What Can be Learned From ASDEX Upgrade on Gas Assimilation and Its Interaction with Runaway Electrons(*)?

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(*) generated during current quench

Introduction

- ASDEX Upgrade (AUG) carries out “bona fide” disruption mitigation studies for ITER
- MGI (noble gases) on AUG has been used to study thermal quench (divertor load and forces) mitigation, and runaway electron (RE) generation and dissipation
- Impurities in plasma are powerful radiators: exp. and modelling works from many devices suggest that thermal load and force mitigation in ITER disruptions **is feasible**
- In what follows: focus on assimilation of injected gas and RE dissipation by collisions with gas (data analysis, basis for code benchmark) because

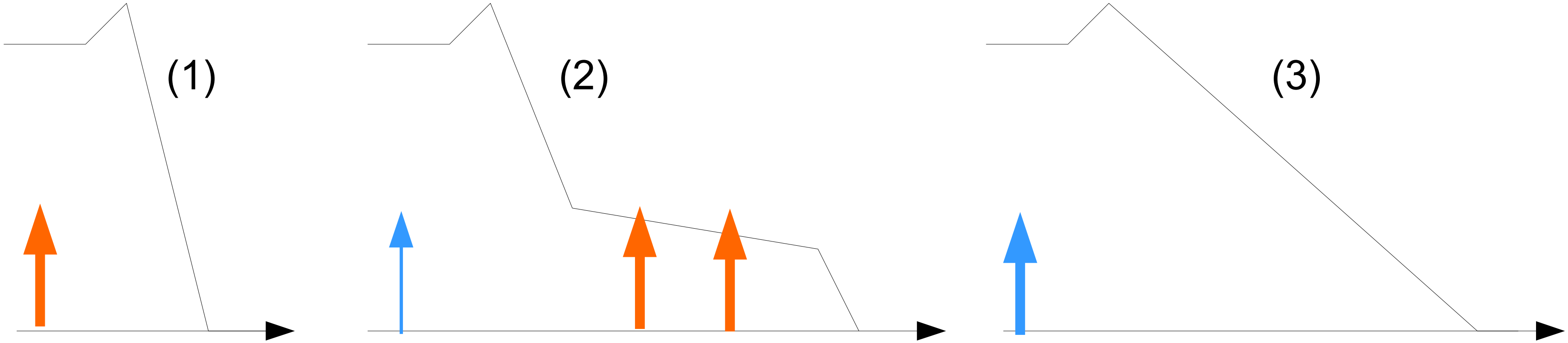
Whether MMI suppression and or dissipation of REs is feasible in ITER disruptions depends on $\Delta n_e(t,\psi)$

- **Ultimate questions:**
  - Is $\Delta n_e(t,\psi)$ physically achievable?
  - Is an injection scheme able to assure needed $\Delta n_e(t,\psi)$ technically feasible?
  - (→ should AUG pursue disruption mitigation experiments further? Or concentrate on modelling? Or invest mainly on plasma control algorithm?)

    Caveat: small device compared to ITER

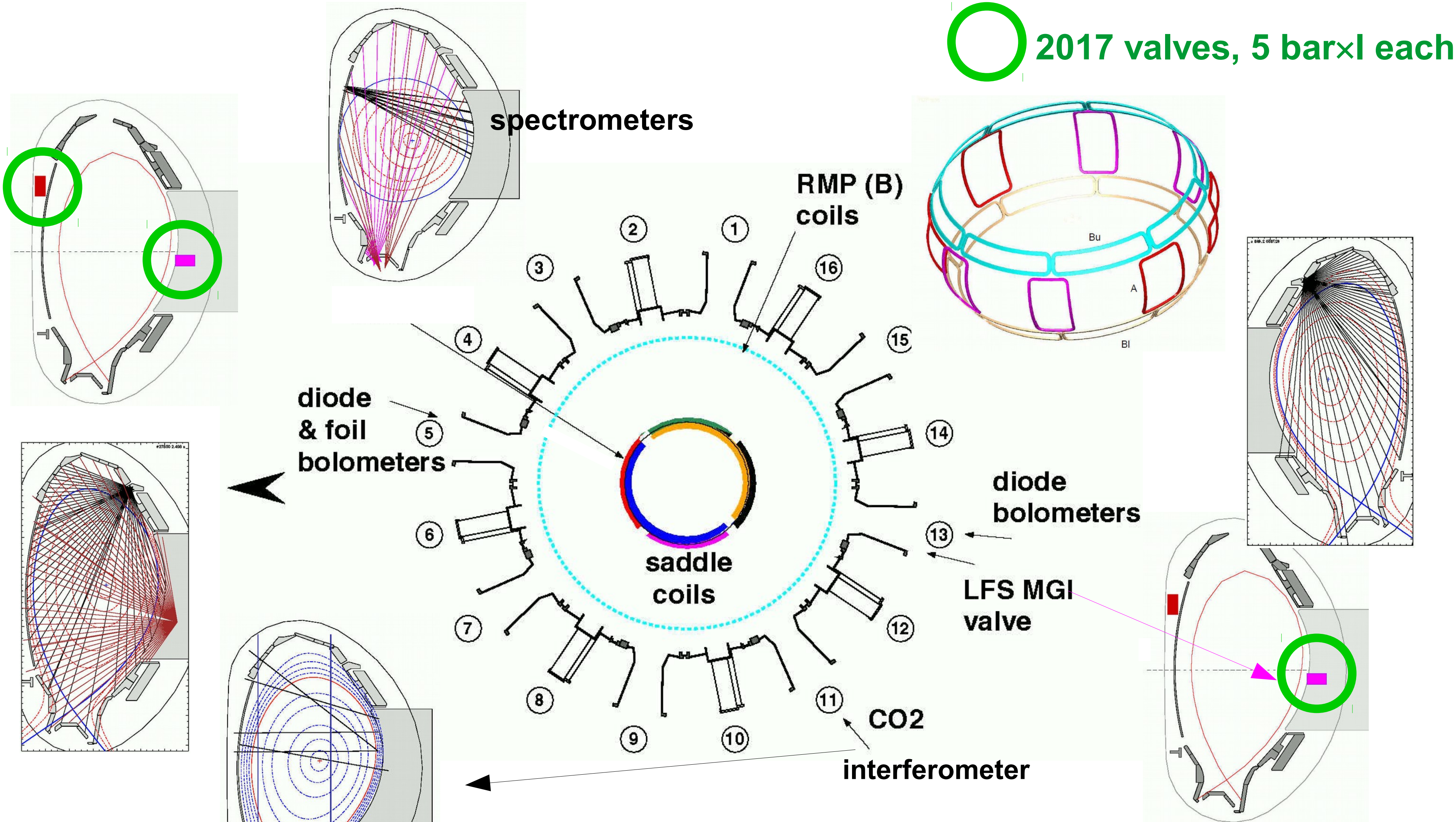
Which $\Delta n_e(t,\psi)$?

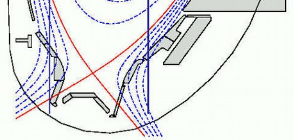
- $n_c > 10^{22}$ -10^{23} /m^3 (ITER Physics Basis, Nuclear Fusion 1999)
- 2nd argon injection into RE beam: $n_{Ar} > 10^{22}$ / m^3 needed to induce RE current decay … *but too late* (S. Konovalov, IAEA 2016)
- Ar/D_2 injection to suppress seed and avalanche (= slow down CQ); within ~10 ms injection of 14 kPa m^3 $\rightarrow$ $n_e \sim 4\times10^{21}$ /m^3 (J.R. Martin-Solis, Nuclear Fusion 2017)



(I believe we should keep considering all three schemes)

AUG: Mitigation valves, relevant diagnostics and coils

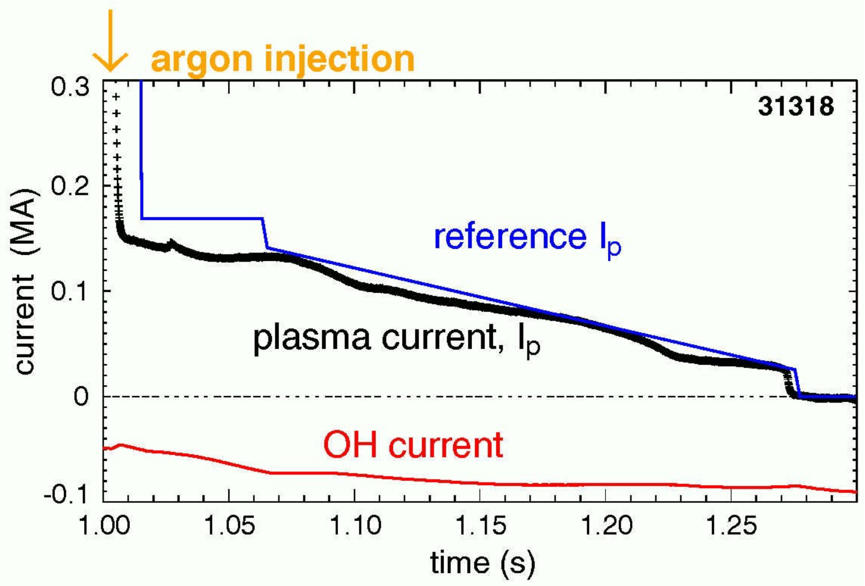




+ SXR, magnetics, gamma spectrometer, thermography
+ fast camera with filter, halo current, strain gauges

