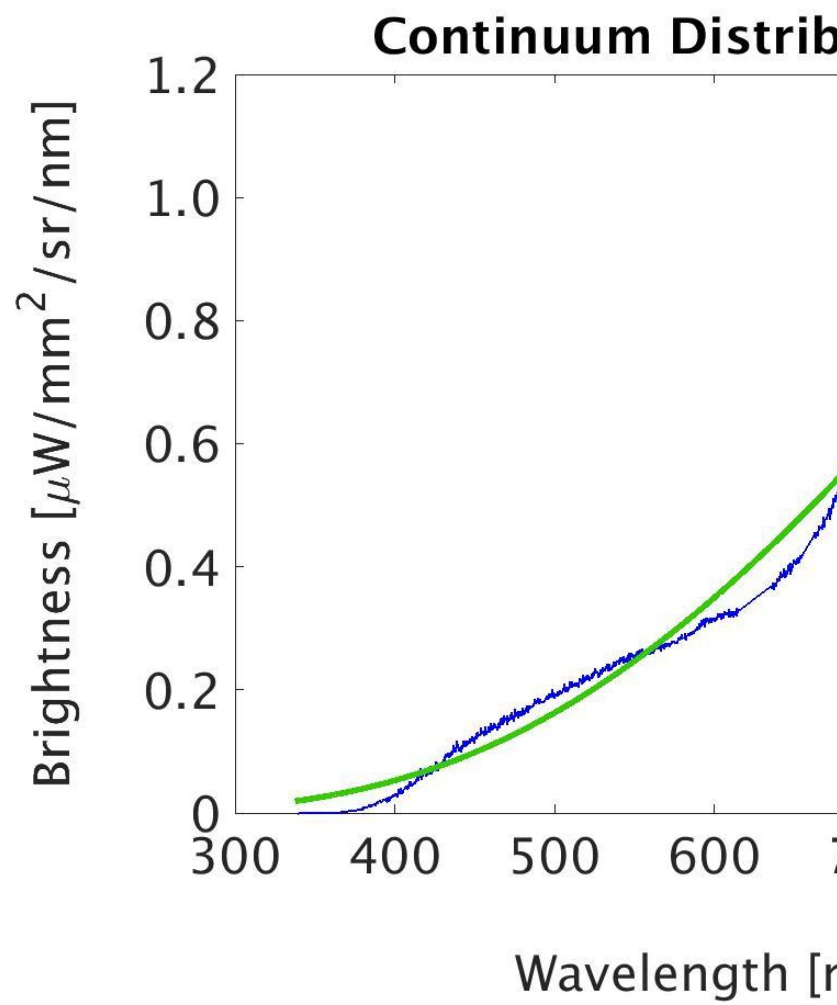
- Assuming all REs emit SR at 28 MeV and pitch of 0.09, this means they only carry ~100 A of the 1 MA plasma current



Continuum distribution matches **flattop**

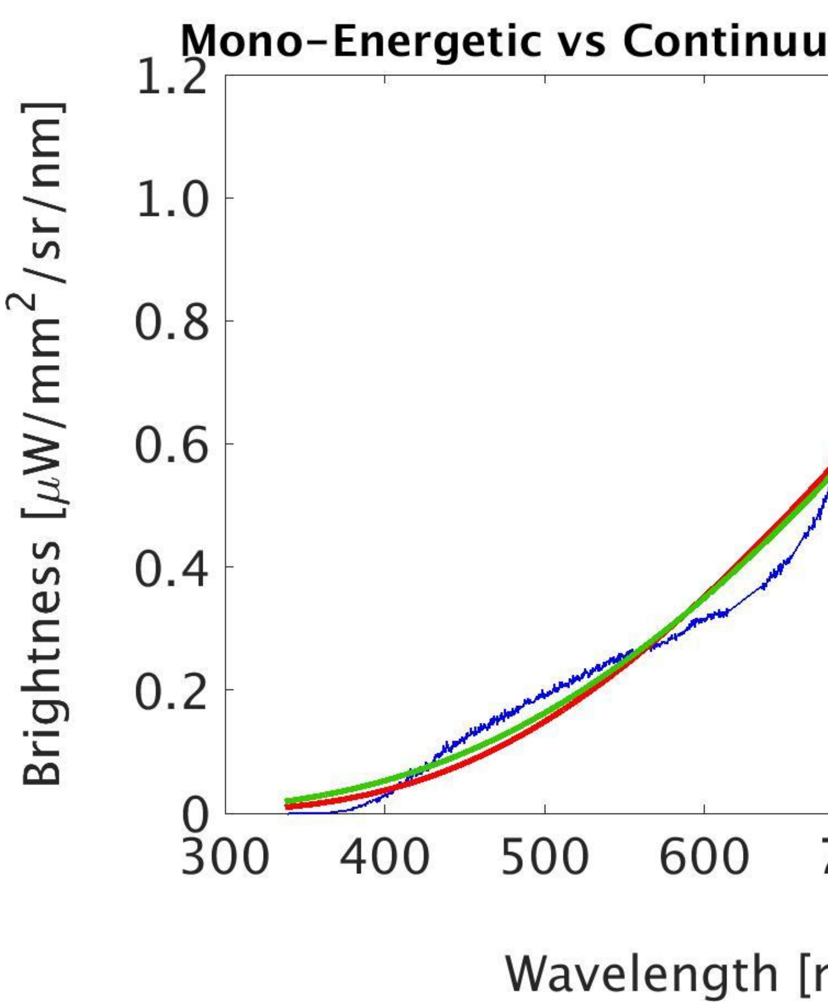
This best fit calculates:

- **$E_{max,dist}$ = 19.7 MeV**
  - About 10 MeV less than E_{mono}
- **$I_{r,dist}$ = 3.5 kA**
  - Accounts for <1% of the total plasma current, but more than $I_{r,mono}$
- **$Z_{eff,dist}$ = 3**
  - Lower bound of fitting range (3 – 7).



Both **flattop** fits are comparable

- The **mono-energetic** and **continuum distribution** fits are very similar, with about the same goodness of fit.



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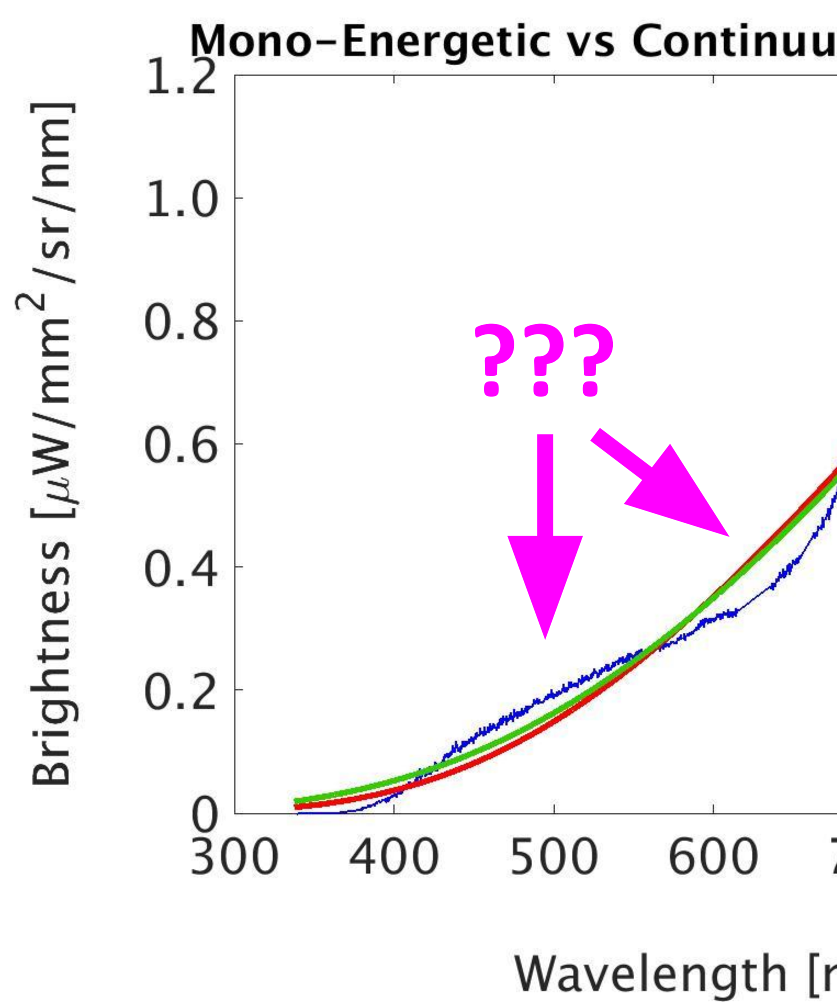
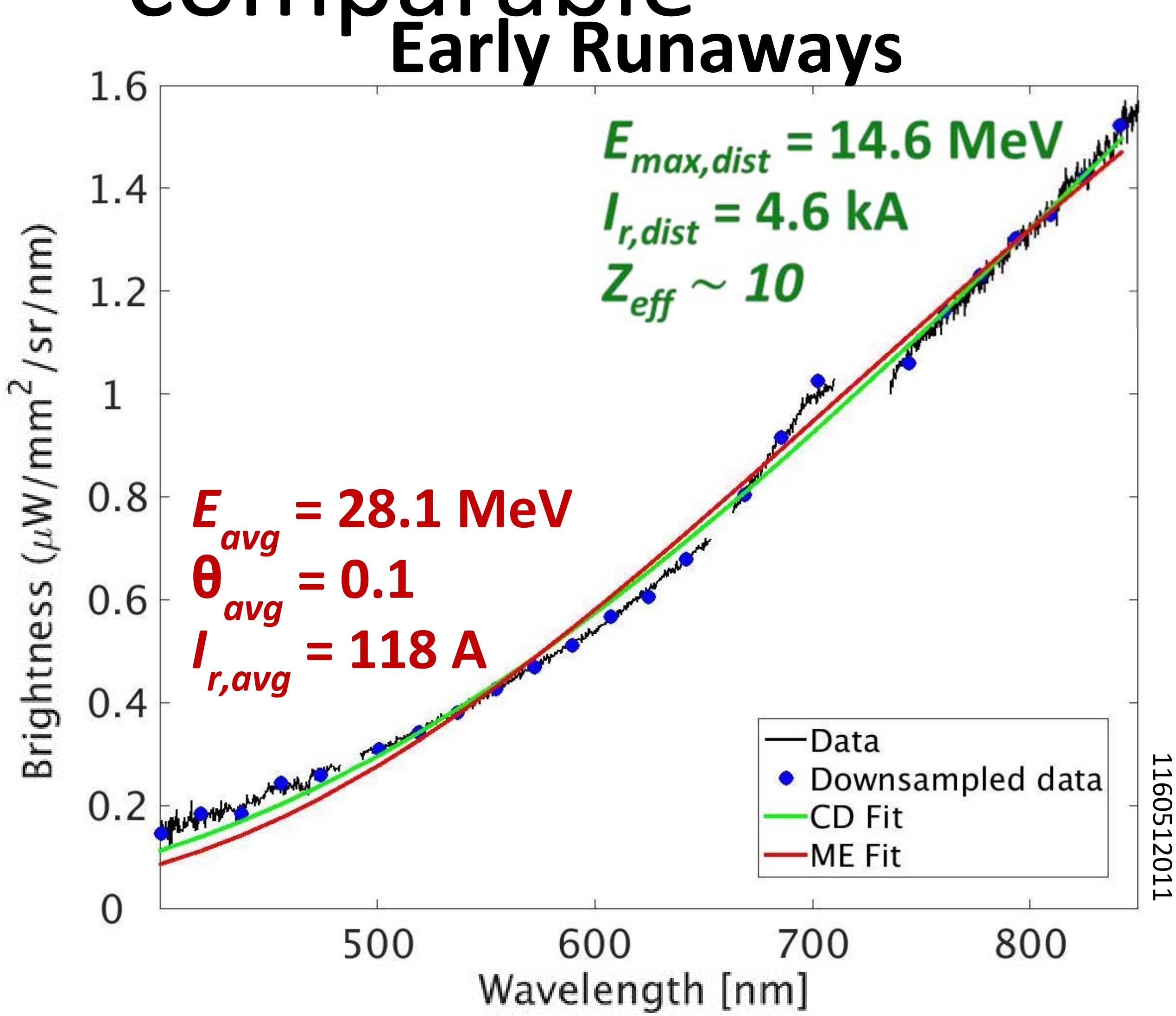
- There is a **brightness feature** that cannot be fit by either.
  - Maybe we need a different RE distribution?
  - Or perhaps this is a result of a calibration error?



