This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

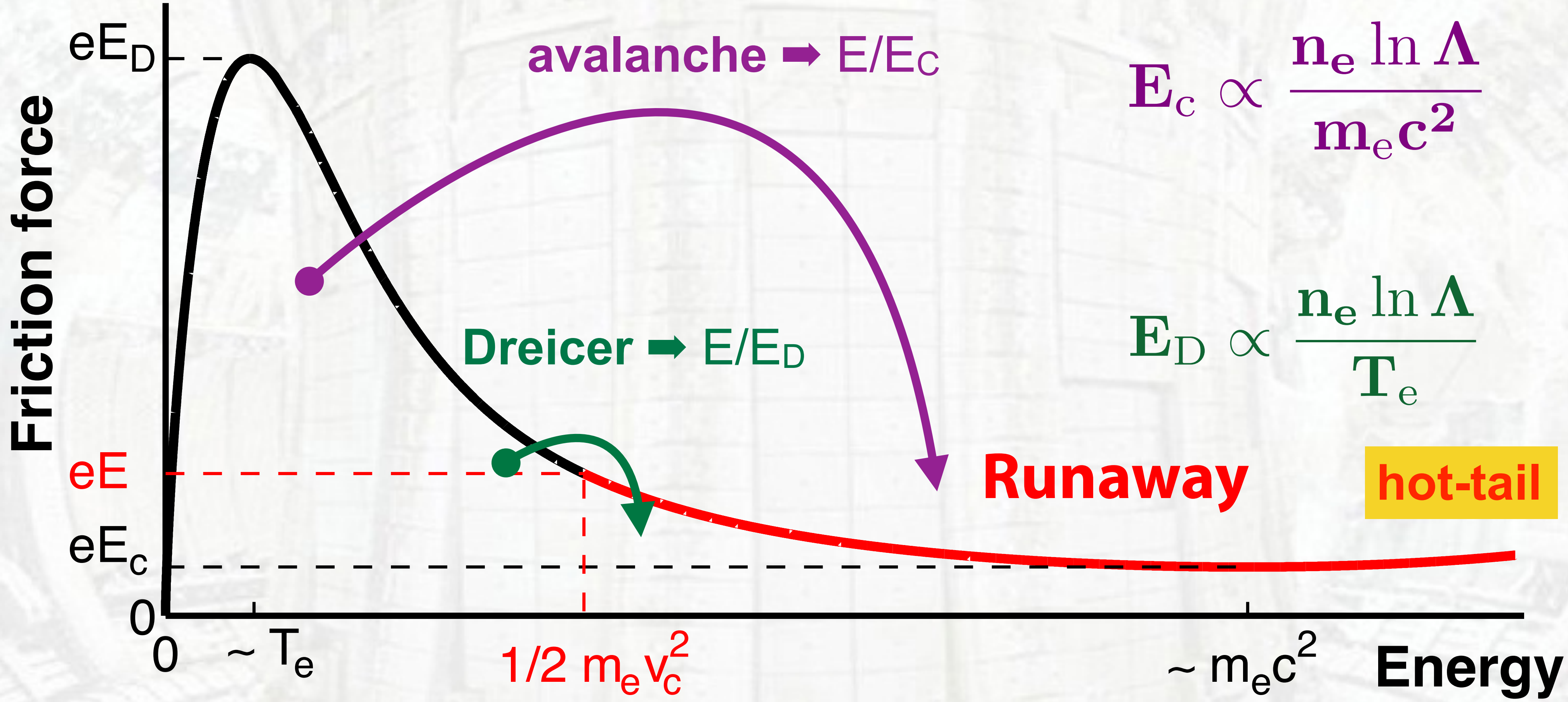
The effect of high-Z material injection on runaway electron dynamics

G. Papp[1], G. Pautasso[1], J. Decker[2]; L. Hesslow[5], M. Hoppe[5]; M. Bernert[1], P. Blanchard[2], A. Bock[1], T. Bolzonella[8], L. Calacci[3], D. Carnevale[3], M. Cavedon[1], J. Cerovsky[4], D. Choi[2], S. Coda[2], P. David[1], M. Dibon[1], M. Dunne[1], B. Duval[2], R. Dux[1], O. Embréus[5], B. Erdős[6], M. Farnik[4], M. Faitsch[1], O. Ficker[4], R. Fischer[1], C. Fuchs[1], M. Gobbin[8], C. Galperti[2], L. Giannone[1], A. Gude[1], M. Iliasova[13], K. Insulander Björk[5], F. Janky[1], E. Khilkevitch[13], O. Kudlacek[1], B. Labit[2], A. Lier[1], O. Linder[1], T. Lunt[1], E. Macusova[4], M. Maraschek[1], L. Marrelli[8], P. Marmillod[2], P.J. McCarthy[10], J. Mlyar[4], A. Mlynek[1], A. dal Molin[11], M. Nocente[11], E. Panontin[11], U. Plank[1], G.I. Pokol[6], V.V. Plyusnin[12], D. Rigamonti[11], O. Sauter[2], B. Sieglin[1], U. Sheikh[2], A. Shevelev[13], W. Suttrop[1], G. Tardini[1], M. Tardocchi[11], D. Testa[2], M. Teschke[1],W. Treutterer[1], L. Unnerfelt[5], M. Valisa[8], O. Vallhagen[5], the ASDEX Upgrade Team[1,*], the TCV Team[2,**], the EUROfusion MST1 Team***

[1]Max-Planck-Institute for Plasma Physics, Garching, Germany;
[2]Swiss Plasma Centre, EPFL, Lausanne, Switzerland;
[3]Universita di Roma “Tor Vergata”, Italy;
[4]Institute of Plasma Physics AS CR, Prague, Czech Republic;
[5]Chalmers University of Technology, Göteborg, Sweden;
[6]Institute of Nuclear Techniques, BME, Budapest, Hungary;
[7]ENEA sulla Fusione, C.R. Frascati, Italy;
[8]Consorzio RFX, Padova, Italy;
[10]Department of Physics, University College Cork, Cork, Ireland;
[11]Universita di Milano-Bicocca, Milano, Italy;
[12]Instituto de Plasmas e Fusao Nuclear, IST, Universidade de Lisboa, Portugal;
[13]Ioffe Physical-Technical Institute (RAS), St. Petersburg, Russia;
*See the author list of "H. Meyer et al 2019 Nucl. Fusion accepted 10.1088/1741-4326/ab18b8"
**See the author list of “S. Coda et al 2019 Nucl. Fusion accepted 10.1088/1741-4326/ab25cb”
*** See the author list of “B. Labit et al 2019 Nucl. Fusion accepted 10.1088/1741-4326/ab2211”

The runaway phenomenon

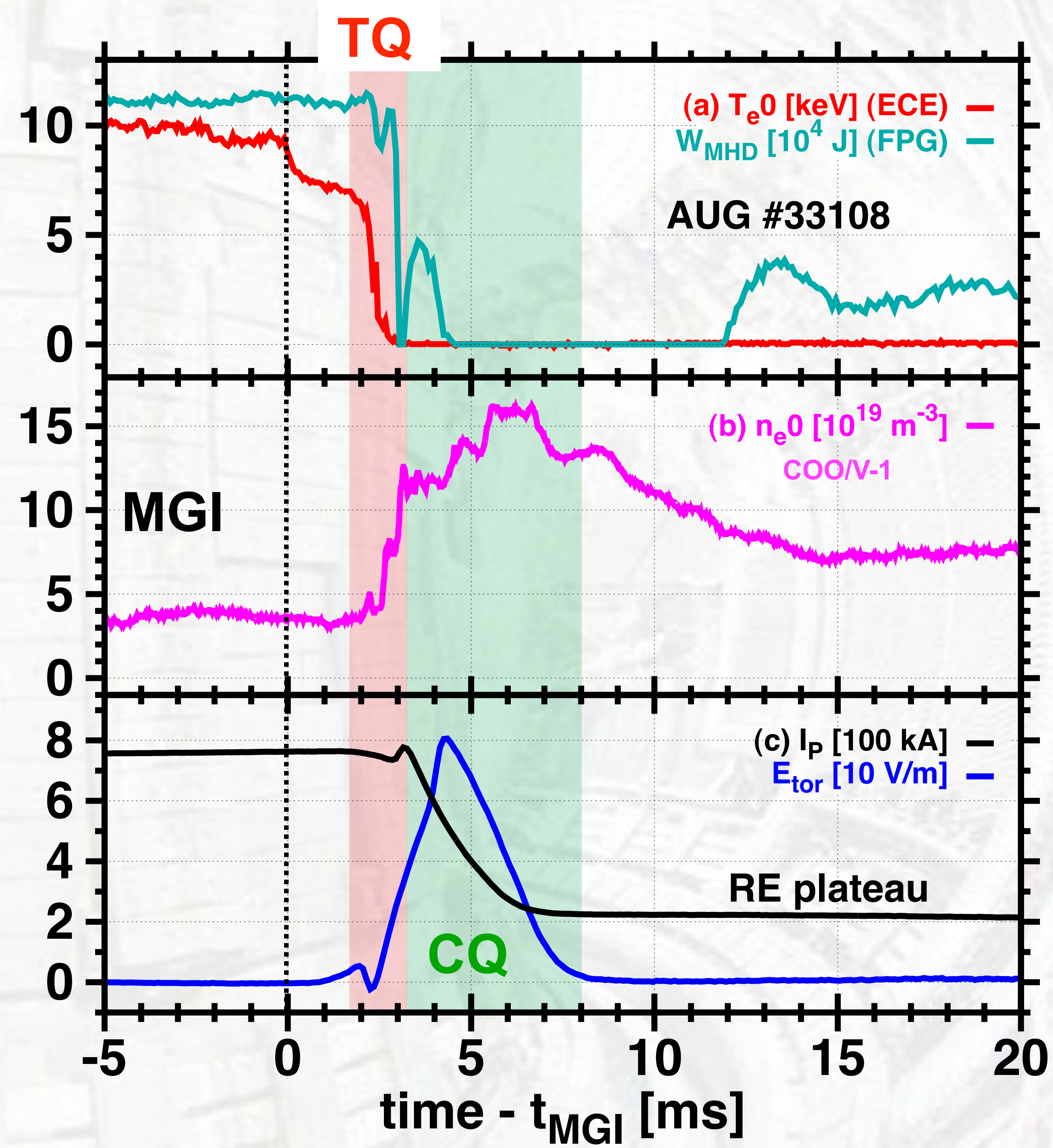
- In plasmas, the **friction force** is a nonmonotonic function of energy
- **If E > E_c (*critical field*), runaway acceleration can happen**



- **Dreicer: Velocity space diffusion (E, n_e, T_e)**
- Hot-tail: Cooling tail of distribution (T_e & cooling rate)
- Tritium decay, Compton generation - for reactors
- **Avalanche: knock-on collisions with thermals (E, n_e)**

Disruptions and runaway electrons

- **Disruptions:** quick cooling of the plasma (*thermal quench* - TQ)
- *Current quench* (CQ) as the conductivity is decreased ($\sigma \sim T^{3/2}$)
  ➡ I_p cannot drop arbitrarily fast - **toroidal electric field is induced**
- **Massive material injection to handle forces & heat loads**
- $N_{ava} \sim \exp\{I_p\}$
- On large machines (e.g. ITER) even a small seed could avalanche into **several MA-s of RE current**
  ➡ Risk to plasma facing components
  [Hollmann PoP 2015, Lehnen JNM 2015, Matthews Phys. Scr. 2016, etc.]



