

TOKALAB
An Open Access Virtual Tokamak
For Education and Research



TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA



TokaLab: an open-access and open-source FAIR framework for tokamak synthetic diagnostics and inverse problems benchmarking

Riccardo Rossi, Vasiliki Anagnostopoulou, Valentina D'Agostino, Pasqualino Gaudio, Michela Gelfusa, Simone Kaldas, Andrea Murari, Alessandro Puleio, Novella Rutigliano, Tayyaba Sajid, and Ivan Wyss

8th International Conference on Frontier in Diagnostic Technologies
Frascati, 19-21 October 2026

The Problems

Steep entry barrier.

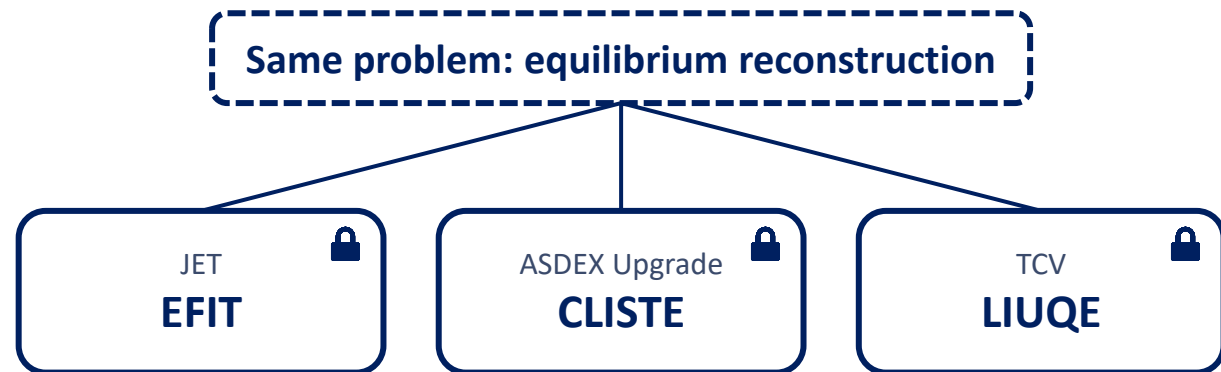
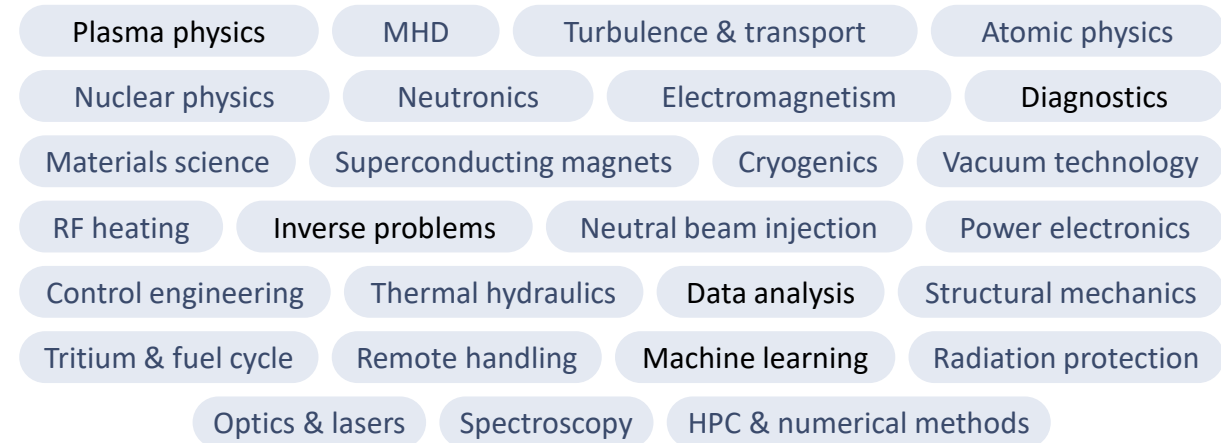
Nuclear fusion is a complex, multidisciplinary field, from plasma physics to engineering, diagnostics and data analysis. This discourages students from starting a career in it.

Closed source.

Most algorithms are closed-source and tailored to a specific machine. As a result, several groups work on the same problem in parallel, with little collaboration.

Missing Benchmarking.

Ad hoc algorithms are validated on machine-specific data, with no common datasets or metrics to benchmark their results.



X Different codes, no common benchmark

Reference equilibrium codes per machine, as compared in Coelho et al., EPS 2016–17

Our Solution

TokaLab is a Virtual Tokamak Laboratory built on four pillars:

Open Source:

Everyone can download, use and contribute to it.

Beginner-Friendly:

Easy to use for non-experts (e.g. bachelor and master students).

Modular:

Modules with different levels of physics fidelity are interchangeable without major modifications.

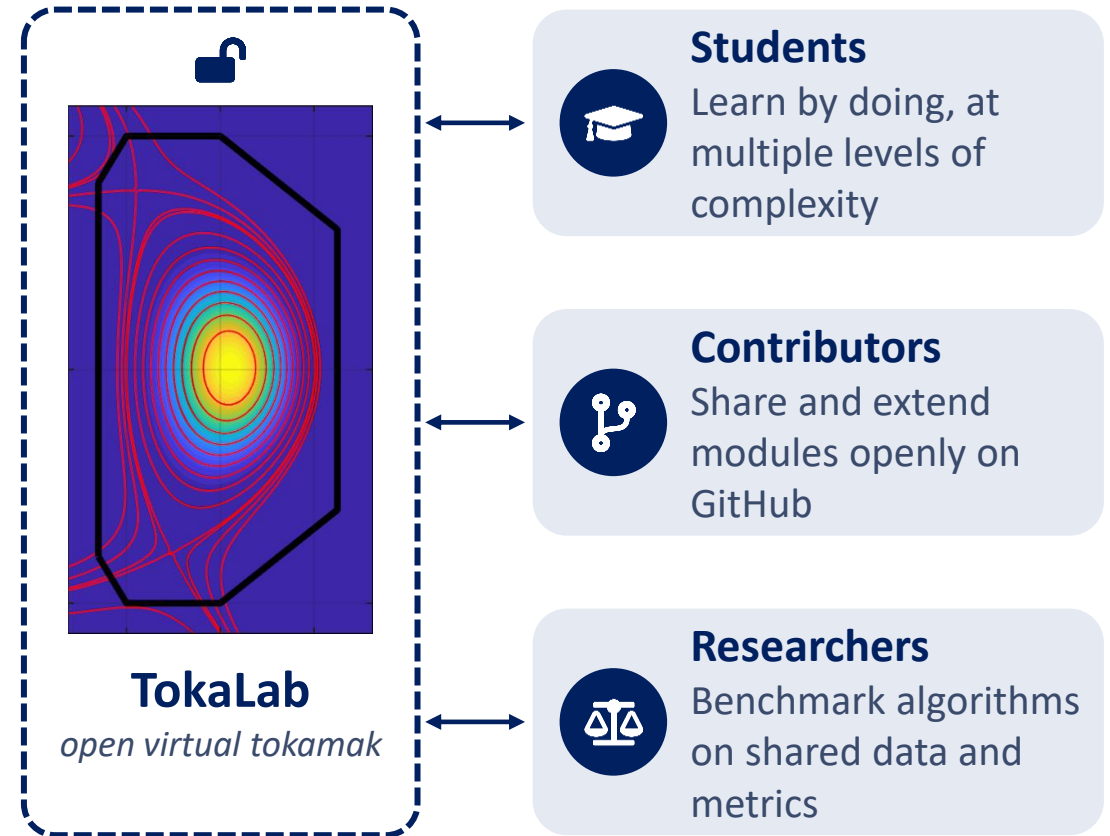
Multi-Machine:

Users can design their own tokamak or apply the methods to existing ones.



