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ASDEX Upgrade

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Theory-supported analysis of runaway distributions using synchrotron radiation

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EUROfusion

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.
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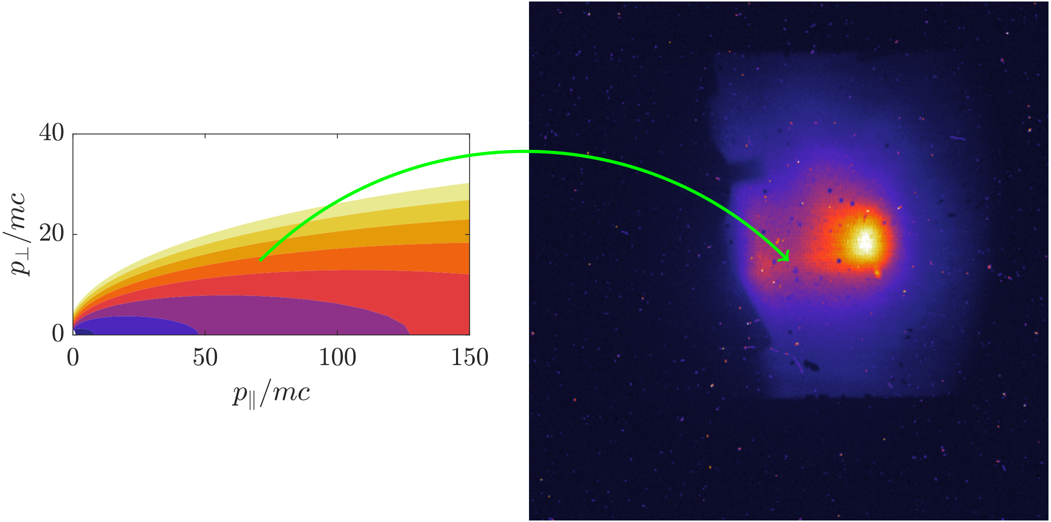
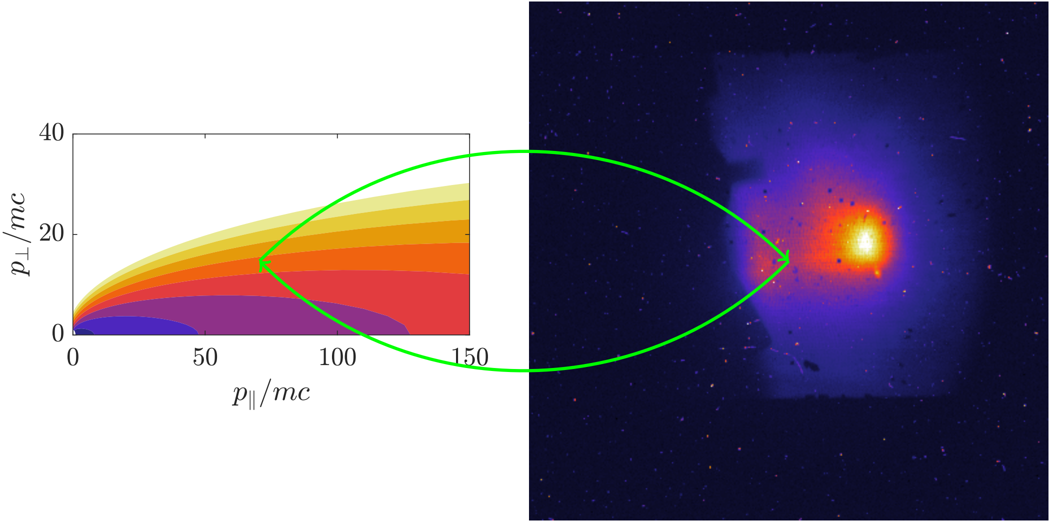
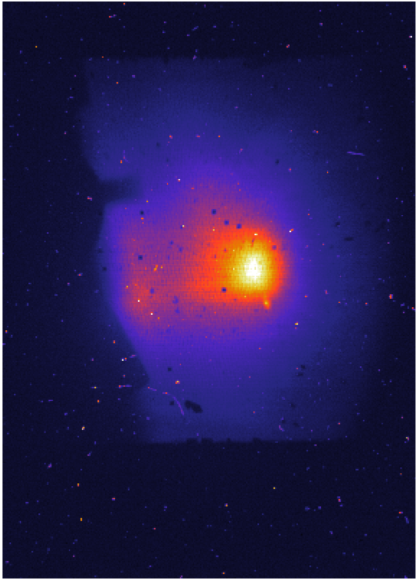

