Overview of the current state of runaway electron measurements at the GOLEM tokamak

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GOLEM introduction

- GOLEM RE team: three doctoral students (Lukáš Lobko, Štěpán Malec, Marek Tunkl) + supervisors
- We all have inclined to HXR or neutron diagnostics during our pregradute studies -> naturally wanted to continue in that -> doctorate at GOLEM, because currently GOLEM only operating machine

→>> then next slide, GOLEM introduction…

Outline

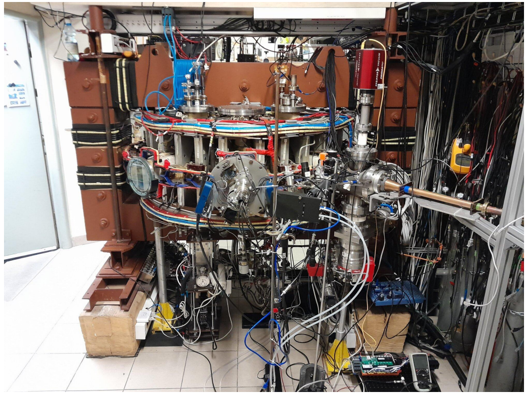
1. **GOLEM tokamak**
2. **Runaway electron diagnostics**
   - Scintillation detectors
   - Timepix3
   - In-vessel RE probe
3. **Modelling / data analysis**
   - Scintillators response functions
   - Energy spectra reconstruction
   - RE strike point determination
   - MHD-RE cross-correlation

1. GOLEM tokamak

GOLEM tokamak introduction

- small size machine from 60s, rebuild in 1984,

  from 2009 operated at CTU in Prague
- basic parameters
  - R = 0.4 m
  - a = 0.085 m (circular limiter)
  - $T_e \cong 100$ eV
  - $n_e \cong 10^{18} - 10^{19}$ m^{-3}
- education on-site and remote
  - high school projects, university training courses, BSc, MSc theses, …
  - 2025 so far ~ 800 discharges, ~ 350 remote



GOLEM scientific missions

- high and cheap discharge repetition rate (3mins) and not so harsh environment

→ good diagnostics testing bed

- probe measurements
  - fast ion-temperature
  - transport barrier in He

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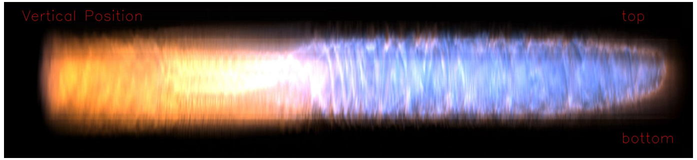
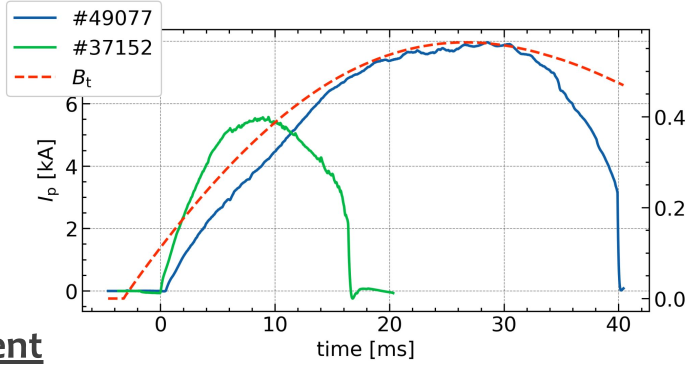


- **recently:** significant technological improvements:
  - $B_t \approx 0.4$ T → $B_t \leq 0.8$ T
  - $I_p \approx 4$ kA → $I_p \leq 14$ kA
  - $t_p \approx 15$ ms → $t_p \leq 41$ ms



- High U_{loop} + low n_e

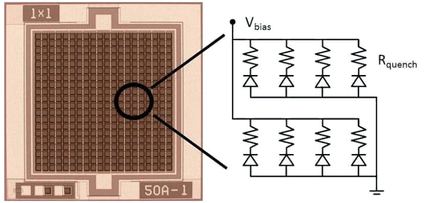
→ easy RE generation

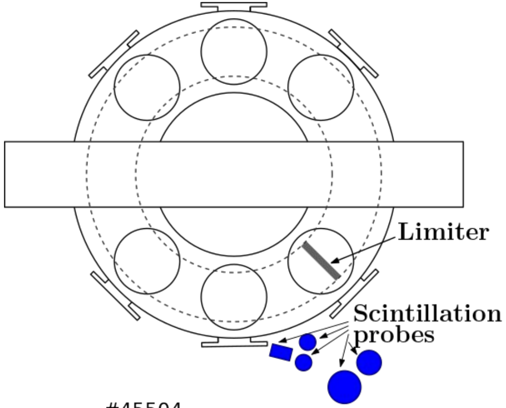
→ **RE diagnostics testing/development**

