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Synchrotron Radiation from Runaway Electrons in COMPASS Tokamak

Milos Vlainic[1,2], Petr Vondracek[2,3], Jan Mlynar[2], Vladimir Weinzettl[2], Ondrej Ficker[2,4], Mykyta Varavin[2], Richard Paprok[2,3], Martin Imrisek[2,3], Josef Havlicek[2,3], Radomir Panek[2], Jean-Marie Noterdaeme[1,5] and the COMPASS Team

[1]Department of Applied Physics, Ghent University, Sint-Pietersnieuwstraat 41, Technicum B4, Ghent B-9000, Belgium
[2]Institute of Plasma Physics AS CR v.v.i., Za Slovankou 3, CZ-18200 Prague 8, Czech Republic
[3]Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, CZ-18000 Prague 8, Czech Republic
[4]Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Brehova 8, CZ-11519 Prague 1, Czech Republic
[5]Max Planck Institute for Plasma Physics, Boltzmannstraße 2, D-85748 Garching, Germany

Abstract: In this paper it is demonstrated that the relative intensity of the infrared radiation is correlated with the critical energy for high energy runaway electron production. Furthermore, analysis of the first direct observation of the RE beam in COMPASS tokamak with the calibrated camera is presented.

1. Introduction

- **Background**: - a relativistic accelerated charged particle in the magnetic field emits the synchrotron radiation
  - the "headlight" effect → a tangential observation
- **Motivation**: - a disruption created Runaway Electrons (REs) can drag significant amount of the pre-disruptive plasma current
  - **possible severe damage of the in-vessel components**
  - **COMPASS has a relatively low safety constraints and a high experimental flexibility**
- **Runaway generation** can be divided as:
  1) Primary mechanism:
     a) Dreicer mechanism
     b) Hot-tail mechanism
  2) Secondary (avalanche) effect
- **Drag forces** acting on REs:
  1) Coulomb force
  2) Synchrotron Radiation (SR)

PARAMETER	VALUE
Major Radius R	0.56 m
Minor Radius	0.23 m
Toroidal Mag. Field	0.9-1.25 T
Plasma Current I_p	<400 kA
Discharge Length	<0.4 (1) s
Electron Density n_e	10^{19}-10^{20} m^{-3}

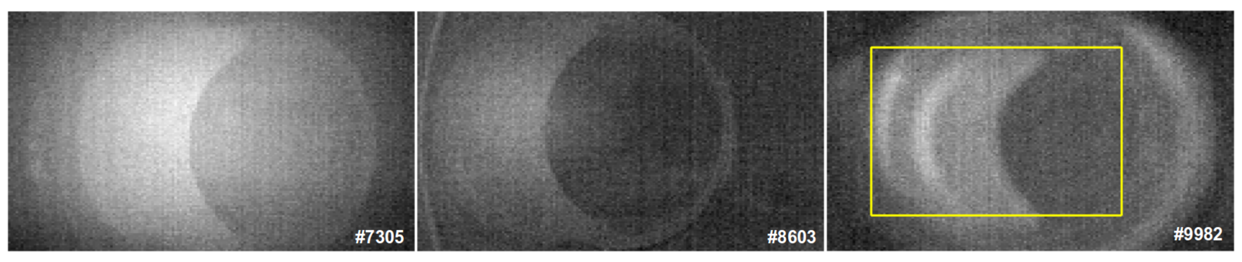
COMPASS tokamak parameters.

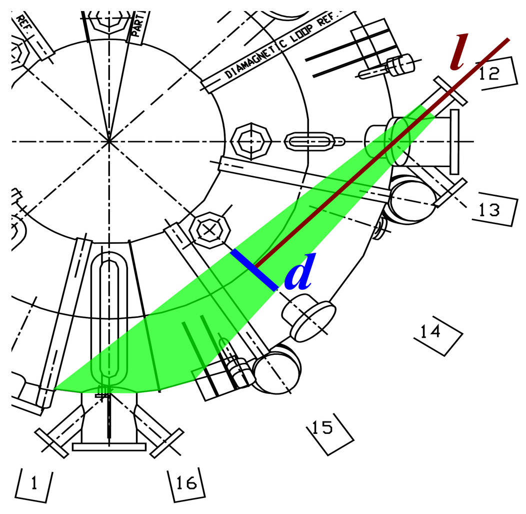
2. Experimental Setup

- **Dedicated RE campaigns:**
  - toroidal magnetic field 1.15 T
  - plasma current varied 100 - 250 kA
  - electron density usually under 5×10^{19} m^{-3}
- **InfraRed (IR) camera**:
  - **a bolometric detector with the characteristic thermal response time of 10ms**
  - **7.5-13 μm is the wavelength detection range**
  - **120 frames per second**

Campaign	Window type	Transparency	Window diameter	l	d
I: #7305	ZnSe	~70%	3.7 cm	111.6 cm	**14.9 cm**
II: #8603	Ge	80-95%	8.5 cm	139.5 cm	**16.9 cm**
III: 9982	Ge	80-95%	8.5 cm	153.5 cm	**15.5 cm**

The characteristic distances of the IR camera experimental setup for each runaway campaign. Distances l and d are defined in the figure below.





