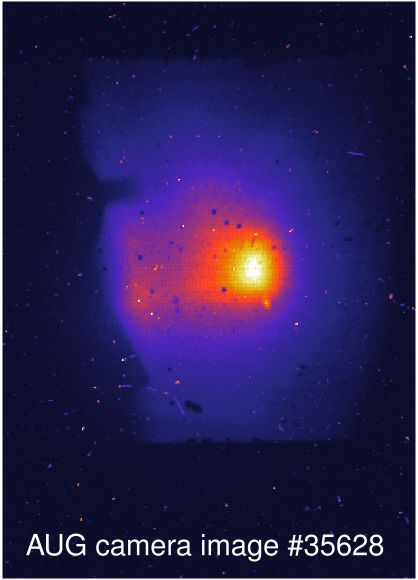
Analysis of the runaway electron distribution in an ASDEX Upgrade disruption using synchrotron radiation

Mathias Hoppe[1]

L. Hesslow[1], O. Embreus[1], L. Unnerfelt[1], G. Papp[2], I. Pusztai[1], T. Fülöp[1], O. Lexell[1], T. Lunt[2], E. Macusova[3], P. J. McCarthy[4], G. Pautasso[2], G. I. Pokol[5], P. Svensson[1], the ASDEX Upgrade team[2*] and the EUROfusion MST1 team[†]

[1] Chalmers University of Technology, Gothenburg, Sweden
[2] Max Planck Institute for Plasma Physics, Garching, Germany
[3] Institute of Plasma Physics of the CAS, Prague, Czech Republic
[4] Physics Department, University College Cork (UCC), Cork, Ireland
[5] NTI, Budapest University of Technology and Economics, Budapest, Hungary
[*] See author list of "*H. Meyer et al. 2019 Nucl. Fusion* **59** *112014*"
[†] See the author list of "*B. Labit et al. 2019 Nucl. Fusion* **59** *086020*"

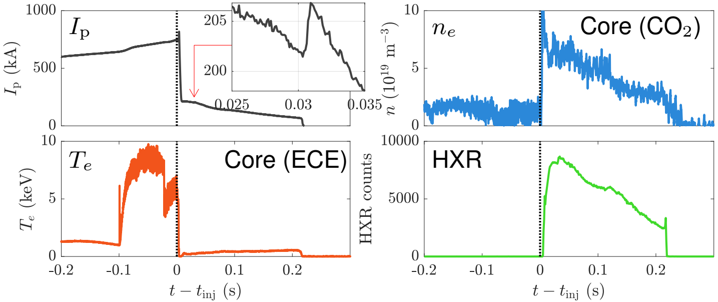
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.



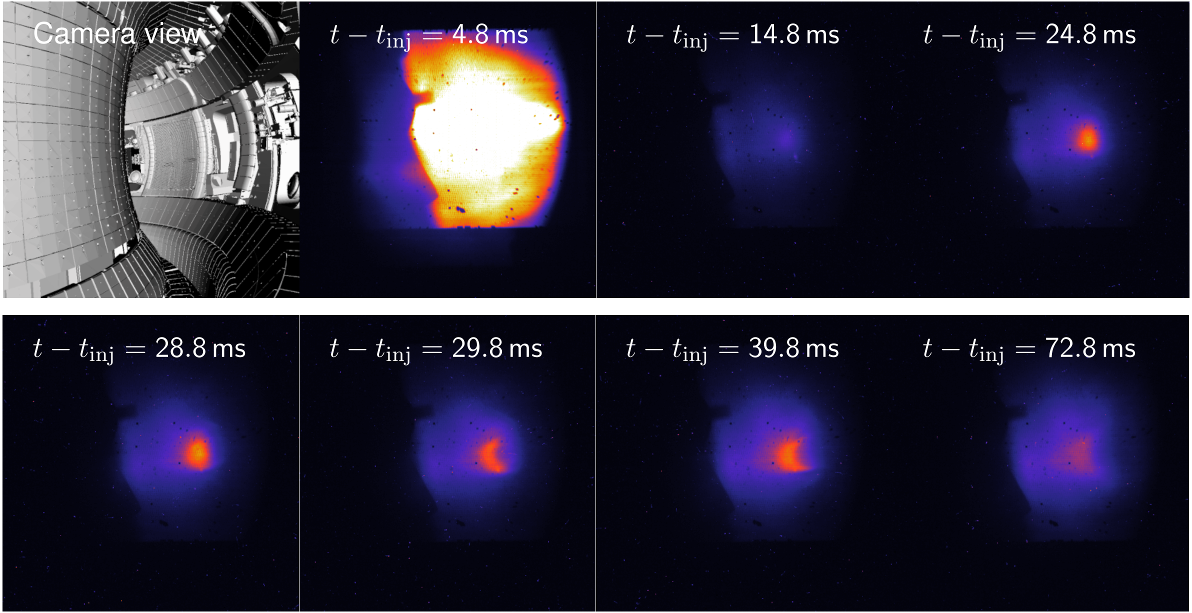
1. Experiment: ASDEX-U #35628
2. Forward modelling (fluid-kinetic)
   - Two-component picture of RE dynamics
   - We observe **remnant seed** electrons
3. Backward modelling (radial profile inversion)
   - Explanation for spot shape transition: **density redistribution**

