# Runaway electron beams: energy and decay

O Ficker et al
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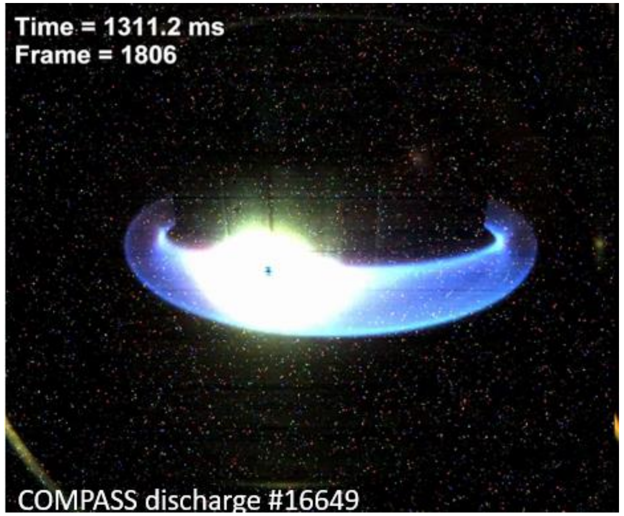
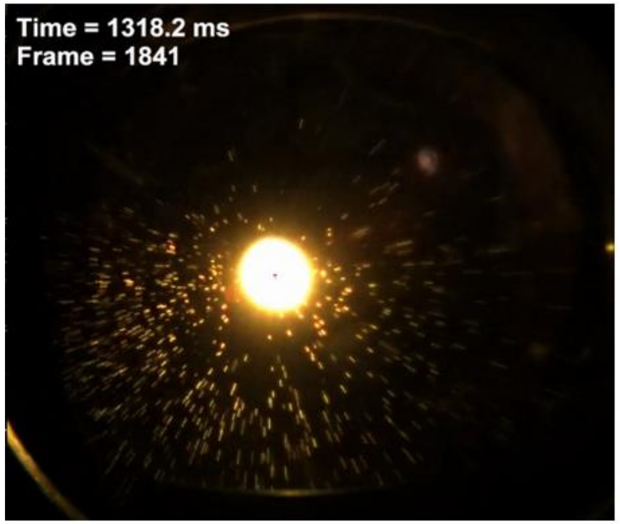
# Outline

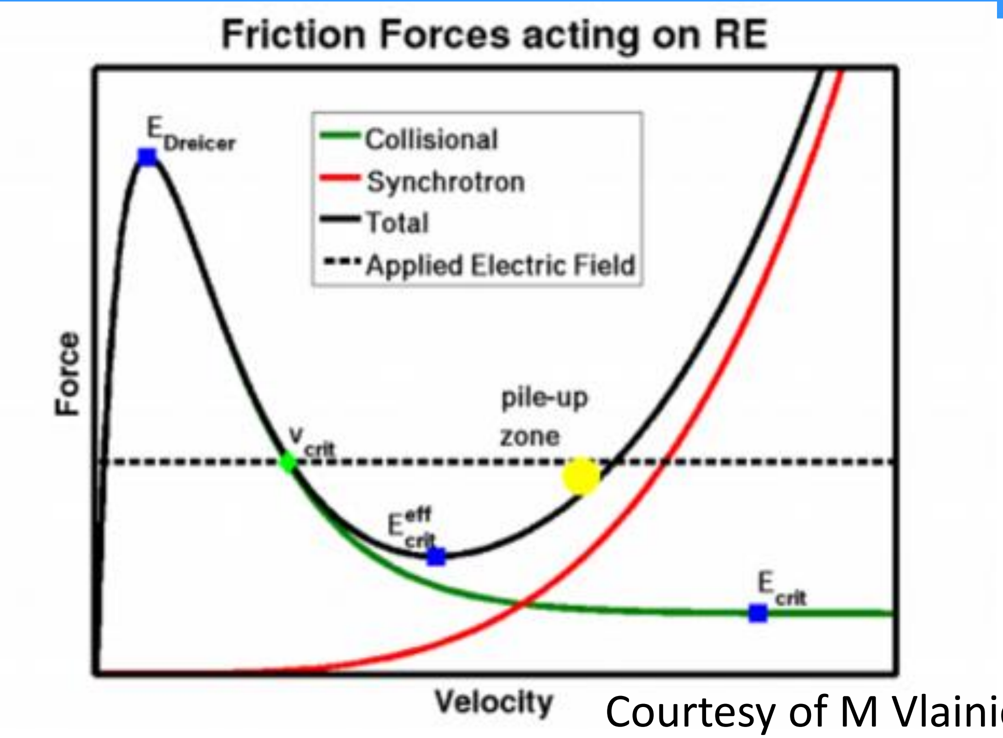
- Reminder: What are runaway electrons
- COMPASS role in RE research
- Methods of energy estimation:
  - HXR radiation
  - Synchrotron radiation
  - Magnetics?
- How to destroy the beam?
- How to diagnose how well it is destroyed?



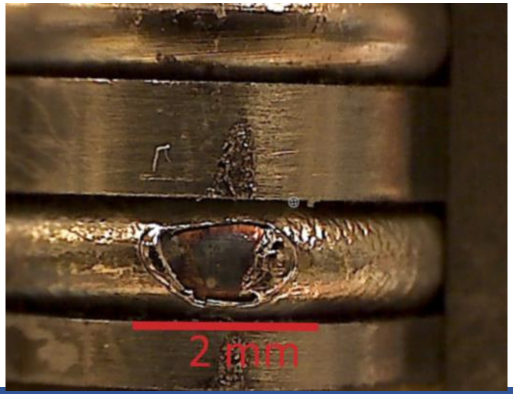



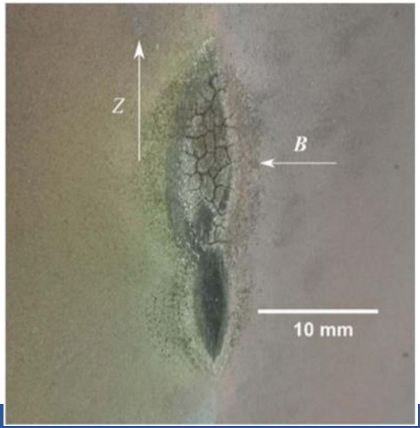
# RE physics basics

- RE = **relativistic electrons** present in plasma due to **imbalanced acceleration** and **friction forces**
- **Toroidal E field –** present in tokamaks
- Collisional friction force – func of $n_e$ ant $T_e$
- Low density and high electric field is risky
  - breakdown, disruption, …
- MeV energies and large currents achievable
- **Significant destructive potential** -> ITER
- **Research on almost all tokamaks**
- **Special diagnostic methods necessary**

