Recent results of analysis of runaway electron experiments at ASDEX Upgrade

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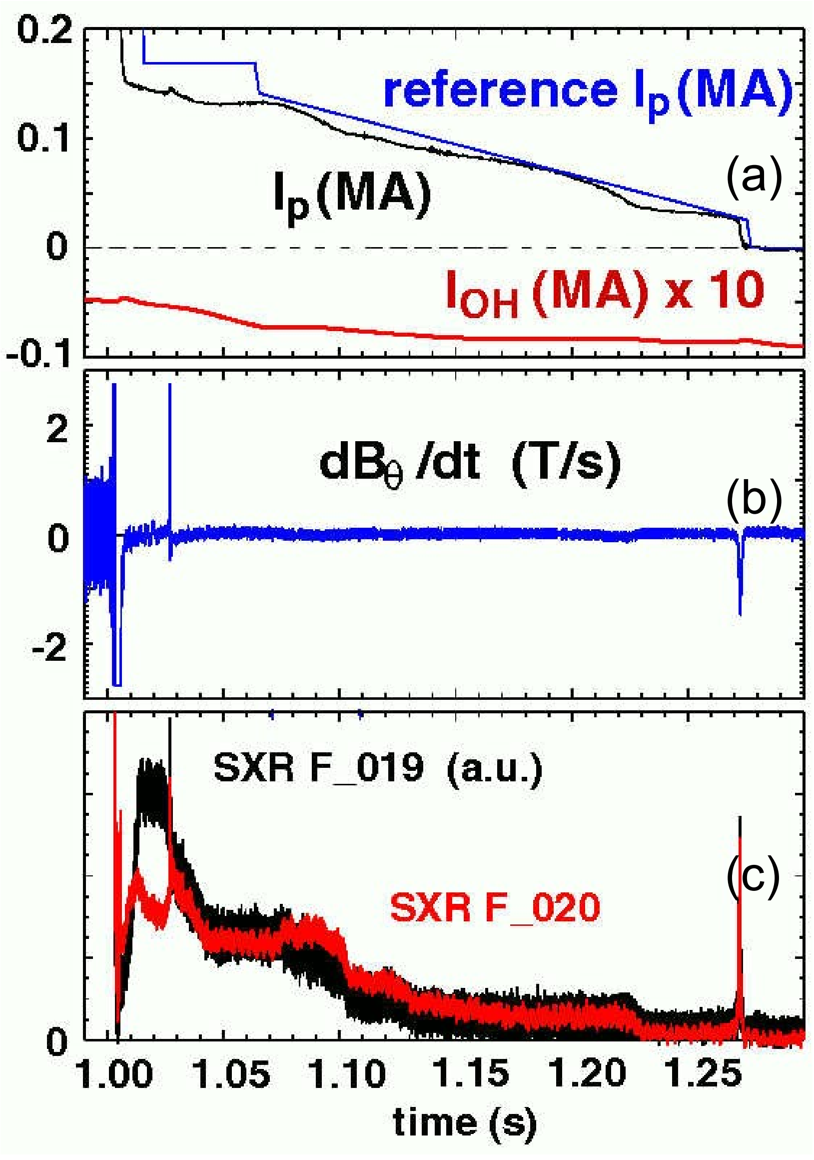
Introduction

- ASDEX Upgrade (AUG): no runaway electron (RE) experiments in last year (water leak in Dec. 2017, restart in July 2018) → further analysis of past exp.s
- Well diagnosed experiments on existing tokamaks are indispensable for validation of RE generation and suppression models, which can then be used for simulation of reactor scenarios
- Quest for RE loss mechanisms during both thermal quench (TQ) and RE beam lifetime, and ways to enhance losses are being pursued
- This talk is about
    - how to pin down origin of RE current (loss or generation) scatter in similar discharges?
    - why 2nd high-Z gas injection is effective for RE suppression in medium-sized tokamaks but not in JET?

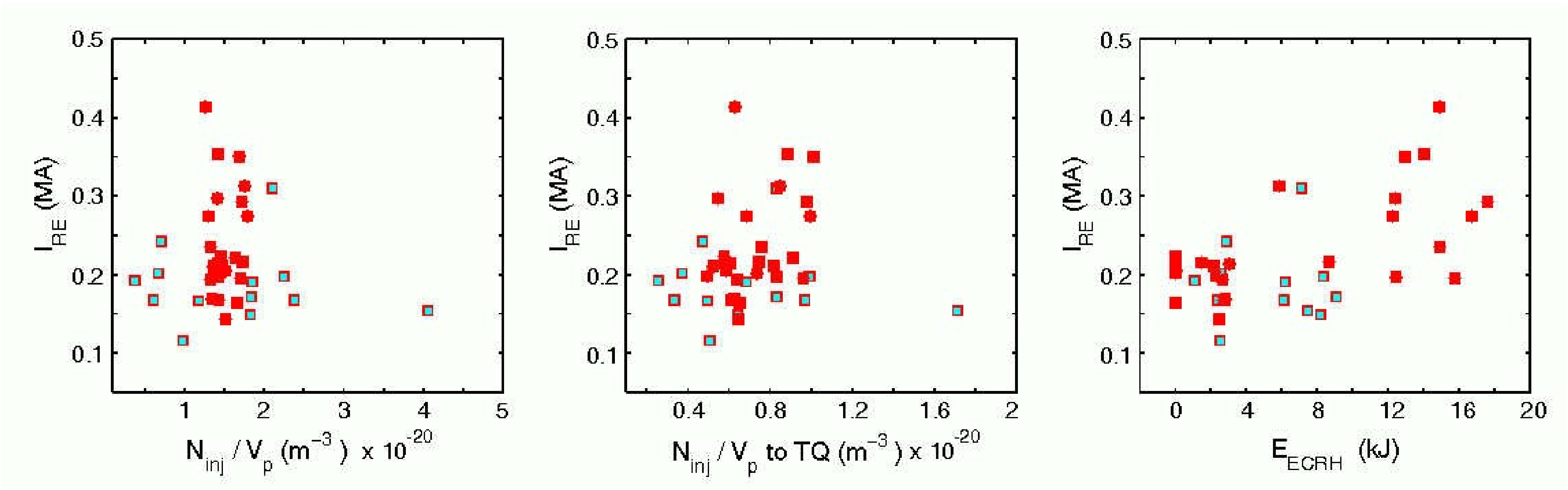
    (both questions will remain questions)

AUG scenario for RE experiments

- First exp.s in 2014
(~ 80 discharges by now)
- otherwise uninteresting target plasma: circular, low n_e, B_t ~ 2.5 T, P_{ECRH} ~ 2 MW, I_p = 0.8 MA
- RE beam (I_{RE} < 400 kA for < 500 ms) is reliably generated with argon puff
- toroidal current is controlled
- plasma has been mostly vertically stable and w/o MHD activity
- use of RMPs not discussed



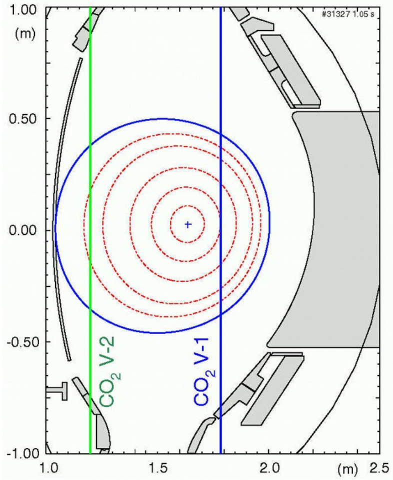
Origin of RE current “scatter”?

