Optimizing the EU-DEMO pellet fuelling scheme: WP TFV and KDII8 collaboration

Preliminary summary

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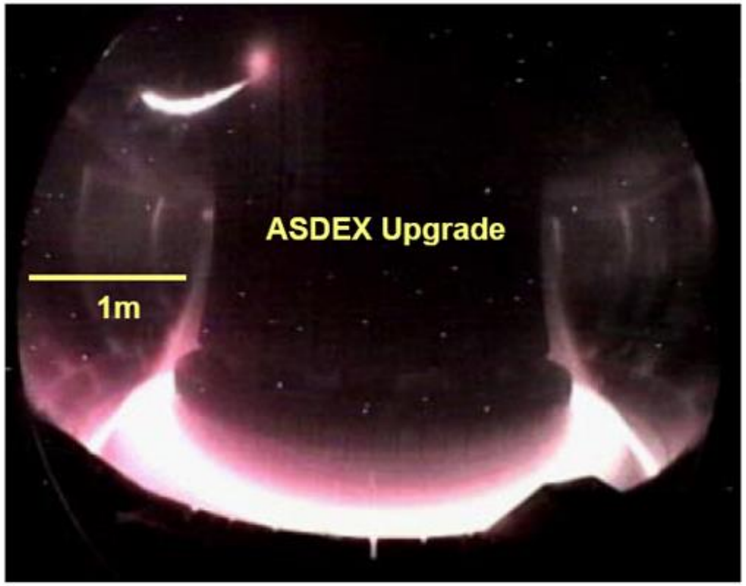
Outline

- Task: Optimise core fuelling
- Integration into plant & vessel
- Integration into breeding blanket
- Optimization of possible variants
- Status as at ISFNT (10/2019)

https://authors.elsevier.com/sd/article/S0920379620301393

- Next steps: update pellet mass requirement and baseline design
- Recent / Ongoing work

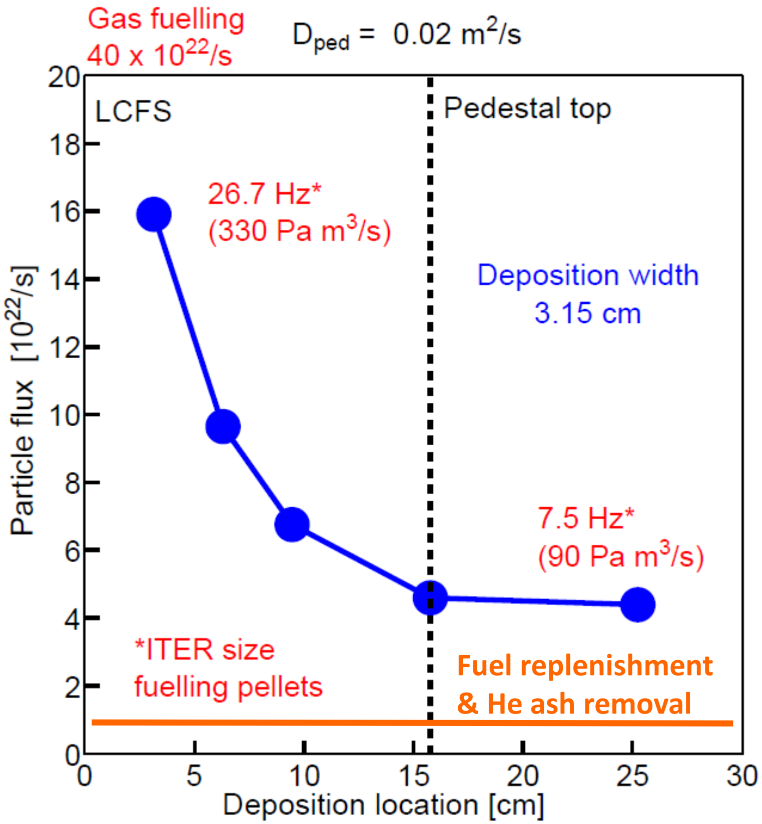


BROCKHAUS Mensch•Natur•Technik
"Technologien für das 21. Jahrhundert"
Leipzig; Mannheim 2000

Task: Core particle fuelling

Task: Develop system for efficient core particle fuelling in EU-DEMO

SECOND IAEA DEMO PROGRAMME WORKSHOP, Vienna 2013



Fuelling particle flux Γ:

► Causes convective losses

$P_{loss} \sim \Gamma \times \langle T \rangle$

➔ Reduced confinement/performance

► Increases fuel/tritium inventory

➔ Burden on pumping system

➔ Burden on fuel cycle

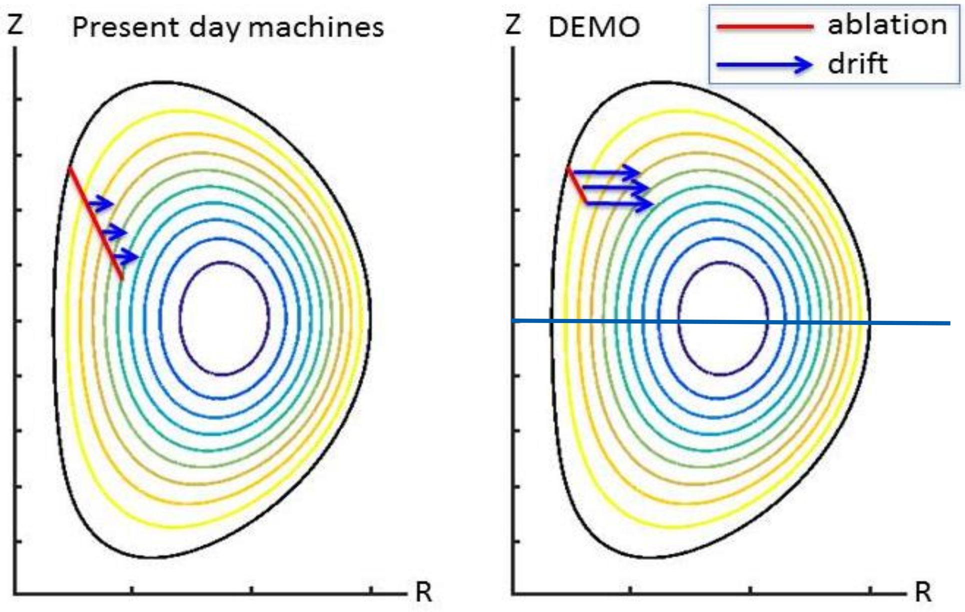
Safety (= Licensing) issue

Economic issue

➔ **Reach requested core density with minimized particle flux $\Gamma = m_P x f_P$**

With the pellet size/mass given: minimize the required f_P

Inboard injection – Basic approach



Modelling single pellet injection
HPI2 code calculates
Ablation & Drift
➔ Particle deposition profile

Present day machines:
Penetration > Drift displacement
DEMO:
Drift displacement > Penetration

B. Pégourié et al., 43rd EPS (2016) P4.076

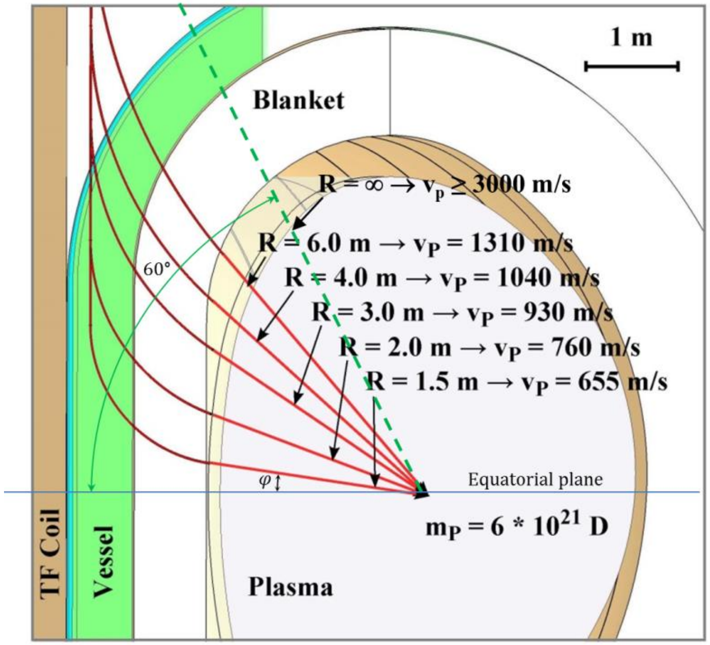
Initial design approach assuming **N_p = 6×10^{21} atoms (ITER's pellet size)** suggests:
High speed pellet injection from inboard (outboard confirmed inadequate)
Close to horizontal mid plane

