

ToFu

An open-source python/cython library for synthetic
tomography diagnostics on tokamaks

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Context

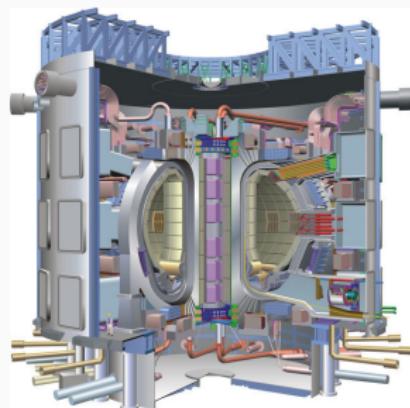
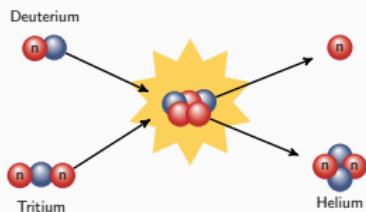
Context: energy needs vs resources and climate change



Worldwide growing energy needs (population, standards of living...)
⇒ high pressure on environment (degrading, changing, exhausting...)
⇒ decrease consumption + alternative production means
⇒ relatively clean, safe, mass-production means with large resources
would be welcome in the mix

Context: Controlled fusion and magnetic confinement

D-T Fusion reaction



- Gas > 100 Million°K composed of positive ions and negative electrons: plasma
- Confinement using electromagnetic fields
- break-even not obtained yet

In a nutshell: toroidal vacuum vessel, filled with H plasma

Tomography diagnostics

Tokamak diagnostics to measure plasma quantities

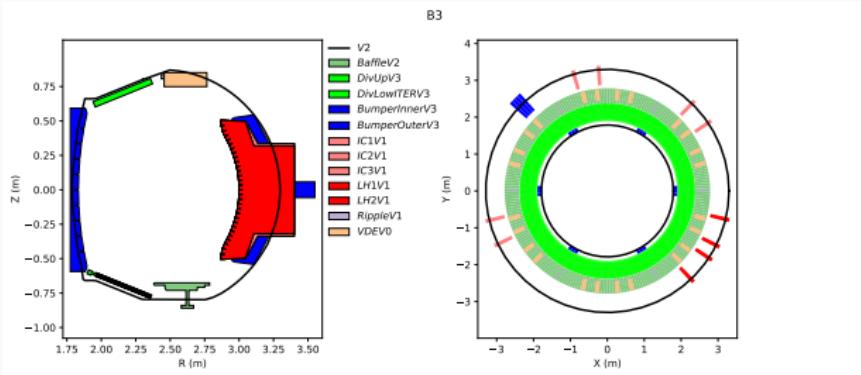
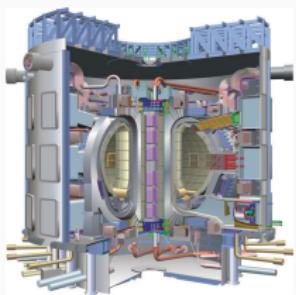
Diagnostics

Set of instruments to measure plasma quantities, for understanding, control, optimization.

e.g: magnetic field, neutrons, **emitted light**, temperature, density...

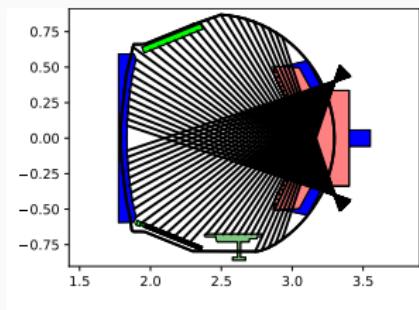
⇒ pinhole cameras (1D or 2D) for measuring light in various wavelengths

A tokamak as a poloidal + horizontal projections



Tomography diagnostics - numerical context

$$M_i(t) = \iiint_{V_i} \overrightarrow{\varepsilon(x,t)} \cdot \vec{n} \Omega_i \, dV$$



