Runaway Electrons in Tokamaks and Their Mitigation in ITER

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ITER Organization

ITER site in the future

Building for manufacturing PF coils

Foundation for tokamak building

Outline

- Introduction
- Physics of RE generation
  - Dreicer acceleration
  - Avalanche
  - Seed sources
  - Plasma instabilities driven by RE
- Plasma disruptions in ITER
- Approach to Mitigation of RE in ITER
- Summary

Introduction

- Runaway Electrons (RE) are produced by acceleration of electrons in toroidal electric field when collisional drag force on energetic electron is less then driving force, eE

- The first numerical analysis of runaway phenomena have been carried our by H.Dreicer (Proceedings of 2nd Geneva conf 1958, **31**, p 57 and Phys Rev., 1959, **115**, p238)

- Frequently cited analytical expression for Dreicer acceleration has been derived by A.V.Gurevich, JETF 1960, **39**, p1296

- RE have been observed in early experiments in tokamaks in 50th and 60th in low density discharges contaminated with impurities and later studied experimentally in more details (Bobrovski 1970, Vlasenkov 1973, TFR group 1973, Alikaev 1975)

MeV runaway electrons can damage FW

- At plasma densities typical for tokamaks, n ~ 10^{19} – 10^{20} m^{-3} the electric field is small and RE can be produced only during abnormal events such as plasma disruption
- It is known from experience in tokamaks that RE can damage in-vessel component (notorious accident in TFR with burning hole in vacuum vessel)
- RE are dangerous for the plasma facing components because of long range in FW materials and possible deep melting
- Massive RE generation is expected during plasma disruptions in ITER (up to 12 MA of RE current)
- RE must be suppressed in ITER

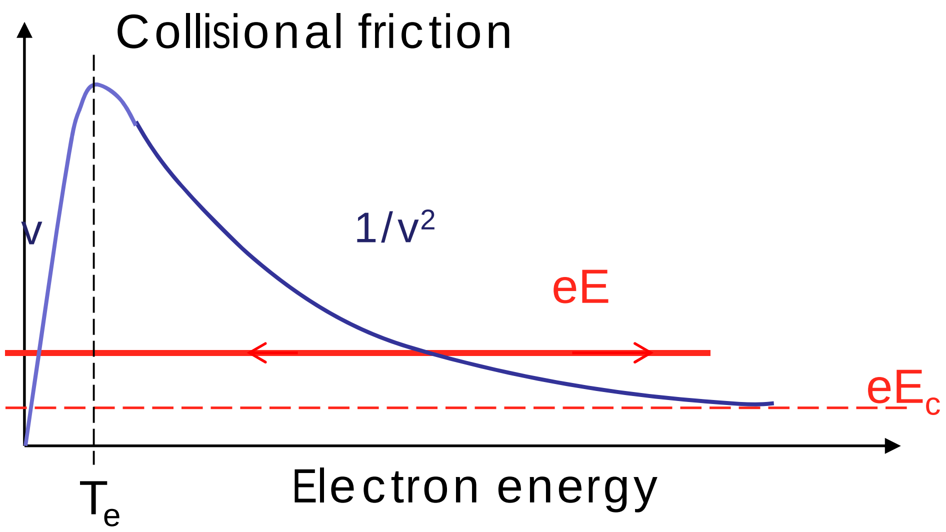
- Movie

Physics of RE generation

- Friction force on electron (non relativistic):

$$< F >= \frac{n_e e^4 \ln(\Lambda)}{4\pi\varepsilon_0^2 m_e}\left\{\frac{ZM}{T_i}\Phi_1(v/v_{Ti}) + \frac{2m_e}{T_e}\Phi_1(v/v_{Te})\right\}$$

$$\Phi_1(x) = \frac{1}{\sqrt{\pi}\xi^2}\left(\int_0^x e^{-\xi^2} d\xi - xe^{-x^2}\right)$$



- Dreicer electric field:

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

- Critical electric field

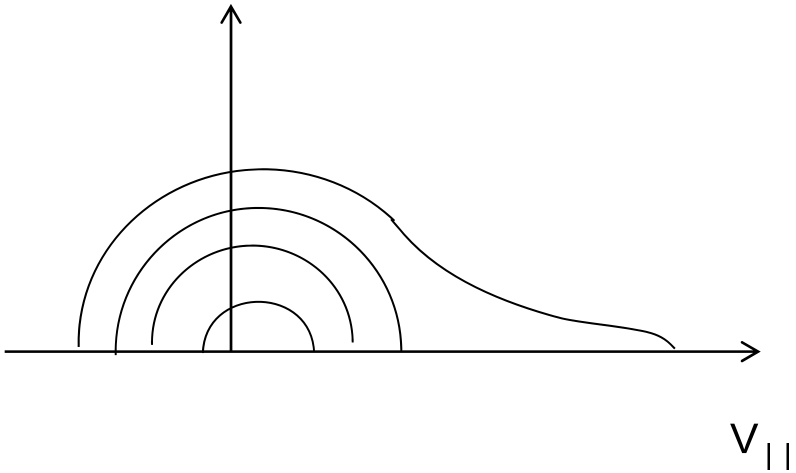
$$E_c = \frac{n_e e^3 \ln(\Lambda)}{4\pi\varepsilon_0^2 m_e c^2}$$

- At $E < E_c \sim n_e$, the runaway electrons can not be produced

- Critical electron velocity $$\frac{v_{cr}}{v_{Te}} = (1 + Z/2)^{1/2}\left(\frac{E_D}{E}\right)^{1/2}$$

Dreicer acceleration rate (Gurevich, 1960)

- At $E \ll E_D$ only far tails on the distribution function are affected by electric field



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

- In this case the runaway generation rate (Dreicer source) can be calculated from kinetic equation (see f.e. Review of plasma physics v. 11, 1982)

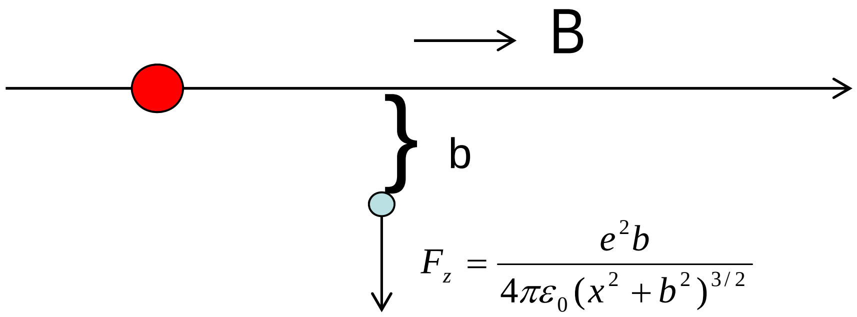
$$dn/dt = \frac{n_e}{\tau}\left(\frac{m_e c^2}{2T_e}\right)^{3/2}\left(\frac{E_D}{E}\right)^{3(Z+1)/16}\exp\left\{-\frac{E_D}{4E}-\sqrt{\frac{(Z+1)E_D}{E}}\right\}$$

Avalanche of runaway electrons

- The avalanche mechanism has been described first by Yu.Sokolov in 80th, forgotten, and re-invented and described in details in mid 90th. (M.Rosenbluth, L.-G. Eriksson, P Hellander, S.Konovalov, and others)

- Numerical codes have been developed and validated in experiments (see f.e. code ARENA, Eriksson, Comp. Phys Comm 154 (2003))

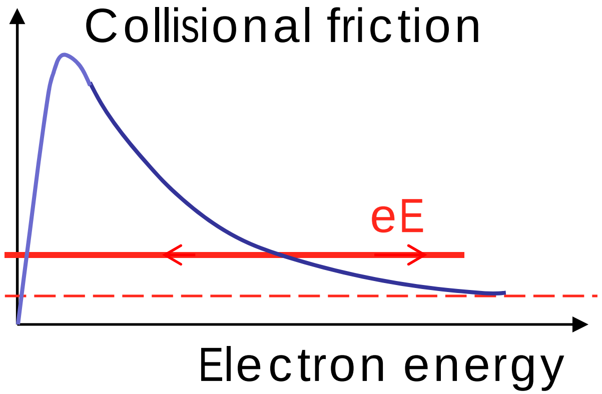
- The avalanche is multiplication of energetic electrons by close Coulomb collisions with plasma electron



$$F_z = \frac{e^2 b}{4\pi\varepsilon_0 (x^2 + b^2)^{3/2}}$$

- Momentum of the secondary electron, $p_\perp = \frac{e^2}{2\pi\varepsilon_0 cb}$

