Summary for Mitigation General

Nick Eidities, Sergey Konovalov, Long Zeng

- **RE modelling**
- **Electromagnetic mitigation of RE**
- **Alternative impurity injection methods**

Outline

- **RE modelling**
  - 105 Energy dependency of runaway-electron transport in perturbed fields *Konsta Särkimäki*
  - 123 Formation and termination of runaway beams during vertical displacement events in ITER disruptions *Jose Ramon Martin-Solis*
  - 129 Modeling and simulation of runaway electrons: spatiotemporal effects in dynamic scenarios *Diego Del Castillo Negrete*
  - 150 Runaway electron energy control via wave-particle interaction *Xianzhu Tang*
- **Electromagnetic mitigation of RE**
- **Alternative impurity injection methods**

Energy dependence of RE transport in stochastic fields
Konsta Särkimäki

➲ to study the transport in perturbed magnetic fields using an orbit-following Monte Carlo method to calculate the energy-dependent transport coefficients

- Transport was studied with orbit following simulations.
- Existing theory says transport scales as 1/E at high energy due to finite orbit width (FOW) effects.
- Tokamak field with ideal (artificial) perturbations was used to verify this result.
- Transport was also studied during JET thermal quench where the 1/E dependence was not observed.
- **FOW effects were dominated by other effects arising from the non-uniform structure of the perturbation.**
- Future work is to couple the numerically evaluated transport coefficients to a reduced kinetic model.

➲ **A simple 0-D model which mimics the plasma surrounded by the conducting structures [*D.I. Kiramov, B.N. Breizman, Phys. Plasmas 24, 100702 (2017)*], including the vertical plasma motion and the generation of runaways, has been used for an evaluation of the runaway current dynamics during the disruption**

Formation of the runaway beam

- In ITER, with a highly conducting wall, the total **plasma current** when the plasma touches the wall is always **the same**, but the runaway current at that time can significantly **decrease for large enough amount of impurities**.
- The plasma velocity is larger and the time to hit the wall shorter for lower runaway currents, when larger amounts of impurities are injected.

Scraping-off and termination of the current

- When the plasma touches the wall, the scrapping-off phase starts. During this phase, **the plasma velocity and electric field** can substantially increase leading to **the deposition of a noticeable amount of energy on the runaway electrons** (more than 100 MJs)
- An earlier second impurity injection can reduce somewhat the amount of energy deposited on the runaways
- Also larger temperatures during the scraping-off might be efficient in reducing the power fluxes due to the runaways onto the PFCs
- The plasma reaches the q = 2 limit before the current is terminated and the amount of energy deposited on the runaways until that time can be substantially lower than that initially expected for the scraping-off phase until the current goes to zero.

Modeling and simulation of runaway electrons: spatiotemporal effects in dynamic scenarios *Diego del-Castillo-Negrete*

➲ Comparative full orbit (FO) and guiding center (GC) study of RE orbits in toroidal geometry

- In the **absence of magnetic perturbations**, FO and GC predict similar prompt losses (due to energy dependent rapid orbit shift)

- In the presence of a **single magnetic island** of width ~ Larmor radius, GC orbits exhibit trapping in island-like structures but not FO that shows dispersion

- In **stochastic** magnetic fields:
  - As the energy increases, RE confinement improves for both FO and GC
  - GC overestimates losses compared to FO (x2 for 1MeV and x4 for 25 MeV)
  - FO exhibits confinement in fully stochastic regions.

Modeling and simulation of runaway electrons: spatiotemporal effects in dynamic scenarios *Diego del-Castillo-Negrete*

➲ Comparative modeling and simulation study of RE dissipation by impurity injection

- ❑ Magnetic field, electric field, and impurity density spatiotemporal models inferred from DIII-D experimental data
- ❑ Best agreement between KORC and experiment found for canonical pitch angle distribution, power law energy distribution, and bound-electrons partially ionized impurities collision model
- ❑ However, the **loss of spatial confinement** due to the magnetic field evolution is the **main mechanism for the reduction of the RE current**, with collisional dissipation playing a relatively minor role.
- ❑ RE beam **energy increases** due to electric field acceleration before loss of confinement

Runaway electron control via resonant wave-particle interaction *Xianzhu Tang*

➲ Resonant WPI with runaways can greatly enhance pitch angle scattering of relativistic runaway electrons, resulting in runaway depletion through magnetic trapping and/or deconfinement

- ***Passive mitigation*: Much experimental evidence exist for modified runaway electron properties due to self-excited wave instabilities**
  - ***Both self-excited whistler waves and Alfvenic waves are observed***
- ***Active mitigation*: direct control of CQ duration and/or runaway energy via external wave injection**
- ***Approach: targeting low-energy as opposed to tail runaways through normal Doppler-shifted cyclotron resonance → wave counter-propagates with respect to runaways***
- ***CQ duration control: enhanced pitch angle scattering → resulting in runaway depletion through magnetic trapping and/or deconfinement → effectively raise E above E_{AV} of the background plasma → shorten CQ duration***
- ***Runaway energy control: enhanced pitch angle scattering → momentum space surgery of runaway vortex → reduce runaway energy from γ ~ 20-30 to γ ~ 2-3.***
  - ***If runaways can not be avoided on ITER, limiting their energy to MeV range while shortening the CQ to acceptable duration is likely the best one can hope for in disruption mitigation***
- ***Collisional damping and hence wave accessibility in the CQ phase are a big challenge, but there are potential work-arounds.***
  - ***Only targets the outer flux surfaces (large trapped zone), D2 purge of high-Z impurity***

Runaway electron control via resonant wave-particle interaction *Xianzhu Tang*

- *Planned experiments on DIII-D and KSTAR will allow first tests*
  - *Initial focus is to demonstrate the physics in warm plasma regime*
  - *Follow-up experiments will address the wave power requirement issue in post-thermal quench plasmas.*
- ***The physics basis is sound and interesting. Design tools exist and we welcome collaboration opportunities to help field runaway WPI experiments on other tokamaks***

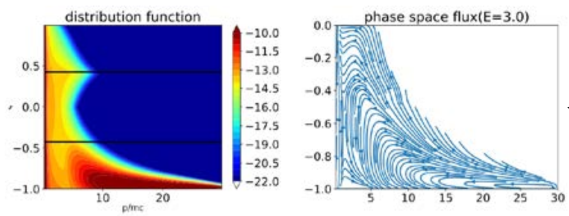


Figure 6.8: No wave injection, just toroidal effect. $\epsilon = 0.1, w_0 = 0, E = 3E_c, v_t = 0.1c, \alpha = 0.1$.