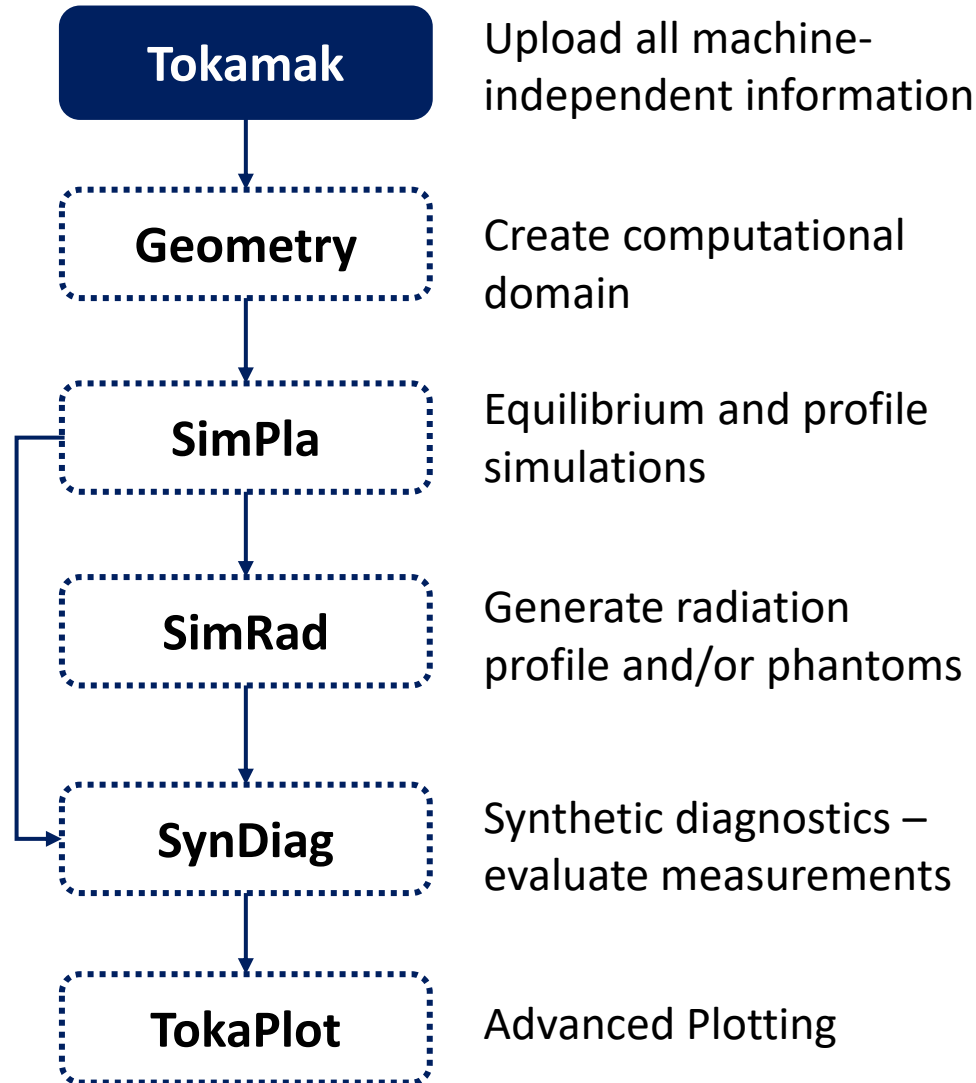
Scan to get started on GitHub

Findable · Accessible · Interoperable · Reusable



Same tools, same data, same benchmarks — for everyone

TokaLab architecture



```
% machine definition
Machine: "TokaLab"

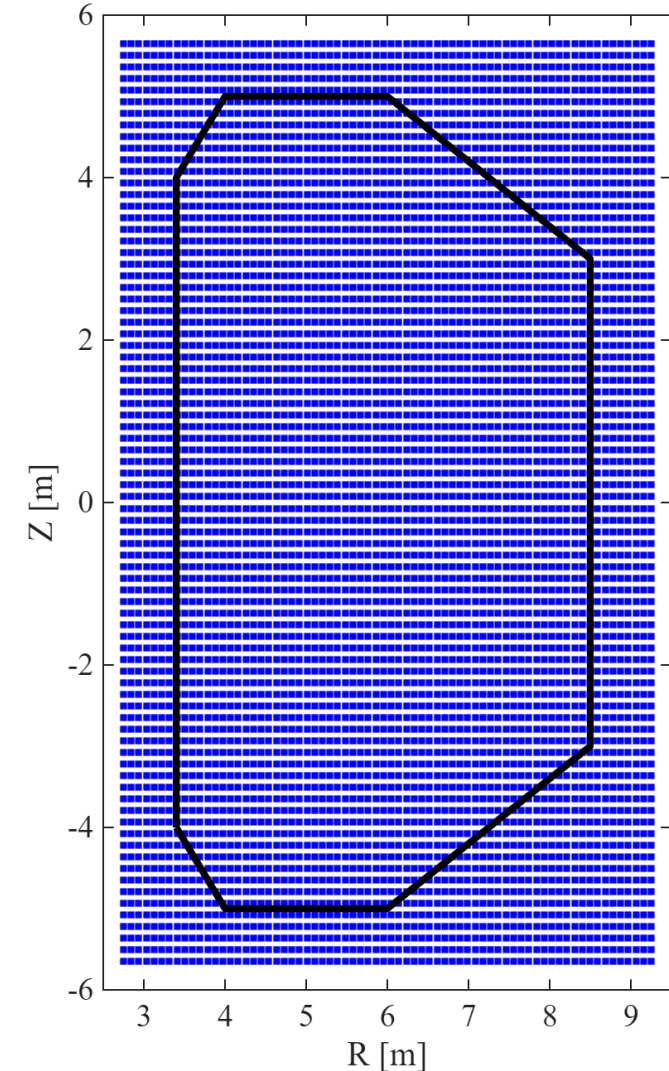
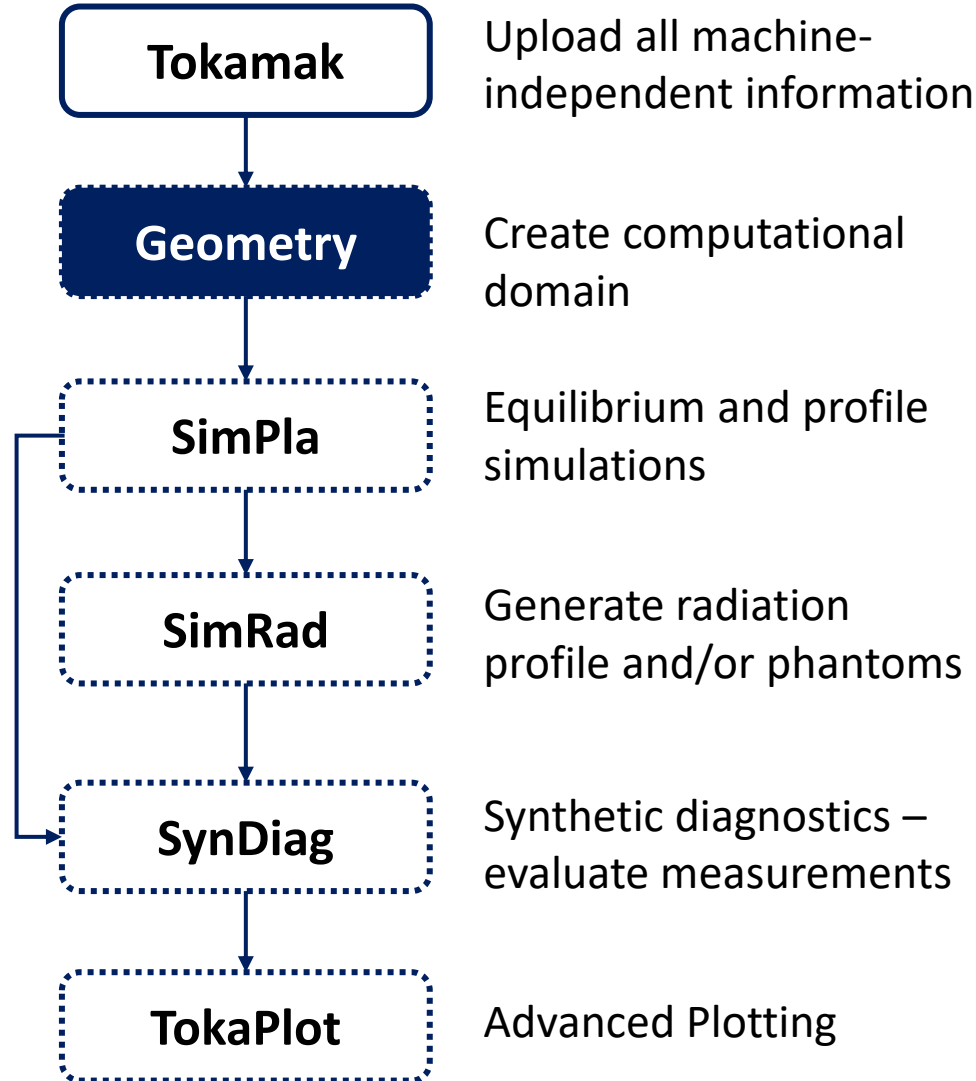
% geometry
Major_radius: 6; %[m]
Minor_radius: 2; %[m]

% wall information
Wall = load("TokaLabWall.mat");

% other information
Other info...
```

