Disruption mitigation studies at ASDEX Upgrade in support of ITER

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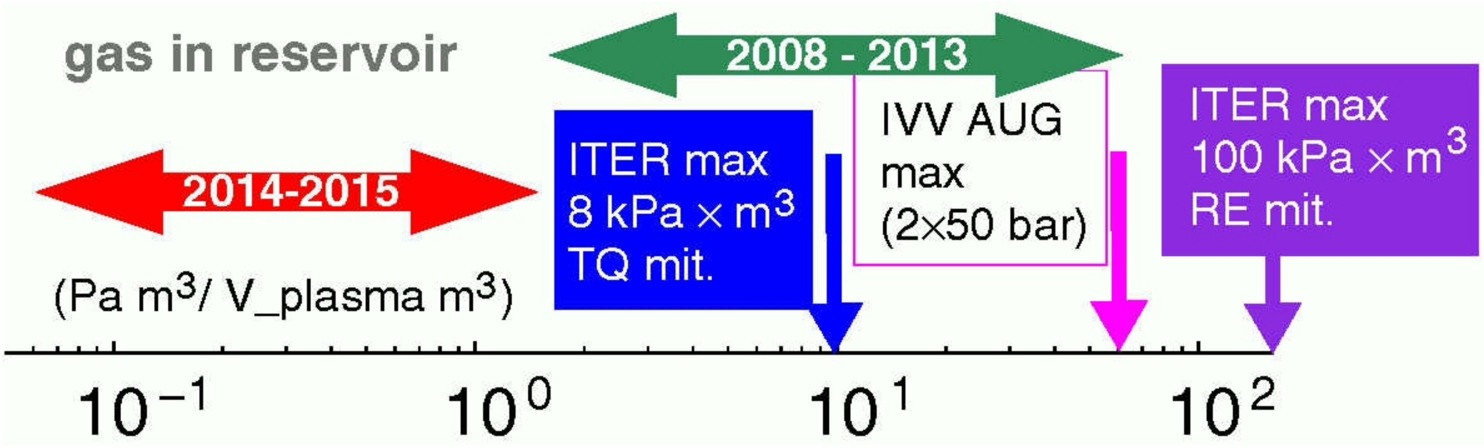
Content

- Experimental scenarios and rational behind
- interpretation of pre-thermal quench
- force mitigation in MGI(*) induced plasma termination;
  focus on small gas quantities
- thermal load mitigation
- runaway electron generation and losses;
  focus on MGI suppression

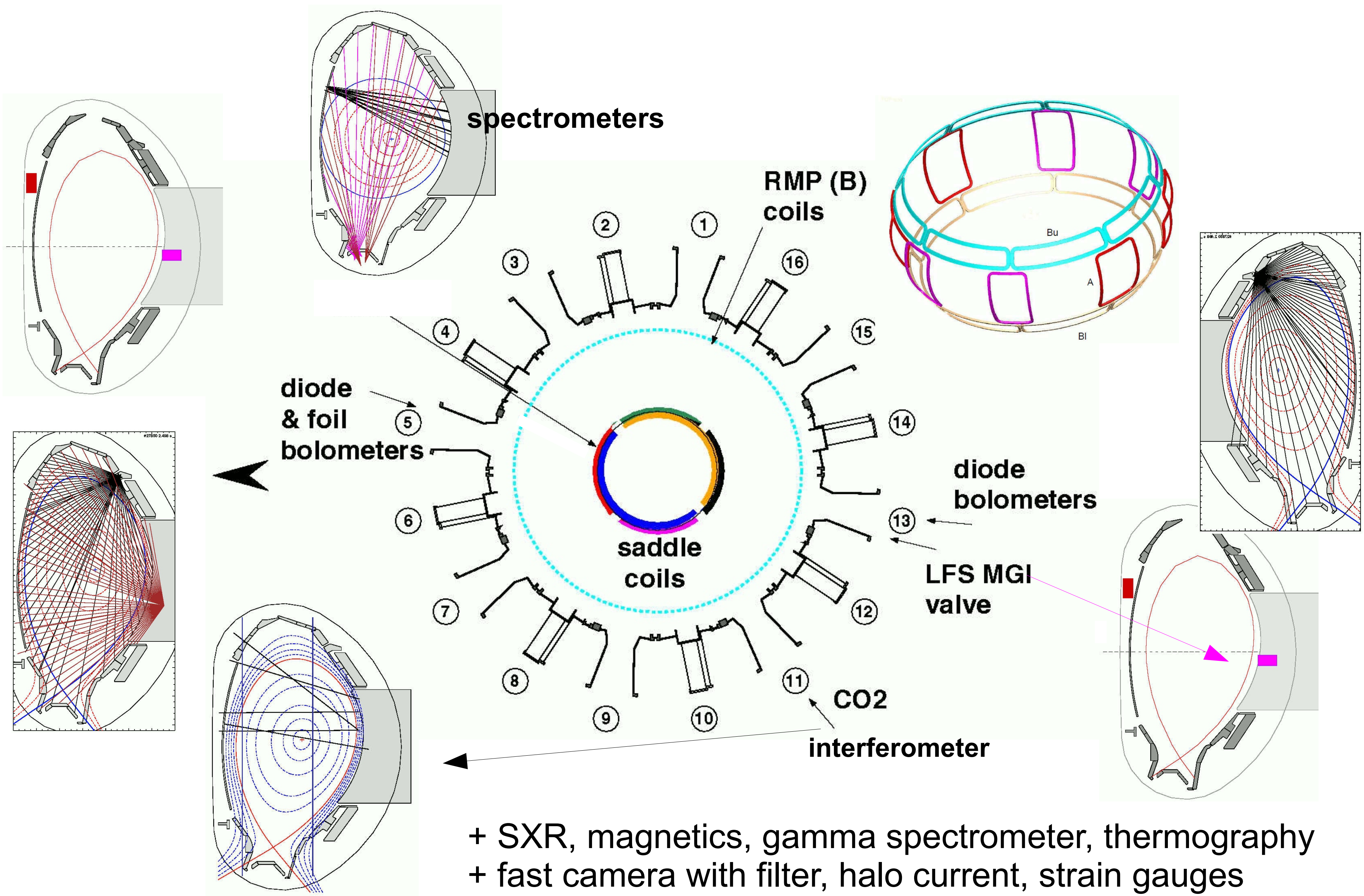
(*) MGI = massive gas injection

Background



- *2008-2013:* MGI exp.s in AUG aimed at reaching $n_e \sim n_c \sim O\,(10^{22})\,/\,m^3$ during or just after TQ for RE suppression
- poor impurity assimilation at large N_{inj} → attempts to reach n_c abandoned
- ITER DMS consists now of several injectors for TQ & force mitigation + RE suppression
- **TQ: Minimum impurity amount for force & thermal load mitigation?**
- **CQ: Is control and/or suppression of REs possible?**

