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FÜR PLASMAPHYSIK

Full-f simulations of neoclassical physics with large gradients

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EUROfusion

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Outline

- Milestones and deliverables
- Full-f code
- Tests
- Internal transport barriers
- Pedestal
- Summary

Milestones and deliverables

- **TSVV1 sub project D2.3, D2.7:**

  Use HAGIS as a full-f code with non-linear collision model

  for calculating the bootstrap current in the pedestal

- **D2.3: First version of full-f HAGIS code was available before 12/2022**

  Full-f code with improved (non-linear) collision operator

- **M2.11: Extend delta-f neoclassical studies with HAGIS to full-f (12/2022)**

  Ongoing studies

- D2.7: Neoclassical bootstrap current studies with full-f HAGIS code (06/2024)

Full-f simulations with HAGIS

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- HAGIS: integration of equations of motion in Boozer coordinates, variable time steps
- Full-f: the entire distribution function is represented by marker particles
- All particle have the same fixed weight,
  number of particles in real space grid cell is proportional to the volume
- Particles are created in the beginning with a Maxwellian velocity distribution
  and with a finite flow velocity for shortening the transient phase
- Separate simulations for ions and electrons, each with intrinsic time scale
- With improved Coulomb collision operator based on an analytic approximation
  of the distribution function. Additional step for momentum and energy conservation
- Electron simulation with mass ratio of $\leq$360: lower number of part. needed

Approximation of the distribution function

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- For calculation of the Rosenbluth potentials, $\boldsymbol{f}(\boldsymbol{v})$ is approximated by

$$\tilde{f} = f_M(v^2)\left(1 + \frac{mv_\parallel V_\parallel}{T} - \frac{mv_\parallel}{T}\frac{q_\parallel}{nT}\left(1 - \frac{mv^2}{5T}\right) - \frac{mV_\parallel^2}{2T}\left(1 - \frac{mv^2}{3T}\right)\right)$$

assuming $\boldsymbol{V} = V_\parallel \boldsymbol{b},\ \boldsymbol{q} = q_\parallel \boldsymbol{b}$ due to strong anisotropy

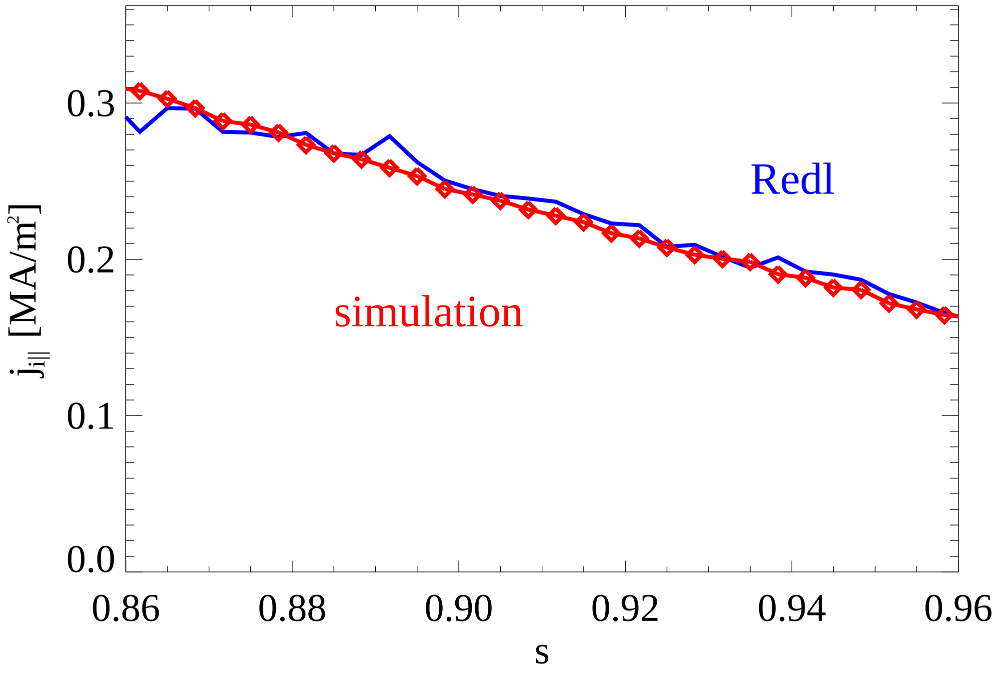
- The **scattering is done in the frame moving with the field particles**
- In this frame the distribution function f_b becomes

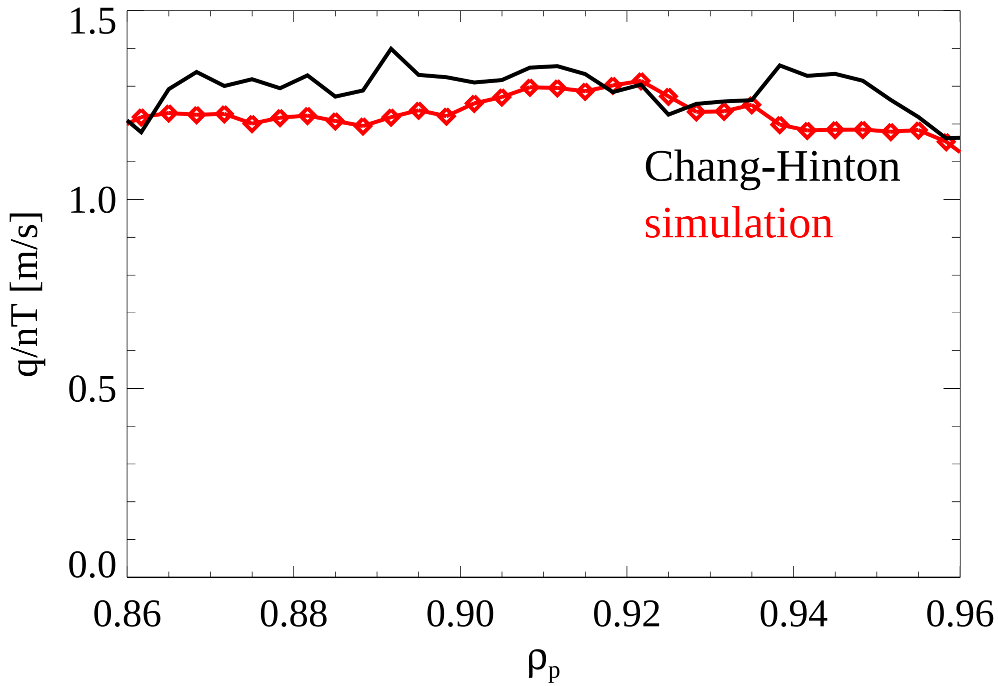
$$f_b \approx f_{bt} = f_M(v^2)\left(1 - \frac{m_b v_\parallel}{T_b}\frac{q_{\parallel b}}{n_b T_b}\left(1 - \frac{m_b v^2}{5T_b}\right)\right)$$

- **Advantage of calculating the collisions in the moving frame:**

  Expressions for friction and diffusion coefficients are simpler

Test: ions with weak gradients





Characteristic time for ion current: τ_{coll}/f_t

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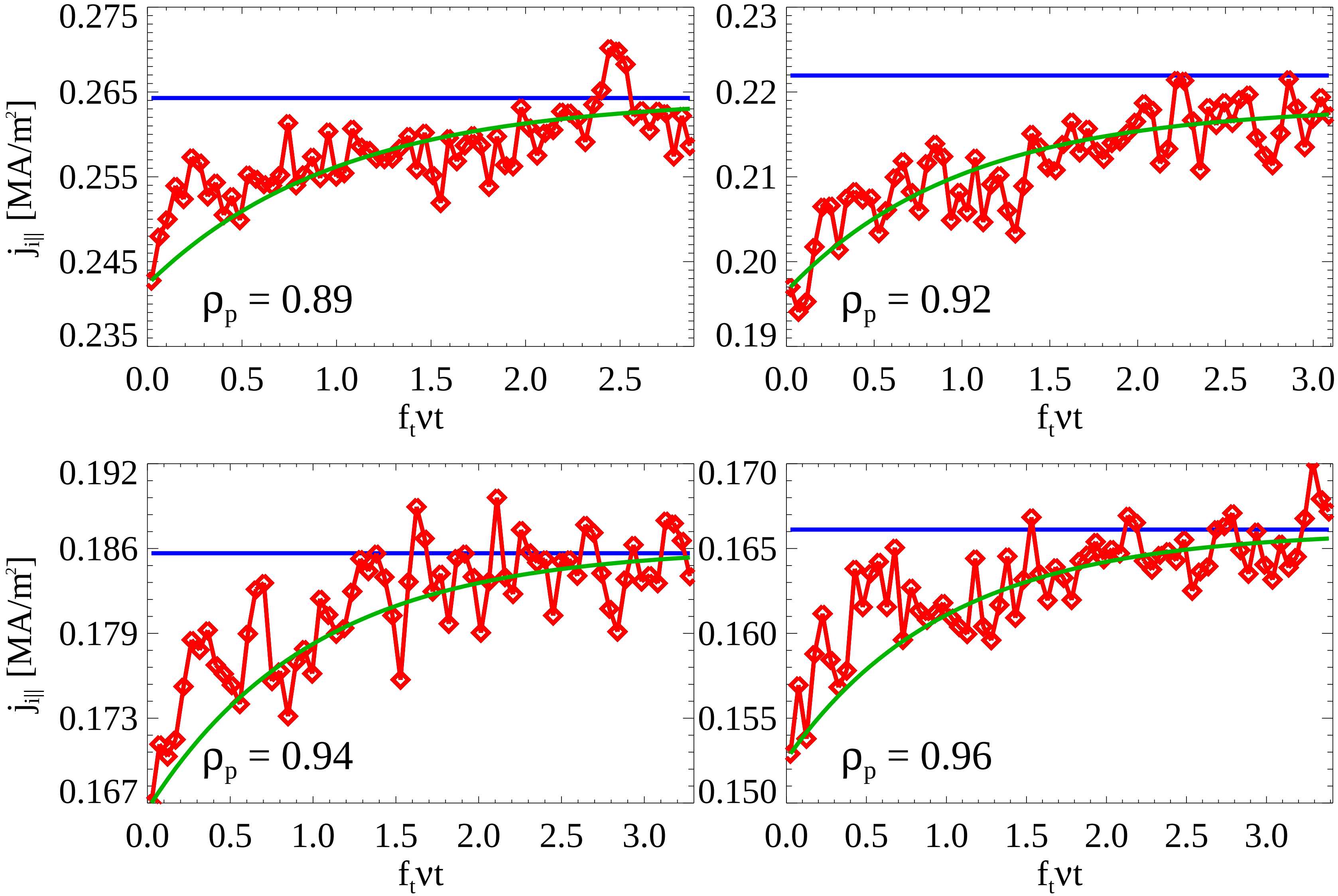