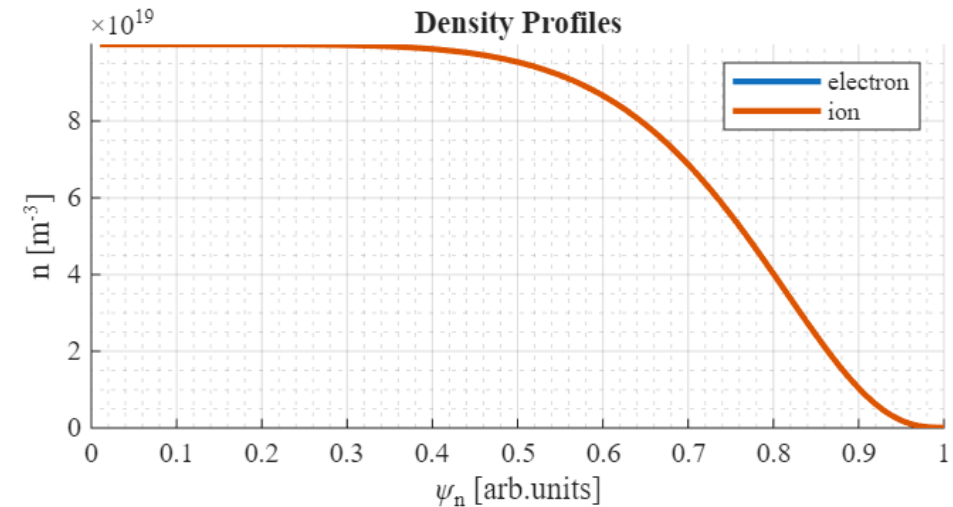
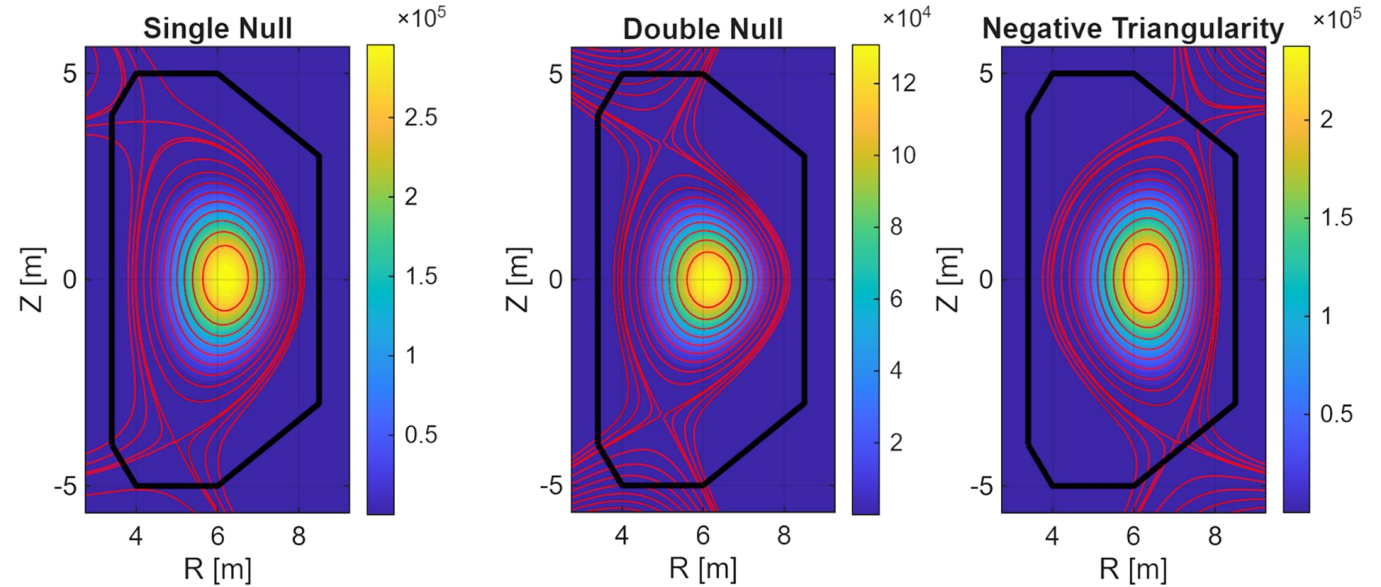
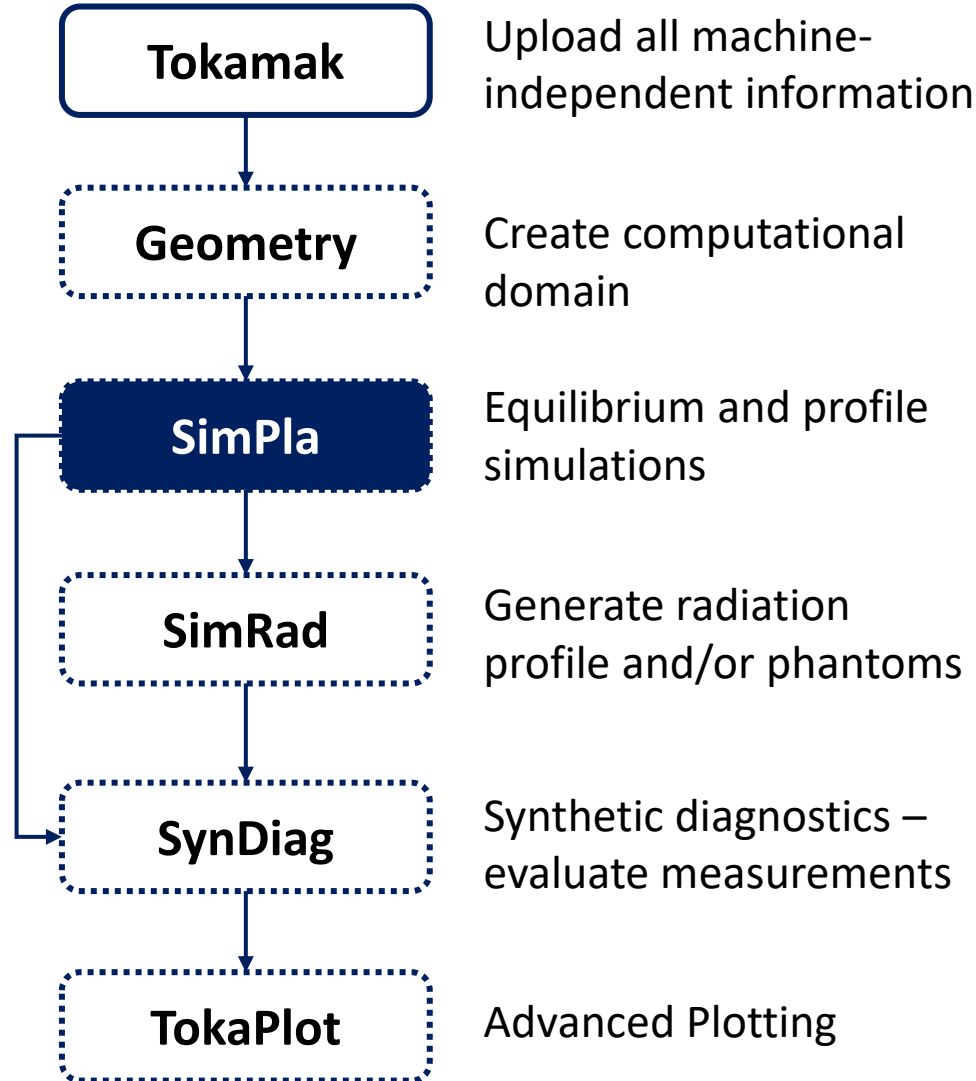
———— Machine Specific Machine Agnostic

