Update on the ITER disruption mitigation system – physics basis and technology

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ITER Organization

Many thanks to
P. Aleynikov (MPI Greifswald), P. de Vries, A. Loarte, R. Pitts

Disclaimer:

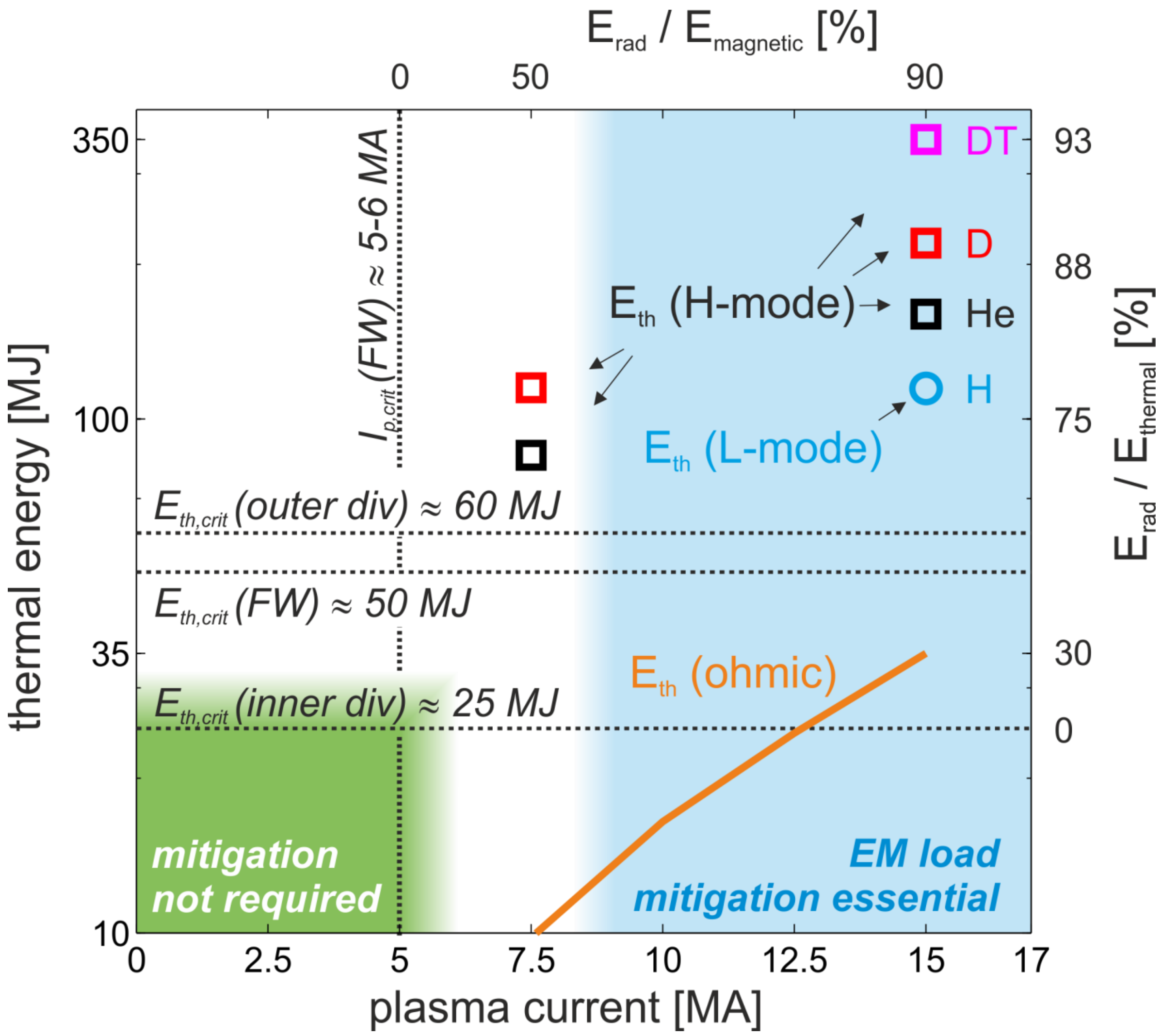
ITER is the Nuclear Facility INB no. 174. This presentation explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Outline

- ☐ Summary of mitigation requirements
- ☐ Update on the ITER Disruption Mitigation System
- ☐ Present Physics Basis: Mitigation of thermal loads (incl. runaways) and electro-magnetic loads

This presentation focusses on R&D for the ITER mitigation system. There are other important disruption related issues that are not mentioned here.

When do we need the DMS?



Required from early operation on (heat loads)

High current operation requires high mitigation success rate (EM loads)

High efficiency needed at high energies

Runaway generation during non-active phase depends on seed mechanism (JET-ILW: no RE generation in unmitigated disruptions)

Lehnen et al., http://dx.doi.org/10.1016/j.jnucmat.2014.10.075

Thermal load mitigation requirement

Thermal load limits to divertor: $E_{th} < 25$MJ (inner) / 60 MJ (outer) [ITER_D_7GFMB6]

Maximum E_{th} = 350 MJ (false alarm): $E_{rad}/E_{th} \geq 93\%$

Maximum disruptive E_{th} = 280 MJ: $E_{rad}/E_{th} \geq 91\%$

Thermal load limits to FW: $I_P < 5$MA

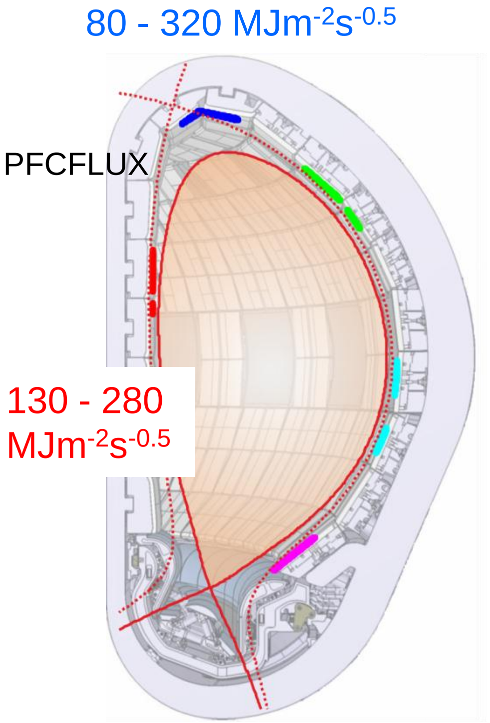
(initial analysis with high uncertainties) [Lehnen et al., PSI 2014]

CQ radiation requirement for 7.5 MA: $E_{rad}/E_{mag} \geq 50\%$

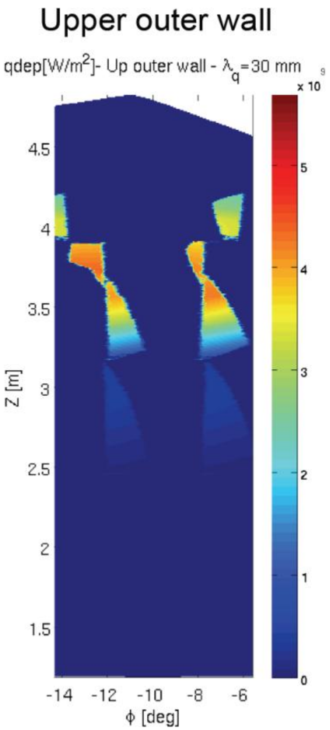
15 MA: $E_{rad}/E_{mag} \geq 90\%$

Thermal Loads – Surface Erosion

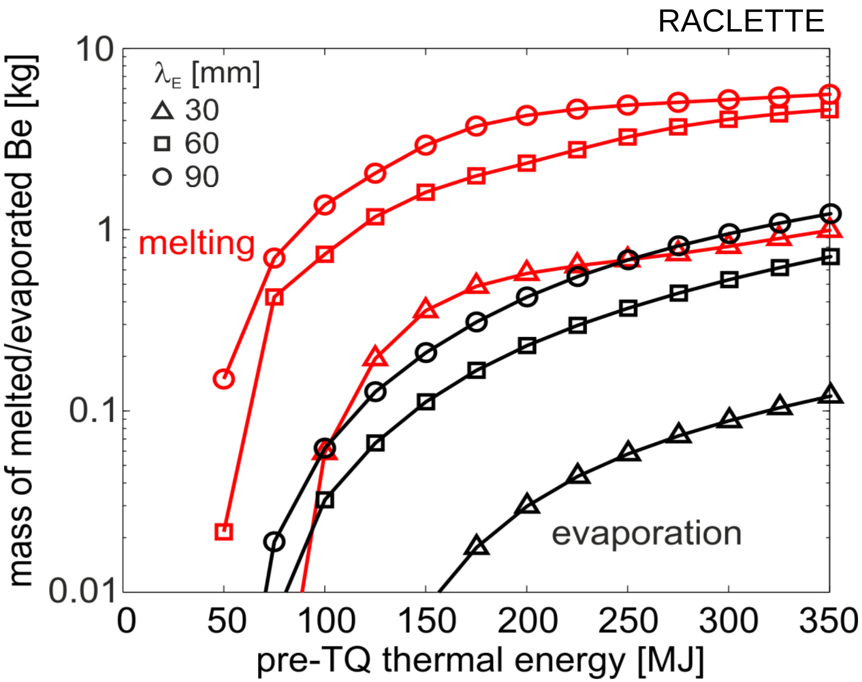
- Estimated erosion depth is critical! Thermal loads will largely define the required **disruption rate and the mitigation success**.
- Improved estimates require attention to: radiation shielding, modification of power exhaust capability and dust formation (surface roughening, cracking, splashing).



H-mode 15 MA 350 MJ



λ_E = 30 - 90 mm ➡ 5 - 23% E_{FW}/E_{th}



M. Lehnen, Yu. Gasparyan, D. Kovalenko, et al., JNM 2014

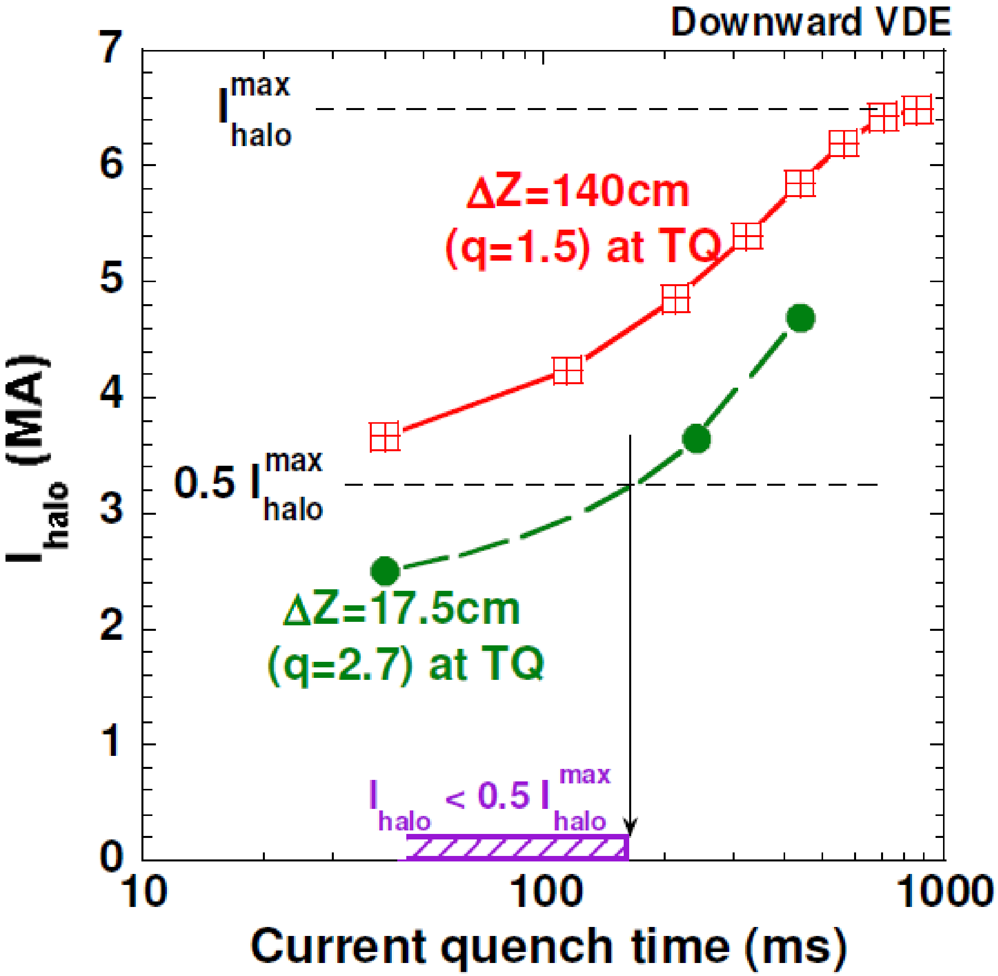
EM load mitigation requirement

I_H/I_P x TPF < 0.42 (cat II)