Characteristic time for electron current: $\tau_{coll}/(1+f_t)$

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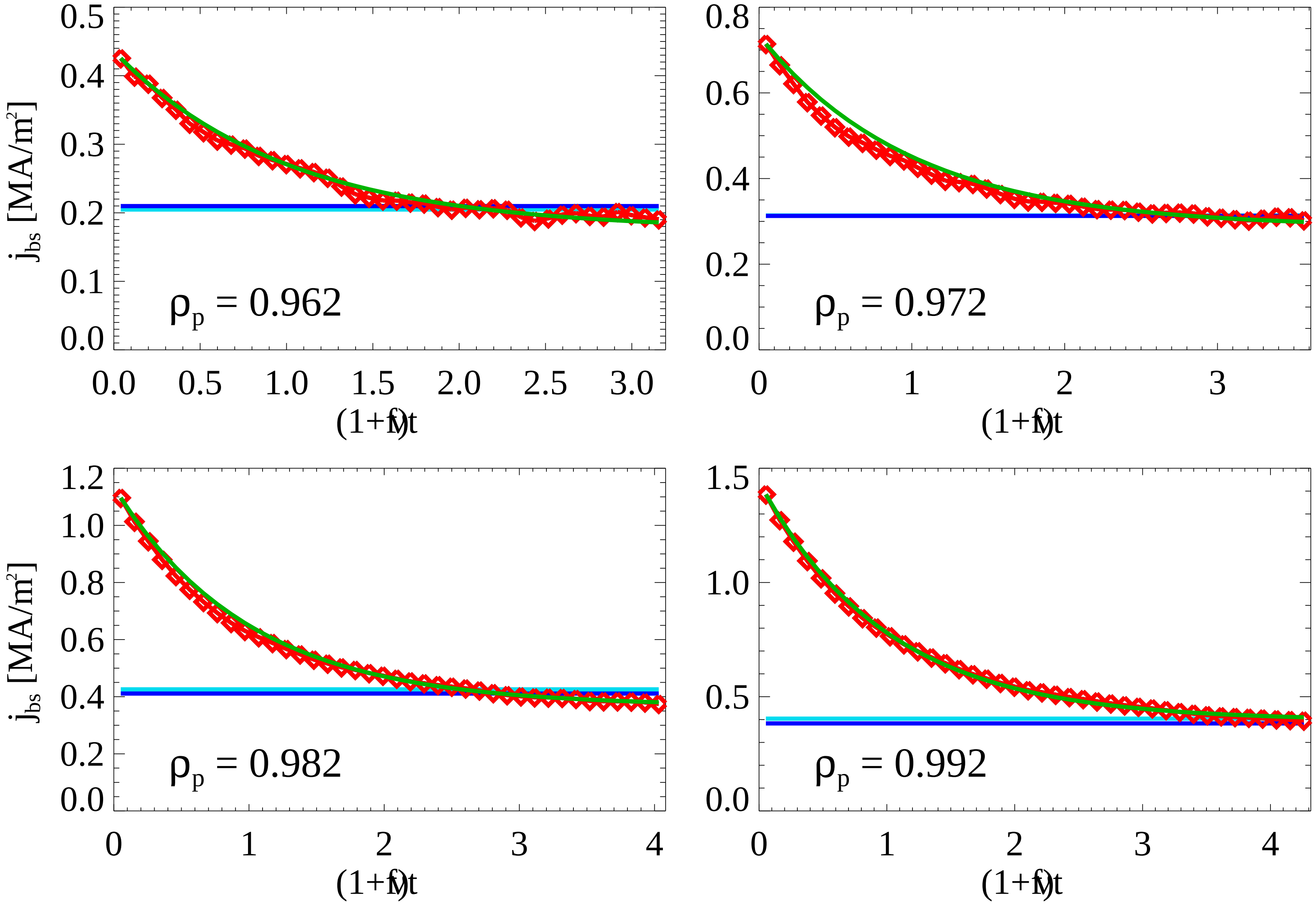
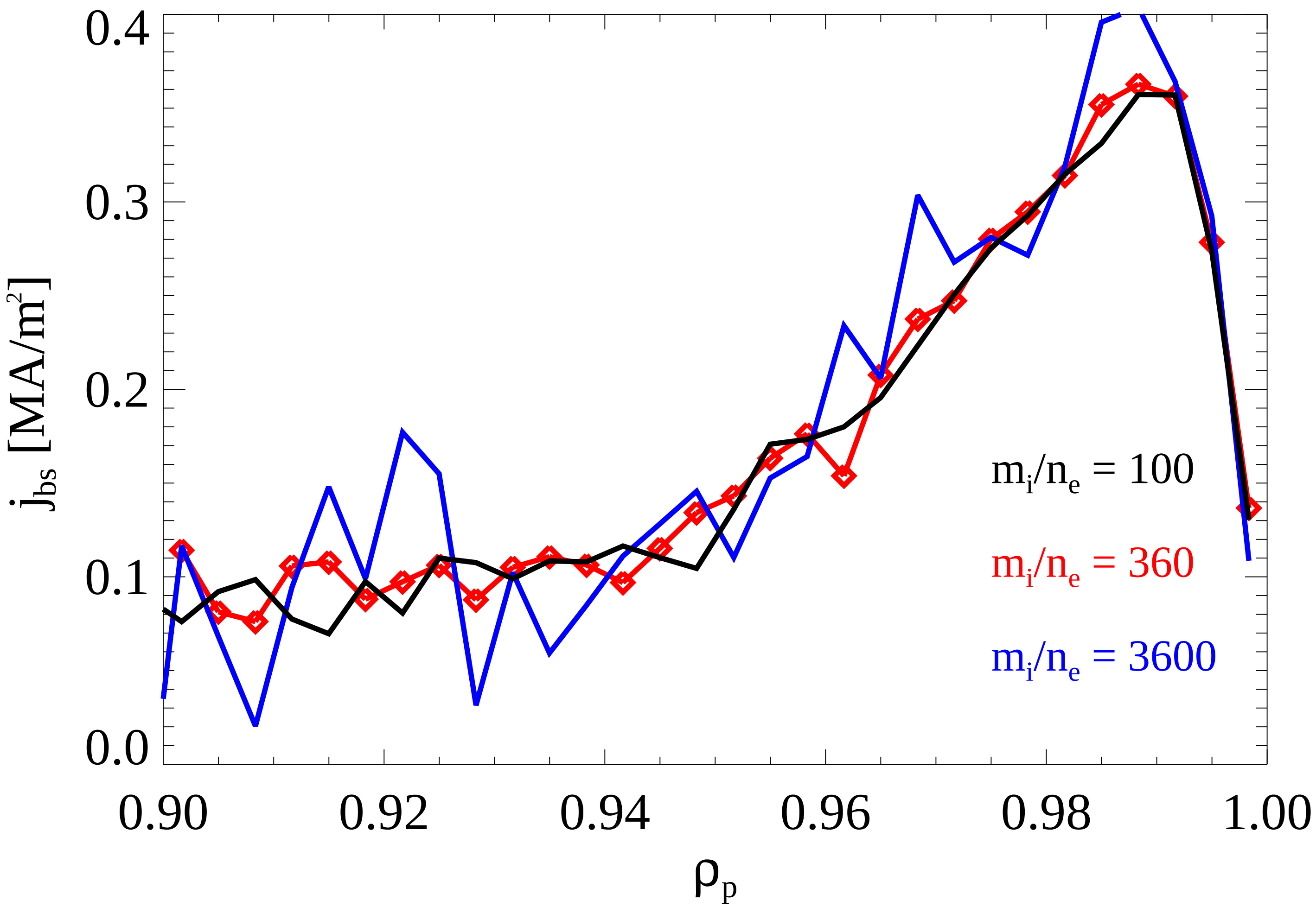
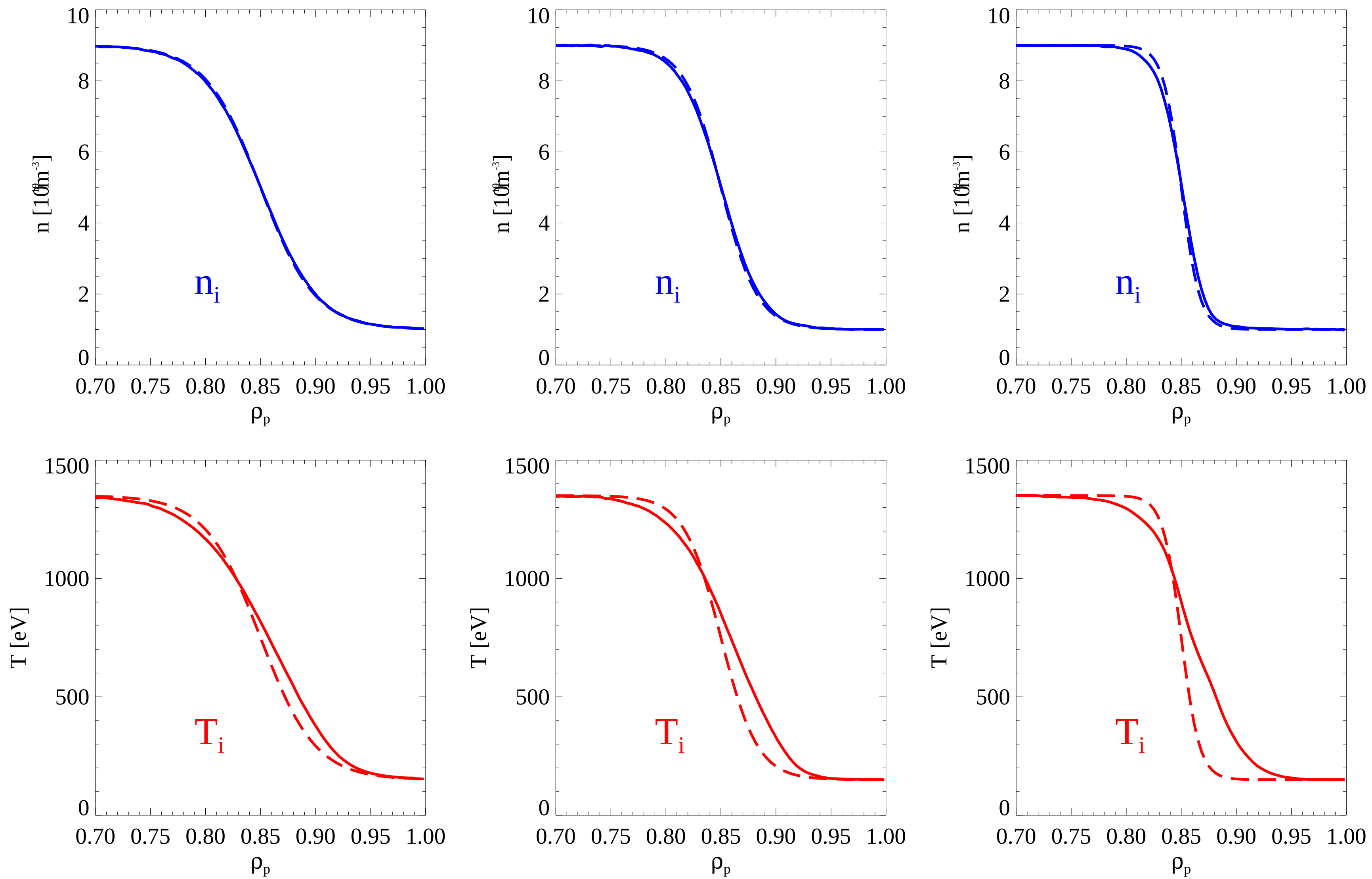


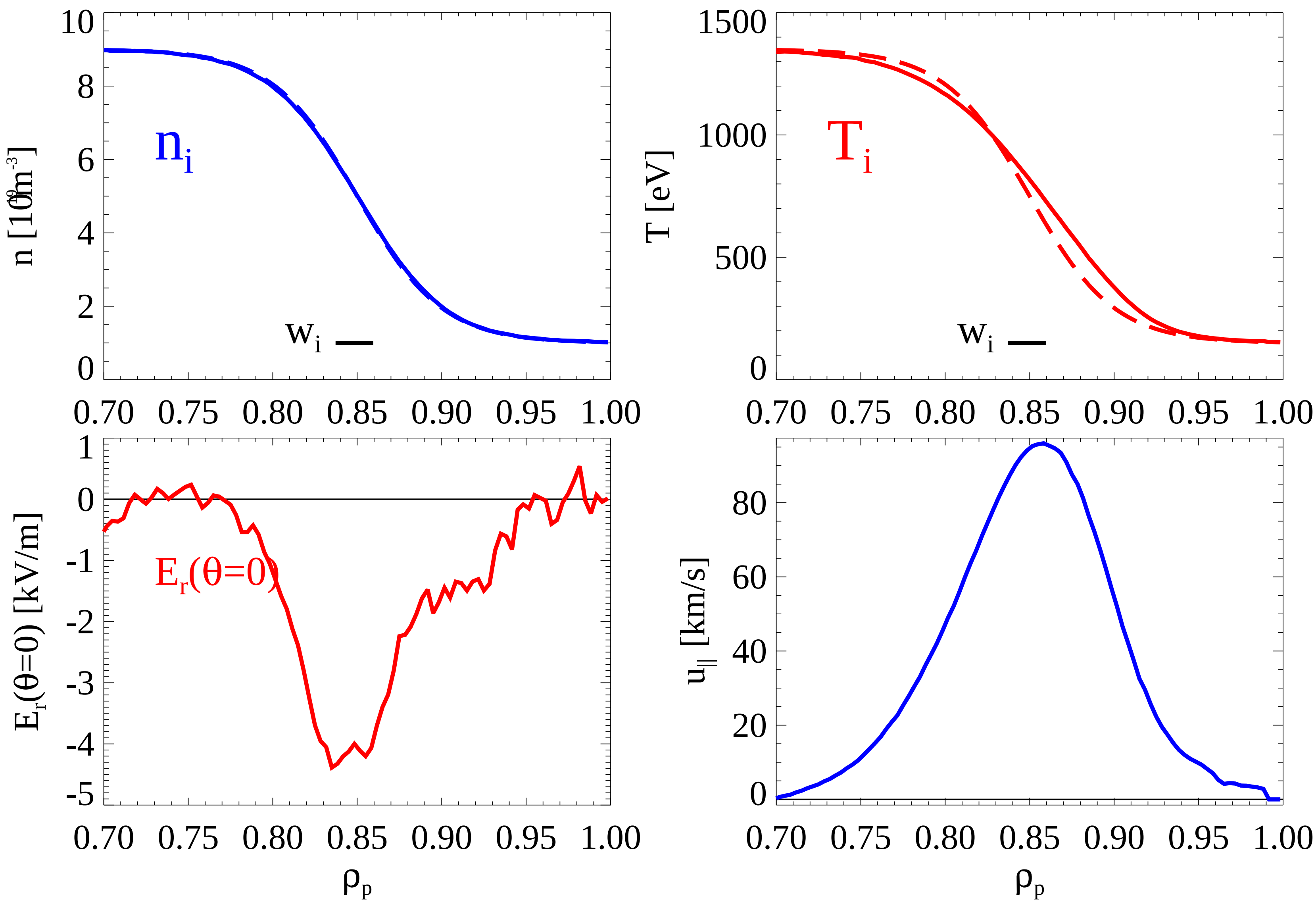
BS current: independent of ion to electron mass ratio



