Runaway Electrons in Tokamaks

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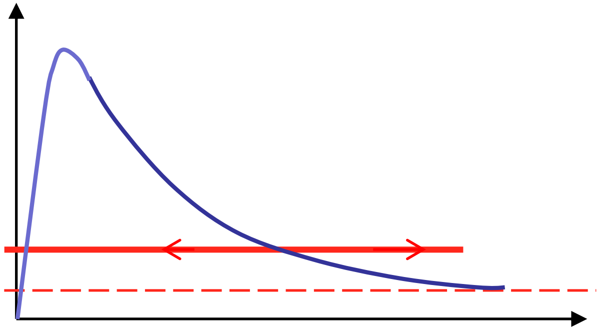
ITER Organization

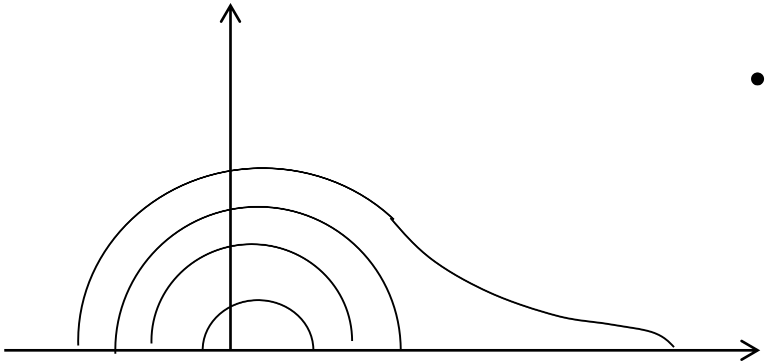
Outline

- Introduction
- Physics of RE generation
  - Dreicer acceleration
  - Avalanche

MeV runaway electrons have long range

Dreicer acceleration





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

$$E_D = \frac{n_e e^3 \ln(\quad)}{4\quad {}_0^2 T_e}$$

- 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)

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

- Home work problem: solve analytically 1D kinetic equation

$$\frac{eE}{m}\ \frac{f}{v} = \frac{\ }{v} n_0 \ \frac{v_{Te}^3}{v^3} \ vf \ \ \frac{T_e}{m}\ \frac{f}{v}$$

- at *E=const* , n_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
- Momentum of the secondary electron,

How to get runaways in tokamak?

- Toroidal electric field: $E = \ j \qquad \frac{Z}{T_e^{3/2}} j$

- Friction force: $F \qquad n_e (Z \quad 2)$

- Runaway electrons are produced in low density cold plasmas (f.e. contaminated by impurities)

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

- 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 R* < 0.003 V/m, Critical field,

$$E_c = \frac{n_e e^3 \ln(\quad)}{4 \quad {}_0^2 m_e c^2} \sim 0.075 n_{e,20} \qquad E$$

- Generation of RE in tokamaks occurs during plasma disruptions

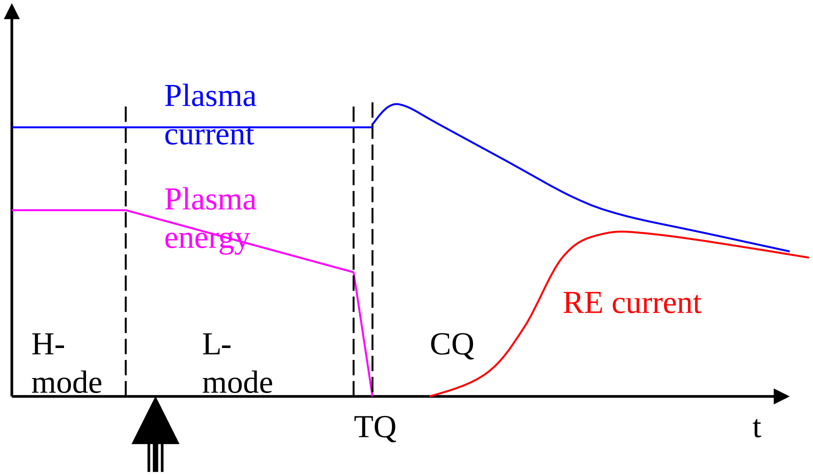
Plasma disruptions

Plasma can abruptly disrupt in a tokamak

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

Plasma disruptions can be very damaging in ITER

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
-

Expected energy loads and their limits

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

$$q = \quad k\frac{dT}{dx}$$

- During transients the depth of the heated layer, dx ~ (kt/r C)$^{1/2}$ and, thus,