***Above**: The different observations corresponding to the different RE campaigns. The yellow rectangle corresponds to the observed area further analysed in Section 4. The moon-like shape is a carbon NBI beam dump. **Right**: Schematic of the tokamak with the IR camera field of view (green area). d and l*

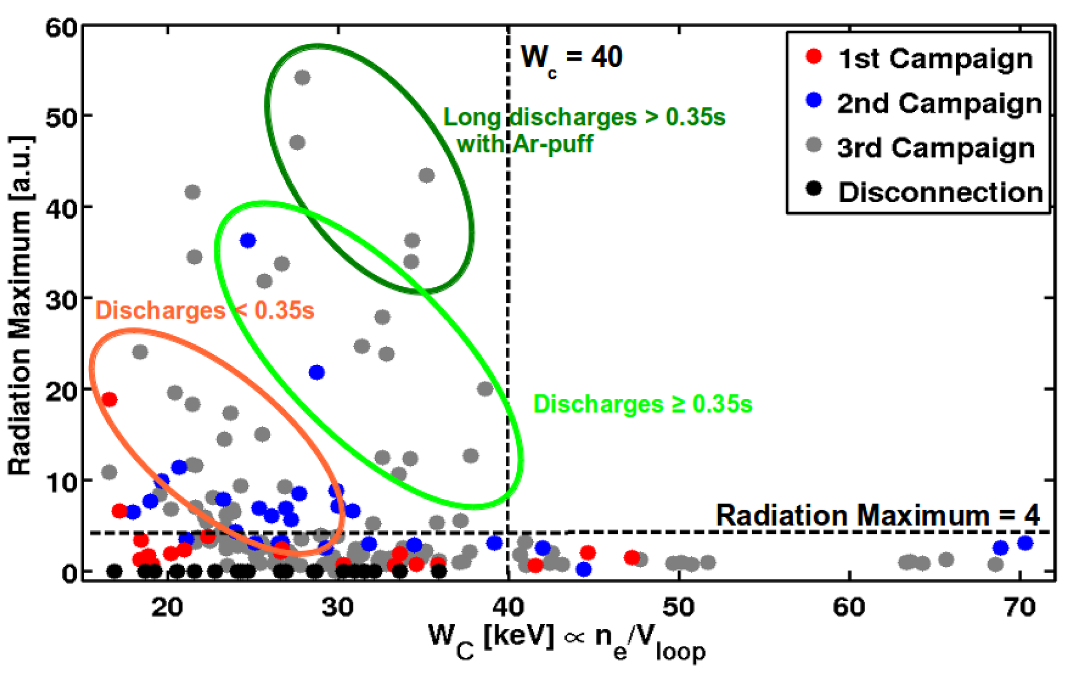
3. IR Radiation Maximum vs Critical Energy

- The critical energy for the runaway generation [1]:

$$W_c = \frac{e^3 \ln\Lambda}{4\pi\epsilon_0^2}\frac{n_e}{E_{tor}}\sqrt{2+Z_{eff}}$$

- Z_{eff} = 2 is assumed
- A threshold around **40 keV** can be observed
- **Relative intensity increases as W_c decreases (three groups):**

1) "long discharges" (>0.35s) with Ar-puff
2) discharges longer than 0.35s
3) discharges shorter than 0.35s



The relative IR intensity dependence of the averaged critical energy during the first 240 ms of the discharge.

5. CONCLUSION

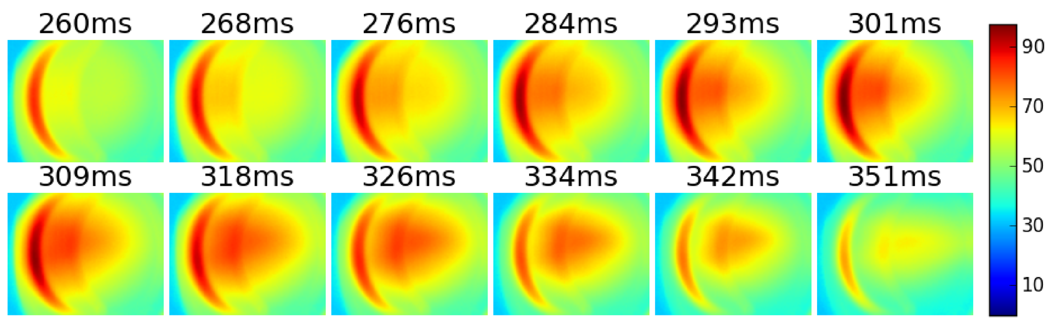
A method of extracting the relevant information from the reflected SR using an appropriate analysis is presented. From here the threshold of the average critical energy W_c=40 keV during the discharge can be estimated.

