Plasma Physics Laboratory - ERM/KMS - Brussels - Belgium

Transient versus steady state solutions: a qualitative study

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Intro: Philosophy of this talk

- Steady state often assumed as "given" —> studies often done using steady state version of equations.

- "Snap shot" approach (using *steady state equations* but plugging in experimentally known or guessed profiles) popular; artificially hides effects that may be key …

- *Reaching+holding+leaving* actual steady state not evident and deserves attention in its own right.

- Most *present-day* machines do not manage to have very long flat tops. Transient effects *rule* rather than *exception* …

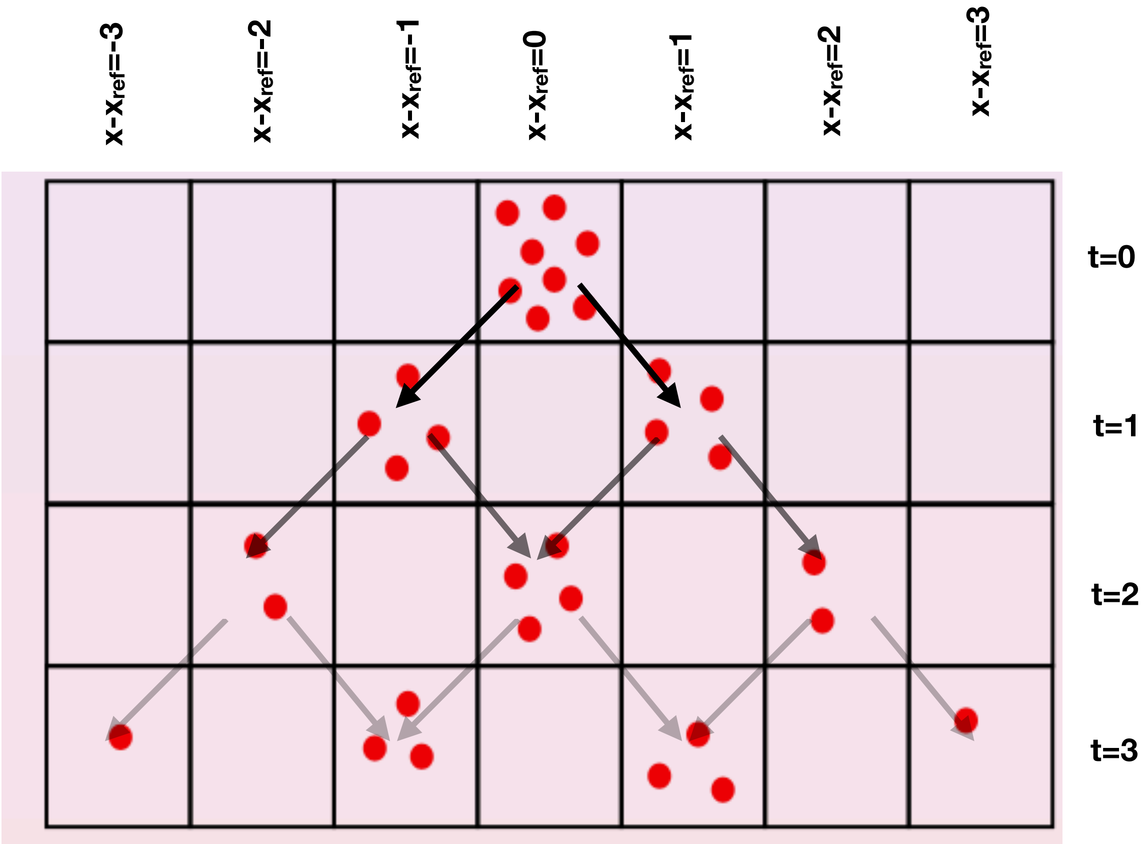
- Solving the actual *time-dependent version of the equations* increases realism, providing better insight and hence steerability.

- *The present talk highlights some transient effects associated with plasma heating using 2 brutally simplified diffusion-convection models.* More sophisticated models (many of which exist) sidestepped to illustrate bare elementary effects. Hopefully this talk is tickling specialists into looking into shown effects with their better suited models …

[All examples in this talk are loosely inspired on high-performance JET discharges.]

Diffusion: the verrrrrrry basics

Random walk dynamics for D=1m²/s & V=0m/s (normalised step and time):



Diffusion: $<(x-x_{ref})^2>=D\ t$: BI-directional

Convection: $<x-x_{ref}>=V\ t$: MONO-directional

Green's function solution:

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial U}{\partial x} + VU\right] + S$$

$$S = \delta(t - t_o)\delta(x - x_o)$$

$$U(x) = \frac{1}{[4\pi D(t-t_o)]^{1/2}} exp - \left[\frac{[x - x_o + V(t-t_o)]^2}{4D(t-t_o)}\right]$$

In steady state bi-directionality diffusion *masked*:

[DdU/dx] + integral S=0 —> net "up-hill" movement

>0 —> <0 >0

[Almost simplest-on-earth] Fokker-Planck equation

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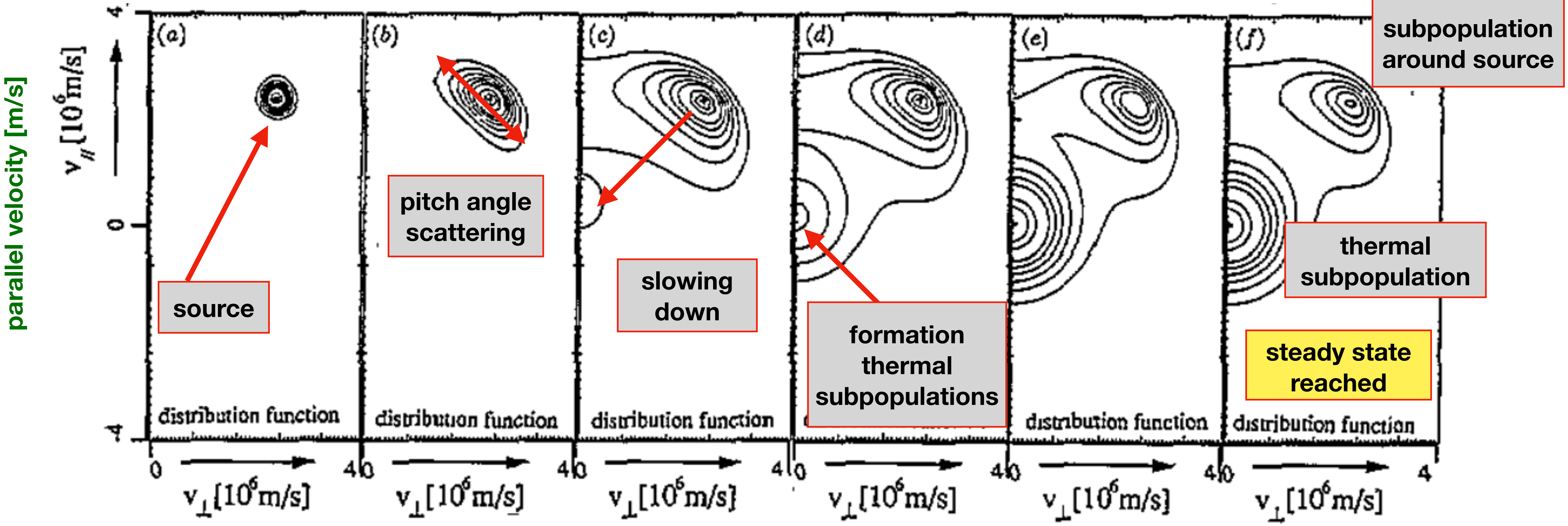
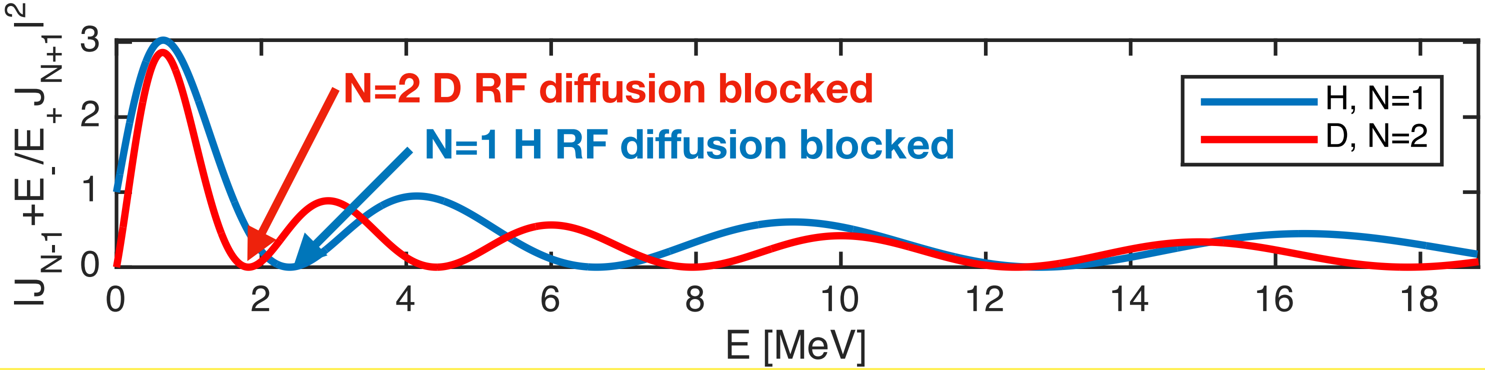