- **Direct problem** (synthetic diagnostic):

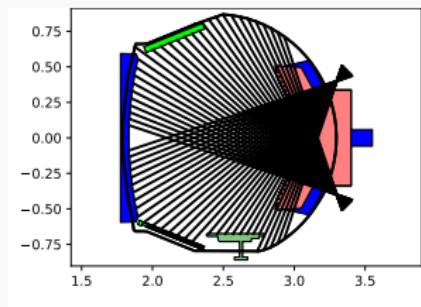
Simulated emissivity \longrightarrow integrated measurements

- **Inverse problem** (tomography):

Integrated measurements \longrightarrow Reconstructed emissivity

Tomography diagnostics - numerical context

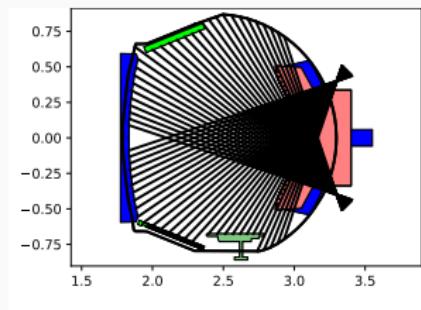
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- **Direct problem** (synthetic diagnostic):
Simulated emissivity → measurements
Spatial integration
- **Inverse problem** (tomography):
Integrated measurements → Reconstructed emissivity
Mesh and basis functions construction, spatial integration, data filtering, inversion routines, etc.

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Tomography is **ill-posed**, very sensitive to errors, noise and bias
→ Reputation for low reproducibility / reliability

The ToFu package

Motivation: “current” state

In the fusion community, codes for tomography diagnostic are often:

- developed by physicists (with little programming experience)
- in Matlab (or IDL)
- written from scratch, re-done by new students
- not distributed (few users), rarely documented

... which means

- waste of resources: time, man-power
- low traceability, reproducibility
- low standardization, unclear assumptions / methods

A code for Tomography for Fusion

Develop a common tool:

- Generic (geometry independent)
- Portable (Python)
- Optimized / parallelized
- Documented online
- Continuous integration



ToFu¹²³ = Tomography for Fusion

¹repository: <https://github.com/ToFuProject/tofu>

²documentation: <https://tofuproject.github.io/tofu/index.html>

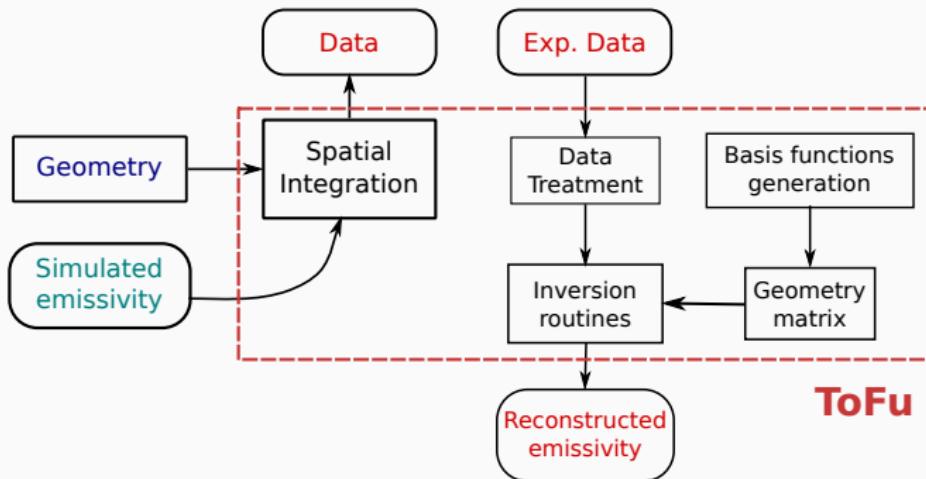
³ D Vezinet et al. "Non-monotonic growth rates of sawtooth precursors evidenced with a new method on ASDEX Upgrade". In: *Nuclear Fusion* 8 (2016).