Halo current mitigation requirement:
$\Delta t_{CQ} < 150$ ms (DINA)

Eddy current limit:
$\Delta t_{CQ} > 36$ms/50ms
(400/2600 disruptions)

DINA simulations



Sugihara et al., IAEA 2012

EM load mitigation requirement

Reliability and success rate (predictor / DMS)

How likely is a high halo current fraction for slow CQs in ITER?*

Requires analysis of experimental data and modeling with an appropriate halo model

Mitigation ➡ $f_H = TPF \times I_H/I_P < 0.42$

Database ➡ $f_H < 0.75$

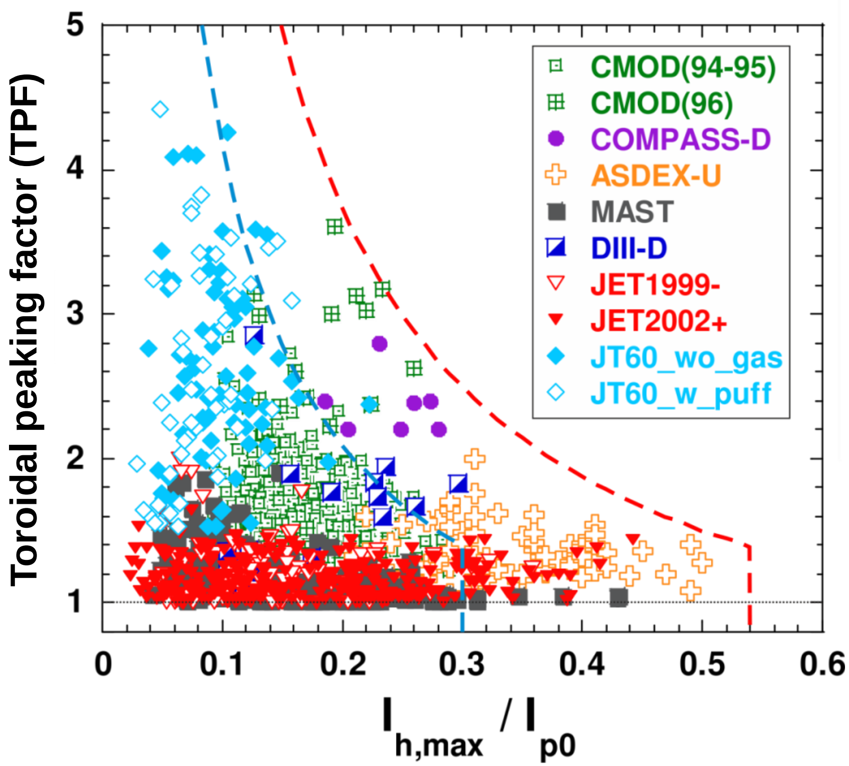
Slow CQs of VDE and MD can increase probability P for $f_H > 0.42$

3000 disruptions at 15MA

success rate $\geq$ (100-0.033/P)%

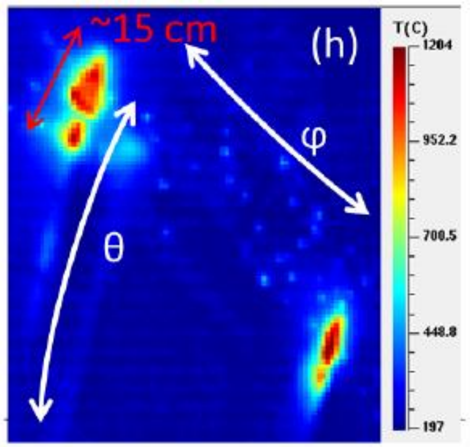
$\geq$ 99.7% (P=10% ?)

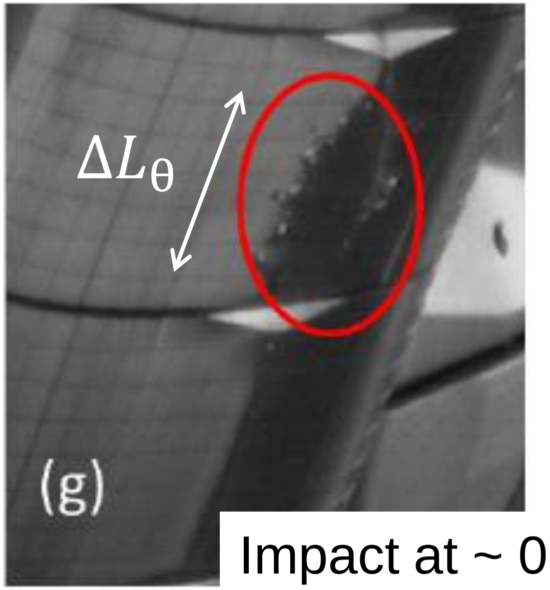
IDDB: mainly C-FW data



*see experience with JET-ILW

Runaway electron mitigation requirement





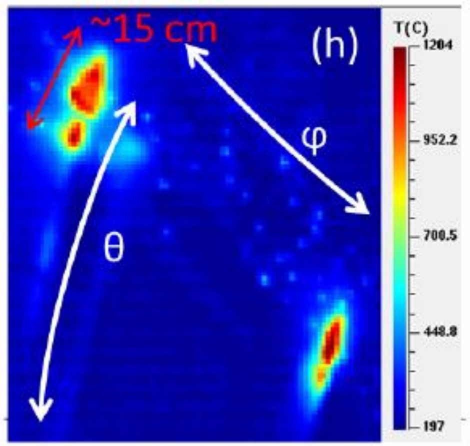
Impact at ~ 0.8 MA

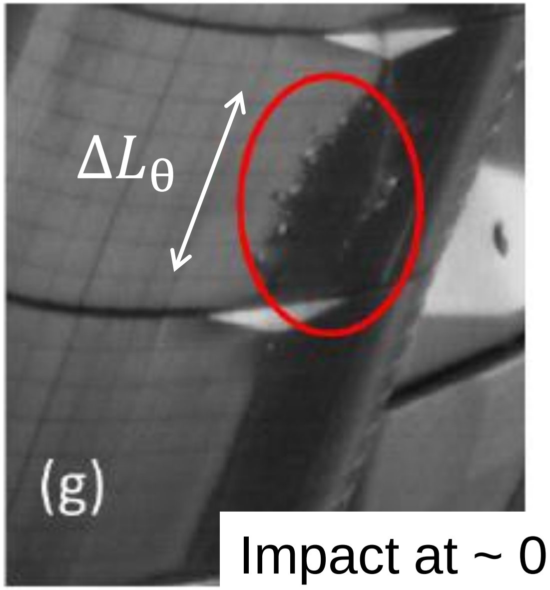
[C. Reux, IAEA 2014]

Maximum tolerable RE energy/current

- Previously a limit of I_{RE} < 2MA has been given for ITER [Sugihara IAEA 2012]
- Maximum tolerable I_{RE} uncertain and depends on <u>energy spectrum</u>
- JET damage threshold much lower ~0.3 MA [Reux, PSI 2014]

Runaway electron mitigation requirement





Impact at ~ 0.8 MA

[C. Reux, IAEA 2014]

RE loss driven by MHD instability (JET values)

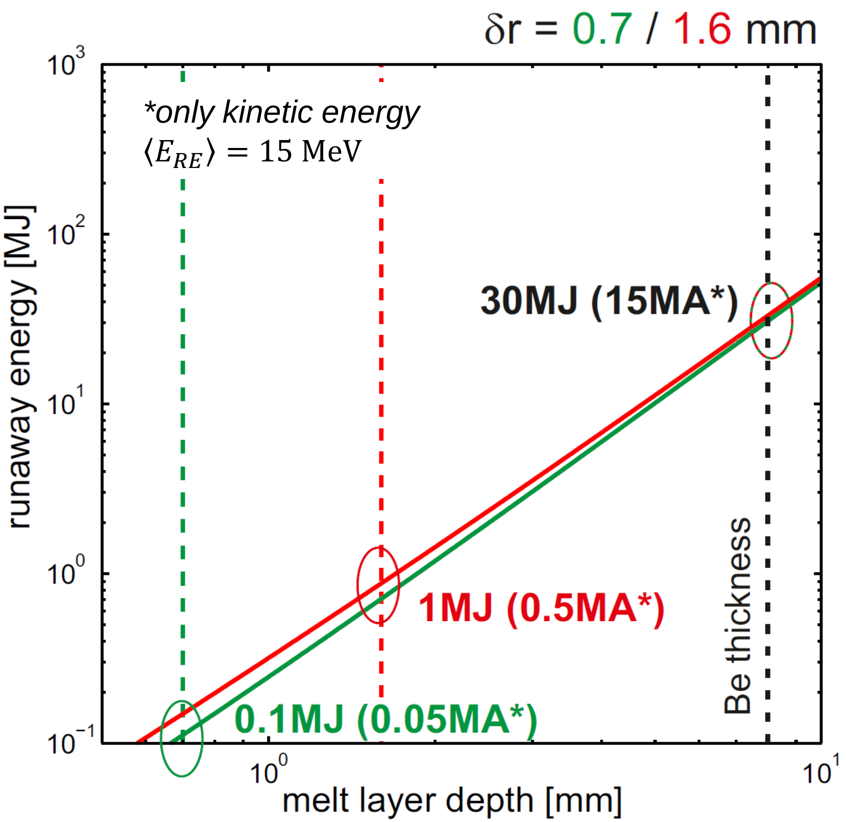
$$\Delta t \;=\; loss\ time$$
$$r_{RE} \approx 0.5\ m$$
$$L_c \approx 50\ m$$
$$v_{perp} = r_{RE}/\Delta t$$
$$t_{par} \;=\; L_c/c$$
$$\Delta r = v_{perp}\, t_{par} = L_c r_{RE}/c\Delta t$$

$\Delta r < r_L$ for about $\Delta t > 0.05ms$

RE deposition width is determined by r_L if RE loss is not extremely fast

Runaway electron mitigation requirement

RE impact on first wall panels,
energy distributed equally on 36 BMs

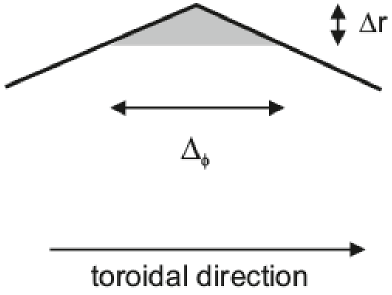


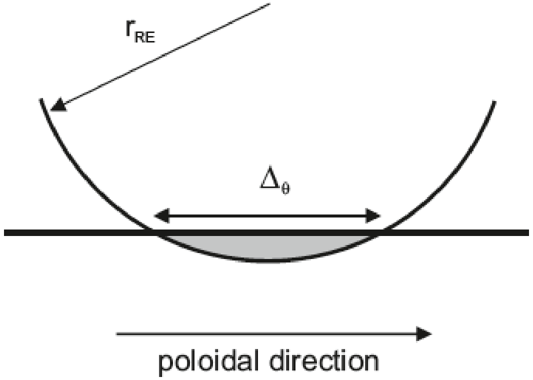
$$\Delta L_\theta = 2\sqrt{(r_{RE} + r_L)^2 - r_{RE}^2} \approx 75\text{ - }113\ \mathrm{mm}$$

$$r_L^{max} \approx \frac{E(\mathrm{eV})}{cB_t} \approx 0.01\mathrm{m}\ (15\mathrm{MeV})$$

$$\alpha = 0.08^{1} - 0.2^{2}$$

$$r_L = r_L^{max}\left(1 + \frac{1}{\sin\alpha}\right)^{-1} \approx 0.7\text{ - }1.6\ \mathrm{mm}$$