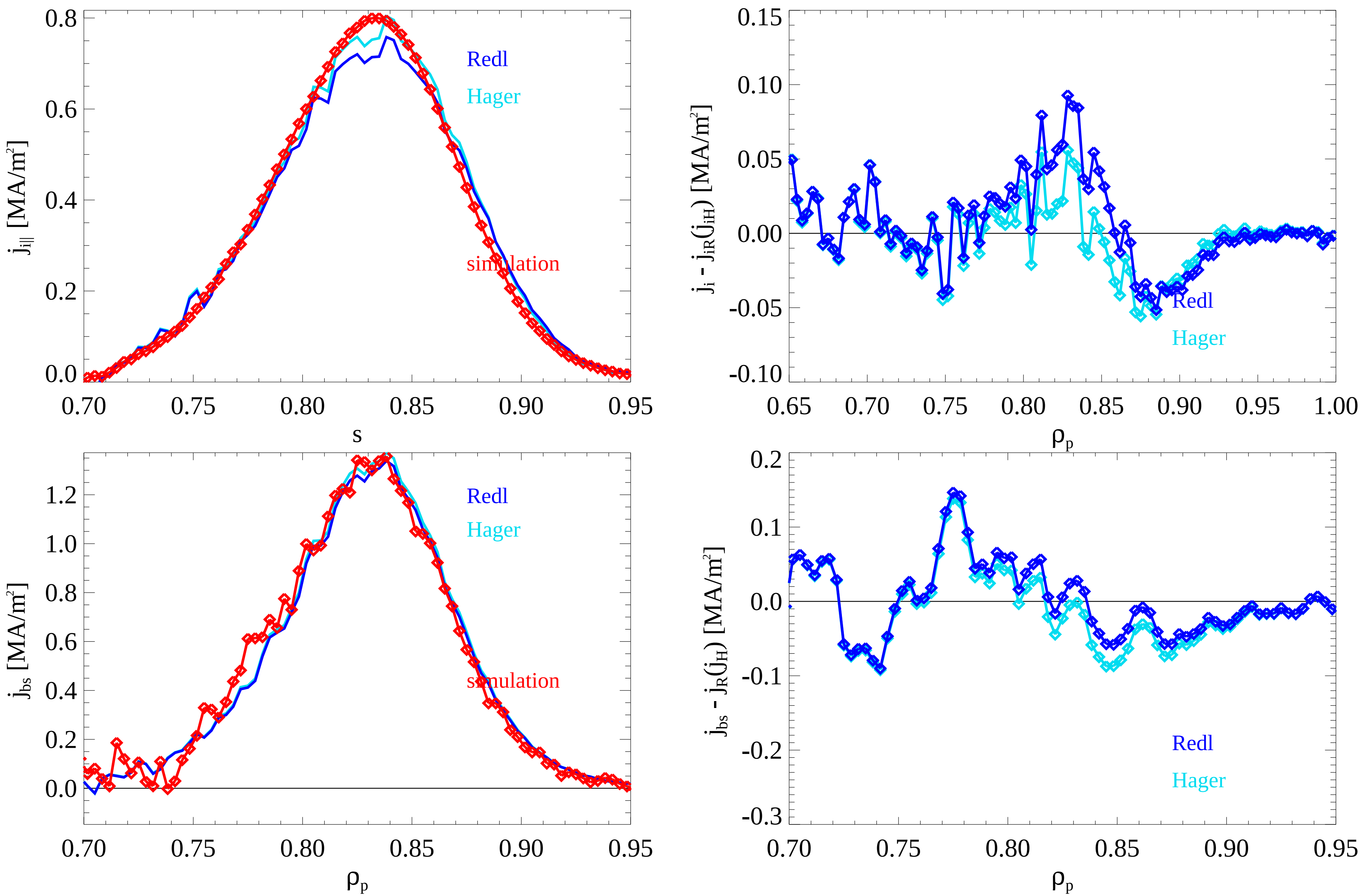
Internal transport barrier: no boundary effects



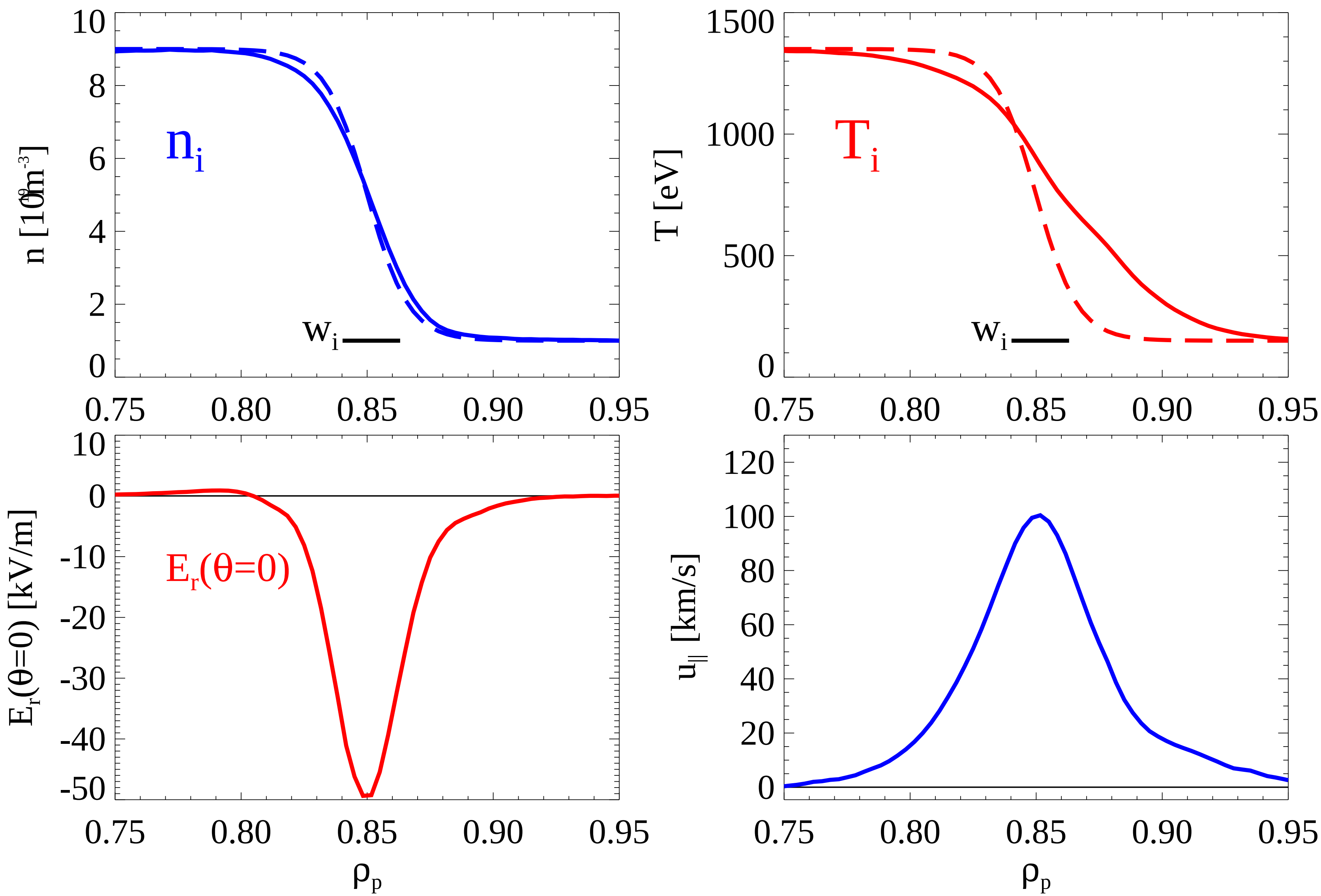
Simulation I $(w/L = 0.3)$



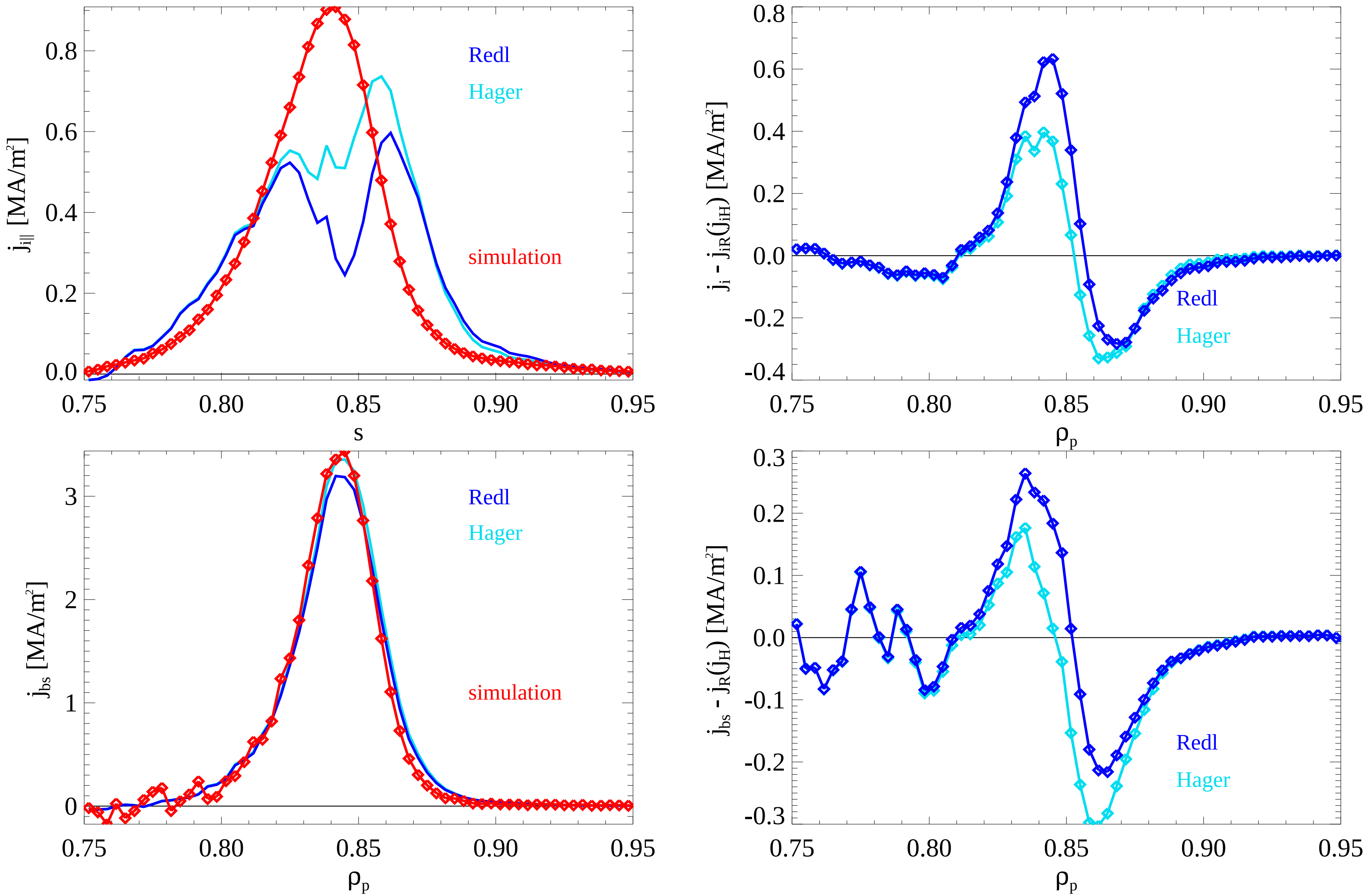
Simulation I ($w/L = 0.3$): Ion and bootstrap current