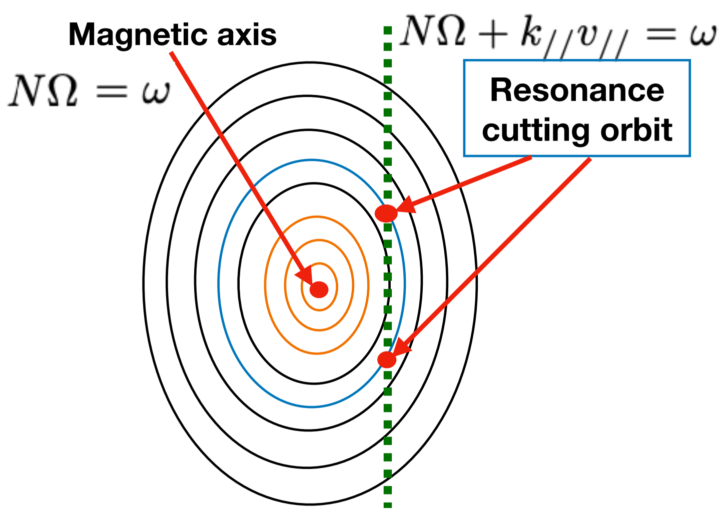
B_o=3.35T

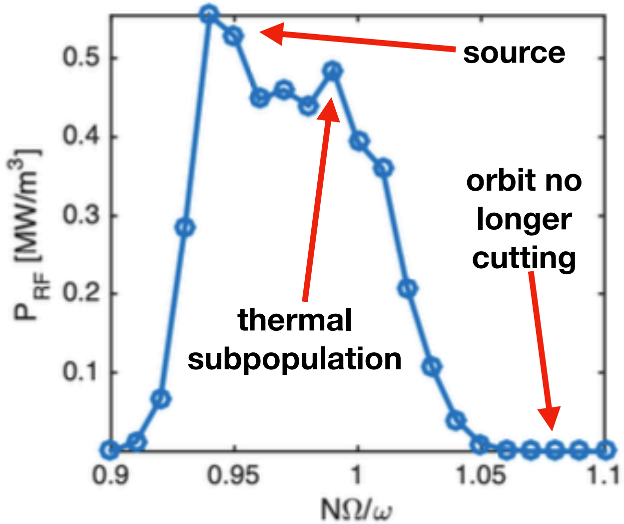
E_-/E_+=4, $k_\perp$=75/m

-Pitch angle scattering more efficient than slowing down
-Slowing down brings particles to thermal region; pitch angle scattering makes distribution uniform

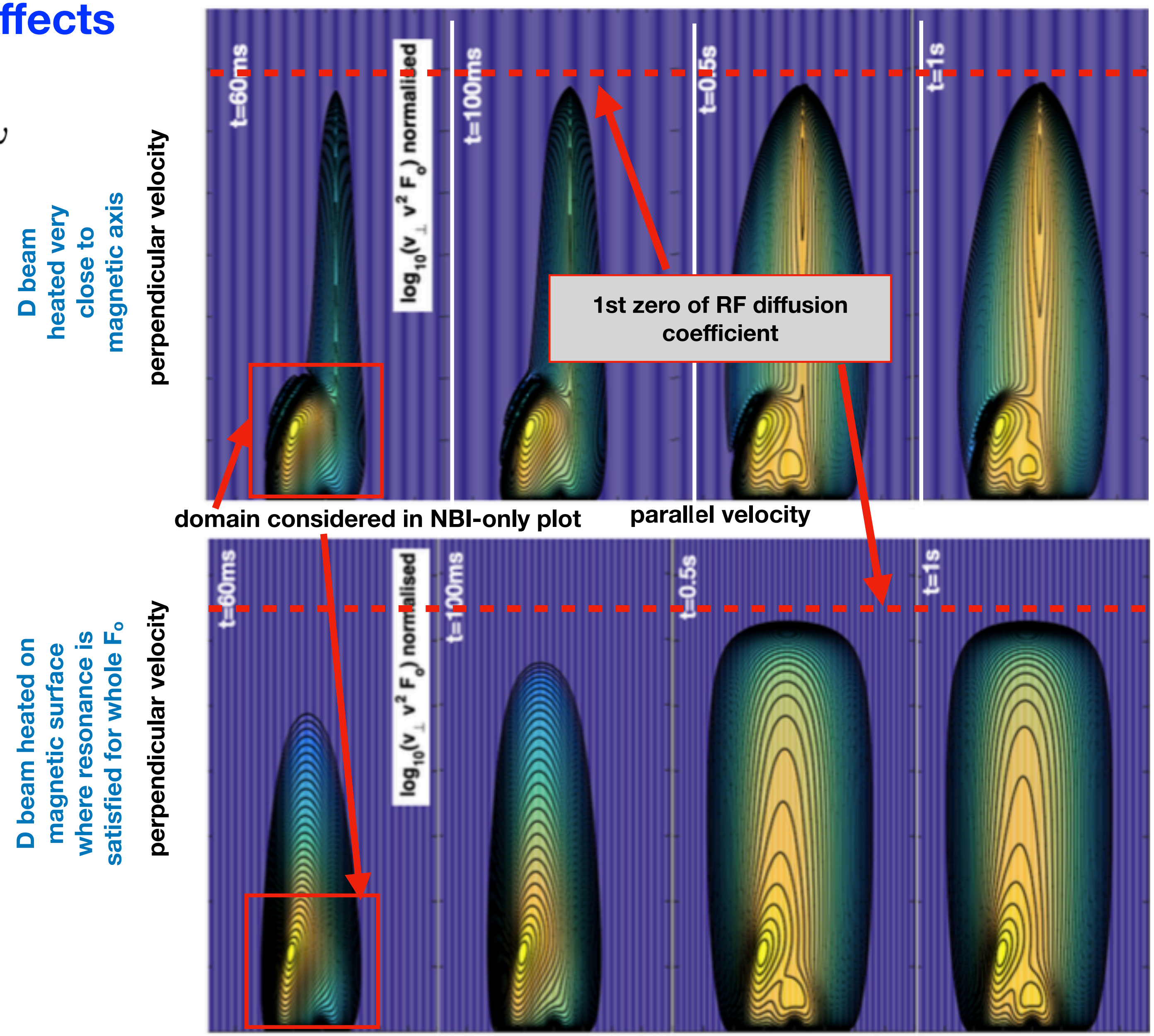
Heating localisation & transient effects

Passing orbits
(~OK close enough to centre)