Criteria imposed to derive best injection geometry:
Pellet enters plasma (= designated trajectory crosses separatrix)
► Not more than 1.5 m above mid plane ($z_P \leq 1.5$ m)
► With maximum speed perpendicular to separatrix ($v_{P\perp}$ criterion)

Inboard injection approaches

“Conventional approach”:

Pellet transfer via guiding tubes (causing mass transfer losses and speed restrictions)
Vessel access via available ports and gaps – Integrated already in existing CAD model
Relying on proven technical capabilities only (Simultaneous speed and rate)



Vertical access through narrow gap between TF and PF coils:

► Injection trajectory close to mid plane with steep inclination require a tight final bend

→ Low transfer speed

► High speed injection with large R

→ Larger z_P and/or less steep inclination

Optimization: **Maximize $v_{P\perp}$ with boundary condition $z_P \leq 1.5$ m**

"Direct Line of Sight" (DLS):

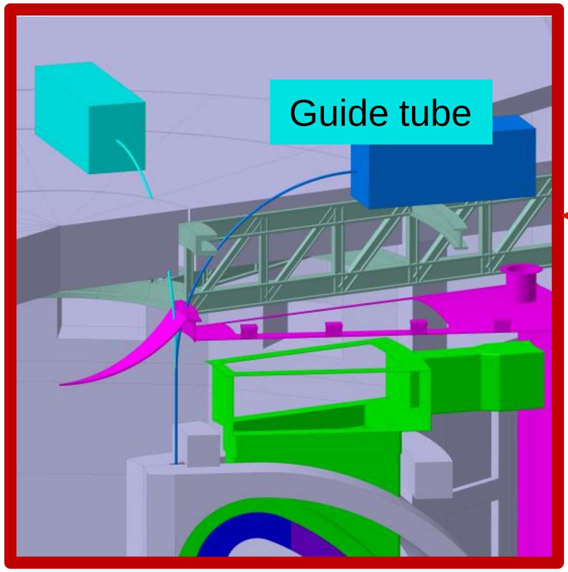
Free flight or straight tube access
Integration still to be achieved – necessitates technology progress

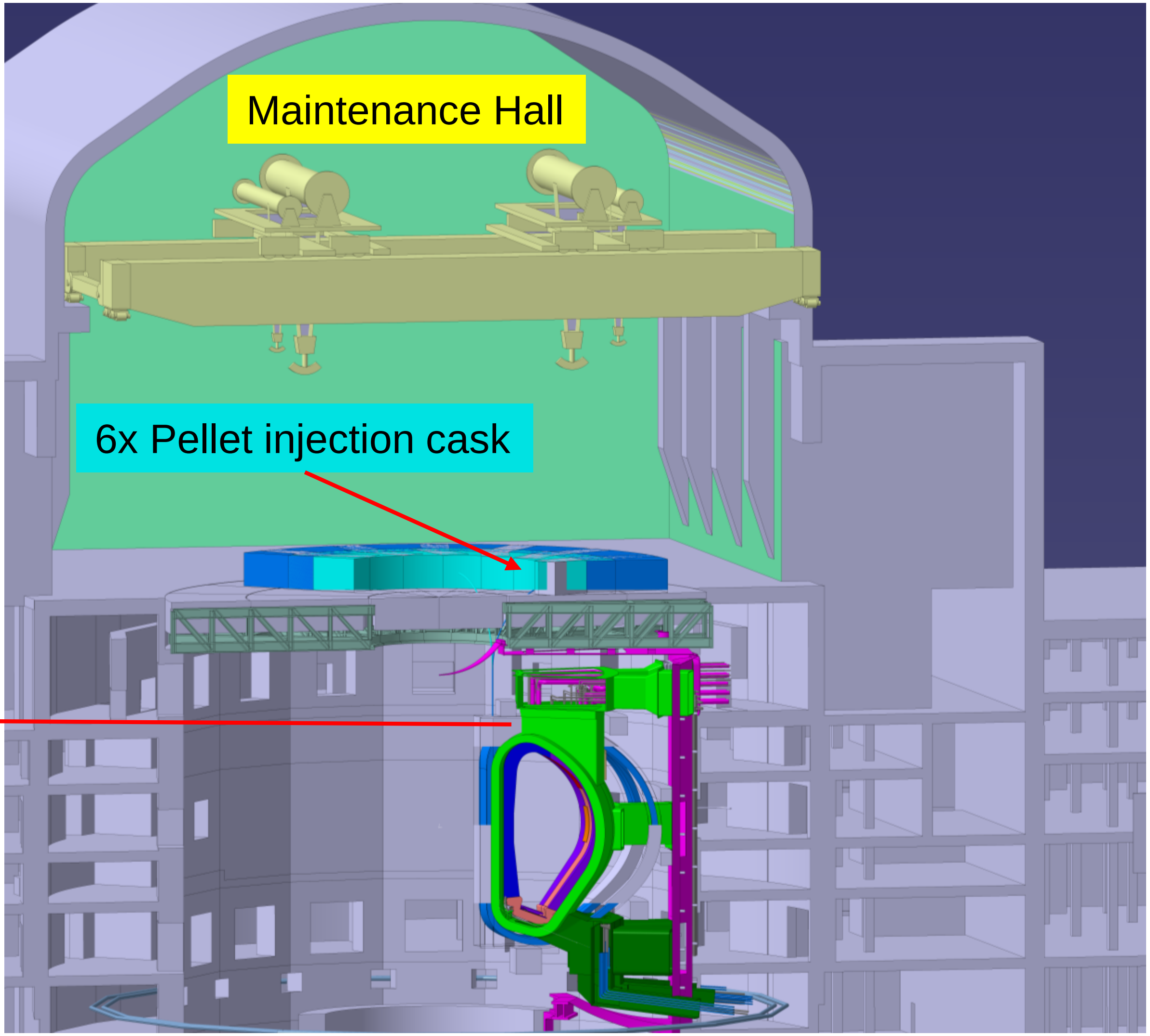
Integration into building configuration

C. Gliss et al.: Tokamak Building configuration

6 full conventional pellet launching systems included!

Short tube avoiding tight bends outside vessel





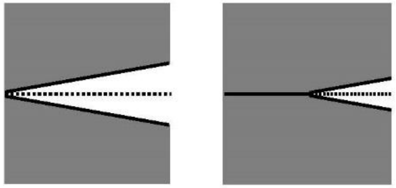
Initial / Reference configuration

Assumes guiding tube can penetrate through entire breeding blanket (BB)
Thermal analysis unveiled unbearable heating at tube exit
➔ Not a valid configuration

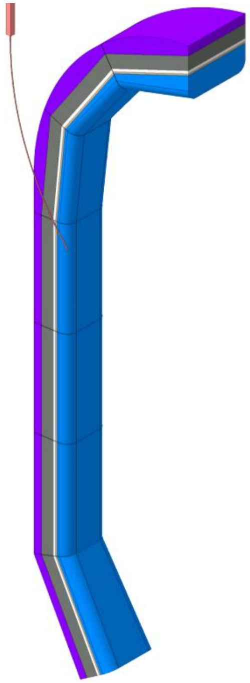
Integration into BB (HCPB variant taken as reference):
Guiding tube ends before or in BB
➔ Straight final part of pellet trajectory
➔ Loss of pellet performance

