ToFu

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

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Context

Context: Energy generation

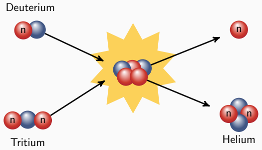
Current solutions present some drawbacks:

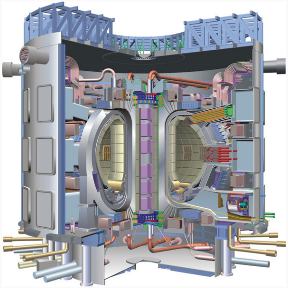
- Limited resources
- Production of carbon dioxide
- Radioactive waste
- Not too efficient
- Harmful to surrounding environment

⇒ Fusion: cleaner, more reliable, more powerful energy source?

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
- Energy break-even point still not obtained: $Q_{\text{max}} = \dfrac{E_{\text{output}}}{E_{\text{input}}} = 0.67$
  - Current reactors: different shapes, sizes, heating methods, confinement techniques, etc.

⇒ Fusion codes: complexity due to the number of parameters, geometry, model, etc.

Tomography diagnostics

Tokamak diagnostics

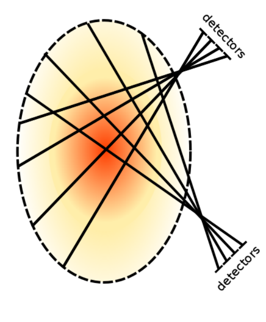
Diagnostics

Set of instruments to measure for the understanding, control and optimization of the plasma performance.

- **Magnetic** diagnostics: currents, plasma stored energy, plasma shape and position;
- **Neutron** diagnostics (ie. cameras, spectrometers, etc.): fusion power;
- Optical systems (**interferometers**): temperature and density profiles;
- Bolometric systems (**tomography**): spatial distribution of radiated power;
- **Spectroscopic**: X-ray wavelength range, impurity species and density, input particle flux, ion temperature, helium density, fueling ratio, plasma rotation, and current density.

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

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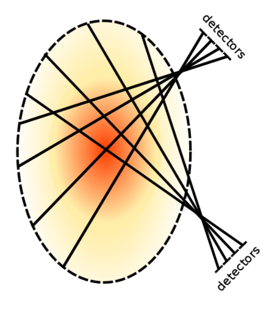

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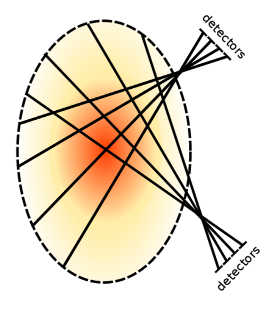

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Tomography very sensitive to errors, noise and bias

$\longrightarrow$ Reputation for low reproducibility / reliability

The ToFu code

Motvation: "current" state

In the fusion community, codes for synthetic diagnostic are developed:

- by physicists (with little to no programming experience),
- in Matlab,
- from scratch,
- in local/private

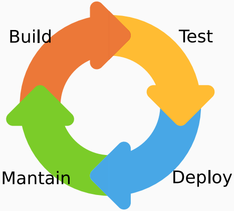
... which means

- repetition of work: lost time, man-power, etc;
- no traceability,
- results impossible to reproduce,
- no standardization of diagnostics

A code for Tomography for Fusion

Develop a common tool:

- Accessible to everyone (open-source)
- Generic (geometry independent)
- Portable (developed in Python)
- Optimized (reliability and performance)
- Documented online
- Continuous integration



For tomography diagnostics:

The **To**mography for **Fu**sion code (**ToFu**[1,2,3])

