Runaway Electrons in Tokamaks

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ITER Organization

Outline

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

Introduction

- Runaway electrons 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)

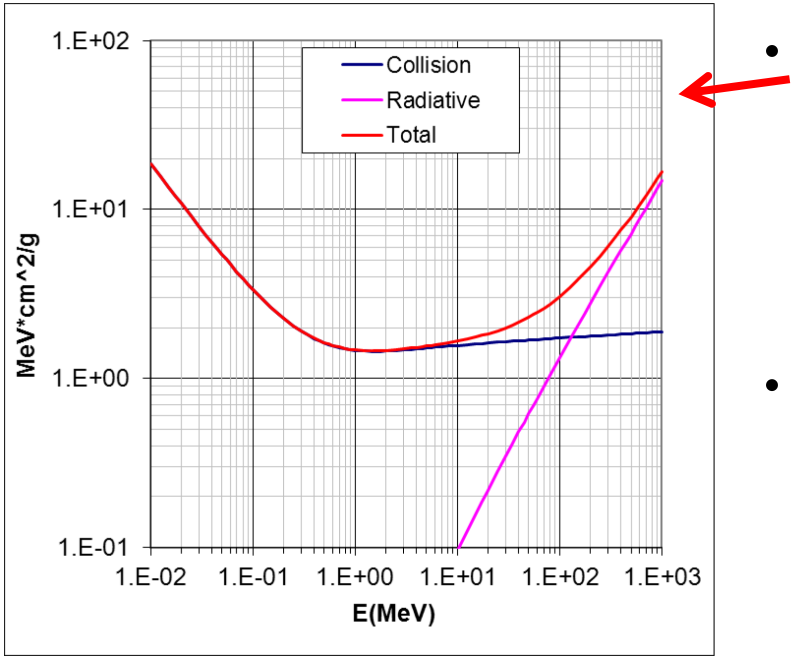
- Frequently cited analytical expression for Dreicer acceleration has been derived by A.V.Gurevich, JETF 1960, **39**, p1296

- They 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)

- At plasma densities typical for tokamaks, $n \sim 10^{19} - 10^{20}\ m^{-3}$ the electric field is small and RE can be produced only during abnormal events such as plasma disruption

MeV runaway electrons have long range

- 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



- Stopping power, s, in Be, (material for ITER wall)

$$dE/dx = s\rho$$

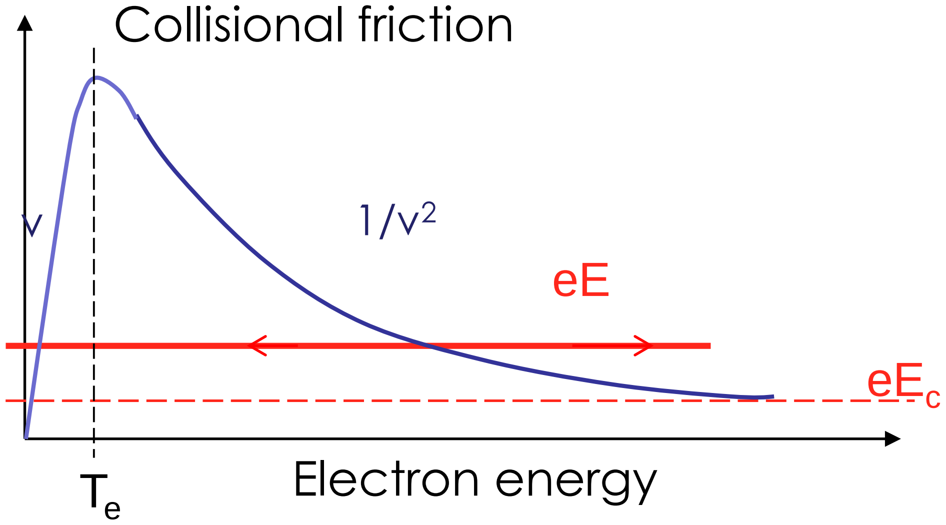
- At Be density $\rho = 1.8$ g/cm^3 and energy of electrons 20 MeV the penetration length is about 5 cm

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:

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

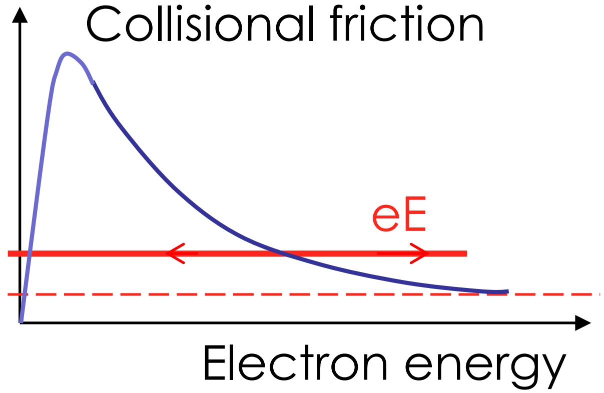
- Critical electric field

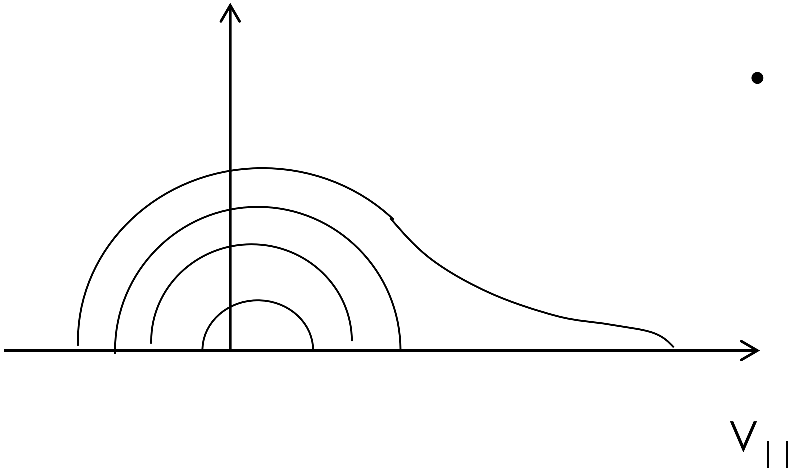
$$E_c = \frac{n_e e^3 \ln(\Lambda)}{4\pi\varepsilon_0^2 m_e c^2}$$

- 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





- Introduce electric field equal to maximum friction force (Dreicer field):

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

- At electric field much smaller than maximum friction force only electrons from far Maxwellian tail can accelerate

- RE electrons form anisotropic tail on distribution function

Dreicer acceleration rate (Gurevich, 1960)

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

- 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)

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

- Home work problem: solve analytically 1D kinetic equation

$$\frac{eE}{m}\frac{\partial f}{\partial v} = \frac{\partial}{\partial v}\nu_0\frac{v_{Te}^3}{v^3}\left(vf+\frac{T_e}{m}\frac{\partial f}{\partial v}\right)$$

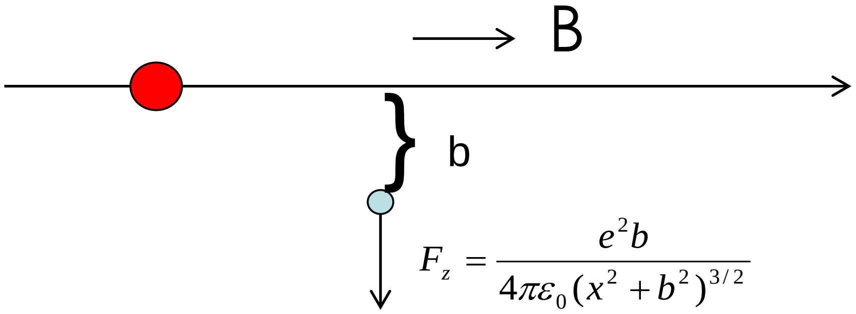
- at *E=const* , ν_0=const and estimate Dreicer source

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))

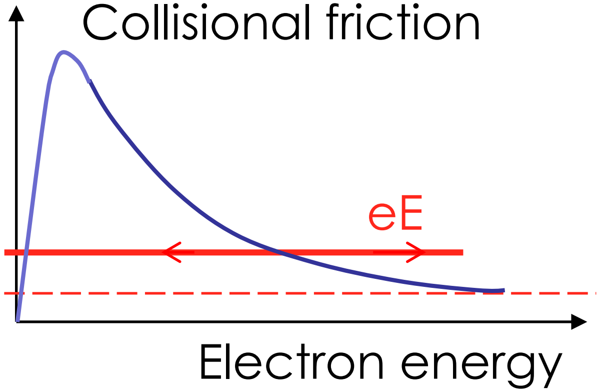
- The avalanche is multiplication of energetic electrons by close Coulomb collisions with plasma electron



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

- Momentum of the secondary electron, $p_\perp = \dfrac{e^2}{2\pi\varepsilon_0 c b}$

Avalanche of runaway electrons



- When $v > v_{cr}$ or

$$b < \frac{e^2}{2\pi\varepsilon_0 c m v_{cr}}$$

- 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

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

How to get runaways in tokamak?

