JOREK simulations of an argon-MGI-triggered disruption in JET

E. Nardon, TSVV 9 progress meeting, 04/02/21

- Context:
  - 3D MHD codes can now « easily » simulate what qualitatively looks like a thermal quench:
    - Burst of MHD activity
    - Full stochastization
    - Temperature collapse in the core
  - However,
    - No published simulation displays an I_p spike comparable to measurements
    - Besides this, quantitative validation has not been pushed very far
  - JOREK simulations of the argon-MGI-triggered disruption in JET pulse #85943 have been going on for… a long time!

The long history of JOREK simulations of JET #85943, or… the saga of the I_p spike

- Progress has been slow because:
  - Simulations take ~1 month to run
  - Numerical instabilities often occur
  - These were among the first simulations with an impurity fluid in JOREK

- In early 2019, simulations displaying a ‘realistic’ I_p spike were obtained…
  - Presented at the Princeton TSDW 2019

- …However, a bug was later discovered which caused an over-estimation of the radiated power
  - After solving the bug, the I_p spike got strongly reduced

- Changing a number of things in the input parameters (position of gas deposition, viscosity, …), the I_p spike came back
  - Present at the REM 2020

- Moving from a temperature-dependent viscosity model ($\mu \sim T^{-3/2}$), which did not seem realistic, to a temperature-independent one… the I_p spike disappeared again!

What's the matter with the I_p spike?

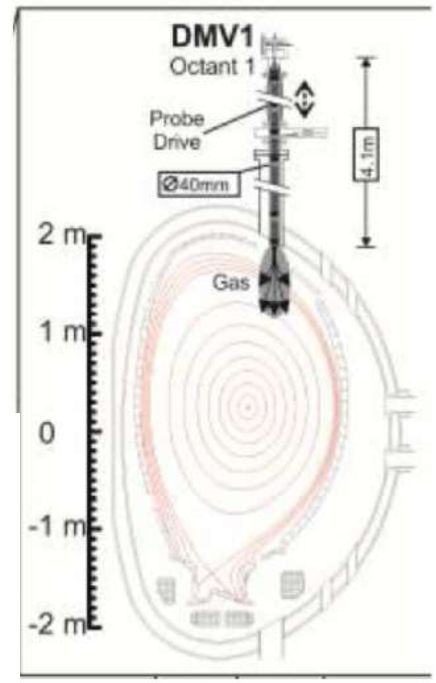
- The presence of a large I_p spike seemed related to strong MHD activity in the very core
  - Stochasticity all the way to the centre not sufficient

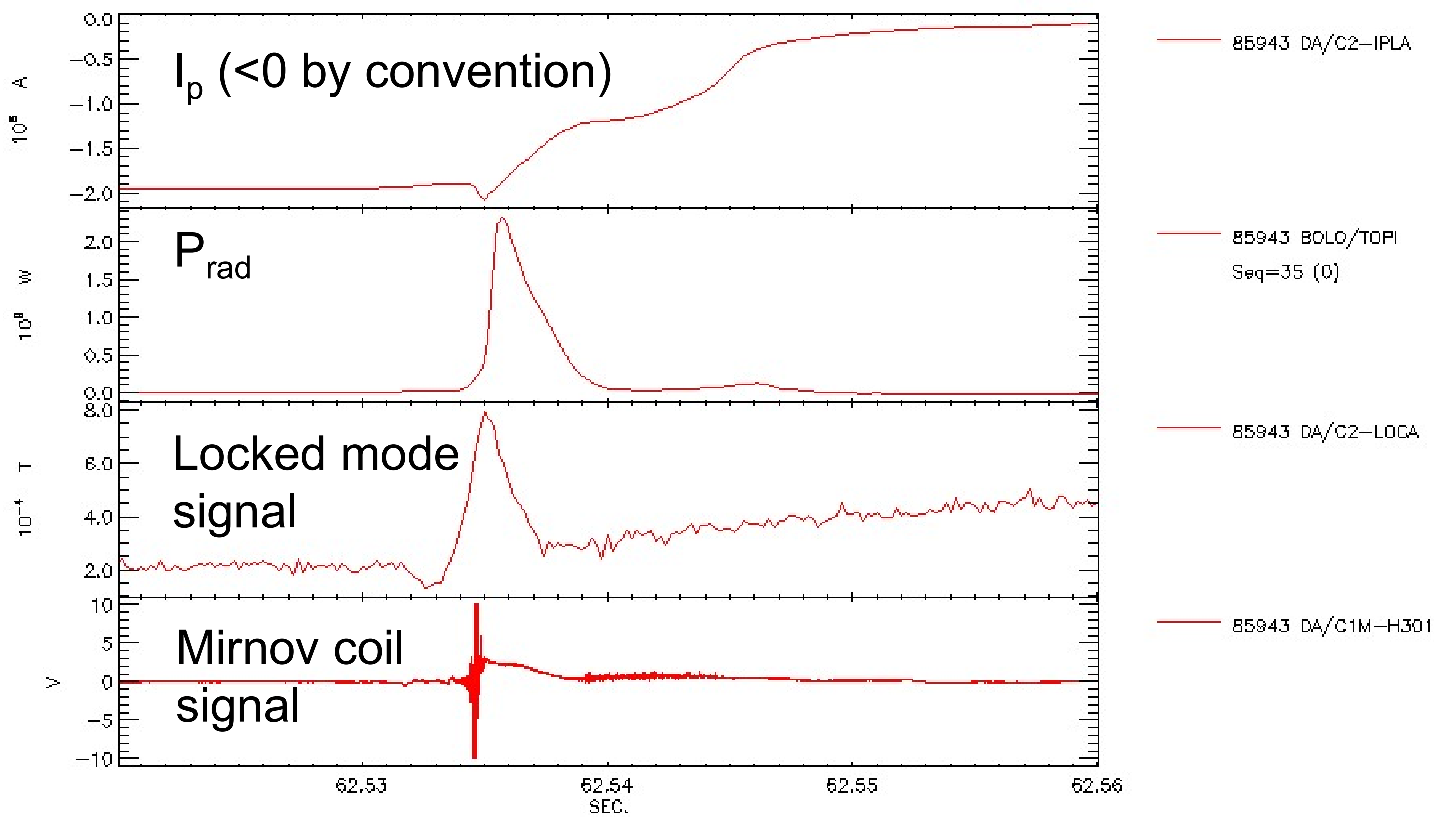
- Recent simulations suggest that what makes the difference is a strong enough radiative cooling inside the 2/1 island
  - Method: scan the amount of impurities deposited in the 2/1 island
  - Will show examples next

- Mechanism:
  - Radiative collapse → current decay → resonant δB → further island growth
    - 'Rebut mechanism', invoked to explain density limit disruptions [Gates PRL 2012]
  - Things get more complicated when the island gets destroyed by magnetic stochasticity (which happens typically at the end of the pre-TQ phase):
    - Parallel heat conduction brings in heat
    - Shear Alfvén wave propagation brings in current

Simulated pulse: JET #85943

- Ohmic, 2 MA, 3 T, T_{e0}=3.3 keV, n_{e0}=2.1x10^{19} m^{-3}
- Pure Ar MGI from Disruption Mitigation Valve (DMV1) at 33 bar into a healthy plasma
- Produces a RE beam (~1 MA)
- Part of a set of 3 pulses with a shot-to-shot B_t scan





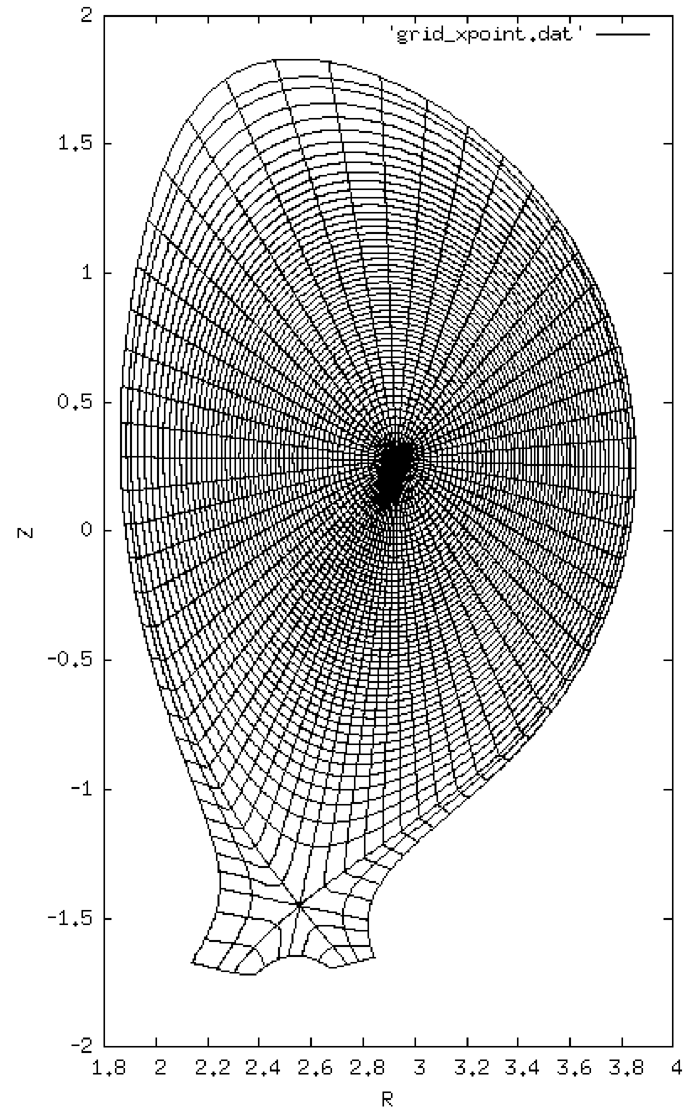
Model details and input parameters

- Argon injection:
  - Argon gas dynamics not described by the model
    - Argon transport = diffusion + convection at plasma velocity

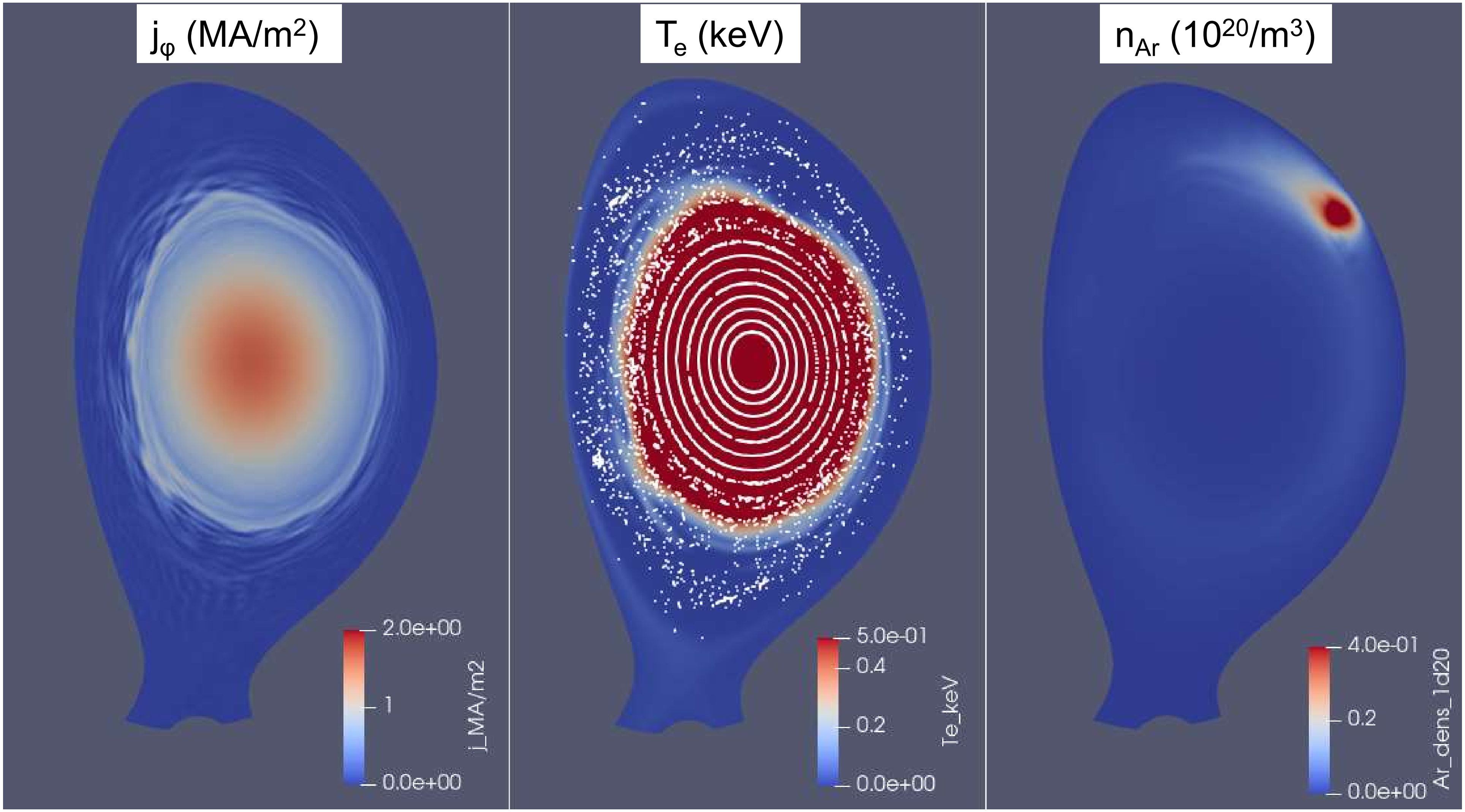
  → Argon injection rate adjusted to match n_{el} from interferometry
  - Argon deposition at the top, in the SOL for the early part of the simulation
  - Then, in some sims., moved into 2/1 island once cold front has reached q=2
    - Justification: recombination in cooled region allows gas to penetrate
  - Source extension: 8 cm poloidally and 2 radians toroidally

- Resistivity: Spitzer with a saturation above 700 eV
  - Ohmic heating on
- Perpendicular viscosity: 'turbulent' (3 m^2/s)
- Parallel hyper-viscosity: very large, to damp parallel flow
- Parallel heat conductivity: Spitzer-Härm
- Perpendicular heat conductivity: 'turbulent' (2 m^2/s)
- Particle perpendicular diffusivity: much larger than 'turbulent' (30 m^2/s)
  - No // diffusion

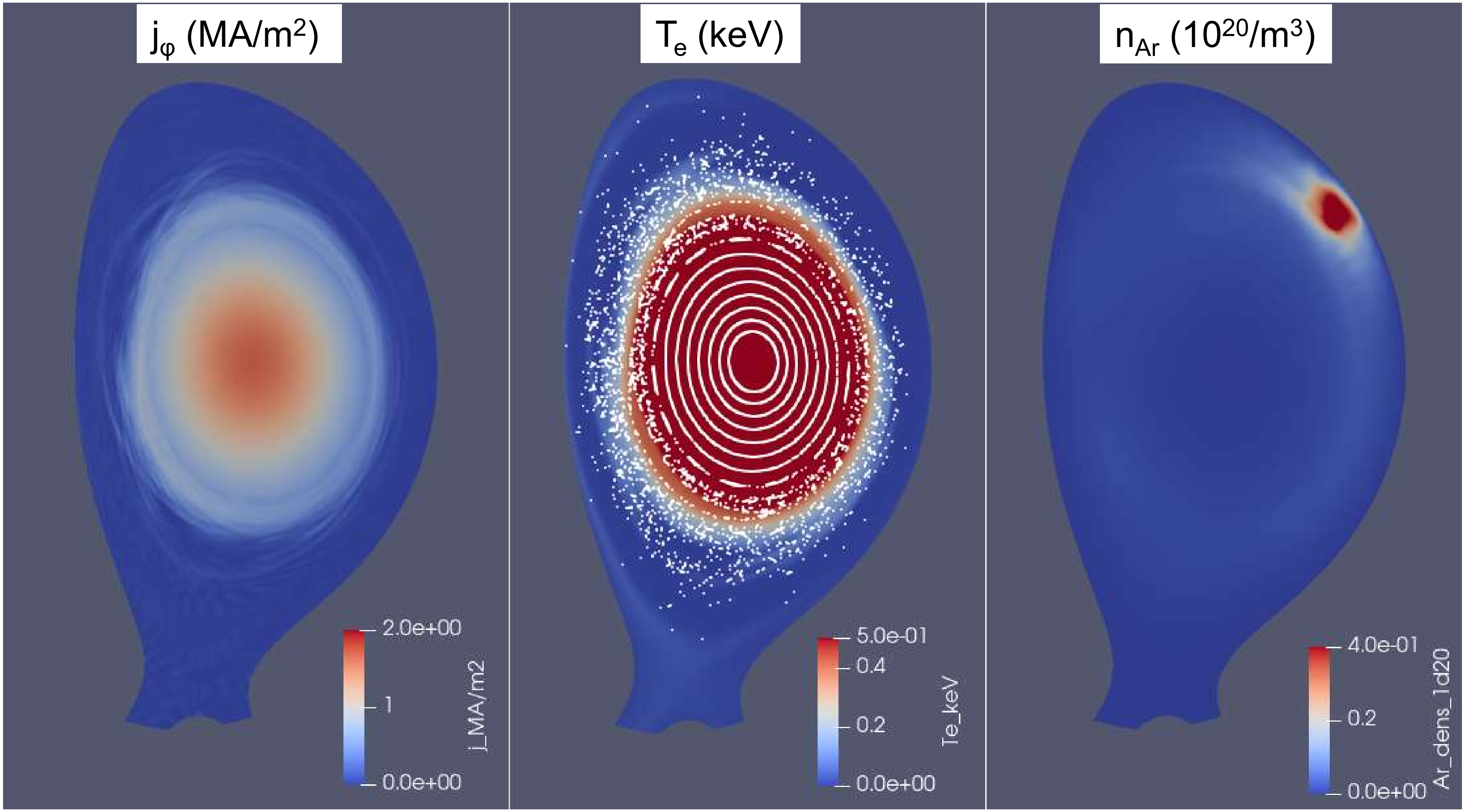
- Flux-surface-aligned poloidal grid
  - Moderate resolution: ~50 (radial) x 60 (poloidal) elements
- Toroidal discretization uses Fourier harmonics
  - n from 0 to 10
- Resistive wall
  - Should be rather realistic, although not checked in detail to what degree