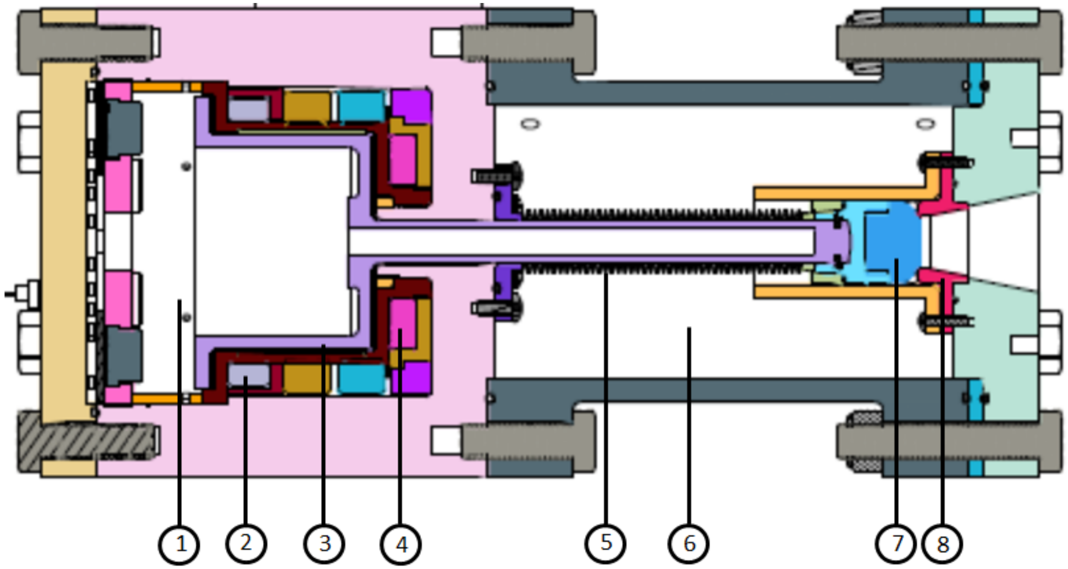




Disruption Mitigation System

Present concept and design of the ITER DMS

Systems – Massive Gas Injection (MGI)



1 – Closing Gas Volume
2 – Counter Torque Coil
3 – Top Hat Flyer Plate
4 – Main Coil

5 – Metal Bellows
6 – MGI Gas
7 – Polyimide Valve Tip
8 – Valve Seat

Development at ORNL focused on

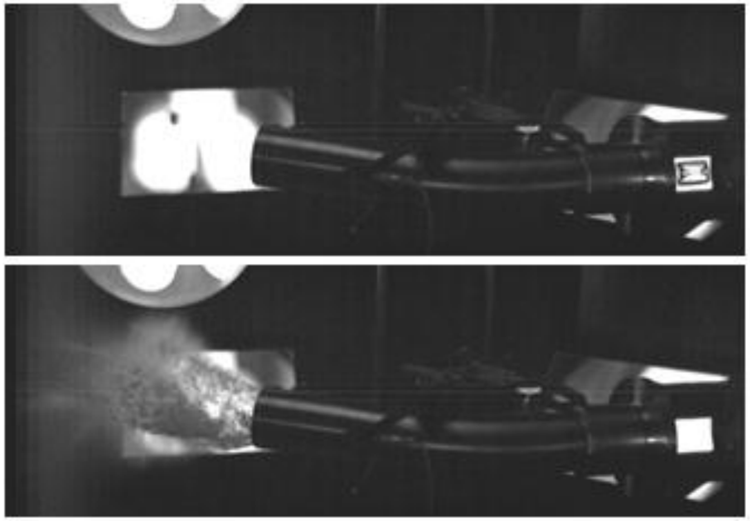
- Mitigation of high EM loads (eddy currents in toroidal magnetic field)
- Sealing in high radiation environment
- Flow simulations

Technique based on the Jülich valve design
[G. Czymek , SOFT 2014]

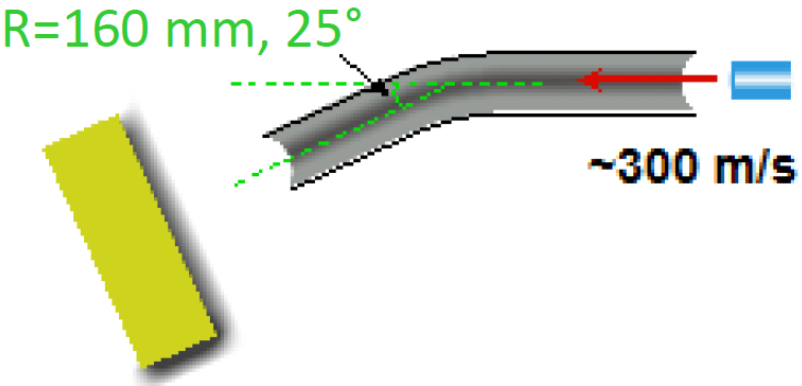
M. Lyttle, SOFE conference 2015

Present concept and design of the ITER DMS

Systems – Shattered Pellet Injection (SPI)



R&D done by ORNL



- Pellet diameters up to 24.4 mm (aiming for 34mm)
- Pure D_2, D_2/Ne shell and mixtures pellets have been successfully made
  Pure Ne is too strong to break free at 8 K, Ar maybe possible in small percentages
- Pellet speeds approaching 775 m/s (pure D_2) and 375 m/s 90% Neon mixture

S. Meitner, L. Baylor, S.K. Combs, SOFE conference 2015

Present concept and design of the ITER DMS

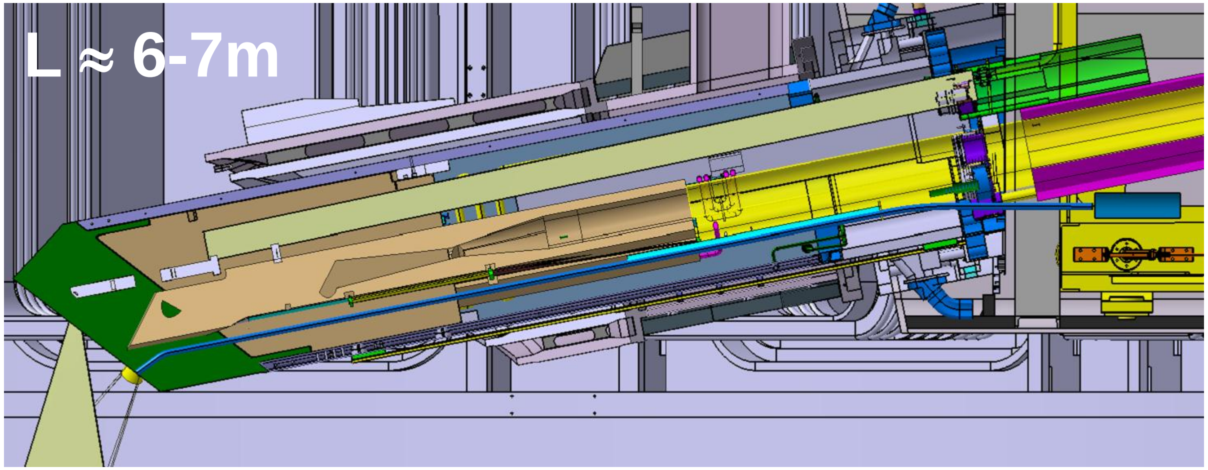
DMS design review workshop 4/5 November 2014

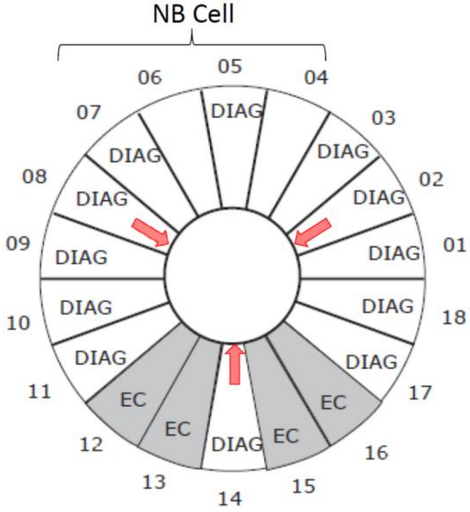
(https://user.iter.org/?uid=Q6JV83)

- ☐ The DMS shall be placed in the port-cell of the allocated port plugs (3 upper port plugs, 1 equatorial port plug).
- ☐ R&D will focus on the design of a SPI/MGI hybrid system.
- ☐ An additional MGI system was proposed inside an upper port plug above the NBI port for the non-active phase. Risk mitigation during commissioning of avoidance, prediction and mitigation systems. Feasibility to be assessed.
- ☐ The reserved in-port-plug space in the allocated port plugs will be kept in case a fall-back solution is needed.

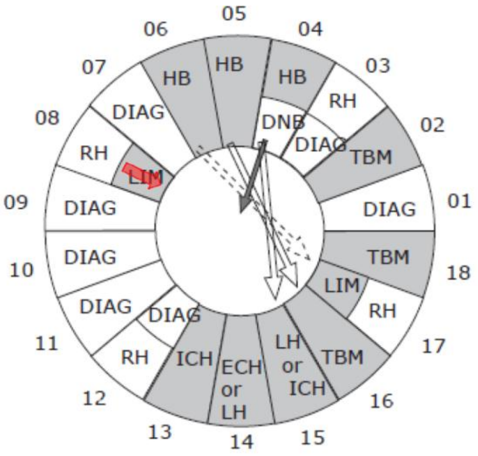
Present concept and design of the ITER DMS

Injector Location

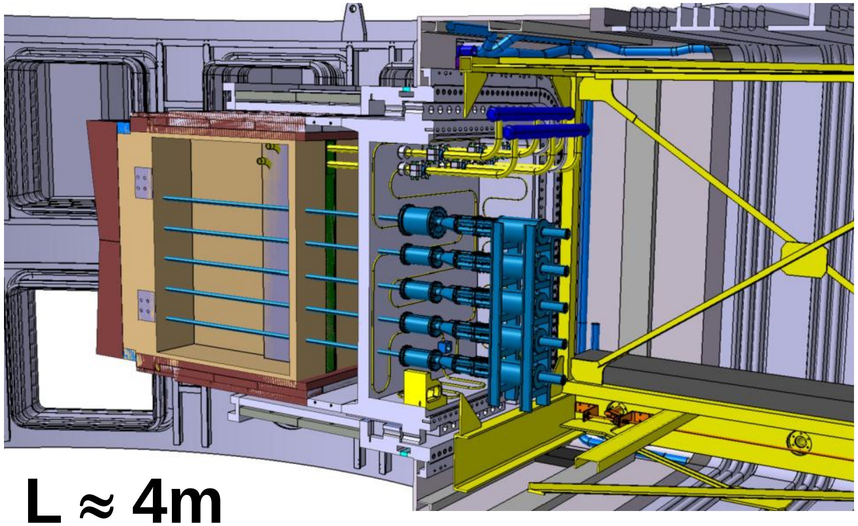




Upper port
#02, 08 and 14



Equatorial port
#08



L ≈ 4m

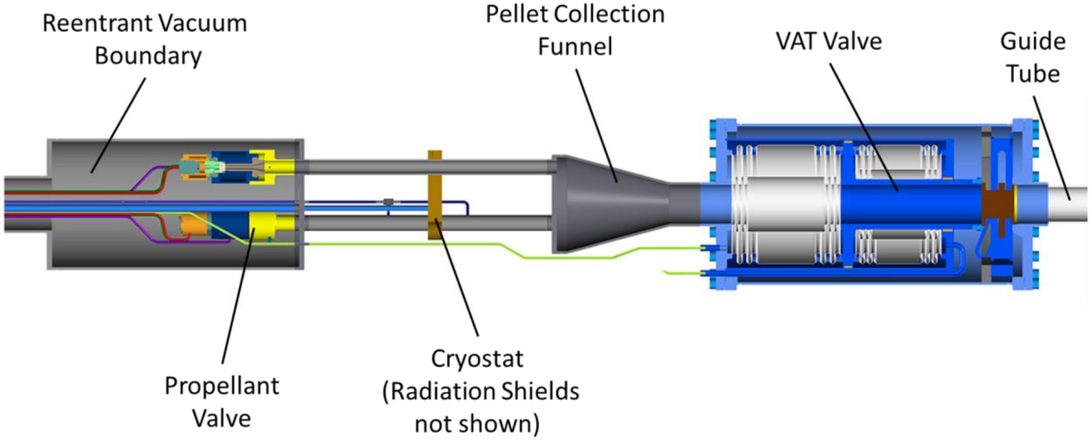
ITER Disruption Mitigation System

Quantities (upper limits)

Thermal Load Mitigation: up to 4 x 2 kPam^3 (Ne or Ar, mixtures with D_2)

Runaway Mitigation: 40 (He), 50 (D_2),100 (Ne or Ar) kPam^3

- Thermal & EM load mitigation: 3 x 3 barrels (UP) + 3 barrels (EP), each pellet: < 3 kPam^3 (Ne) or < 1.7 kPam^3 (Ar)
- Runaway mitigation/suppression: 5 x 3 barrels (EP) , each pellet: < 8.3 kPam^3 (Ne) or < 4.7 kPam^3 (Ar)
- Staggered injection to reach maximum throughput required for runaway suppression



