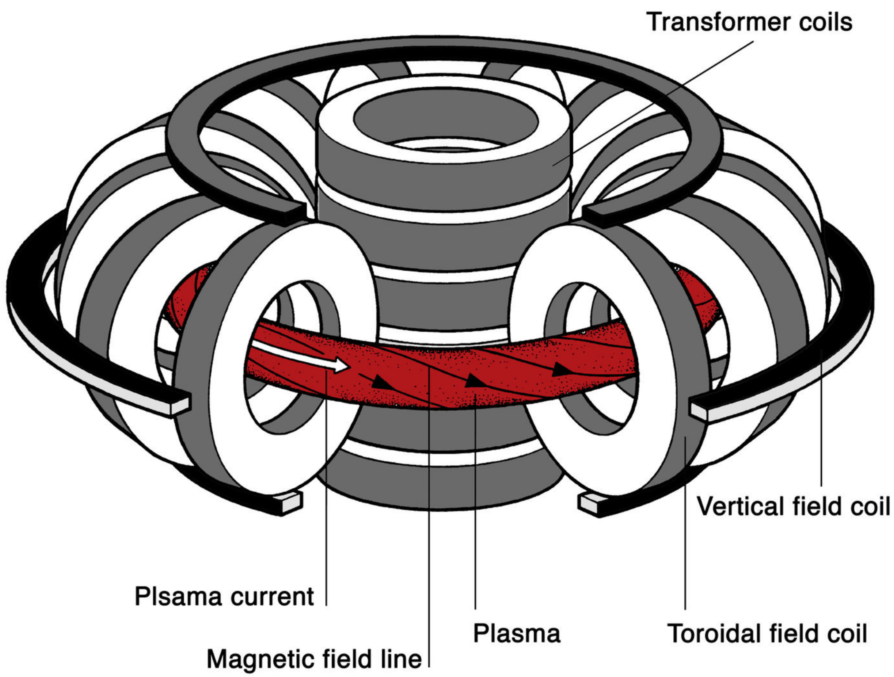
Runaway Electrons

Zixuan Guo,
Seminar for Plasma Physics

Magnetic Confinement in Tokamaks



* https://www.ipp.mpg.de/14869/tokamak

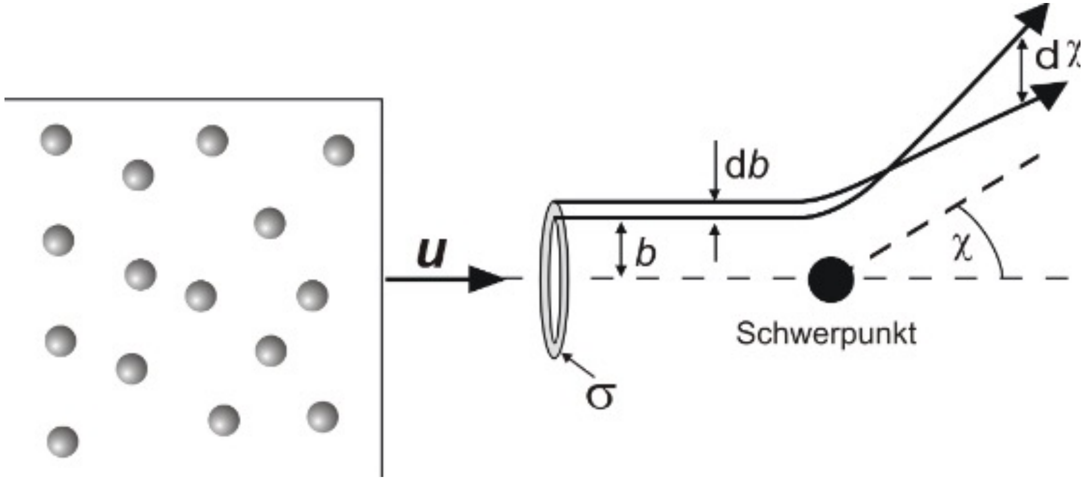
Disruptions

Happens when the control over plasma is lost. The energy in the plasma can reach the Tokamak wall.

-Thermal quench: on time scale ~ms, the rapid cool down of the plasma caused by loss of confinement.

-Current quench: on time scale ~s, the current decay due to the increasing resistivity.

