Study of runaway electron dynamics at the ASDEX Upgrade tokamak during impurity injection using fast gamma-ray spectrometry

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ABSTRACT

- Two high-performance gamma-ray spectrometers with fast $LaBr_3$(Ce) scintillation-detectors, advanced electronics and analysis algorithms have been developed and commissioned at the ASDEX Upgrade tokamak (AUG).
- HXR measurements were carried out in the RE beam generation regimes by injecting argon gas into a deuterium plasma.
- The electron energy distributions were reconstructed from the measured HXR spectra by deconvolution methods.
- Argon density in AUG plasma after Massive Gas Injection was estimated using HXR measurements.
- The experimentally obtained maximum RE energies at different discharge stages were compared with relativistic test particle simulations that include the effect of toroidal electric field, plasma collisional drag force, synchrotron deceleration force.

BACKGROUND

Gamma-ray spectroscopy of hot plasma allows estimation of the energy distribution of runaway electrons (RE). Observation of confined REs is possible on medium and large tokamaks such as DIII-D, ASDEX Upgrade (AUG) and JET. Experiments of RE generation and suppression, following the onset of plasma disruptions, are conducted in ASDEX Upgrade to validate theoretical models, which can then be used to evaluate post-disruption levels of RE current and design RE mitigation schemes in larger devices like ITER and DEMO. This report is devoted to using gamma-spectrometric measurements provided by two high-performance LaBr3(Ce) gamma-ray spectrometers and the RE dynamics analysis based on the data obtained in experiments with gas injection the AUG plasmas.

INSTRUMENTATION AND APPLIED METHODS

Instrumentation

Two $LaBr_3$(Ce) spectrometers are used in the HXR measurements in during experiments at AUG with MGI in deuterium plasmas. They allow conducting γ-ray measurement in the range of **0.1-30 MeV** with energy resolution **~3.5% (at 662 keV)** and counting rate up to **~10^7 s^{-1}**

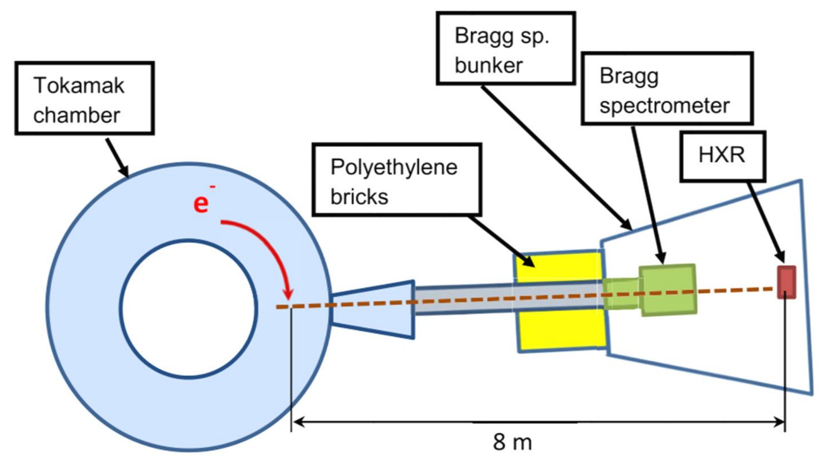

Fig. 1- AUG-HXR spectrometer:
- $LaBr_3$(Ce) Ø25x17 mm installed in the bunker behind the Bragg spectrometer
- DAQ: 14-bit resolution ADC operating in the segmented mode; 400 MHz sampling rate.