$$T = T_0 \quad \frac{q}{k} {\frac{kt}{rC}}^{1/2} \qquad \frac{P}{t^{1/2}} =$$

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

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

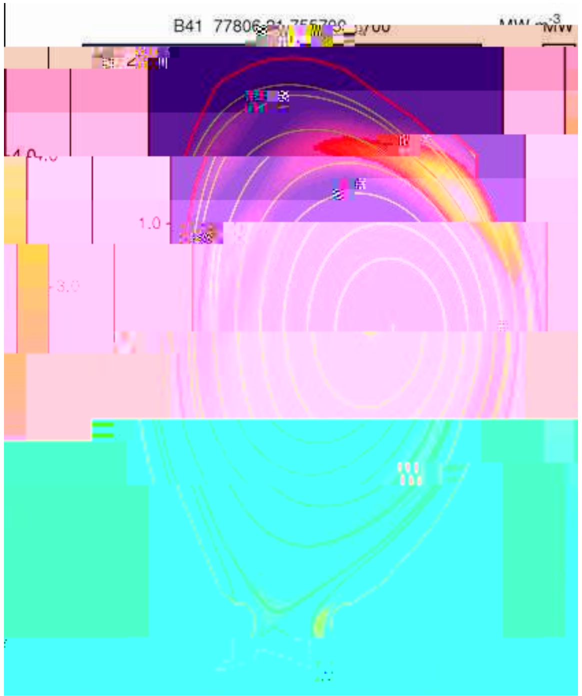
- Surface melting occurs at:

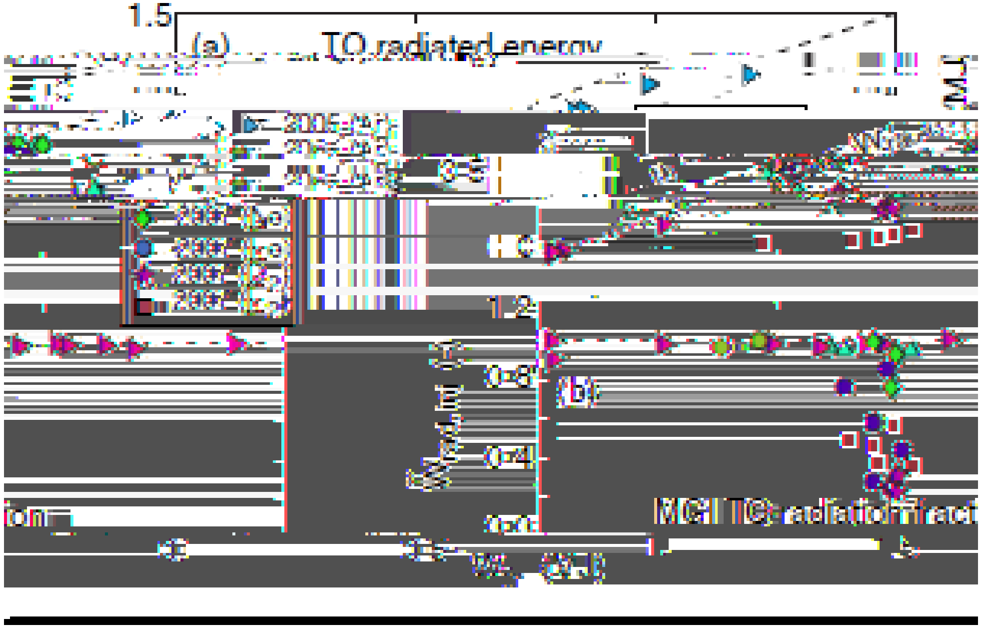
= 23 MJ/m^2/s$^{1/2}$ for Be,
= 50 MJ/m^2/s$^{1/2}$ for W,
= 12 MJ/m^2/s$^{1/2}$ for SS,

