Runaway Electrons in Tokamaks

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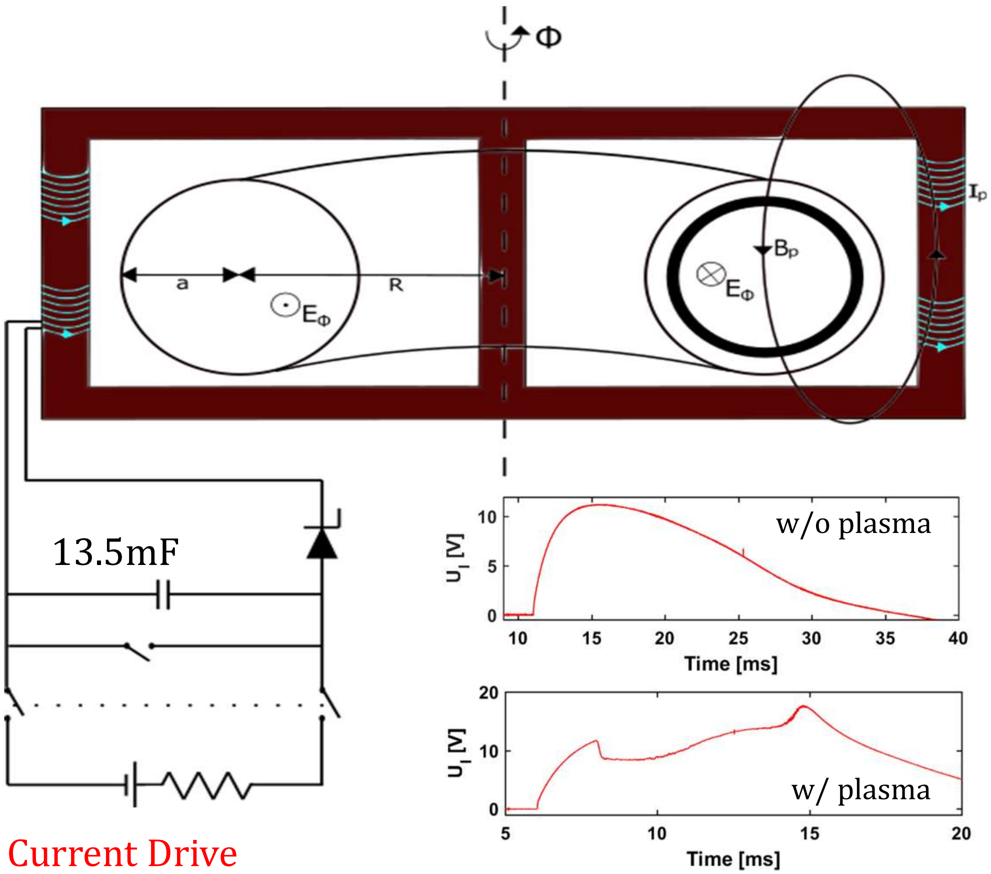
Outline

Runaway electrons in tokamaks
Toroidal electric field in tokamaks
Generation of runaway electrons
Radiation Generation Due to Energetic Particles
Measurement of runaways using scintillation material
An example of runaway measurements at GOLEM

Toroidal electric field (E_ϕ) in Tokamaks



Current Drive
Power Supply

Loop voltage with and without plasma

- A time varying current in primary coil generates toroidal electric field
- Ampere's Circuital law (with Maxwell's addition):

$$\nabla \times B = \mu_0 \left(J + \varepsilon_0 \frac{\partial E}{\partial t} \right)$$

For a time varying current: $\nabla \times \frac{\partial B}{\partial t} = \mu_0 \frac{\partial J}{\partial t}$

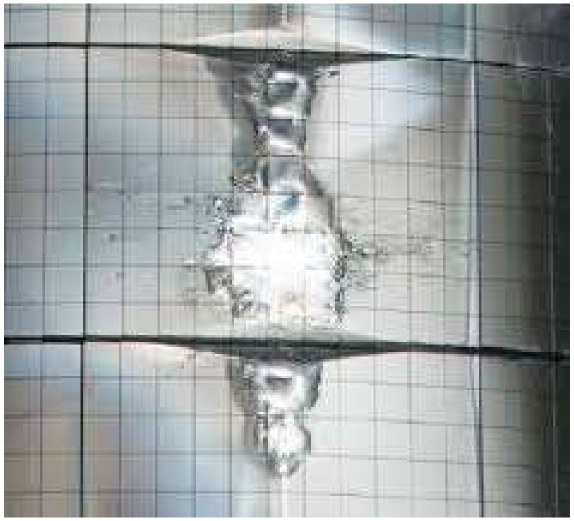
- Maxwell- Faraday induction (Faraday's law of induction): $\nabla \times E = -\frac{\partial B}{\partial t}$