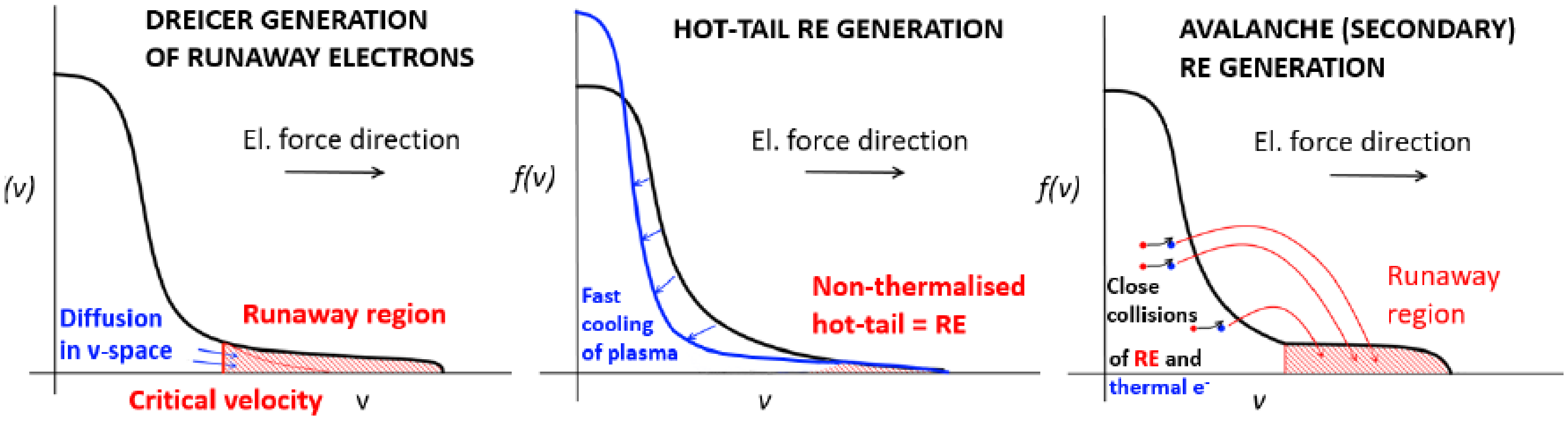



Courtesy of M Vlainic

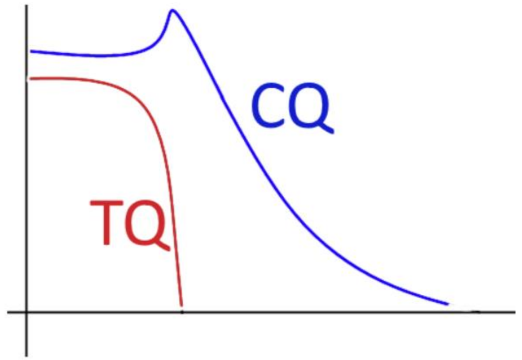


# Generation of runaway electrons, disruptions




- Primary and secondary generation of RE
- Compton scattering, Tritium decay also cosidered




**Disruption** = sudden loss of energy confinement, temperature (TQ) and plasma current (CQ)

Common in tokamaks, but in ITER must be avoided or well mitigated

Consequences:

**Large forces (-> vessel, support structure, coils)**
**Local overheating of plasma facing components**
**Large electric field -> Generation of RE beam (up to 70% of pre-disruptive current)**

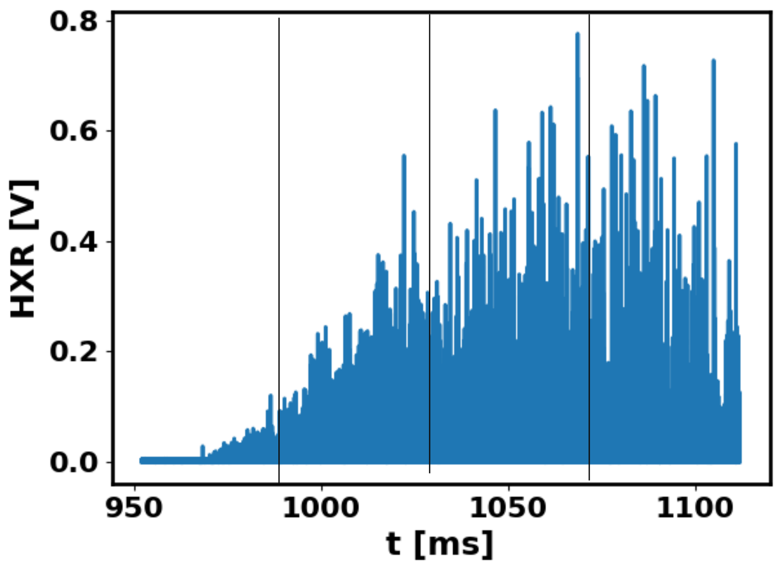
Mitigation necessary!!!

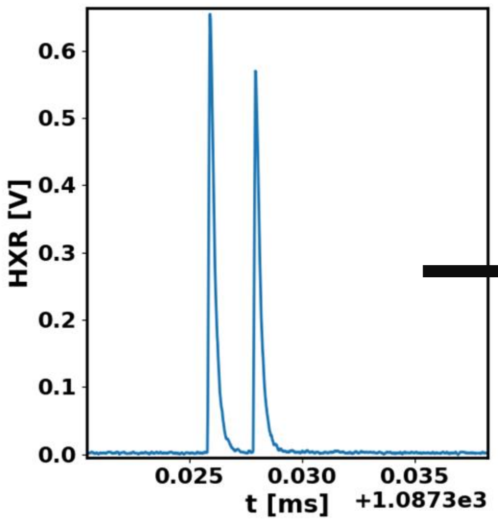
# How to estimate the RE energy?

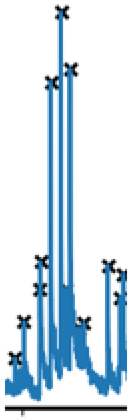
- Secondary effects – EM radiation, necessary magnetic field to confine them, etc
- HXR radiation
  - The braking radiation (breamstrahlung) of relativistic electrons (100 keV – MeVs spectral region)
  - Week from interaction with plasma ions
  - Strong from interaction with wall/limiter material atoms – lost RE
  - Can be measured using external detectors (scintilators, semiconductor detector etc.)
- Synchrotron radiation
  - EM radiation of relativistic particles in magnetic field, continuous spectra (unlike ECE)
  - In typical tokamak conditions: IR up to visble range
  - Spectra can be calculated and measured – complex relation of electron distribution function with spectra, at least limit values can be found
- Magnetic measurement
  - Electric field – accelerating force – vacuum approximation
  - Vertical magnetic field / Radial position – for small currents directly related to average energy

# HXR energy spektra

- Time evolution of scintillator signal – peaks of lenght of several microseconds

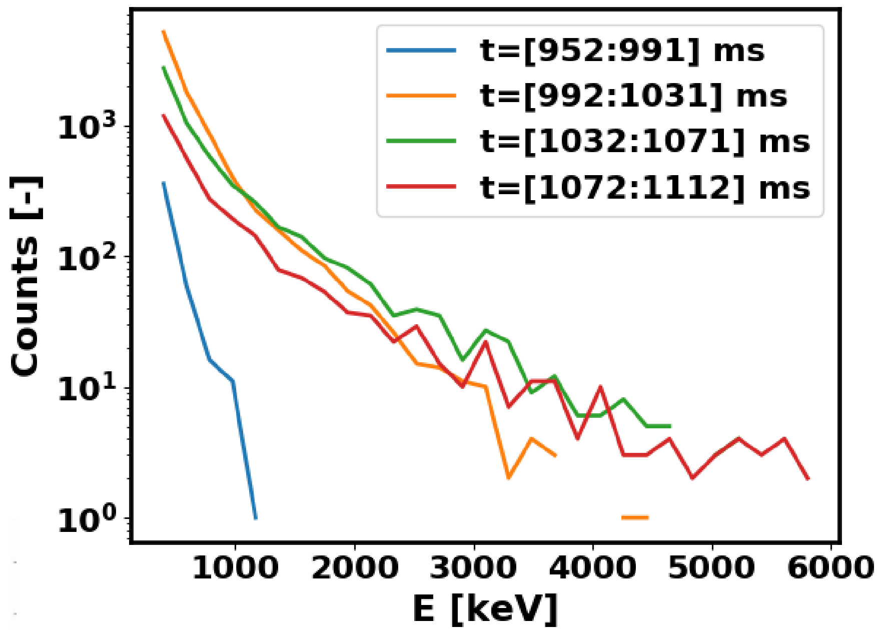


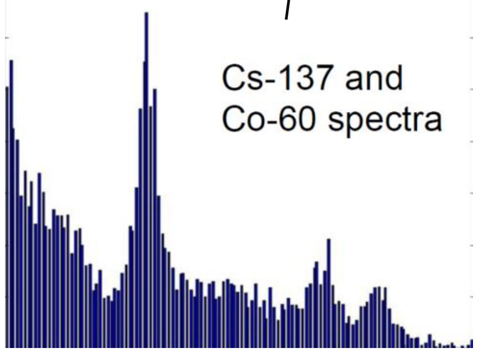



**<u>HXR spectra evolution</u>**

**– peak detection + calibration**




Complicated relation to RE distribution function but still useful – comparison, energy limits, etc