The first estimation of the RE pitch angle in COMPASS tokamak is reported and the corresponding density of the high-energetic REs using the calibrated IR camera is presented.

OUTLOOK: Usage of the more complex codes for the estimation of the runaway population behavior. Installing the IR spectrometer in the wavelength range of interest.

4. Direct Observation of the Runaway Electrons

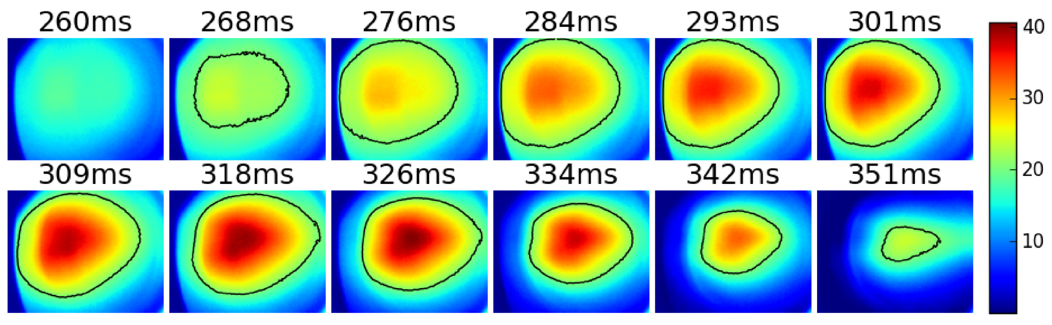
- Almost all of the recorded intensity is rather a reflection of SR from the vessel
- Analysis of the discharge **#9814** with the direct SR observation is presented here
- The pitch angle θ and the number of the high-energetic runaway electrons are estimated from the Fig. 4
- SYRUP code [2] is used for the theoretical calculation of the SR



A raw IR camera data for the discharge #9814. The analysed camera region is marked with yellow rectangle in Section 2. The color bar is in W $sr^{-1}m^{-2}$.

4.1. Background Subtraction

- IR camera disconnects during the intensive SR, but not for some **weak SR** **→ subtraction of the background thermal radiation is necessary**

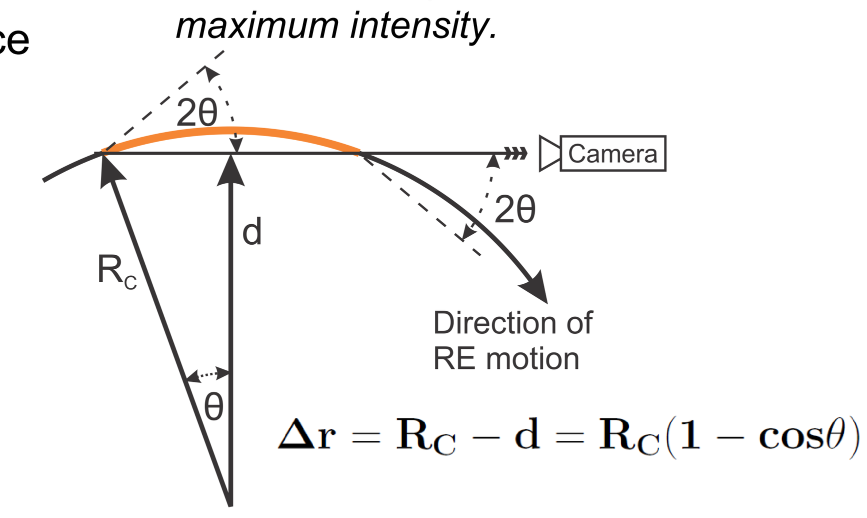


Subtracted frame from 227ms is time when the SR starts to be intensified. Black line corresponds to 50% of the maximum intensity.

4.2. Pitch Angle θ Estimation

- The opening half-angle of the radiation source
- It can be estimated from the difference between the height and the width Δr of the observed SR contour [3]:

$$\theta = \arccos\left(1 - \frac{\Delta r}{R_C}\right)$$



Geometry of the SR observation.

