DE LA RECHERCHE À L'INDUSTRIE

TOFU

***TO**MOGRAPHY FOR **FU**SION*

AN OPEN-SOURCE PYTHON LIBRARY FOR SYNTHETIC DIAGNOSTICS AND TOMOGRAPHY

D. VEZINET, L. MENDOZA, A. DA ROS, K. OBREJAN, O. CHELLAI

4th IAEA Technical meeting on Fusion Data Processing | D. VEZINET

TOFU
29.11.2021

www.cea.fr

OUTLINE

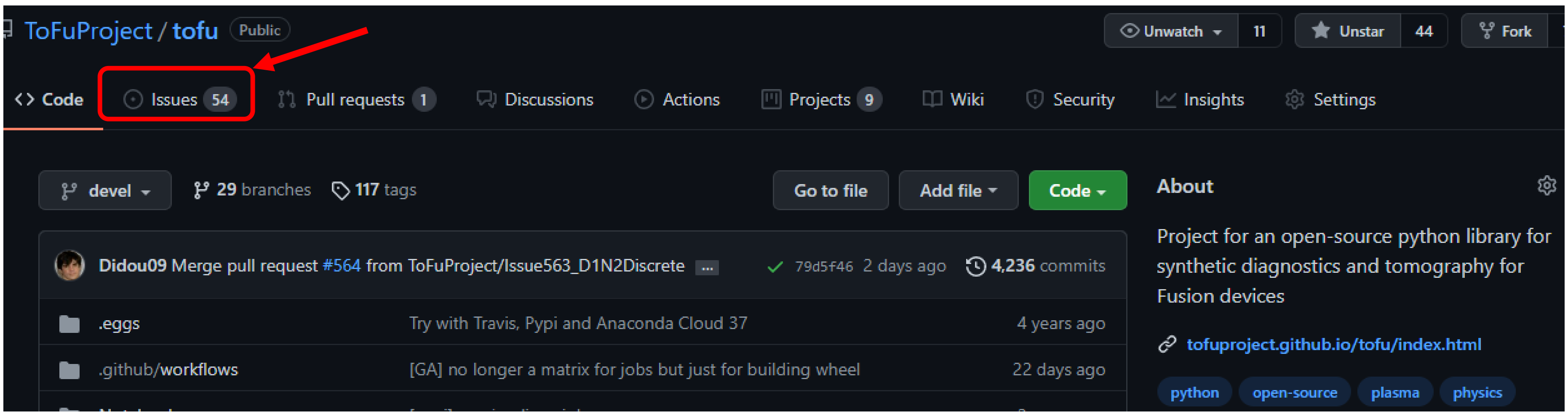
- **Why is it relevant for data processing, validation and analysis?**
  - **Open-source**
  - **Quality standards**

- What it does:
  - Tokamak and diagnostic modelling and synthetic diagnostics
  - Inversions (priority of 2021-2022)

- Perspectives

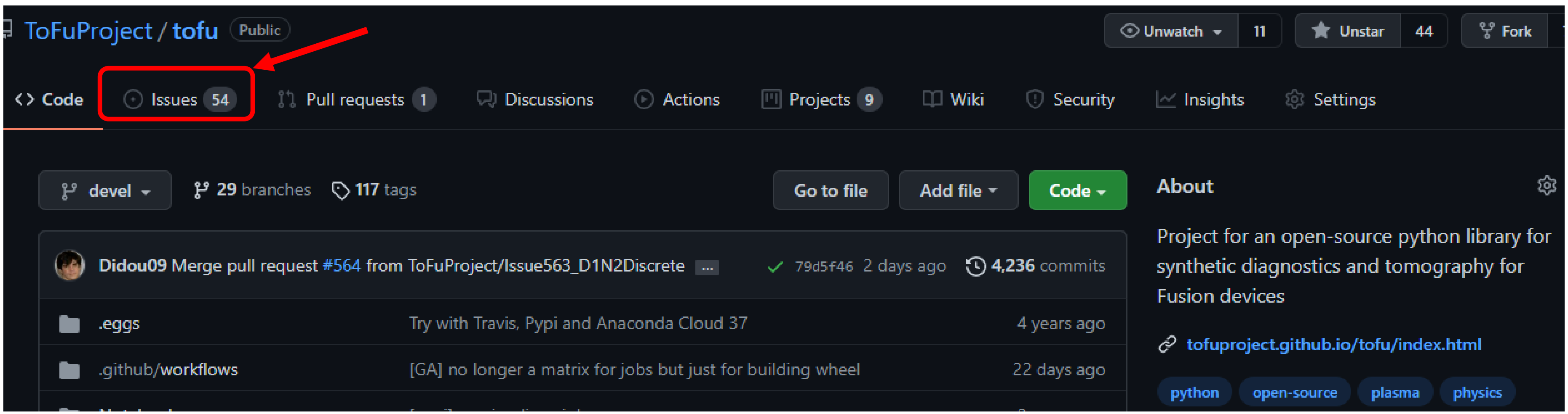
WHY IS IT RELEVANT FOR DATA VALIDATION?

- Open-source python library (object-oriented)
  - License: MIT (permissive, free)
  - Transparent: code on Github



WHY IS IT RELEVANT FOR DATA VALIDATION?

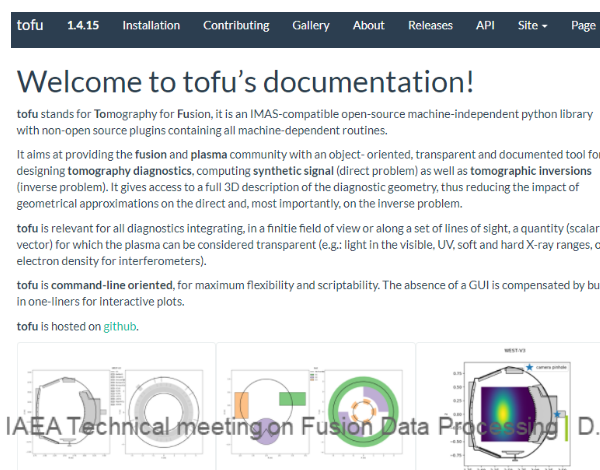
- Open-source python library (object-oriented)
    - License: MIT (permissive)
    - Transparent: code on Github



- Online documentation:

https://tofuproject.github.io/tofu/index.html

(continued effort)



WHY IS IT RELEVANT FOR DATA VALIDATION?

- Good practices:
  - Version-control: git
  - Issue tracker: github
  - Pull Requests and code review process:
    Dedicated branches vs protected master branch
  - Unit tests: ~60 % of the code, multiple platforms
  - Standardized benchmarks: to quantify speed-ups and detect slow-downs
  - Automated deployment: on tags

WHY IS IT RELEVANT FOR DATA VALIDATION?