ITER Disruption Mitigation System

Timing

Minimum response time ➡ increase mitigation success rate

Delivery time SPI (gas gun model):

25-30 ms (UPP), 15-20 ms (EPP), 3-8 kPam^3 Ne pellets

Delivery/pre-TQ time MGI (ASTRA simulations for Ne and Ar):

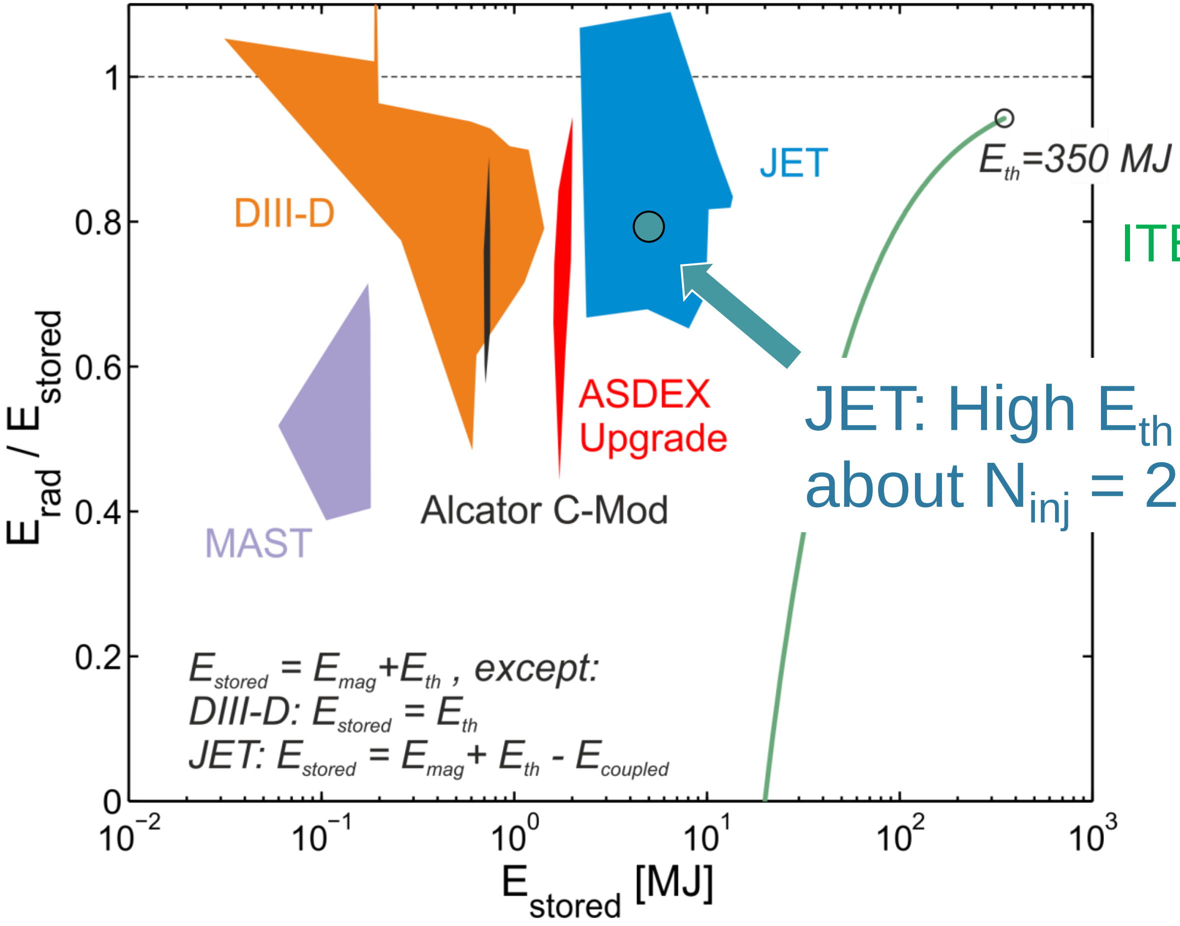
10-15 ms (UPP); 10% of $N_{reservoir}$ delivered
2-3 ms (in port-plug); 20-40% of $N_{reservoir}$ delivered

- *Each valve/pellet can be triggered individually*
- *Delay times challenging for acting on input during the disruption (e.g. detection of runaways) ➡ fixed injection sequence to be triggered by PCS (via CIS)?*
- *PCS can update injection sequence, quantities and species (depending on pre-pulse system configuration) during the pulse to adapt to mitigation requirements (0.5 ms time basis)*

Thermal Load Mitigation

Gas Quantity and species for thermal load mitigation

Radiated energy / stored energy
(data envelopes*)



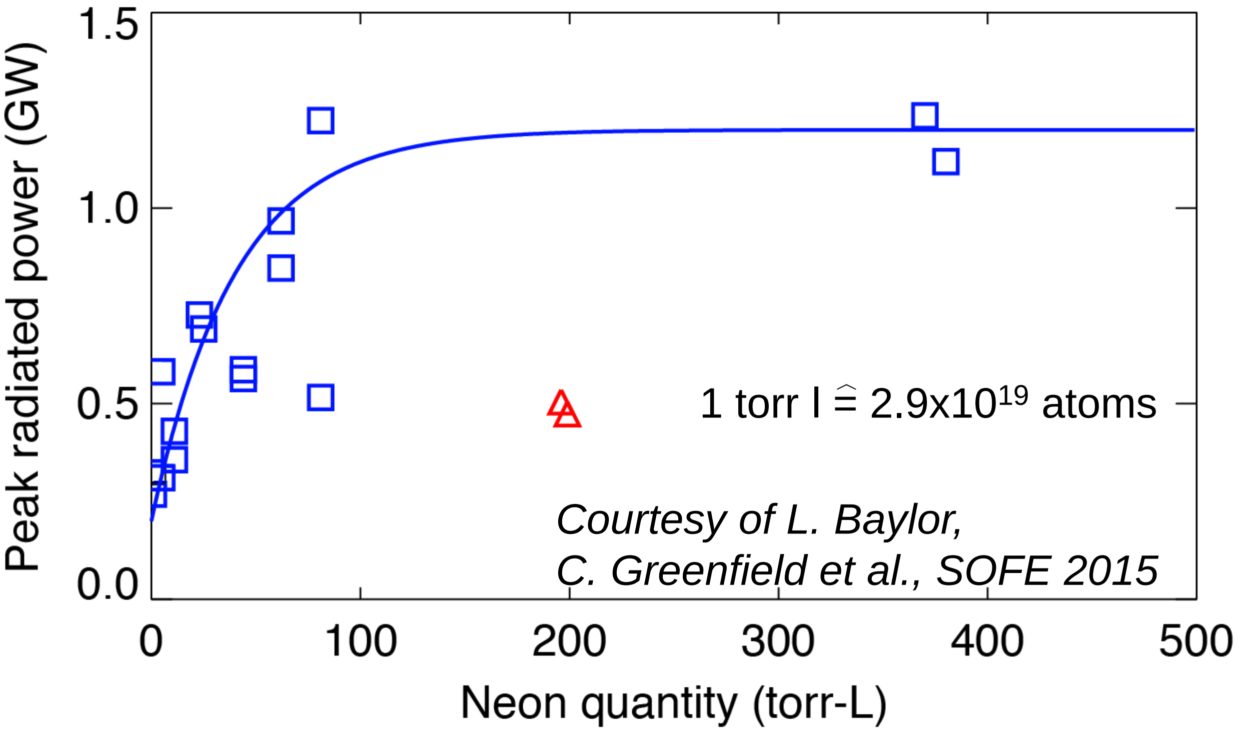
ITER ultimately requires > 90%

JET: High E_{th} shows saturation at about $N_{inj} = 2x10^{21}$ Ar atoms

*See Lehnen et al., http://dx.doi.org/10.1016/j.jnucmat.2014.10.075 for references

Gas Quantity and species for thermal load mitigation

SPI



1 torr l ≙ $2.9\mathrm{x}10^{19}$ atoms

Courtesy of L. Baylor,
C. Greenfield et al., SOFE 2015

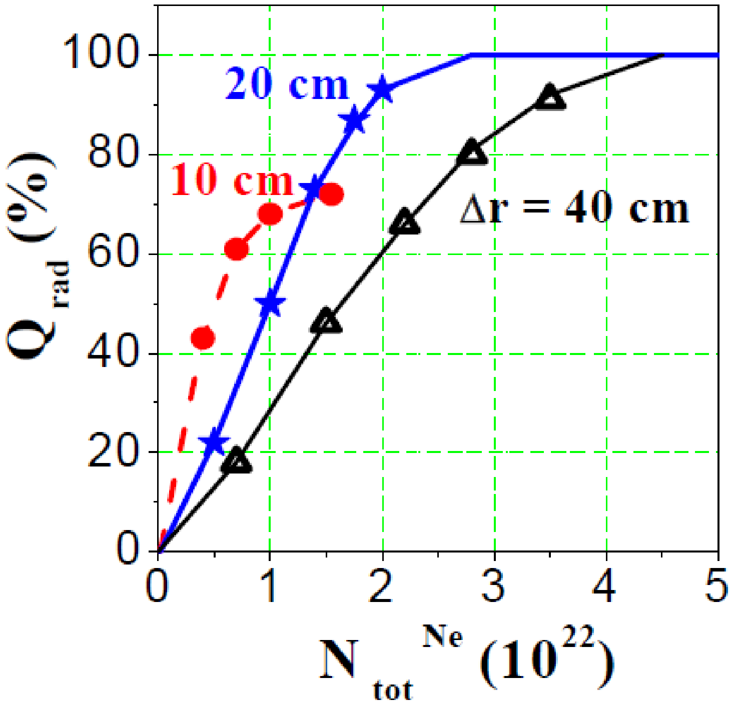
- factor ~4 increase in TQ radiated power over range of scan
- two outliers from broken pellets
- saturation at large quantities (similar to Ar MGI in JET)
- Consistent with observations of high radiation fractions in DIII-D with MGI using similar quantities

Gas Quantity and species for thermal load mitigation

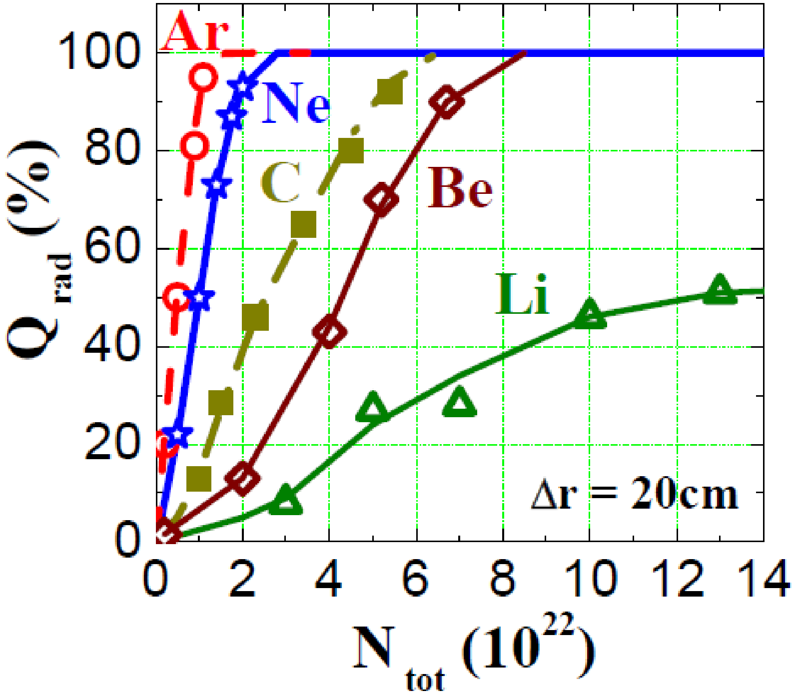
ASTRA simulations (1D) of the TQ (E_{th} = 300MJ)

Unmitigated TQ of 3 ms using $\chi_i = \chi_e = D_e = D_Z = 210\ \mathrm{m}^2/\mathrm{s}$

Efficiency depends on radiating layer width



Efficiency for fixed layer width of 20cm



Leonov et al., EPS 2011

Gas Quantity and species for thermal load mitigation

Requirements for a 90% radiation fraction (TQ)

	Quantity [10^{21}]	dE/dt [GW]
ASTRA (Ne/Ar)	20 / 10	100
NIMROD (Ne)	10	250
SPI DIII-D (Ne)	1.5	1.5
MGI JET (Ar)	2	2

