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FÜR PLASMAPHYSIK

Real time coupling of the equilibrium solver with the current diffusion equation on ASDEX Upgrade

O. Kudlacek[1], B. Sieglin[1], M. Weiland[1], L. Giannone[1], R. Schramm[1], A. Bock[1], R. Fischer[1], F. Felici[2], W. Treutterer[1], J. Stober[1], E. Poli[1], M. Reich[1], M. Rampp[3] and the ASDEX Upgrade Team[4]

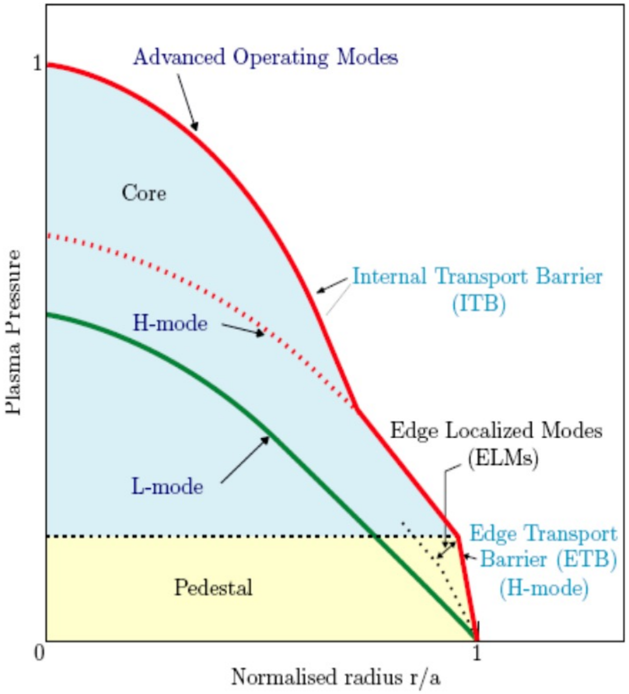
[1] Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland
[3] Max Planck Computing and Data Facility Giessenbachstr. 2, D-85748 Garching, Germany
[4] see the author list of H. Meyer et al. 2019 Nucl. Fusion 59 112014

Content of the talk

1. Motivation: advanced tokamak scenarios and current profile
2. Current profile measurement and impact of diffusion equation
3. Status of RT implementation
4. Conclusions and future works