- Good practices:
  - Version-control: git
  - Issue tracker: github
  - Pull Requests and code review process:
    Dedicated branches vs protected master branch
  - Unit tests: ~60 % of the code, multiple platforms
  - Standardized benchmarks: to quantify speed-ups and detect slow-downs
  - Automated deployment: on tags

⇒ Contribute to tracability, address the replicability crisis [1-3]

⇒ towards Open Science and FAIR4Fusion

⇒ Natively compatible with IMAS and regularly updated to follow IMAS standards

[1] M. Baker, Nature 2016, 533 (7604)
[2] Fang et al., PNAS 2012, 109 (42), 17028-17033
[3] Ioannidis JPA (2005) PLoS Med 2(8)

WHY IS IT RELEVANT FOR DATA VALIDATION?

- Good practices:
  - Version-control: git
  - Issue tracker: github
  - Pull Requests and code review process:
    Dedicated branches vs protected master branch
  - Unit tests: ~60 % of the code, multiple platforms
  - Standardized benchmarks: to quantify speed-ups and detect slow-downs
  - Automated deployment: on tags

⇒ Contribute to tracability, address the replicability crisis [1-3]

⇒ towards Open Science and FAIR4Fusion

⇒ Natively compatible with IMAS and regularly updated to follow IMAS standards

- Packaged, easy to install on Windows, MacOS, Linux
  - Using **pip**: `pip install tofu`
  - Using **conda**: `conda install -c conda-forge tofu`

[1] M. Baker, Nature 2016, 533 (7604)
[2] Fang et al., PNAS 2012, 109 (42), 17028-17033
[3] Ioannidis JPA (2005) PLoS Med 2(8)

OUTLINE

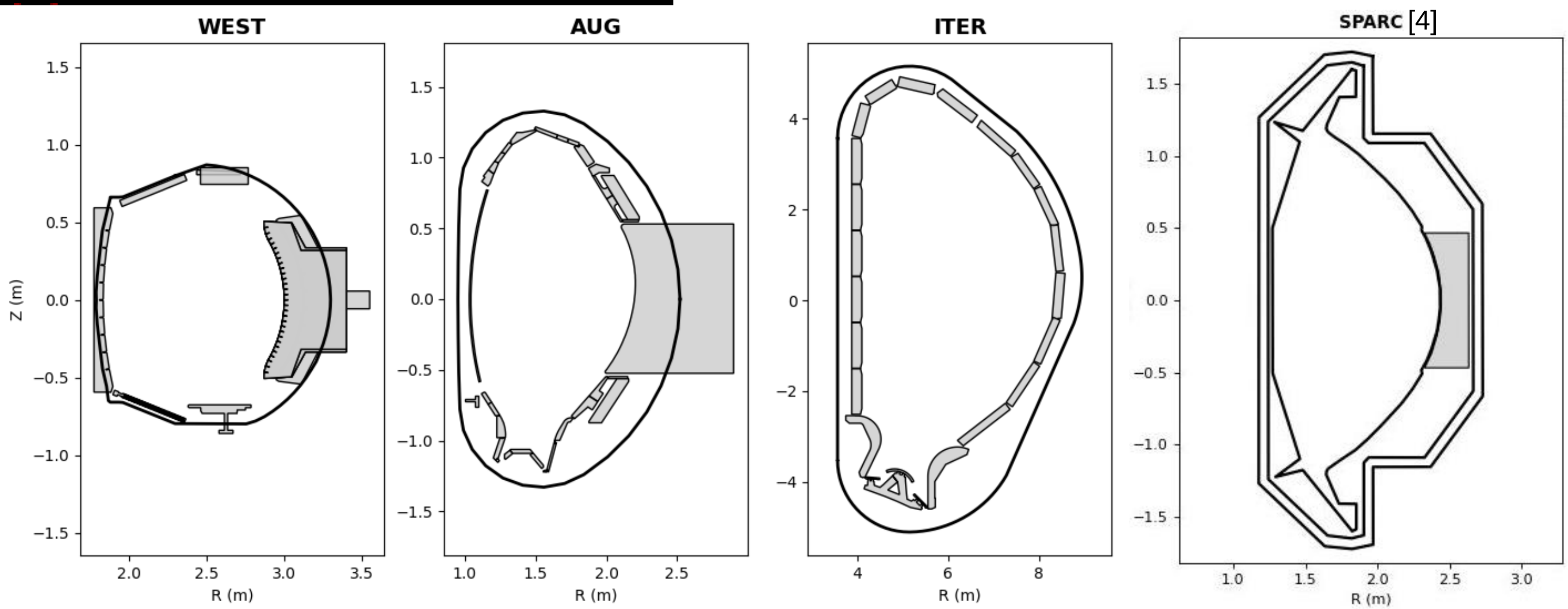
- Why is it relevant for data processing, validation and analysis?
  - Open-source
  - Quality standards
- **What it does:**
  - **Tokamak and diagnostic modelling and synthetic diagnostics**
  - **Inversions (priority of 2021-2022)**
- Perspectives

GEOMETRY MODELLING

- 2.5D tokamak representation:

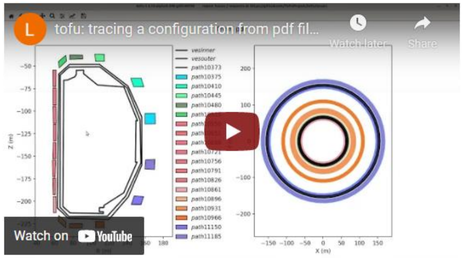
```
In [2]: conf = tf.load_config('ITER')

In [3]: conf.plot()
```