TokaLab architecture

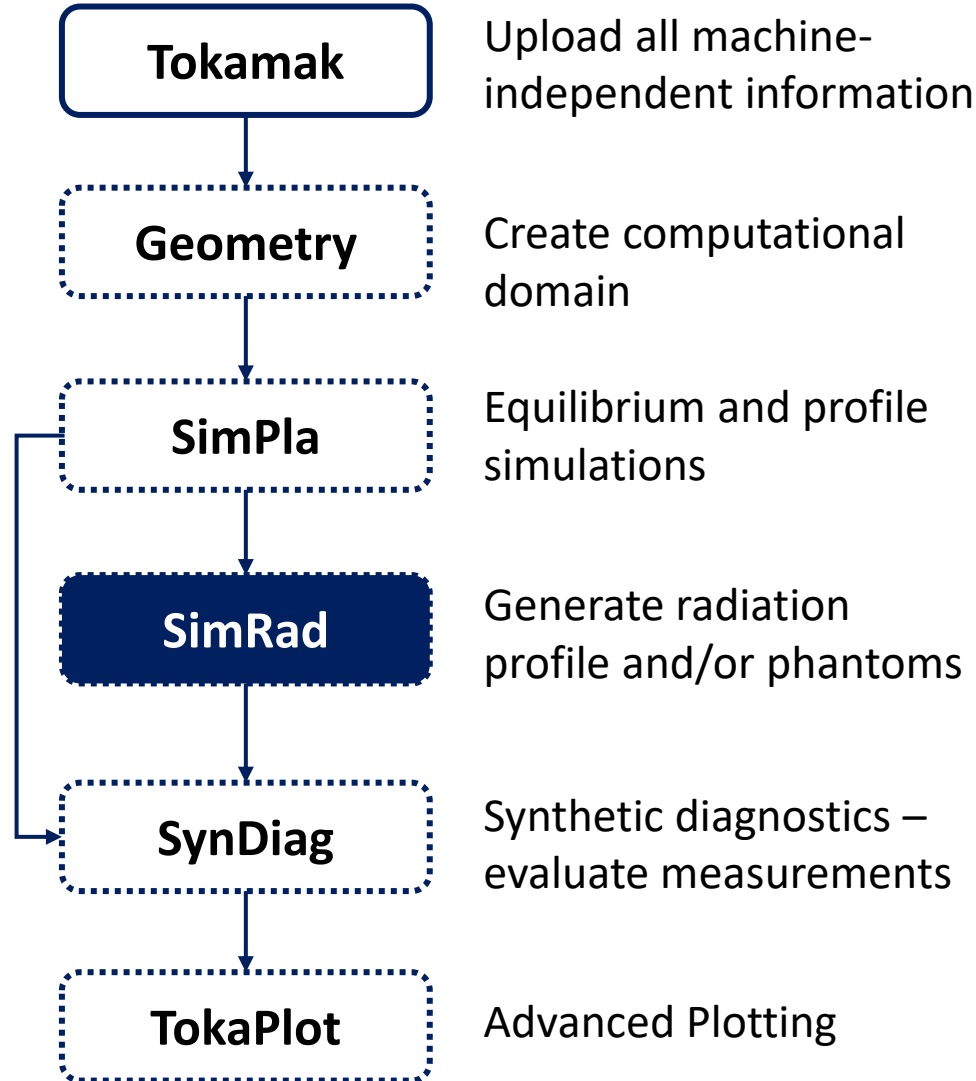


———— Machine Specific Machine Agnostic

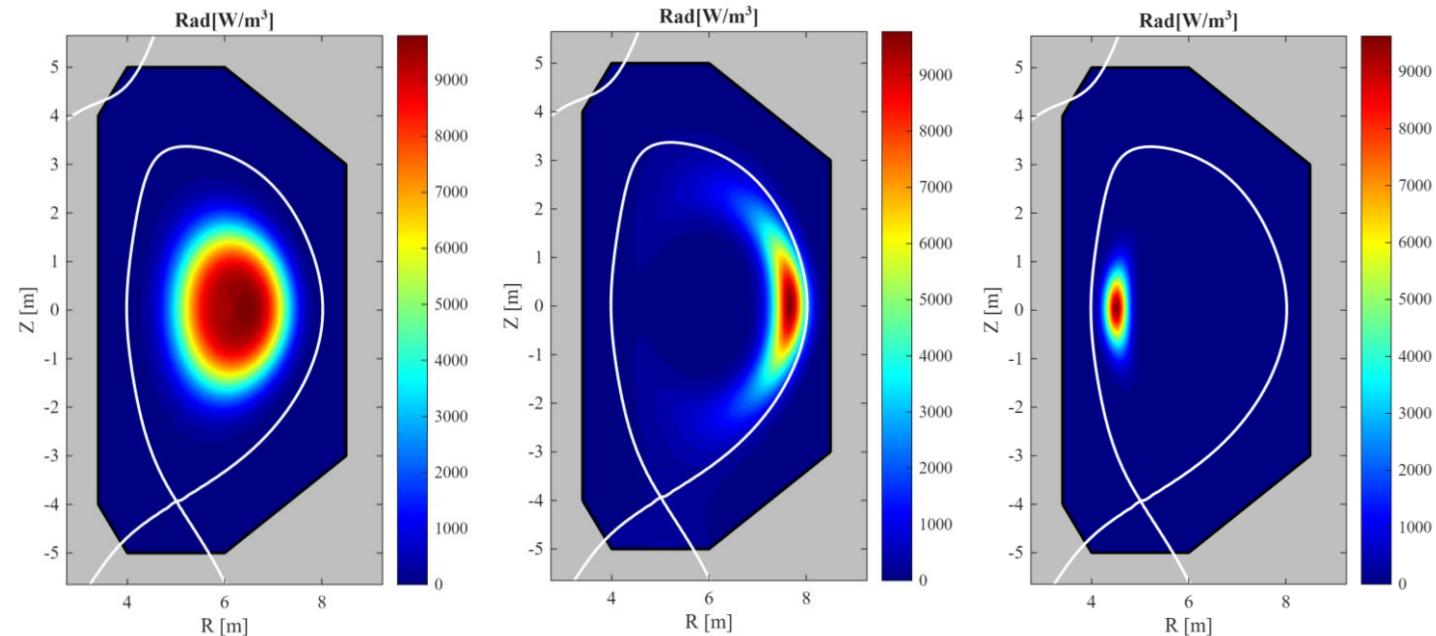