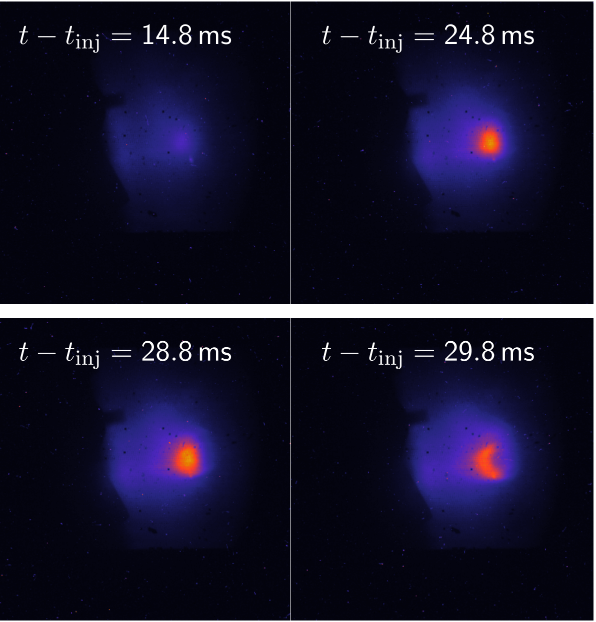
ASDEX-U #35628

- Deliberately triggered disruption
  - Massive Gas Injection at $t = 1\,\text{s}$ (Ar, $\sim 10^{21}$ particles)
  - Current $\sim$ 800 kA to $\sim$ 200 kA
  - ICRH applied
- Fast (1 kHz) visible-light camera
  - Filtered at $\lambda = 709\,\text{nm}$ (FWHM $9\,\text{nm}$)
- Small current spike at $t \approx 1.030\,\text{s}$
  - Correlated with synchrotron pattern transition
  - $(m, n) = (1, 1)$ mode



ASDEX-U #35628 – Fast camera synchrotron





Three questions to answer:

1. Can RE theory explain the **round shape**?
2. Why does the **intensity increase**?
3. What casuses the spot **shape transition**?

Forward modelling

We simulate the Thermal Quench (**TQ**) + Current Quench (**CQ**) + **Runaway plateau** using the coupled codes GO[1,2,3] (**fluid**) and CODE[4,5] (**kinetic**) in the cylindrical limit:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_\parallel}{\partial r}\right) = \mu_0\frac{\partial j}{\partial t}, \qquad \text{(GO)}$$

$$\frac{\partial f}{\partial t} + eE_\parallel\frac{\partial f}{\partial p_\parallel} = C\left\{f\right\} + S_{\mathrm{ava}}, \qquad \text{(CODE)}$$

$$j(r) = e\int v_\parallel f(r,p,\xi)\,\mathrm{d}^3p, \qquad \text{(coupling)}$$

[1] Smith *et al.*, (2006) PoP **12** 122505; [4] Landreman *et al.*, (2014) CPC **185** 847
[2] Fehér *et al.*, (2011) PPCF **53** 035014; [5] Stahl *et al.*, (2016) NF **56** 112009
[3] Papp *et al.*, (2013) NF **53** 123017

- **Several unknowns** from experiment:
  - pre-TQ plasma current density
  - impurity deposition/charge profile
  - final temperature
  - …
- But, if **avalanche** RE generation dominates, mainly $\boldsymbol{\Delta\psi}$ matters, which can be estimated from $\boldsymbol{\Delta I_{\mathrm{p}}}$