Without waves, broad high energy runaway tail

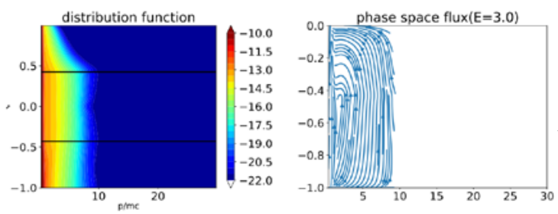


Figure 6.10: With wave injection, $\epsilon = 0.1, w_0 = 5e-11, k_{\parallel 0} = 0.2, k_{\perp 0} = 0.1, \Delta k_{\parallel} = 0.1, \epsilon = 0.1$.

Broad spectrum /resonance region, high enough amplitude to remove runaway vortex and hence suppress avalanche

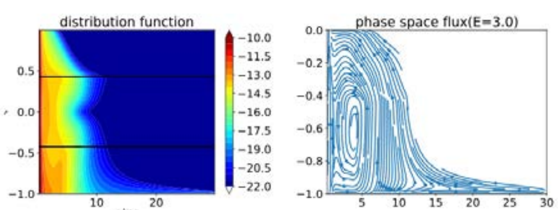


Figure 6.9: With wave injection. $\epsilon = 0.1, w_0 = 1e-11, k_{\parallel 0} = 0.2, k_{\perp 0} = 0.1, \Delta k_{\parallel} = 0.1$.

Broad spectrum /resonance region, not high enough amplitude to suppress avalanche, but adequate to drastically lowers the runaway energy

Narrow resonance layer can perform runaway vortex surgery at precisely targeted (low) runaway energy upper bound

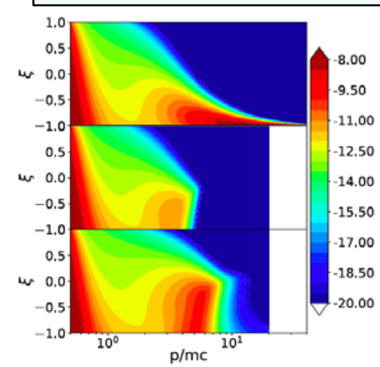
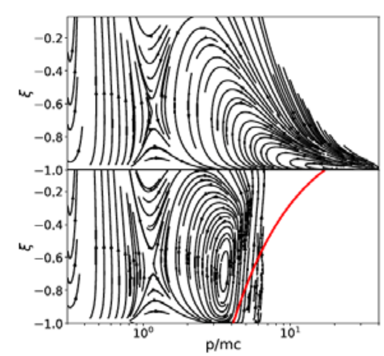


FIG. 3. The contour plots for steady-state distribution of primary runaway electrons with and without whistler waves. The figure shows the contour of $\log_{10} f(p, \xi)$ without waves (top) and with waves (middle with $\alpha = 0.2$ and bottom with $\alpha = 0.05$).



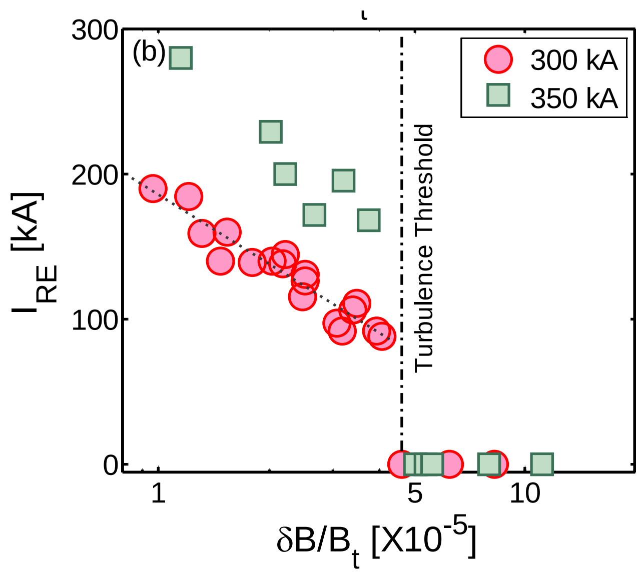
Guo, McDevitt, Tang, PoP (2018)

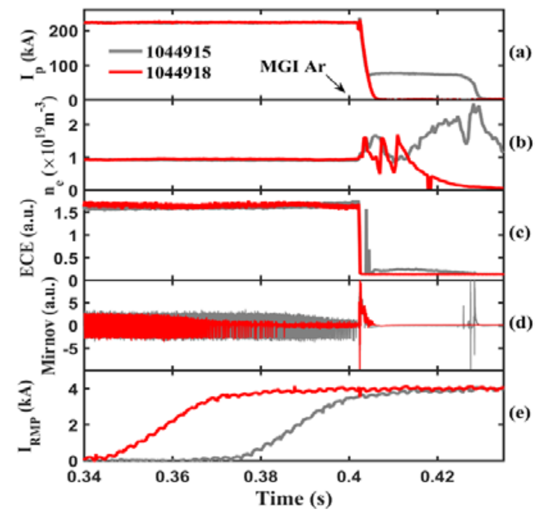
Outline

- RE modelling
- **Electromagnetic mitigation of RE**
  - 94 Full suppression of runaway electrons by magnetic perturbation during disruptions *Zhongyong Chen*
  - 106 DIII-D Exploration of the D2+Kink Path to Runaway Electron Mitigation in Tokamaks *Carlos Paz-Soldan*
  - 108 Prospects for runaway electron avoidance with massive material injection in tokamak disruptions *Tünde Fülöp*
- Alternative impurity injection methods

Full suppression of runaway electrons by magnetic perturbation during disruptions *Zhongyong Chen*