Review of Collisions in Plasmas



* “Plasmaphysik-Phänomene, Grundlagen und Anwendungen“, U.Stroth, 284, Abb 8.2

The Rutherford cross section is :

$$\sigma(u,\chi) = (\frac{q_1 q_2}{4\pi\varepsilon_0}\frac{1}{2\mu u^2 sin^2(\chi/2)})^2$$

Review of Collisions in Plasmas

Consider the particle scattered at $b = \lambda_D$ for the angle $\chi = \chi_{min}$

Assume there is no scatter for $\chi < \chi_{min}, b > \lambda_D$

The Ratio between small angle $\chi < 90$ and large angle $\chi > 90$ scattering is Λ,

$$\Lambda^2 = \frac{\lambda_D^2 - b_{90}^2}{b_{90}^2} = (12\pi)^2 \lambda_D^6 n^2$$

The Coulomb logarithm is given by:

$$\ln \Lambda = \ln(12\pi\lambda_D^3 n)$$

Runaway Electrons

Use the definition of the Relaxation time:

$$-\frac{p_1}{\tau_\parallel}\left\langle\frac{\partial p_{1\parallel}}{\partial t}\right\rangle = -\frac{p_1}{\tau_\parallel}\ (1)$$

For electrons:

$$\tau_e = \left(\frac{4\pi\varepsilon_0}{e^2}\right)^2 \frac{m_e^2 v_e^3}{8\pi n_e \ln\Lambda}\ (2)$$

Runaway Electrons

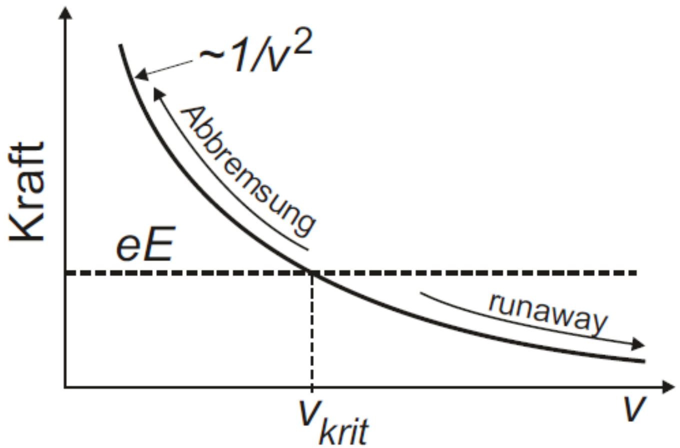
Force on the electrons:

$$\frac{\partial p}{\partial t} = \left(\frac{\partial p}{\partial t}\right)_{coll} + eE (3)$$

Plug (1) and (2) into (3), the critical electric field (Dreicer Field):

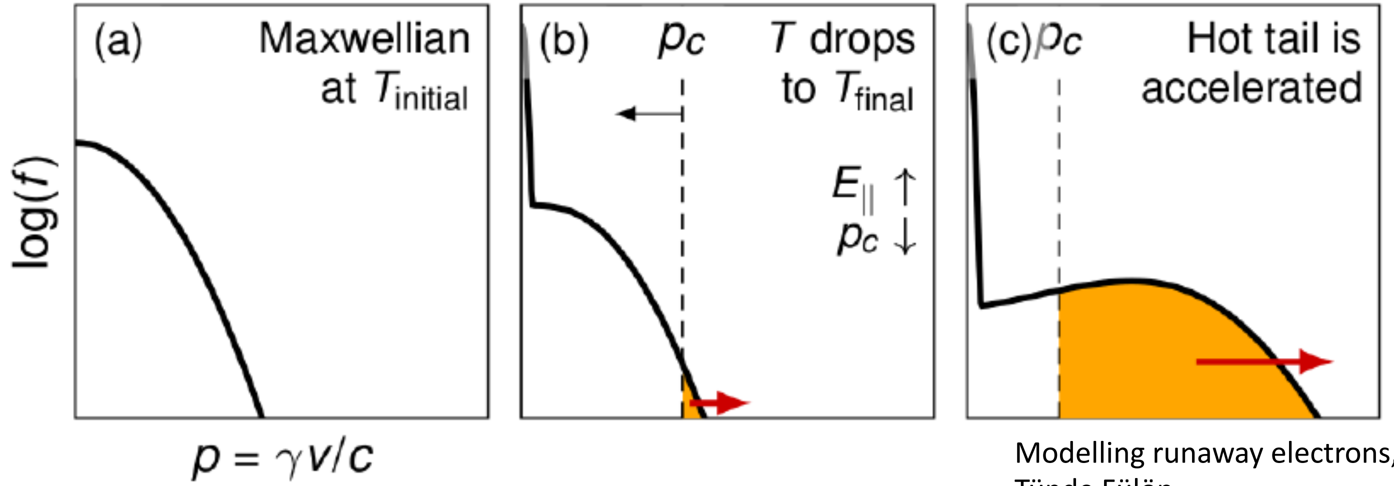
$$E_D = \frac{n_e e^3 \ln \Lambda}{4\pi \varepsilon_0^2 T_e} \ (4)$$