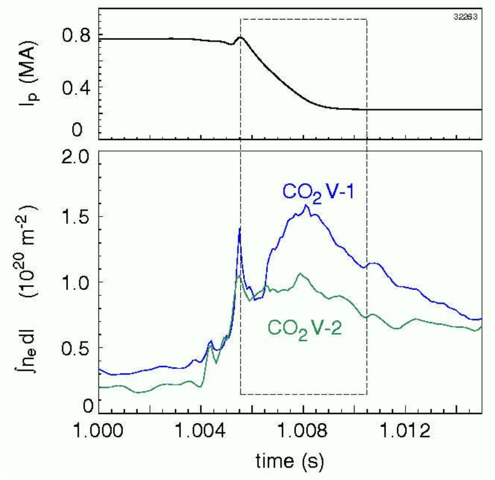


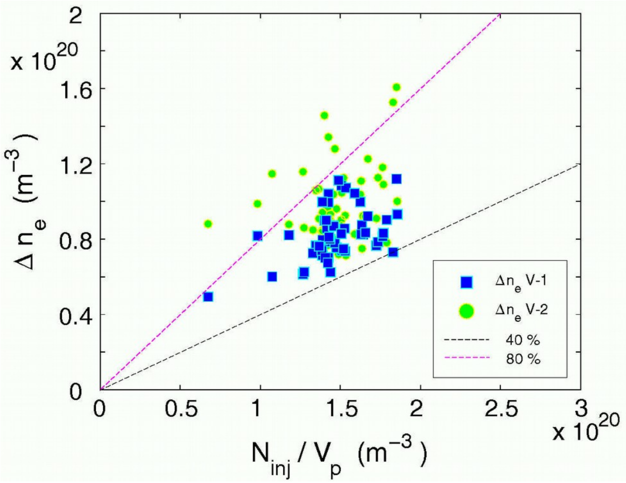
- Set of similar discharges, only 1st MGI, argon amount (N_{inj}) varied
- I_{RE} versus (left) N_{inj} per plasma volume (V_p), (center) N_{inj}/V_p during pre-TQ and (right) ECRH energy injected (and absorbed?) after beginning of pre-TQ
- No other parameter dependence found (pre-TQ time, Δl_i, ΔI_p, equilibrium ...)

Density measurements

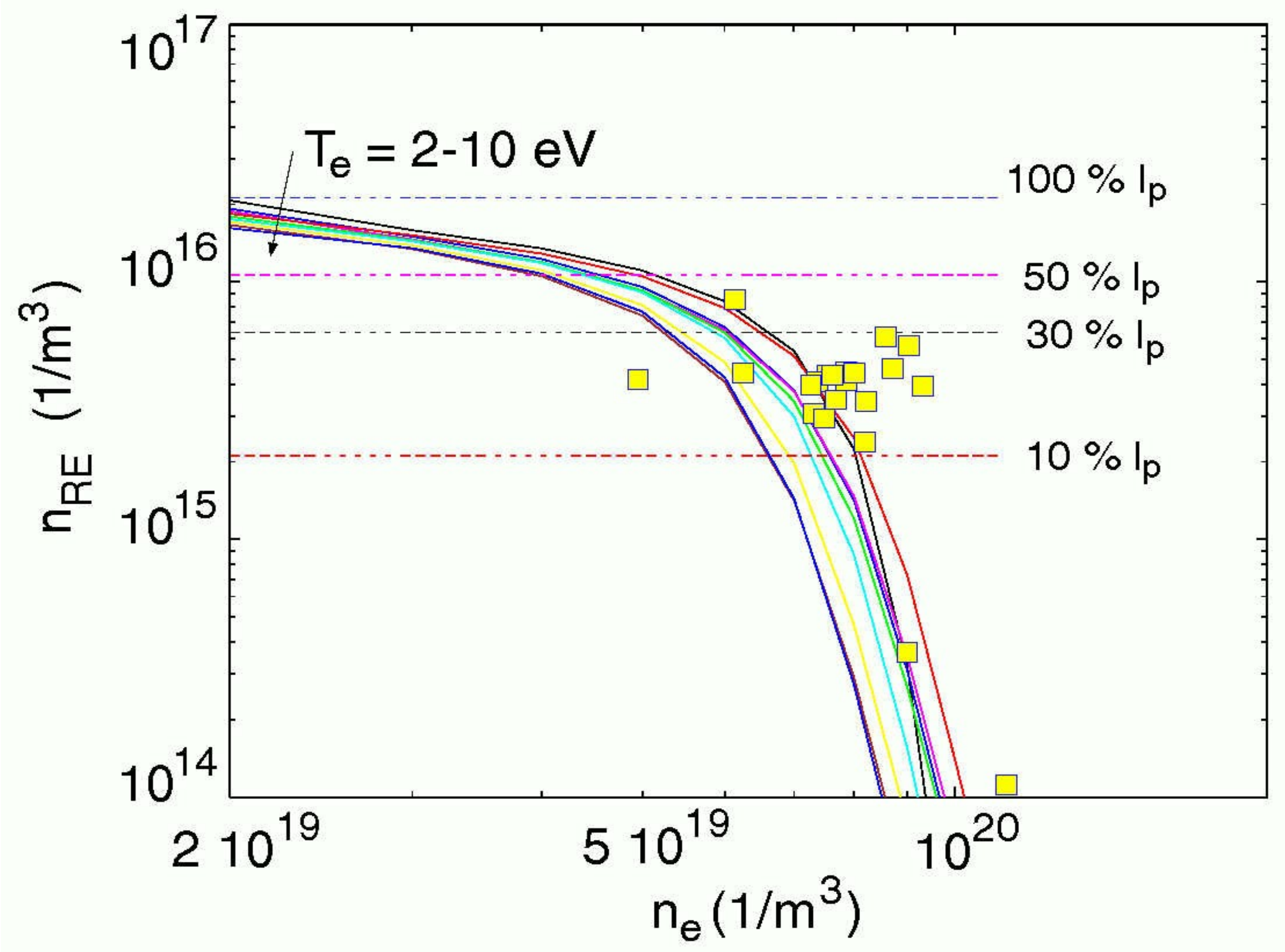
- RE generation/suppression depend strongly on local densities (n_e, n_I, Z, Z_{eff})
- no detailed density profiles during fast CQ (~ 2 ms)
- n_e from CO_2 interferometer V-1 chord on AUG – used as proxy for n_e seen by REs