More about Tofu

- Created in 2014
- Open Source: **MIT license**
- Python 2.7 and **Python 3 + Cython**
- Continuous integration: **Travis CI**
- **conda, pip**
- Two (main) developers:
 - ▶ Didier Vezinet (creator, Physics)
 - ▶ Laura S. Mendoza (since 06.2018, Applied Maths)
- Contributors:
 - ▶ Jorge Morales
 - ▶ Florian Le Bourdais
 - ▶ Arpan Khandelwal



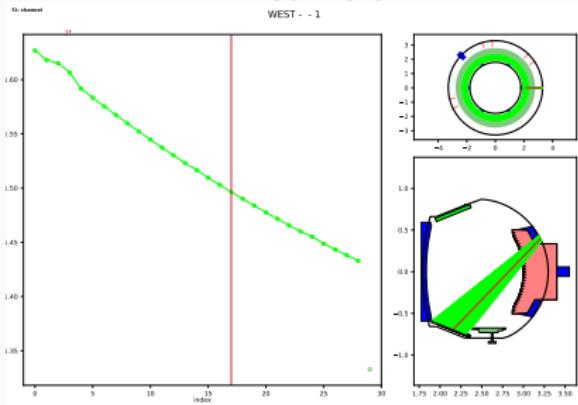
Tofu's structure



ToFu

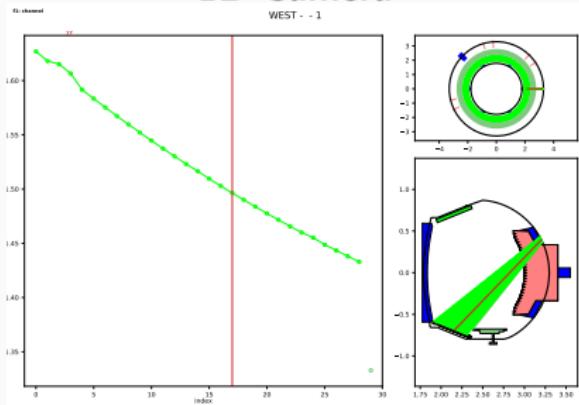
tofu.geom: modeling of simplified geometry

1D Camera

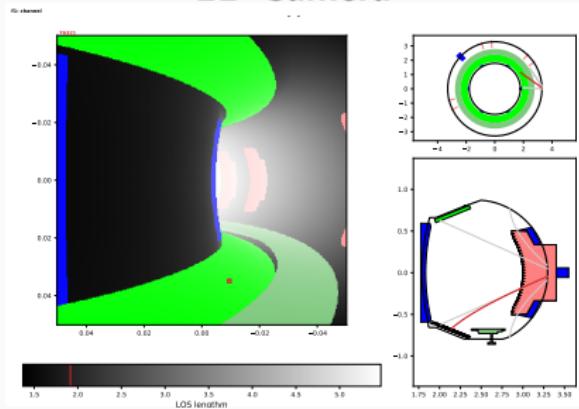


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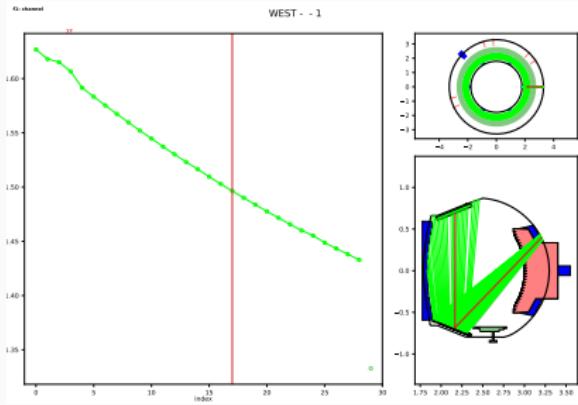