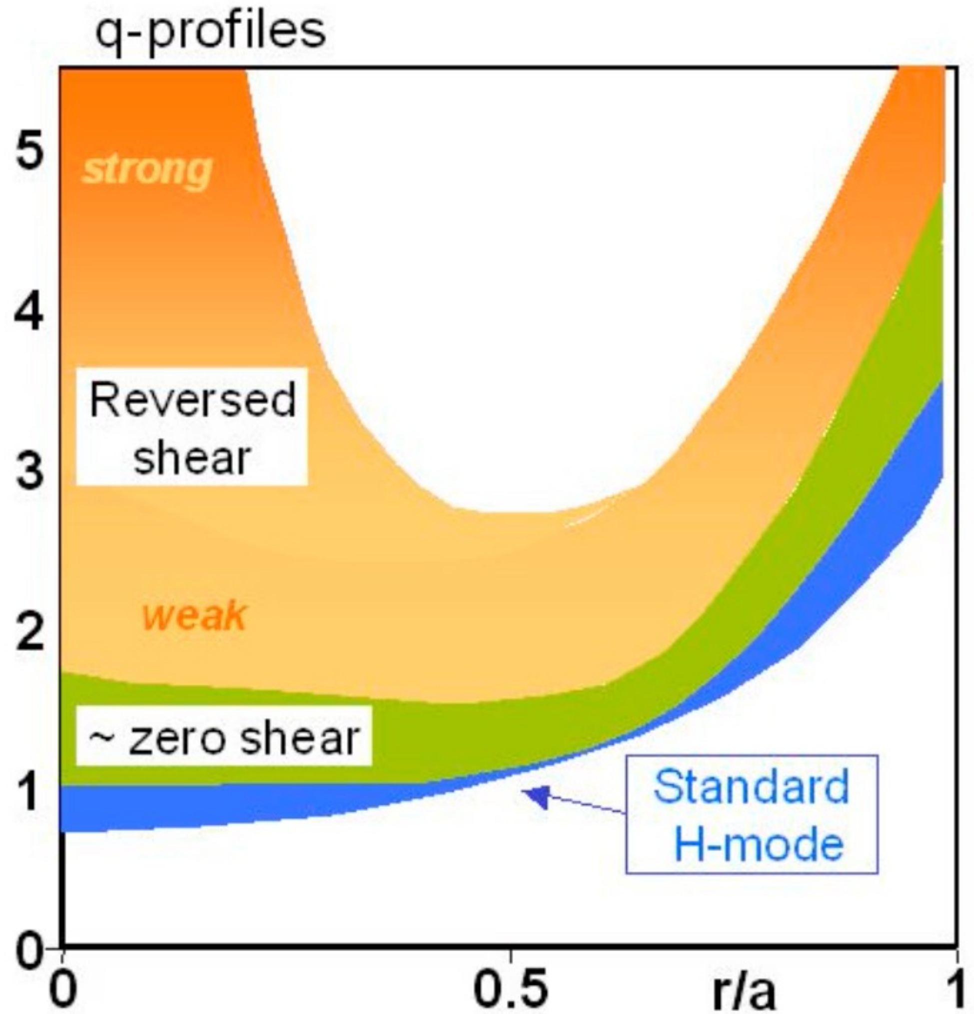
Advanced tokamak scenarios

- **Fusion power ~ p^2 => desire of high pressure**
  - L mode
  - H mode with edge transport barrier
  - Advanced tokamak with edge and internal transport barrier
- Steady-state operation requires **high non-inductive current fraction**
  - Driving current by external systems is ineffective => preference for scenarios with high bootstrap fraction $\sim q \cdot p$
- **Advanced tokamak characteristics**:
  - Elevated q profile in the center
  - Internal transport reduction in the core => high pressure
  - High bootstrap fraction



Current profile and advanced tokamak scenario

- Key ingredient: elevated q profile (hollow j profile) in the plasma center
- Naturally, plasma current profile relaxes to the state with peaked profile and q <= 1
- For AT scenarios, the natural relaxation has to be overcome
  - Feedforward scenario optimisation
  - Feedback control of the current profile
- FB control requires reliable RT measurement



Current profile measurement

- Current profile reconstruction: solve the Grad-Shafranov equation!

$$\frac{\partial^2\psi}{\partial R^2} - \frac{1}{R}\frac{\partial\psi}{\partial R} + \frac{\partial^2\psi}{\partial Z^2} = -2\pi\mu_0 R j_\phi \quad R j_\phi = 2\pi\left(R^2\frac{\partial p(\psi)}{\partial\psi} + \frac{1}{\mu_0}\frac{\partial}{\partial\psi}\left(\frac{F(\psi)^2}{2}\right)\right) \quad \mathrm{F} = \mathrm{R\bar{B}}$$

- Ill posed problem: strong coupling of *j* and *p*
  - *j* and *p* are computed iteratively using least square fit of the diagnostics measurements
    - Magnetic diagnostics (pick-up coils, flux loops, …)
    - Internal measurements (polarimetry, MSE, iMSE, …)
  - Internal measurements are not available in RT on AUG
- Additional inputs:
  - **Pressure profile** from kinetic measurements
  - **Current profile from current diffusion equation**
  - Improves the equilibrium reconstruction both offline [R. Fischer et al, FST 2016] and in real time [F. Carpanese et al, NF 2020]
- This talk: ongoing work on inclusion of these quantities on AUG as input to the GS solver

Current diffusion and pressure profile

- Flux/current diffusion described by the following equation:

Parallel plasma conductivity
- **Proportional to $T_e^{1.5}$**
- **=> T_e profile needed**

