The use of pellets for the suppression of runaway electrons in reactor-relevant disruptions: a discussion

G. Pautasso[1], E. Fable[1], F. Köchl[2], P. Lang[1], M. Siccinio[3], F. Maviglia[3]

1 Max-Planck-Institut für Plasma Physik, D-85748, Garching, Germany
2 CCFE, Cuhlam Science Centre, Abingdon, OX143DB,United Kingdom
3 EUROfusion Programme Management Unit, 85748 Garching, Germany

Is RE suppression by MMI possible (from physics PoV)?
Is it just an engineering problem?
How to design a DMS?

Use of pellets for RE suppression

- Suppression of avalanche generation of runaway electrons (REs) during disruption by massive material injection:
  - increase of electron density (n_e) by factor 20 – 40 for reactor-relevant (e.g. DEMO, R. Martin-Solis) case to suppress avalanche seed;
  - n_e increase must occur in plasma center;
  - within pre- thermal quench duration of some (assume 2-3) ms;
  - gas inventory is limited;

    → proxi requirements:

(1) amount of gas atoms injected: $N_{needed} = 2\times10^{21} \times Vol_{plasma}$

(2) pellets w speed v_p > 1 km/s

(3) pellets penetrate up to plasma center

Use of pellets for RE suppression

- (DMS parameters?)
  - pellet parameters:
    - gas type: D_2 (in reality: impurities needed in pellet & plasma)
    - velocity v_p
    - $r_p(a)$ radius, one size (or distribution), N_p number of D atoms in pellet
    - Number of pellets: $\mathcal{N}_p$

- DEMO plasma parameters
  - minor radius a = 2.9 m
  - major radius R_0 = 9 m
  - elongation k = 1.7
  - central density $n_e(0) = 10^{20}$ m^{-3}
  - central temperature $T_e(0) \leq 40$ keV

- Limits on gas inventory from pumping/exhaust system

Neutral gas shielding (NGS) model for D_2 pellet ablation

Pellet ablation rate (= matter deposition) is given by (T_e in eV, MKS units)

$$\frac{dN_p}{dt} = C_* \, n_e^{1/3} \, r_p^{4/3} \, T_e^{5/3}, \qquad C_* = 4.12 \times 10^{16}$$