Avalanche of runaway electrons



- When $v > v_{cr}$ or

$$b < \frac{e^2}{2\pi\varepsilon_0 cmv_{cr}}$$

- the secondary electron will runaway

- Source of secondary electrons

$$\frac{dn_{RE}}{dt} = n_{RE} n_e \pi b^2 c = n_{RE} \frac{eE}{2mc\ln(\Lambda)}$$

- Accurate treatment needs to take into account that some of secondary electrons are born on banana orbits and can not accelerate until they scatter to the transit particles

$$\frac{dn_{RE}}{dt} = n_{RE} C(Z, R/a) \frac{e(E - E_c)}{mc\ln(\Lambda)}$$

Conditions for generation of RE in tokamaks

- Toroidal electric field: $E = \eta j \propto \frac{Z}{T_e^{3/2}} j$
- Friction force: $F \propto n_e (Z + 2)$
- Runaway electrons are produced in low density cold plasmas (f.e. contaminated by impurities)

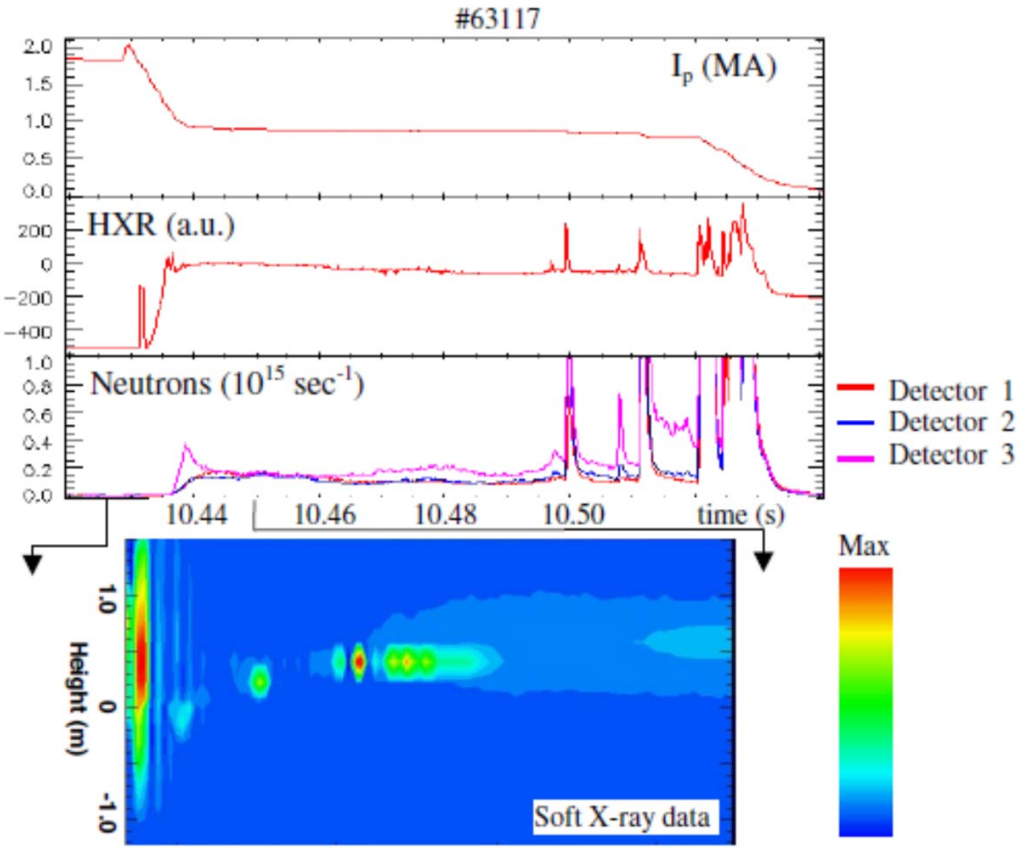
$$\frac{E}{F} \propto \frac{1}{n_e T_e^{3/2}}$$

- In a "normal" discharge the loop voltage is small and electric field is below critical field. Example (ITER): Loop voltage during flat top U < 0.1 V, Electric field $E = U/2\pi R$ < 0.003 V/m, Critical field,

$$E_c = \frac{n_e e^3 \ln(\Lambda)}{4\pi\varepsilon_0^2 m_e c^2} \sim 0.075 n_{e,20} >> E$$

- Generation of RE in ITER occurs during plasma disruptions

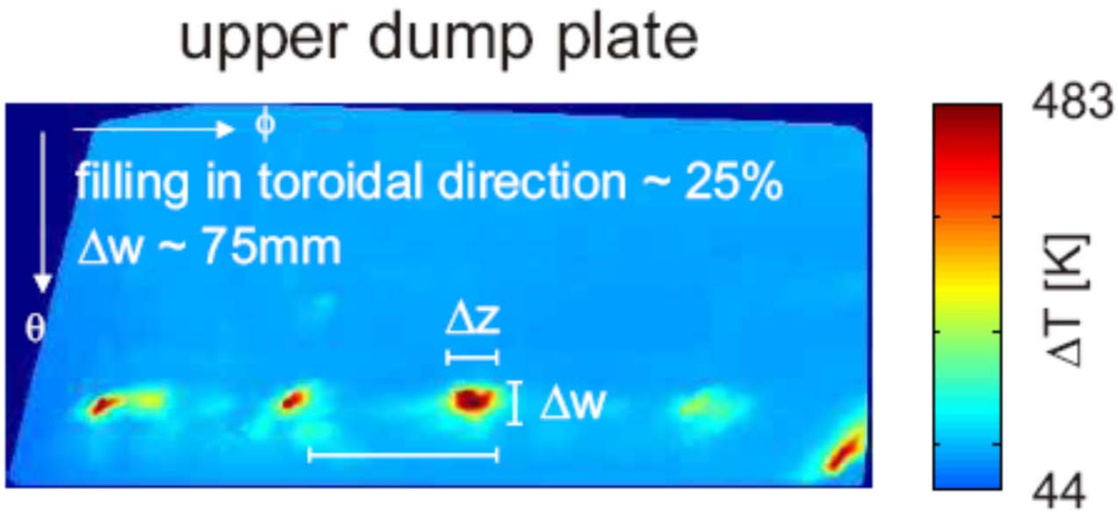
Runaway electrons are often observed during plasma disruptions



- Runaway electrons in JET (Pluschin, NF,1999)

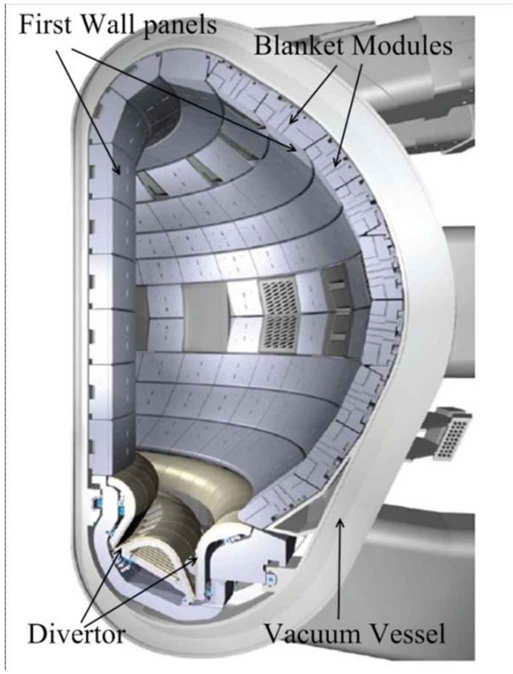
- Large loop voltage can accelerate electrons to > 10 MeV
- Plasma resistive current is replaced by current of relativistic electrons
- Hard X-rays and photoneutrons are typical signature of energetic electrons
- Soft x-rays from chord array show that RE current is peaked near magnetic axis

