Physics basis for ITER disruption mitigation – gaps and present R&D

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ITER Organization

Many thanks to

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Outline

Review of the mitigation/suppression strategy for the three types of loads:

- ❑ *Thermal Loads (Thermal and Current Quench)*
- ❑ *Electro-Magnetic Loads*
- ❑ *Runaway Electrons*

Presentation based on the "Report on progress on the development of ITER disruption mitigation scenarios" for STAC-20 (May 2016)

Present R&D in direct collaboration with IO or through ITPA, not an exhaustive overview of all research activities in the field

Mitigation of Thermal Loads

- **Required quantities for the thermal quench**
  Difficult to identify in experiments, uncertainties in the scaling parameter

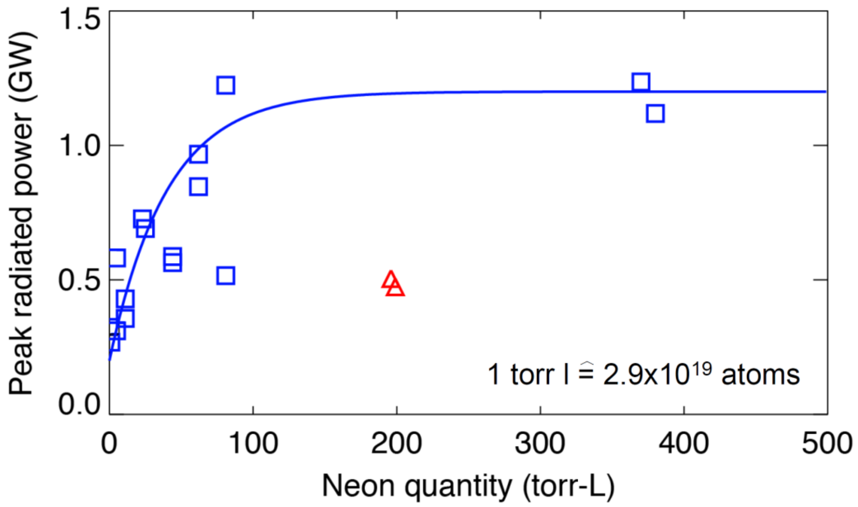
- **Heat fluxes during the current quench**
  Mechanism understood, mitigation confirmed

- **First wall heat fluxes from the radiation flash**
  Understanding well advanced, surface melting at high energies, but no impact on operation

Required quantities for the thermal quench

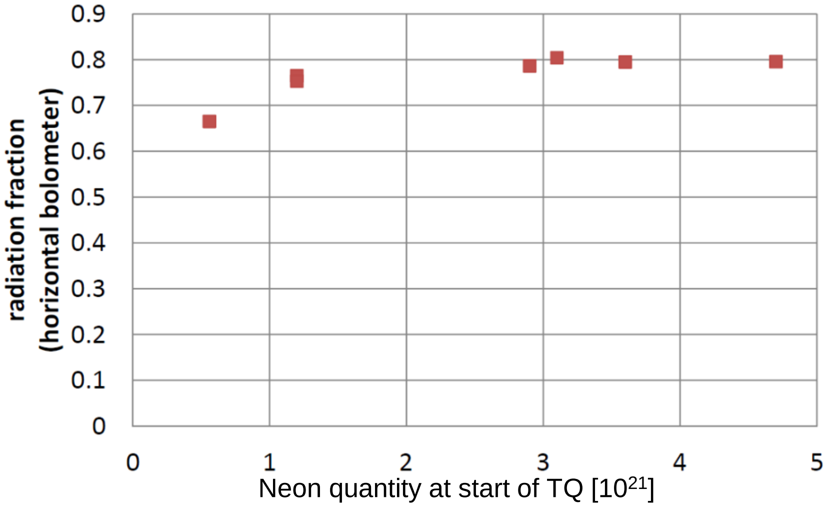
- ❑ Confirmation of radiation fraction in experiments is difficult (asymmetries)
- ❑ Saturation observed for MGI and SPI indicating critical Ne quantities ~10^{21}
- ❑ Scaling parameter not identified yet: **medium size ➡ ITER: x 15 to 300**
  - *lower value consistent with ASTRA simulations (Leonov, EPS 2011)*
  - *upper value achievable with SPI, MGI marginal*