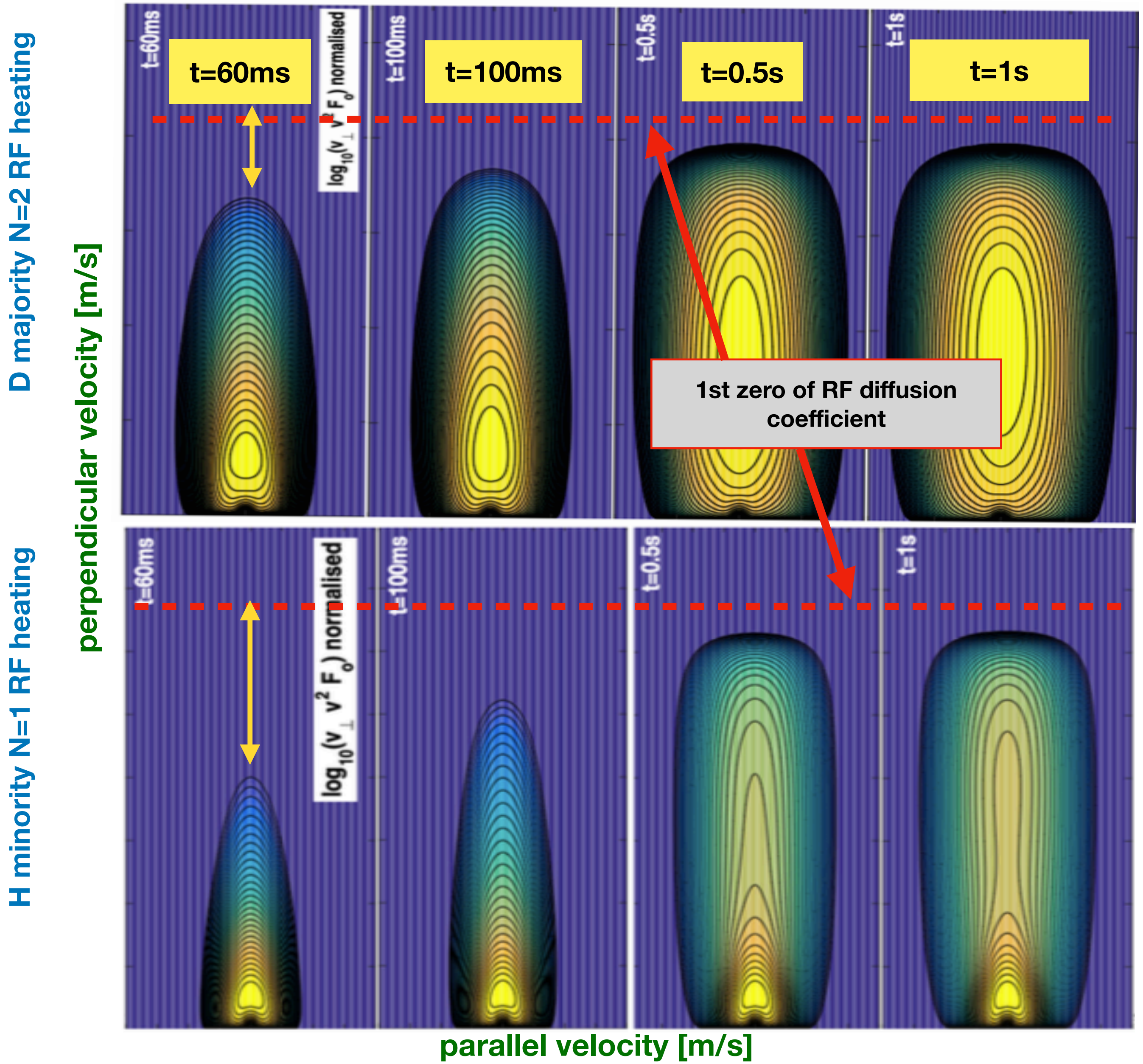


≠ location ≠ tail evolution



RF scenario

$\log_{10}$ energy density in terms of v_{perp} & v_{par}

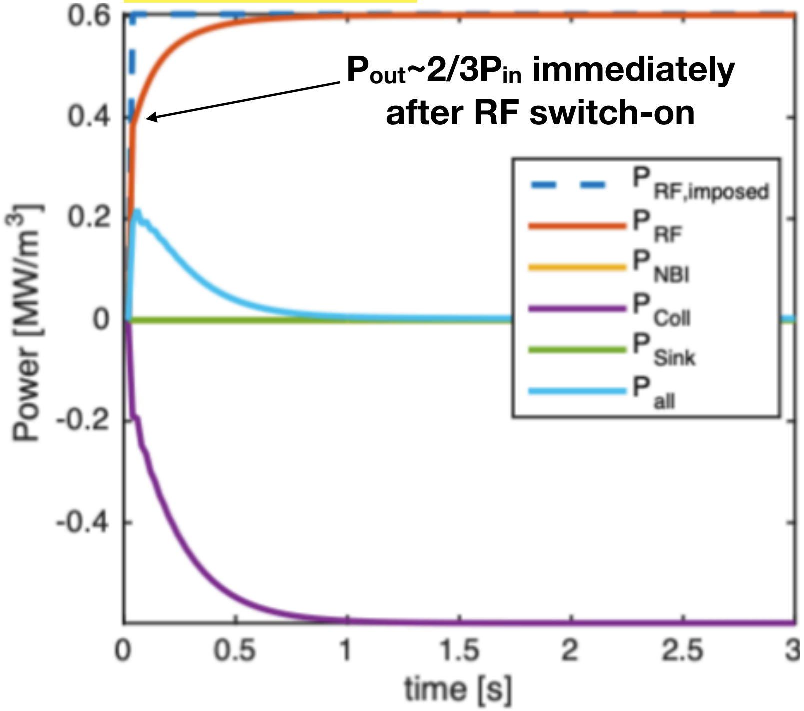


It takes time to build a saturated tail; N=1 more "fat" in // direction and more populated at low v. Details depend on RF scheme as well as on type of population

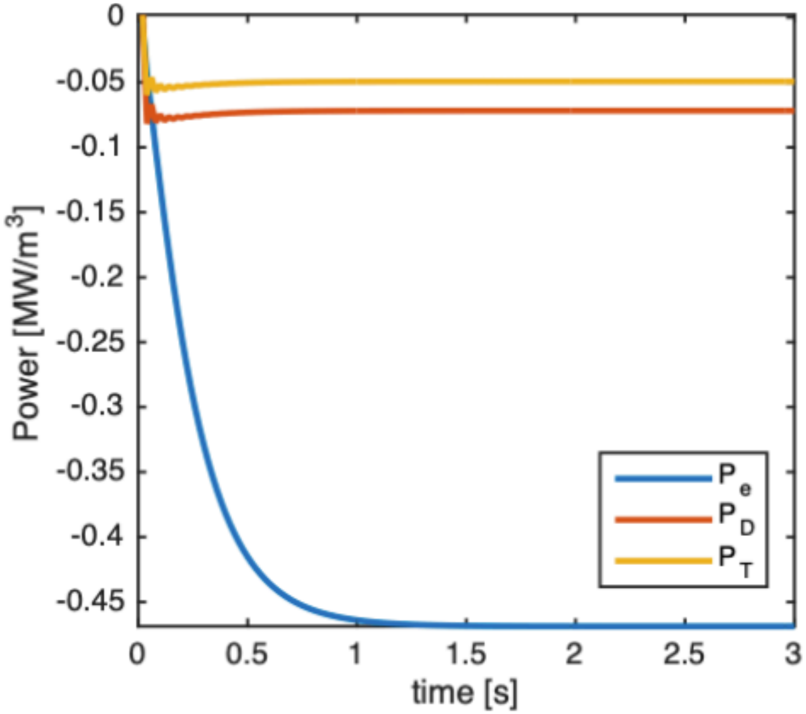
Convergence towards steady state

Power balance

N=1 H minority



Collisional power redistribution



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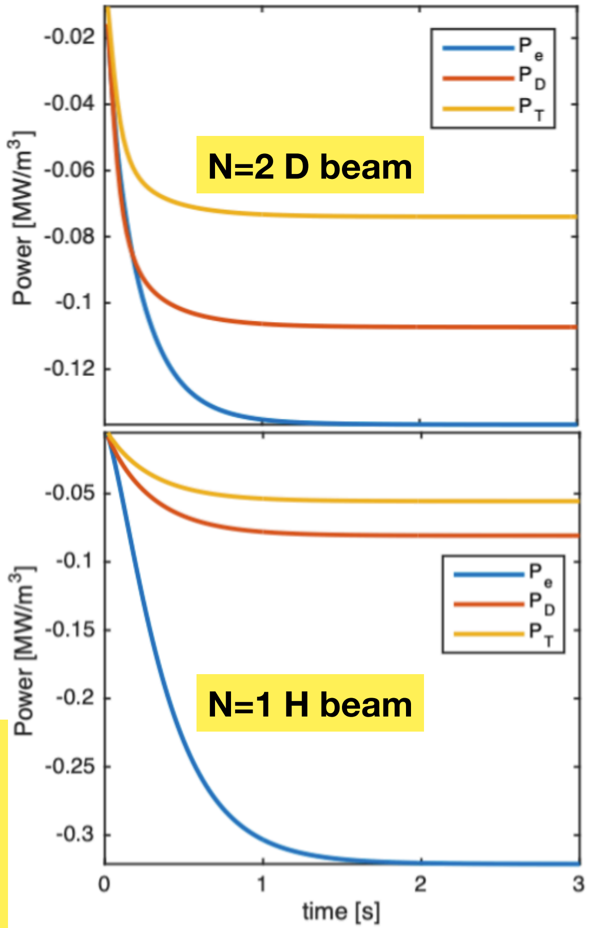
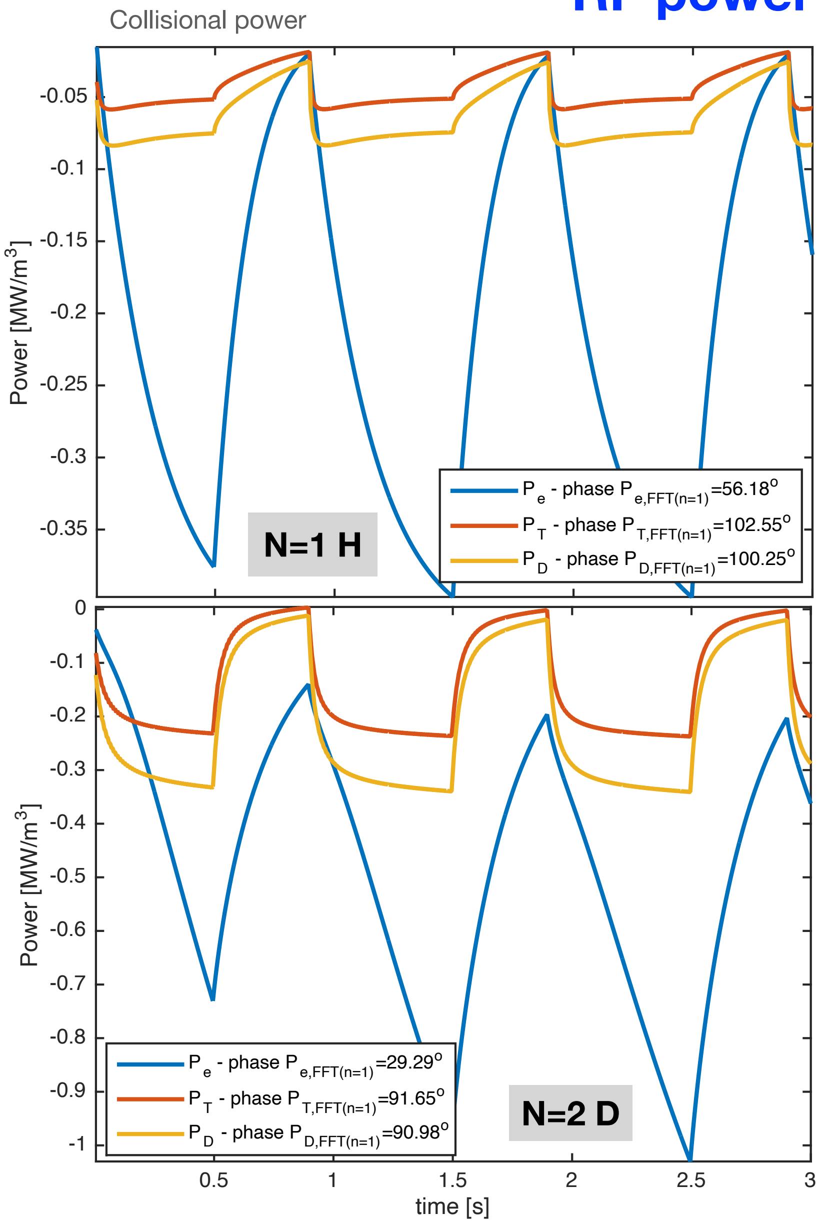
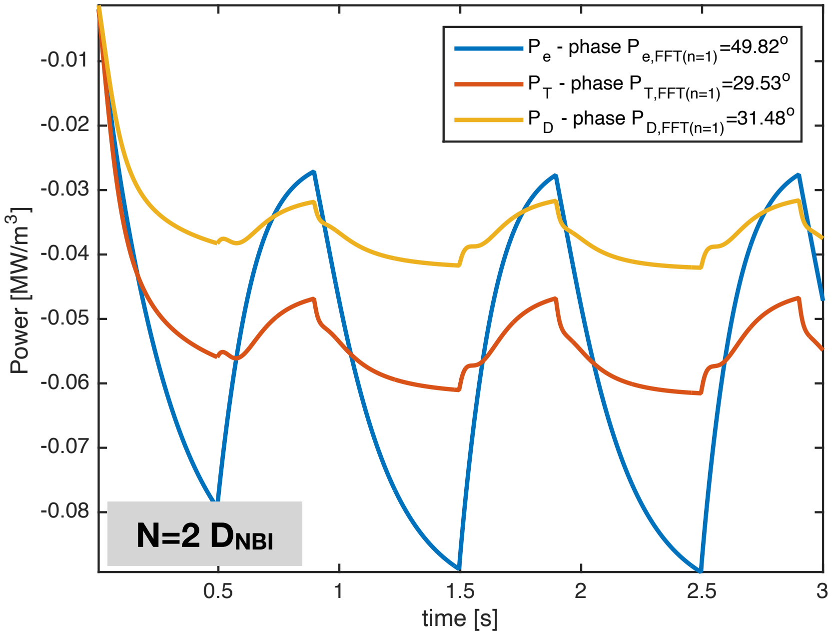


