IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

GBS SIMULATION OF THE COMPASS TOKAMAK

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TA ČR Tento projekt je spolufinancován se státní podporou Technologické agentury ČR v rámci Programu THÉTA.
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MOTIVATION

- Magnetic confinement fusion does not provide perfect confinement of plasma.
- Collisions and turbulence cause transport particles and heat across the field lines.
    - The heat can have devastating impact on tokamak components.
    - Loose of confinement.
- Theoretical model of turbulence transport still not known.
- Turbulent transport leads to non-linearity => difficult to extrapolate.
- Transport codes reproduce transport based on effective diffusion coefficients, not the turbulence (SOLPS-ITER).
    - Difficult to obtain effective diffusion coefficients (turbulence codes can help).
- Turbulence must be simulated using turbulence codes.
- **Necessity of code validation for the development of future predictive simulations.**

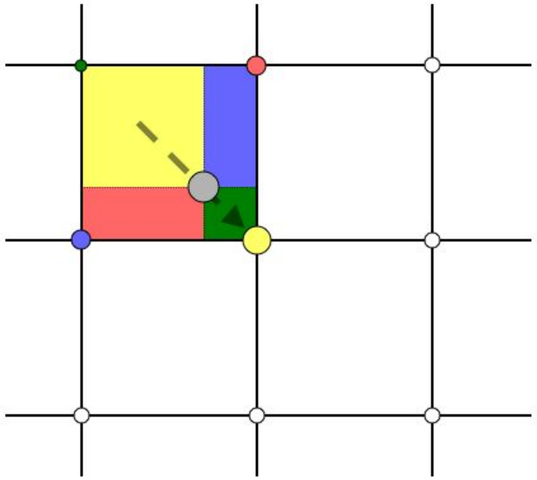
PARTICLE-TO-PARTICLE

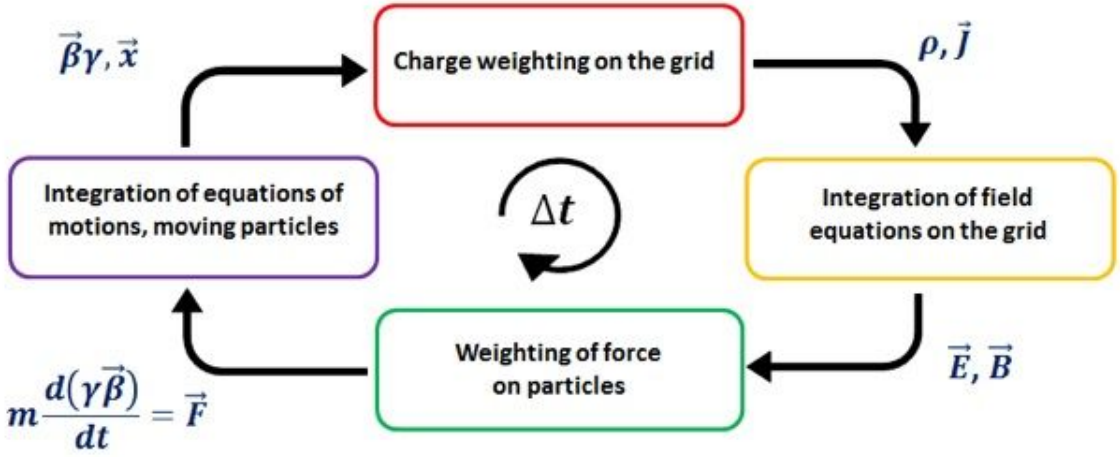
$$m\ddot{x}_k = \sum_i F_{k,i}$$

- Most simple approach, simple implementation, no assumptions.
- Extremely computationally demanding => scales as NxN => maximum of N=1000.
- Not usable for tokamak plasma simulations.

PARTICLE-IN-CELL

- Simplification of P2P approach.
- Scales as N x log(N).
- Particles weighting - fields distributed into grid points.
- Principle:
    1. Charge weighted into grid points (rho).
    2. Poisson equation integration (phi), electric field calculation.
    3. Weighting of force on particles.
    4. Integration of the motion equation, moving particles.
- Possibility to simulate small volumes (~ cm).
- 1D3V, 2D3V, 3D3V





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FLUID CODES

- From kinetic equation to fluid equations.
- **Maxwellian distribution is assumed (high collisionality)!**
- Several first moments (up to temperature equations) + closure.
- Much faster compared to kinetic simulations, several 3D models exists (GBS, TOKAM3X, GRILLIX).
- Full-size simulations of medium size machines (COMPASS, TCV, etc).
- Kinetic effects are neglected.
- Describes edge plasma only => unable to simulate core plasma (ITGs, ETGs, TEM neglected).

SIMPLE FLUID MODEL

Perpendicular transport:

$$\boldsymbol{v}_\perp = \overbrace{\frac{1}{B}\boldsymbol{b}\times\boldsymbol{\nabla}\phi}^{\text{ExB drift}} + \overbrace{\frac{1}{qnB}\boldsymbol{b}\times\boldsymbol{\nabla}p}^{\text{diamagnetic drift}} + \overbrace{\frac{m}{qB}\boldsymbol{b}\times(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v}}^{\text{polarization drift}},$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{v}_E = \overbrace{\boldsymbol{\nabla}(\frac{1}{B})\cdot\boldsymbol{b}\times\boldsymbol{\nabla}\phi}^{(1)} + \overbrace{\frac{1}{B}\boldsymbol{\nabla}\times\boldsymbol{b}\cdot\boldsymbol{\nabla}\phi}^{(2)} = \mathcal{C}(\phi),$$

Kinetic equation

$$\frac{\partial f}{\partial t} + \nabla\cdot(vf) + \nabla\cdot(\frac{F}{m}f) = C$$

Density equation

$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla}\cdot(n\boldsymbol{v}) = 0,$$

Temperature equation

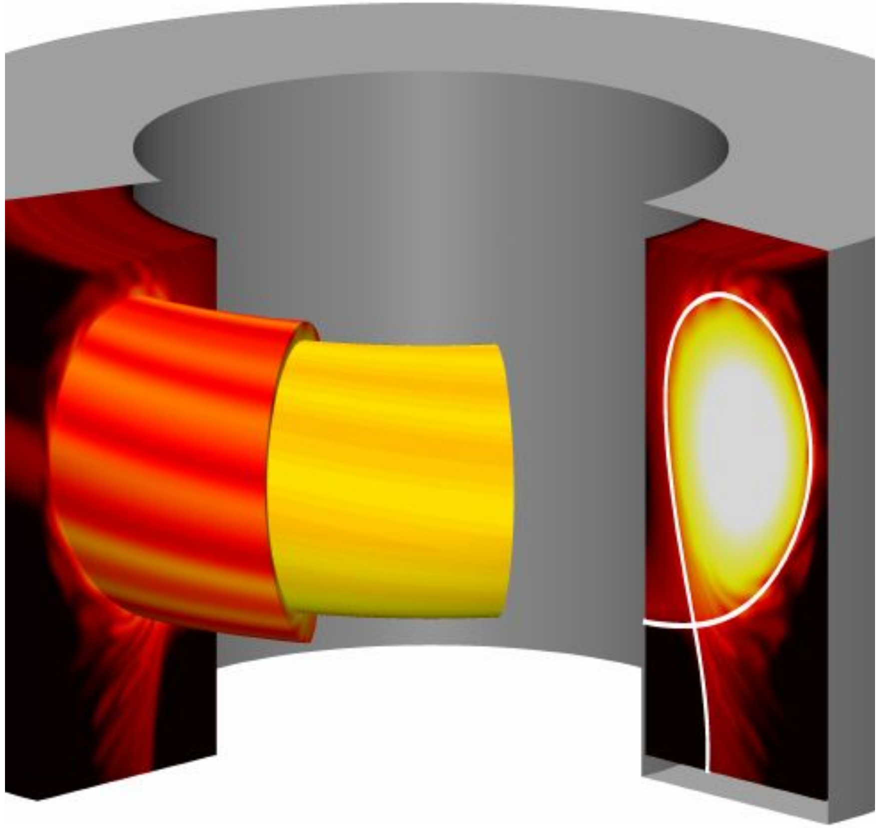
$$\frac{3}{2}n(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla})T + nT\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{\nabla}\cdot\boldsymbol{q}_\perp = 0,$$

$$\begin{aligned}
\frac{\mathrm{d}n}{\mathrm{d}t} + n\mathcal{C}(\phi) - \mathcal{C}(nT) &= \Lambda(n)\\
\frac{\mathrm{d}T}{\mathrm{d}t} + \frac{2T}{3}\mathcal{C}(\phi) - \frac{7T}{3}\mathcal{C}(T) - \frac{2T^2}{3n}\mathcal{C}(n) &= \Lambda(T)\\
\frac{\mathrm{d}\Omega}{\mathrm{d}t} - \mathcal{C}(nT) &= \Lambda(\Omega)
\end{aligned}$$

$$\Omega = \boldsymbol{\nabla}\times v_E = B^{-2}\boldsymbol{\nabla}\times(\boldsymbol{B}\times\boldsymbol{\nabla}\phi) = \nabla_\perp^2\phi.$$