Primary Generation of RE: Dreicer Seed



* “Plasmaphysik-Phänomene, Grundlagen und Anwendungen“, U.Stroth, 284, Abb 8.8

Primary Generation of RE: Hot-tail Seed



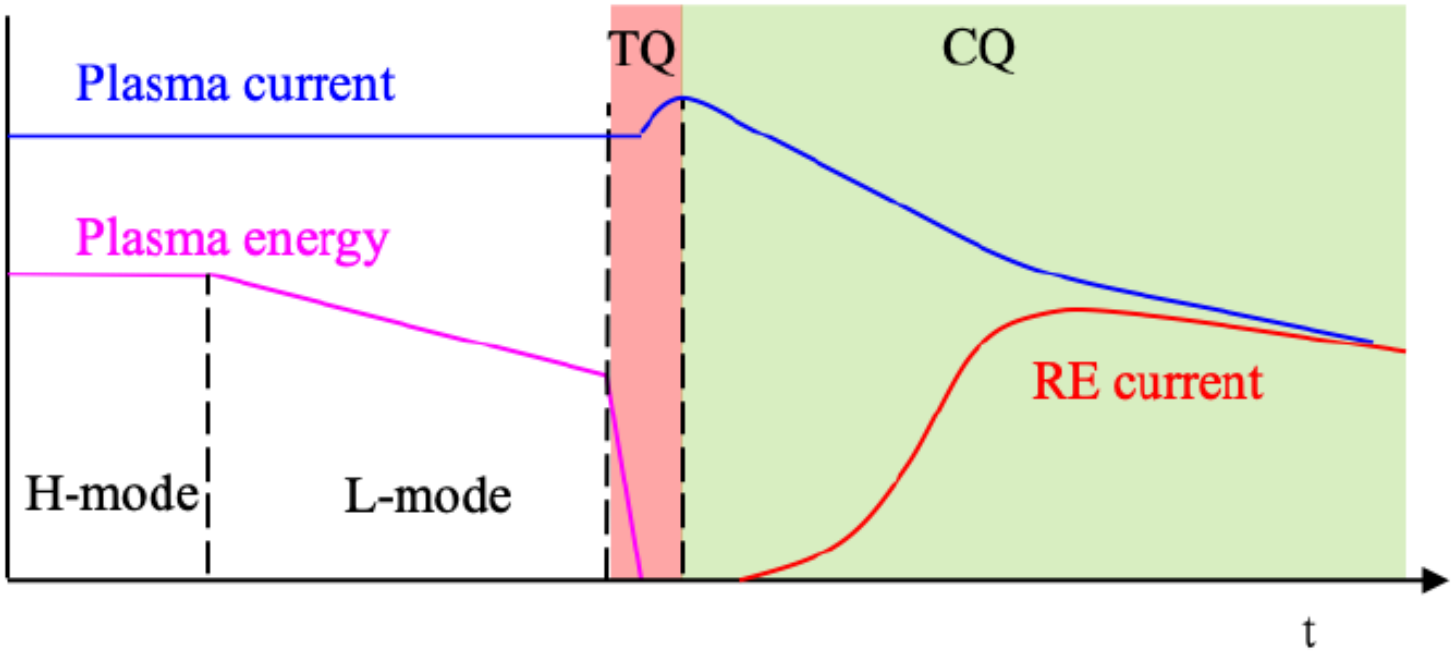
Modelling runaway electrons,
Tünde Fülöp

-It takes longer for electrons with higher speed to cool down.

-Resistivity and the electrical field increase rapidly, critical momentum decreases.

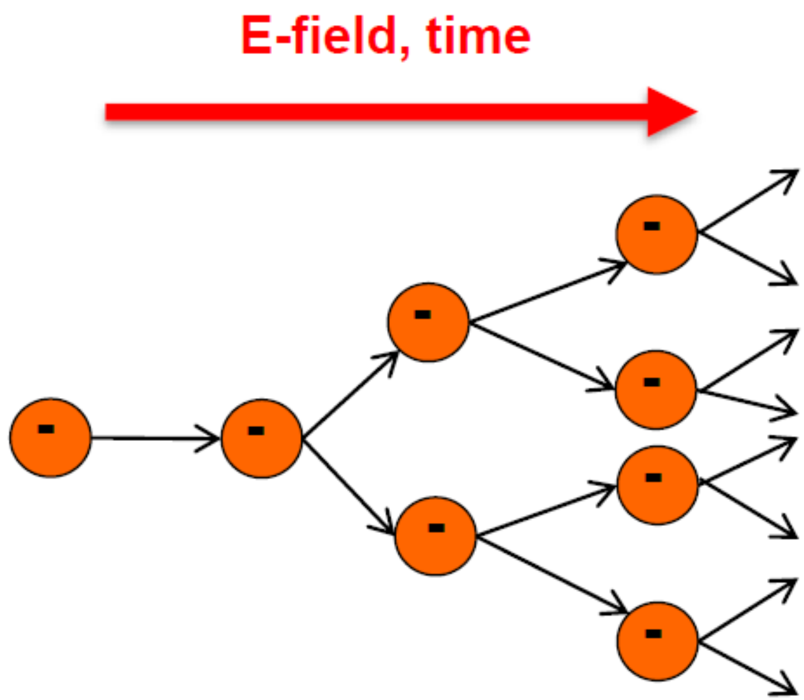
-Electrons in the “tail” are accelerated.

