Progress on Studies of Runaway Electrons Formed During Tokamak Disruptions

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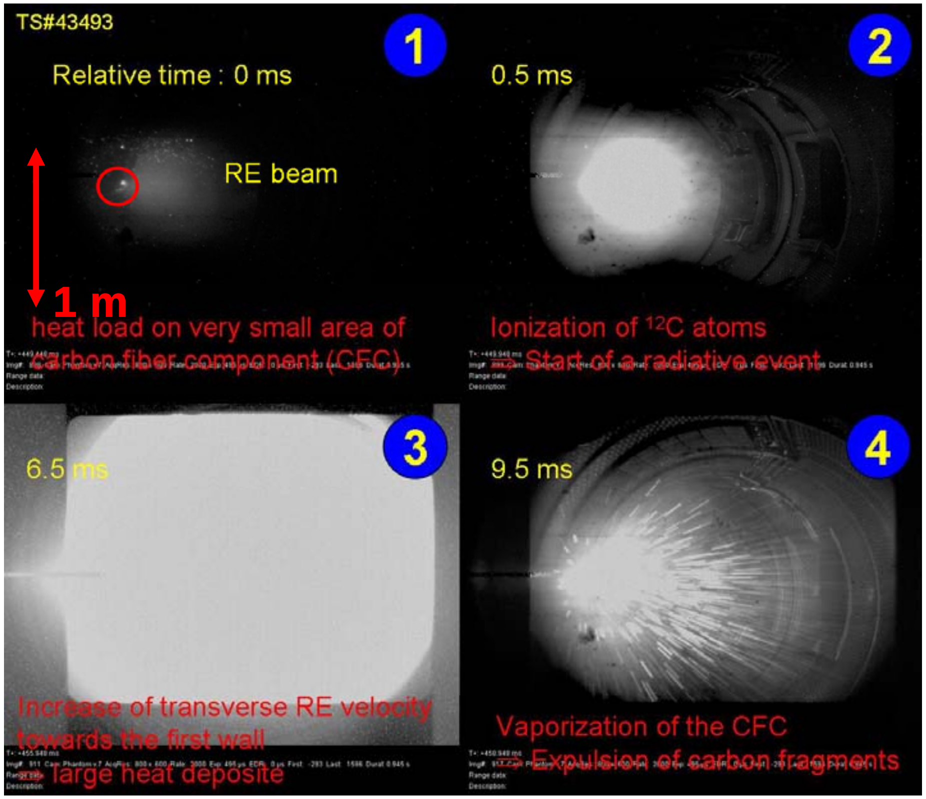
Runaway electron beam striking wall in Tore-Supra



(from F. Saint-Laurent, EPS 2009)

Time Evolution of Runaway Electrons During Disruption

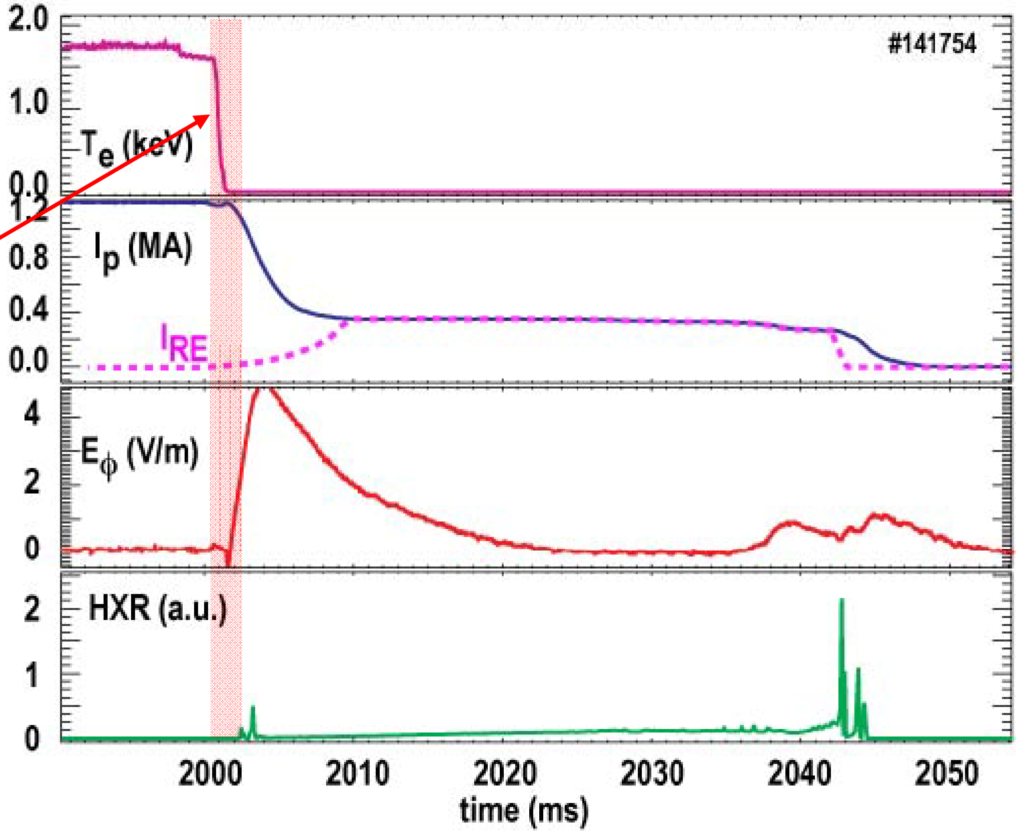
- **Runaway electrons (REs) form in tokamaks during periods of strong electric fields**

- Startup
- RF current drive
- Disruptions

- **Runaway evolution during disruption has several phases**

- Thermal quench
  (RE seed formation)

DIII-D disruption time sequence



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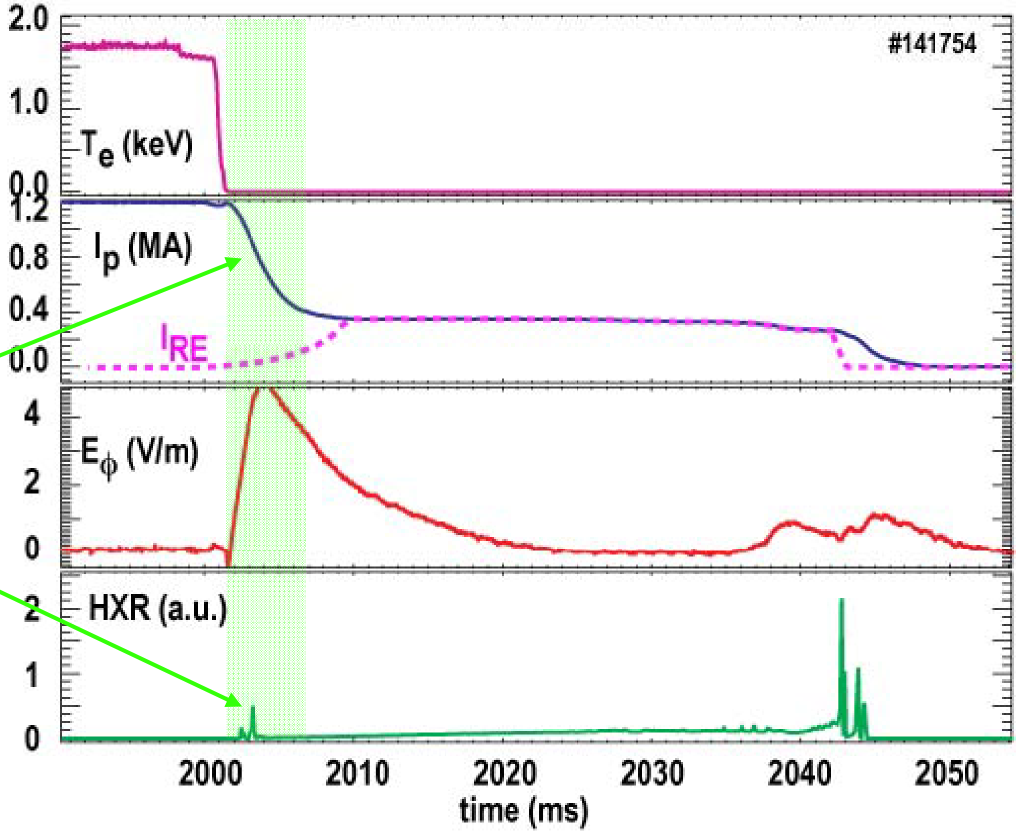