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



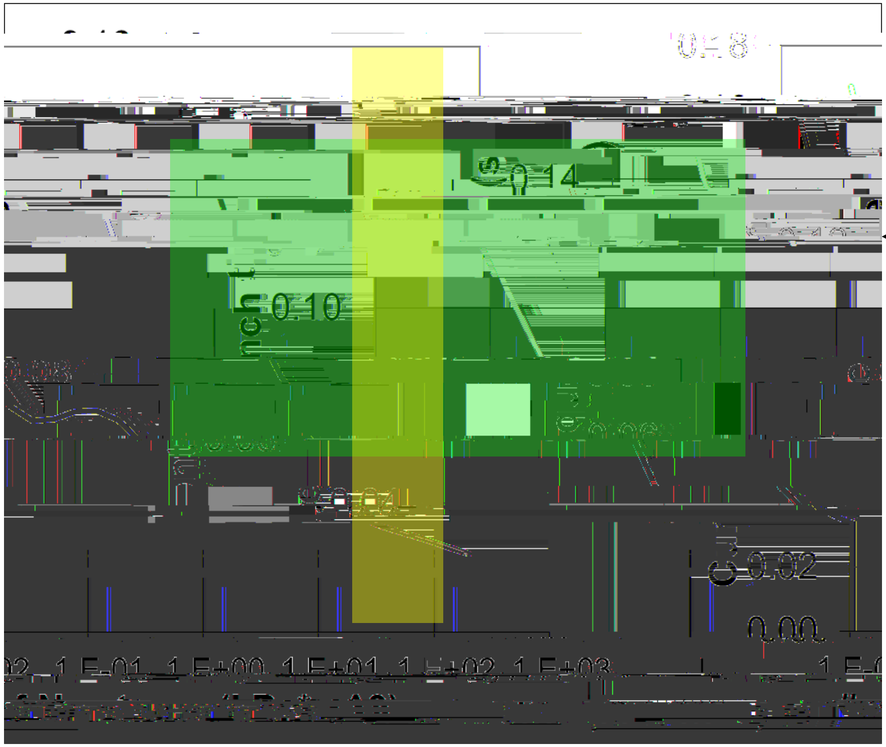


– ASDEX-Upgrade	60-100%	G.Pautasso, Pl.Phys,2009
– Alcator C-mod	~75%	R.S. Granetz, NF 2007
– JET	~ 90%	M.Lehnen, ITPA 2011

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

- Assuming assimilation factor of injected impurity of 5-10% the gross amount of injected impurity must be:
  - Ne ~ 1-2 kPa*m^3

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, $j^2/s = P_{rad}$, 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/2 R ~20 V/m >> Ec*

- Avalanche during plasma disruption can result in massive RE current

$$\frac{1}{I_{RA}}\frac{dI_{RA}}{dt} = \frac{E}{E_c} \quad 1 \qquad \frac{}{2\ RE_c}\quad\frac{dLI}{dt}\quad\frac{dLI_{RA}}{dt}$$

- Integrating over time

Large RE current can be generated

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

$$\ln \frac{I_{RE}}{I_{RE,0}} \qquad \frac{e \quad {}_0 l_i I_0}{6 \quad mc \ln} \sim 2.4 I_0 [MA]$$

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

$$\frac{d}{dt} = eEc \quad \frac{n_{RA}}{n_{RA}}$$

- In steady state

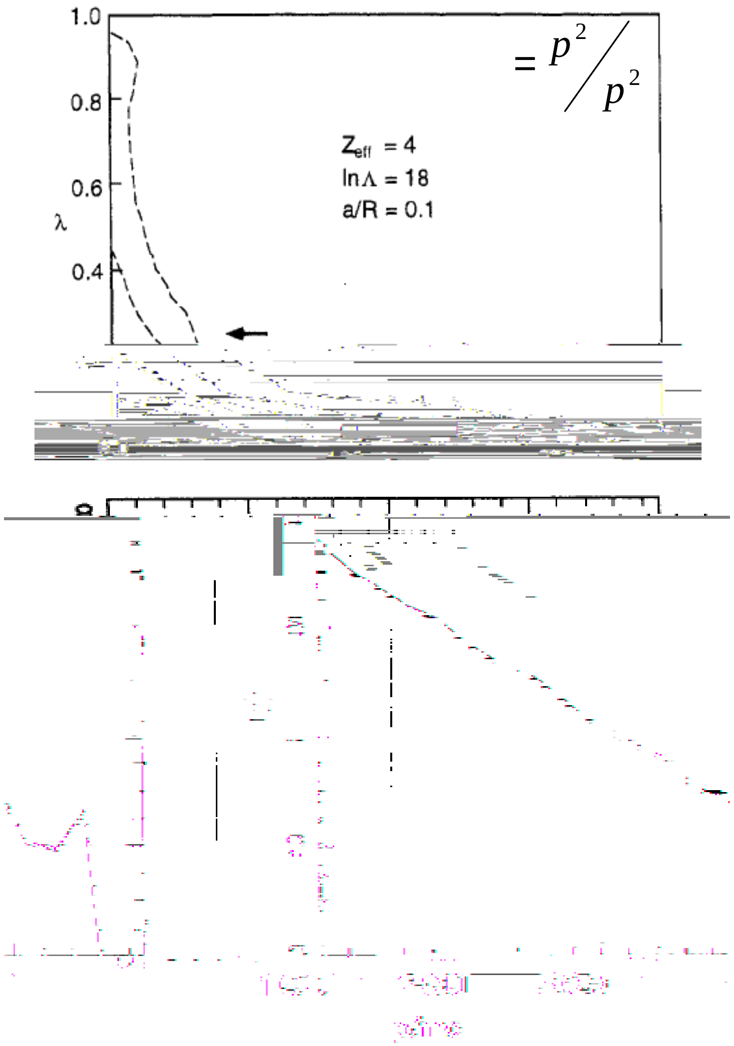
- What about background plasma? Ohmic heating of the background plasma by RE current is significant

- 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, $E_c \sim 0.075 n_e \sim 0.1$ V/m, $U_c \sim 3$V, $I_{RE}=10$ MA