GLOBAL BRAGINSKII SOLVER

- First principle, 3D, flux-driven, global, turbulence code for plasma edge simulations based on Braginskii equations [1].
- Full plasma volume, Divertor geometry, electromagnetic effects, kinetic neutrals, ion temperature dynamics, self-consistent turbulence evolution.
- High computational requirements (~2000 cores, ~5-10 M CPU hours).
- Validation on COMPASS tokamak – first validation of full-size simulation after TCV.
- Validation on COMPASS will include electron temperature and plasma potential fluctuations.



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EQUATIONS

- Braginskii equations are solved, Boussinesq approximation is not used.
- 7 fields are evolved during each step:
  - Density, electron and ion parallel velocity, vorticity, electron and ion temperature, and psi (if electromagnetic effects are enabled).
- If kinetic neutrals are included:
  - Neutral density, and neutral parallel velocity.

Poisson and Ampere equations are solved:

$$\nabla\cdot\left(n\nabla_\perp\phi\right)=\Omega-\frac{\nabla_\perp^2 p_i}{e},$$

$$\left(\nabla_\perp^2-\frac{e^2\mu_0}{m_e}n\right)v_{\parallel e}=\nabla_\perp^2 U_{\parallel e}-\frac{e^2\mu_0}{m_e}nv_{\parallel i}+\frac{e^2\mu_0}{m_e}\bar{j}_\parallel .$$

$$U_{\parallel e}=v_{\parallel e}+e\psi/m_e$$

Particle confinement

$$\frac{\partial n}{\partial t}=-\frac{1}{B}[\phi,n]+\frac{2}{eB}\Big[C(p_e)-nC(\phi)\Big]-\nabla_\parallel(nv_{\parallel e})+D_n\nabla_\perp^2 n+s_n+\nu_{\rm iz}n_{\rm n}-\nu_{\rm rec}n, \quad (1)$$

Vorticity

$$\frac{\partial\Omega}{\partial t}=-\frac{1}{B}\nabla\cdot[\phi,\omega]-\nabla\cdot\left(v_{\parallel i}\nabla_\parallel\omega\right)+\frac{B\Omega_{ci}}{e}\nabla_\parallel j_\parallel+\frac{2\Omega_{ci}}{e}C(p_e+p_i)+\frac{\Omega_{ci}}{3e}C(G_i)+D_\Omega\nabla_\perp^2\Omega-\frac{n_{\rm n}}{n}\nu_{\rm cx}\Omega, \quad (2)$$

Electron inertia

$$\frac{\partial U_{\parallel e}}{\partial t}=-\frac{1}{B}[\phi,v_{\parallel e}]-v_{\parallel e}\nabla_\parallel v_{\parallel e}+\frac{e}{m_e}\left(\frac{j_\parallel}{\sigma_\parallel}+\nabla_\parallel\phi-\frac{1}{en}\nabla_\parallel p_e-\frac{0.71}{e}\nabla_\parallel T_e-\frac{2}{3en}\nabla_\parallel G_e\right)+D_{v_{\parallel e}}\nabla_\perp^2 v_{\parallel e}+\frac{n_{\rm n}}{n}(\nu_{\rm en}+2\nu_{\rm iz})(v_{\parallel n}-v_{\parallel e}), \quad (3)$$

ion inertia

$$\frac{\partial v_{\parallel i}}{\partial t}=-\frac{1}{B}[\phi,v_{\parallel i}]-v_{\parallel i}\nabla_\parallel v_{\parallel i}-\frac{1}{m_i n}\nabla_\parallel(p_e+p_i)-\frac{2}{3m_i n}\nabla_\parallel G_i+D_{v_{\parallel i}}\nabla_\perp^2 v_{\parallel i}+\frac{n_{\rm n}}{n}(\nu_{\rm iz}+\nu_{\rm cx})(v_{\parallel n}-v_{\parallel i}), \quad (4)$$

electron energy confinement

$$\frac{\partial T_e}{\partial t}=-\frac{1}{B}[\phi,T_e]-v_{\parallel e}\nabla_\parallel T_e+\frac{2}{3}T_e\left[0.71\frac{\nabla_\parallel j_\parallel}{en}-\nabla_\parallel v_{\parallel e}\right]+\frac{4}{3}\frac{T_e}{eB}\left[\frac{7}{2}C(T_e)+\frac{T_e}{n}C(n)-eC(\phi)\right]+\nabla_\parallel(\chi_{\parallel e}\nabla_\parallel T_e)+D_{T_e}\nabla_\perp^2 T_e+s_{T_e}-\frac{n_{\rm n}}{n}\nu_{\rm en}m_e\frac{2}{3}v_{\parallel e}(v_{\parallel n}-v_{\parallel e})-2\frac{m_e}{m_i}\frac{1}{\tau_e}(T_e-T_i)+\frac{n_{\rm n}}{n}\nu_{\rm iz}\left[-\frac{2}{3}E_{\rm iz}-T_e+m_e v_{\parallel e}\left(v_{\parallel e}-\frac{4}{3}v_{\parallel n}\right)\right], \quad (5)$$

ion energy confinement

$$\frac{\partial T_i}{\partial t}=-\frac{1}{B}[\phi,T_i]-v_{\parallel i}\nabla_\parallel T_i+\frac{4}{3}\frac{T_i}{eB}\left[C(T_e)+\frac{T_e}{n}C(n)-eC(\phi)\right]-\frac{10}{3}\frac{T_i}{eB}C(T_i)+\frac{2}{3}T_i\left[(v_{\parallel i}-v_{\parallel e})\frac{\nabla_\parallel n}{n}-\nabla_\parallel v_{\parallel e}\right]+\nabla_\parallel(\chi_{\parallel i}\nabla_\parallel T_i)+D_{T_i}\nabla_\perp^2 T_i+s_{T_i}+2\frac{m_e}{m_i}\frac{1}{\tau_e}(T_e-T_i)+\frac{n_{\rm n}}{n}(\nu_{\rm iz}+\nu_{\rm cx})\left[T_n-T_i+\frac{1}{3}(v_{\parallel n}-v_{\parallel i})^2\right], \quad (6)$$