Both ME and CD fits are again comparable

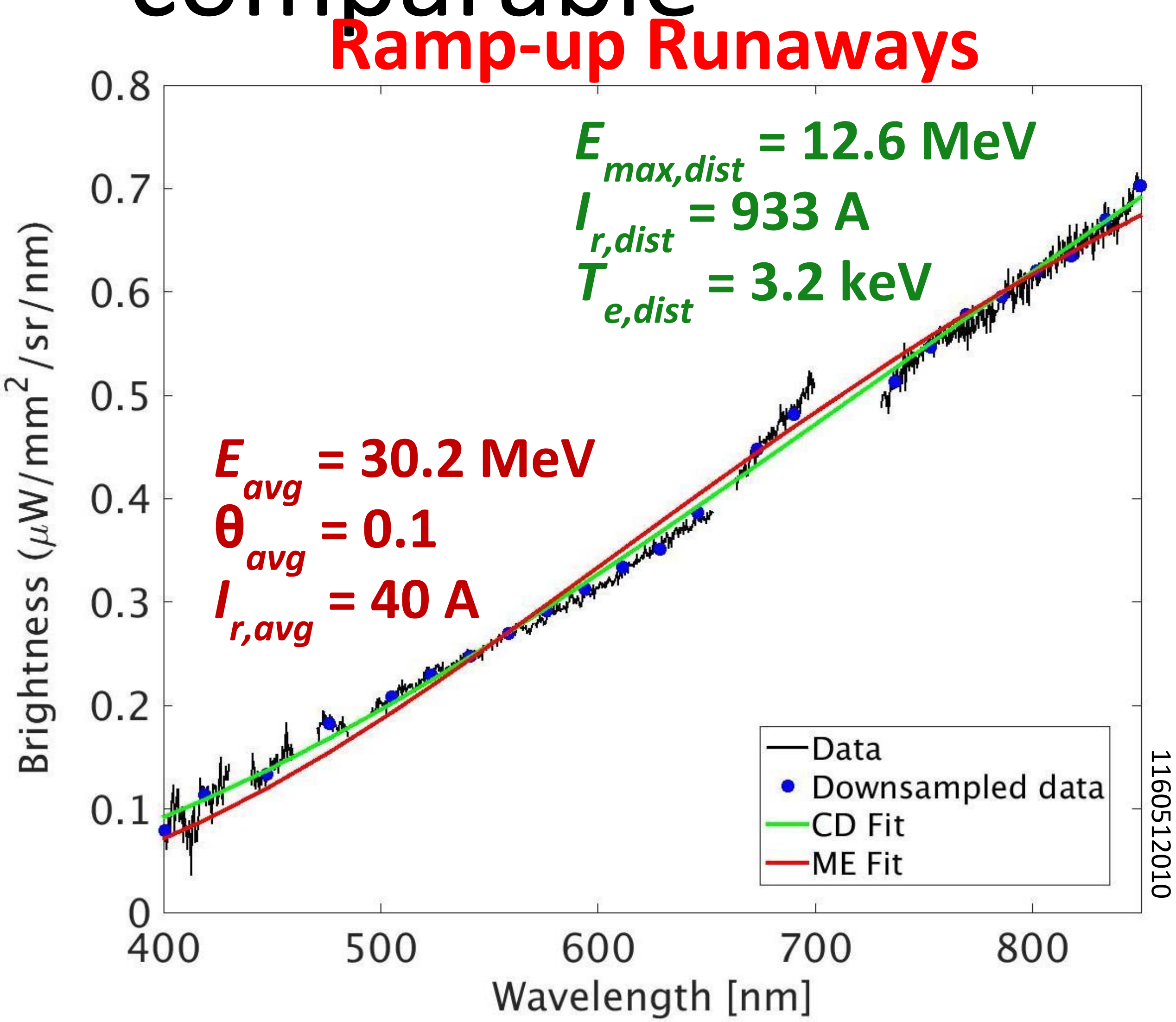


- Plasma parameters at t
- B_t = 5.24 T
- **I_p ≈ 670 kA**
- $\bar{n}_e = 5.9 \cdot 10^{19}$ m^{-3}
- T_{e0} = 2.5 keV
- a_{beam} ≈ 6 cm (as seen by
- V_{loop} ≈ 2.3 V

  → E = 0.54 V/m

  → **E/E_c ≈ 11**

Both ME and CD fits are again comparable



Plasma parameters at t

- B_t = 5.36 T
- **I_p ≈ 800 kA**
- $\bar{n}_e = 6.6 \cdot 10^{19}\ m^{-3}$
- T_{e0} = 2.3 – 3.2 keV
- a_{beam} ≈ 7 cm (as seen by
- V_{loop} ≈ 1.1 V

  → E = 0.26 V/m

  → **E/E_c ≈ 4.8**

Use CODE [5,9] to solve the forward prol

- Time dependent parameters:
  - $T_{e0}(t)$
  - $\bar{n}_e(t)$
  - $V_{loop,0}(t) \rightarrow E(t)$
  - $Z_{eff}(t)$
  - $B \rightarrow$ Synchrotron
- Secondary avalanching source:
  - Rosenbluth-Putvinskii (**RP**) [10]
  - Chiu-Harvey (**CH**) [11,12]

[5] M. Landreman, et al. Computer Physics Communications 185, 847 (2014).
[9] A. Stahl, et al., to appear in Nucl. Fusion. arXiv:1601.00898 [physics.plasm-ph]
[10] M. N. Rosenbluth, S.V. Putvinskii. Nucl. Fusion 37, 10 (1997).
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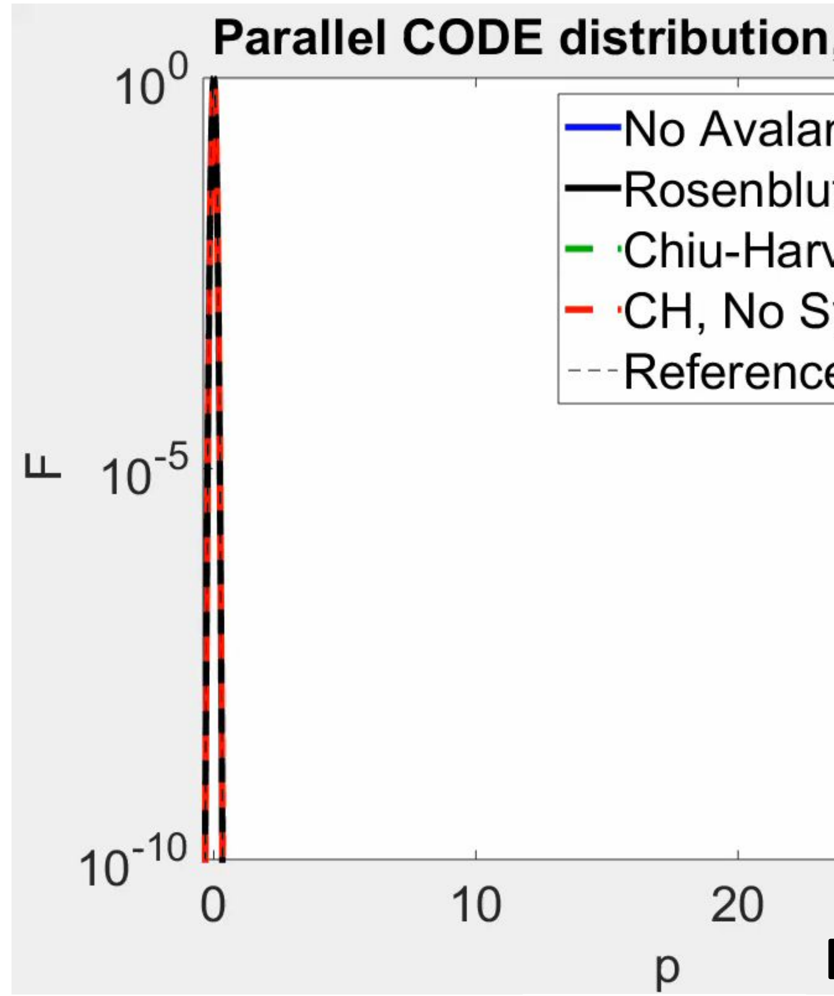
Distribution function



$\sim 2E_{MeV}$

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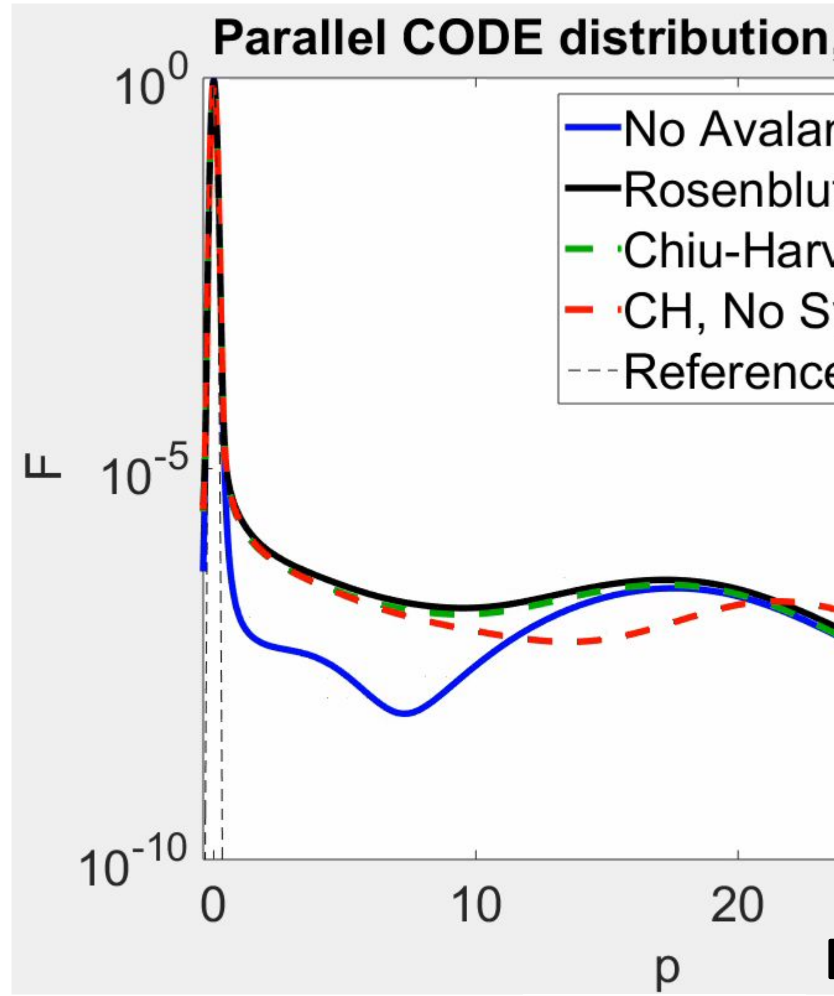