Secondary RE Generation: Avalanche Mechanism



Physics of observations of runaway electrons, R. Granetz

Secondary RE Generation: Avalanche Mechanism



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Secondary RE Generation: Avalanche Mechanism

-Runaway electrons can also bring thermal electrons to runaway region via Coulomb's collision.

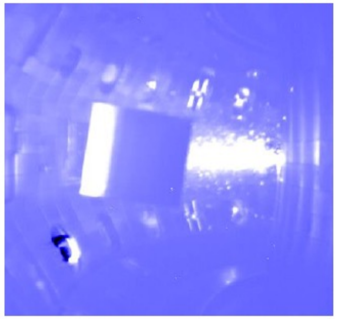
-The growth is exponential, the growth rate:

$$\gamma_R = \frac{1}{n_R}\frac{dn_R}{dt} \simeq \frac{eE}{2m_e c \ln \Lambda}$$

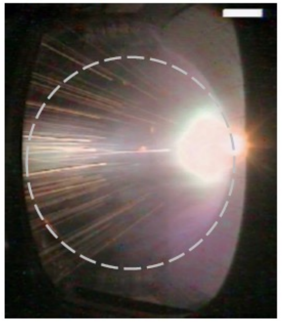
-Proportional to the toroidal electric field

Impacts of Runaway Electrons

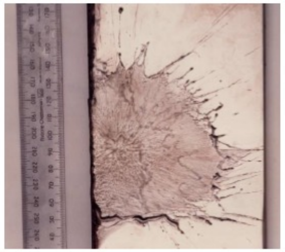
RE impact (DIII-D, USA)



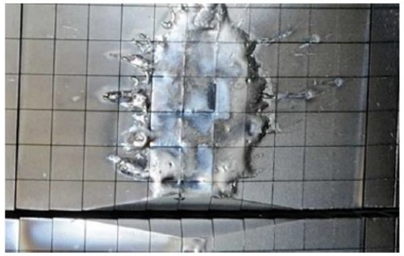
RE impact (TEXTOR, Germany)



Post-Impact on Carbon (JET, UK)



Post-Impact on Beryllium (JET, UK)



above only ~ 1% energy of a potential RE strike in ITER!

Physics of observations of runaway electrons, R. Granetz

Mitigation of REs: Massive Gas Injection (MGI)

By injecting massive noble gas:

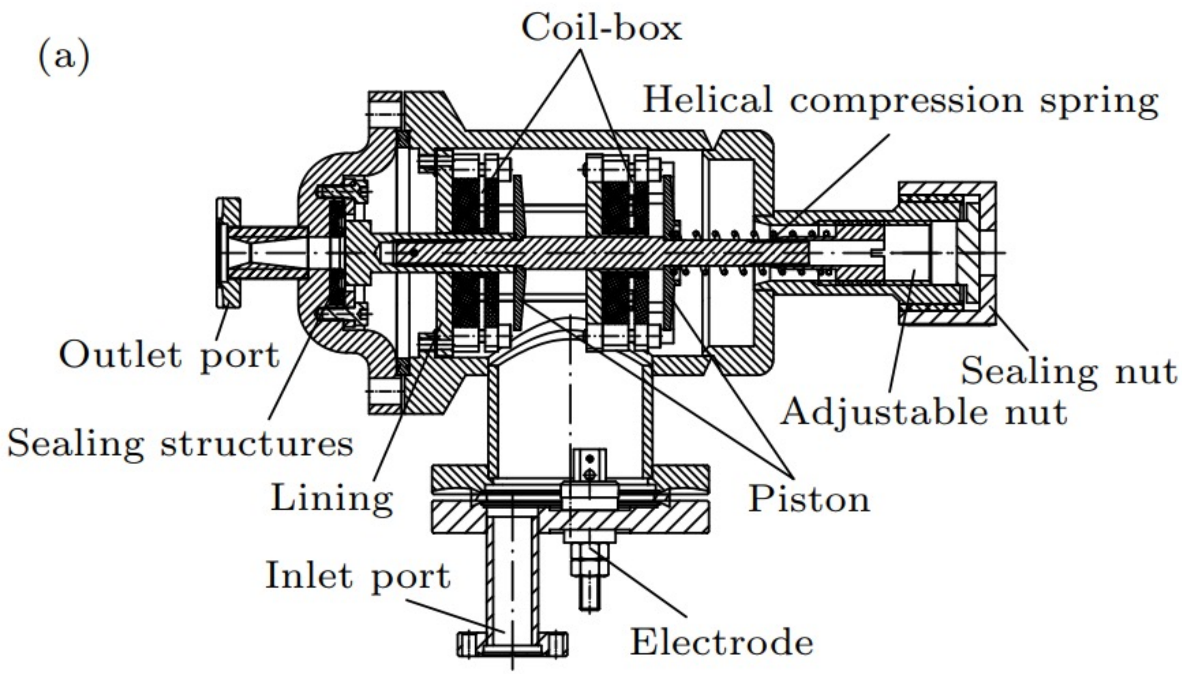
- Gas particles radiates thermal energy uniformly by ionization.