2. Runaway electron diagnostics

Scintillation detectors

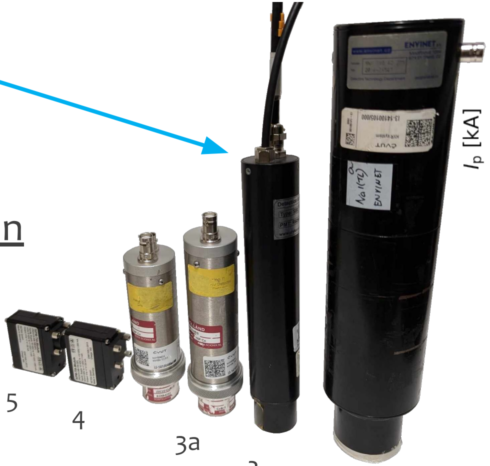
- use of various scintillation crystals
  - NaI:Tl
  - YAP:Ce
  - $CeBr_3$
  - LYSO:Ce:
  - GAGG:Ce
- traditional PMTs or SiPM

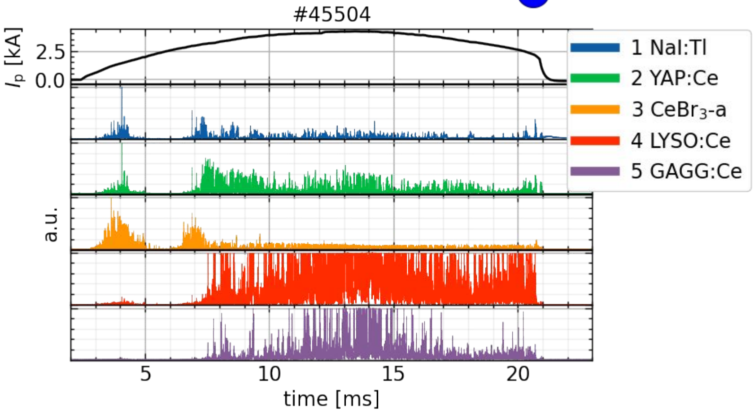




- powerful DAS (250 MS/s, 15bit)

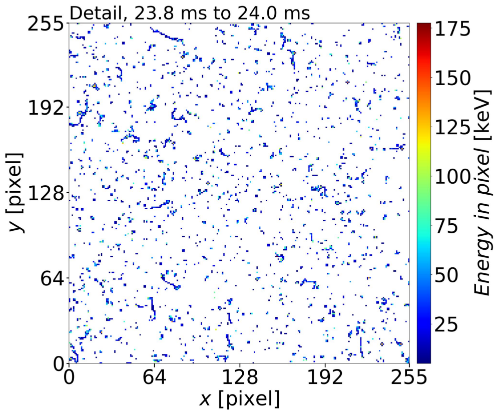
→ <u>peak energy discrimination</u>

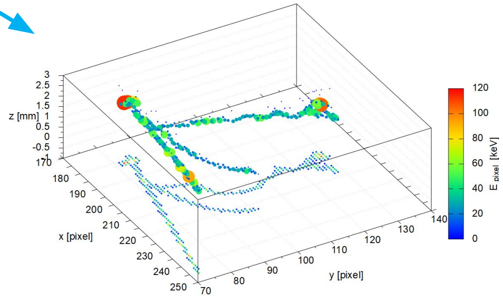


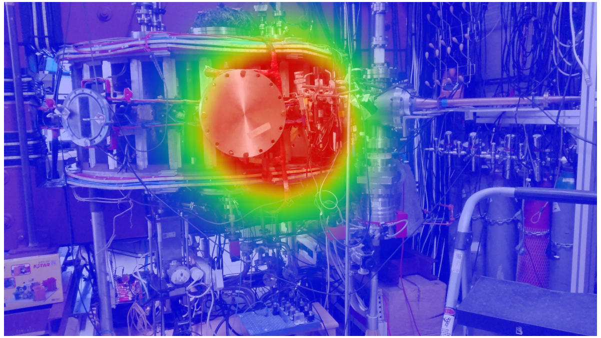


Timepix3 semiconductor pixel detector

- compact high energetic particle detector (developed by CERN)
- pixel array (256 x 256 pixels)
- CdTe and Si sensors → various energy detection efficiency
- thermal stabilization is usually needed
- easier avoidance from pileups than typical scintillators
- various applications:
  - spatial measurements
  - Compton camera
  - 3D interaction reconstructions