⇒ Feel free to add you tokamak

⇒ See the video tutorial on how to do it using **Inkscape**

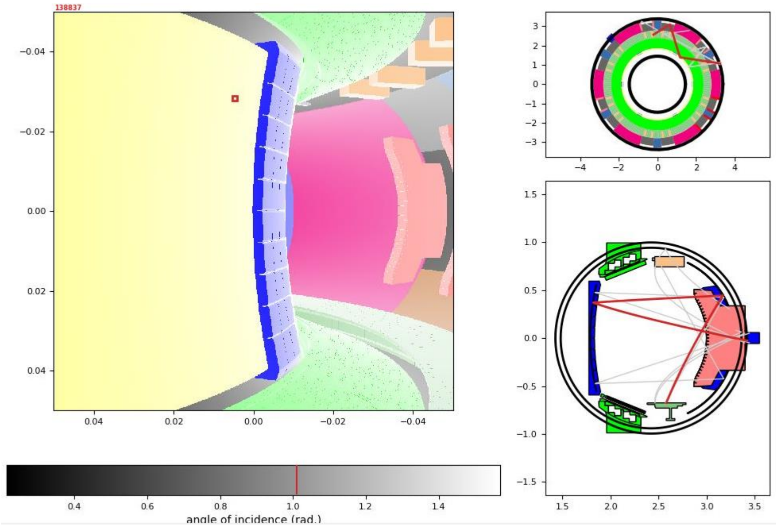


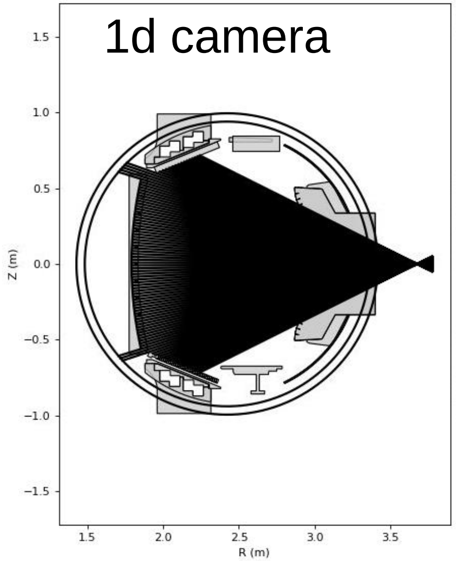
[4] A. J. Creely, J. Plasm. Physics, 86, 2020, 865860502

- Fast 1d and 2d camera modelling: (with simple specular reflections)

```
import tofu as tf                                   # import
conf = tf.load_config('WEST')                       # load tokamak geometry (configuration)
cam = tf.geom.utils.create_CamLOS2D(                # create pinhole camera
            pinhole=[3.1, 1.1, 0],
            orientation=[np.pi, np.pi/6, 0],
            focal=0.15,
            sensor_size=0.1,
            sensor_nb=800,
            config=conf,
            Name='test',
            Diag='diag')
```

2d camera

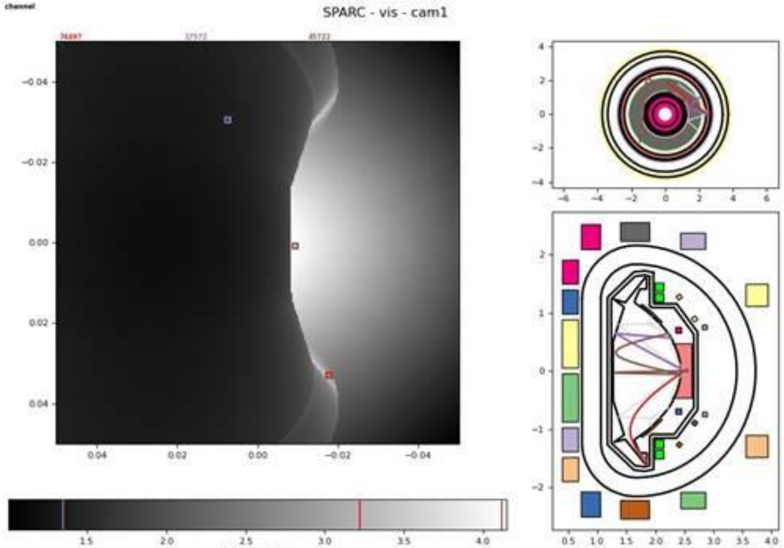




- Fast 1d and 2d camera modelling: (with simple specular reflections)

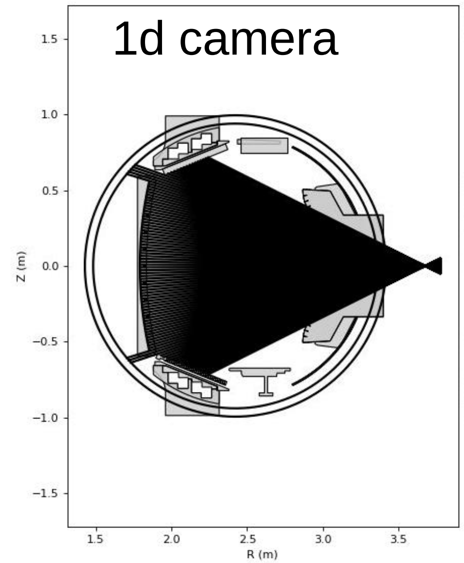
```
import tofu as tf                                   # import
conf = tf.load_config('WEST')                       # load tokamak geometry (configuration)
cam = tf.geom.utils.create_CamLOS2D(                # create pinhole camera
            pinhole=[3.1, 1.1, 0],
            orientation=[np.pi, np.pi/6, 0],
            focal=0.15,
            sensor_size=0.1,
            sensor_nb=800,
            config=conf,
            Name='test',
            Diag='diag')
```