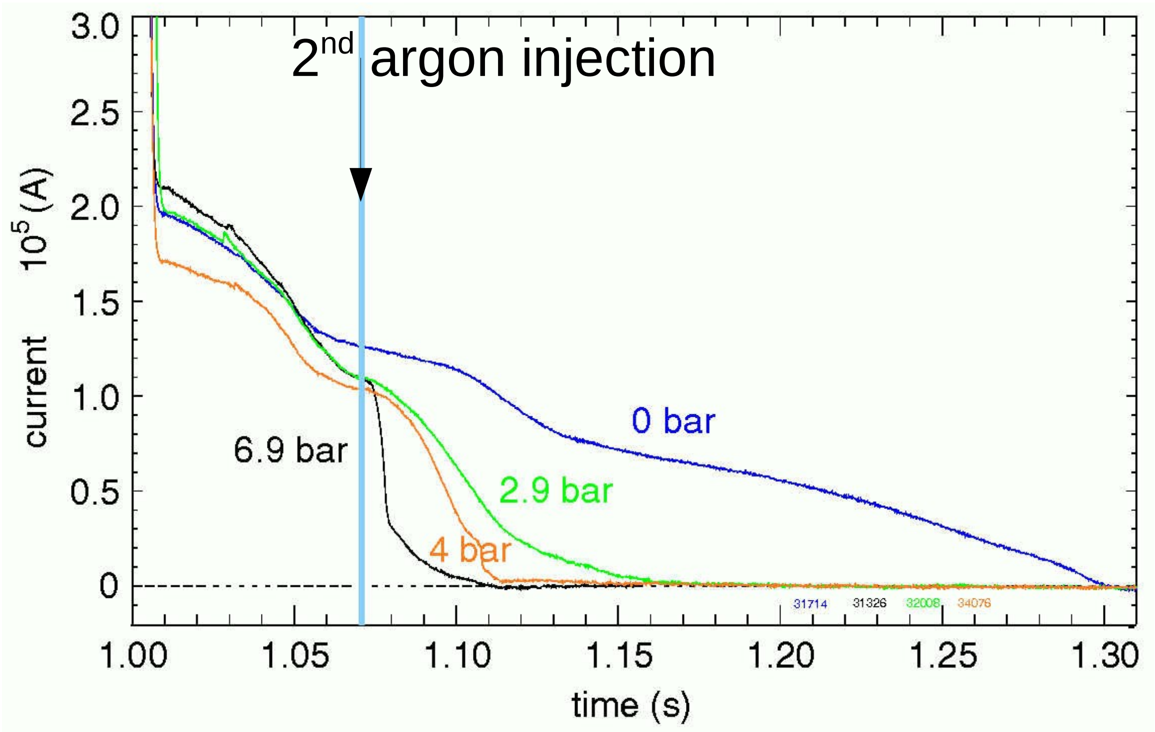
RE beam generation: 1st injection

- First exp.s in 2014 (~ 80 discharges by now)
- RE beam (I_{RE} < 400 kA for < 500 ms) is generated with argon puff and mostly reproducible
- typically: circular plasma, I_p = 0.8 MA, B_t ~ 2.5 T, low n_e, P_{ECRH} > 2 MW,
- plasma has been vertically stable and w/o MHD activity; often vertically unstable in 2017
- RE current after 1st Ar injection can follow reference I_p; faster or slower depending on argon injected; → E_ϕ from OH system adds to self-inductance

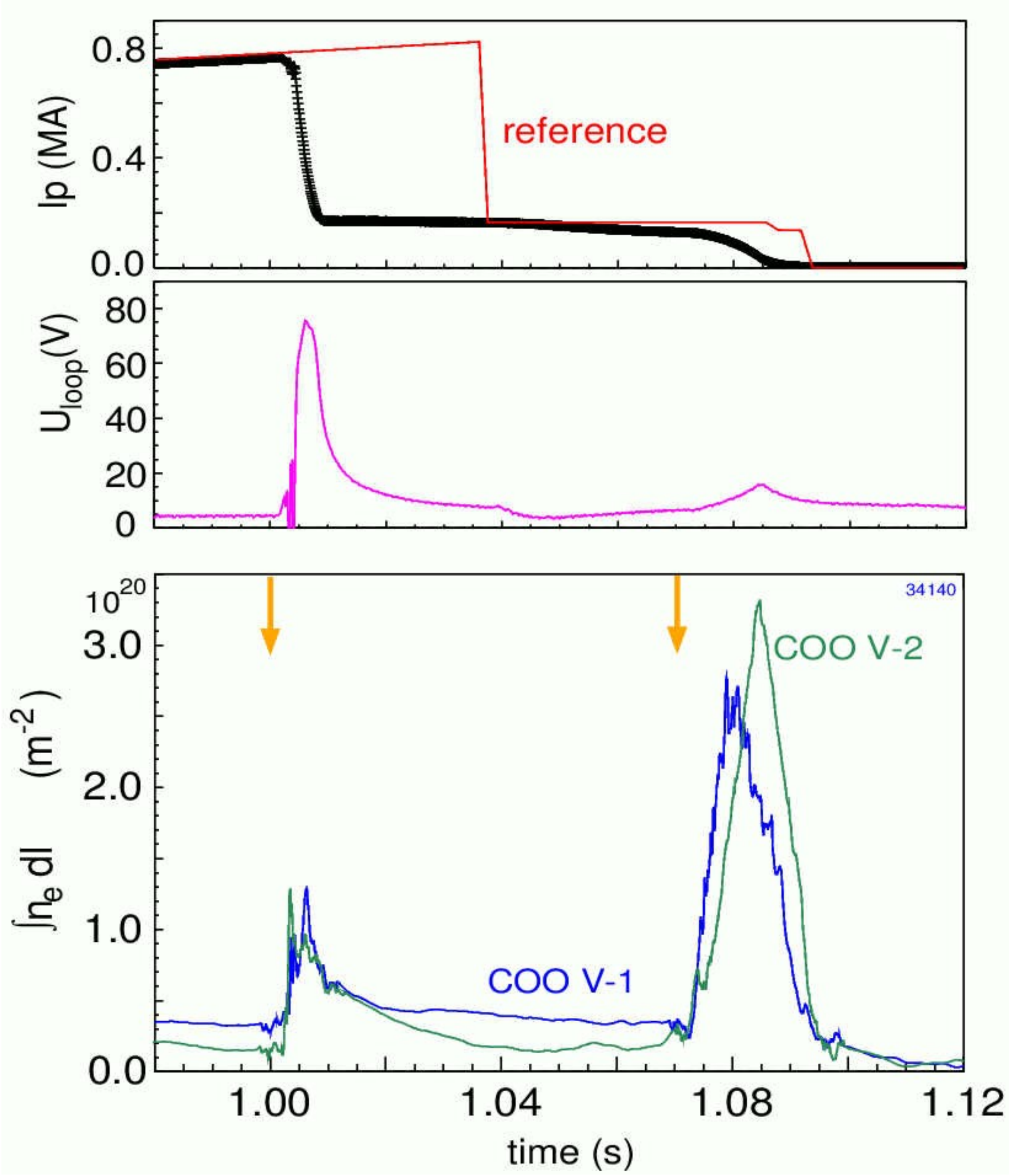


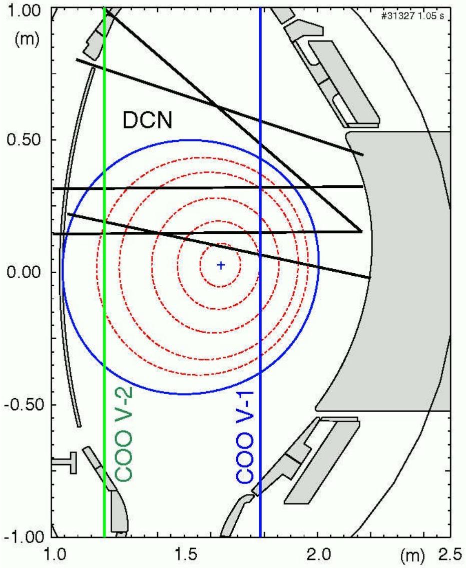
RE beam suppression by 2nd gas (argon and neon) injection

- relevant for injection schemes (1) and (2)
- argon and neon (not shown) effectively suppress RE beam
- $N_{inj} \leq 2\times10^{22}$ argon atoms; $N_{inj} \leq 4.3\times10^{22}$ neon atoms



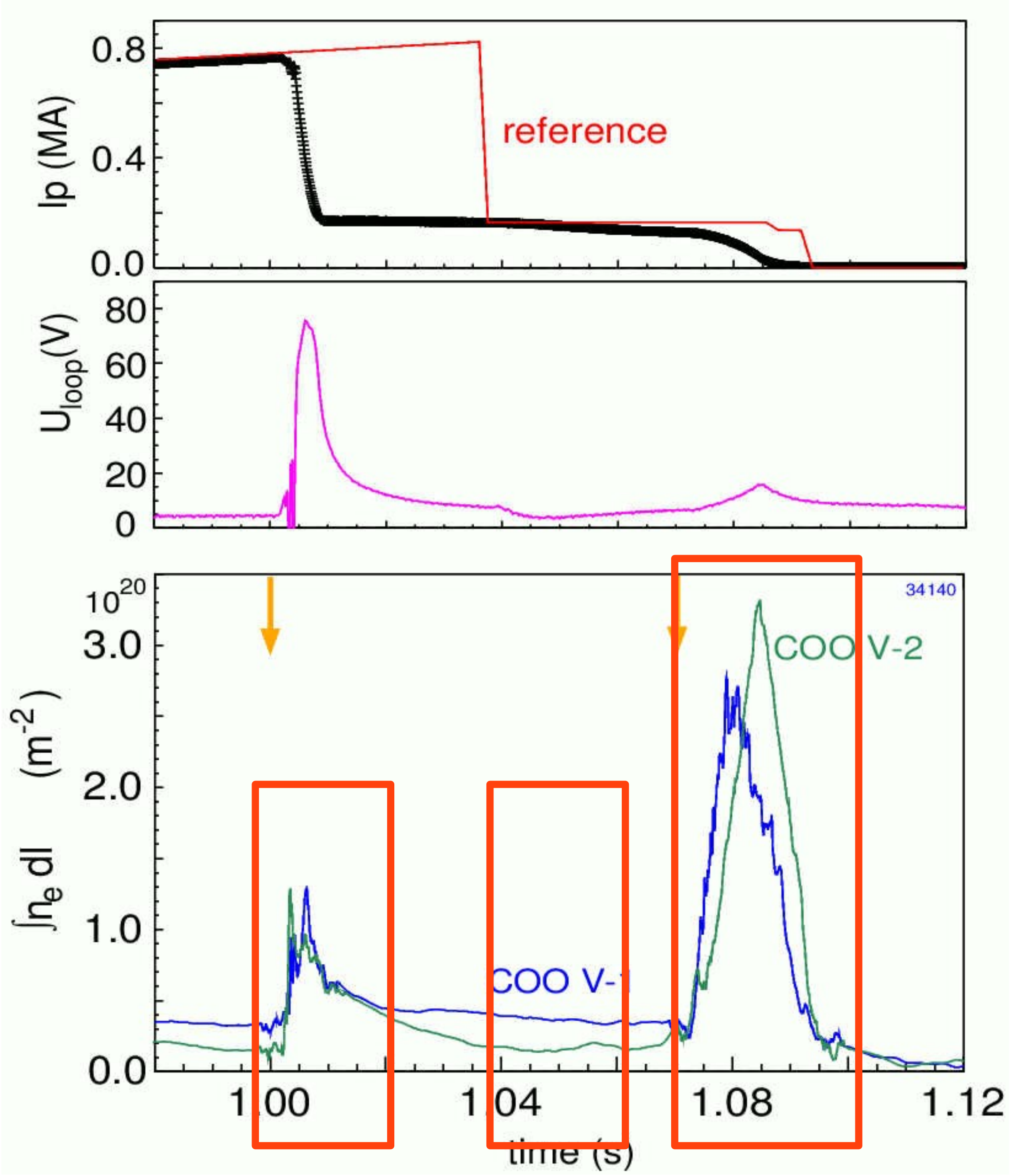
Density and REs





- Electron density is measured by COO
  - can follow fast transients but noisy; only 2 chords
- and DCN diagnostics
  - can follow slow transients, 5 chords, 1 toroidal position; correct ~ 50 ms after injection