Reaching steady state ≠ for ≠ scenarios and populations:

- balance with ions faster than balance with electrons (if fast ion response desired, heat ions directly!): slower convergence in high energy region where collisions are less efficient
- overall convergence ~4x slowest characteristic time
- N=1 heating quickly reaches P_{in}~P_{out}
- N=2 heating steady-state slower although RF faster: fast tail & thermal distribution need to reach equilibrium
- vessel = Faraday cage: prefer N=1 heating even when N=2 is efficient in steady state

RF power modulation





parameters inspired on JET high density H-mode

full to 10% power - f_{mod}=1/s - duty cycle 60/40

Phenomena evolving over various modulation periods render interpretation modulation effects more complex …

[Definitely simplest-on-earth] Heat and particle transport equations

[Definitely the simplest-on-earth] Transport equations

Diffusion Convection Source

Particles

$$\frac{\partial N(\rho,t)}{\partial t} = \frac{1}{\rho}\left[\rho[D_N N' + V_N N]\right]' + S_N$$

Energy

$$\frac{\partial E(\rho,t)}{\partial t} = \frac{1}{\rho}\left[\rho[D_E E' + V_E E]\right]' + S_P$$

Assume a *circular* cross section *without magnetic shift*, omit about toroidal curvature, take known D and V, and simple sources.
1-fluid instead of e, i_{bulk}, $i_{impurities}$

BC: flux=0 at axis and (negligible) N & T imposed at edge.

Steady state conservation equation:

particle flux F_N

$$\left[\rho(D_N N' + V_N N)\right]\Big|_{a_p} = -\int_0^{a_p} d\rho\rho S_N$$

$$\left[\rho(D_E E' + V_E E)\right]\Big|_{a_p} = -\int_0^{a_p} d\rho\rho P$$

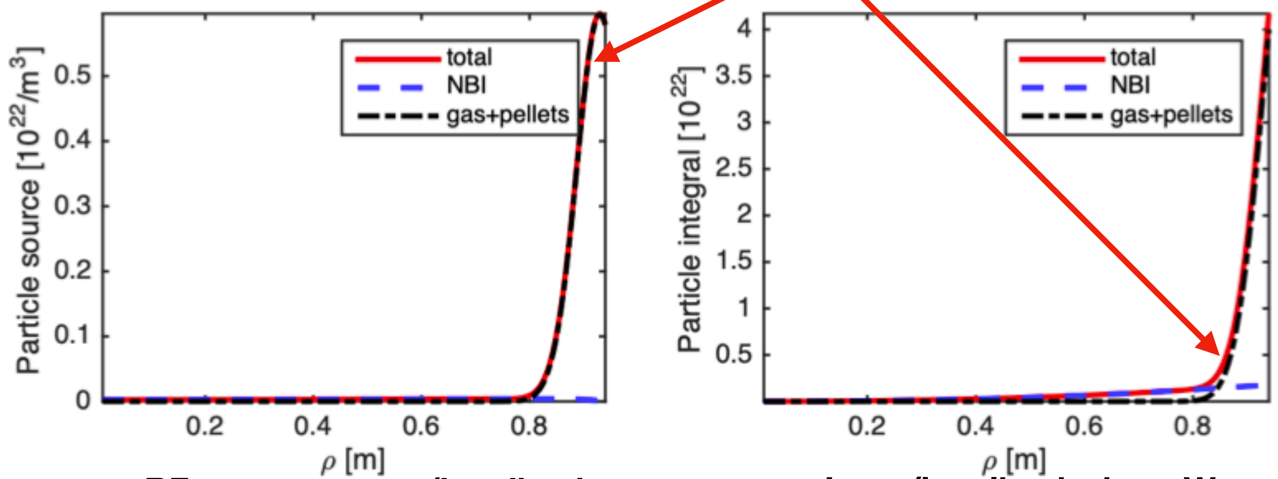
energy flux F_E

Whatever escapes or is brought in has to escape or enter via the edge

e.g. larger *integrated* source requires larger *edge* D or larger edge gradient if V=0

Source profiles (steady state)

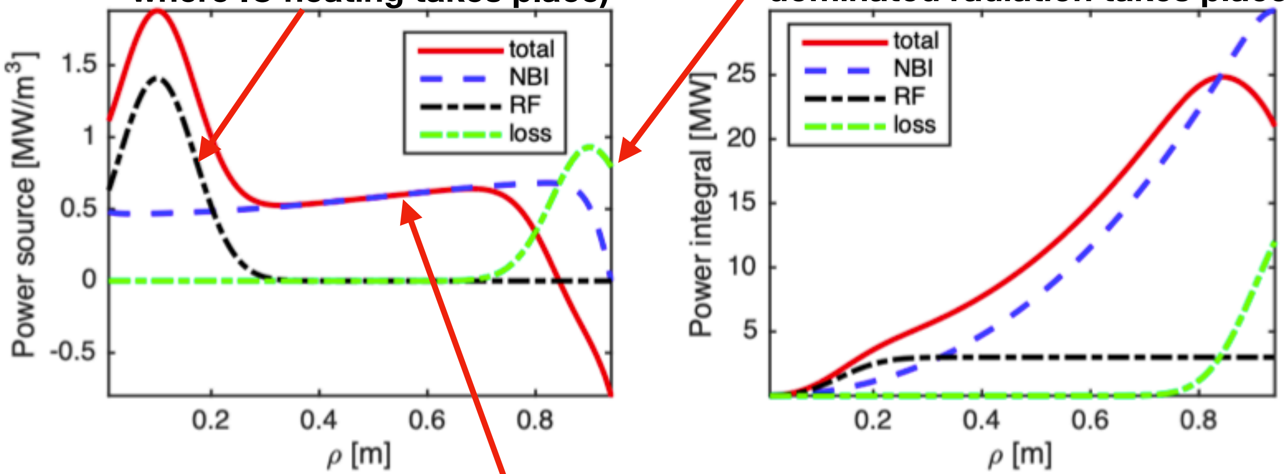
Gas or pellet source (ionisation): localised near edge