2d camera

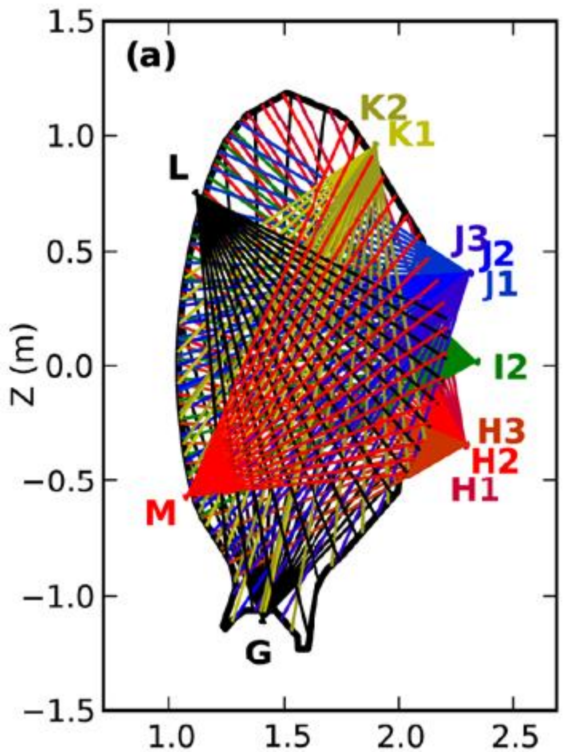


Provides tools for fast LOS-integration for synthetic diagnostics

1d camera



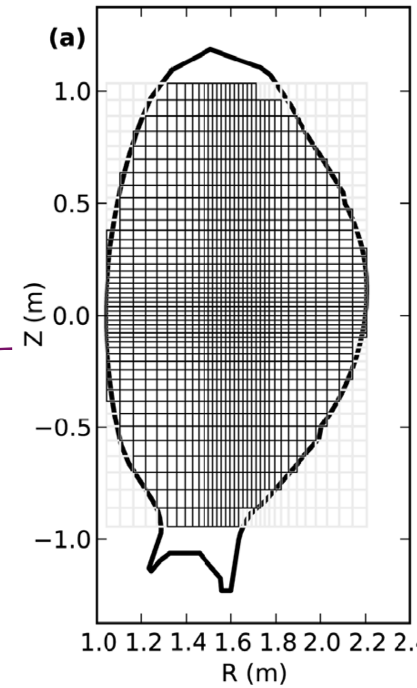
Diagnostic geometry



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

$$\underline{m} = \underline{\underline{T}}\,\underline{\varepsilon}$$

Solution discretization



$$\varepsilon(x) = \sum_i C_i b_i(x)$$

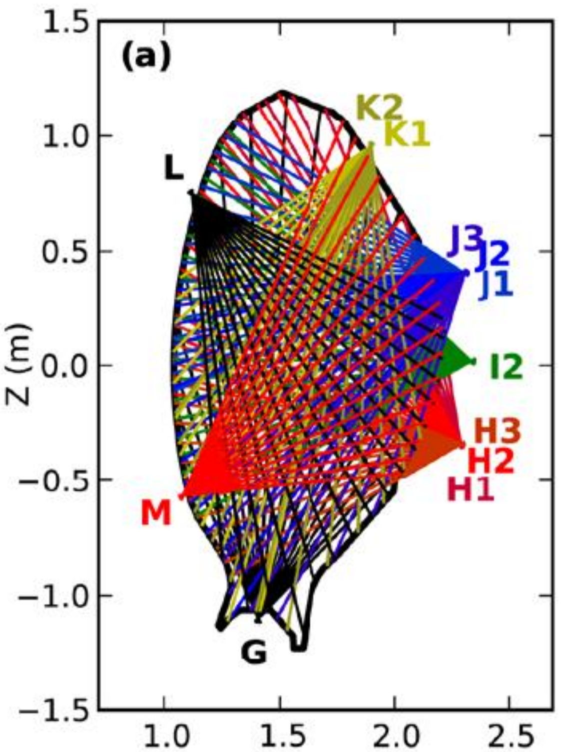
Geometry / transfer matrix

Regularization choice → Algorithm → Inversion

Exp. measurements

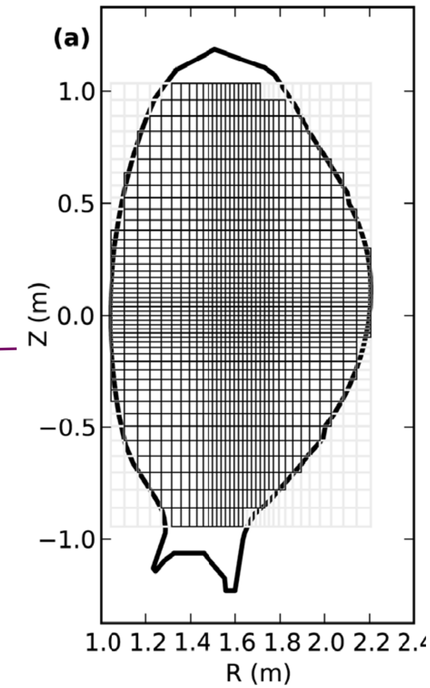
INVERSIONS

Diagnostic geometry **1**



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

Plasma meshing (axisymmetric)