GBS - SIMULATION DOMAIN

Set of **Mag**netic boundary conditions
(Bohm Chodura boundary conditions)

$$v_{\parallel i} = \pm c_s \sqrt{1 + \frac{T_i}{T_e}}\,,$$

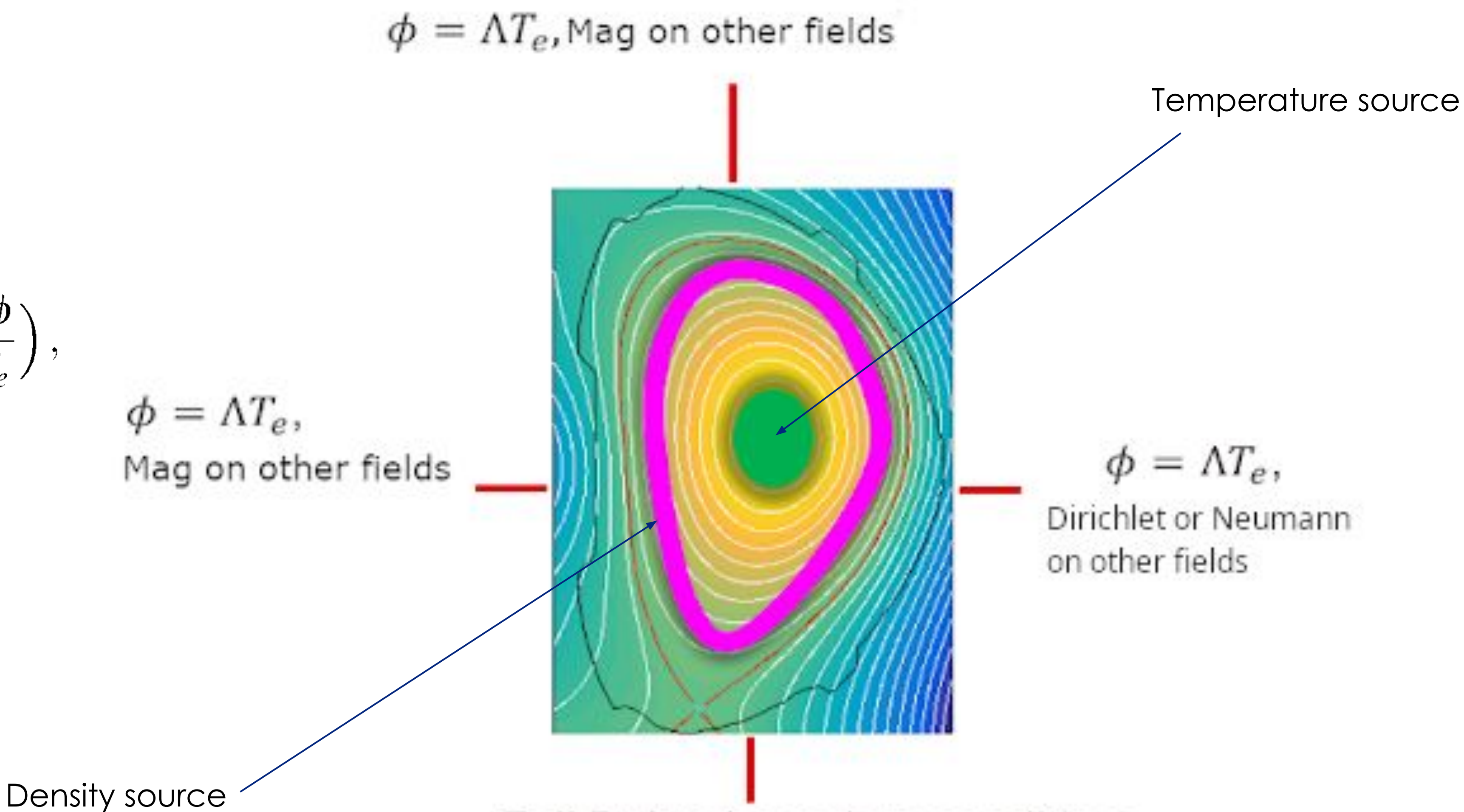
$$v_{\parallel e} = \pm c_s \sqrt{1 + \frac{T_i}{T_e}}\, \exp\left(\Lambda - \frac{e\phi}{T_e}\right),$$

$$\partial_s n = \mp \frac{n}{c_s \sqrt{1 + \frac{T_i}{T_e}}} \partial_s v_{\parallel i}\,,$$

$$\partial_s T_e = \partial_s T_i = 0\,,$$

$$\Omega = \mp \frac{m_i n}{e} c_s \sqrt{1 + \frac{T_i}{T_e}}\, \partial^2_{ss} v_{\parallel i}\,,$$

$$\partial_s \phi = \mp \frac{m_i c_s}{e \sqrt{1 + \frac{T_i}{T_e}}} \partial_s v_{\parallel i}\,,$$

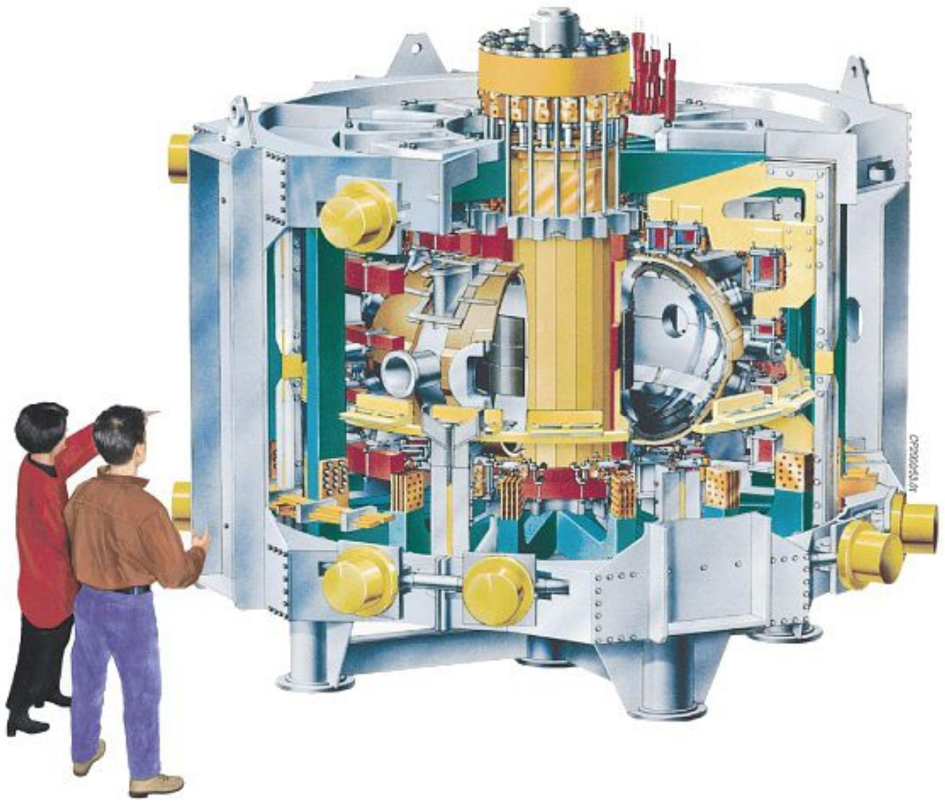


Full Bohm boundary conditions
(J. Loizu PoP 2012)

COMPASS

- Smaller tokamak on IPP (since 2011), already disassembled.
- To be replaced by COMPASS Upgrade.
- NBI, H-mode, D-shaped, divertor.
- Number of diagnostics(TS, Li-beam, probes, etc).

Major radius R	0.56 m
Minor radius a	0.23 m
Plasma current Ip (max)	400 kA
Magnetic field Bt (max)	0.9 - 2.1 T
Pulse length t	~ 1 s
Beam heating	2 x 0.4 MW