- 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/2πR* < 0.003 V/m, Critical field,

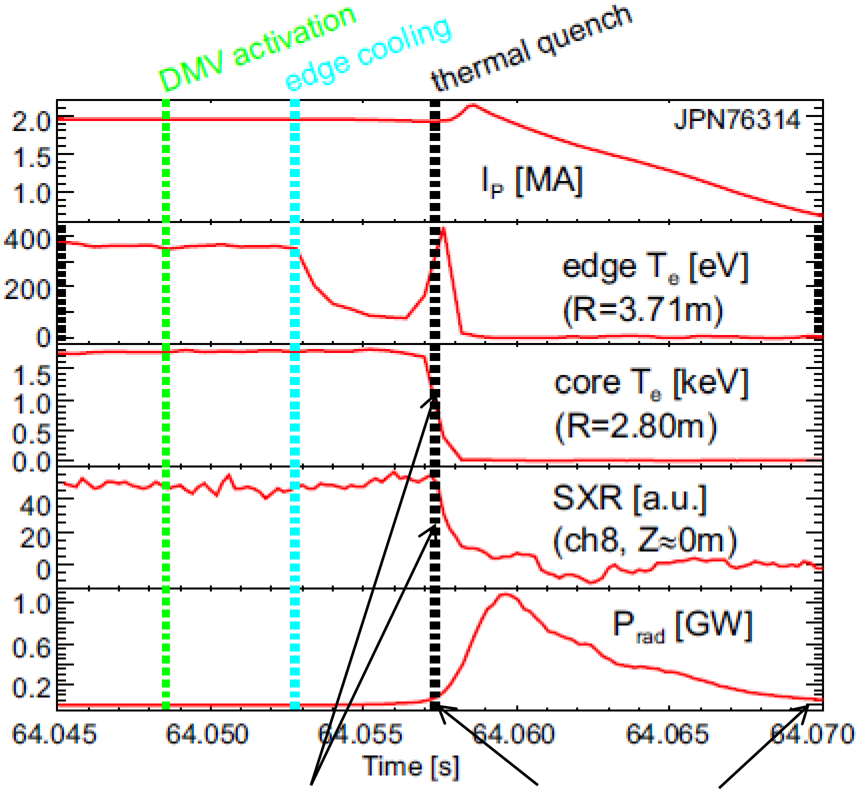
$$E_c = \frac{n_e e^3 \ln(\Lambda)}{4\pi\varepsilon_0^2 m_e c^2} \sim 0.075 n_{e,20} >> E$$

- Generation of RE in tokamaks occurs during plasma disruptions

Plasma disruptions

Plasma can abruptly disrupt in a tokamak

- This disruption is triggered by Ne injection and following edge cooling



Thermal
Quench

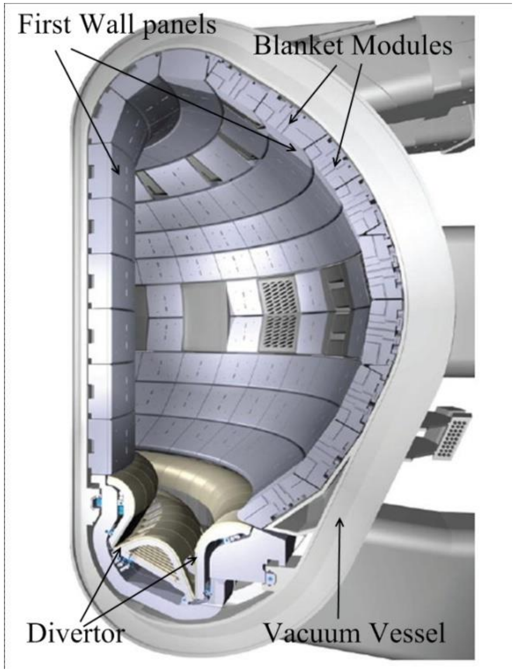
Current
Quench

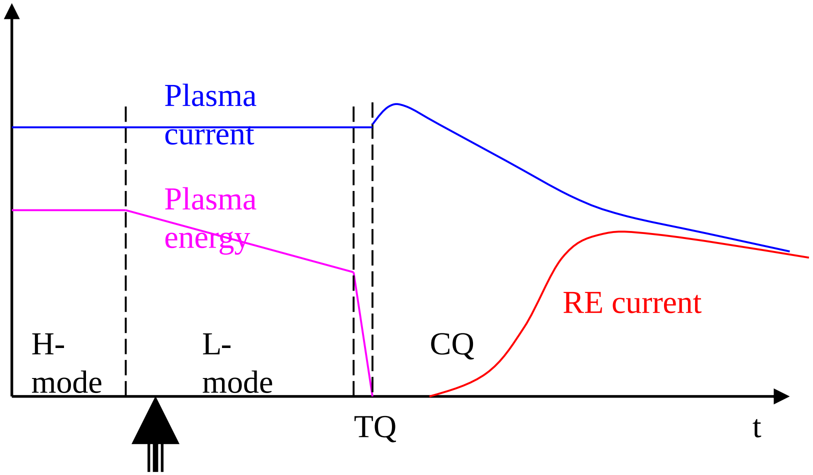
M.Lehnen,
EPS2009

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

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

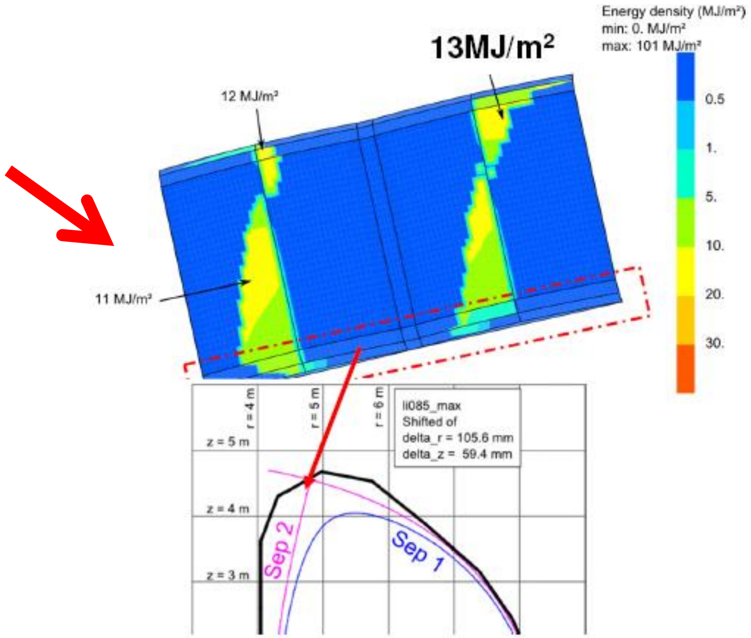
Expected energy loads and their limits

- Maximum energy loads are expected on the divertor targets. Energy density scales as R^3 and in ITER it will be 10 times larger than in JET

- At total plasma thermal energy of 200 MJ and estimated areas of the wetted surfaces of about 10 m^2, P ~ 20 MJ/m^2.

- Similar energy loads are expected on the first wall panels near the top of the machine

- Results of the modeling



Expected energy loads and their limits

- Surface temperature under pulse loads can be estimated from heat conduction equation:

$$q = -\kappa \frac{dT}{dx}$$

- During transients the depth of the heated layer, dx ~ $(\kappa t/\rho C)^{1/2}$ and, thus,

$$T = T_0 + \frac{q}{\kappa}\left(\frac{\kappa t}{\rho C}\right)^{1/2} \propto \frac{P}{t^{1/2}} = \varepsilon$$

- Parameter ε shows how close surface is to the melting temperature.

- Thermal quench time is expected 3 ms and thus during ITER disruptions ε ~400 MJ/m^2/s$^{1/2}$

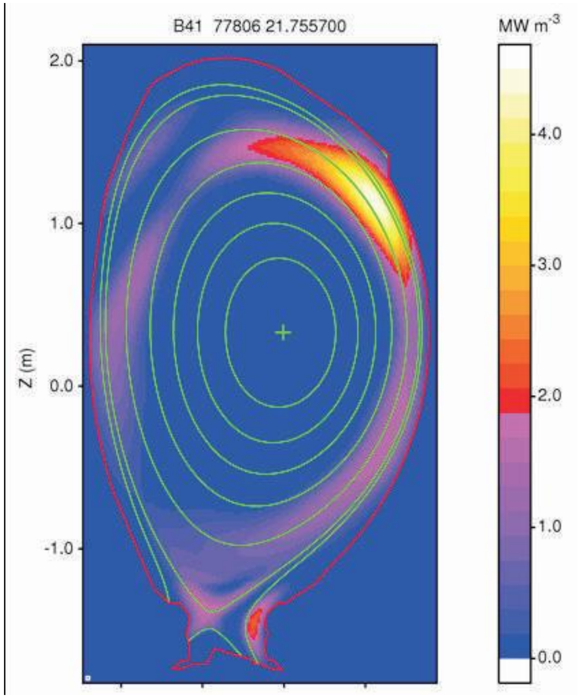
- Surface melting occurs at:

ε = 23 MJ/m^2/s$^{1/2}$ for Be,
ε = 50 MJ/m^2/s$^{1/2}$ for W,
ε = 12 MJ/m^2/s$^{1/2}$ for SS,