[1] repository: `https://github.com/ToFuProject/tofu`

[2] documentation: `https://tofuproject.github.io/tofu/index.html`

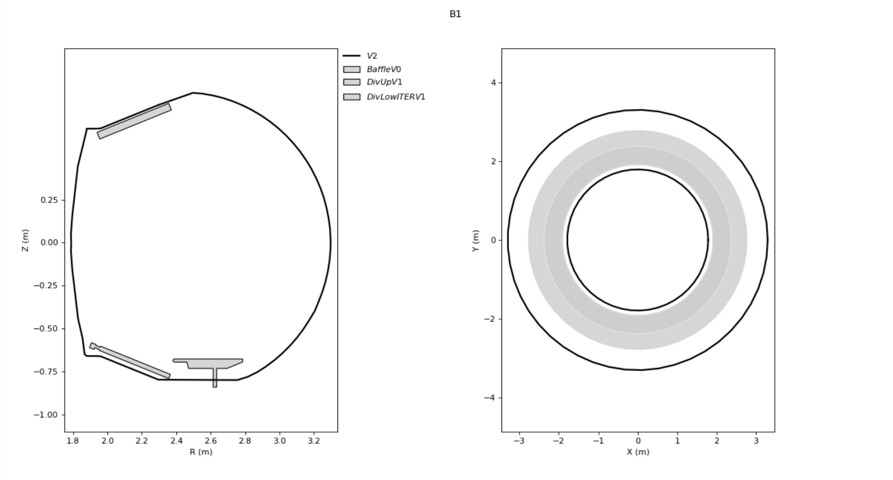
[3] D Vezinet et al. "Non-monotonic growth rates of sawtooth precursors evidenced with a new method on ASDEX Upgrade". In: *Nuclear Fusion* 8 (2016).

More about Tofu

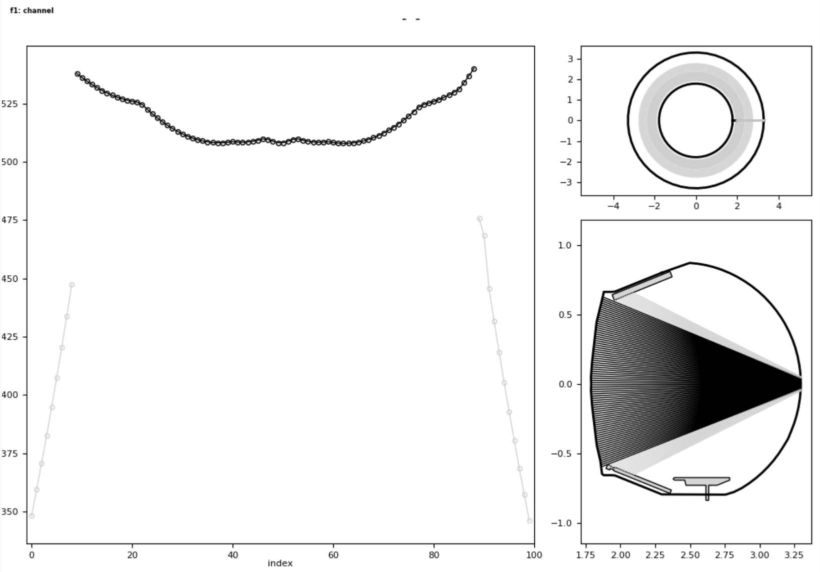
- Created in 2014
- Open Source: **MIT license**
- Python 2.7 and **Python** 3 + **Cython**
- Continuous integration: **Travis** CI
- **conda**, **pip**
- Two (main) developers:
  - Didier Vezinet (creator, PhD in Physics)
  - Laura S. Mendoza (since June 2018, PhD in Applied Mathematics)
- Contributors:
  - Jorge Morales (PhD in Physics)
  - Florian Le Bourdais
  - Arpan Khandelwal (intern)

Travis-CI passing | Anaconda Cloud 1.4.0 | downloads 55 total | Last updated 02 May 2019 | Platforms linux-64 | license MIT | Install with conda
codecov 55% | pypi package 1.4.0