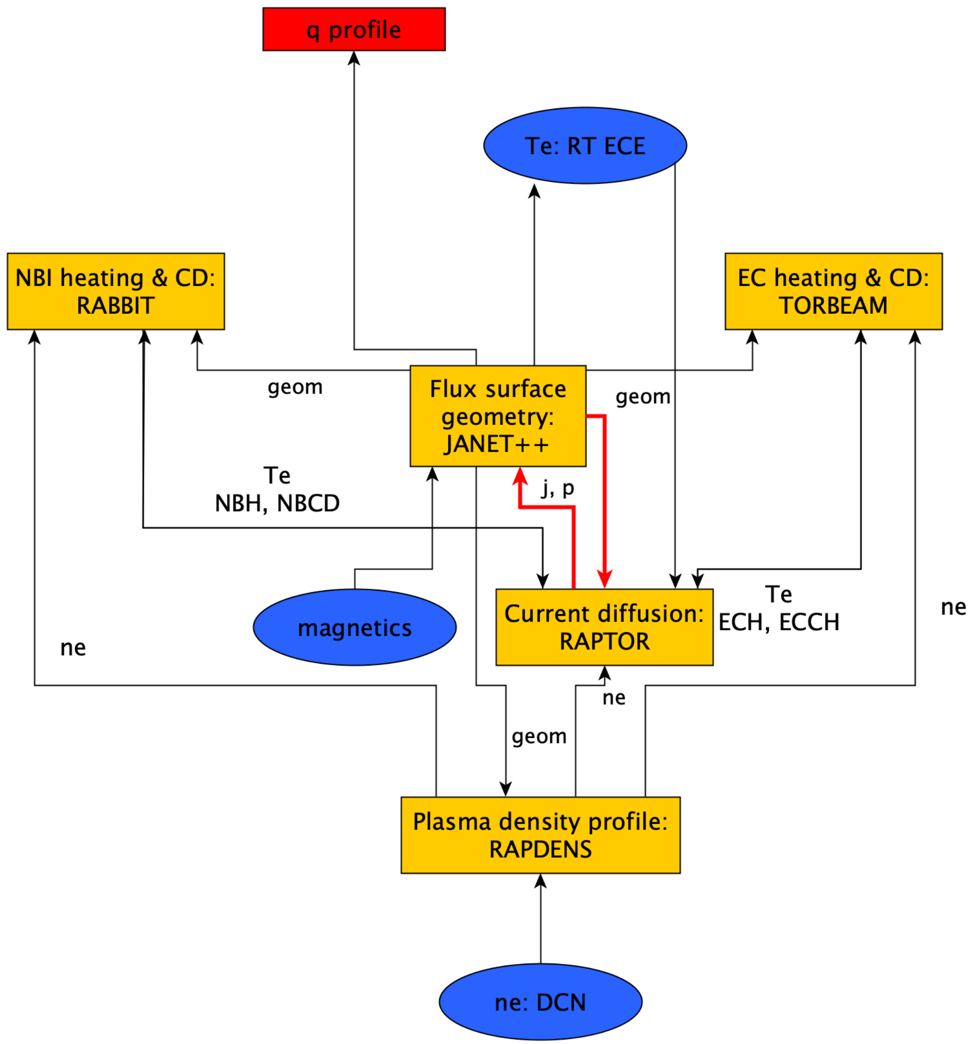
Geometric information
- **Post-processing of GS solver outputs**

Non-inductive current (bootstrap and current drive)
- **Bootstrap current computation from q and p**
- **NBI and EC current drive is needed => RT computation by dedicated coded in RT**
- **Both requires T_e and n_e profile as input**

$$\sigma_{||}\frac{\partial\psi}{\partial t} = \frac{R_0 J^2}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}\left(j_{bs}+j_{cd}\right)$$

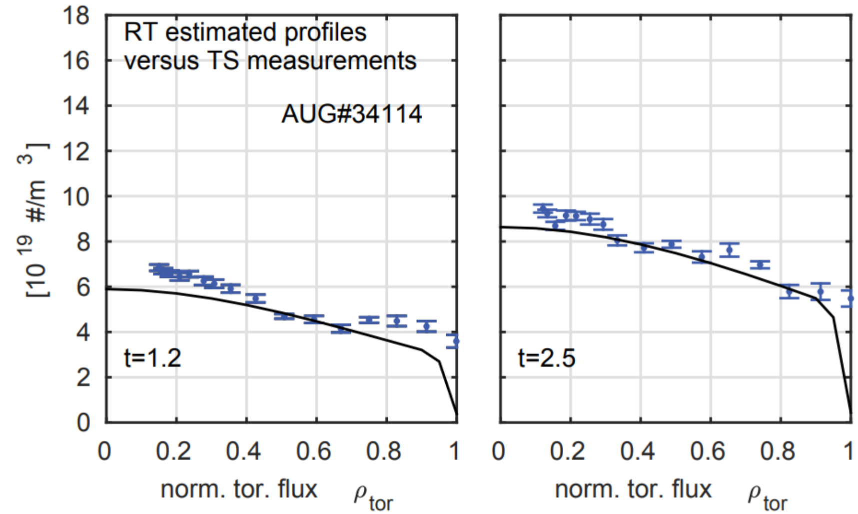
- With the knowledge of T_e and n_e, pressure profile can be approximated provided:
  - Assumes $T_e = T_i$ and low fast particle pressure
  - Not always true, but acceptable for the start