M. Nocente, et al., RSI 89 (2018) 10I124

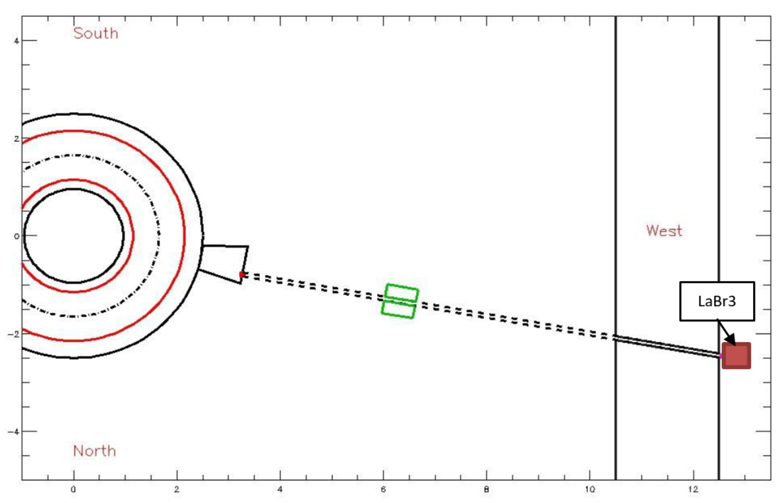

Fig. 2 - REGARDS spectrometer
- $LaBr_3$(Ce) Ø25x25 mm installed behind the bio-shield. Lead collimator Ø10×100 mm
- DAQ: 14-bit resolution ADC recording the **whole signal**; 400 MHz sampling rate.

A. Dal Molin, et al., 46th EPS CPP 2019 P1.1015

REDF reconstruction

ML-EM (maximum likelihood estimation using expectation maximization) method was realized in the DeGaSum code for the RE distribution function (REDF) reconstruction

$$y(\varepsilon) = \int_0^\infty d\varepsilon'\, h_d(\varepsilon,\varepsilon') \int_0^\infty d\varepsilon''\, h_e(\varepsilon',\varepsilon'') f(\varepsilon'') + n(\varepsilon),$$

y – recorded HXR spectrum; ε, ε', ε" – energies; n(ε) – statistical noise; f - runaway electron distribution function; h_d - gamma-ray detector response function; h_e is HXR generation function. h_e and h_d calculated with MCNP code in the range of **0.1-30 MeV**