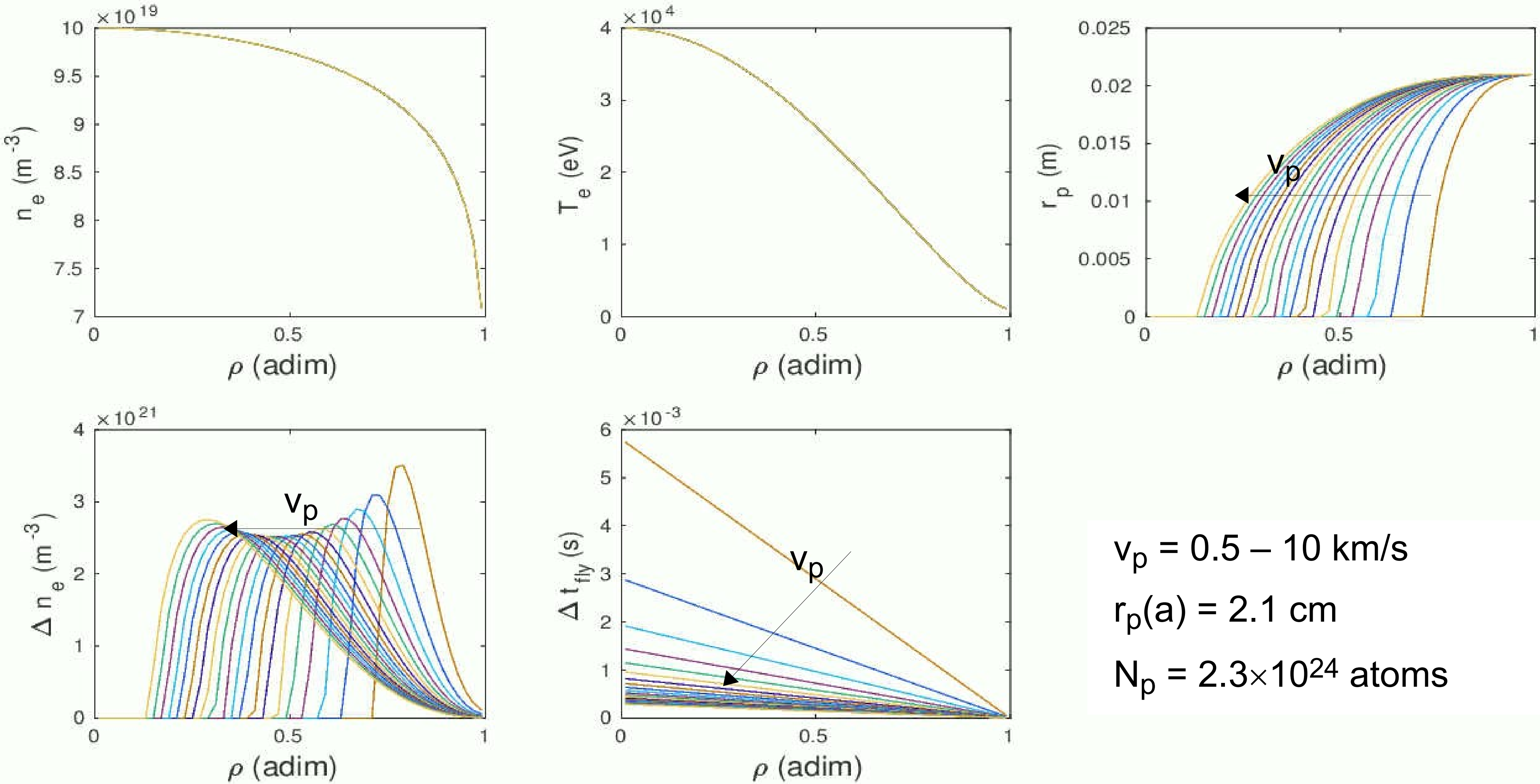
$$N_p = \frac{4}{3}\pi\eta_p r_p^3, \qquad \frac{dN_p}{dt} = 4\pi\eta_p r_p^2 \frac{dr_p}{dt}$$

or equivalently by

$$\frac{dr_p}{dt} = C \, n_e^{1/3} \, r_p^{-2/3} \, T_e^{5/3}, \quad C = \frac{C_*}{4\pi\eta_p}, \quad r_p(r) = \left(r_p(a)^{5/3} - \frac{5}{3}\frac{C}{v_p}\int_a^r n_e^{1/3} \, T_e^{5/3} dr \right)^{3/5}$$

$$\Delta n_e(r) \equiv \frac{\Delta N_p(r)}{\Delta V_{ol}} = \frac{dN_p(r)}{\cancel{dr}} \frac{\cancel{dr}}{dt} \frac{1}{4\pi^2 r R_0 k v_p}$$

NGS model: massive D_2 pellet in DEMO, v_p scan



v_p = 0.5 – 10 km/s

$r_p(a)$ = 2.1 cm

$N_p = 2.3 \times 10^{24}$ atoms

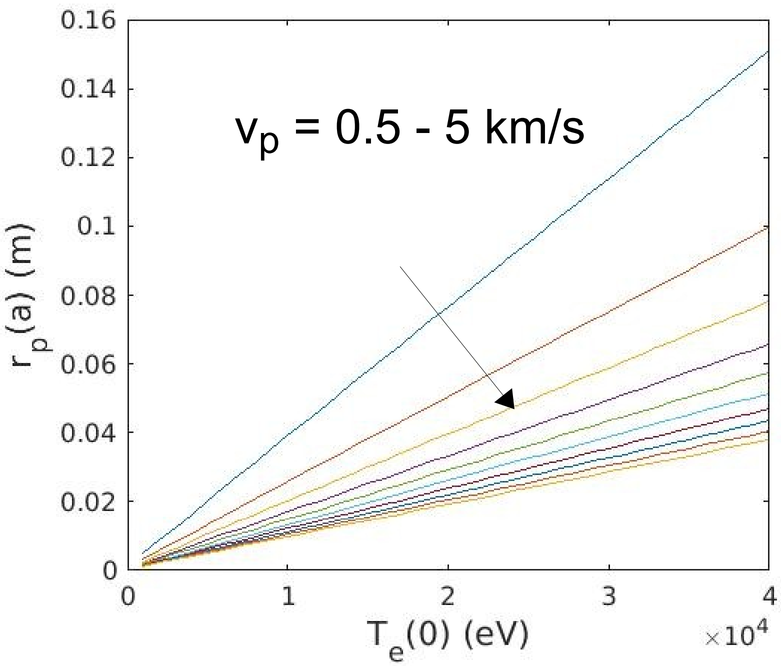
Can one D_2 pellet give rise to $\Delta n_e \sim 20\ n_e$ in DEMO case?
Not with “reasonable” (e.g. 1500 m/s) velocities. Larger r_p (larger D_2 inventory) or v_p needed