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Bump forms on tail of **Early Runaway** distribution

- Avalanche populates lower energies

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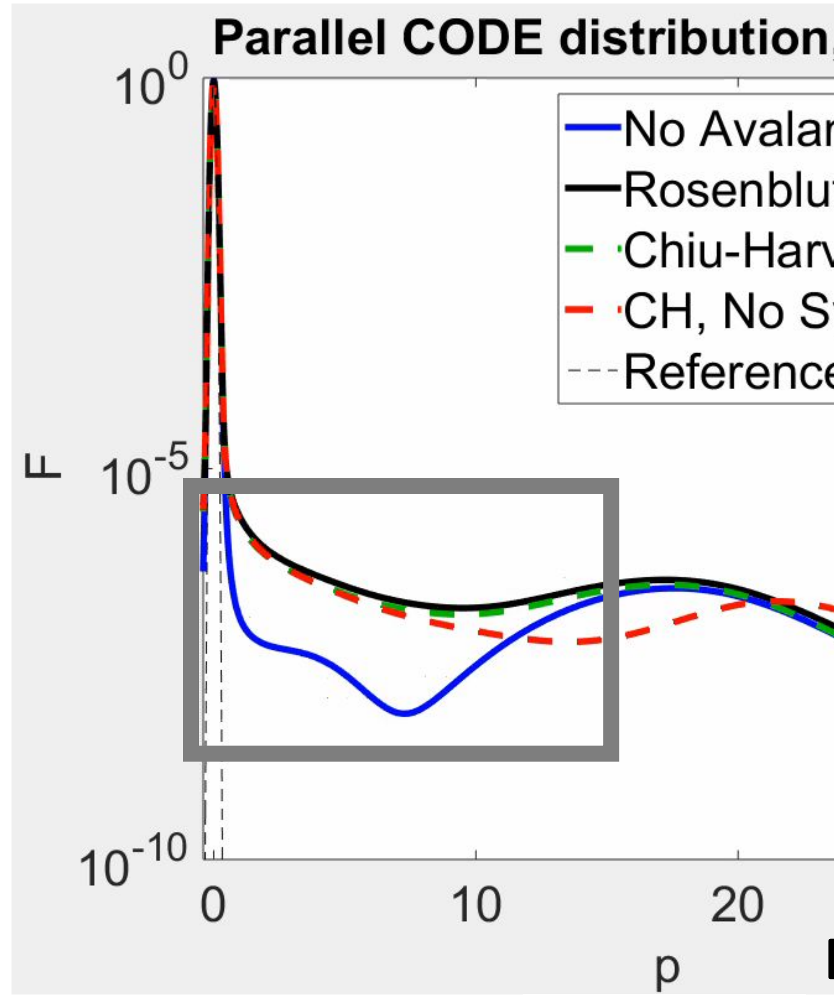

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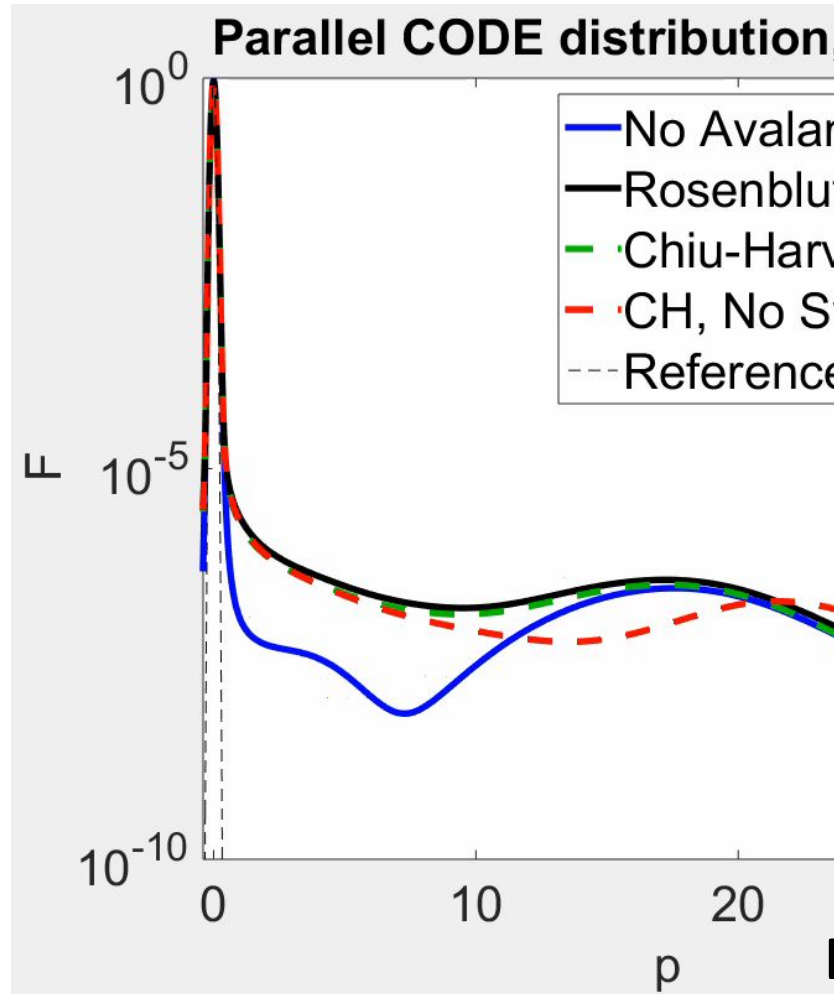

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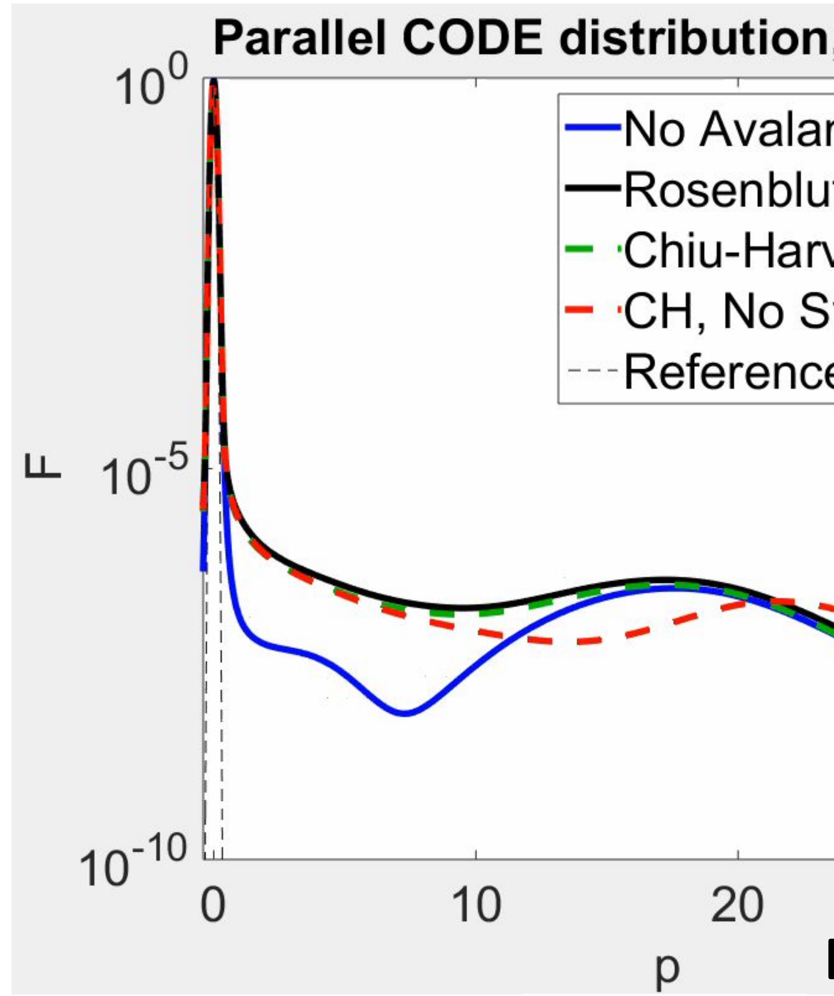

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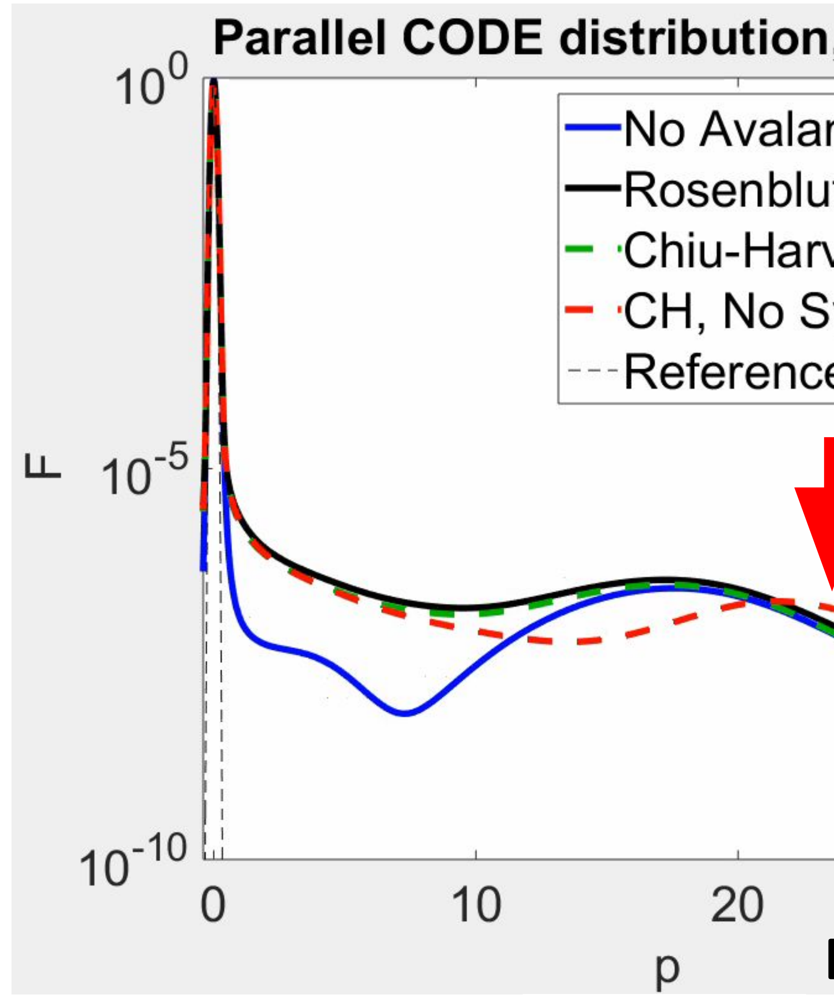