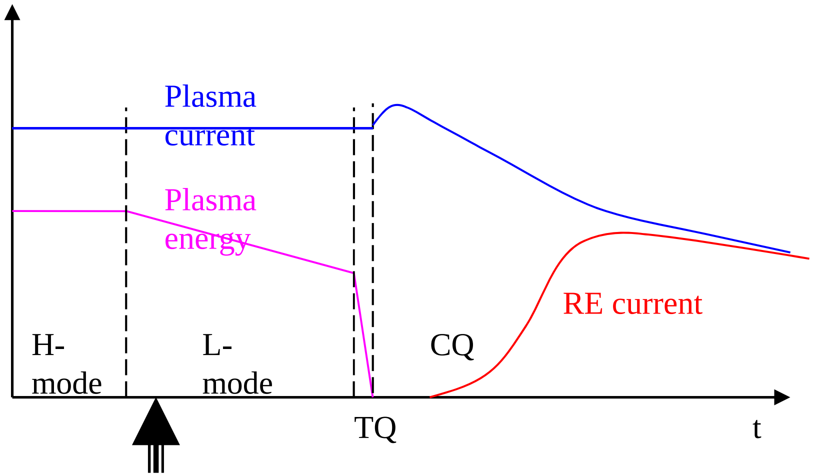
Energy deposition on the wall



- Due to small ratio V_{perp}/c loss of runaway electrons is extremely localized
- Expected wetted area in ITER is only 0.3-0.6 m^2

Thermal and Current quench phases





Typical chain of events during plasma disruption

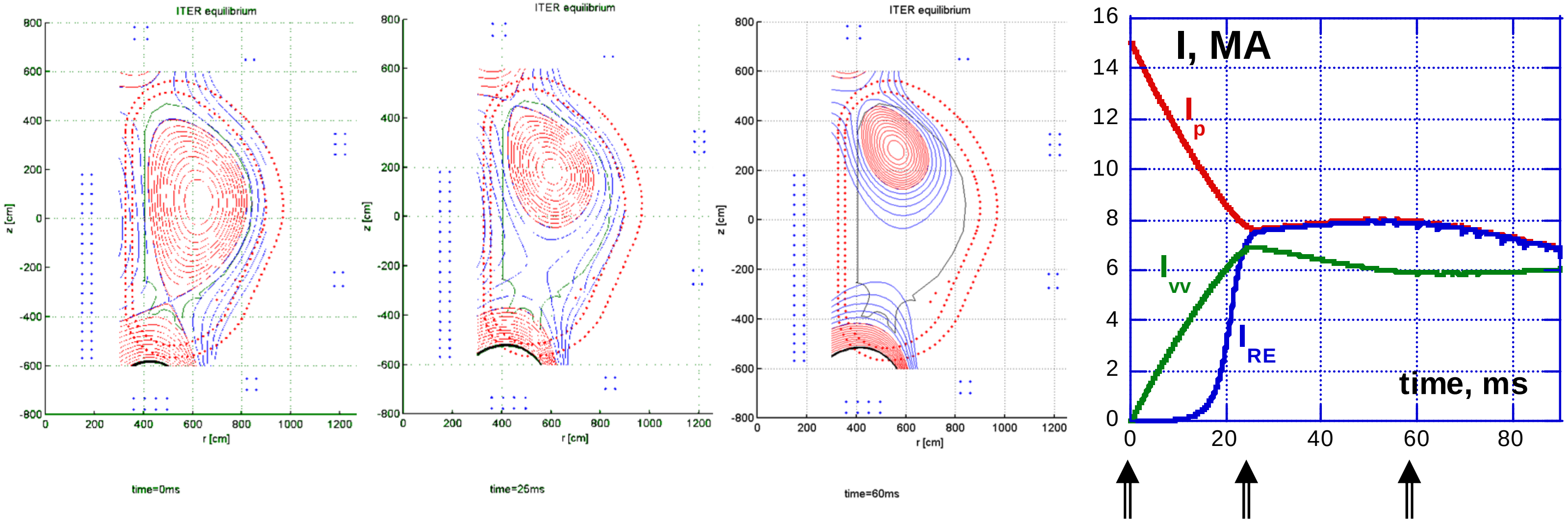
- The largest thermal loads occur during Thermal Quench
- Major mechanical forces act on plasma facing components during Current Quench
- Runaway electrons can be generated during Current Quench

Plasma disruptions can be very damaging in ITER

- ITER vacuum vessel and in-vessel components are designed mechanically to withstand EM loads from the expected 2600 “typical” 15 MA disruptions (current quench time 50-150 ms) and 400 “typical” VDE
- However, local thermal loads during plasma disruptions significantly (10 times!) exceed melting threshold of divertor targets and FW panels
- A reliable Disruption Mitigations System (DMS) must be developed and installed in ITER prior to the full scale operation which will start in 2022. Presently it is at conceptual design phase
- 95% of plasma disruptions shall have pre-emptive injection of high Z (Ne or Ar) for reduction of TQ energy loads on PFC
- Injection of Ne or Ar will likely result in massive RE current in ITER (up to 10 MA)

Runaway electrons must be suppressed in ITER

- Massive runaway electrons can be produced during CQ of plasma disruptions in ITER. Avalanche is primary mechanism for ITER



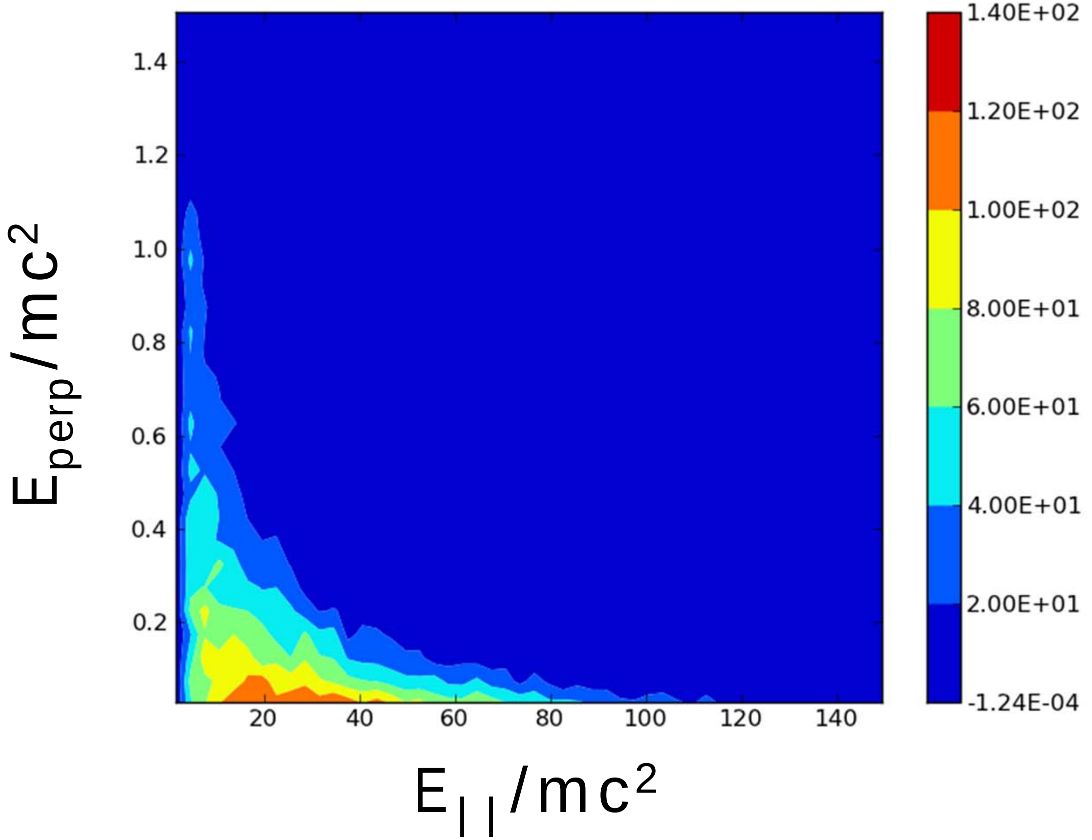
Numerical simulation of CQ in ITER by DINA code. n_{DT}=5·10^{19} m^{-3}, Ar impurity, 7%