-High particle density leads the collision frequency high enough to weaken runaways.

-Higher resistivity makes the current decay faster.

Mitigation of REs: Massive Gas Injection (MGI)

Example of MGI fast valve



Chin. Phys. B, 2023, Vol. 32(7): 075207, Fig 1(a)

Mitigation of REs: Massive Gas Injection (MGI)

However MGI is inefficient:

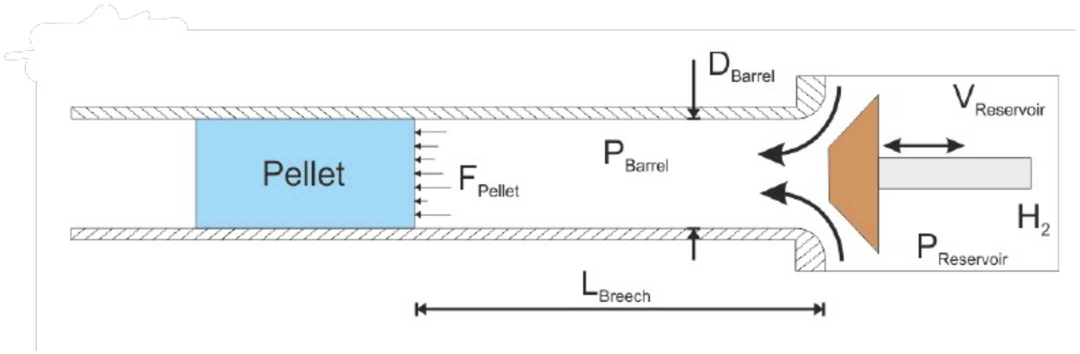
-Plasma cool down from the edge.

-Only small proportion of the gas arrive after thermal quench, not helping for mitigation

-Can we deliver particles directly to the plasma?

Mitigation of REs: Shattered Pellet Injection (SPI)

Injecting frozen D_2 pellets and impurity pellets (Ne, Ar) via injector.