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

Energy spectrum has been calculated numerically



- 2D distribution function of RE after saturation of RE current, t = 200

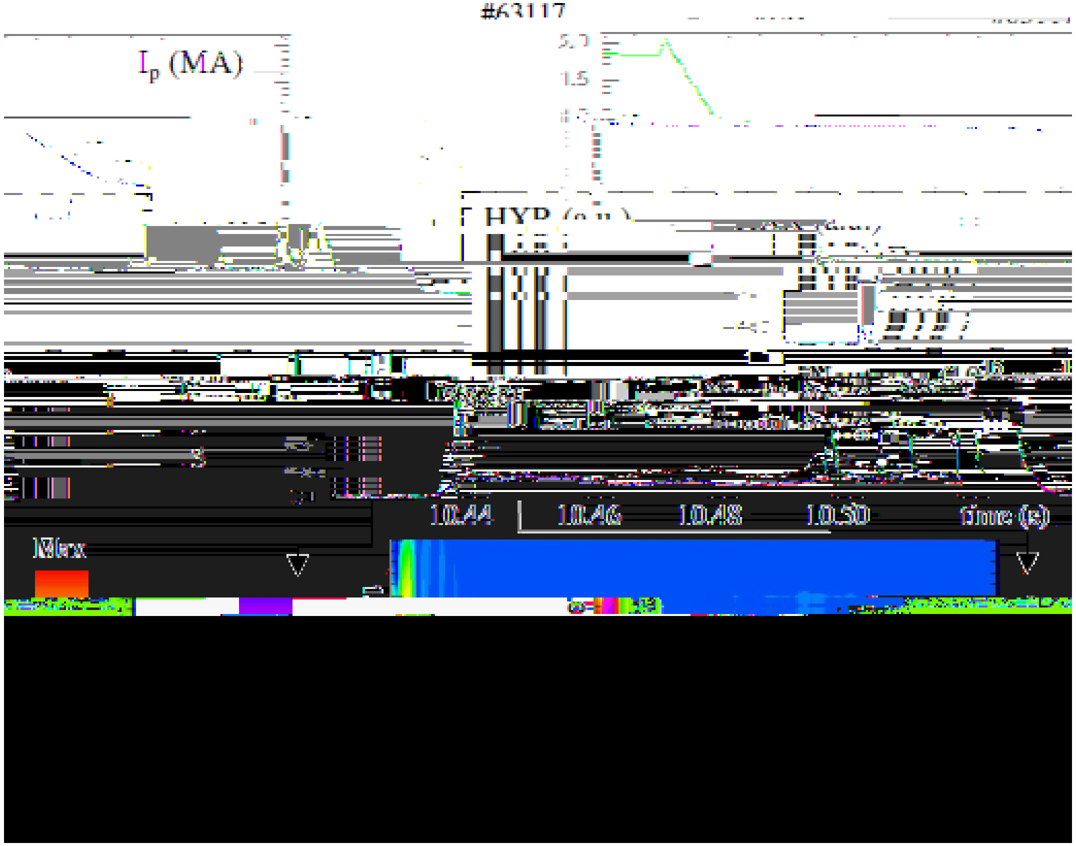
- Monte-Carlo calculations of avalanche in plasma with a/R = 0.1, Z_{eff} = 4, and initial electric field $E/E_c = 15$

- Energy distribution averaged over pitch angle is close to Maxwellian

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

- with T ~ mc^2ln( ) as has been estimated above

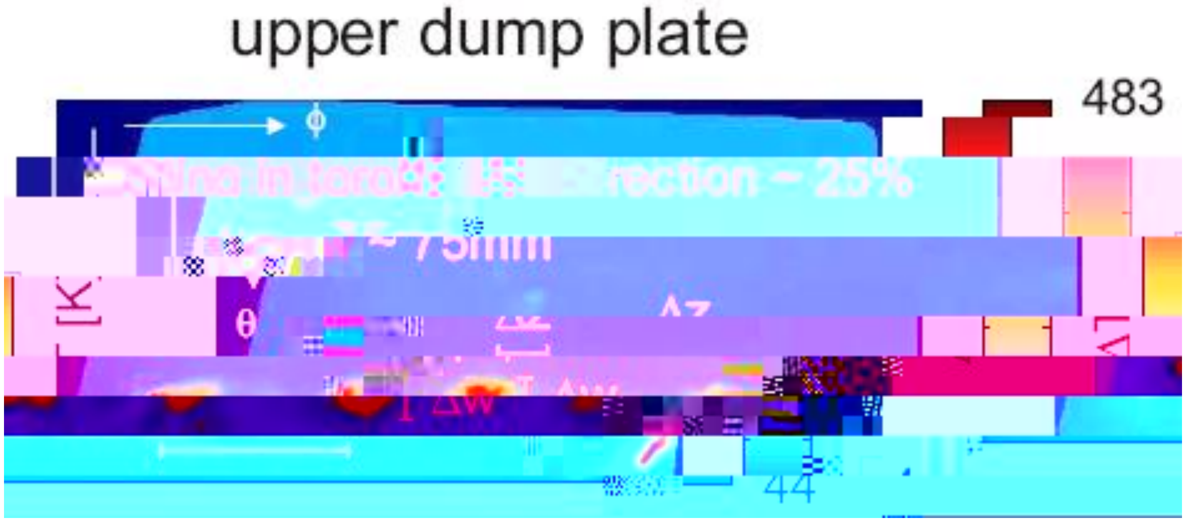
Runaway electrons are often observed during plasma disruptions