MGI can to re-radiate most of plasma thermal energy

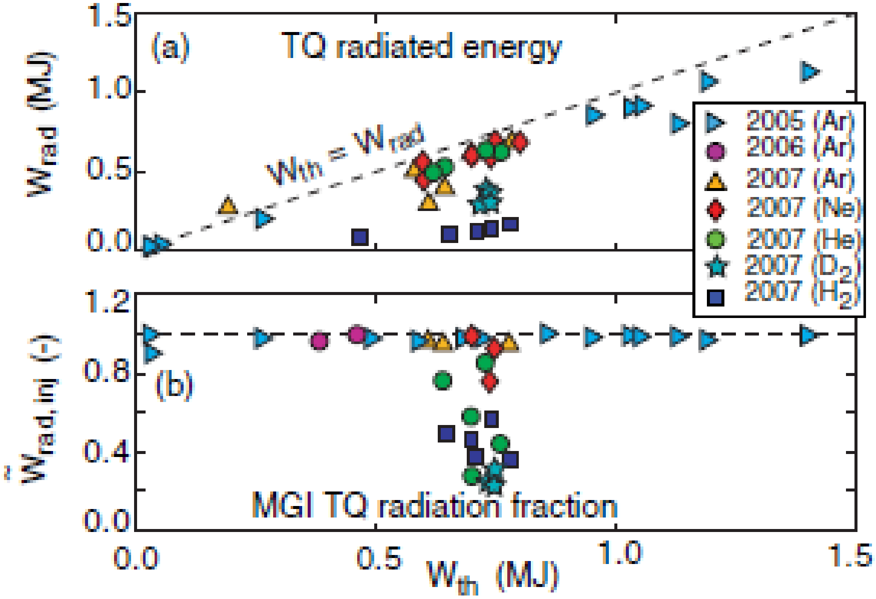
- Challenge for ITER DMS: re-radiate ~300 MJ of plasma thermal energy in about 3 ms and distribute it uniformly over FW

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



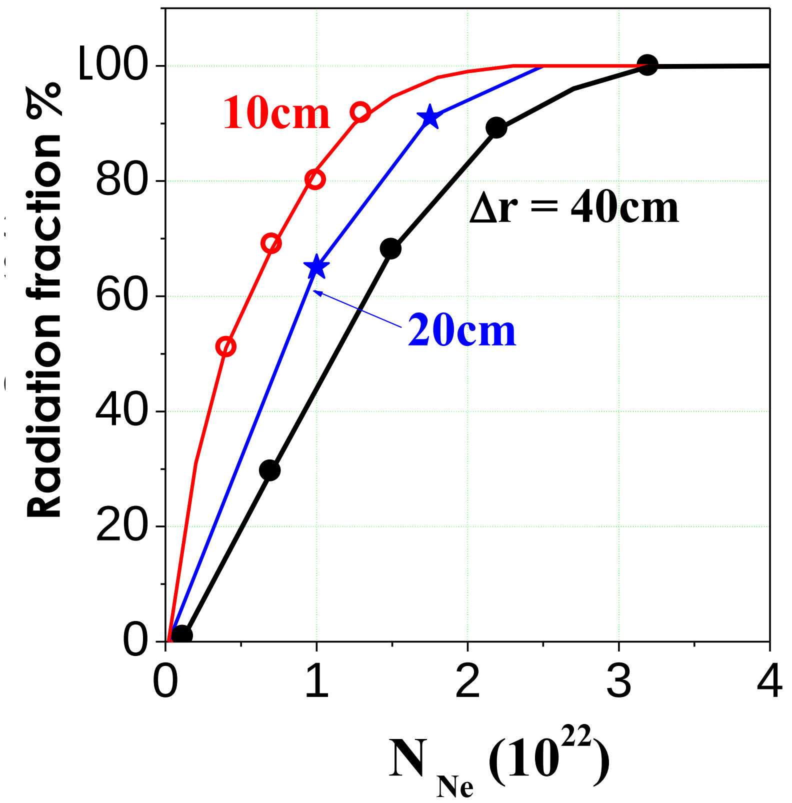
M. Lehnen, IAEA 2010

E.Hollmann, NF 2008



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

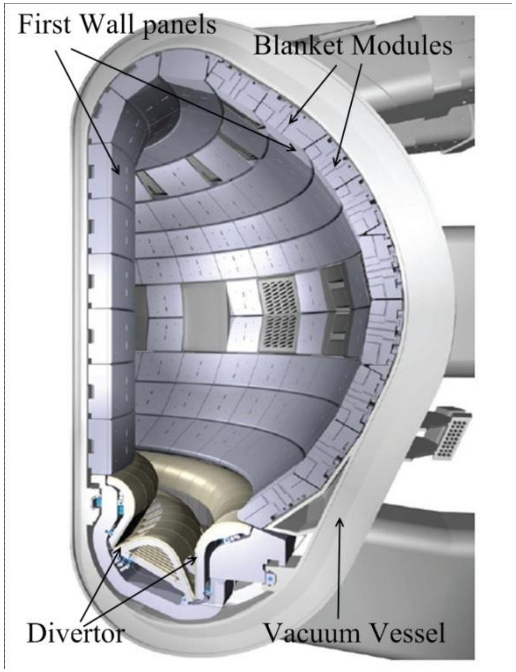
Few kPa*m^3 is needed to radiate plasma energy in ITER

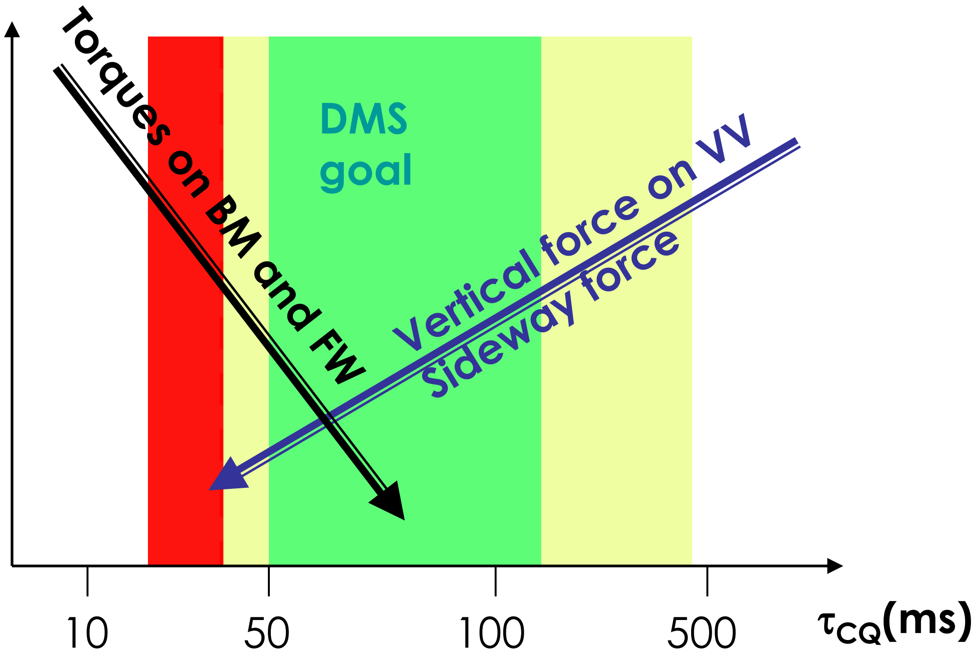


- 1D numerical simulation by ASTRA + ZIMPUR codes. Plasma density 10^{20} m^{-3}, plasma thermal energy 350 MJ.

- Assuming assimilation factor of injected impurity of 5-10% the gross amount of injected impurity must be:
  - Ne ~ 1-2 kPa*m^3
- It is well within the capability of pumping and gas processing systems
- Uniform distribution of radiation over the wall is important. Not much margin for peaking 300MJ/800m^2 = 0.375 MJ/m^2
- Better understanding of physics processes during TQ is needed
- 3D codes accounting for MHD perturbations, atomic physics, and radiation transport should be developed

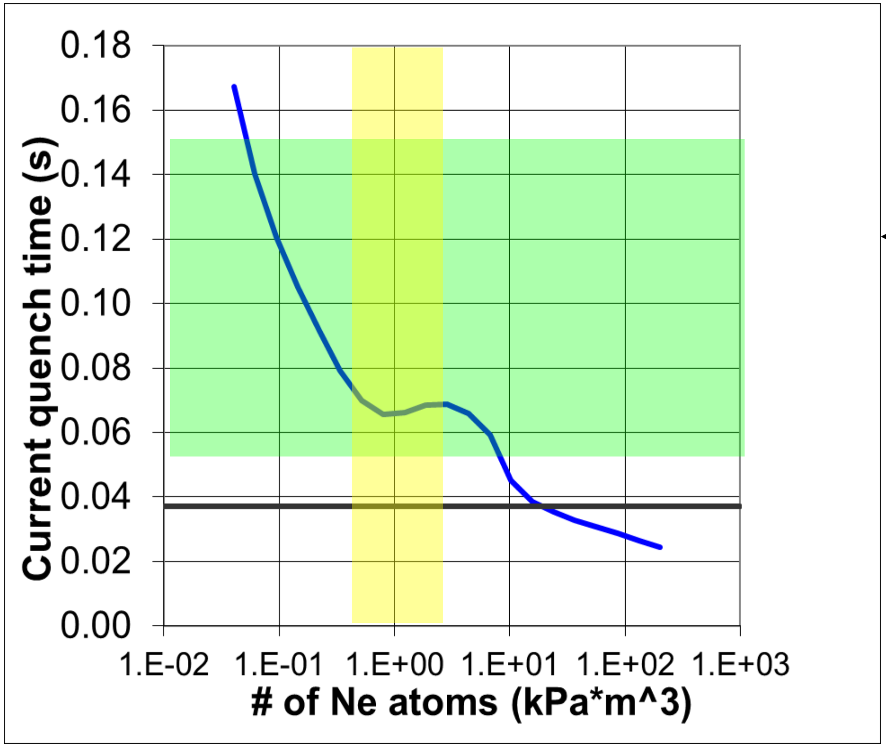
Forces impose constrain on maximum amount of gas