Beam source small for particles w.r.t. gas but dominant for energy w.r.t. RF

RF power source (localised where IC heating takes place)

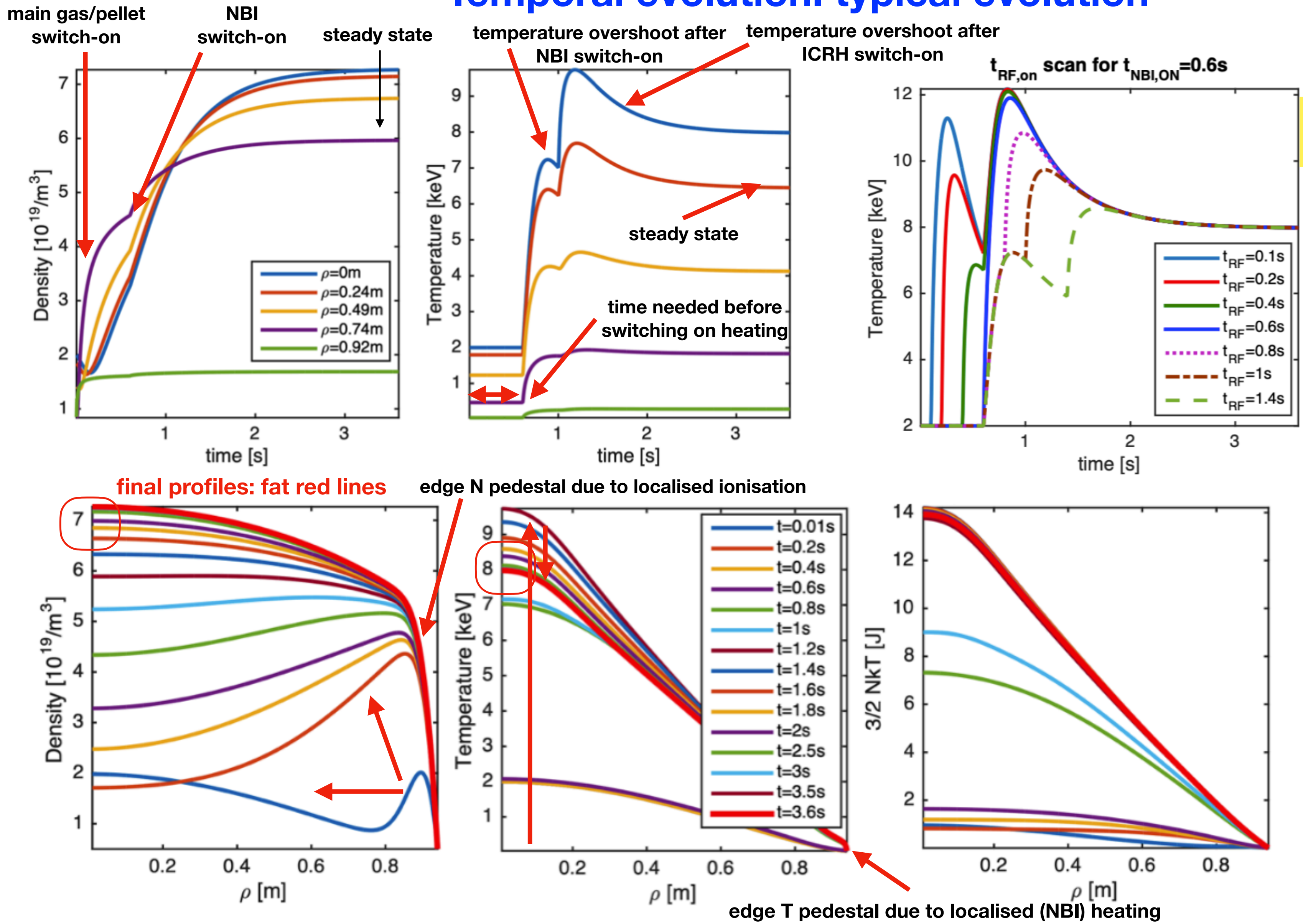
Loss (localised where W-dominated radiation takes place)



NBI source computed from ionisation path with actual density

Beam power source (broad: ionisation & beam intensity)

Temporal evolution: typical evolution



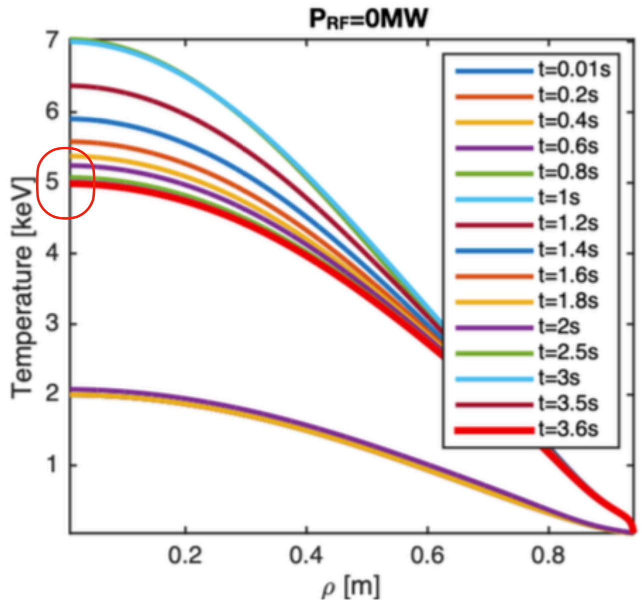
Optimisation timing allows (transiently) boosting performance

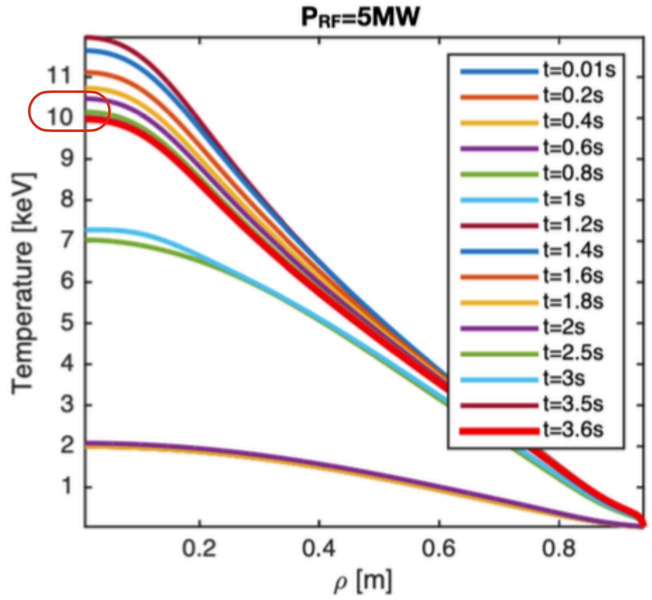
Actual start-up phase faked: start when low density profile already set up.
Strongly inverted density profile at start (with impact on NBI profile …)

Temperature overshoot, then gradual convergence towards steady state; relative timing switch-on important!