2D Camera

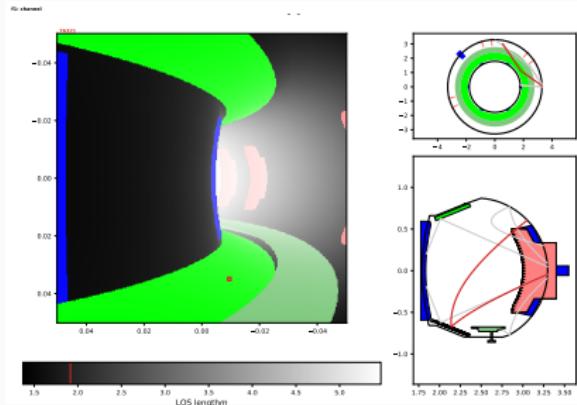


tofu.geom: handle basic reflexions

1D Camera with reflexions



2D Camera with reflexions



What ToFu can do

- Model simplified 3D geometry
- 3D modeling of a 1D and 2D camera
- Handle basic reflections
- Computing synthetic signals
- native support for IMAS interfacing
- data easy interactive visualization and basic treatment

What ToFu can do

- Model simplified 3D geometry
- 3D modeling of a 1D and 2D camera
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- native support for IMAS interfacing
- data easy interactive visualization and basic treatment
- ...and soon (being re-written / developed):
 - ▶ meshing and basis functions
 - ▶ tomographic inversion
 - ▶ dust particle trajectory tracking (new, Arpan)
 - ▶ faster Matplotlib + PyQtGraph visualization
 - ▶ magnetic field line tracing (new)
 - ▶ statistical data analysis (pandas) integrated

Demo

Demo

Code Optimization

Geometry reconstruction: ray-tracing techniques

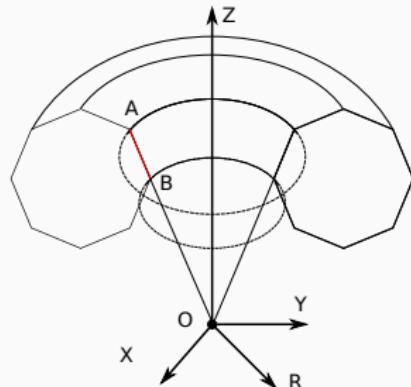
To reconstruct emissivity we need to take account:

- Up to hundreds of structural elements in vessel
 - Scale of the vessel: 10^4 bigger than smaller structural detail
- ⇒ Geometry defined with minimal data polygon (R, Z)
extruded along φ
- ⇒ Symmetry of vessel along φ



Optimization of ray-tracing algorithm

- Description of geometry:
 - ▶ Vessel and structures: set of 2D polygon
$$\mathcal{P}_j = \bigcup_{i=1}^n \overline{A_i B_i}$$
 - ▶ Extruded along $[\varphi_{min}, \varphi_{max}]$
 - ▶ Detectors defined as set of rays (of origin D and direction u)
⇒ Light memory-wise
- ⇒ Equivalent to: set of truncated cones
(frustums) of generatrix $A_i B_i$



Ray-tracing algorithm on fusion device → Computation of cone-Ray intersection

$$\exists (q, k) \in [0; 1] \times [0; \infty[, \quad \left\{ \begin{array}{l} R - R_A = q(R_B - R_A) \\ Z - Z_A = q(Z_B - Z_A) \\ DM = ku \end{array} \right.$$

Optimization of ray-tracing algorithm

Cone-Ray intersection algorithm:

- Main steps:
 - ▶ Test intersection **bounding-box**
 - ▶ **special cases** (ray direction, segment, etc.)
 - ▶ General case: solution of a **quadratic equation**
- Pre-computation of variables
- Core functions in **Cython**
- Parallelization (**prange** loops)