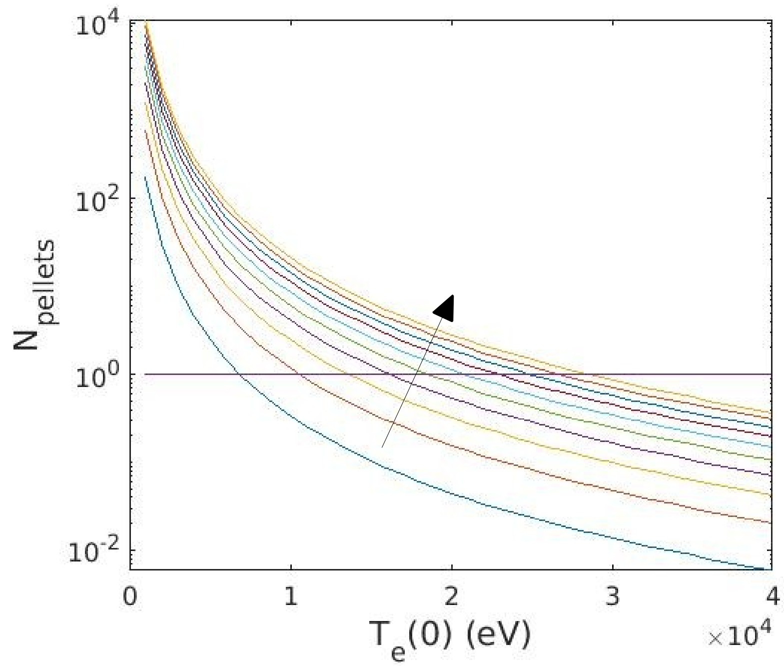
Penetration depth = minor radius

Which pellet penetrates up to r = 0? → relation between $r_p(a)$ and $T_e(0)$, v_p

$$r_p(0) = 0 \rightarrow r_p(a) = \frac{T_e(0)\, n_e(0)^{1/5}}{v_p^{3/5}} \left(\frac{5}{3} C \int_a^0 \left(\frac{n_e}{n_e(0)} \right)^{1/3} \left(\frac{T_e}{T_e(0)} \right)^{5/3} dr \right)^{3/5} \propto \frac{T_e(0)}{v_p^{3/5}}$$