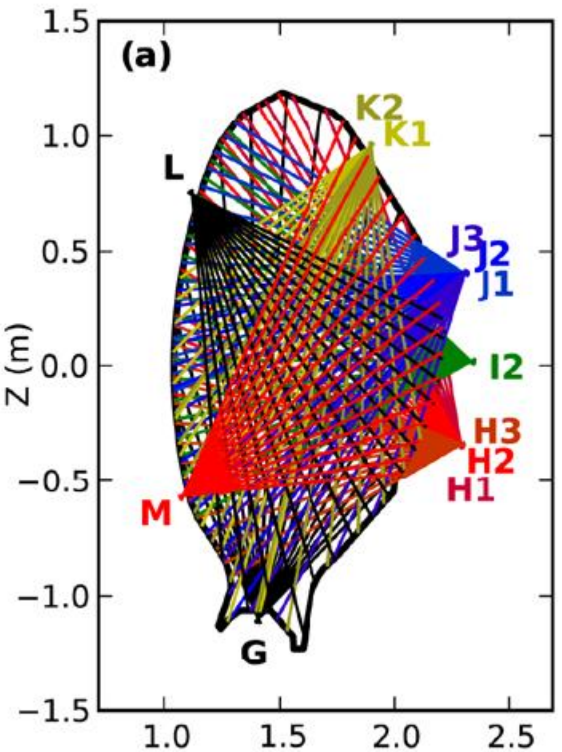
Geometry / transfer matrix

Regularization choice → Algorithm → Inversion

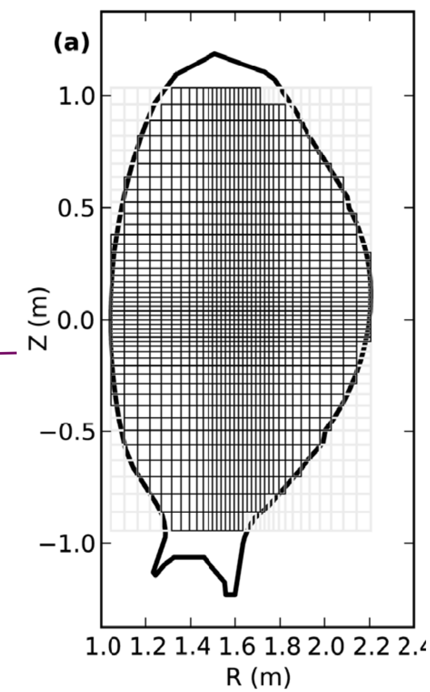
Exp. measurements **1**

INVERSIONS

Diagnostic geometry 1



[1] D. Vezinet et al, Nuc. Fus, 56, 2016



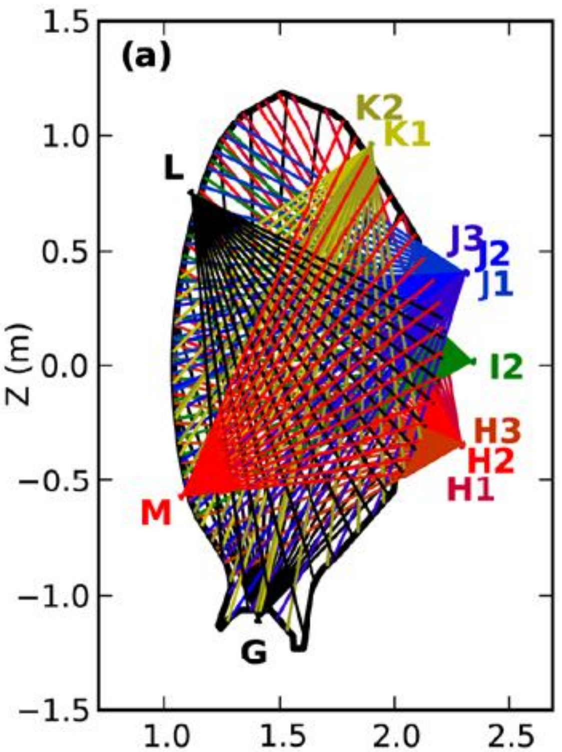
2

Geometry / transfer matrix

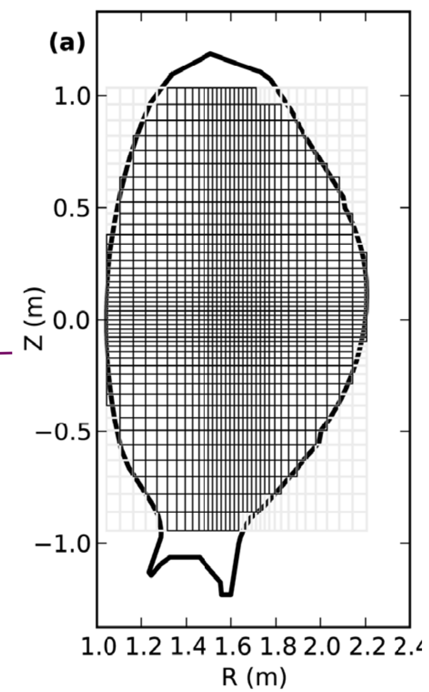
Regularization choice → Algorithm → Inversion

Exp. measurements 1

Diagnostic geometry 1



[1] D. Vezinet et al, Nuc. Fus, 56, 2016



2

Geometry / transfer matrix

Regularization choice 3 → Algorithm → Inversion

Exp. measurements 1

INVERSIONS

Diagnostic geometry
Exp. measurements

1 Set at design (hardware), fixed

Basis functions
Geometry / transfer matrix

2

Regularization choice
Algorithm

3

(2, 3) Changeable from software

INVERSIONS

Diagnostic geometry
Exp. measurements

1 Set at design (hardware), fixed

Basis functions
Geometry / transfer matrix

2

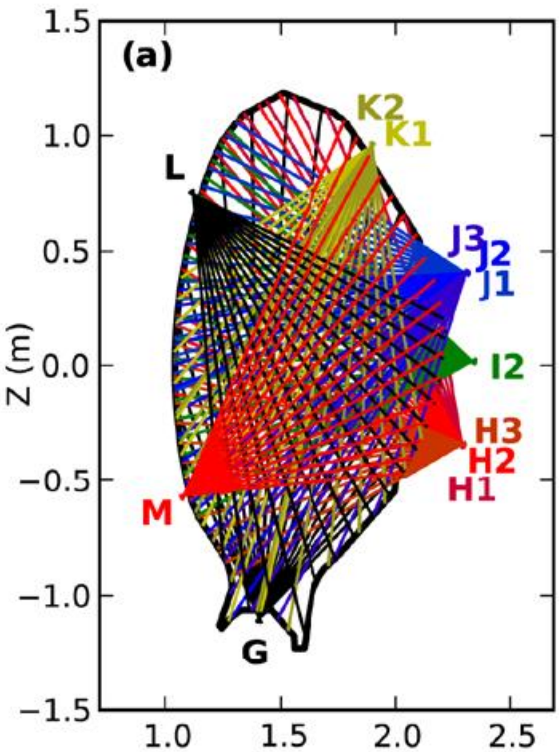
Regularization choice
Algorithm

3

Changeable from software

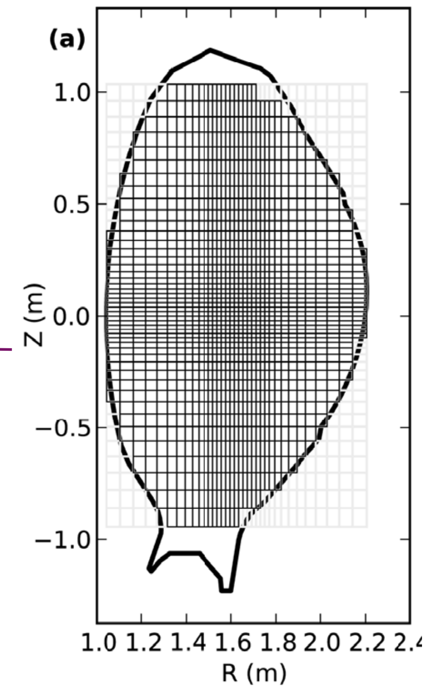
tofu

Diagnostic geometry



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

Plasma meshing (axisymmetric)



Geometry / transfer matrix

$$G_{ij} = \iiint_{FOVi} \iint_{\Omega i} b_j d\Omega dV$$

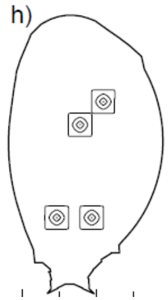
2 Choices:

- **On which basis functions to discretize?**
- **Which approach to compute the integral?**

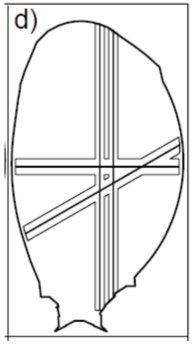
INVERSIONS

[5] L. Ingesson et al., *Plasma Physics and Controlled Fusion*, vol. 42, p. 161, 2000.

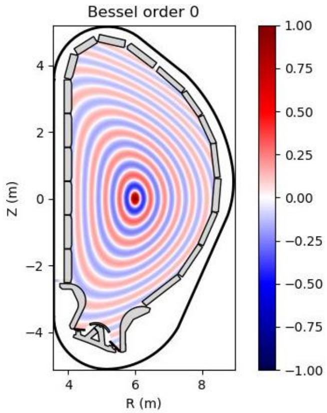
LBF
(local …)
Ex. pixels



NBF
(natural …)



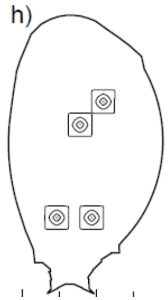
GBF
(global …)
Ex.: fourier-bessel



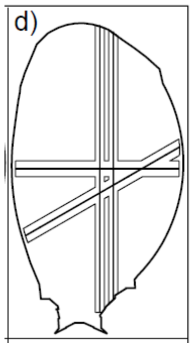
INVERSIONS

[5] L. Ingesson et al., *Plasma Physics and Controlled Fusion*, vol. 42, p. 161, 2000.