These are indicative values that do not result from a comprehensive assessment

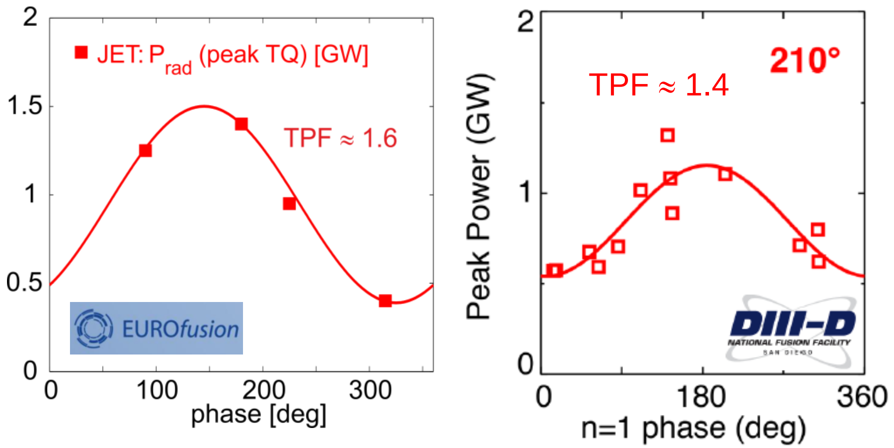
N_{inj} (experiments) > N_{inj} (simulation) if scaled with dE/dt

Thermal loads during CQ: similar quantities as for halo current mitigation (see EM load mitigation)

Radiation heat loads during thermal load mitigation

Critical heat flux peaking (pre-TQ & TQ):

$\langle TPF \rangle \times \langle PPF \rangle \leq 360$ MJ/E_{th} (SS)
720 MJ/E_{th} (Be)



- ☐ DIII-D and JET experiments are in line with NIMROD simulations with respect to the impact of the n=1 mode on the radiation distribution
- ☐ Discrepancy: maximum radiation in JET at the o-point
- ☐ TPF with external error fields: < 2.0
- ☐ PPF to be assessed, initial results (DIIID, ITPA-MHD*): < 2.0

⇨ shallow melting of SS possible ≳ 90MJ

* *N. Eidietis*

EM Load Mitigation

Gas Quantity and species for EM load mitigation

All IDDB MGI data points:
$t_{CQ} > 36\text{ms}$

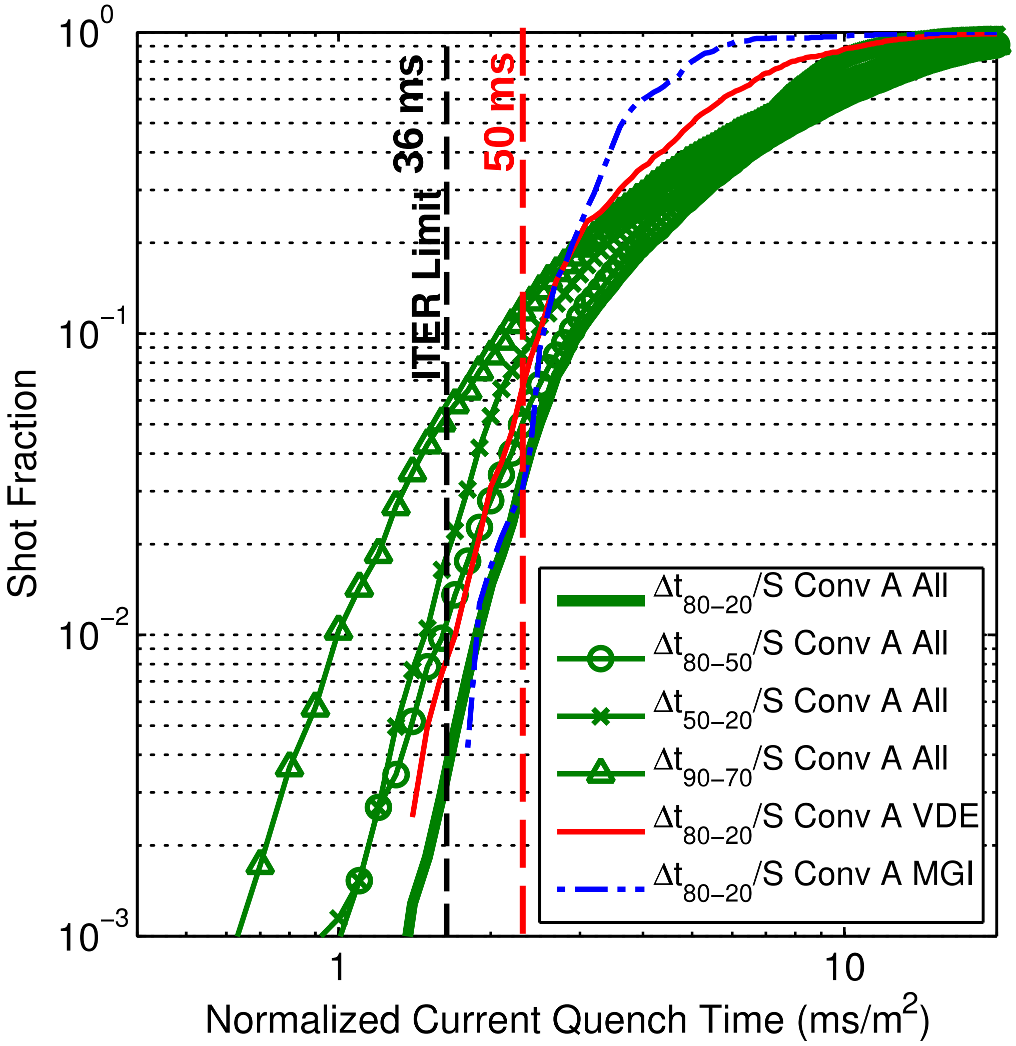
But: fast CQ sometimes generate RE plateaus

5% of all MGI disruptions:
$36 \text{ ms} < t_{CQ} < 50 \text{ ms}$

To be done
(before drawing conclusions):

Select by N_{inj}, current density, gas species, τ_{VV}/τ_{CQ}, etc.

CQ times from the IDDB

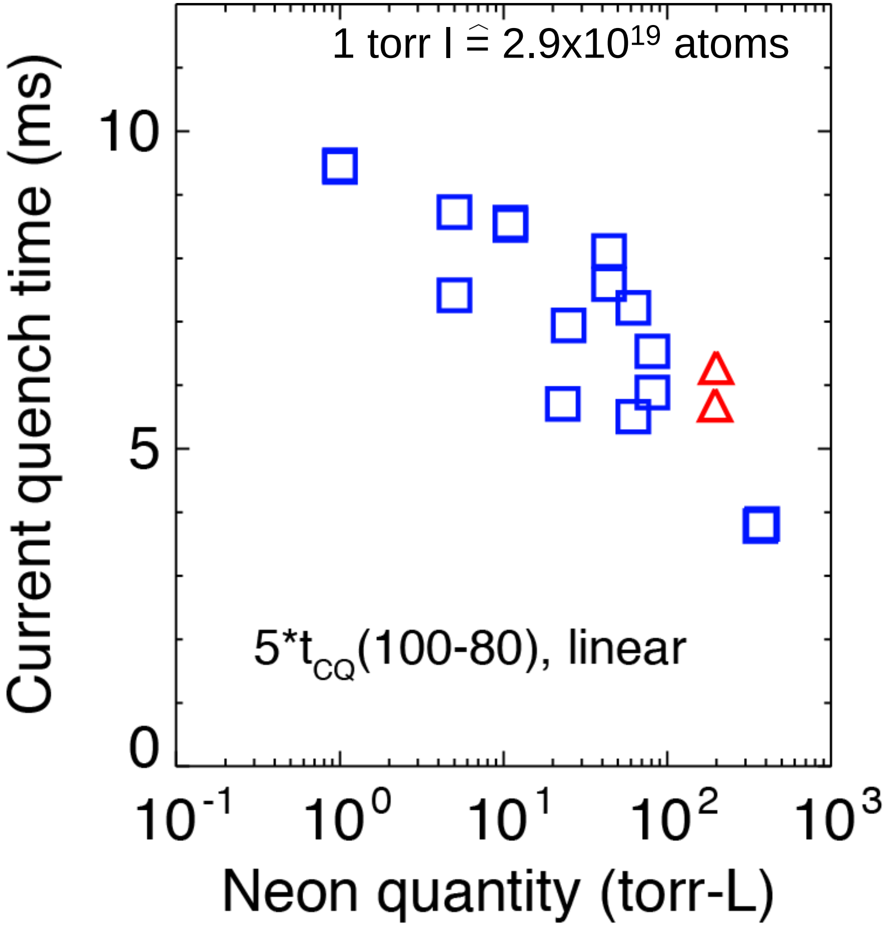


N. Eidietis and ITPA collaborators, Nucl. Fusion 55 (2015) 063030

Gas Quantity and species for EM load mitigation

SPI

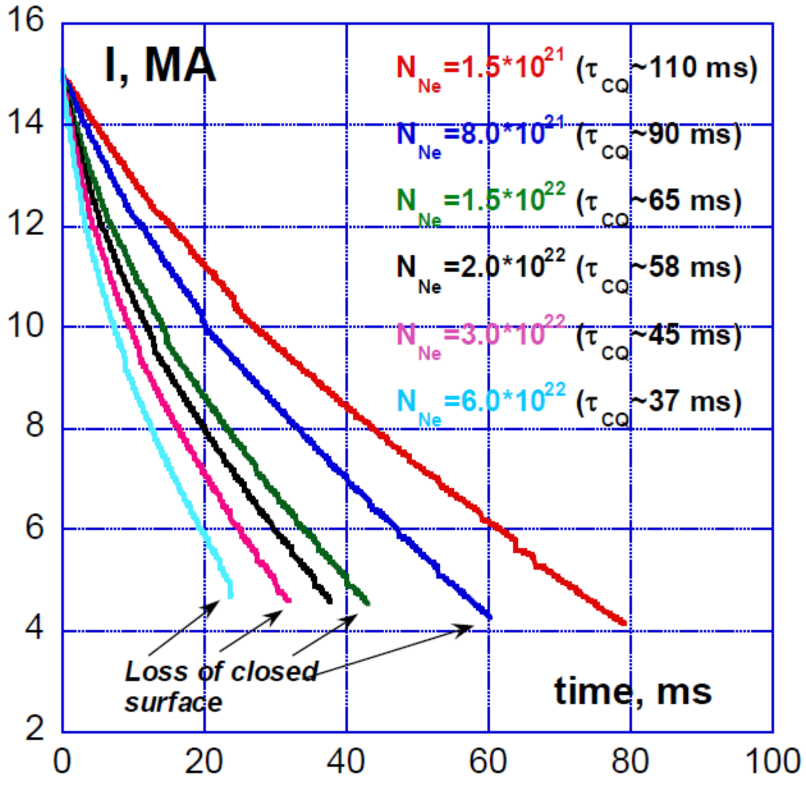
- ☐ Current quench time can be controlled by SPI using different ratio between Ne and D_2
- ☐ Outliers (broken pellets) fit overall trend

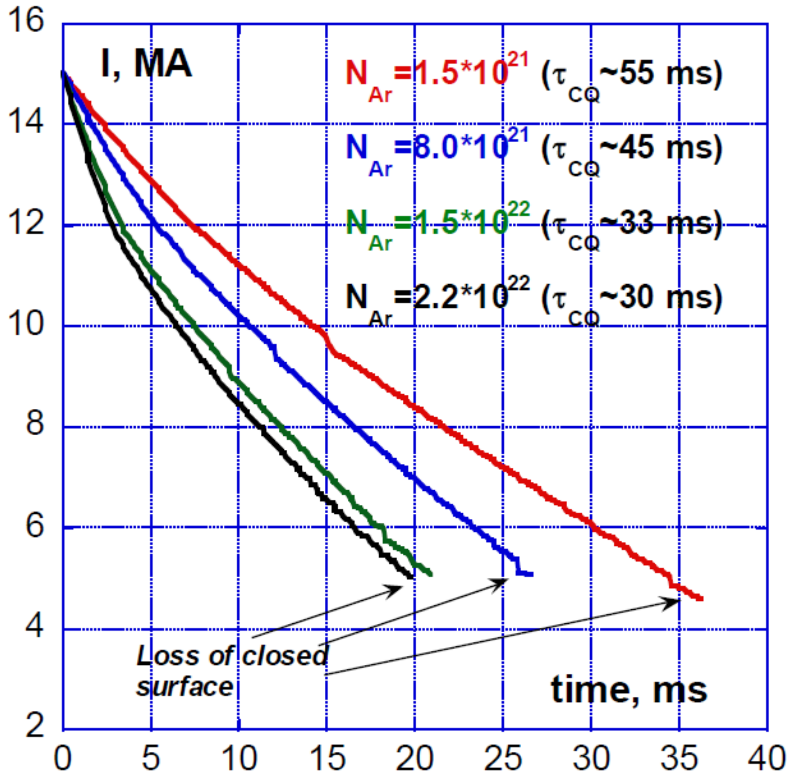


Courtesy of L. Baylor (presented at ITPA MHD 2015)