- 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

MGI of noble gas can significantly reduce CQ time



CQ time (linear) vs amount of injected Ne for mitigation of TQ (corona radiation).
$I = 15$ MA, $n_{DT}=1\cdot10^{20}$ m^{-3}

- Simple 0D model, $j^2/\sigma = P_{rad}$, reasonably well describes current decay at CQ
- There is still a reasonably large window of 0.1 -10 kPa*m^3 to mitigate thermal loads without excessive forces on the in-vessel components
- Mitigation of TQ energy loads by MGI is consistent with acceptable CQ duration

Large loop voltage during Current Quench

- ITER example: plasma current 15 MA, Current decay time 100 ms, plasma inductance 5 mH result in

U = dLI/dt ~ 750 V; *E = U/2πR ~20 V/m >> Ec*

- Avalanche during plasma disruption can result in massive RE current

$$\frac{1}{I_{RA}}\frac{dI_{RA}}{dt}=\gamma\left(\frac{E}{E_c}-1\right)\approx-\frac{\gamma}{2\pi RE_c}\left(\frac{dLI}{dt}+\frac{dLI_{RA}}{dt}\right)$$

- Integrating over time

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

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

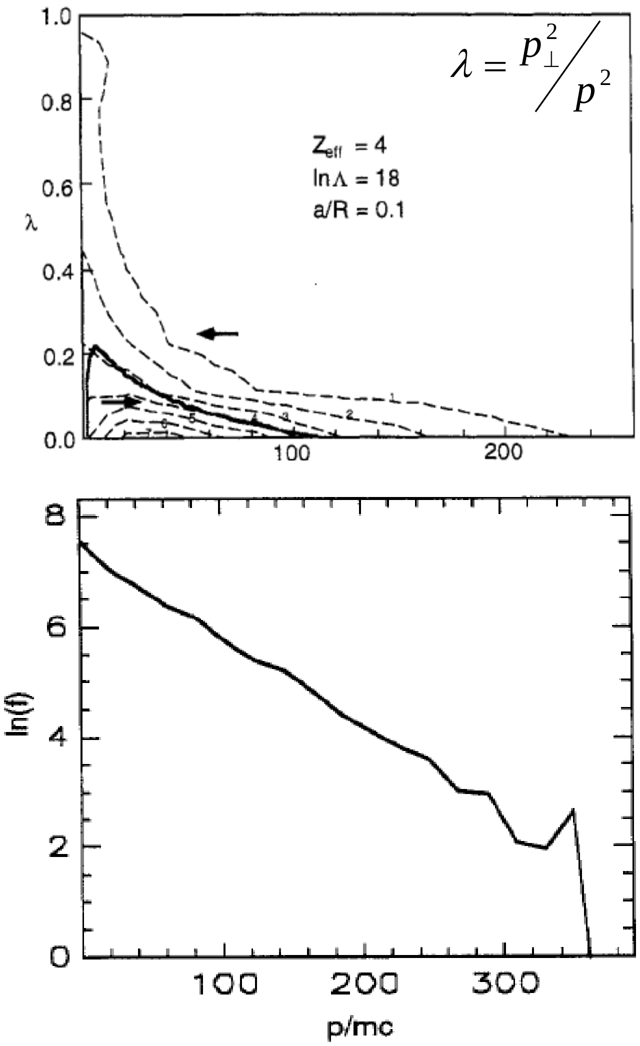
- What about background plasma? Ohmic heating of the background plasma by RE current is significant

- 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

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

Energy spectrum has been calculated numerically



From Rosenbluth NF, 1996

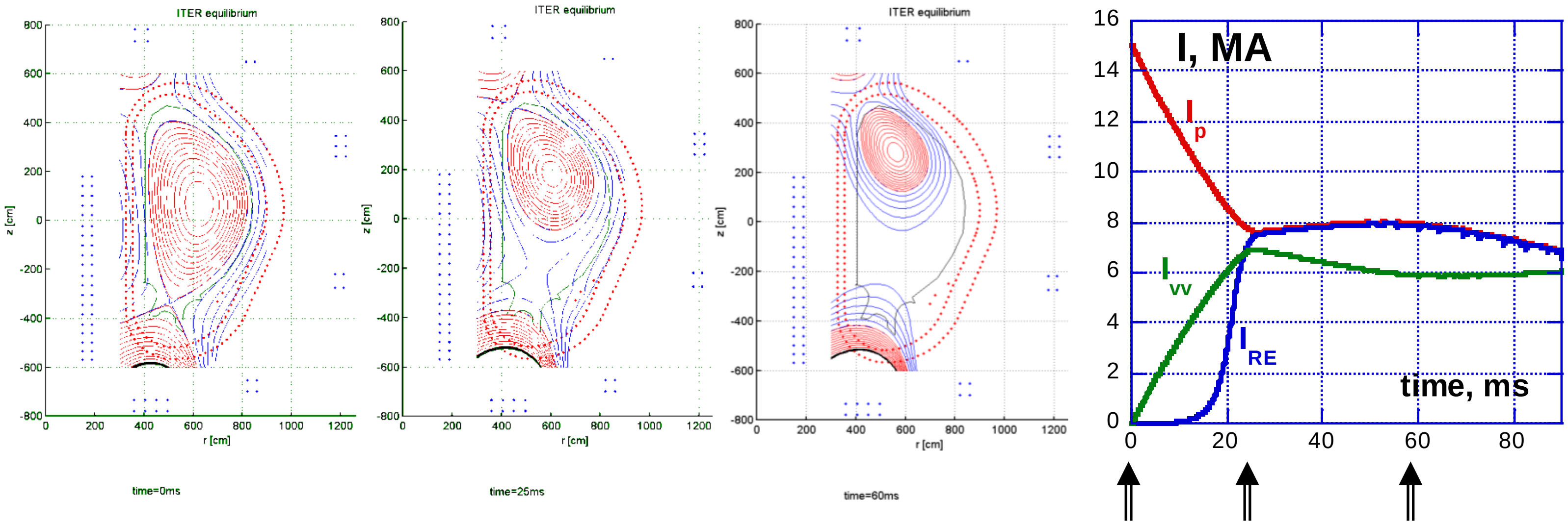
- 2D distribution function of RE after saturation of RE current, t = 200τ
- Monte-Carlo calculations of avalanche in plasma with a/R = 0.1, Z_{eff} = 4, and initial electric field E/E_c = 15
- Energy distribution averaged over pitch angle is close to Maxwellian

$$f \sim \exp(-E/T)$$

- with $T \sim mc^2 \ln(\Lambda)$ as has been estimated above

Runaway electrons must be suppressed in ITER

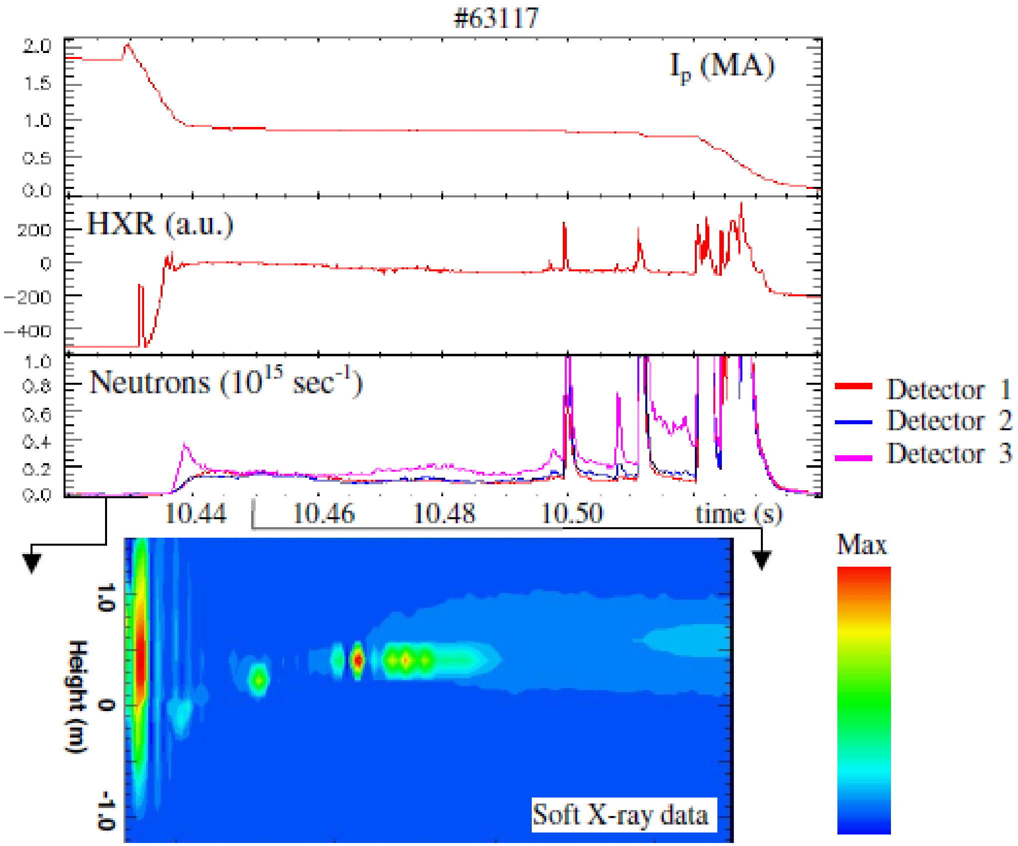
- 2D simulation of CQ in ITER by code DINA. $n_{DT}=5\cdot10^{19}$ m^{-3}, Ar impurity, 7%