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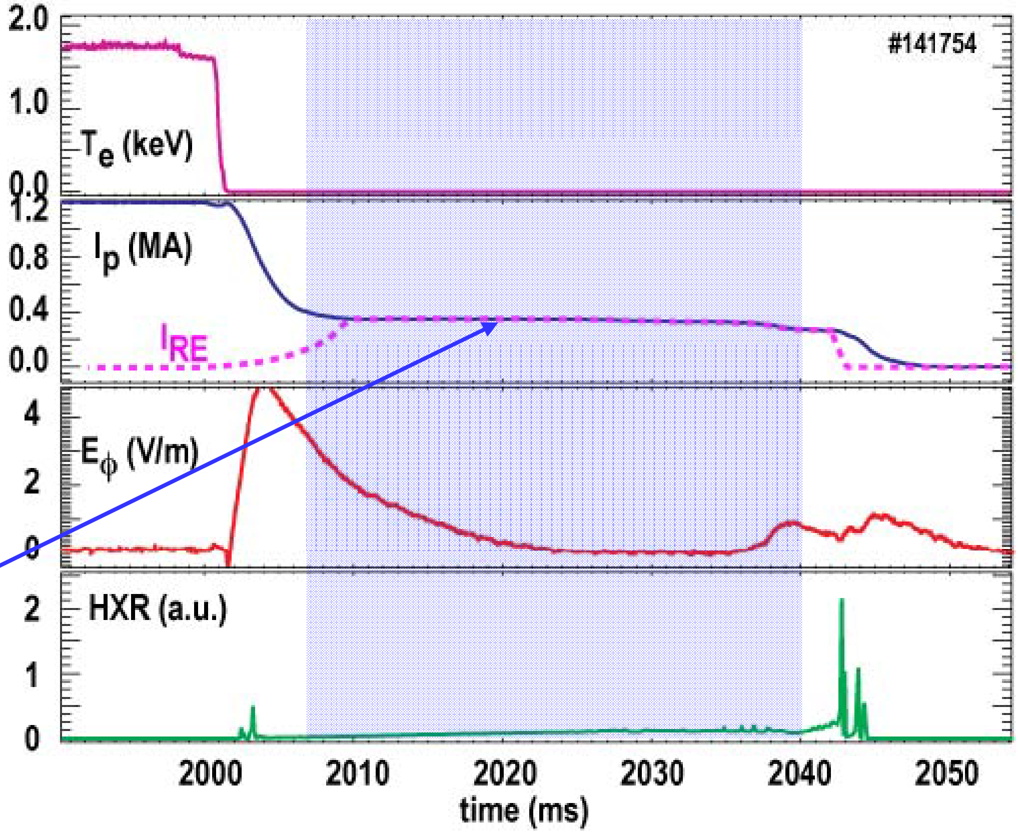

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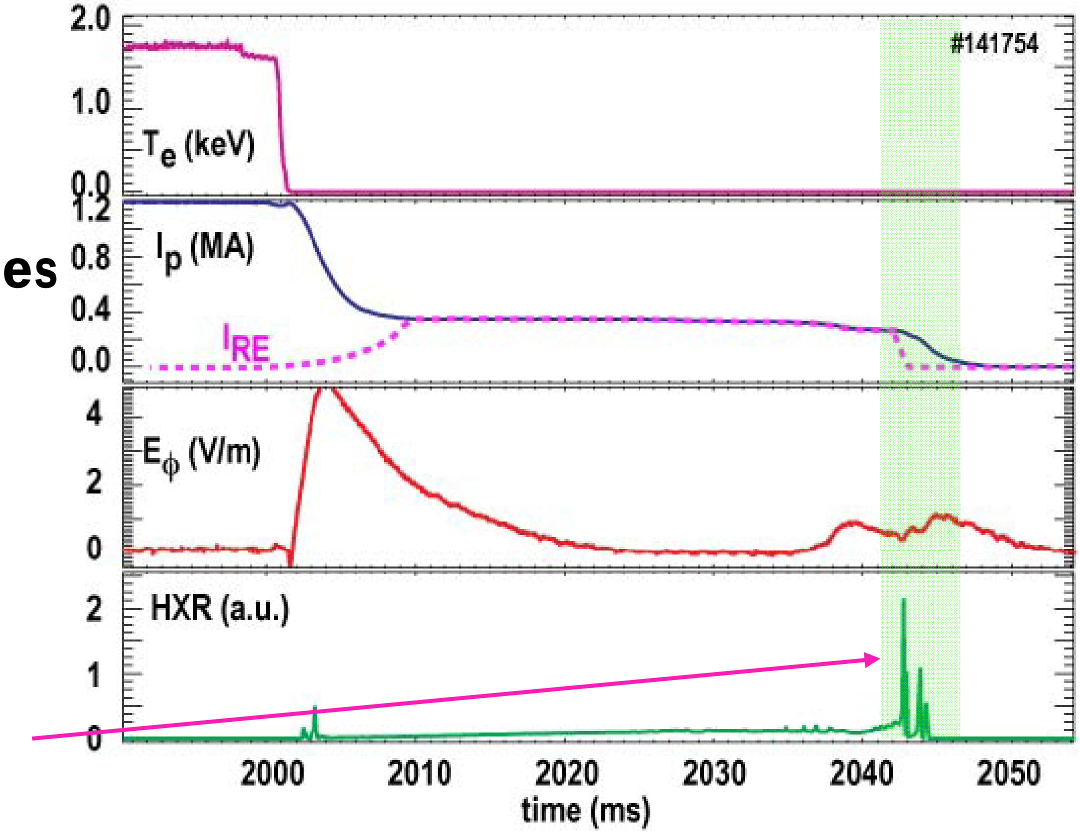
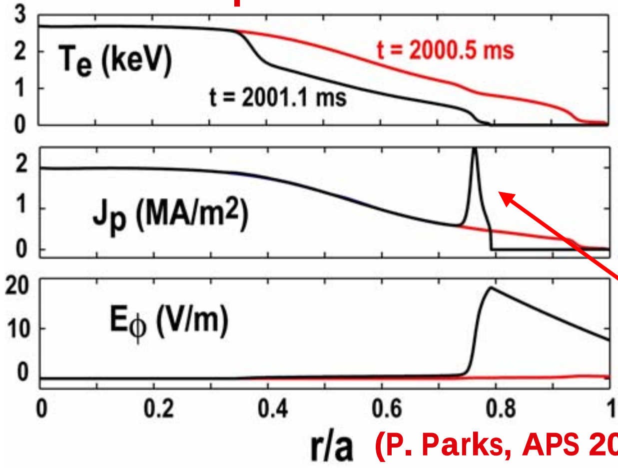
  - RE final loss (most dangerous for wall)

DIII-D disruption time sequence



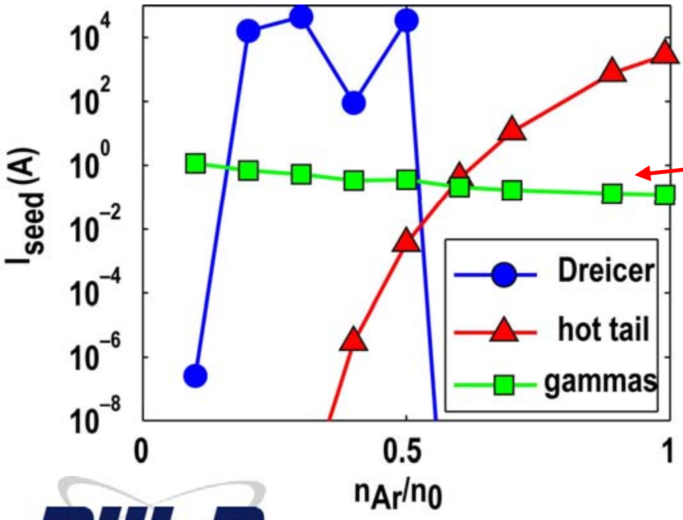
Disruption RE Seed Formation in Present Devices Could be a Profile Effect