TokaLab architecture



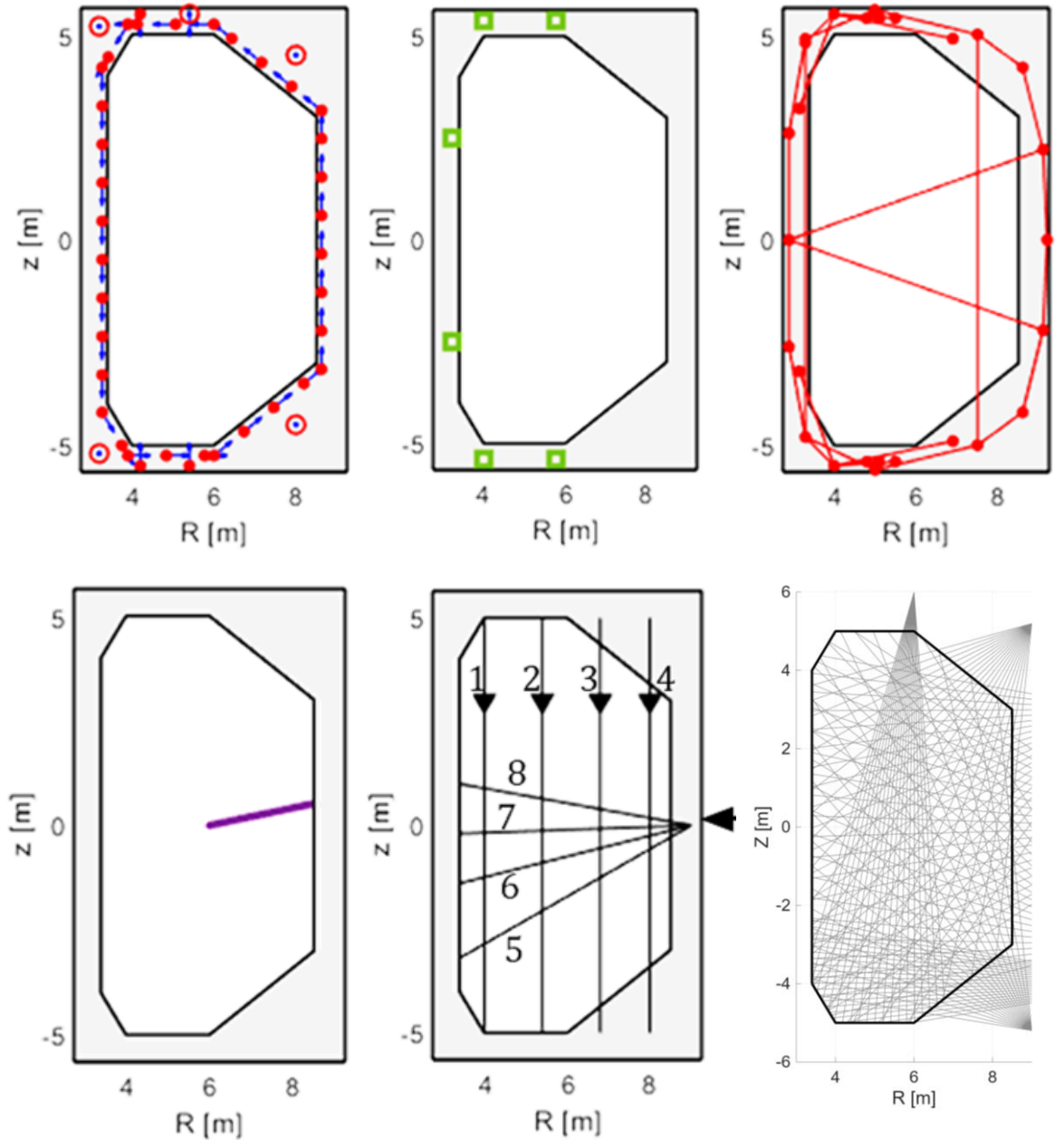
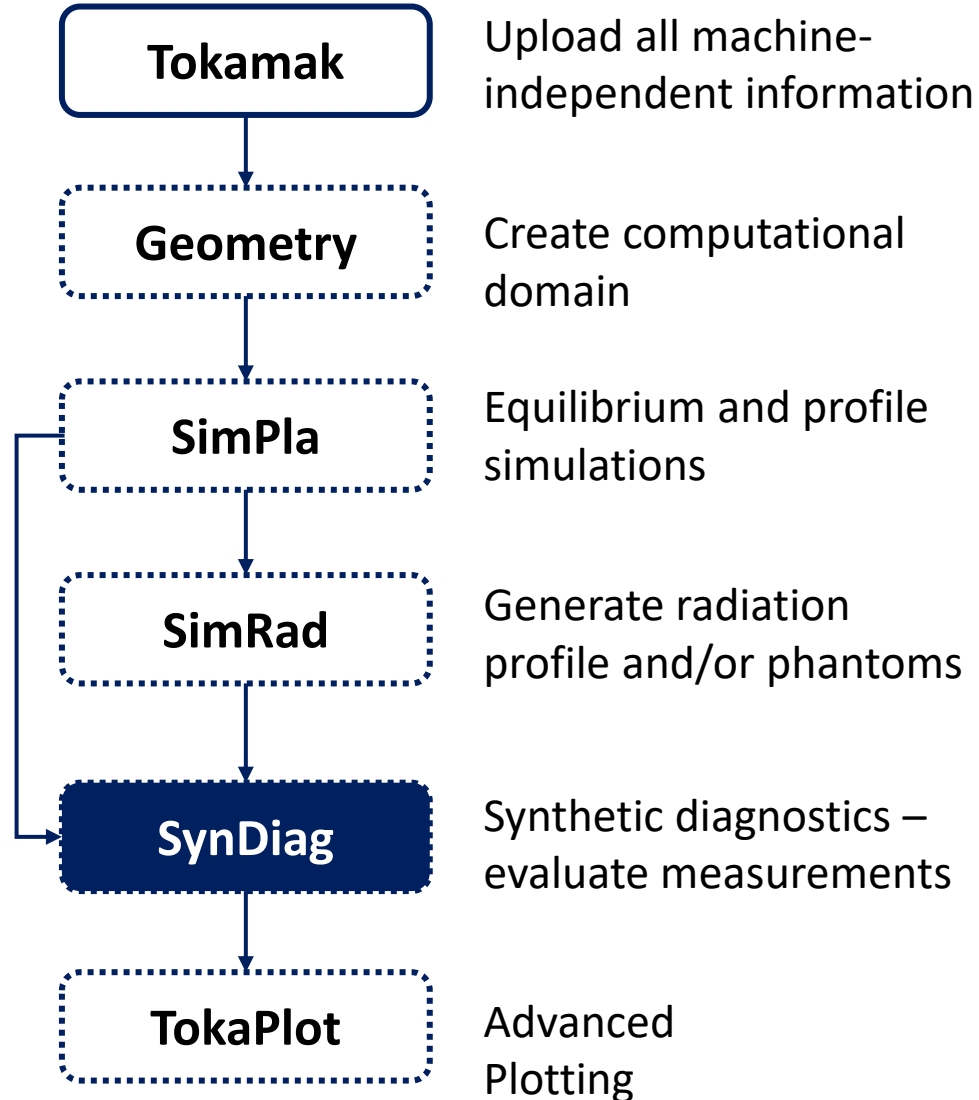
TokaLab architecture



