Spatiotemporal analysis of the runaway current from synchrotron images in a tokamak disruption

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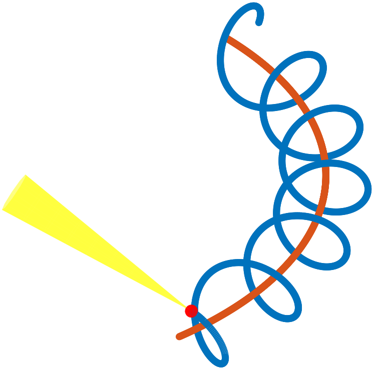
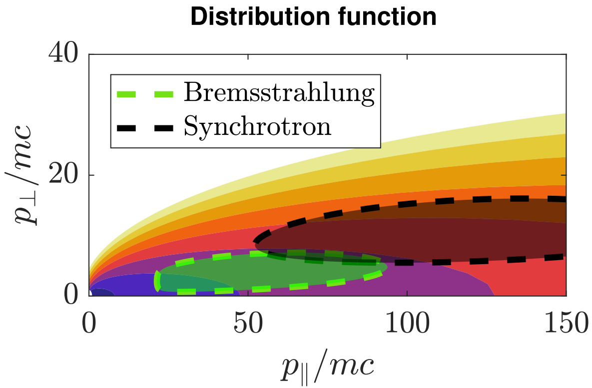
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

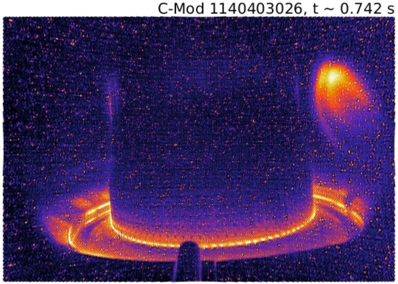
1. Synchrotron radiation basics
2. Runaway experiment at ASDEX Upgrade
3. Experiment analysis
    - Dominant particles
    - Determining radial distribution

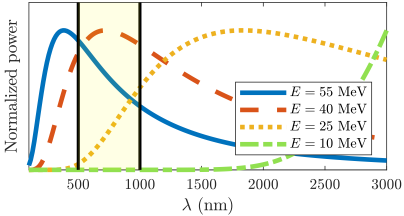




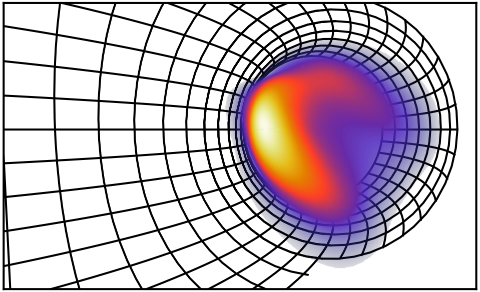
- Relativistic beaming along velocity
- Useful for measuring (parts of) distribution function

- **Camera images**[1]
  - Visible/IR
  - Available in most tokamaks
- **Spectra**[2]
  - Continuum
  - Usually peaks in IR
- **Polarization data (MSE)**[3]
  - Motional Stark Effect (MSE) usually used for *q*-profile
  - Measures polarization of synchrotron radiation
  - (Neutral beam is turned off)





[1] R. A. Tinguely, M. Hoppe et al. PPCF **60** *124001* (2018)
[2] R. A. Tinguely, M. Hoppe et al. NF **58** *076019* (2018)
[3] R. A. Tinguely, M. Hoppe et al. NF **59** *096029* (2019)

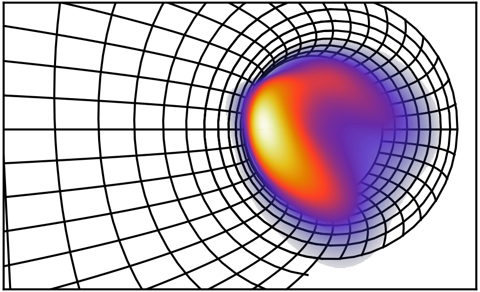


- **Synthetic** synchrotron and bremsstrahlung **diagnostic** from Chalmers
- Given $\mathbf{f}(\mathbf{r}, \mathbf{p}, \theta)$, reproduces radiation pattern in given **magnetic field**
- Applied to Alcator C-Mod, DIII-D, JET, and now ASDEX Upgrade