Simulation in which the argon source is left in the SOL



DI_501_JET85943_R3P5Z1P1_N5_VISCO1EM6TDEPFALSE_RST2500_N10



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0.0e+00
j_MA/m2
T_e (keV)
5.0e-01
0.4
0.2
0.0e+00
Te_keV
n_{Ar} (10^{20}/m^3)
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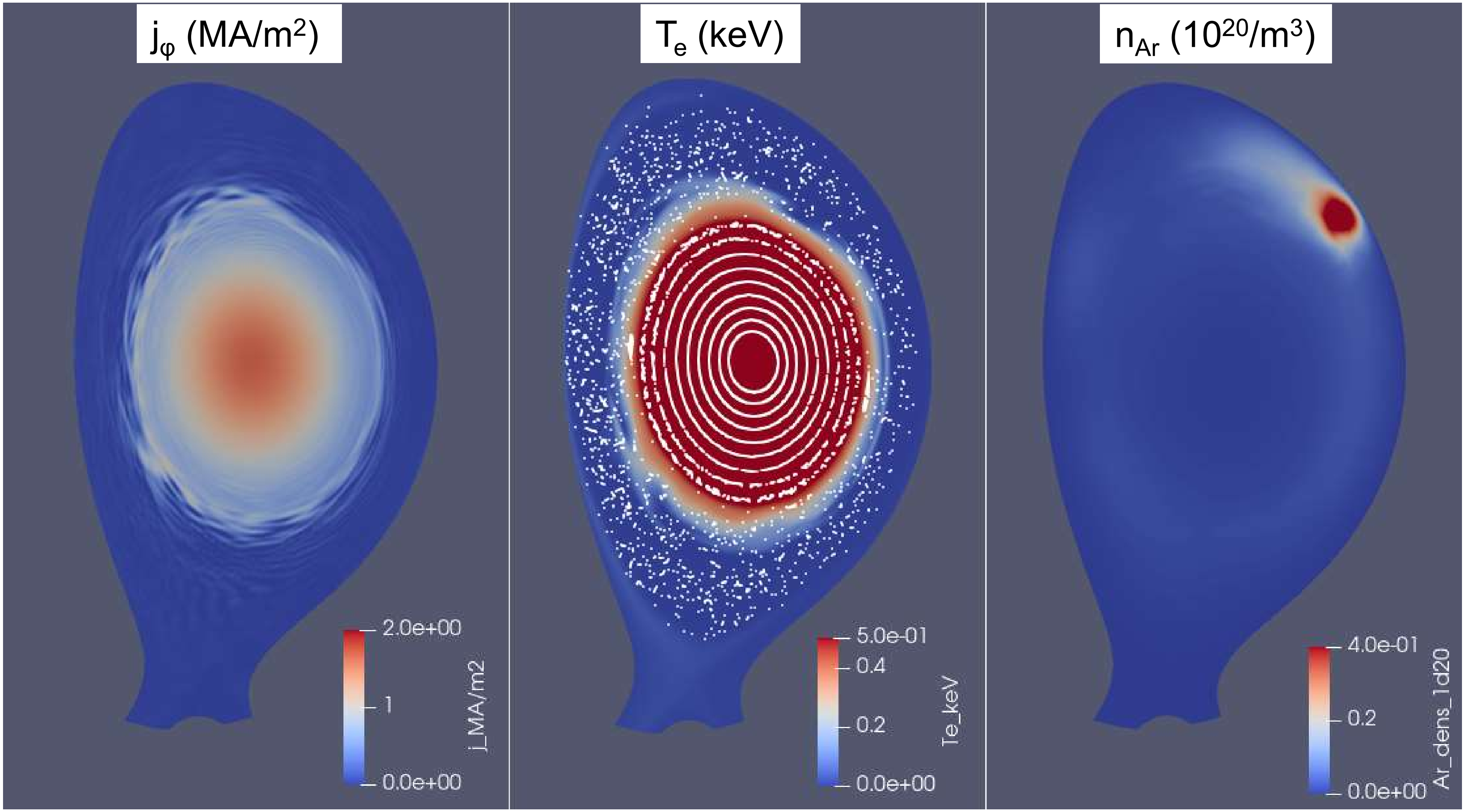
0.2
0.0e+00
Ar_dens_1d20



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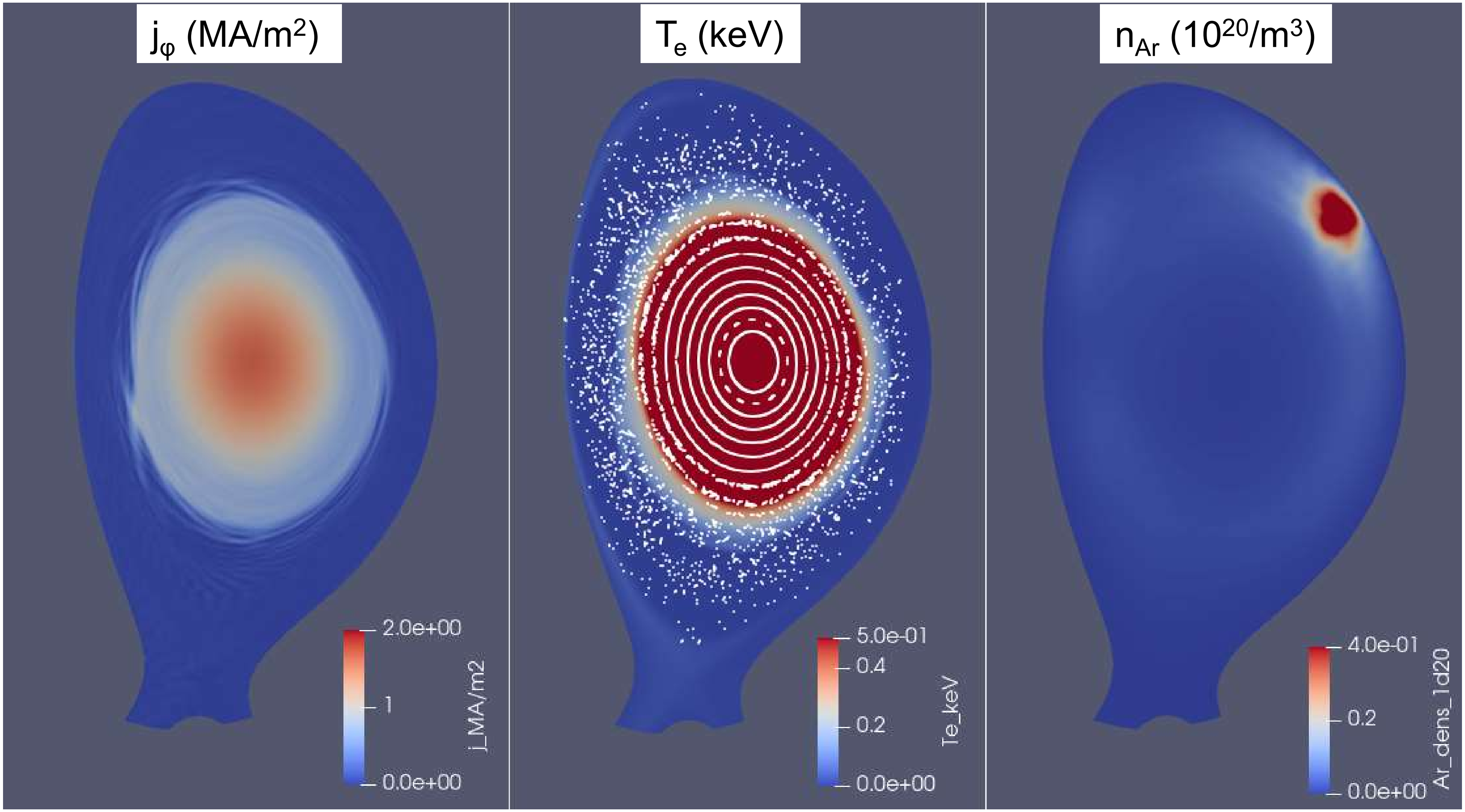

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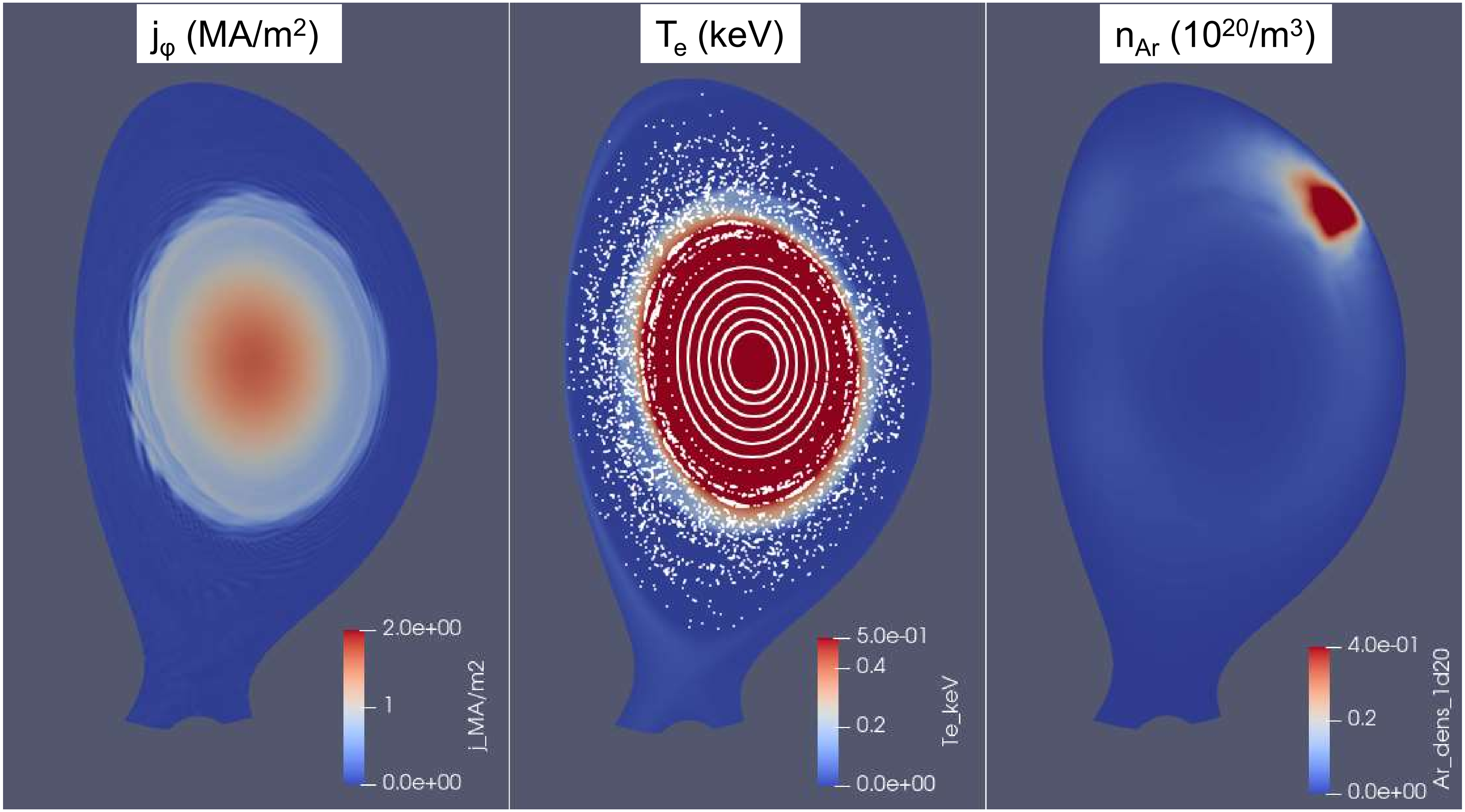

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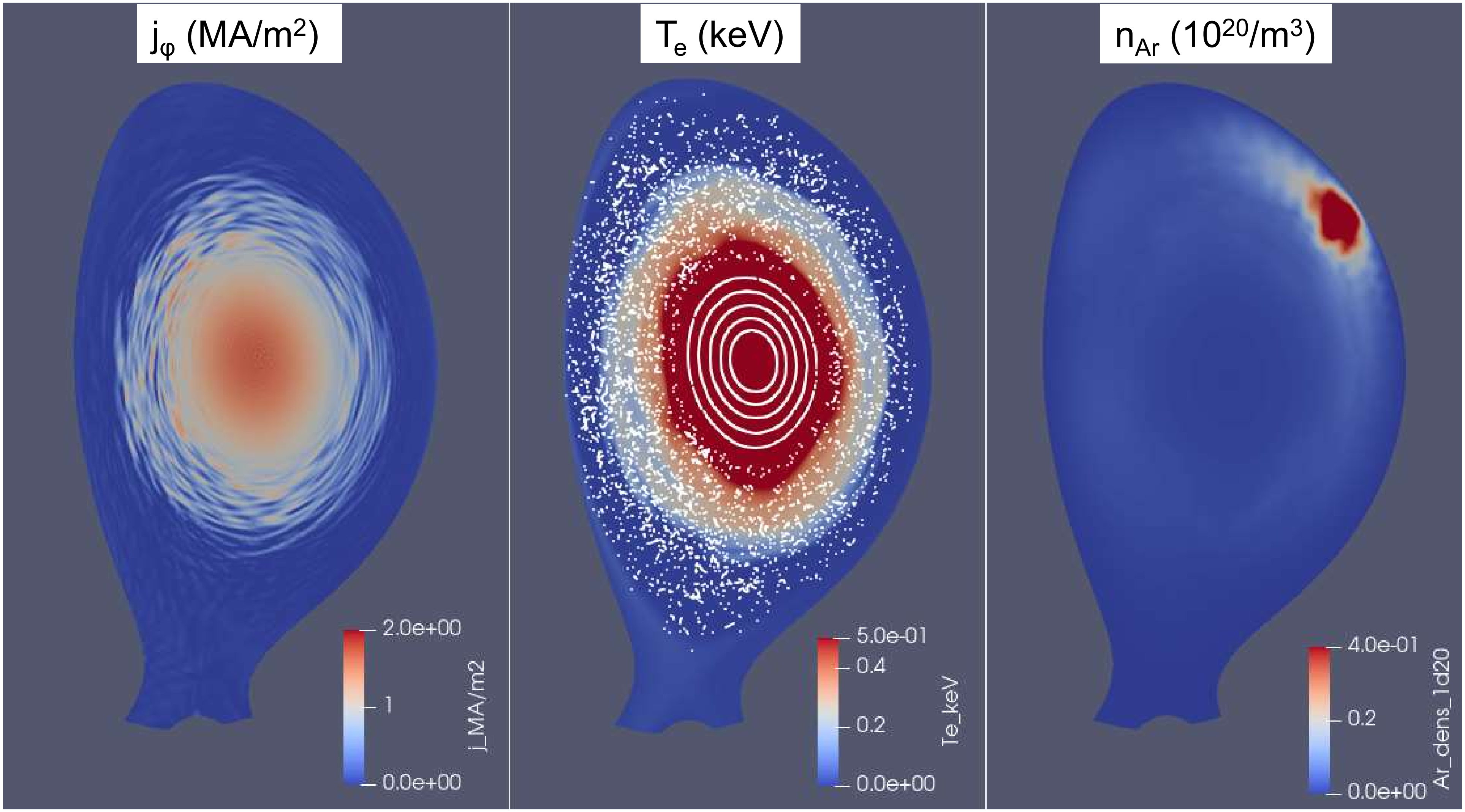

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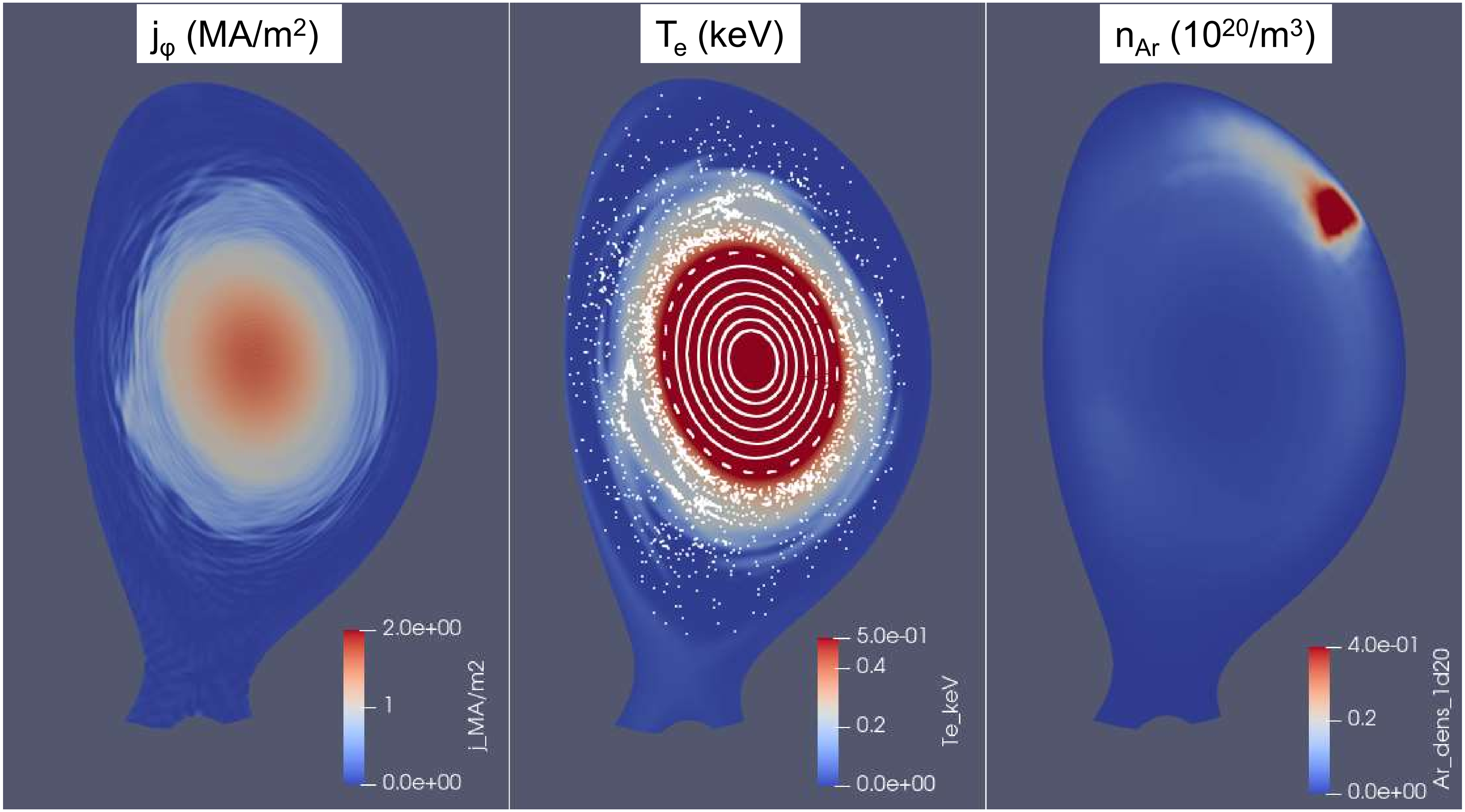