Pellet scatter at exit requires conic BB cut-out
➔ Loss of BB performance

No penetration



Partial penetration



DEMO1 2015 half (10°) sector with HCPB-2015 v3

Integration into BB: Variants considered

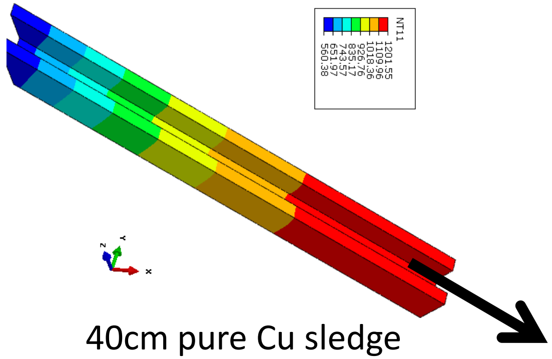
Deeper penetration of guiding tube into BB:
➔ Handling more difficult (e.g. for BB exchange, thermal load on tube)

But other issues become less troublesome (less BB cut-out)
- ► Reduction of tritium breeding rate
- ► Nuclear heating of vacuum vessel
- ► Neutron streaming causing damage in vacuum vessel steel

F. Cismondi et al., SOFT 2016, P3.128

No penetration solution still possible, but already close to acceptable limits

Dedicated layout (tube connected to vacuum vessel)
and thermal analysis by LTCalcoli
Worked out three possible variants:



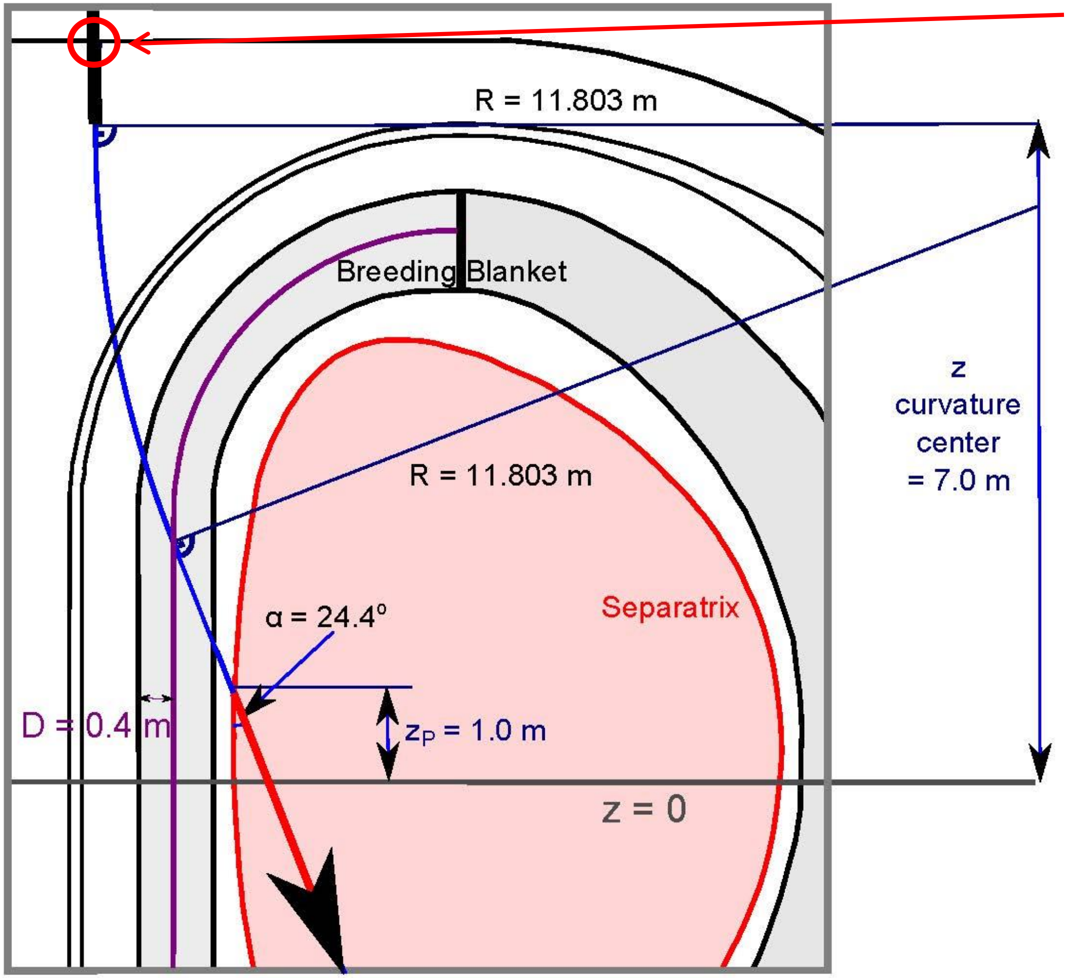
40cm pure Cu sledge

No guiding tube penetration into BB
0.4 m guiding tube penetration – passive cooling
0.6 m guiding tube penetration – active cooling

Deeper penetration = Better performance = More technical effort

Integration into BB: Possible geometries

Example: 0.4 m tube penetration into BB



CAD modelling:

- Vertical entrance point fixed
- At **Δ = 0.4 m contour**:
  Guiding tube → Free flight
- Arc as connection segment

➔ R, v_c, trajectory, $v_{P\perp}$ fixed

All possible solutions covered by Scanning z and z_P

Any reasonable injection geometry covered by all possible (z_P, α) tuples

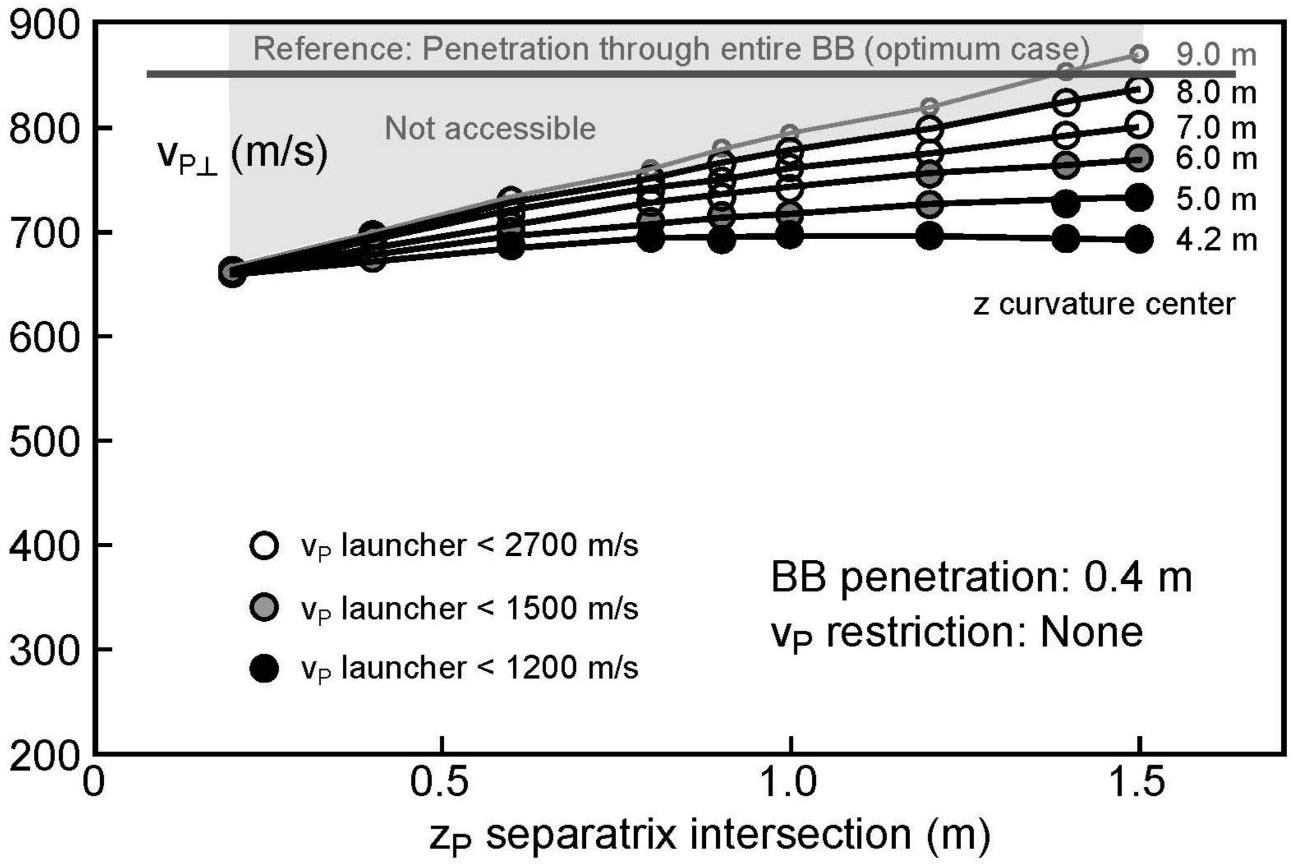
Bijective mapping

(z_P, α) ↔ (z, z_P)