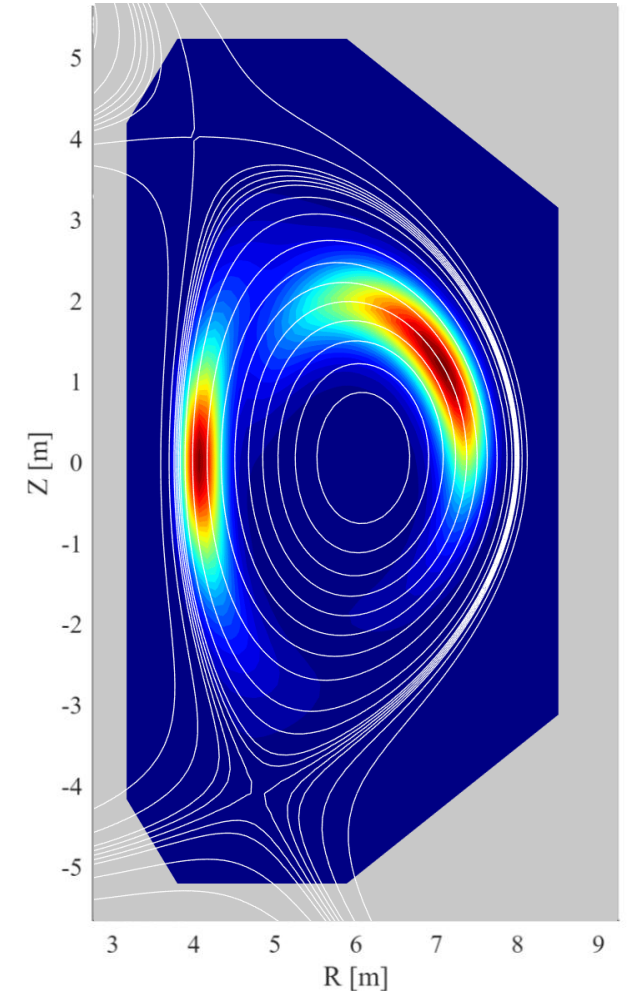
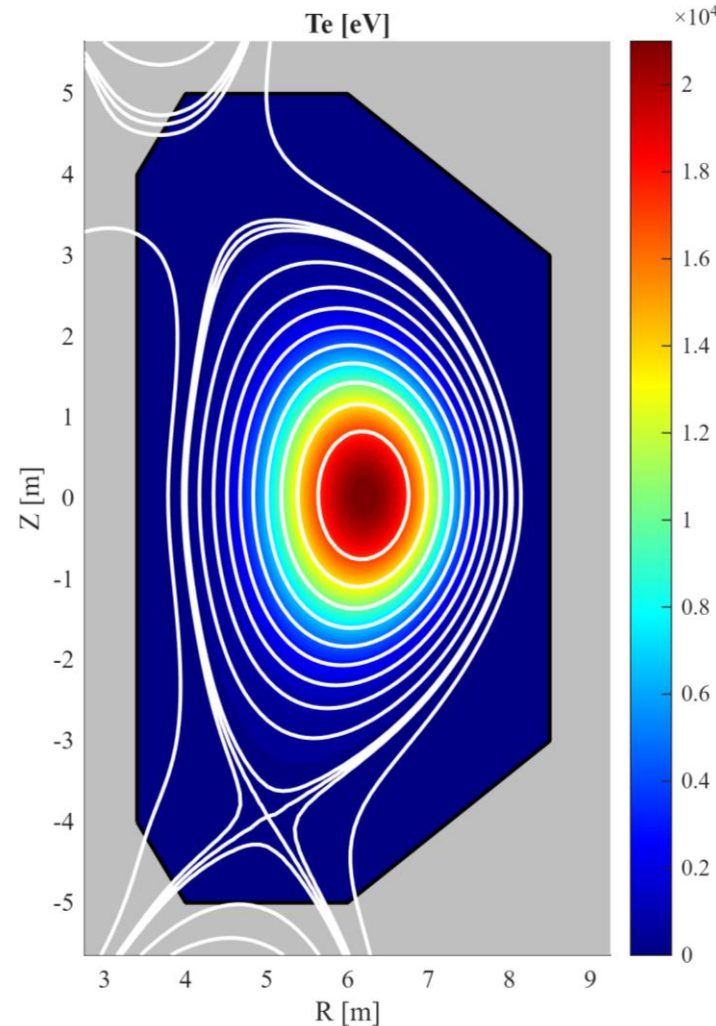
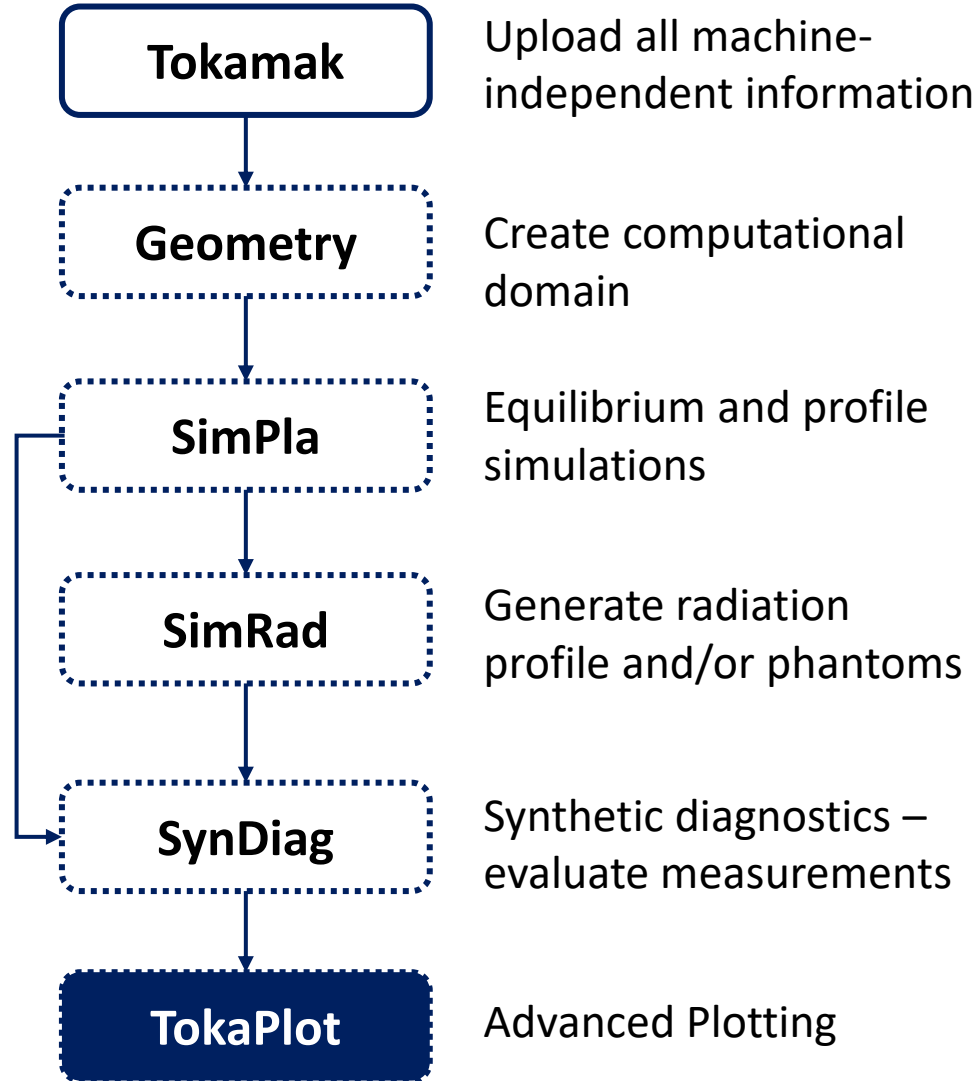
- **Physics models**: high-fidelity physics, slow (e.g. Bremsstrahlung)
- **Analytical models (or phantoms)**: lower fidelity, fast (e.g. MARFE-like)



TokaLab architecture



TokaLab architecture



TokaLab applications

Sharing

- Open-Source repository to share methods, algorithms, solutions and problems

Education

- Development of computational resources to support education

Research

- Synthetic tokamak for methods **verification**
- **Integrable in workflow for diagnostic design**
- Open-Source repository for **benchmarking**
- **Data generation for machine/deep learning training and test, data augmentation.**

In this conference:

AI session (Tuesday)

- Novella Rutigliano, Integrating magnetic and kinetic measurements in the equilibrium reconstruction of tokamaks with Physics Based Neural Networks

In this conference:

AI session (Tuesday)

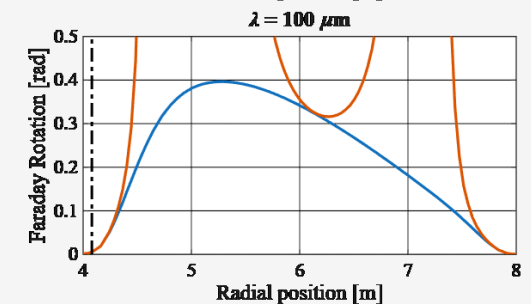
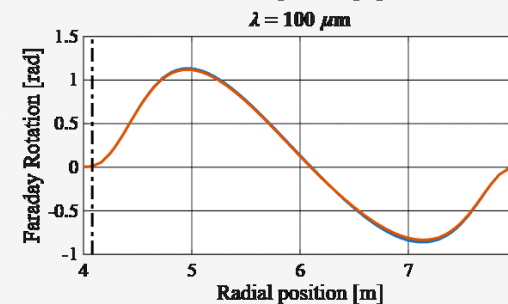
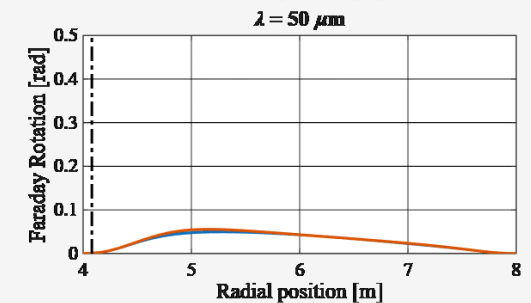
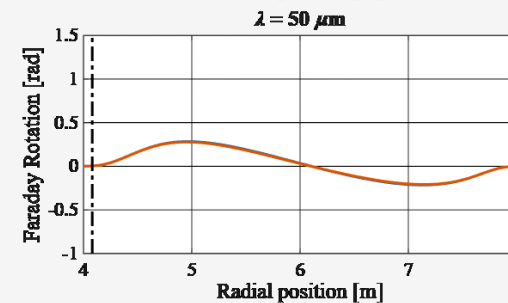
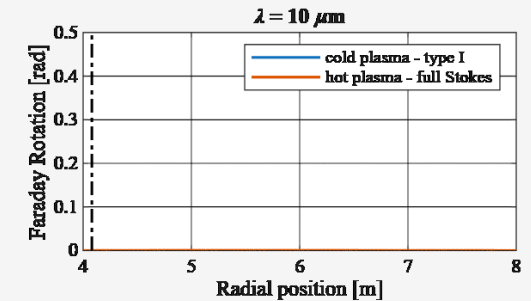
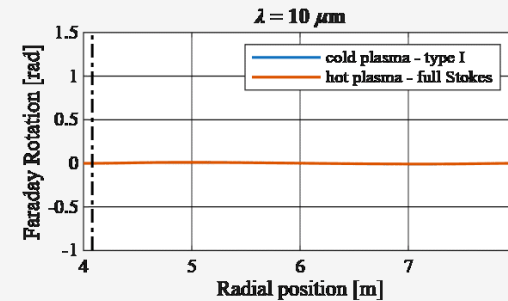
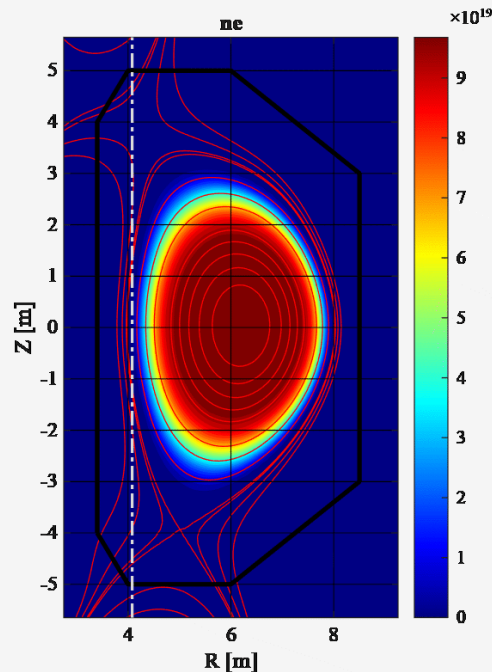
- Ivan Wyss, Optimising the layout of tomographic diagnostics with Genetic Programming

Diagnostic design

It can be used to develop methods for diagnostics design, data analysis, approximation validity, etc.