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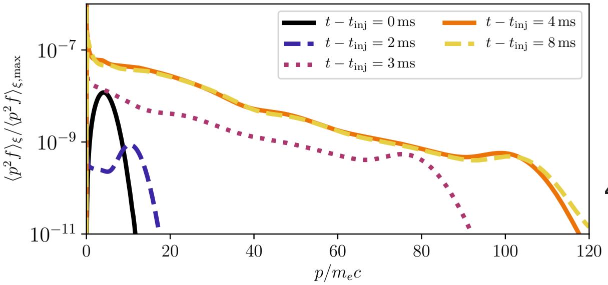
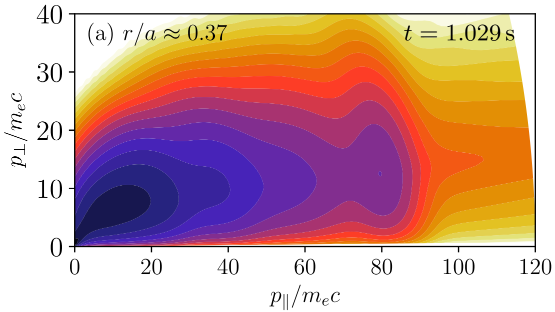
Hence, we

1. Run only GO through TQ to get $T_{e,\mathrm{final}}$, $E_\parallel(r,t)$, ion charge distribution
2. Initialize CODE **after TQ**, just before CQ, with **prescribed hot-tail seed**
3. Evolve GO+CODE together through **CQ and plateau**





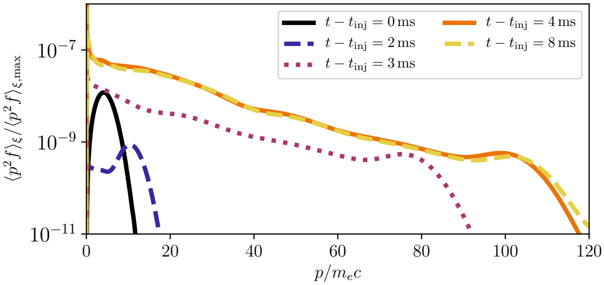
0-4 ms: Seed **accelerated** and **multiplied** during CQ

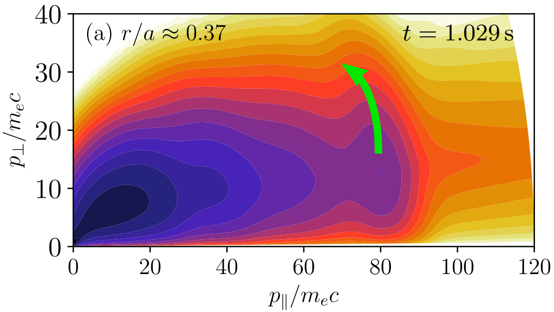
4-30 ms: Pitch angle **relaxation**

$\Longrightarrow$ RE distribution consists of **two components**:

- Exponential **avalanche component** (carrying current)
- Remnant **seed component** at “max” energy