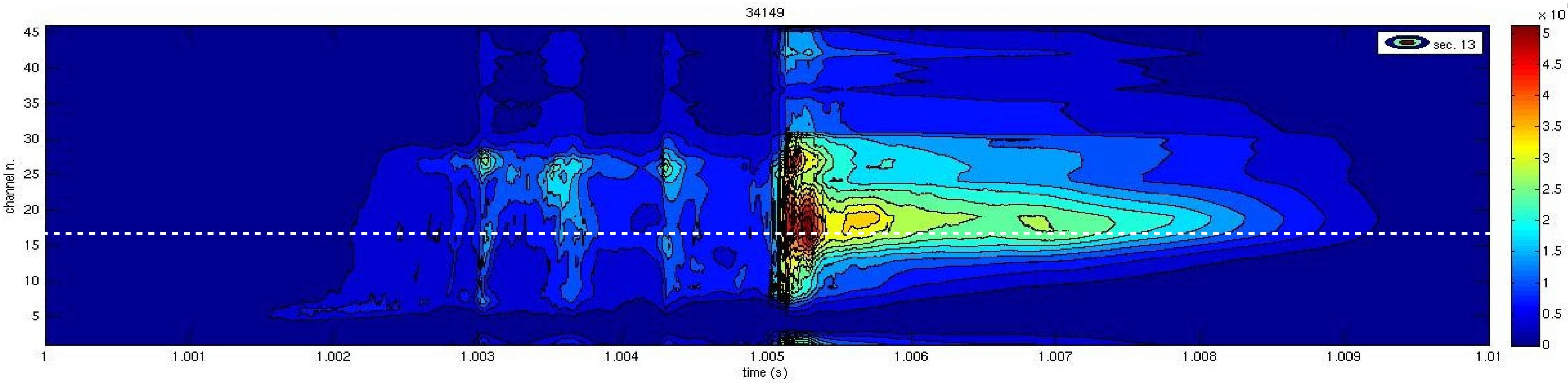




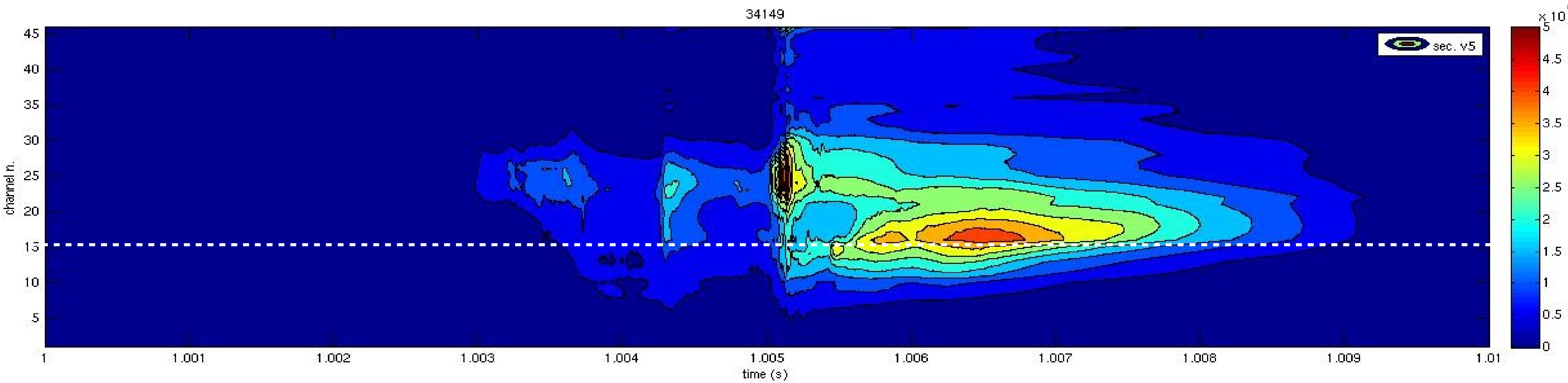
I_{RE} versus n_e and T_e

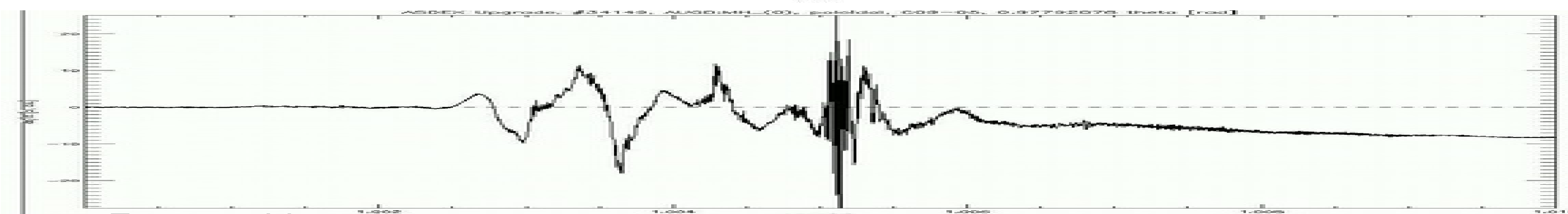


RE current calculated with 0-D model for several n_e, argon density and T_e, values (lines with different colours) and experimental measurements (yellow squares)