"The biggest challenge: avoid runaway electron formation when mitigating heat loads and forces" **[Lehnen EPS 2017]**

Scope / outline

- **We have to rely on theory predictions for ITER**

➡ **Goal: better understand RE dynamics following high-Z MMI, and provide datasets for model validation**

- **MST allows multi-machine studies for theory comparison**

➡ COMPASS ➡ **TCV** ➡ **AUG** ➡ JET

1. Global parameters: Density, (temperature,) shaping, q, ...
2. Impact of high-Z materials on RE dissipation & generation
   ➡ Experimental validation of [Hesslow] quantum-kinetic model
   ➡ RE suppression by deuterium admixture
3. Runaway distribution measurements & simulations
   ➡ Hard X-ray (Bremsstrahlung) & synchrotron emission

AUG & TCV RE experiments

➡ **Goal: better understand RE dynamics following high-Z MMI, and provide datasets for model validation**

- Disruption **triggered** with MGI of argon / neon / krypton (reproducible)
- Different scenarios developed on AUG and TCV:

	I_P [kA]	B_T [T]	q_{95}	$\langle n_e \rangle$ [m^{-3}]	T_e^0 [keV]	N_{MGI}		κ
AUG	800	2.5	> 3	$\sim 3 \cdot 10^{19}$	~10	$[0.2 - 4.8] \cdot 10^{21}$	Ar	1.1
TCV	200	1.4	> 2	$\sim 2 \cdot 10^{18}$	~1	$[3 - 4] \cdot 10^{19}$	Ne	<1.5

- **Machines complement eachother (different parameter ranges)**
- Typical RE currents of 200-400 kA, up to 650 ms plateau length
  - ➡ Good position & OH control of the beam, safe operation
  - ➡ TCV: seemingly full conversion of Ohmic to RE current
  - ➡ Max RE energy ~25 MeV
- No isotope effect: RE dynamics in H, D and He plasmas is comparable

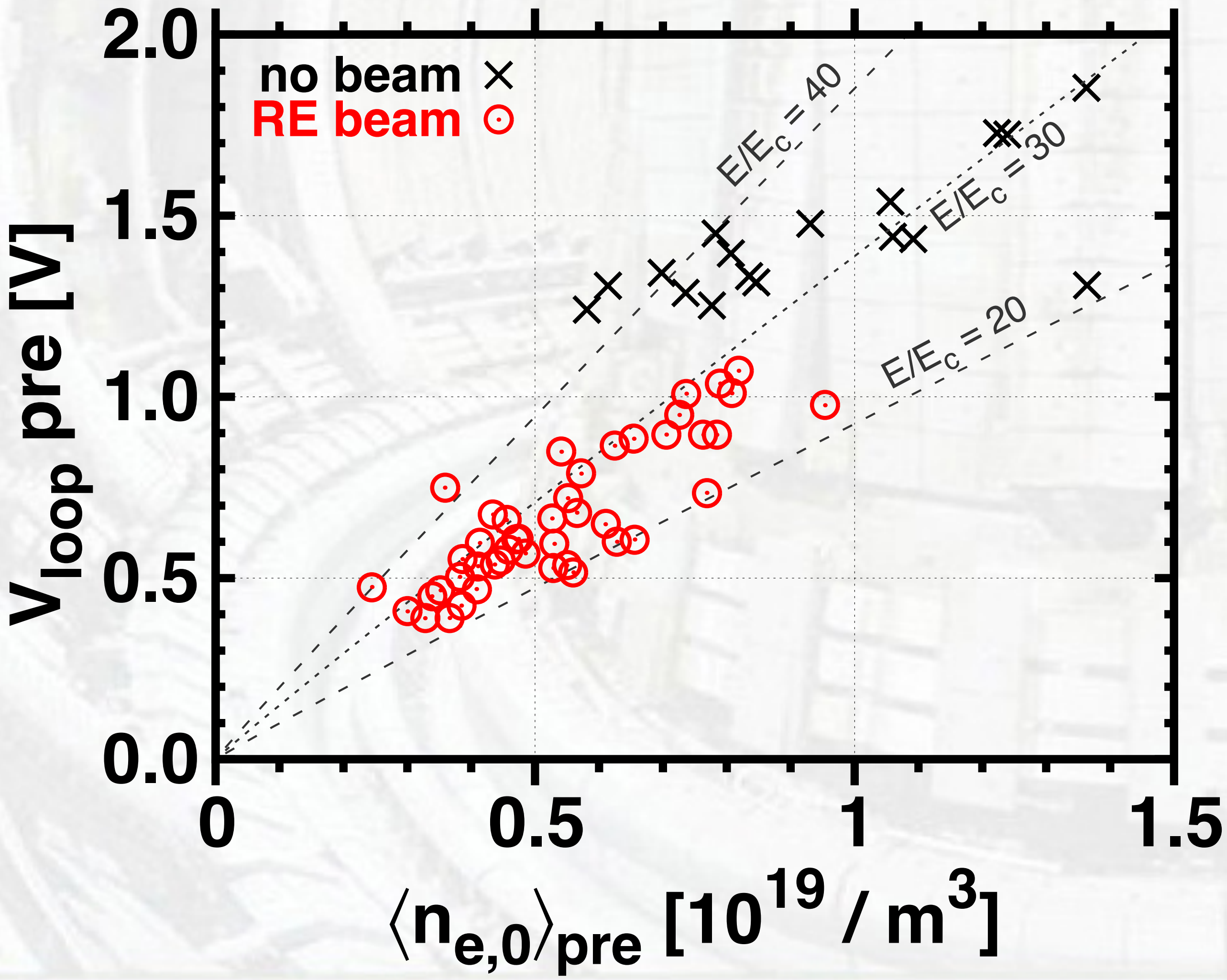
[Papp IAEA-FEC 2016, Pautasso PPCF 2017, Coda NF 2017, Gobbin PPCF 2018, Carnevale PPCF 2018, Nocente RSI 2018, Pautasso PPCF 2019, Decker NF 2019, etc]

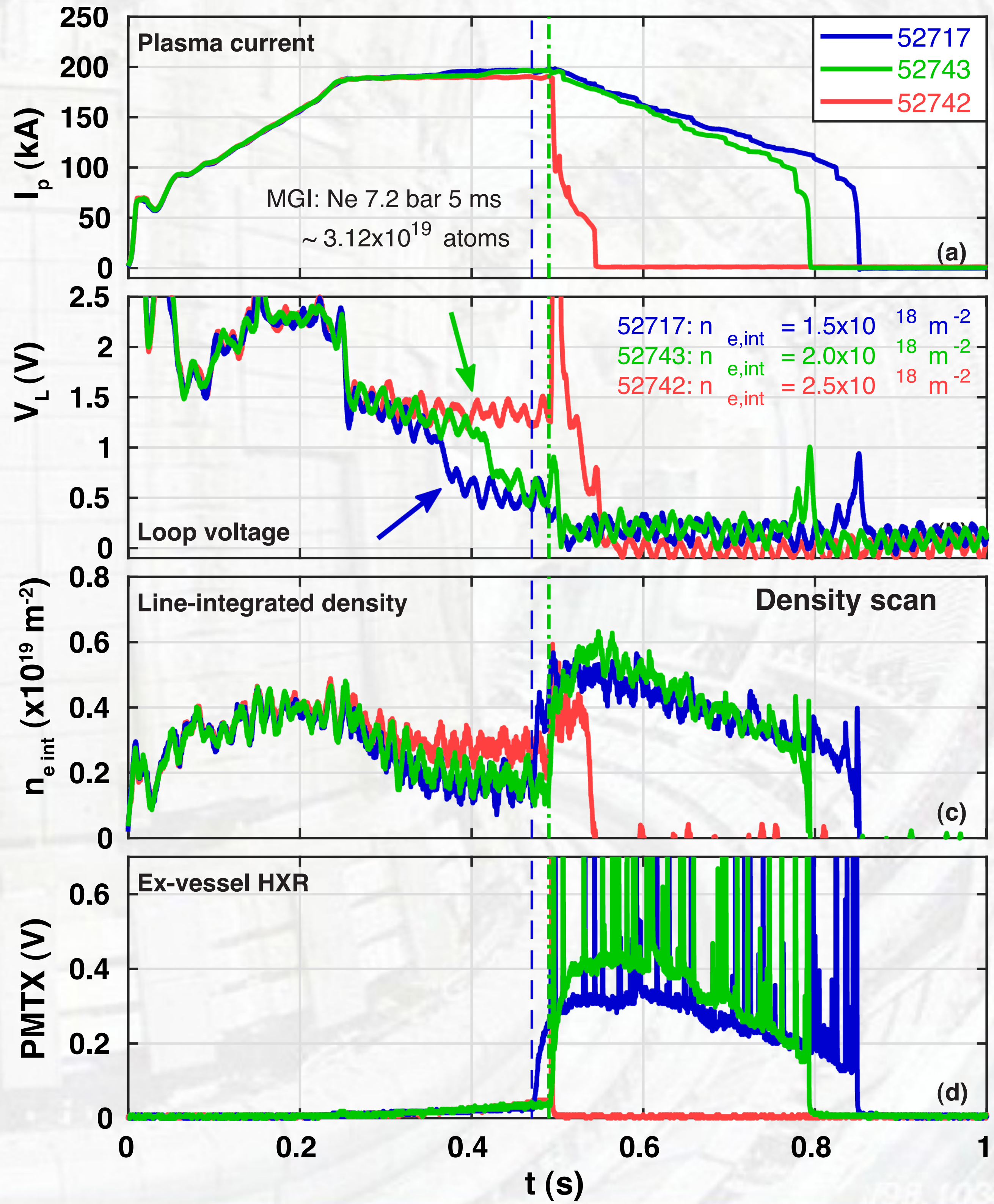
TCV: RE beam formation vs pre-MGI density

- **TCV: RE beam formation requires $n_{e,0} \lesssim 1.0 \times 10^{19}\ m^{-3}$**

➡ Role of pre-MGI RE seed

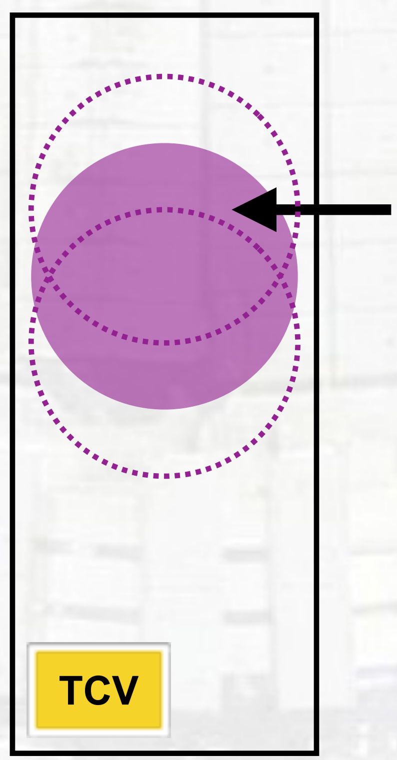
- Unique scenario
- Threshold effect valuable for kinetic model validation
[e.g. LUKE+METIS]