DIII-D Ne SPI



Courtesy of L. Baylor and DIII-D team

JET Ne MGI

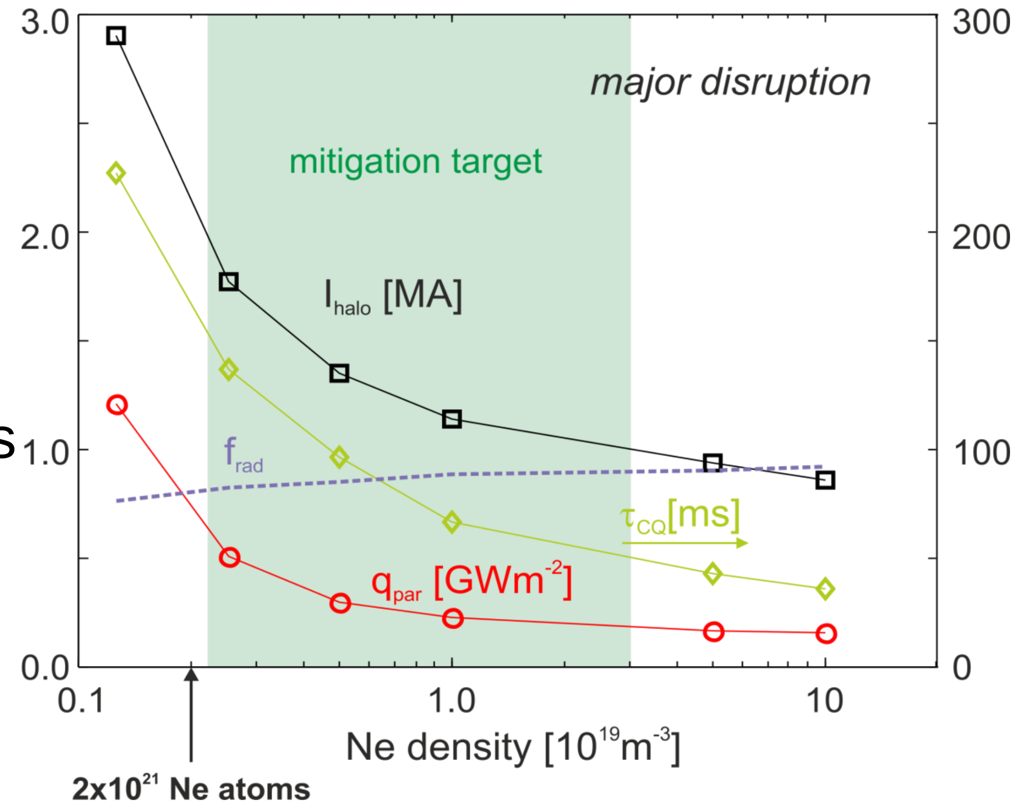


S. Jachmich et al., PSI & EPS 2016

Heat fluxes during the current quench

- Radiation-less current quenches cause high heat fluxes from parallel energy losses in the halo
- Halo current mitigation requires acceleration of the current quench
- An issue for both VDEs <u>and</u> MDs
- DINA has been recently updated to include this loss mechanism
- Mitigation requires > 2 x 10^{21} Ne atoms (100% assimilation), well within the DMS capabilities