An electromotive force is induced in the wire:
$V = -\oint E.dl$

$E_\Phi = -U_{loop}/2\pi R$

Runaway Electrons in Tokamaks

- Electrons and ions accelerate in toroidal electric field
- Electron temperature ~0.1-5keV
- Runaways are energetic particles ~100keV- tens MeV
- Dangerous for plasma facing components
  E_{RE}~$10MJ$ at I_{RE}~$10MA$; magnetic energy~200kJ
  [S.Putvinski talk, IAEA TCM- 2011]
- Primarily hit limiter (Mo, W, C), divertor plate

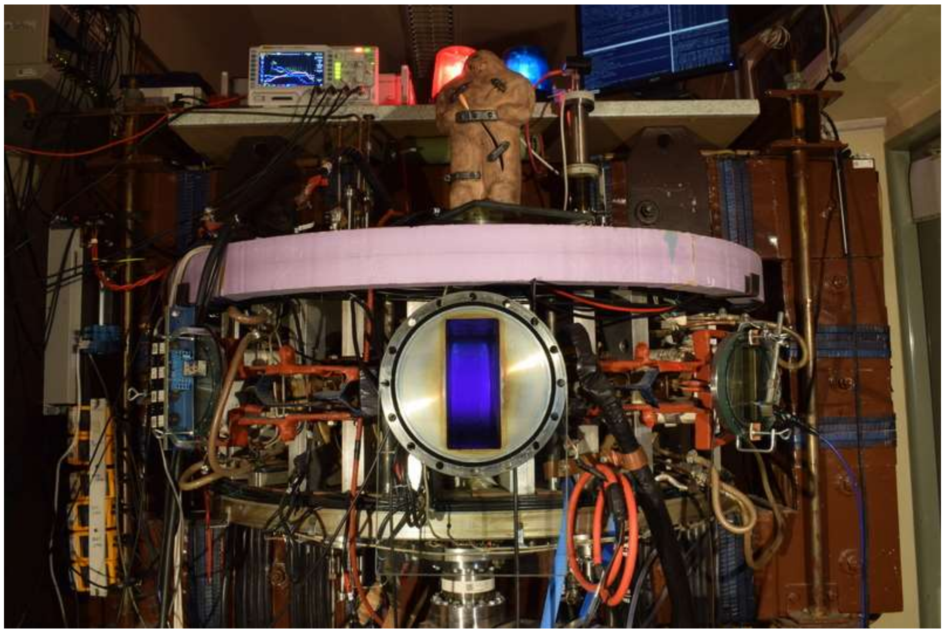


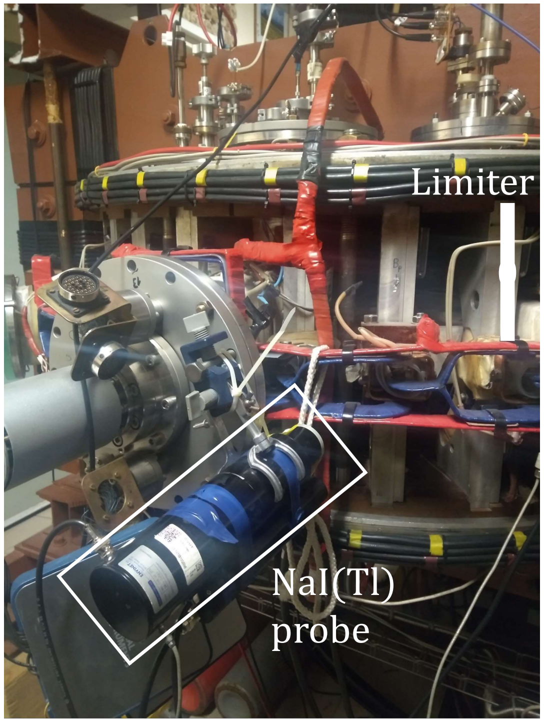
In-vessel image of melt damage due runaway electrons in JET

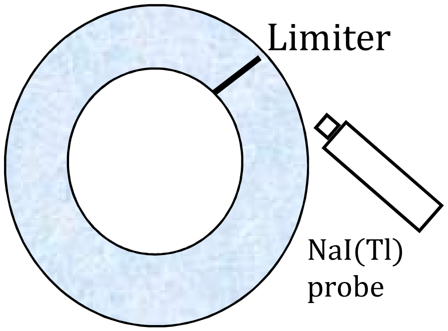
[Matthews, et al-2016]

Runaways measurements in GOLEM tokamak

Radiation measurement, indeed!!