Gas Quantity and species for EM load mitigation

DINA simulation with self-consistent power balance ($P_{rad} = P_{OH}$)





EM loads: Ne preferable compared to Ar

Maximum assimilated(!) Ne quantity about ≤ $3x10^{22}$

S. Konovalov et al., IAEA 2014

Gas Quantity and species for EM load mitigation

Requirements for EM load mitigation

quantities for halo currents not an issue:

- DINA: CQ in the order of 100 ms for $N_{inj} \sim O(10^{21})$ (Ne, assimilated)

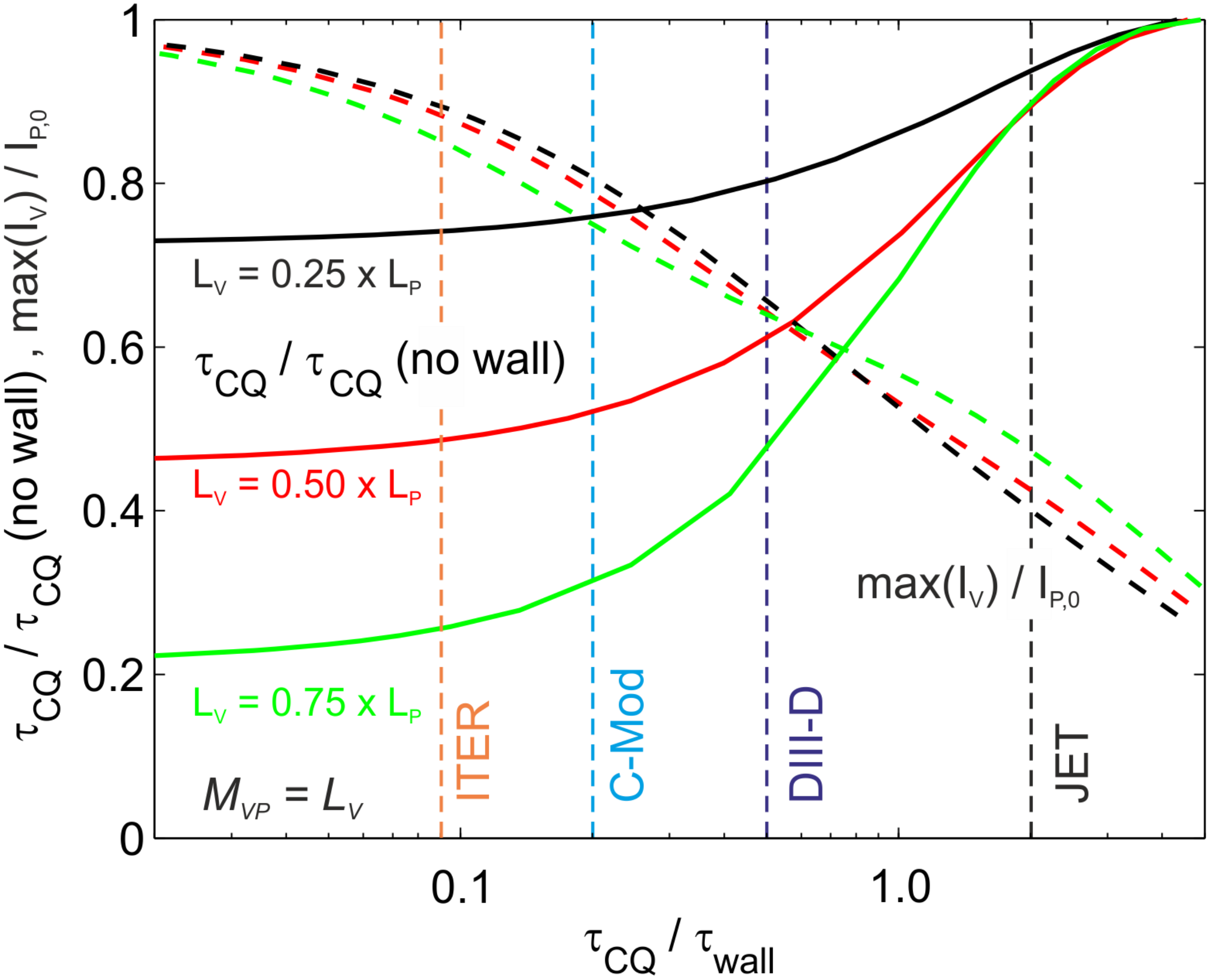
limiting factor are eddy current loads ($t_{CQ}/S \geq 2.3\ ms/m^2$):

	Quantity [10^{21}]	t_{CQ}/S [ms/m^2]
DINA (Ne)	20-30	2.3
DINA (Ar)	1-2	2.3
SPI DIII-D (Ne)	10	2.5
MGI JET (Ar)	2	3-4

Extrapolation not necessarily straightforward: impact of VV currents, vertical displacement and carbon release!

Gas Quantity and species for EM load mitigation

Extrapolation from existing data to ITER: τ_{wall} can have a strong impact on τ_{CQ}



Runaway Mitigation Scheme

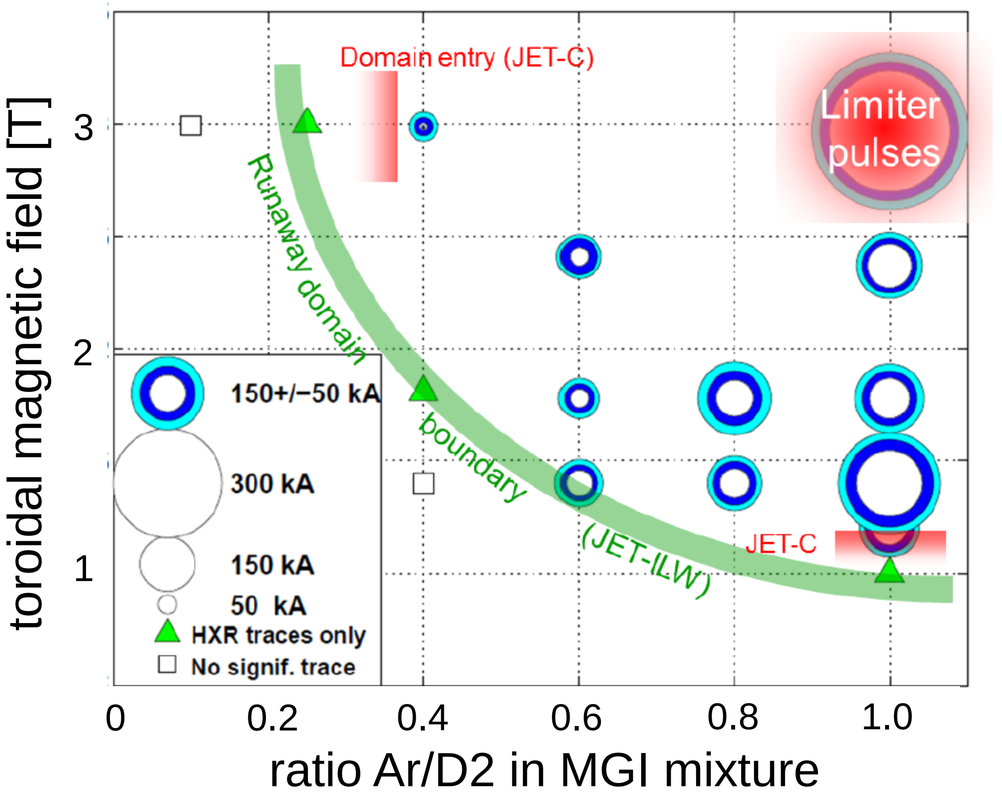
Avoid seeding Runaways

JET RE domain:
high B and high Ar fraction
facilitates RE generation

➡ right <u>species</u> and <u>quantities</u>
for thermal load mitigation

ITER avalanche multiplication
up to 10^{21}

How can the JET results be transferred to ITER?

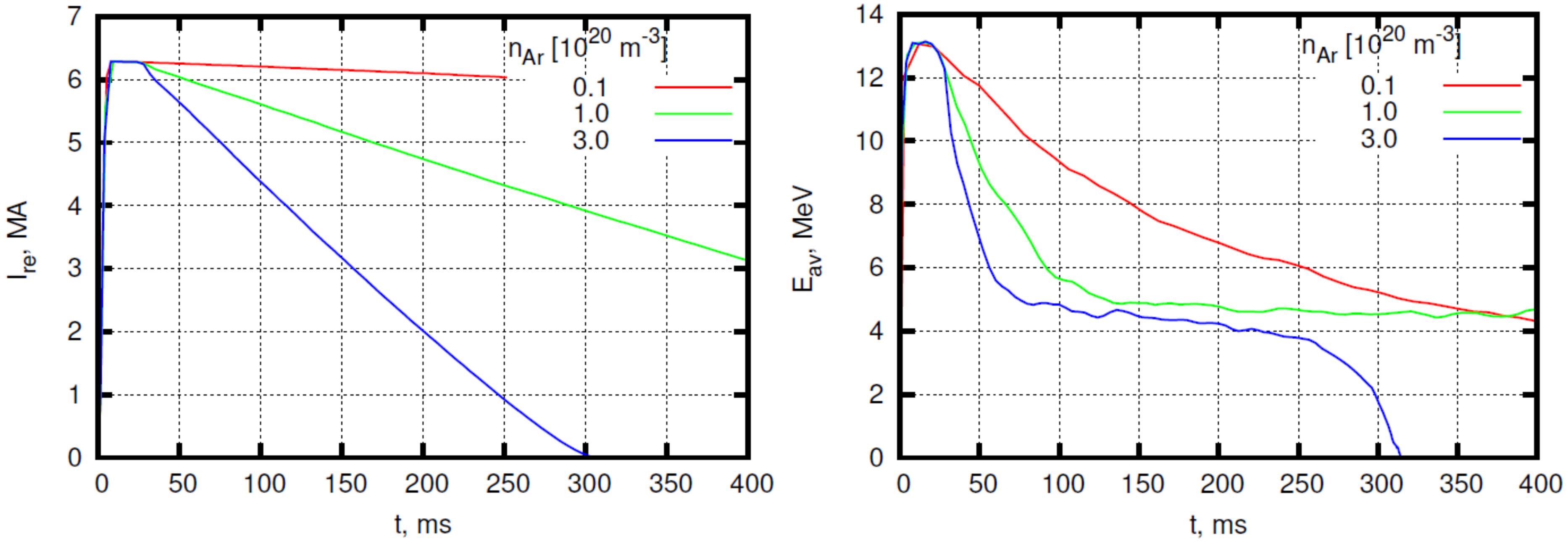


C. Reux et al., NF 2015, accepted

Note: additional seeds from Compton scattering and tritium decay during active phase

Mitigation by runaway energy dissipation

Kinetic Simulations: Decrease of runaway current and energy depends on Ar density

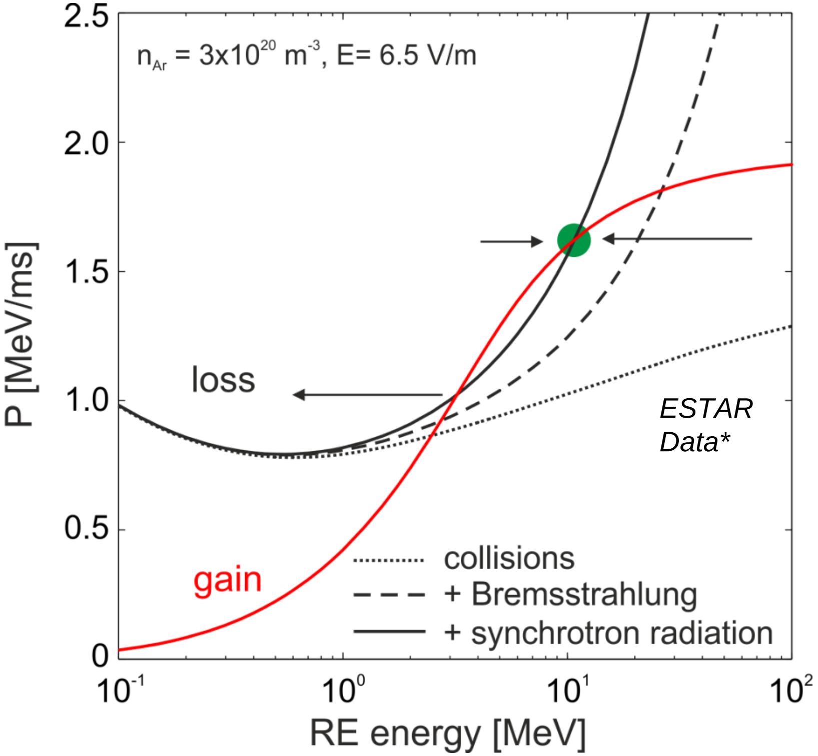


P. Aleynikov et al., IAEA 2014

Instantaneous increase of n_{Ar} at t = 30 ms, avalanche spectrum

Vertical loss time of the RE beam of the order of 100 ms
(stability analysis pending / critical q ?)