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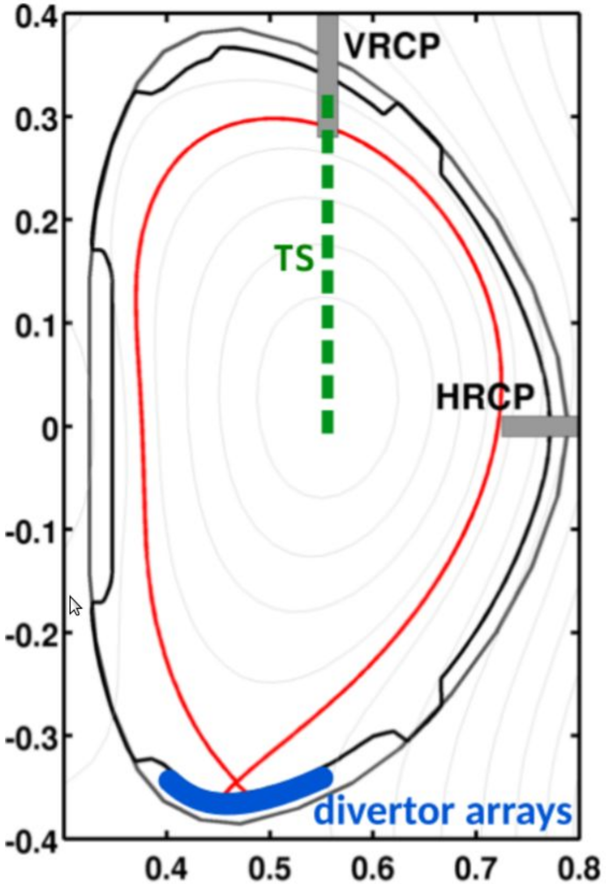
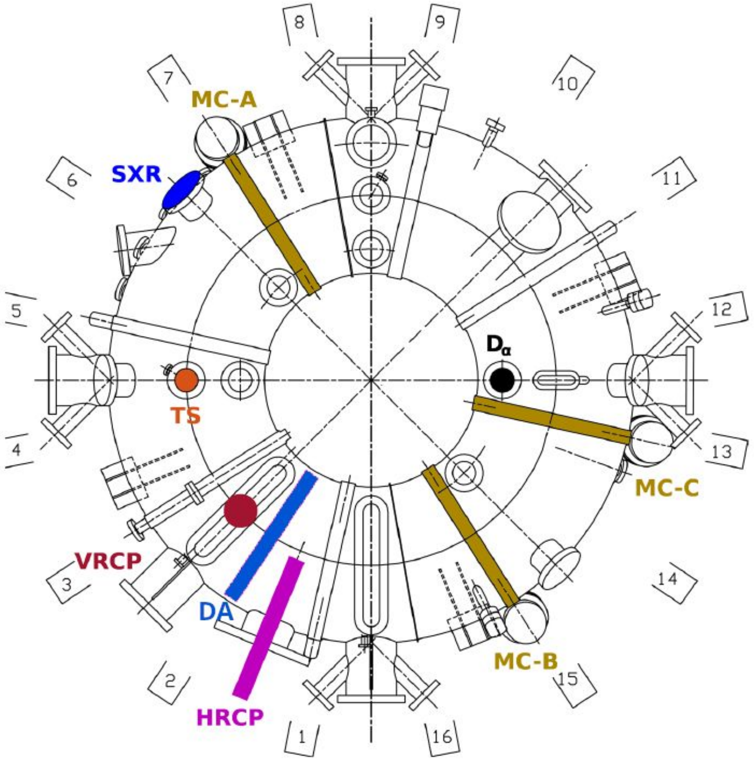
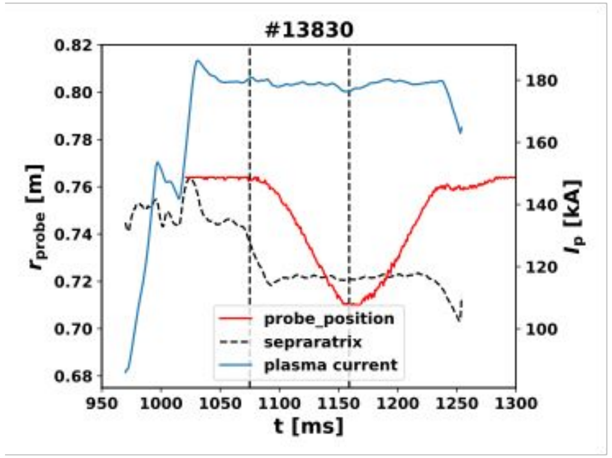
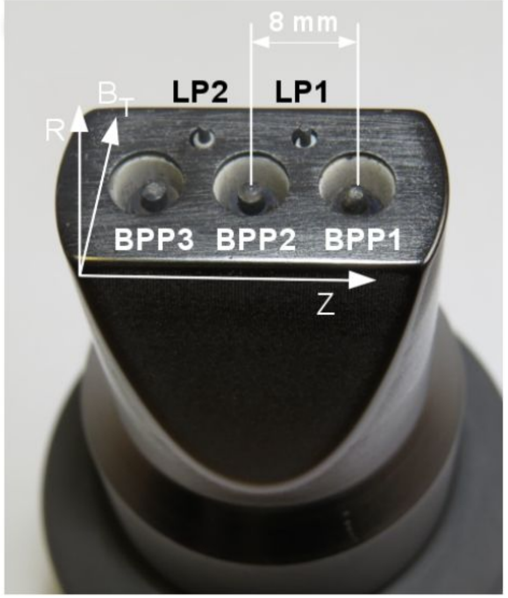
STUDY CONTENT - SIMULATED DISCHARGE

- Discharge #13830 - standard, L-mode, ohmic, wide SOL and clearance.
- Many available diagnostics: probes, Thomson scattering, Lithium beam, …