**Too many peaks or pile ups?**

**Distance, shielding/collimation, speed**

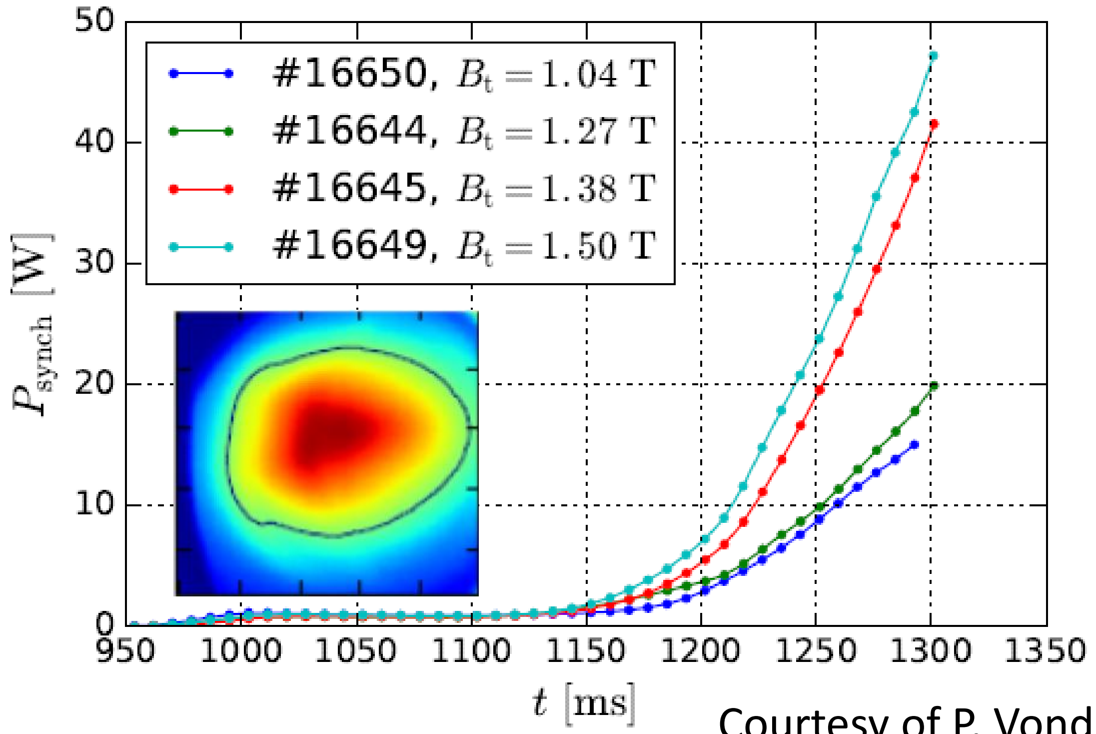
**Too large HXR energy?**

**Bigger or heavier scintillator**

# Synchrotron radiation - COMPASS

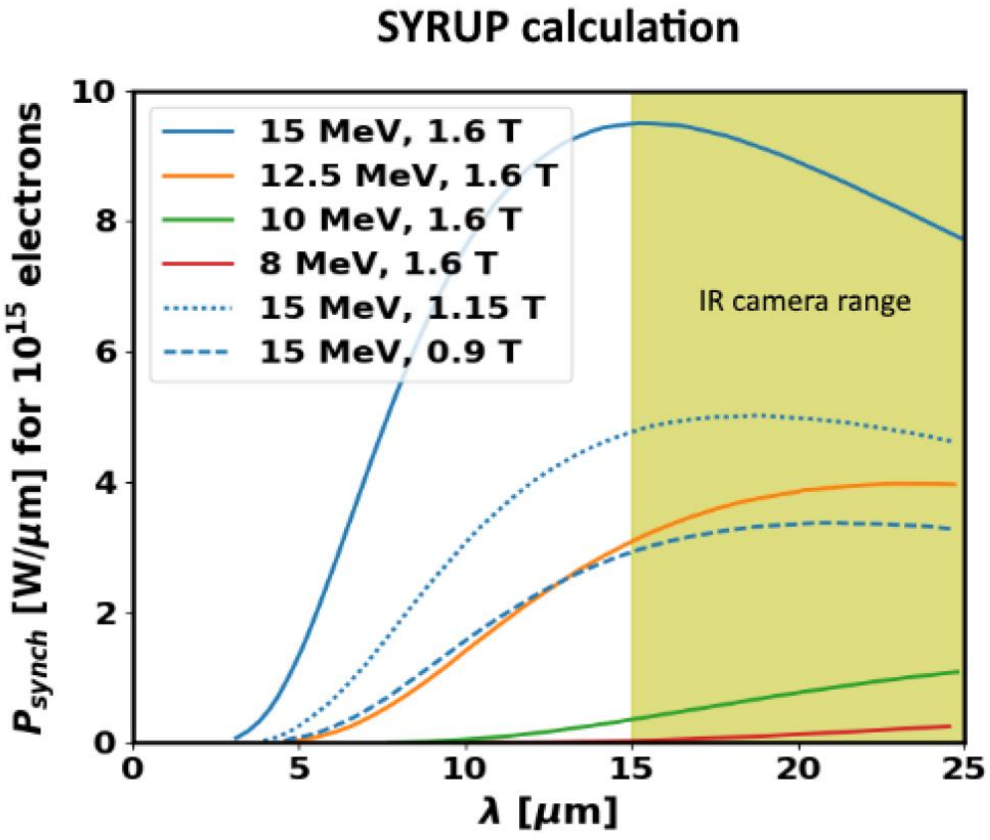
- Radiationreleased tangentially in the direction of flight
- Can be observed by spectrometers/cameras

$$P_{\rm tot} = \frac{e^2}{6\pi\varepsilon_0}\frac{\omega_{\rm c}^2}{v_\perp}\beta_\perp^3\gamma^4 = \frac{e^4}{6\pi\varepsilon_0 m_{\rm e}^2 c}B^2\beta_\perp^2\gamma^2 = \frac{e^4}{6\pi\varepsilon_0 m_{\rm e}^2 c}B^2 p_\perp^2 .$$