Energy reaches steady state much quicker than N or T

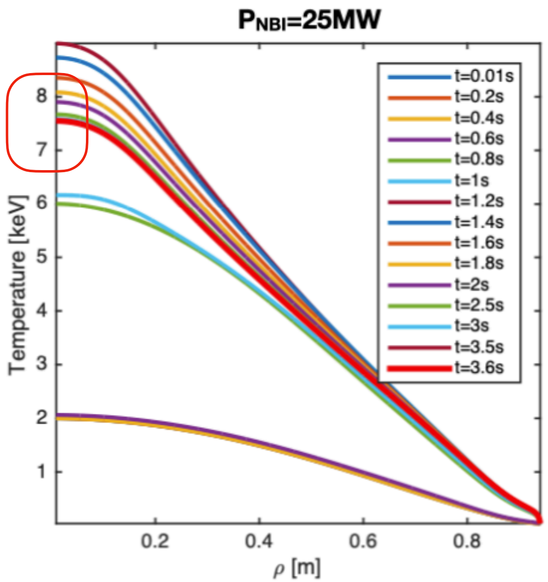
Impact power sources

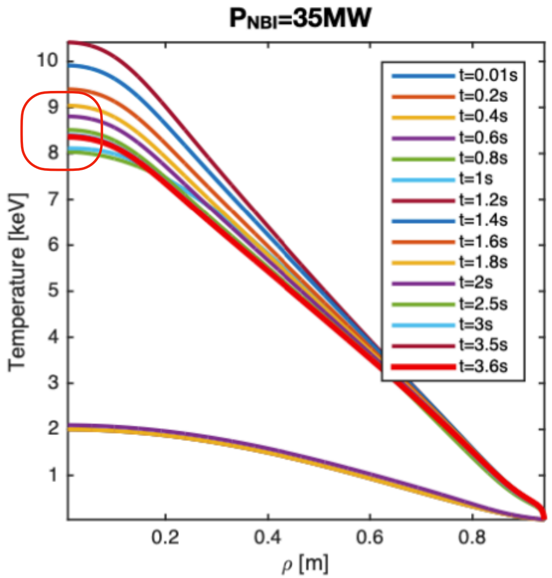


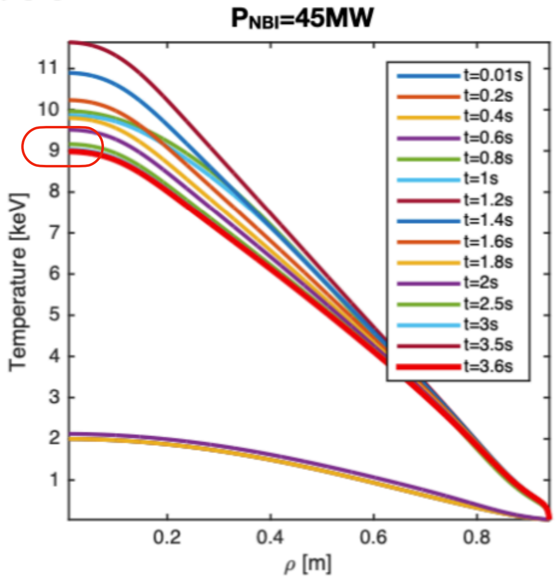


Reference:
P_{RF}=3MW
P_{NBI}=30MW

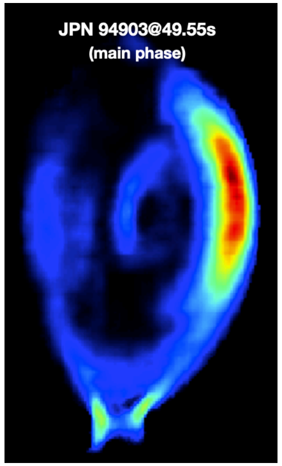
Core localised **ICRH is much more efficient than NBI (volume effect); combination RF & NBI allows high T_{core} and broad T profile but P near edge yields increased loss by diffusion …**



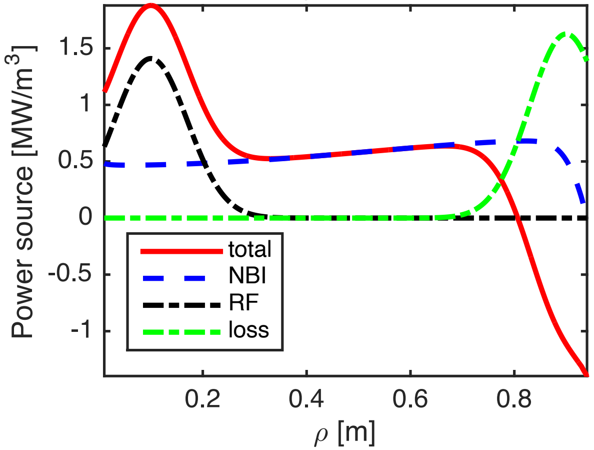




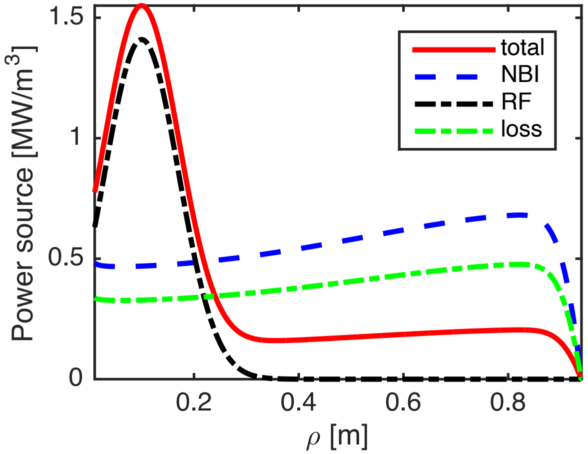
Temporal evolution: increased losses



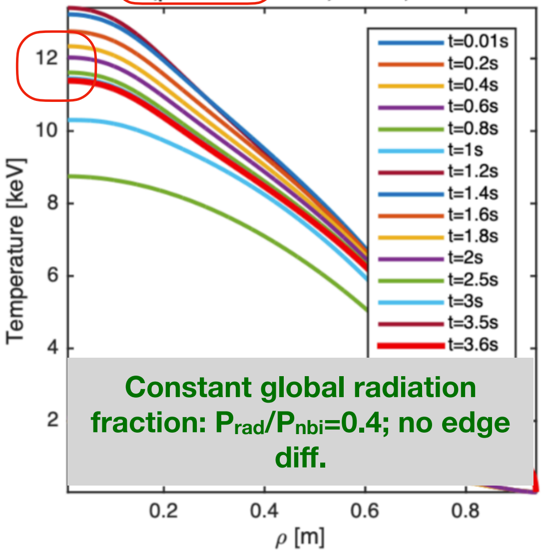
$P_{Loss,tot}$ proportional to $P_{NBI,tot}$ but "LFS blob" edge localised loss



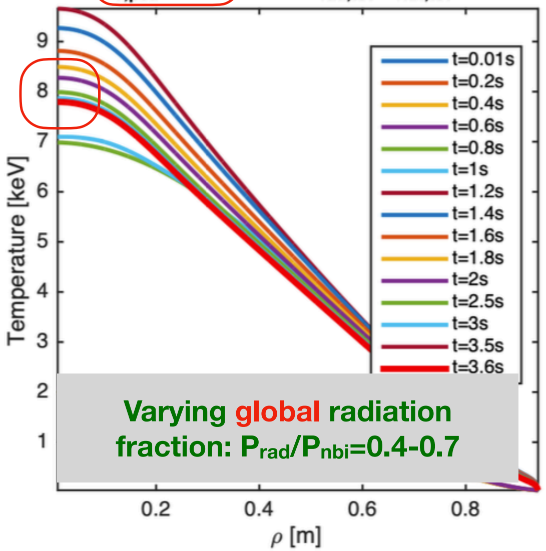
$P_{Loss,tot}$ proportional to $P_{NBI,tot}$ *everywhere* (impurities entering plasma core)



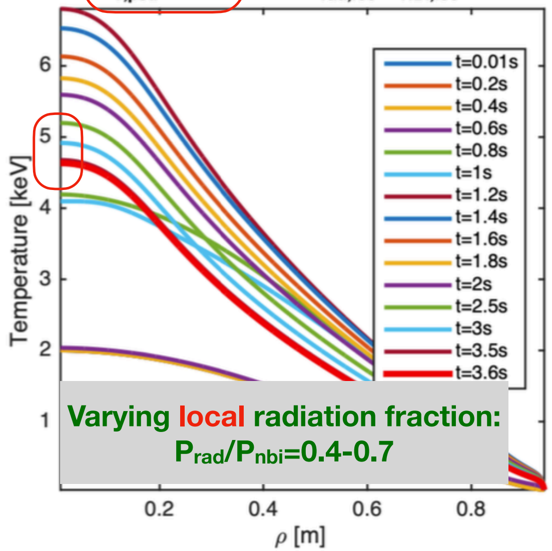
$D_{T,ped}=0m^2/s$ - $P_{rad,tot}/P_{NBI,tot}=0.4$