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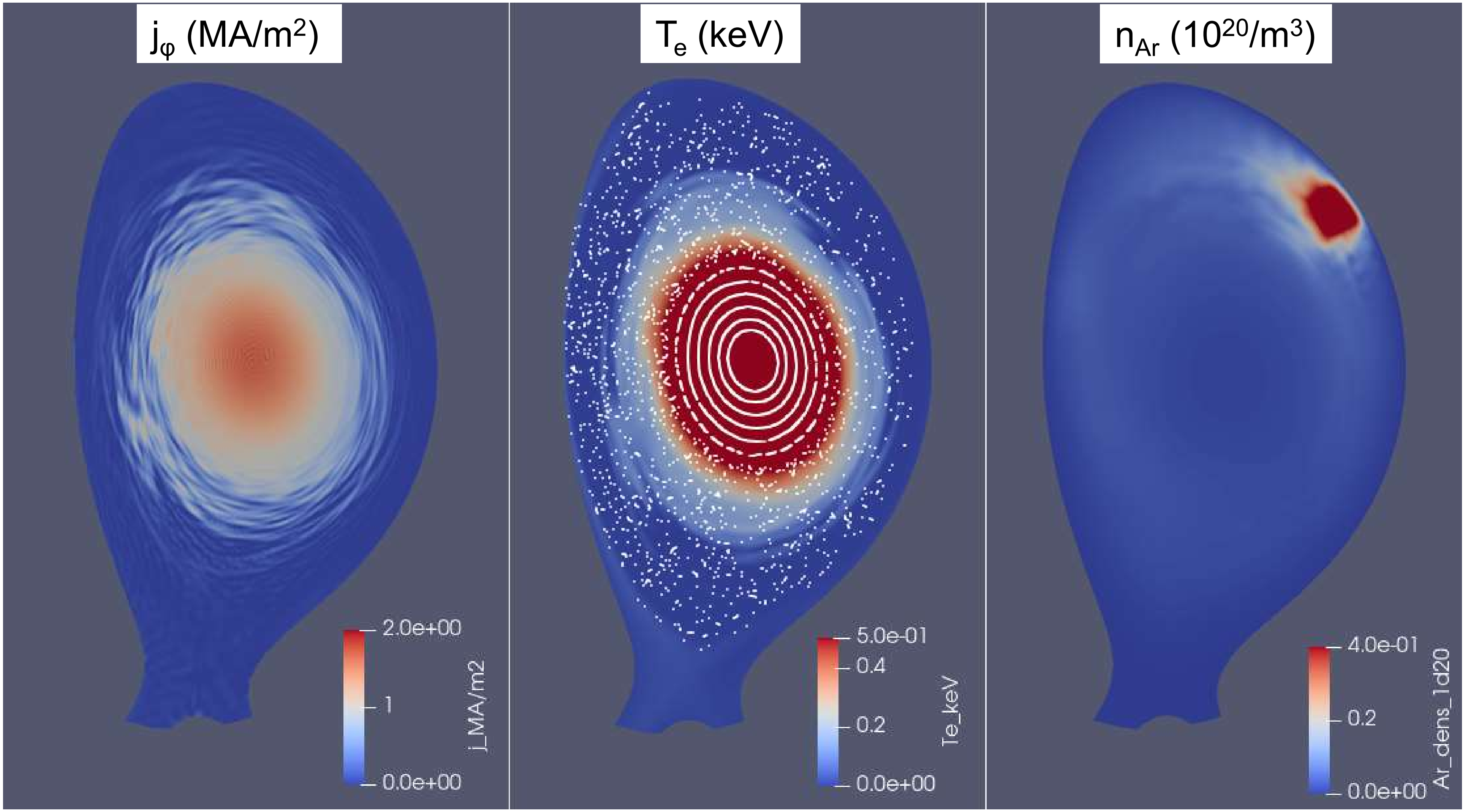
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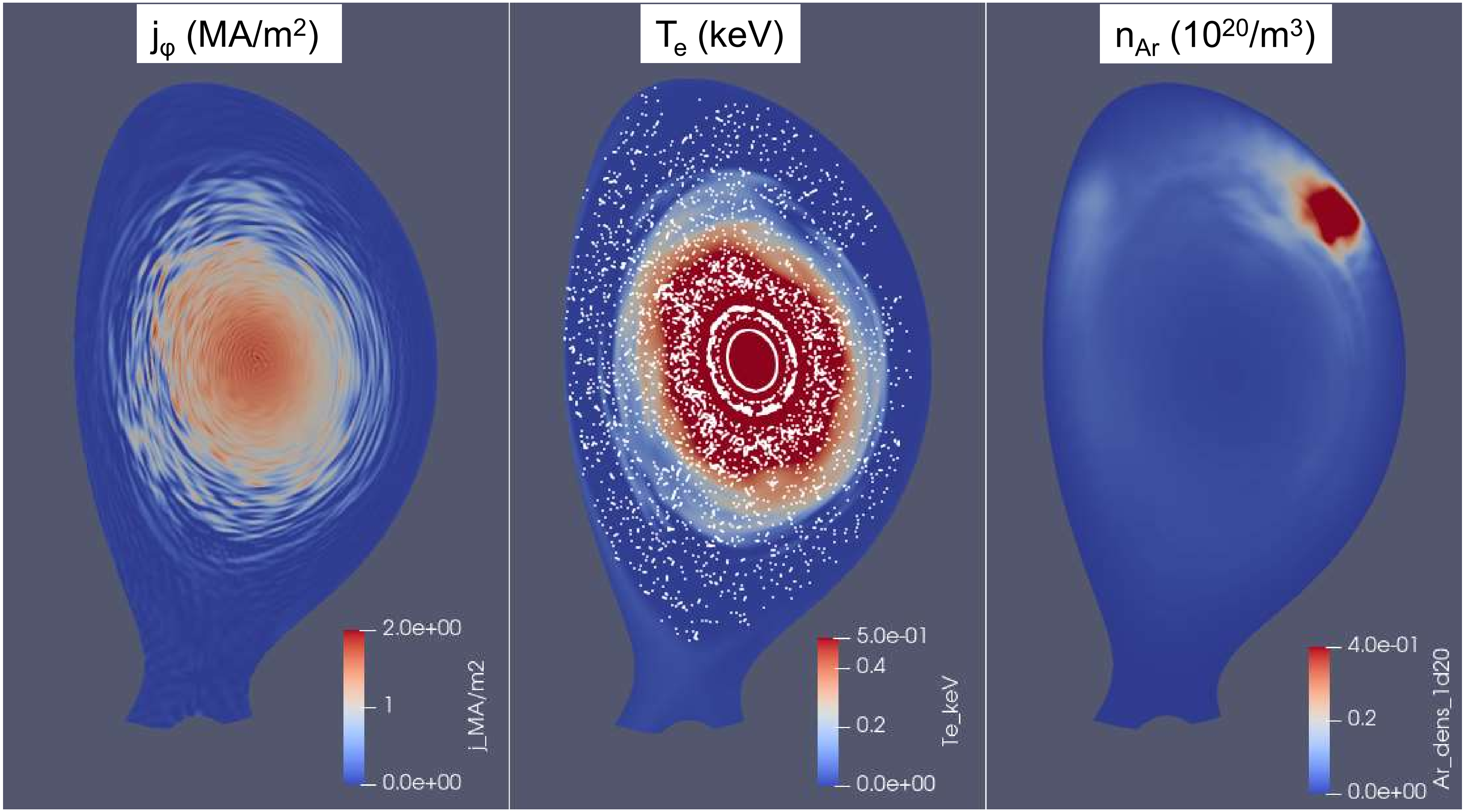

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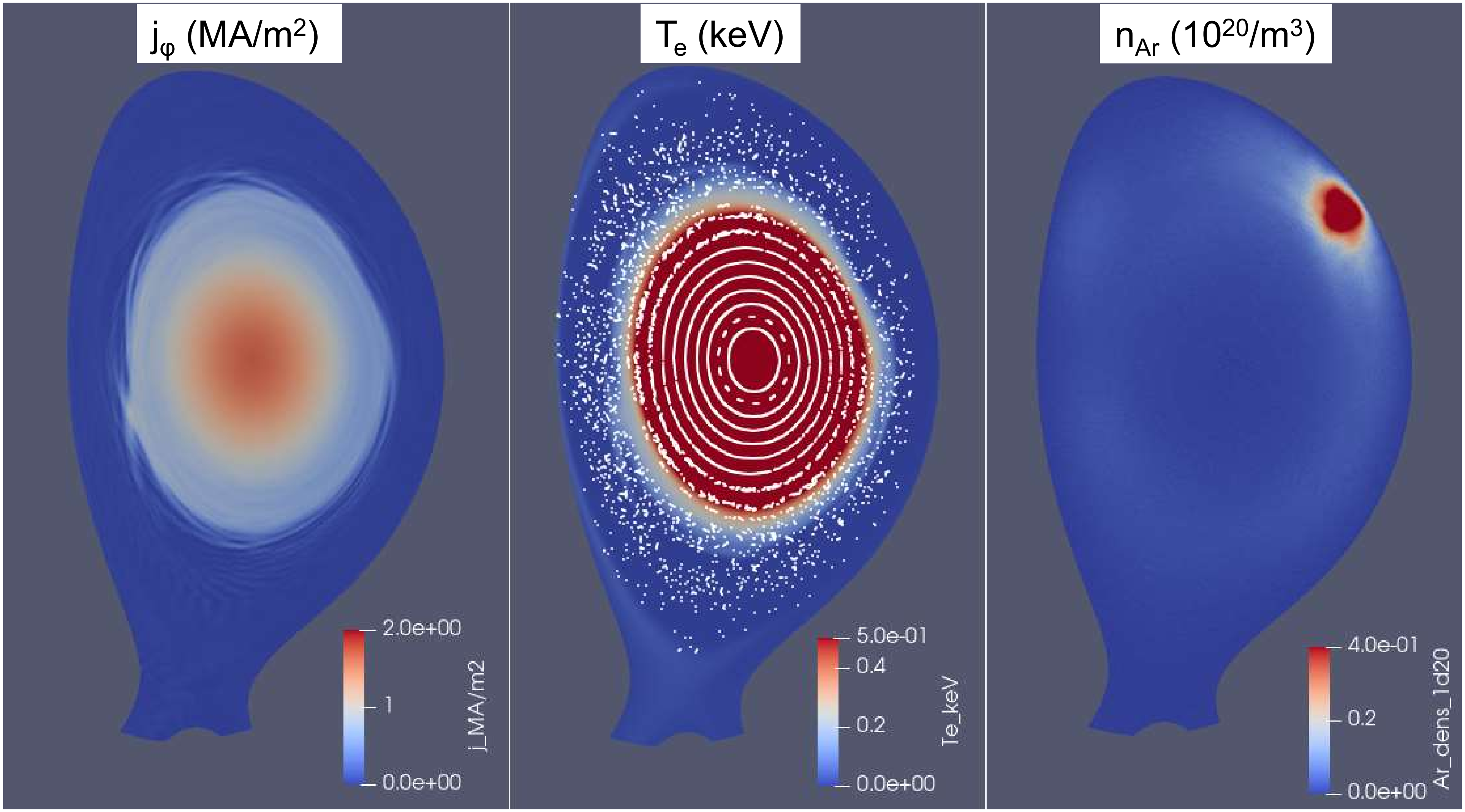
Ar_dens_1d20

Simulation in which the argon source is moved into the 2/1 'island' once the cold front has reached q=2



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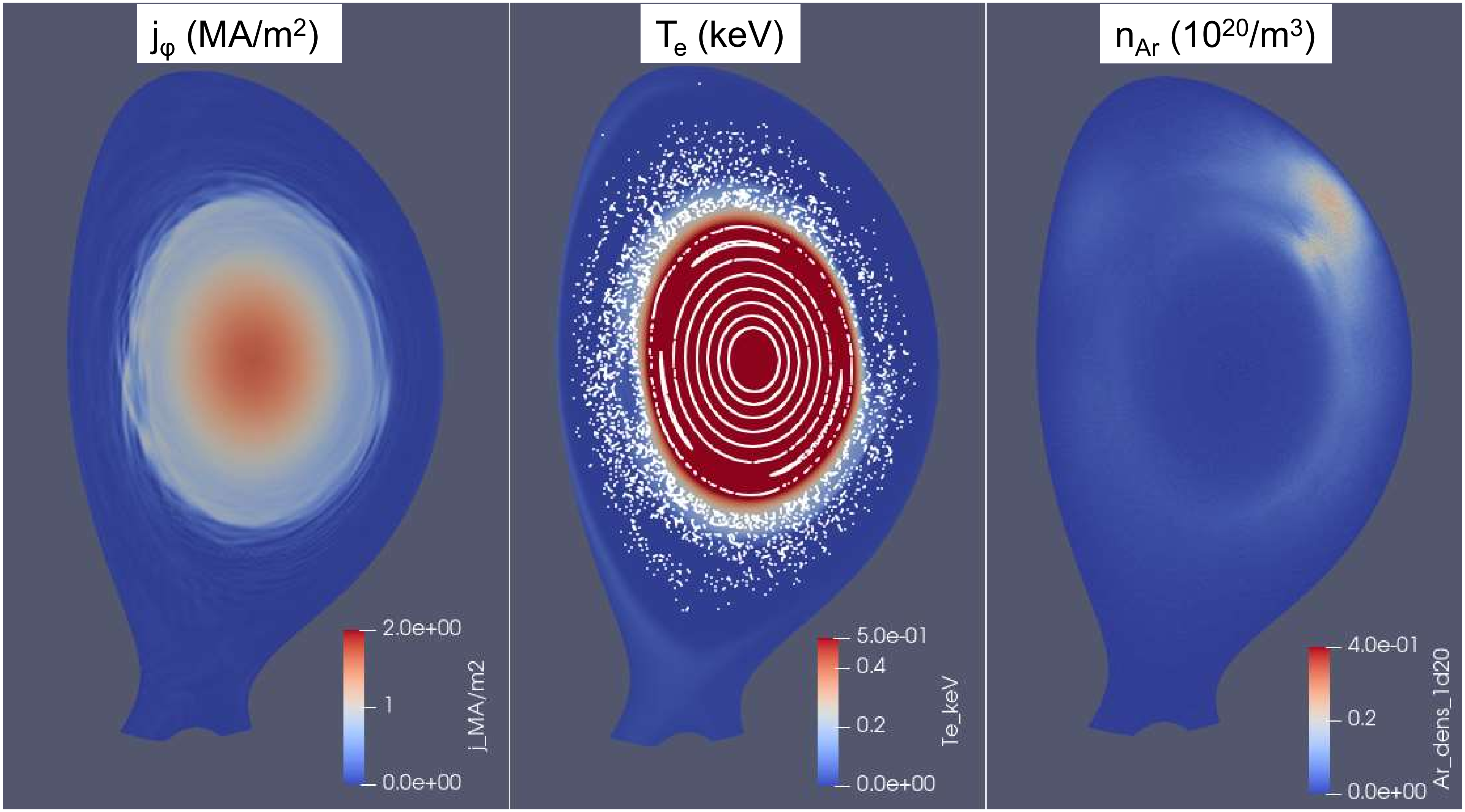

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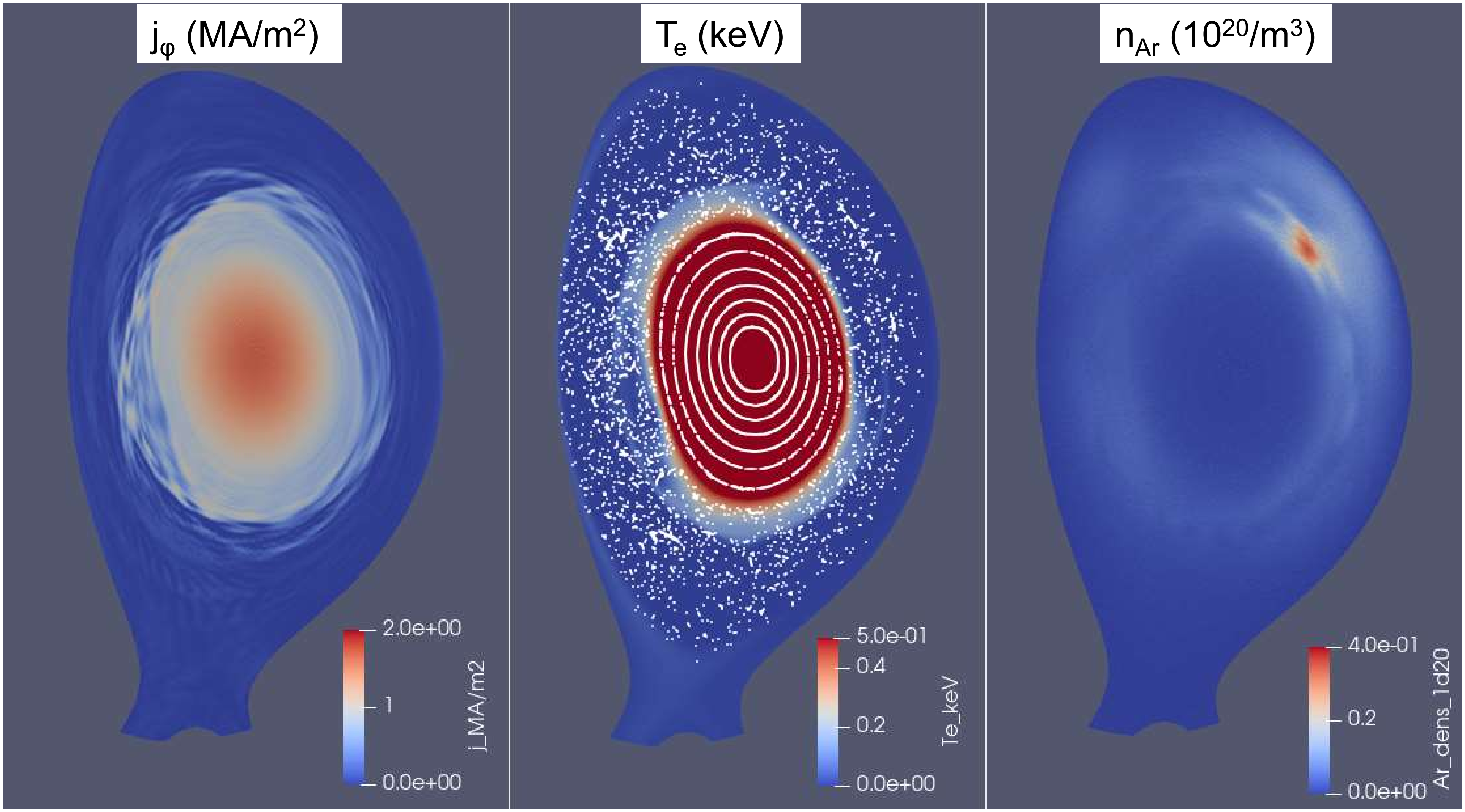
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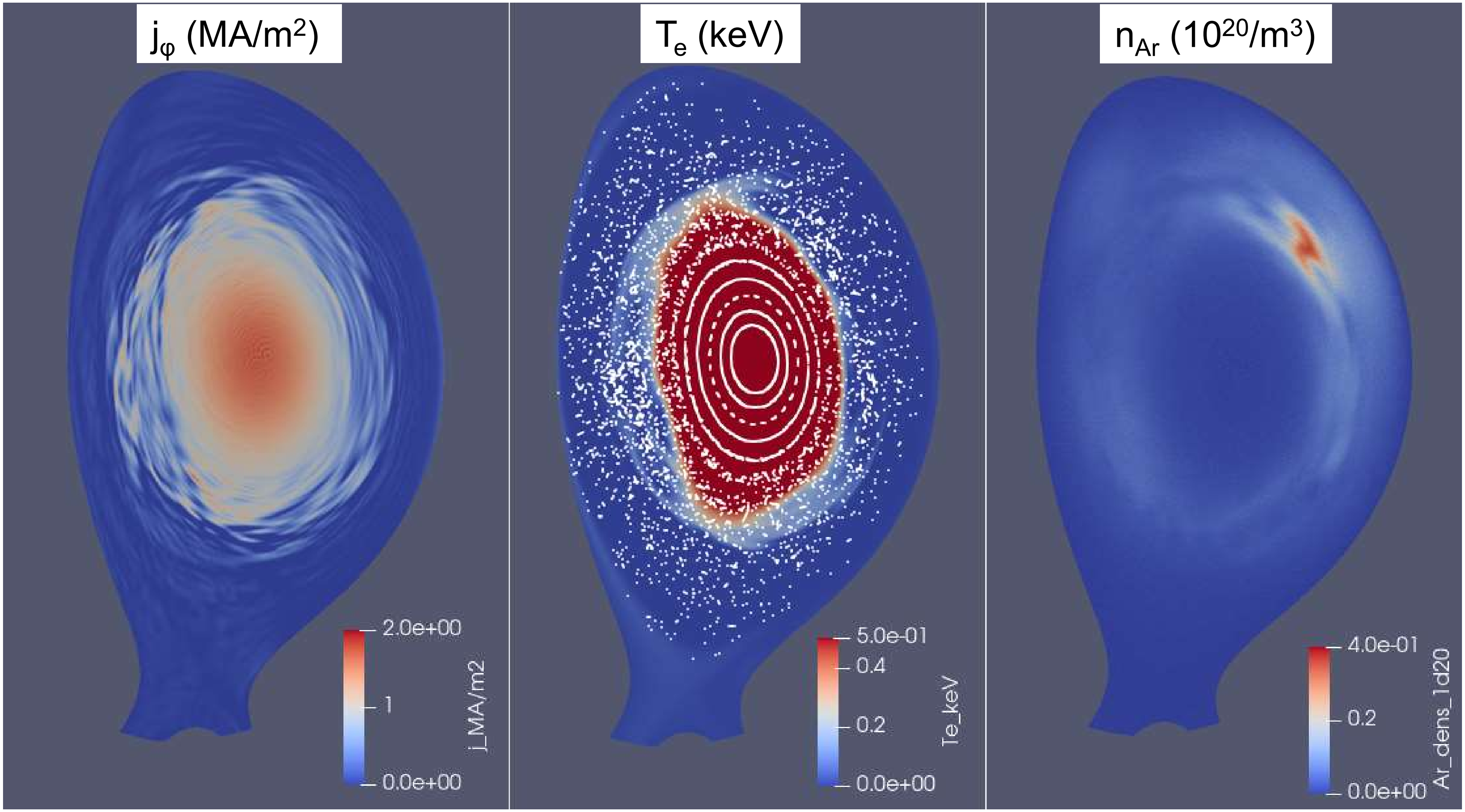