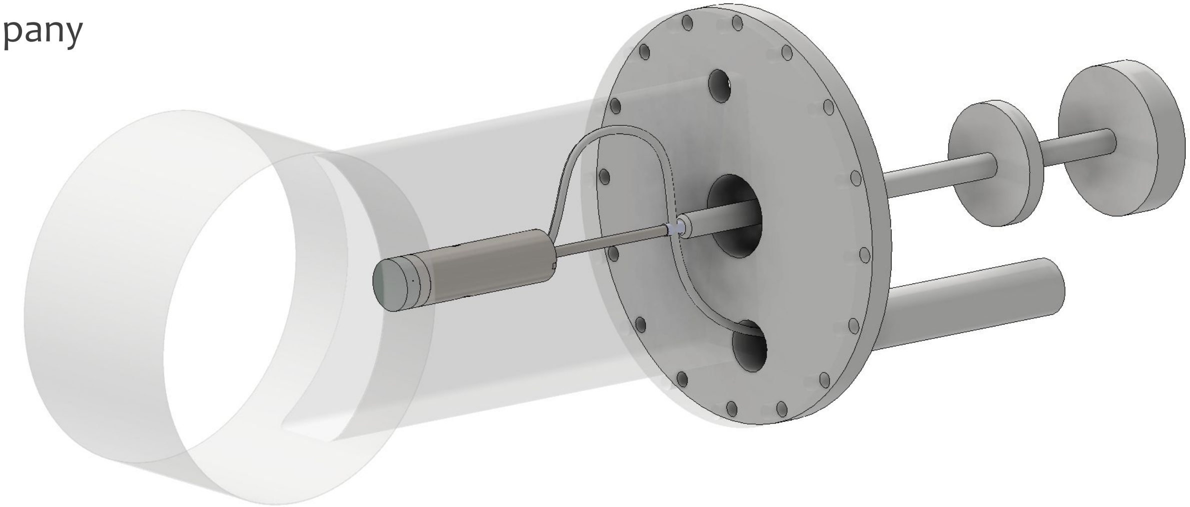






New in-vessel scintillation probe

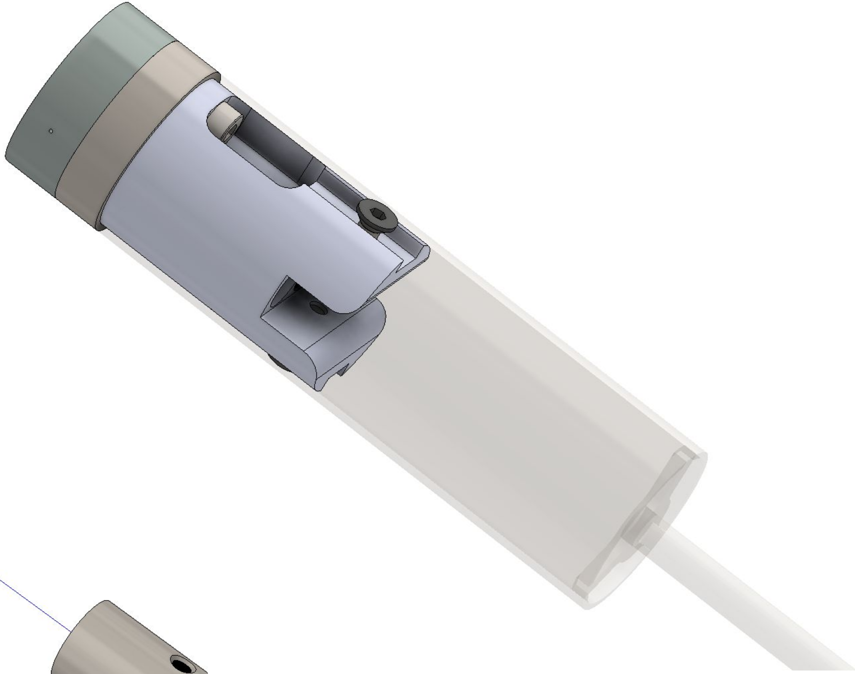
- Goal: **<u>direct measurement of REs</u>**
- scintillation probe placed inside the tokamak chamber
- REs → direct hit of scintillation pins → optical fibers → SiPM (outside the chamber) → oscilloscope
- manipulator → <u>easy to change radial position and the observed angle</u>
- collaboration with **crytur** company

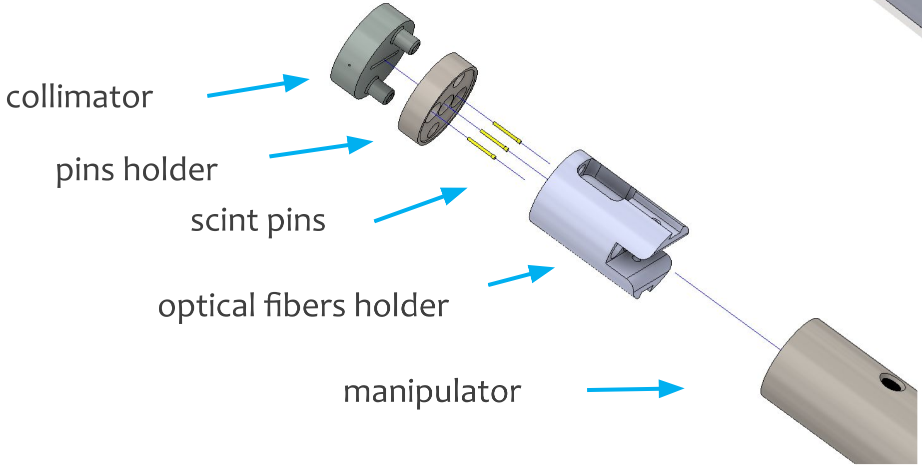


Current Probe design

- Compact size of the whole probe - 93 x 25 mm
- Very flexible design (no glued parts)