The example shows Type-I cold plasma approximation against full-Stokes hot plasma approach for plasma polarimetry variables: **Faraday rotation** and **Cotton-Mouton** phase shift.

Longer wavelengths increase the polarimetric signals, and so the **SNR**, but also leads to strong **non-linearities**, making measurements **harder to interpret**.



Benchmarking

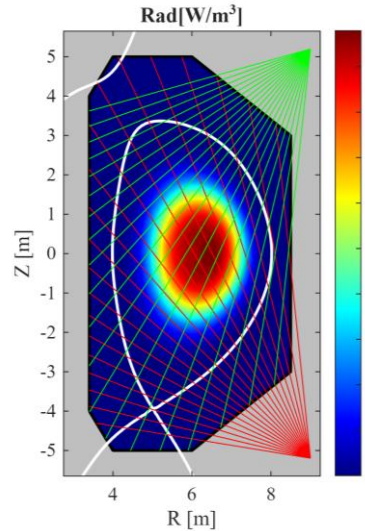
With TokaLab it is possible to generate different synthetic/numerical scenarios that are open to everyone.

A new repository, **BenchLab** has been developed for benchmarking.

The example reports the **workflow for inverse problems**:

1. Scenario simulation (Target)
2. Synthetic diagnostics simulation
3. Inverse problem (from diagnostics to field)
4. Comparison between target and prediction.

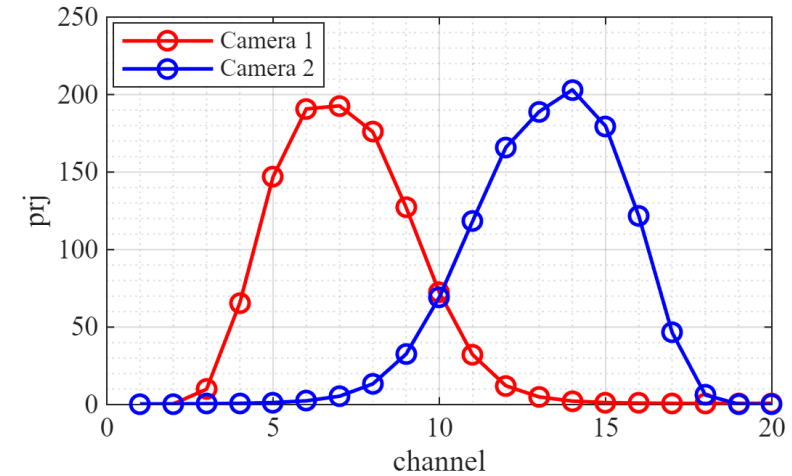
SimPla + SimRad
Generates scenarios



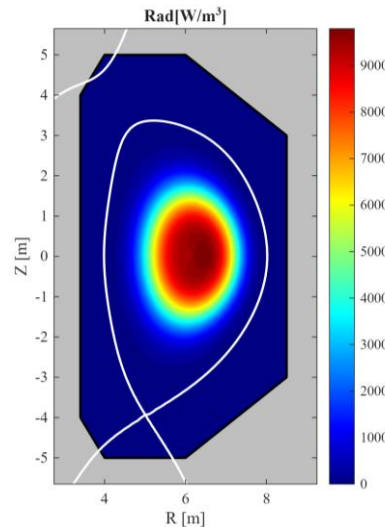
Evaluate
measurements
from fields



SynDiag
Evaluate measurements



Comparison with target



Data analysis
algorithms
outputs



Measurements are
used by data analysis
algorithms

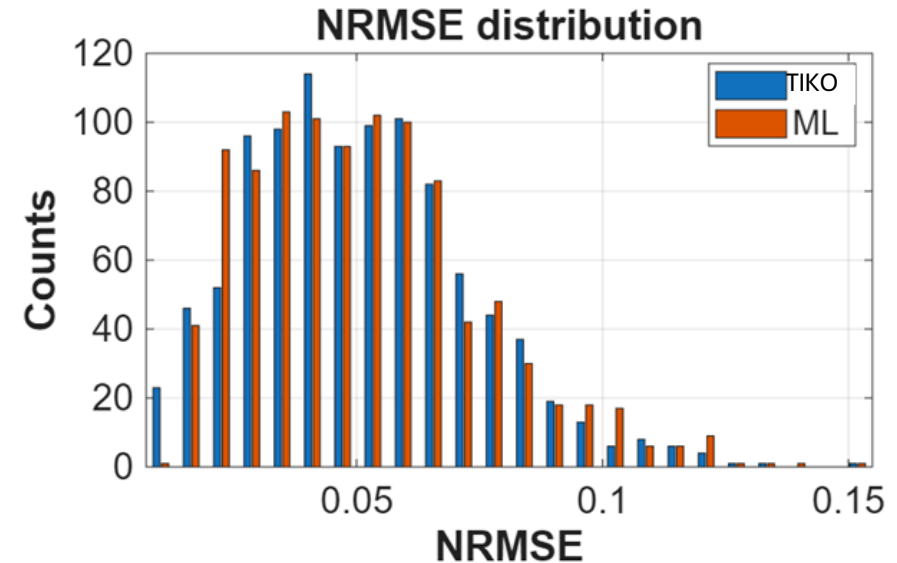
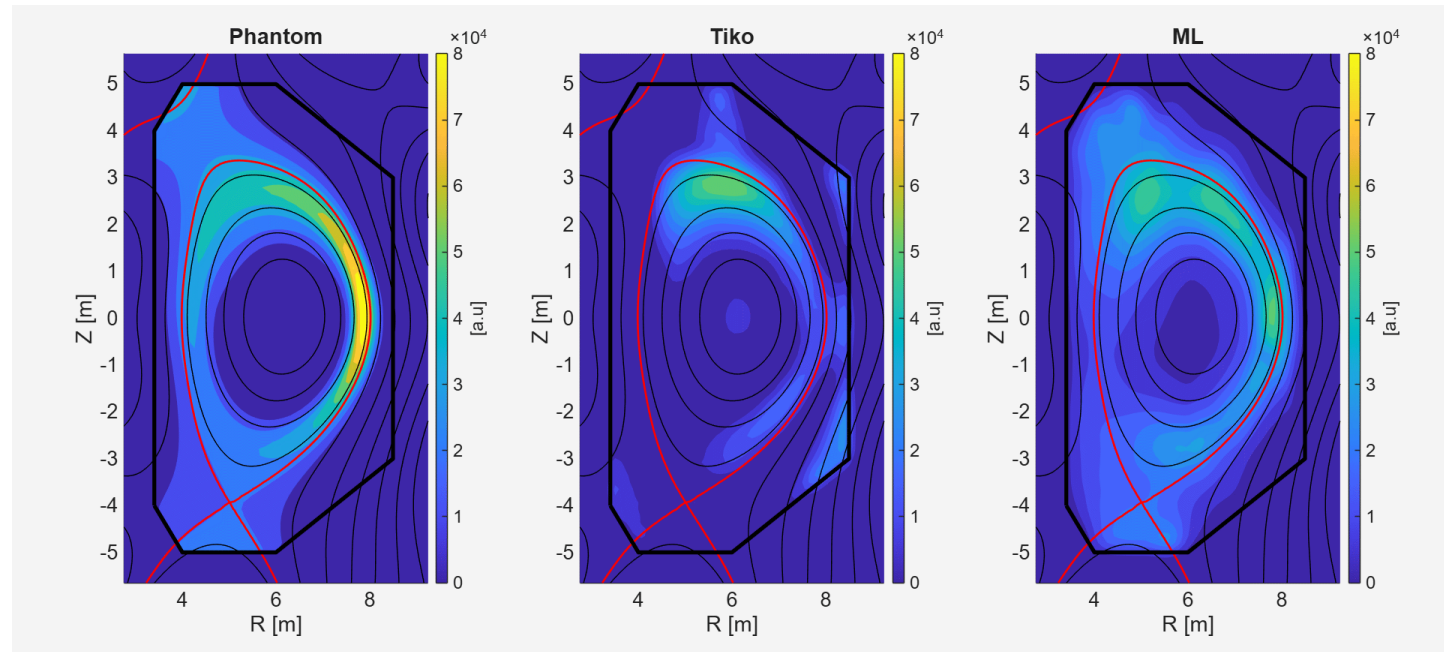
Algorithms to be benchmarked

Benchmarking

At the moment BenchLab contains only tomographic algorithms (from line-integrated emissivity to local emissivity) and compares two algorithms:

- Tikhonov
- Maximum Likelihood (ML)

New algorithms can be easily integrated.