Plasma radiation, top-down view, sectors $\Delta\phi=\pi$

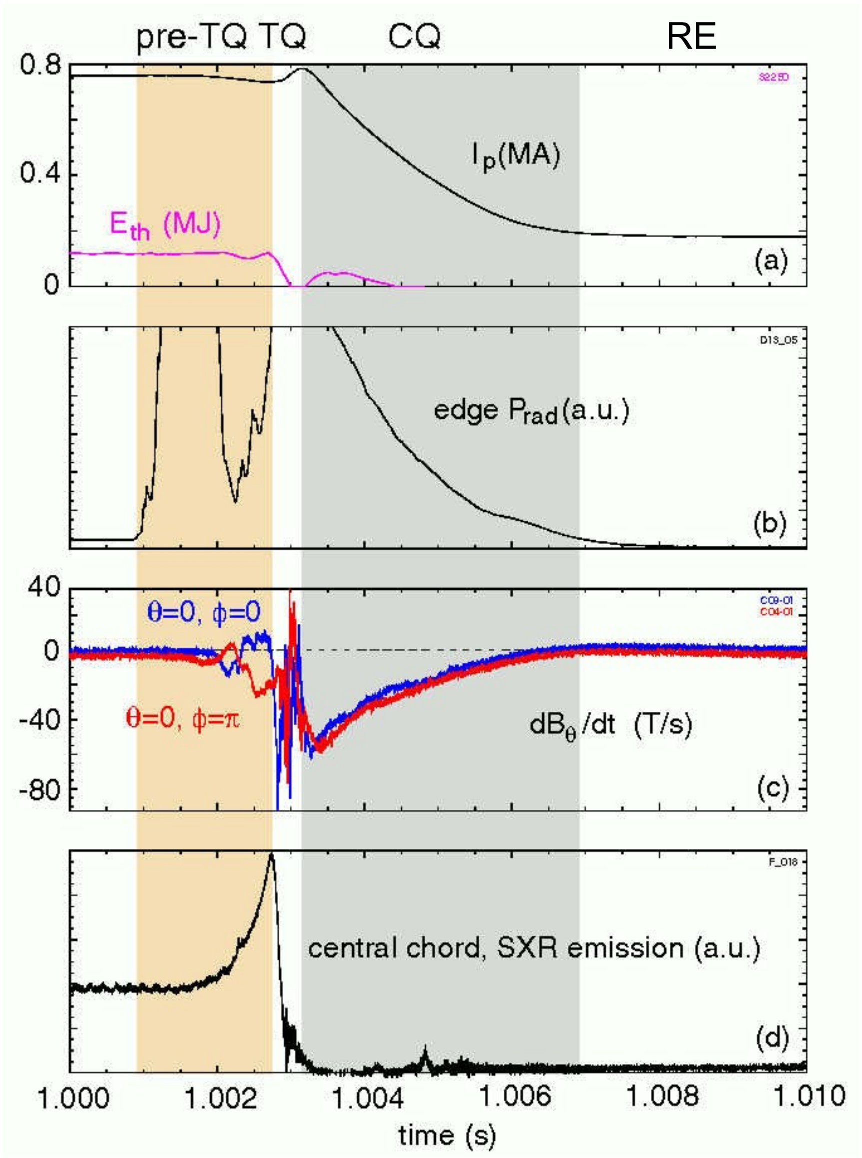


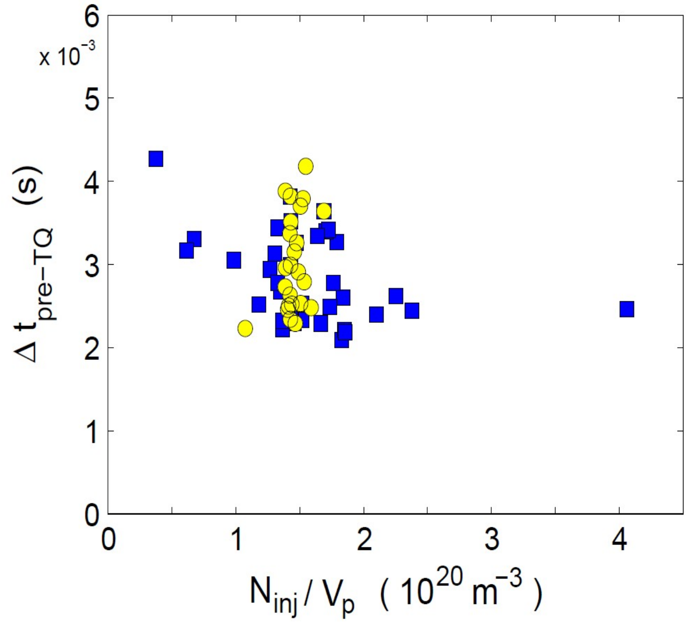


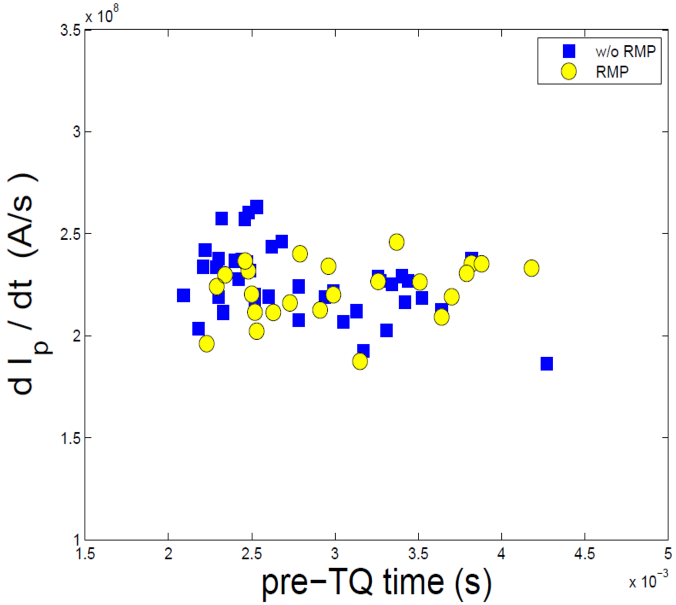
Fast poloidal coil measurement

TQ fast CQ

Duration of disruption phases, scatter, → I_{RE}







0D RE generation and suppression model

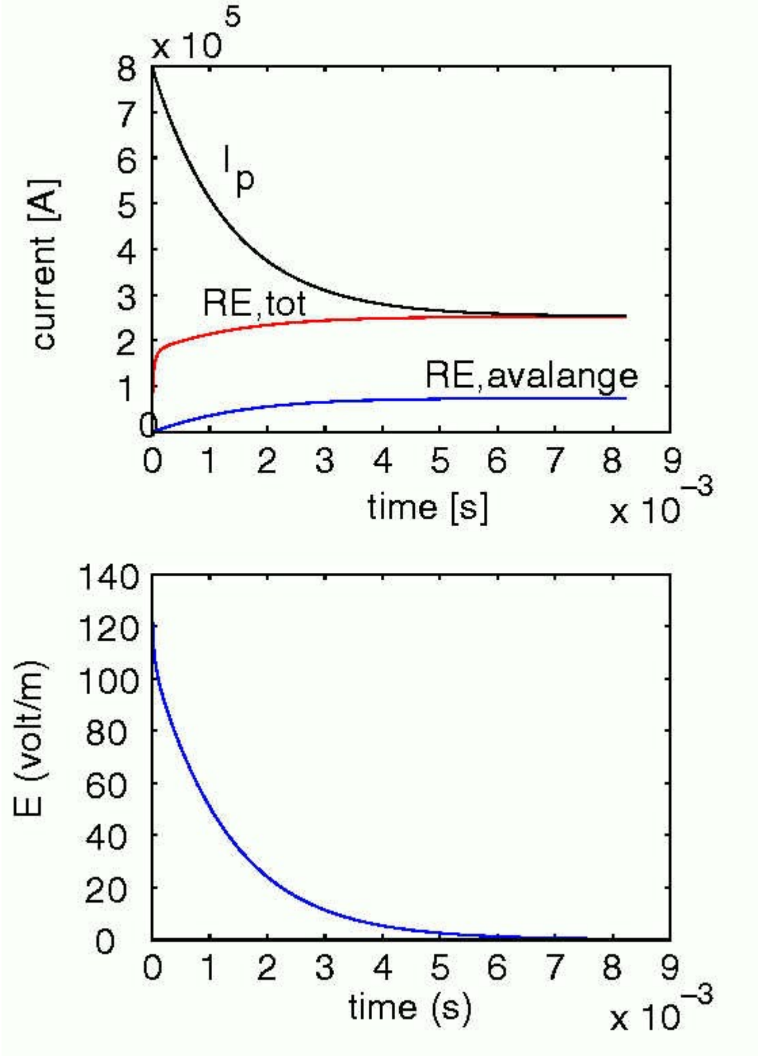
$$E = -\frac{dI_p}{dt}\frac{L}{2\pi R_0}F_{mag}$$

$$E = \rho\left(j_p - j_{RE}\right)$$

$$\frac{dn_{RE}}{dt} = \left[\frac{dn_{RE}}{dt}\right]_1 + \left[\frac{dn_{RE}}{dt}\right]_2$$