➔ **All possibilities covered**

Integration into BB: Performance analysis

Example: 0.4 m tube penetration into BB

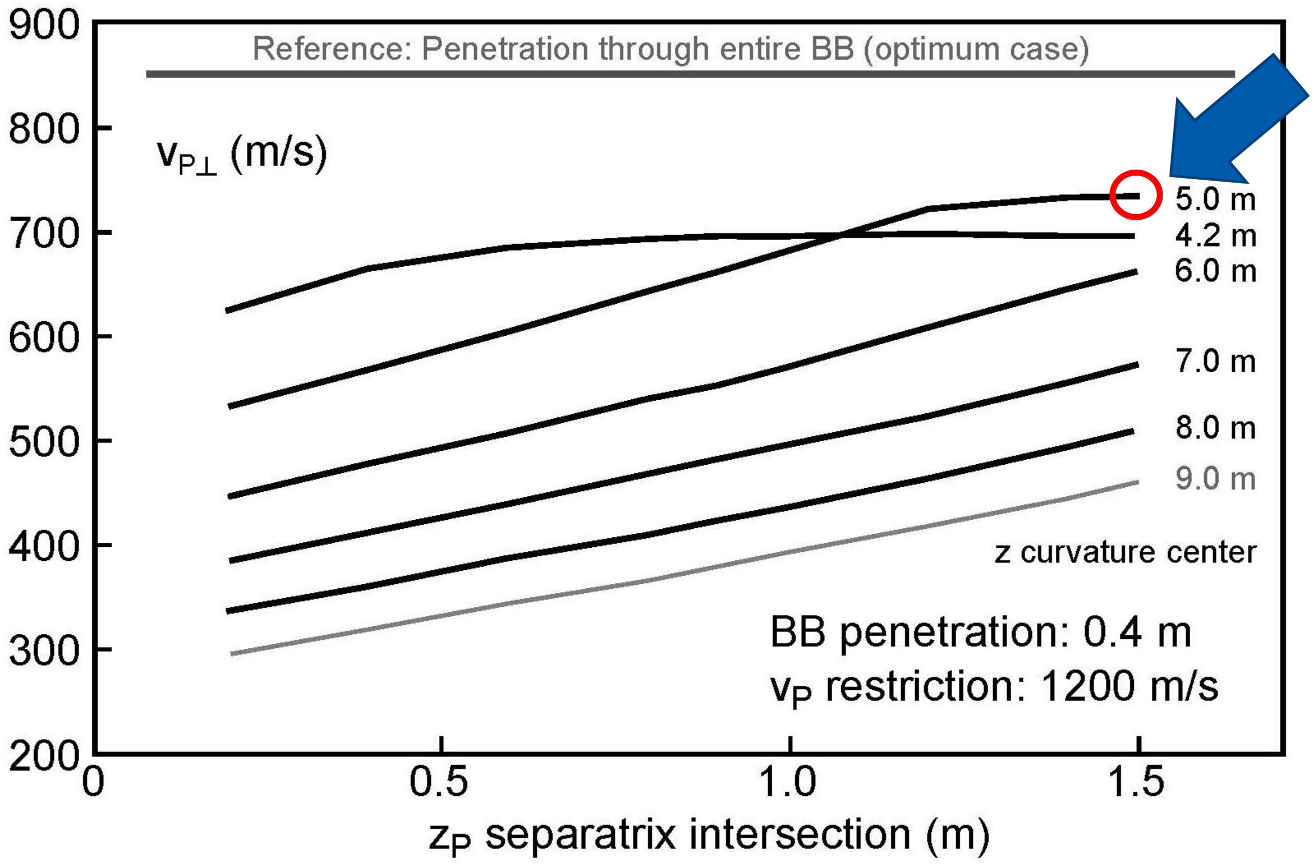


Performance qualifier: $v_{P\perp}$ - scan z_p for fixed z, vary z → Array of curves

Best solution would require very high pellet speed (≈ 2300 m/s)

Integration into BB: Performance analysis

Example: 0.4 m tube penetration into BB



Conventional approach: Stay within proven technology limits ($v_P \leq 1200$ m/s)

Select the best option - for any of the 3 variants

Performance analysis: Fuelling modelling

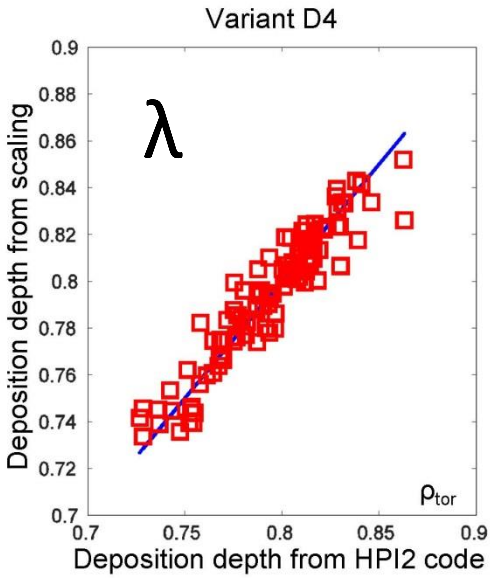
Best options for the 3 "Conventional approach" variants
+ 1 representing the "Direct Line of Sight" (z_P = 1.5 m, v_P = 3000 m/s)

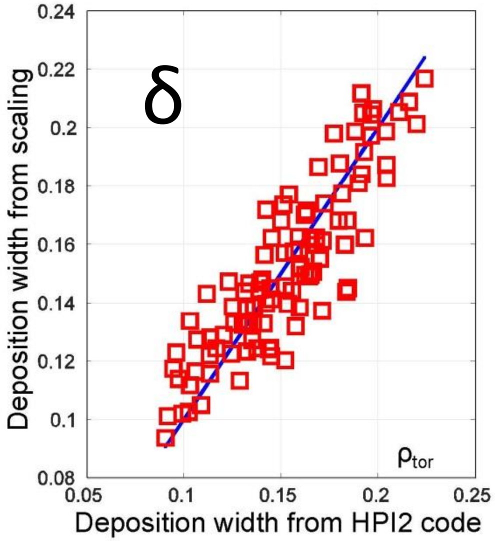
Scenario	Absolute pellet speed (m/s)	Perpendicular pellet speed (m/s)	Injection angle
D0	1200	593	64.7
D4	1120	734	53.4
D6	1150	797	50.3
DLS	3000	353	77.6

Provides all information on the pellet actuator (m_P, v_P, injection geometry)
Taken as input modelling the core density control
Apply pellet injection, adapt pellet rate f_P until require target is achieved

f_P x 6×10^{21} = Γ_P **becomes validation parameter for any variant**

Fuelling modelling - Strategy





Transport code ASTRA models analyzing evolution of pellet particle deposition

HPI2 **Pellet ablation and deposition code** calculates deposition for target plasma

Vary pellet repetition time dt = 1/f_P until required plasma conditions are reached