A. Shevelev, et al., NIM A 830 (2016) 102–108

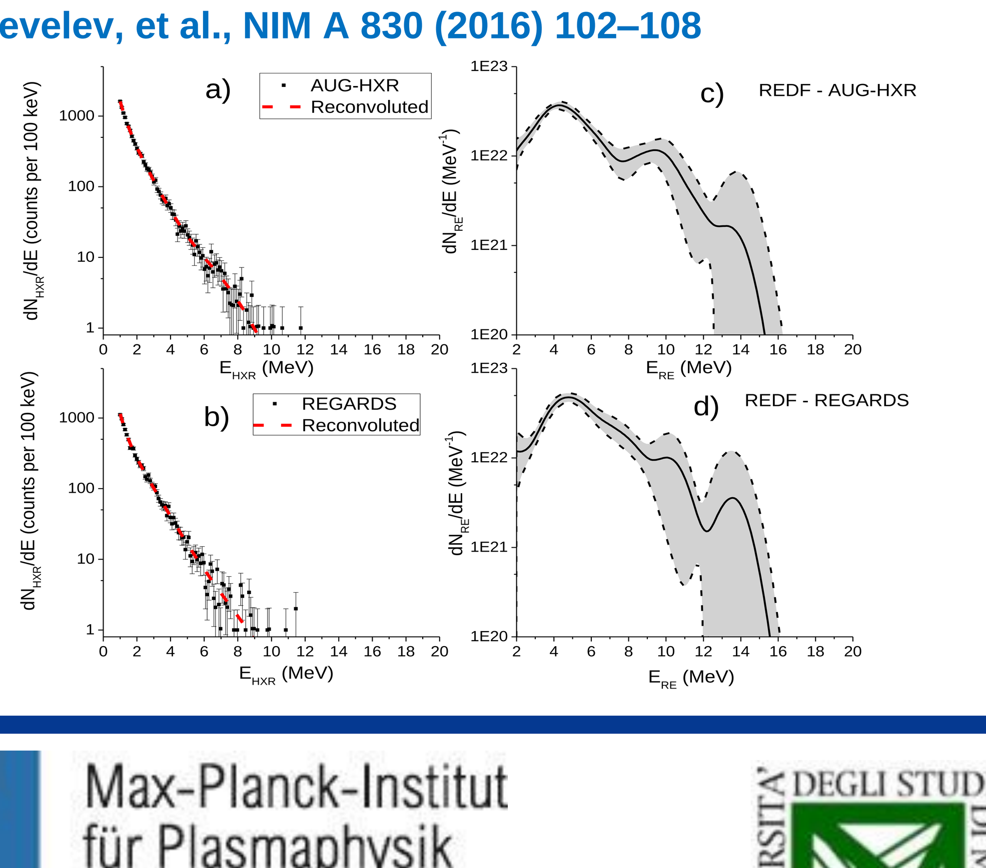

Fig. 3 - 1.03-1.06 s of the AUG discharge #36431: a) HXR spectrum measured by AUG-HXR (black dots); b) HXR spectrum measured by REGARDS (black dots); c) REDF reconstructed from the AUG-HXR spectrum; d) REDF reconstructed from the REGARDS spectrum

OUTCOME

Argon density evaluation

The analysis of the obtained runaway electron distributions provided the assessments of the gas target's density and the RE beam fraction visible for spectrometers. Assessed argon density coincides with argon fueling efficiency after the first injection, 60 ± 20%, provided in [**Pautasso, G., et al., Nucl. Fusion 60 (2020) 086011**]

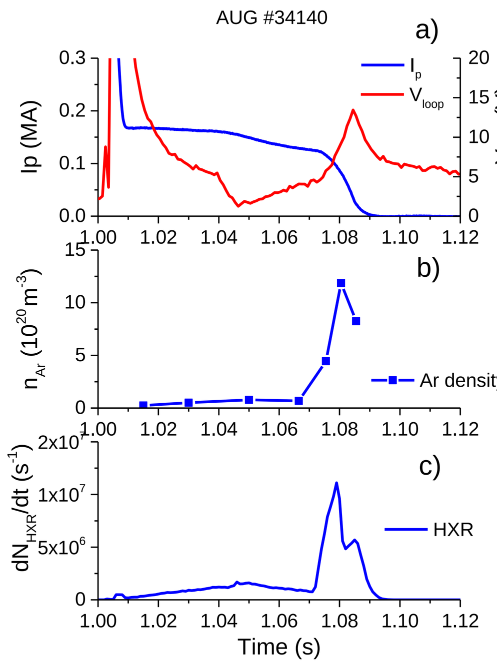

Fig. 4 - Discharge #34140 with the second argon injection: a) I_p and V_{loop}; b) argon density reconstructed from HXR measurements; c) AUG-HXR spectrometer count rate

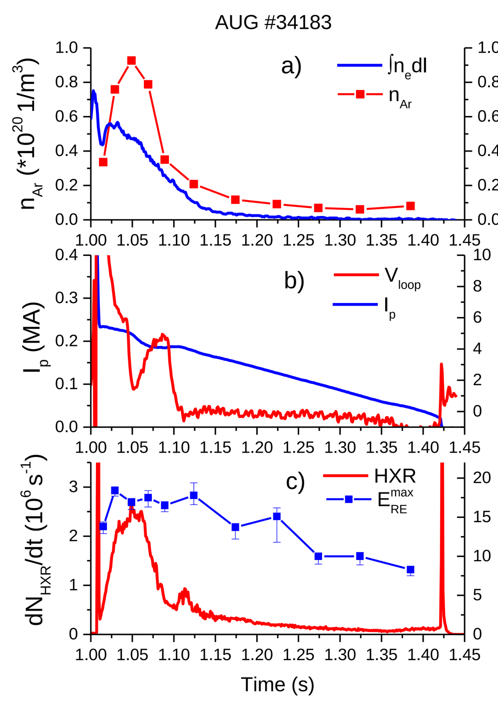

Fig.5 - Discharge #34183 with D_2 pellet injections: a) Line integrated n_e and argon density assessed from HXR measurements; b) I_p and V_{loop}; c) AUG-HXR detector count rate and obtained E_{RE}^{max}