Mitigation by runaway energy dissipation



After CQ and RE formation

- E_0: electric field to sustain RE population (note: $E_0 > E_c$)
- E_a: electric field to allow avalanche (energy balance!)
- Electric field adjusts itself to just sustain RE population

*stopping power for e-e collisions and Bremsstrahlung taken from: http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

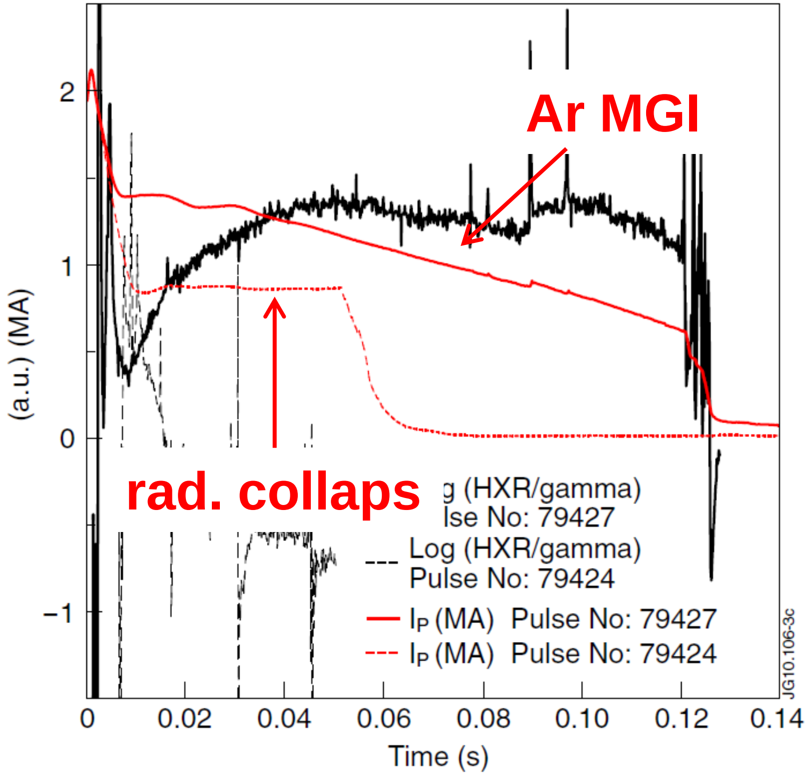
Mitigation by runaway energy dissipation

Consequences

[see Pavel's presentation and P.Aleynikov and B. Breizman, PRL 2015]

- **Linear current decay**
- Energy limited by synchrotron radiation 1-10 MeV, low energy / high pitch angle dominates
- Electric field to sustain the RE population is higher than E_c

seen at many machines, example: JET runaway plateaus



V. Riccardo et al., PPCF 2010

Mitigation by runaway energy dissipation

Consequences

[see Pavel's presentation and P.Aleynikov and B. Breizman, PRL 2015]

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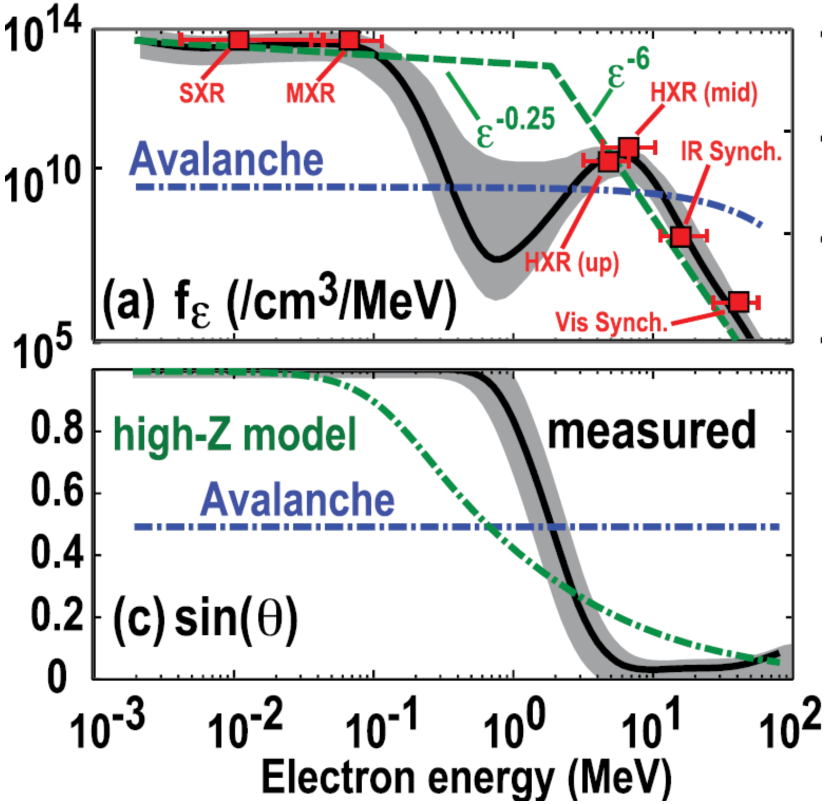
- Electric field to sustain the RE population is higher than E_c

DIII-D shows very similar spectrum and pitch angle distribution



E. Hollmann, P. Parks et al., PoP 2015

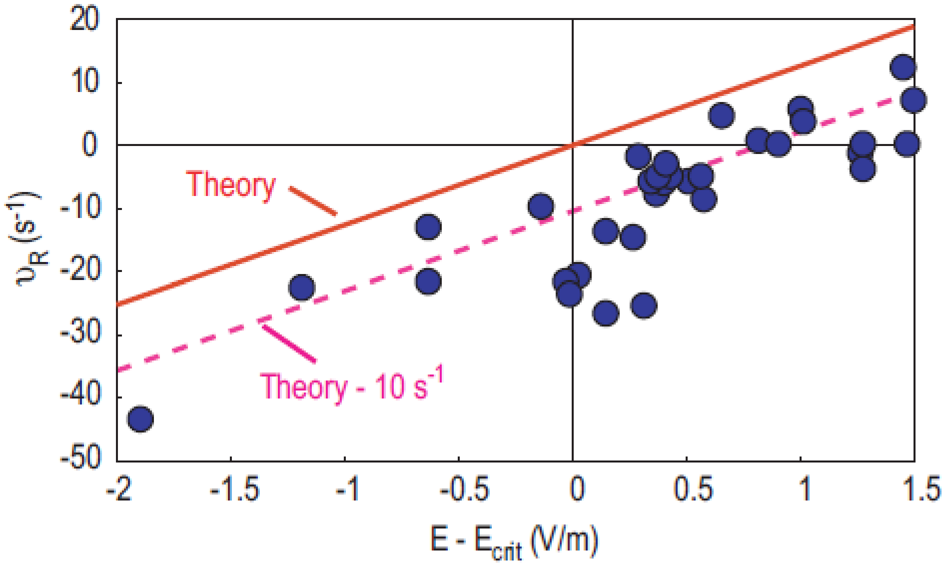
Mitigation by runaway energy dissipation

Consequences

[see Pavel's presentation and P.Aleynikov and B. Breizman, PRL 2015]

- Linear current decay
- Energy limited by synchrotron radiation 1-10 MeV, low energy / high pitch angle dominates
- **Electric field to sustain the RE population is higher than E_c**

DIII-D shows positive growth for fields E >> E_c only*



E. Hollmann et al., NF 2013

**experimental rate based on HXR (impact of energy spectrum)*

Gas Quantity and species for RE mitigation

Requirements for RE energy dissipation

- Kinetic simulations:
  - high-Z more efficient (Ar or higher)
  - Assimilated Ar quantity > 2×10^{23} ($V_{plasma} = 830 m^3$)
  - Uncertainties: 1D and RE stability analysis required

Required high-Z quantities more than a factor 10 higher than what can be tolerated for the CQ rate

⇨ Solution: second, delayed injection

- Experiments:
  - I_{RE} decay observed in many devices after impurity injection, DIII-D confirmed energy dissipation for high-Z, but not yet conclusive for second injection (JET)
  - Main uncertainty: interaction between neutrals and background plasma

Injection into a mature RE beam

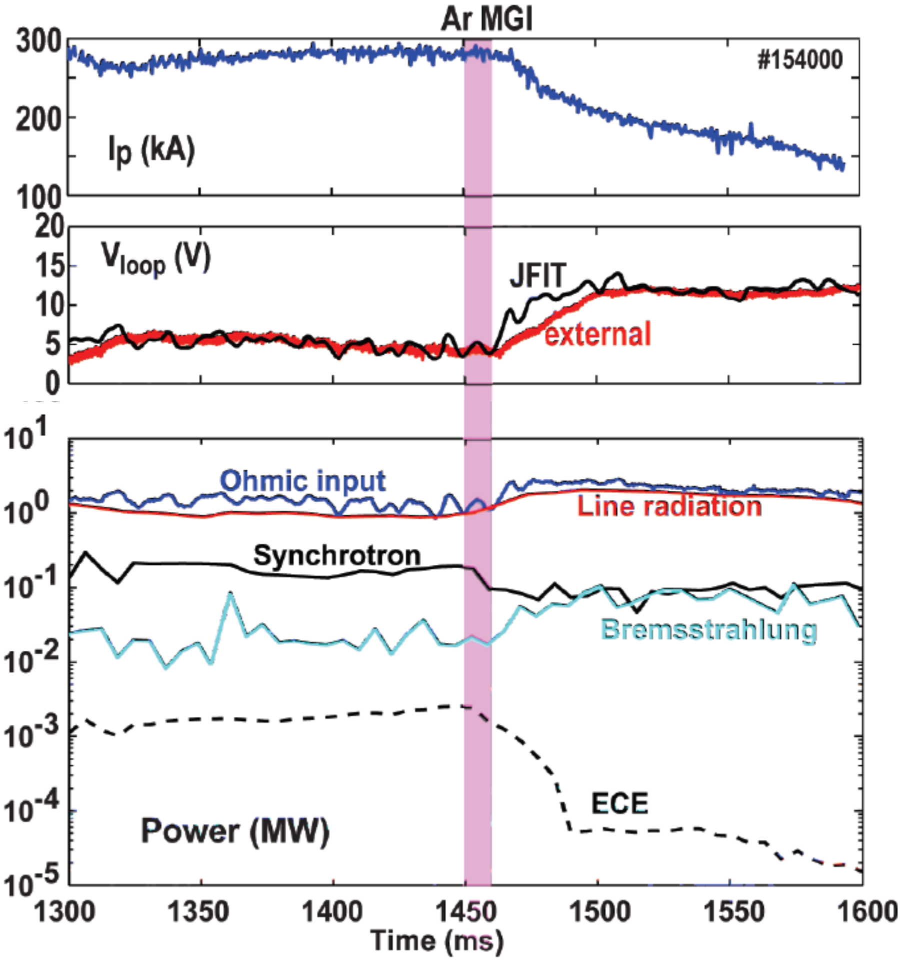
2nd injection affects the RE in DIII-D, AUG, Tore Supra, but <u>not</u> in JET!