Generation of runaway electrons

Net force on electrons $\left(m\frac{\partial v}{\partial t}\right)$ = frictional drag + due to the electric field $(q\boldsymbol{E})$

$(\propto n_e)$

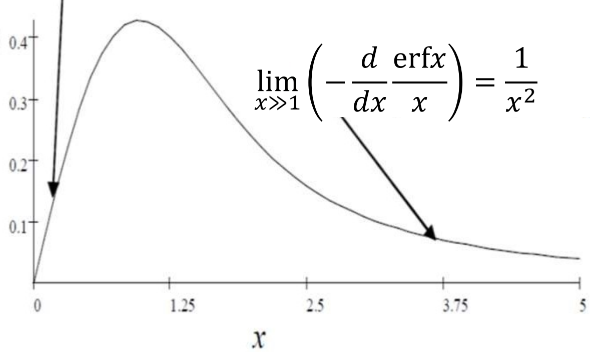
In the steady state- frictional drag and applied electric force balance each other

$$E = -\frac{n_e q_i e^2 ln\Lambda}{4\pi\varepsilon_0^2 \mu_e}\left\{\frac{\partial}{\partial v}\left[v^{-1}\mathrm{erf}\left(\sqrt{\frac{m_e}{2\kappa T_e}}v\right)\right]\right\}$$

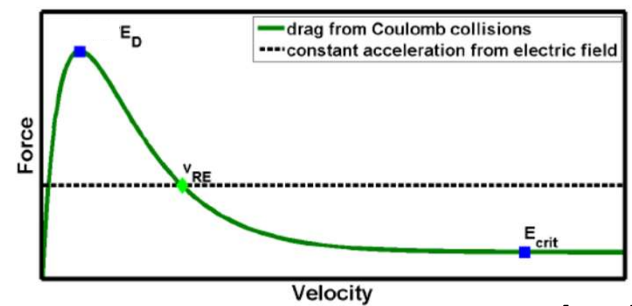
$$\lim_{x\ll 1}\left(-\frac{d}{dx}\frac{\mathrm{erf}x}{x}\right) = \frac{4x}{3\sqrt{\pi}}$$

$$-\frac{d}{dx}\left(\frac{\mathrm{erf}x}{x}\right)$$

$$\lim_{x\gg 1}\left(-\frac{d}{dx}\frac{\mathrm{erf}x}{x}\right) = \frac{1}{x^2}$$



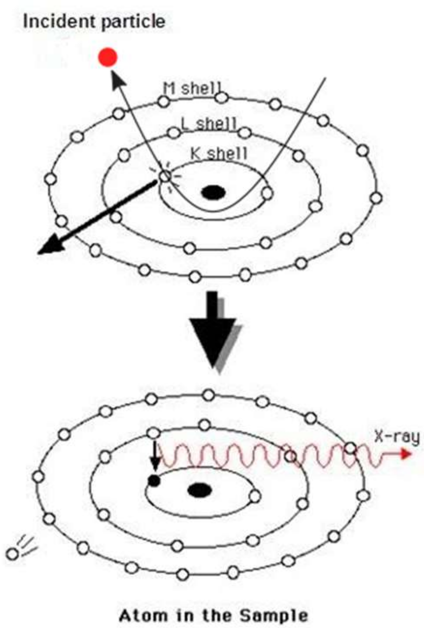
$$E_{Dreicer} = 0.43\frac{n_e Z e^3 ln\Lambda}{8\pi\varepsilon_0^2 \kappa T_e}$$



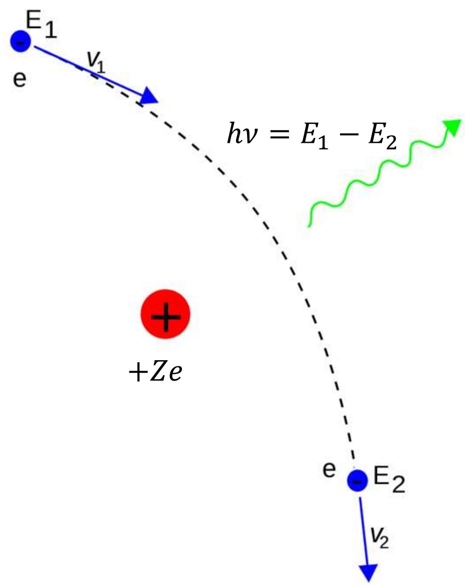
[M. Vlainic thesis-2018]