AUG: Mitigation valves, relevant diagnostics and coils



+ SXR, magnetics, gamma spectrometer, thermography
+ fast camera with filter, halo current, strain gauges

Thermal quench (TQ) and force mitigation: Experimental conditions

2014 – 2015:

- $N_{inj} = 10^{20}$-10^{22} atoms neon with one or two in-vessel valves
- mitigated shut-down evolution?
- I_p ~ 1 MA (E_{mag} ~ 1.4 MJ)
- E_{th} = 30 - 750 kJ
- q_{95} ~ 4.2

results discussed in terms of pre-TQ and CQ times →

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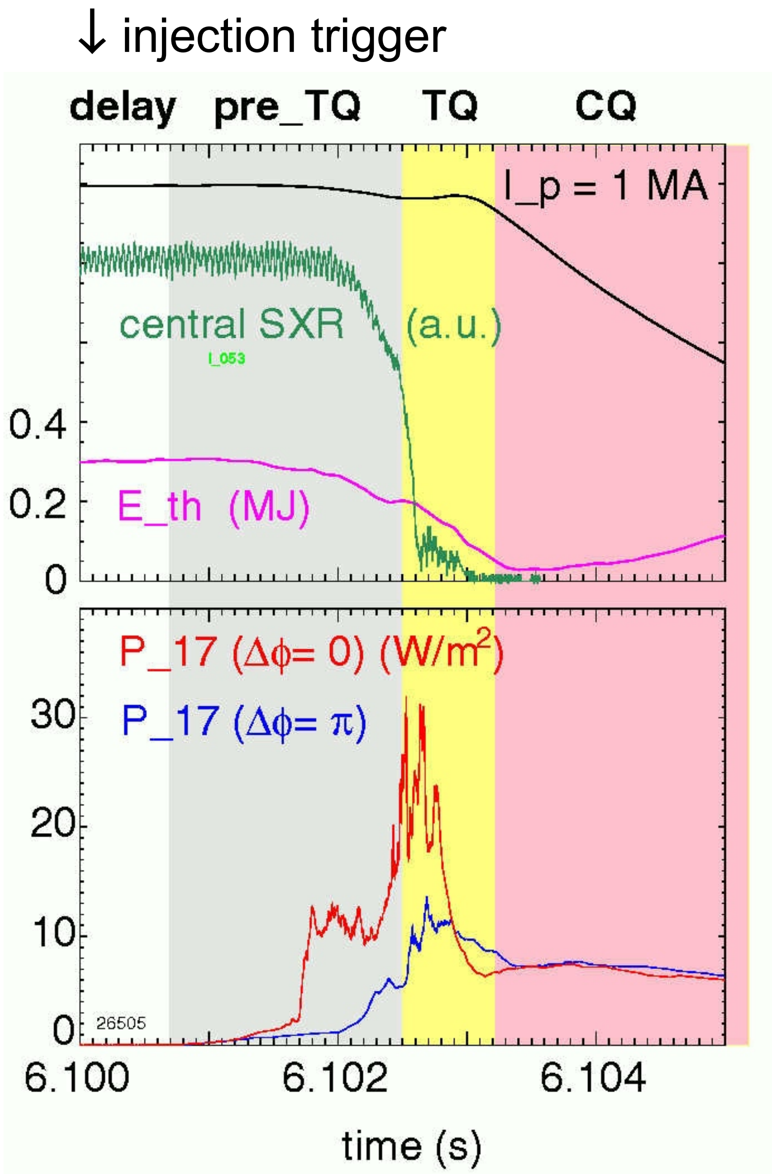
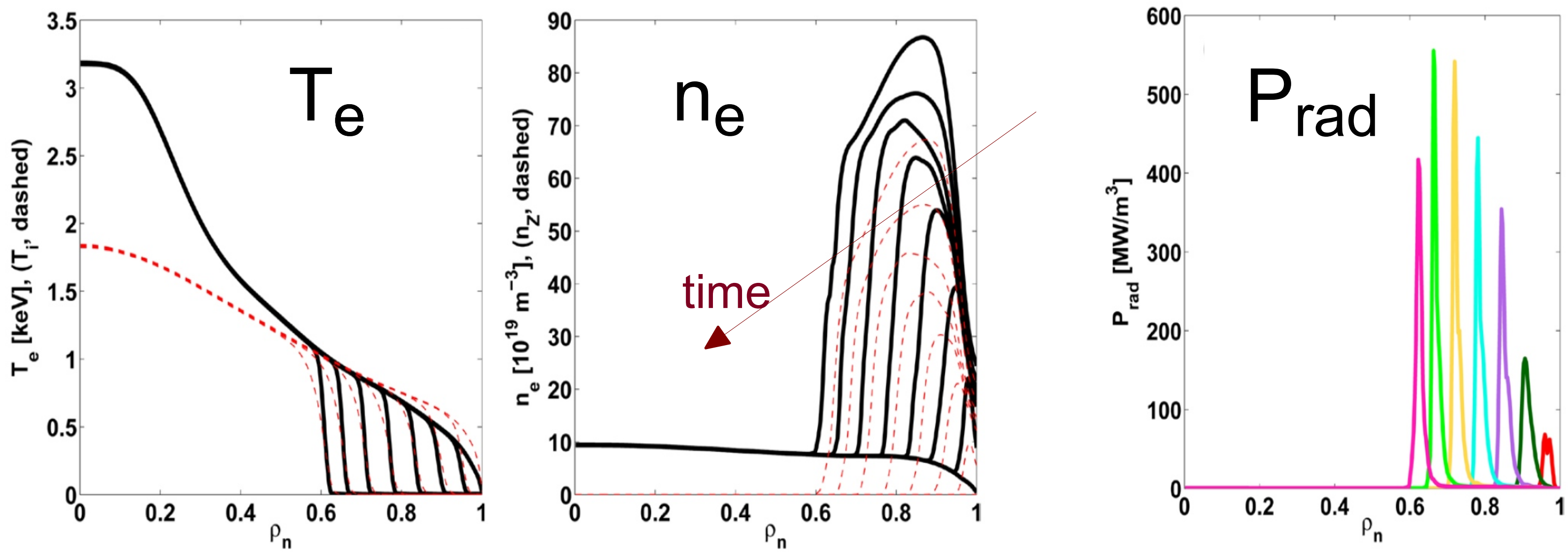