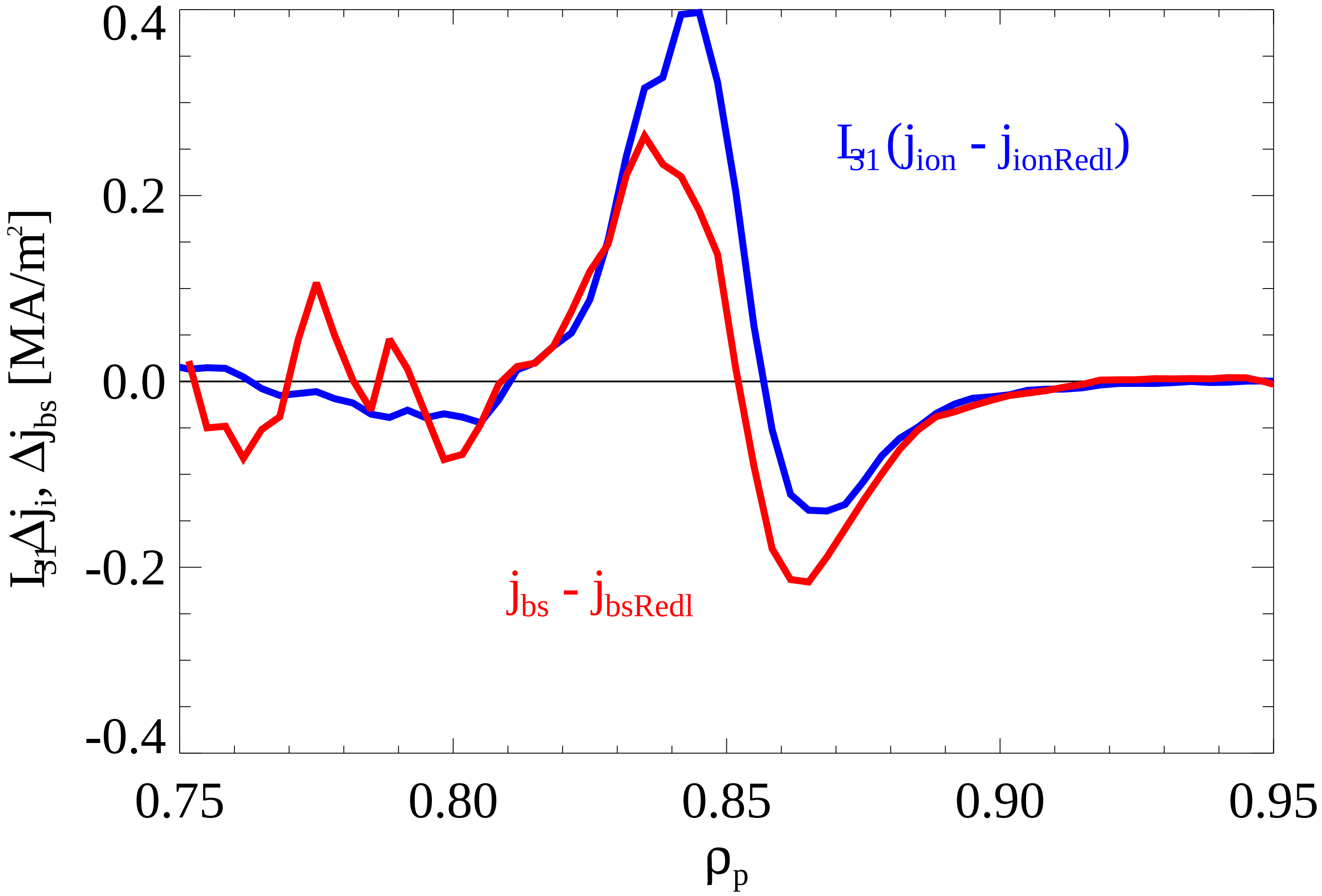
Simulation III ($w/L = 1$)



Simulation III ($w/L = 1$): Ion and bootstrap current



BS current: deviation from Redl-formula



$\boldsymbol{L_{31}}$: coefficient of ion contribution to the bootstrap current

BS current: deviation from Hager-formula

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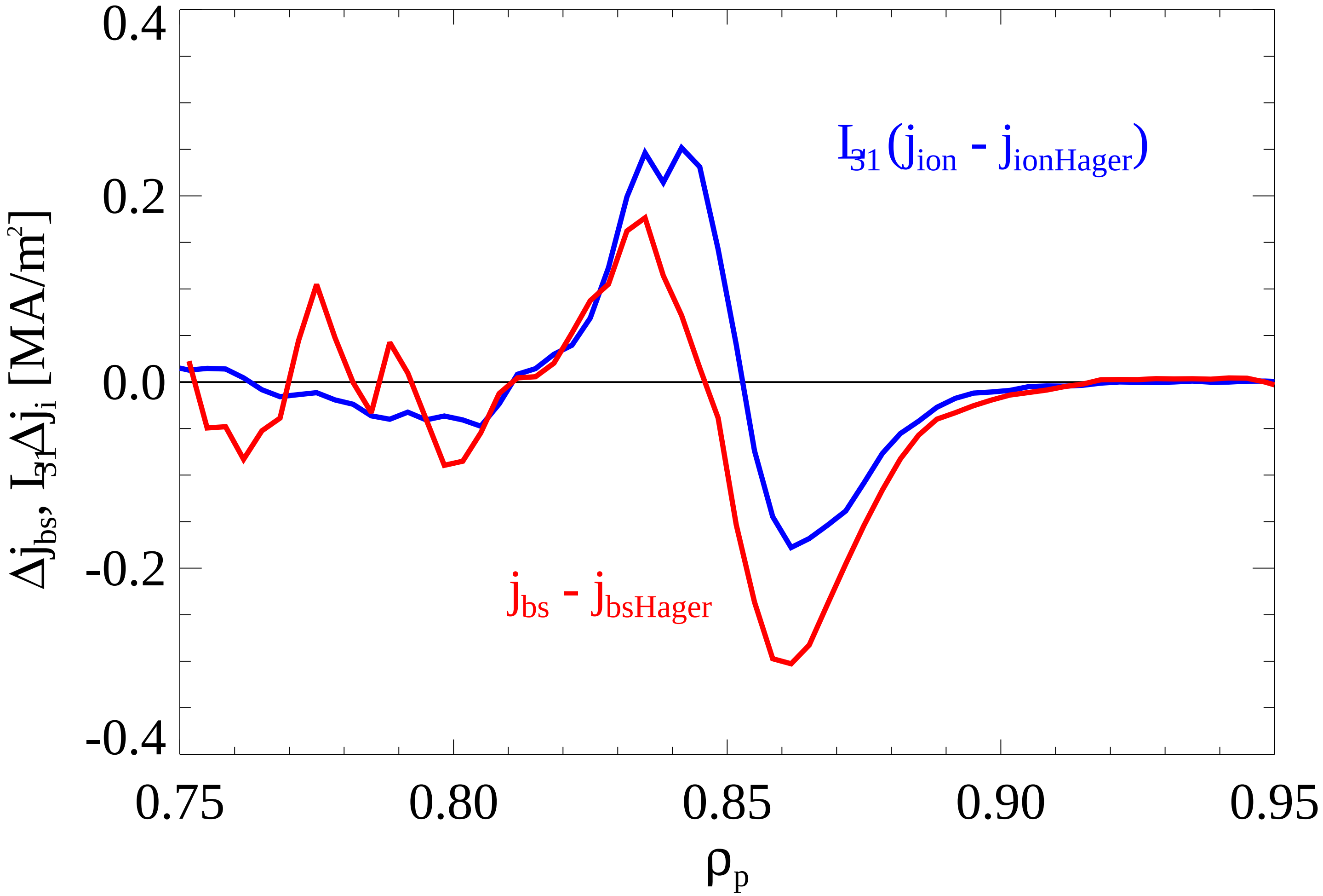

L_{31} : coefficient of ion contribution to the bootstrap current

Ion density: poloidal variation

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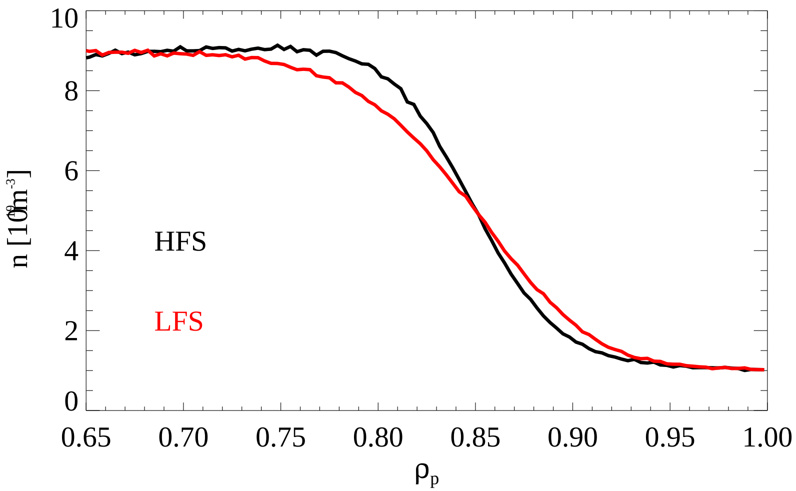