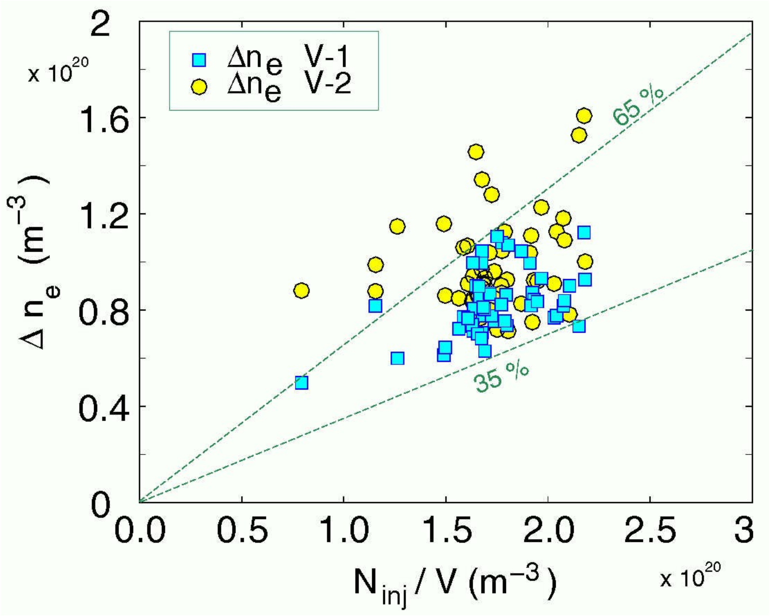
Density and REs

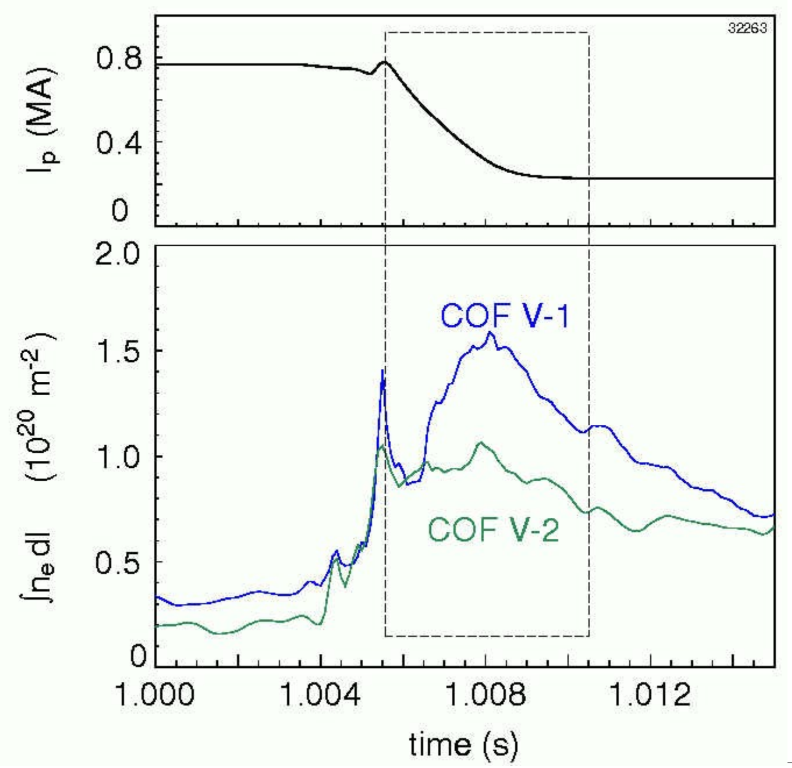


- discussion of **1st injection, RE beam and 2nd injection phases**

1st argon injection – to create RE beam

- argon MGI in AUG not documented in literature → shown here
- small argon amount injected – to avoid suppressing the REs
- → argon assimilation is not small
- Δn_e / (N_{inj}/V) = 50 +-15 % from V-1 (averaged 5 ms after TQ); but
  - argon ionization stage not known; recombination possible
  - line integrated n_e decays in RE beam also because V-1 chord length decreases



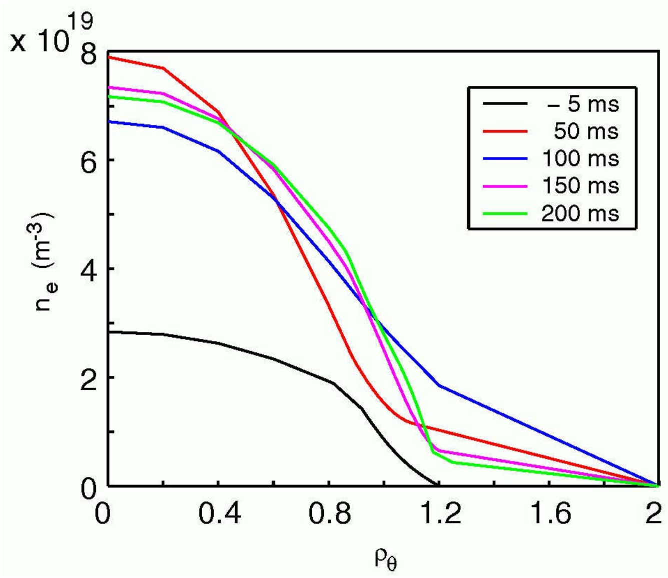


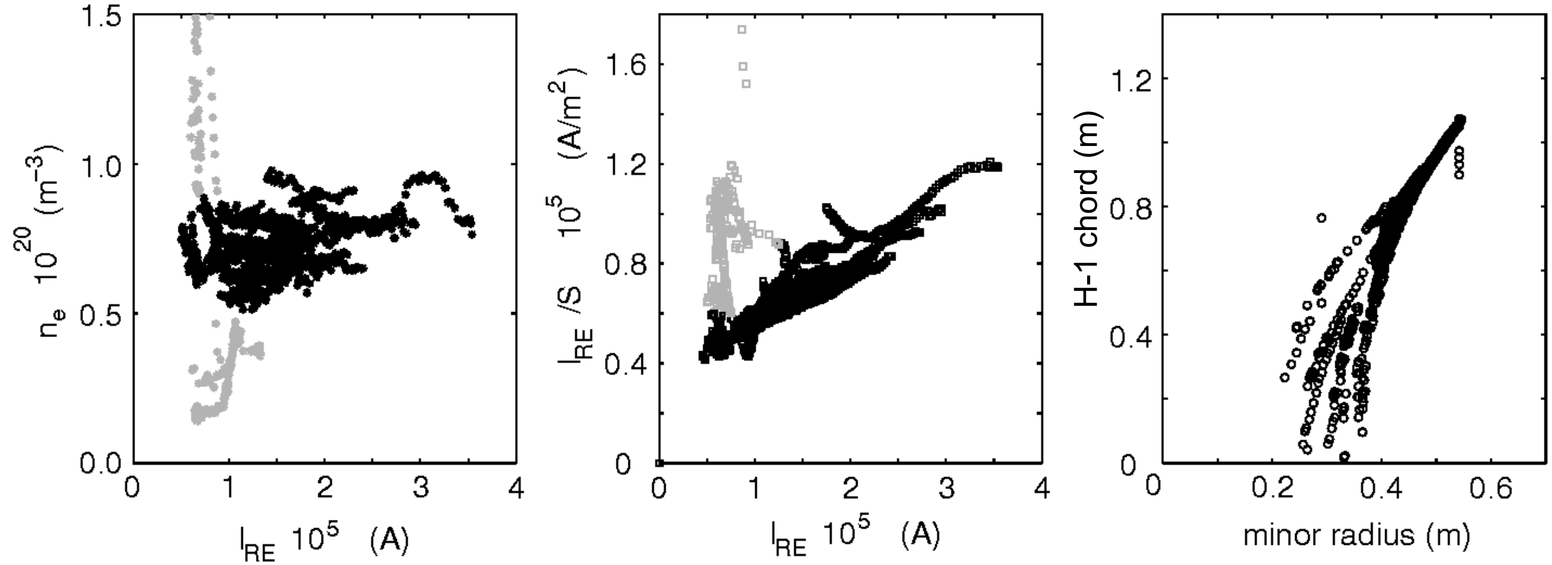
n_e in RE plateau

- DCN density (→ profile reconstruction) and spectroscopic measurements (→ mostly argon; T_e ~ 1.7 eV) available in RE plateau
- density outside of LCFS → large diffusion coefficients
- n_e ~ 6-9 10^{19} /m^3 ~ weak f(I_{RE});

  why this (not a larger or smaller) density?