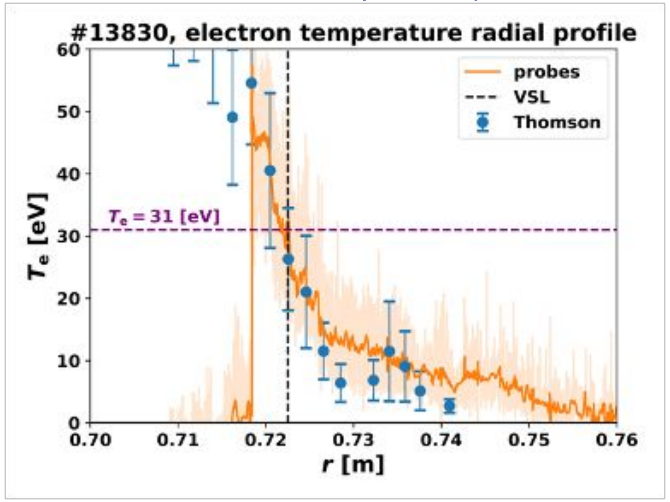


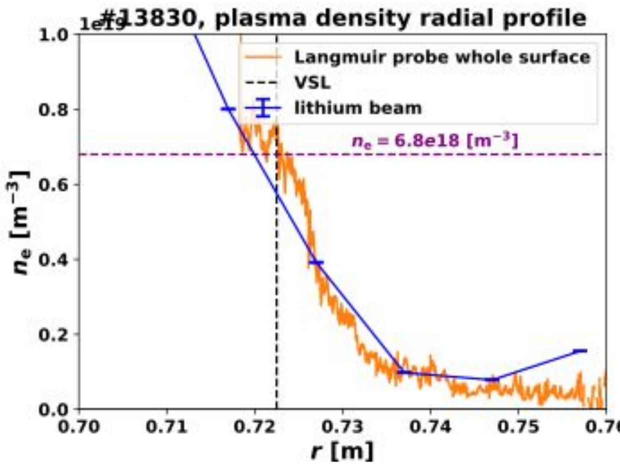


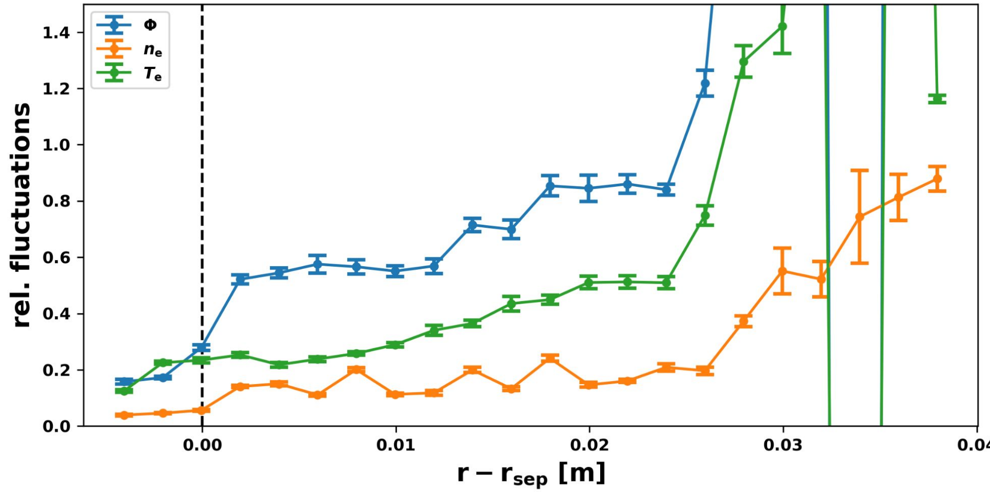


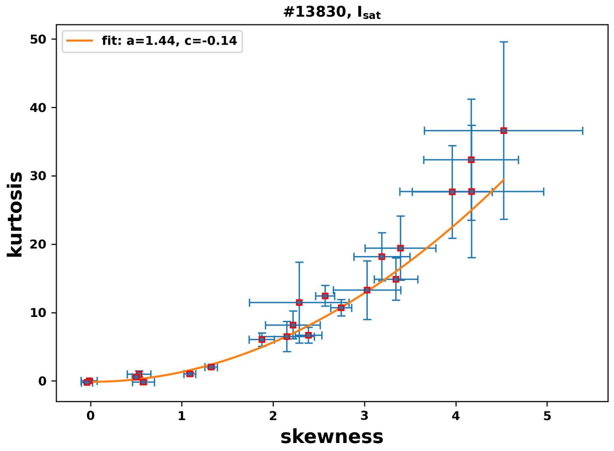
STUDY CONTENT - DISCHARGE ANALYSIS

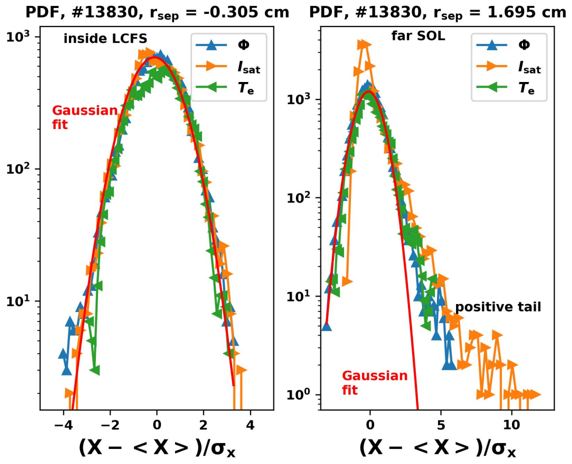
- Examples of turbulence analysis (profiles, moments, blob time trace, waiting times, distribution function, cross-phase).
- Will be directly compared with simulation results.