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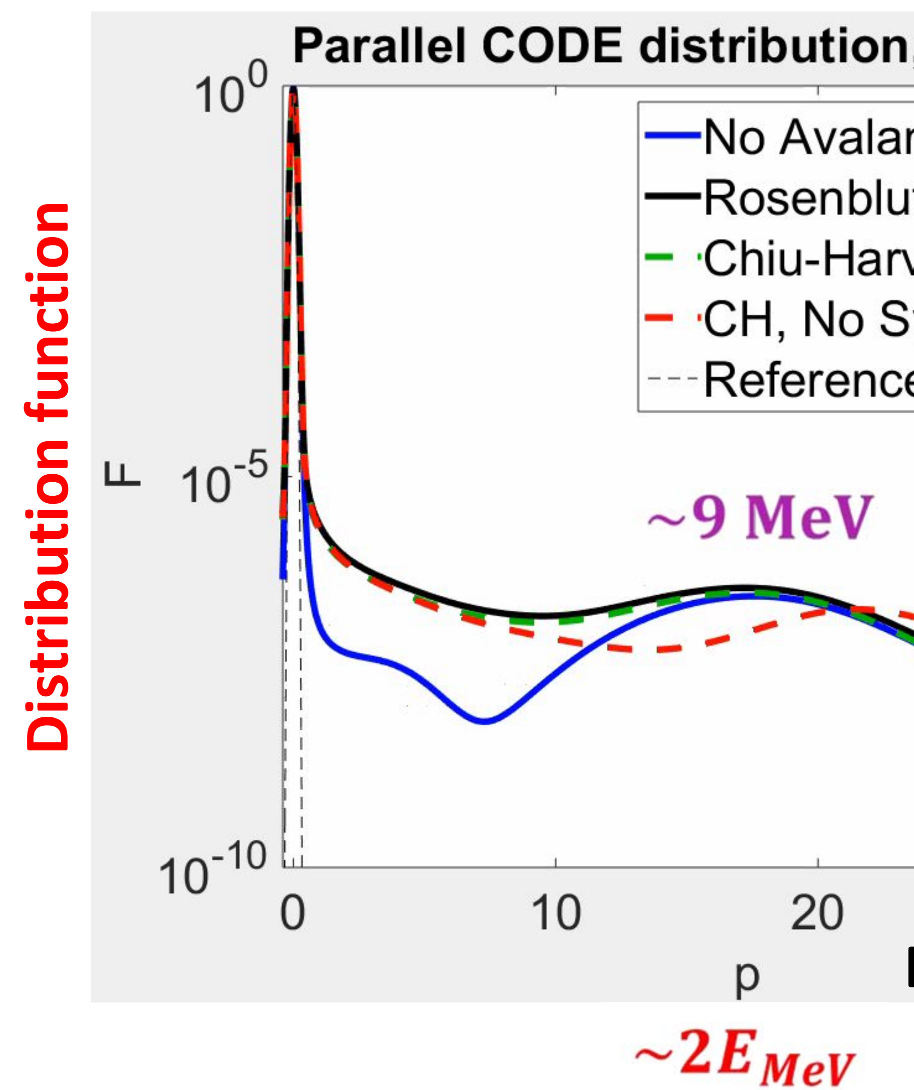
- **Synchrotron limits bump energy**



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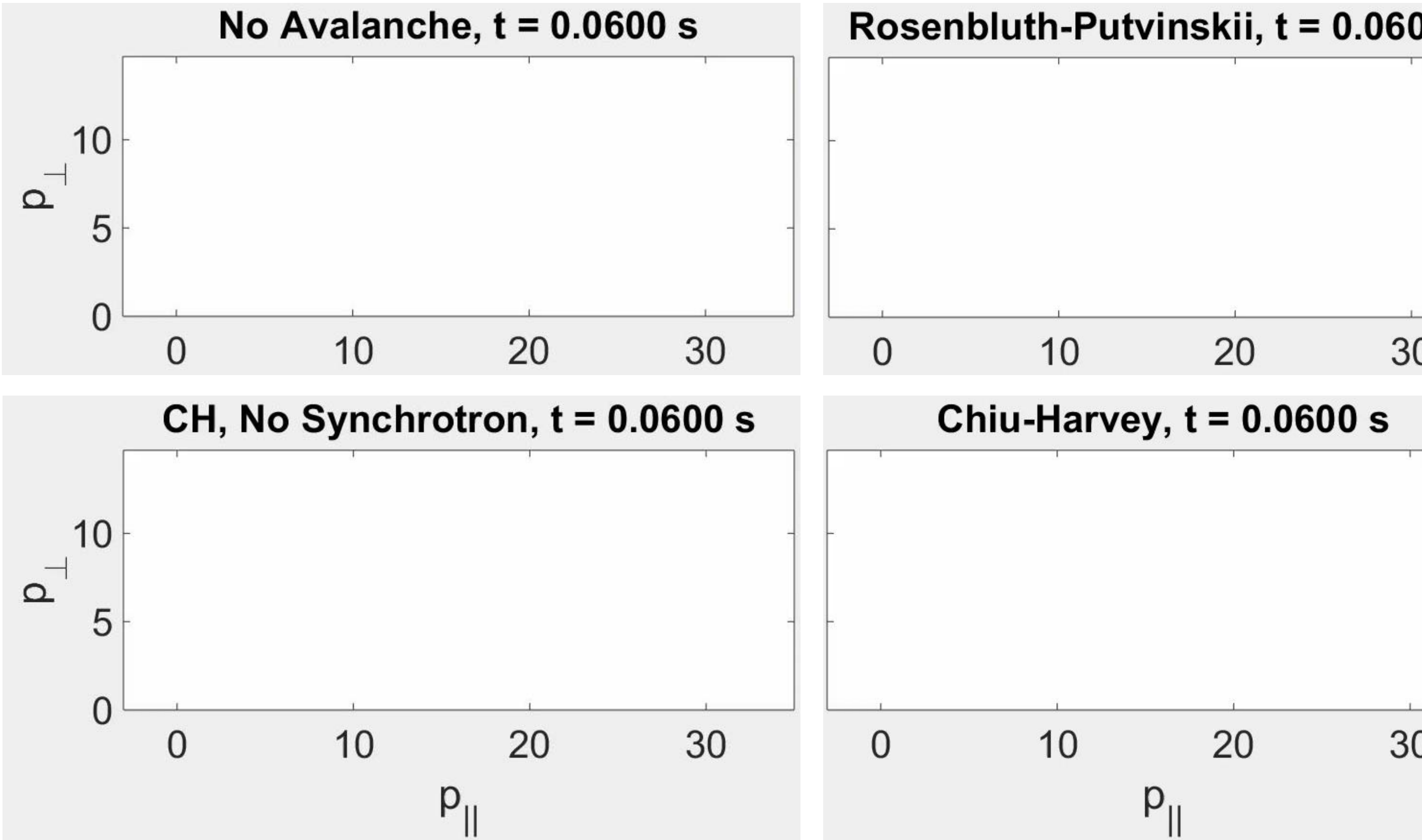
Synchrotron power loss more easily seen 2D



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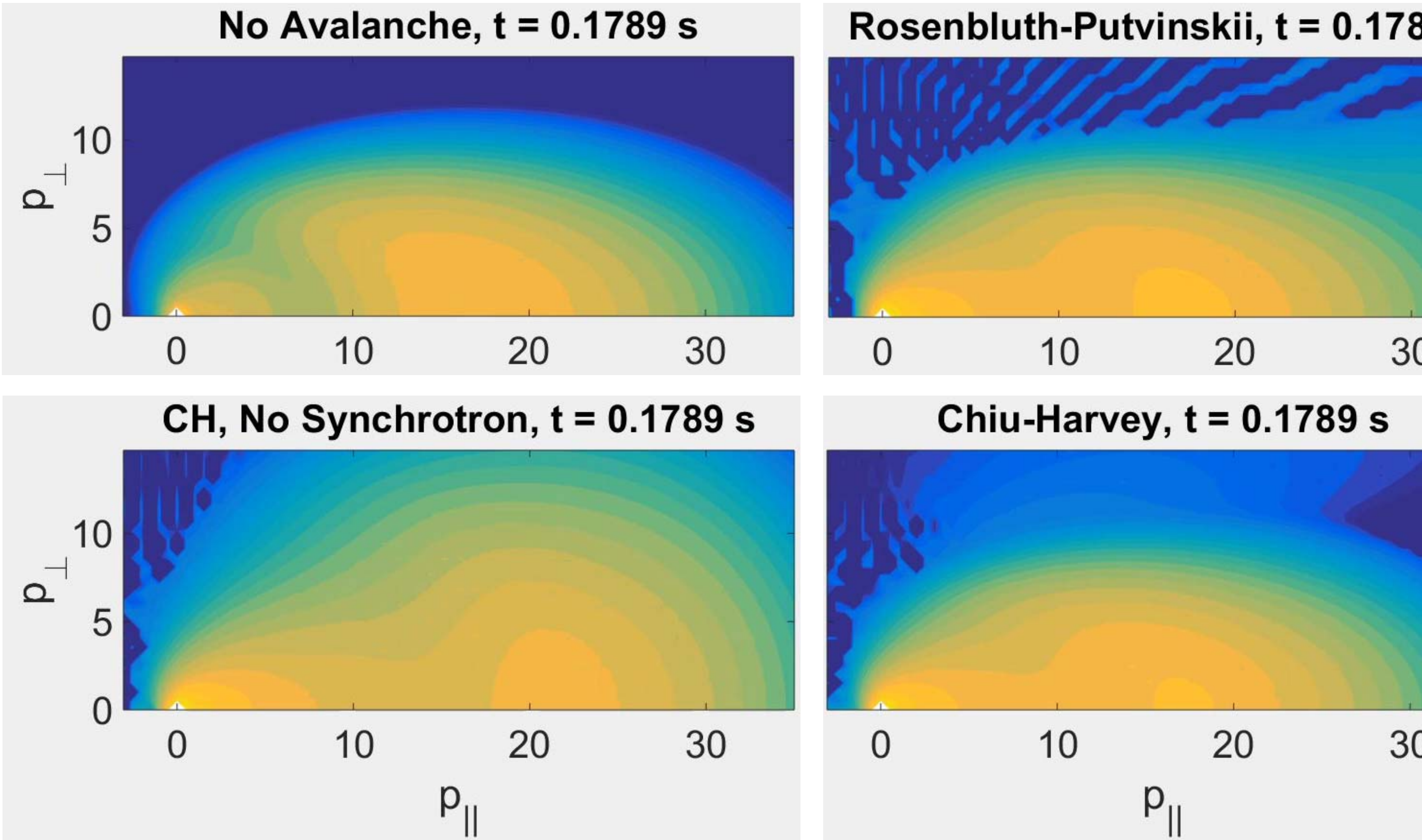
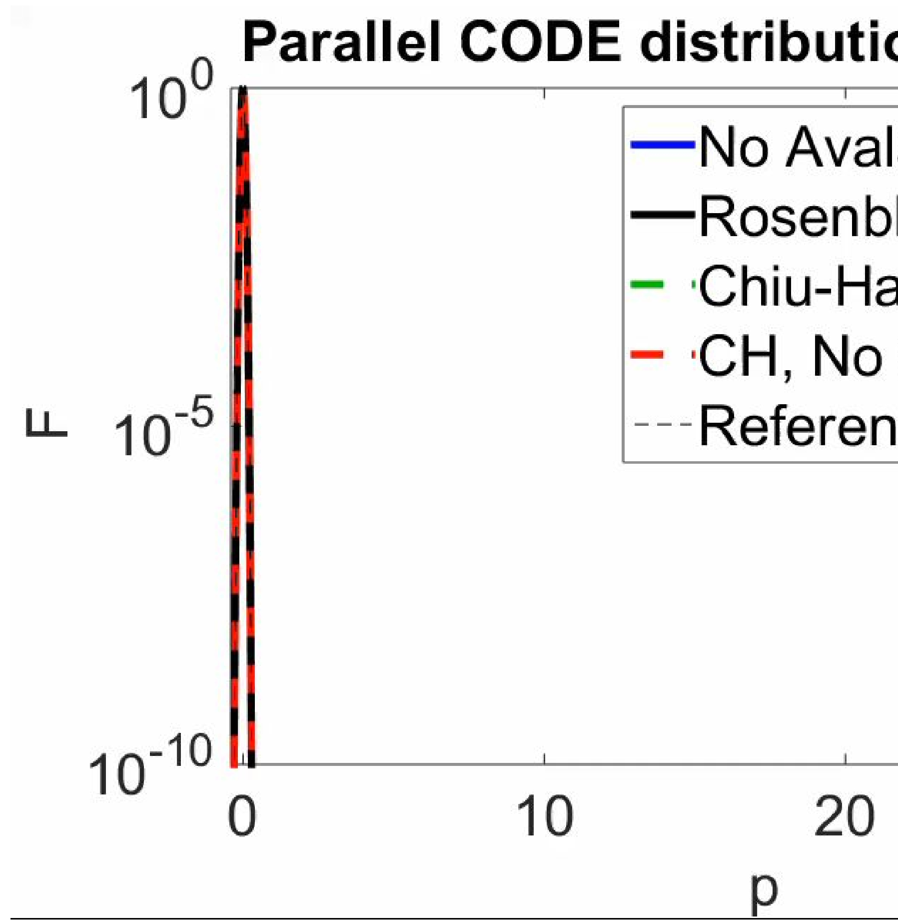