Simulation of pre-TQ

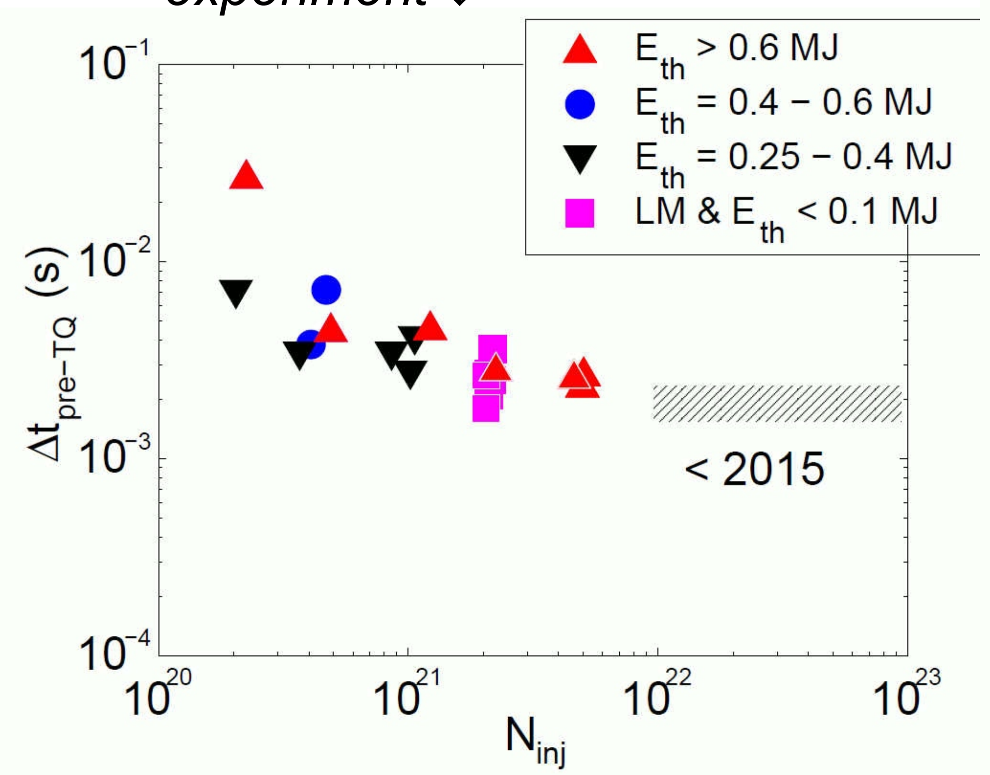
- ASTRA-STRAHL 1-D transport (current, energy, densities, radiation) code + SPIDER 2-D equilibrium E. Fable et al, NF (2016)
- P_{rad} radially localized; impurity layer radiates
  → saturation of pre-TQ time as N_{inj} increases
- reproduces cold front penetration velocity (not shown)



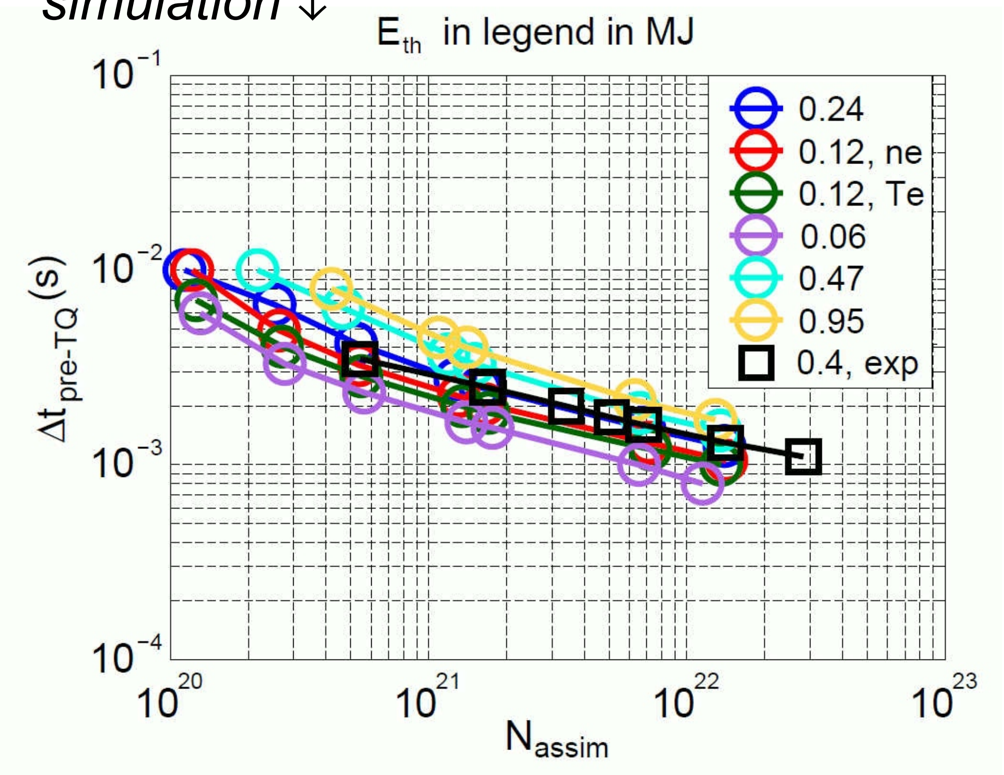
Pre-TQ phase: experiment versus simulation

- TQ onset in ASTRA: T_e at q=2 surface < 5 eV
- comparison experimental times with ASTRA simulations (neon)
- correct N_{inj} and E_{th} dependence