$$j_p = I_p/\left(\pi a^2 k\right)$$

$$j_{RE} = I_{RE}/\left(\pi a^2 k\right) = c\,e\,n_{RE}$$



n_e = 6e19 / m^3 n_D= 2e19 / m^3 T_e = 3 eV

neither losses nor hot-tail; 1 = primary generation; 2 = avalanche + impurities

T_e and Z_{eff} from 0D model

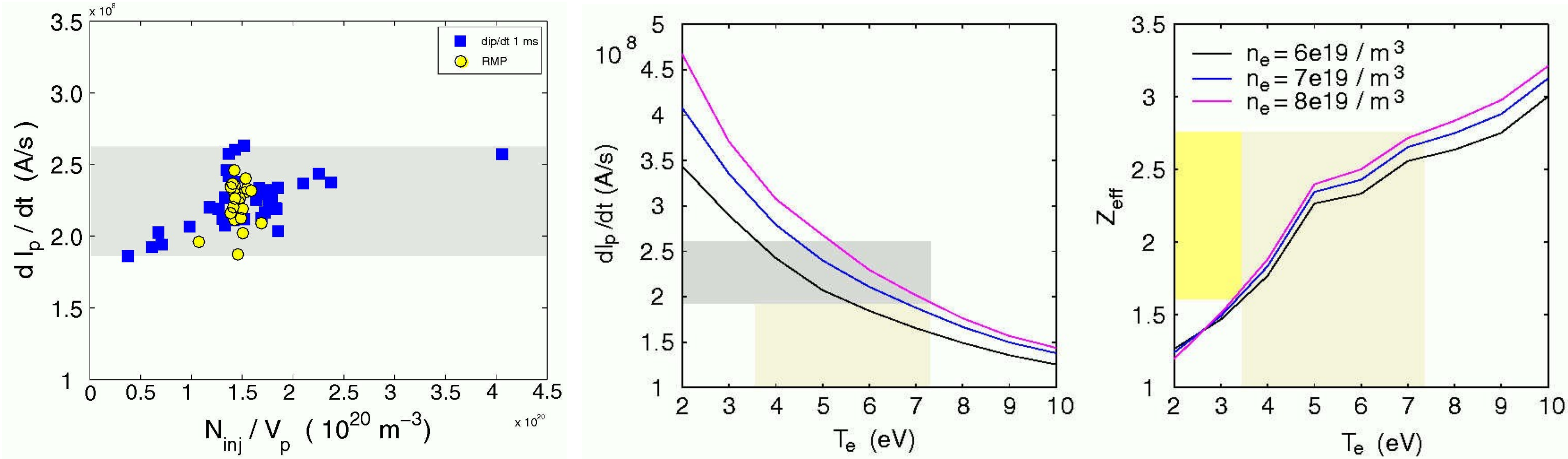
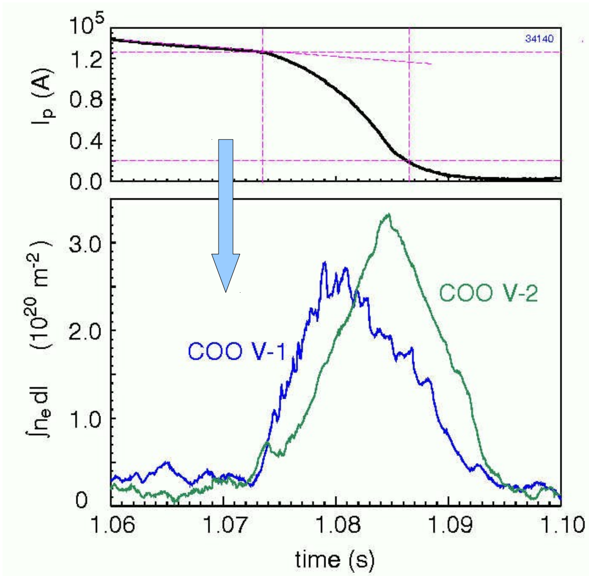


Fig. left: Measured fast I_p decay rate after TQ

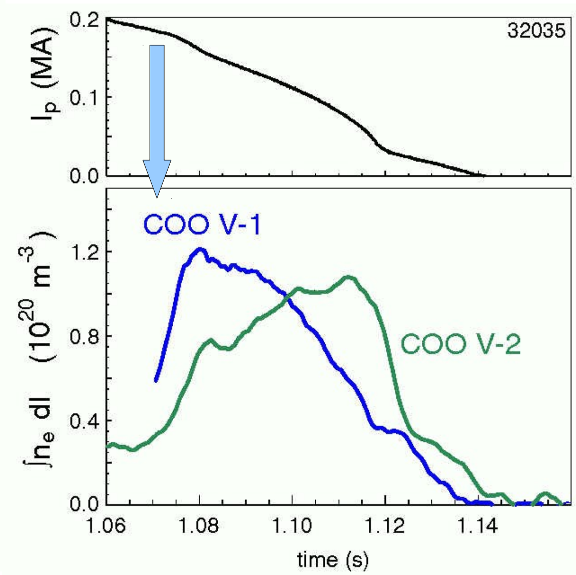
Centre: calculated I_p decay versus T_e

Right: calculated effective charge (Z_{eff}) versus T_e

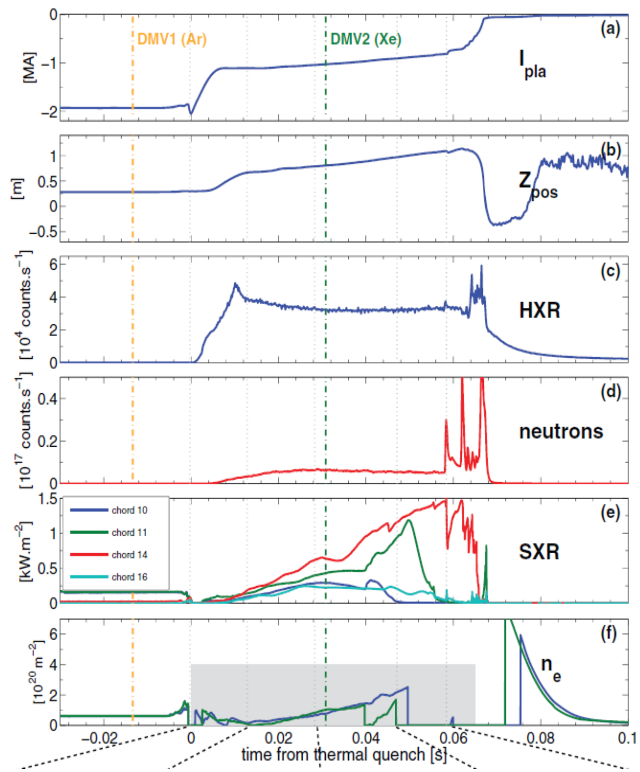
MGI injection (2^{nd}) in RE beam



argon (AUG)



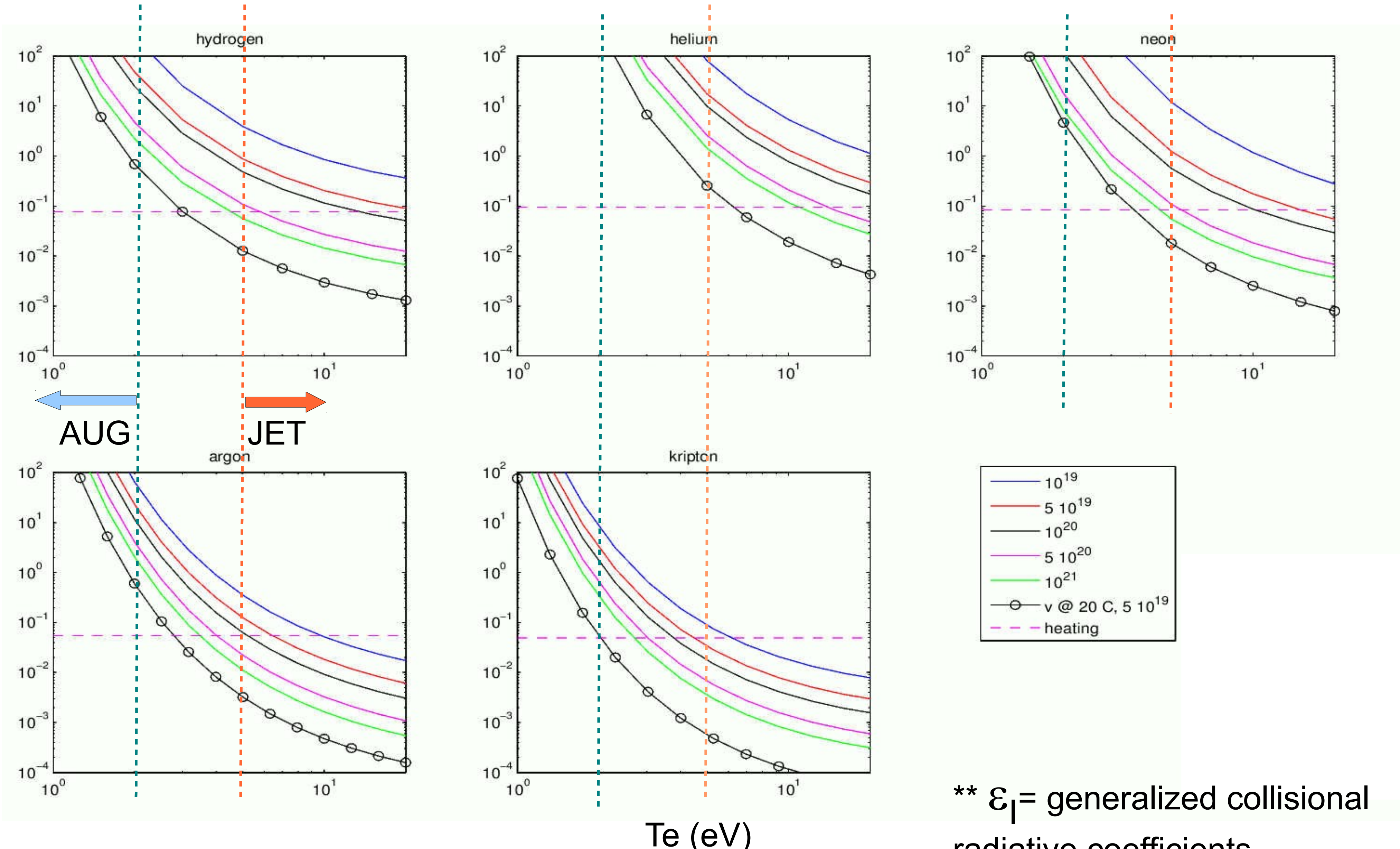
neon (AUG)