DINA simulation

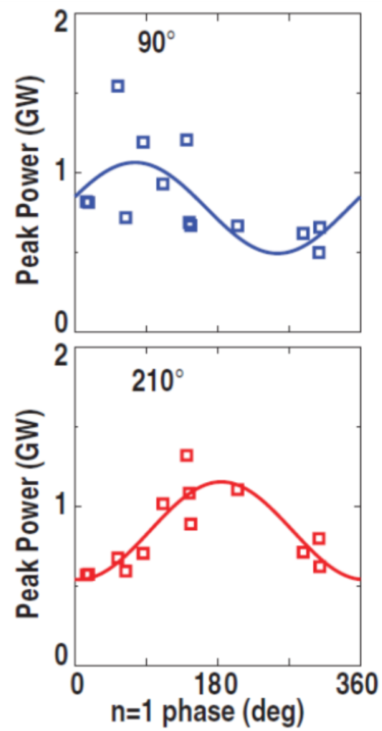


D. Kiramov, M. Lehnen et al., EPS 2016

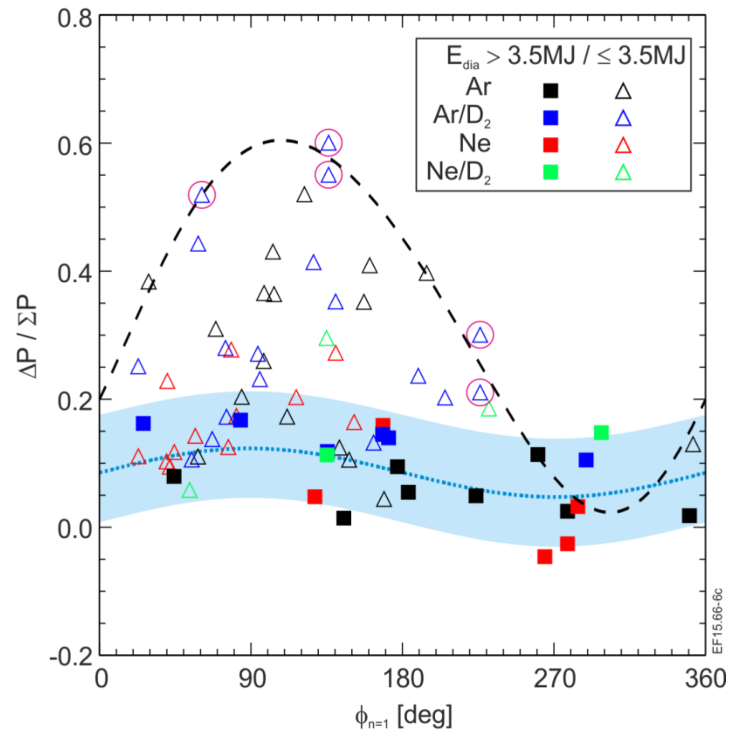
First wall heat fluxes from the radiation flash

- The understanding of asymmetries improved significantly due to efforts in 3D MHD modelling and increased experimental efforts (since last ITPA report)
- Asymmetry driven by impurity distribution and n=1 mode
- TPF < 2 in most experiments, more uncertainty on poloidal distribution, but PPF < 2 likely
- Melt threshold is reached at $E_{th} \approx 70$ MJ (SS) and 150 MJ (Be)
- Experimental tests performed at 22.4 $MJm^{-2}s^{-0.5}$ show increase in surface roughness (~1μm/event)

DIII-D



JET



D. Shiraki et al., Nucl. Fus. 2015 *M. Lehnen et al., Nucl. Fus. 2015*

Mitigation of electro-magnetic loads

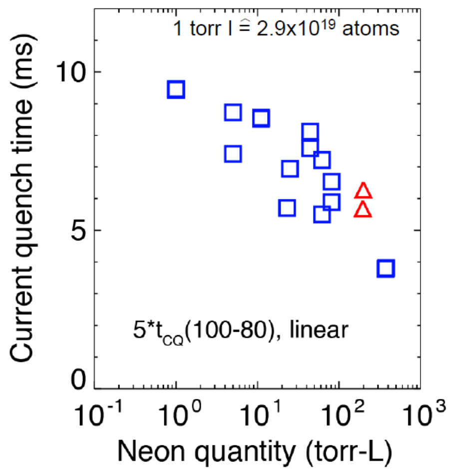
- **Mitigation of halo currents**
  Widely demonstrated in experiment, required quantities for ITER no issue

- **Compatibility of thermal load mitigation with eddy current limits**
  Confirmation pending, scaling parameter to be identified for required TLM quantities