- 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

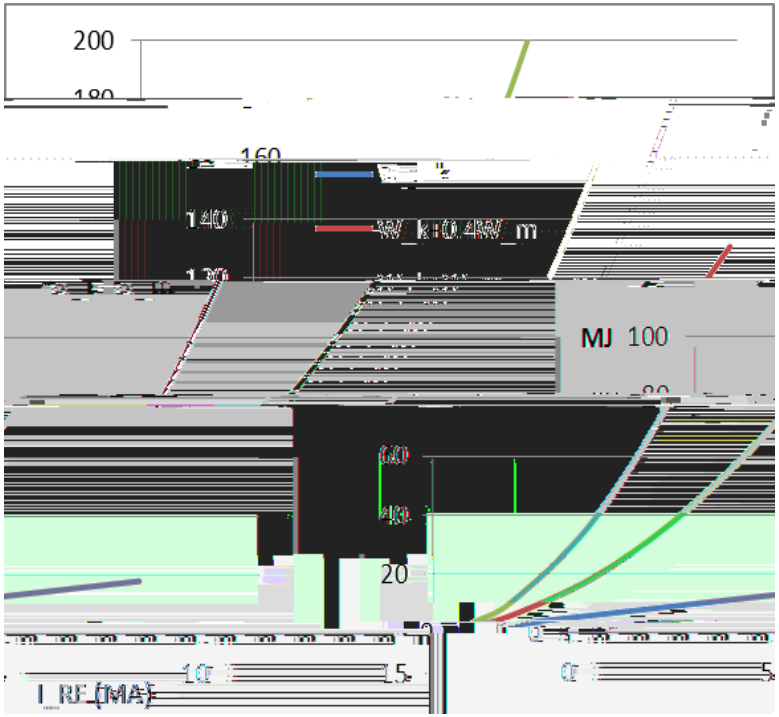
Energy deposition on the wall



- 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 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, $_{CQ}$ ~ 40 ms
- Ion and electron mean free path in CQ plasmas: $_i$ ~ $_e$ ~1 cm
- Pressure equilibration time along the field lines: $_p$ ~2 R/C_s ~ 1 ms -> pressure is constant along magnetic field lines.
- Temperature equilibration time: $_c$ ~ L^2/c > 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 **E** = $\mathbf{E}_0$ – ***grad*** 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

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

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

$$\exp \quad \frac{\quad}{4} \qquad \ln(\quad) \quad 2 \;\; 10^4 \qquad {}_{20} \,/ \qquad 130$$

- Other sources:
  - Tritium b 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?
- Solution (Maxwellian as initial condition):

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-

MHD stability of RE beams

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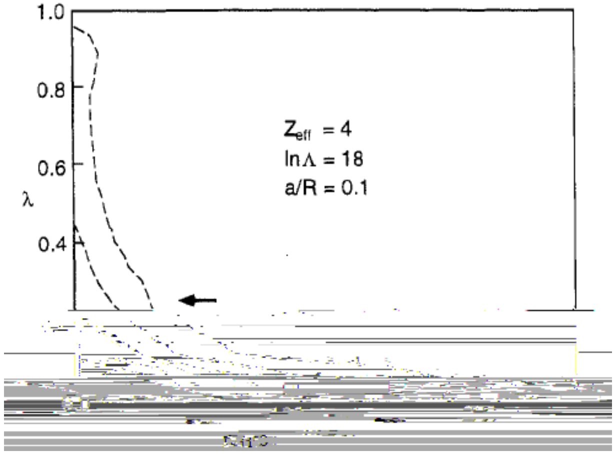
Kinetic instabilities



- Resonance in magnetize plasmas

- At w ~ nw$_{Be}$, k$_z$v$_z$ = w-nw$_{Be}$ << nw$_{Be}$ plasma is unstable when

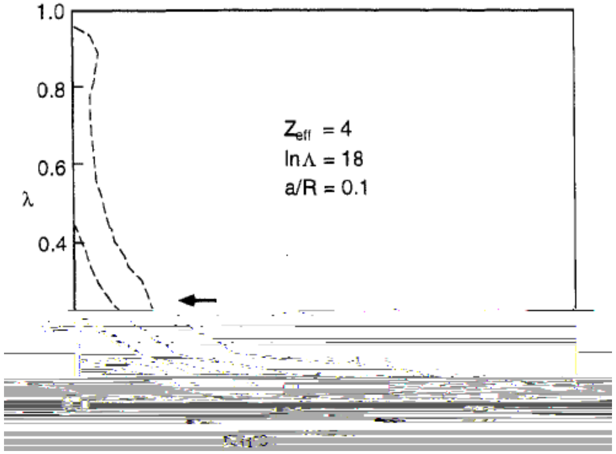
$$\frac{f}{v_z} \quad \frac{f}{v}$$

- Runaway electron tail can not make cyclotron wave unstable

- Cherenkov resonance w = k$_z$v$_z$ results in stable oscillations for monotonic distribution function of RE

- Anomalous Doppler effect k$_z$v$_z$ = -nw$_{Be}$, at n<0 can provide energy

Magnetize Langmuir waves



- Dispersion relation $w = k_z w_{pe} / k$
- Linear theory for Dreicer distribution function, non relativistic, see V.Parail, Reiew of Plasma Physics v.11
- Stability threshold at $v \quad 3 \quad \frac{w_{Be}}{w_{pe}}^{3/2} \quad v_{cr}$
- In ITER, $w_{Be} > w_{pe}$ 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.