Equilibrium reconstruction scheme in RT



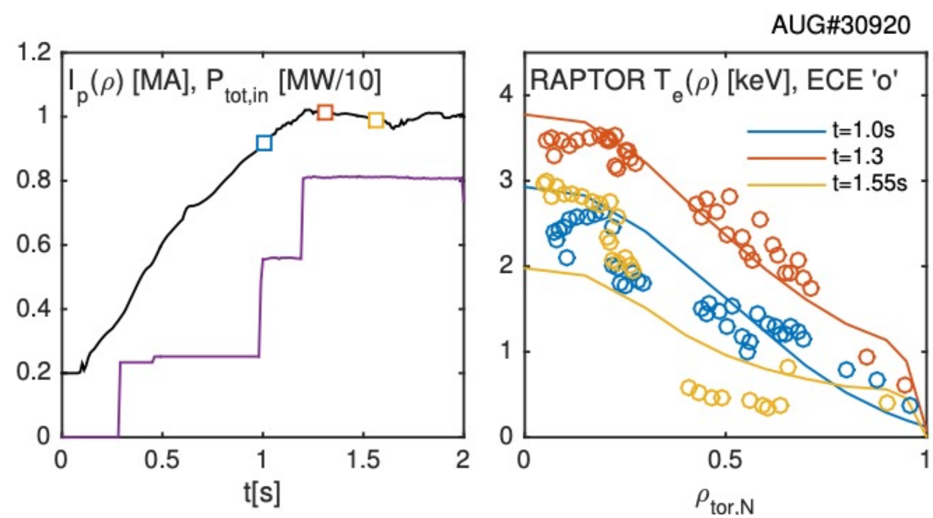
Kinetic profiles

- Both n_e and T_e routinely measured
- **Electron density profile (RAPDENS)**
  - State observer
  - 5 interferometers to correct the profile
  - 2 bremsstrahlung measurements
  - n_e profile available every control system cycle (1.5 ms)



T. Blanken et al, FED 2019

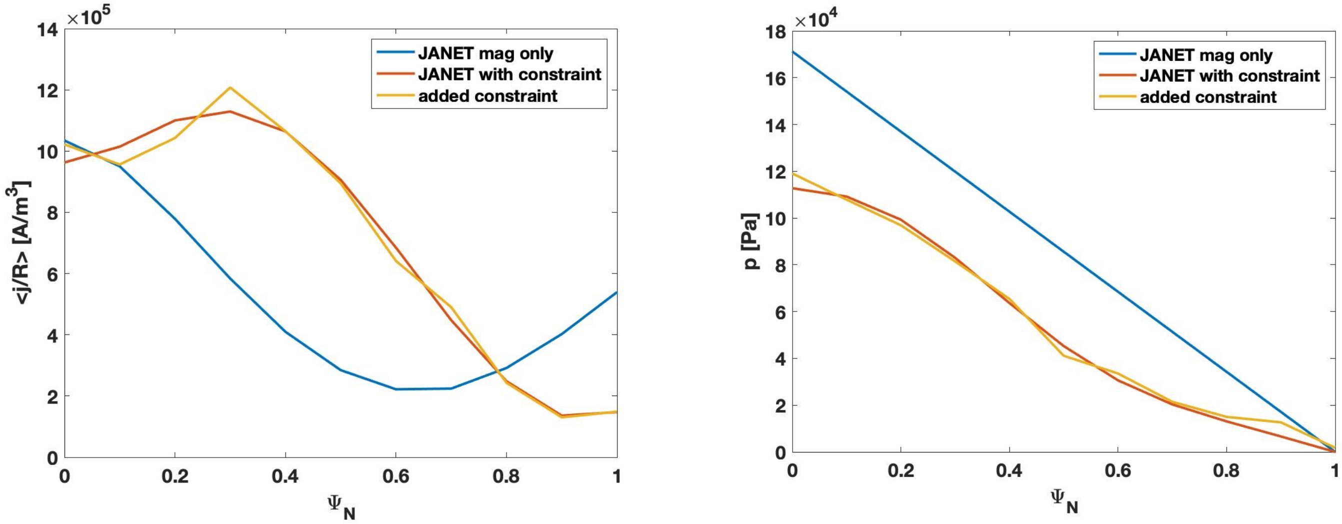
- **Electron temperature profile (RAPTOR)**
  - State observer using ECE diagnostics for correction of the estimate
  - Performs also current diffusion
  - Computes pressure and bootstrap current using density from RAPDENS
  - Computation time: 6 ms