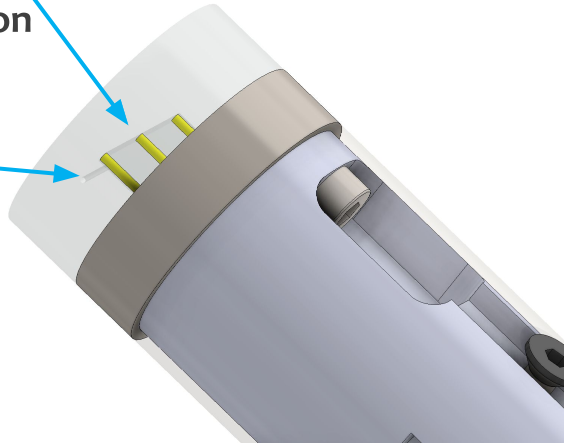
→ **testing of various types of collimators, pins/coating thickness, etc.**

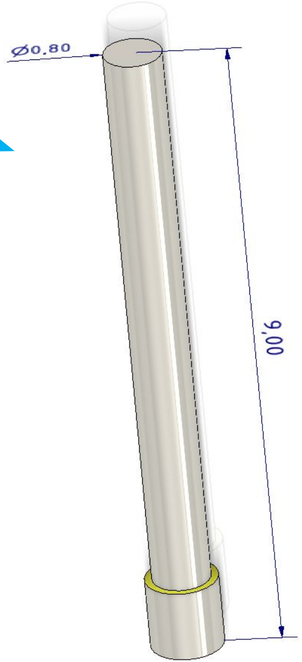




Detailed design of in-vessel probe

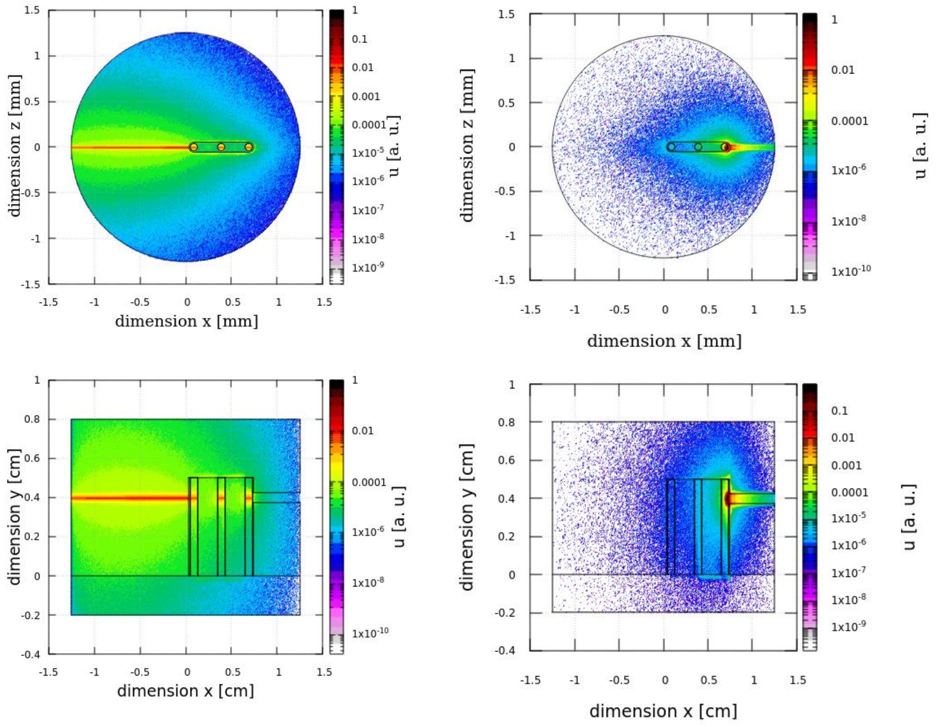
- Very small scintillation pins are used - 0.8 mm diameter with 1 μm Ti cover
- **YAP:Ce** scintillator (CRYTUR crystals) - fast decay time (approx. **25 ns**) → possible **peak energy resolution**
- First approach - line of three scintillation pins → possible **additional energy discrimination**
- Mo collimator with 5 x 0.5 mm pinhole → possible **pitch angle measurement**





HXR vs electron absorption

- FLUKA modelling
- testing of various material and thicknesses of scintillation pins, coating and collimator
- 1 MeV HXR (left fig.) vs electron (right fig.) beam penetration comparison