Ramp-up Runaway has (basically) no bump

- **RP** and CH Avalanche match better than **No Avalanche**
- Knock-on collisions play a larger role than primary generation

- **No Synchrotron** case forms bump which moves to p > 35
- Synchrotron still limits energy, but no clear bump is formed



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Ran

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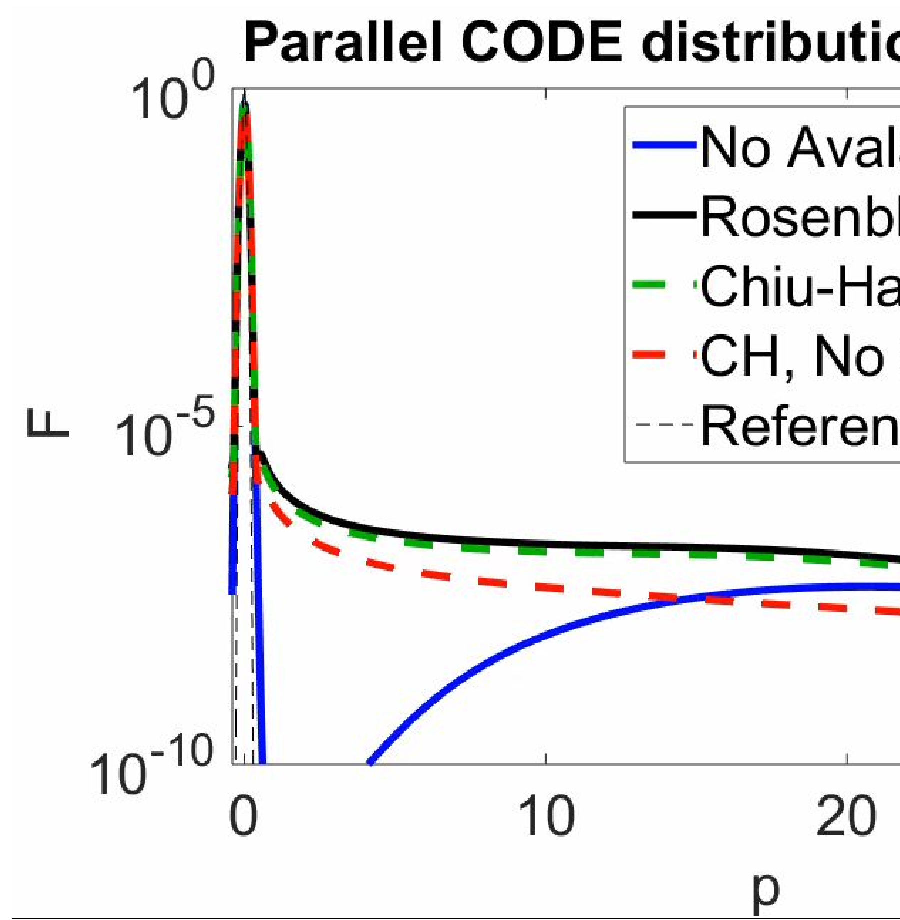
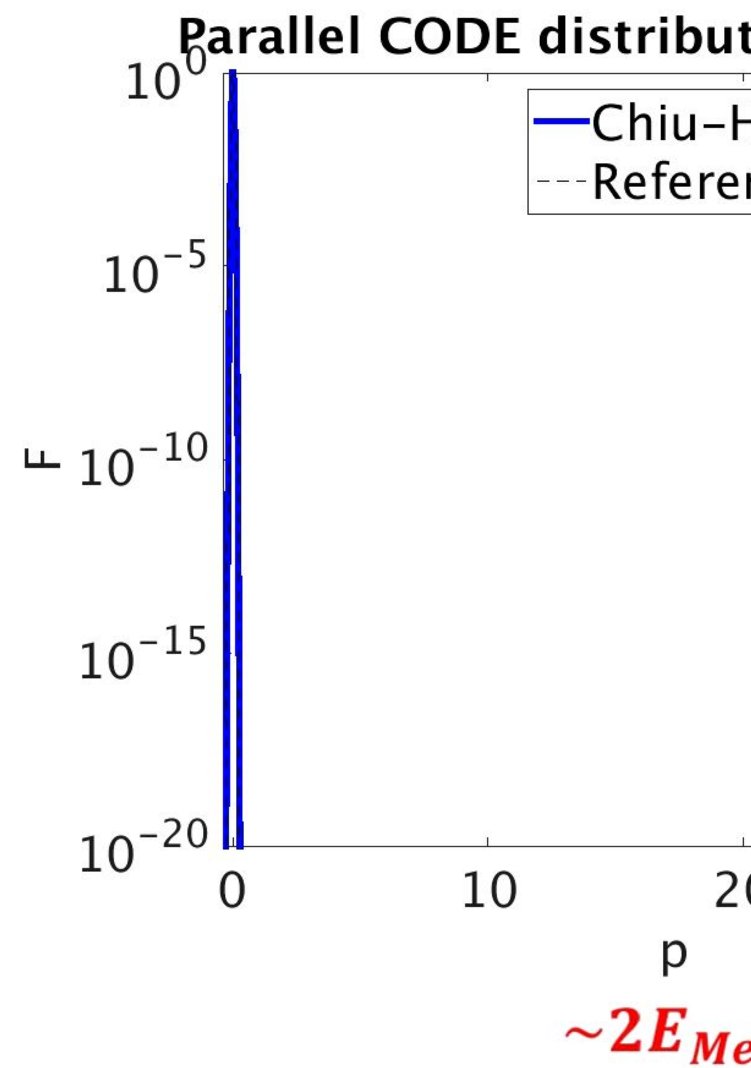


$\sim 2E_{MeV}$

Ran

Flattop Runaway breaks CODE! Needs NORS [14]

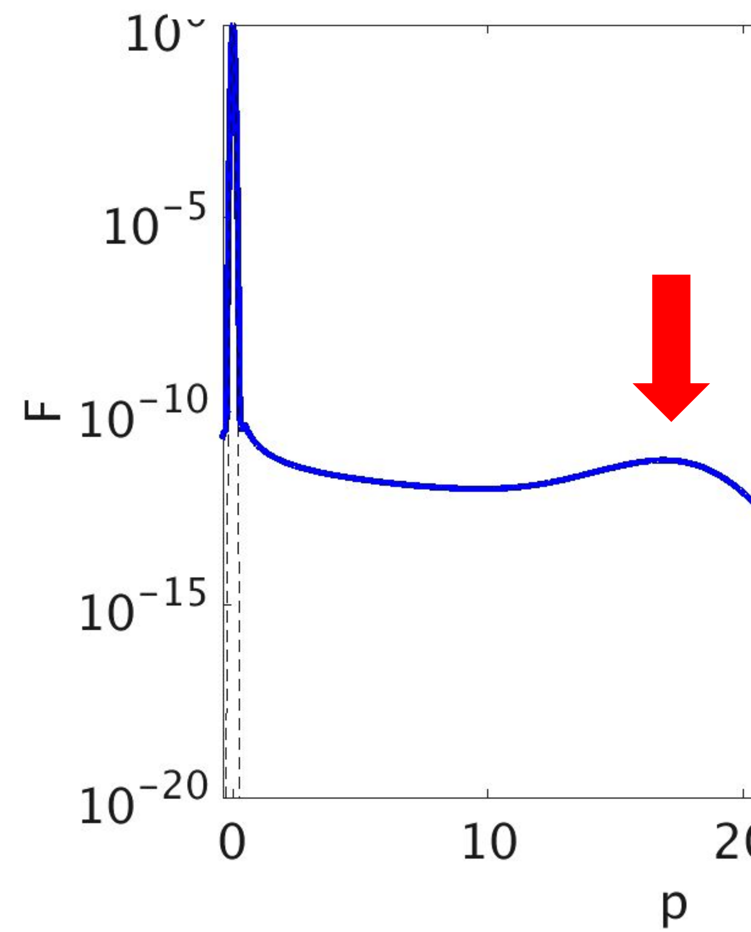
- Bump forms early on…
- But CODE breaks down when a significant fraction (> ~ 15-20%) of the bulk population runs away.
- This avalanche seems to be triggered by a jump in loop voltage, possibly caused by an injection.
- Need the non-linear solver NORSE [14] (in development).



[14] A. Stahl, et al. Presentation at the 4th Runaway Electron Meeting in Pertuis, France, June 2016. Submitted to CPC.

Is the bump on tail actually stable

- “Two stream” instability?
- Inverse Landau damping?
- Anomalous Doppler effect?
- MHD instabilities?
- Others?