40
20
0
0
50
100
150
$p_\perp/mc$
$p_\parallel/mc$

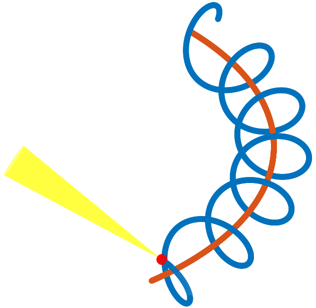


40
20
0
$p_\perp/mc$
0
50
100
150
$p_\parallel/mc$

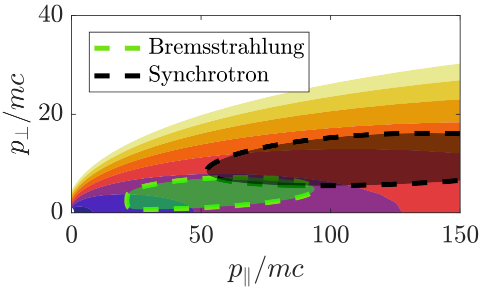
Outline

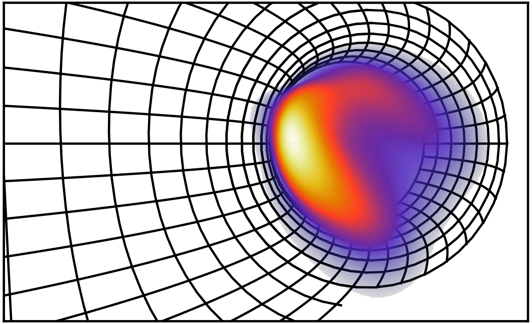


1. Synchrotron radiation
2. SOFT
3. Theory-supported analysis in ASDEX-U
   - Fluid-kinetic simulations
   - Model to fit radial dynamics



- Emitted by **highly relativistic** particles...
  - (such as runaways)
  - ...in **forward** direction...
  - ...with **continous spectrum**...
- Typically observed at **visible wavelengths** in tokamaks
- Sensitive to details of $f(r, p, \theta)$

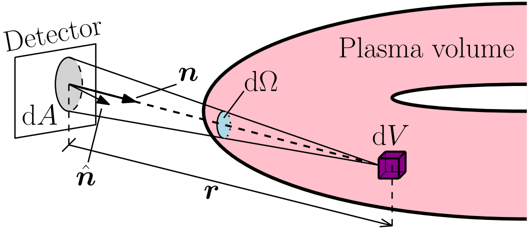




- **Synthetic** synchrotron (and bremsstrahlung) **diagnostic**
- Given $f(r, p, \theta)$ and **magnetic field**, reproduces radiation pattern
- Applied to Alcator C-Mod, ASDEX Upgrade, DIII-D, JET and TCV
- **Freely available** on GitHub[‡]
- Python **analysis framework** under continuous development[*]

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

SOFT evaluates radiation from plasma



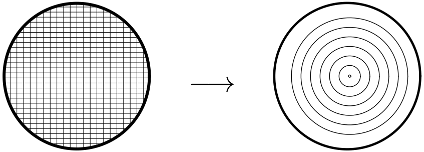
$$I = \iiint \Theta\left(\frac{\boldsymbol{r}}{r}\right) \frac{\boldsymbol{r}\cdot\hat{\boldsymbol{n}}}{r^3} \frac{\mathrm{d}I(\boldsymbol{x},\boldsymbol{p},\boldsymbol{r})}{\mathrm{d}\Omega} f(\boldsymbol{x},\boldsymbol{p})\,\mathrm{d}\boldsymbol{p}\mathrm{d}V\mathrm{d}A$$