Required quantities for the thermal quench

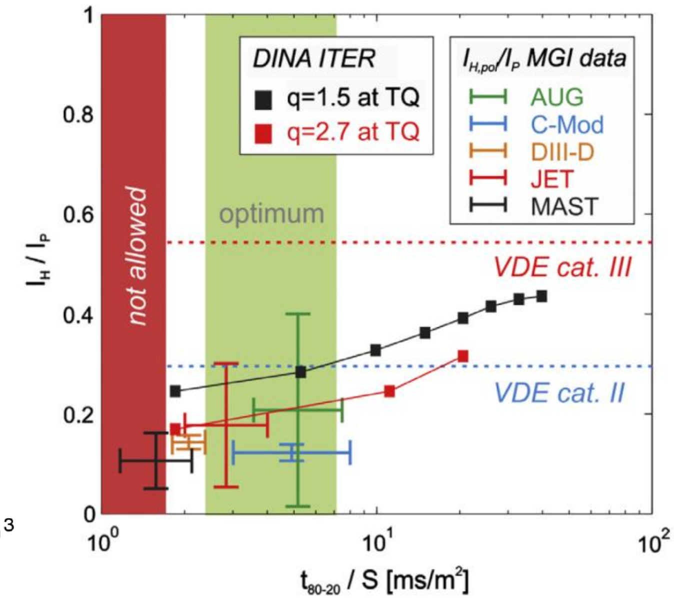
- Halo current mitigation works through increasing the CQ rate
- Confirmation from MGI and SPI experiments
- Target CQ time at 15 MA is 50 ms to 150 ms
- Quantities required are well within the injection capabilities
- Not only are the symmetric forces reduced, but also asymmetries are negligible for mitigated disruptions

DIII-D Ne SPI



Courtesy of L. Baylor and DIII-D team

MGI and DINA data

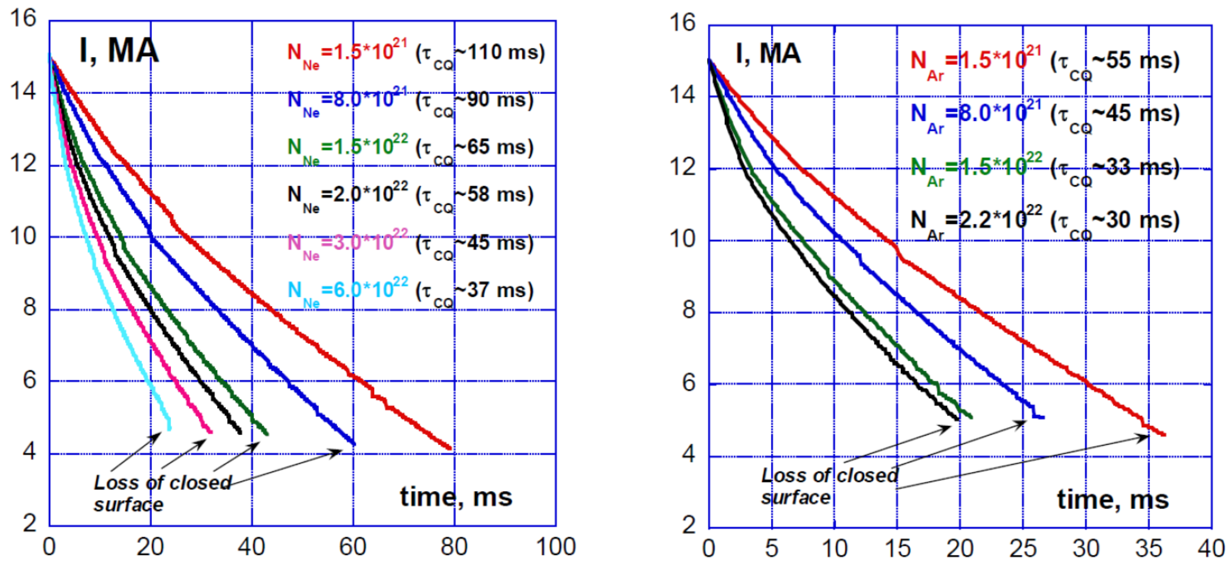


M. Lehnen et al., J. Nucl. Mater. 2015

Compatibility of TLM with eddy current limits

- ITER Load Specifications: 13% disruptions with 36 ms and 87% with 50 ms
- DINA simulations: $N_{Ne} < 3x10^{22}$ and $N_{Ar} < 8x10^{21}$, experimental validation within a factor of 2, more analysis needed taking into account vessel times and fuelling efficiencies
- Lower scaling factor for thermal load mitigation compatible with eddy current limits