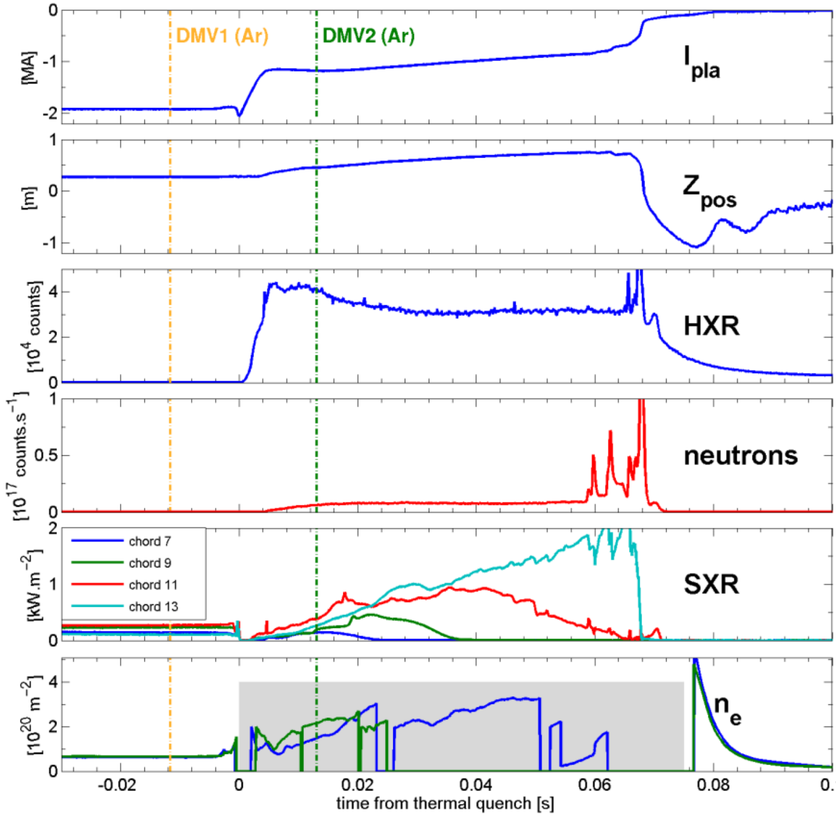
DIII-D

E. Hollmann, Runaway workshop, Göteborg 2014

JET

C. Reux, IAEA 2014

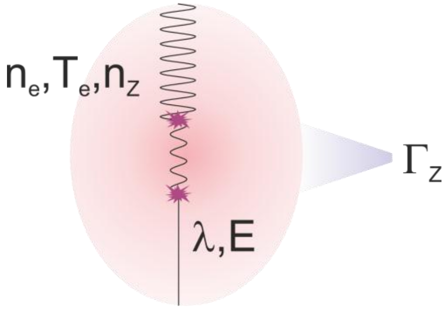




Open questions related to the ITER DMS

- How efficient is **Shattered Pellet Injection** in ITER?
  What is the optimum design? (e.g. shard size – penetration depth)

- How efficient is a second injection in ITER for **RE energy dissipation**?
  - Interaction background plasma / neutrals and REs
  - Impurity penetration efficiency
    (like a detached high density divertor?)
  - Instability limits (available time, residual E_{RE})



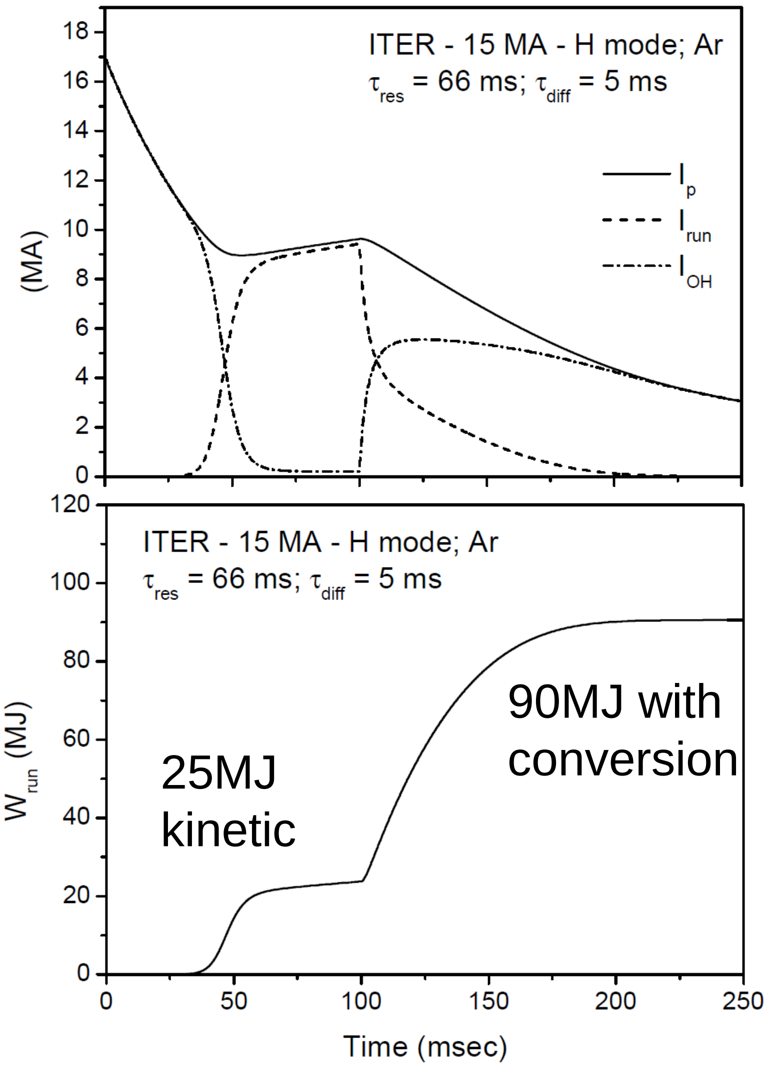
- How much margin is there for **thermal load mitigation**? Avoiding runaway generation, avoiding too high eddy currents. Required quantities? Radiation asymmetries?

- How much **erosion** do we expect per unmitigated disruption? Vapour shielding, thermal quench dynamics, magnetic energy dissipation.

- How likely are high **halo currents** during slow CQs in ITER?

Back-up slides

Runaway electron mitigation requirement



Martín-Solís, IAEA 2014

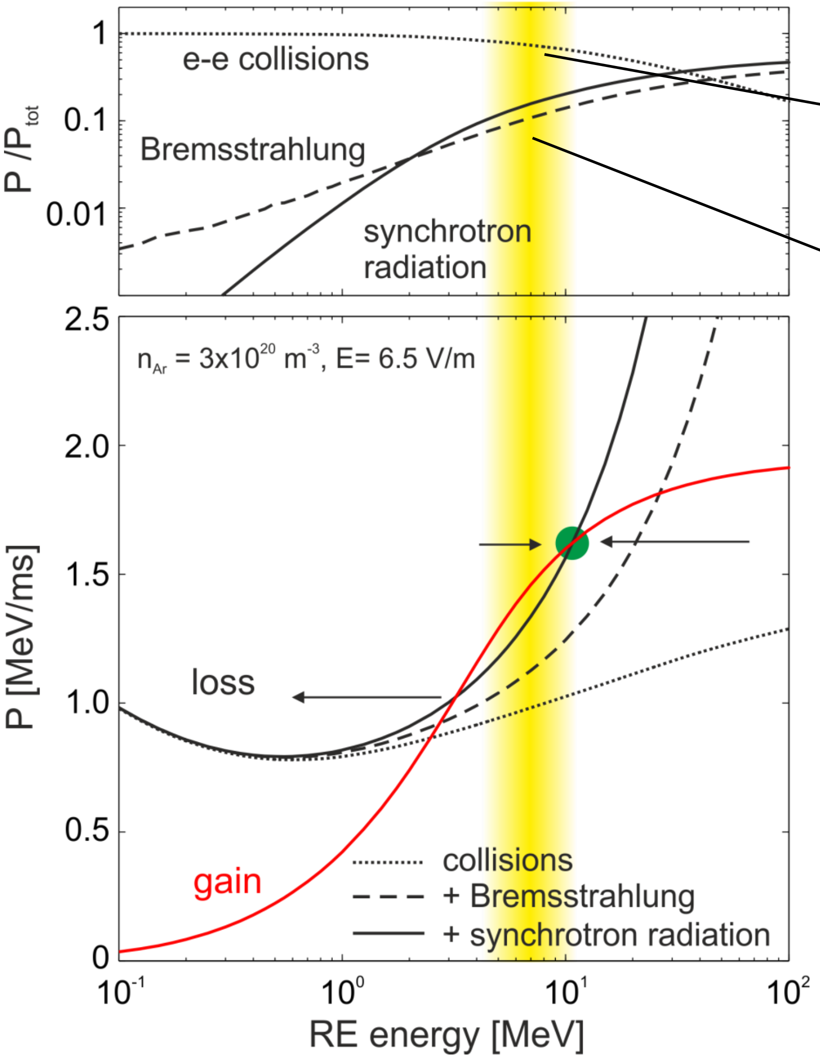
Magnetic energy conversion

Self-consistent resistive time for Ar injection (upper t_{CQ} limit)

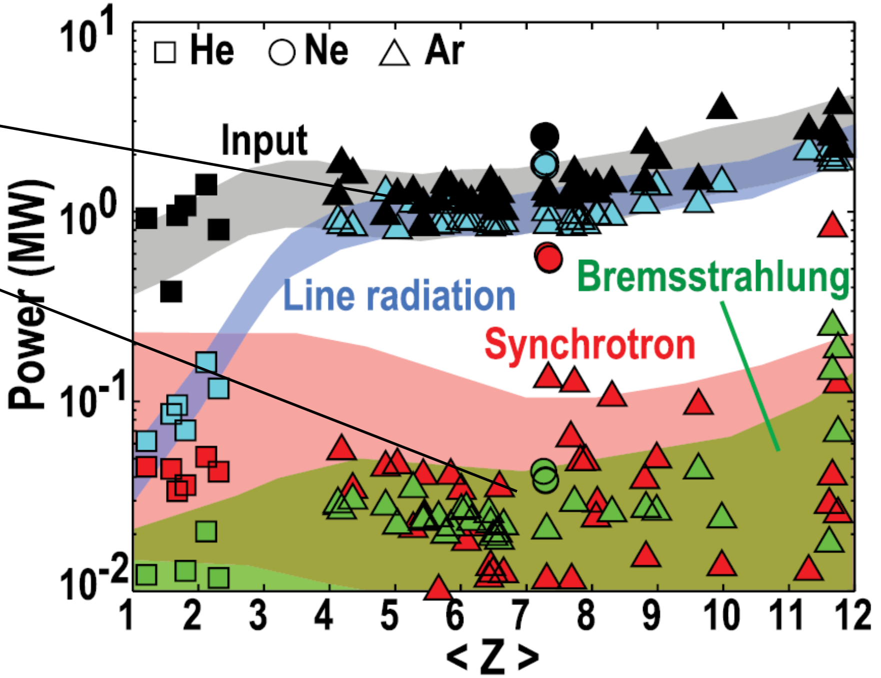
Single loss event at 100 ms (vertical displacement time)

- What happens if equilibrium evolution is taken into account? $t_v < \Delta t_{conversion}$
- Repetitive fast events can cause high conversion rate – RE beam stability?
- What are the characteristics of the instability? Timescale, deposition…

Mitigation by runaway energy dissipation



DIII-D RE plateau data

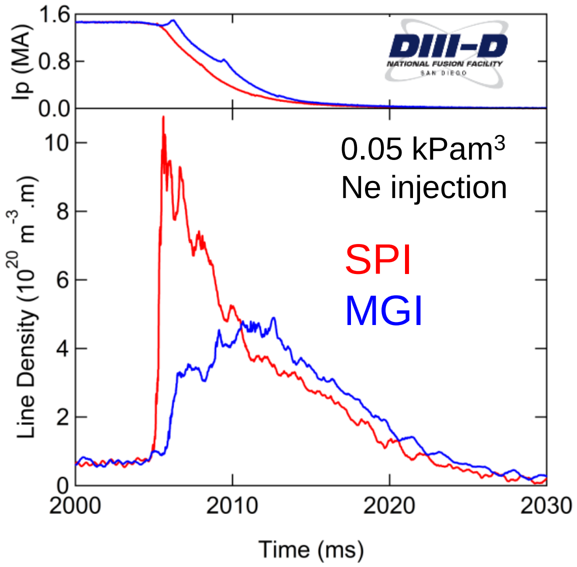


E. Hollmann, P. Parks et al., PoP 2015

Energy dissipation dominated by e-e collisions

SPI: open questions

How efficient is **Shattered Pellet Injection** in ITER? How do mitigation scenarios have to be designed?



Initial results from DIII-D are promising, but many open questions:

- Thermal load mitigation efficiency, radiation asymmetries?
- Efficiency of multiple injection, staggered injection?
- RE energy dissipation?
- How to scale SPI parameters (e.g. shard sizes, speed) to ITER?
- Impact of plasma parameters on efficiency (e.g. penetration depth)?
- What is the impact of the ITER specific injection geometry?
- Quantitative comparison to MGI needed