Physics of observations of runaway electrons,
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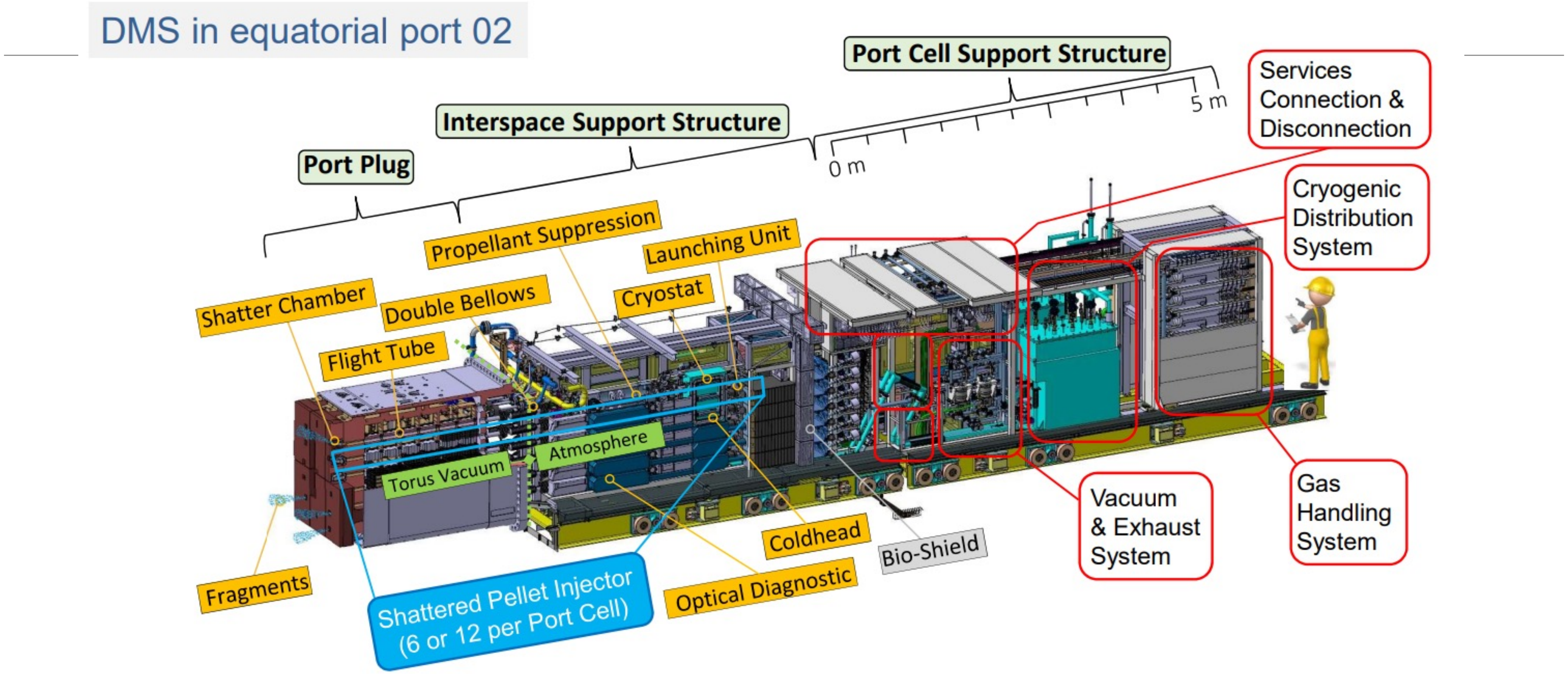
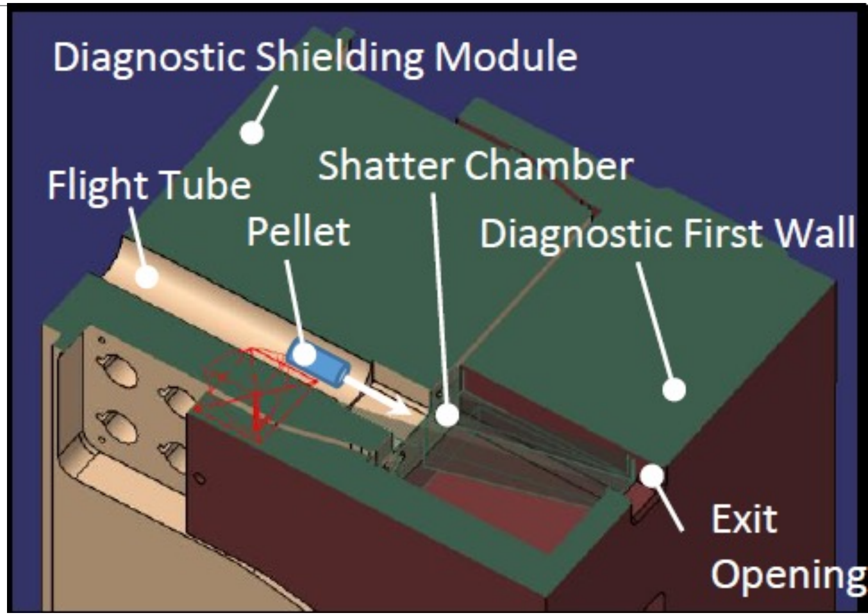
Mitigation of REs: Shattered Pellet Injection (SPI)



The ITER Disruption Mitigation System design progress and validation, Stefan Jachmich

Mitigation of REs: Shattered Pellet Injection (SPI)