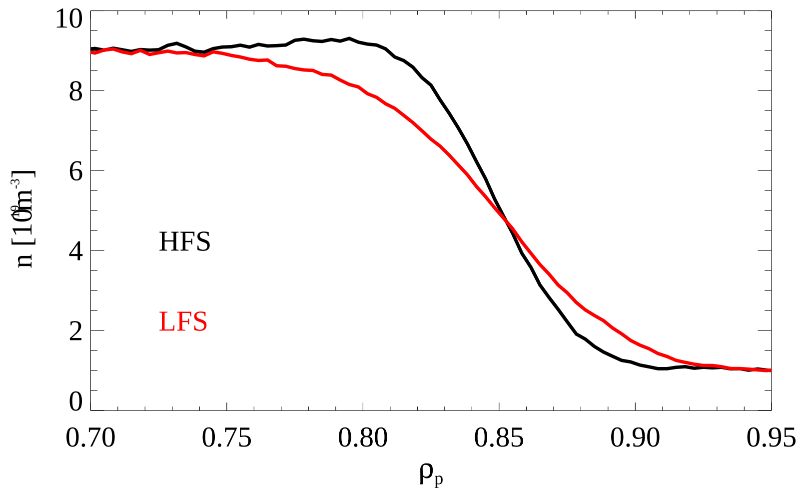

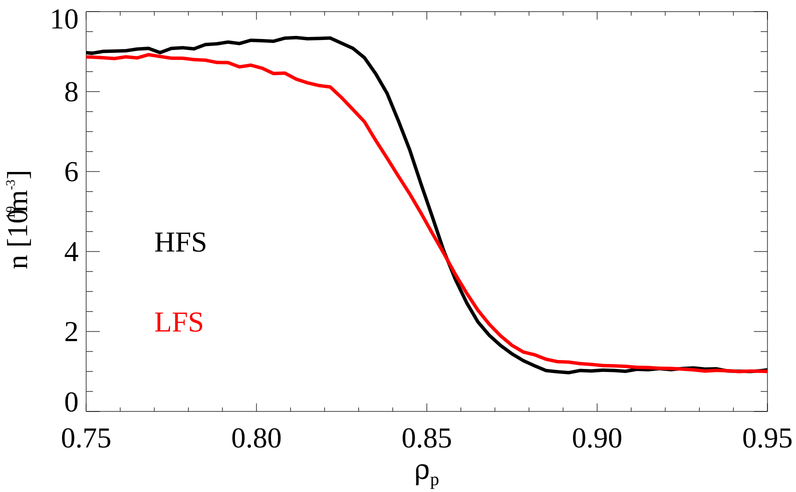

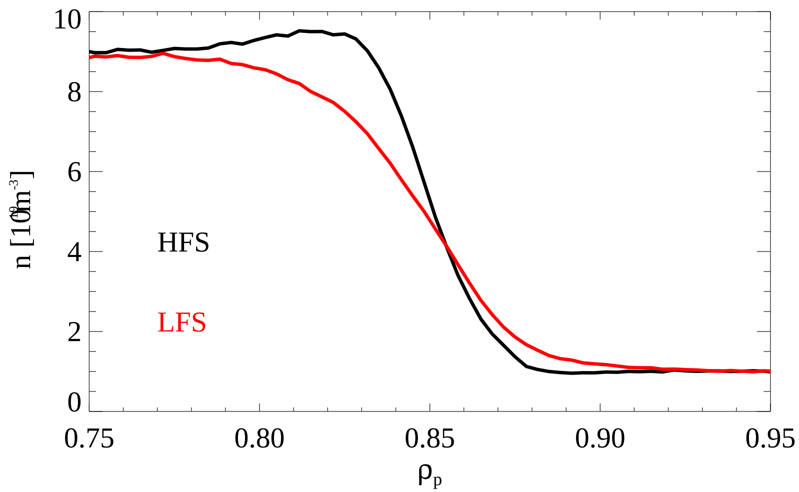

Ion density: poloidal variation

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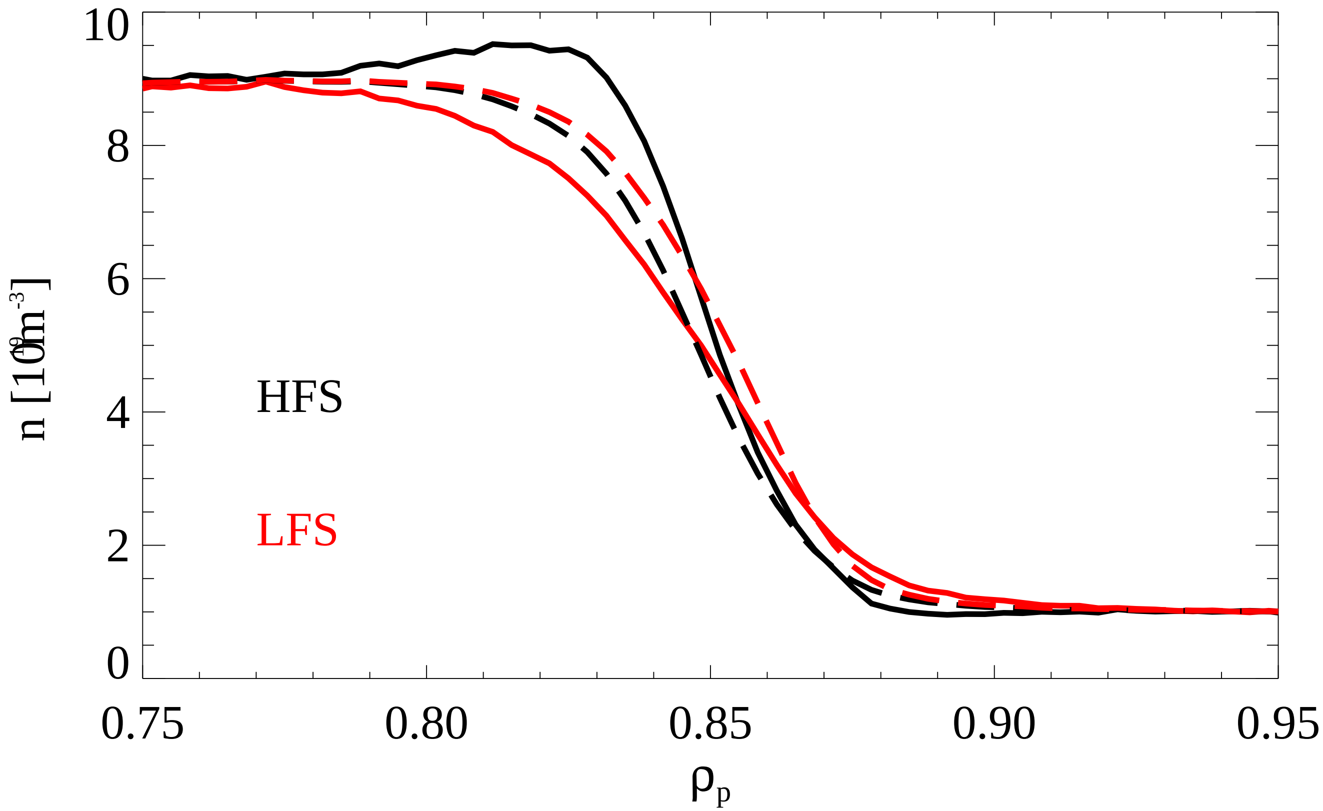
The poloidal density variation is different from that is caused by the centrifugal force



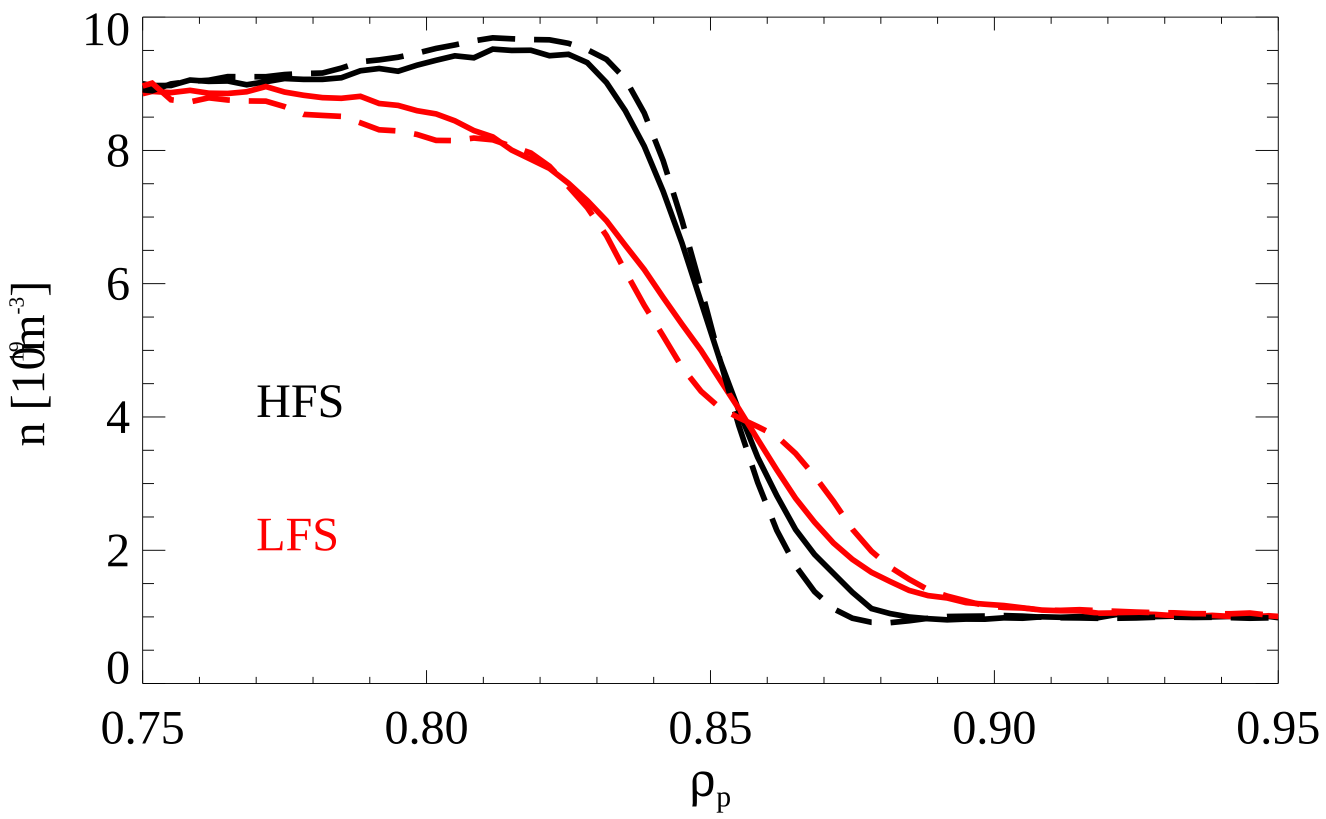
dashed lines:

$$n(\psi, \theta) = \langle n \rangle \exp\left(\frac{m\omega^2 R^2}{2T_0}\right)$$

$$\omega R = v_{\mathrm{tor}} - v_{\mathrm{pol}} B_{\mathrm{tor}} / B_{\mathrm{pol}}$$

Ion density: poloidal variation

Poloidal density variation due to radial variation of the rotation velocity



dashed lines:

$$n(\psi,\theta) = \langle n \rangle \exp\left(\frac{m\omega^2 R^2}{2T_0}\right)$$

$$\times \exp\left(-\frac{m\omega' R^2}{2e}\right)$$

$$\omega' = \frac{d\omega}{d\psi}$$

Pedestal simulation I: ions

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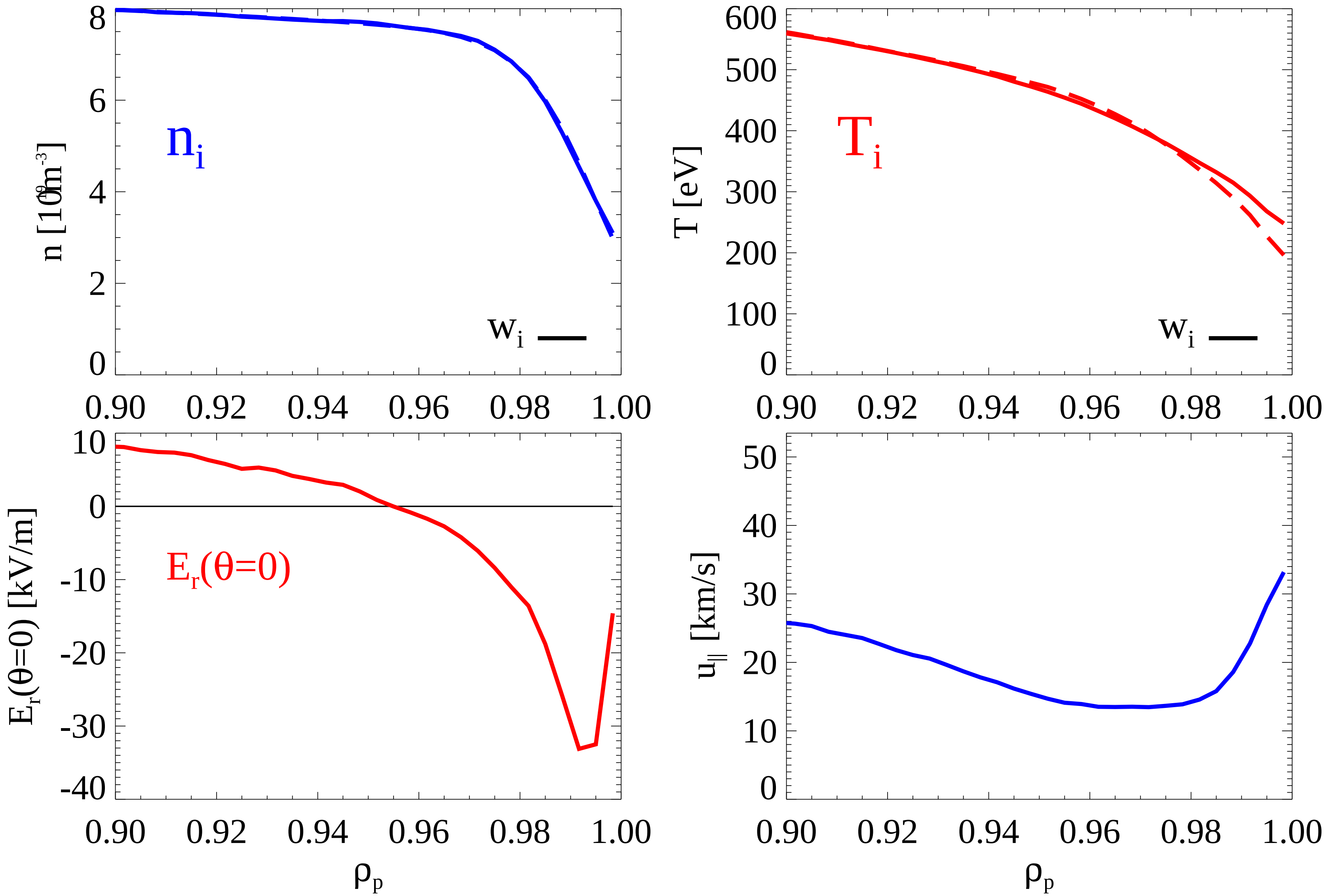
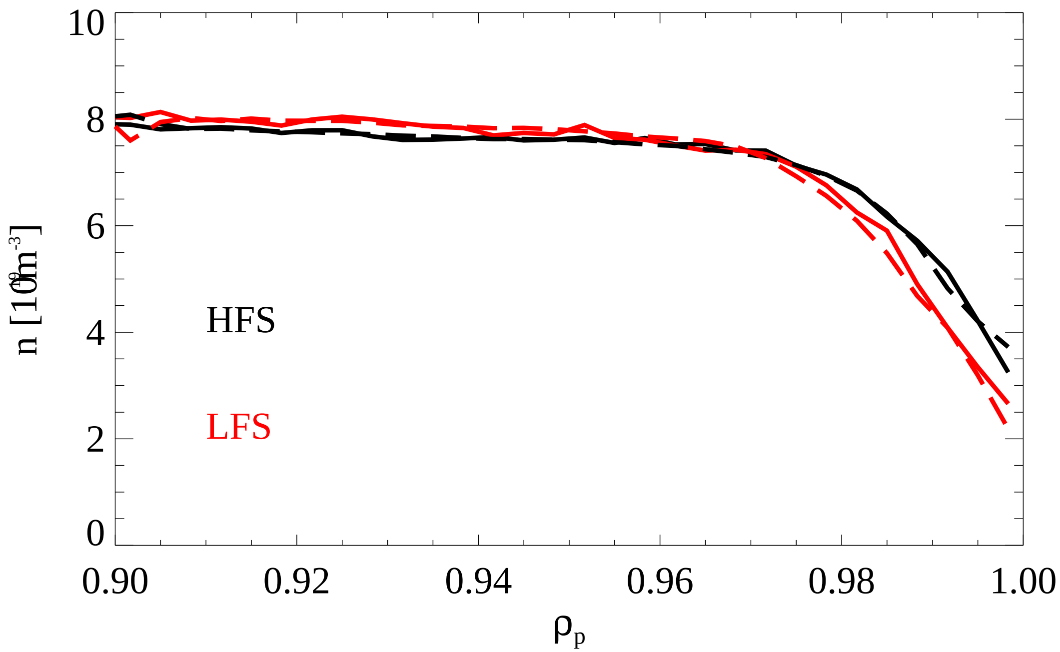
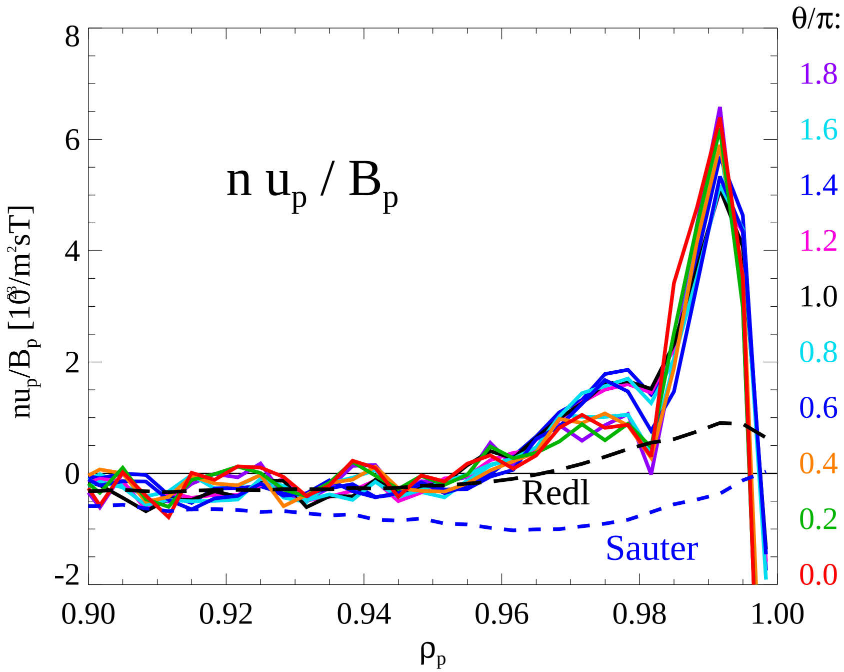