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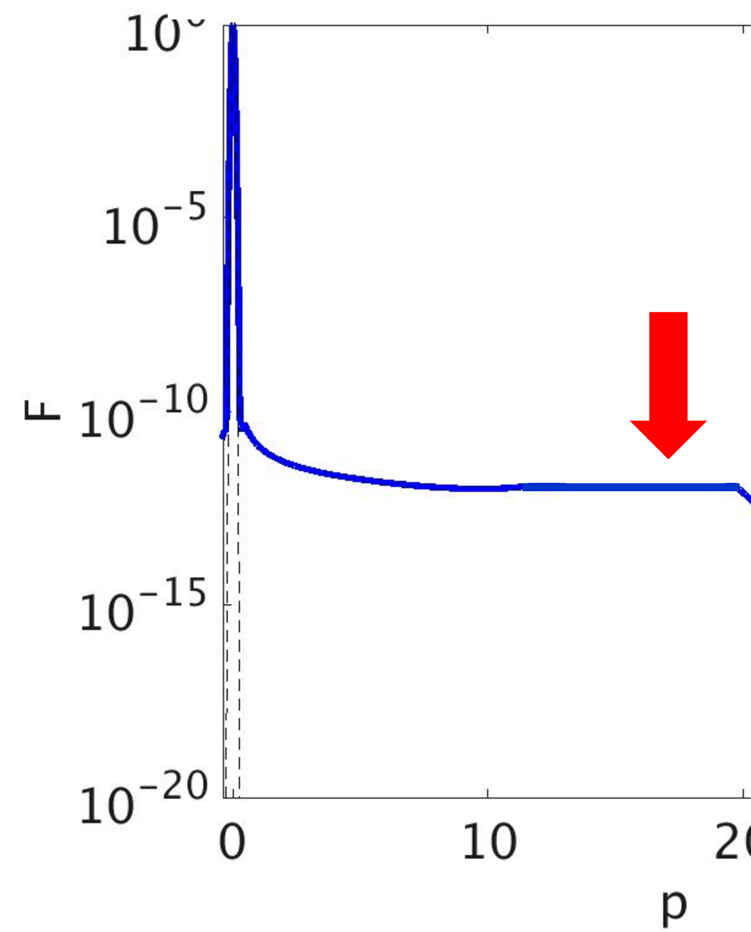
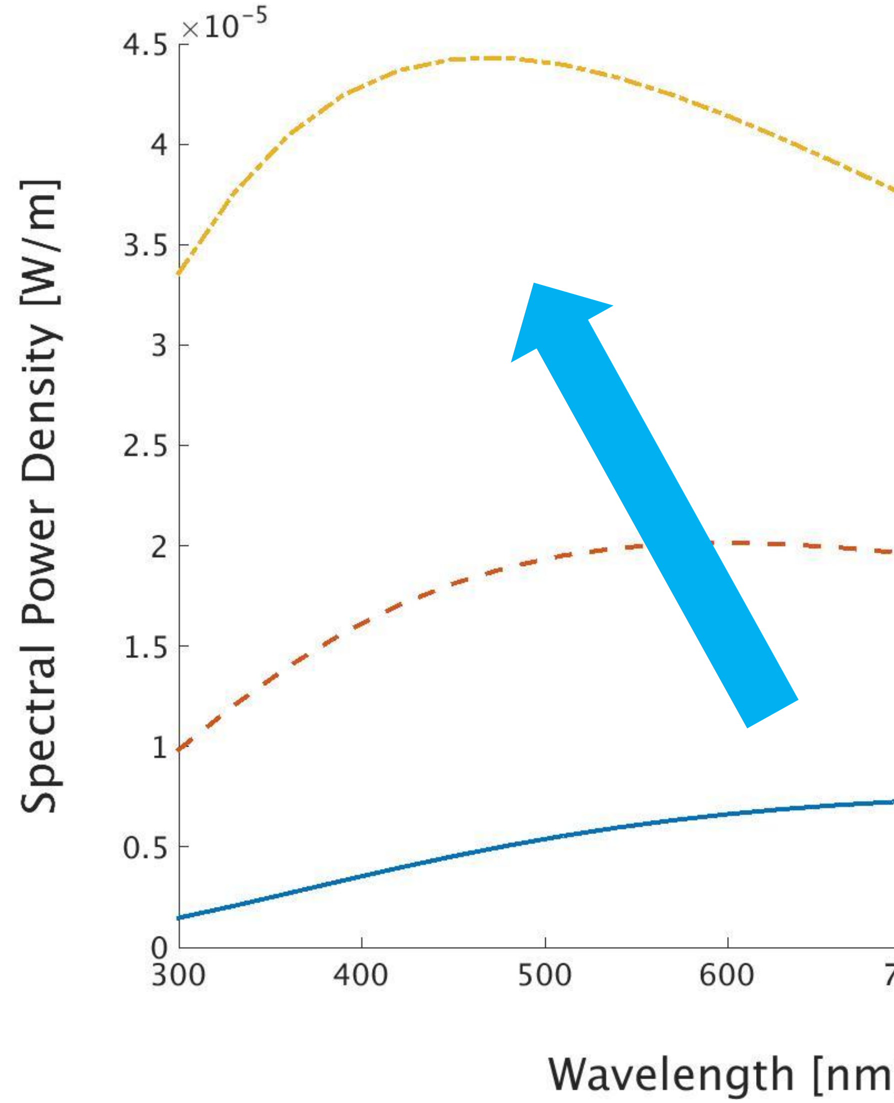
- MHD instabilities?
- Others?

- Maybe a runaway "cliff"?



Upcoming runaway experiment in C-Mod

- Next Wednesday, July 27
- Scan the B-field from 2–8 T
- Synchrotron power ~ B^2
- Shift peak measurement toward shorter wavelengths
- Goal: Determine if synchrotron is the primary power loss mechanism for REs, limiting their maximum energy



Summary and future work

Mono-energetic and **continuum distribution** calculations both fit C-Mod experimental data equally well.

C-Mod has a variety of runaway discharges. Time-dependent CODE calculations show a

- bump formed from primary generation,
- broad distribution from secondary avalanching, and
- code-breaking bulk runaway

Next steps:

- Calculate the **synchrotron bri** from CODE's distribution func **compare to experiment**
- Run simulations with LUKE
- Use NORSE (when available)

References

[1] P. Aleynikov, et al. Phys. Rev. Lett. 114, 155001 (2015).

[2] J. Decker, et al. Plasma Phys. Contr. Fusion 58, 025016 (2016).

[3] E. Hirvijoki, et al. J. Plasma Phys., vol. 81, 47810502 (2015).

[4] A. Stahl, et al. Phys. Plasmas 20, 093302 (2013).

[5] M. Landreman, et al. Computer Physics Communications 185, 847 (2014).

[6] J. H. Yu, et al. Phys. Plasmas 20, 042113 (2013).

[7] T. Fülöp, et al. Phys. Plasmas 13, 062506 (2006).

[8] R. S. Granetz, et al. Phys. Plasmas 21, 072506 (2014).

[9] A. Stahl, et al. “Kinetic modelling of runaway electrons in dynamic scenarios,” to appe Fusion. arXiv:1601.00898 [physics.plasm-ph]

[10] M. N. Rosenbluth, S.V. Putvinskii. Nucl. Fusion 37, 10 (1997).

[11] S. C. Chiu, et al. Nucl. Fusion 38, 1711 (1998).

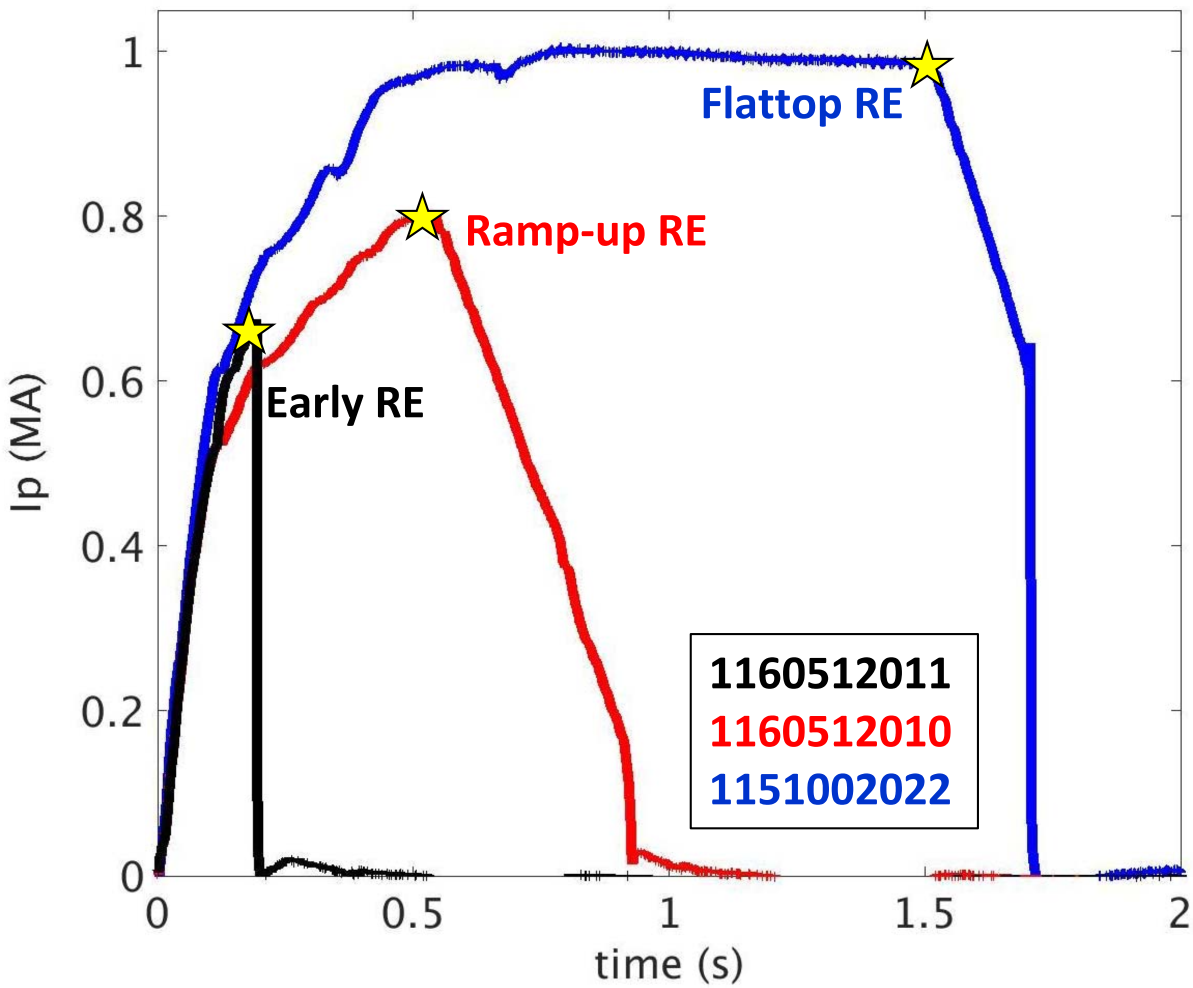
[12] R. W. Harvey, et al. Phys. Plasmas 7, 4590 (2000).

[13] H. Dreicer. Phys. Rev. 115, 2 (1959).