Radial profiles from 1D model of DIII-D disruption→



(P. Parks, APS 2007)

RE seeds generated in 1D model of ITER disruption



- **Observe RE seeds (post prompt loss) of order 0-10 kA in present devices**
- **RE seed formation requires high electric field plus high temperature**
- **Typically,no REs predicted using 0D models**
- **1D models find seed enhancement in narrow current sheet**
- **Seed formation greatly enhanced by high-Z impurities**
- **Reactor always has RE seeds due to radioactivity**
  - Beta decay of tritium
  - Gammas (Compton collisions)

(T. Feher, PPCF 2011)

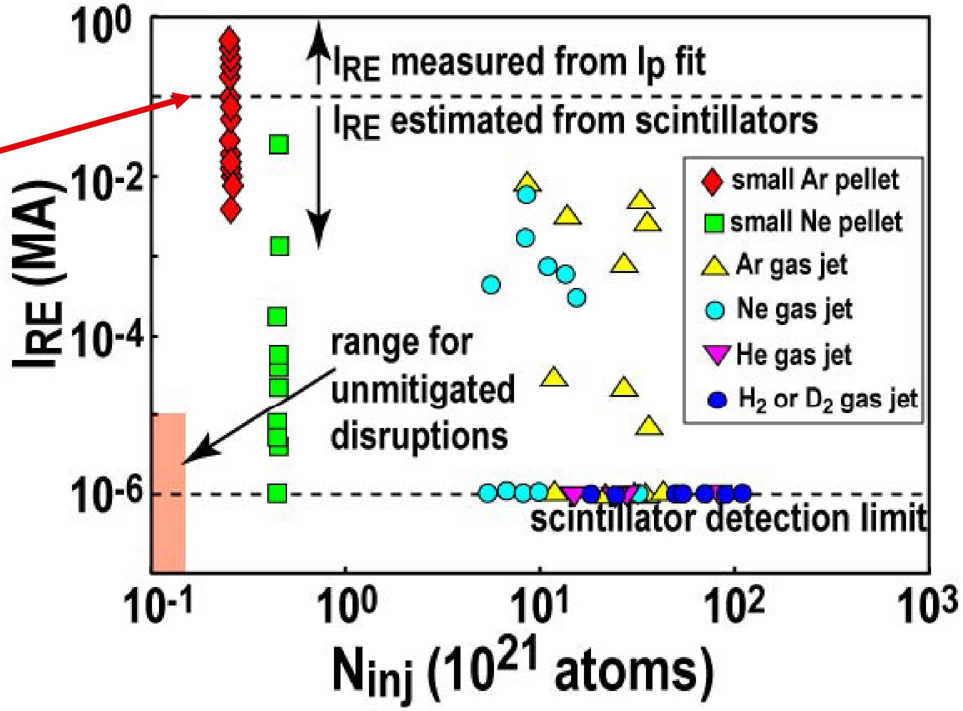
DIII-D
NATIONAL FUSION FACILITY

CHALMERS

Large Variation in Final RE Current Due to Variation in Prompt Loss Term?

- **Final RE populations can vary by orders of magnitude, even on repeat shots**
- **Highest RE populations seen for disruptions initiated by high-Z injection (DIII-D, TEXTOR, JET)**
- **Large scatter in final RE current may arise from scatter in prompt loss?**
- **Variation in seed term cannot be ruled out yet, though**

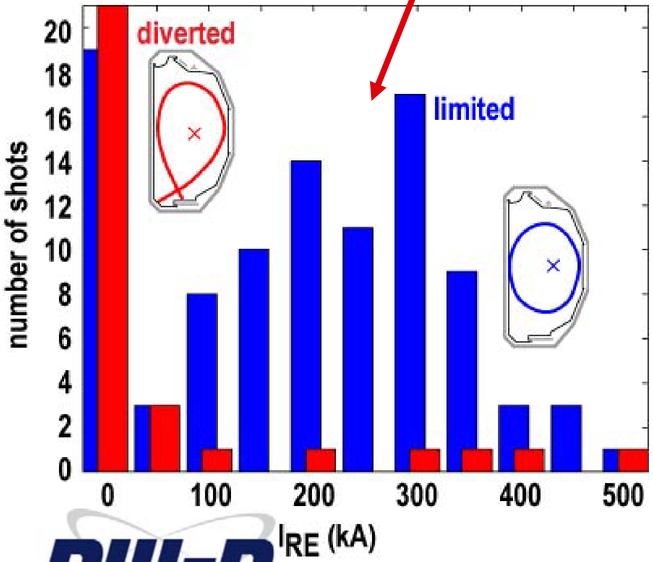
Final RE current in DIII-D vs number of injected atoms



(E. Hollmann, PoP 2009)

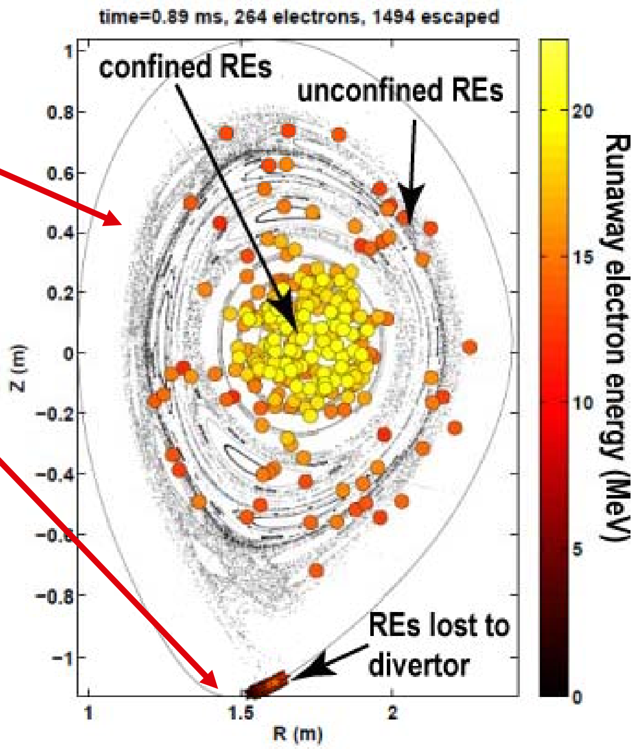
Prompt Loss of Runaways Thought to be Due to TQ MHD Destroying Good Confinement

- **NIMROD simulations predict large prompt loss of REs due to destruction of flux surfaces by TQ MHD in DIII-D diverted shots**
  - Predicted prompt loss to divertor, consistent with observations (A. James, to be submitted, NF 2011)
- **Lower prompt loss predicted for limited plasmas; consistent with observations (DIII-D, JET)**



DIII-D final RE current for diverted vs limited shots

(A. James, to be submitted, NF 2011)