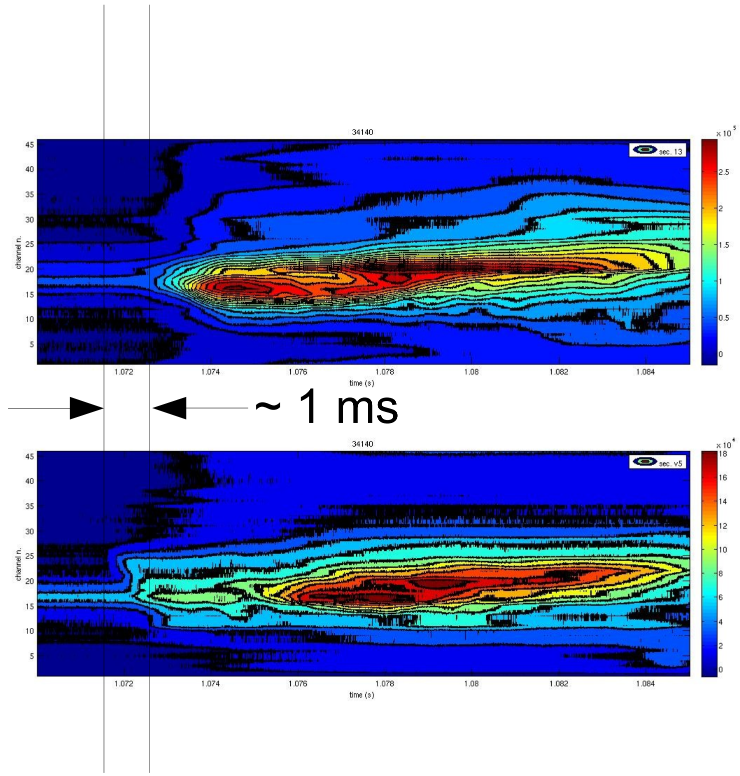
Density profiles in RE beam

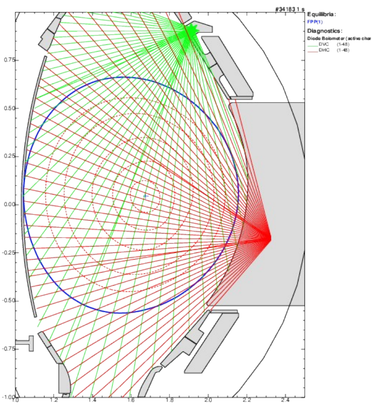


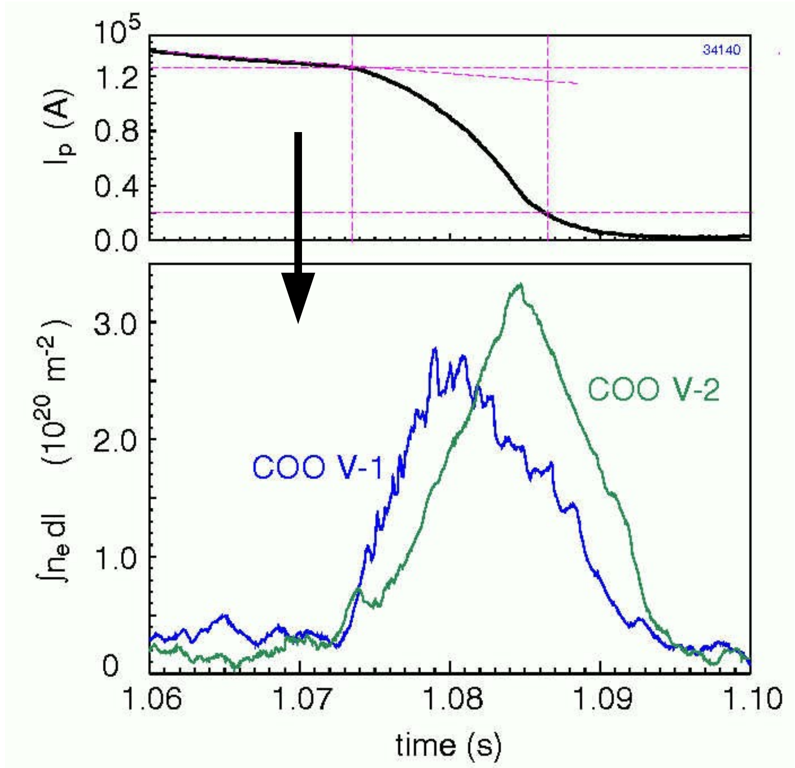


2^{nd} argon injection – to dissipate RE beam

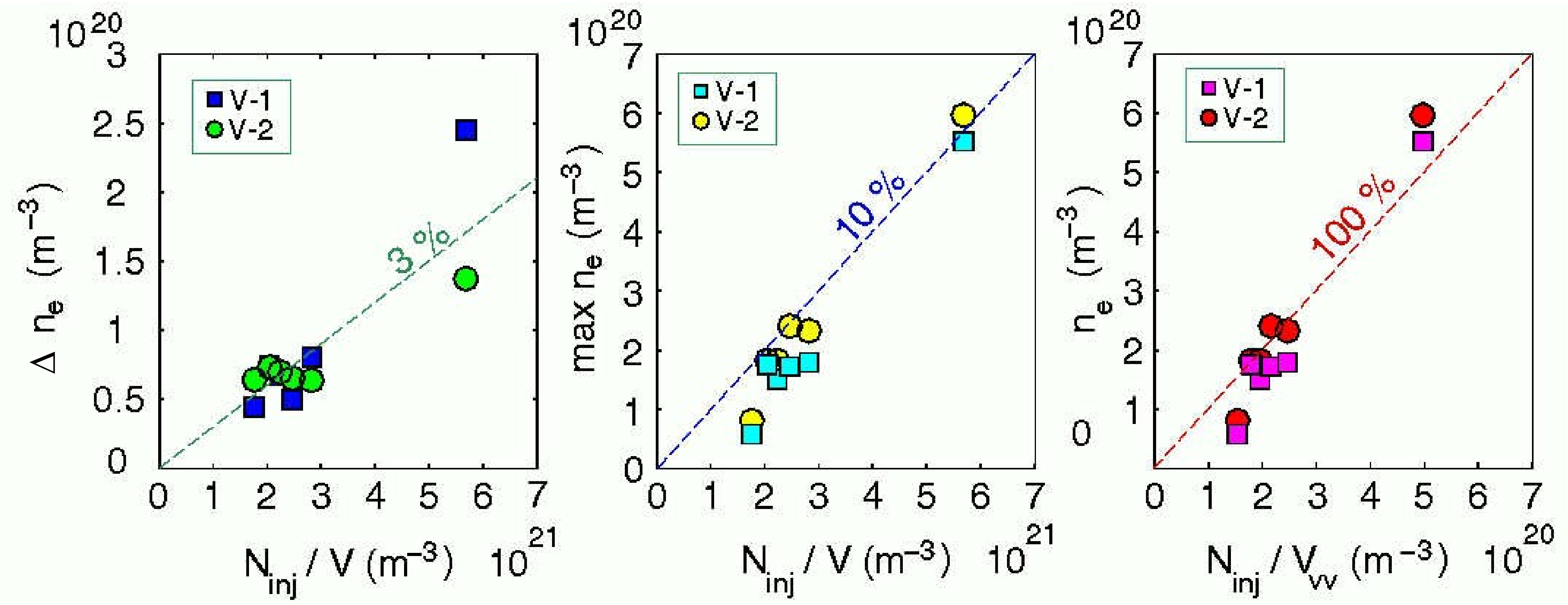
- argon // velocity ~ 5 m / 1ms (vertical diode cameras, $\Delta\varphi = 2\pi$)
- slow density rise ~ gas penetration, consistent with perp. classical ion diffusion (but also gas flow)





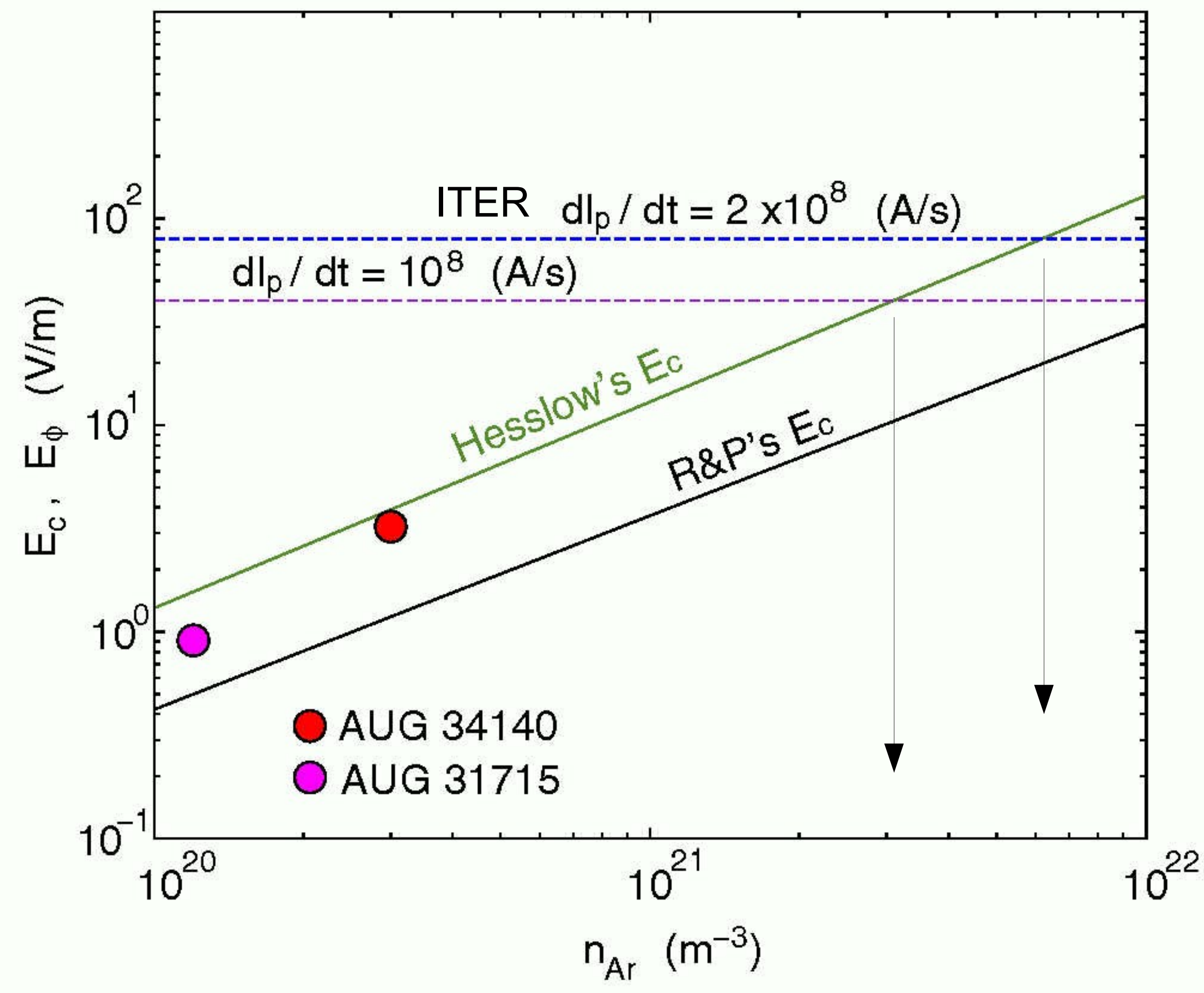


2^{nd} argon injection – to dissipate RE beam



- Δn_e averaged within 10 ms after 2^{nd} argon injection shows no significant increase
- max n_e versus N_{inj} / (plasma volume) after 2^{nd} inj.: up to 10 % increase
- max n_e versus N_{inj} / (vessel volume) after 2^{nd} inj. (100 %; meaning?)