SOFT integral:

$$I = \int \frac{\boldsymbol{n} \cdot \hat{\boldsymbol{n}}}{r^2} \Theta\left(\frac{\boldsymbol{r}}{r} \in \Omega_{\mathrm{FOV}}\right) \left\langle \frac{\mathrm{d}^2 I}{\mathrm{d}\lambda \mathrm{d}\Omega} \right\rangle f(r, p_{\|}, p_{\perp})\, J\, \mathrm{d}r \mathrm{d}\tau \mathrm{d}\phi \mathrm{d}p_{\|} \mathrm{d}p_{\perp} \mathrm{d}\lambda \mathrm{d}A$$

† M. Hoppe et al. NF **58** *026032* (2018)
`https://github.com/hoppe93/SOFT2`



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SOFT integral:

$$I = \int G(r, p_{\|}, p_{\perp}) f(r, p_{\|}, p_{\perp})\, \mathrm{d}r \mathrm{d}p_{\|} \mathrm{d}p_{\perp}$$

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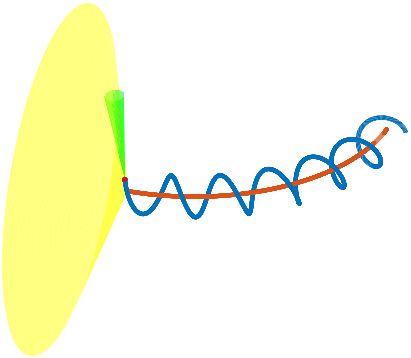
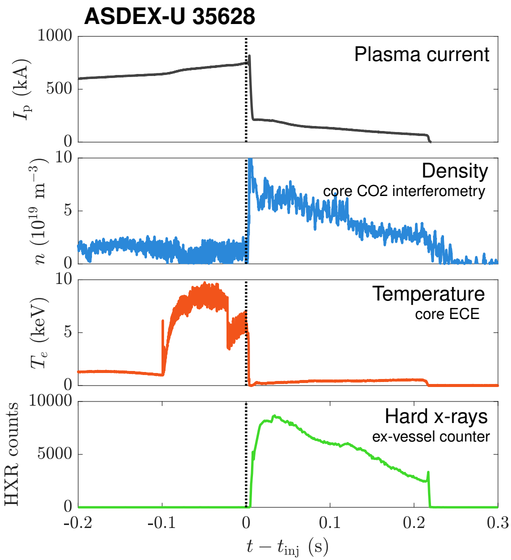
Different models for radiation

- Synchrotron, hard X-rays
- Cone model
  - Forward emission approximation: $\mathrm{d}P/\mathrm{d}\Omega \sim \delta(\cos\alpha - \cos\theta_{\mathrm{p}})$
  - Very fast!
- Angular and spectral distribution of radiation
  - More accurate