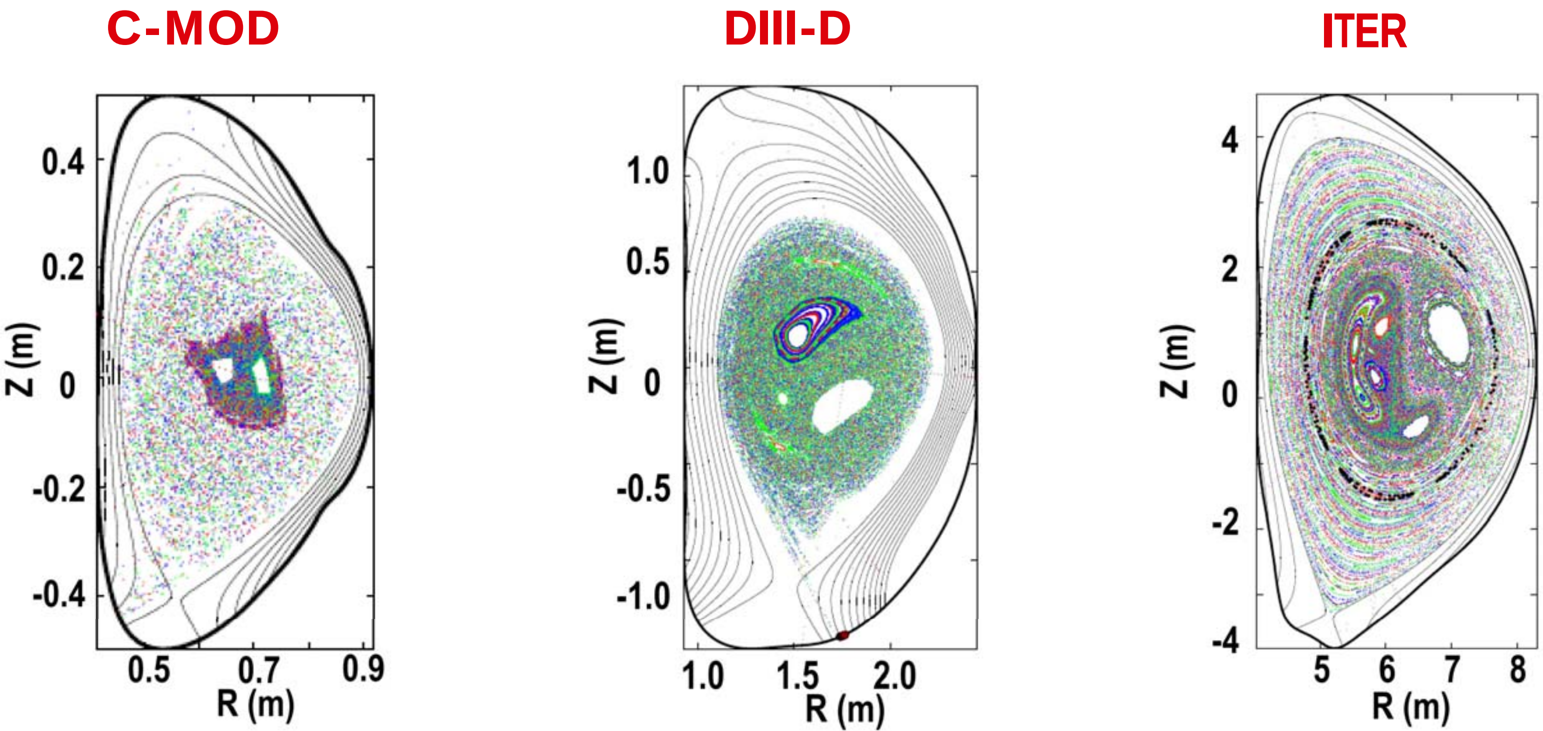


(V. Izzo, Sherwood 2010)

NIMROD simulation of RE prompt loss into divertor during rapid shutdown

Prompt RE Predicted to be Reduced in Larger Tokamaks

- **NIMROD predicts reduced prompt RE loss in larger tokamaks:**
  - 100% loss in C-Mod, consistent with observations (Whyte, ITPA 2010)
  - 32% loss in DIII-D, consistent with observations (but huge scatter)
  - 0% in ITER



(V. Izzo, IAEA 2010)

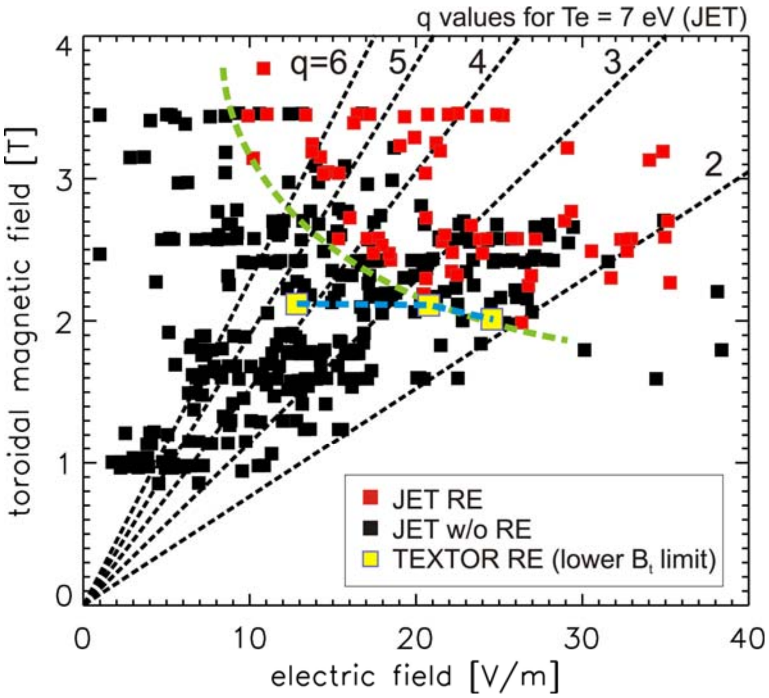
Is Prompt Loss MHD Responsible for Observed B = 2 T Lower Bound for RE Formation?

- **Many tokamaks observe B = 2 T threshold for RE formation (JET, JT-60U)**

- **Experiments to isolate B_T vs q_{95} effect not totally clear yet (M. Lehnen, PPCF 2009)**

- **Many mechanisms speculated**
  - Effect of B on TQ MHD
  - Whistler waves (T. Fulop, PoP 2009)

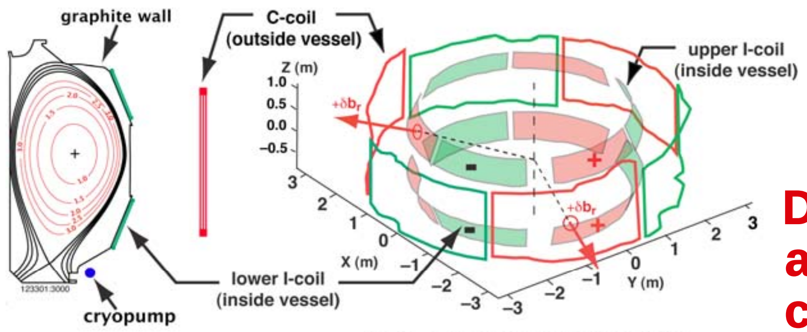
Disruptions in JET suggesting B = 2 T threshold for RE formation



(M. Lehnen, PPCF 2009)

Can External Non-axisymmetric Magnetic Perturbations Affect RE Prompt Loss?

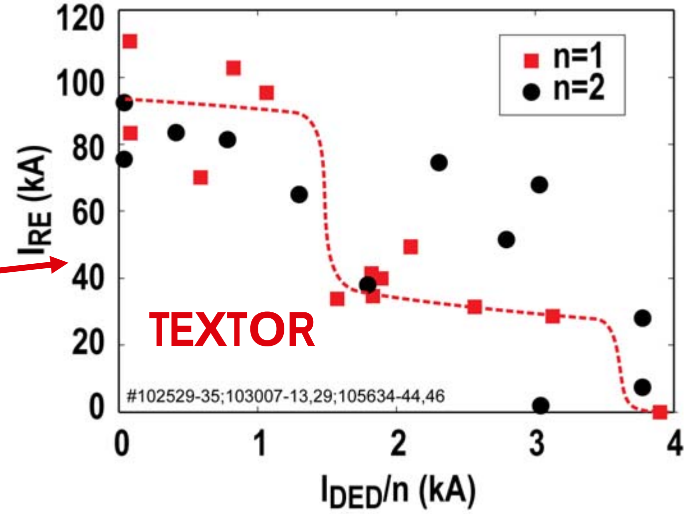
- Changing applied magnetic fields could effect TQ MHD and prompt RE loss
- Reduction in REs with applied n=2 RMP seen in JT-60U (R. Yoshino, NF 2000)
- Clear reduction in REs seen in TEXTOR for n=1 perturbation, not as clear for n=2
- Some possible reduction in REs seen in DIII-D for n=3 perturbation?
- NIMROD simulations indicate applied fields could <u>reduce</u> RE prompt loss (V. Izzo, Sherwood 2010)