$I =$ Radiation quantity

$f =$ Distribution function

$\frac{\mathrm{d}I}{\mathrm{d}\Omega} =$ Angular distribution of radiation

$$\Theta\left(\frac{\boldsymbol{r}}{r}\right) = \begin{cases} 1, \text{if } \boldsymbol{r}/r \text{ is in the FOV} \\ 0, \text{otherwise} \end{cases}$$



$$I = \int f(\rho, p_\parallel, p_\perp)\Theta\left(\frac{\boldsymbol{r}}{r}\right)\frac{\boldsymbol{r}\cdot\hat{\boldsymbol{n}}}{r^3}\frac{\mathrm{d}I}{\mathrm{d}\Omega}\underbrace{p_\perp J\,\mathrm{d}\rho\mathrm{d}\tau\mathrm{d}\phi}_{\mathrm{d}\boldsymbol{X}}\,\underbrace{\mathrm{d}p_\parallel\mathrm{d}p_\perp\mathrm{d}\zeta}_{\mathrm{d}\boldsymbol{p}}\,\mathrm{d}A.$$

where

$\rho =$ Maximum major radius along orbit

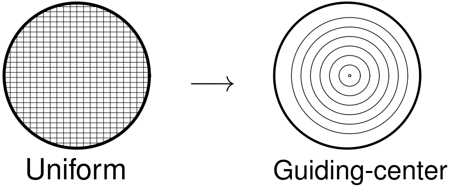
$\tau =$ Time parameter along orbit

$\phi =$ Toroidal angle

$\zeta =$ Gyro angle

$J =$ Trajectory Jacobian

SOFT uses guiding-center orbits



$$I = \int f(\rho, p_\parallel, p_\perp) \underbrace{\Theta\left(\frac{\boldsymbol{r}}{r}\right) \frac{\boldsymbol{r}\cdot\hat{\boldsymbol{n}}}{r^3} \frac{\mathrm{d}I}{\mathrm{d}\Omega} J\,\mathrm{d}\tau\mathrm{d}\phi\mathrm{d}\zeta\mathrm{d}A}_{\mathcal{G}(\rho,p_\parallel,p_\perp)}\, p_\perp \mathrm{d}\rho\mathrm{d}p_\parallel\mathrm{d}p_\perp.$$

where

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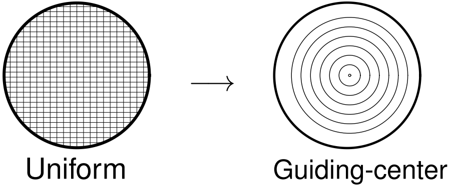

$$I = \int f(\rho, p_\parallel, p_\perp) \mathcal{G}\left(\rho, p_\parallel, p_\perp\right) p_\perp \, \mathrm{d}\rho \mathrm{d}p_\parallel \mathrm{d}p_\perp .$$