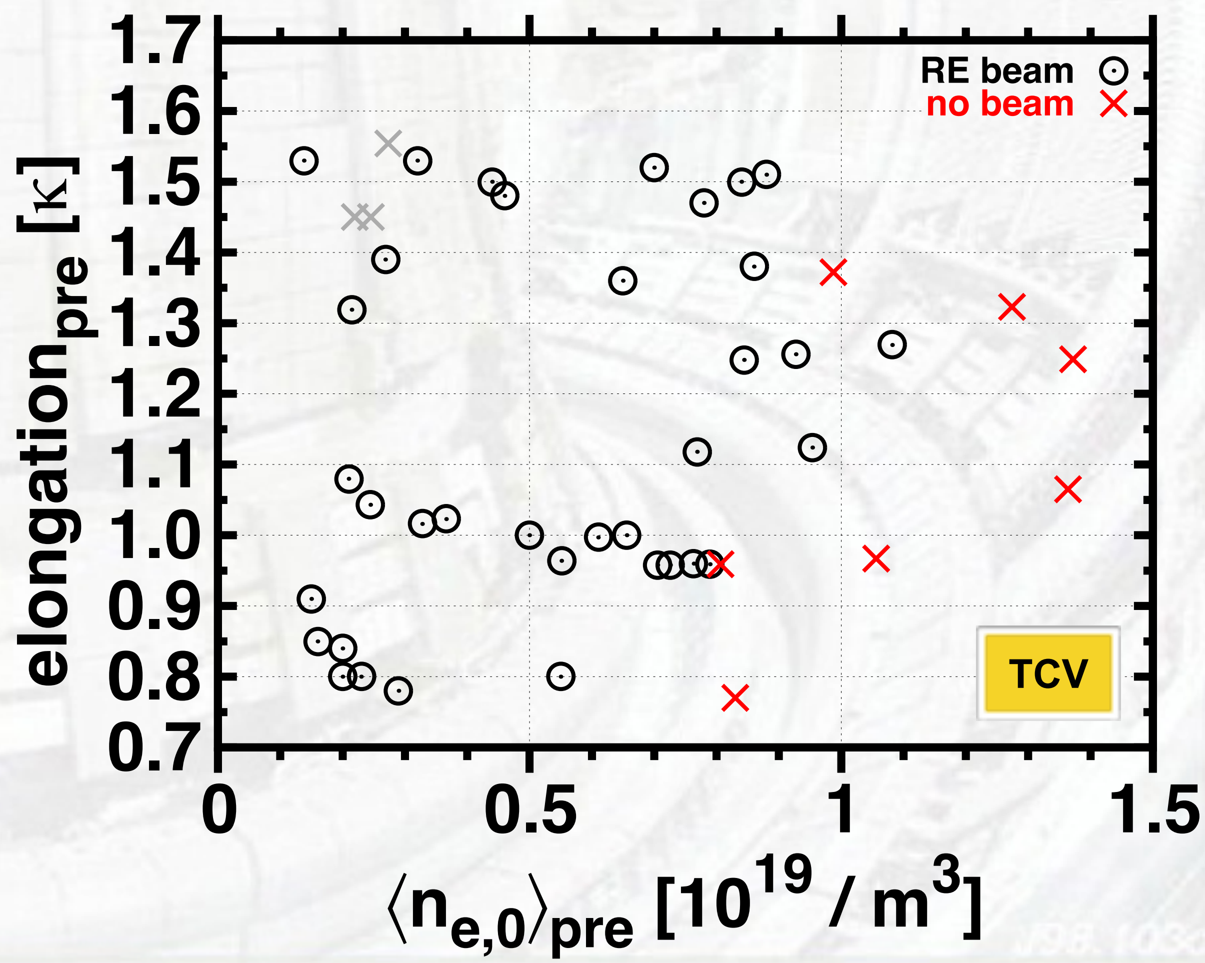




TCV: shaping, position and control

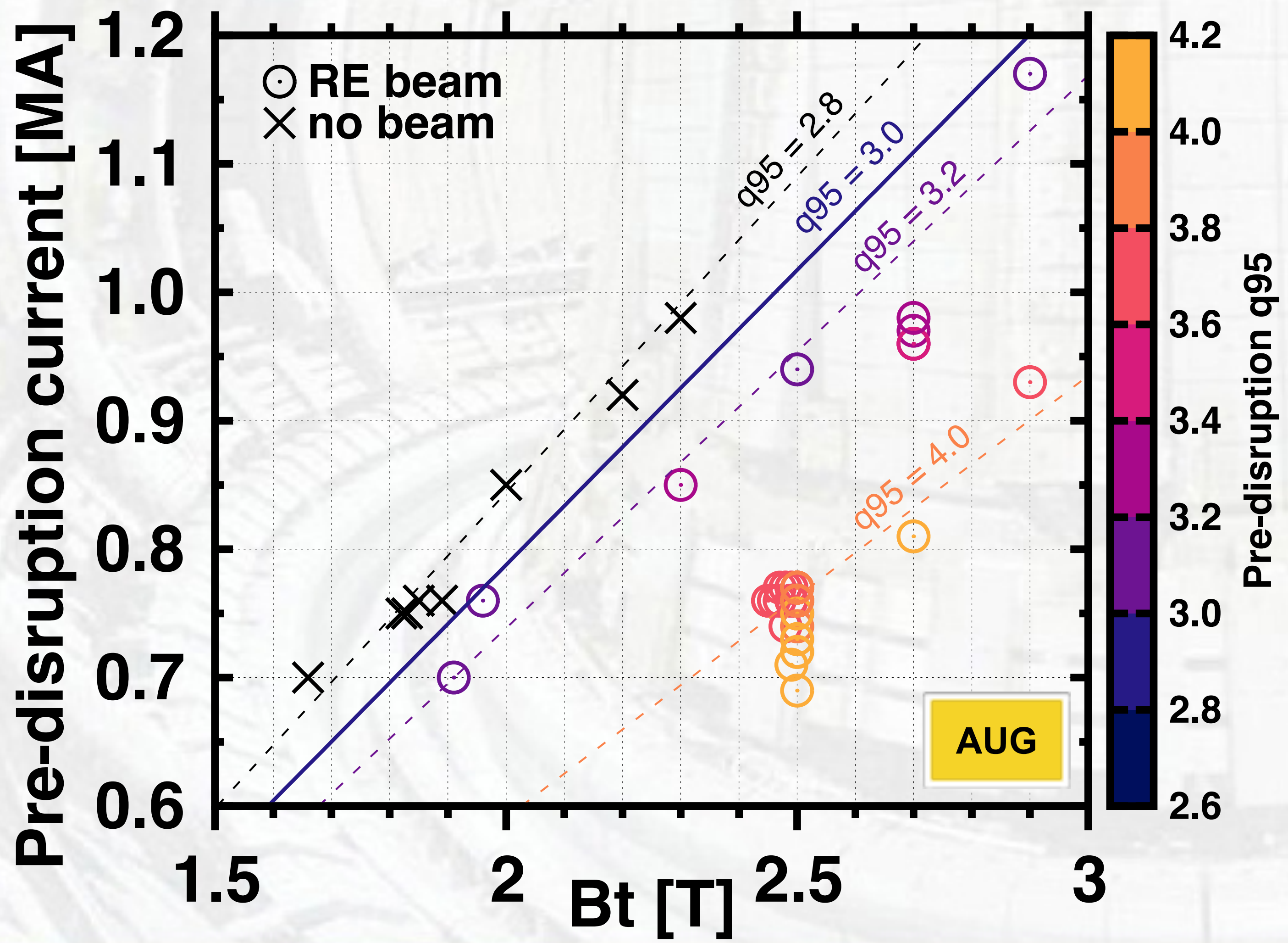
- Most runaway experiments are done in circular plasmas
  - ➡ Shaping poses a control challenge (VDE)
  - ➡ Reactor plasmas are expected to be shaped
- **TCV: RE beam control obtained up to k ~ 1.5**
  - ➡ Challenge: post-disruption stabilization [Carnevale PPCF 2018]
  - ➡ No obvious kinetic / MHD effect found
- **Is there an optimal MGI position?**
  - ➡ At low gas flow rates, injection at z ~ a/2 seems most efficient
  - ➡ If the gas flow rate is high, no impact of vertical position

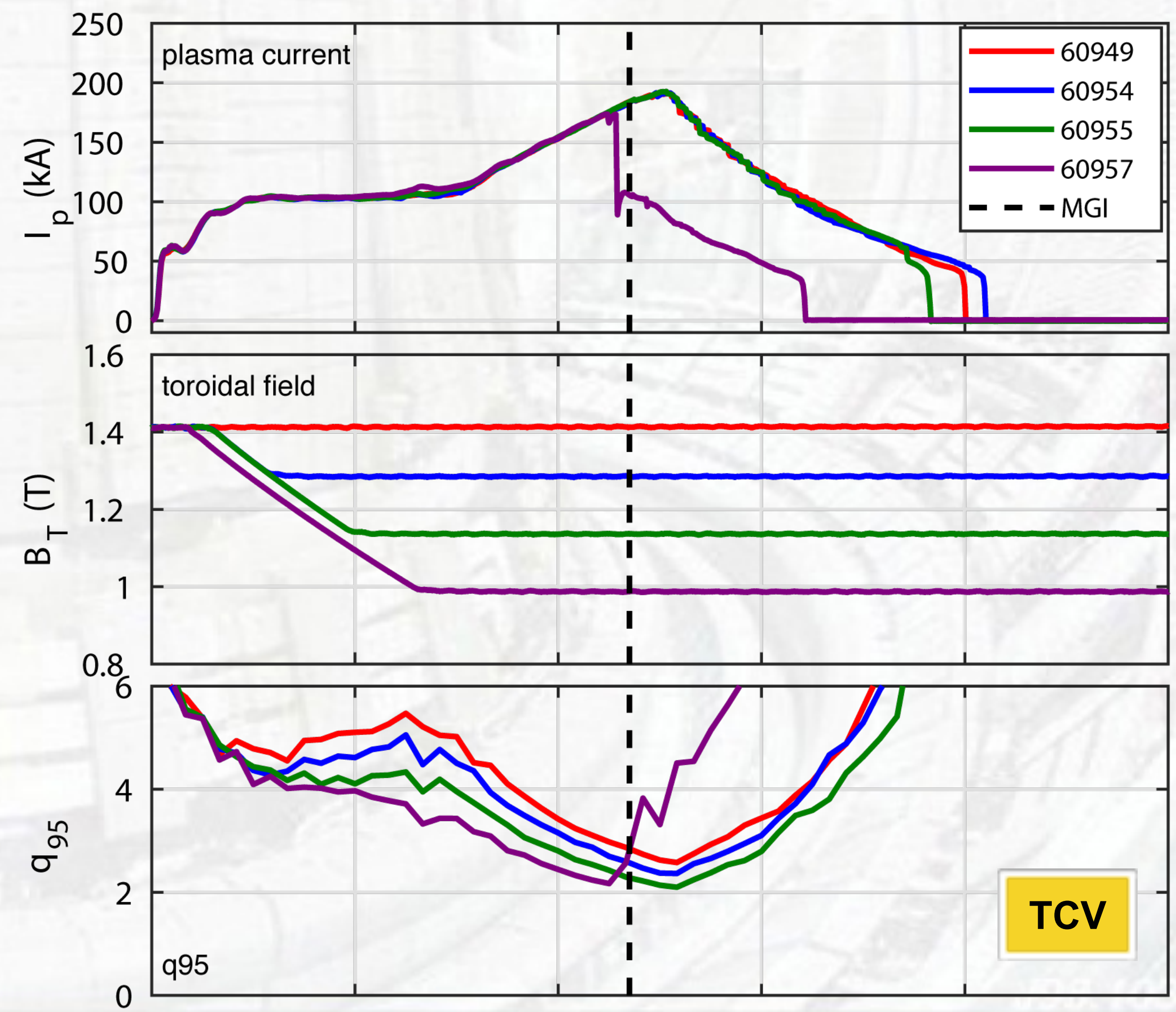




AUG: q_{95} dependence

- **AUG: $q_{95} > 3$ threshold - not yet understood**
  - ➡ Exists in a wide range of I_p (0.7-1.2 MA) & B_t (1.6-2.9 T), scanning around the $q_{95} = 3$ threshold
  - ➡ To be studied by MHD modeling [e.g. JOREK]
- TCV: RE beam creation is insensitive to $q_{95} > 2$
  - ➡ No q_{95} threshold on JET [Plyusnin P4.1046]