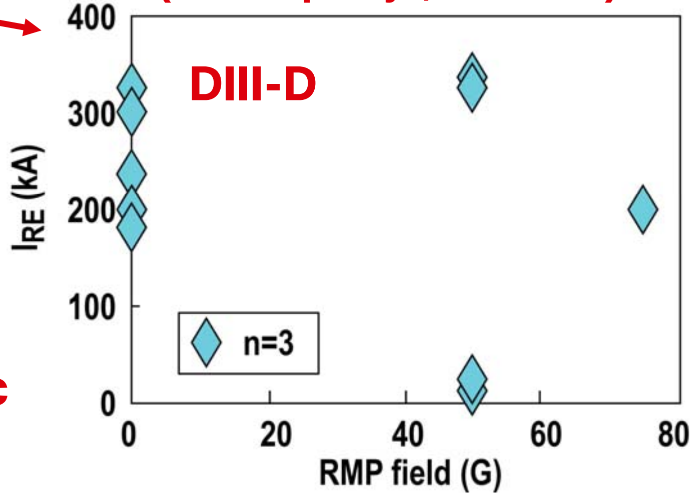
n=3 I-coil and C-coil configuration
(with even parity I-coil)

DIII-D non-axisymmetric coils

(M. Lehnen, PRL 2008)



(D. Humphreys, APS 2009)



Runaway Electron Growth During Current Quench Qualitatively Consistent with Avalanche

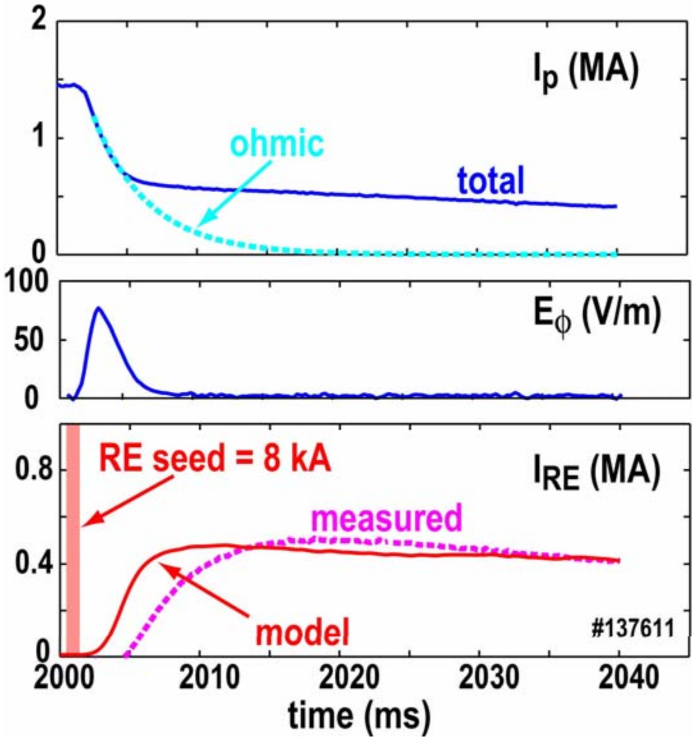
- **During CQ RE formation expected to be dominated by knock-on avalanche (A. Sokolov, JETP 1979)**

$$\frac{\partial n_{RE}}{\partial t} \approx n_{RE} \nu_0 \left(E / E_{crit} - 1 \right)$$

- **CQ avalanche gain moderate (~50) in mid-sized tokamaks (TEXTOR, DIII-D) and large (10^{15}) in ITER**

- **Qualitative indications of RE avalanche seen in many tokamaks (JT-60U, TEXTOR, JET, DIII-D, etc)**

Avalanche model qualitatively captures DIII-D RE current growth in CQ

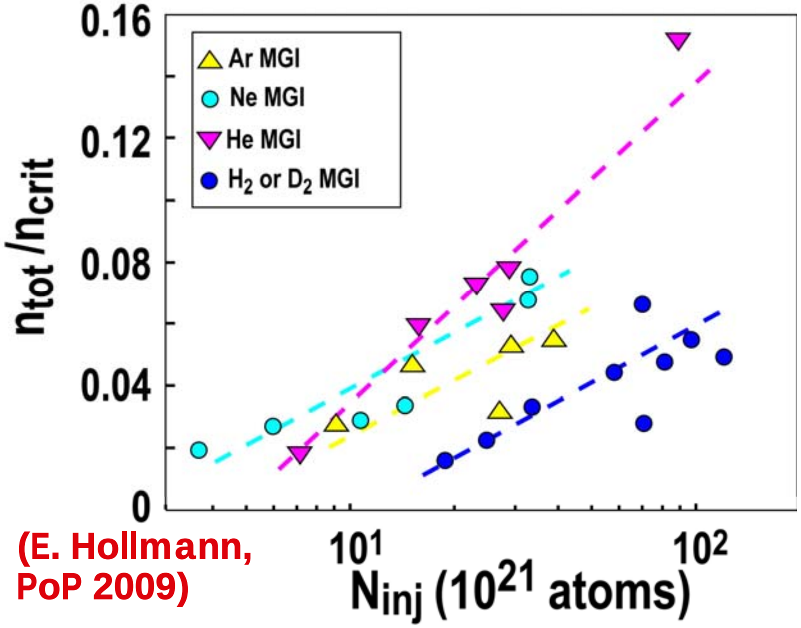


(E. Hollmann, APS 2009)

Very High Impurity Injection Could Suppress Runaway Avalanche During CQ

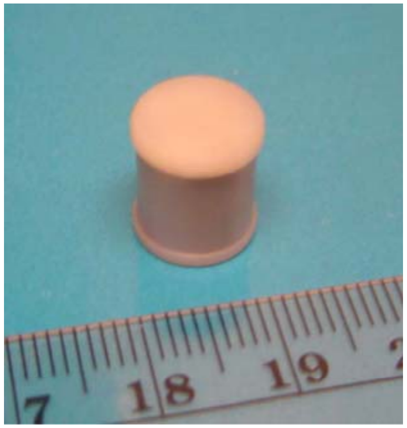
- **Complete suppression of CQ RE avalanche at total electron density $n_{crit} \sim 5\text{x}10^{16}/cm^3$**
- **Many mass injection schemes (massive gas injection, large cryogenic pellets, laser ablation, shell pellets) tested**
- **Best results to date are $n_{tot} \sim 0.2\ n_{crit}$ (DIII-D, TEXTOR, ASDEX-U)**

Total mid-CQ electron density after MGI shutdown in DIII-D

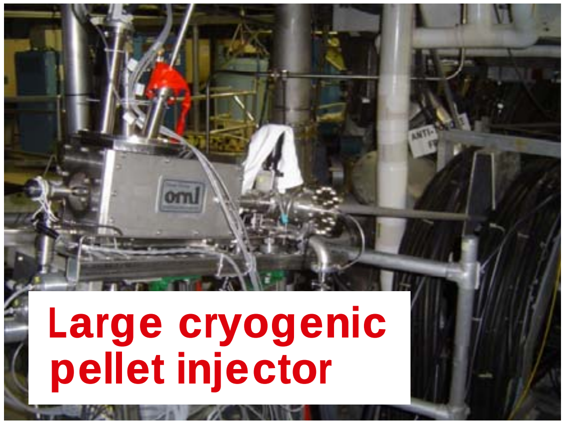


(E. Hollmann, PoP 2009)