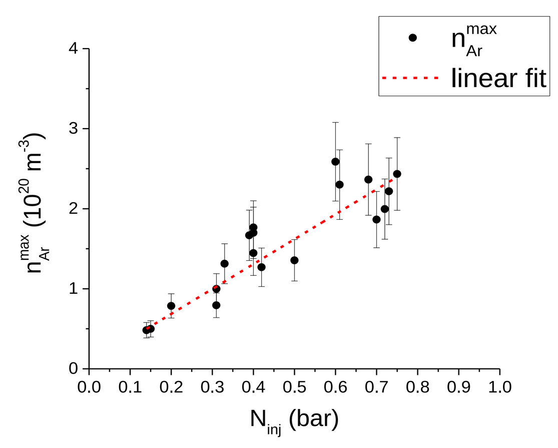

Fig. 6 - Dependence of the maximum Ar density estimated using DeGaSum calculations vs injected argon value

Evolution of RE maximum energy

- REs attain their maximum energies of about 20 MeV within 50-100 ms after the gas injection. After that it gradually decreases
- Test particle calculations with the PREDICT code demonstrated that E_{RE}^{max} to correspond to the measured values, the argon density must be by order of magnitude lower than the values provided by HXR measurements.
- E_{RE}^{max} value decreases from about 18 to 16 MeV when N_{inj} rises from 0.14 to 0.75 bar
- The similarity in the E_{RE}^{max} evolution dynamics for discharges with different amounts of injected argon