Forward modelling: GO+CODE simulation results





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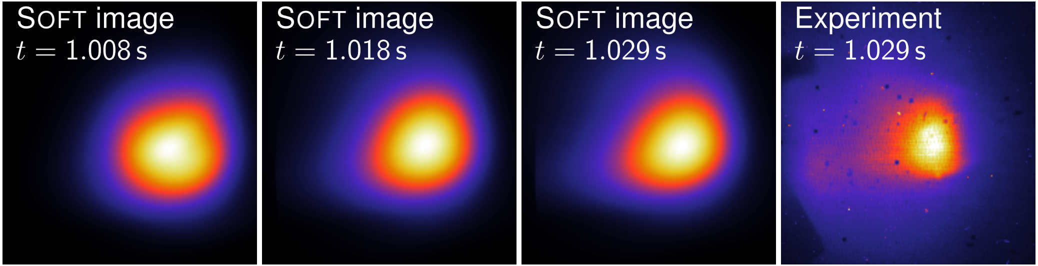
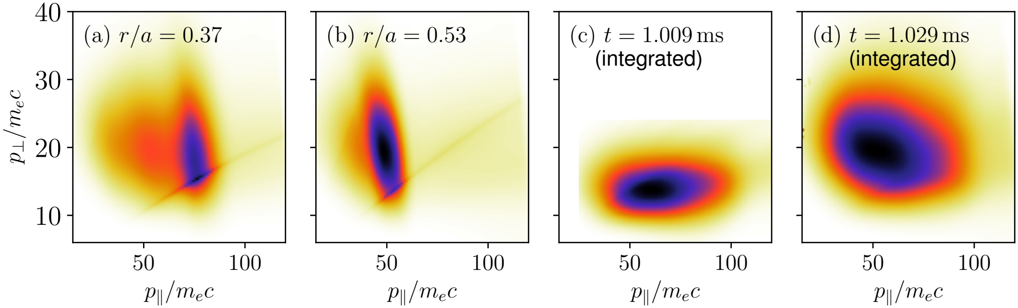
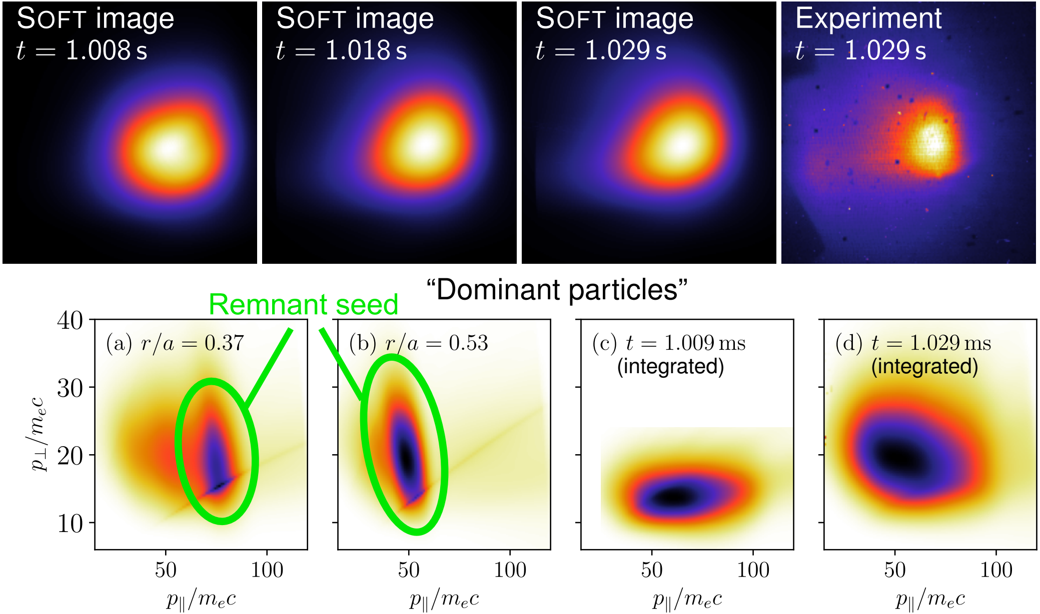
Forward modelling: SOFT[6] simulation results



"Dominant particles"

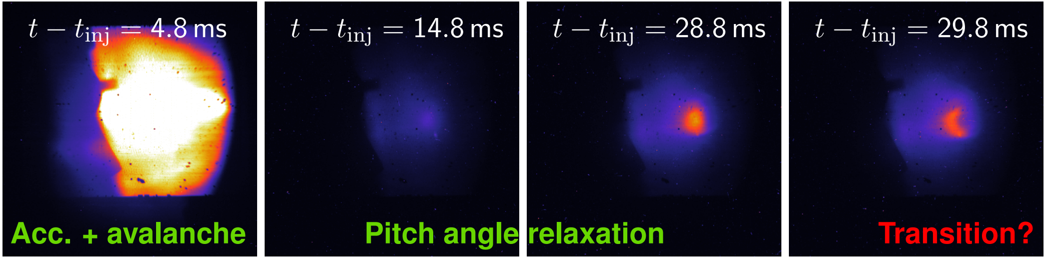


[6] Hoppe *et al.*, (2018) Nucl. Fusion **58** 026032



[6]Hoppe *et al.*, (2018) Nucl. Fusion **58** 026032

Forward modelling – evolution understood until 30 ms



Q1 Can RE theory explain the round spot shape?

- **Yes**. Shape determined by electron pitch angles.
- More accurate seed profile $\implies$ better agreement with **spot size**

Q2 Why does the intensity increase?