➲ Full suppression of RE by magnetic perturbation



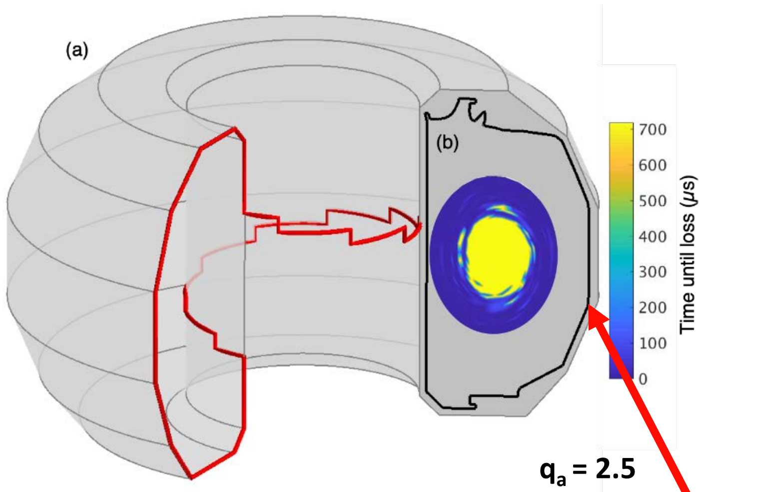


- ☐ Runaway suppression has been experimentally found when magnetic turbulence larger than a threshold.
- ☐ High magnetic turbulence is favor for the runaway suppression.

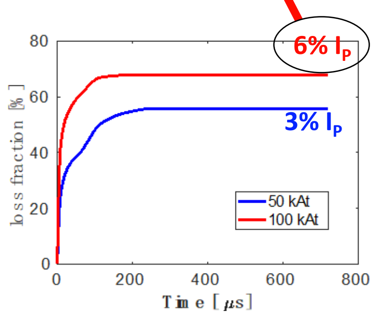
- ◆ The mode locking implemented large magnetic islands inside the plasma which led to stronger stochasticity in the whole plasma cross section which deconfine the runaway seed!
- ◆ Full runaway suppression has been achieved by mode locking/ mode penetration.

Full suppression of runaway electrons by magnetic perturbation during disruptions *Zhongyong Chen*

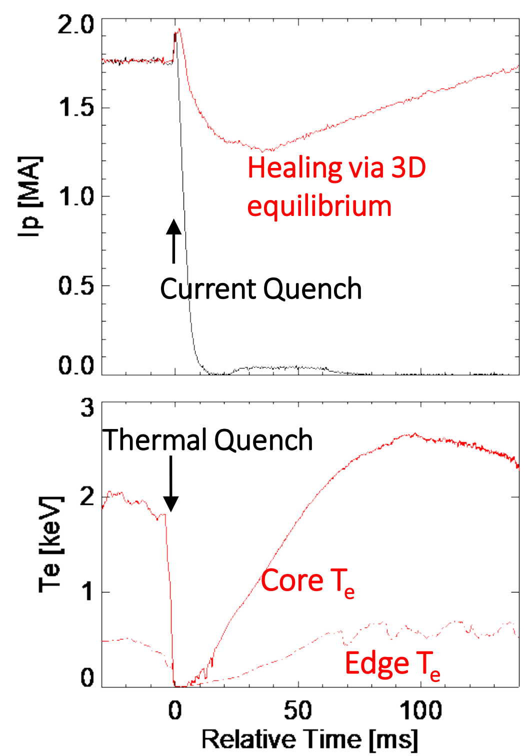
Runaway avoidance: by Passive Helical Coil



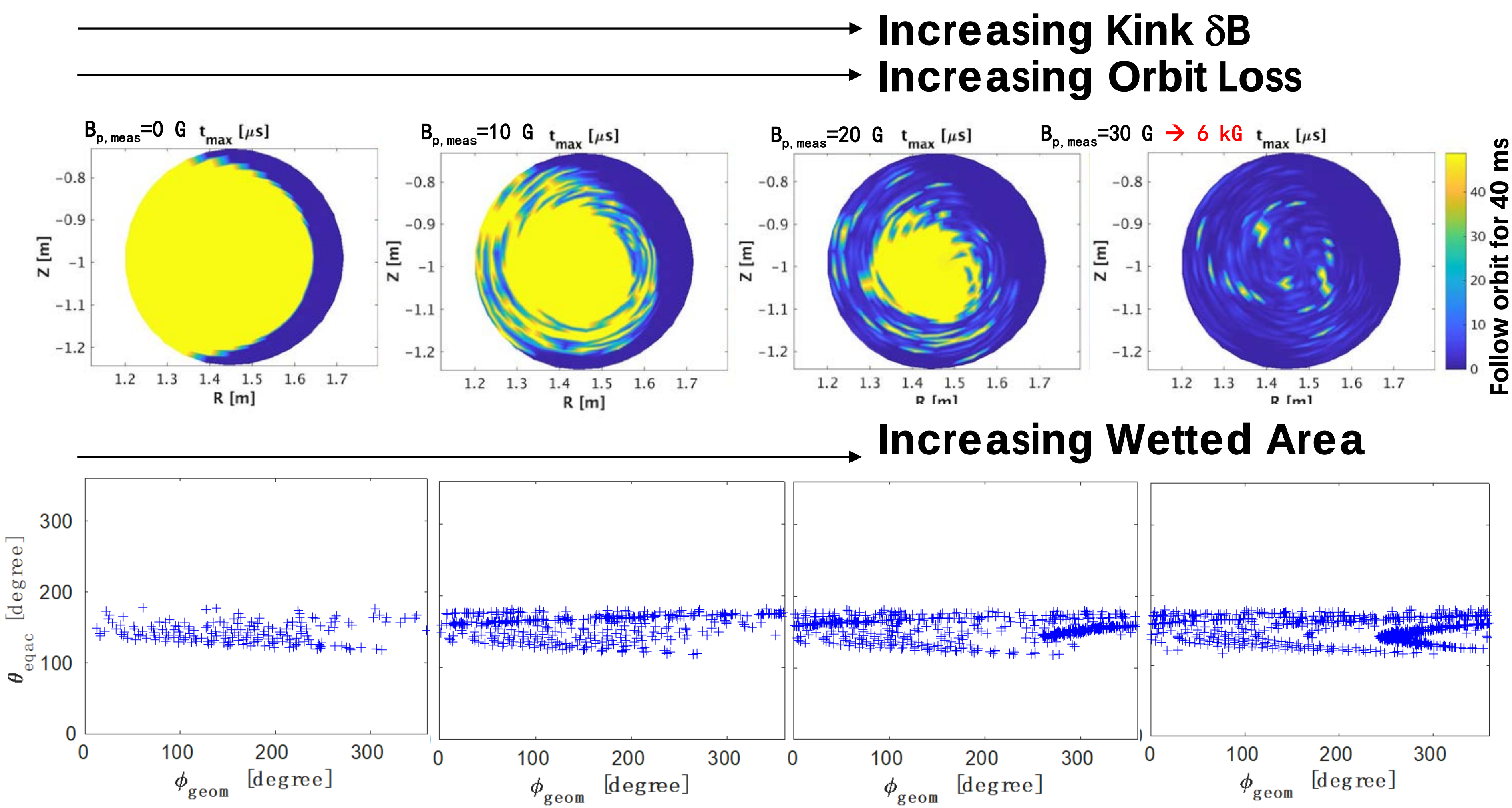
MHD modeling shows that a passive helical coil is effective at deconfining runaway electrons in DIII-D