- Very large peaking of RE loads and long range of 10-20 MeV electrons in FW materials can result in a deep melting of FW Be panels

- To avoid melting of the wall the RE current must be suppressed to less then 2MA in ITER

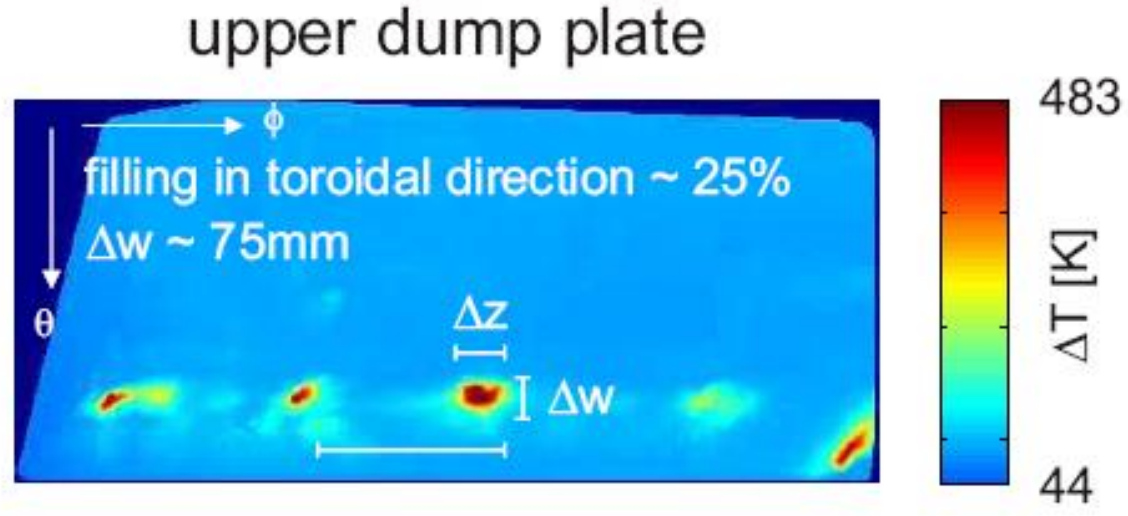
Runaway electrons are often observed during plasma disruptions



- 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

- Movie

RE carry large kinetic and magnetic energy

- Density of RE electrons:

  $j = en_{RE}c;$ $n_{RE} = I_{RE}/ecS;$ $N_{RE} = n_{RE}V = I_{RE}2pR/ec.$

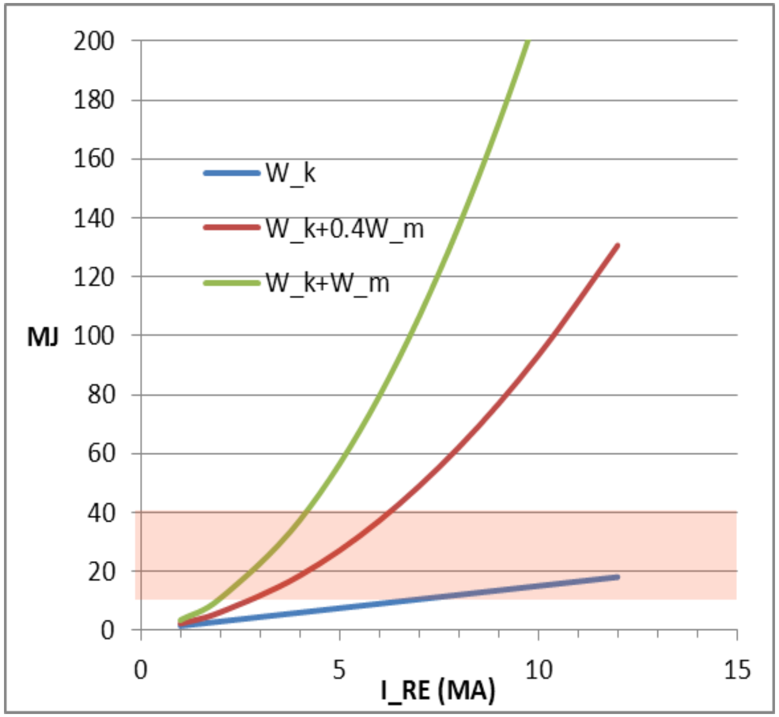
- Kinetic energy in all RE: $W_{kin} = e_{RE}N_{RE} \sim I_{RE}$

- Magnetic energy: $W_{mag} = LI_{RE}^2/2 \sim I_{RE}^2$

- An example:

	JET	ITER
RE current (MA)	1	8
RE density (1/m3)	$5\ 10^{15}$	$8\ 10^{15}$
Kinetic energy (MJ)	1	15
Magnetic energy (MJ)	1.5	150

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

Better understanding CQ plasmas is needed

- Plasma parameters during CQ: $n= 1\ 10^{20}\ m^{-3}$, $T = 10$ eV, $\tau_{CQ} \sim 40$ ms
- Ion and electron mean free path in CQ plasmas: $\lambda_i \sim\lambda_e \sim 1$ cm
- Pressure equilibration time along the field lines: $\tau_p \sim 2\pi R/C_s \sim 1$ ms -> pressure is constant along magnetic field lines.
- Temperature equilibration time: $\tau_\chi \sim L^2/\chi > 100$ ms! Temperature and, hence, electrical resistance can be not constant on magnetic surface after MGI
- Variation of plasma resistivity will result in electrostatic perturbations $\mathbf{E} = \mathbf{E}_0 - \boldsymbol{grad}\Phi$ and magnetic perturbations. How long does it takes for them to decay?

Problem of missing seed current

- Avalanche results in exponential amplification of the seed current

$$\ln(I_{RE} / I_{seed}) \approx 2.5 I_0 \sim 30 - 40$$

- Dreicer source is exponentially small in 10 eV plasmas and many orders of magnitude smaller than needed for avalanche!

$$S \propto \exp\left\{-\frac{E_D}{4E}\right\} \quad or \quad \ln(S) \approx 2 \cdot 10^4 \tau_{CQ} n_{20} / I_{MA} \approx 130$$

- Other sources:
  - Tritium β decay produces 10 keV electrons with the rate 3 10^{11} 1/m^3s. Not enough
  - Compton scattering of gammas. Could work but there is no gammas during CQ!

- It should be some other sources.

Relict tails

- What if far Maxwellian tails survive thermal quench (H.Smith 35th EPS)?

- How long will it take to cool down in 10 eV CQ plasmas?

$$\frac{\partial f}{\partial t} = \frac{1}{v^2}\frac{\partial}{\partial v}\nu_0 v_{Te}^3 f \qquad \nu_0 = \frac{e^4 n_e \ln(\Lambda)}{4\pi\varepsilon_0^2 m_e^2 v_{Te}^3}$$

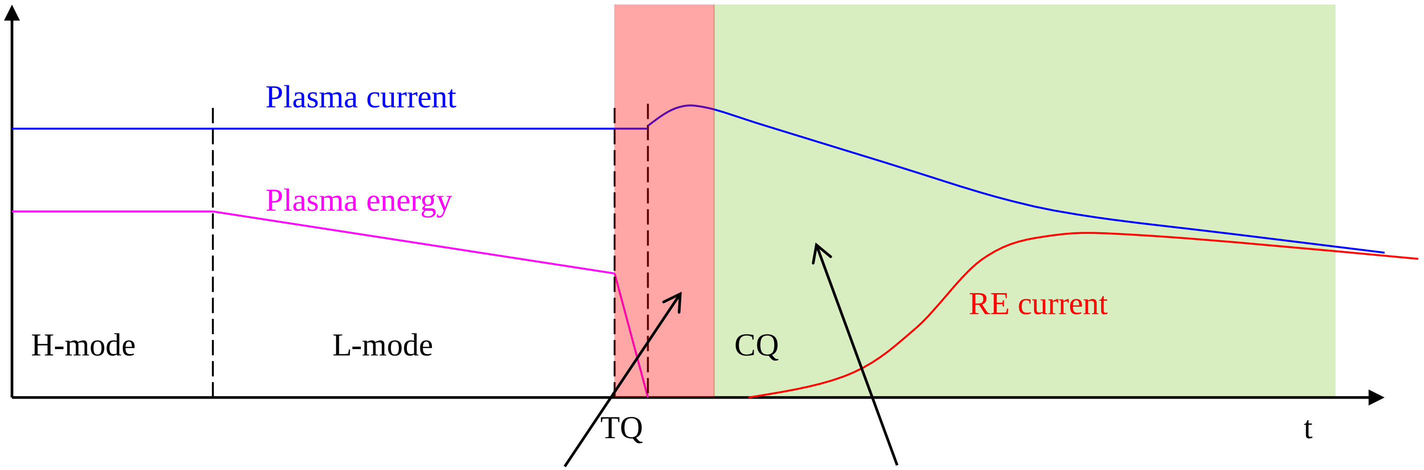
- Solution (Maxwellian as initial condition): $f \sim \exp\left\{-\left(v^3 \middle/ v_{Te}^3 + 3\nu_0 t \right)^{2/3}\right\}$

- Slowing down time will be

$$\nu_0 t \approx v^3 \big/ 3v_{Te}^3$$

- At typical parameters $\nu_0 \sim 10^8\ s^{-1}$. Only very far tail can survive on ms time scale. Not enough particles if the tail is Maxwellian.