experiment ↓

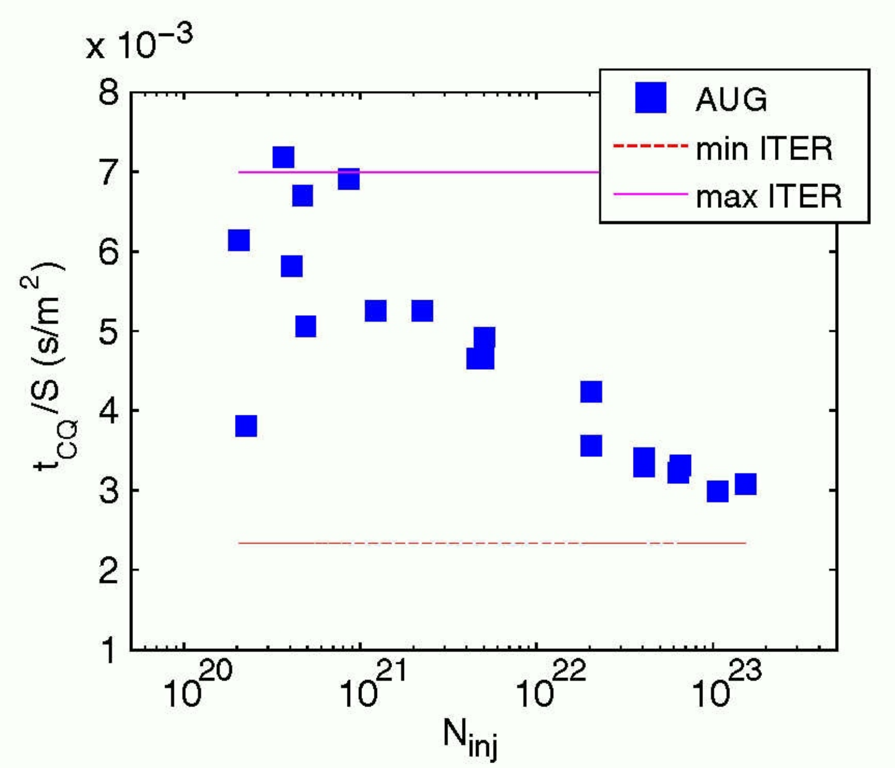


simulation ↓



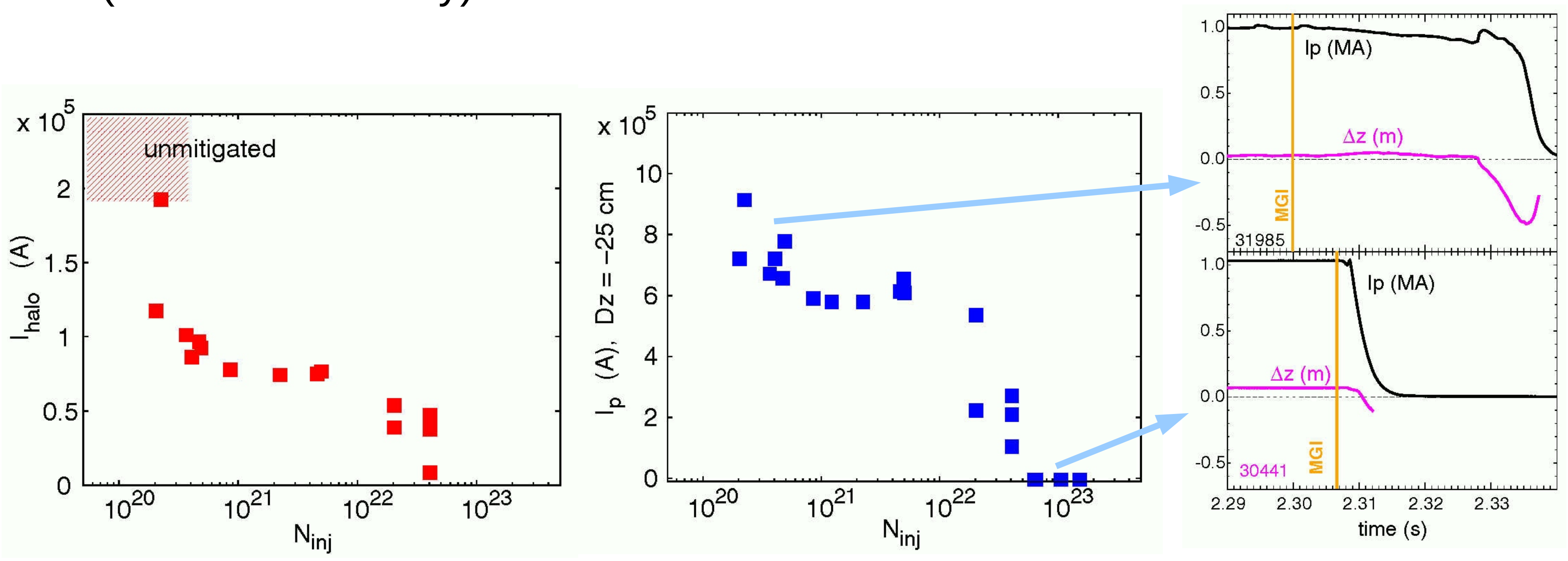
Current quench duration, Δt_{CQ}

- Δt_{CQ} is a design parameter for ITER (Δt_{CQ} = 50 – 150 ms)
  $\rightarrow$ magnitude of eddy currents, vertical force, E_ϕ generating REs
- $P_{rad} \sim - dE_{mag} / dt \rightarrow \Delta t_{CQ} / S \sim$ resistivity
  (S = plasma cross section)
- AUG Δt_{CQ}/S within prescribed
  ITER Δt_{CQ}/S range



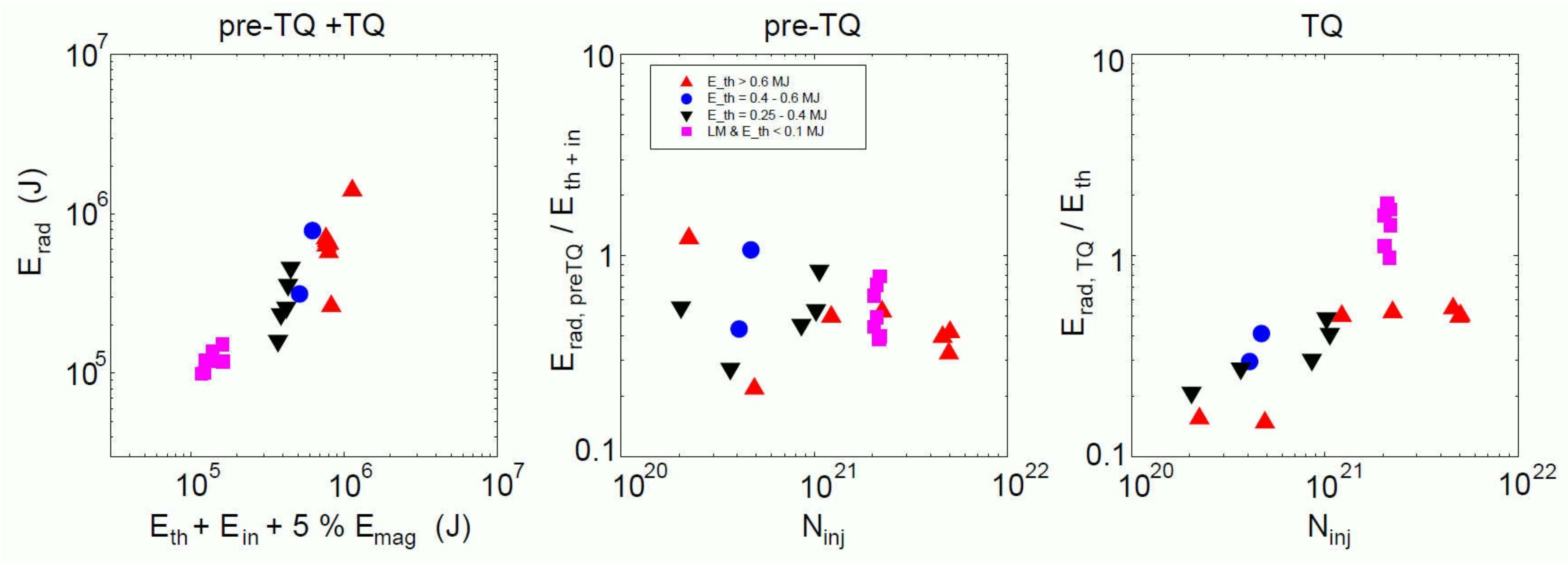
Halo current (I_{halo}) mitigation

- Loss of plasma position control after TQ → vertical force on vessel
- I_{halo} x B_t = large component of vertical force
- stepwise behavior ↔ I_p after Δz = 25 cm (competition Δz - ΔI_p)
- simulations needed for extrapolation to ITER
  (ITPA MHD activity)