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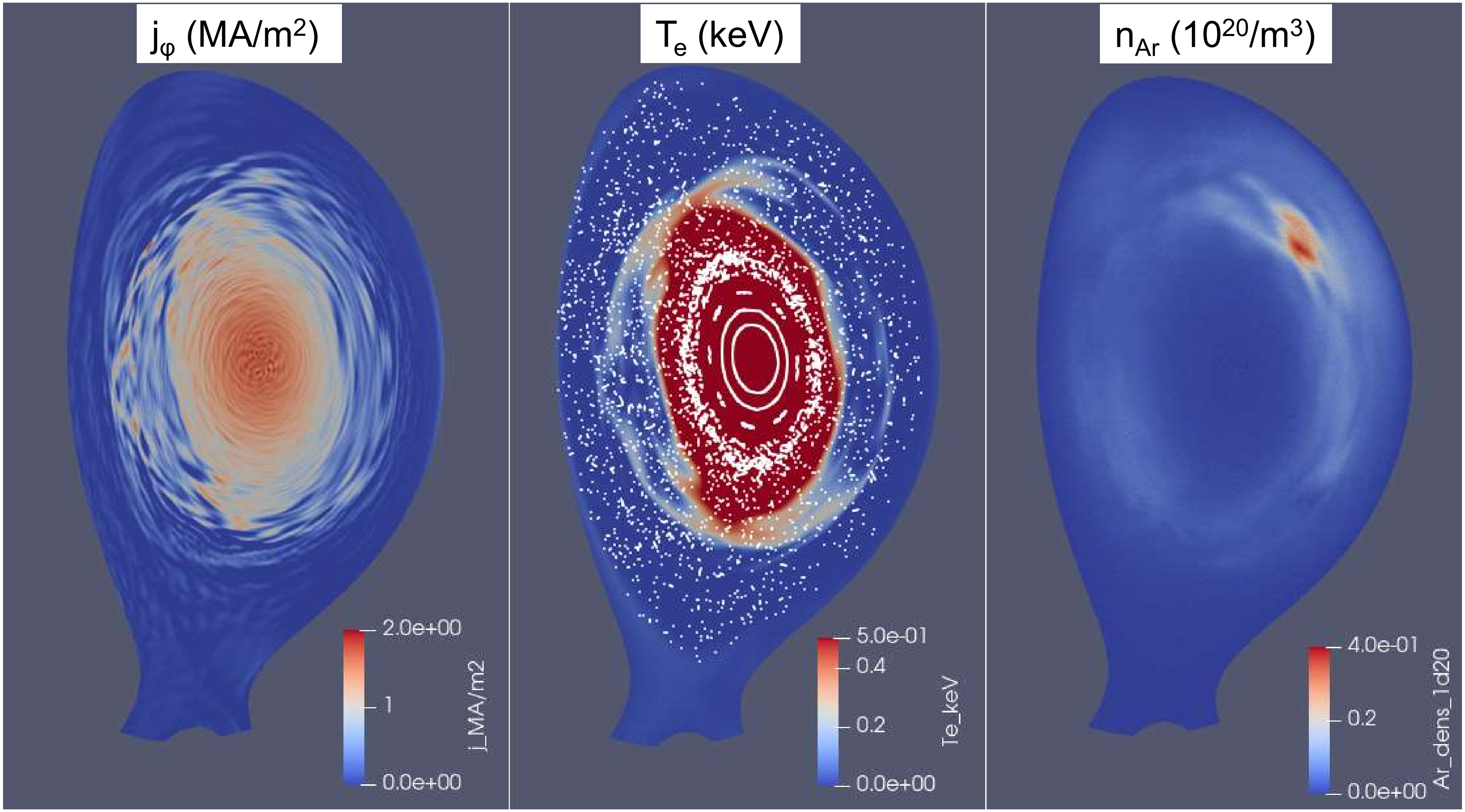
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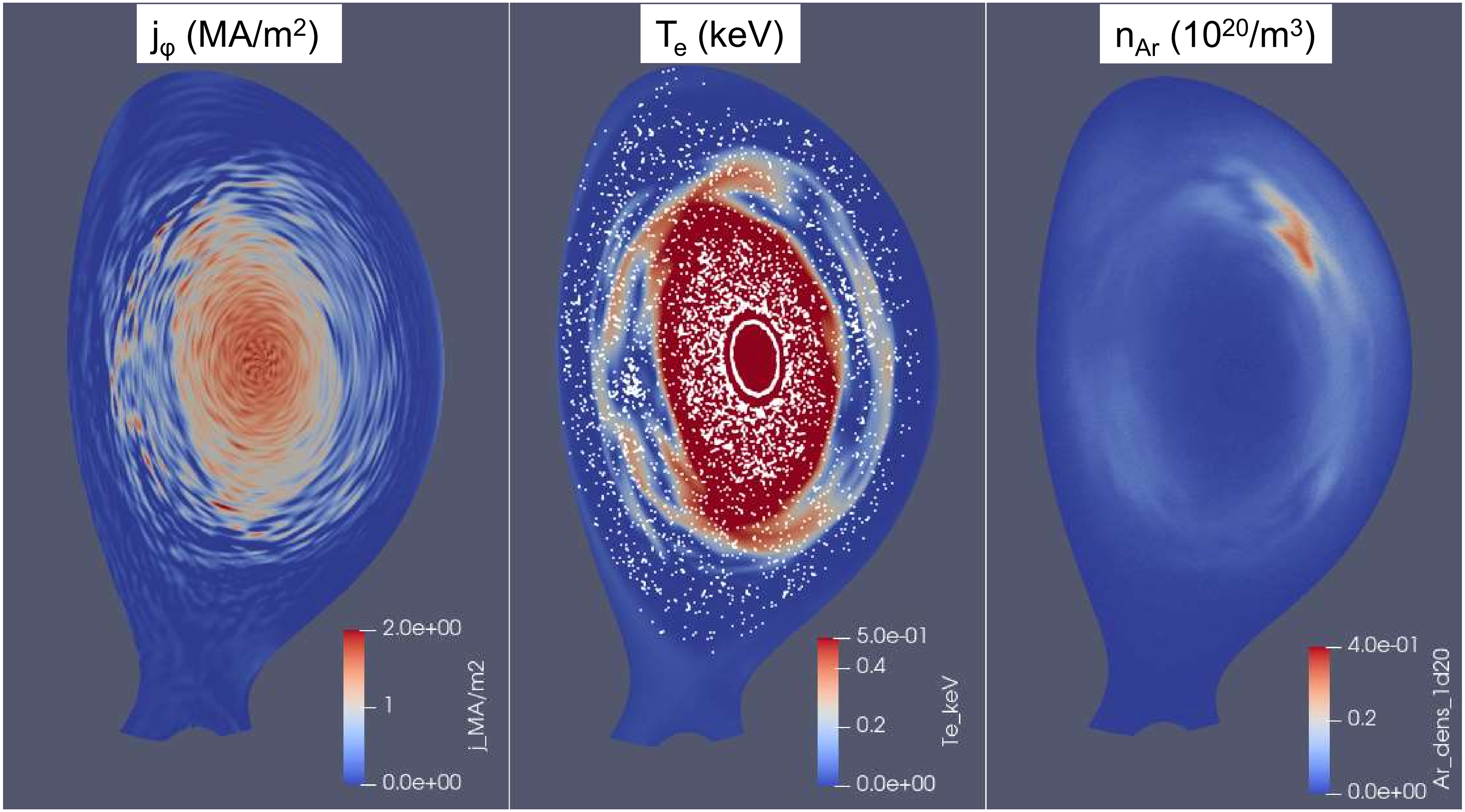
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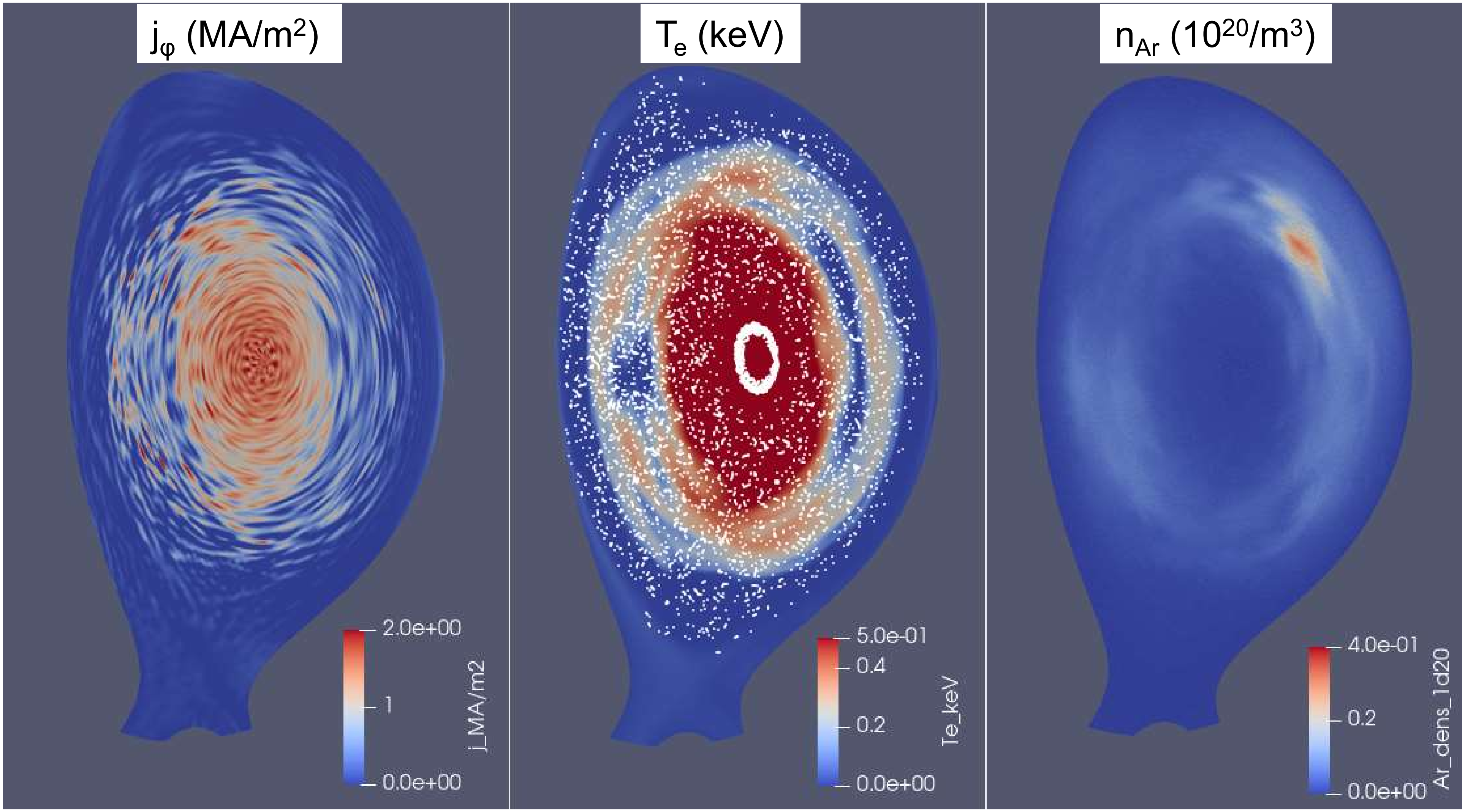

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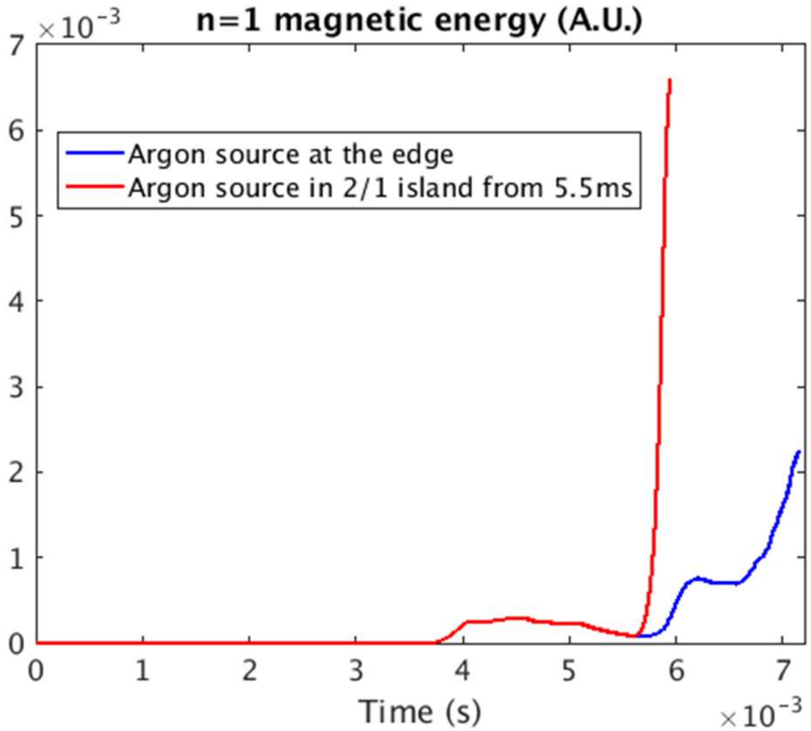
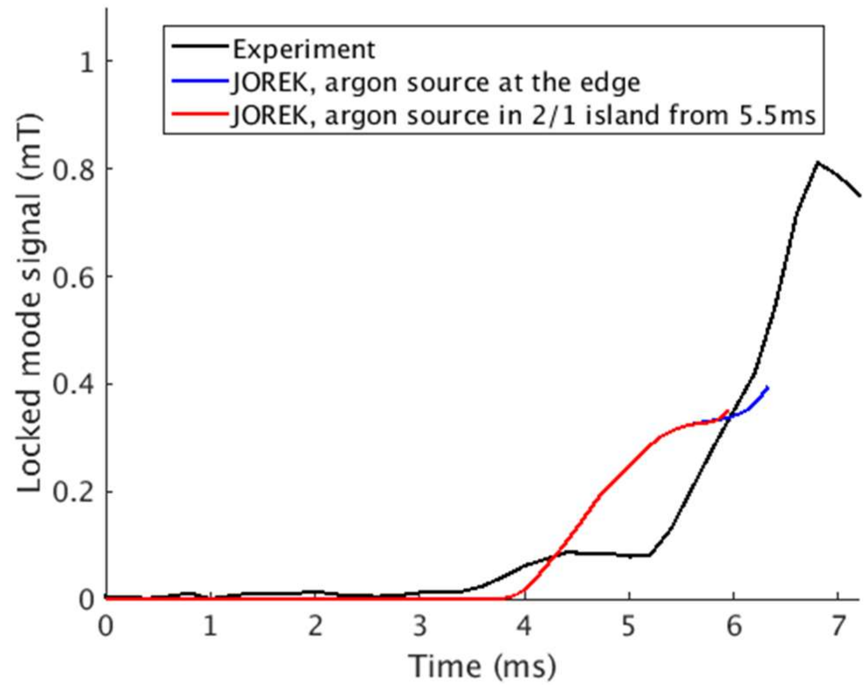
Te_keV
n_{Ar} (10^{20}/m^3)
4.0e-01
0.2
0.0e+00
Ar_dens_1d20

So, which simulation is most realistic?