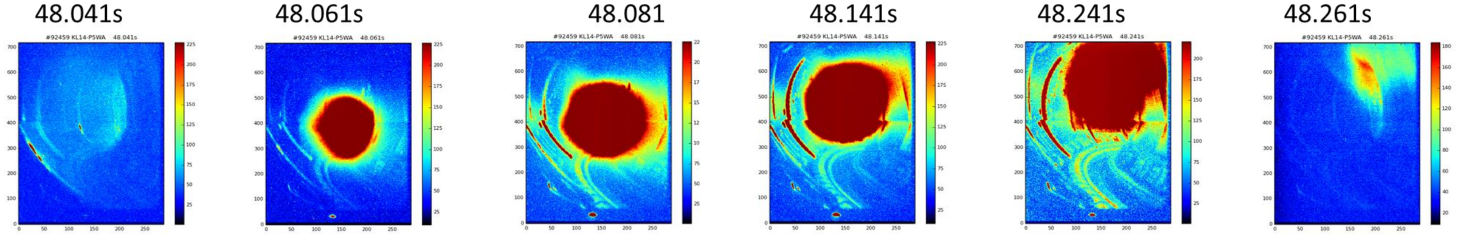

Courtesy of P. Vondráček

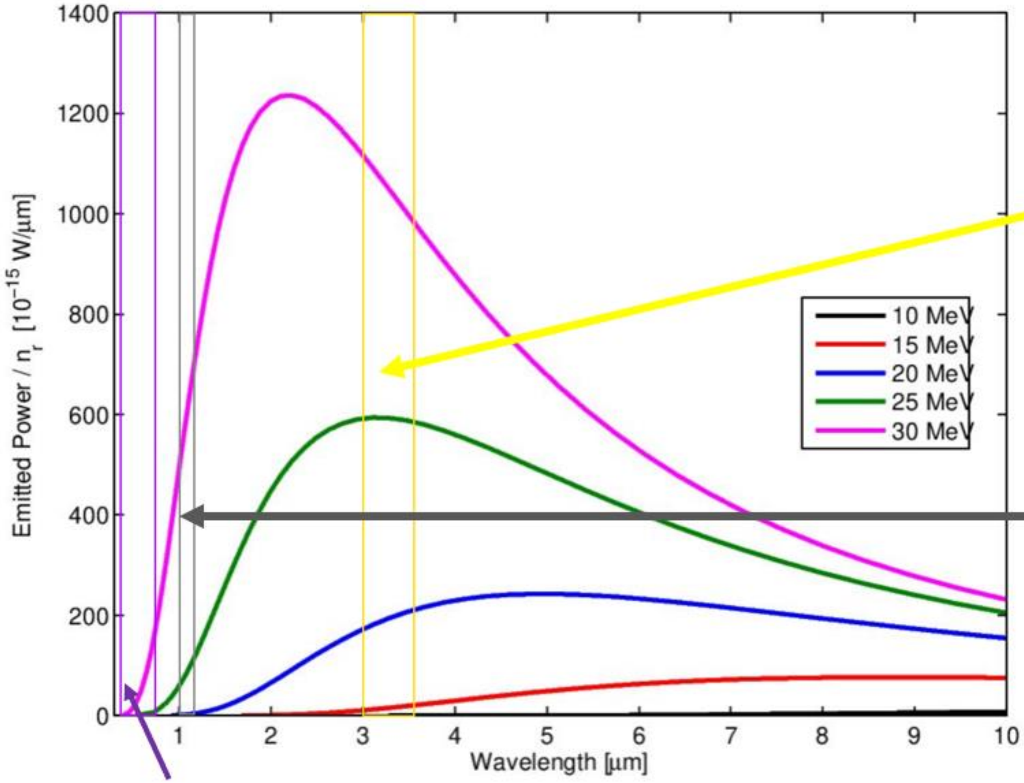
Spectra can be calculated by various tools, e.g. SYRUP (Stahl et al., 2013) - RE energy discriminaion



# Synchrotron radiation: JET

- No dedicated measurements so far, one nice shot recorded by protection cameras

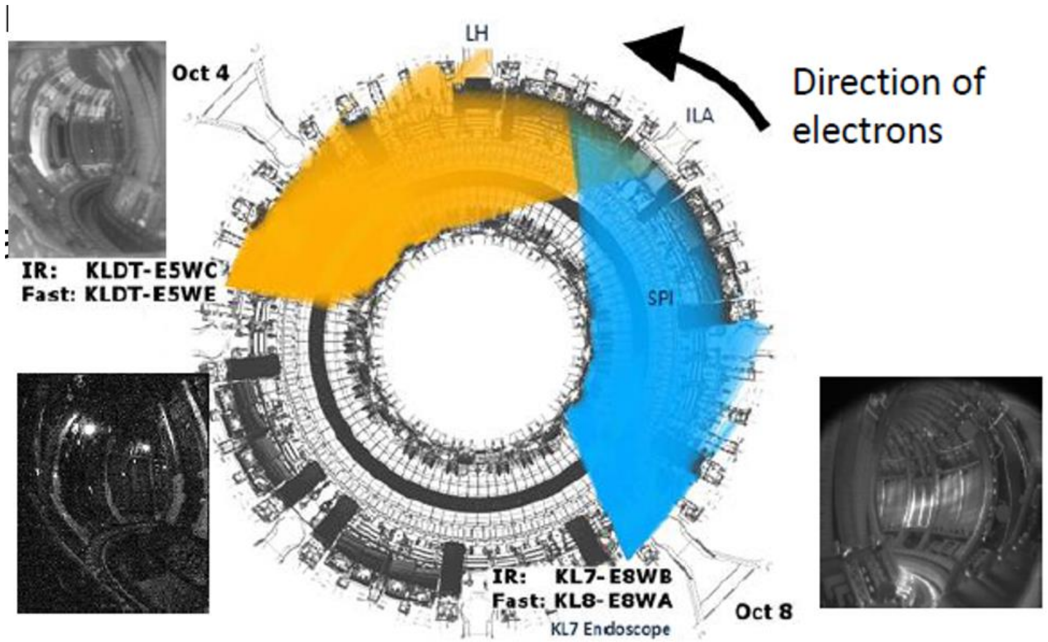



KLDT mid-IR range

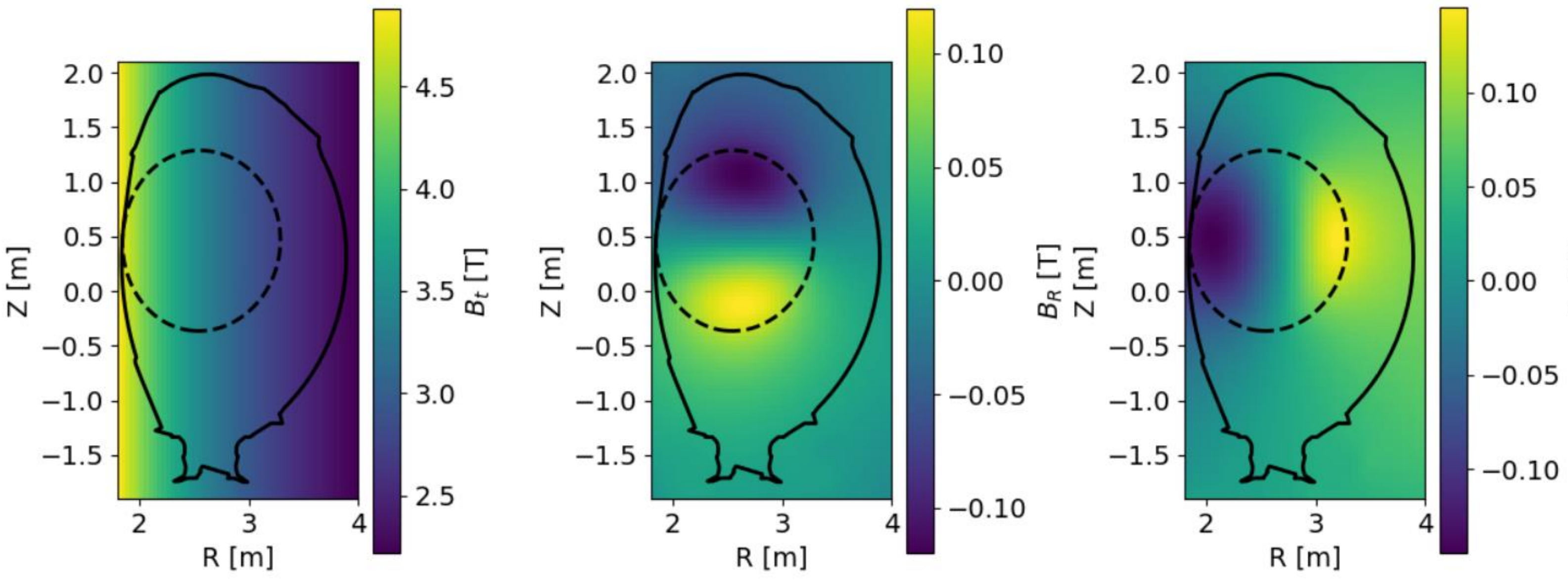
KL14-P5WC range – suspicious synchrotron spot