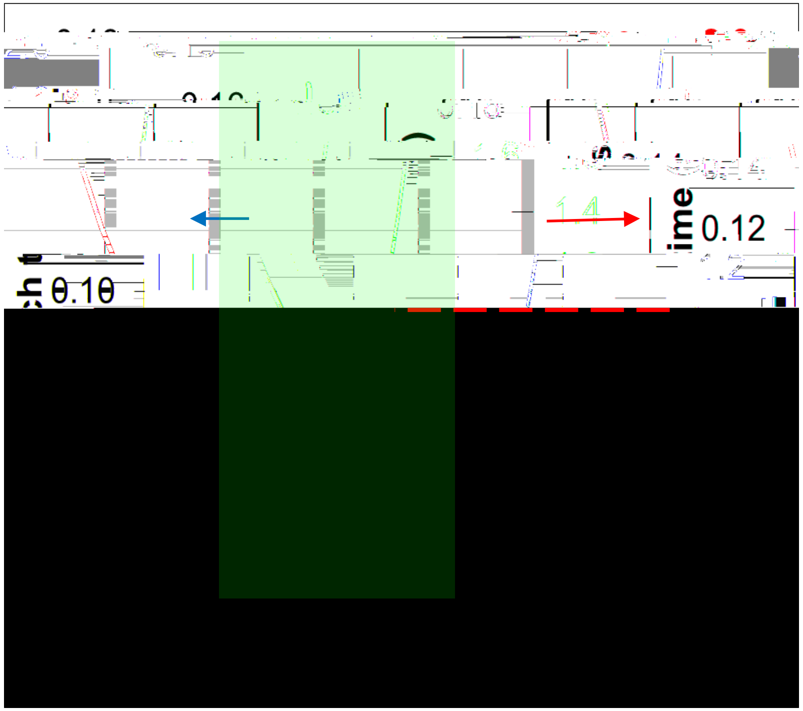
Runaway mitigation/suppression

Collisional suppression of RE is challenging in ITER

- Avalanche can be suppressed by:
  - increase of electron density to enhance collisional slow down of RE ($E_c = 0.075n_e$

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

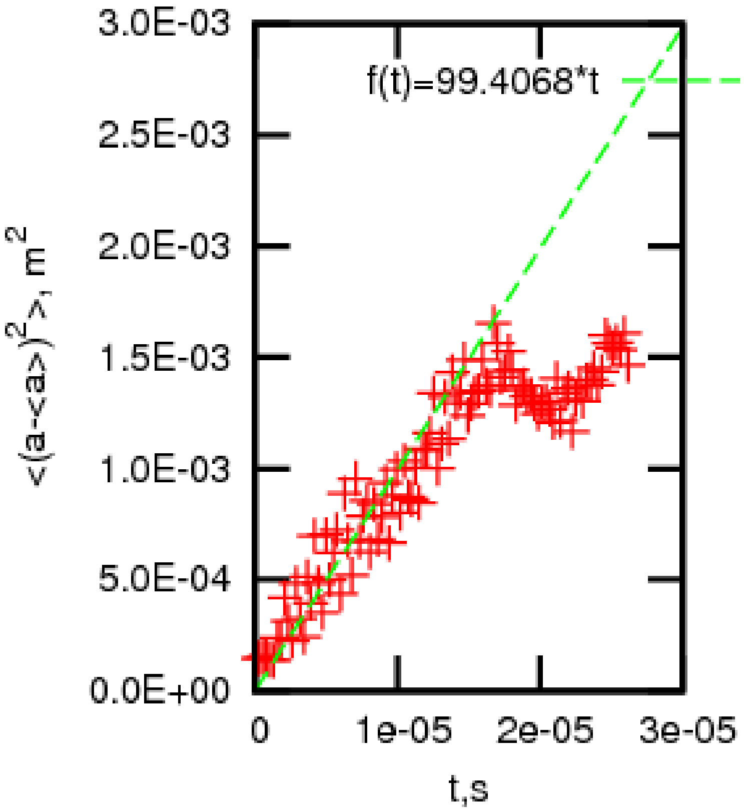
- Collisional suppression might work if RE will be suppressed at density 30-50% of critical (Rosenbluth's) density