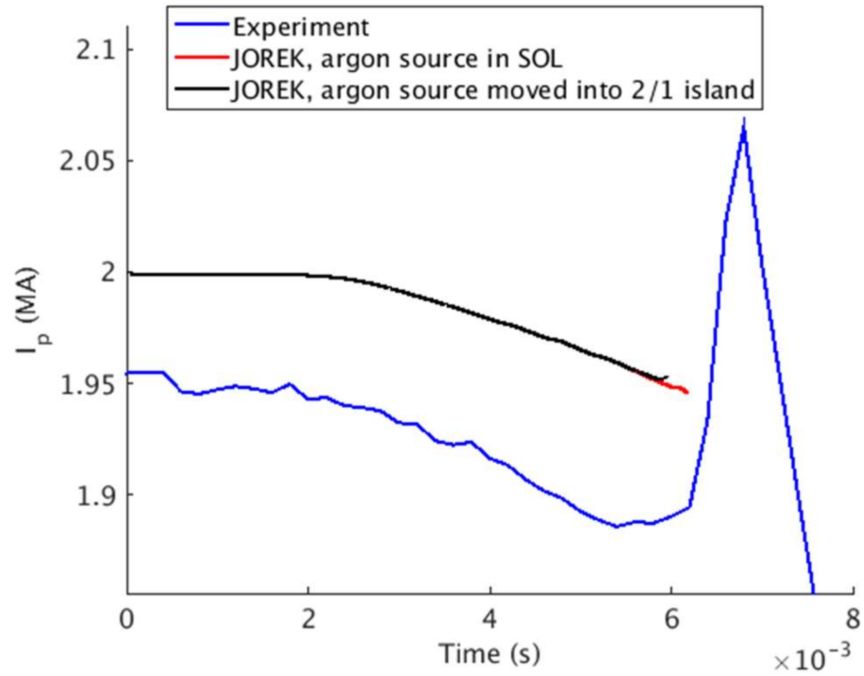
- Massive difference in n=1 mode growth…



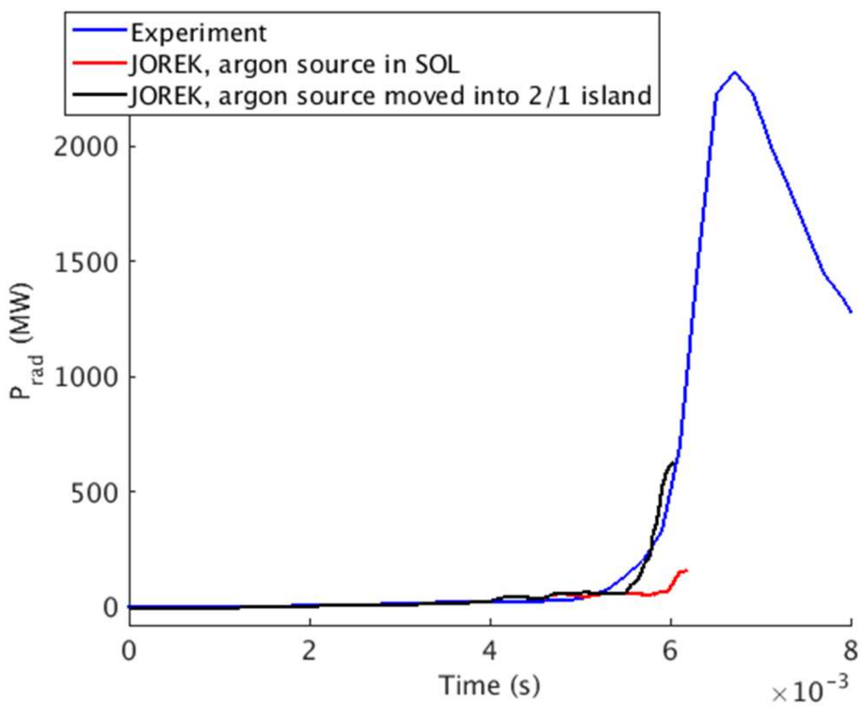
- But not (immediately) visible on the locked mode signal
  - Likely reason: dynamics faster than wall penetration time



- Cannot discriminate based on I_p spike in this case due to numerical issues
  - However, one can see the very beginning of an I_p spike in the second simulation



- The radiated power is the clearest sign that the 2nd simulation is more realistic

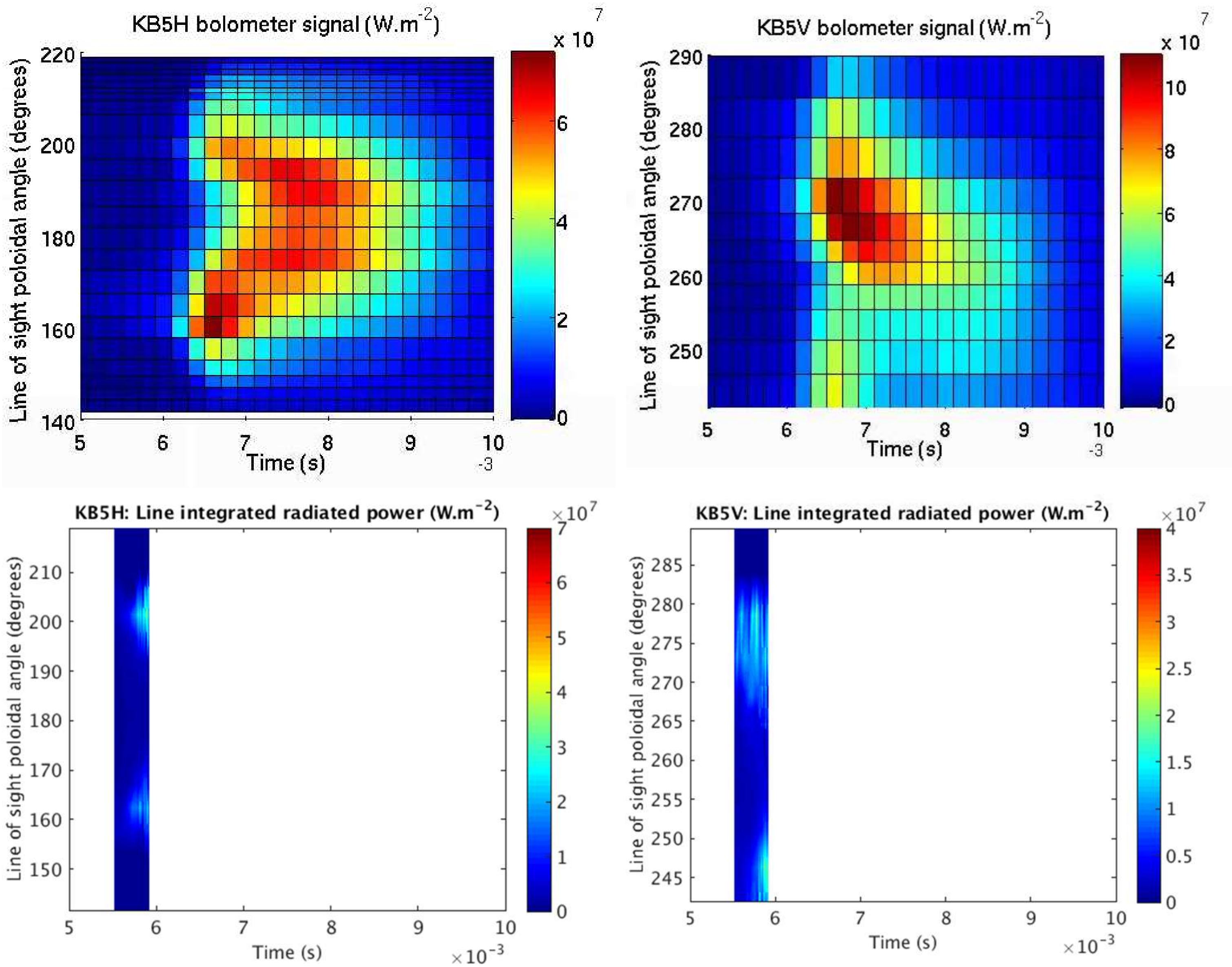


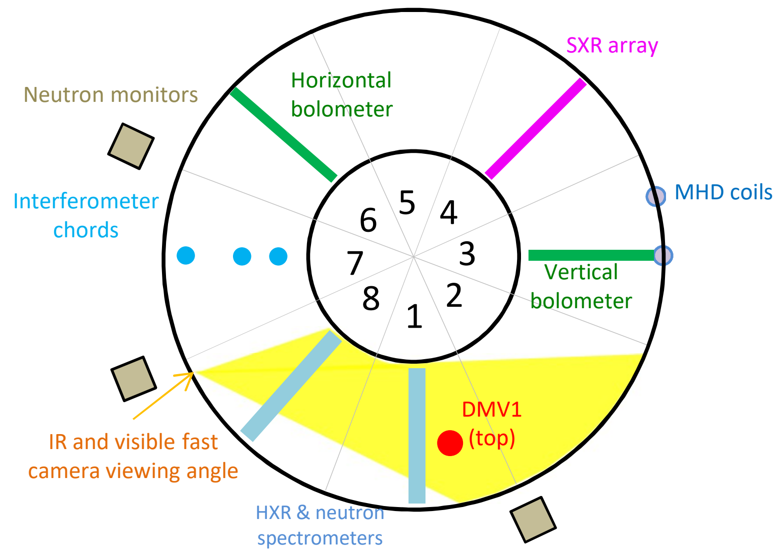
- Note that the spatial distribution of the radiated power is consistent with measurements (→ confirms that radiation mainly localized in 2/1 'island' region)

Horizontal bolometer | Vertical bolometer

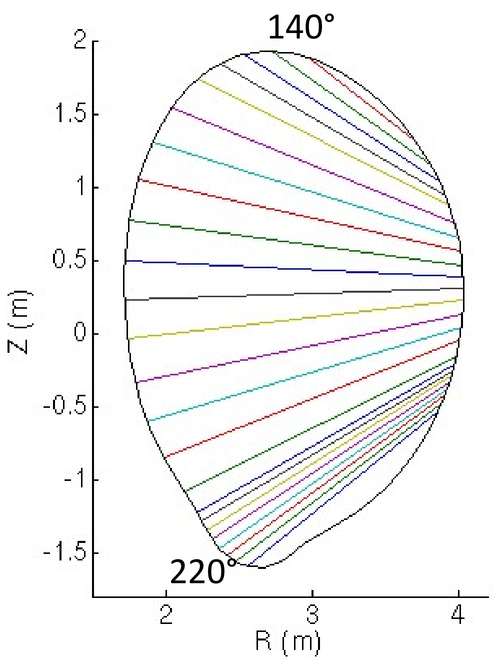
Experiment

JOREK

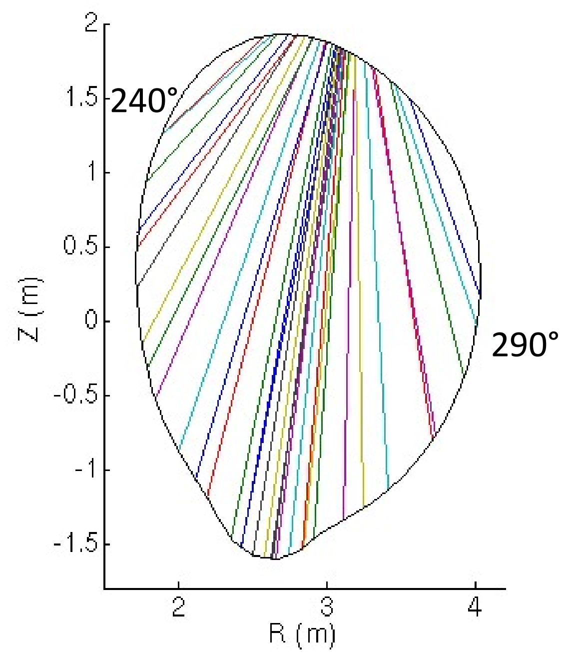




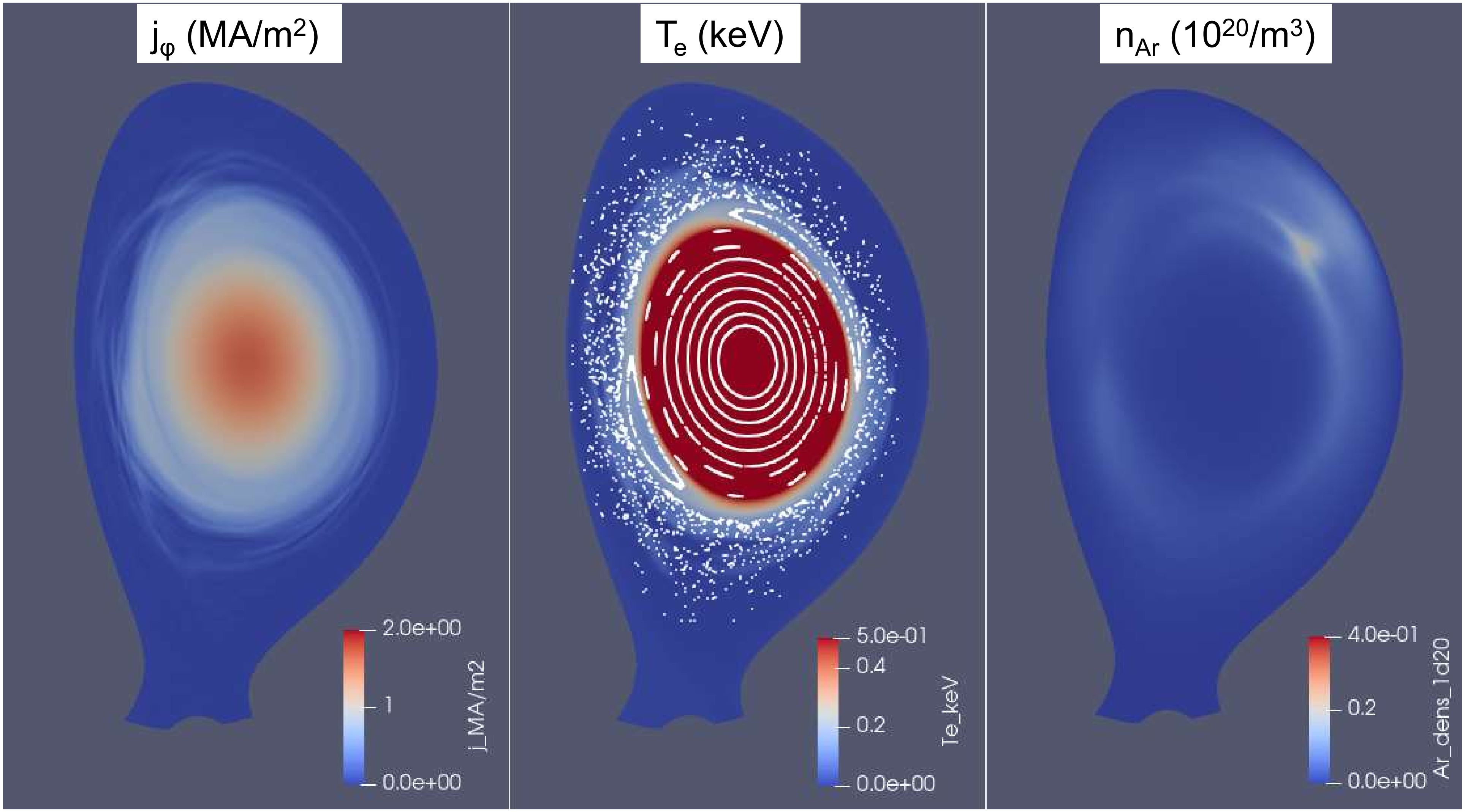
Horizontal bolometer lines



Vertical bolometer lines



Another simulation in which the argon source is moved into the 2/1 'island' (this one survives for longer)



5.26ms

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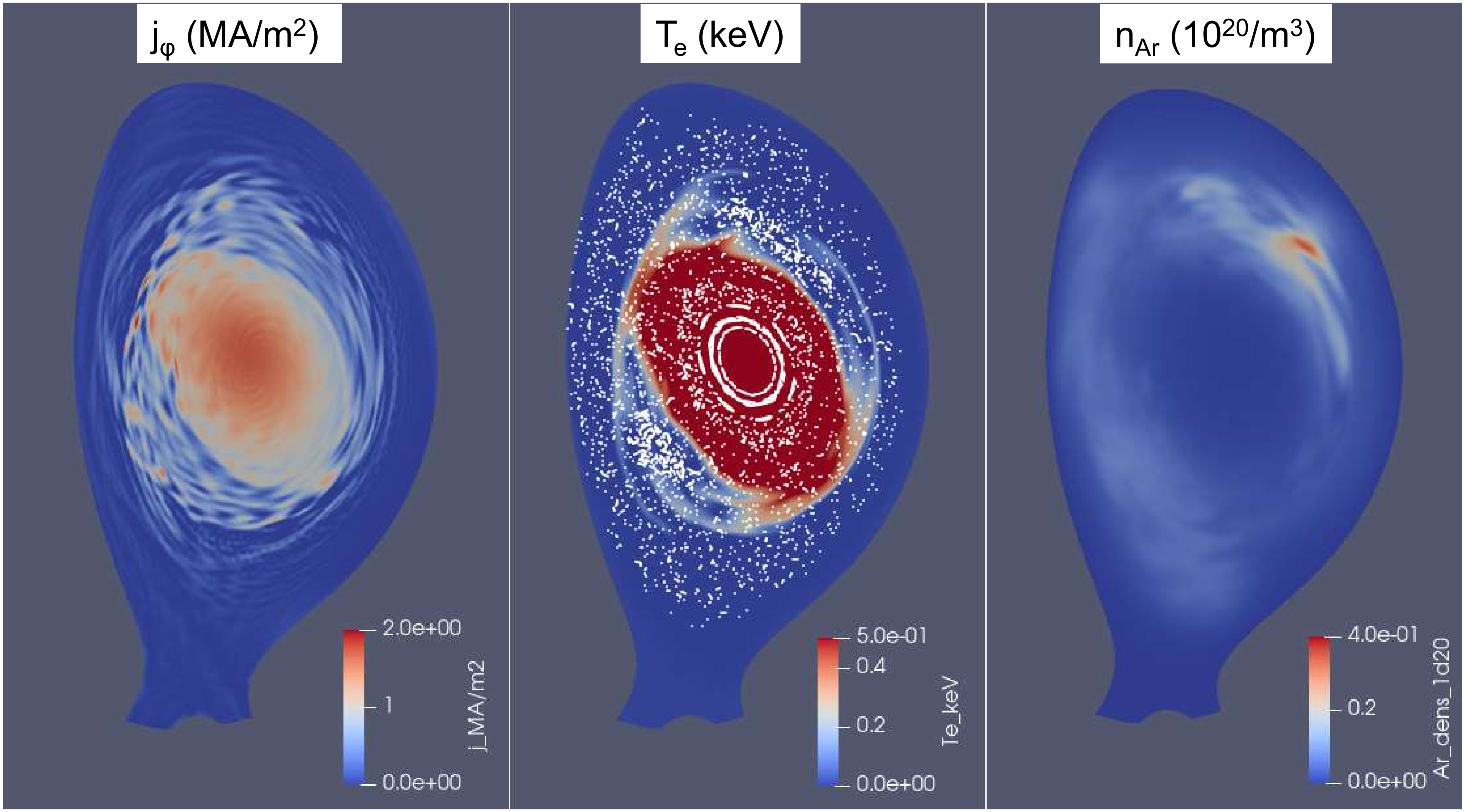
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T_e (keV)
n_{Ar} (10^{20}/m^3)
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0.0e+00
j_MA/m2
5.0e-01
0.4
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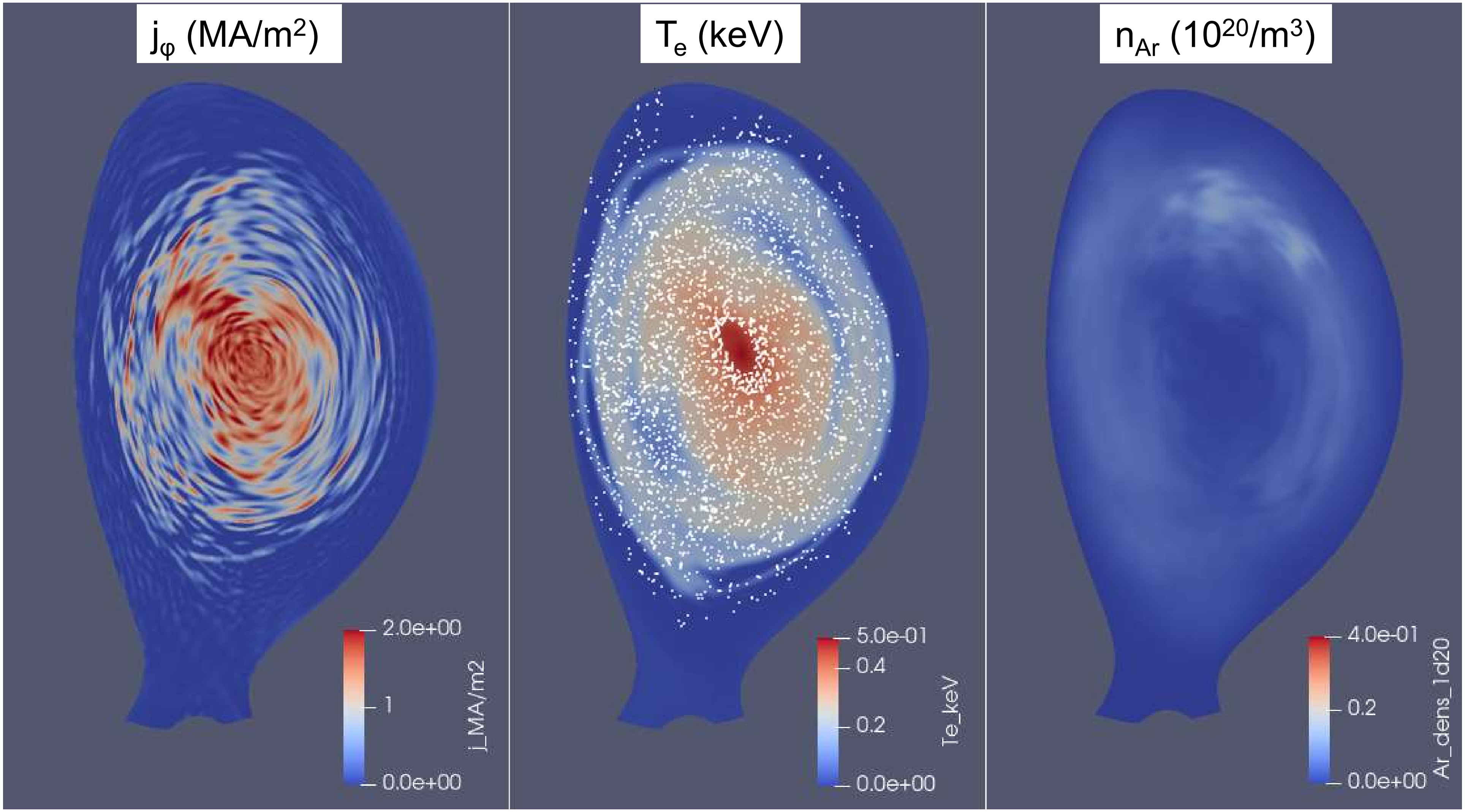
Te_keV
4.0e-01
0.2
0.0e+00
Ar_dens_1d20