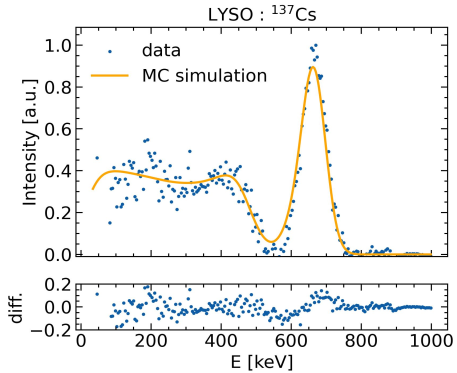
→ low sensitivity to HXR background

→ <u>mostly direct RE detection</u>

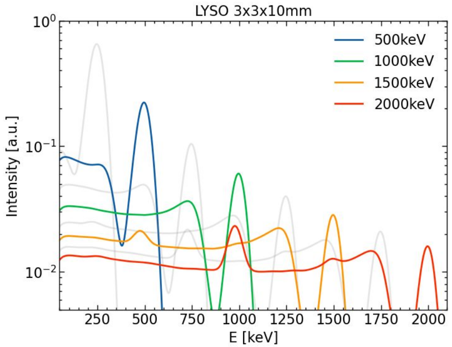
3. Modelling / data analysis

Modeling of scintillators response functions

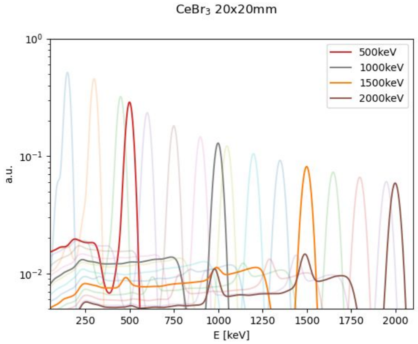
- Geant4 modelling of detector response functions
- Results compared to real data (^{137}Cs - 661 keV)



- too small scintillation crystal
  → rapid response decrease to higher energies



bigger CeBr3 for comparison



RE Energy spectra reconstruction

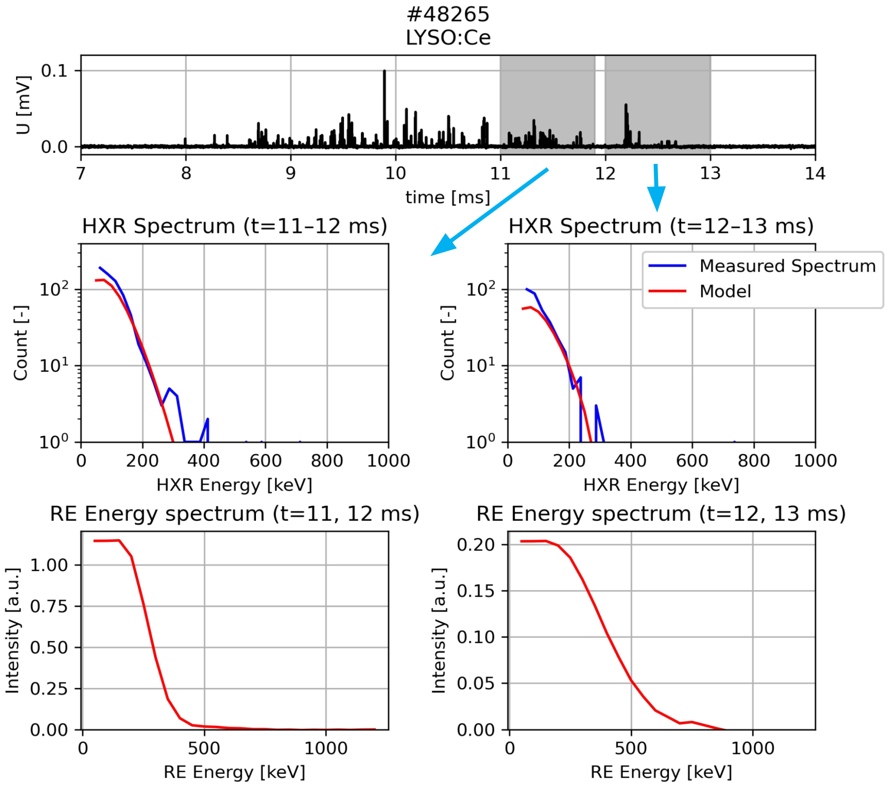
- detector response functions ($\mathbf{D}$)
  + bremsstrahlung ($\mathbf{B}$) modeled in Geant4
- measured signal (S), runaway distribution (F)