F. Felici et al, IAEA FEC 2016

Equilibrium reconstruction: JANET++

- Iterative solver of the GS equation
- Inputs: magnetic sensors, optionally <j/R>(ψ) (representation of <j> readily available in RAPTOR) and p(ψ) constraint

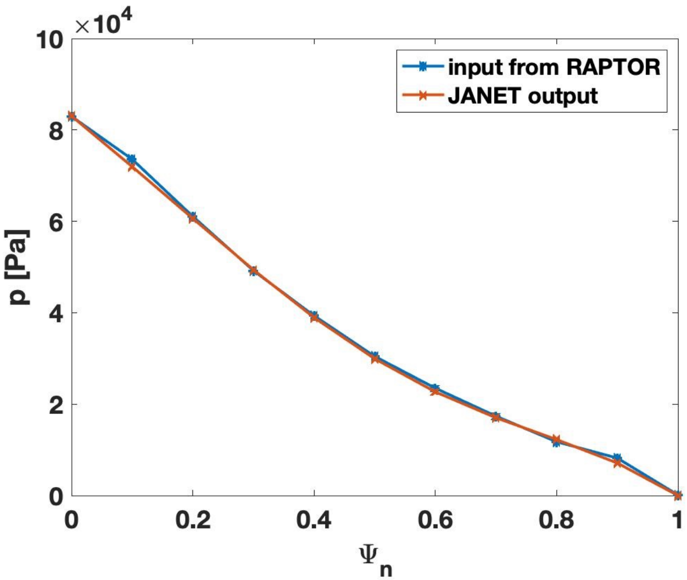


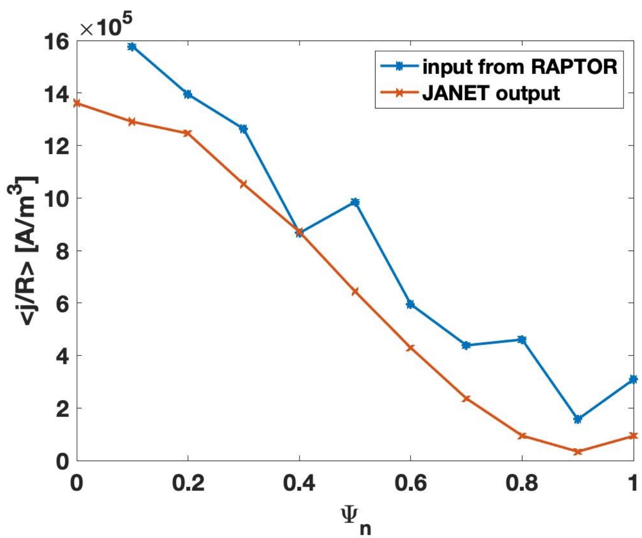
- Outputs:
  - Poloidal flux matrix
  - Geometry information (flux surface averages of several quantities) required by other codes
- Execution time on single 3.2 GHz core without hardware optimisation, 33x65 grid: ~0.15 ms
- Multiple iterations in single DCS cycle (1.5 ms) will be possible