5.62ms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T_e (keV)
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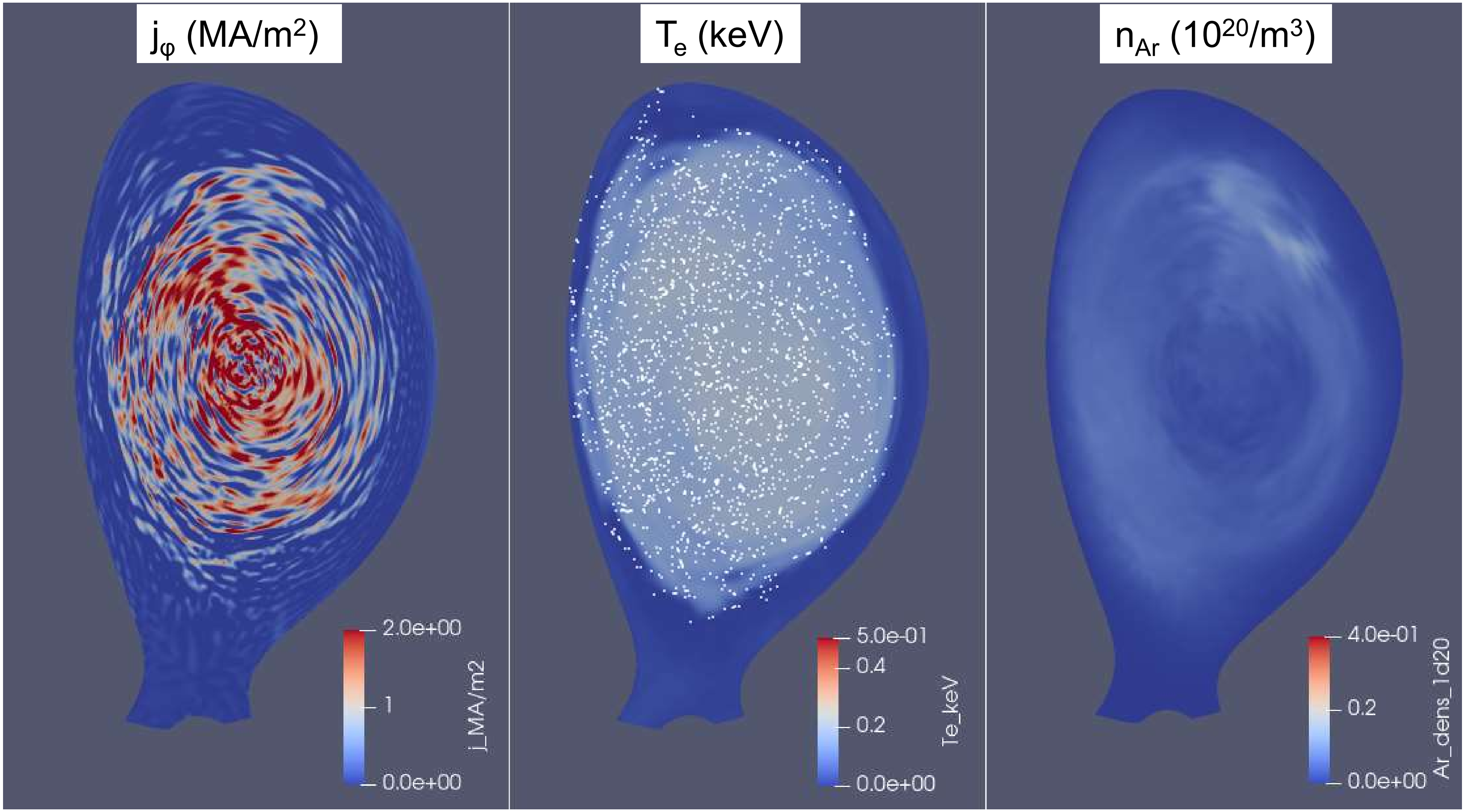
Ar_dens_1d20

5.78ms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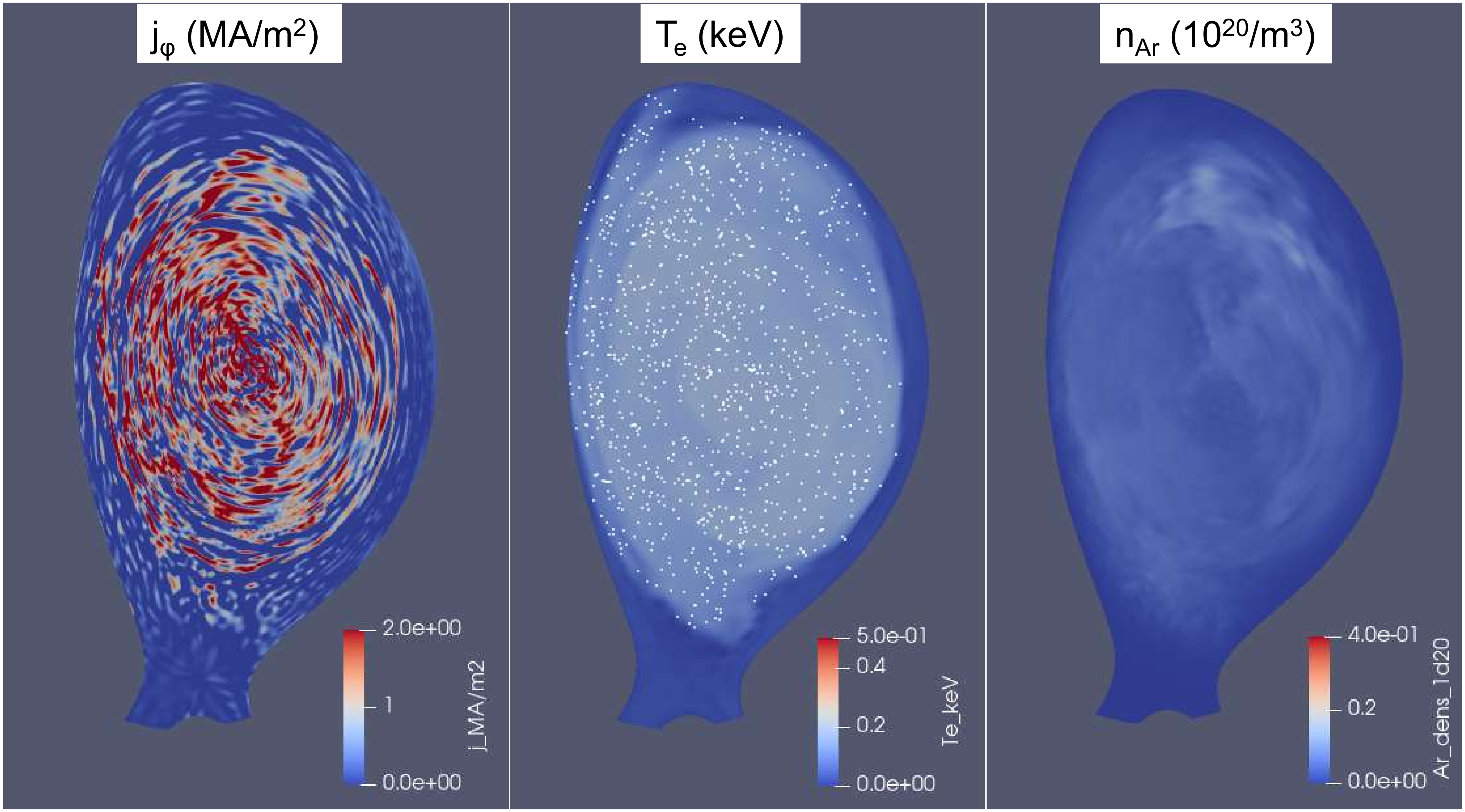
Ar_dens_1d20

5.90ms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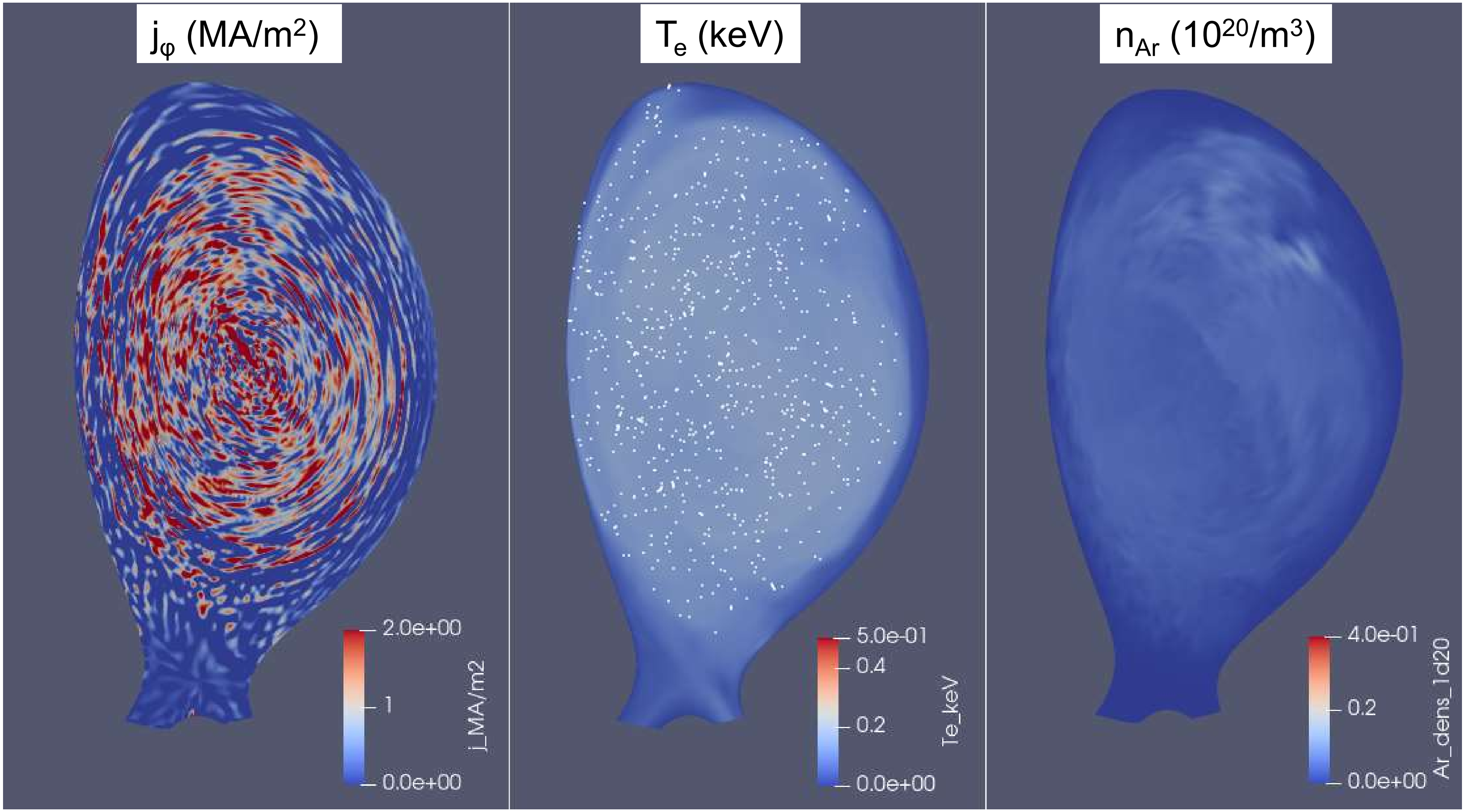
Ar_dens_1d20

5.96ms



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Te_keV
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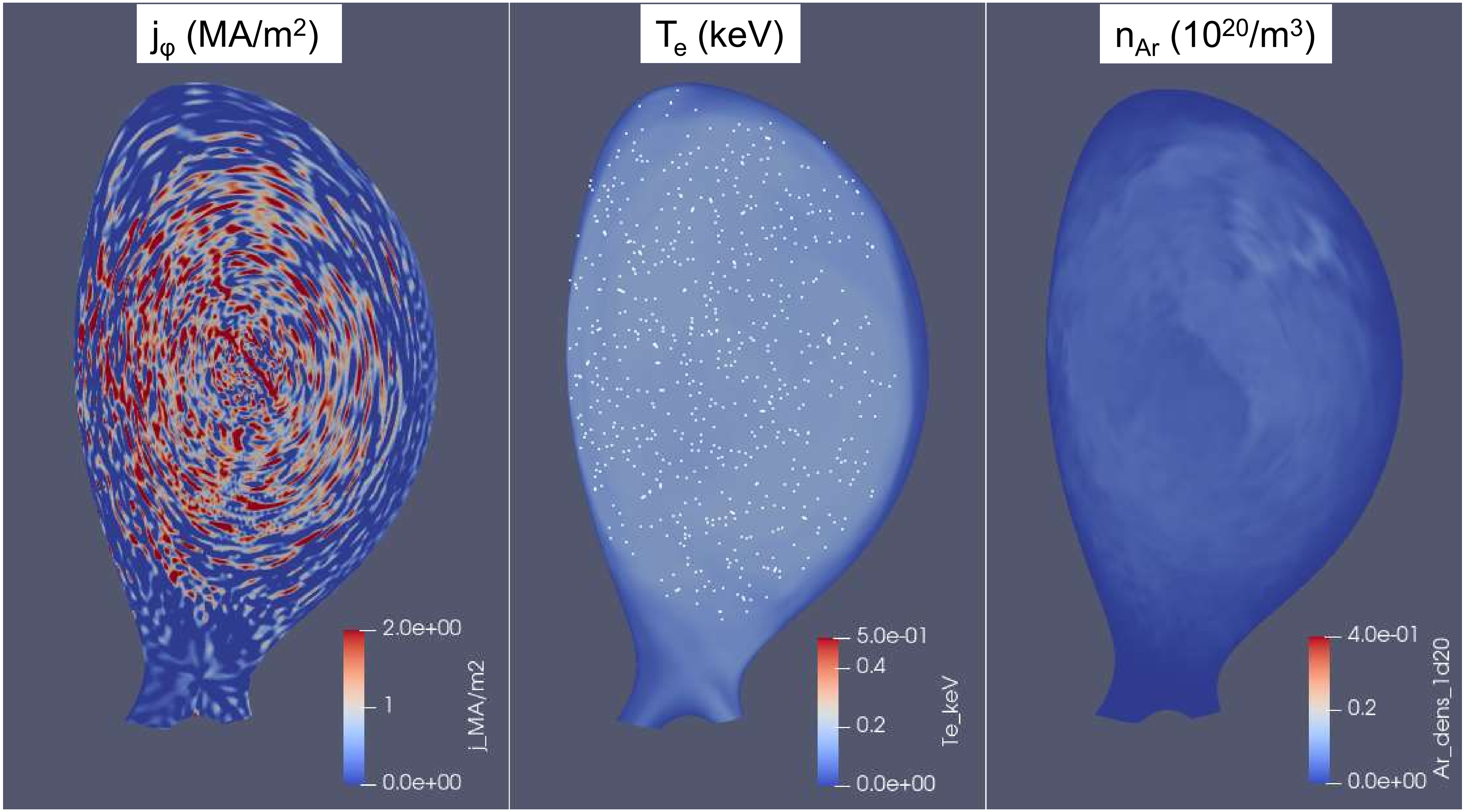
Ar_dens_1d20

5.99ms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0.0e+00
Te_keV
n_{Ar} (10^{20}/m^3)
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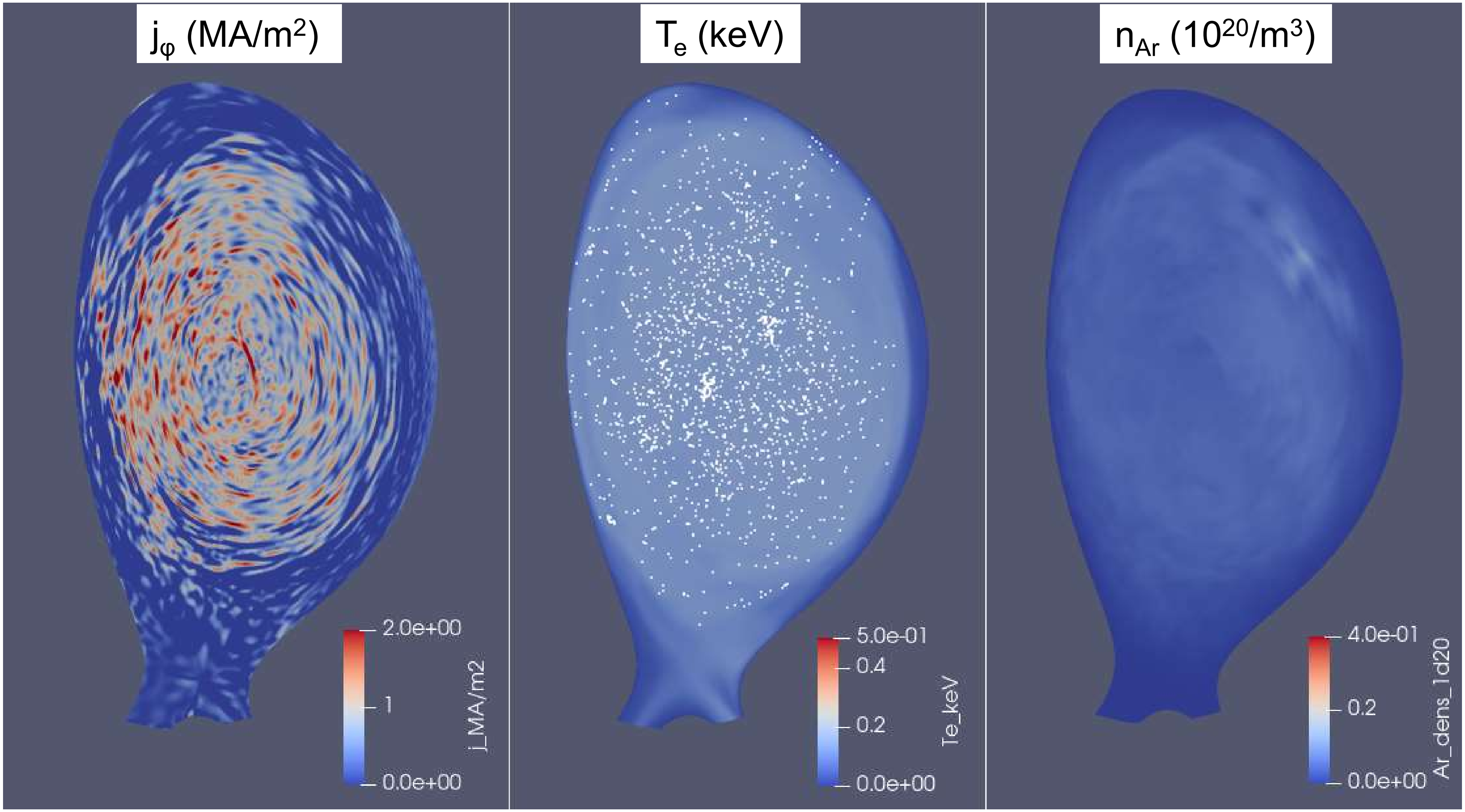
Ar_dens_1d20