Pedestal simulation I: ions





- Poloidal density variation is dominated by the ω' contribution
- Poloidal flow differs from the usual value in pedestal region

Pedestal simulation I: ion current

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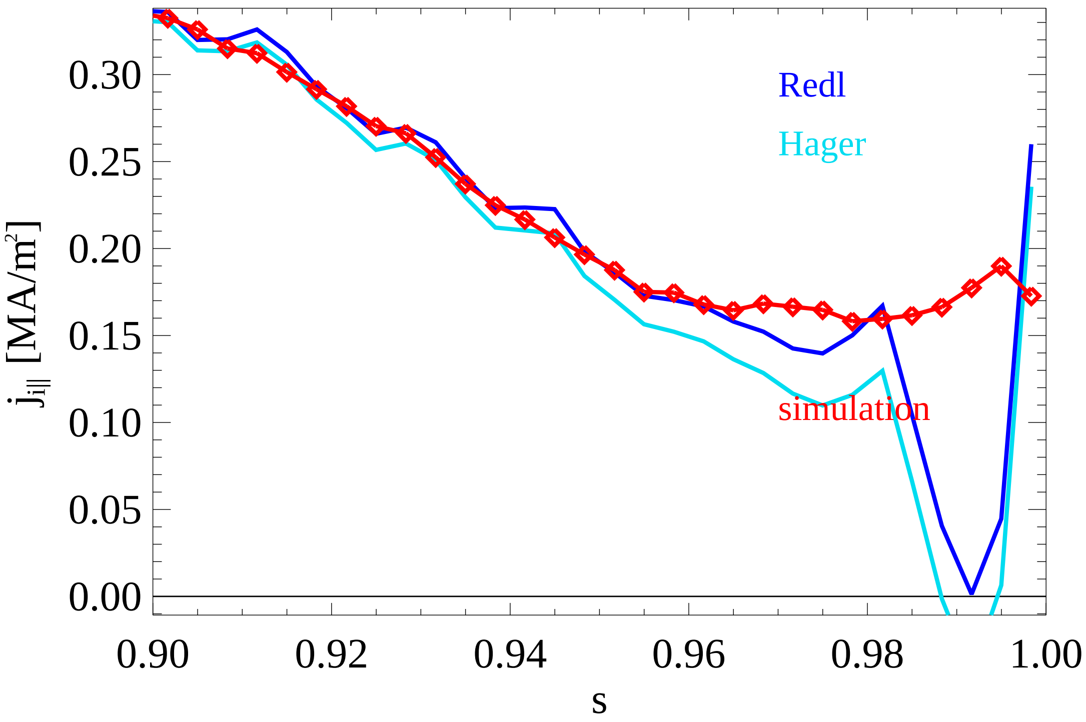
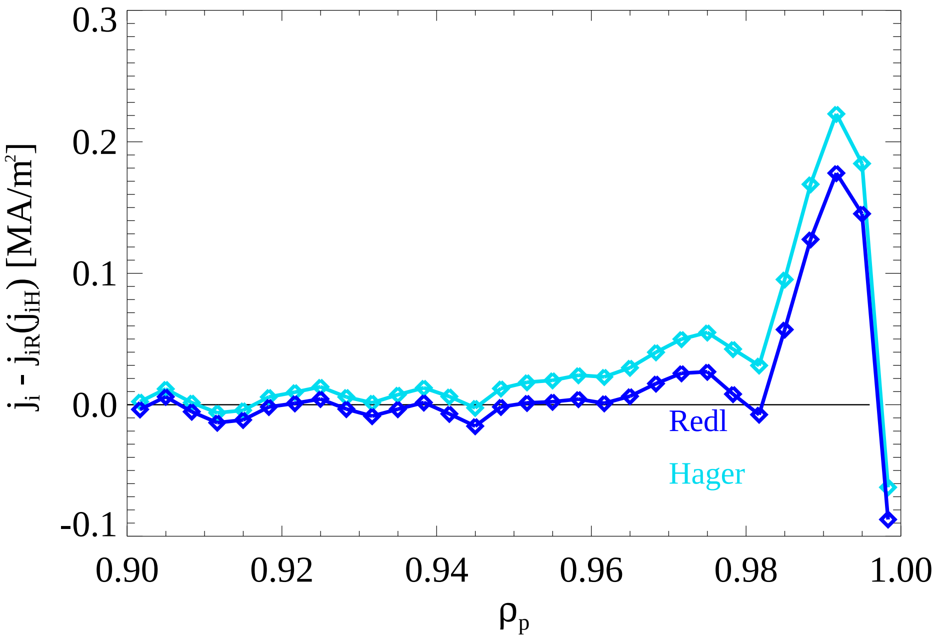
current



deviation from Redl/Hager



Pedestal simulation I: bootstrap current

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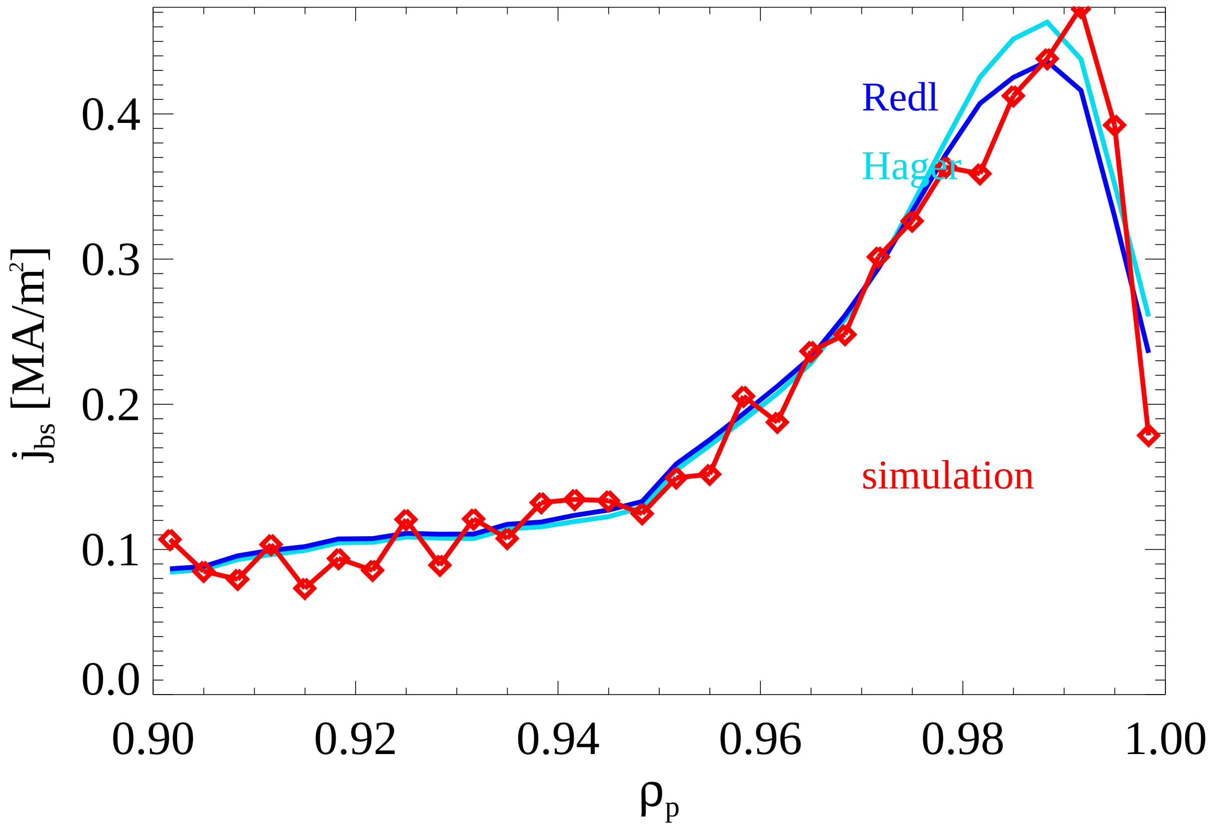
Bootstrap current compared to Redl/Hager formulas