Plasma Recovery from CQ can be acheived by Generating large Core Magnetic Islands.



MHD Modeling indicates most/all REs lost at critical δB
RE Wetted Area Increases with δ B – Less Heating !? *C. Paz-Soldan*

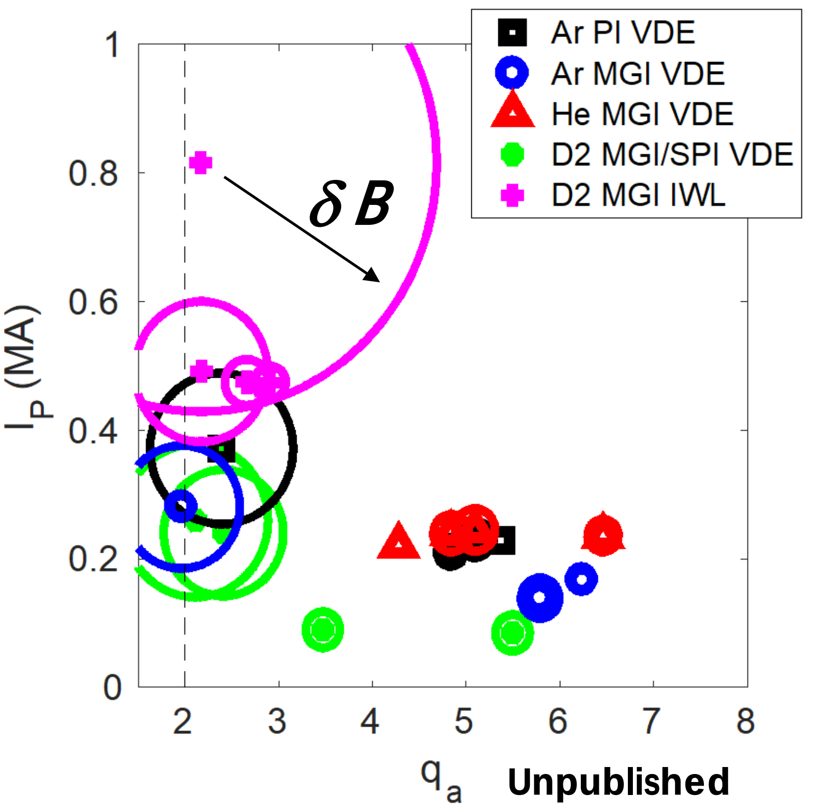


Courtesy Y.Q. Liu

DIII-D Database Reveals Largest δB at low q_a & high I_P
No Clear δ B Difference with Species if I_P/q_a matched *C. Paz-Soldan*

- Highest δB @ high I_P & low q_a
  - Only accessed with D_2 so far
- Roughly similar MHD (δB) so long as I_P & q_a matched
  - Systematic matches lacking
- Unique final loss dynamic requires high purity D_2 plasma
  - Reason why under investigation

Radius = size of MHD (δ B)

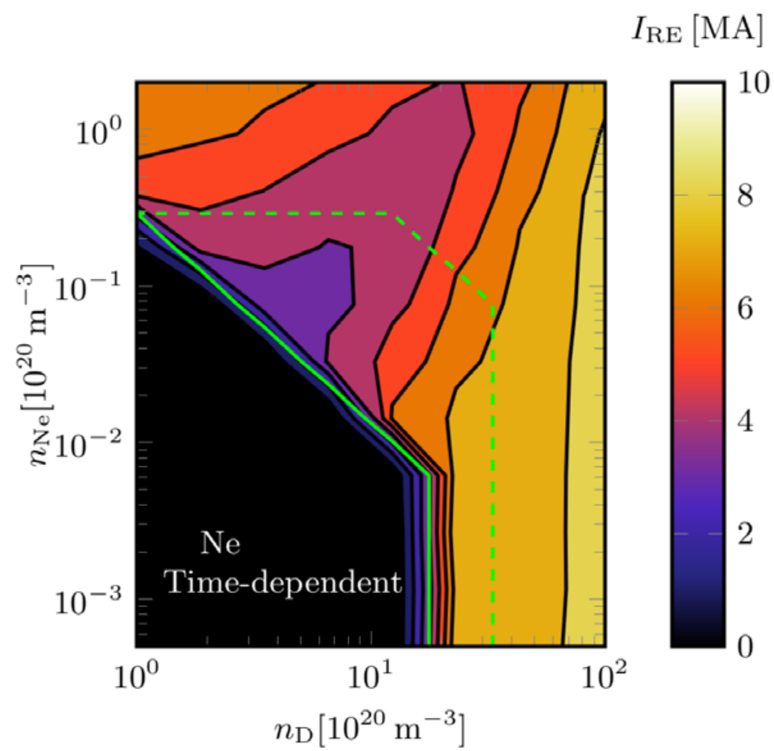


Unpublished

Prospects for runaway electron avoidance with massive material injection in tokamak disruptions *Tünde Fülöp*