6.02ms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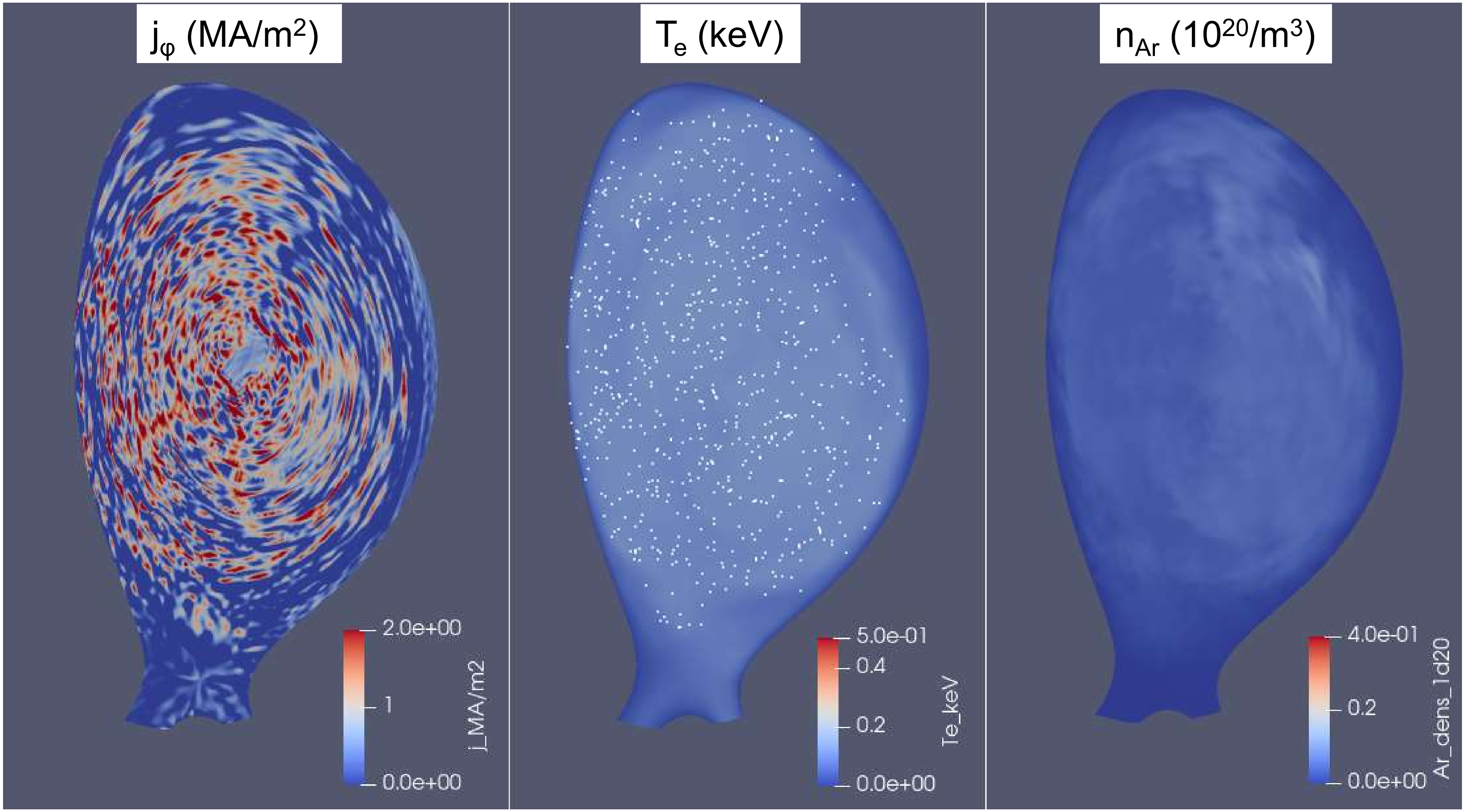
Ar_dens_1d20

6.05ms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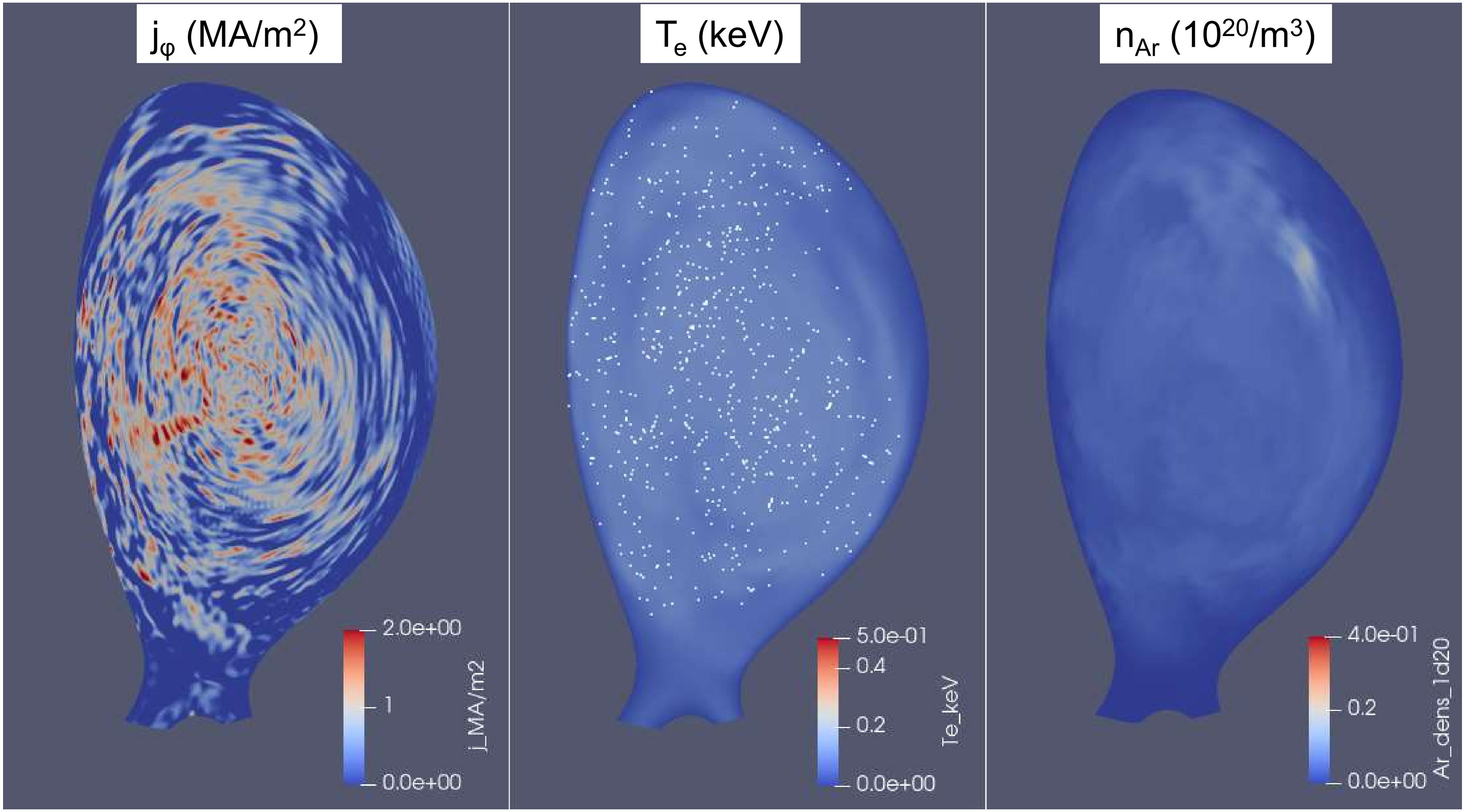
6.16ms



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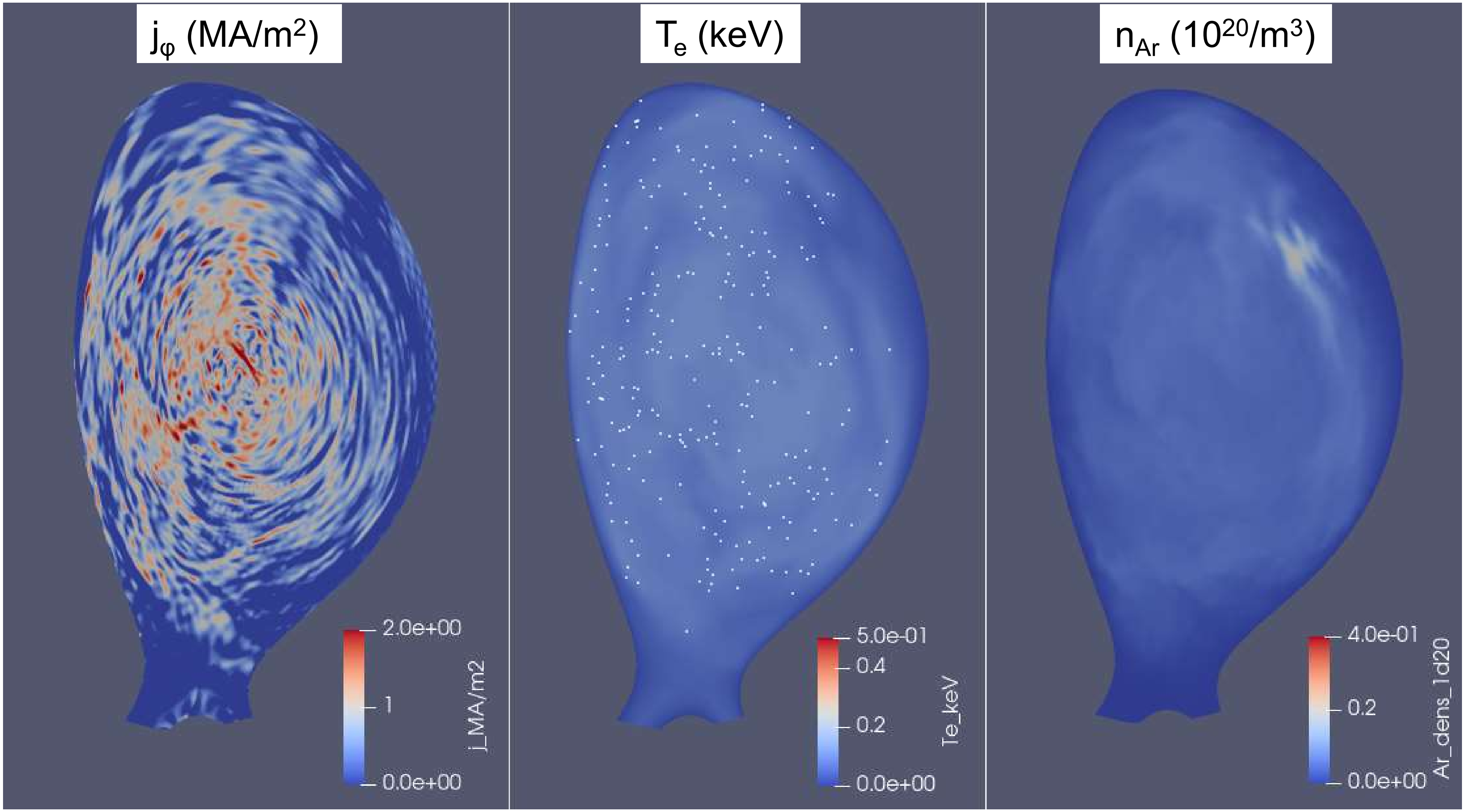
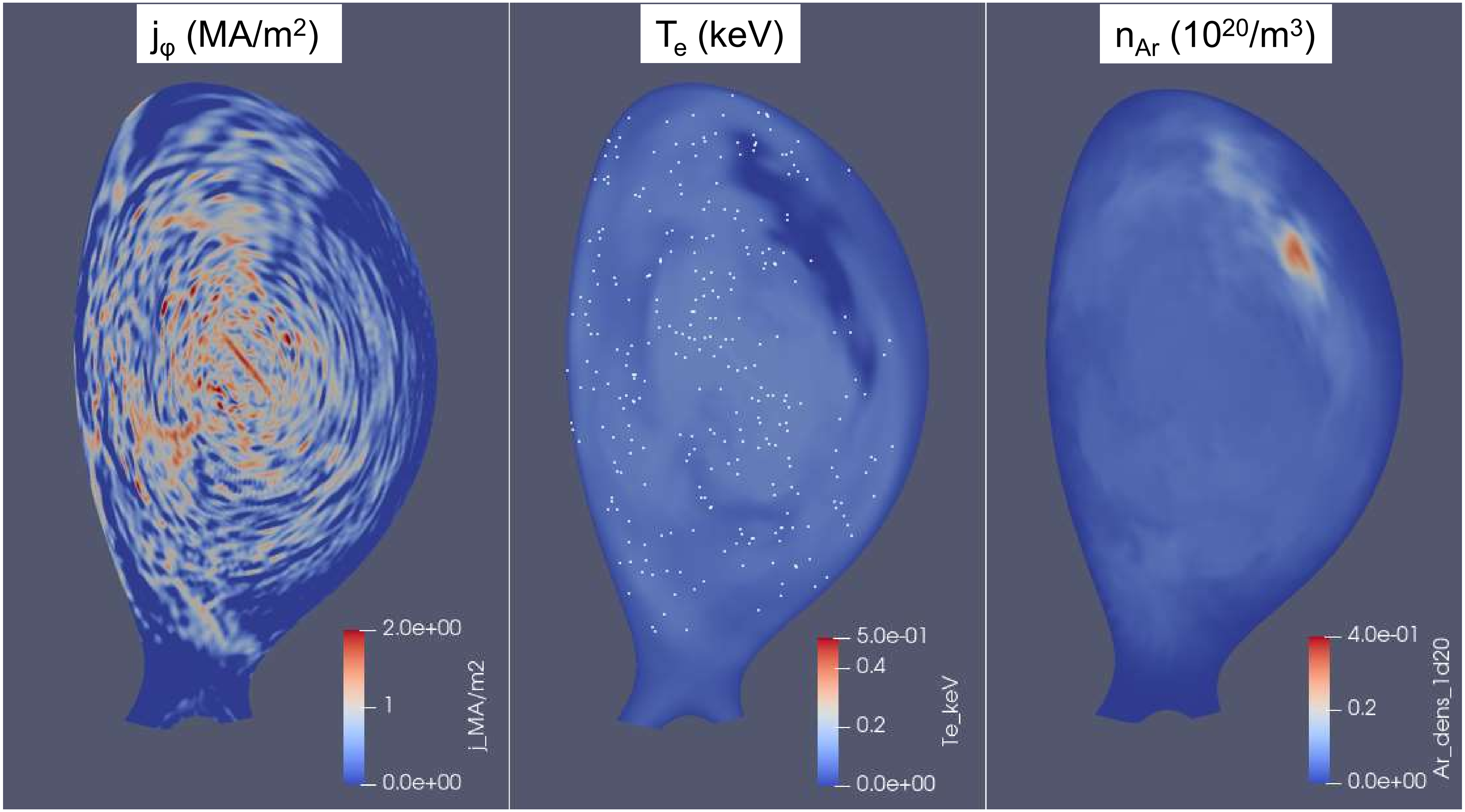
0.2
0.0e+00
Ar_dens_1d20

6.28ms



j_φ (MA/m^2)
2.0e+00
1
0.0e+00
j_MA/m2
T_e (keV)
5.0e-01
0.4
0.2
0.0e+00
Te_keV
n_{Ar} (10^{20}/m^3)
4.0e-01
0.2
0.0e+00
Ar_dens_1d20

6.40ms


j_φ (MA/m^2)
2.0e+00
1
0.0e+00
j_MA/m2
T_e (keV)
5.0e-01
0.4
0.2
0.0e+00
Te_keV
n_{Ar} (10^{20}/m^3)
4.0e-01
0.2
0.0e+00
Ar_dens_1d20

6.54ms

- The current sheet in the center may be interpreted as a consequence of the 2/1 island* ‘running into itself’
    - *which is not a proper island anymore because of stochasticity

- Reminiscent of publications from 30+ years ago!

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Are Vacuum Bubbles a Cause of Major Disruptions in Tokamaks?

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(Received 1 March 1984)

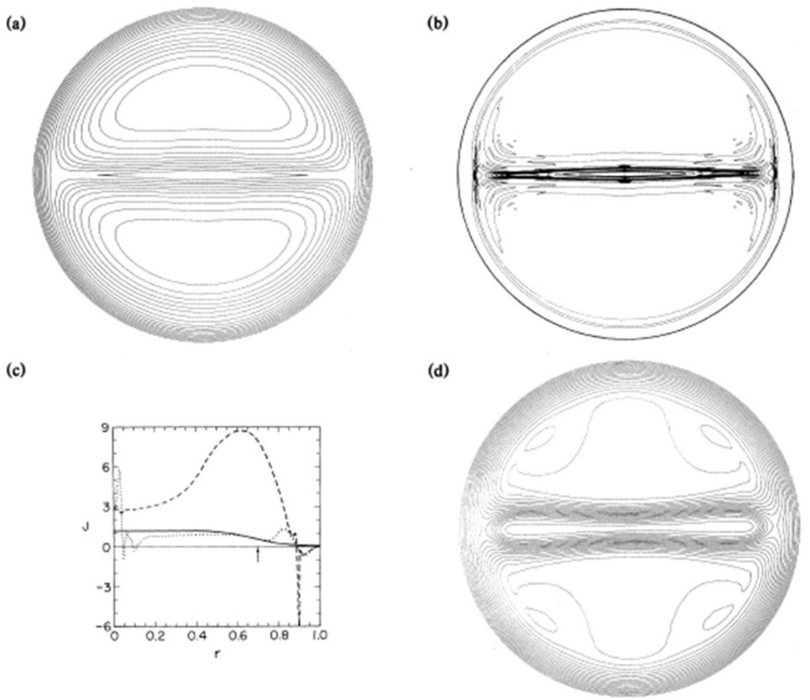


FIG. 2. The contours of constant (a) ψ and (b) J at maximum island size for $q(0)-1.7$. Cuts of the current profile across the O point (dotted line) and X point (dashed line) compared with the equilibrium (solid line) are shown in (c). The contours in (d) are the constant-ψ contours at maximum amplitude of a mode which is linearly ideally unstable with $\lambda = 20$ and other parameters as in (a).