Large shell pellet



6-valve massive gas injection flange

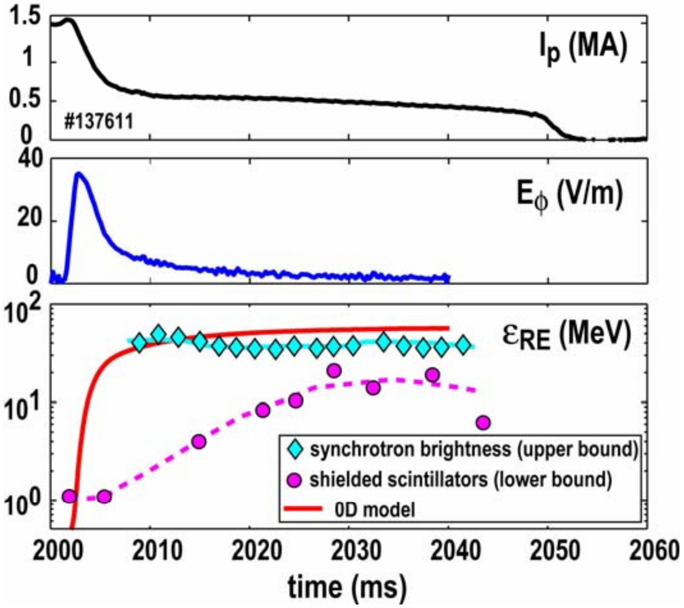


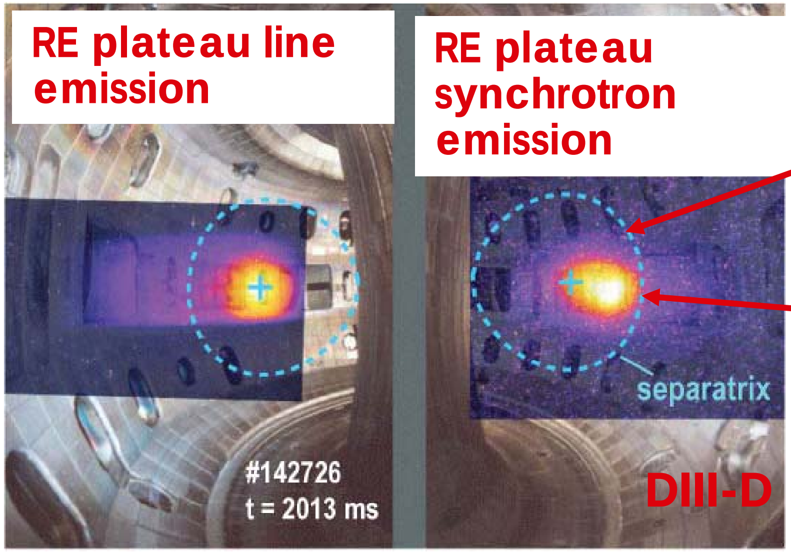
Large cryogenic pellet injector

RE Plateau Consists of Two-temperature Plasma with Current Carried by Runaway Electrons

- In DIII-D plateau, RE energy is ~20 MeV or less and density ~ 10^9 cm^{-3}
- Energy consistent with integration of CQ 0D loop voltage
- Background cold plasma has T ~ 1.5 eV and n ~ 10^{13} cm^{-3}
- Current dominantly carried by REs
- System energy dominated by RE magnetic energy; RE kinetic energy ~ 5x lower

RE plateau energy measurement





RE plateau line emission

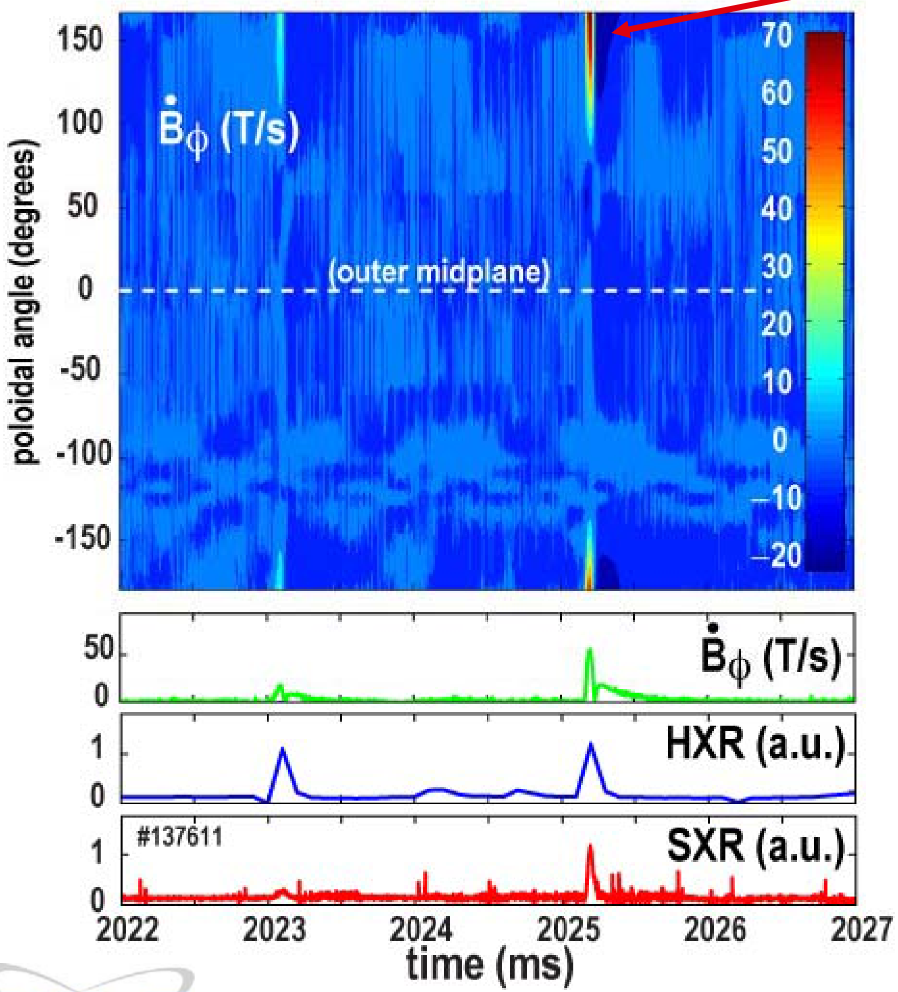
RE plateau synchrotron emission

- Current profile much broader than region of brightest emission
- Outward shift of highest energy REs qualitatively consistent with ~10 cm relativistic drift orbit shift

(J. Yu, APS 2009)

Instabilities Observed in RE Plateau

Contours of Bdot measured inside DIII-D vessel wall

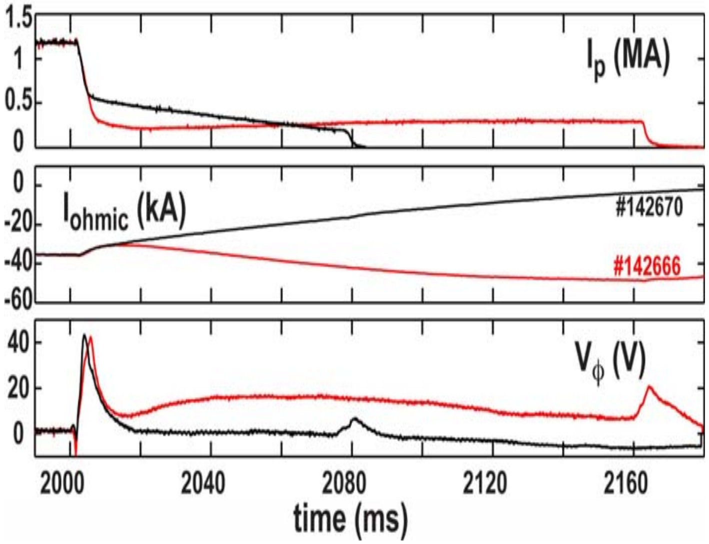


- **Occasionally, instabilities observed in RE plateau**
- **Very narrow, localized spikes in magnetic activity coincide with HXR spike from RE-wall strike**
- **Overall loss of RE current typically quite small, however**
- **Instability not identified at present**