Faster by parameterization of HPI2 results

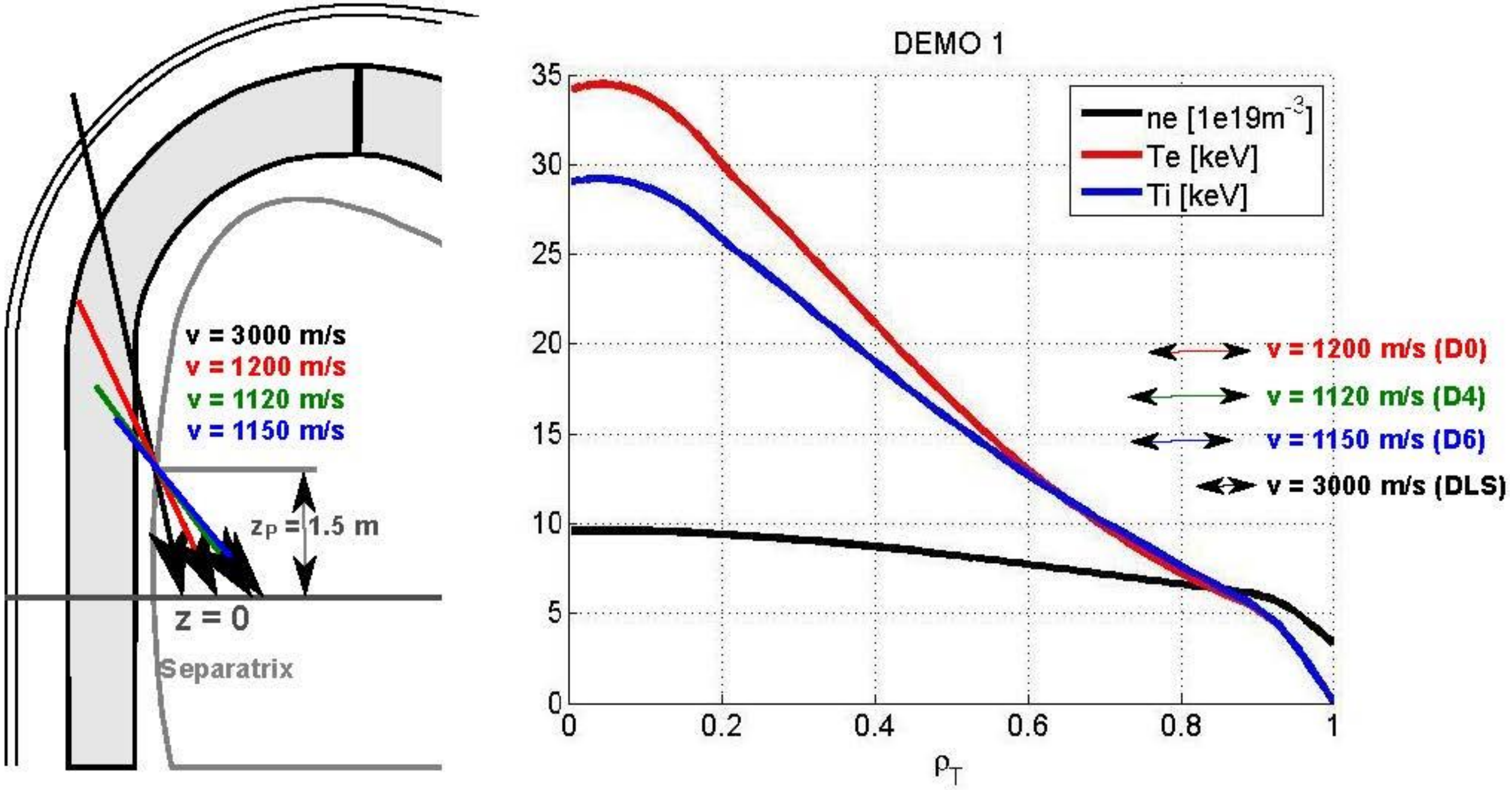
$$\lambda = 1 - C_a\,(I_P)^{a1}(T_e^{Sep})^{a2}\,(T_e^{Ped})^{a3}\,(T_e^{0})^{a4}\left({n_e^{Sep}}/{n_{Gw}}\right)^{a5}\left({n_e^{Ped}}/{n_{Gw}}\right)^{a6}\left({n_e^{0}}/{n_e^{Ped}}\right)^{a7}(m_P)^{a8}$$

$$\delta = C_b\,(I_P)^{b1}(T_e^{Sep})^{b2}\,(T_e^{Ped})^{b3}\,(T_e^{0})^{b4}\left({n_e^{Sep}}/{n_{Gw}}\right)^{b5}\left({n_e^{Ped}}/{n_{Gw}}\right)^{b6}\left({n_e^{0}}/{n_e^{Ped}}\right)^{b7}(m_P)^{b8}$$

Separate parameter set for any variant

Fuelling modelling - Results

Performance: 3 conventional very similar, DLS more shallow



Modelling of burn control: pellet perturbation too drastic

➔ **Reduce size to about 1/3 (= 2×10^{21} e)**

Conclusions -> Next step

Closed loop modelling core fuelling prediction:

Need to reach target central density **$\Gamma_P \approx 0.7 \times 10^{22}\ s^{-1}$**

This is less than expected from previous open loop modelling!

Simple estimation replenishment:

For 2 GW fusion power burn **$\Gamma_{DT} \approx 0.14 \times 10^{22}\ s^{-1}$**

Keep He ash concentration below about 5%

➔ Aim at burn about 10% of fuel

➔ Needs fuel throughput of ≈ **$1.4 \times 10^{22}\ s^{-1}$**

Detailed scenario modelling including recycling and pumping efficiencies needed to provide consistent values!

To note: Total particle flux to be processed by vacuum pumps contains additional matter flow, e.g. buffering gas through scrape-off layer

Conclusions -> Next step

Modelling confirms this approach is suitable!

We have established an efficient work flow

However, some issues have to be improved/rectified:

- ► Adaptation of pellet mass, re-modelling range $6\times10^{21} \rightarrow 0.4\times10^{21}$
- ► Extension of z range beyond 1.5 m