xenon (JET) **

- high Z gas dissipates RE current in AUG, immediate effect (ms); effect consistent with collisional dissipation → *= trigger time*
- no significant effect in JET (30 ms) ***C. Reux et al, Nuclear Fusion 55 (2015)*
- note: background plasma T_e < 2 eV in AUG; T_e ~ 5-15 eV in JET *(C. Reux et al, TSDW 2017)*
- note: $d(n_e)/dt$ measured reflects particle flow from valve

Ionization mean free path, $mfp_i = v_{th,I} / (\varepsilon_I \, n_e)$ (m) **



** ε_I= generalized collisional radiative coefficients

Gas diffusion into RE beam

The diffusion equation in cylindrical coordinates

$$\frac{\partial n(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r D(r,t) \frac{\partial n(r,t)}{\partial r} + S(r,t) \qquad (1)$$

was solved explicitly by the finite difference method and the assumptions

$$D_i = \rho_i^2 \, \nu_{ii}, \qquad \rho_i = \frac{m_i \, v_{\perp,i}}{e Z_i B_t}, \qquad v_{\perp,i} = \sqrt{2}\, v_{th,i} = \sqrt{2\, T_i/m_i}, \qquad [14] \qquad (2)$$

$$\frac{1}{\nu_{ii}} = \tau_{ii} = 12\pi^{3/2} \frac{\epsilon_0^2 m_i^{1/2} T_i^{3/2}}{n_i Z_i^4 e^4 ln\Lambda_{ii}} \qquad [14], \qquad (3)$$

$$ln\Lambda_{ii} = 23 - ln(\frac{Z_i^3}{T_i}\sqrt{\frac{n_i}{T_i}}), \quad T_i \ in \ eV \qquad [15] \qquad (4)$$

and a source of particles at the plasma edge of intensity

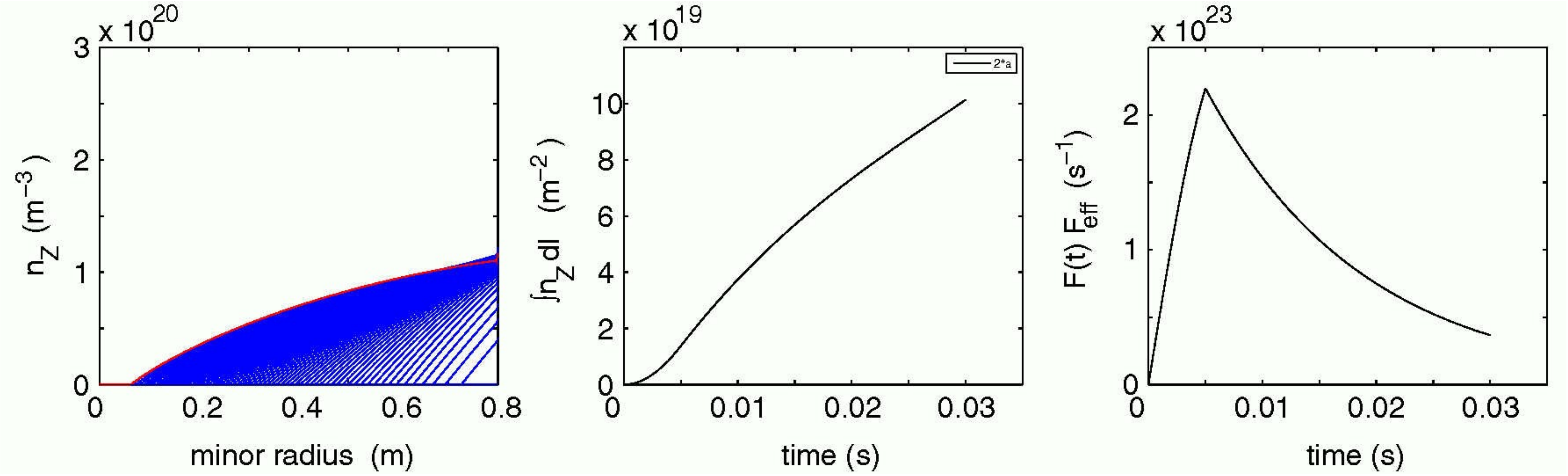
$$S(r,t) = \frac{F(t)}{4\,\pi^2 a\, R_0}\, \delta(r-a)\, F_{eff} \qquad (5)$$

were $F(t)$ is the gas flow from the valve, F_{eff} is the fueling efficiency, a and R_0 are the minor and major radius of the circular plasma.