➲ **To present results of simulations using a fluid model for RE dynamics in the presence of material injection, including Dreicer, tritium decay, and Compton seed runaway generation as well as avalanche process with an accurate model of partial screening effects, benchmarked to kinetic simulations.**

- In the presence of partially ionized impurities, avalanche gain is higher than previously expected.
- If losses due to magnetic perturbations are neglected, impurity injection leads to high runaway currents in ITER, even if it is combined with deuterium injection.
- Large amount of injected material → low temperatures → recombination → high n_e^{tot} / n_e → large avalanche growth rate.
- **Final runaway current is logarithmically weak function of seed.**



Outline

- RE modelling
- Electromagnetic mitigation of RE
- **Alternative impurity injection methods**
  - 115 Alternate disruption mitigation methods for fast time response and core impurity deposition *Roger Raman*
  - 104 MHD modeling of dispersive shell pellet injection for disruption mitigation in DIII-D *Valerie A. Izzo*
  - 95C-pellet simulations in NSTX-U with M3D-C1 *Cesar Clauser*
  - 96 Disruption mitigation in tokamak reactor via reducing the seed electrons of avalanche *Boris Kuteev*

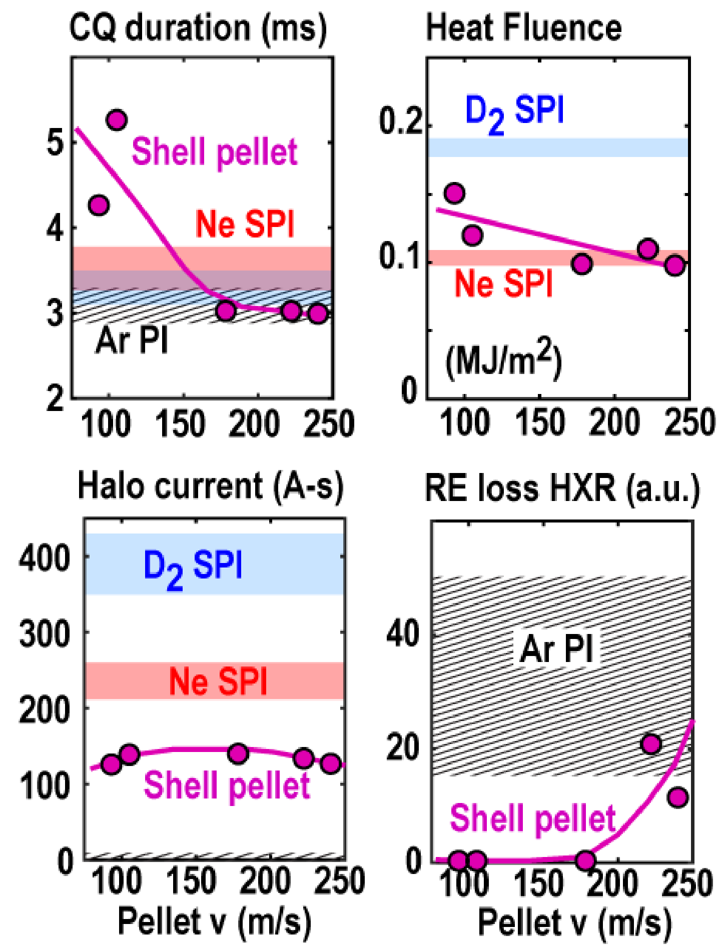
Alternate disruption mitigation methods for fast time response & core impurity deposition

R. Raman[1], E.M. Hollmann[2], L.R. Baylor[3],
R. Lunsford[4], V.A. Izzo[5], C. Clauser[4]

[1]University of Washington, Seattle, WA, USA
[2]University of California San Diego, La Jolla, CA, USA
[3]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[4]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[5]Fiat Lux, San Diego, CA, USA

Initial Studies of Shell Pellet Injection in DIII-D Shows Encouraging Potential for an Inside to Outside TQ

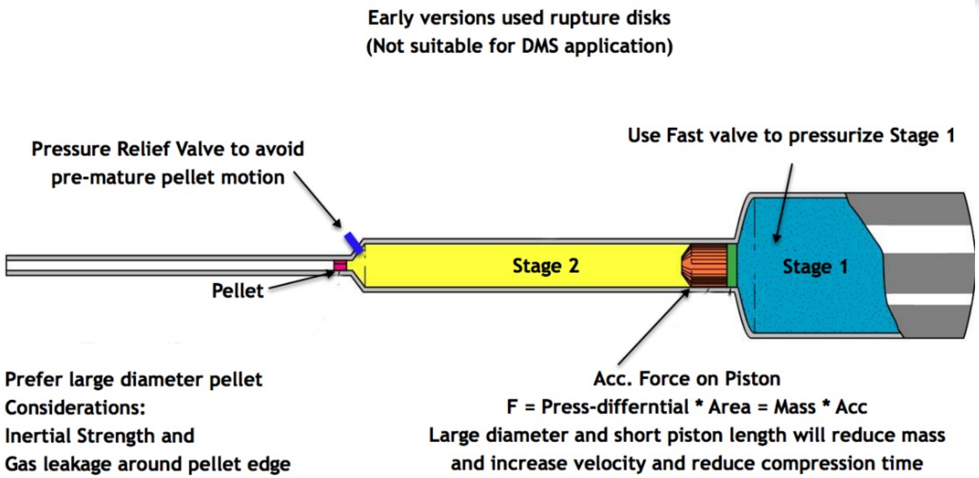
- Goal is to get impurities into the core without current channel contraction and then cause a radiative collapse of the core.
  - To induce an inside-out TQ with low wall heat loads without the high-Z impurity deposition normally required to achieve >90% radiated fraction
- For heat flux mitigation as good as Ne SPI, get slightly shorter CQ duration
- Halo currents lower than Ne SPI
- Do get some runaway seed formation for fast shell pellets
- Some preliminary evidence of hollow T_e profile during TQ
- Supporting NIMROD modeling largely consistent with experimental results