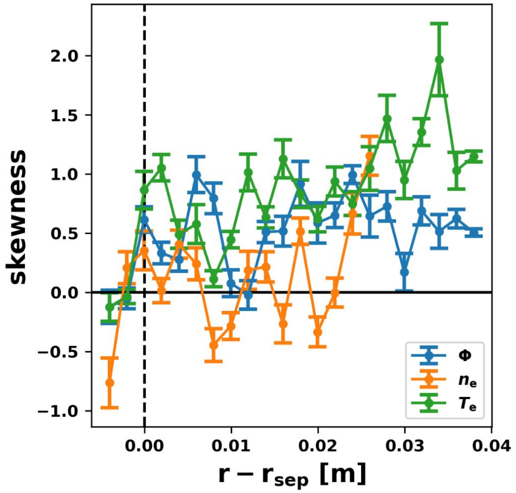


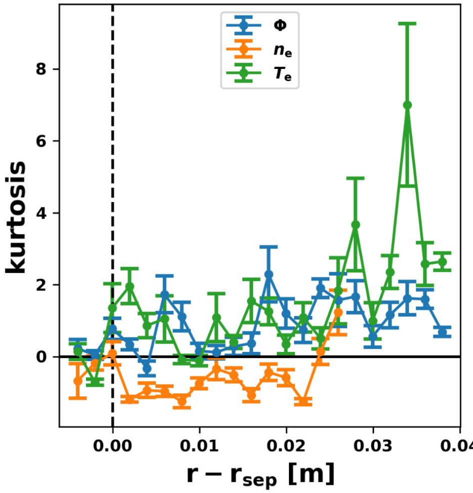






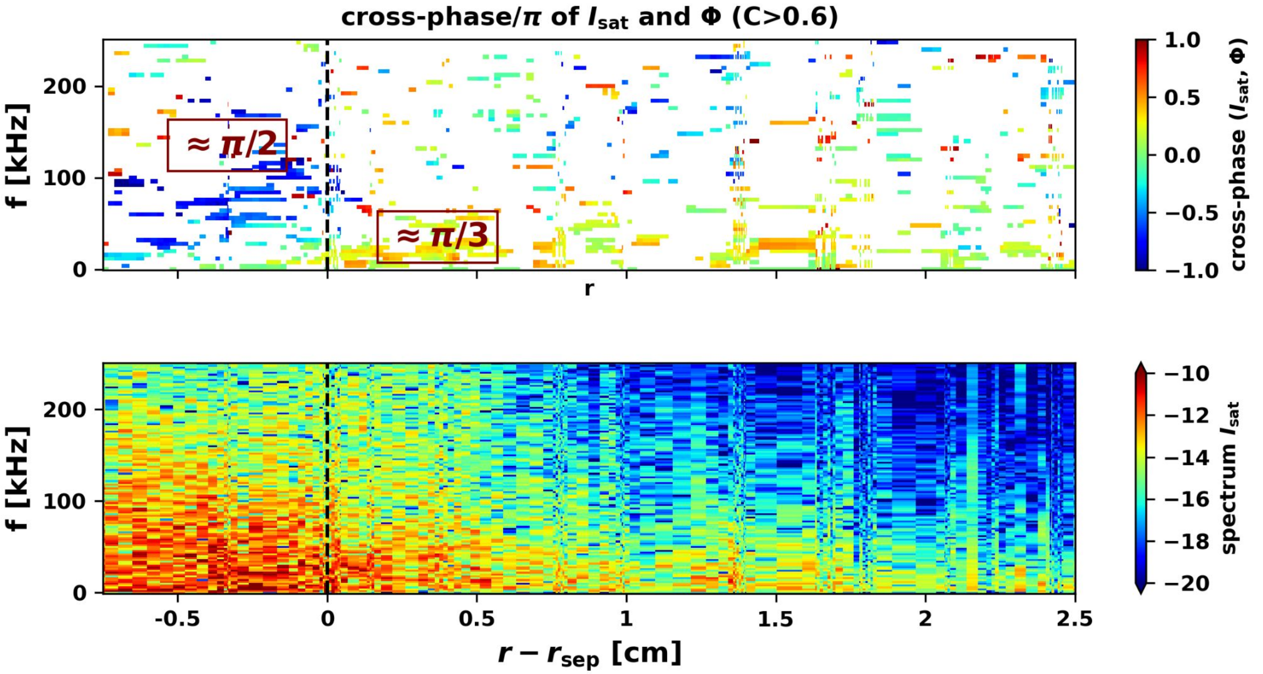


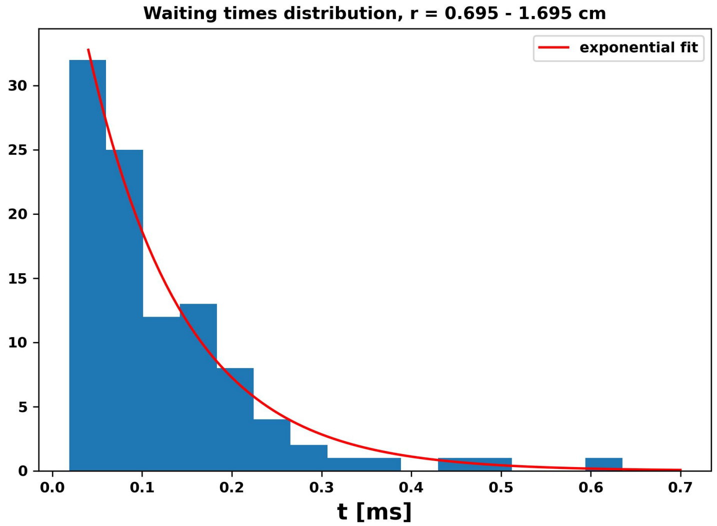


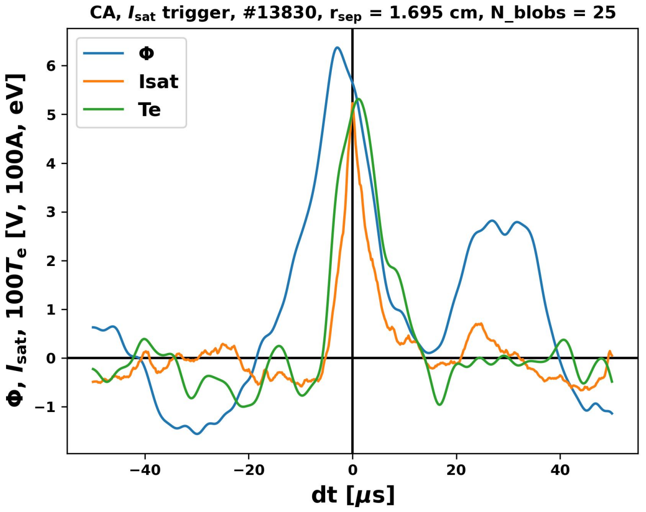


STUDY CONTENT - DISCHARGE ANALYSIS

- Python module for experimental data analysis was developed.
- Experimental data were analyzed and are ready for the validation.



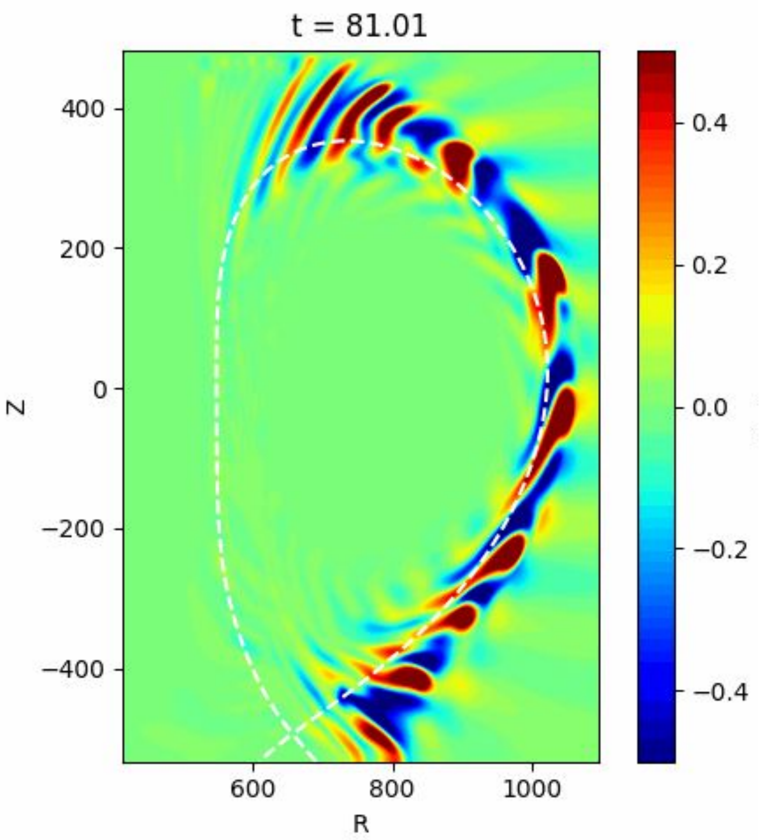




SIMULATION RESULTS AND PLANS

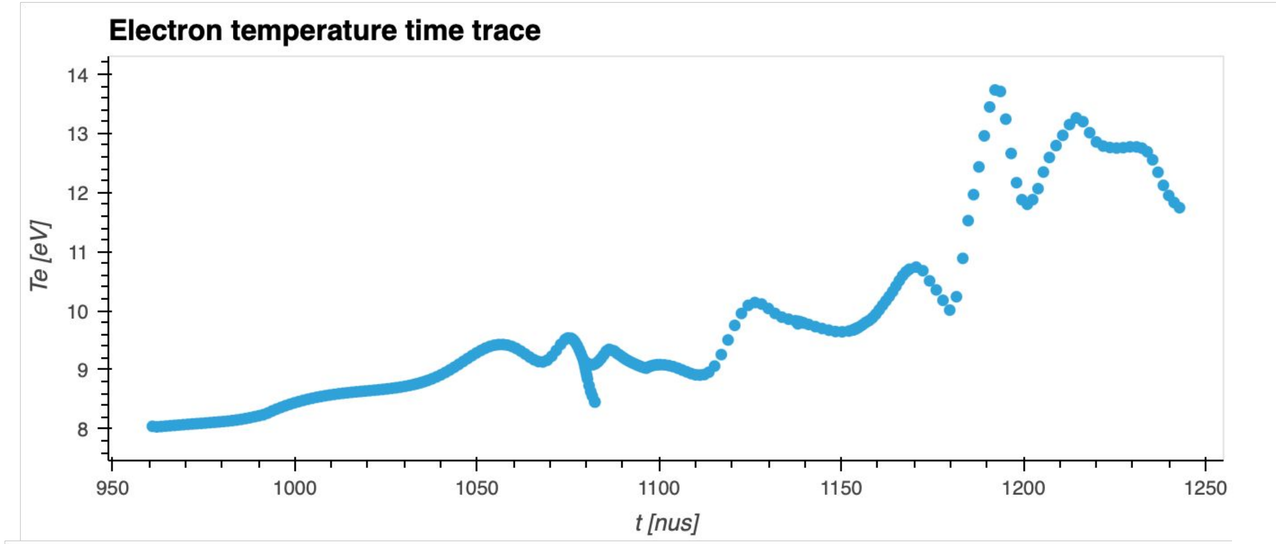
What was done:

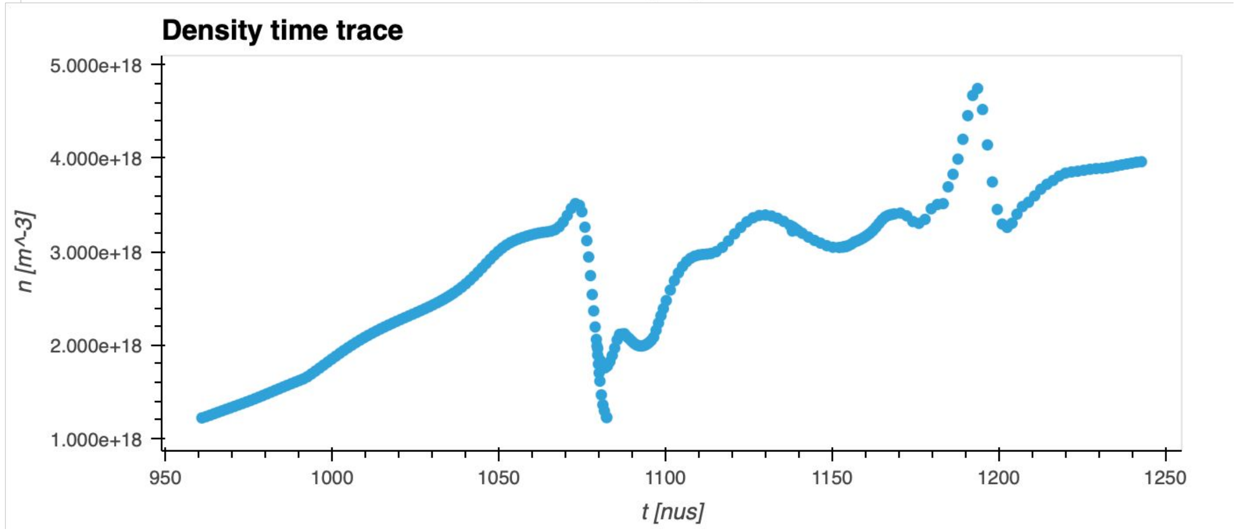
- Based on the code research, GBS was chosen for COMPASS simulation.
- GBS code was adapted, and the very first full-size COMPASS simulation was started.
- Most of the numerical issues solved (sources, boundary conditions, etc).
- The Laminar phase was handled.
- First turbulence was observed and handled.
- Python module for simulation output analysis GBSPy was developed.
- First results presented on 2021 EU-US Joint TTF meeting.