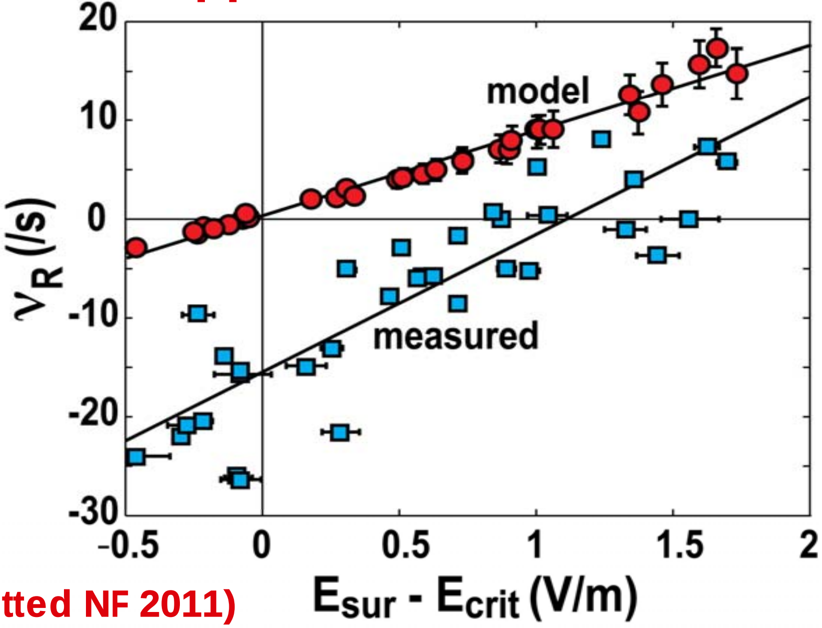
RE Plateau Current can be Ramped up or down with Externally Applied Toroidal Electric Field

- **First experiments done on JT-60U (R. Yoshino, NF 2000)**
- **More detailed comparison experiments done at DIII-D**
  - Assumption of background RE loss term (~10/s) consistent with data
  - Consistent with RE diffusion to wall with D ~ 0.4 m^2/s, qualitatively consistent with expected values (P. Helander, PPCF 2002)

Effect of toroidal E field on REs



RE current growth rate vs applied electric field

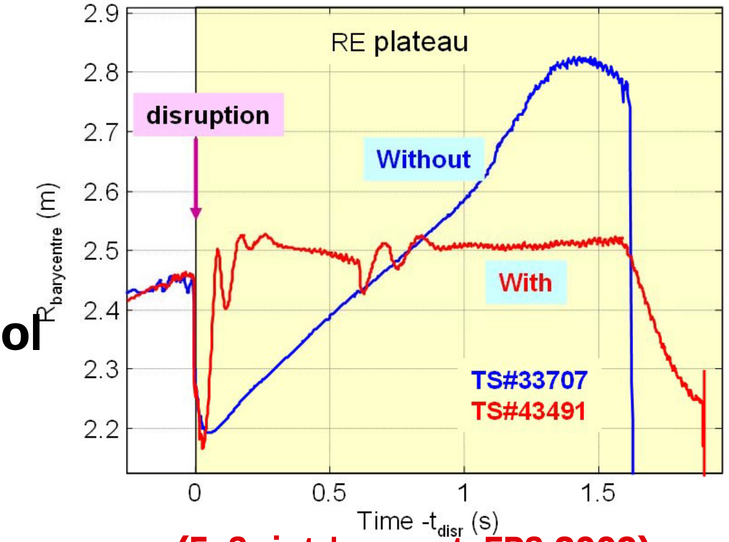


(E. Hollmann, to be submitted NF 2011)

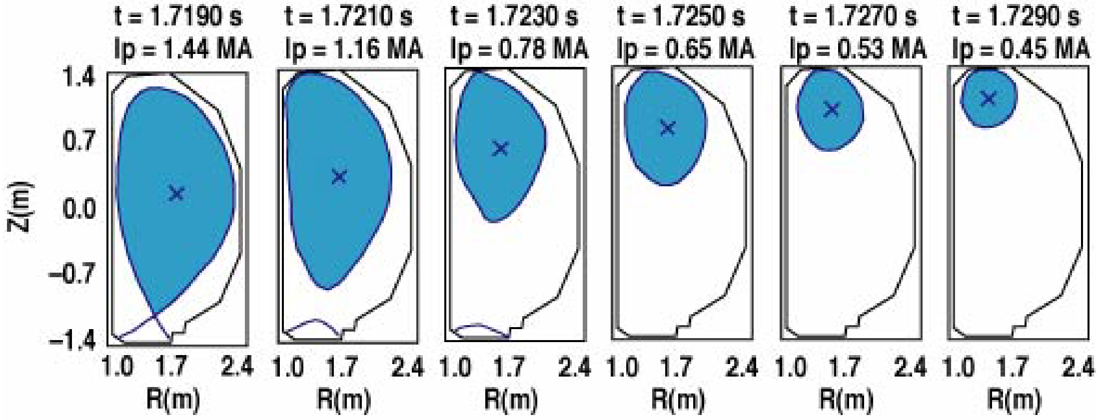
RE Plateau Current can be Moved Vertically or Radially with External Coils

- **Uncontrolled RE-dominated plasmas tend to limit on center post and then drift vertically in DIII-D.**
- **Tokamak control systems typically not optimized for control of RE current (low elongation, high l_i)**
- **Radial (Tore Supra) and vertical (DIII-D) control of RE plateau have been demonstrated**
- **Possibly allow pushing RE beam into sacrificial limiter?**

Radial control in Tore Supra



(F. Saint-Laurent, EPS 2009)

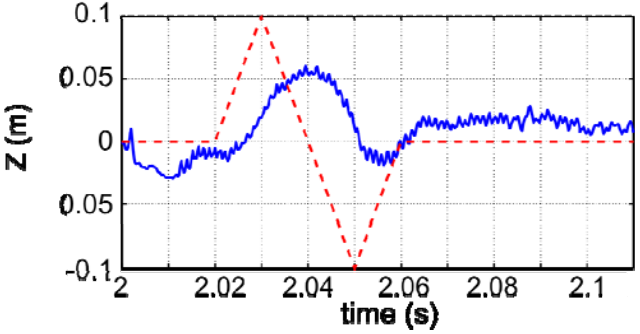


Vertical loss of RE plateau in DIII-D

(T. Evans, IAEA 1998)

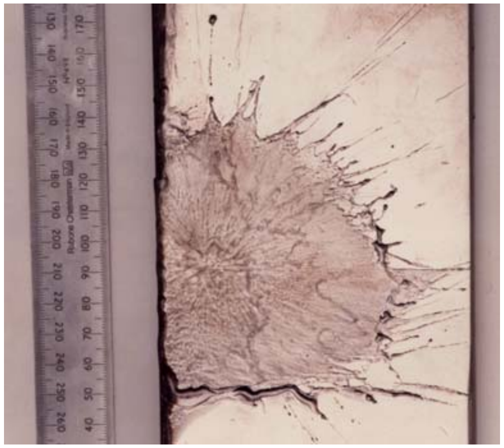
Vertical control in DIII-D

(N. Commaux, IAEA 2010)

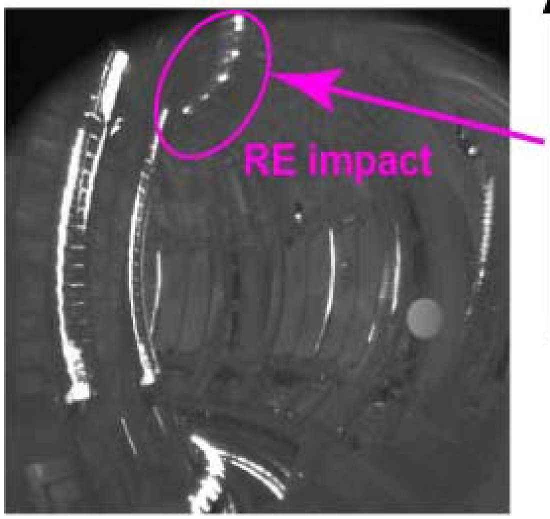


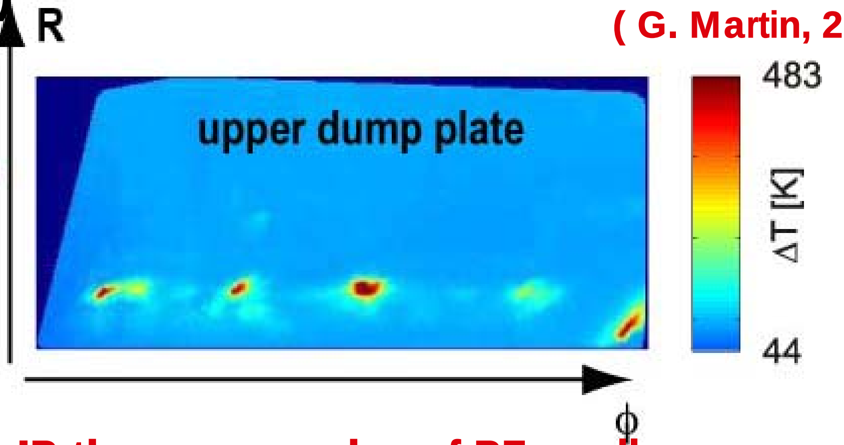
Runaway Electron-wall Strike Serious Concern Because of Very Localized Heating