where

$\rho =$ Maximum major radius along orbit

$\tau =$ Time parameter along orbit

$\phi =$ Toroidal angle

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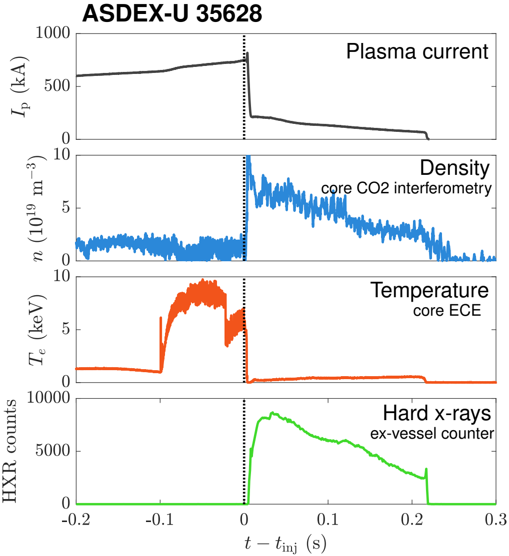
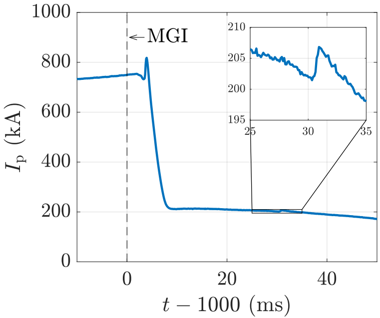
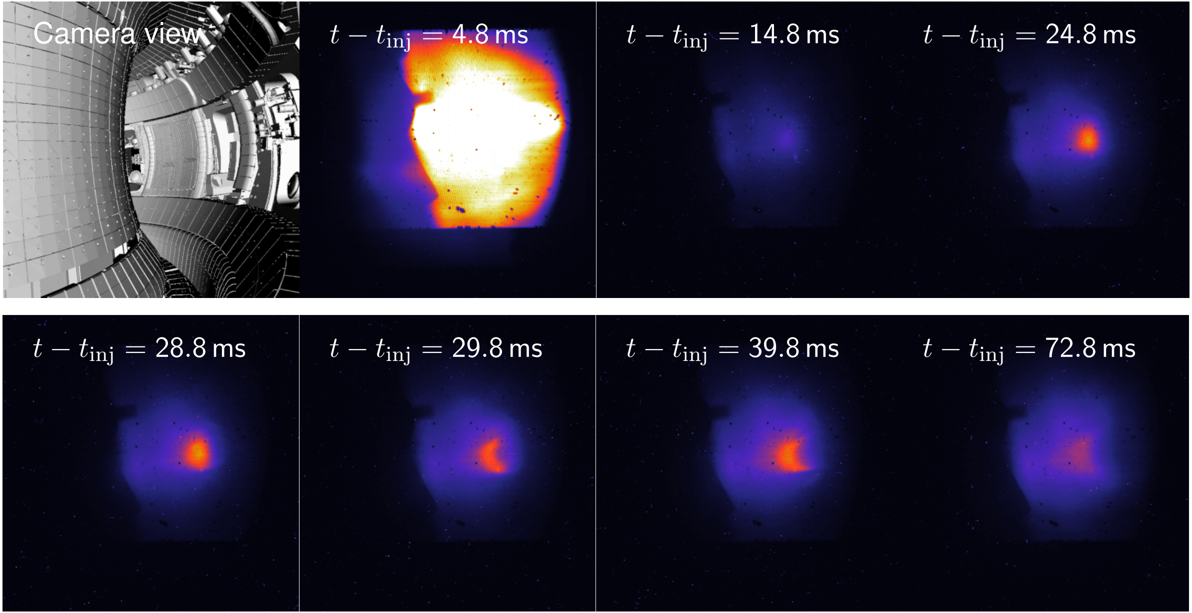
Experiment: ASDEX-U 35628



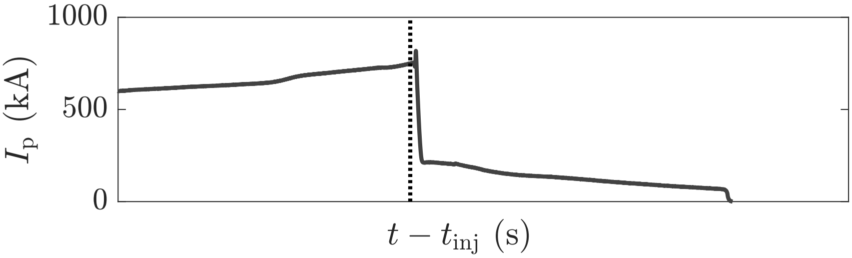
- Deliberately triggered disruption
  - Massive Gas Injection (Ar), $N_{Ar} \approx 10^{21}$ particles
  - Current: $\sim$ 800 kA to $\sim$ 200 kA
  - Temperature: $\sim$ 5 keV to $\sim$ 1 eV
  - ICRH applied
- Fast (1 kHz) visible-light camera
  - Equipped with 709 ± 9 nm filter (to remove line radiation)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