Visible range cameras

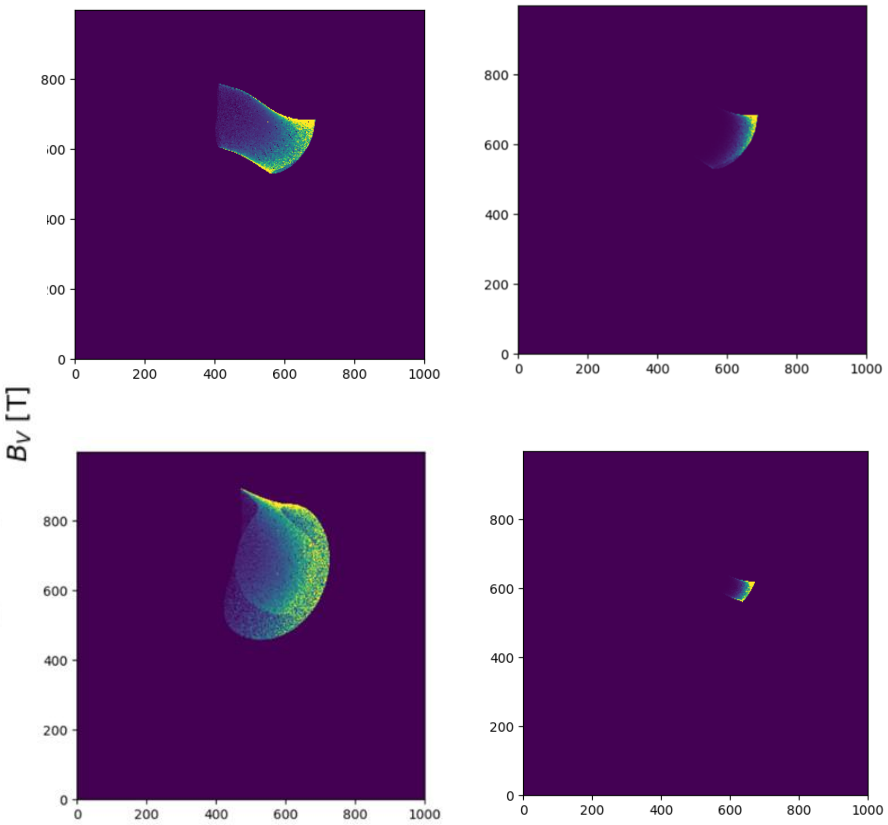


- SOFT = Synchrotron-detecting Orbit Following Toolkit, developed at Chalmers university (Hoppe et al, 2018)
- Simple or numeric equilibria, various distribution functions, equations of motion, detection tools

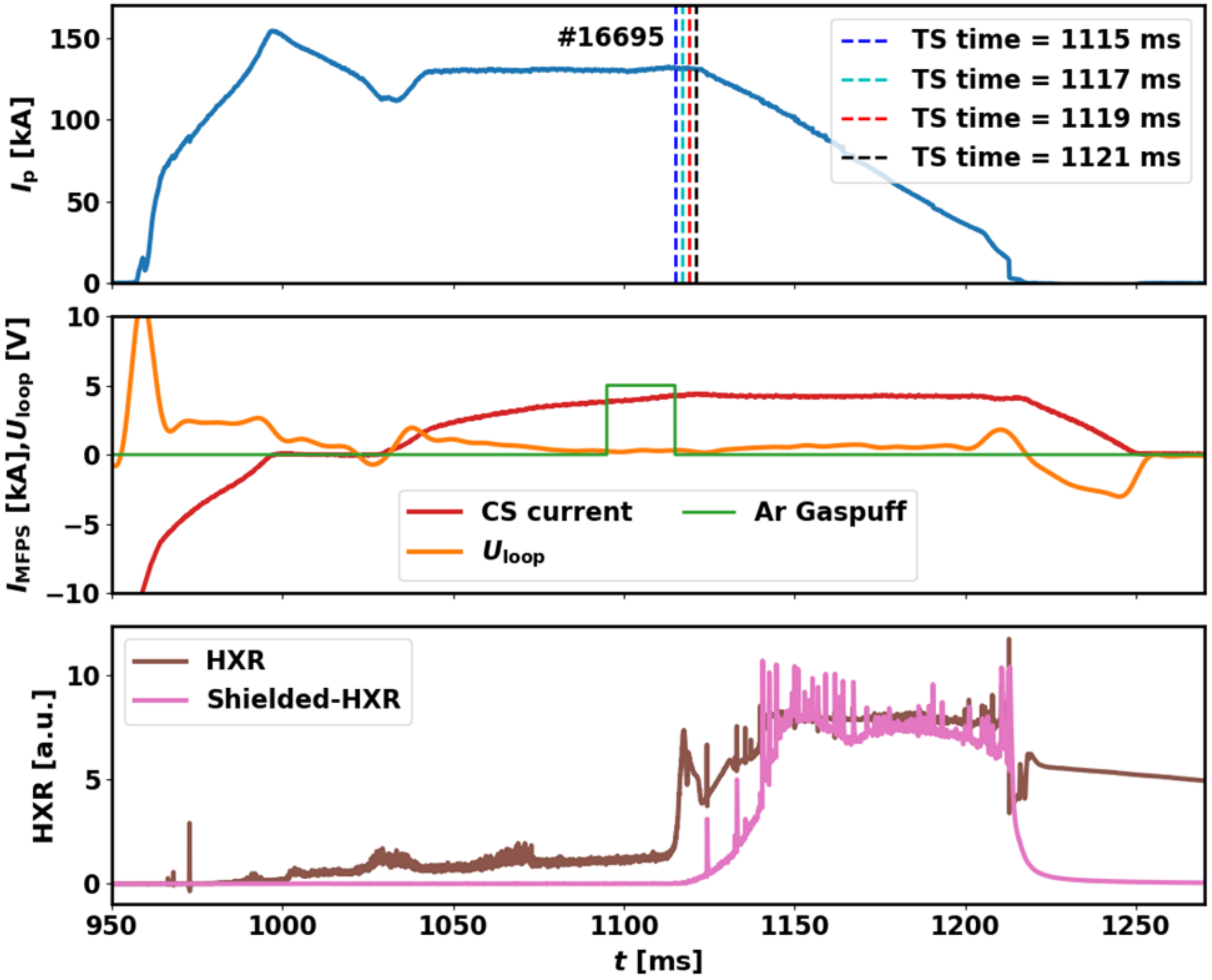
Magnetic field components as an input – pleque and sal packages used