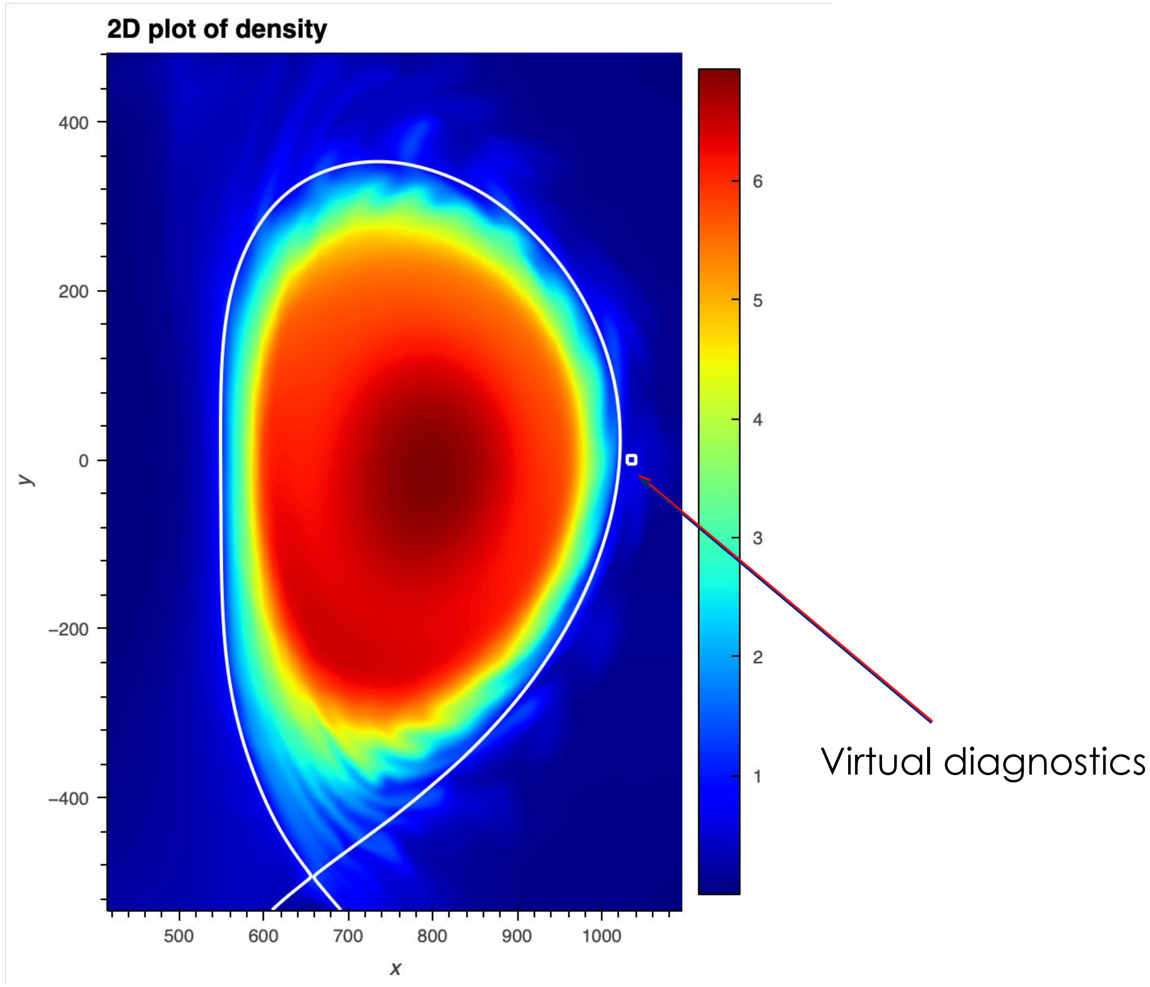


An example of density fluctuations during pre-quasi-stationary phase.

SIMULATION RESULTS EXAMPLES







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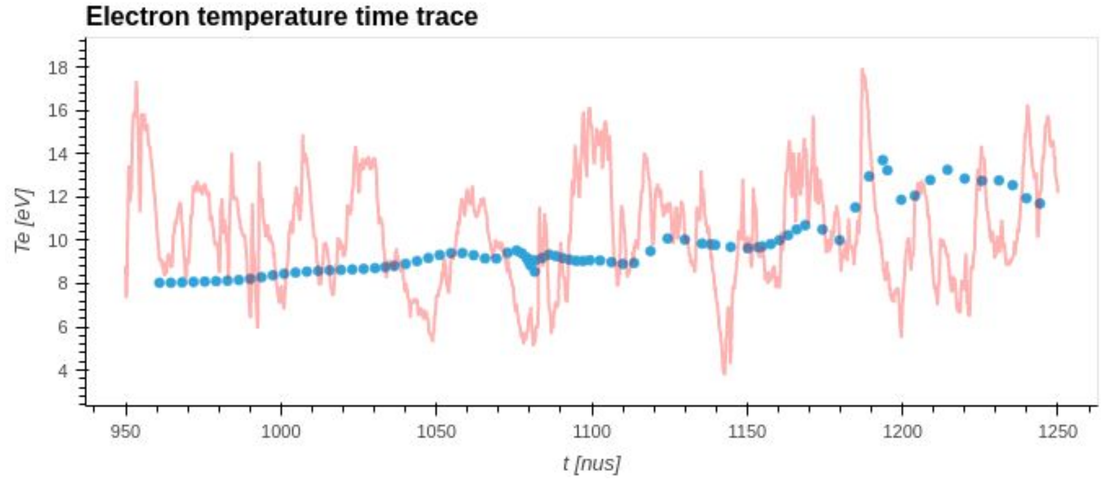