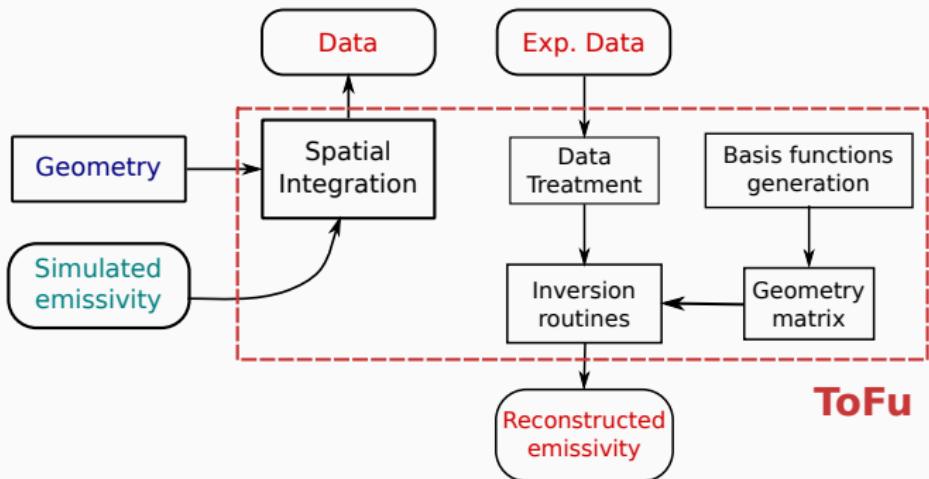
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| Nb LOS | 10^3 | 10^4 | 10^5 | 10^6 | |
|------------|----------------------|----------------------|----------------------|-------------------|-----------|
| original | $3.26 \cdot 10^1$ | $3.10 \cdot 10^2$ | $3.20 \cdot 10^3$ | $3.17 \cdot 10^4$ | (8h48) |
| optimized | $2.58 \cdot 10^{-2}$ | $2.72 \cdot 10^{-1}$ | 2.74 | $2.66 \cdot 10^1$ | (< 30s) |
| 32 threads | $1.36 \cdot 10^{-2}$ | $4.66 \cdot 10^{-2}$ | $3.64 \cdot 10^{-1}$ | 2.92 | |

Tofu's structure



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Optimization of spatial integration routines

Integration of **user-defined function** along a LOS:

- Integration of a python function **func** defined by user by:
 - ▶ **numpy.sum** (quad: **midpoint**)
 - ▶ Cython based sum (quad: **midpoint**)
 - ▶ **Scipy.integrate.simps**
 - ▶ **Scipy.integrate.romb**
- Optional optimizations:
 - ▶ calls to **func**: avoid Cython-Python conversion, user-defined
 - ▶ memory: fine resolutions, high number of LOS
 - ▶ hybrid: compromise

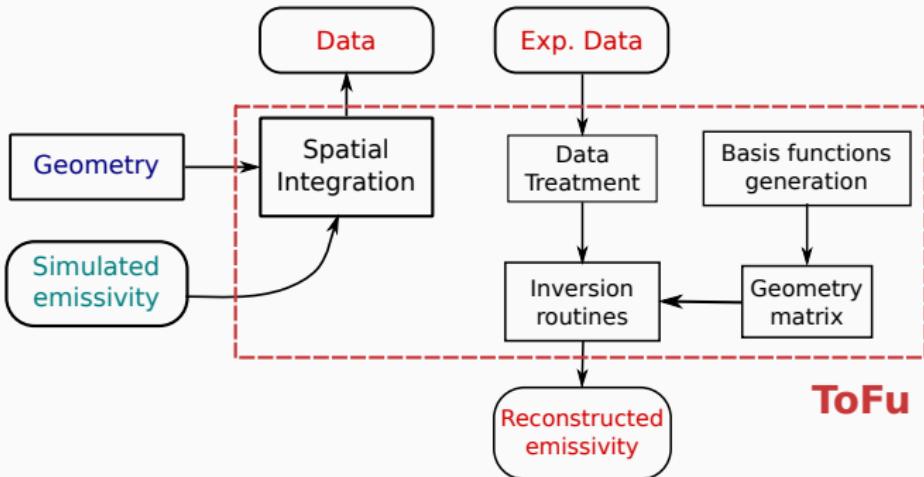
Optimization of spatial integration routines