[A. Bondeson et al., Nucl. Fusion 1991 **31** 1695]

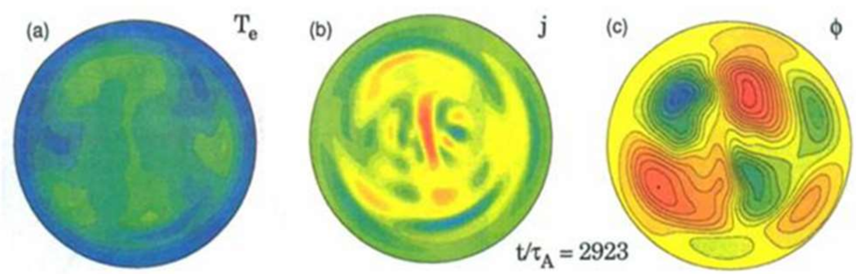
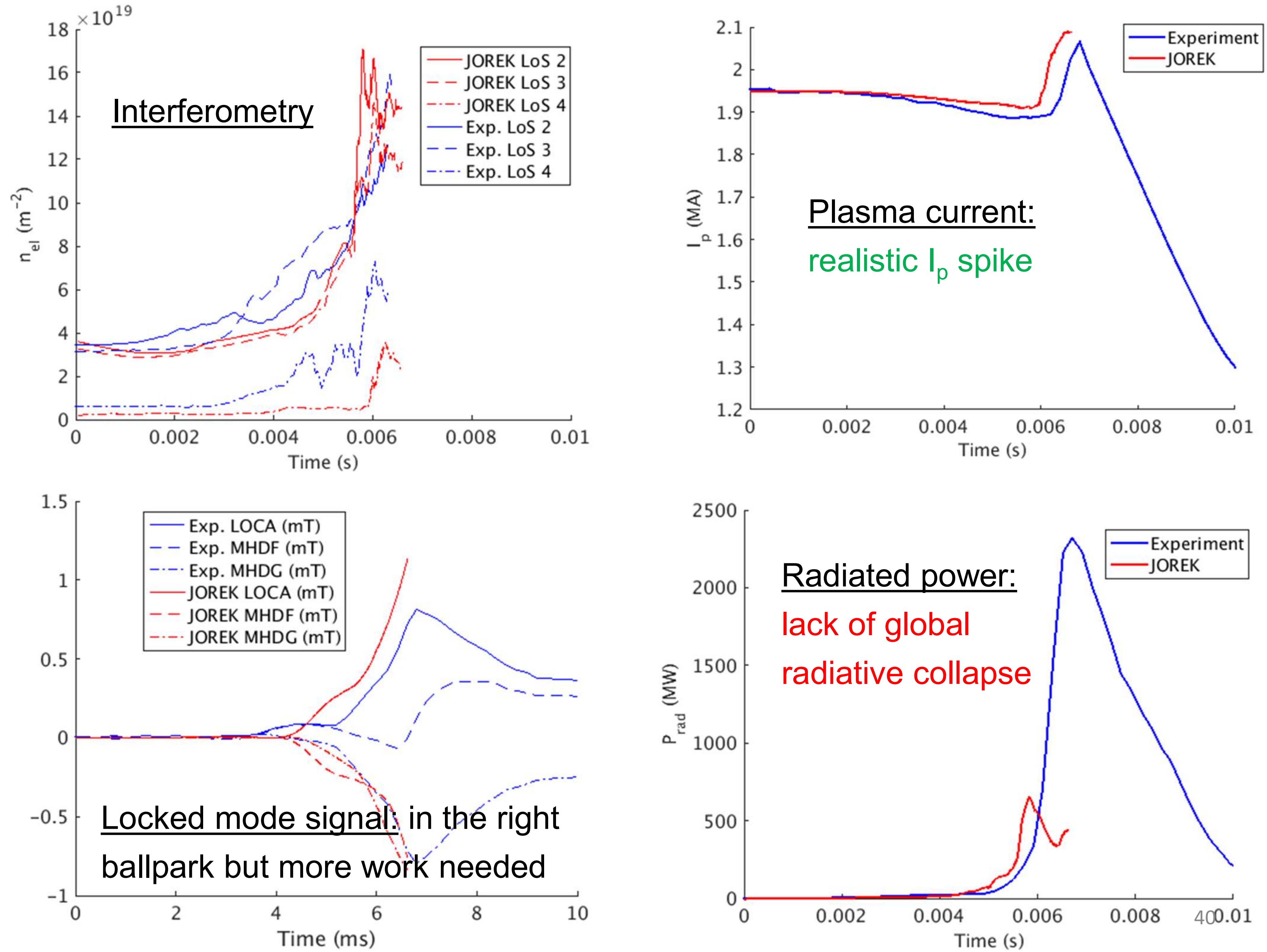
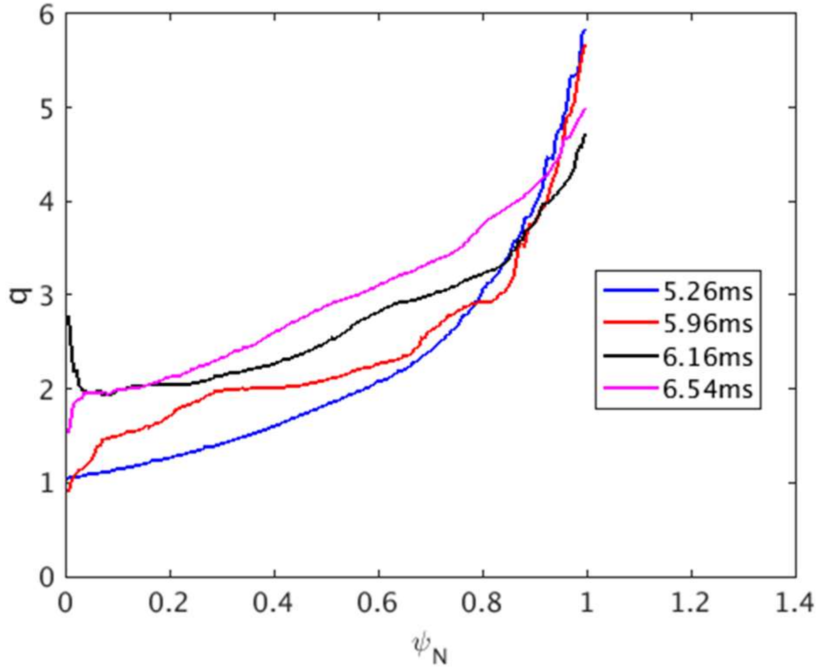
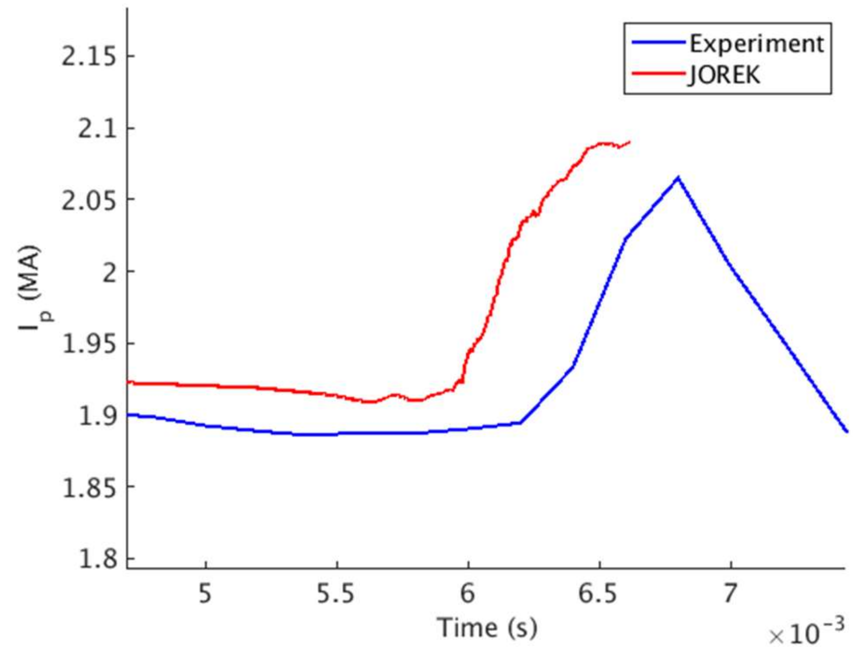
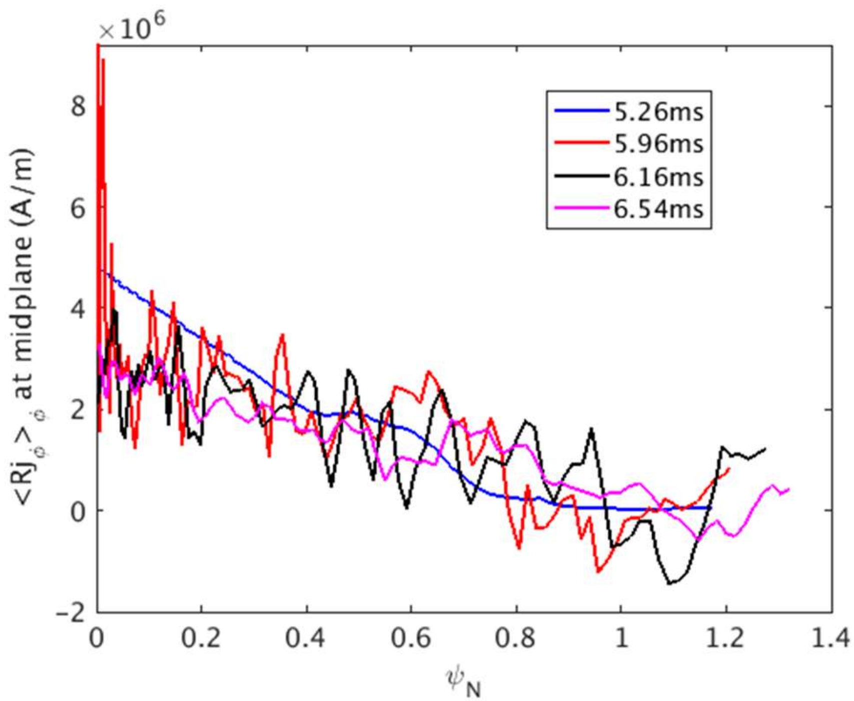


FIG. 18. (a) Electron temperature T_e, (b) current density j, and (c) stream function ϕ, at time t/τ_A = 2923, during the final phase at maximum $m = 3/n = 1$ amplitude.


Interferometry
$\times 10^{19}$
n_{el} (m^{-2})
Time (s)
JOREK LoS 2
JOREK LoS 3
JOREK LoS 4
Exp. LoS 2
Exp. LoS 3
Exp. LoS 4
Plasma current:
realistic I_p spike
I_p (MA)
Time (s)
Experiment
JOREK
Locked mode signal: in the right ballpark but more work needed
Time (ms)
Exp. LOCA (mT)
Exp. MHDF (mT)
Exp. MHDG (mT)
JOREK LOCA (mT)
JOREK MHDF (mT)
JOREK MHDG (mT)
Radiated power:
lack of global radiative collapse
P_{rad} (MW)
Time (s)
Experiment
JOREK







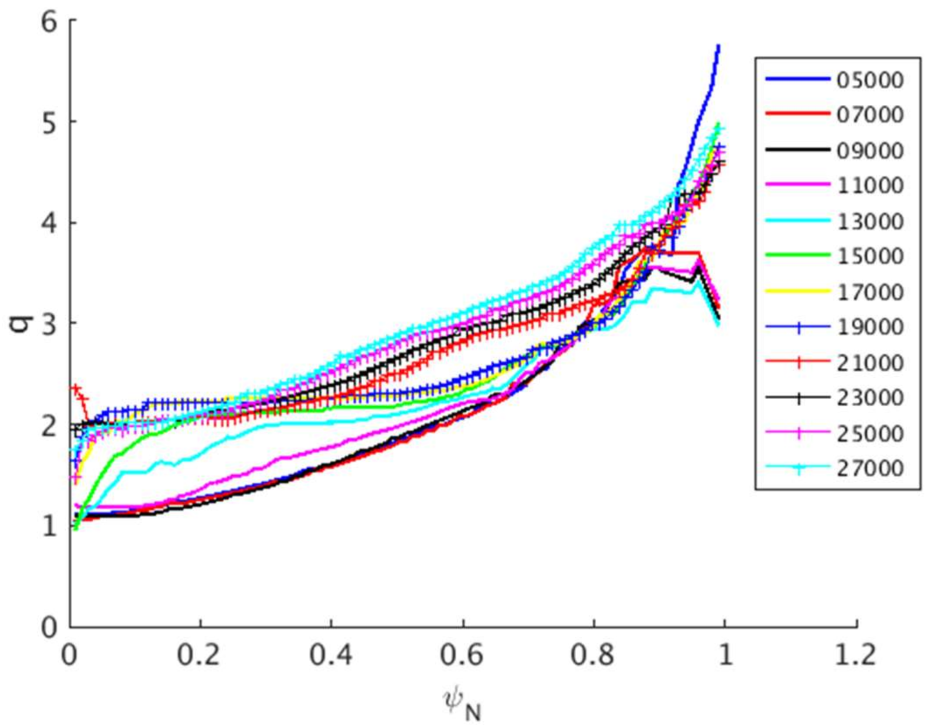
- q profile flattening inside q=2 as 2/1 mode grows
- I_p inside $\psi_N < 1$ peaks before total I_p (compare black and magenta q profiles)
  - Reason: negative 'skin current' induced in region $\psi_N > 1$, which takes some time to decay
  - As described in Biskamp's book 'Nonlinear magnetohydrodynamics'

Conclusion and perspectives

- Seems like the I_p spike saga is finally coming to an end ☺
  - Now running some more simulations and will try to publish

- Many questions remain to be explored:
  - Why no global radiative collapse?
    - Possibly not enough impurities deposited
    - Parallel flow damping may artificially reduce impurity penetration
  - Role of the q profile?
    - Here we had q_0 slightly above 1 → No 1/1 mode
  - Why do JET neon SPI simulations by D. Bonfiglio do not (yet) produce a realistic I_p spike in spite of having a radiative collapse in the 2/1 island?
    - q profile effect? Viscosity effect?
  - Electron dynamics: stochastic losses, parallel momentum, …?
    - Need to push JOREK simulations into the current quench (tough…)

Backup slides



5000: 5.259263938370858E-03
7000: 5.624201557610554E-03
9000: 5.778798349468042E-03
11000: 5.897718958589353E-03
13000: 5.958338739088233E-03
15000: 5.988068891368020E-03
17000: 6.017799043647807E-03
19000: 6.050145449328215E-03
21000: 6.158244283019291E-03
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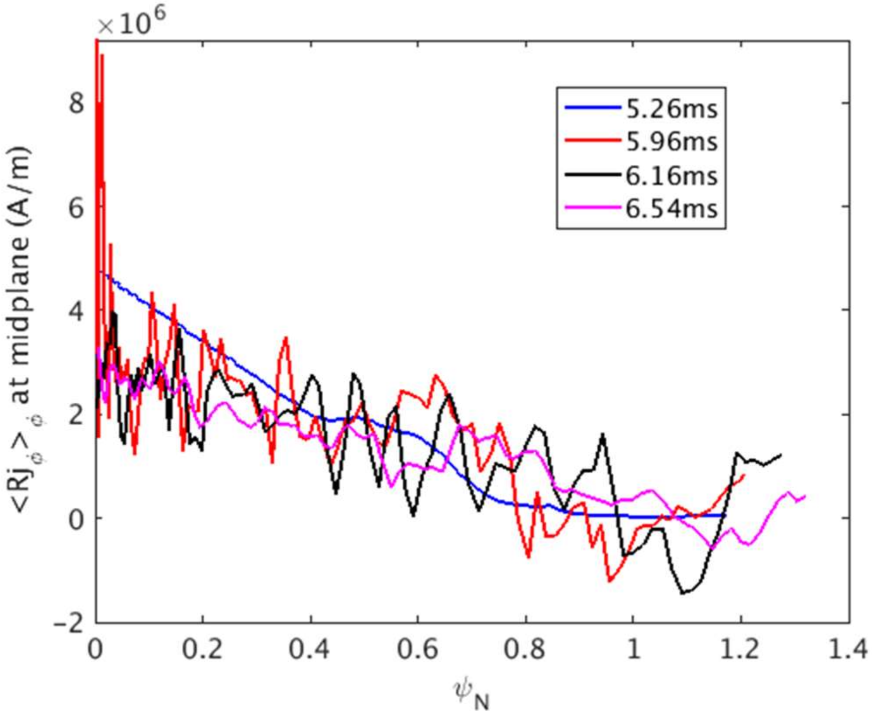
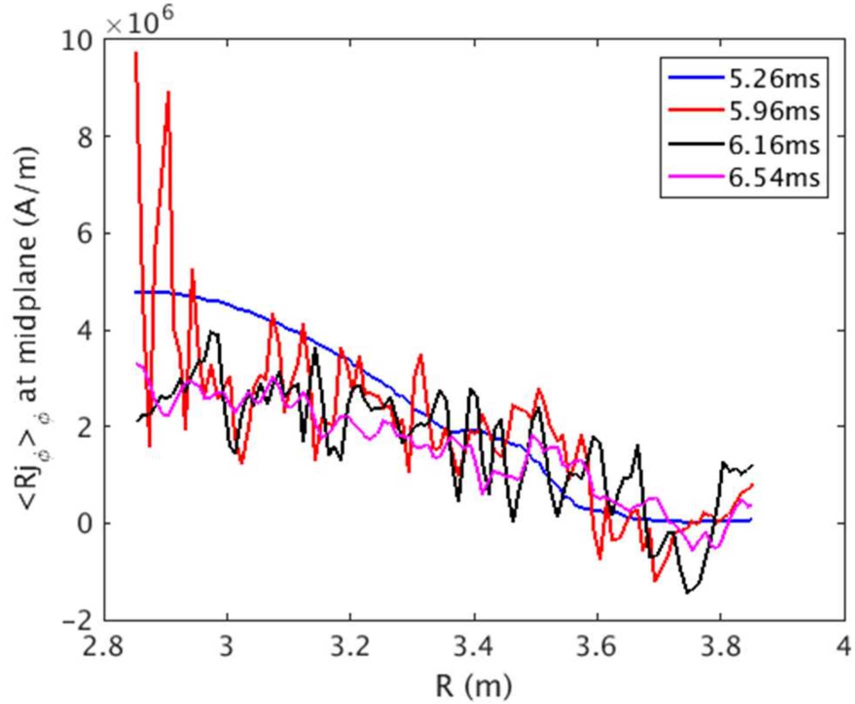


×10^6
8
6
4
2
0
−2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
ψN
<Rjφ>φ at midplane (A/m)
5.26ms
5.96ms
6.16ms
6.54ms



×10^6
10
8
6
4
2
0
−2
2.8
3
3.2
3.4
3.6
3.8
4
R (m)
<Rjφ>φ at midplane (A/m)
5.26ms
5.96ms
6.16ms
6.54ms