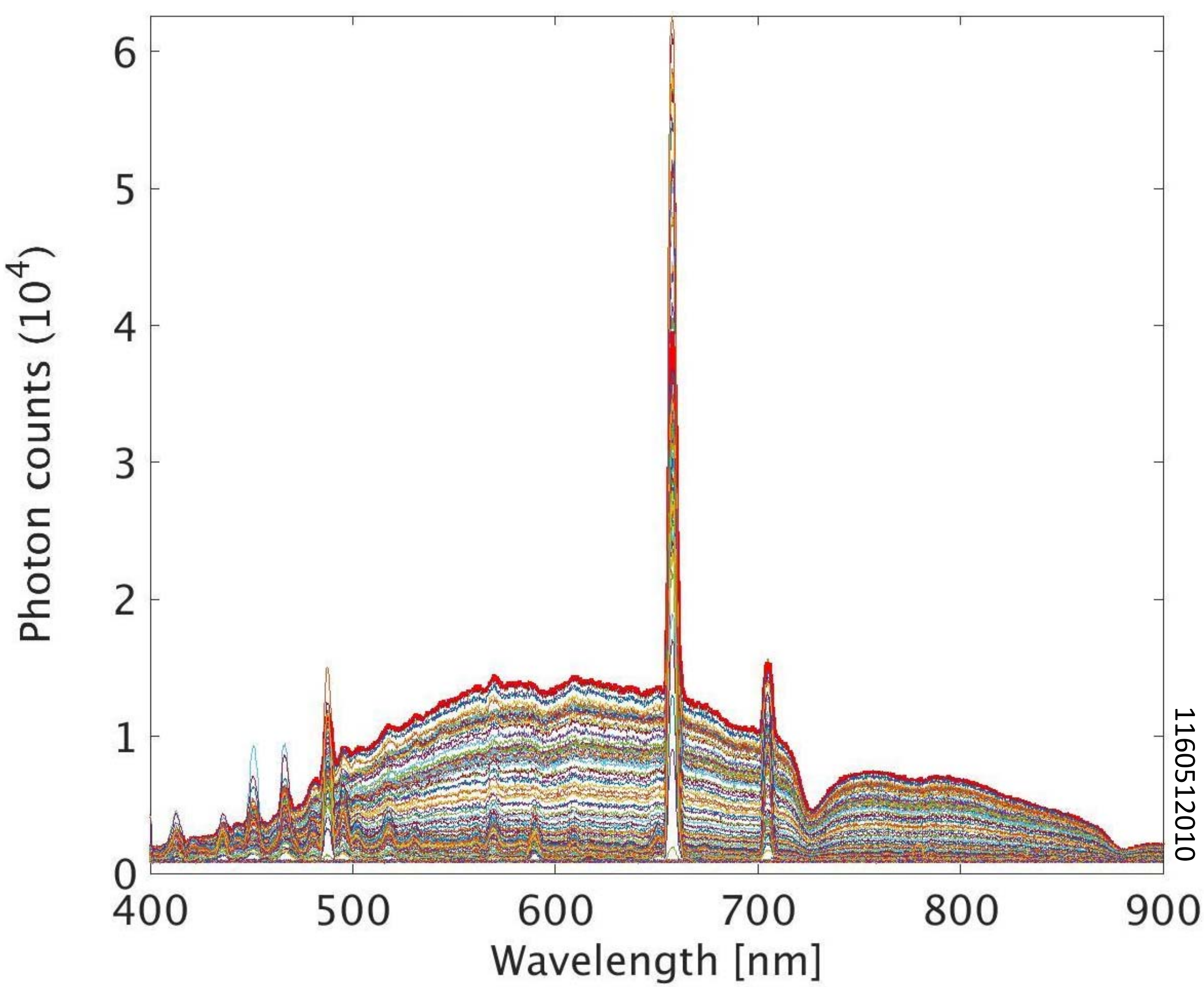
[14] A. Stahl, et al. Presentation at the 4th Runaway Electron Meeting in Pertuis, France, J Submitted to CPC.

Backup slides

Look at 3 different runaway shots



Ramp-up synchrotron emission c



Plasma parameters at **t =**

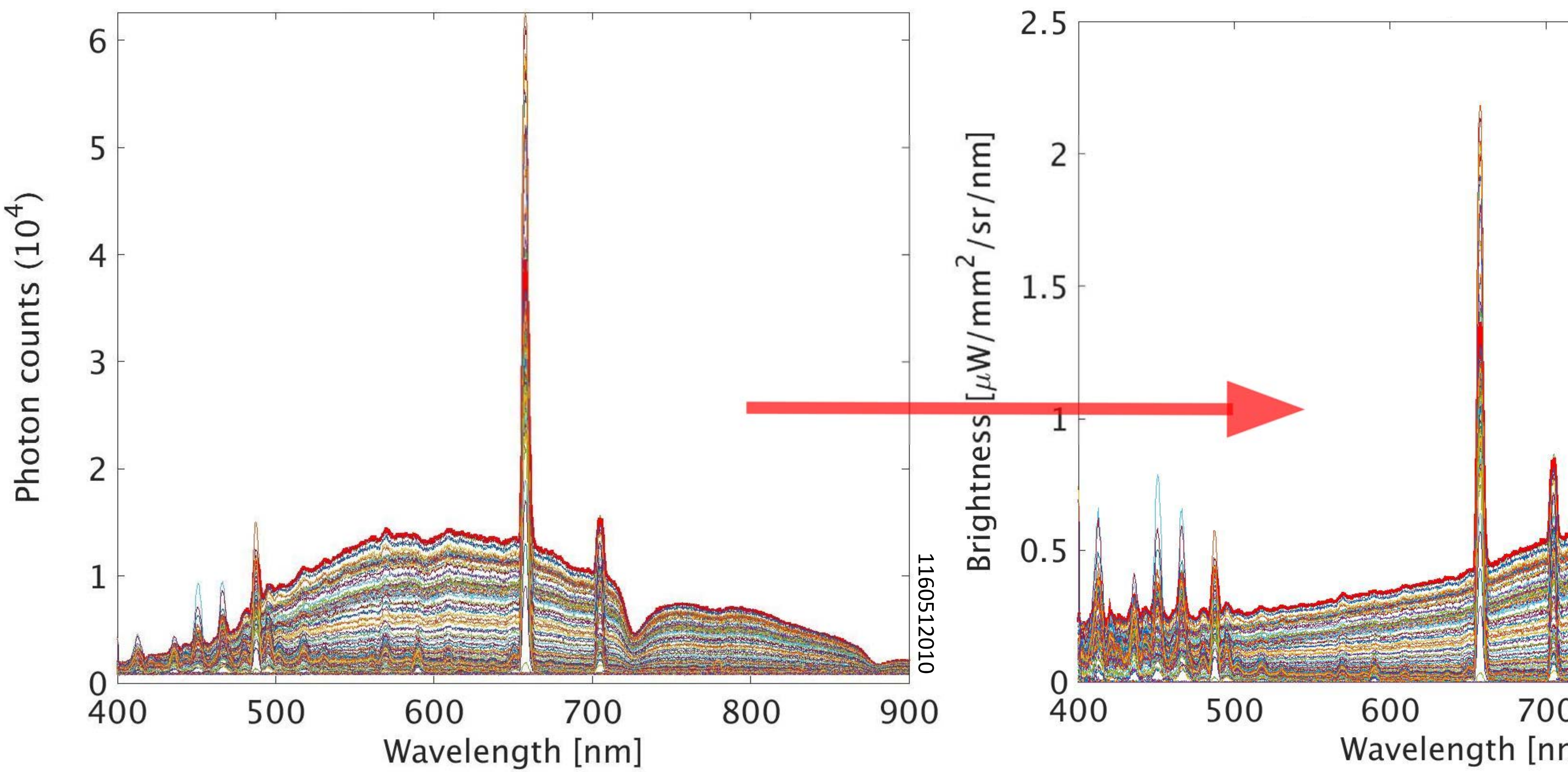
- B_t = 5.36 T
- $I_p \approx$ 800 kA
- $\bar{n}_e = 6.6 \cdot 10^{19}$ m^{-3}
- T_{e0} = 2.3 – 3.2 keV
- $a_{beam} \approx$ 7 cm (as seen by
- $V_{loop} \approx$ 1.1 V

→ E = 0.26 V/m

→ **$E/E_c \approx$ 4.8**

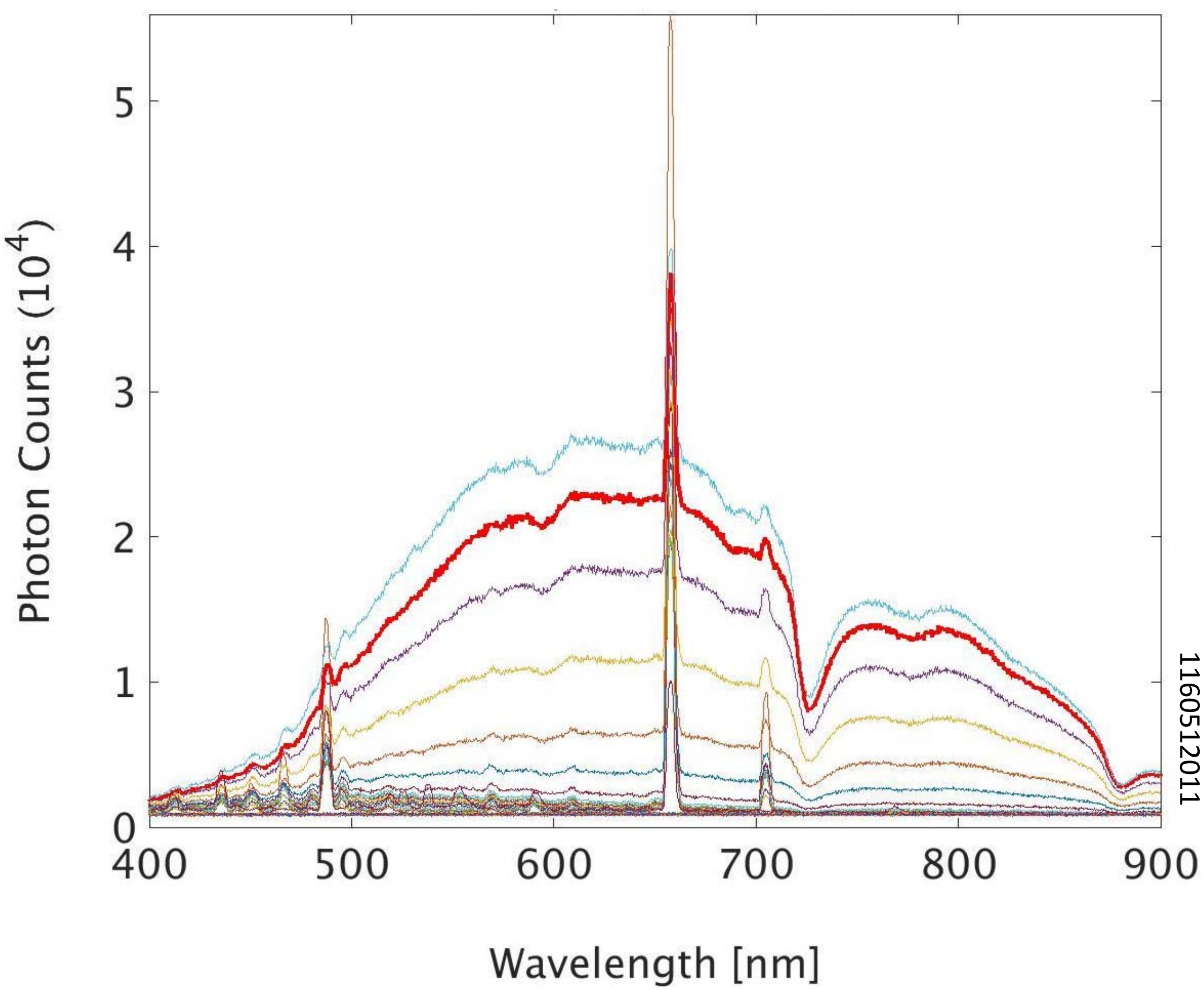
The red highlighted data is at t = 0.54 s and is used in this analysis.