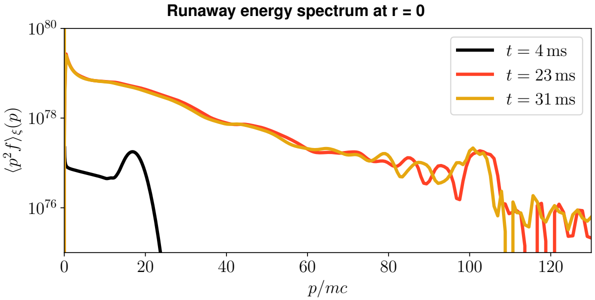



Camera view
$t - t_{\mathrm{inj}} = 4.8\,\mathrm{ms}$
$t - t_{\mathrm{inj}} = 14.8\,\mathrm{ms}$
$t - t_{\mathrm{inj}} = 24.8\,\mathrm{ms}$
$t - t_{\mathrm{inj}} = 28.8\,\mathrm{ms}$
$t - t_{\mathrm{inj}} = 29.8\,\mathrm{ms}$
$t - t_{\mathrm{inj}} = 39.8\,\mathrm{ms}$
$t - t_{\mathrm{inj}} = 72.8\,\mathrm{ms}$

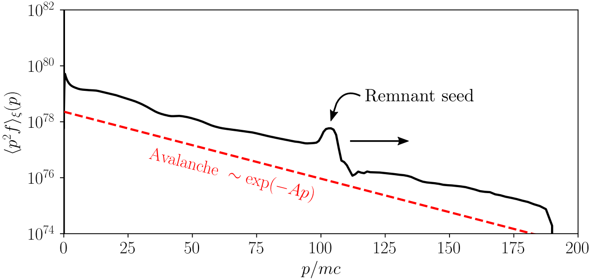
Theory-supported analysis

- Fluid (GO) + Kinetic (CODE)
- Disruption $\implies$ many experimental uncertainties
- Avalanche dynamics robust $\implies$ try match final current (200 kA)
  - Skip TQ
  - Start with appropriately sized hot-tail seed
  - Evolve through CQ and plateau

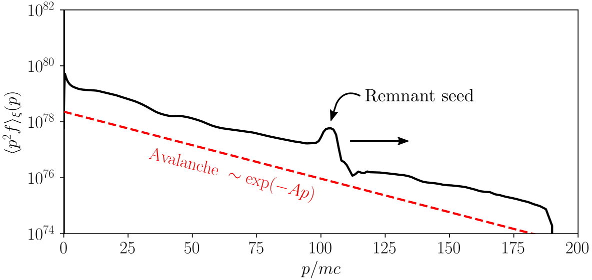




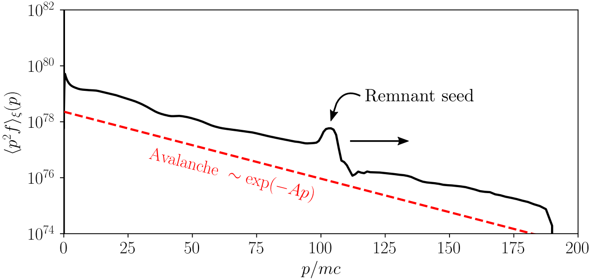
- Seed is accelerated ($\tau_{\mathrm{acc}} \lesssim$ 5 ms)



- Seed is accelerated ($\tau_{\rm acc} \lesssim 5$ ms)

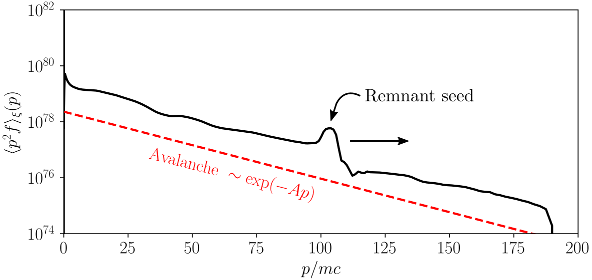


- Seed is accelerated ($\tau_{\mathrm{acc}} \lesssim 5$ ms)
- Gradual formation of avalanche distribution