4.3. Maximum Energy Calculation

- A 0D model from [4] is used
- Solely a power gain due to the electric field P_E and a power loss from the SR P_{synch} are taken into account

$$\frac{dW_{max}}{dt} = P_E - P_{synch}$$

$$P_E = ecE_{tor} = \frac{ecV_{loop}}{2\pi R}$$

$$P_{synch} = \frac{2m_e c^3 r_e \gamma^4}{3R_C^2}$$

- For the discharge #9814 at the time of interest the maximum energy W_{max} is found to be between **20 and 30 MeV** (see Fig.6 bottom-left)

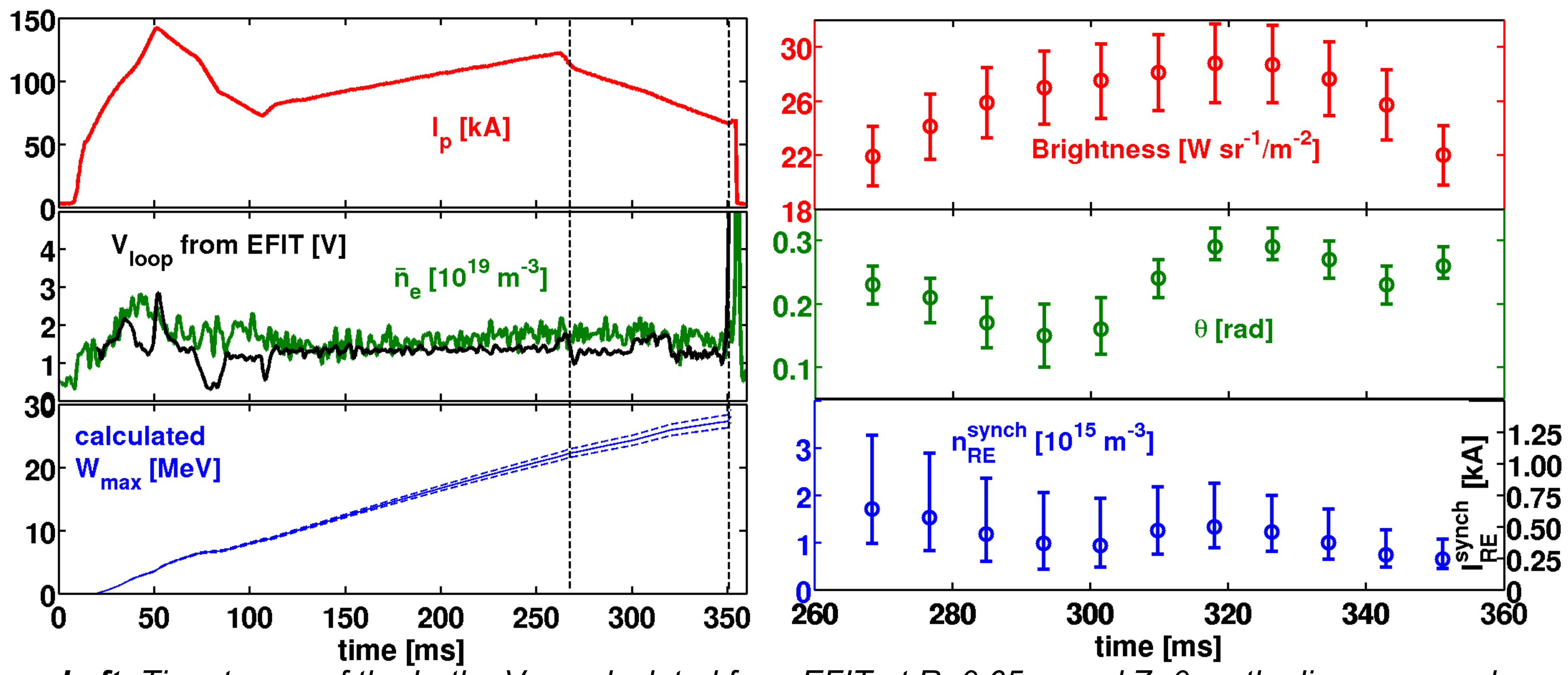
4.4. Result - Discharge #9814

- SYRUP gives the SR spectral power density **dP/dλ** per RE
- plasma parameters used in code: $\bar{n}_e$ = (1.6±0.2)x10^{19} m^{-3}, T_e = 530±60 eV, E_{tor} = 0.33±0.04 V/m and Z_{eff} = 2
- A theoretical estimation of the brightness [4]:

$$B(\lambda,\theta,W_{max}) = \frac{dP}{d\lambda}\frac{2R_C}{\pi\theta}n_{re}^{synch}$$

- A value comparable with the measured signal [4]:

$$S(\theta, W_{max}) = \int B(\lambda,\theta,W_{max})T(\lambda)d\lambda$$



***Left:** Time traces of the I_p, the V_{loop} calculated from EFIT at R=0.65 m and Z=0 m, the line-averaged n_e and the estimated maximum RE energy W_{max} (dashed lines represent the error) for the discharge #9814. **Right:** Time traces extracted from figure above – brightness for the contours, pitch angle and the density of the high-energy REs with corresponding RE current for beam radius of 5cm.*

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