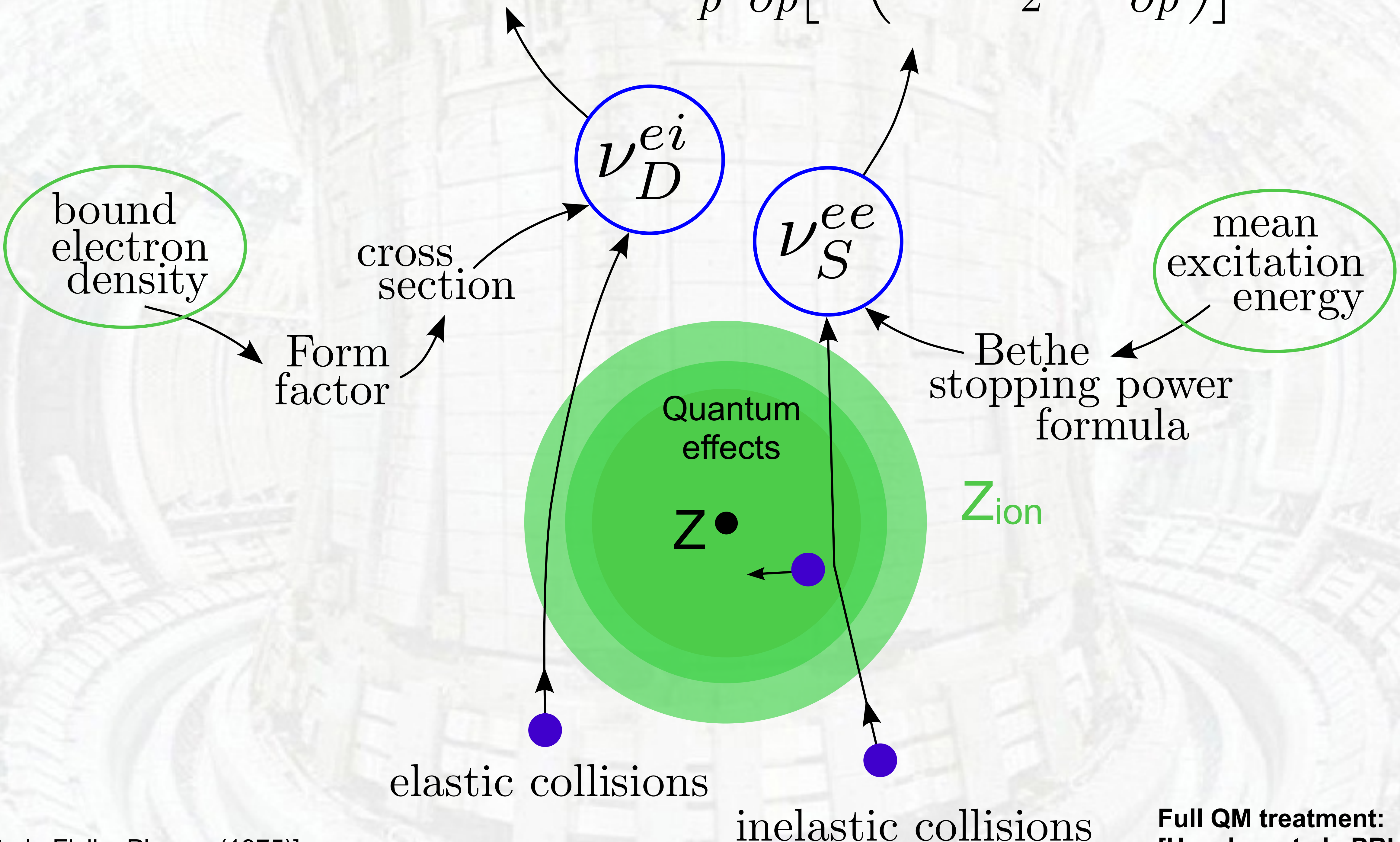




Avalanche - what can MSTs contribute?

Runaway interaction with high-Z material

$$C^{e}_{\text{test}} = \nu_D \mathscr{L}(f_e) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^3\left(\nu_S f_e + \frac{1}{2}\nu_\parallel p \frac{\partial f_e}{\partial p}\right)\right]$$



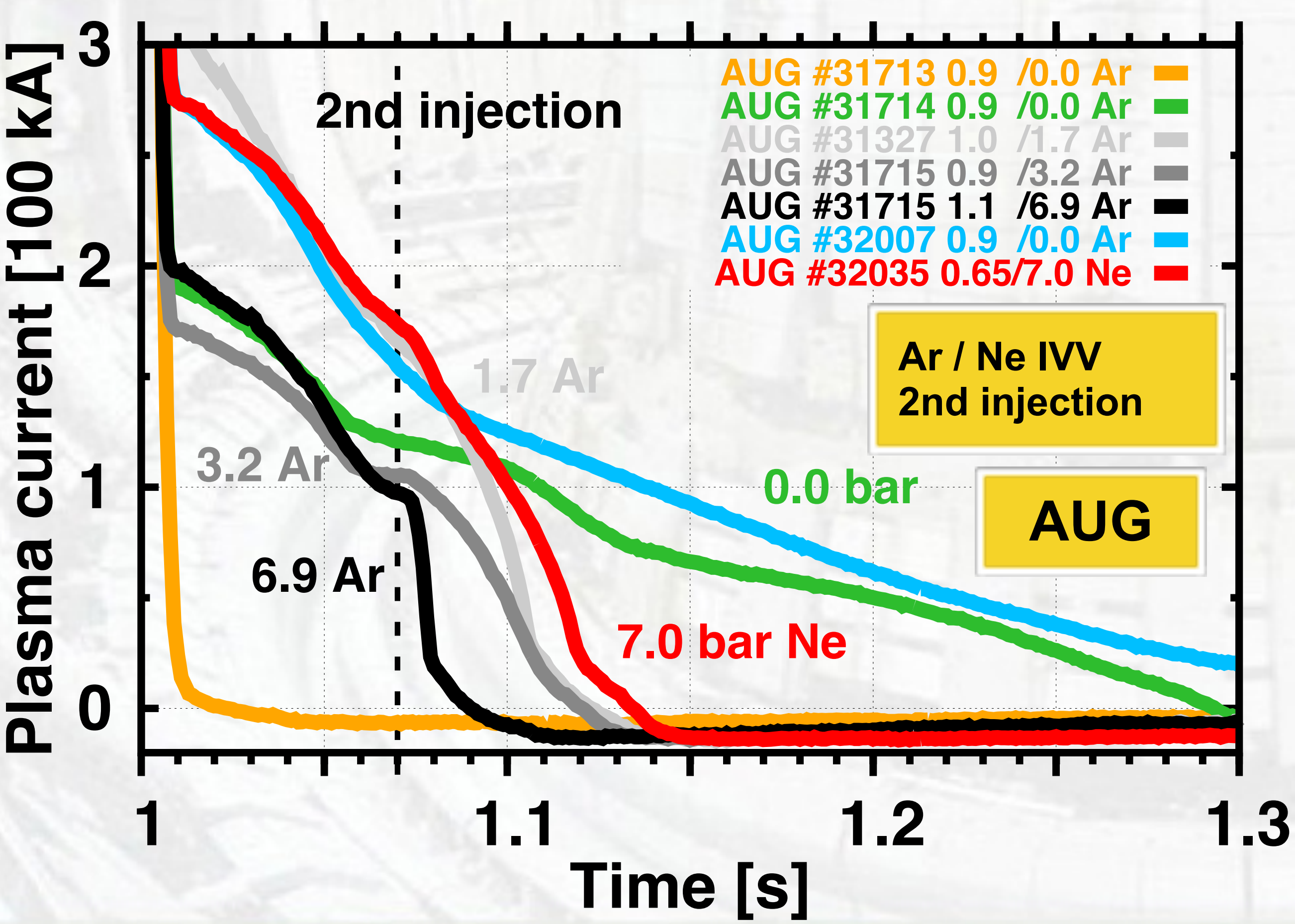
partial screening

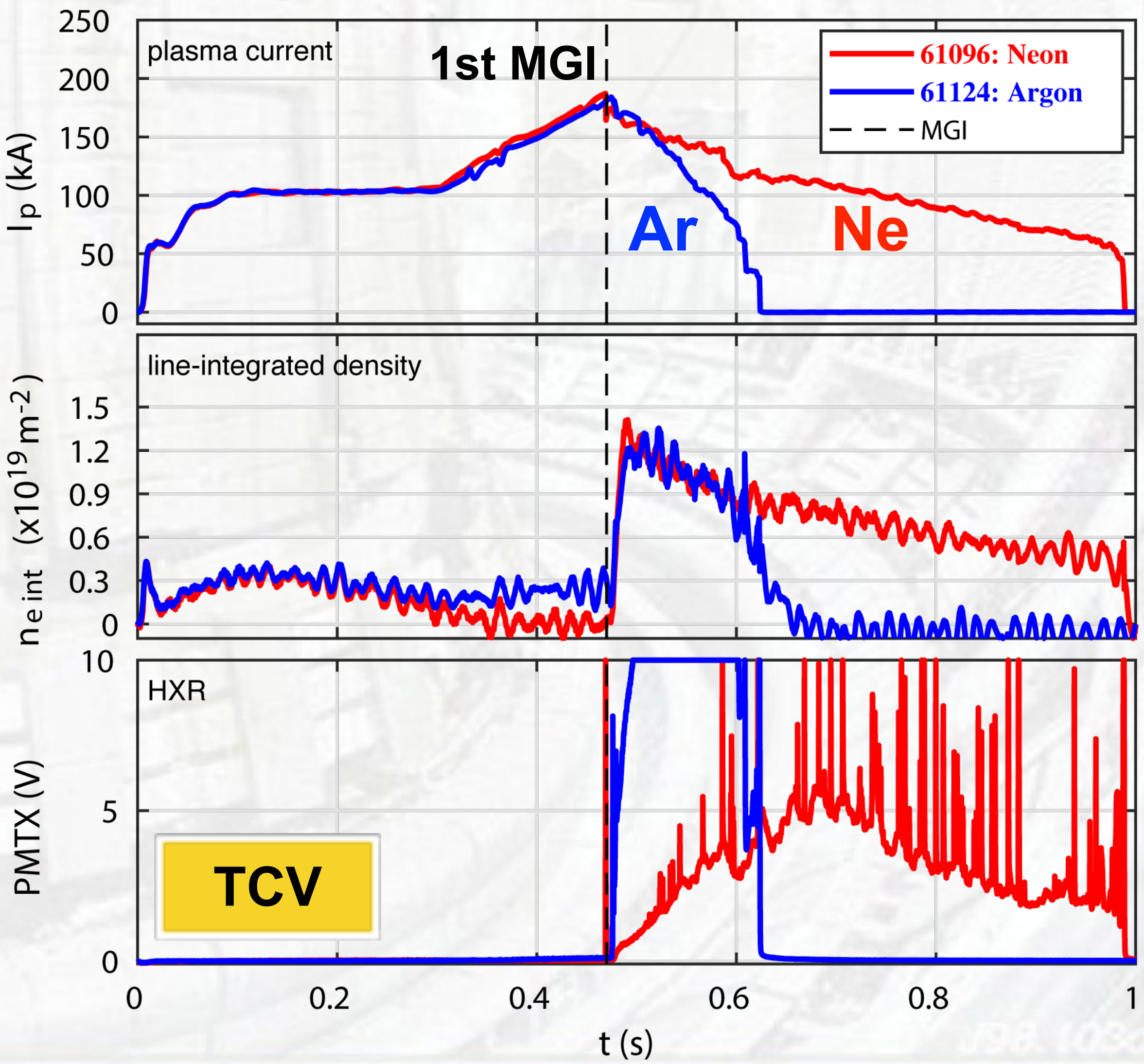
[Kirillov et al., Fizika Plasmy (1975)]
[Zhogolev and Konovalov, VANT (2014)]
[Martin-Solis et al., PoP (2015), NF (2017)],
[Aleynikov & Breizman, PRL (2015)]

Full QM treatment:
[Hesslow et al., PRL 2017]
[Hesslow et al., PPCF 2018]
[Hesslow et al., JPP 2018]
[Hesslow et al., NF 2019]

Runaway dissipation by high-Z material

- **1st MGI to trigger RE beam - followed by dissipation**
  - ➡ Avalanche dominates decay stage, E ~ $E_{c,eff}$ [Breizman NF 2014]
- **Extended range: 2nd injection into a formed beam**
  - ➡ Can lead to full suppression of RE beam
- **Compare decay rate with theory**
  - ➡ Scan gases & quantity