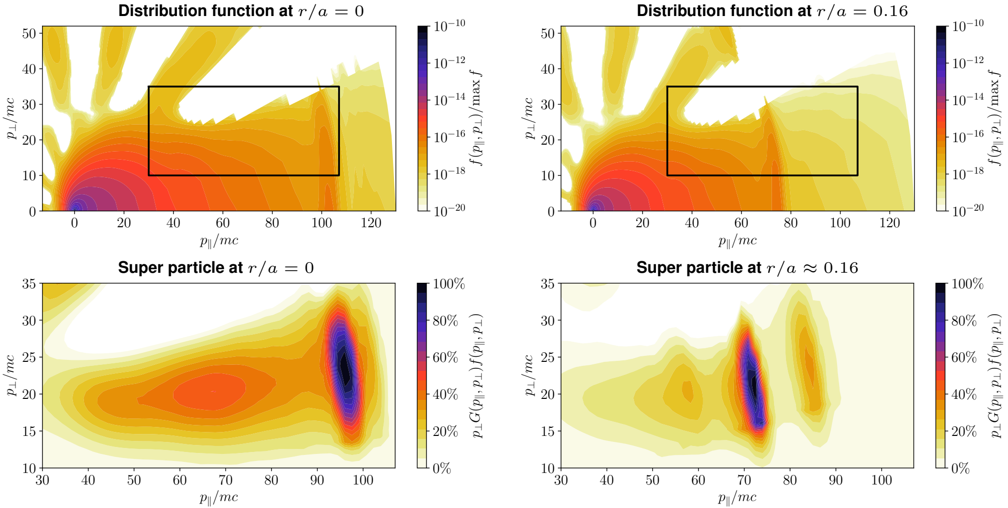


- Seed is accelerated ($\tau_{\mathrm{acc}} \lesssim 5$ ms)
- Gradual formation of avalanche distribution
- Spot shape change after ~ 27 ms

Theory: Fluid-kinetic simulations (Go+Code)

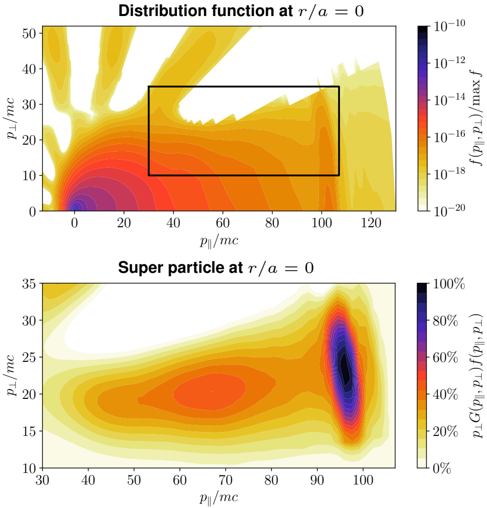


- Seed is accelerated ($\tau_{\mathrm{acc}} \lesssim$ 5 ms)
- Gradual formation of avalanche distribution
- Spot shape change after $\sim$ 27 ms
- Slow avalanching ($\tau_{\mathrm{ava}} \gg$ 27 ms)

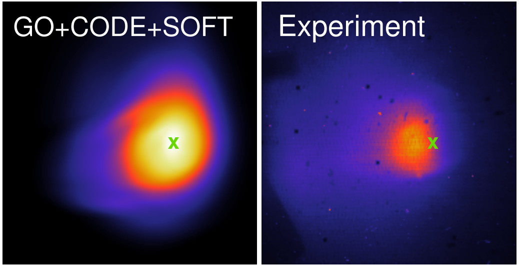


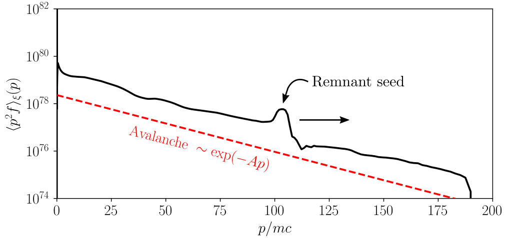
Distribution function at $r/a = 0$
Distribution function at $r/a = 0.16$
Super particle at $r/a = 0$
Super particle at $r/a \approx 0.16$
$p_\perp/mc$
$p_\parallel/mc$
$f(p_\parallel, p_\perp)/\max f$
$p_\perp G(p_\parallel, p_\perp) f(p_\parallel, p_\perp)$
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
100%
80%
60%
40%
20%
0%

Theory: Fluid-kinetic simulations (GO+CODE)



- Synchrotron dominated by **seed**
- Seed energy varies with radius
- Spot shape **type** matches — but **too large**