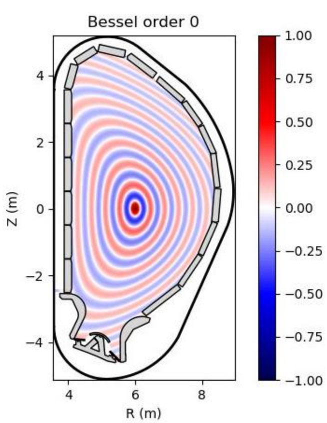
LBF
(local …)
Ex. pixels



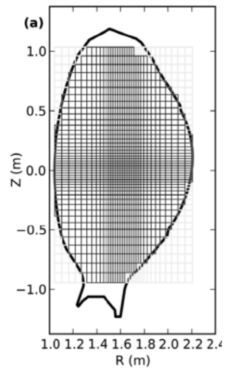
NBF
(natural …)

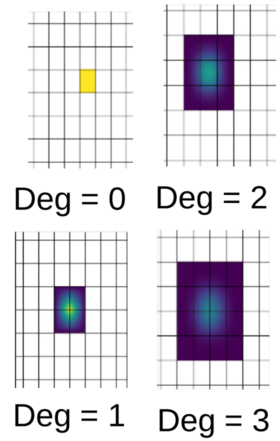


GBF
(global …)
Ex.: fourier-bessel



Rectangular variable size mesh
=> 4 types of **bsplines**

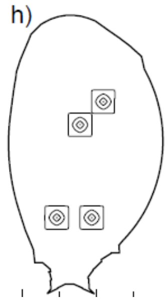




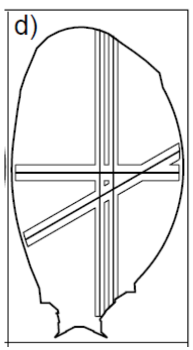
INVERSIONS

[5] L. Ingesson et al., *Plasma Physics and Controlled Fusion*, vol. 42, p. 161, 2000.

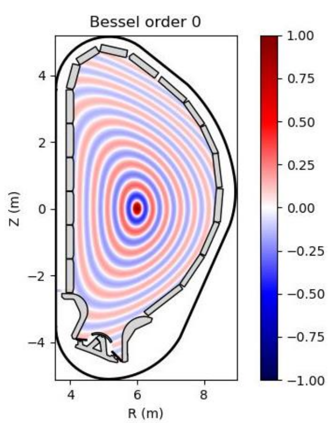
LBF
(local …)
Ex. pixels



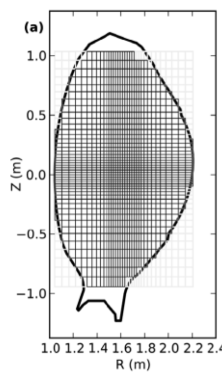
NBF
(natural …)

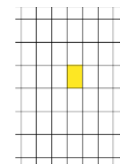


GBF
(global …)
Ex.: fourier-bessel

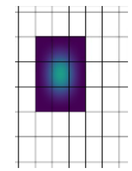


Rectangular variable size mesh
=> 4 types of **bsplines**

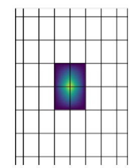




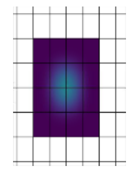
Deg = 0



Deg = 2

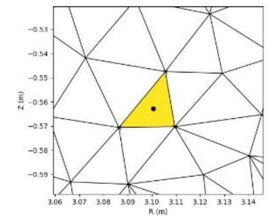


Deg = 1

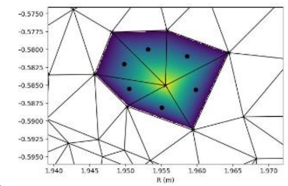


Deg = 3

Triangular meshes
(ongoing)



Deg = 0

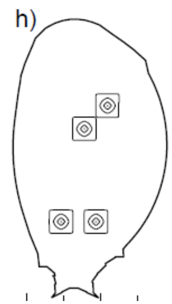


Deg = 1

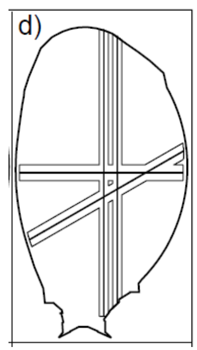
INVERSIONS

[5] L. Ingesson et al., *Plasma Physics and Controlled Fusion*, vol. 42, p. 161, 2000.

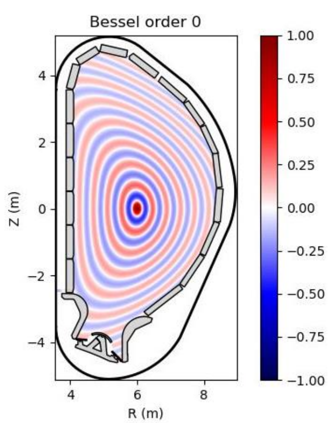
LBF
(local …)
Ex. pixels



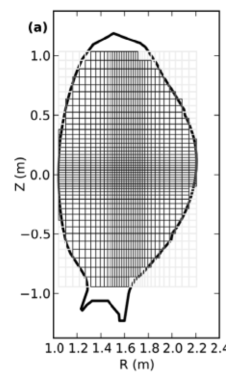
NBF
(natural …)

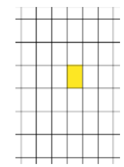


GBF
(global …)
Ex.: fourier-bessel

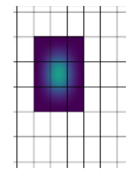


Rectangular variable size mesh
=> 4 types of **bsplines**

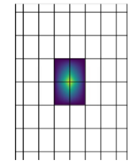




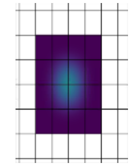
Deg = 0



Deg = 2

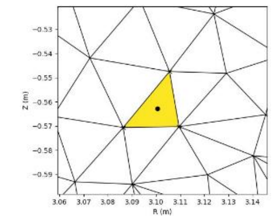


Deg = 1

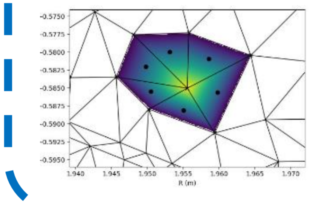


Deg = 3

Triangular meshes
(ongoing)



Deg = 0

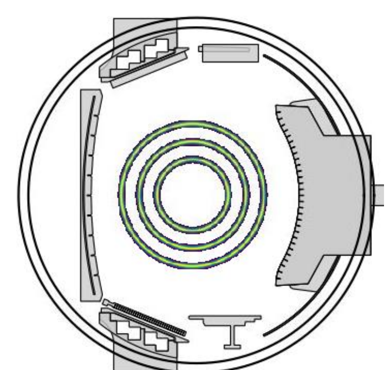


Deg = 1

(low priority)