- **RE-wall strikes frequently observed to be quite localized**
- **Suggests that RE beam doesn't always "scrape off" on wall smoothly but can kink into wall suddenly**
- **Simulations indicate that RE-wall strikes could melt cooling line braze joints in ITER if REs have sufficient incident angle, $\alpha > 4^o$, energy $E > 25$ MeV, and duration, $\Delta t > 5$ ms (V. Sizyuk, NF 2009; G. Maddaluno, JNM 2003)**



RE wall damage on JET
(G. Martin, 2004)

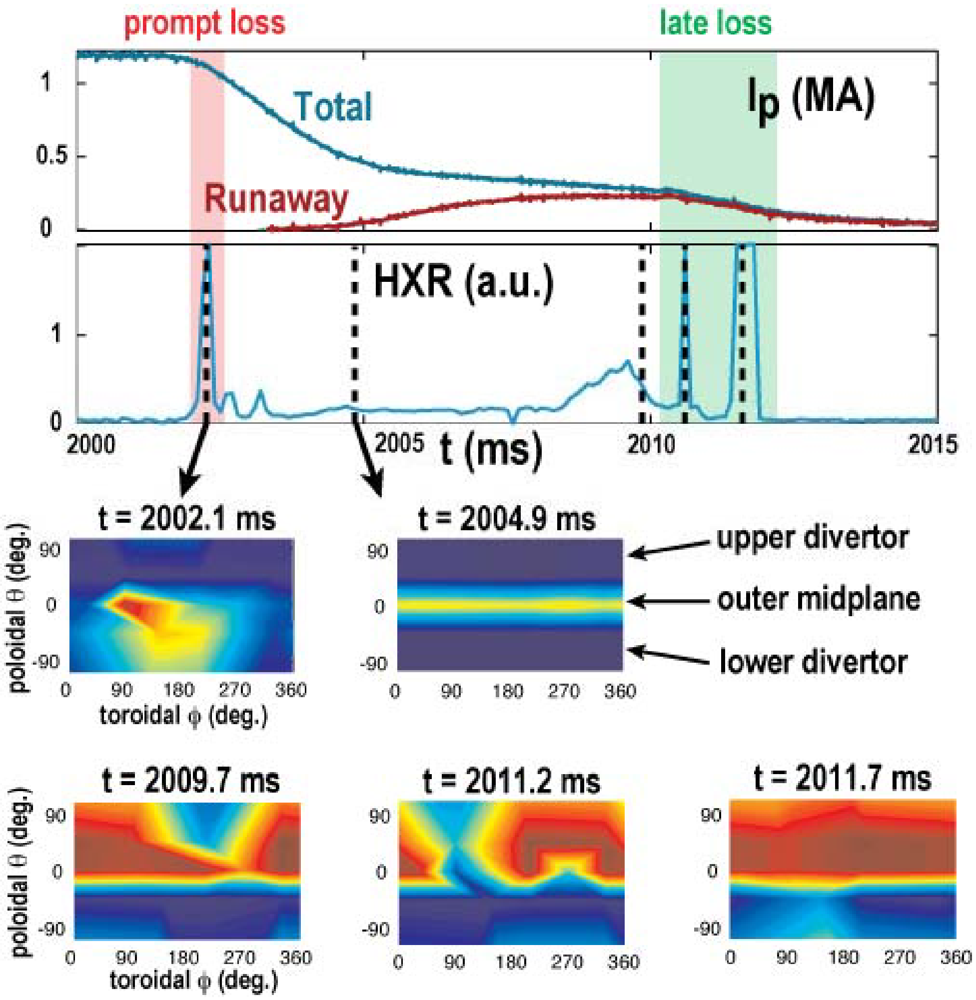




IR thermography of RE-wall strike on JET **(M. Lehnen, PPCF 2009)**

RE-wall Strikes Show Strong Toroidal Localization both in Prompt Loss and Late Loss Phases

HXR contours of RE-wall strikes in DIII-D

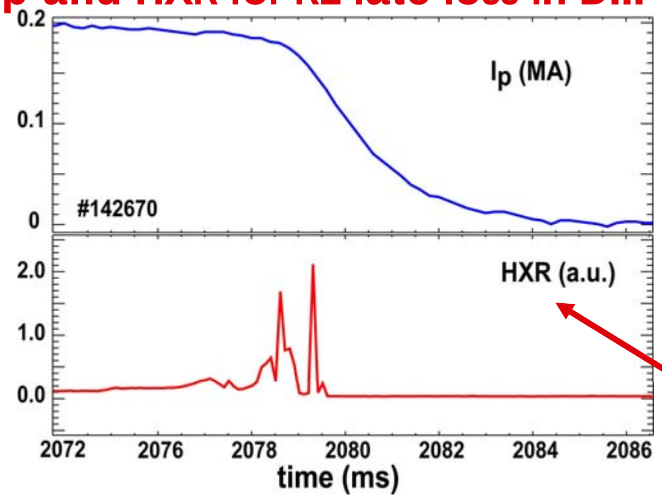


(A. James, APS 2009)

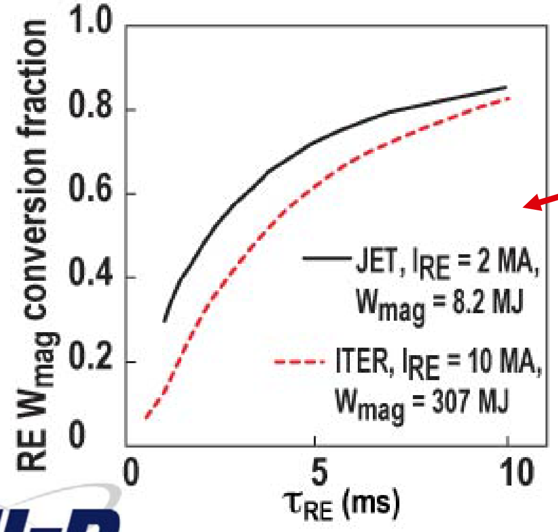
- **Loss not toroidally symmetric, except in middle of plateau**
- **Not clean *n*=2 or *n*=1 kink structure either**
- **RE beam current profile knowledge not good enough for ideal kink stability analysis**

Energy Transfer Between Magnetic Energy and Kinetic Energy may Occur During RE-wall Strike

Ip and HXR for RE late loss in DIII-D



Simulation of magnetic-kinetic energy transfer in RE late loss strike



- RE beam energy dominantly magnetic (W_{mag} ~ 100 kJ, W_{th} ~ 20 kJ in DIII-D)
- DIII-D RE current appears to converted rapidly to thermal current
- Simulations and data from JET suggest RE magnetic energy can convert into RE kinetic energy instead

(A. Loarte, NF 2011)

Summary: Progress in Disruption RE Understanding in Recent Years but Still many Unknowns

- RE seeds form during disruptions at end of TQ; 1D models appear to be able to explain RE seed formation in some cases
- Large fraction of RE seeds lost due to TQ MHD. Loss fraction has huge scatter but appears larger in diverted plasmas and larger in smaller plasmas, consistent with MHD simulations
- Avalanche gain during CQ appears moderate (~50x) in present devices, expected to be huge (~10^{15}) in ITER
- RE energy during plateau phase of order 20 MeV or less, consistent with avalanche theory
- Small instabilities occasionally observed during RE plateau, but no significant loss of current
- Present control systems not optimized for RE plateau but some preliminary success in RE beam position/current control
- RE final loss can be highly localized. Shows some evidence of conversion of magnetic to kinetic energy