$D_{T,ped}=1m^2/s$ - $0.4<P_{rad,tot}/P_{NBI,tot}<0.7$



$D_{T,ped}=1m^2/s$ - $0.4<P_{rad,loc}/P_{NBI,loc}<0.7$

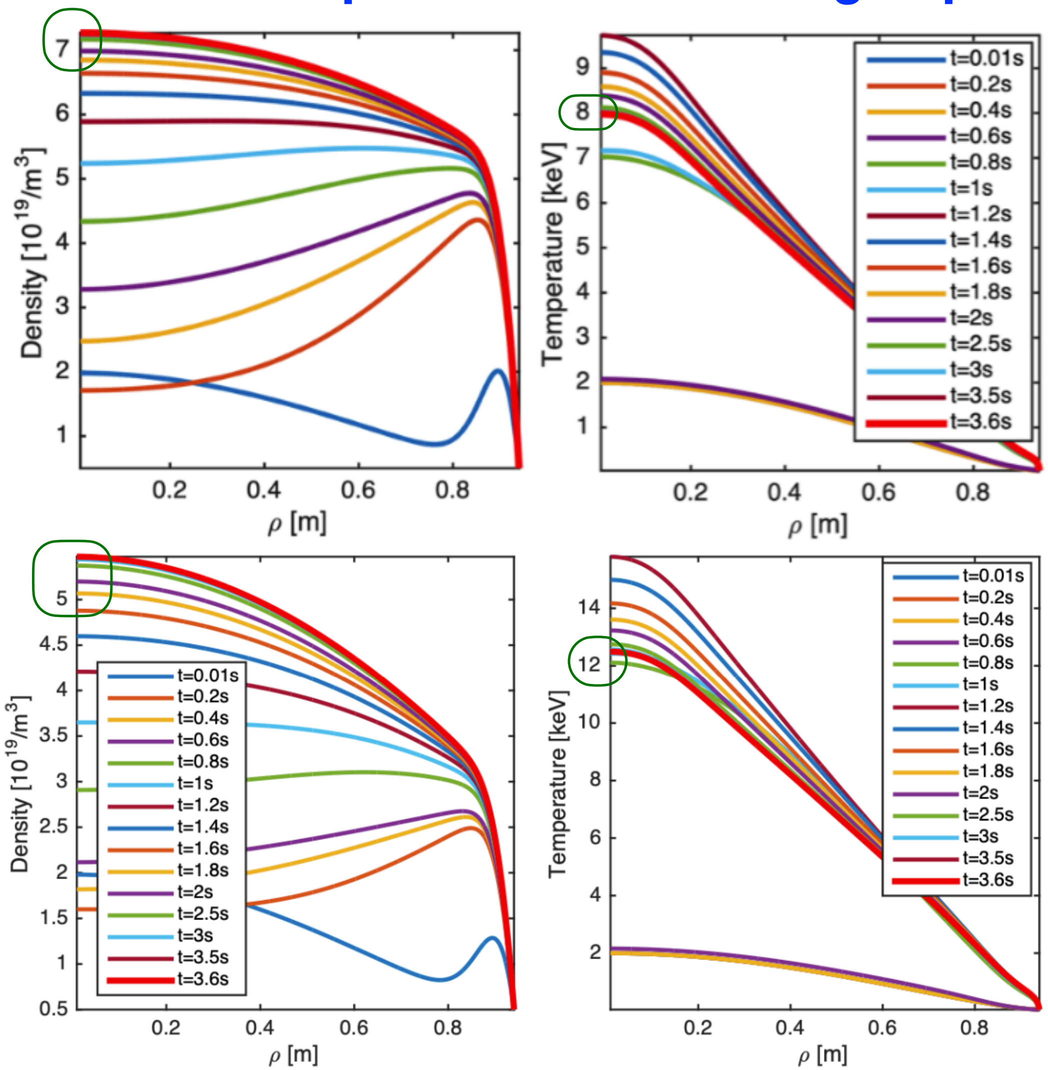


≠ impact of ≠ localisation: ≠ sensitivity relative position sources/losses
(e.g. core loss much more damaging than edge loss: edge loss first requires transport to make effect sensed …)

Forcing increased temperatures: reduced gas/pellets source

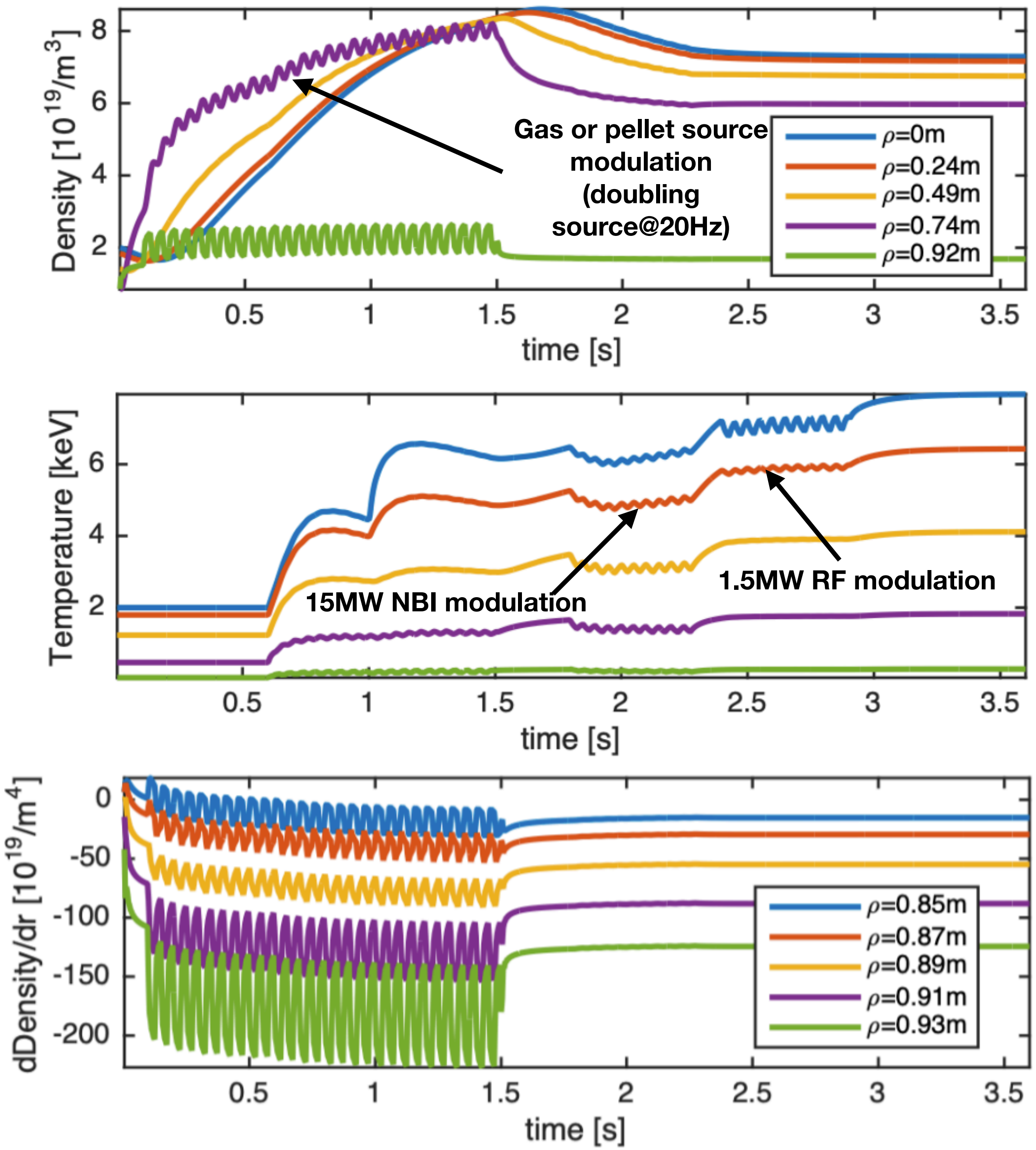
S=4x10²²/s

S=2x10²²/s



Reduced gas or pellets yields lower density and hence allows higher temperatures, transiently as well as in steady state; high T may be profited from in practice to trigger entering ≠ path of the discharge

Particle or energy source modulation



Particle source modulation strongly affects edge (e.g. pedestal gradients cranked up) but weakly affects core (if at all)

NBI source modulation weak w.r.t. RF modulation (due to ≠ localisation)

RF excellent tool for transport analysis, pacing (impacting on ST), …

Pellets as tool for forcing ELMS: increased spatial gradients

(simple tool describes steepening gradient but cannot provide info on dependence critical gradient to cause ELM crash …)

Multiple species interacting: coupled FP & transport equations

Proportionality factor cross-talk species Fokker-Planck:

Usual reasoning "heated heavy ions heat (lighter) fuel ions" but power partly "stolen" from fuel ions when considering back-reaction when accounting from all ion species interacting

$$\Gamma^{a/b} = \frac{n_b q_a^2 q_b^2 \ln \Lambda^{a/b}}{4\pi\epsilon_0^2 m_a^2}$$

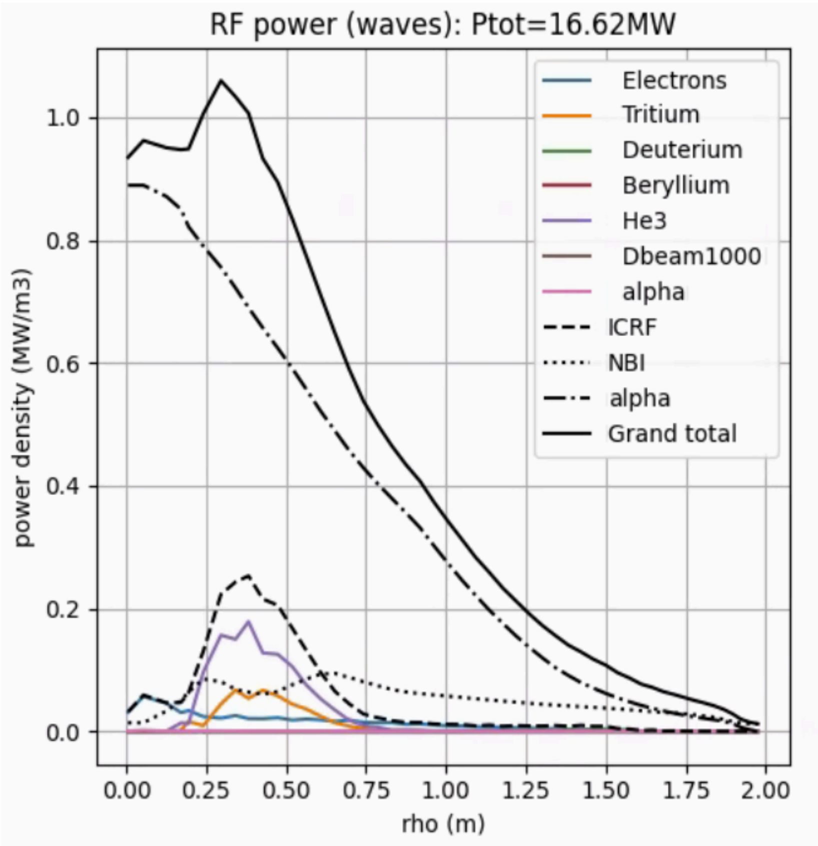
a/alpha: test species
b/beta: background species