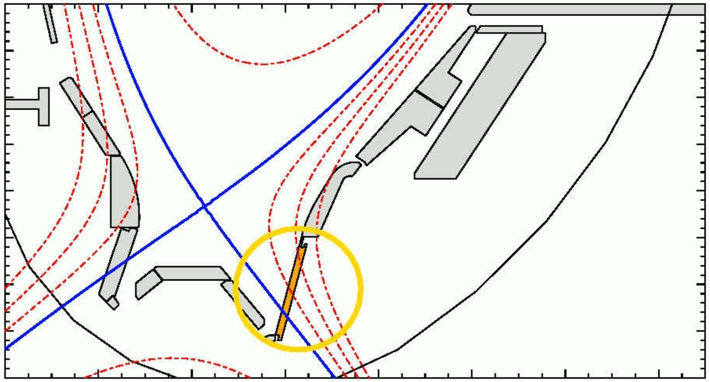
TQ mitigation: radiated energy

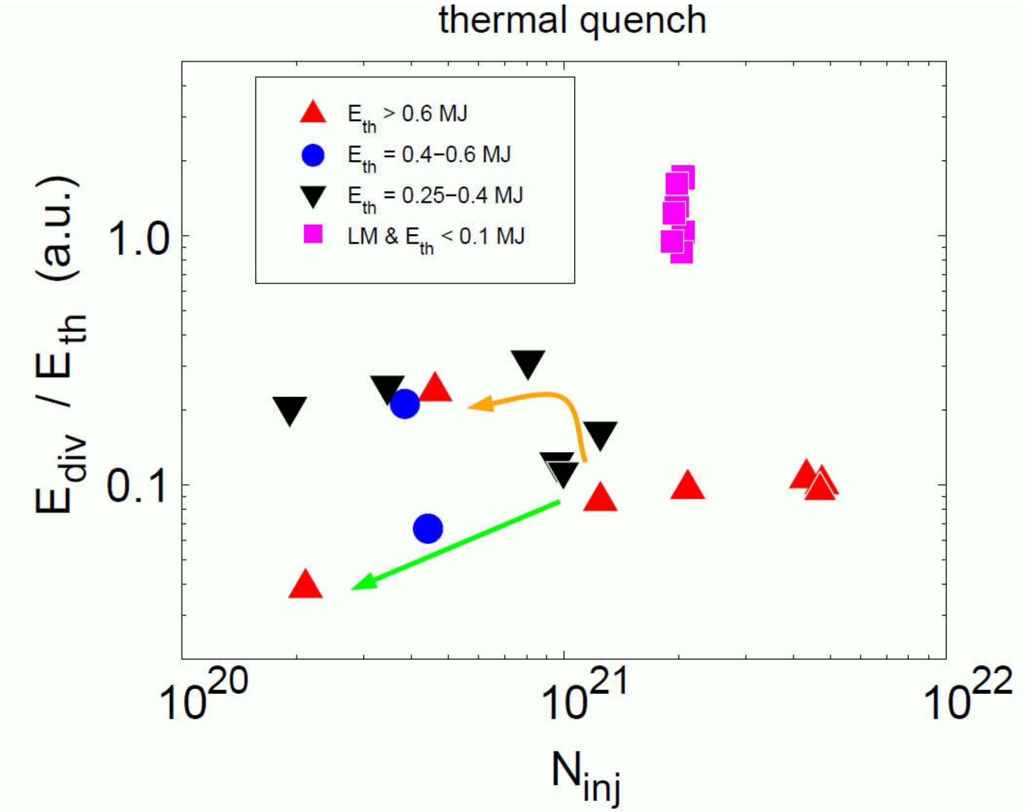
- Repartition radiated/deposited energy as N_{inj} decreased?
- E_{rad} ~ (E_{th} + E_{in} + 5 % E_{mag}) in pre-TQ + TQ is N_{inj} independent
- no clear dependence of E_{rad} / (E_{th} + E_{in}) during pre-TQ
- E_{rad} / E_{th} decreases during TQ



TQ mitigation: power onto divertor

- power on outer divertor strike point module (~ 20 x 1 cm^2) from infra-red camera (trade-off spatial-temporal resolution; TQ power deposition is poloidally broader)

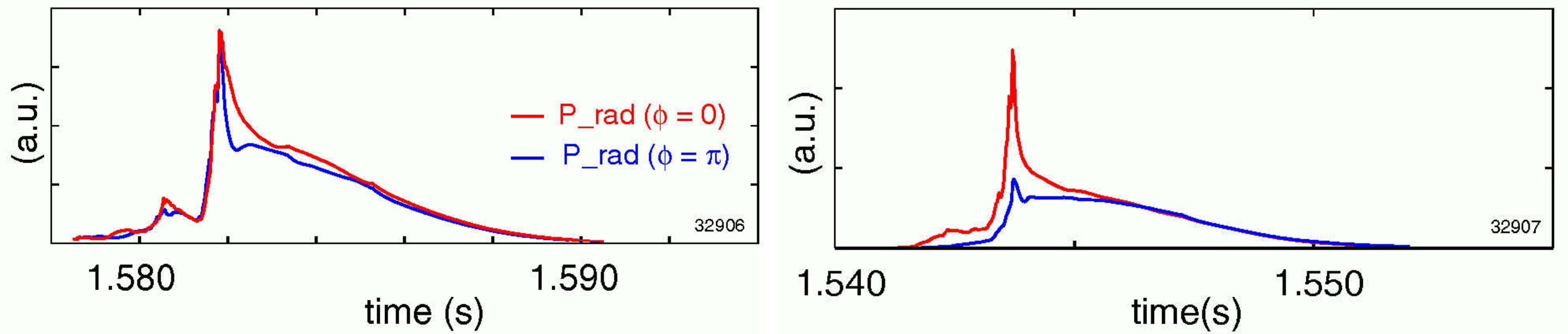




- E_{div} / E_{th}: two branches @ low N_{inj}
  - single spike & larger E_{div} / E_{th}
  - energy losses in sequence of spikes (one spike in E_{div})