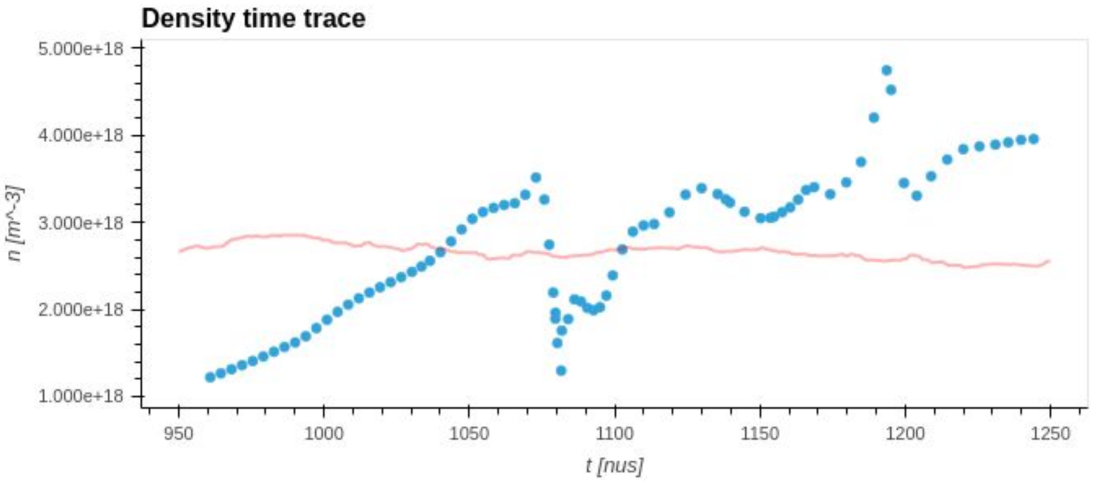

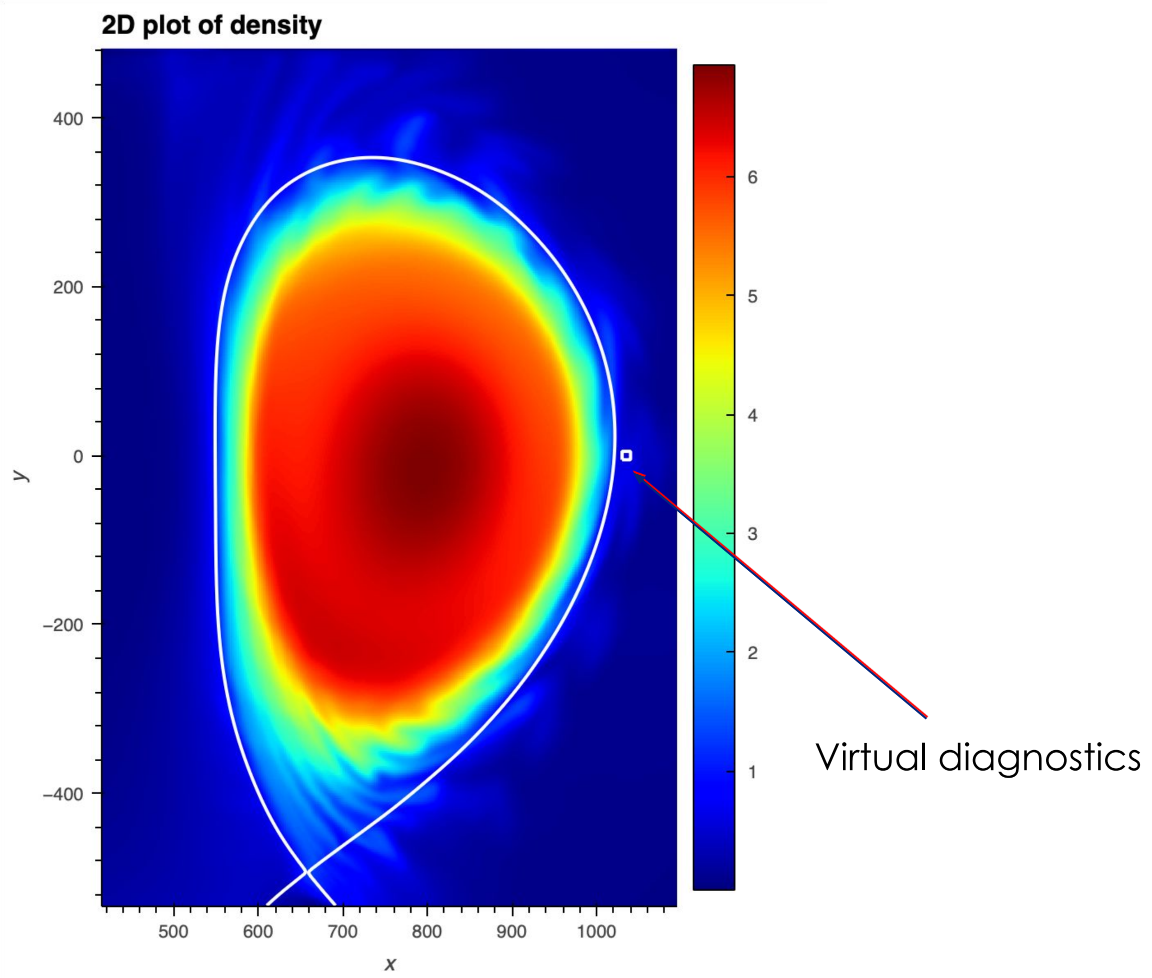

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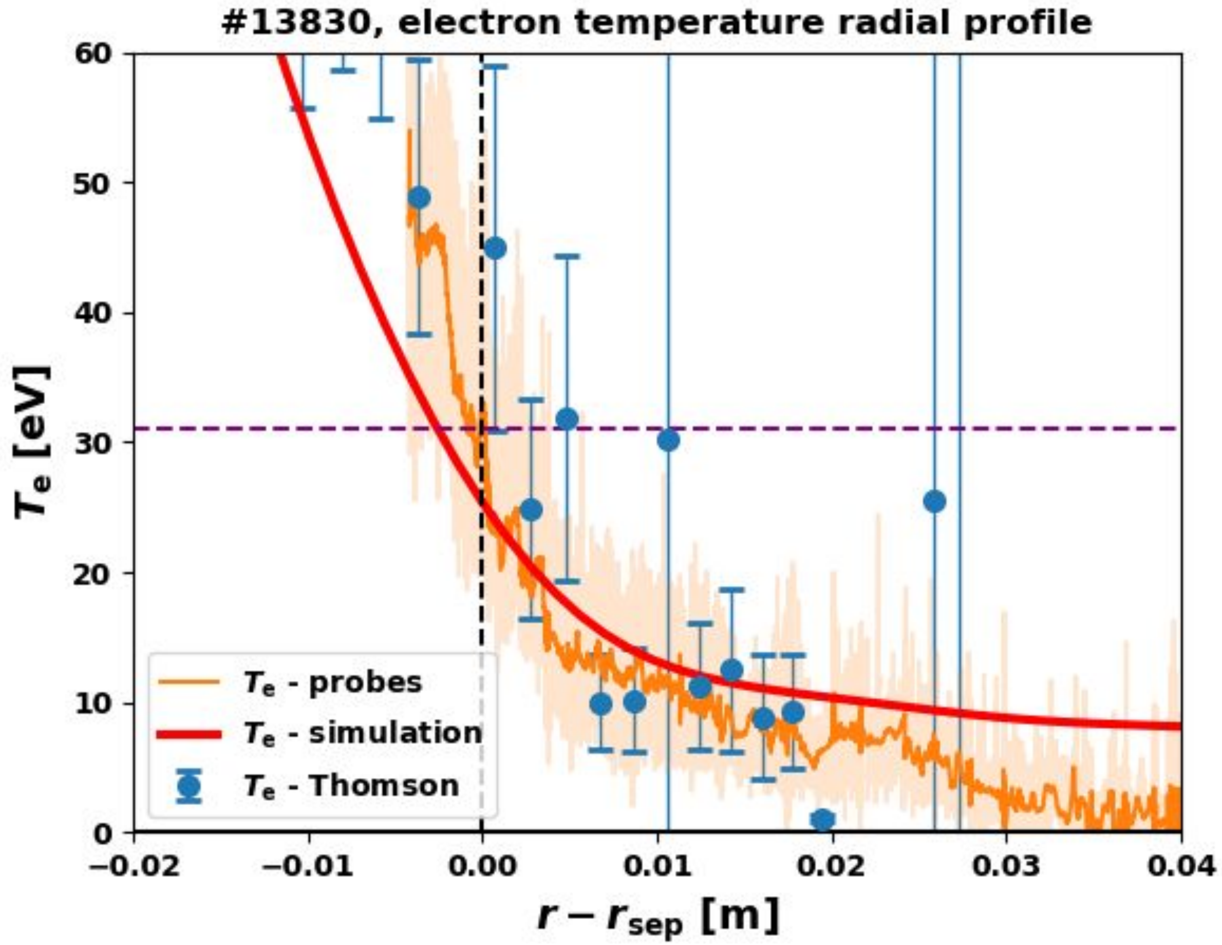

SIMULATION RESULTS AND PLANS

What needs to be done:

- Input parameters must be set closer to experimental values.
- Simulation has to be carried into the quasi-stationary phase.
- Blob statistics must be captured in order to compare with experiment.
- **The validation itself.**
- **Extended simulation with neutrals.**

(validation of GBS on TCV tokamak and TORPEX device was recently performed, resulting in several publications in impacted journals)

SUMMARY

- Various approaches for the tokamak plasma simulation:
    - P2P highly demanding.
    - PIC for kinetic approach
    - Fluid models offer higher speeds, neglecting kinetic effects.

- Discharge for simulation was selected and analyzed.
- The first full-size COMPASS simulation already started, turbulence was already observed.
- Input parameters have to be still changed a bit to meet experimental values.
- Blob statistics have to be captured in order to perform the validation.

REFERENCES

1. M. Giacomin et al J. Comput. Phys. 463 (2022) 111294 (The GBS code for the self-consistent simulation of plasma turbulence and kinetic neutral dynamics in the tokamak boundary)
2. M. Giacomin *et al* 2021 *Nucl. Fusion* **61** 076002 (Theory-based scaling laws of near and far scrape-off layer widths in single-null L-mode discharges)

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