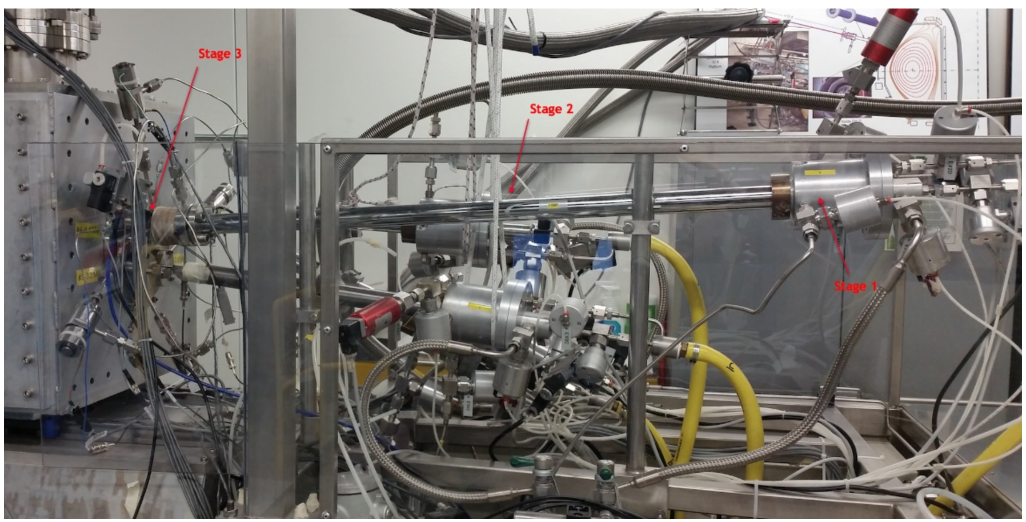


E.M. Hollmann, et al., Phys. Rev. Lett. **122,** 065001 (2019)
V.A. Izzo, Nuclear Fusion, **60** (2020) 066023

DIII-D NATIONAL FUSION FACILITY SAN DIEGO
UCSD

Existing EU-US collaboration on 2-Stage Gas Gun for Pellet Fueling has Accelerated 20 mg Pellet to 2.7 km/s





- For DMS applications, **present ~25ms to pressurize Stage 1 could be reduced to ~10 ms**
- Single stage SPI takes ~2-3ms to release the pellet
- The SPI pellet speed may be increased by more than a factor 2 (to ~750m/s), thus reducing the time of flight from ~23ms to ~9ms
- A more shallow shatter tube will be required for a 2-stage SPI
- Implementation of sabot will extend usage to propel Shell Pellet
- **Overall response time of accelerating ~5-10g pellets and reliability of multiple components need to be characterized**

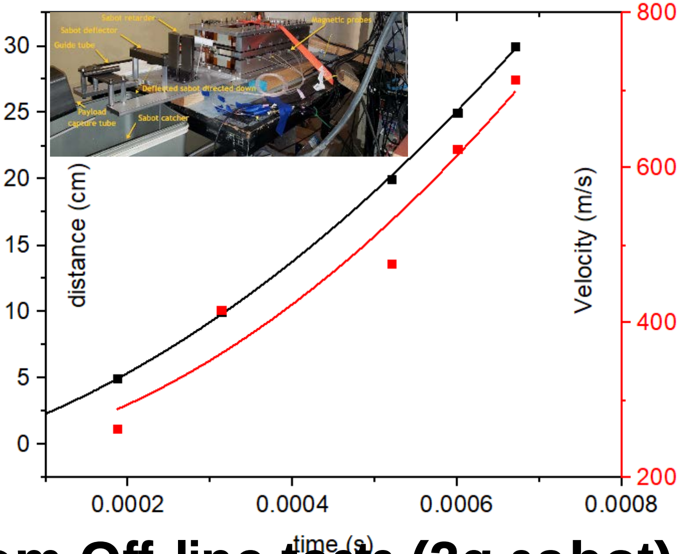
ENEA

OAK RIDGE National Laboratory

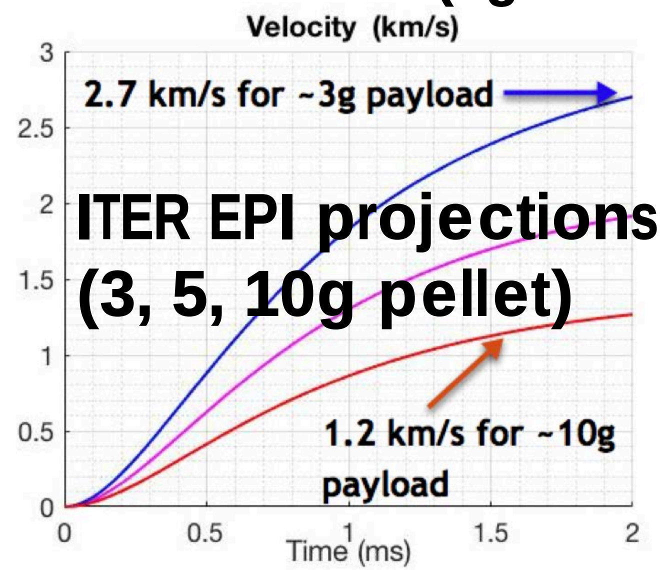
G. D'Elia et al. J. Vac. Sci. Technol. B **36**(1), JanFeb 2018, 01A103-1-9
S.K. Combs et al. Rev. Sci. Instrum. **67** (3), March 1996, 837-839

Present EPI Capable of reaching >0.5km/s in 1ms; ITER Class EPI Projected to have <10ms Overall Response Time

- Because EPI injects payload of known size and velocity, one can precisely calculate the needed parameters for penetrating to the center of any given plasma, including the ITER plasma
  - Can control shape, size, and velocity of payload
  - Peak force does not appear at t=0 (important for avoiding impact fracture of Shell Pellet)
  - Modeling and projection to ITER should be more reliable
- With 3T boost coil and at 1kV, sabot capture and payload separation demonstrated at >200m/s
  - Based on concept tested at LLNL at ~2km/s
- All materials in an ITER-EPI would consist of materials allowed in ITER
  - Tungsten rails, Be sabots, Vespel insulators & Tungsten, Inconel or SS for external assembly



from Off-line tests (2g sabot)