- $S = \mathbf{D} \cdot \mathbf{B} \cdot F$

- inversion problem – solved by Tikhonov Regularization using Tomotok code

- sensitive to data quality

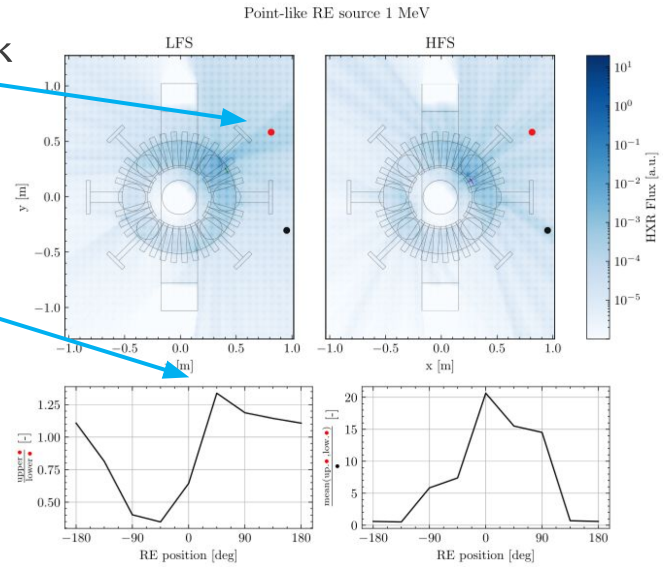
  → now only possible for moderate RE discharges
  (= no pileups, no PMT gain loss)



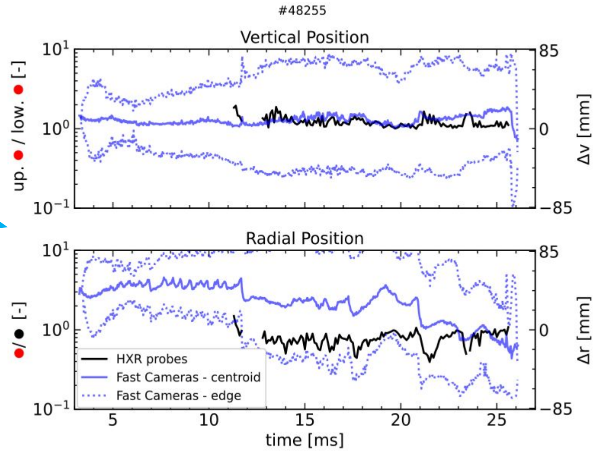
RE strike point determination

- Goal: recover strike point position and RE pitch angle (not yet)
- 3 LYSO detectors placed at different positions (2 red and 1 black dots)

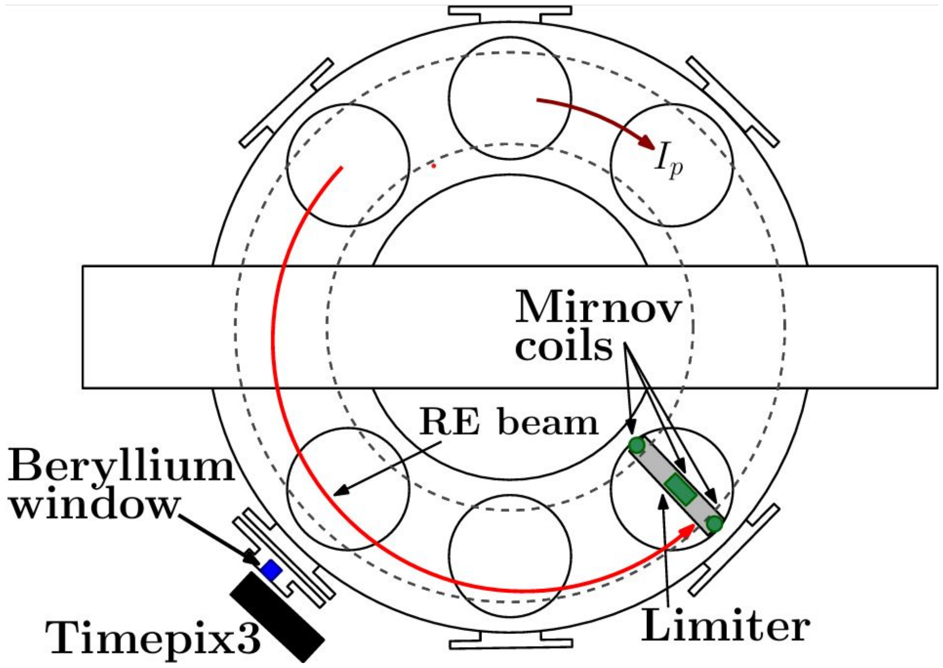
seems enough for RE strike point determination



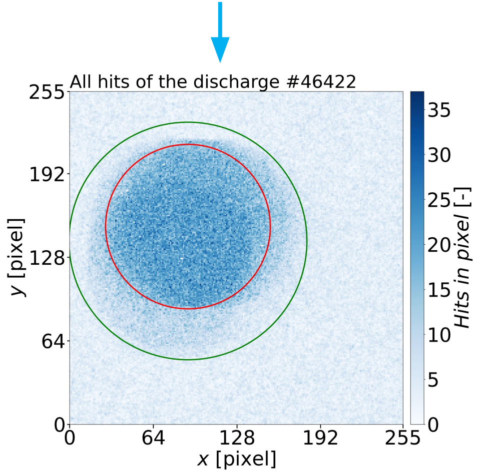
- <u>Comparison of plasma position by fast visible cameras</u>