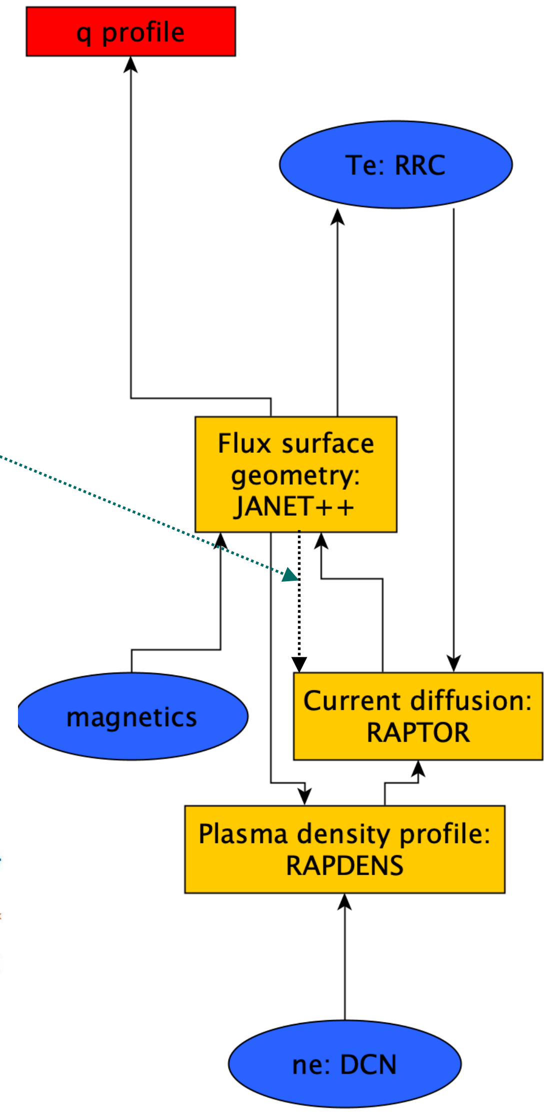
Coupled RAPTOR and JANET++ in RT

- On the top of magnetics, we have added <j/R>(ψ) and p(ψ) constraint from RAPTOR
  - Inconsistent geometry between RAPTOR and JANET

40827, t = 1 s

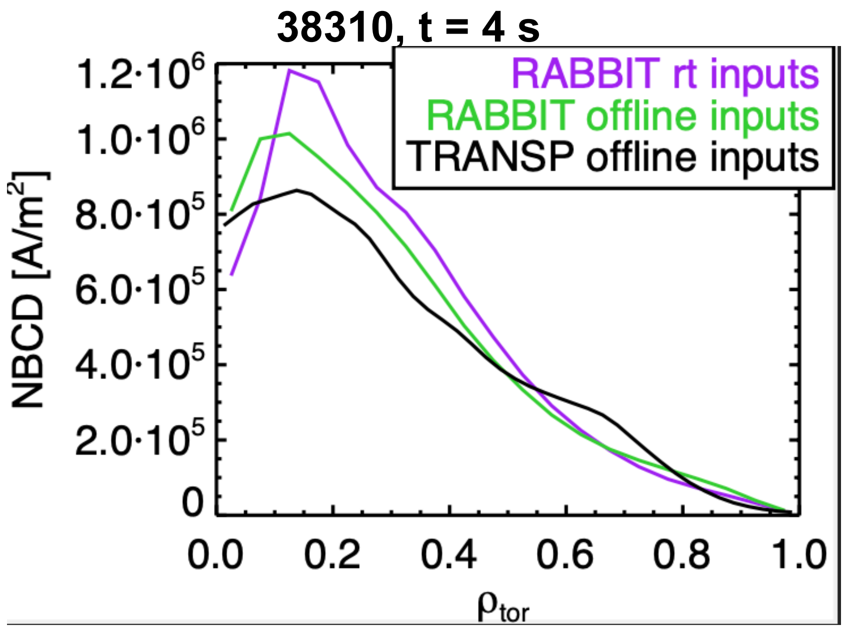






Heating and current drive profiles

- RABBIT: NBH & NBCD
  - Computation of electron heating, ion heating, **fast particle pressure**, and **current drive**
  - The results match well TRANSP/NUBEAM as long as the inputs (T_e, n_e profiles)
  - Asynchronous application, execution time ~ 20 ms
- TORBEAM: ECH & ECCD
  - Computation of **power deposition** and **current drive** in RT
  - Results of RT version match the offline version as long as the inputs (T_e, n_e profiles) are identical
  - Asynchronous application, execution time ~15 ms



j_{NBI} profile [M. Weiland et al, paper in preparation]

Conclusions & Outlook

- Ongoing work on inclusion of the current diffusion and pressure profile to the GS solver
- AUG is equipped by extensive set of advanced RT observers
  - RAPDENS for **plasma density**
  - RAPTOR for $\mathbf{T_e}$ and **current diffusion**
  - JANET++ for **equilibrium reconstruction**
  - TORBEAM for **EC power deposition and current drive**
  - RABBIT for NI **power deposition, fast particle pressure, and current drive**
  - Coupling of those is in progress
- Together, these are expected to improve the RT equilibrium reconstruction
- First application: feedback control of the q profile in the advanced tokamak scenarios
  - Improve scenario accessibility by making it less sensitive to the machine conditions
  - Aiding further scenario optimisation