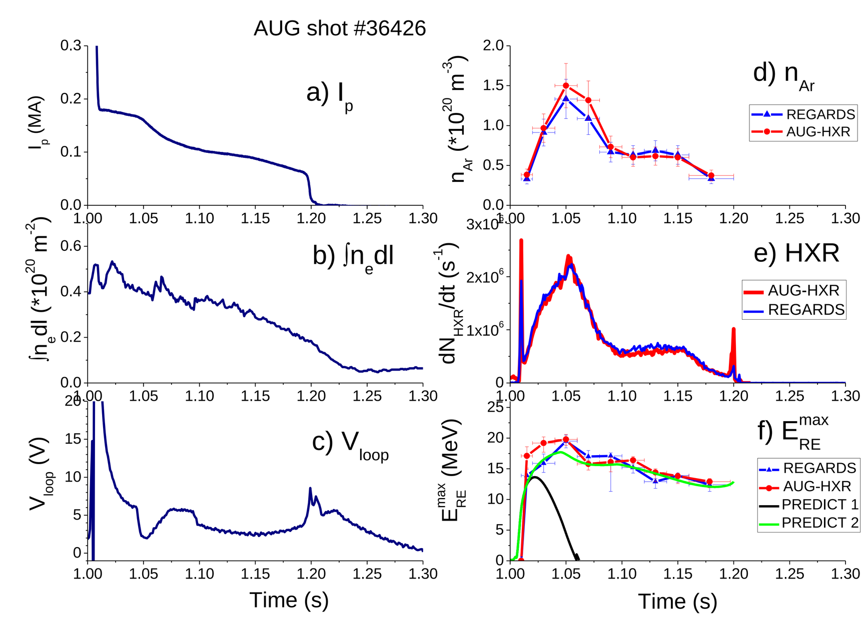

Fig.7 - Signals of AUG discharge #36426

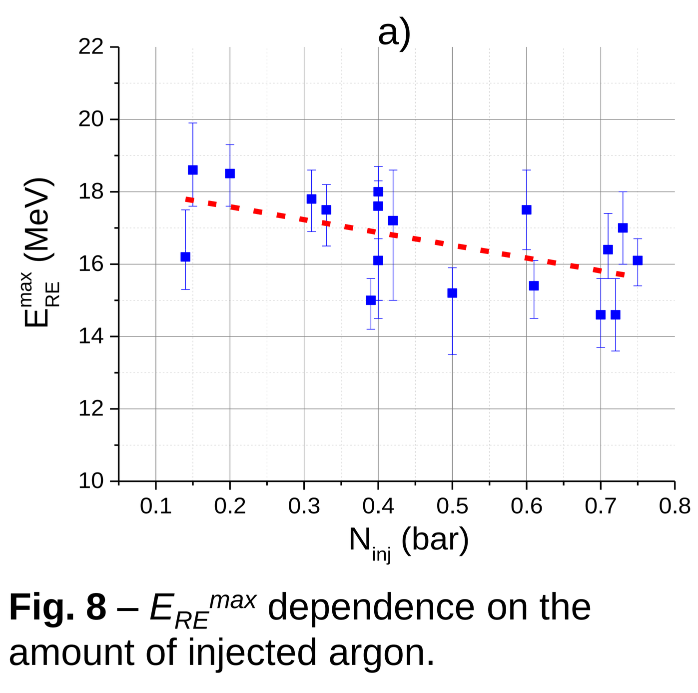

Fig. 8 – E_{RE}^{max} dependence on the amount of injected argon.

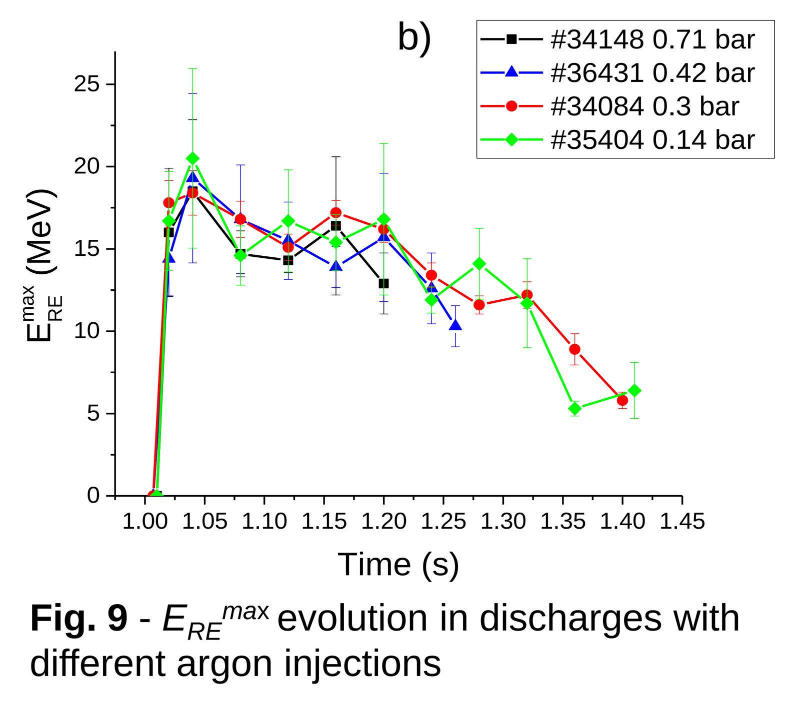

Fig. 9 - E_{RE}^{max} evolution in discharges with different argon injections

CONCLUSIONS

- Two high-performance $LaBr_3$(Ce) spectrometers have been developed
- HXR measurements were carried out in MGI experiments with RE beam generation
- RE distributions were reconstructed from measured HXR spectra using the DeGaSum code
- Two spectrometers with small scintillators made it possible to analyze gamma radiation caused by runaway electrons in the energy range up to 30 MeV.
- The evolution of RE Emax was studied for various amounts of injected argon: runaway electrons attain their maximum energies of about 20 MeV within 50-100 ms after the gas injection. After that it gradually decreases
- The density of argon interacting with the RE beam was estimated
- Test particle calculations demonstrated that E_{RE}^{max} to correspond to the measured values, the argon density must be by order of magnitude lower than the values provided by HXR measurements.
- The realized system allowed testing the technical solutions and data processing algorithms for ITER runaway diagnostics.

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