- Very large number of e-folds

$$\ln\left(\frac{I_{RE}}{I_{RE,0}}\right) \sim \frac{e\mu_0 l_i I_0}{6\pi mc \ln\Lambda} \sim 2.4 I_0[MA] \sim 30!$$

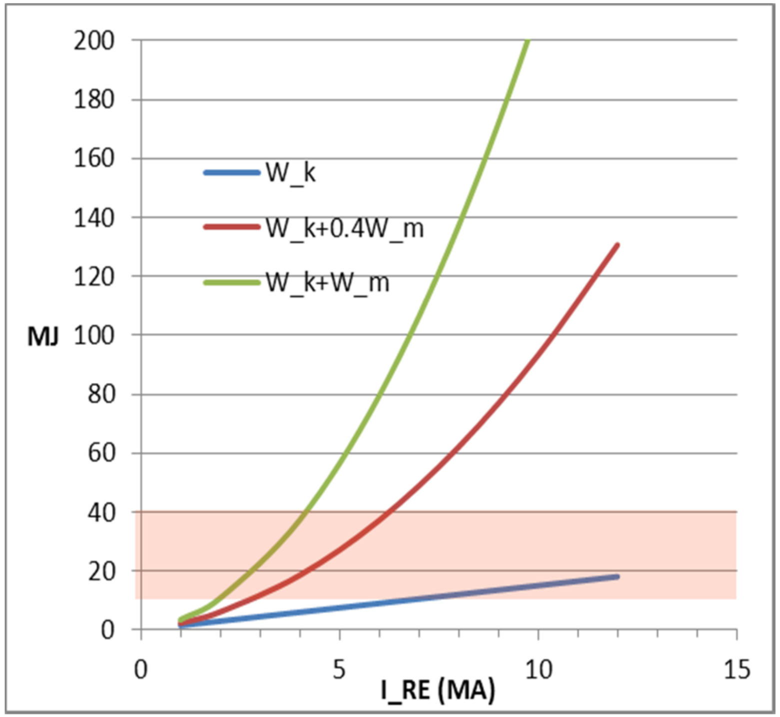
makes finite RE current in ITER insensitive to amount of seed electrons

Expected energy spectrum



- Anisotropic tail with average energy 10-20 MeV. 2D kinetic calculations for ITER (S.Konovalov)

RE current has to be reduced to < 2 MA



Total energy of RE as function of RE current. Average electron energy = 12 MeV and l_i = 1 for the RE current

- Kinetic energy of RE scales as I_{RE} and is expected to be ~10 MJ at I_{RE}~10 MA. Magnetic energy of RE scales as I_{RE}^2 and is about 200 MJ
- The critical question: how much magnetic energy will be transferred to RE kinetic energy during CQ?
- Results of analysis of experimental data from JET (A.Loarte et.al. NF, 2011) suggest that up to 40% of magnetic energy have been transferred in some shots
- More theoretical and experimental work is needed to resolve this uncertainty

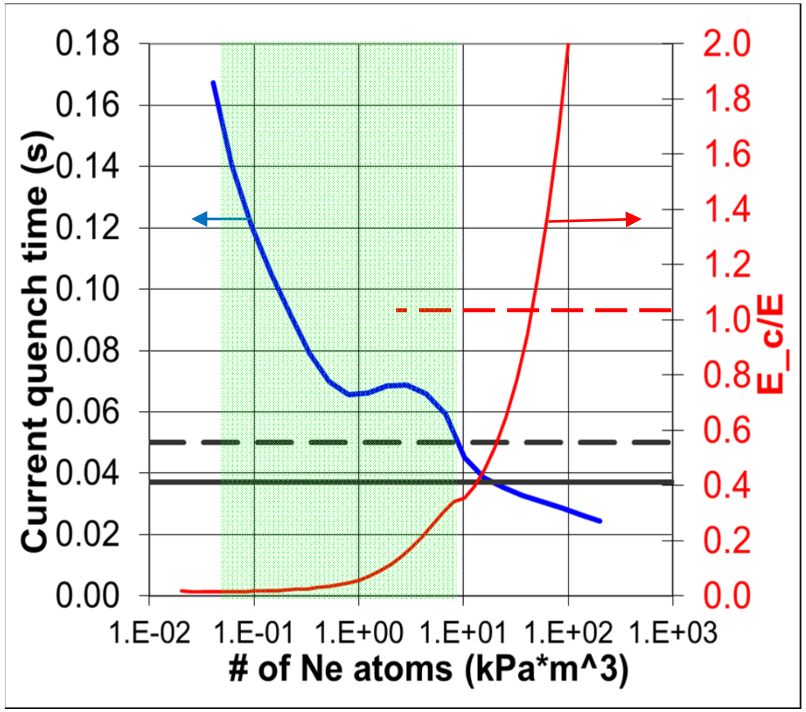
Possible strategies

$$\frac{dI_{RA}}{dt} = I_{RA}\left(\gamma\left(\frac{E}{E_c}-1\right)-\frac{1}{t_{loss}}\right)+S$$

- Disruption
  - Suppress avalanche
    - Collisional $E/E_c < 1$
      - Increase density (Rosenbluth's density)
      - Reduce E
    - RE de-confinement $t_{loss} < \gamma^{-1}(E_c/E)$
  - Magnetic confinement of RE current → In ITER decay of RE current is determined by MGI t_{CQ_RE} ~ 5-6 s

Collisional suppression of RE is challenging in ITER

- Massive gas injection for reaching critical density will reduce current quench time beyond low limit acceptable for mechanical loads



Ratio E_c/E as function of Ne amount in the plasma (red). CQ time is also shown (blue)

- Modeling of current quench with Ne injection
- Reaching critical density will likely be above capability of the machine
- Collisional suppression might work if RE will be suppressed at density 30-50% of critical (Rosenbluth's) density

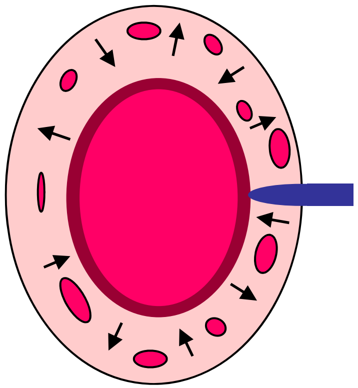
RE suppression by de-confinement

$$\frac{1}{I_{RA}}\frac{dI_{RA}}{dt}=\gamma\left(\frac{E}{E_c}-1\right)-\frac{1}{\tau_{loss}}$$

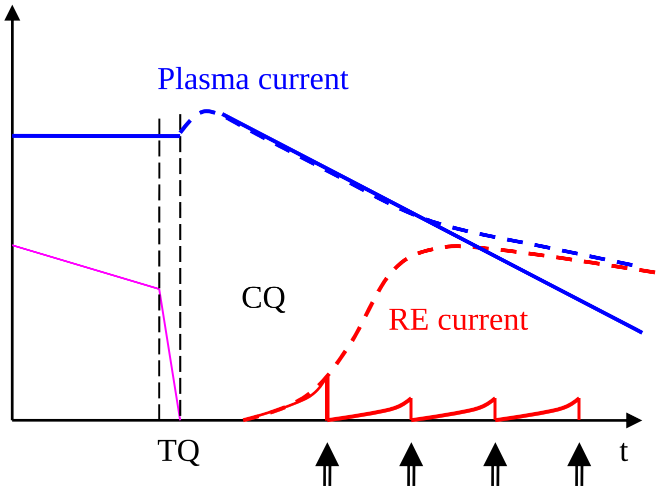
- Fast loss of RE, $\tau_{loss}\gamma << \frac{E}{E_c}$, can suppress avalanche
- Keep magnetic surfaces from healing by applying external MHD perturbations produced by external coils (works in experiments)
- 1) To achieve fast loss amplitude of external perturbations has to be sufficiently large
- 2) These perturbations have to be quickly switched on prior to RE generation
- ELM coils in ITER are two weak and too slow to do the job

De-confinement of RE electrons by repetitive gas jets

- Large magnetic perturbations and secondary disruptions can be produced by dense gas jets injected repetitively in the CQ plasma



Dense and resistive gas jet contracts current channel



- Required gas pressure in the jet ~ 1 atm, gas amount ~1 kPa*m^3, 5-6 jets during CQ (staggered in time by >= 5 ms).