2nd argon injection – to dissipate RE beam



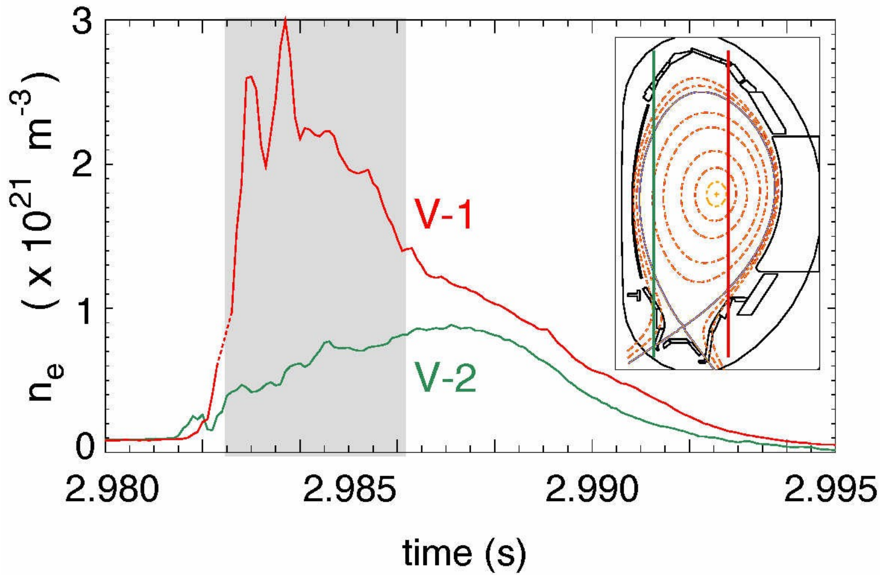
$$E_\varphi \propto \frac{dI_p}{dt}\frac{l_i}{2}$$

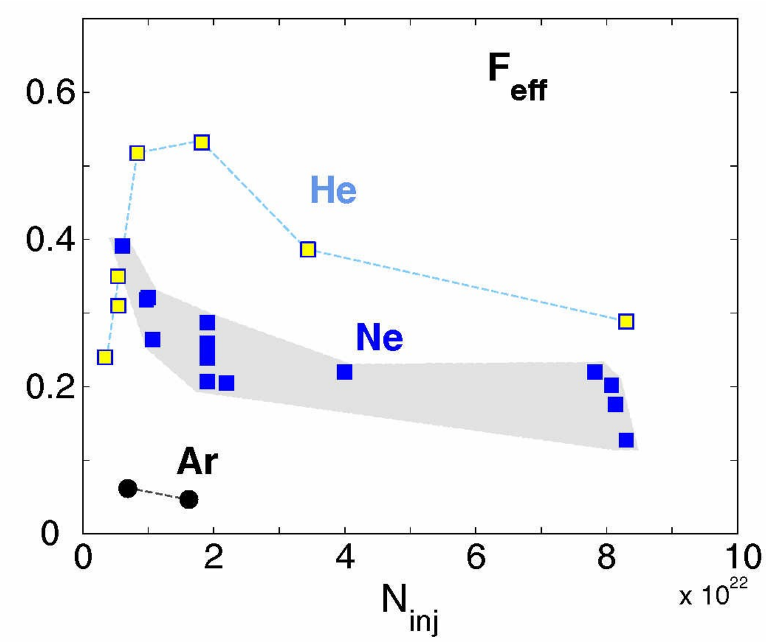
$$l_i = 4$$

n_{Ar} = 3-6 10^{21} /m^3 becomes interesting for ITER

10 times larger than in AUG

Fuelling efficiency at large neon N_{inj} EPS 2009





At large neon-N_{inj} :

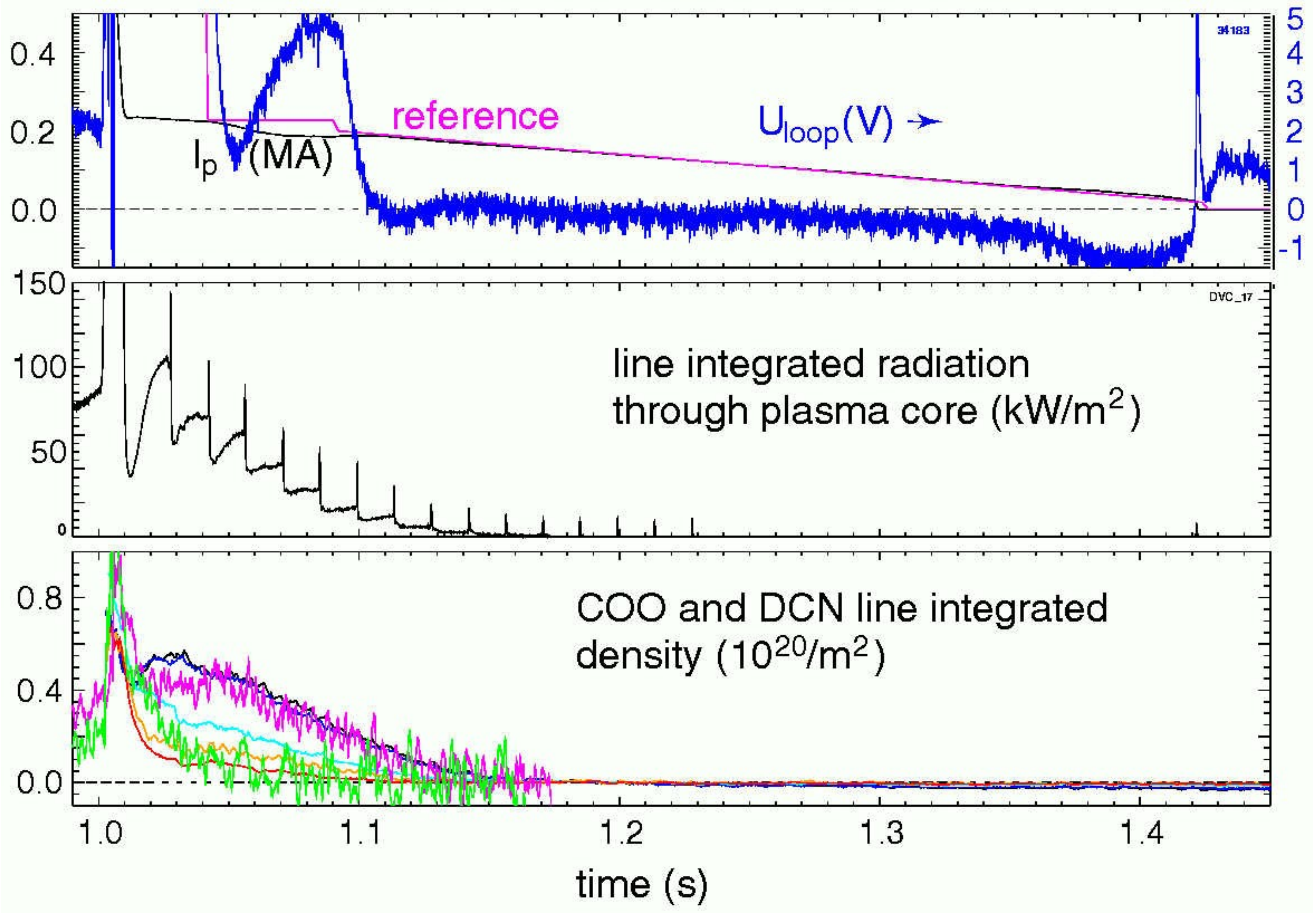
- F_{eff} decreases
- large poloidal density asymmetry = cold ions, low mobility
- + F_{eff} degradation at large thermal energy (?)

D_2 pellets in RE beam

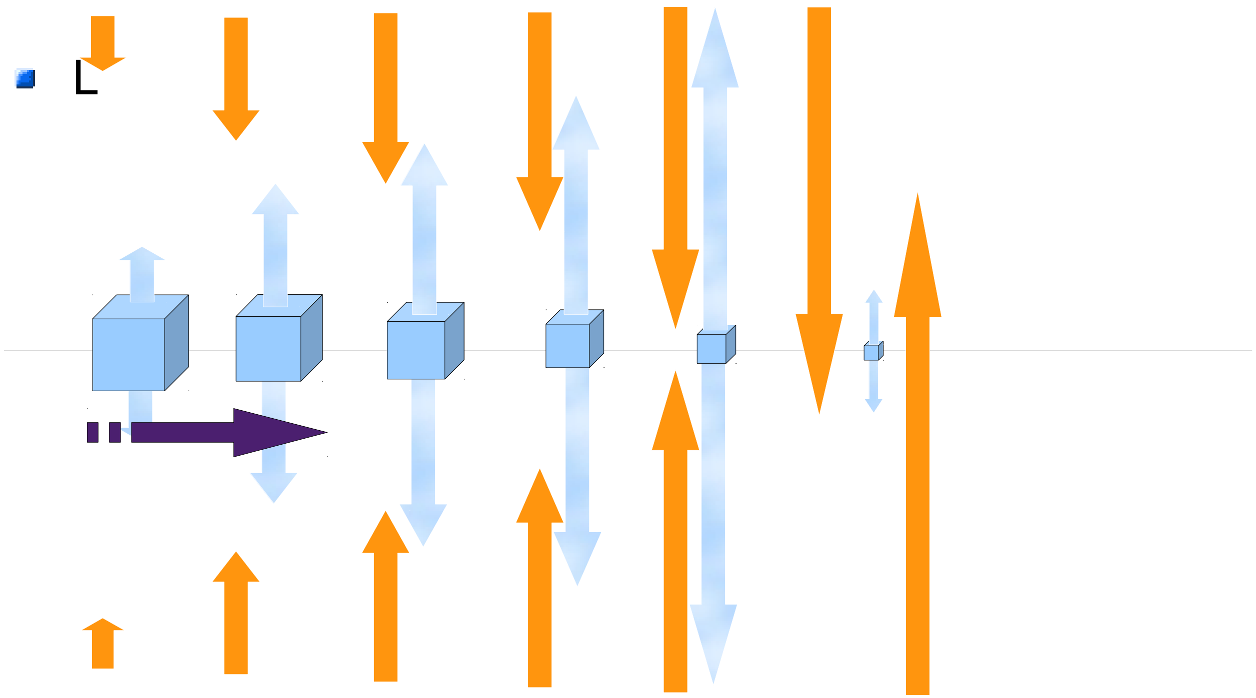
- Small contribution to animated discussion on ITER DMS and RE suppression
- *I (GP) do not know of similar exp.s*
- Shot 34183: 15 pellets, $1.9 \times 1.9 \times 2.0$ mm^3 $\rightarrow$ $15 \times 5 \times 10^{20}$ D_2
- 400 ms of RE beam ramped down by control system; Uloop </= 0 $\rightarrow$ “clean” plasma; spectroscopic measurement underway
- 0-D energy balance calculations: pellet should sublimate at “edge” of RE beam

  Q: how to show it? Important for modelling and more
- diode bolometer measurements seem to confirm calculations
- density decays probably because Te not large enough to ionize D