$N_{needed} = 2\times10^{21} \times Vol_{plasma}$



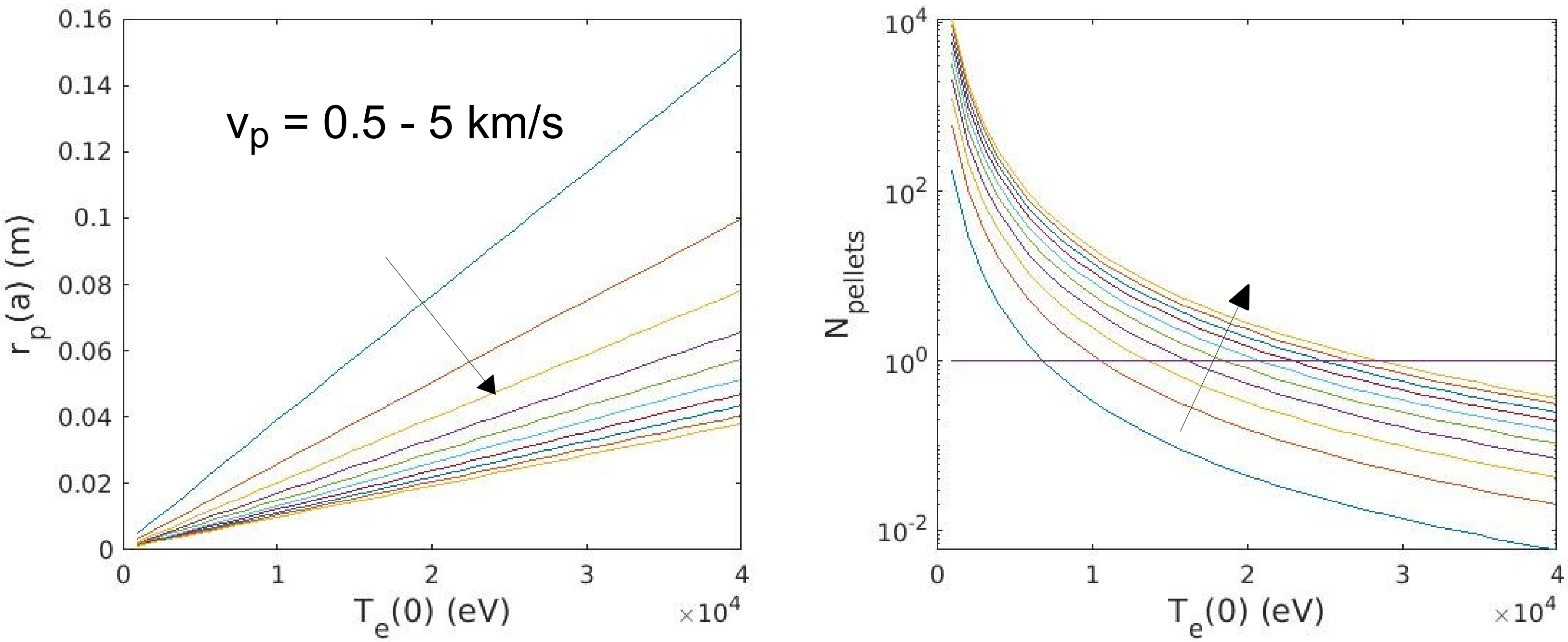


(Unrealistically) flexible injector ...

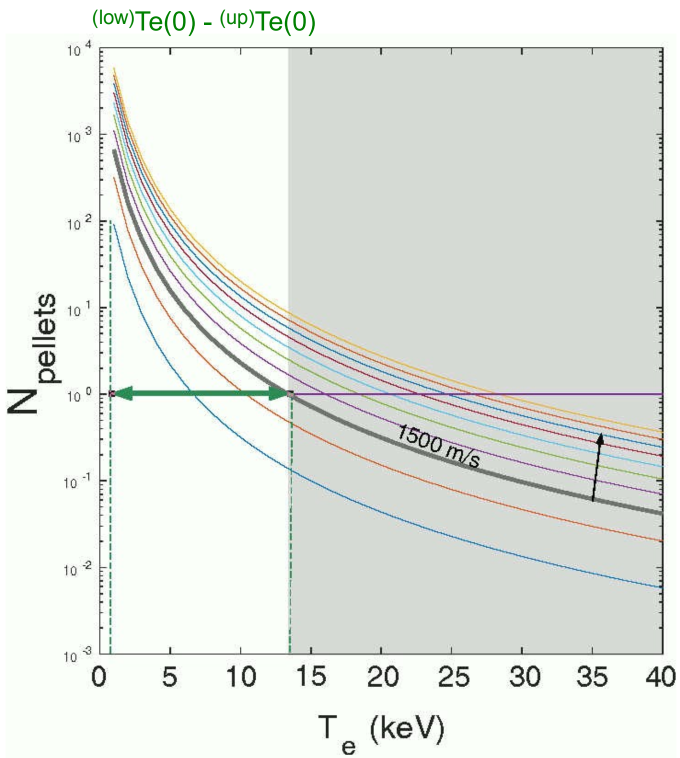
single D_2 pellet injection
$$\frac{max\, v_p}{min\, v_p} = \left(\frac{max\, T_e(0)}{min\, T_e(0)}\right)^{5/3} = 40^{5/3} = 468$$