DINA simulations



S. Konovalov et al., IAEA FEC 2014

Runaway electron suppression and mitigation

The ITER strategy for the prevention of runaway electron events has two layers of defense:

- ❑ **Avoidance**

  Present experiments can avoid RE formation during halo current mitigation, but much lower avalanche multiplication, size effects in MHD cannot be excluded, initial modelling for ITER to be extended to 3D MHD

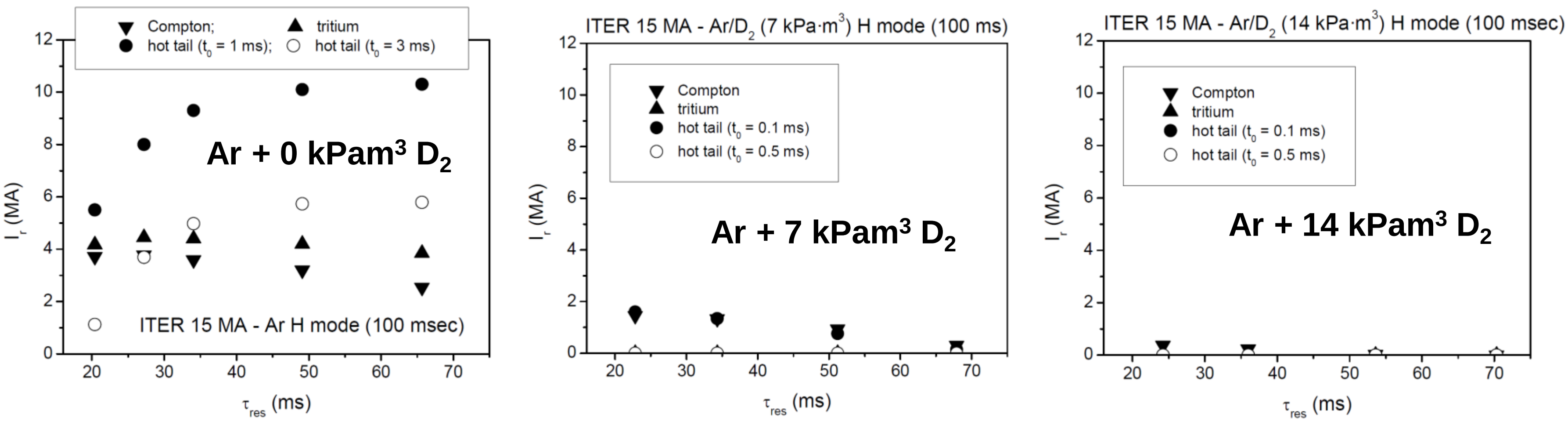
- ❑ **Mitigation**

  Experiments not conclusive, SPI to be tested at JET

Avoidance – gas mixture for mitigation

- JET data shows absence of RE generation for up to 3.5 MA with sufficient admixture of D_2 for thermal load mitigation
- 1D simulations with self-consistent power balance / impurity densities: reduction of RE current with sufficient D_2 admixture
- The ITER research plan foresees an assessment of the appropriate ratio
- Strong uncertainties: strong avalanche at 15 MA, no simulation available yet combining TQ MHD with RE formation: *gas mixing and RE loss?*

1D simulations on runaway seed suppression (IO contract with U3CM)



J.R. Martín-Solís 2016 (to be published)

Avoidance – impact of TQ MHD

Long-lasting open question:
Can seed electrons survive the thermal quench?