[14] J. Wesson, Tokamaks

[15] NRL plasma formulary

High Z gas diffusion into JET RE beam



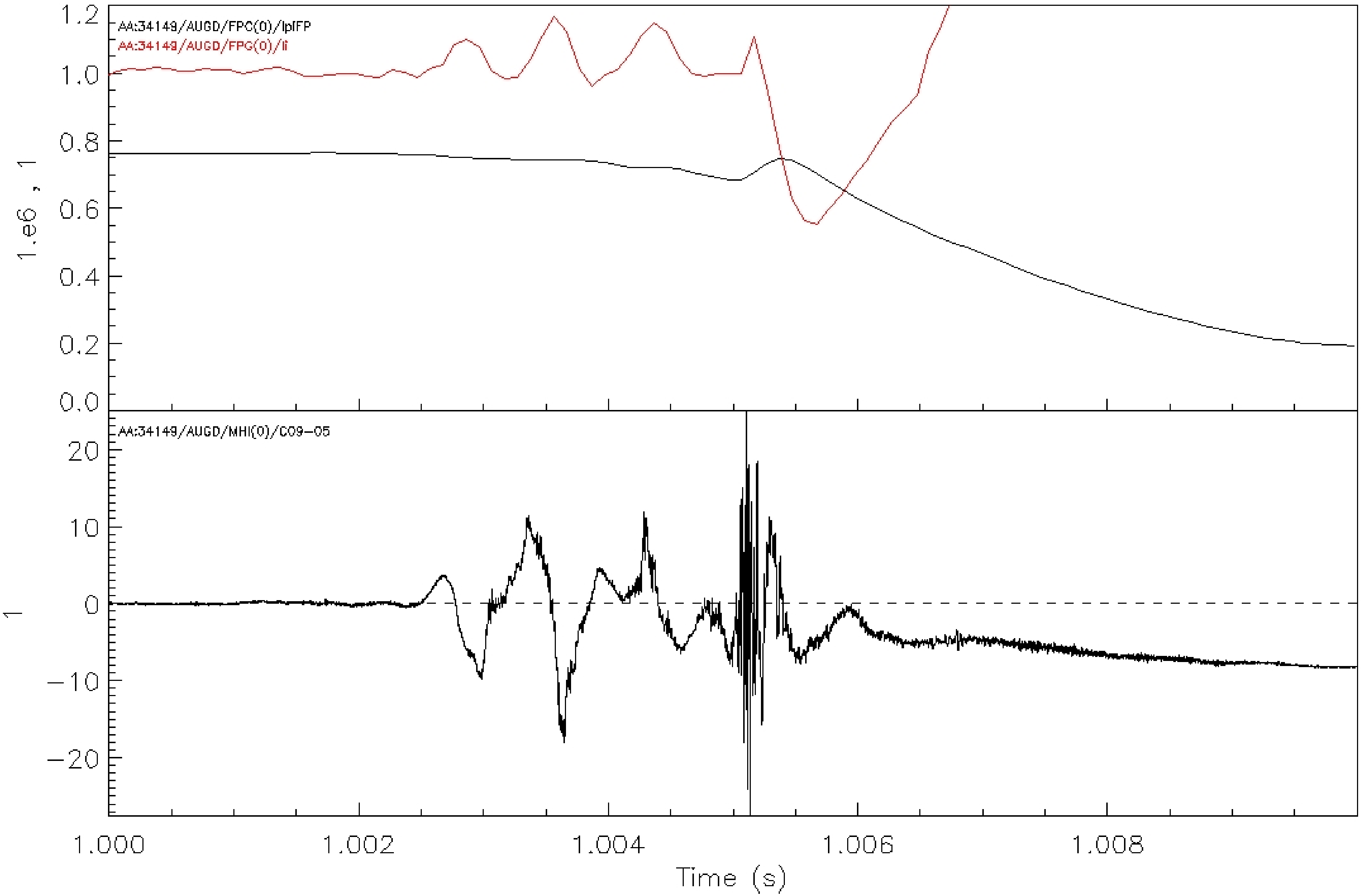
- JET RE beam like, injection of 2472 Pa×m^3 xenon *C. Reux et al, Nuclear Fusion 55 (2015)*
- T_e = 5 eV and Z_{Xe} = 3; 30 ms run
- DMV2 vol. = 9.75 10^{-4} m^3, diameter orifice = 30 mm (Kruezi SOFT 2014)
- **F_{eff} = 0.6 %** (to approximate n_e measured – from publication)
- <u>small F_{eff} is limiting gas penetration towards RE beam</u>

Summary

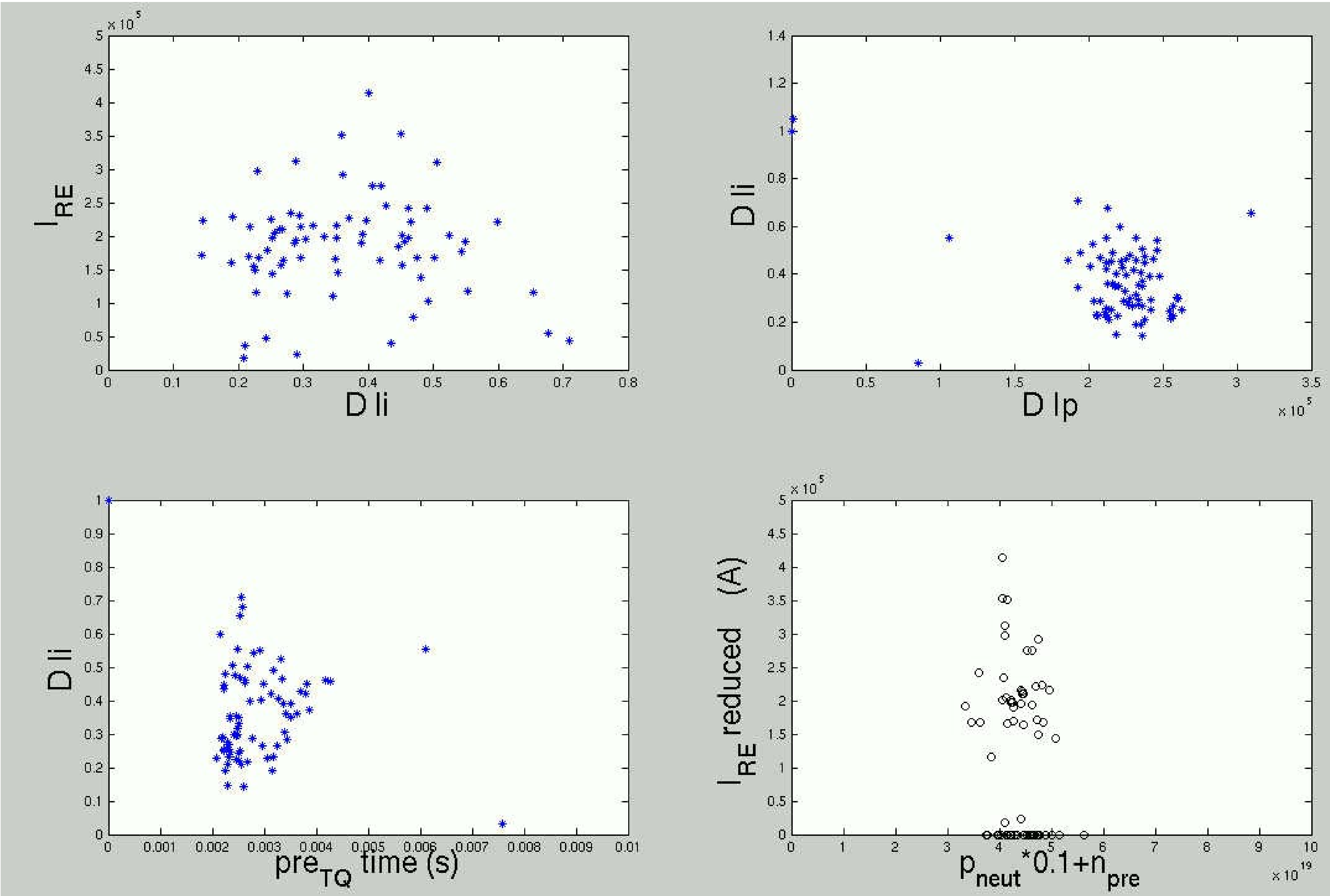
- Scatter of I_{RE}after argon-induced disruptions and lack of N_{inj} dependence motivated (1) careful analysis of density measurements and (2) calculation of RE generation with simple 0-D fluid model
- Within uncertainties affecting density profile, experimental measurements fall into ballpark of calculated I_{RE}; scatter difficult to explain