Take to opportunity to update to considered baseline design

➔ Considerable increase of cases to be investigated

“Step description”: Coordinated WP TFV – KDII8 task list

Optimise m_P with respect to fuelling efficiency & burn control

Identified tuples of possible geometrical solution

3 D variants, n z scans, m z_P sets: 3 x n x m CAD analyses

→ Derive geometry parameters

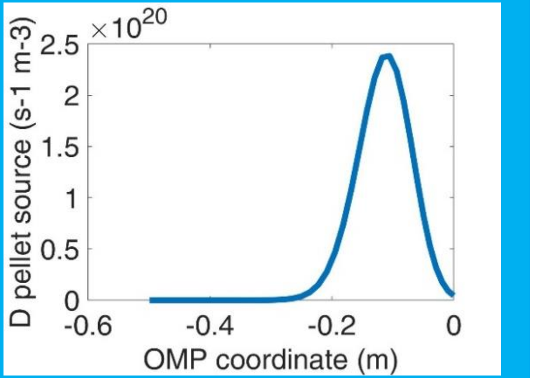
→ Derive pellet parameters

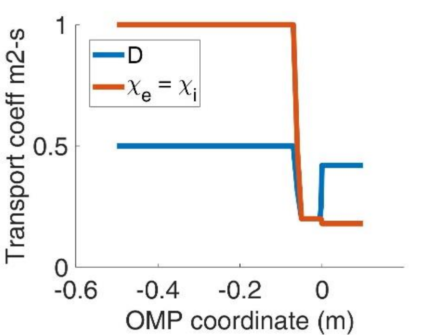
→ Perform HPI2/ASTRA modelling

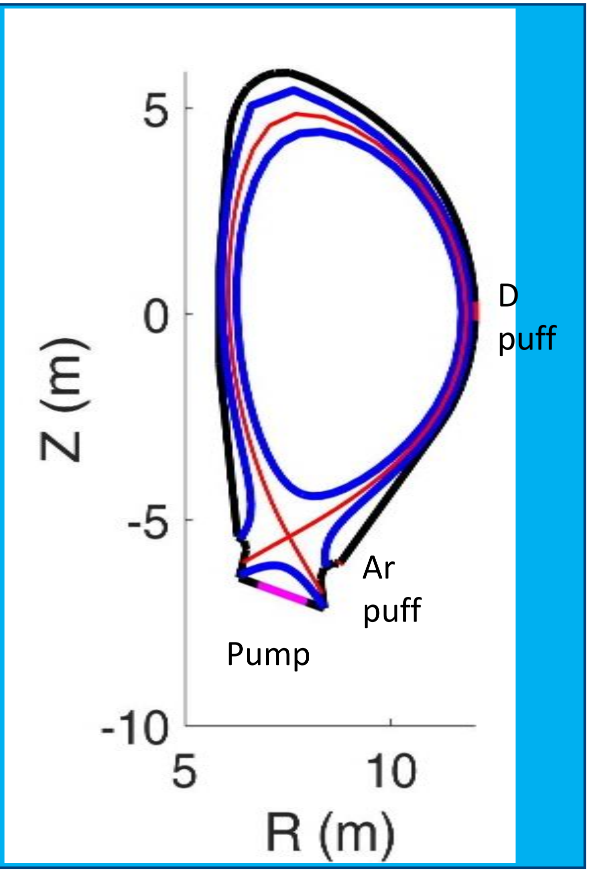
Recent work: Contribution to total flux

Fabio Subba: SOLPS modelling D+He+Ar Plasma

- Input power: 150 MW
- Input particles:
  - D puff: 10^{23} D/s
  - D pellet: 7×10^{21} D/s
  - Impurities: 1.5×10^{19} Ar/s
- Transport coefficients optimized for $\lambda_E \sim 3$ mm
- SOLPS version compiled mid-2019 (likely to be updated now)
- Effective source acceleration scheme on
  - For all species
  - But does not include pellet





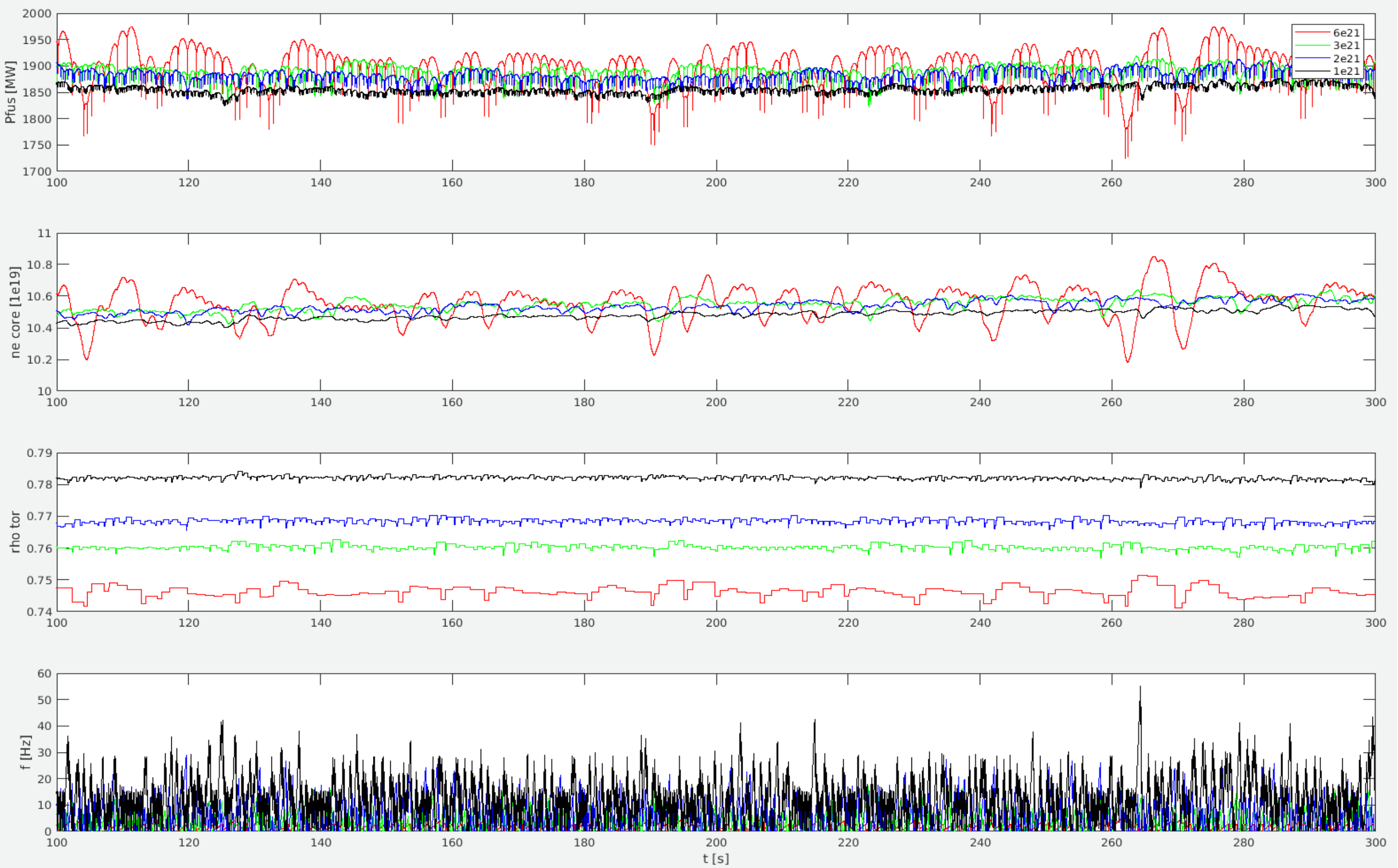


Γ Gaspuff ≈ 10 x Γ Pellet

➔ Pellet flux impact on fuel inventory moderate!

Recent work: Pellet mass scan

Filip Janky: ASTRA modelling of density control – pellet mass scan

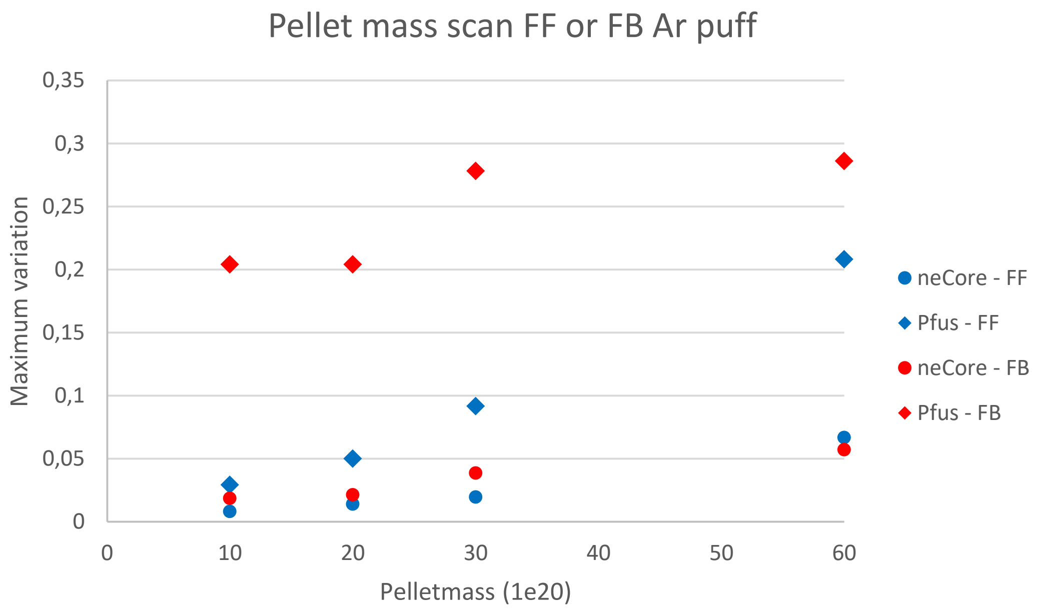


Here with FF Ar gas puff; T_{div} < 3 eV resp. fully detached

Controller gain optimized individually for m_P

Recent work: Pellet mass scan

Filip Janky: ASTRA modelling of density control – pellet mass scan



Smooth control requires simultaneous optimization of many actuators

If done well, significant improvement when lowering m_P

Revised choice: 2×10^{21} ➔ $(3.2\ \mathrm{mm})^3 \approx$ JET fueling size pellet