Critical path for generation of RE

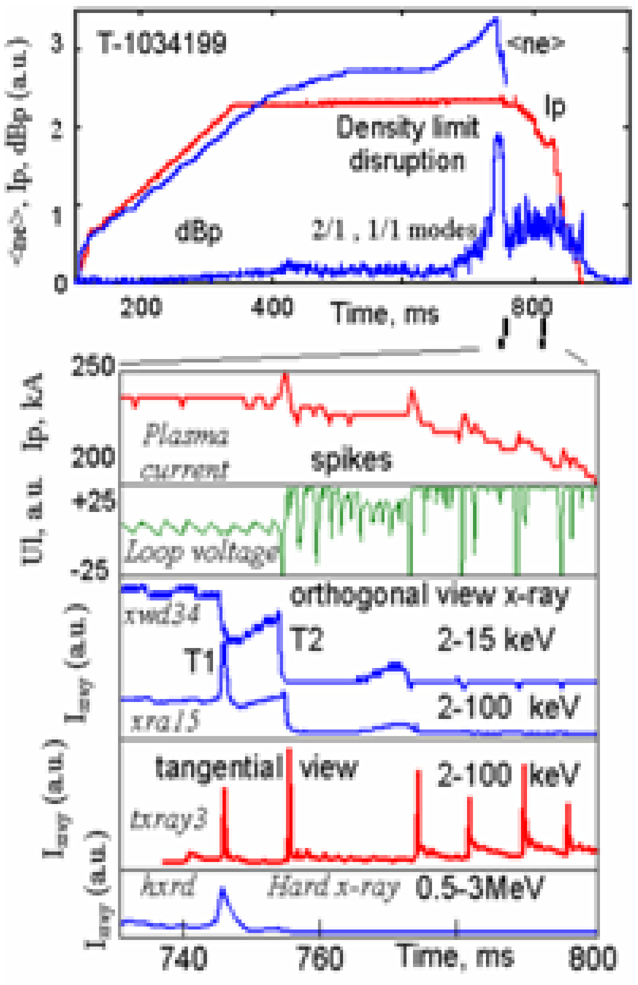


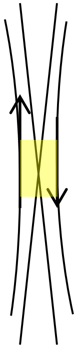
Large MHD,
magnetic surfaces destroyed

MHD decays
magnetic surfaces re-healed

- No runaways until magnetic field re-heal
- After cooling down no sources for avalanche left
- Is something else happening during beginning of current quench?

Tangential x-rays during reconnection





- Two X-ray cameras: tangential and normal
- Every event of current spike (redistribution of current density) is accompanied by tangential x-ray burst
- Magnetic reconnection -> large local electric fields -> energetic electrons?
- Could it be that seed electrons are produced by reconnection events?

MHD stability of RE beams

- Ideal MHD is oblivious of what plasma component carries the current as long as E + [vB] = 0

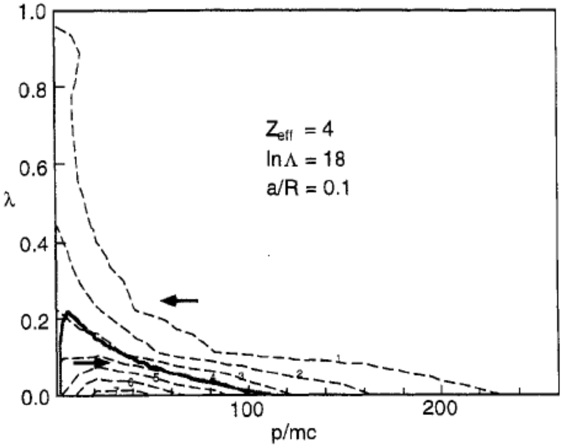
- Plasma equilibrium, vertical stabilization (n=0), and ideal kink modes are the same as in “normal” plasmas

- Resistive MHD modes (tearing)? What component determines the resistive stability properties: the collisionless runaways or the resistive bulk?

- P. Helander et.al.,Phys. Plas **14**, 122102, 2007

- Main results:
  - linear growth rate is determined by main resistive plasmas
  - saturated island width is about twice larger in RE plasmas

Kinetic instabilities



- Resonance in magnetize plasmas

$$\gamma \propto \int \delta(\omega - n\omega_{Be} - k_z v_z)\left(k_z \frac{\partial f}{\partial v_z} + \frac{n\omega_{Be}}{v_\perp}\frac{\partial f}{\partial v_\perp}\right) dv$$

- At $\omega \sim n\omega_{Be}$, $k_z v_z = \omega - n\omega_{Be} << n\omega_{Be}$ plasma is unstable when

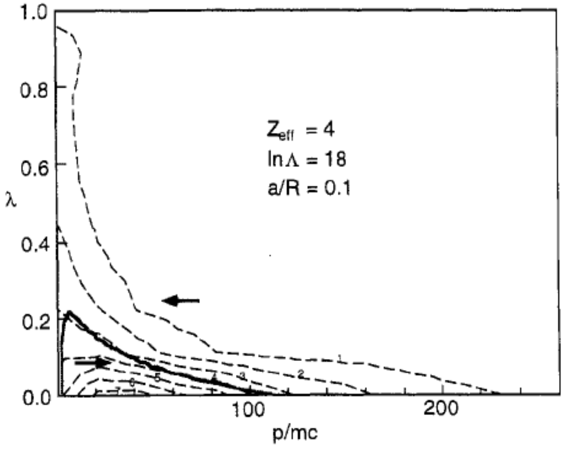
$$\frac{\partial f}{\partial v_z} > \frac{\partial f}{\partial v_\perp}$$

- Runaway electron tail can not make cyclotron wave unstable

- Cherenkov resonance $\omega = k_z v_z$ results in stable oscillations for monotonic distribution function of RE

- Anomalous Doppler effect $k_z v_z = -n\omega_{Be}$, at n<0 can provide energy transfer from electrons to the waves. Parallel particle energy is transfered in perpendicular energy –> anomalous scattering of RE

Magnetize Langmuir waves



- Dispersion relation $\omega = k_z \omega_{pe} / k$

- Linear theory for Dreicer distribution function, non relativistic, see V.Parail, Reiew of Plasma Physics v.11

- Stability threshold at $v > 3\left(\frac{\omega_{Be}}{\omega_{pe}}\right)^{3/2} v_{cr}$

- In ITER, $\omega_{Be} > \omega_{pe}$ and RE beam much be much faster than critical velocity for

- Quasilinear analysis predicts periodic bursts of instability with anomalous scattering of RE

- Could result in reduction of avalanche growth rate but analysis has not been done yet.

Runaway mitigation/suppression

Collisional suppression of RE is challenging in ITER

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

- Avalanche can be suppressed by:
  - increase of electron density to enhance collisional slow down of RE ($E_c = 0.075n_e$)
  - enhancement of RE loss, $\gamma\tau_{loss}<1$

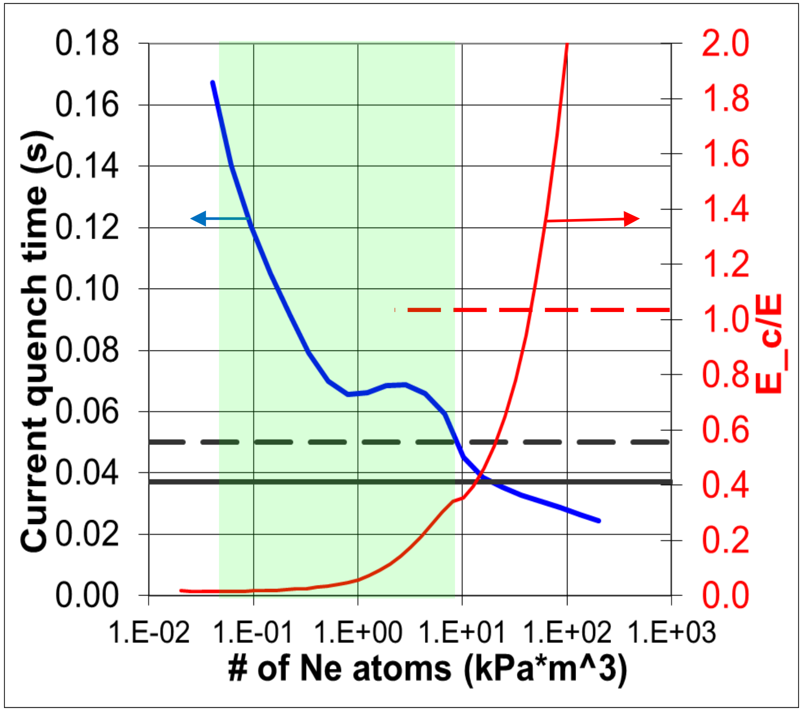
- During current quench of a disruption E = 20-50 V/m. To reach collisional suppression of RE the electron density must be increased by factor of 300-700 times!