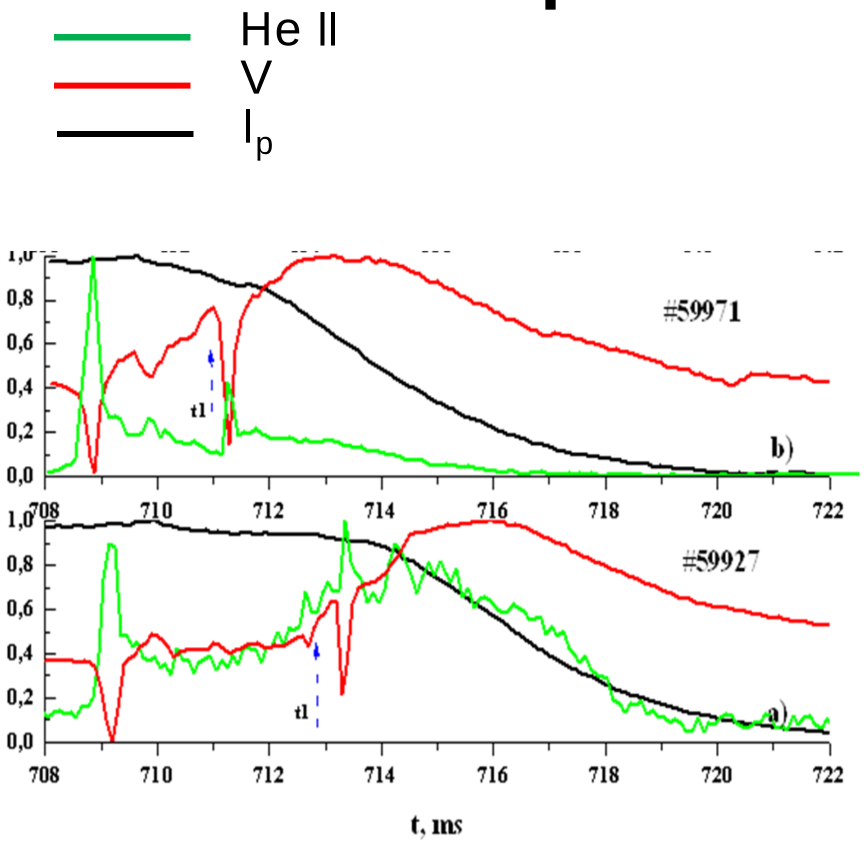
- Based on estimates the total amount of gas can be 10 times less then for collisional damping!

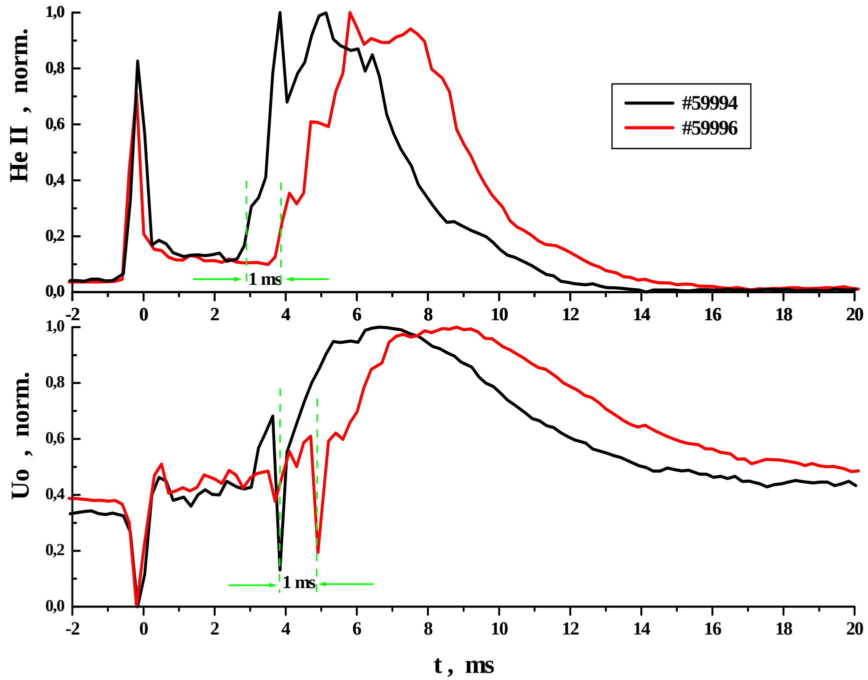
- R&D is in progress to test this scheme in Tore-Supra, ASDEX-U, T-10.

Experiments in Tore-Supra, AUG, and T-10

- The goal is to inject high pressure gas jet into CQ plasma to trigger secondary disruption
- The disruption if occur would be characterized by MHD burst, spike on current trace, negative spike on loop voltage etc.
- To inject high pressure gas jet the nozzle has to be close to the plasma edge.
- Tore-Supra has developed fast gas injector based on rupture disk opened by exploding wire. Pressure in the plenum = 100 atm. Opening time 1 ms.
- T-10 has built a new fast valve with plenum pressure 40 atm and opening time few ms.
- ASDEX Upgrade has fast valves near the plasma edge.

Correlation of He injection with secondary disruption at long CQ's in T10

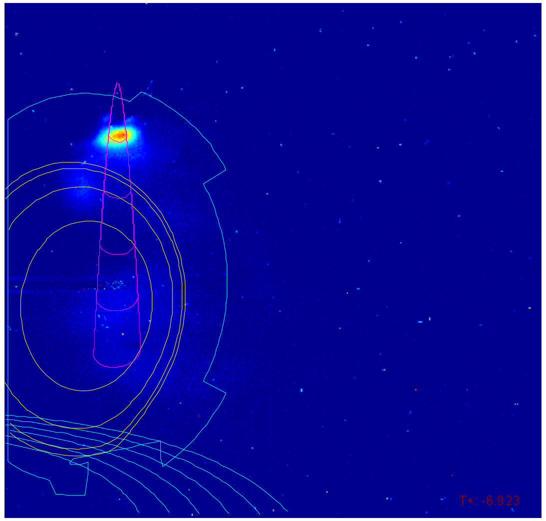




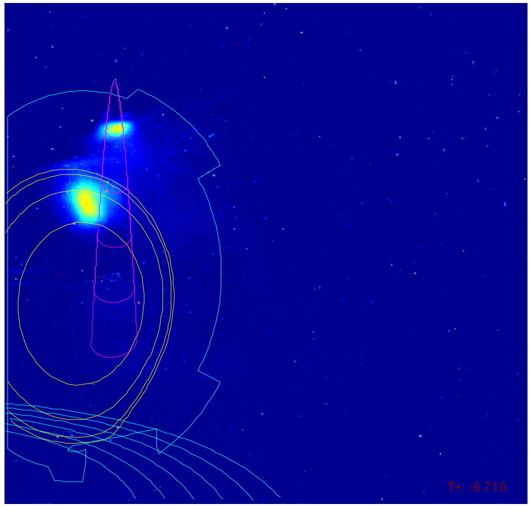
- Left: t1 and t2 marked arrival gas jet to the plasma
- Right: Negative spike appear at the same He II emission level
- Work is in progress