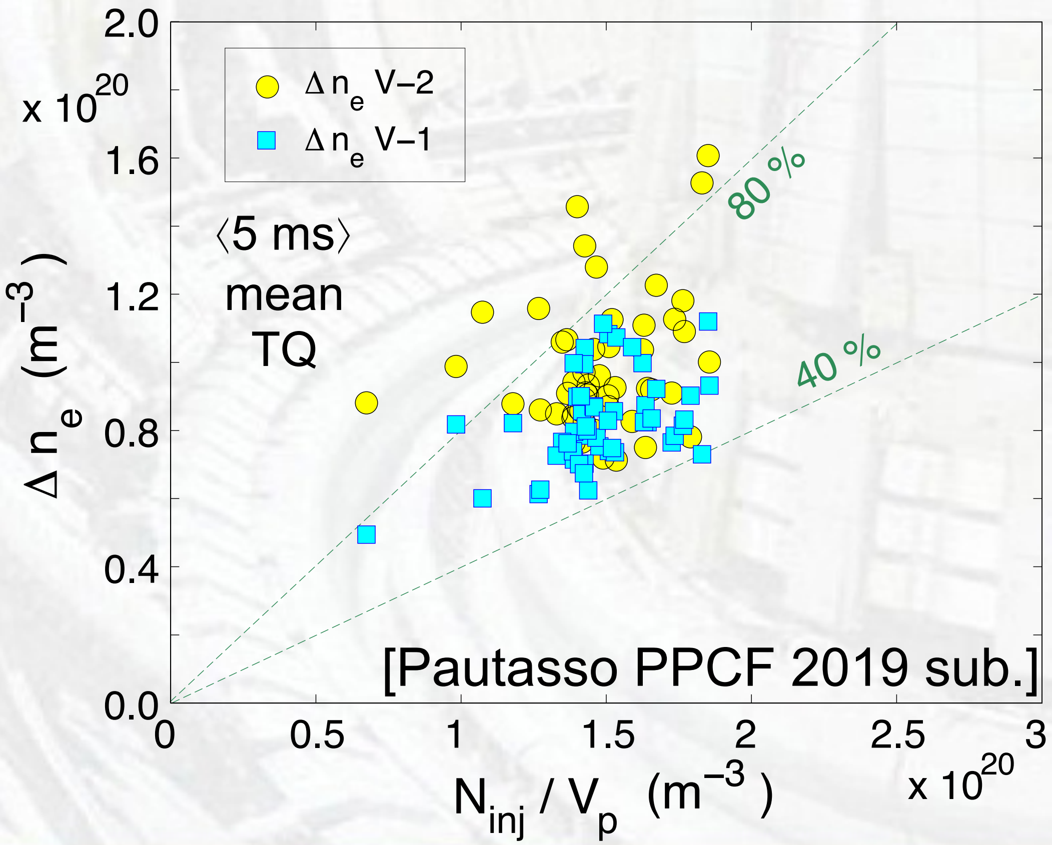


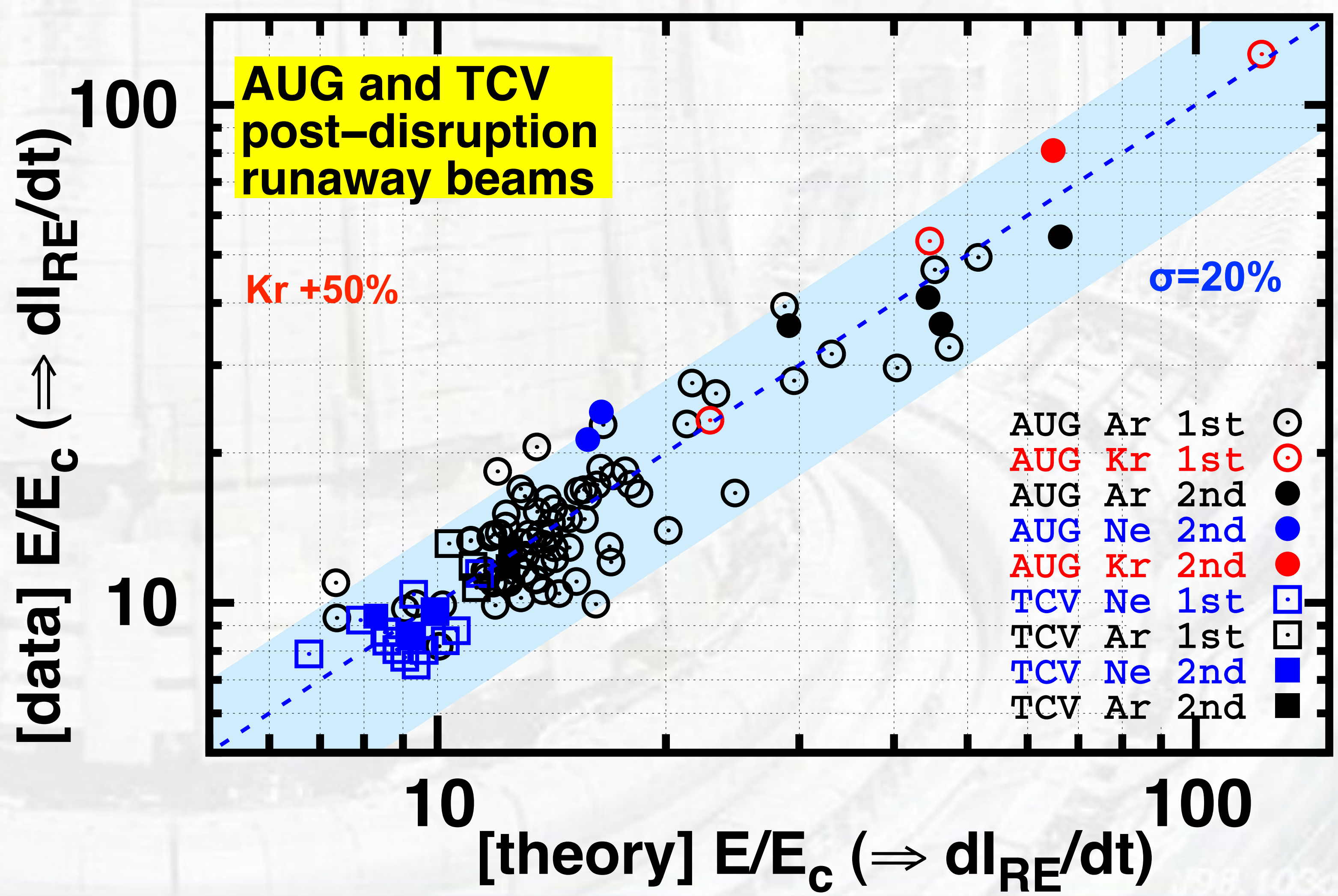


Experimental comparison of RE damping

- **Comparison is based on [Hesslow PPCF 2018]**
- **AUG 1st**: analyse right after CQ, before control system action. n_Z assuming ~60% in interaction with REs (1st injection).
- **AUG 2nd**: assuming ~10% assimilation into beam volume.
- **TCV**: $dI_{OH}/dt = 0$ ➡ measure dI/dt in the entire plateau. n_Z / n_e from increase in n_e.

✓ **Reasonable statistical agreement found**

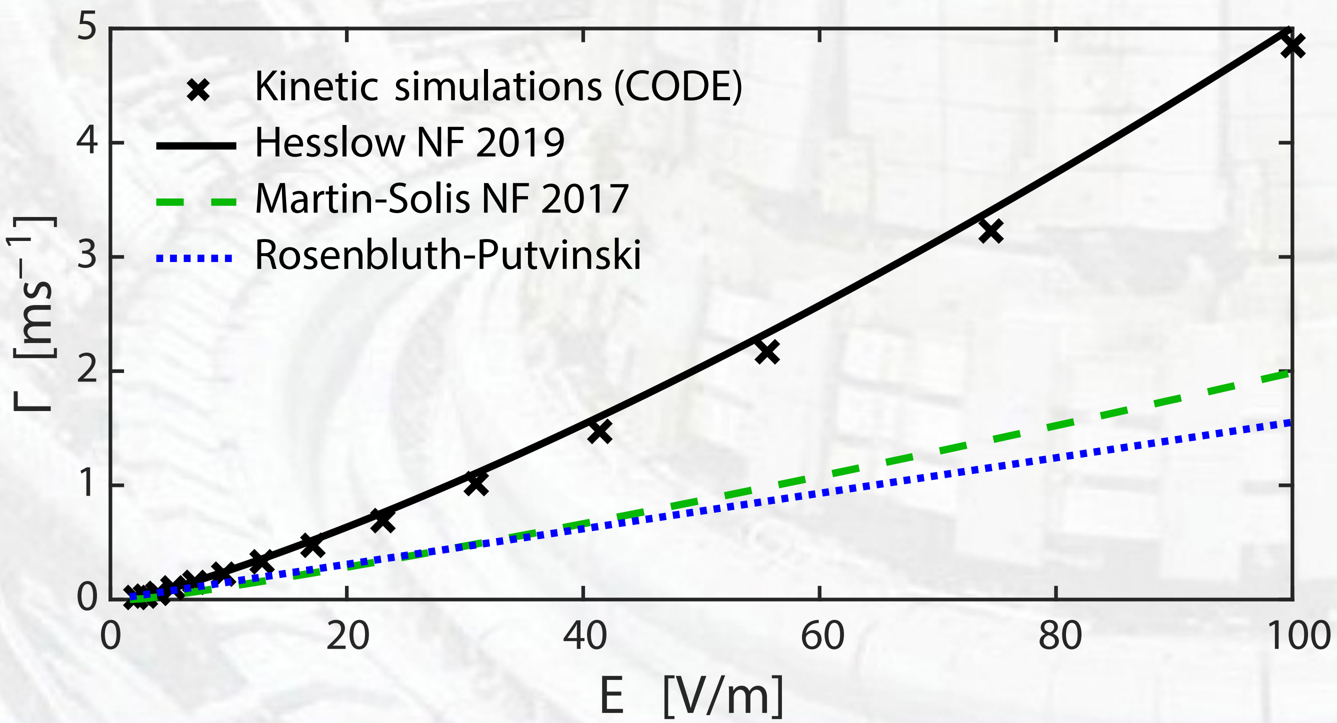




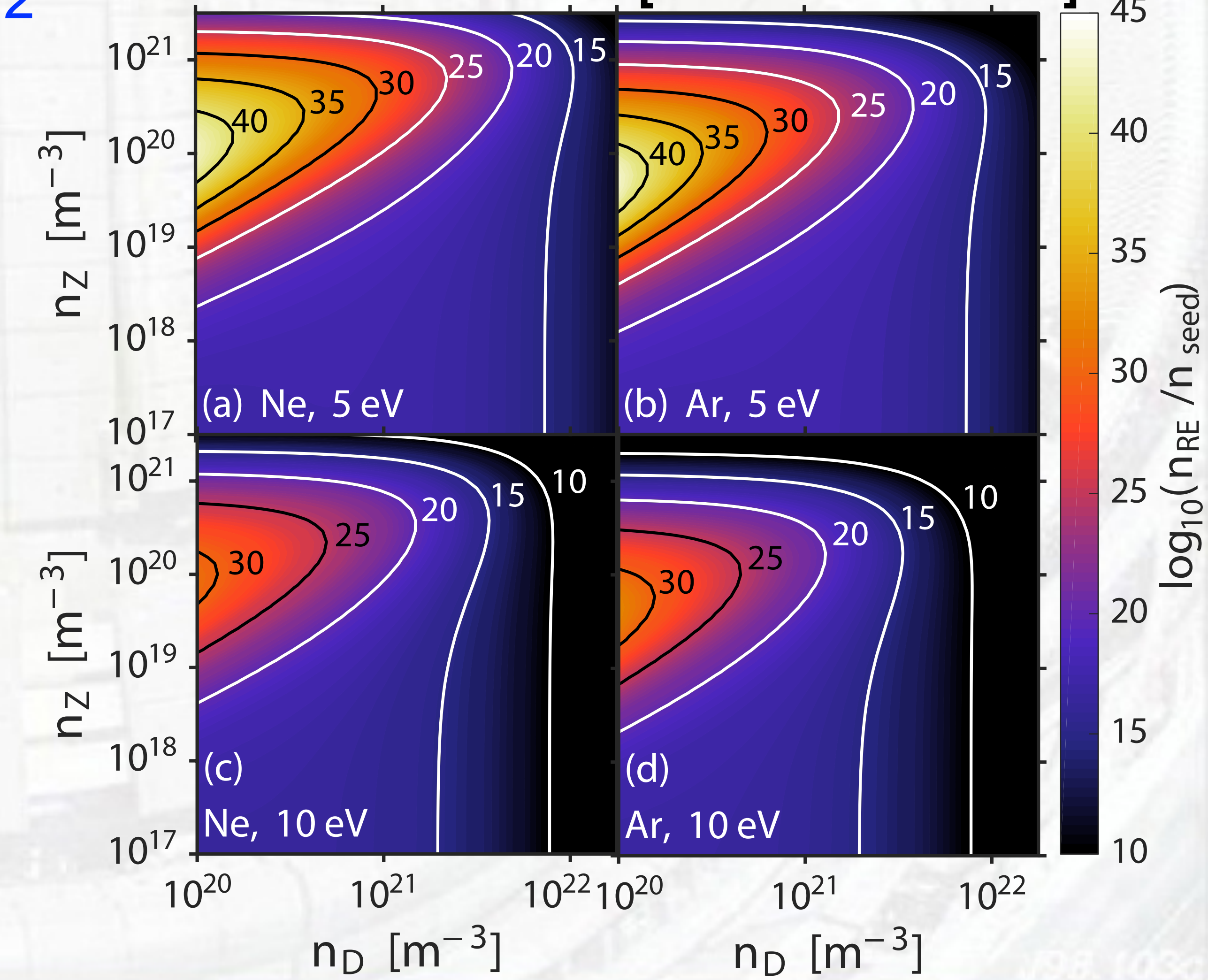
High-Z impact on RE *generation*

- Interaction of REs with bound electrons
  - ➡ Increases the collisional drag & scattering of REs
  - ➡ **BUT**: provides more electrons to avalanche scatter!
- **At large currents (ITER), the high-Z material can even increase RE generation! [Hesslow NF 2019]**
- Possible to counteract with D_2 admixture [Martin-Solis NF 2017]

➡ In experiments?