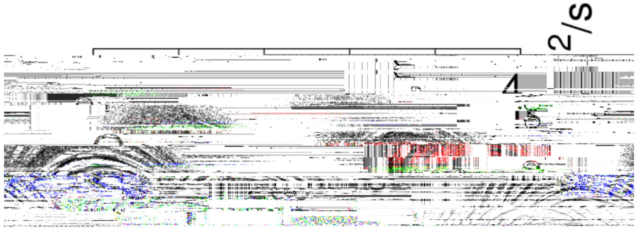
RE suppression by de-confinement

$$\frac{1}{I_{RA}}\frac{dI_{RA}}{dt} = \quad \frac{E}{E_c} \quad 1 \quad \frac{1}{\quad_{loss}}$$

- Fast loss of RE, $_{loss}$ $\frac{E}{E_c}$, 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

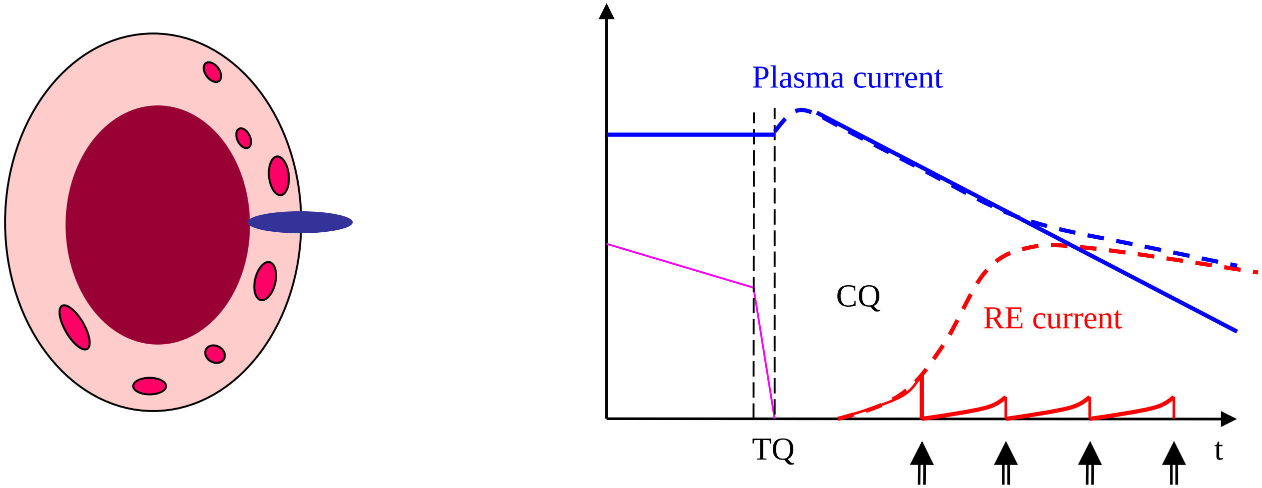




- No global loss of RE (only redistribution) at maximum coil current

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

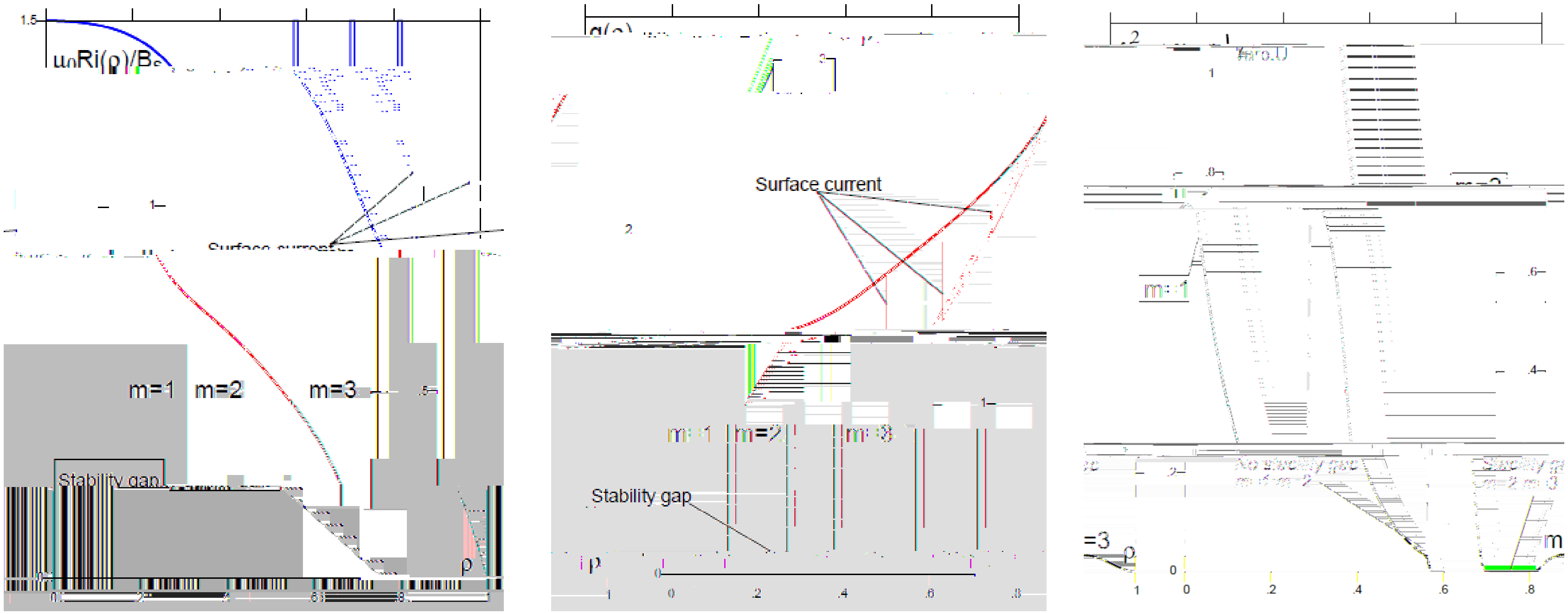


- Required gas pressure in the jet ~ 1 atm, gas amount ~1 kPa*m^3, 5-6 jets during CQ (staggered in time by >= 5 ms).

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

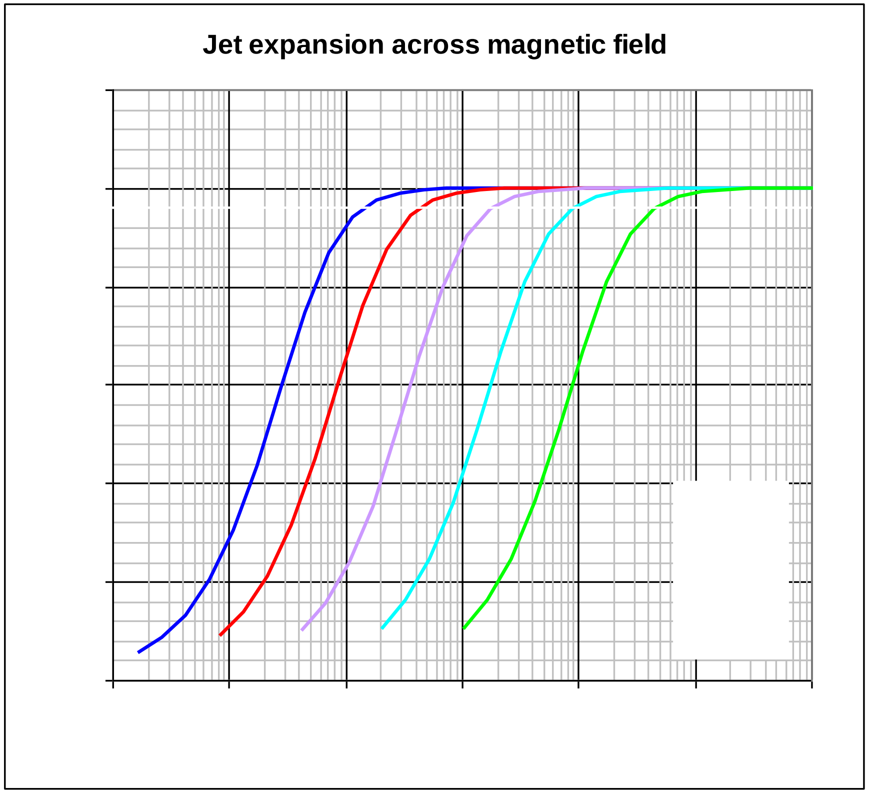
- R&D is in progress to test this scheme in Tore-Supra, ASDEX-U, T-10.

Triggering MHD by contracting current profile