Ne gas jet propagates almost freely in CQ plasmas of Tore-Supra

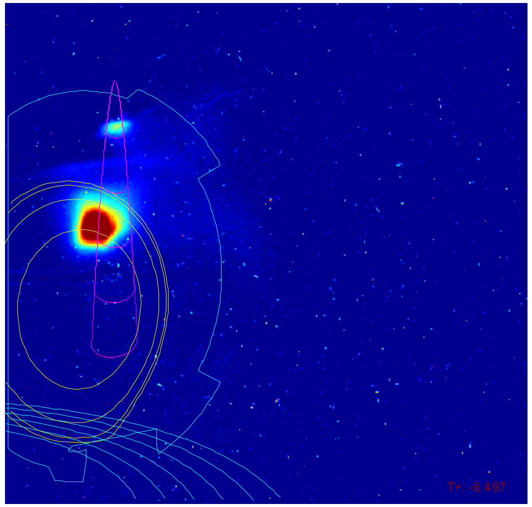
TS#47378 @ -6.9ms / Ip = 636 kA



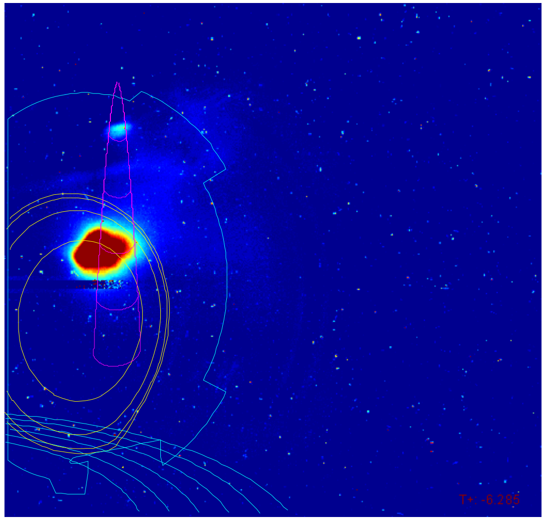
TS#47378 @ -6.66ms / Ip = 596 kA



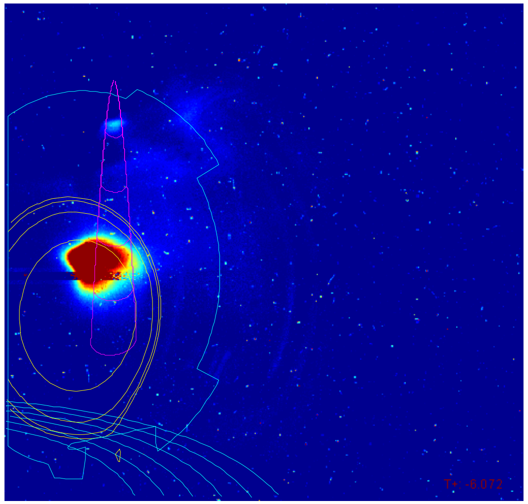
TS#47378 @ -6.42ms / Ip = 557 kA



TS#47378 @ -6.26ms / Ip = 530 kA

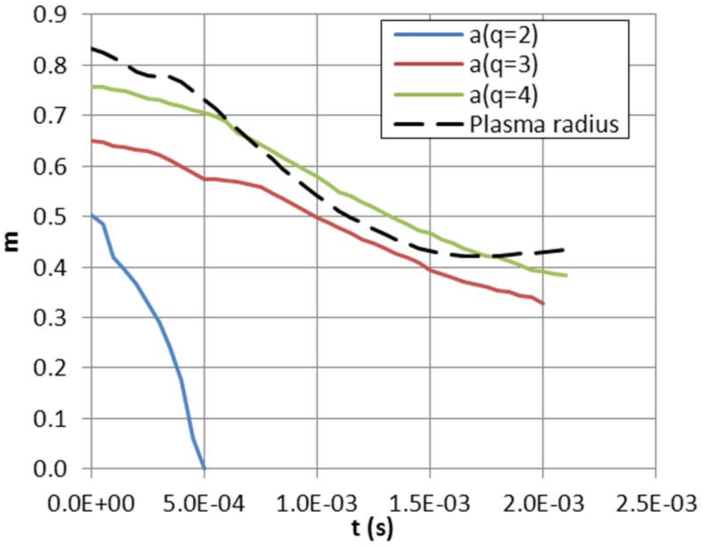


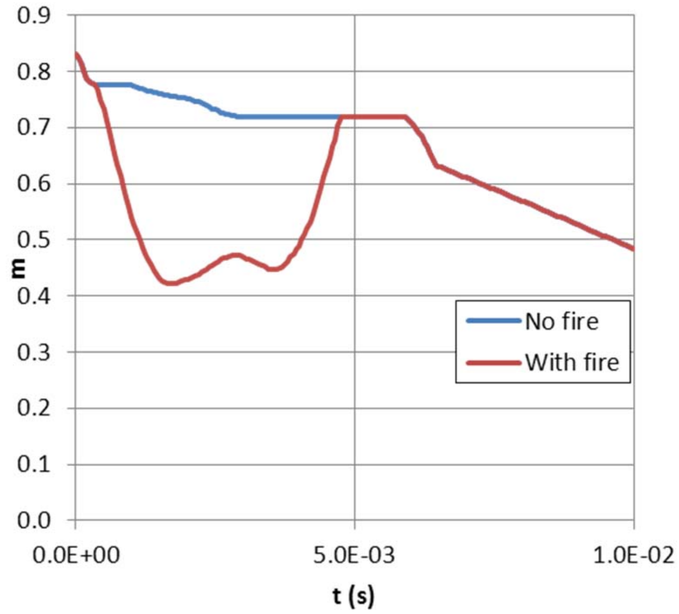
TS#47378 @ -6.02ms / Ip = 497 kA



- Fast camera images of Ne light (200 μs between frames)
- Pressure in gas plenum 100 atm
- Gas front velocity in CQ plasmas, $V_f \sim 500$ m/s

1D modeling of CQ in TS shots #48035-37-39





- Gas jet should result in significant contraction of current channel
- However, it can not catch up q=2 and even q=3 surfaces. This would be necessary to trigger secondary disruption
- In ITER q=2 surface moves 10 times slower and similar gas jet will reach it if V_{jet} > 100 m/s

Magnetic confinement of RE current

- If ITER PF system can control RE current then it would be possible to avoid contact RE with FW and safely reduced RE energy
- Active program at DIII-D disruption studies
- However, first estimates for ITER show that PF system can control only high RE current with I_{RE} > 11 MA!
- Work is in progress to improve (or develop special) control algorithms to extend controllability range

Reduction of loop voltage

- E/E_c < 1 without significant increase of plasma density can be achieved if light impurities (Li, Be, B) are used for re-radiation of thermal energy during TQ

- These regimes has not been explored yet:
  - Would it be possible to re-radiate 300 MJ during TQ with light impurities?
  - Are EM loads during the long CQ acceptable for conducting structures?
  - Dust production could be an issue
  - Etc.

Instabilities driven by RE

- Thresholds for MHD instabilities (kink, tearing modes, etc) are almost the same in plasma with RE (see for tearing modes, P.Helander et.al. 2007)

- No new studies of kinetic instabilities since 70th (Parail&Pogutse 1972)

- Anomalous Doppler resonance can make magnetize Langmuir waves unstable

$$\omega = k_z \omega_{pe} / k$$

- This instability can result in anomalous scattering of RE and suppression of avalanche

- How about AE?