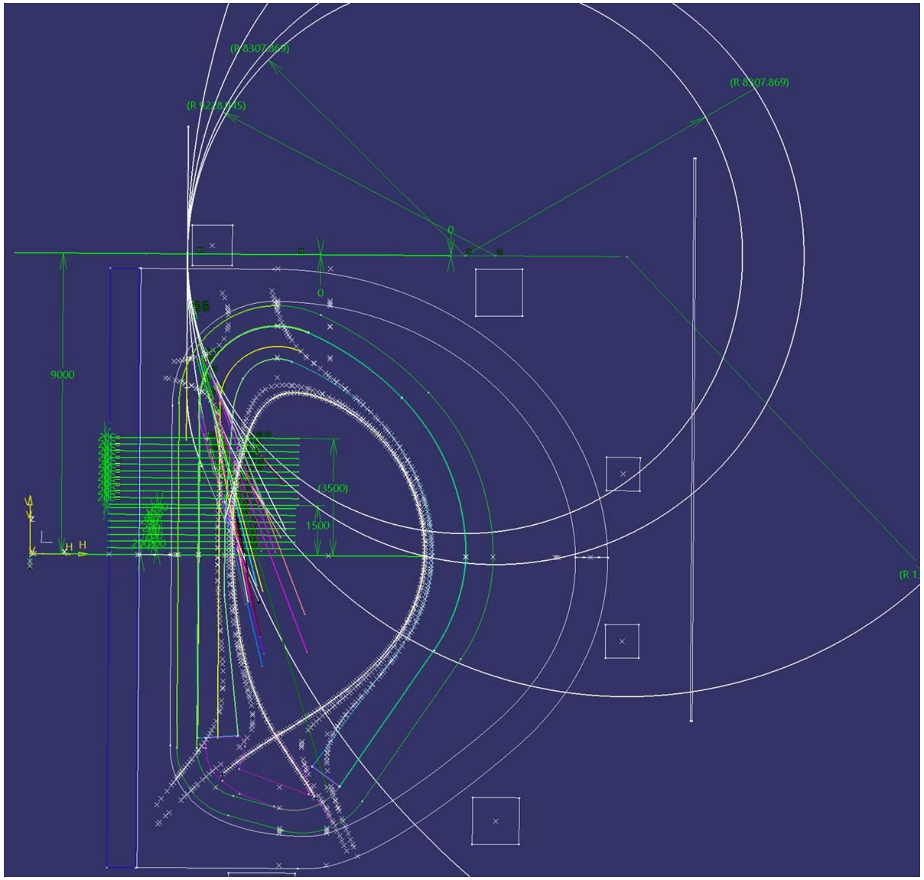
Further reduction of m_P ➔ Better technical performance (e.g. higher v_P)

Ongoing work: CAD of possible tube routes

Curt Gliss: CAD analysis of possible configurations

Change to DEMO Baseline 2017 and removed limit on z_P

➔ Much wider z/z_P range, much more configurations (3x9x21 = 567)



For every set provide:

- Injection path
- Pellet speed

➔ Prepares grid for modelling

Qualifier/figure of merit:

Γ_P to reach requested core density

Ongoing work: Xe doped pellets

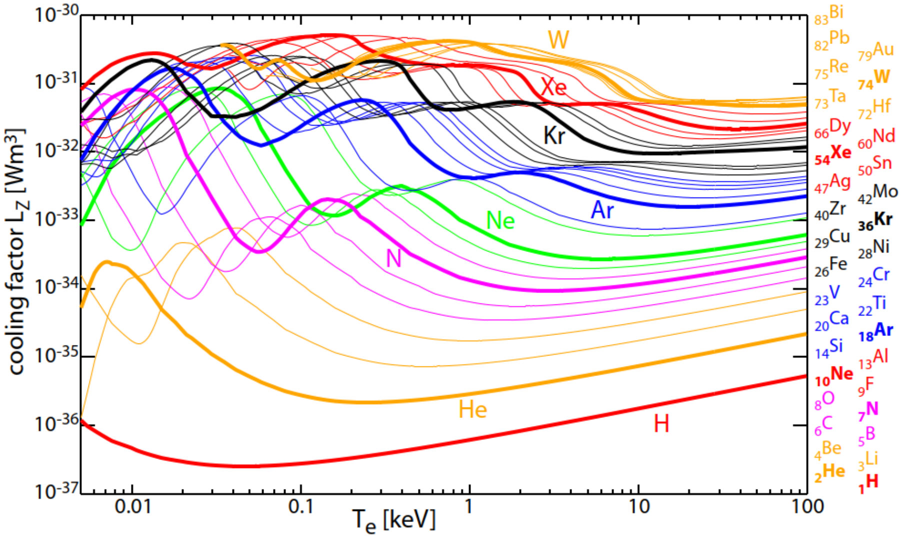
IPP experiment 2020_TF4_ACTR_5
Development of a reactor relevant pellet actuator

AUG Shot Request 4148
Xe doped pellets
P.T. Lang, B. Ploeckl, M. Siccino, M. Bernert, R. Dux

DEMO request / Investigation aim:
Investigate admixture of core radiator species (e.g. Xe) to pellets

Why:
Xe puffing in DEMO is likely not very efficient
➔ High Xe flux burdens the fuel cycle
➔ High effort (= costly) to remove
Pellets – if suitable to carry the Xe – are considered more efficient
Successful pellet doping has ready been shown for Ne and N_2

Ongoing work: Xe doped pellets



Estimation:

$P_{rad} \approx 2 \times 10^{-31}$ Wm^3 $\times N_{Xe} \times N_e$

$c_{Xe} = 10^{-4}$, $n_e = 10^{20}$ m^{-3}, 13 m^3

➔ $P_{rad} \approx$ 2.6 MW

$N_{Pellet} \approx 0.1 \times N_{plasma}$ ➔ $c_{Xe} = 10^{-3}$

Xe/D = 0.1 % ➔ Xe/D_2 = 0.2 %

Premixed gas sample with 0.2 % vol. $_{54}Xe^{124\text{-}136}$ in D_2

Ice/pellet production straight forward, but 1 h recovery time (warming up)

37794:Small pellets, flux scan 1.5 – 10 x 10^{18} Xe/s (assumed perfect freeze)

Moderate amount detected, no significant impact on plasma

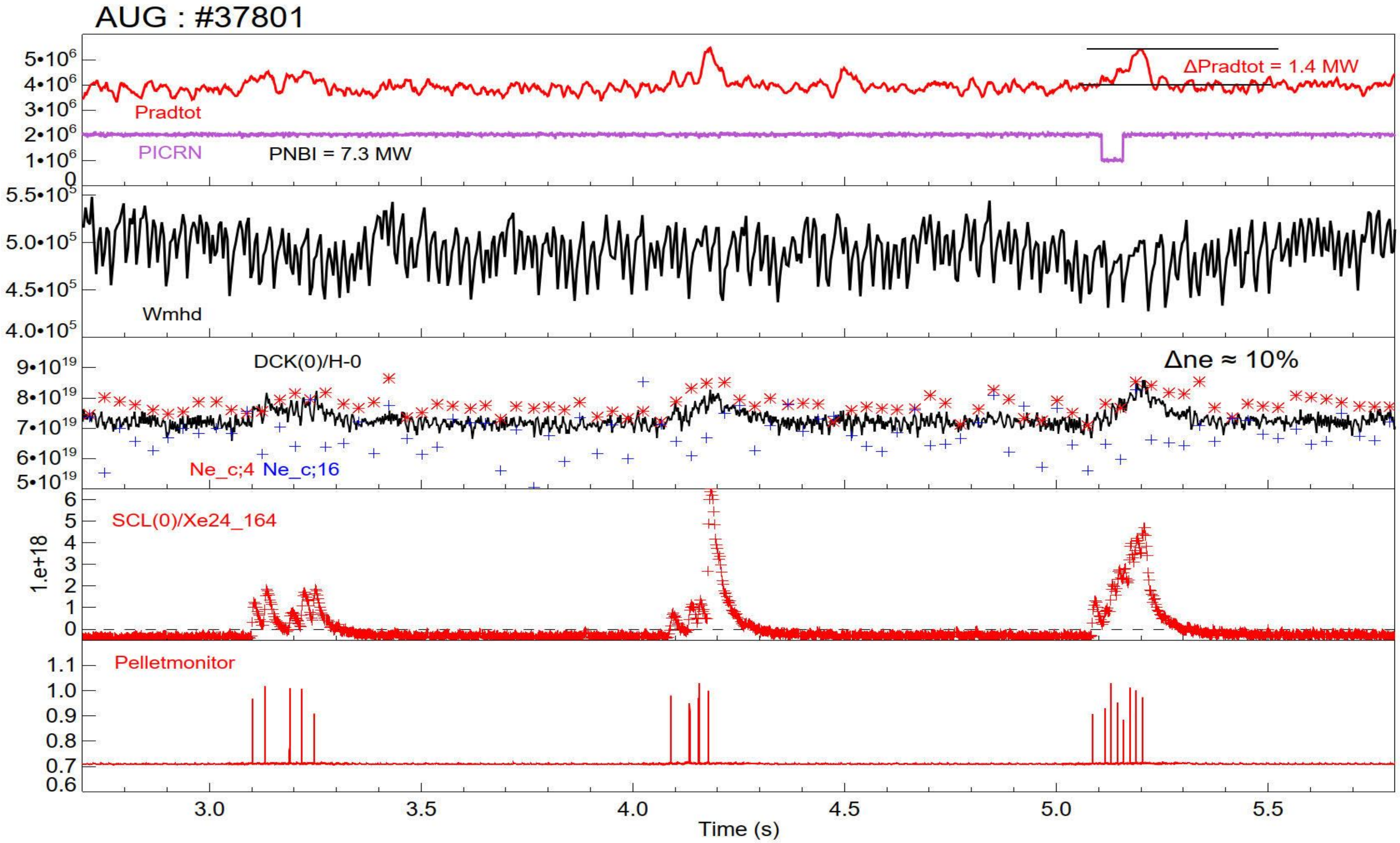
37797:Large pellets, intended Xe flux scan 9 – 52 x 10^{18} Xe/s