Pedestal simulation I: bootstrap current

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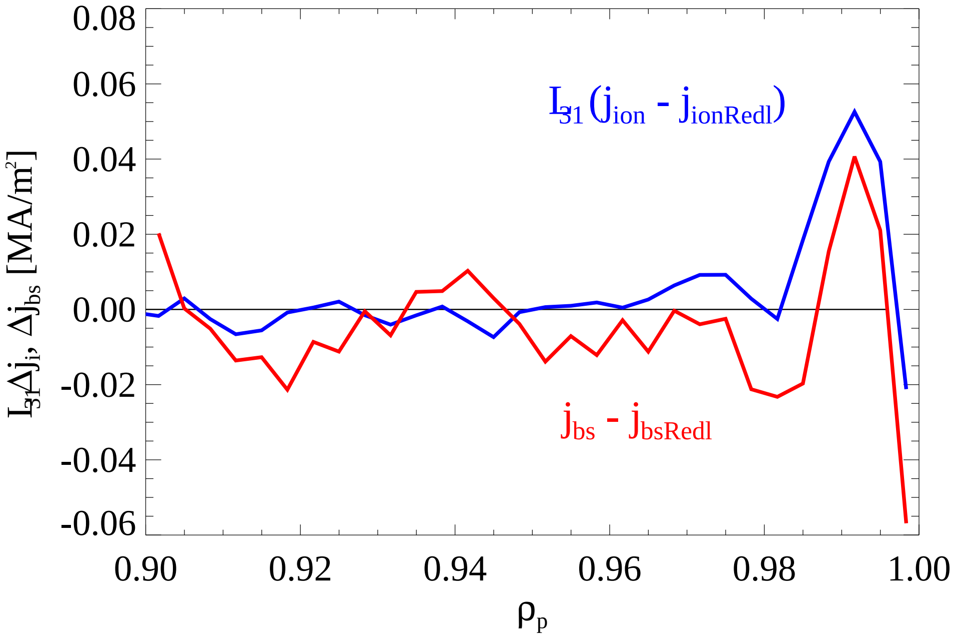
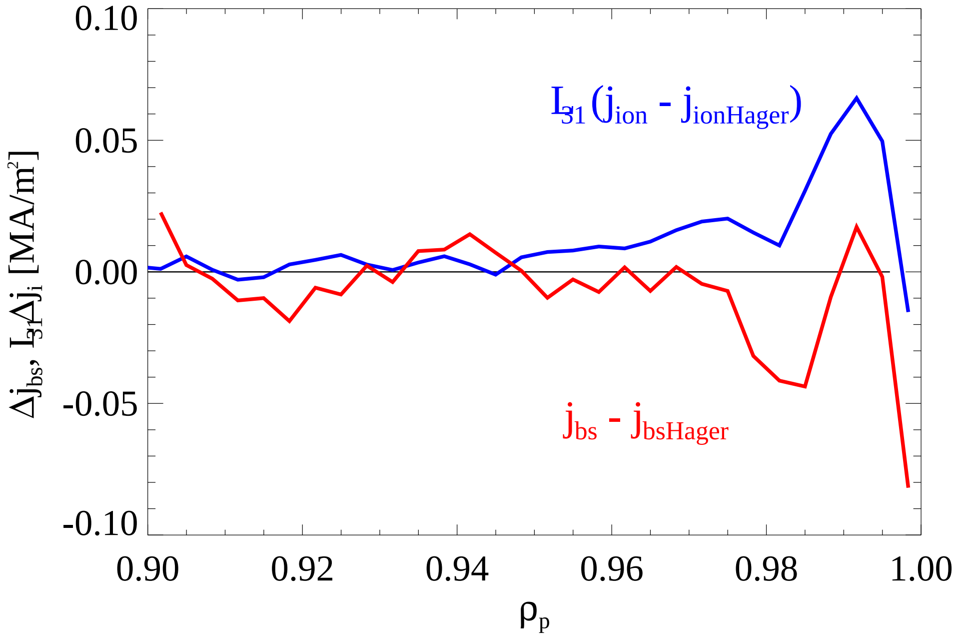
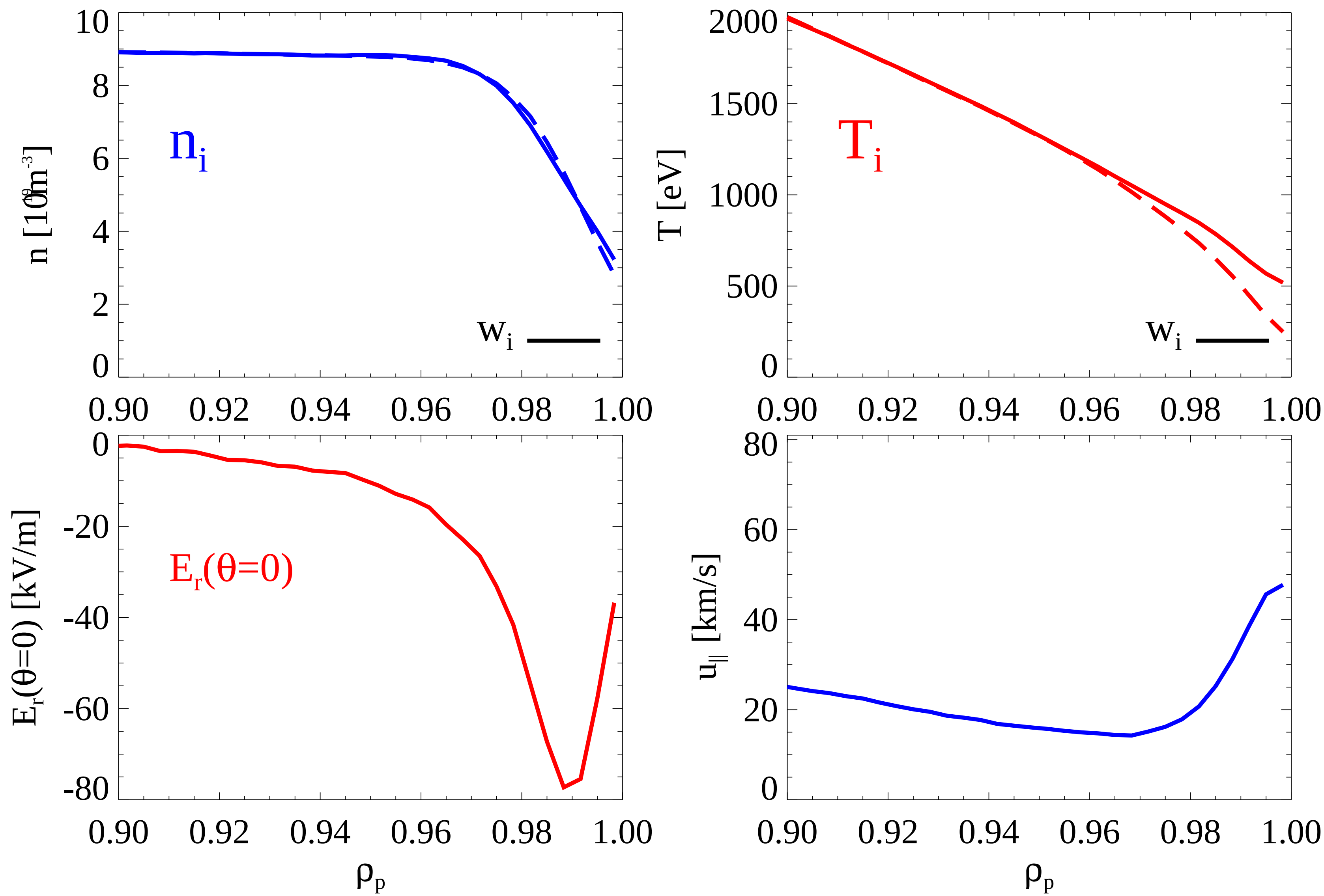
Comparison between bs current and ion current deviations multiplied by L_{31}



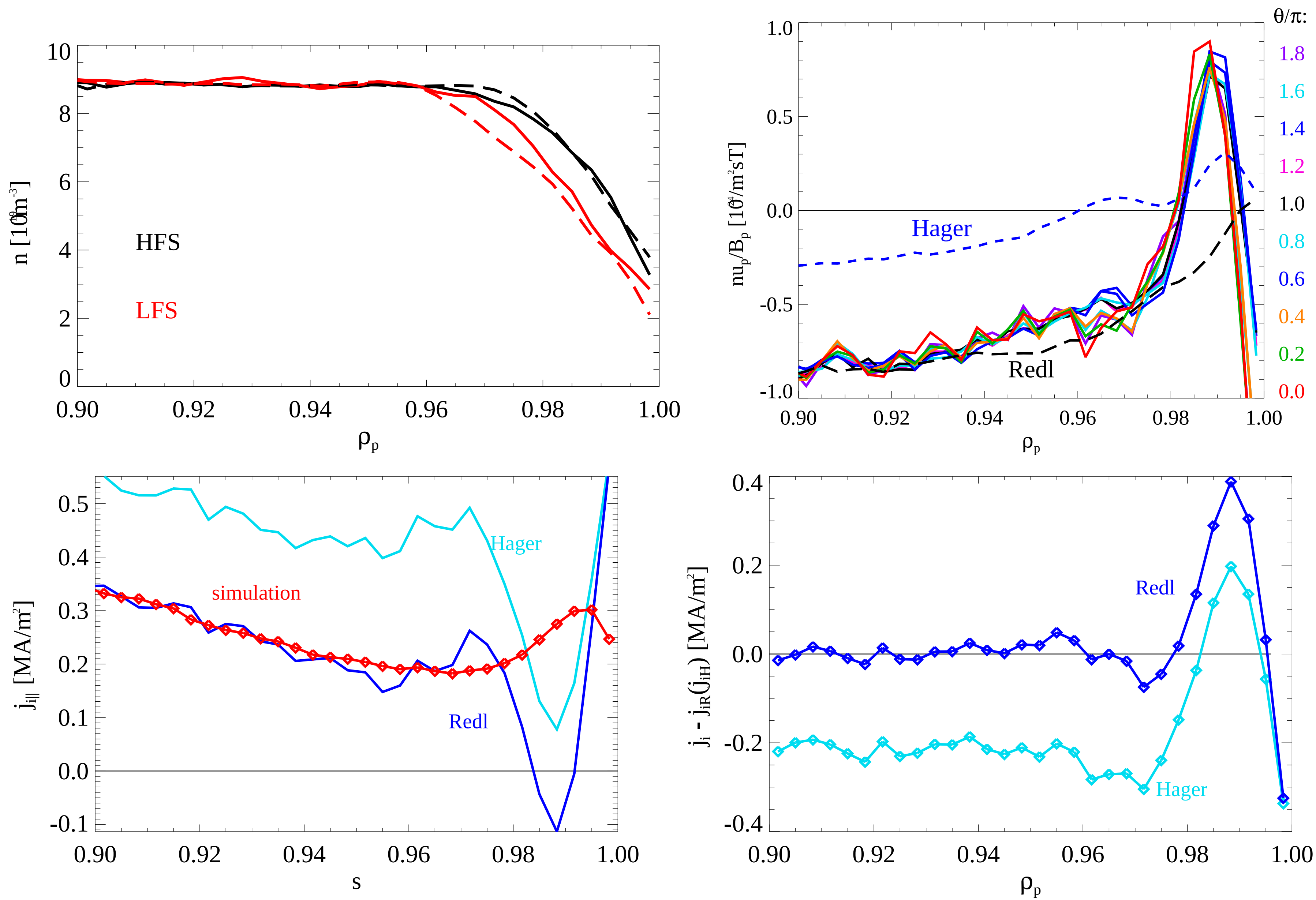


$\boldsymbol{L_{31}}$: coefficient of ion contribution to the bootstrap current

Pedestal simulation II (steeper profiles): ions



Pedestal simulation II: ions



Pedestal simulation II: bootstrap current

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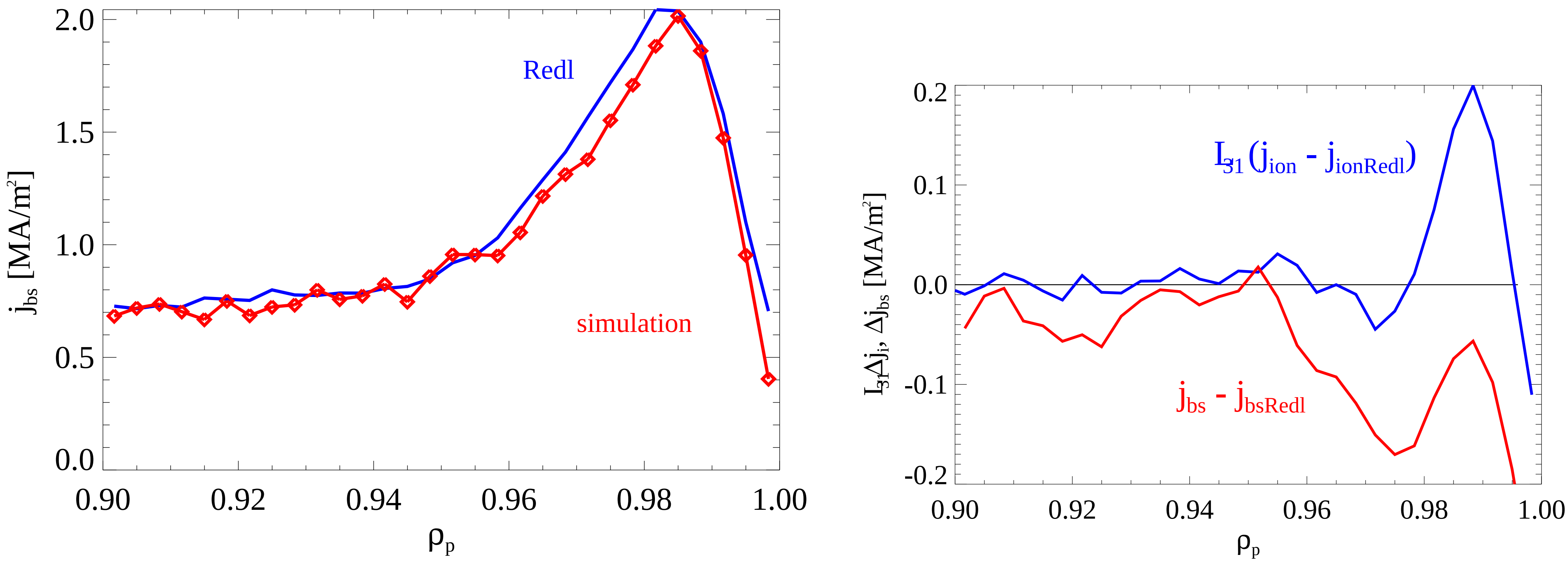
Bootstrap current compared to Redl formula and deviation compared to $L_{31}\times$ ion current



Pedestal simulation III: ions with different pol. vel.