- CQ background plasmas have not been studied also. Plasma is very cold and collisional and tokamak basic assumptions T = T(ψ), n=n(ψ) might not be valid

Summary and conclusions

- Runaway electrons can be produced in a tokamak during plasma disruption
- It is expected that machines with large current such as ITER shall be more susceptible to the runaway electrons than the present tokamaks
- Modeling shows that ITER shall have massive runaway electrons during disruptions with current up to 10 MA and total energy 20-200 MJ
- Runaway electrons must be suppressed in ITER to provide required life time of the plasma facing components
- Better understanding of physics during CQ is needed to develop robust RE suppression scheme (ne?, plasma profiles, etc)
- Reliable RE suppression scheme has yet to be developed for ITER

Additional slides

Large RE current can be generated

$$I_{RE} = \frac{L}{L_{RE}} \left(I_0 - \left(\frac{2}{\pi} \right)^{1/2} \frac{6\pi Rmc \ln \Lambda}{eL} \ln(I_{RE} / I_{RE,0}) \right)$$

1) It must be a seed current for avalanche to work

$$\ln\left(\frac{I_{RE}}{I_{RE,0}} \right) < \frac{e\mu_0 l_i I_0}{6\pi mc \ln \Lambda} \sim 2.4 I_0 [MA]$$

2) Maximum current is not sensitive to the plasma parameters

$$I_{RE} = \frac{L}{L_{RE}} I_0$$

Electron energy is 10-20 MeV

- Electron acceleration is diluted by multiplication of electrons

$$\frac{d\varepsilon}{dt} = eEc - \frac{\dot{n}_{RA}}{n_{RA}}\varepsilon$$

- In steady state $\varepsilon = eEc\frac{n_{RA}}{\dot{n}_{RA}} \approx mc^2\left(\frac{2}{\pi}\right)^{1/2} 3\ln\Lambda \approx 10 - 20\ MeV$

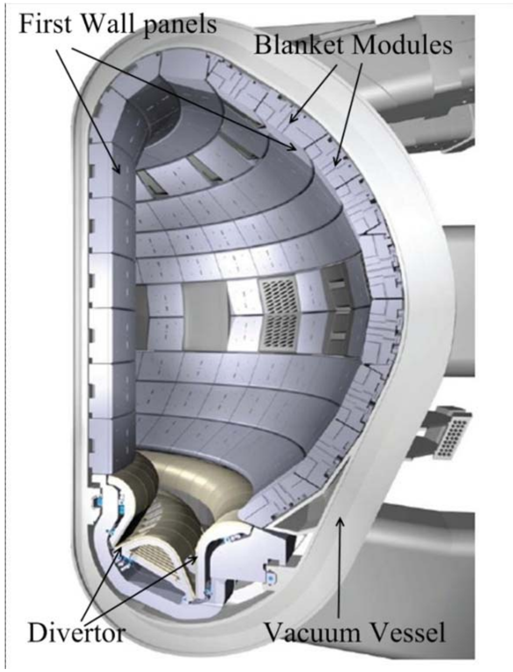
- What about background plasma? Ohmic heating of the background plasma by RE current is significant

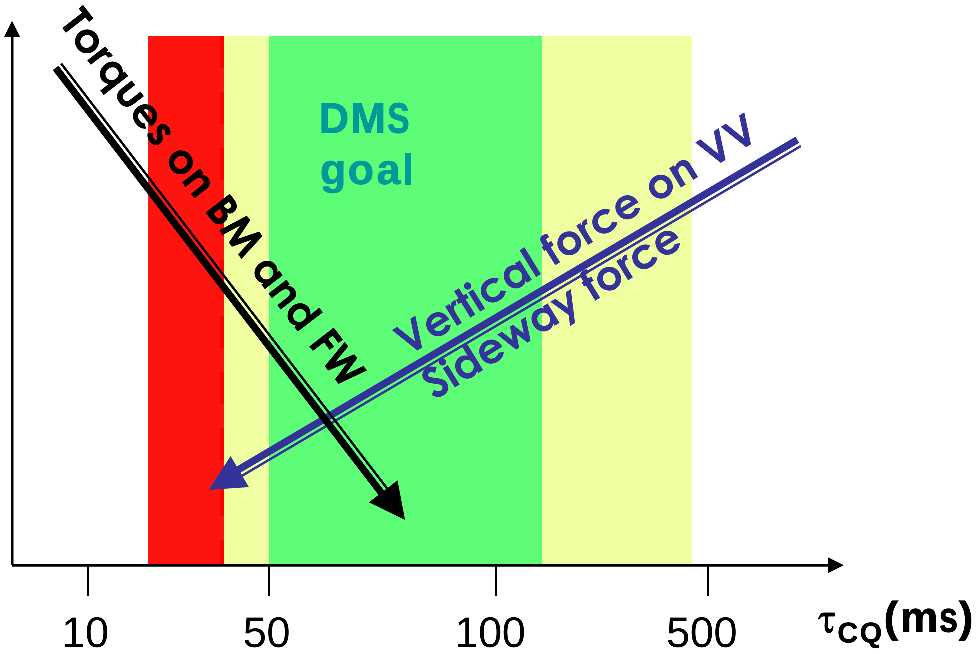
- Power density, $p_{RE} = j_{RE}E_c$, and total heating power, $P_{RE}=Vp_{RE} = I_{RE}U_c$

- An example for ITER parameters, i.e., j = 500 kA/m^2, E_c ~0.075n_e ~0.1 V/m, U_c ~ 3V, I_{RE}=10 MA

$$P_{RE} = 30\ MW$$

Forces impose constrain on maximum amount of gas

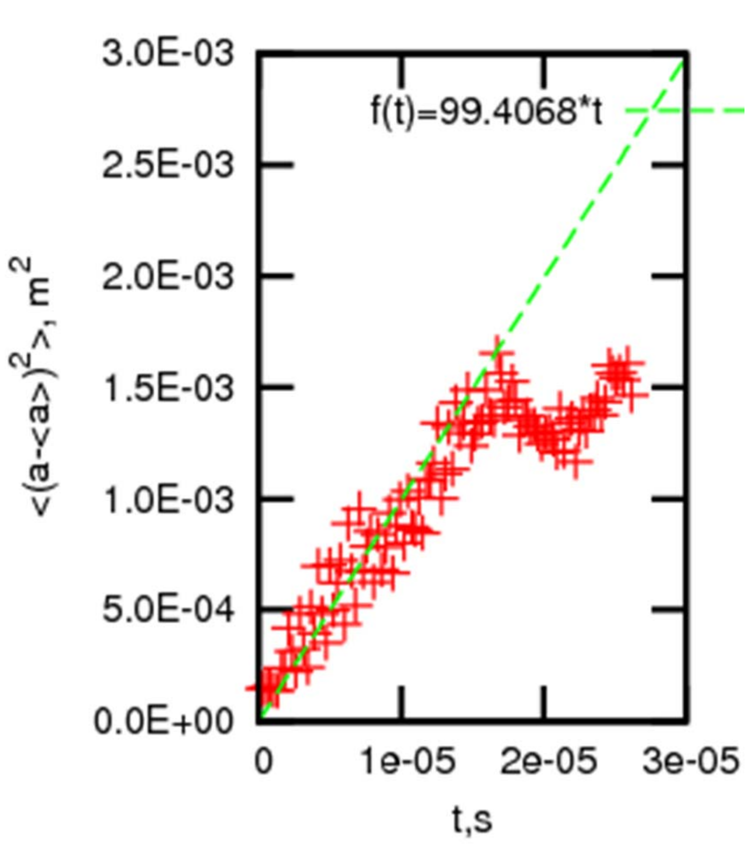




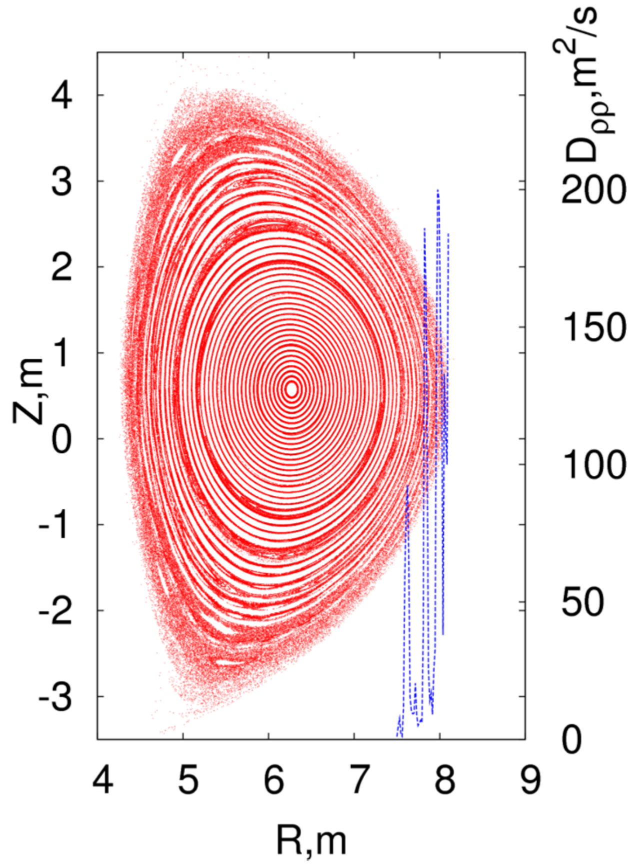
- The major EM loads on the VV and in vessel components occur during current quench of a disruption and following plasma VDE

- DMS goal is to transform very short and very long CQ into disruptions with CQ time 50-150 ms

Modeling of RE confinement with ELM coils



Typical evolution of the second central momentum in fully stochastic region.