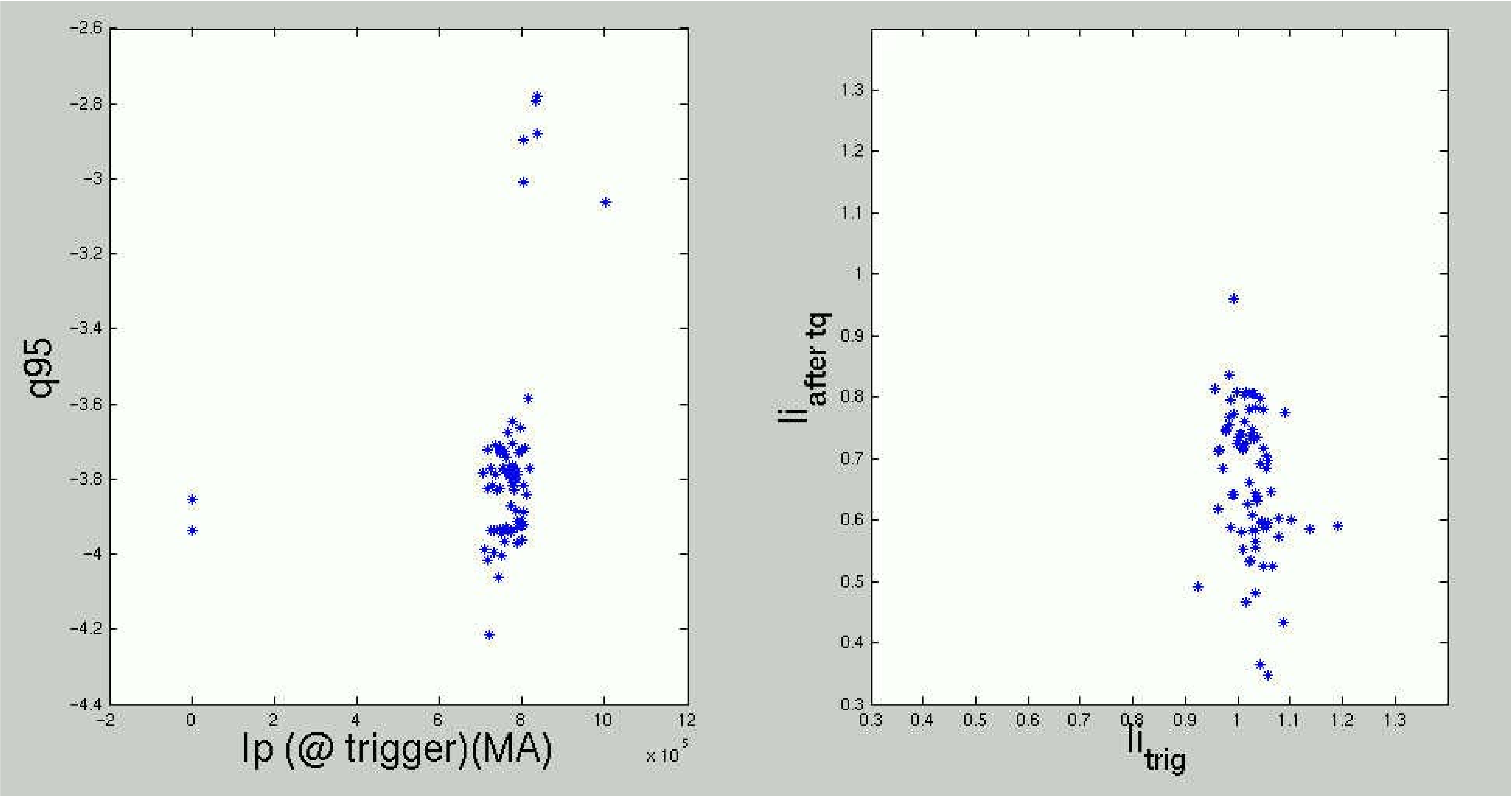
- In AUG, RE beam background plasma has $T_e < 2$ eV → it is transparent to injected impurities
- JET plasma is has hotter plasma (7 eV) → gas injected must diffuse from edge into core
- Nevertheless, gas assimilation and not (or not only) diffusion limits effectiveness of 2nd high Z MGI

Additional slides

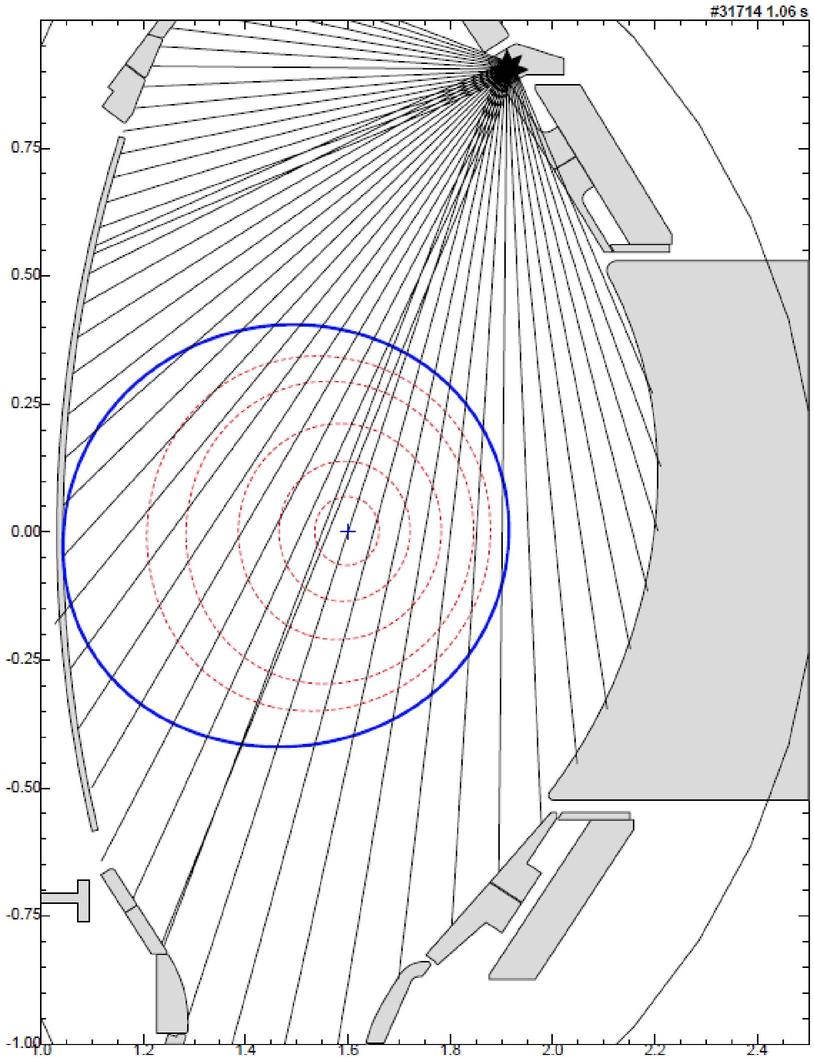


AA:34149/AUGD/FPC(0)/IpIFP
AA:34149/AUGD/FPG(0)/li
1.e6 , 1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
AA:34149/AUGD/MHI(0)/C09-05
1
20
10
0
−10
−20
1.000
1.002
1.004
1.006
1.008
Time (s)


x 10^5
I_RE
D li
D li
D Ip
x 10^5
D li
pre_TQ time (s)
x 10^5
I_RE reduced (A)
p_neut*0.1+n_pre
x 10^19



q95
Ip (@ trigger)(MA)
x 10^5
li after tq
li trig


#31714 1.06 s
0.75
0.50
0.25
0.00
-0.25
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-0.75
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1.0
1.2
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1.8
2.0
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