(high priority)

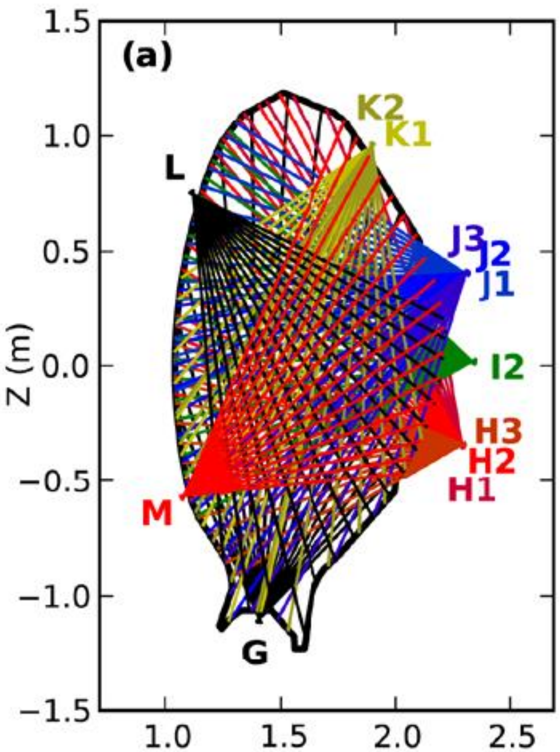
(early 2022?)



Ex: radial/poloidal bsplines

Introduce dependency on **equilibrium**
=> Possible source of systematic error

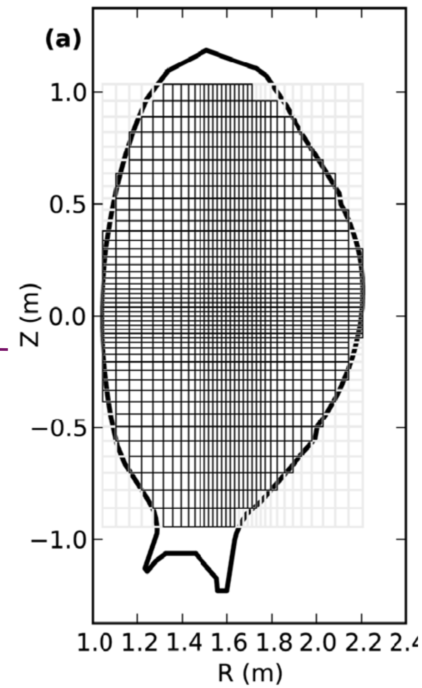
Diagnostic geometry



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

Geometry / transfer matrix

Plasma meshing (axisymmetric)

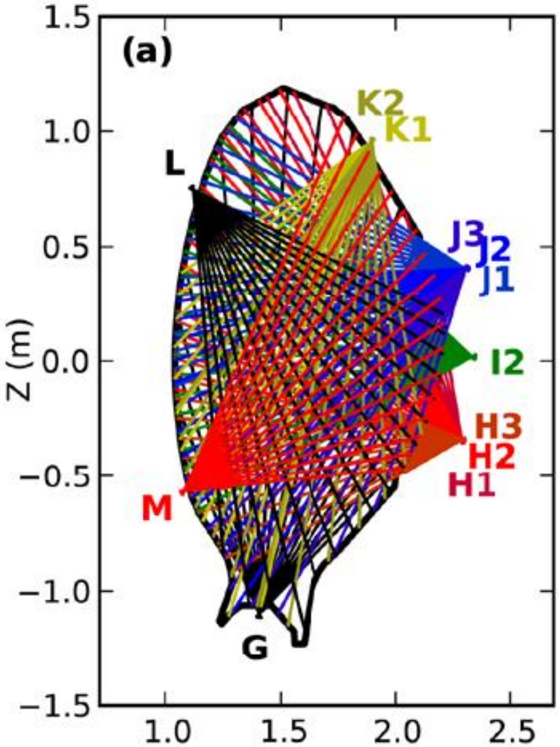


$$G_{ij} = \iiint_{FOVi} \iint_{\Omega i} b_j d\Omega dV$$

2 Choices:

- **On which basis functions to discretize?**
- **Which approach to compute the integral?**

Diagnostic geometry



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

$$G_{ij} = \iiint_{FOVi} \iint_{\Omega i} b_j d\Omega dV$$

Fast
Low accuracy
Assumes isotropy

Slow
High accuracy

$$G_{ij} = E_i \int_{LOS_i} b_j \Omega dV d\Omega$$

LOS

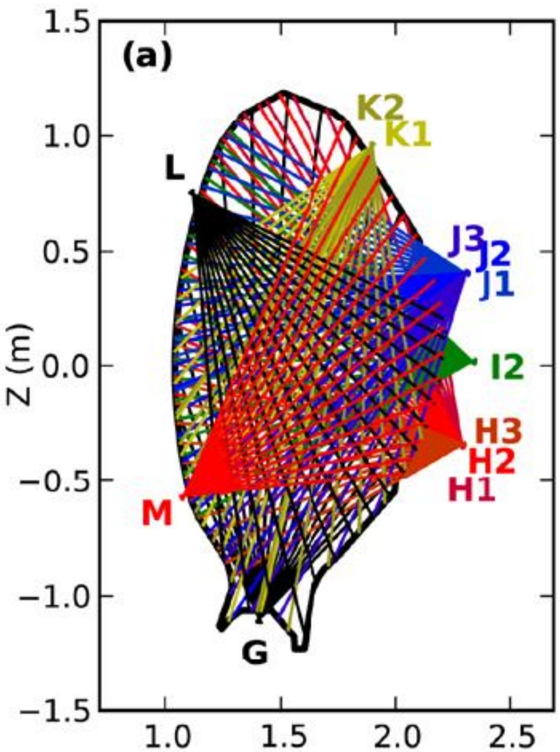
$$G_{ij} = \iiint_{FOVi} \iint_{\Omega i} b_j \Omega d\Omega dV$$