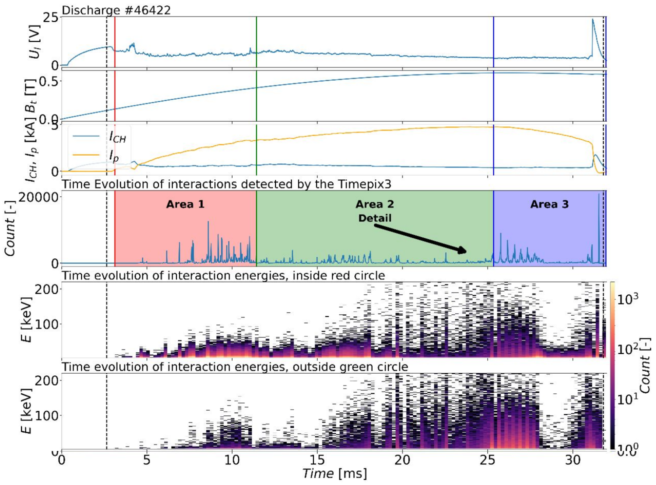
MHD-RE cross-correlation analysis experimental setup



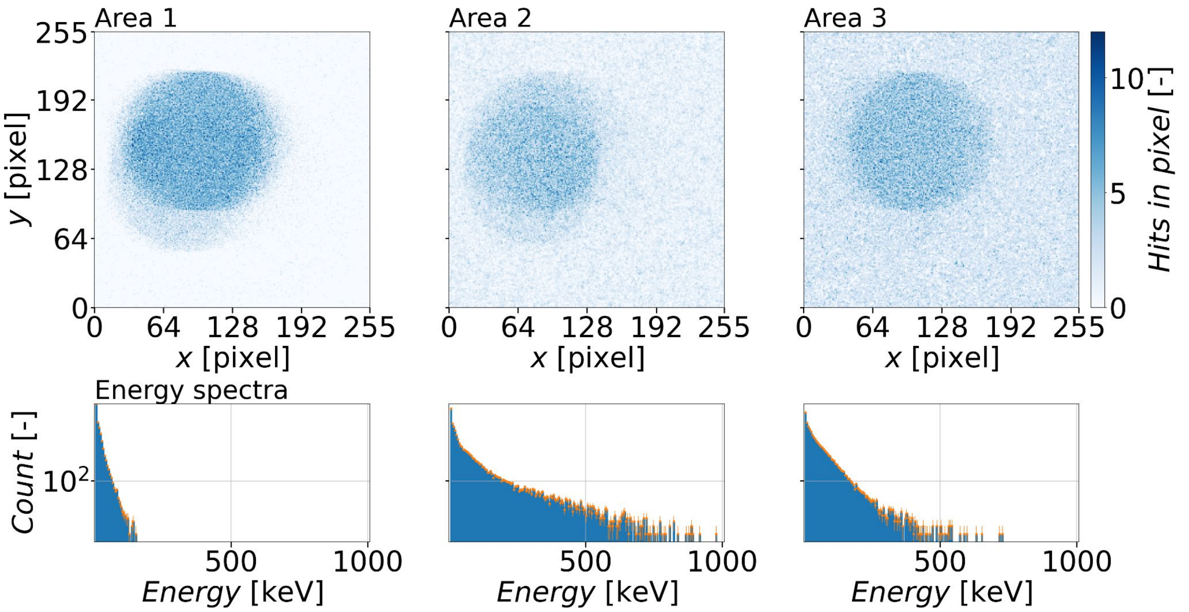
- First attempt to find MHD correlations with Timepix3 signal
- 4 mirnov coils poloidally placed near Mo limiter
- Timepix3 placed behind Be window (to access lower X-ray energies)