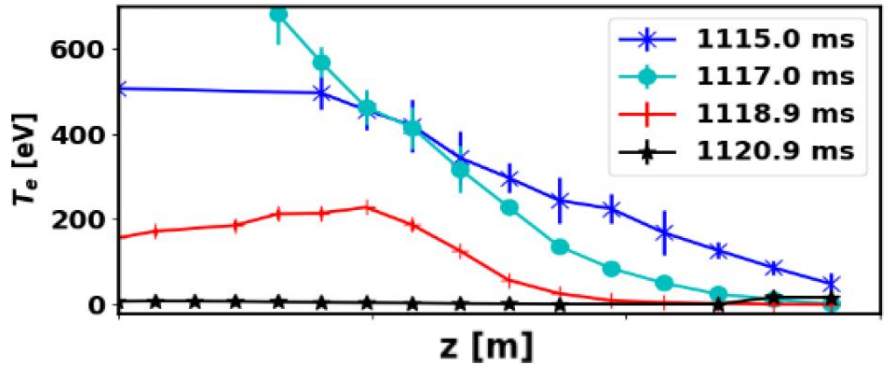

$B_T$ $B_R$ $B_V$



# Beam decay studies

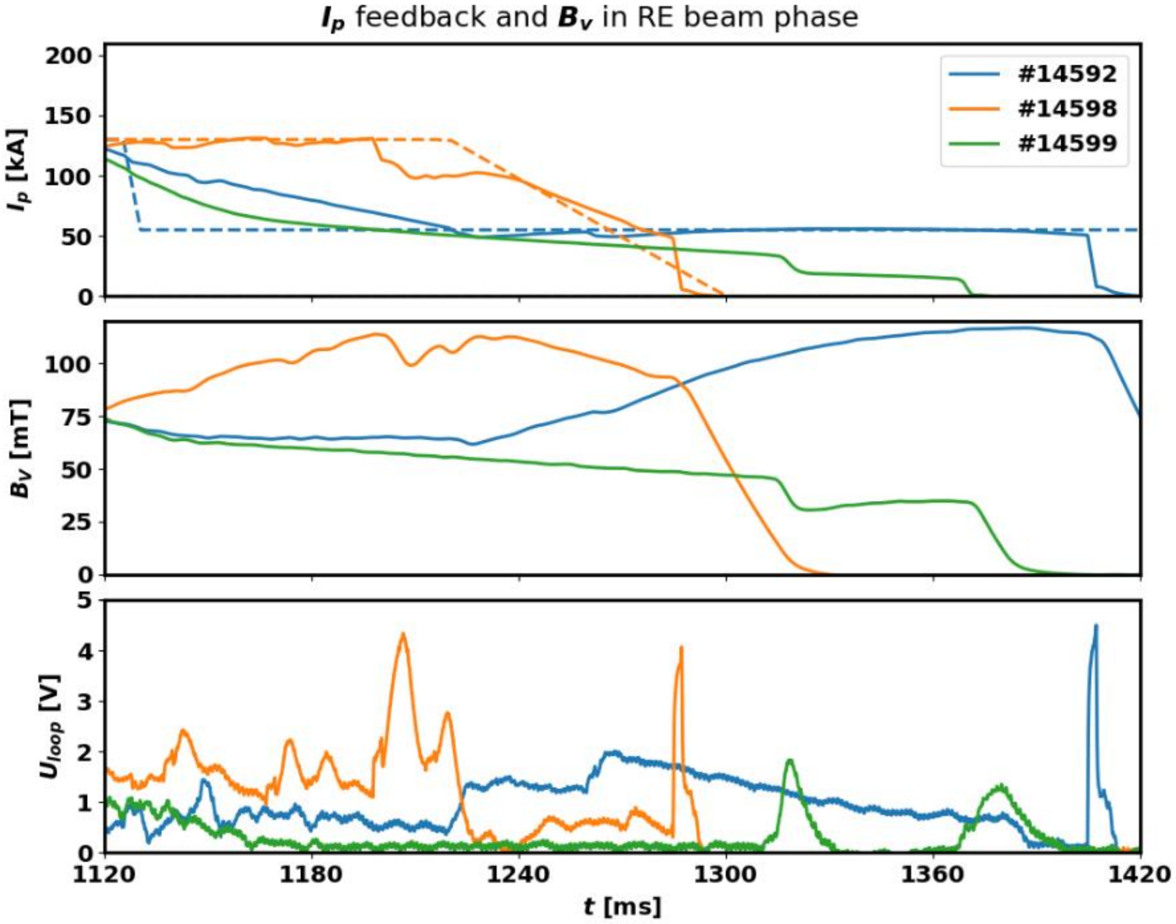


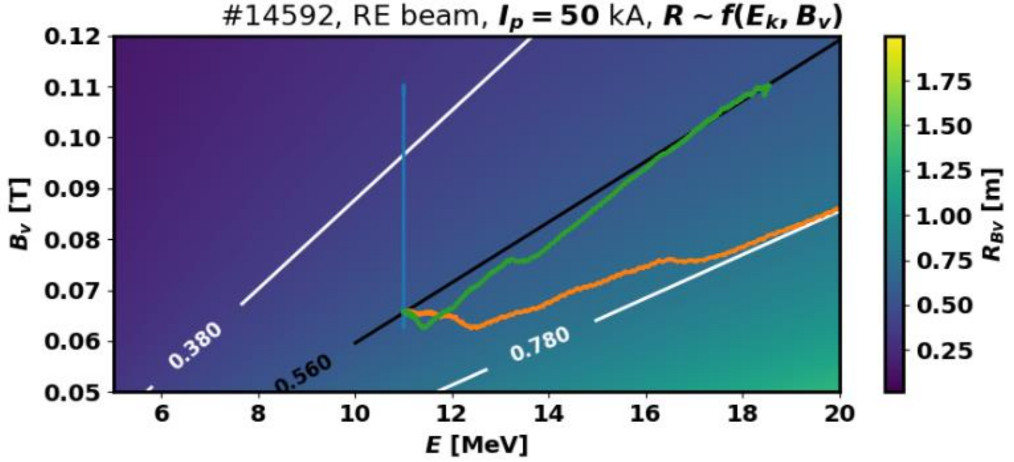

- Reproducible scenario with injection during the flattop of low dnesity discharge
- Thermal componet destroyed, zero-external loop voltage
- Suitable for scans – gas type and amount, evolution of energy during the decay, etc

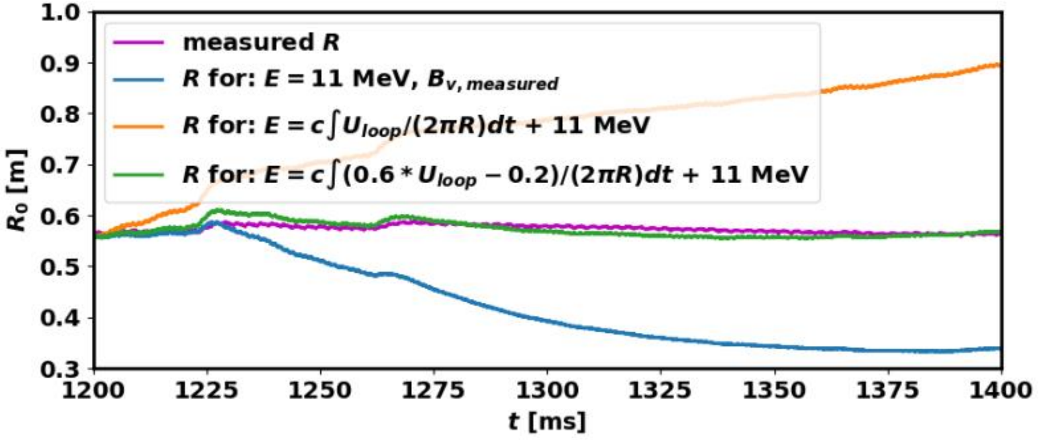


# Feedback of RE beam and relativistic Larmor radius in vertical field

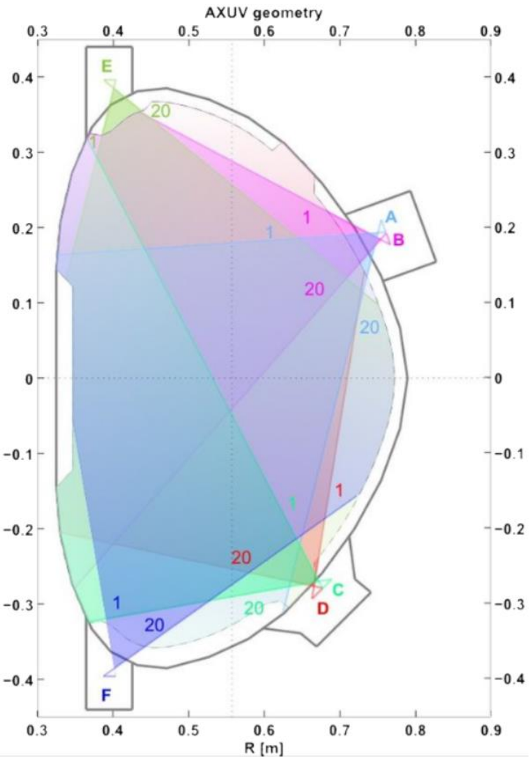
Stable orbit in classical betatron: $B_v \approx E_k/(ecR_0)$