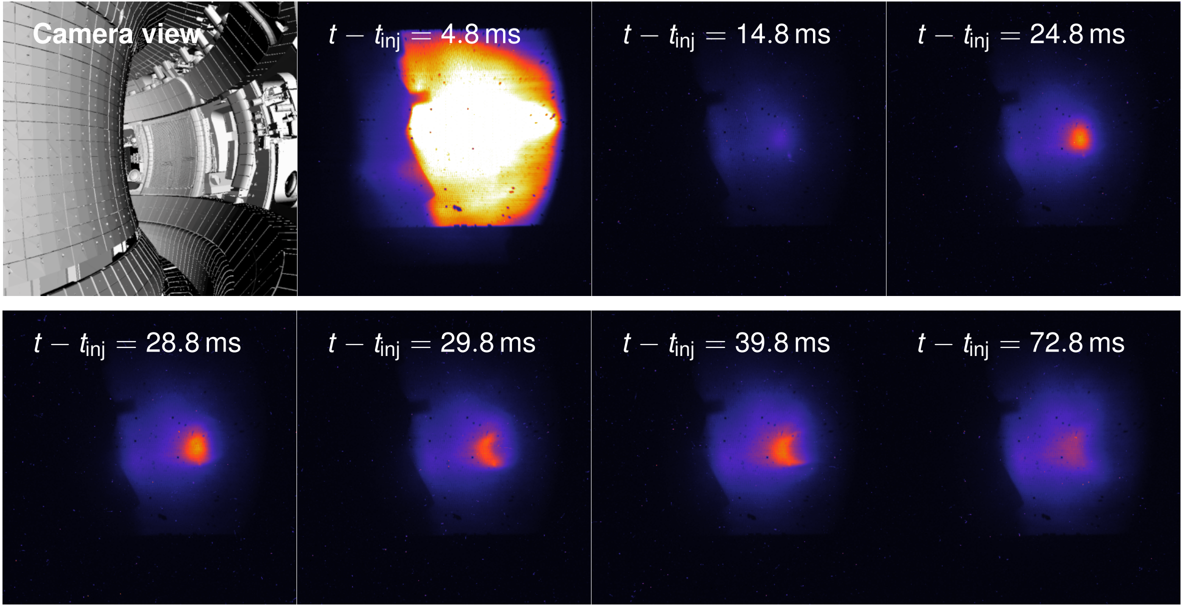


2. Experiment

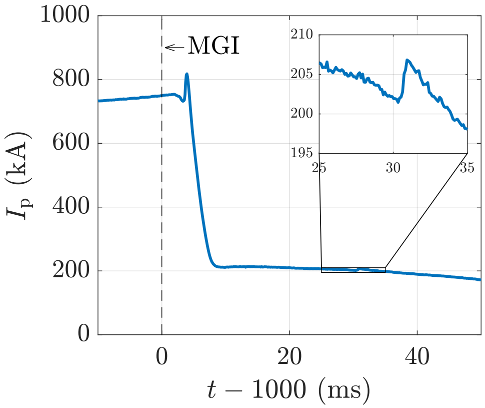


- Deliberately triggered disruption
  - Massive Gas Injection (Ar), $N_{Ar} \approx 10^{21}$ particles
  - Current: ~ 800 kA to ~ 200 kA
  - Temperature: ~ 5 keV to ~ 1 eV
  - ICRH applied
- One in a series of similar shots
- Fast (1 kHz) visible-light camera
  - Equipped with 709 ± 9 nm filter (to remove line radiation)
  - Excellent video data!

ASDEX Upgrade — discharge 35628



- Small (but clear) current spike 30 ms after the injection
- Correlated with $(m, n) = (1, 1)$ MHD structure
- Synchrotron spot shape changes
- Possible reconnection[1]



[1] G. Pautasso et al, in preparation

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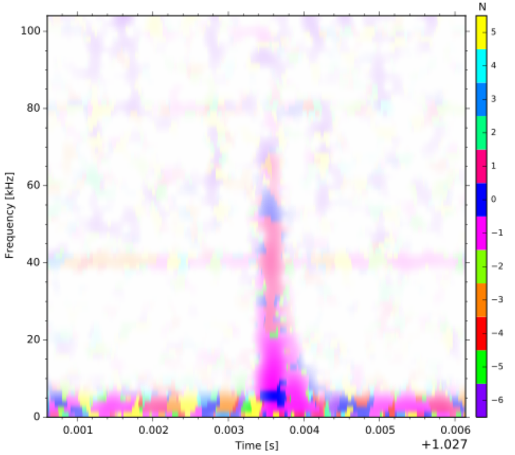

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3. Synchrotron fitting procedure

Goal Determine beam **size** and radial **density profile**

Ansatz:

$$f(r,p,\theta) = f_r(r) f_p(p) f_\theta(\theta)$$

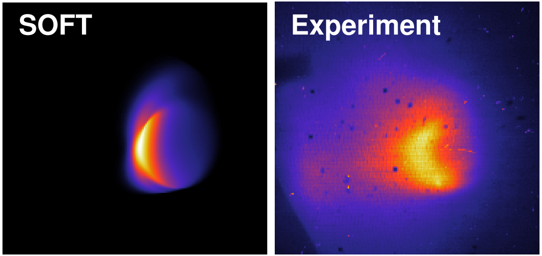
with

$$f_p(p) = \delta\left(p - p^\star\right)$$
$$f_\theta(\theta) = \exp\left(C\ \cos\theta\right)$$

1. Guess runaway beam radius $r_{\text{beam}}^{(0)}$, start with $f_r(r) \equiv$ const within $r \leq r_{\text{beam}}$
2. Determine **dominant particle** by varying $p^\star$ and C
3. Determine radial density, $f_r(r)$

Good fit:

$$p^{\star}/mc = 37$$
$$C = 200$$



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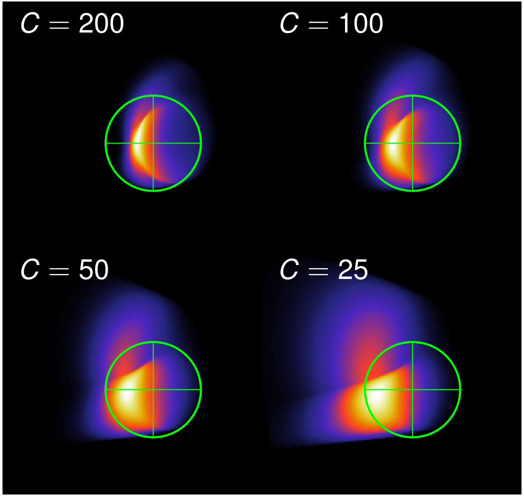
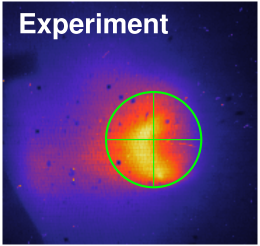
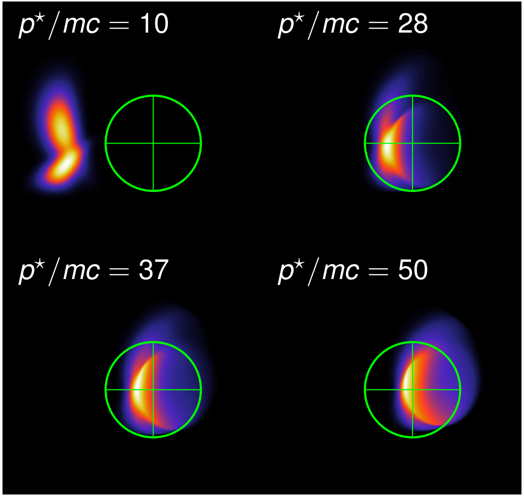
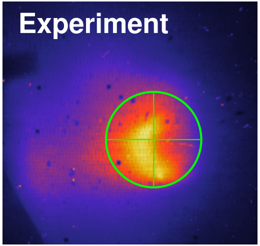