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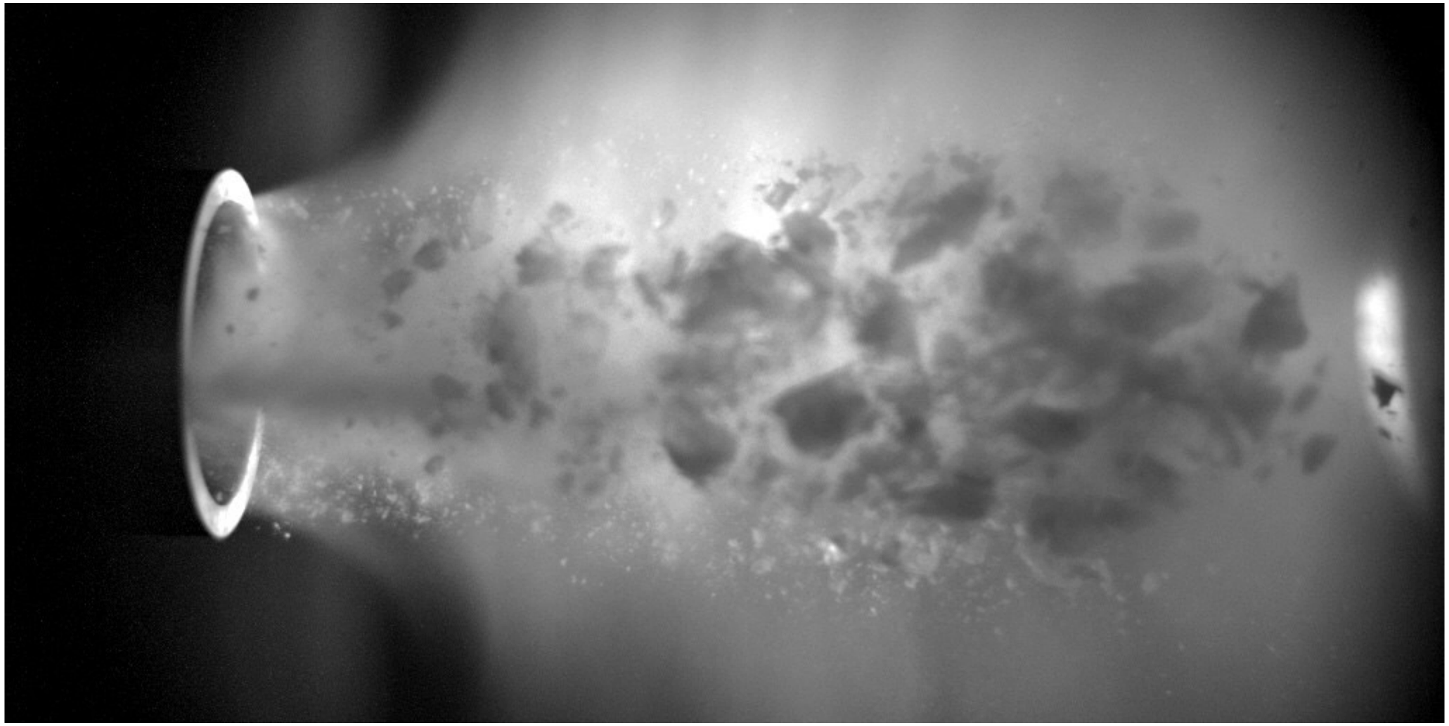
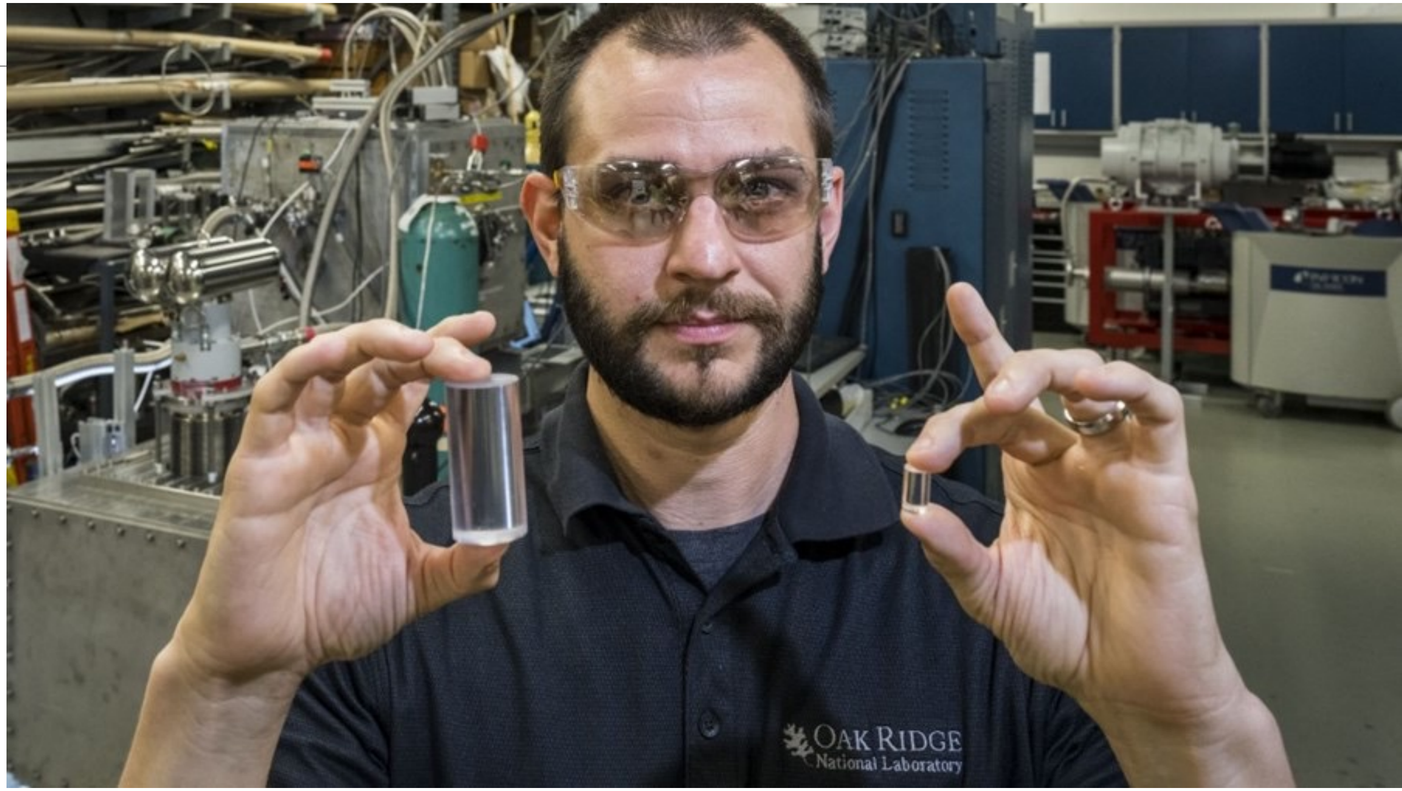