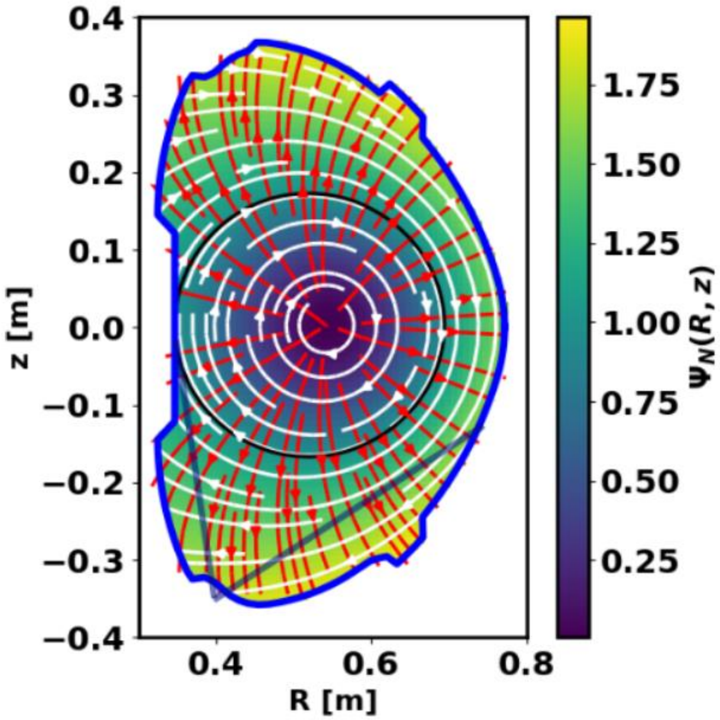



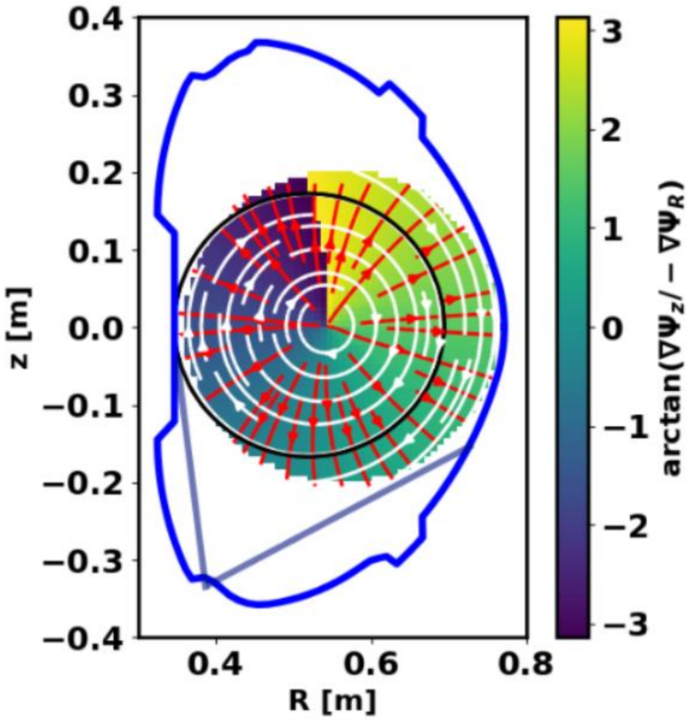



# TOMOGRAPHY OF RE beam – Radiated power during the decay

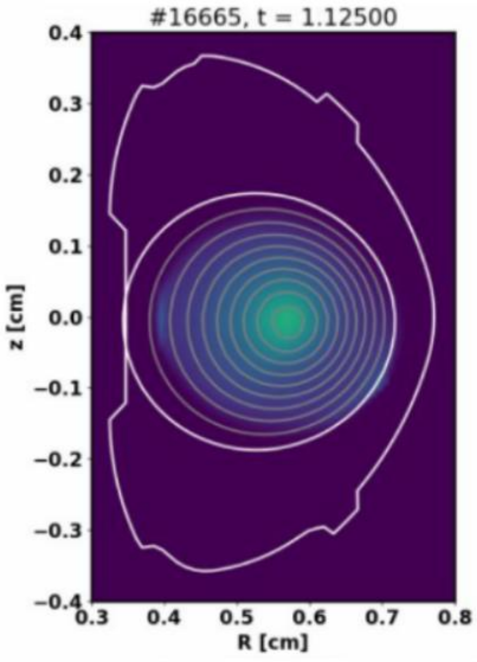



SMOOTHING MATRIX + BOUNDARY CONDITIONS



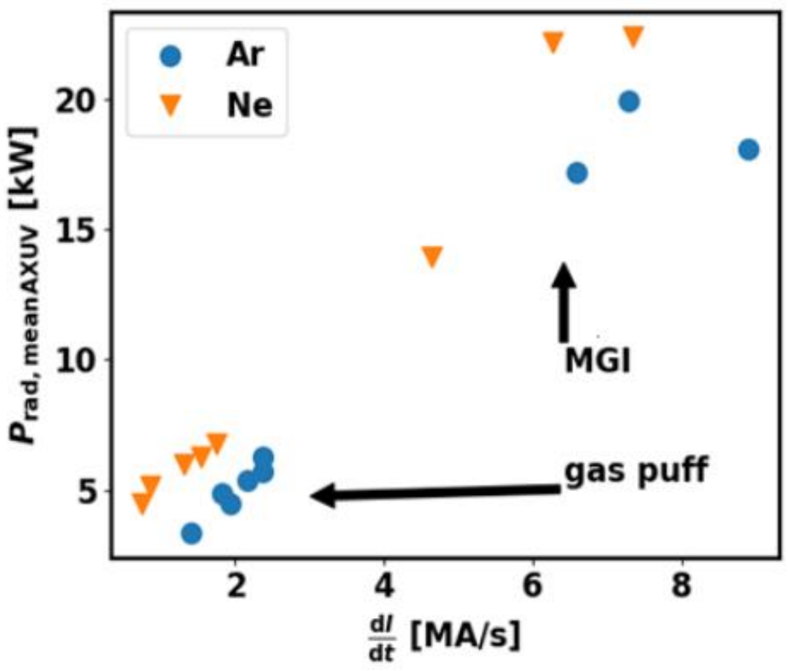



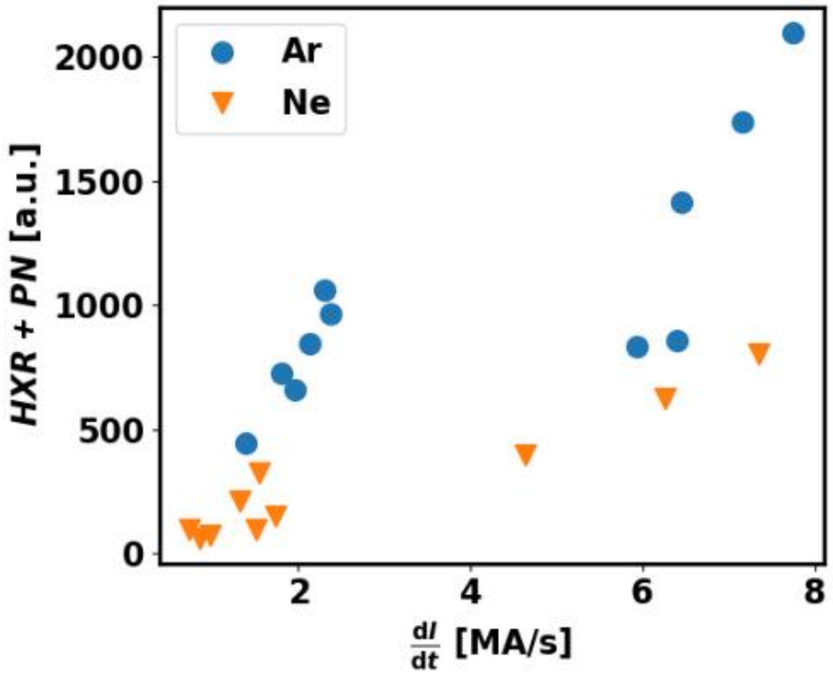

RECONSTRUCTED EMISSIVITY OF RE - Ar gas INTERACTION

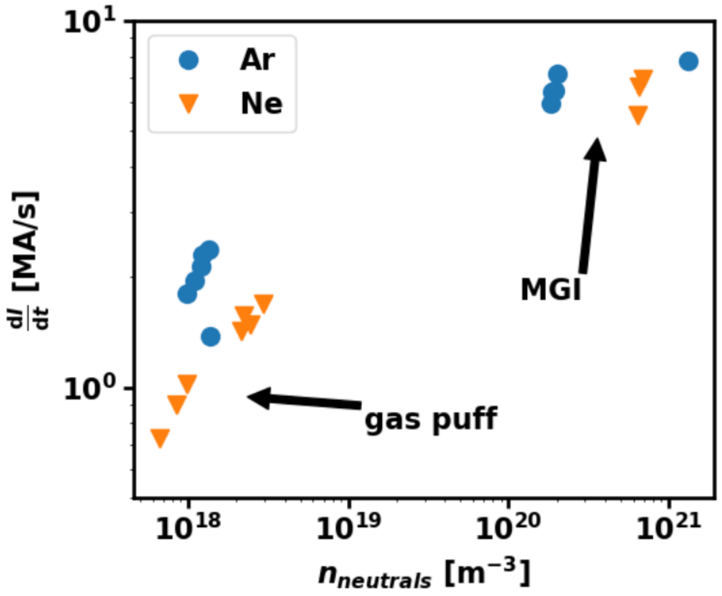


# Effects of gas puffs

- Gas amount / type scan
- Some signatures of saturation with high injected amount
- Slightly faster dI/dt for Ar
- More AXUV radiation for Ne
- More HXR/Photoneutrons for Ar

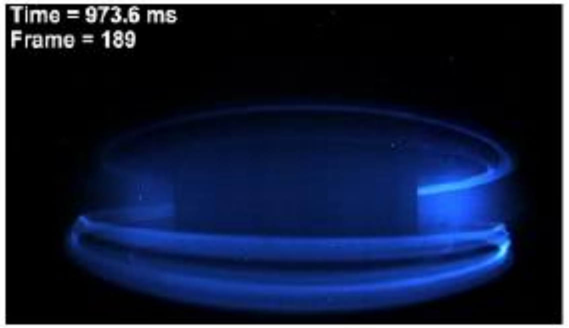