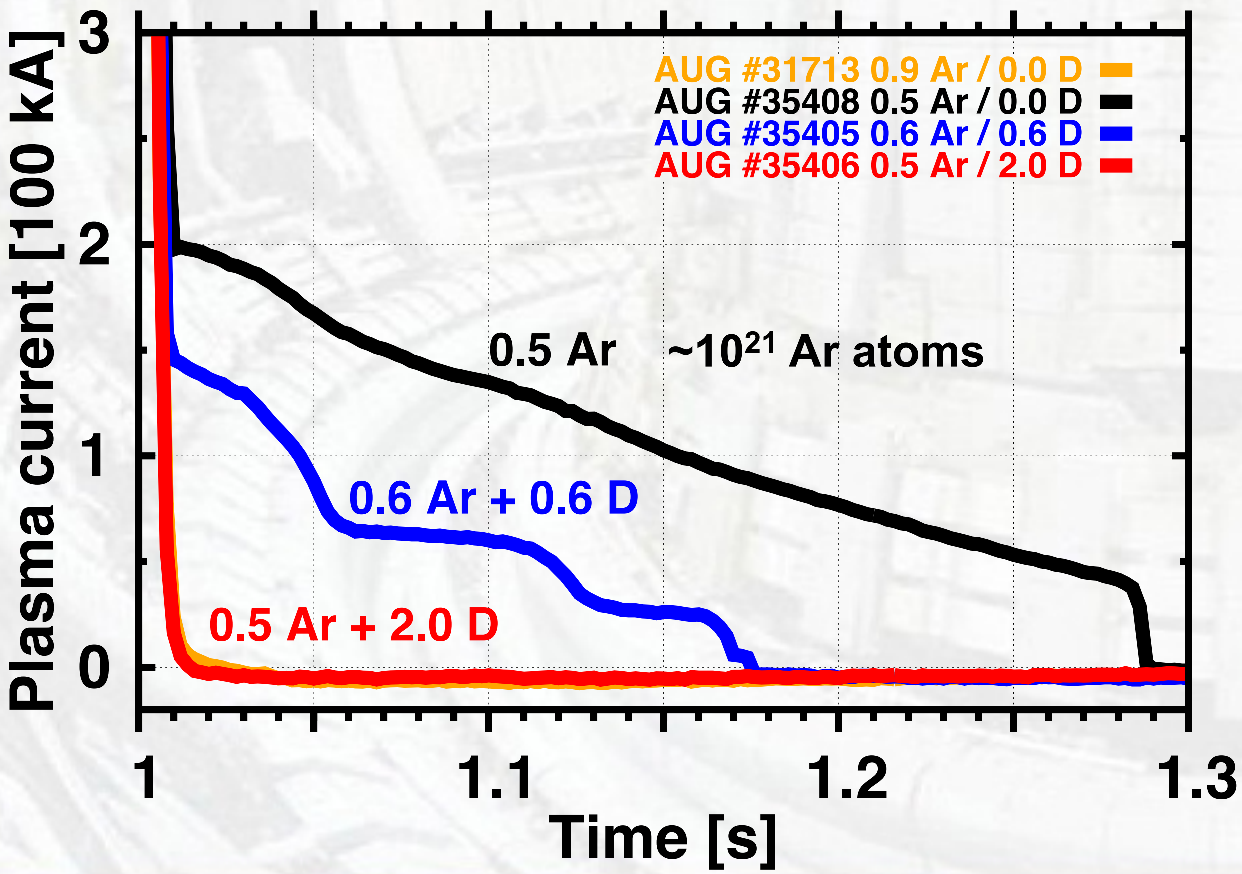
ITER-like case - [Hesslow NF 2019]

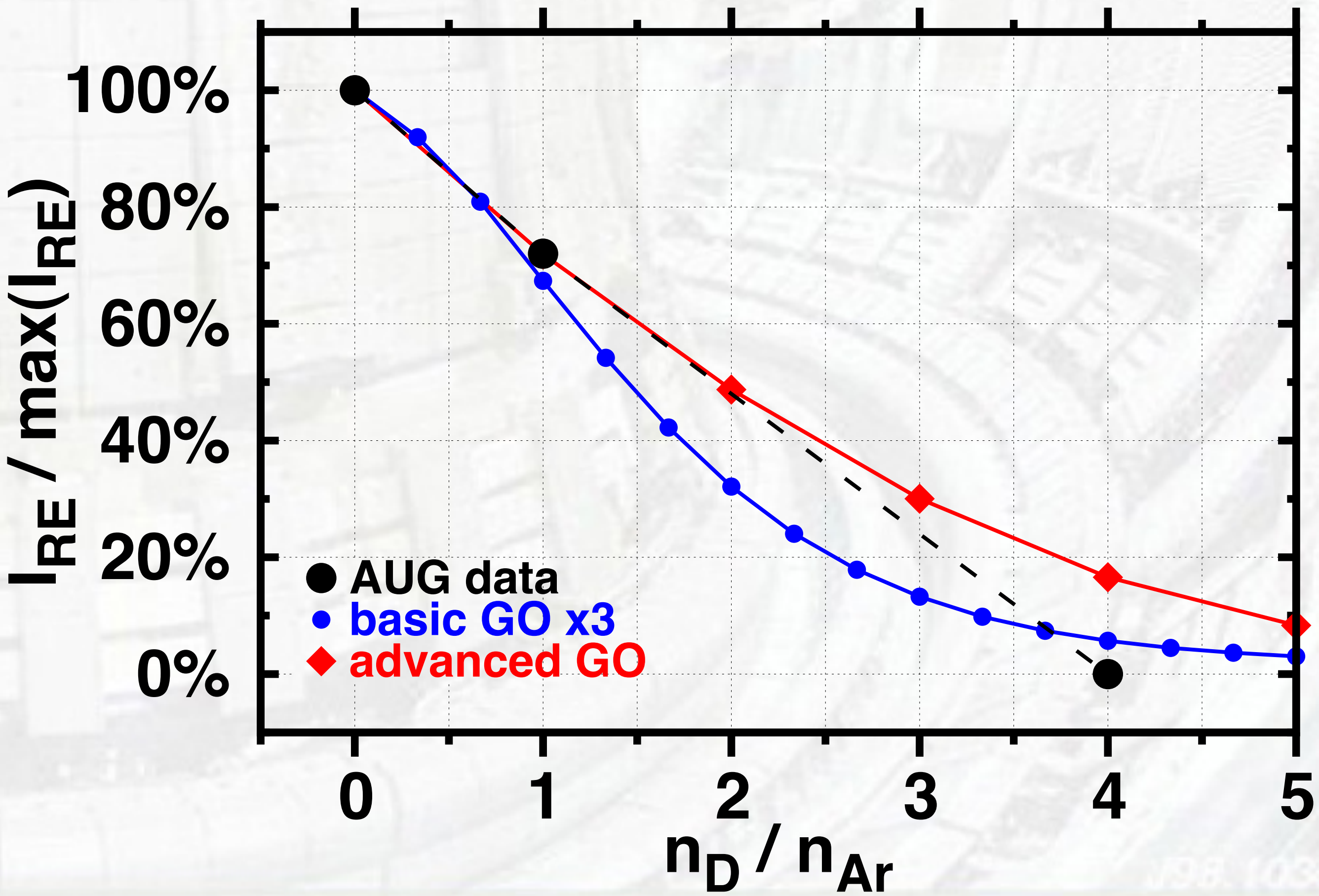


Argon + deuterium mixture injections

- **Argon + deuterium mixture injections suppress REs**
  - ➡ Extra density expected to mitigate RE generation
  - ➡ 50/50 (1:1) partial-, 20/80 (1:4) full suppression
- **Model comparison**: "basic" GO [Papp NF 2013] vs GO with updated avalanche growth rates [Hesslow 2019 NF] +CODE-based neural network for Dreicer generation

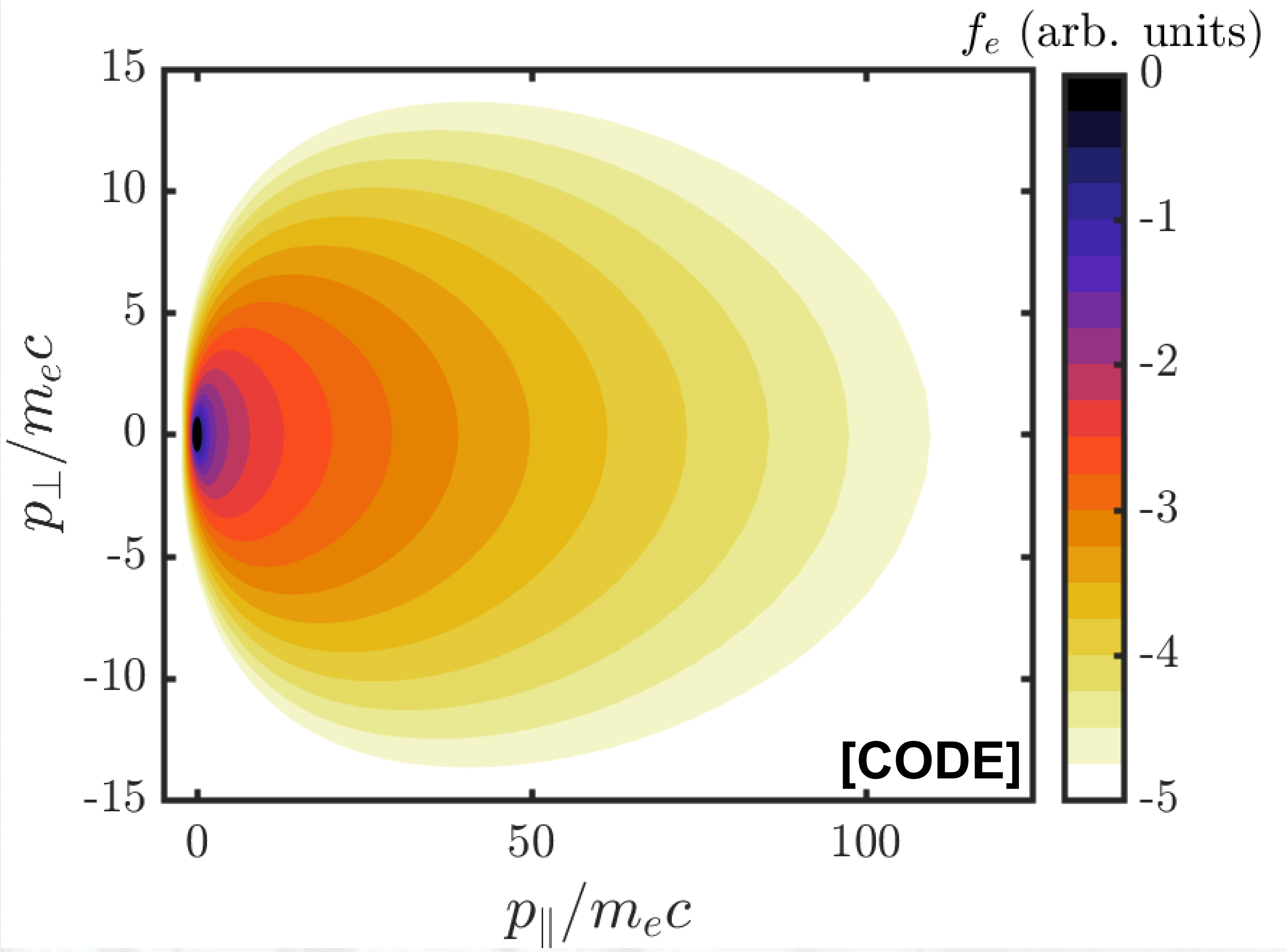
➡ **Future work for ASTRA-STRAHL+RE [Linder P4.1034]**