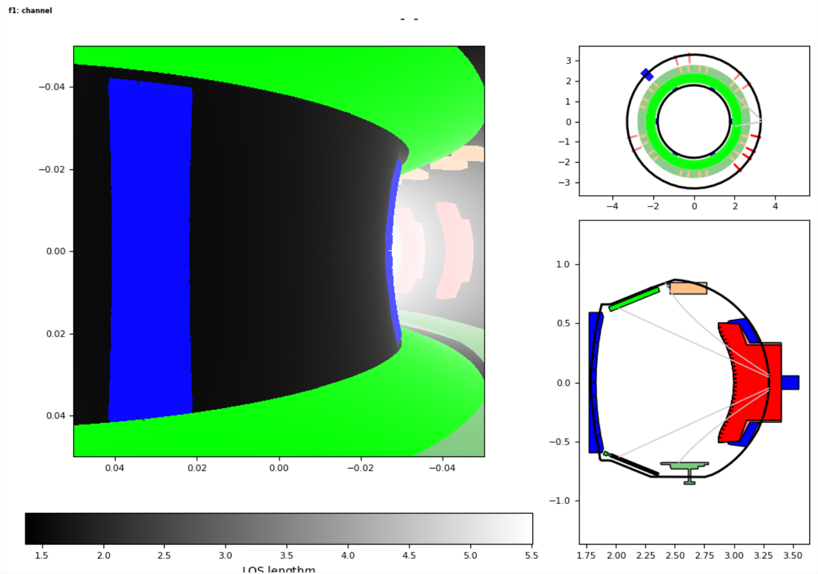
What ToFu can do: modeling of simplified geometry



What ToFu can do: 3D modeling of a 1D camera



What ToFu can do: 3D modeling of a 2D camera



What ToFu can do: handle basic reflexions

What ToFu can do: computing synthetic signals

What ToFu can do

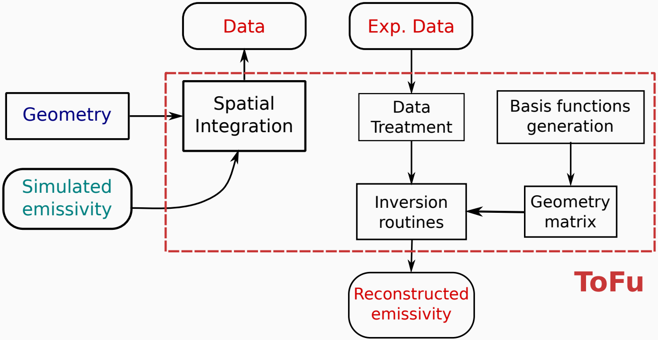
ToFu can:

- Modeling of simplified geometry
- 3D modeling of a 1D camera
- 3D modeling of a 2D camera
- Handle basic reflexions
- Computing synthetic signals
- ...and soon:
    - meshing and basis functions
    - tomographic inversion
    - dust particle trajectory tracking
    - faster Matplotlib + PyQtGraph visualization
    - magnetic field line tracing
    - data visualization and statistical tools (pandas)

Demo

Demo

Tofu's structure



Optimization of the code

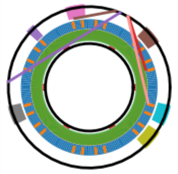
Geometry reconstruction: ray-tracing techniques

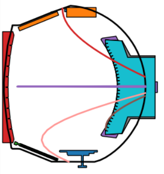
To reconstruct emissivity we need to take account:

- Up to hundreds of structural elements in vessel
- Scale of the vessel: 10^4 bigger than smaller structural detail

$\Rightarrow$ Geometry defined with minimal data polygon (R, Z) extruded along φ

$\Rightarrow$ Symmetry of vessel along φ



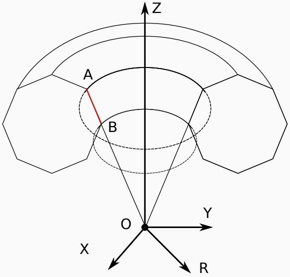


Optimization of ray-tracing algorithm

- Description of geometry:
  - Vessel and structures: set of 2D polygon $\mathcal{P}_j = \cup_{i=1}^{n} \overline{\mathrm{A}_i\mathrm{B}_i}$
  - Extruded along $[\varphi_{min}, \varphi_{max}]$
  - Detectors defined as set of rays (of origin D and direction u)