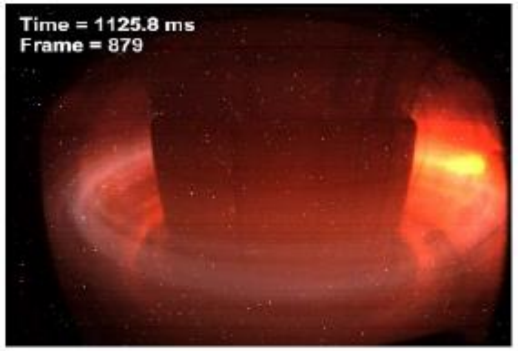



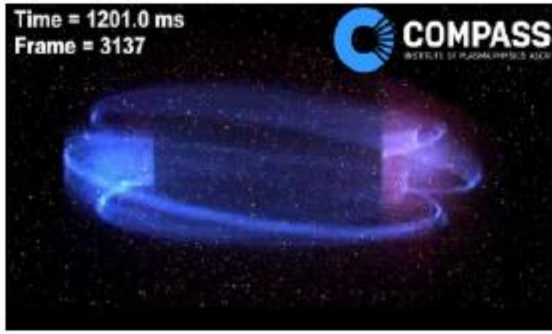



# Conclusions

- Runaways are still a big issue for ITER
- Disruption mitigation strategy further optimised
- COMPASS strongly involved
- Energy measurement
  - HXR spectrometry (shielding+collimation)
  - Synchrotron radiation (complicated relation)
  - Modified magnetic equilibrium (better understanding needed)
- Radiation of RE beam decay can be studied using tomography
  - There are problems with radiation, etc.

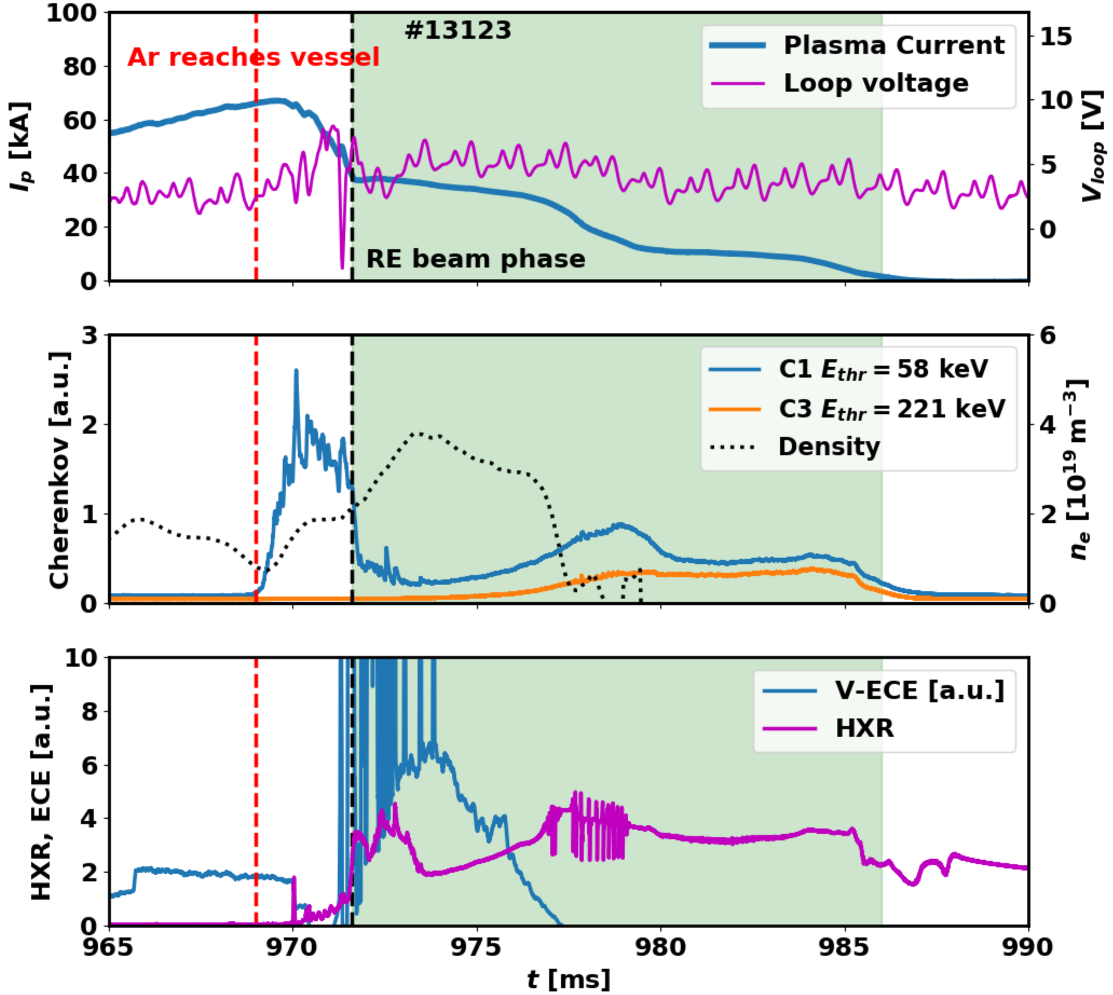


# Spare slide: scenarios

- Ramp-up RE beam generation




- Flattop destruction of thermal plasma