Algorithms development and test

TokaLab capabilities are well suited for Artificial Intelligence applications:

- **Methods verification**
- AI and developer “**Gym**” where specific algorithms can be designed, developed, and tested before going on real scenario and real data
- **Data augmentation**

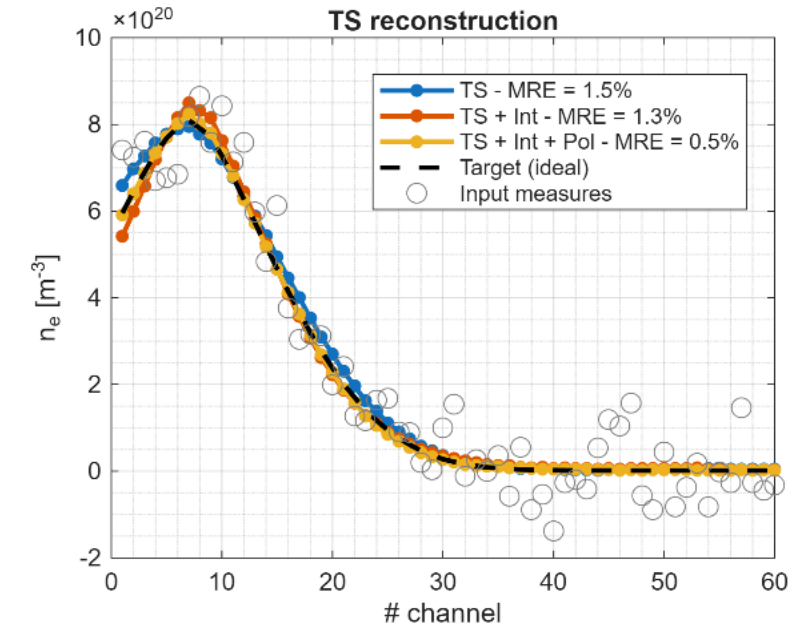
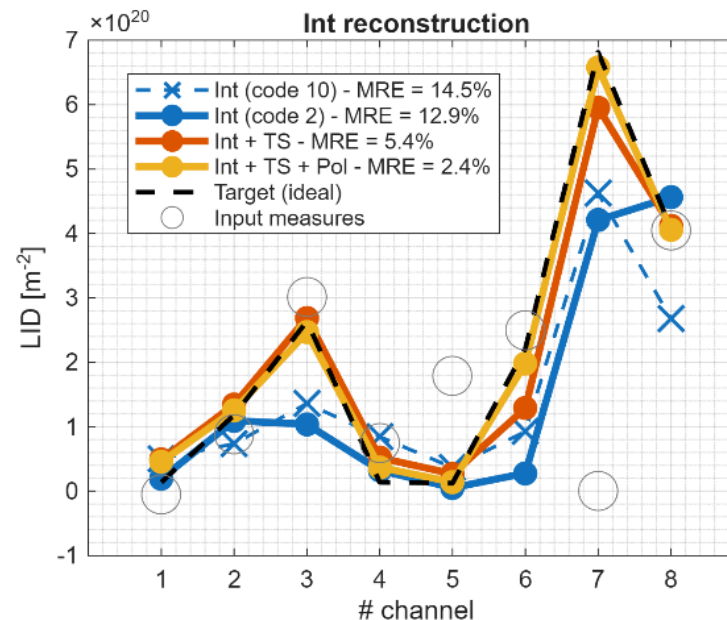
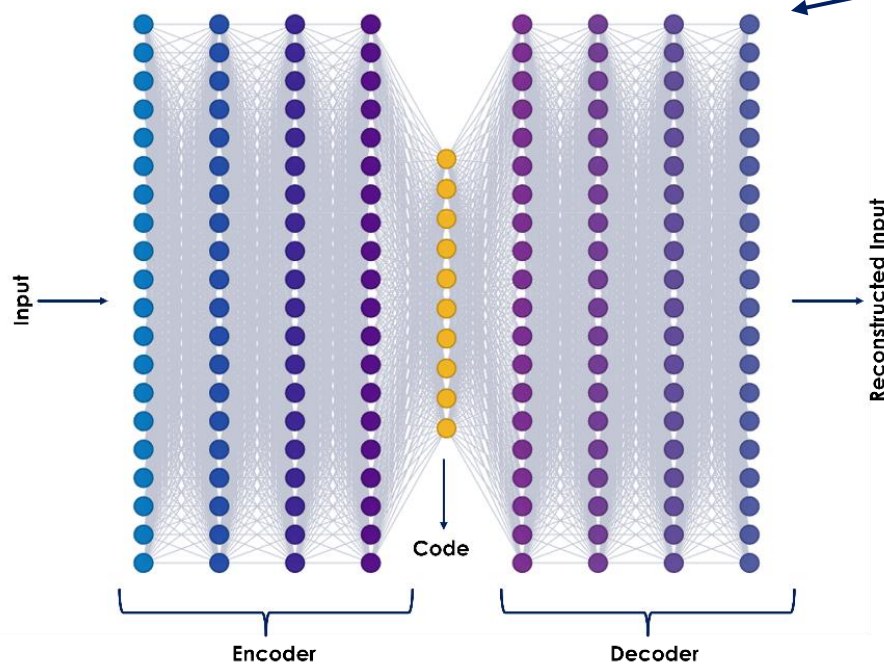
In this conference:

Poster Session A (Monday)

Tayyaba Sajid, A Neural Network Approach for DTT Plasma Profile Reconstruction validated on data-driven TCV kinetic surrogates

Simone Kaldas, Journal of Fusion Energy, 2026

<https://doi.org/10.1007/s10894-026-00568-w>



Beyond coding

We built not just lines of code, but a **team**.

Research

- Used in more than five peer-reviewed scientific articles
- Presented at several international conferences
- Adopted in national and international collaborations and projects

Education

- Integrated into several university courses
- Development of an educational game (TokaCards)

Dissemination

- Organisation of workshops and events at Tor Vergata University

Contribution

- Everyone can contribute by joining the team or by just developing/implementing new methods



Conclusions and Next Steps

Conclusions

We built a virtual tokamak laboratory for **sharing codes and methods**.

Everything is based on **multi-fidelity**: from simple, easy-to-use tools to research-grade methods. It has found applications in many research works (more than initially expected).

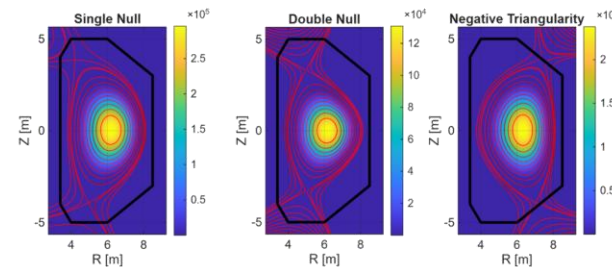
Next Steps

New modules: free-boundary equilibria, impurity transport, new benchmarks (e.g. equilibrium reconstruction).

New initiatives: more educational activities and wider collaborations.

TokaLab

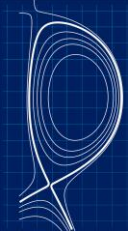
- VirtualLab
- BenchLab



TokaCards

Educational Card Game





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