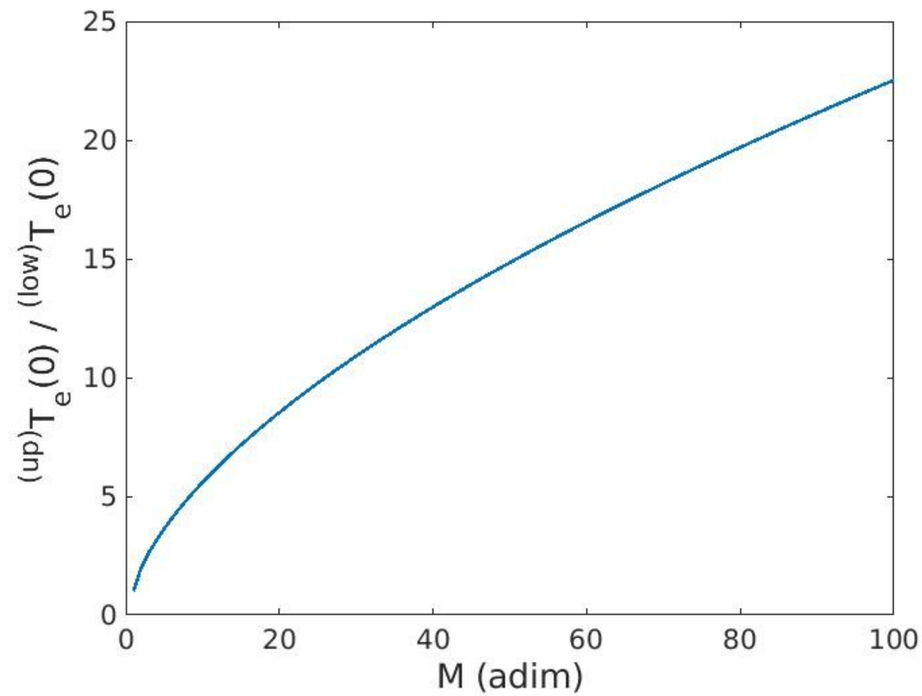
simultaneous multiple D_2 pellet injection
$$N_{pellets} = N_{needed}/N_p \propto T_e(0)^{-3}, \qquad \left(\frac{min\, T_e(0)}{max\, T_e(0)}\right)^{-3} = 40^3 = 64000$$

… if $r_p(0) = 0$



Discretization of pellet/plasma parameter space for injector design





M = max gas quantity allowed by pumping/exhaust system / N_{needed}

E.g.: $M = 3^3 \rightarrow \frac{^{(up)}T_e(0)}{^{(low)}T_e(0)} = [1-(\frac{M-1}{M})^{5/9}]^{-3/5}$ = 10...

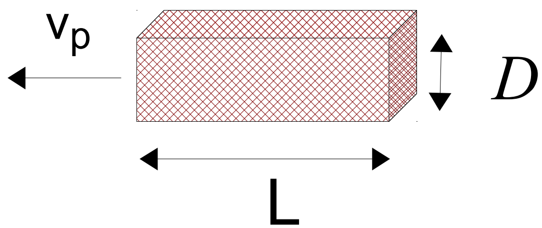
→ use $r_p(a) \sim 3\, r_p(a)\{^{(up)}T_e(0)\}$ in range $^{(low)}T_e(0)$ – $^{(up)}T_e(0)$

→ r(a) = 3×2.6 cm for T_e = 1.4 – 14 keV

doable?