Lower the plasma density, Higher the applied electric field ⟶ Higher the chances of runaway generation

Radiation Generation Due to Energetic Particles



Characteric HXRs generation



Bremsstrahlung
(braking radiation)

Charged particles acceleration in a curved path

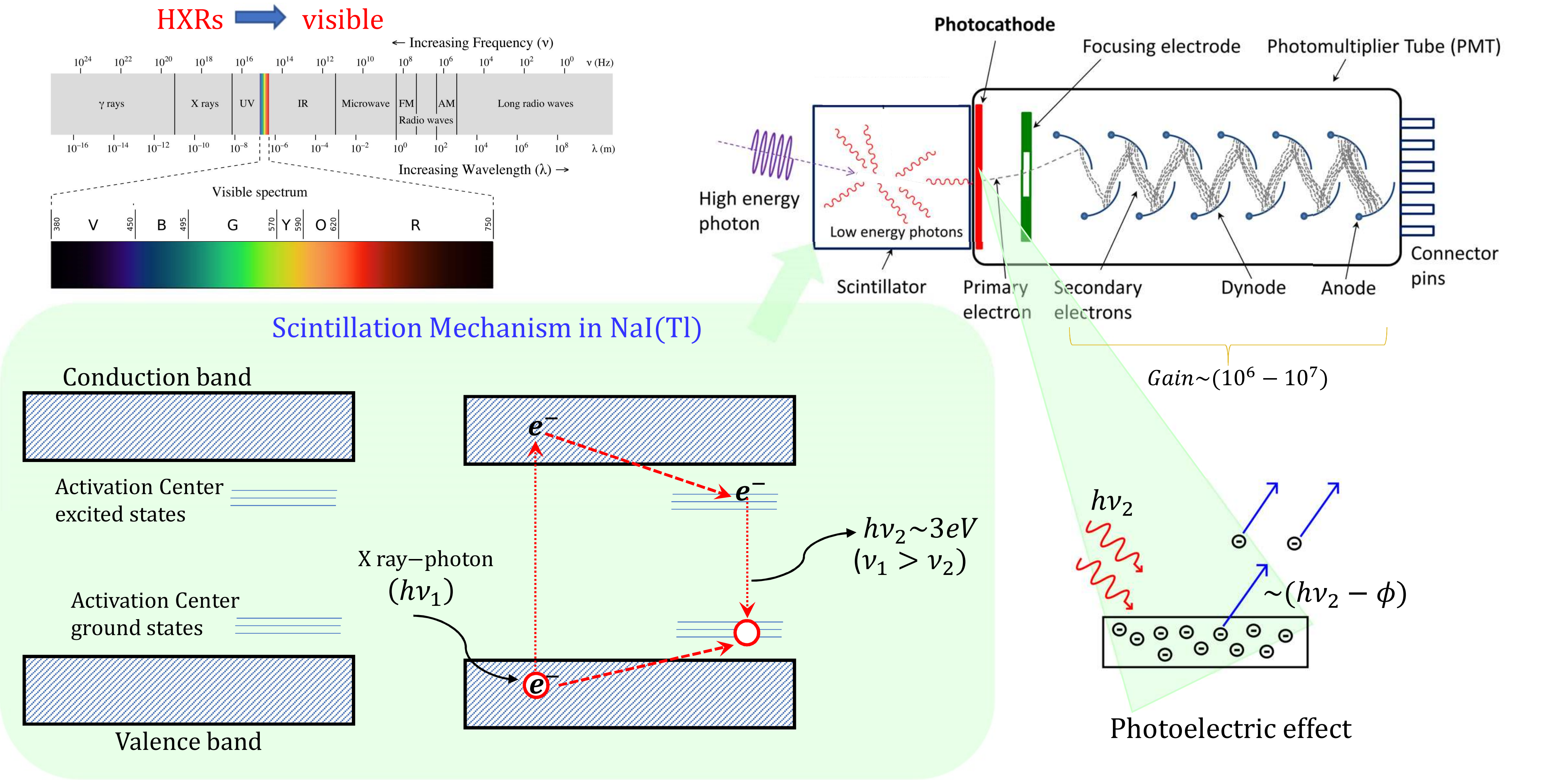
- **Synchrotron radiation:** Relativistic
- **Cyclotron radiation:** Non-relativistic

- **Cherenkov radiation:** emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium

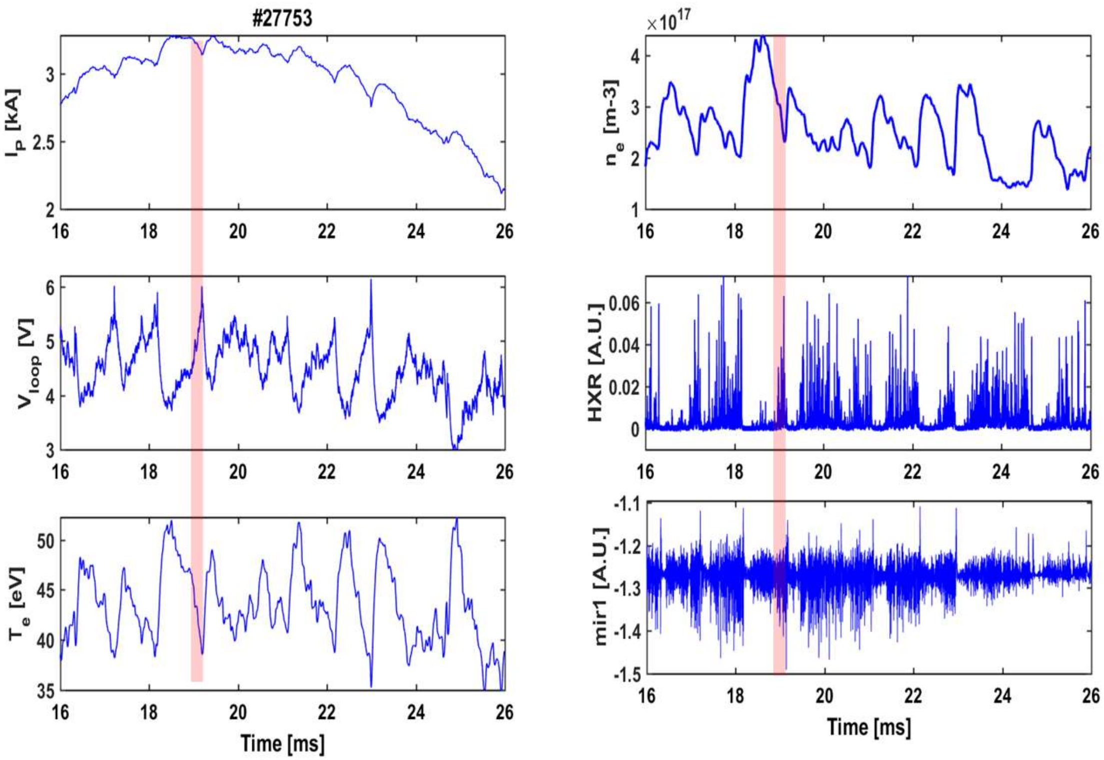
Diagnostic for runaway study

- Strip and pixel silicon radiation detectors
- Cherenkov detector, ECE diagnostic
- Scintillation crystals

Measurement of HXRs using scintillation material



Interplay Between MHD Fluctuations and Runaways: Role of Electric Field



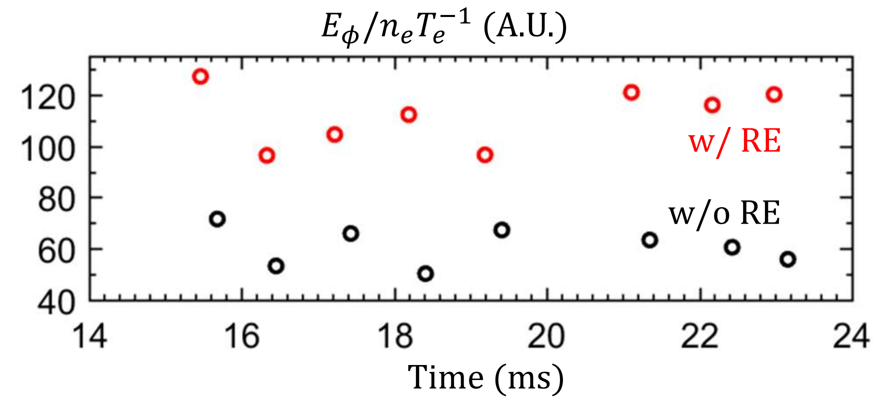
Observation:

- Higher U_{loop} (or E_Φ)
- Lower density (weaker F_{drag})
- Larger $\dot{B}_\theta$ amplitude

→ Higher HXR amplitude

Toroidal electric field ($E_\phi = V_{loop}/2\,\pi R$) normalized

by Dreicer electric field, $E_{Dreicer} = 0.43\, n_e Z e^3 ln\Lambda / 8\pi\varepsilon_0^2 \kappa T_e$



Thank you !!