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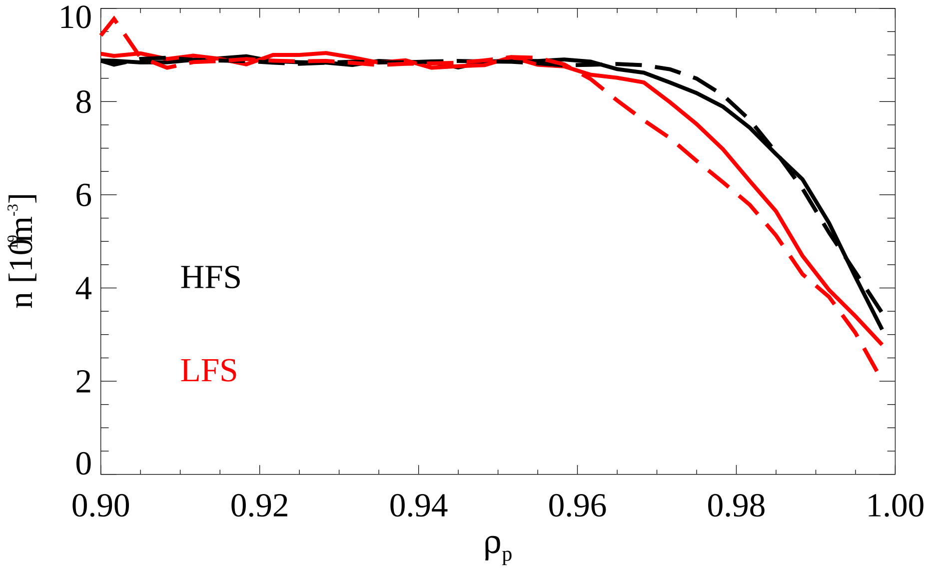

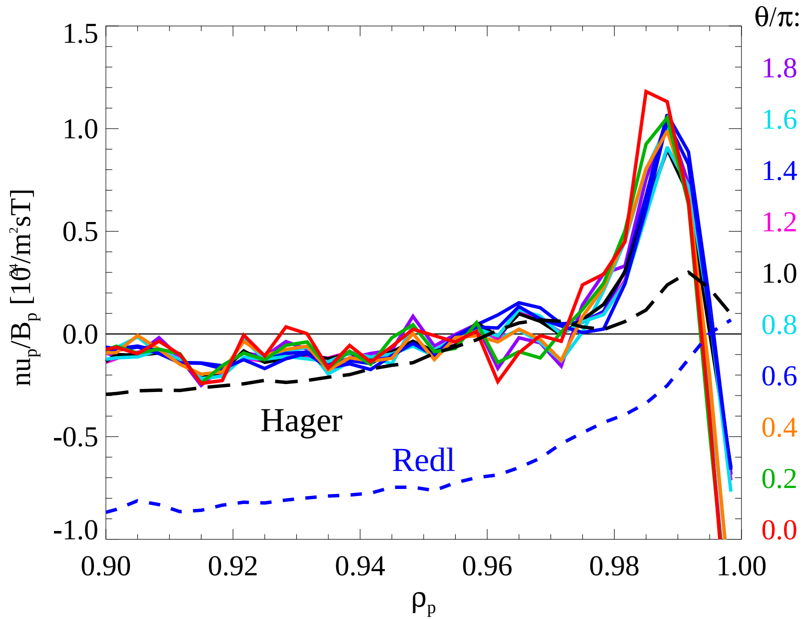

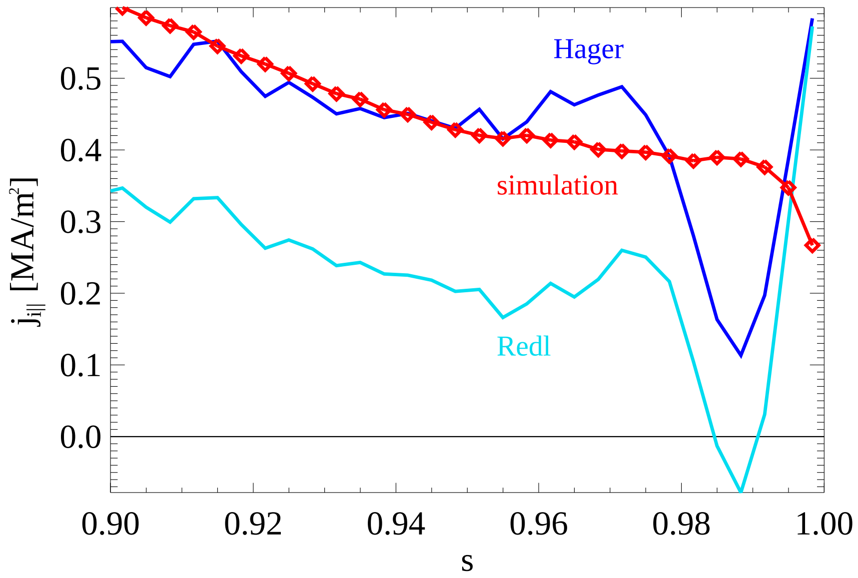

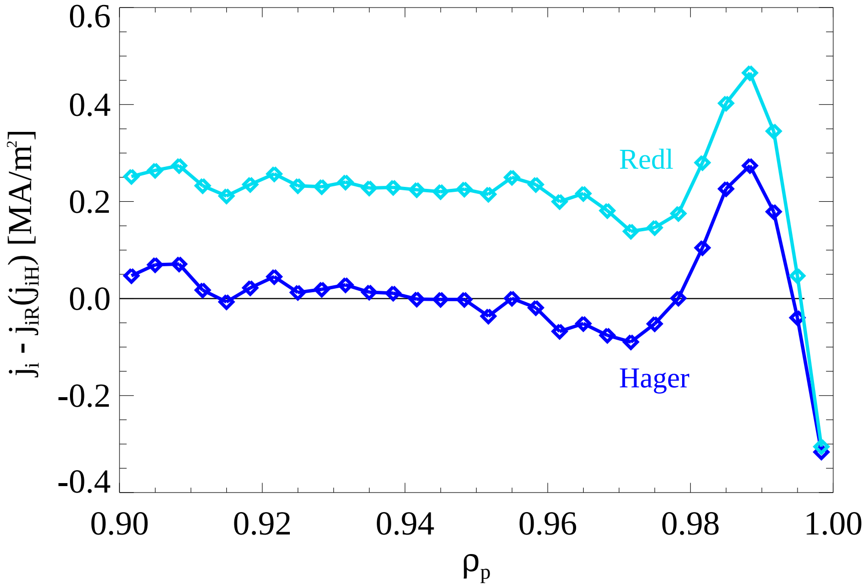

Pedestal simulation III: bootstrap current

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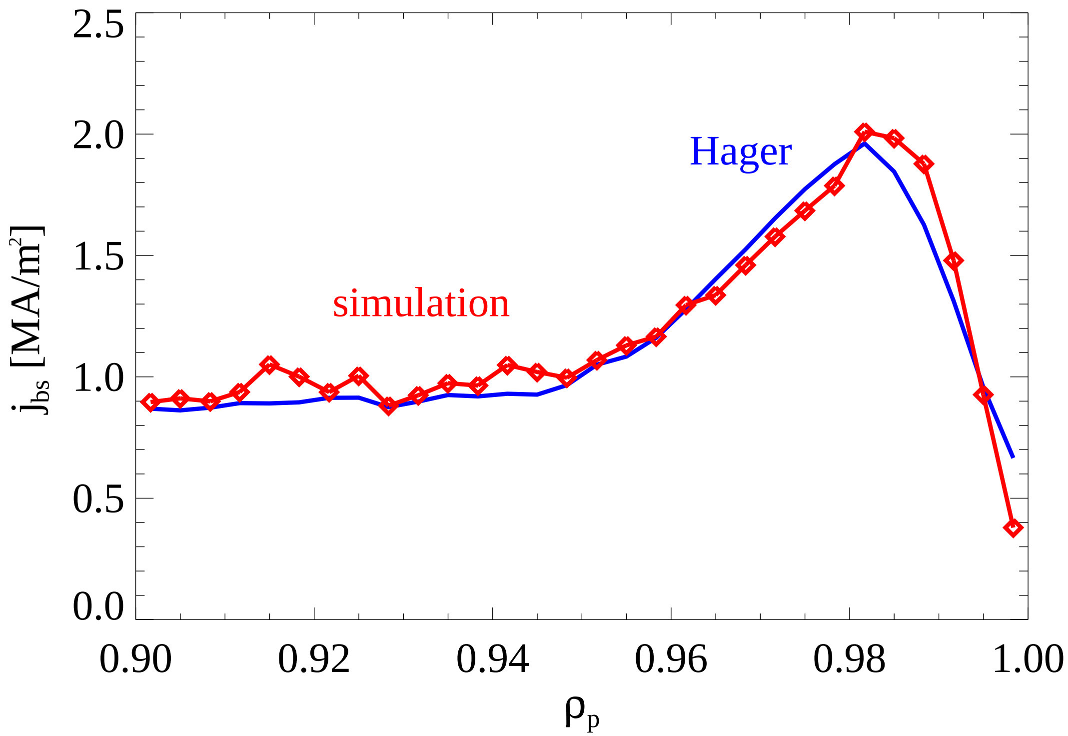
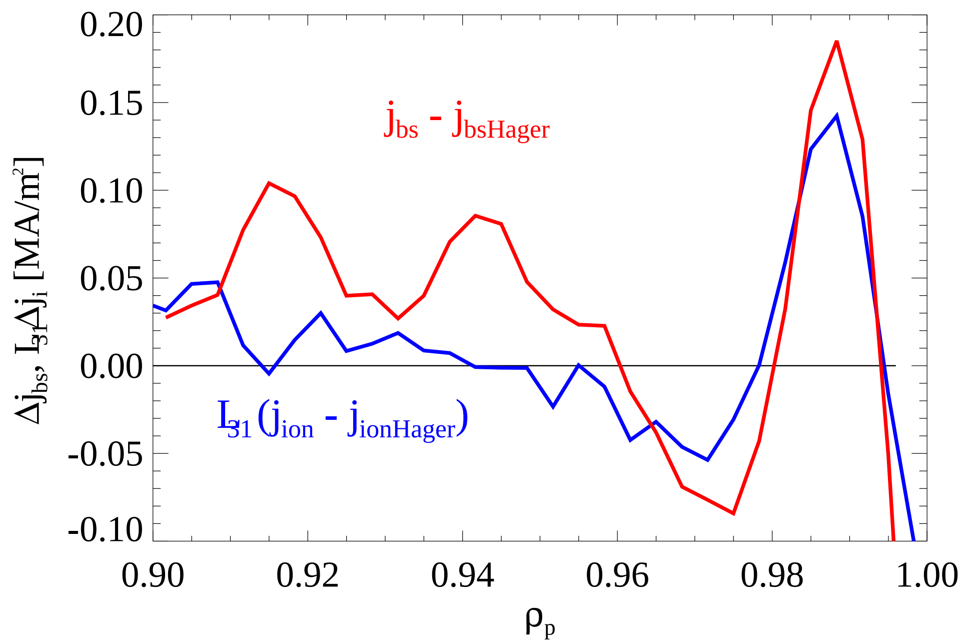
Bootstrap current compared to Redl formula and deviation compared to $L_{31}\times$ ion current





Summary

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- Full-f HAGIS simulations of neoclassical physics with large gradients
- Improved collision operator for scattering from modified Maxwellian was used
- Bootstrap current simulations done with mass ratio of $\leq$360
- Study of steep density/temperature profiles in the bulk plasma
- Poloidal density variation due to the rotation shear
- Bootstrap current deviation consistent with deviation of ion current
- Simulations of pedestal cases: no uniform picture yet