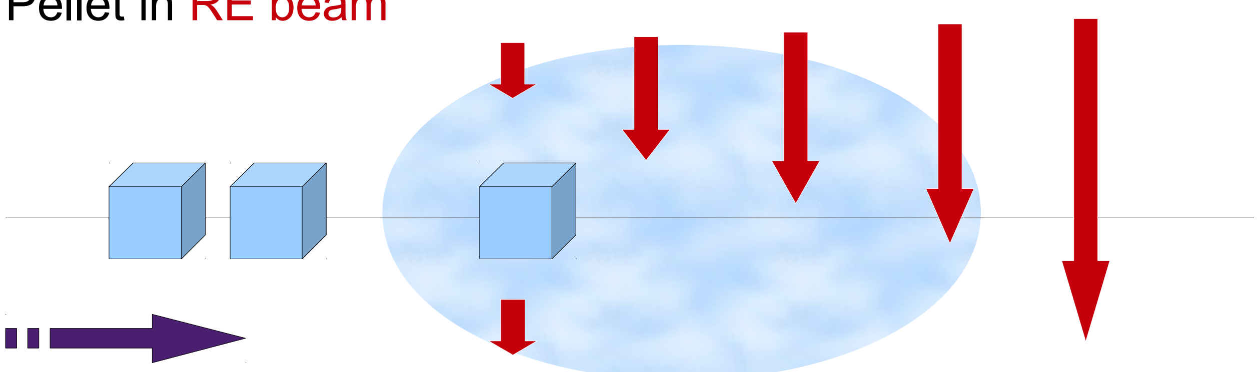
D_2 pellets in RE beam

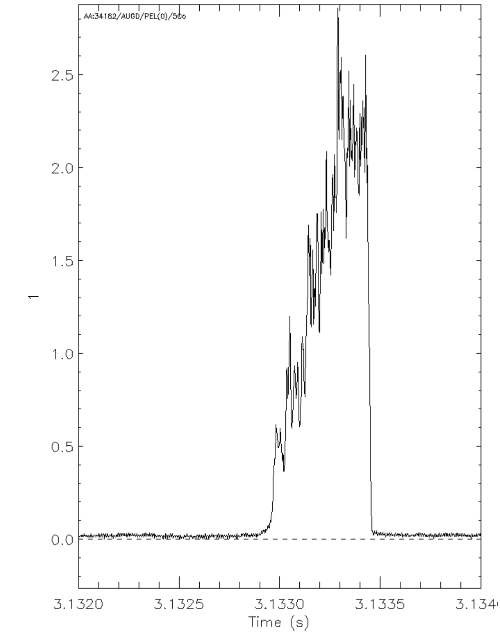


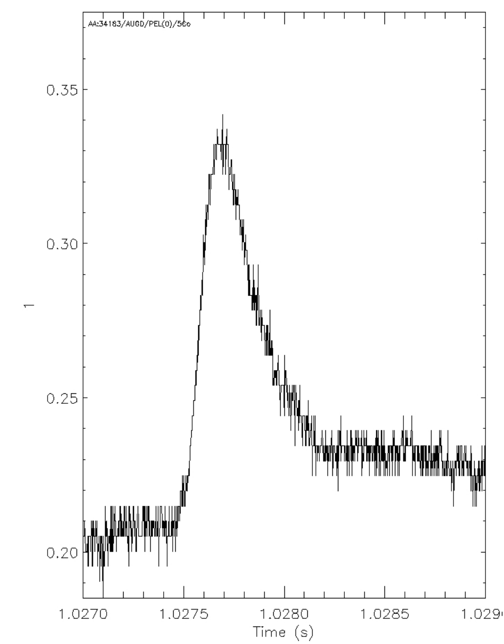
Pellet in “hot” thermal plasma (cartoon)



Pellet in RE beam



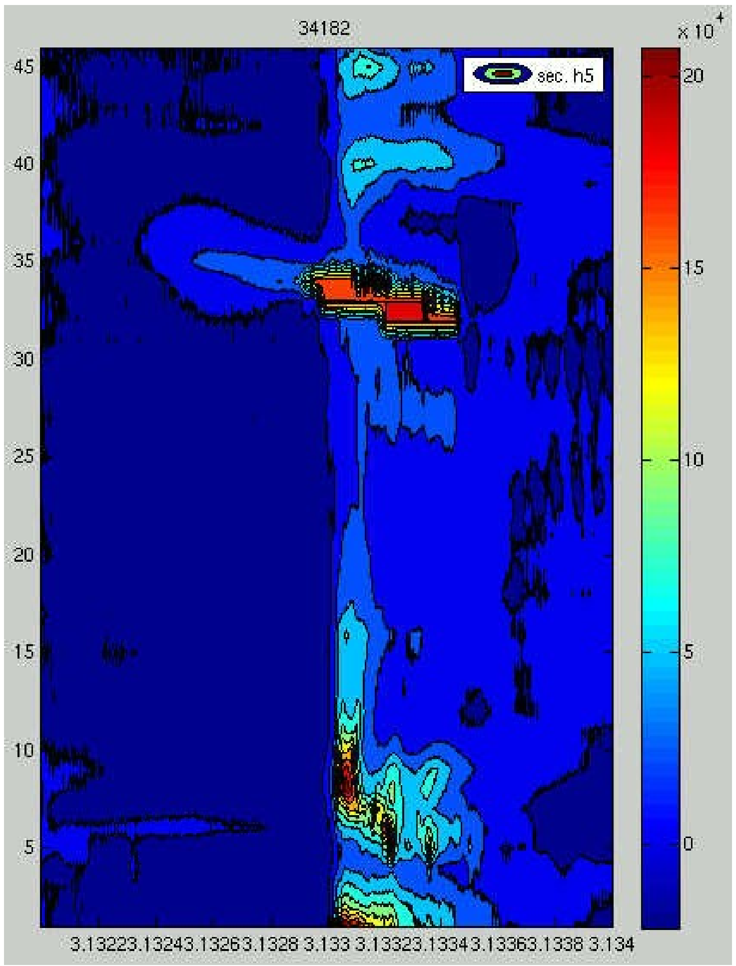


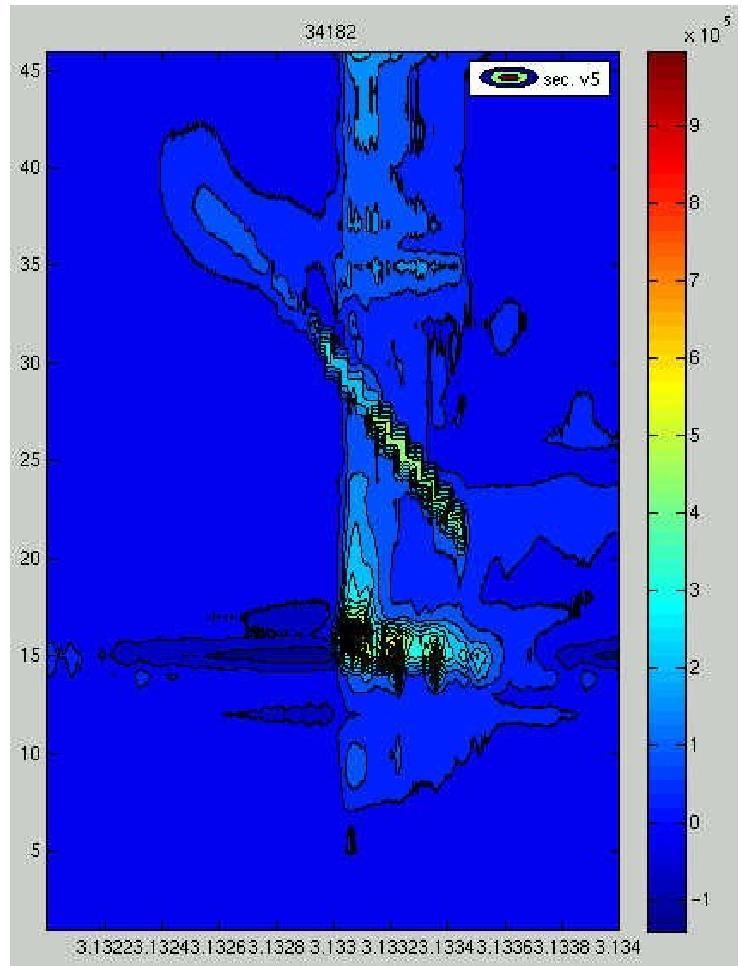


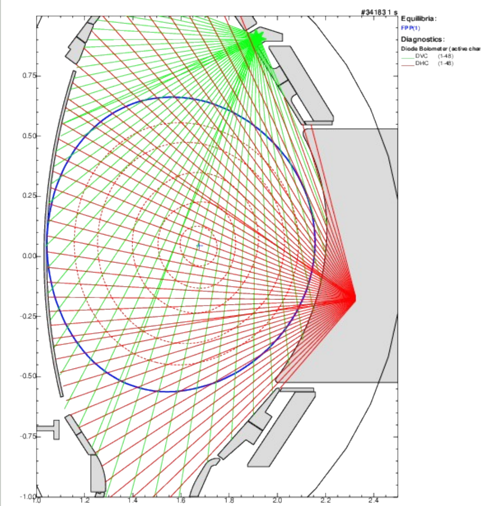
pellet monitor

pellet in thermal plasma; horizontal (left) and vertical (right) diode bolometer background subtracted

channel n.