  $\Rightarrow$ Light memory-wise

$\Rightarrow$ Equivalent to: set of truncated cones (frustums) of generatrix A_iB_i



Ray-tracing algorithm on fusion device $\longrightarrow$ Computation of cone-Ray intersection

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

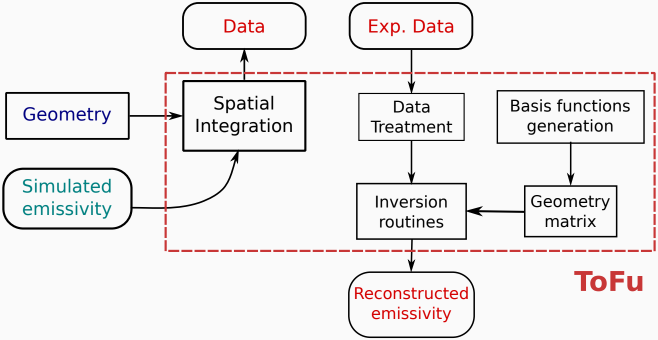
Optimization of ray-tracing algorithm

Cone-Ray intersection algorithm:

- Main steps:
  - Test if intersection with bounding-box
  - Computation of special cases of segment AB
  - Computation of special cases of ray directional vector
  - General case: solution of a quadratic equation
- Pre-computation of geometry-independent variables
- Core functions written in **Cython**
- Parallelization over ray-loop (**prange** loops)

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



Optimization of spatial integration routines

For the integration along a LOS:

- Sample (discretization) of a 3D ray:
  - Different quadrature rules: midpoint, simpson, romberg
  - Resolution given by user
  - Possible to define a sub-domain of discretization
- Integration of a python function **func** defined by user by:
  - **numpy**.sum
  - Cython based sum
  - **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

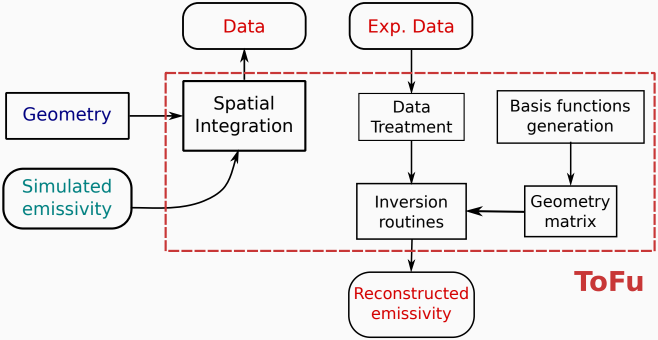
Optimization of spatial integration routines

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



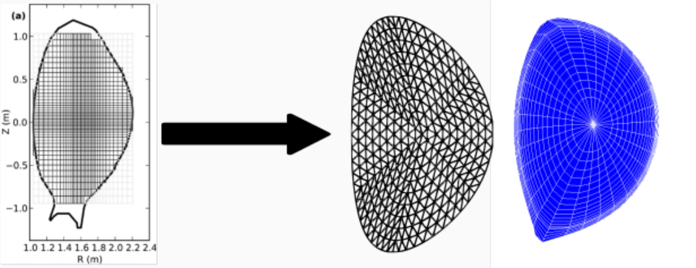
On geometry discretization: meshing

Several options for poloidal cut meshing:

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

For basis functions:

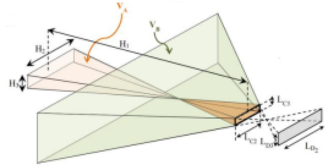
- Lagrange polynomials
- B-splines
- NURBS
- Box-splines



Tofu's main algorithms

Visualization and geometrical tools:

- Ray-tracing algorithm
- Distance 3D objects and rays
- Vignetting: 3D polygon - Ray
- Solid angles computation (reflexions)



For direct and inverse problem:

- Basis functions
- Discretization: Geometry, Lines, Volumes
- Spatial integration
- Regularization-inversion routines (Bayesian, non linear, etc.)
- Filtering

Thank you for your attention!

B(asis)-Splines basis*

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

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

Some important properties about B-splines:

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