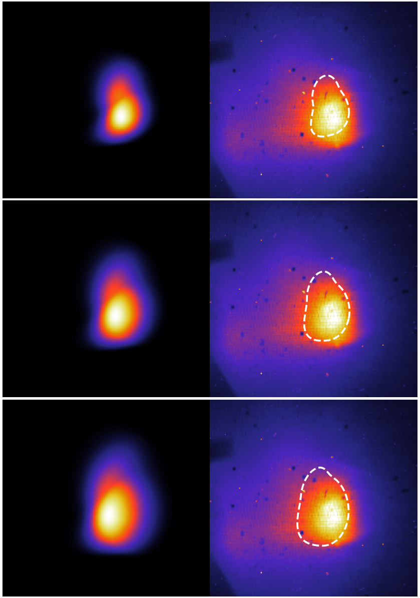


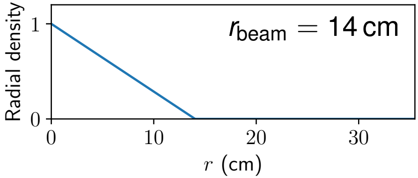
$C = 200$

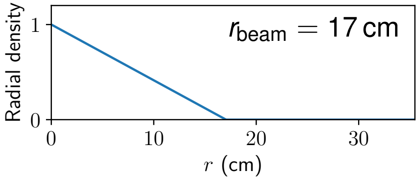


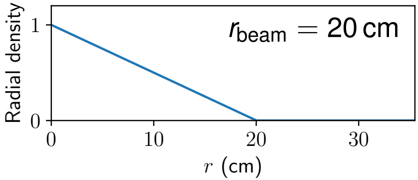


Before current spike, $t - t_{inj} = 28.8\,\text{ms}$



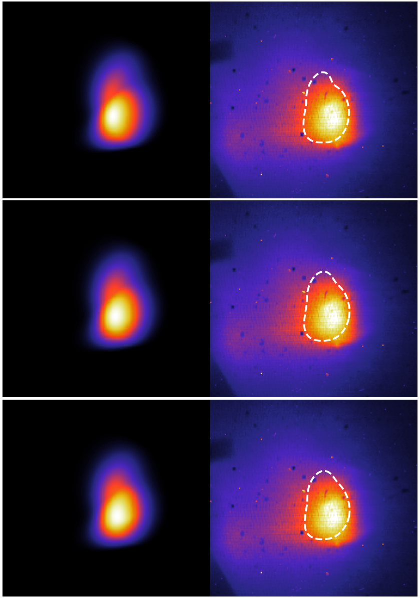


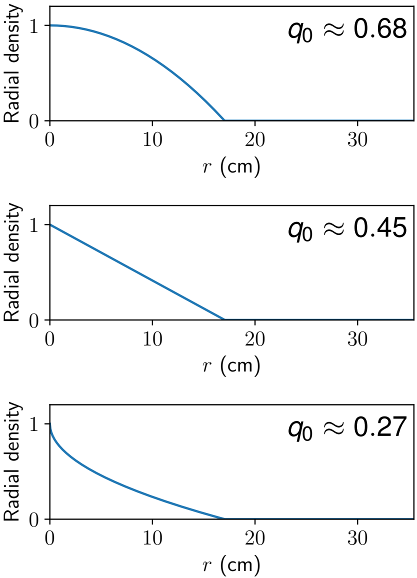




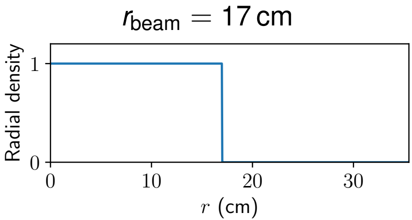
Fitting procedure — radius

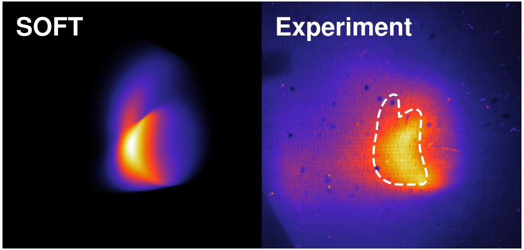
Before current spike, $t - t_{\mathrm{inj}} = 28.8\,\mathrm{ms}$, $r_{\mathrm{beam}} = 17\,\mathrm{cm}$



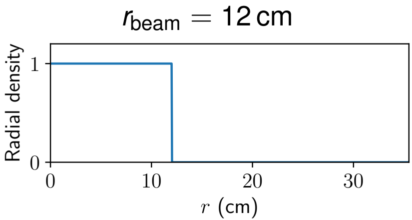


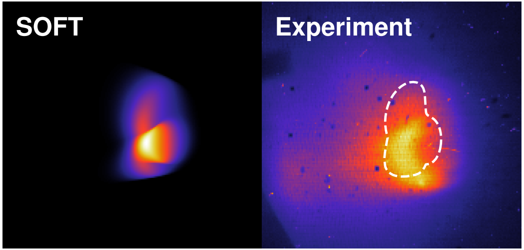
After current spike, $t - t_{\text{inj}} = 29.8\,\text{ms}$





After current spike, $t - t_{inj} = 29.8\,\text{ms}$





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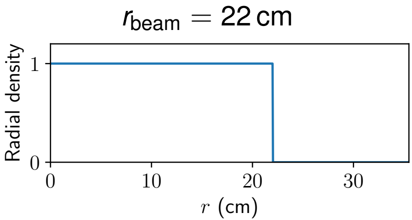
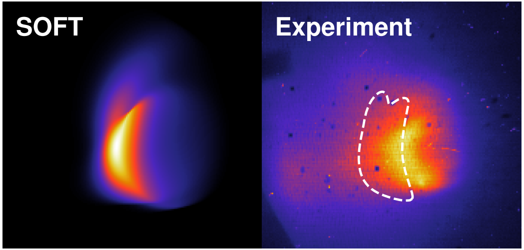
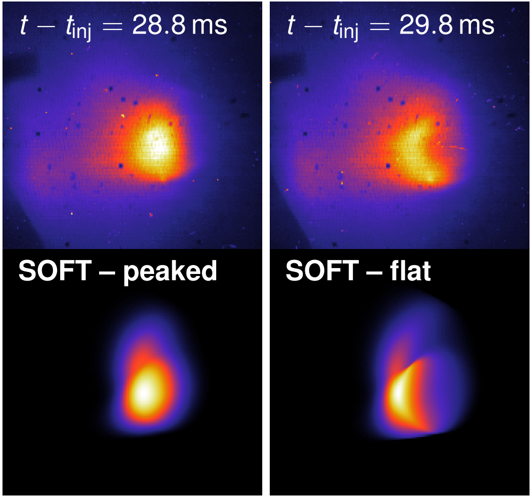
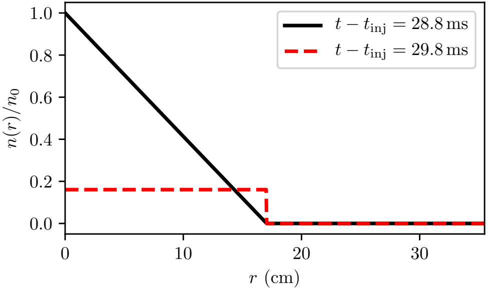




$\Longrightarrow$ Current spike correlated with runaway profile flattening.





- Runaway dynamics can be studied using synchrotron radiation
- Peaked runaway density profiles found in ASDEX Upgrade disruptions
- Radial density redistribution clearly distinguishable on visible camera

Future developments

- Automating inversion of parameters
- Compare to (fluid+)kinetic simulations
- Feeding inverted profiles to equilibrium reconstruction