Equipartition term transport equation

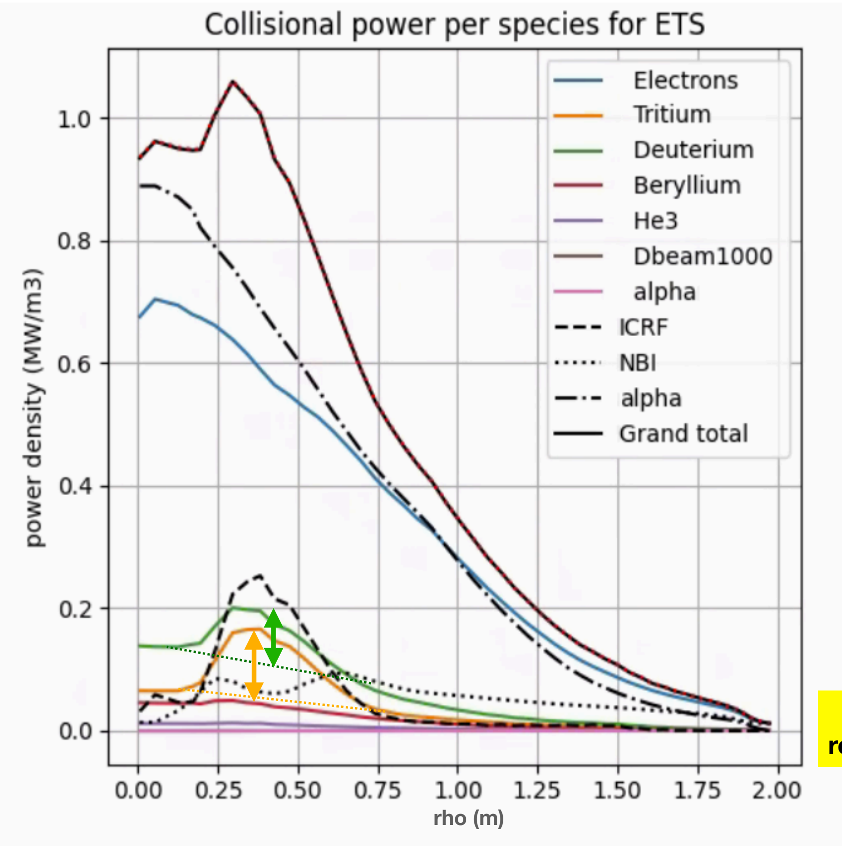
collisional interaction between e & i much slower than between i & i; reaching steady state takes time: distributions do not at all fill same v-space

$$\bar{\nu}_\epsilon^{\alpha\backslash\beta} = 1.8 \times 10^{-19} \frac{(m_\alpha m_\beta)^{1/2} Z_\alpha{}^2 Z_\beta{}^2 n_\beta \lambda_{\alpha\beta}}{(m_\alpha T_\beta + m_\beta T_\alpha)^{3/2}} \sec^{-1}$$

ITER example: (^{3}He)-D-T



P_{RF}=17MW, 2% He^3, off-axis



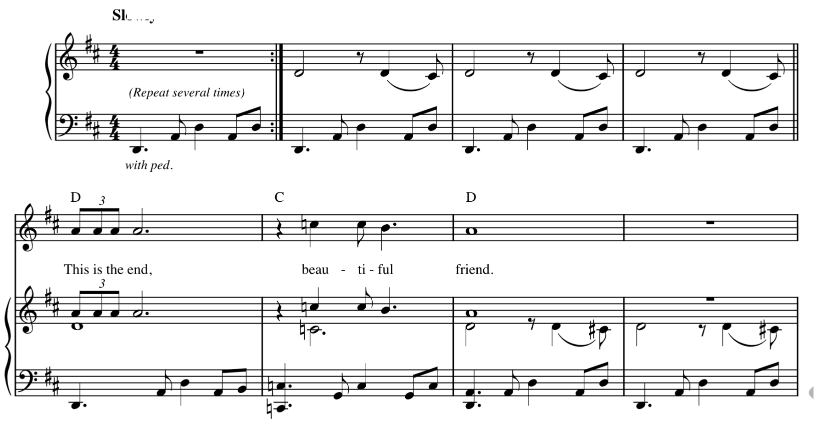
Be not directly heated but receiving power via collisions

Conclusions / discussion

- Simple models do not allow to describe physics quantitatively but they allow to qualitatively highlight that transient solutions may differ significantly from steady state solutions, something that can be exploited for shot optimisation.
- Tail formation takes time, ≠ time scales of ≠ mechanisms (N=1 vs N=2; RF vs NBI or vs collisions; pitch angle w.r.t. slowing down; i vs e)
- N=2 in Faraday cage forces |E| to increase while N=1 yields good absorption; use N=1 minority before switching on N=2 [reason for problematic behaviour initial stage with only N=2?]
- Absorption close to axis yields faster tail formation, higher power density in less particles
- NBI deposition ≠ for ≠ density and ≠ species -> has impact on overall performance (e.g. T has more external deposition than D, and D than H)
- Diffusion being 2-directional allows more externally deposited energy "spilled" over the edge sooner
- dFlux/drho=P_{local} i.e. any outward flux overcompensated by bigger inwards flux if $P_{local}>0$
- Temperature often overshoots and then relaxes to final state [as seen in DTE2]. Heating time matters.
- No steady state can be reached when radiation varies [as seen in DTE2]; exp. effort needed to ensure radiation is kept
- Location sources and losses strongly influences profiles; transient solutions can be very different depending e.g. on relative timings heat sources
- ICRH much more capable than NBI to modify core temperature for given density [as seen in DTE2]; NBI deposition always very broad (broadening T profile); hollow if high density or heavier beam ion
- Particle source modulation (e.g. pellets) mainly visible in edge; allows to force higher gradients (and force ELMs [as used in DTE2])
- Heat source modulation much more efficient for ICRH than for NBI [as used in transport studies]: localised absorption for given integrated power; fraction flowing to e and i is time dependent
- Operating at reduced gas/pellets allows higher temperatures [as seen in many exp. e.g. Hybrid and L-mode] (immediate from energy equation: P=dE/dt)

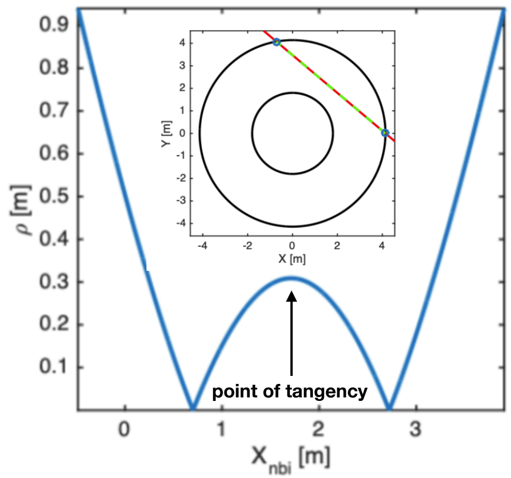
The End

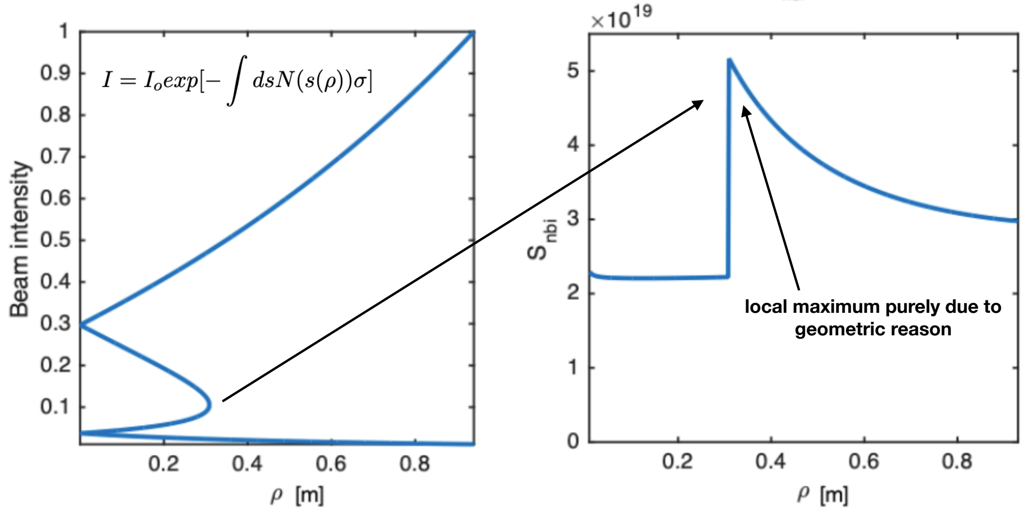
Words & Music by The Doors



extra slides

Introductory notes: beam heating (here for N_e=ct)





simplified sigma: [Kazakov, CMSS course on heating schemes]

$I(\Delta l) \simeq I_{\mathrm{NBI},0}\, e^{-\Delta l / L_{\mathrm{NBI}}}$ $\quad L_{\mathrm{NBI}} = \lambda_{1/e} \simeq \frac{1}{n\sigma_{\sum}}$