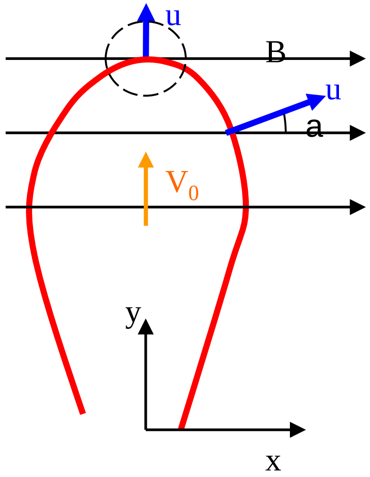
- Cylindrical geometry, ideal wall at b = 1.3a, low m modes
- Current profile changed by introduction of high resistivity at the plasma edge. Skin current added to the edge of current channel to conserve flux at the moving edge
- Current profile has to shrink up to q = 2 (r ~0.7a) to trigger major MHD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

High gas pressure is needed for fast gas propagation



$$1 \quad \frac{u}{V_0} = \frac{}{2} \quad \frac{n_{pl}}{n_0} \quad {}^{2} \quad \frac{u}{V_0} \quad {}^{2} \quad \frac{E_{iz} \quad T_{pl}}{T_{iz}} \quad {}^{2} \quad \frac{V_0 d}{c}$$

$p_{pl} << p_0 << B^2/2 \quad {}_0$



- 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}

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?
-

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