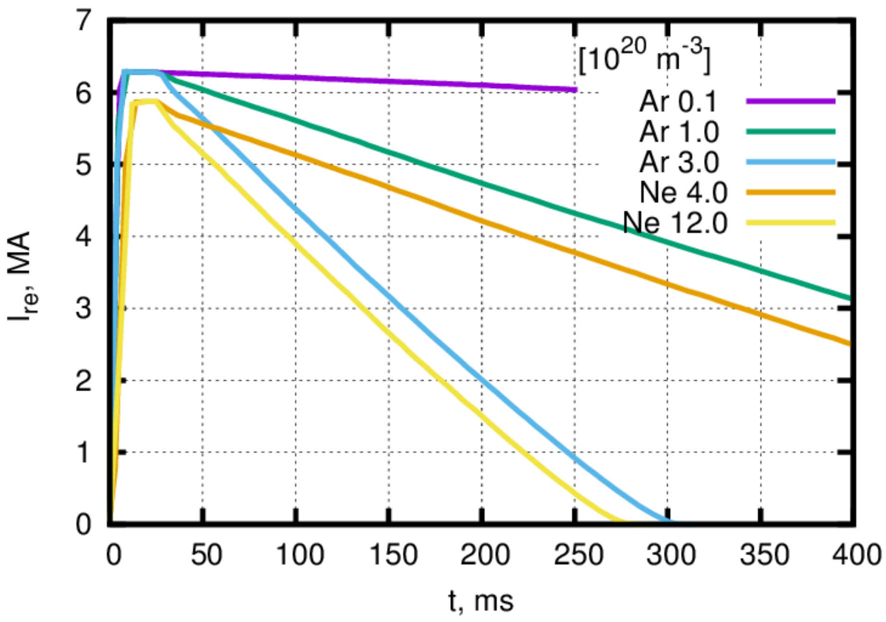
- ❑ Timescale of RE loss in stochastic fields versus timescale of re-healing of flux surfaces?
- ❑ Stochasticity complete enough (islands)?

Not accessible through TSD website: controlled under the Export Administration Regulations (EAR) of the U.S.

Mitigation – RE energy dissipation

- Mitigation is based on energy dissipation through high-Z injection
- Late injection during the CQ is required to avoid eddy current limits
- Improved physics understanding*, but feasibility for ITER not yet confirmed.