2nd pellet followed by strong raise of P_{rad} and radiative collapse

37801:Small pellets, 3 short bursts 1.8 – 2.7 x 10^{18} Xe

Cleary visible response, significant transient raise of P_{rad}

Ongoing work: Xe doped pellets



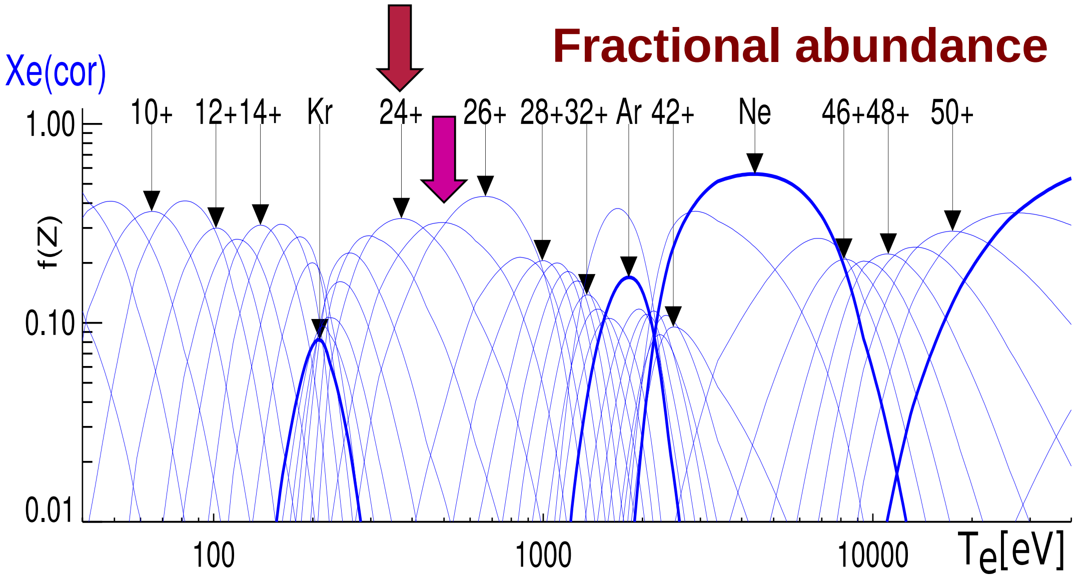
Xe pulses clearly visible, resulting radiation close to predictions

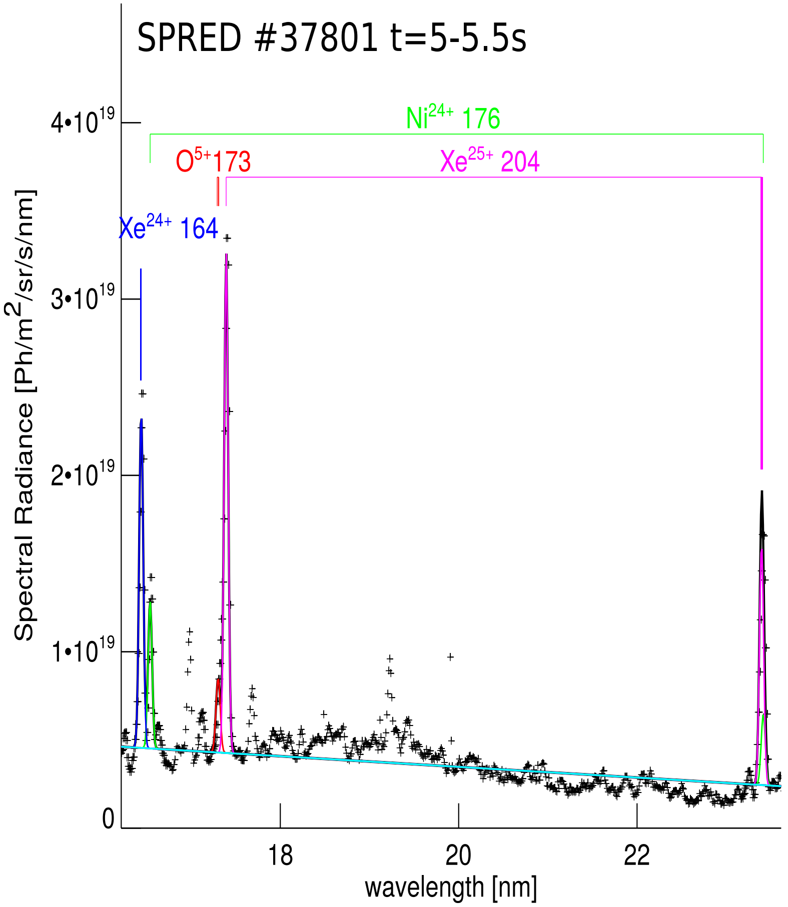
Ongoing work: Xe doped pellets

Good signals from transitions

- Xe^{24+} (Zn-like): $3d^{10}4s^2\ {}^1S - 3d^{10}4s4p\ {}^1P$
- Xe^{25+} (Cu-like): $3d^{10}4s\ {}^2S - 3d^{10}4p\ {}^2P$

Emitted in a region around T_e=500eV





Summary

Elaborated efficient core fuelling approach for EU-DEMO:
Conventional pellet technology – Inboard launched

Integration into power plant design
“Conventional” and “Direct Line of Sight” approach considered

Integration into functional elements – breeding blanket
Optimization likely more dependent on BB requirements

Integration into actuator tool kit
Optimization taking into account controlling requirements
Investigate potential improvements as e.g. pellet doping

Next iteration step under way utilizing well developed procedure

Back up: Critical transfer speed

Guiding tube bend ➔ Stress destroys pellet beyond critical transfer speed

Lacking dedicated investigations, collected data from literature

Seem to fit well to simple model when “calibrated” to typical performance

Centrifugal force

$$F_c = m\frac{v^2}{R}$$

balanced by yield strength σ

$$v_c = \sqrt{{\sigma R}/{\rho l}}$$

Literature values (D at 12K)

$$\sqrt{{\sigma}/{\rho}} \approx 50 \text{ m/s}$$

“AUG calibrated” estimation

$$v_c = 36\left[\frac{m}{s}\right]\sqrt{{R}/{l}}$$