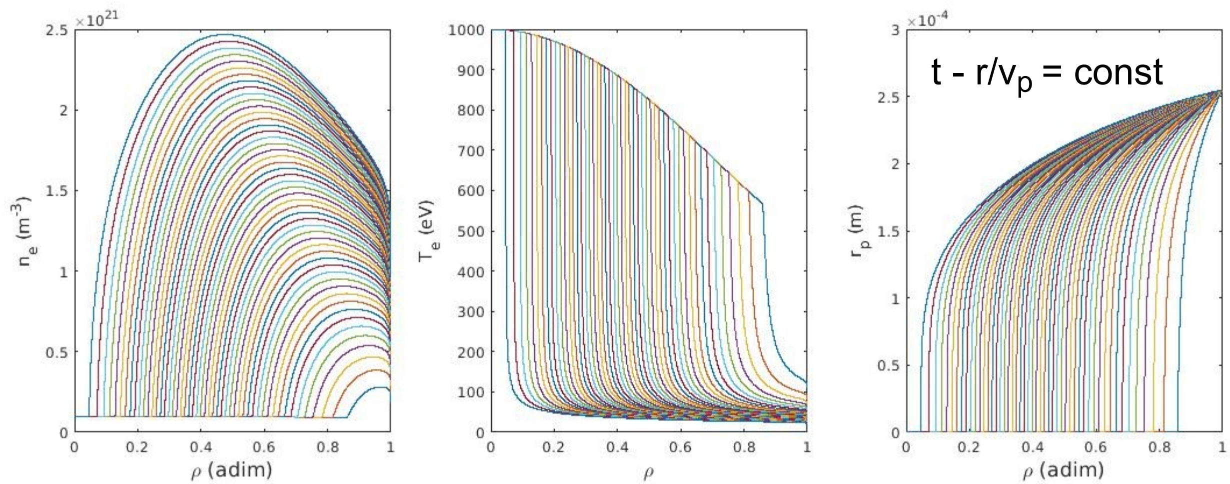
Multiple D_2 pellet injection

$\mathcal{N}_p = L\, D^2\, n_p$: n. of pellets in packet



$$\frac{\partial n_e}{\partial t} = \frac{dN_p}{dt}\,\frac{n_p D^2 \Delta r}{4\pi^2 r R_0 k \Delta r} = \frac{dN_p}{dt}\,\frac{\mathcal{N}_p}{4\pi^2 r R_0 k L}$$