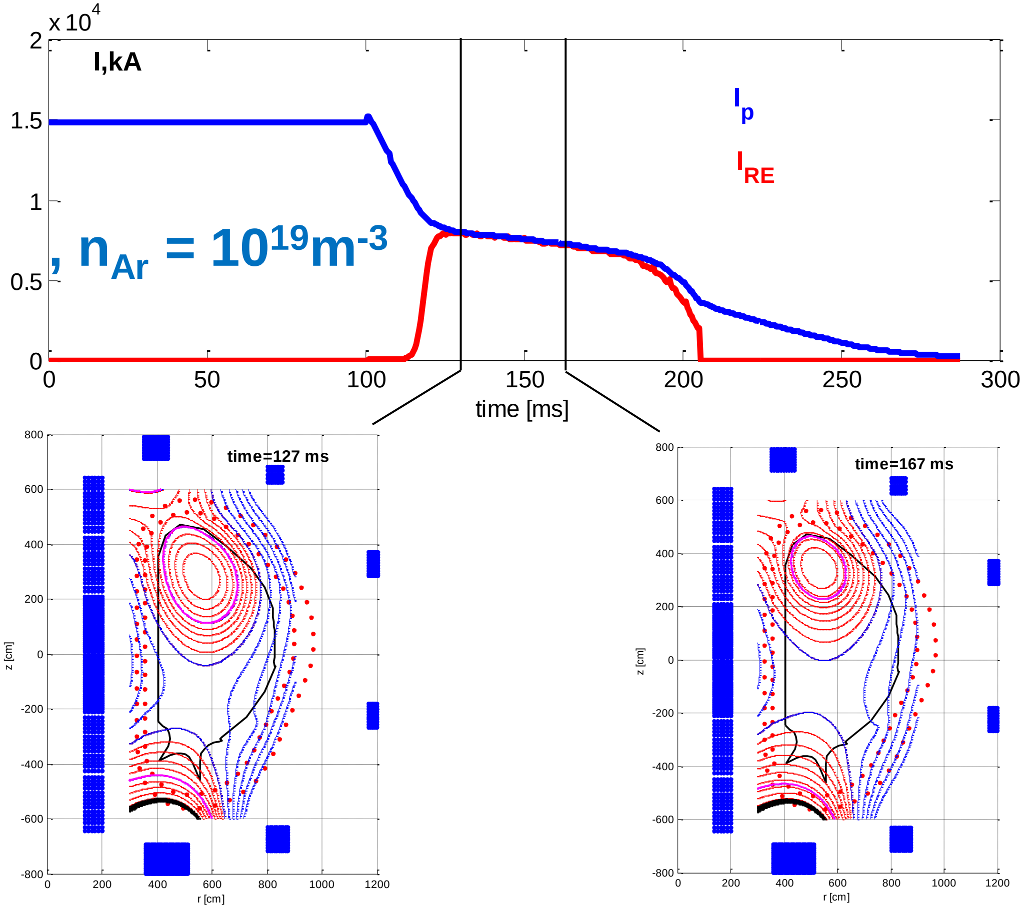
Kinetic simulations



*Aleynikov et al., Proceedings IAEA FEC 2014, TH/P3-38; Aleynikov and Breizman, Phys. Rev. Lett. **114** (2015) 155001; J.R. Martín-Solís et al., Phys. Plasmas **22** (2015) 092512.

Mitigation – Impact of equilibrium evolution

The equilibrium evolution (vertical movement) after the TQ determines the timescale available for mitigation and, thus, the impurity quantities required.



DINA simulation: upward VDE with RE formation
(IO contract 2015-2016)

Ar present from 100ms,
j_{re_seed}=80kA / S

- *Not a 'near threshold situation' $E >> E_c$ during plateau phase (also for higher n_{Ar}!)*
- *Strong magnetic energy conversion*
- *Energy deposition through RE 'scrape-off'*

S. Konovalov et al., report to IO 2016

Mitigation – Fuelling efficiency

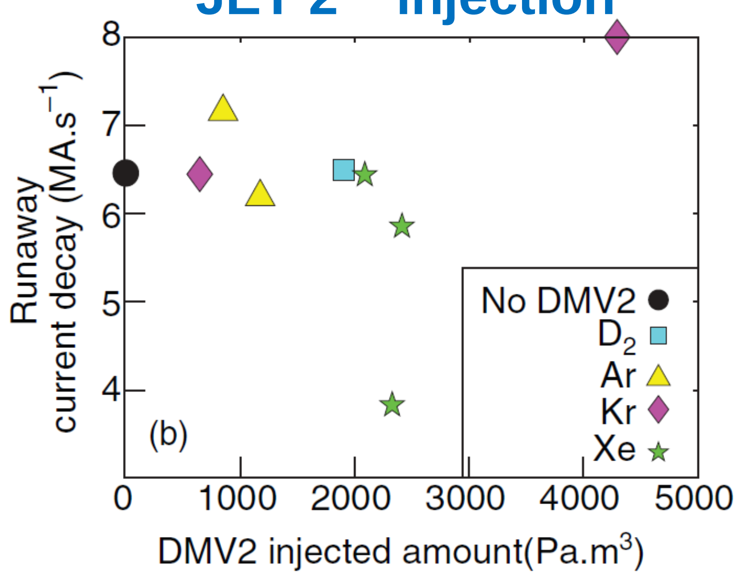
Penetration of impurities is likely to depend on

- Injection parameters (especially injection geometry)
- CQ / RE plasma parameters

Low assimilation reported from experiments

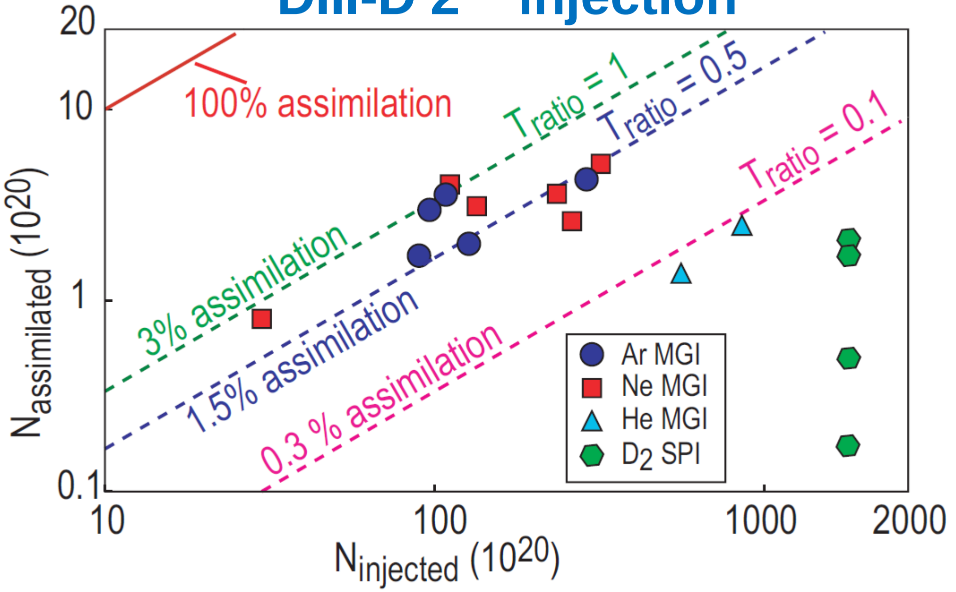
- JET: f_{assim} = 0 (from current decay and n_e)
- DIII-D: f_{assim} = 1 % range (from pressure balance)