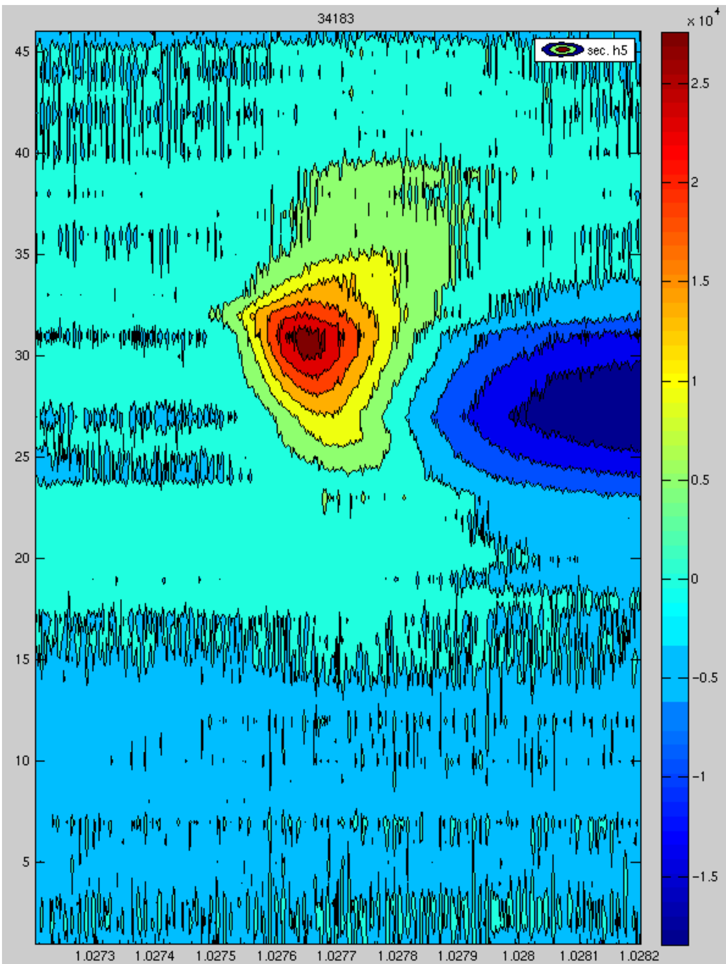


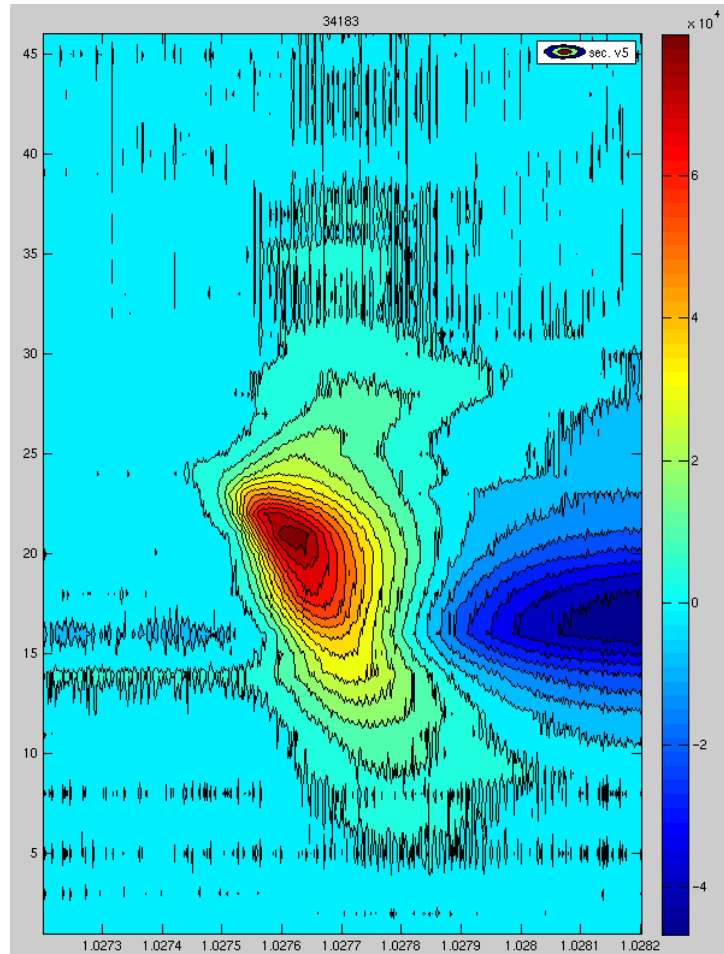
Δt = 2 ms

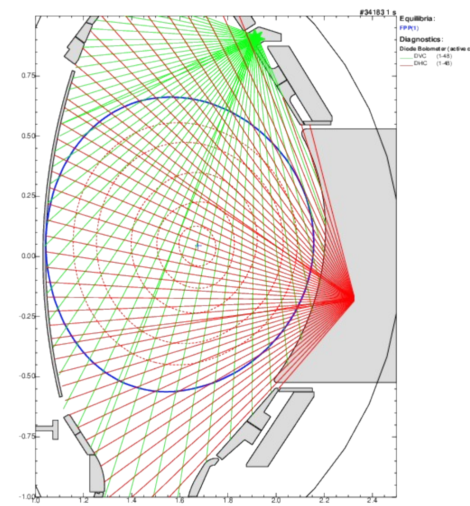
Δt = 2 ms

pellet in RE beam; horizontal (left) and vertical (right) diode bolometer background subtracted

channel n.





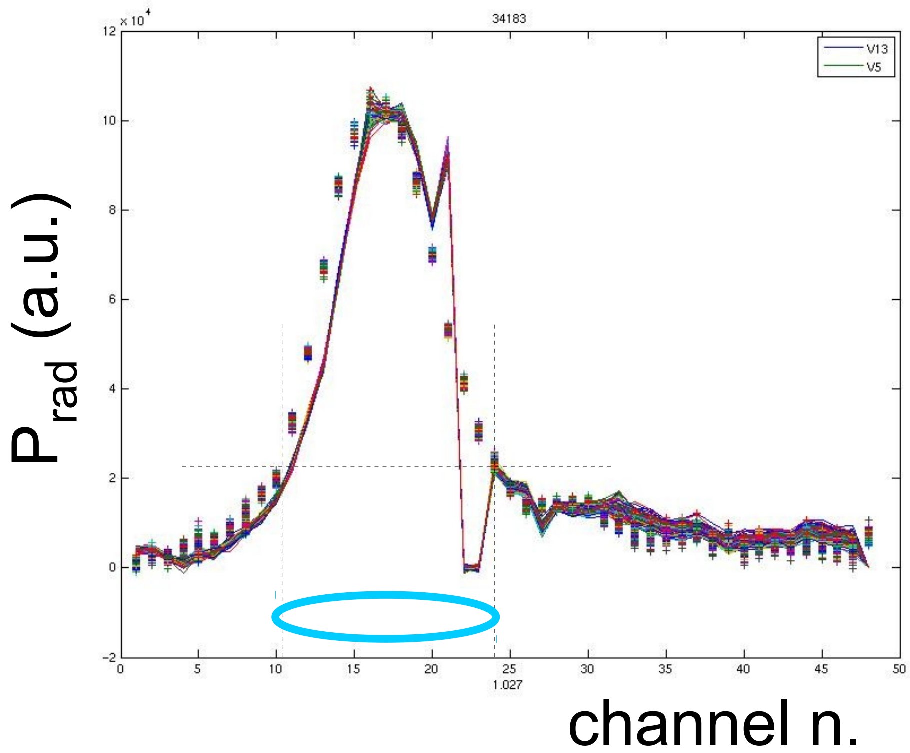


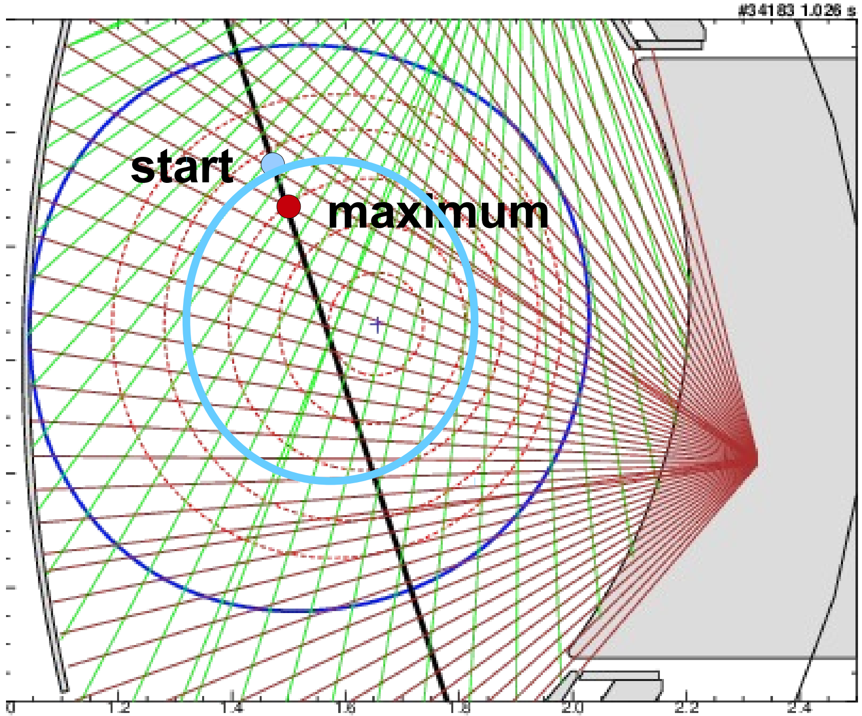
Δt = 2 ms

Δt = 2 ms

Why D does not refuel the plasma?

vertical diode bolometer sec. 5





- radiating region in plasma core needs input power from RE beam (left)
- radiation from pellet-plasma interaction starts at edge of RE beam (right)
- small P_{rad} and n_e decay → neutral Ds crosse plasma w/o ionizing (hypothesis)

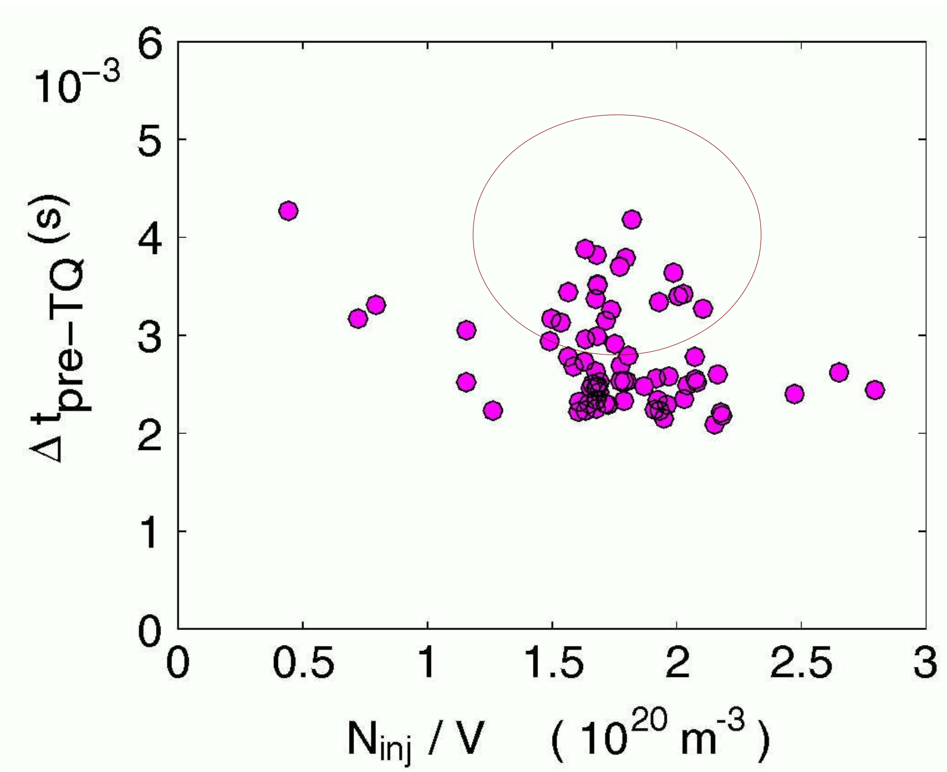
Summary

- Relatively large argon assimilation after 1st injection (~ 50 %)
- density rather constant in the RE beam phase (no clear dependence on current)
- up to 10 % argon assimilation after 2nd injection; probably radial diffusion coefficient can be inferred
- just trowing mass into plasma does not help (D_2 pellets)
- understand whether RE suppression/dissipation is feasible with MMI means understanding particle and energy (which T_e?) transport in these plasmas
- plenty of experimental data to benchmark models