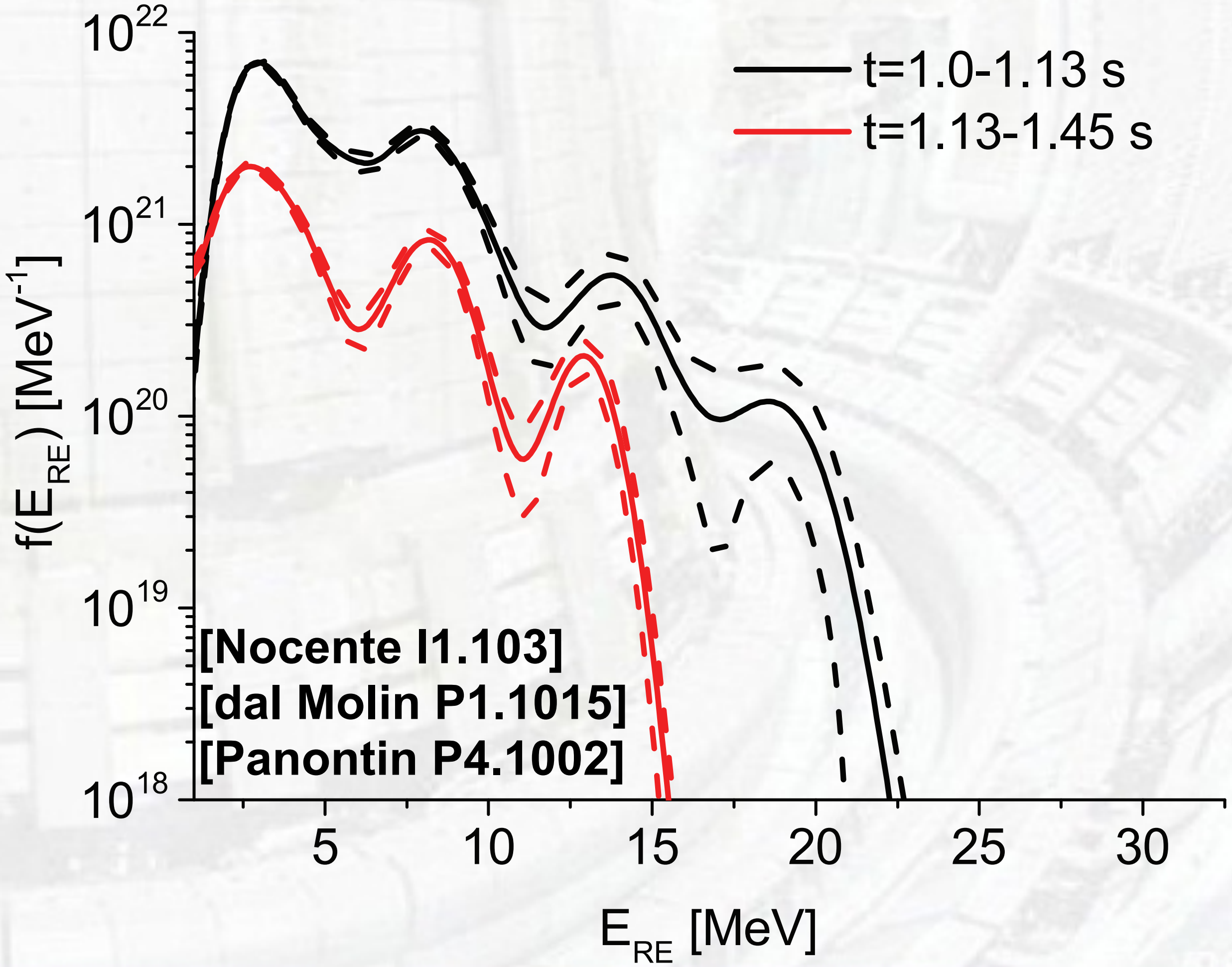




Runaway energy distributions

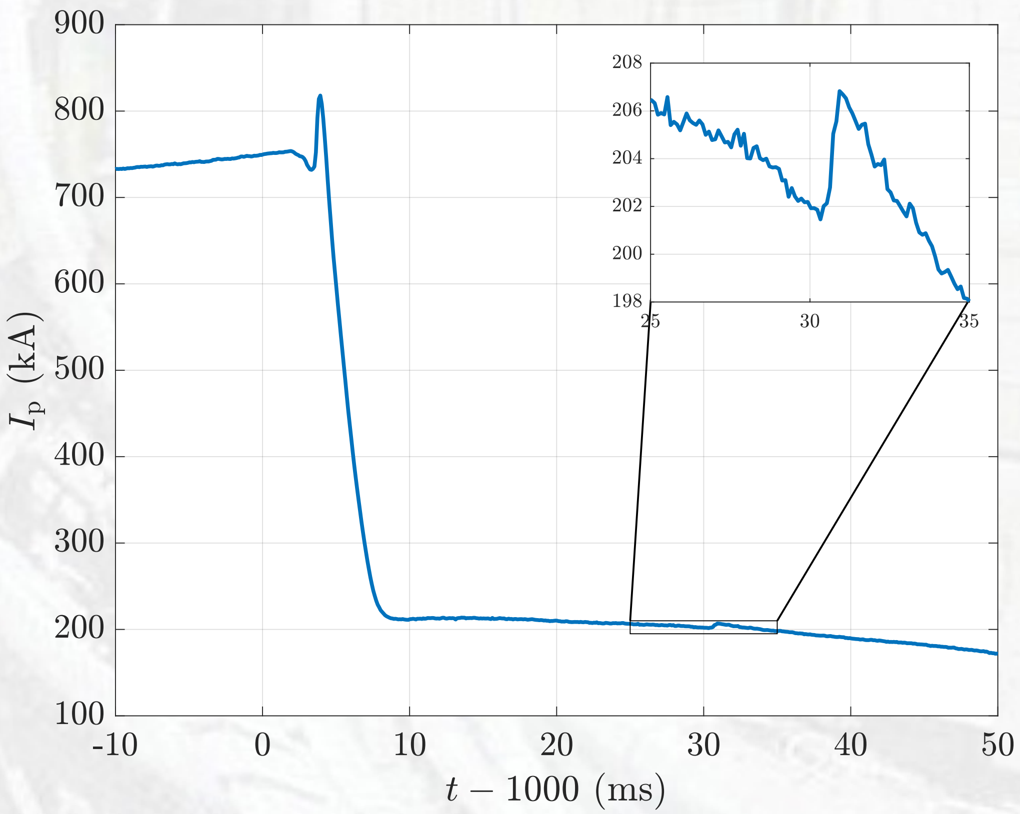
- **Full-f kinetic simulation of the complete CQ cycle**
  - ➡ Using CODE [Stahl NF 2016] with high-Z interaction
  - ➡ Plasma parameters taken directly from the experiment
  - ➡ Self-consistent electric field evolution
- **Enables comparison with distribution measurements**
  [HXR: Nocente I1.103, RSI 2018] [Synchr.: Hoppe EFTC 2019]

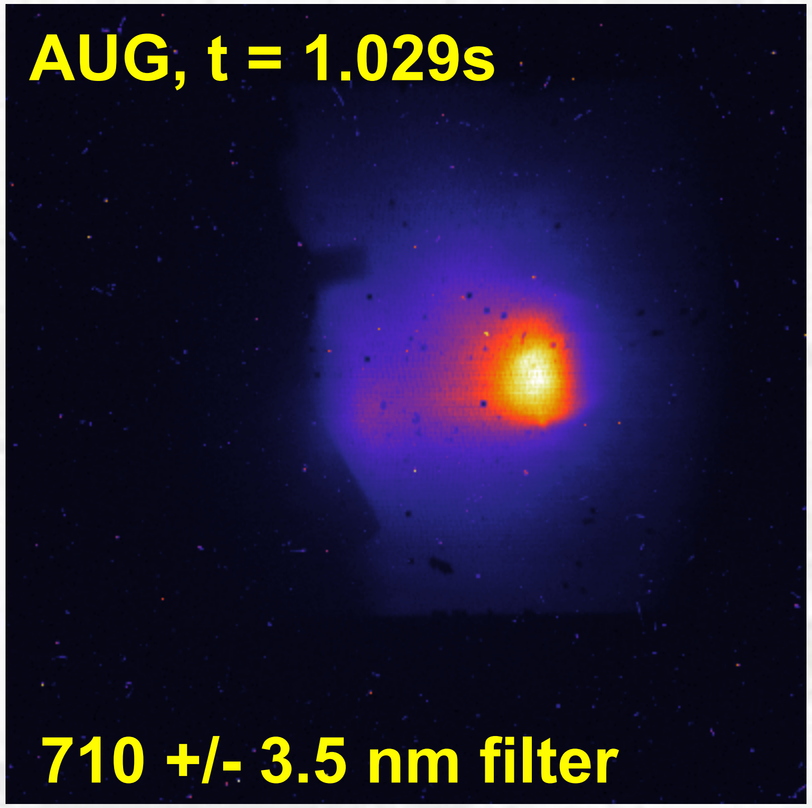


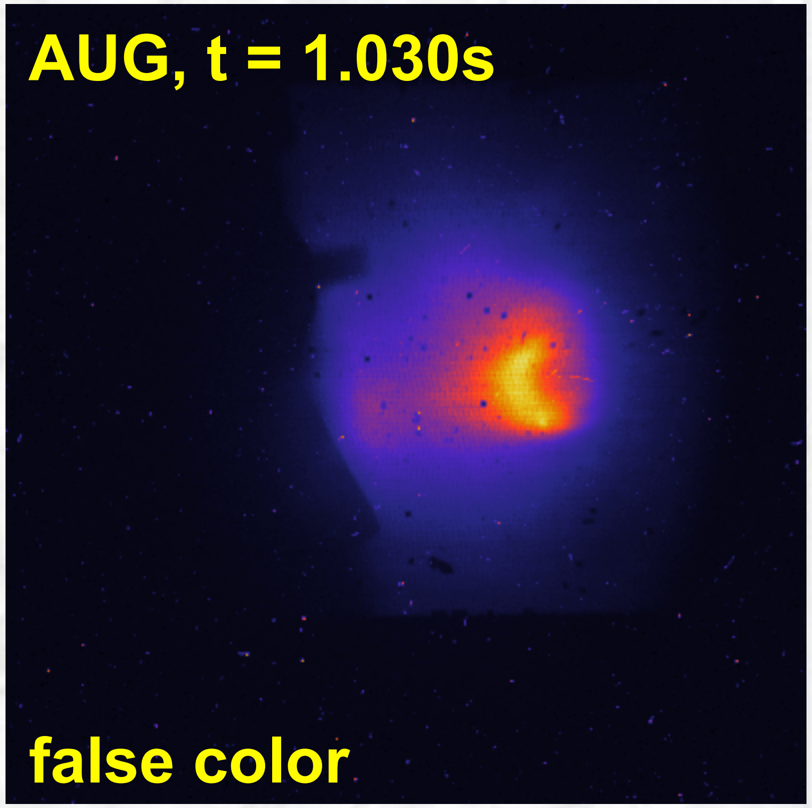


Reconnection in the RE beam

- **m/n=1/1 reconnection** event is sometimes observed in the RE beam stage [Pautasso PPCF 2019, Hoppe EFTC 2019]
- **Sudden change in synchrotron spot shape**
  ➡ Oval to crescent in < 1ms
- Indication of change in the runaway distribution
  ➡ But which aspect?