- This requires injection of massive amount of gas which is beyond capability of ITER pumping and gas processing system

- Maximum density increase that has been achieved in experiments is less then 20% of critical

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

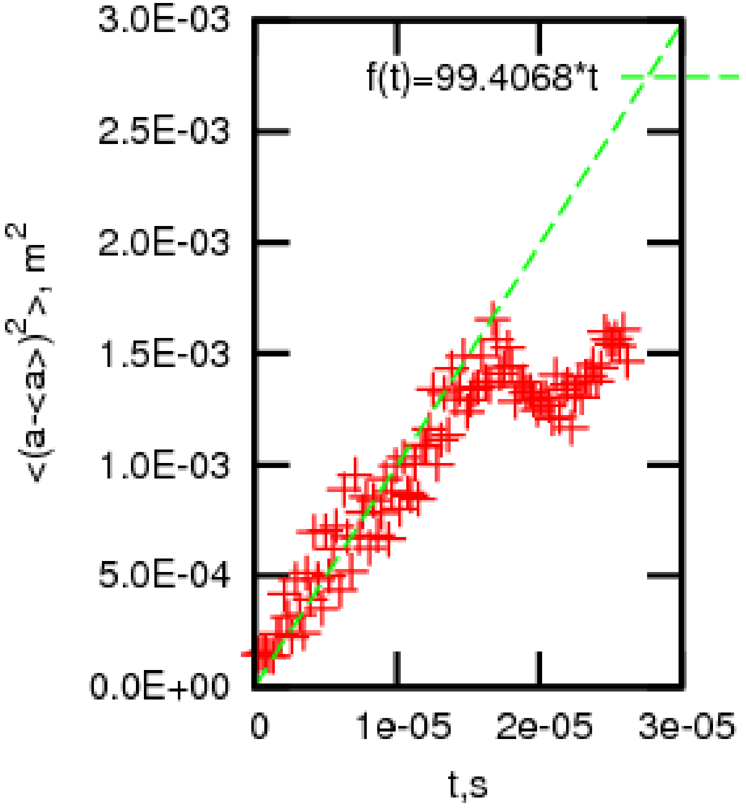
- Modeling of current quench with Ne injection
- Reaching critical density will likely be above capability of the machine
- Collisional suppression might work if RE will be suppressed at density 30-50% of critical (Rosenbluth's) density

RE suppression by de-confinement

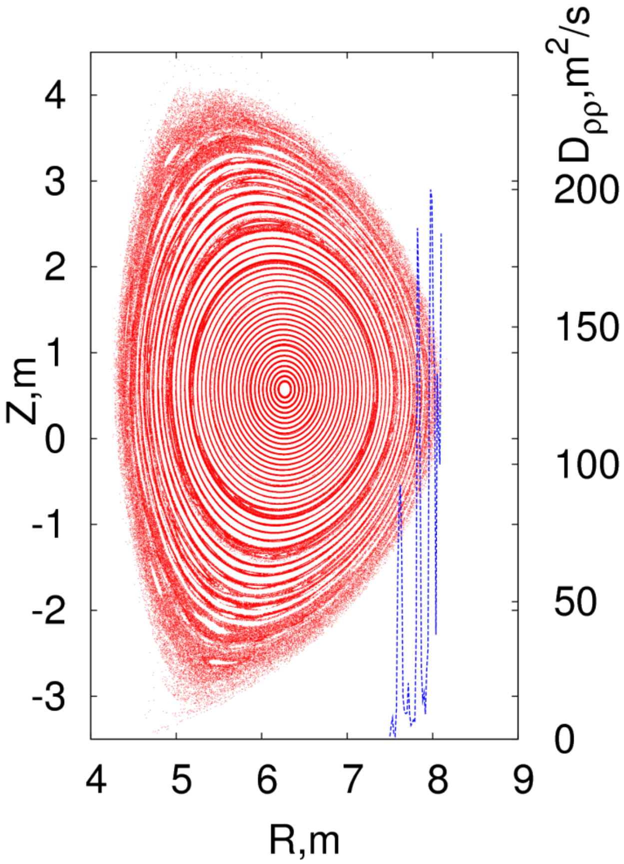
$$\frac{1}{I_{RA}}\frac{dI_{RA}}{dt}=\gamma\left(\frac{E}{E_c}-1\right)-\frac{1}{\tau_{loss}}$$

- 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

Modeling of RE confinement with ELM coils



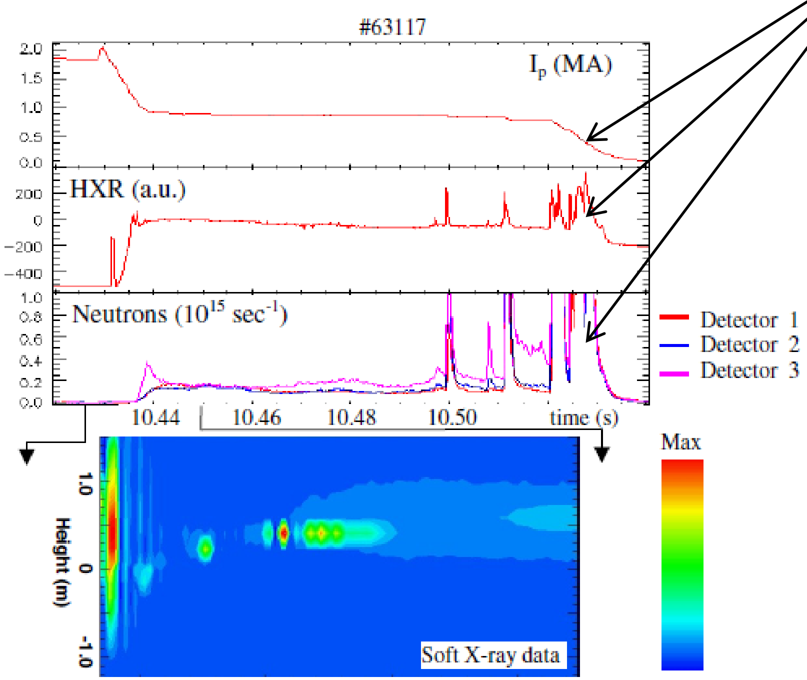
Typical evolution of the second central momentum in fully stochastic region.



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

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

RE are expelled by MHD instability at q<2



- Massive loss of RE occurs in experiment when q < 2 at the plasma edge

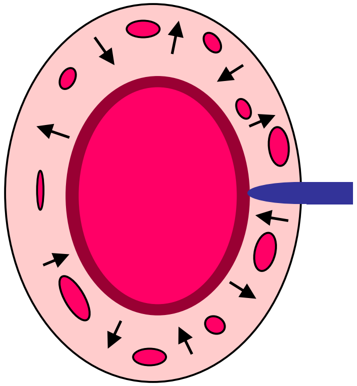
$$q = aB/RB_\theta < 2$$

- q reduces because minor radius of the current channel, a, shrinks when plasma moves to the wall

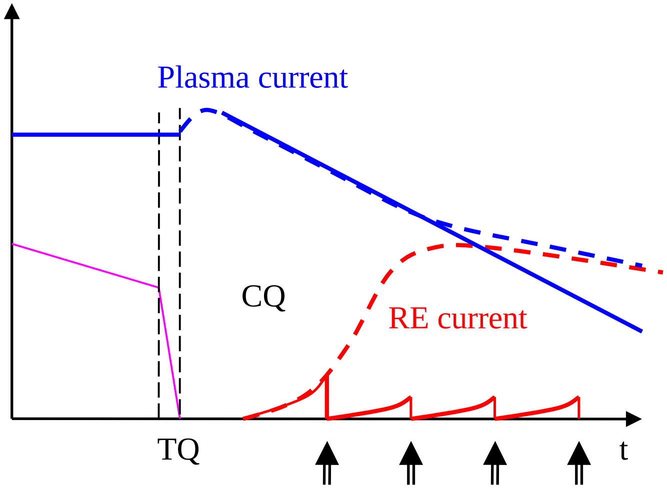
- Is it possible to reduce minor radius, a (to peak current profile) before massive RE are generated and trigger MHD?

Suppression 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

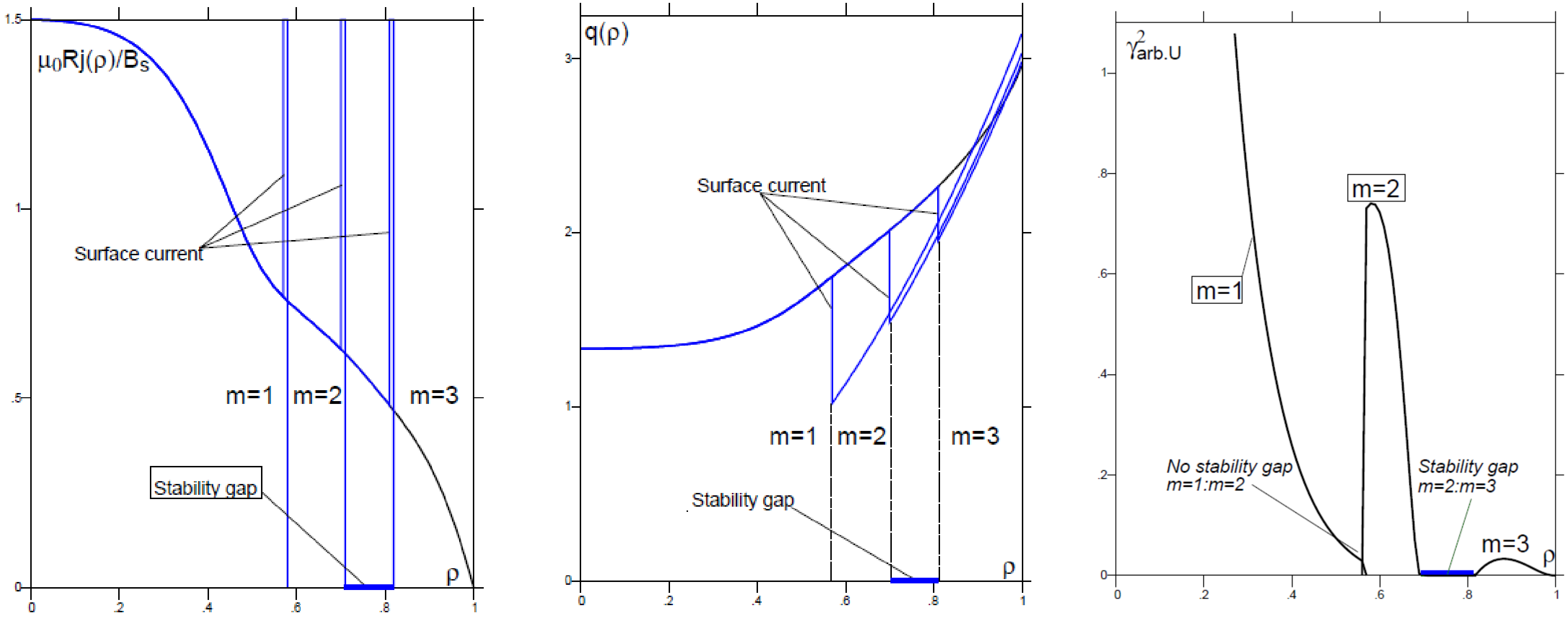


- Required gas pressure in the jet ~ 1 atm, gas amount ~1 kPa*m^3, 5-6 jets during CQ (staggered in time by >= 5 ms).