$$n_e(r,t)T_e(r,t) \simeq n_e(r,0)T_e(r,0)$$



$T_e(0) = 1$ keV

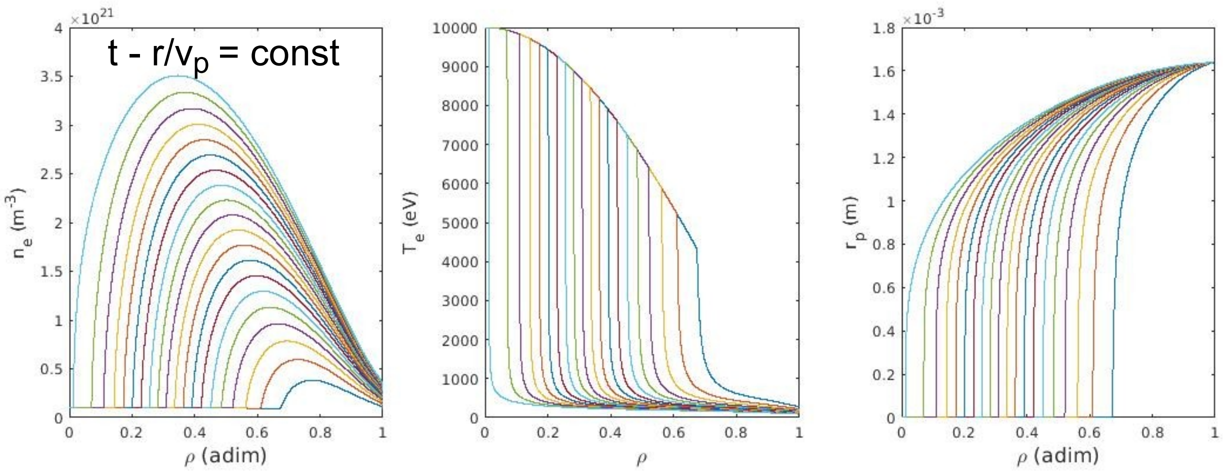
$v_p = 1500$ m/s

$r_p(a) = 0.25$ mm

$\mathcal{N}_p = 8.4\times10^5$

$N_{needed} = 2\times10^{21} \times \mathrm{Vol}$

Multiple D_2 pellet injection



$T_e(0)$ = 10 keV

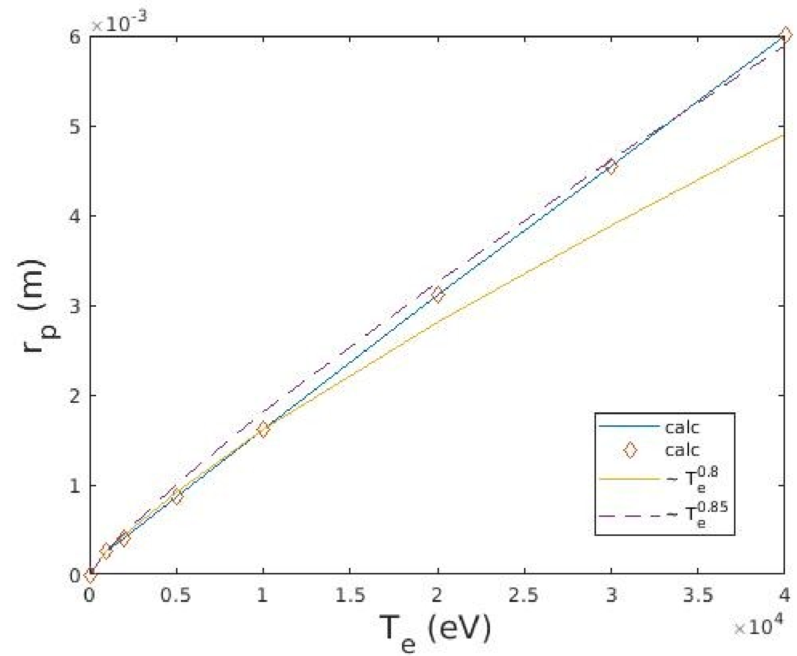
v_p = 1500 m/s

$r_p(a)$ = 1.63mm

$\mathcal{N}_p$ = 4582

$N_{needed} = 2\times10^{21} \times$ Vol

- Pellet penetration up to plasma center possible also in high T_e regime
- still strong r_p and $N_{pellets}$ dependence on T_e, e.g. **$r_p(a) \propto T_e(0)^{0.8}$**
- large M needed to decrease n. of injectors
- how to create and launch $\{\mathcal{N}_p, r_p, v_p\}$ pellets?