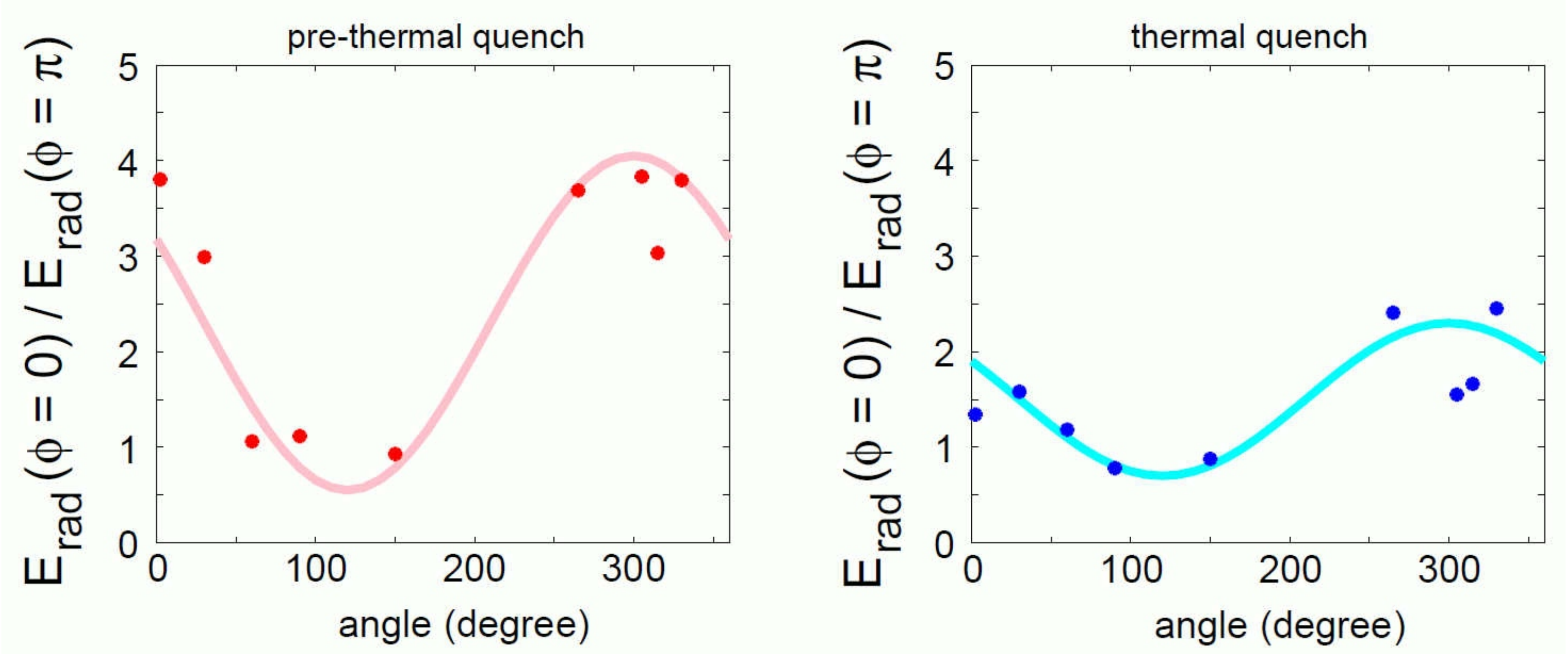
Toroidally asymmetric radiation distribution

- $\mathscr{P}_{rad}$ is poloidally & toroidally asymmetric in pre-TQ & TQ
- multiple injectors and mode/plasma rotation reduce asymmetry
- relative n=1 X-point – valve position influences radiation asymmetry
  (V. Izzo POP, 2013)
- AUG: DL induced tearing modes locked by n=1 resonant MP coils @ several toroidal location; MGI after LM
- P_{rad} asymmetry during pre-TQ & TQ clearly influenced by LM position



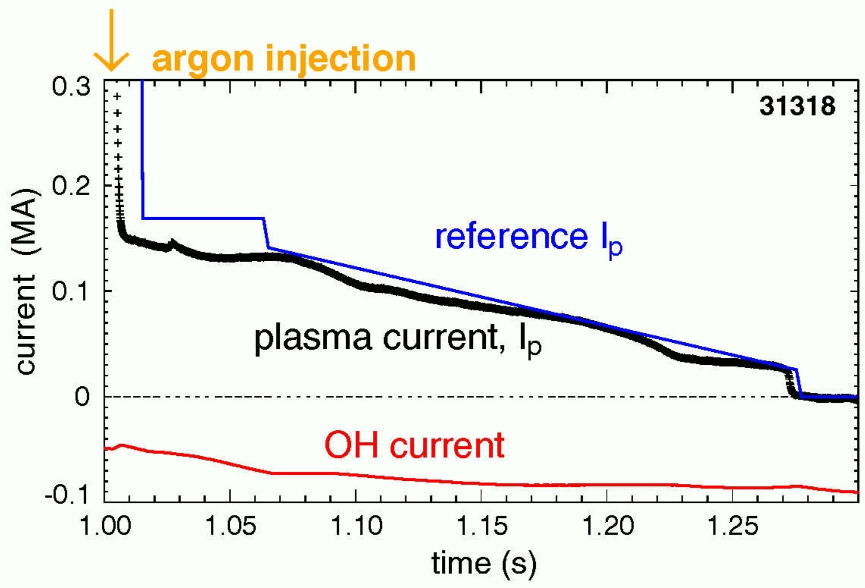
Toroidally asymmetric radiation distribution

- Max $E_{rad}(\phi=0)/E_{rad}(\phi=\pi)$ ~ 4 (pre-TQ) and ~ 2 (TQ)
- consistent w max when injecting into n=1 X point
- w/o rotation effects → data-set for benchmark of 3-D models (e.g. JOREK)