| LOS | 10 | 10^2 | 10^3 | 10^4 |
|----------|-------|--------|--------|-------------|
| original | 0.46 | 2.24 | 18.1 | x |
| memory | 0.9 | 8.9 | 96 | 945 (6Gb) |
| calls | 0.207 | 0.53 | 4.32 | x |
| hybrid | 0.08 | 0.44 | 4.2 | 40.3 (32Gb) |

- Space resolution: 10^{-3}
- Number of time steps: 10^3
- Integration method: **sum** (Cython or numpy) on midpoint

What's next

Tofu's structure

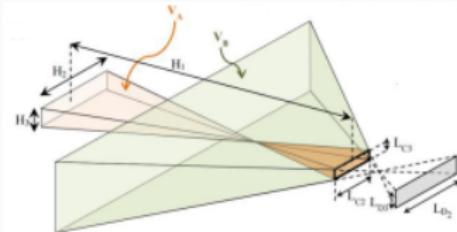


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Tofu's main algorithms

Geometry:

- Finite beam width ($\text{LOS} \Rightarrow \text{VOS}$)
- thermal heat load computation
- More advanced reflections



Meshing and Inversions:

- Meshing and Basis functions (local and global) with visualization
- geometry matrix (fast) computation and introspection plots
- Multiple Inversion-Regularization (linear and non-linear) and visualization
- post-inversion analysis tools

On the side:

- Statistical data analysis (tofu / pandas interface)
- Basic magnetic field line and particle trajectory tracing
- continued IMAS support

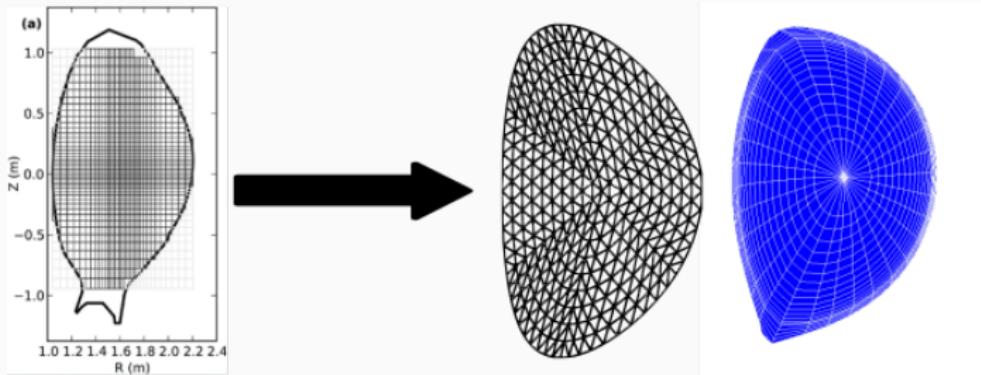
On geometry discretization: meshing

Several options for poloidal cut meshing:

- Cartesian mesh
- Polar mesh
- Adaptive polar mesh
- Hexagonal mesh
- Triangular mesh

For basis functions:

- Lagrange polynomials
- B-splines
- NURBS
- Box-splines



Thank you for your attention!

B(asis)-Splines basis*

B-Splines of degree d are defined by the **recursion formula**:

$$B_j^{d+1}(x) = \frac{x - x_j}{x_{j+d} - x_j} B_j^d(x) + \frac{x_{j+1} - x}{x_{j+d+1} - x_{j+1}} B_{j+1}^d(x) \quad (1)$$

Some important properties about B-splines:

- Piece-wise polynomials of degree $d \Rightarrow$ **smoothness**
- Compact support \Rightarrow **sparse matrix system**
- Partition of unity $\sum_j B_j(x) = 1, \forall x \Rightarrow$ **conservation laws**