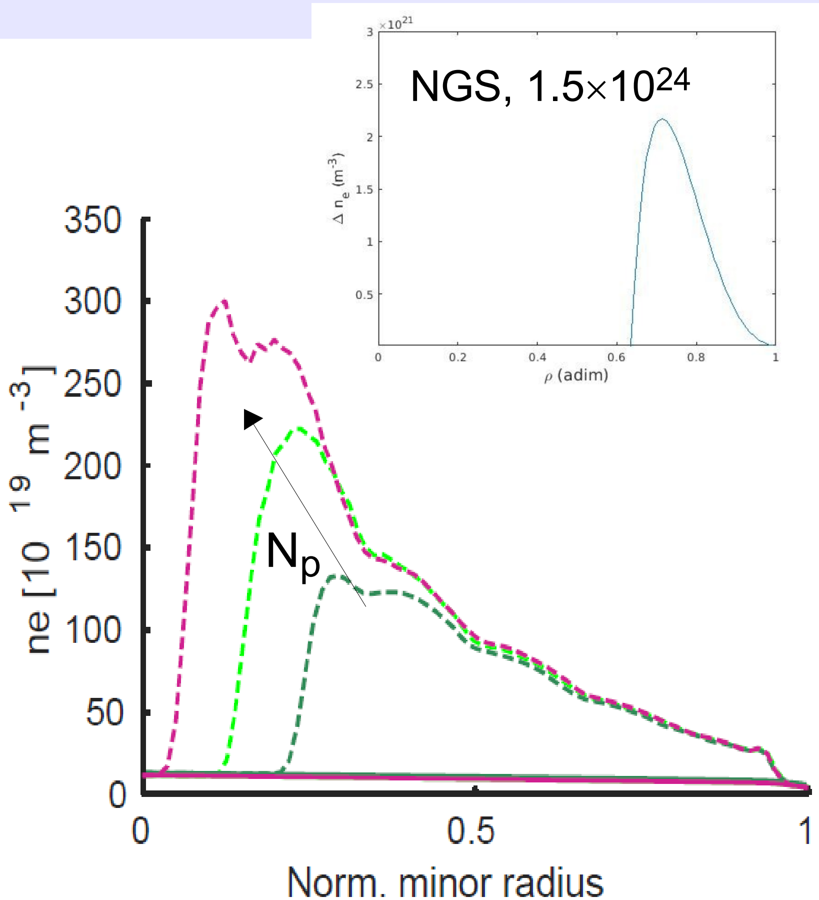


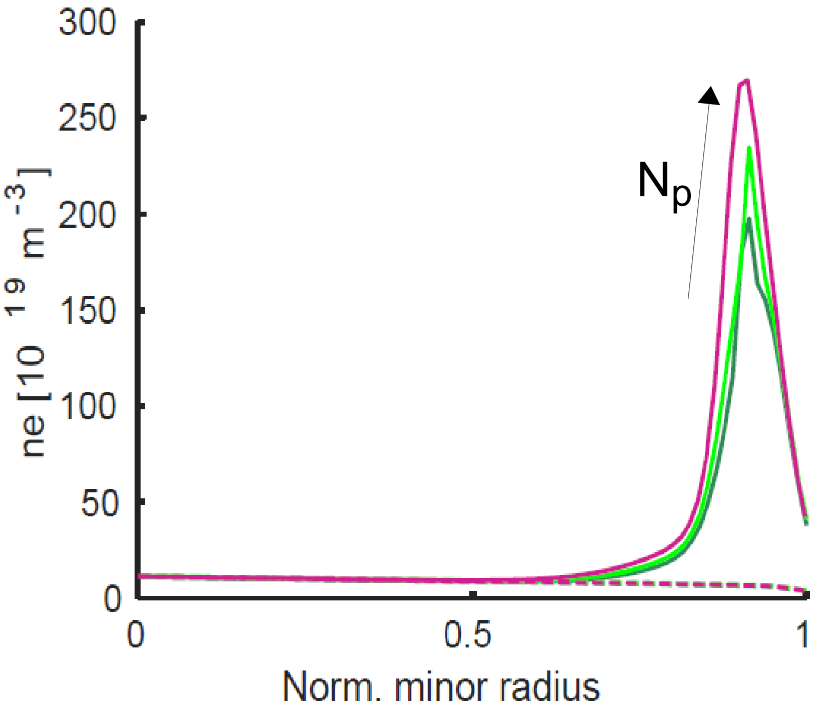
HPI2-ASTRA versus NGS

- NGS: simple pellet ablation model (P.B. Parks, 1978)
  - monoenergetic electrons, no electrostatic and plasma shielding, no E×B drift
  - consistent w exp. data (IPADBASE, L.R. Baylor, 1997) and modelling (K. Gal, 2008)

- HPI2: code developed by F. Köchl, B. Pegourie et al. (EFDA-JET-PR(12)57)
  - neutral gas, plasma and electrostatic shielding, maxwellian energy distribution for thermal plasma, fast ions and electrons, E×B drift, rocket effect
  - coupled to ASTRA (1.5 transport code)

Modelling with HPI2





Three cases of final density (n_e) calculated by the HPI2 code after the ablation and assimilation of one massive deuterium pellet in a DEMO-like plasma ($N_p = 1.0, 1.3, 1.5 \times 10^{24}$ deuterium atoms) without (left) and with (right) plasmoid drift.

v_p = 1200 m/s, injection from LFS midplane

Discussion

- Ablation of cryogenic deuterium pellet and material deposition fully determined by plasma and pellet parameters

- Pellet radius and pellet velocity **must** be varied (only within range of technical feasibility) to create needed Δn_e

- NGS model indicates strong dependence of ablation rate on T_e and **$r_p(a) \propto T_e(0)^{0.8}$**

  - RE suppression system must work for wide range of T_e, e.g. 1 – 40 keV;

    several injection systems (designed for different **$r_p(a)$ and $\mathcal{N}_p$**) must be available to deliver - **alone** – whole amount of needed gas

  - RE suppression in T_e= 10-40 keV range requires multiple pellet injection or unreasonable large pellets and **v_p ~ several km/s**

  - large M decreases number of different injectors

- HPI2 code pellet deposition very different from NGS calculation → code needed to refine DMS design (but remarks on M, v_p and r_p likely to remain valid)

Outlook: complex (solvable?) problem

RE losses/suppression/generation determine N_{needed} profile

Validated **pellet ablation + uncertainty model**
pellet ablation theory must be revisited/resumed
Plasma dimension, T_e, v_p and N_{needed} outside of accessible exp. range

Plasma reaction: drift, convection and // diffusion during nonlin. MHD

Pumping/exhaust system: constrains on gas quantities? can they be relaxed?

Injection technology: limits on v_p, r_p and N_p? Synchronization? Pellet integrity? reliability? All unknown technology.

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