https://www.iter.org/newsline/-/3668

Mitigation of REs: Shattered Pellet Injection (SPI)



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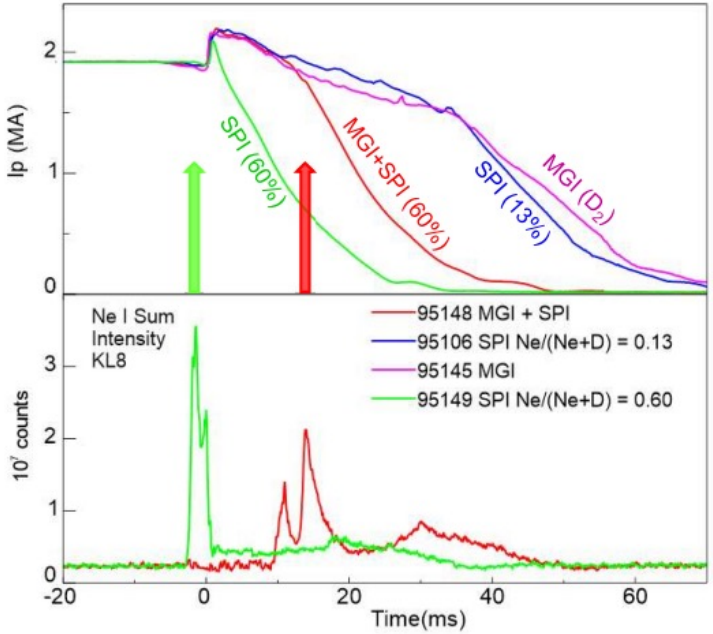
Mitigation of REs: RE Mitigation Coils



S. Gerasimov et al, IAEATM “Disruptions”, 2020

Summary

- Friction force is provided by Coulomb collisions, which declines with increasing velocity.
- Electrons become runaways when the electric force higher than the friction force, runaway electrons will keep accelerate.
- In the process of disruption, particles cool down immediately, while plasma current decays slower, which will generates a huge toroidal electric field.
- The electron with higher energy cooling down slower than those with lower energy, makes them unable to runaway from the runaway region, and being accelerated.
- Existed runaway electrons can generate new REs via collision exponentially, called avalanche mechanism.

Summary

- Runaway electrons can carry huge energy and damage the devices
- Massive Gas Injection is to inject noble gas into the plasma when disruption about to happen.
- Noble Gas can weaken the runaways by ionization, radiation, increasing the resistivity and density.
- MGI is not efficient enough for the big fusion reactor like ITER. Because the gas could only start from the edge, only small proportion of gas reach the plasma column when thermal quench begins.
- Shattered Pellet Injection is adopted by ITER, which is to inject the shattered frozen pellet of Deuterium and Noble gas impurity with high speed, directly to the plasma column.