Ramp-up synchrotron emission c



The red highlighted data is at t = 0.54 s and is used in this analysis.

Early synchrotron emission data



Plasma parameters at **t =**

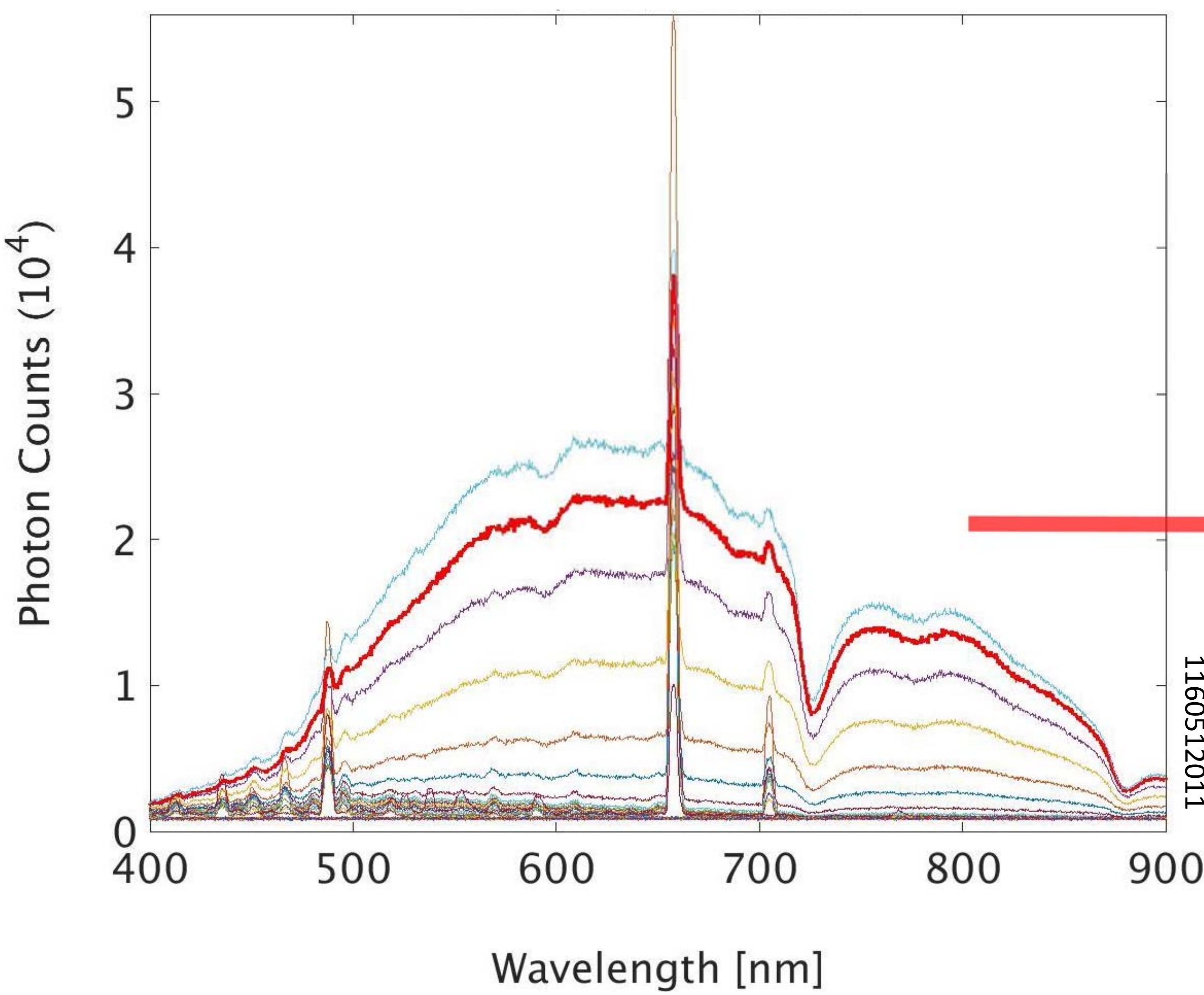
- B_t = 5.24 T
- $I_p \approx$ 670 kA
- $\bar{n}_e = 5.9 \cdot 10^{19}\ m^{-3}$
- T_{e0} = 2.5 keV
- $a_{beam} \approx$ 6 cm (as seen by
- $V_{loop} \approx$ 2.3 V

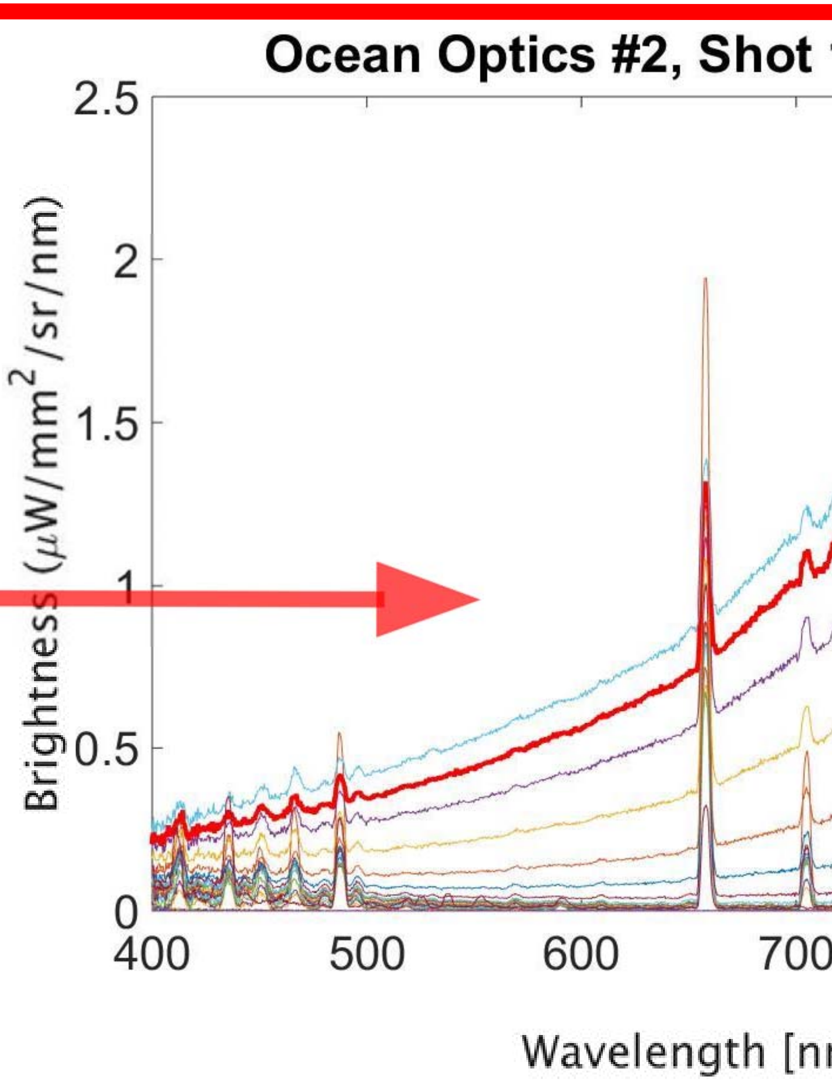
→ E = 0.54 V/m

→ **$E/E_c \approx 11$**

The red highlighted data is at t = 0.18 s and is used in this analysis.

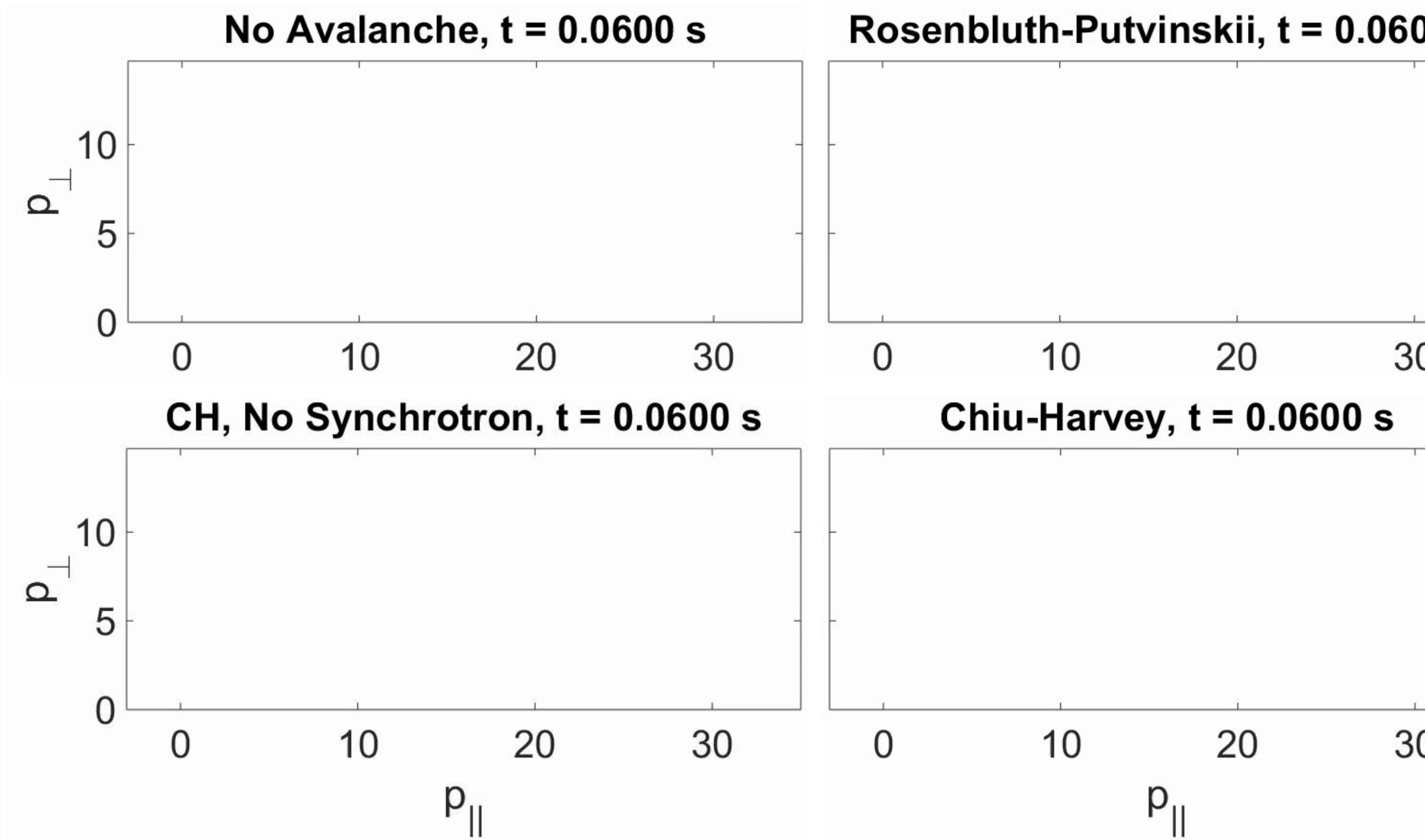
Early synchrotron emission data





The red highlighted data is at t = 0.18 s and is used in this analysis.

Ramp-up Runaway evolution in 2D



Ramp-up Runaway evolution in 2D