MHD-RE cross-correlation analysis

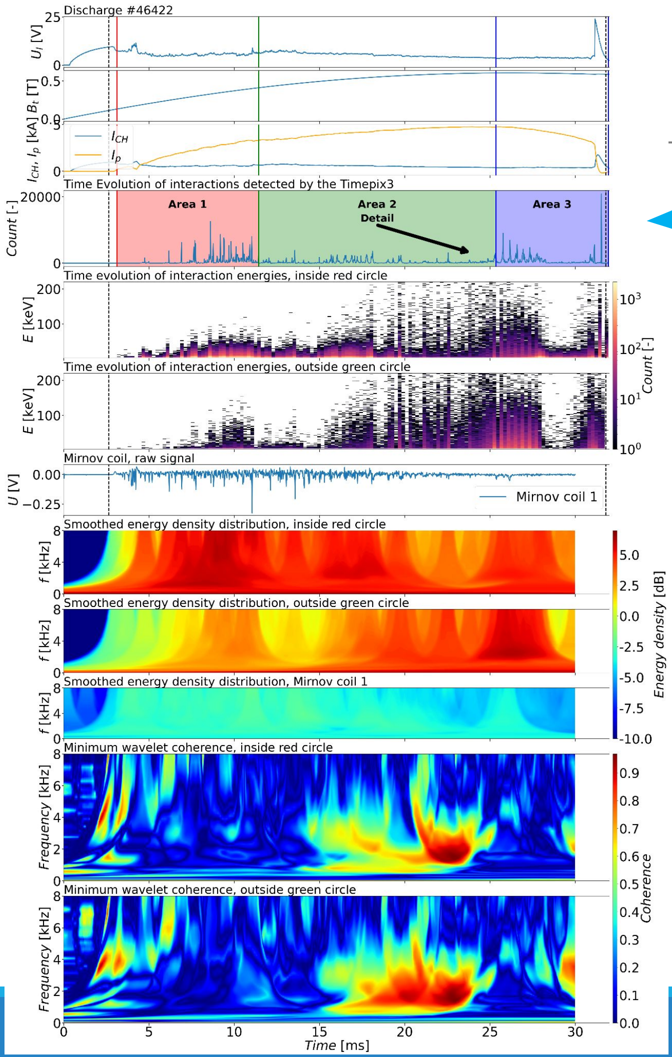


- Three intervals evenly split by total count
- Energy spectra from each interval is shown



- <u>Middle interval with highest MHD-correlations corresponds to highest energies in Timepix3 spectra</u>

MHD-RE cross-correlation analysis



- The discharge is divided into three intervals with equal interaction counts.
- Visible difference in low energies (Be window)
- Each signal is analysed via **continuous wavelet transform** (order-3 analytic **Morlet wavelets)**
- Wavelet coherence is calculated by the formula:

$$\mathrm{COH}_{x,y}(\mu,\xi) = \frac{\left|\overline{W_x(\mu,\xi)W_y^*(\mu,\xi)}\right|}{\sqrt{\overline{W_x(\mu,\xi)W_x^*(\mu,\xi)}\;\overline{W_y(\mu,\xi)W_y^*(\mu,\xi)}}}$$

W_{Be}

$W_{\mathrm{non-Be}}$

$W_{\mathrm{Mirrnov\ 1}}$

- Minimum wavelet coherences highlight the HXR–MHD correlation.

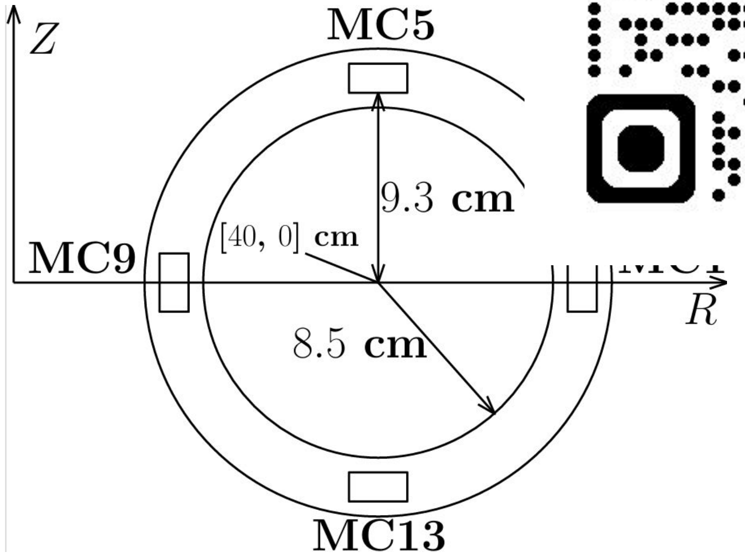
$$\min_i \mathrm{COH}_{\mathrm{Mirrnov}\ i,\, W_{\mathrm{Be}}}(\mu,\xi)$$

$$\min_i \mathrm{COH}_{\mathrm{Mirrnov}\ i,\, W_{\mathrm{non-Be}}}(\mu,\xi)$$

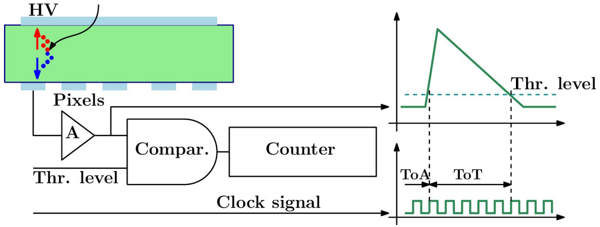
Conclusion

- GOLEM tokamak is used as RE diagnostics testing bed.
- Various RE detectors were presented:
  - Scintillation detectors - combination of different crystals with signal readout
  - Timepix3 - excellent spatial, energy and time resolution, enabling the study of individual interactions.
  - In-vessel probe - designed for direct RE measurement (energy, pitch angle)
- Progress in data analysis:
  - Successfully modelled scintillators response functions
  - Promising energy spectra reconstruction
  - Demonstration of simple inference of RE target position
  - Wavelet analysis points to MHD driven runaway losses

Backup



Z
MC5
9.3 cm
[40, 0] cm
MC9
R
8.5 cm
MC13



HV
Pixels
A
Compar.
Counter
Thr. level
Clock signal
Thr. level
ToA
ToT