- Due to **pitch-angle relaxation** (increase)
- Synchrotron radiation power $\sim p_\perp^2 \sim \theta_\mathrm{p}^2$

Backward modelling

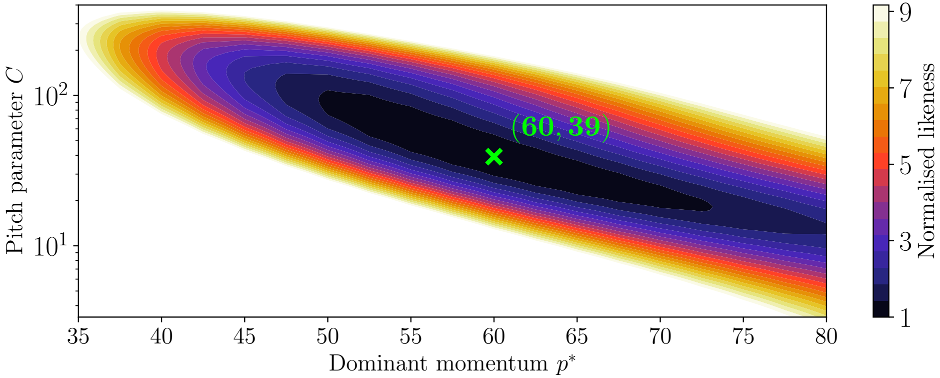
- Forward modelling suggests that **remnant seed dominates** synchrotron
- The remnant seed has
  - $f_p(p) \sim \exp\left[-(p-p^\star)^2/\Delta p^2\right] \sim \delta\left(p-p^\star\right)$
  - $f_\xi(\xi) \sim \exp(C\xi)$ ($\sim$ relaxed in pitch angle)

For the purpose of **fitting to synchrotron radiation**, fluid-kinetic modelling therefore suggests we take

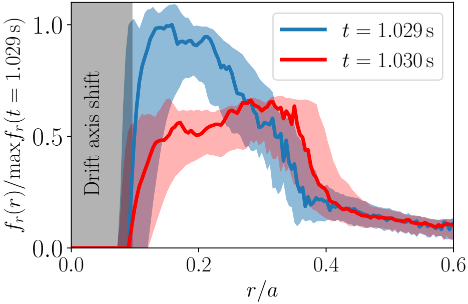
$$f(r,p,\xi) = f_r(r)\delta\left(p-p^\star\right)\exp\left(C\xi\right).$$

(preferably, $p^\star$ and C should vary with radius, but for simplicity we neglect this here)

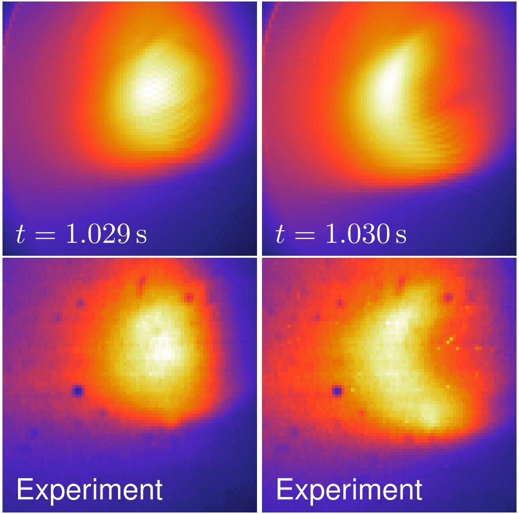
Scanning over $(p^\star, C)$ space yields



While C varies a lot, the more visually relevant "dominant pitch angle" $\theta^\star$ is fairly close to $\theta^\star \approx 0.3$ rad



(Shaded red/blue indicate maximum deviation with normalized image likeness ≤ 2)



Q3 What causes the spot shape transition?

- Spatial redistribution of electrons

Summary

- Synchrotron radiation observed in ASDEX-U #35628
  - Pattern **intensity grows** steadily for $\sim 25\,\mathrm{ms}$ post-disruption
  - Pattern **shape change** at $30\,\mathrm{ms}$ – correlated with small **current spike**
- Fluid-kinetic model provides two-component picture of RE evolution
  - Good, albeit not perfect, agreement
  - Remnant **hot-tail seed** quickly accelerated to max energy (dominate SR)
  - Runaways multiplied through **avalanche mechanism** (carry current)
  - Gradual **pitch angle relaxation** during plateau (increased SR intensity)
- Backward modelling indicates cause of synchrotron pattern transition
  - With help of model derived from fluid-kinetic simulations
  - Rapid **expulsion** of some particles from core

For details:

Hoppe et al, *"Spatiotemporal analysis of the runaway distribution function from synchrotron images in an ASDEX Upgrade disruption"*, submitted to JPP 2020 (arXiv:2005.14593).