JET 2nd injection



C. Reux et al., Nucl. Fusion 2015

DIII-D 2nd injection



E.M. Hollmann et al., Nucl. Fusion 2013

Open issues

- Confirmation of the runaway mitigation and avoidance scheme
- More data from modelling and experiments are required to conclude on the SPI design
  pellet speed and shard size, injection direction, staggered injection (impact of time delay on assimilation)
- Confirmation of quantities for thermal load mitigation
  compatibility with the CQ rate limits
- Scale prediction and detection success rates and warning times to ITER

Open issues – dedicated experimental activities

- Tests of SPI at JET in preparation (collaboration IO-CT, USIPO, ORNL, US DoE, EUROfusion, and CCFE)

- Upgrade of the DIII-D SPI capabilities: 2 injectors, pure Ar injection, rotatable injection tube

- New ITPA activities in the MHD group:

  - Working group to establish database and quantify dI/dt as function of injected species and quantity

  - Joint experiment with focus on RE characterisation, seed generation and mitigation during disruptions

- ITPA activity on disruption prediction for multiple-threshold approach

- Post-doc and PhD student in collaboration with IO to address prediction, detection and timescales

Open issues – dedicated modelling activities

- **3D MHD simulations for SPI with NIMROD (IO contract)**
  - Qualitative and quantitative assessment of *thermal load mitigation*, *radiation distribution*, *seed runaway electrons*
- **3D fluid modelling for SPI with TOKES (through F4E contract with KIT)**
  - Qualitative and quantitative assessment of *thermal load mitigation* and *radiation flash heating* of the first wall
- **RE model development (IO contract with IPP)**
  - Extend the original avalanche theory for better quantification of the runaway energy dissipation process, Provide RE code to be implemented in DINA, Assess the RE formation during the TQ phase
- **DINA simulations with improved RE model (IO contract with PSC)**
  - Study runaway formation and energy dissipation phase including equilibrium evolution, Quantification of the total deposited energy, Quantification of the post-formation mitigation efficiency

ITER Science Fellows' Network

- Extended network of scientific expertise in which members work closely with each other, with the ITPA and with the ITER Organization to address key R&D issues for ITER, supporting, in particular, the preparations for ITER operation.

- Four priority areas one of which is *Disruption/Runaway Electron mitigation theory and simulation* with presently **5 fellows** being nominated, including these topics:

  - *3D MHD simulations of mitigated und unmitigated ITER disruptions;*
  - *Theory of runaway electron generation, stability, mitigation and suppression scheme;*
  - *Simulations in support of building a disruption predictor/detector;*
  - *Simulations of impurity penetration and radiation for thermal quench mitigation and runaway mitigation/suppression;*
  - *Studies of the impact of TQ MHD and instabilities on the runaway evolution;*

- Kick-off workshop with the ITER Science Fellows beginning of September

Conclusions

- The present physics basis confirms the ability of the ITER DMS design to mitigate electro-magnetic loads and to avoid excessive heat loads; the efficiency of the latter is subject to a) the extent of radiation flash melting, b) the limits on current quench rates;
- It remains to be shown that the present mitigation scheme through high-Z injection can avoid runaway formation and that a mitigation scheme is at hand as a second layer of defense;
- Although confidence is gained from JET experiments and from initial modelling that a mitigation scheme can be found that avoids runaway formation, further extensive R&D is required to extrapolate reliably to ITER.