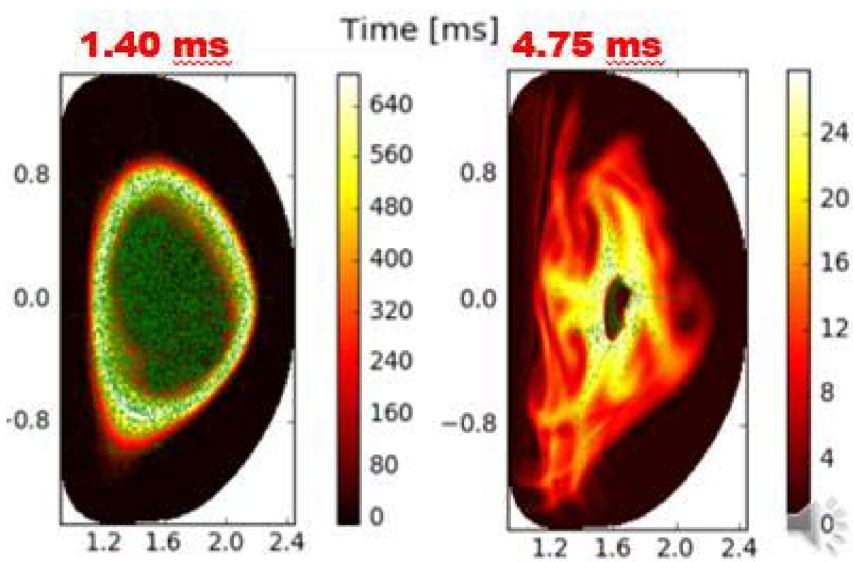
* R. Raman, et al., Nucl. Fusion **59** (2019) 016021

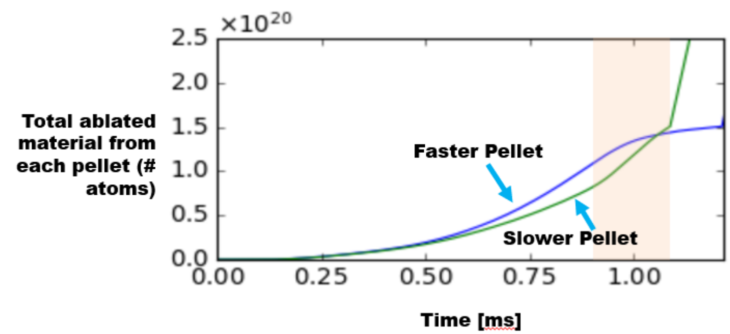
MHD modeling of dispersive shell pellet injection for disruption mitigation in DIII-D *V. Izzo*

1) Radiation of core thermal energy while maintaining edge confinement

2) Fast loss of REs at end of TQ due to large MHD

3) Initially promising results for multiple DSPs (both payloads delivered, surprisingly, the slower first)

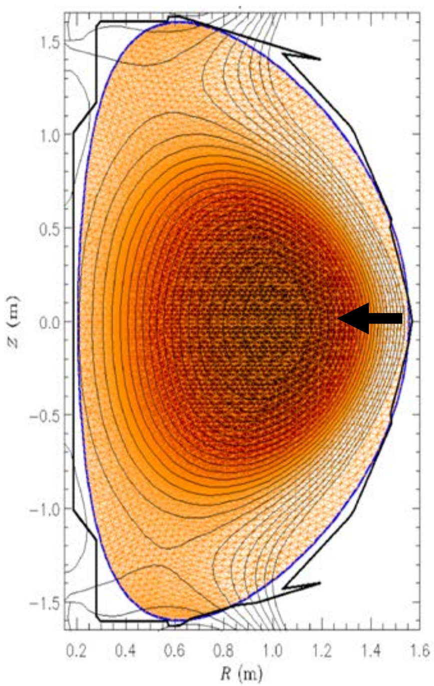




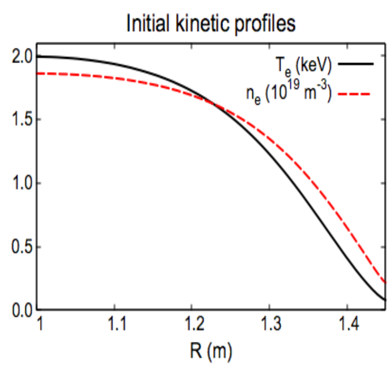
NSTX-U C-pellet Disruption Mitigation Simulations

Cesar Clauser

➲ To use M3D-C[1] to study single C-pellet injection in NSTX-U to support electromagnetic particle injector (EPI) proposal

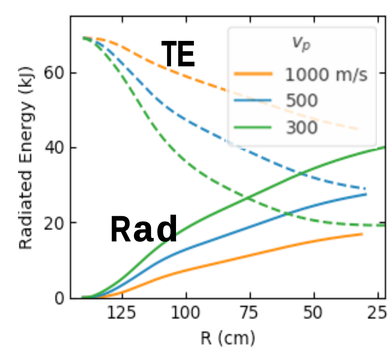


- Injected radially at the midplane
- Pellet Radius = 1 mm

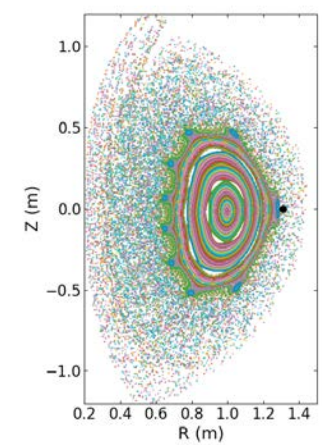


We scanned over different parameters to evaluate their role on the TQ

Figure below shows the plasma thermal energy (TE) and radiated energy (Rad) as a function of the pellet position, for three different velocities