Recall: Only *dominant* emitters matter

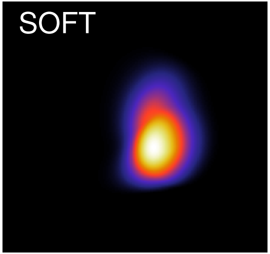
$\implies$ in a seed dominated scenario, GO+CODE simulations suggest

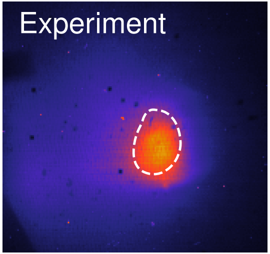
$$f(r,p,\xi) = f_r(r)\delta\left(p - p^*\right)\exp\left(C\xi\right)$$

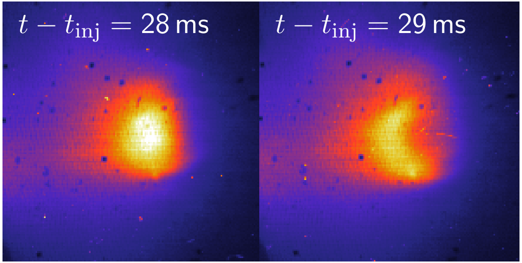
- Synchrotron simulations insensitive to exact p^*
- Pitch distribution is (approximately) steady state

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

$$\text{Good fit:} \begin{cases} f_r(r) & \propto 1 - r/(17\,\text{cm}), \\ p^* & = 42mc, \\ C & = 100, \end{cases}$$

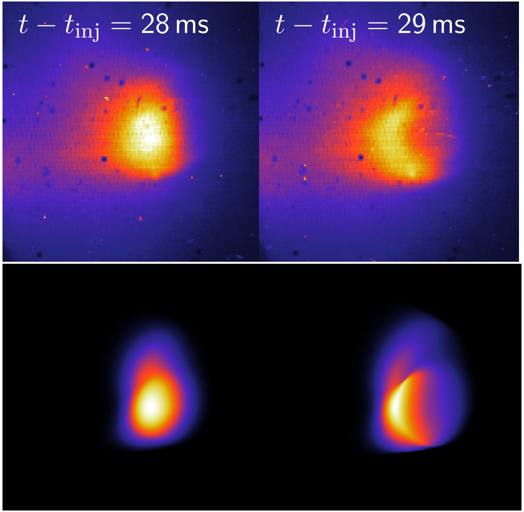




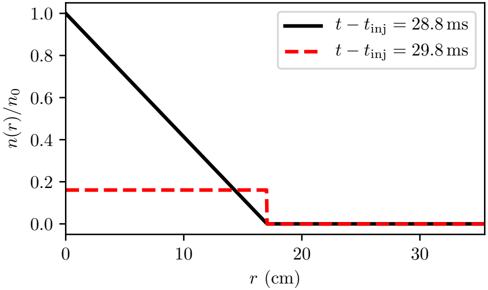


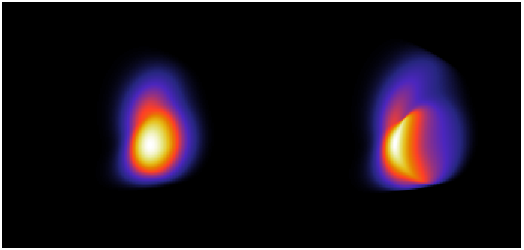
- Synchrotron spot transition, ellipse $\rightarrow$ crescent
- Sub-ms event: assume momentum distribution changes negligibly

Model: Spot shape transition



- Synchrotron spot transition, ellipse $\rightarrow$ crescent
- Sub-ms event: assume momentum distribution changes negligibly
- $\Longrightarrow$ Consistent with runaway profile flattening (reconnection)





- Synchrotron spot transition, ellipse $\rightarrow$ crescent
- Sub-ms event: assume momentum distribution changes negligibly
- $\implies$ Consistent with runaway profile flattening (reconnection)

- GO+CODE+SOFT simulations of ASDEX-U disruption suggest we observe the **runaway seed** on visible camera
- Motivates **simple model** for synchrotron fitting purposes
- Synchrotron **spot shape change** in ASDEX-U #35628 consistent with **flattened** runaway **density profile**