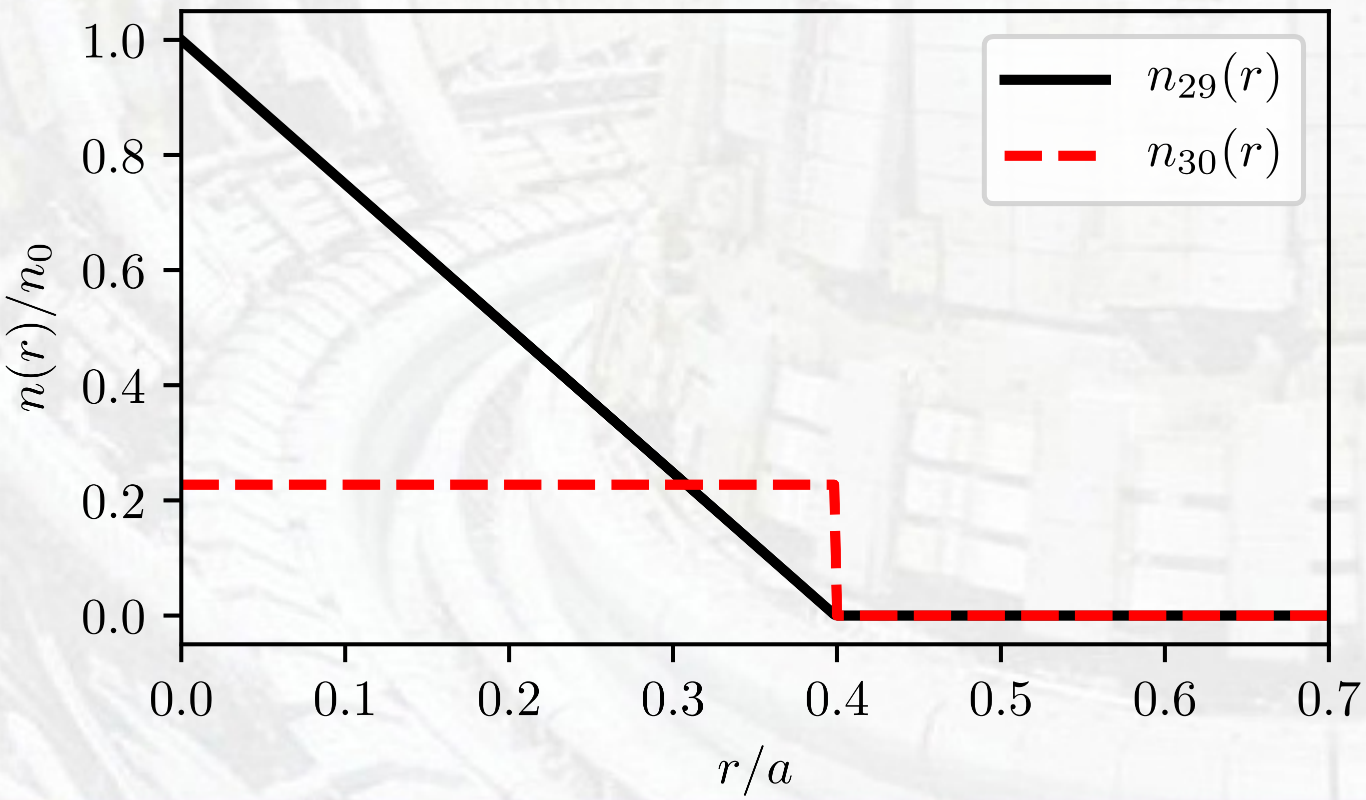


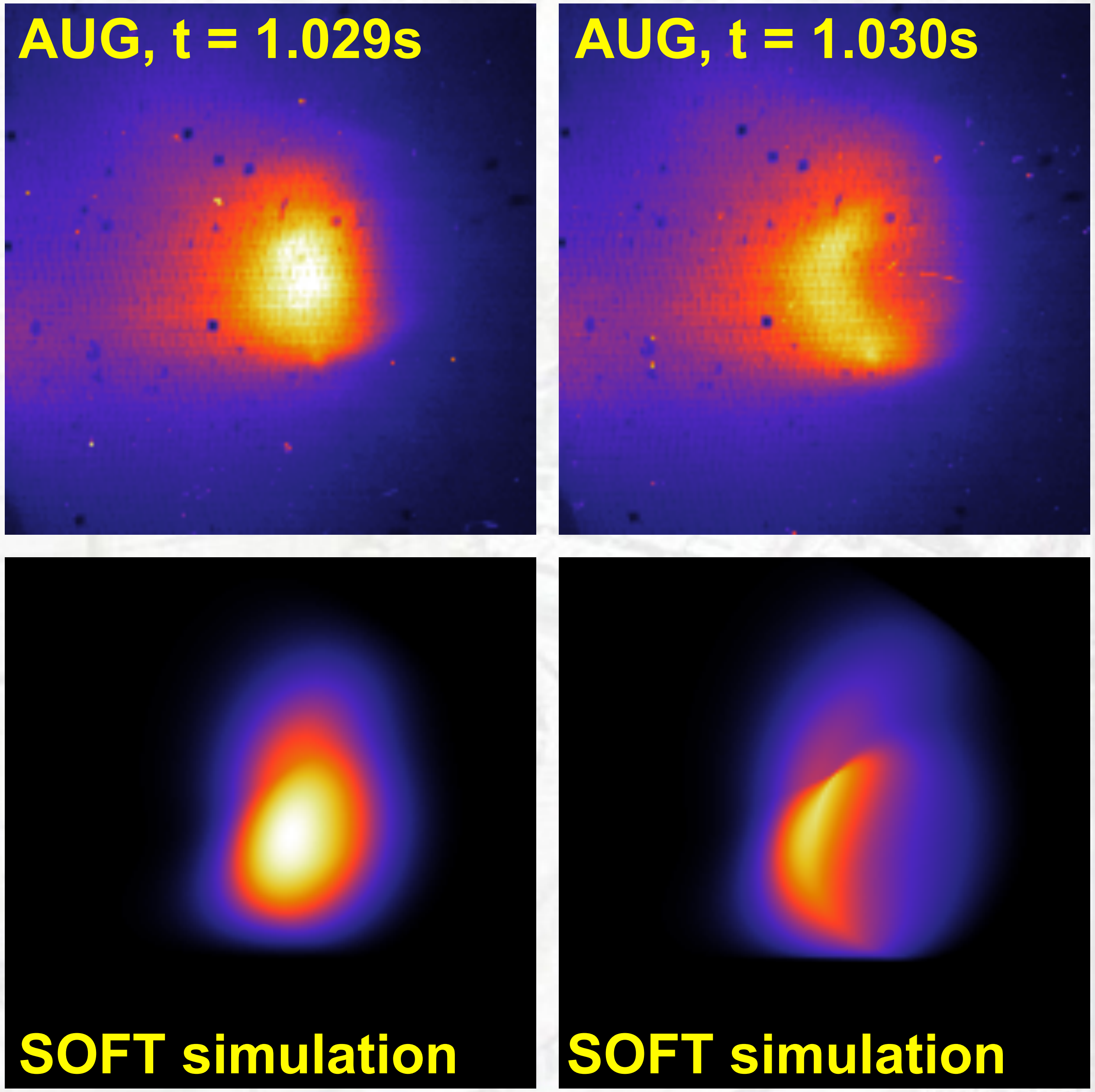




Reconnection in the RE beam

- SOFT [Hoppe NF 2018] forward modeling of synch. emission "Superparticle" energy + pitch distribution
- **Good qualitative match found**
  - ➡ **Current profile flattening explains the spot shape change**
  - ➡ Estimate of RE beam size





Summary

- ITER & beyond needs reliable & robust RE physics model validated with experimental data
- **AUG & TCV: datasets provided on parameter scalings**

  ➡ **Isotope, density, shaping, temperature, q_{95}, wide range of type & quantity of MMI material, etc**
- Reduced models useful for large-scale parameter scans, but further development is necessary

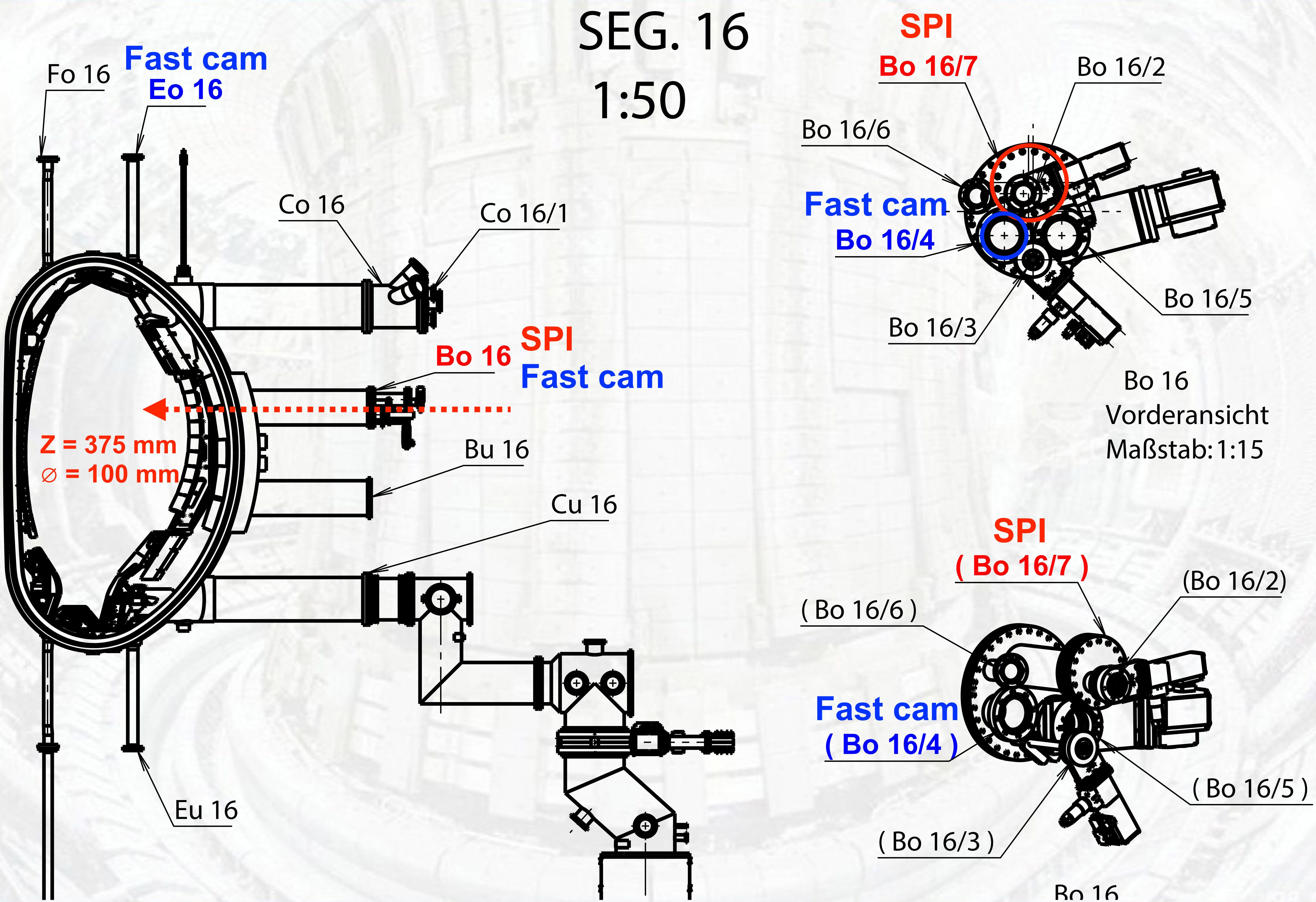
  ➡ Penetration of neutrals, 2D/3D effects, MHD, ...
- QM+kinetic models well describe the interaction of relativistic electrons and partially ionized high-Z impurities

  ➡ Higher level modeling provides insight into distribution
- **Future: aid the development of non-MGI DM systems, such as Shattered Pellet Injection**

AUG SPI plans

- **ITER-IPP collaboration to install SPI on AUG in 2020/21**
  - ➡ **Goal: Test different shattering angles on the plasma**
  - ➡ Tight timeline: ~2y long shutdown planned for upper divertor installation in ~late 2021, have to finish SPI project before
- **3(+1?) shattered tubes planned, shatter angles not yet decided**
  - ➡ 3-view fast video system (toroidal, upper, radial)
  - ➡ Upgraded bolometry (diodes & foils in 5 sectors)
- Experiments & analysis is expected in broader teamwork

AUG SPI plans



AUG SPI plans