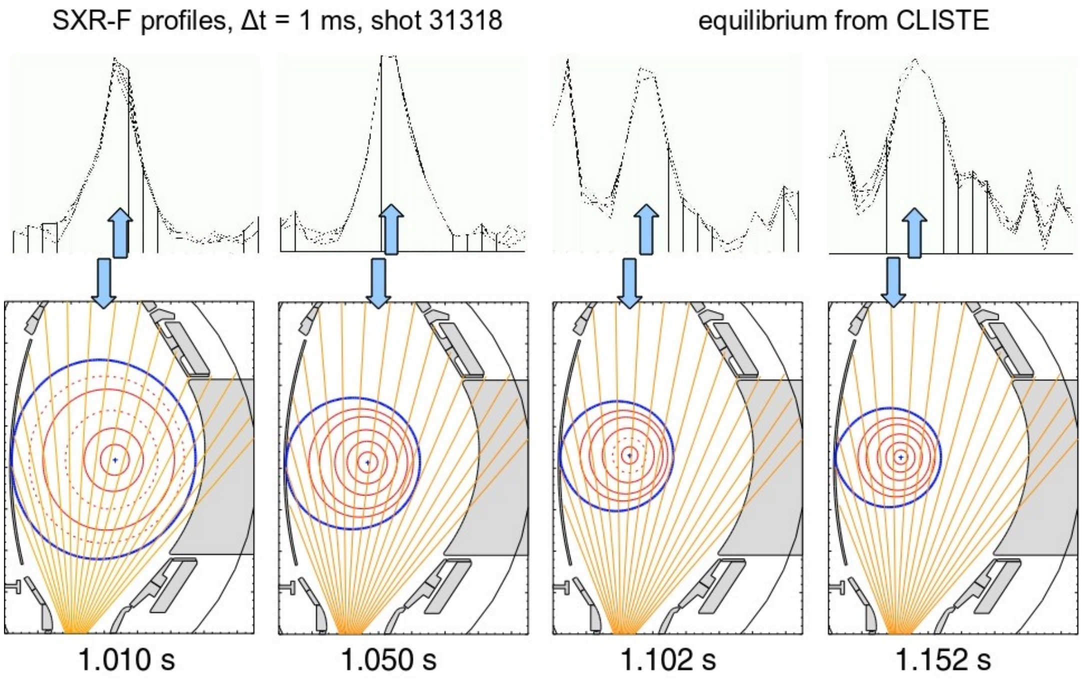
Additional slides

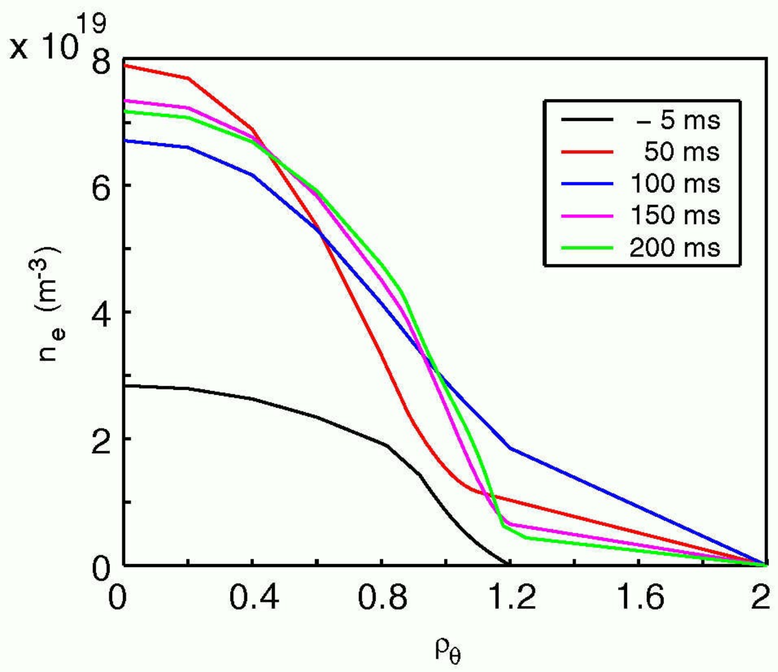
Pre-TQ time

- pre-TQ lasts > 2 ms (variables behind scatter data not yet identified



Equilibrium, density profile

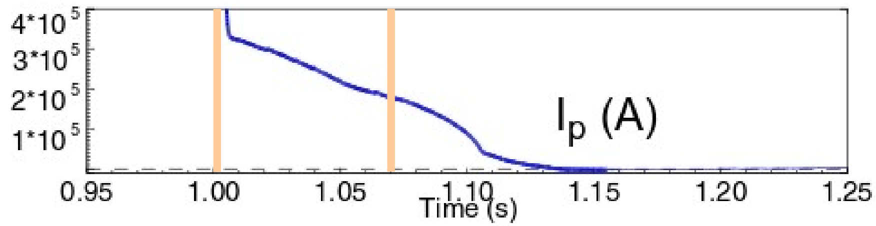


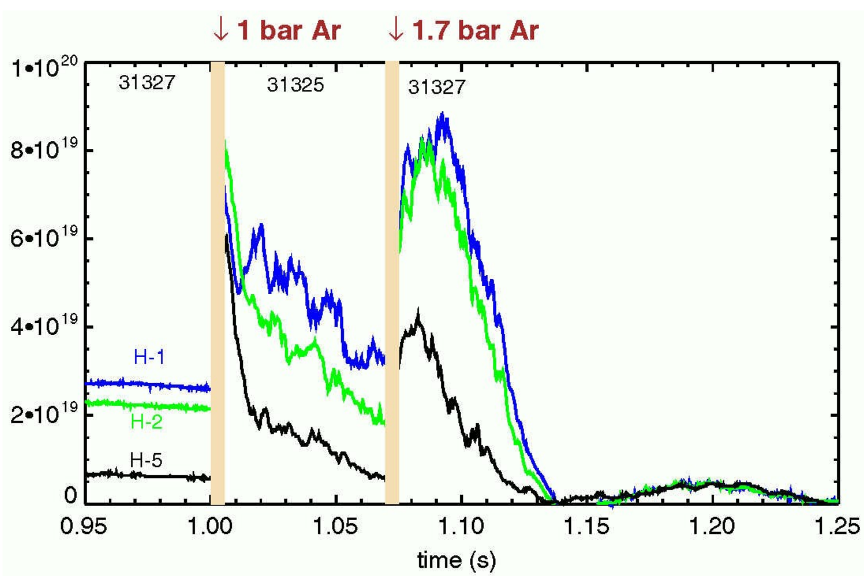


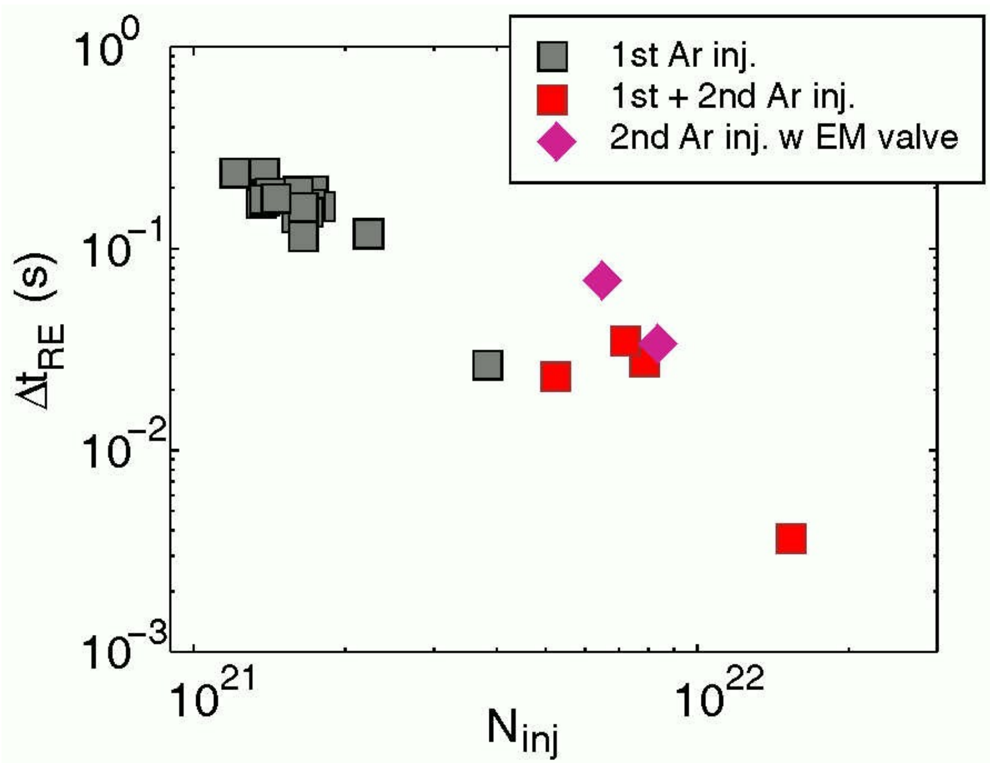
Series of equilibria;
beam position confirmed by SXR

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)

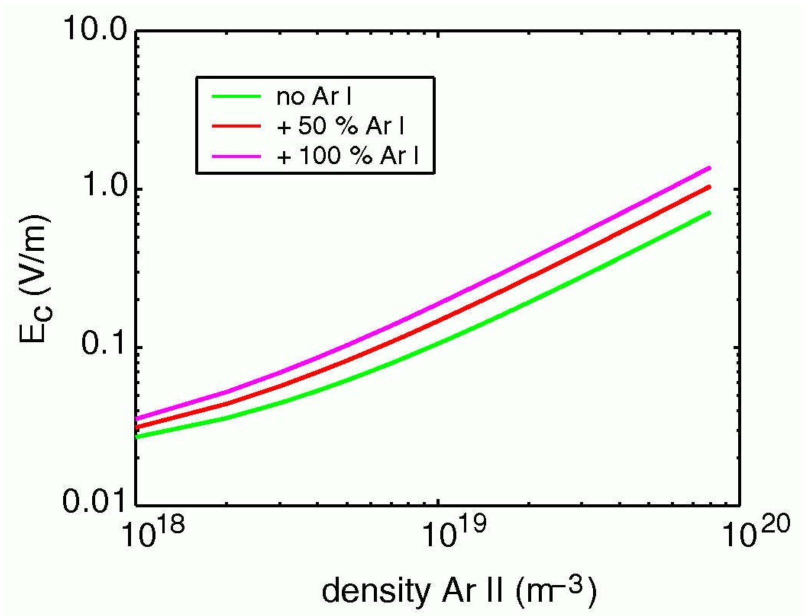
Formally:

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

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

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

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



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

E_c versus E_ϕ

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_ϕ**

(uncertainties in atomic data for argon)