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

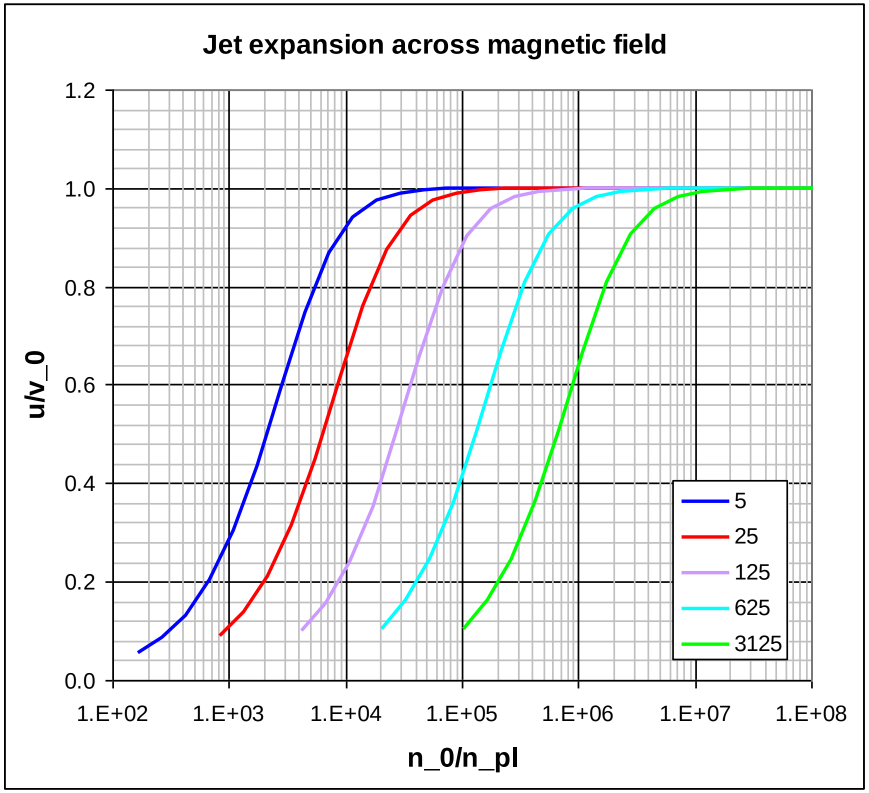
- R&D is in progress to test this scheme in Tore-Supra, ASDEX-U, T-10.

Triggering MHD by contracting current profile



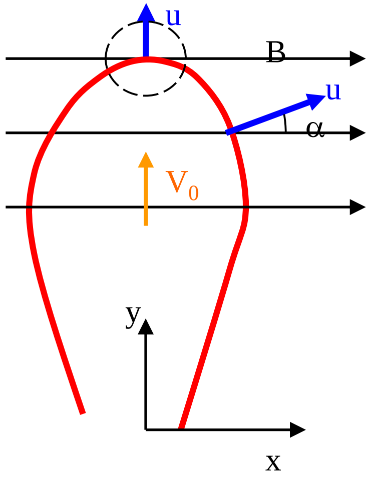
- Cylindrical geometry, ideal wall at b = 1.3a, low m modes
- Current profile changed by introduction of high resistivity at the plasma edge. Skin current added to the edge of current channel to conserve flux at the moving edge
- Current profile has to shrink up to q = 2 (r ~0.7a) to trigger major MHD event

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}

Experiments are in progress to test this scheme

- Goal of experiments – to see if high density gas jet can trigger major MHD event
- T-10 Kurchatov Inst, Russia
- Ture Supra, Cadarache, France (first 6 shots done)
- ASDEX-Upgrade, Garching, Germany

Gas delivery systems for DMS

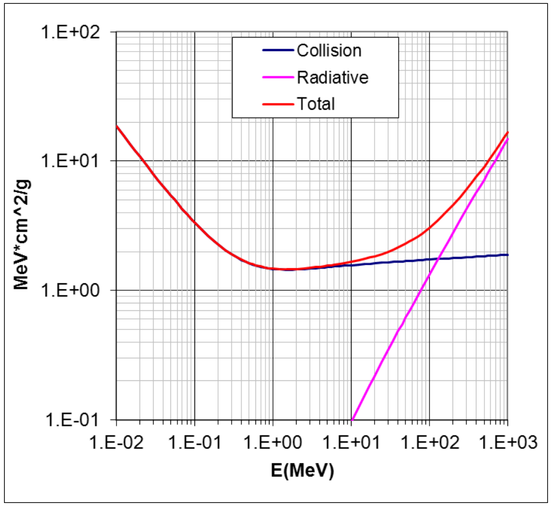
- DMS requires gas delivery time ~10 ms for TQ mitigation and < 5 ms for RE suppression. To achieve high pressure in the gas jet “valve” must be close to the plasma. Harsh environment in ITER make it difficult.

- Several concepts of gas delivery systems with response time ~1-2 ms have been suggested for ITER and are presently in the development phase

- Injector for large cryogenic pellets shuttered upon entry into the chamber is an alternative way to mitigate TQ (under development in ORNL)

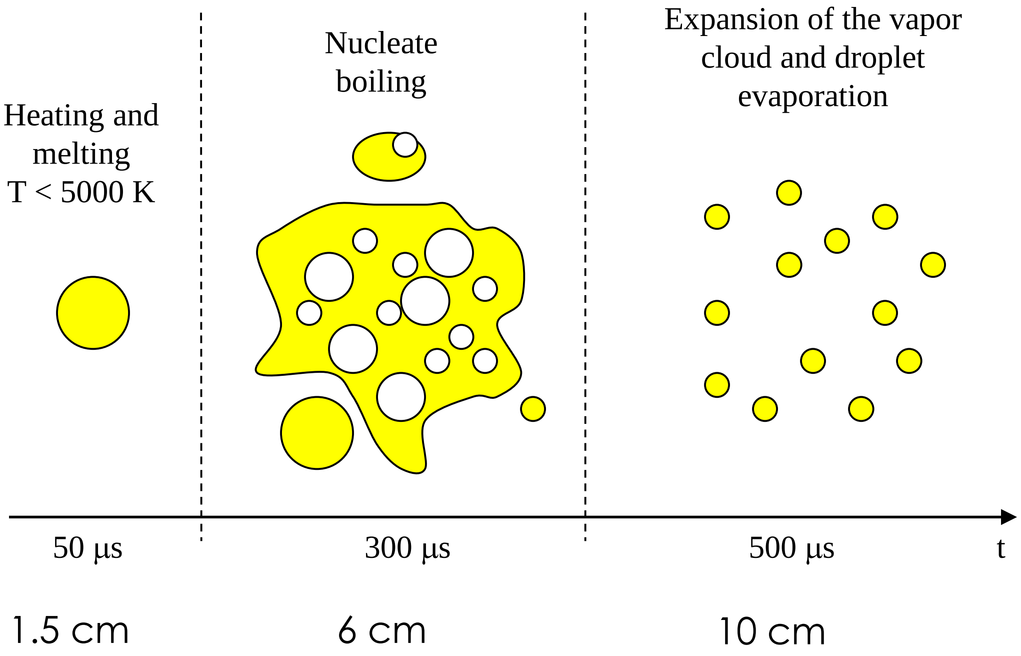
Pellets in RE plasmas

- Can pellets (cryogenic or solid Be bullets) be used to suppress RE?
- What will happens with solid pellet injected in RE discharge?
- Consider Be pellet with diameter about 1-2 cm injected in plasma with RE current density j = 50 A/cm^2 (as in ITER). RE energy 10-20 MeV
- RE range in Be is ~5 cm and thus electrons shall pass pellet through. Volumetric power density:



$Q = (E_0\text{-}E_1)j/d \sim jdE/dx = j\rho s = 50*2*2 =$ 200 MW/cm^3

Cascade of pellet destruction by RE



- Pellet with velocity 300 m/s will evaporate after travelling ~10 cm in RE plasma
- Observed in experiments with hollow pellets on DIII-D

Summary and conclusions

- Runaway electrons can be produced in a tokamak during plasma disruption
- It is expected that machines with large current 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
- Reliable runaway suppression scheme has yet to be developed for ITER