Magnetic surfaces and diffusion coefficient profile for t=20ms after Thermal Quench.

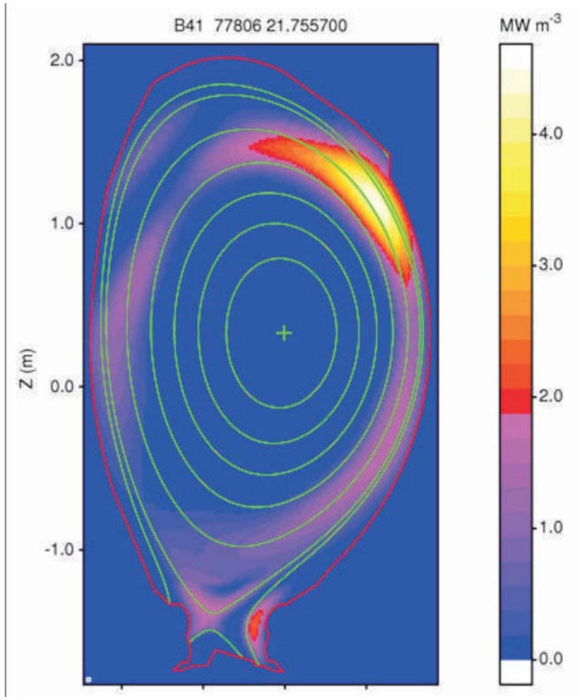
- No global loss of RE (only redistribution) at maximum coil current

MGI can to re-radiate most of plasma thermal energy

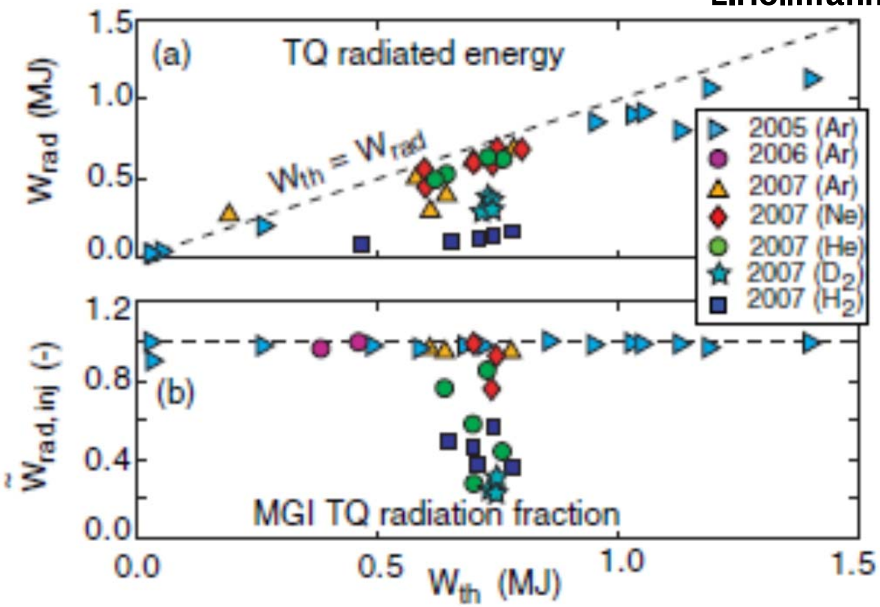
- Challenge for ITER DMS: re-radiate ~300 MJ of plasma thermal energy in about 3 ms and distribute it uniformly over FW

- Experimental results from present tokamaks with pre-emptive injection of high Z gases are very encouraging

E.Hollmann, NF 2008

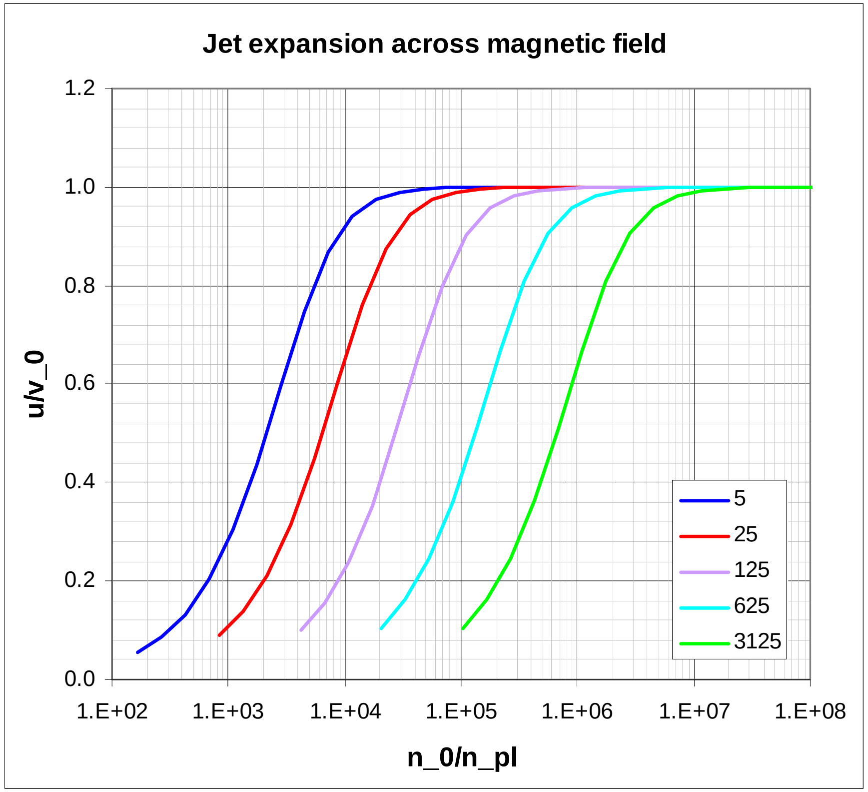


M. Lehnen, IAEA 2010



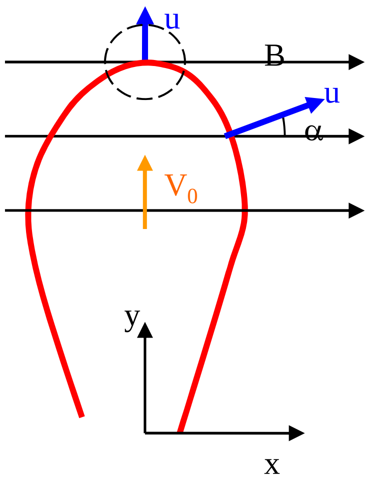
– ASDEX-Upgrade 60-100% G.Pautasso, Pl.Phys,2009
– Alcator C-mod ~75% R.S. Granetz, NF 2007
– JET ~ 90% M.Lehnen, ITPA 2011

High gas pressure is needed for fast gas propagation



$$1-\frac{u}{V_0}=\frac{\pi}{2}\left(\frac{n_{pl}}{n_0}\right)^2\left(\frac{u}{V_0}\right)^2\left(\frac{E_{iz}+T_{pl}}{T_{iz}}\right)^2\frac{V_0 d}{\chi}$$

$p_{pl} << p_0 << B^2/2\mu_0$



- Recombination front velocity across magnetic field is defined by energy balance on the gas front
- For fact propagation into the plasma gas density in the jet n ~ 10^{24}-10^{25} m^{-3}