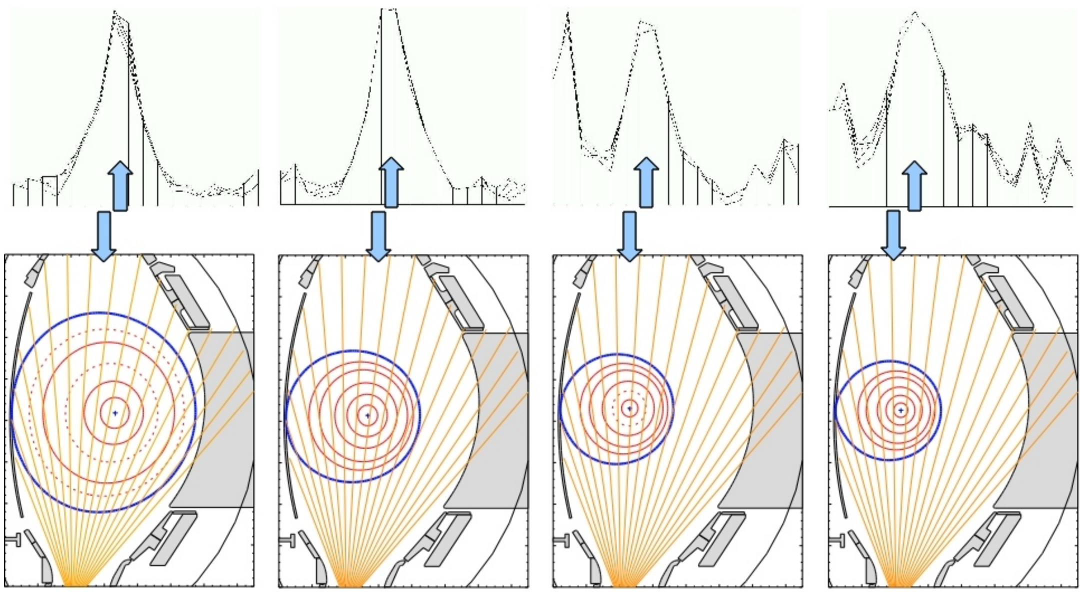


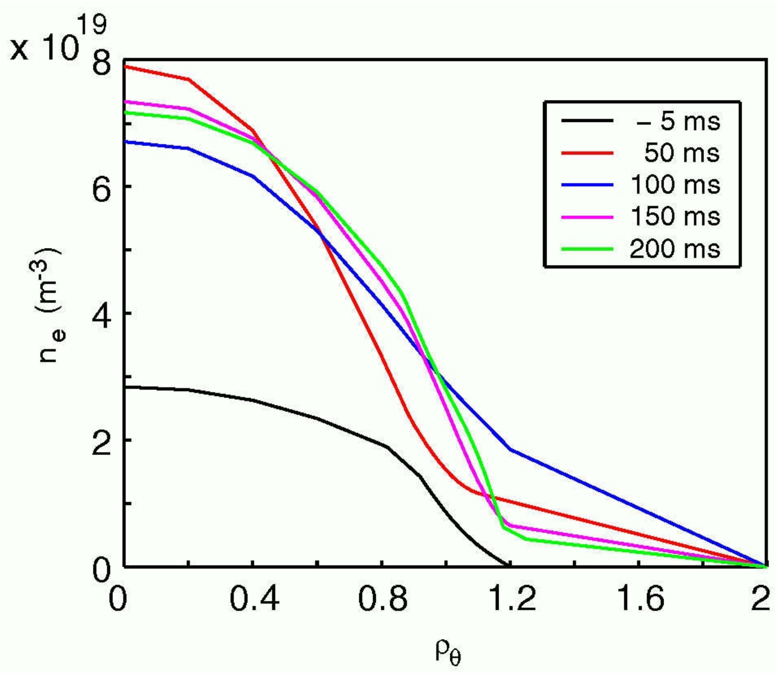
RE beam generation

- First exp.s in 2014; follow-up in 2015
- circular plasma, I_p = 0.8 MA, B_t ~ 2.5 T, n_e ~ 2.5 10^{19} /m^3, P_{ECRH} > 2 MW, $N_{inj} \leq 2\times10^{21}$ argon atoms
- RE beam (I_{RE} < 400 kA for < 400 ms) reproducible but sensitive to I_p ramp-up
- plasma is vertically stable; no major MHD instabilities
- RE current after 1[st] Ar injection can follow reference I_p – often faster → E_ϕ from OH system