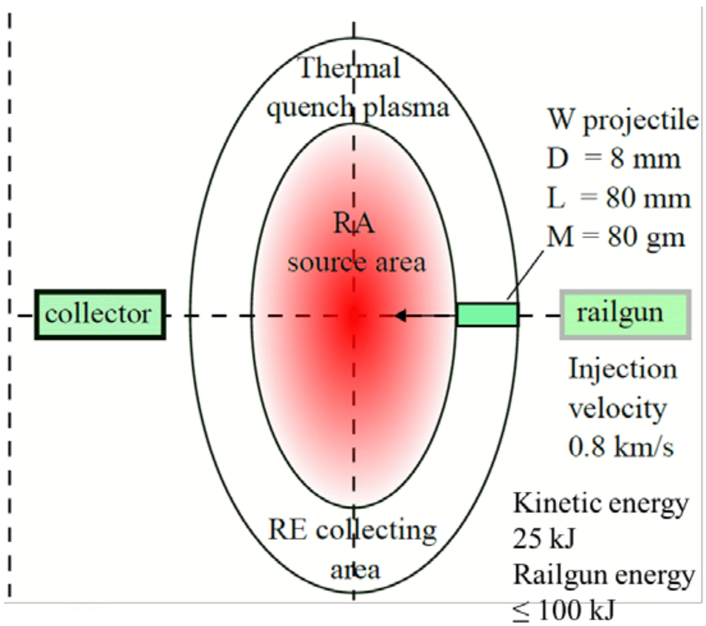


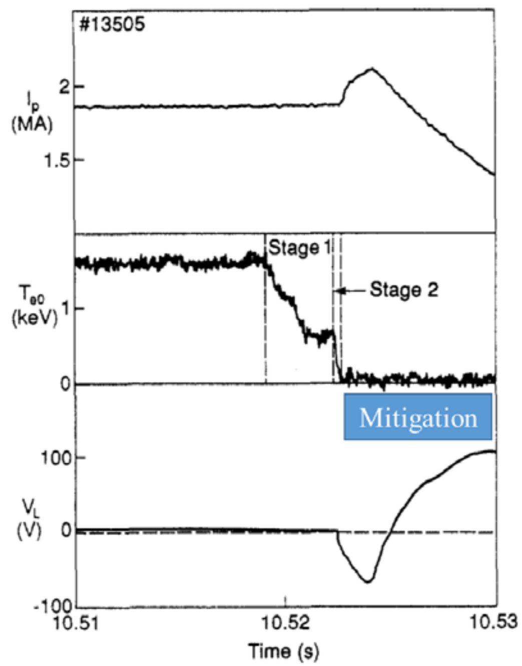
Increasing parallel heat flux can increase the ablation. However, very large parallel heat flux can reduce the ablation increasing the wall heat flux through field stochastization



Disruption mitigation in tokamak reactor via reducing the seed electrons of avalanche *Boris Kuteev*

- **A novel approach is proposed to disruption mitigation via reduction of the seed runaway electron population after TQ.**
  - Mitigation scenario is similar to the JET unintended disruption.
- **The tungsten projectile crosses the magnetic surface up to 4 times during the 5-15 ms travel time.**
- **The railgun provides the projectile acceleration.**

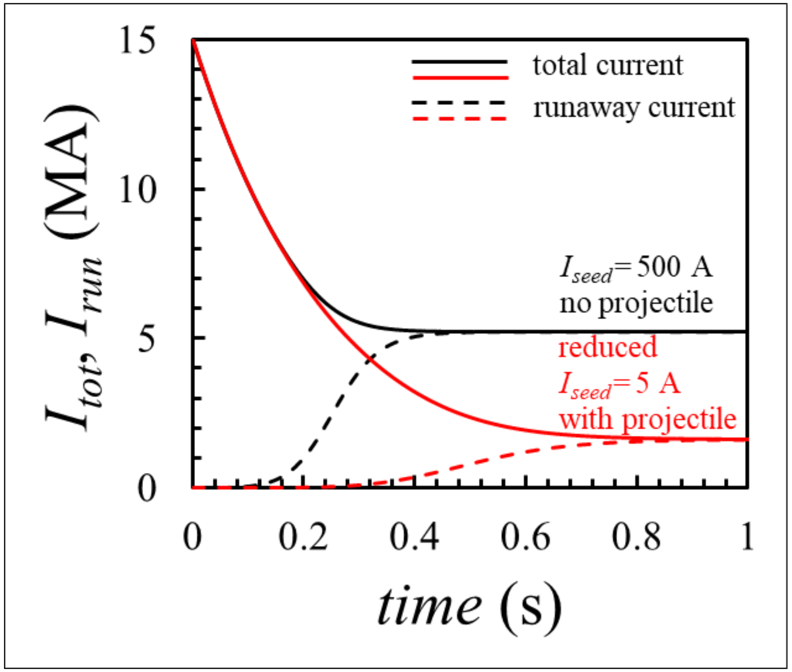




(D. Ward, NF 1992)

- Negative voltage spike is used as the trigger for the railgun shot
- Spatial and time scales for the projectile in ITER
  - Distance to plasma ~1 m
  - Acceleration time +1.25 ms
  - Time to plasma +1.25 ms
  - Time at plasma center +2.50 ms
  - Time at inner wall +2.50 ms
  - Total time 7.50 ms

Disruption mitigation in tokamak reactor via reducing the seed electrons of avalanche *Boris Kuteev*



- **For 100-fold reduction of the seed current in ITER, delay of RA development of ~90 ms is expected.**
- **Collecting the seed is capable to reduce the runaway current to a MA level.**

Advantages of the approach proposed

- Direct impact on RE seeds ⇒ Seeds reduction at the avalanche start
- No high pressure gases ⇒ Lower loading on tokamak systems
- Fast reaction time ⇒ Pure electro-technique
- FW-material ⇒ Small impact on FW and divertor
- Wide RE energy affected ⇒ 1-25 MeV effectively terminated
- Compactness of railgun ⇒ Dimensions are in decimeters range
- Neutron environment ⇒ Compatible
- High RAMI level of injection technology ⇒ Research railguns
- Multiple penetration ⇒ up to 4 crossings of magnetic surface

Problems

- Vacuum railgun ⇒ Fragments of rails and projectile
- Collecting technology ⇒ Energy of the projectile is in bullet range

Thanks!