Equilibrium, density profile

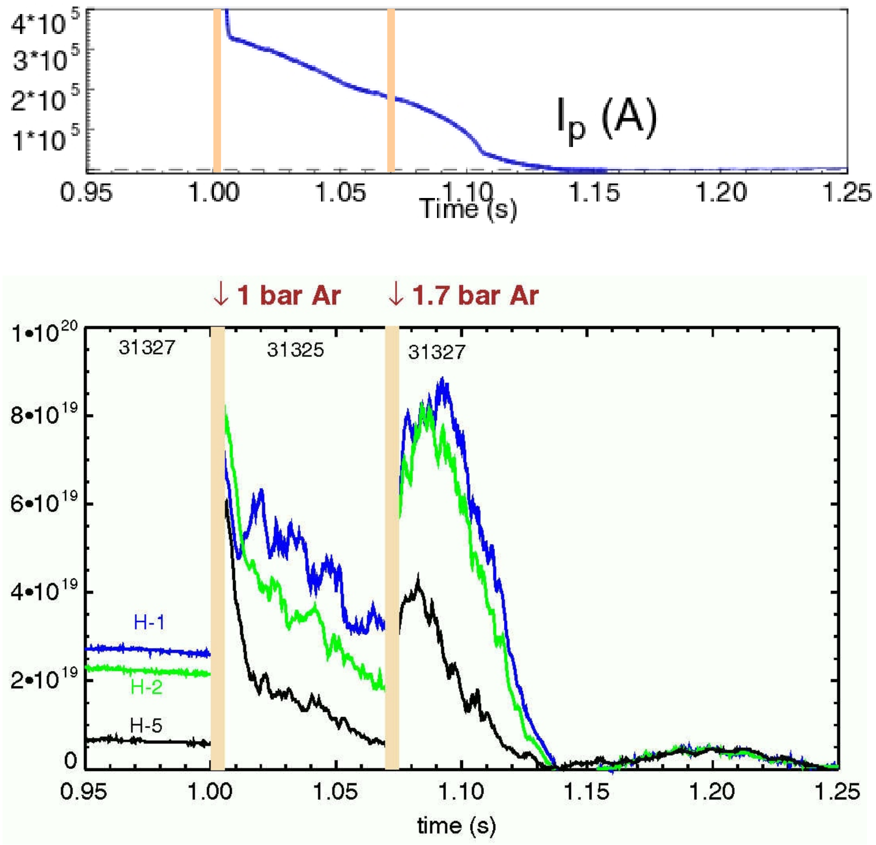




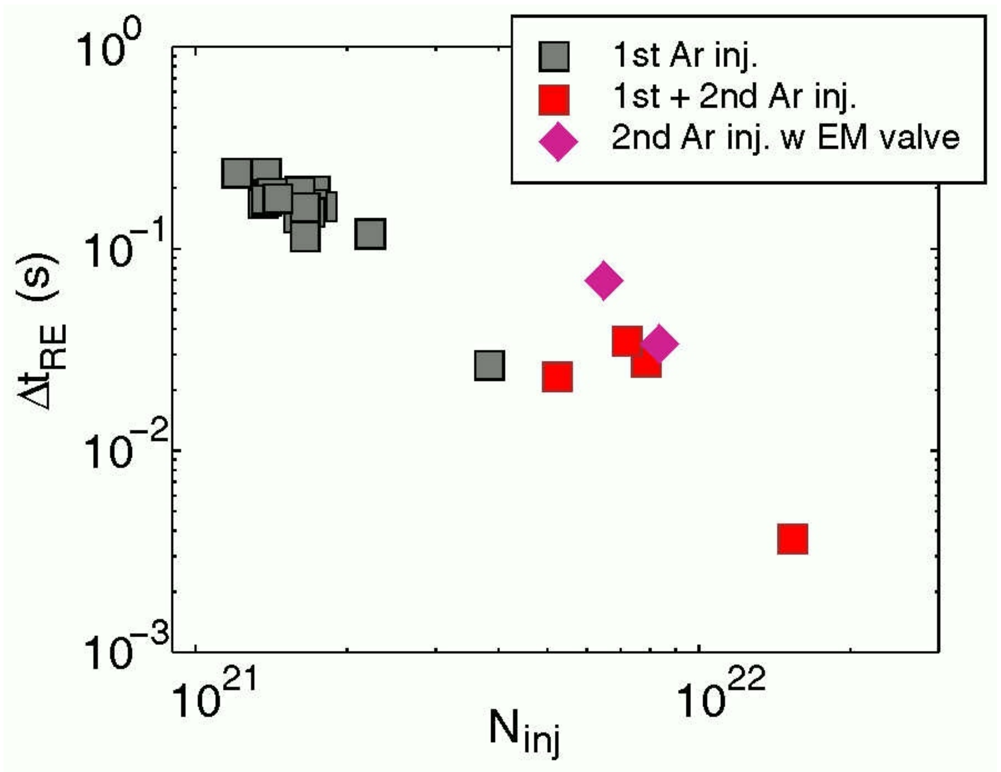
Series of equilibria;
beam position confirmed by SXR

Density profiles in RE beam

RE suppression with argon



Line integrated density after 1st and 2nd argon injection (70 ms apart)



RE beam lifetime versus argon N_{inj}

Friction force (eE_c) on REs from free and bound electrons

Several known mechanisms of RE losses

Only inelastic collisions RE–electrons considered (energy losses)

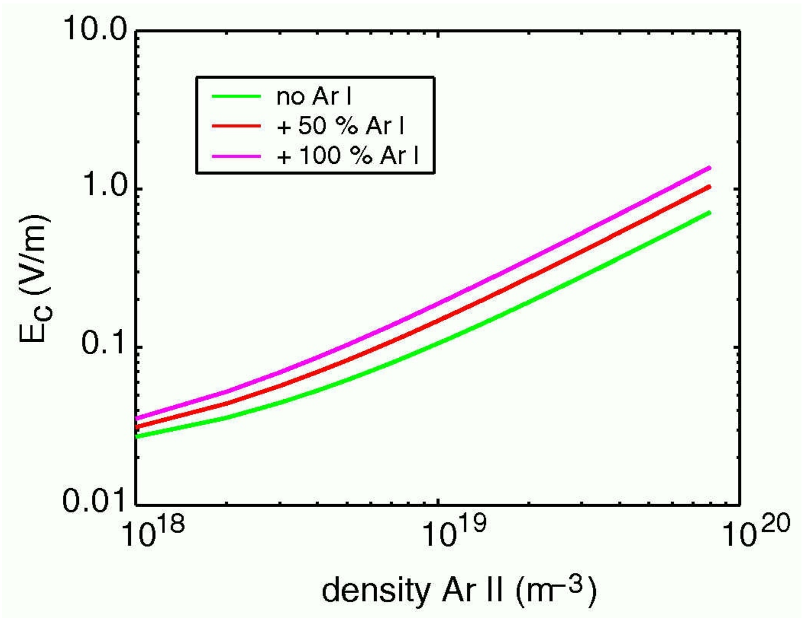
Formally:

$$\frac{1}{\tau_{RE}} = \frac{dI_{RE}}{dt}\frac{1}{I_{RE}} = \frac{e(E_\Phi - E_c)}{p_{RE}}$$

$$E_\Phi = V_{loop}/(2\pi R)$$

$$E_c = e^3 n_e \ln(\Lambda_{e,free})/(4\pi\epsilon m_e c^2)$$

$$n_e = n_{e,free} + \ln(\Lambda_{e,bound})/\ln(\Lambda_{e,free})\, n_{e,bound}$$



E_C depends on plasma composition (atomic species and ionization state)

E_c versus $E\phi$

Several spectrometers configured to measure Ar-I, Ar-II, C-II and C-III line emission; allow to determine T_e, n_{Ar} and n_C (n_e is known)

line radiance: $$L = \frac{1}{4\pi}\int n_e n_z f_f X_{eff}\, dl$$

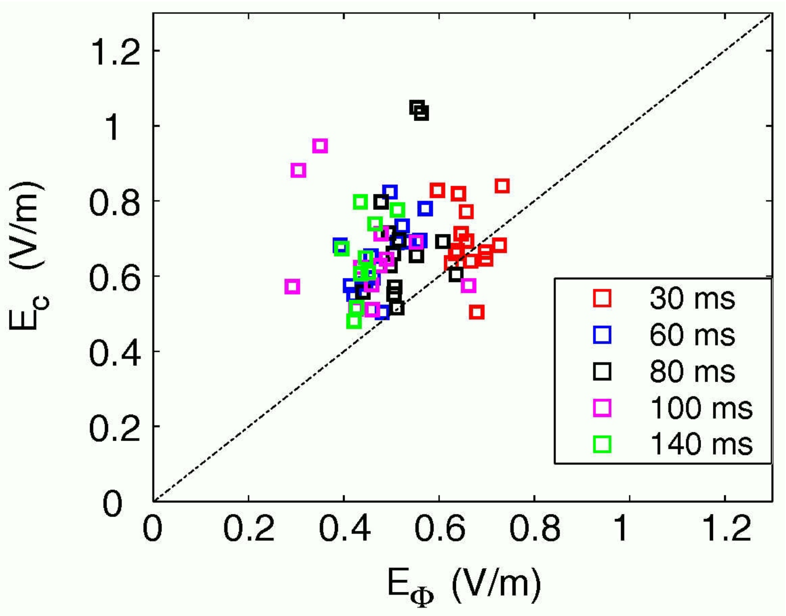
X_{eff}: photon emissivity coefficients calculated with a collisional radiative model and ADAS208-code (R. Dux)

f_z: fractional abundance

comparison of line radiance of C-II and C-III with (f_z X_{eff}) suggests
T_e < 2 eV and **n_{Ar} / n_e ~ 100 %**

→ **$E_c > E_\phi$**

(uncertainties in atomic data for argon)



Summary

- N_{inj} range has been extended: force and thermal load mitigation deteriorates below 10^{21} neon atoms
- modelling needed to extrapolate min N_{inj} to ITER
- ASTRA modelling of pre-TQ benchmarked on AUG → can be used for MGI in ITER
- dedicated exp.s on radiation asymmetry w/o velocity effects to benchmark 3-D codes
- argon injection causes RE current decay largely accounted for by e-RE friction