VOS

$$G_{ij} = \int_{Rays_i} b_j \Omega dV d\Omega$$

Ray tracing

Diagnostic geometry



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

$$G_{ij} = \iiint_{FOVi} \iint_{\Omega i} b_j d\Omega dV$$

Fast
Low accuracy
Assumes isotropy

Slow
High accuracy

$$G_{ij} = E_i \int_{LOS_i} b_j \Omega dV d\Omega$$

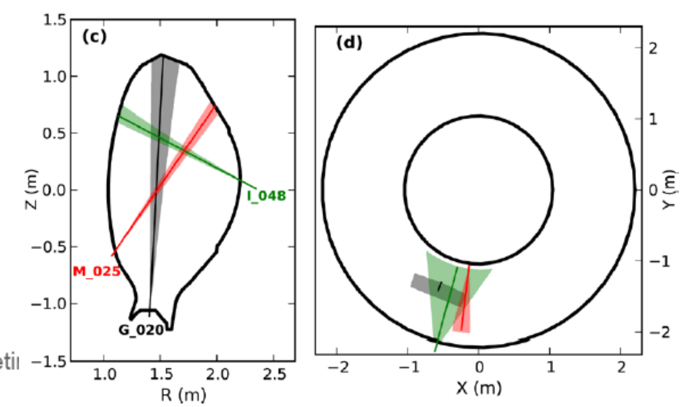
LOS

$$G_{ij} = \iiint_{FOVi} \iint_{\Omega i} b_j \Omega d\Omega dV$$

VOS

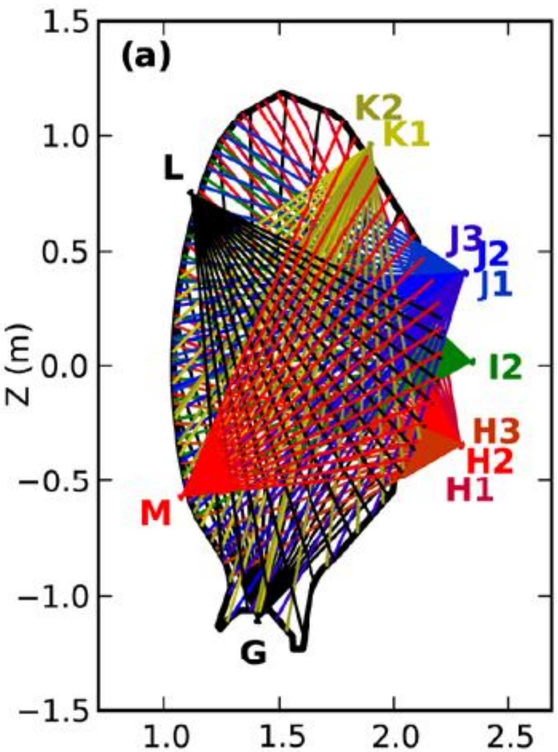
$$G_{ij} = \int_{Rays_i} b_j \Omega dV d\Omega$$

Ray tracing



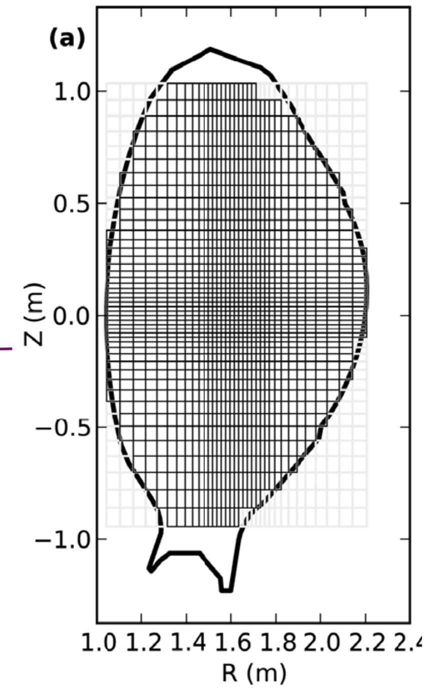
INVERSIONS

Diagnostic geometry **1**



[1] D. Vezinet et al, Nuc. Fus, 56, 2016

Plasma meshing (axisymmetric)



Geometry / transfer matrix

Regularization choice → Algorithm → Inversion

Exp. measurements

Philipps-Tikhonov regularization

Main choice

Geometry matrix

Regularization operator

$$\Phi_{t_n}(\underline{\epsilon}^{\eta}) = \|\underline{\underline{T}}\,\underline{\epsilon}^{\eta} - \underline{f}(t_n)\|_2^2 + \alpha H(\underline{\epsilon}^{\eta})$$

Measurements

Regularization parameter (scalar)

Philipps-Tikhonov regularization

Main choice

Geometry matrix

Regularization operator

$$\Phi_{t_n}(\underline{\epsilon}^{\eta}) = \|\underline{\underline{T}}\,\underline{\epsilon}^{\eta} - \underline{f}(t_n)\|_2^2 + \alpha H(\underline{\epsilon}^{\eta})$$

Measurements

Regularization parameter (scalar)

Bsplines	$\|\|\epsilon\|\|^2$	$\|\|\nabla\epsilon\|\|^2$	$\frac{\|\|\nabla\epsilon\|\|^2}{\epsilon}$	$\|\|\Delta\epsilon\|\|^2$	SVD	BOB
Degree 0	✓ (Done)	✓ (In progress)	✓ (In progress) ✓ (tomotok)		✓ (tomotok)	✓ (tomotok)
Degree 1	✓ (Done)	✓ (Done)				
Degree 2	✓ (Done)	✓ (Done)		✓ (Done)		
Degree 3	✓ (In progress)	✓ (In progress)		✓ (In progress)		

Done **In progress** **tomotok**

Tomotok: interoperability with another tomography library

Philipps-Tikhonov regularization

Main choice

Geometry matrix

Regularization operator

$$\Phi_{t_n}(\underline{\epsilon}^{\eta}) = \|\underline{\underline{T}}\,\underline{\epsilon}^{\eta} - \underline{f}(t_n)\|_2^2 + \alpha H(\underline{\epsilon}^{\eta})$$

Measurements

Regularization parameter (scalar)

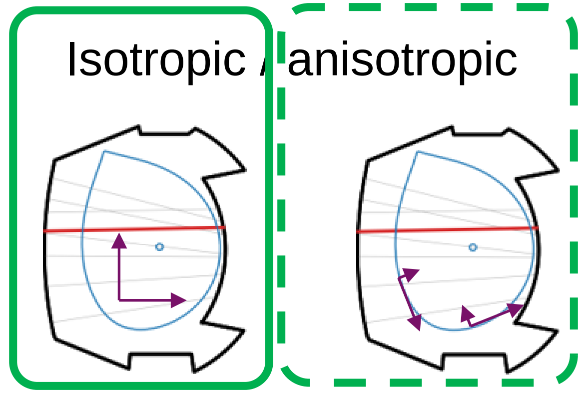
Bsplines	$\|\epsilon\|^2$	$\|\nabla\epsilon\|^2$	$\frac{\|\nabla\epsilon\|^2}{\epsilon}$	$\|\Delta\epsilon\|^2$	SVD	BOB
Degree 0	✓ (Done)	✓ (In progress)	✓ (In progress) ✓ (tomotok)		✓ (tomotok)	✓ (tomotok)
Degree 1	✓ (Done)	✓ (Done)				
Degree 2	✓ (Done)	✓ (Done)		✓ (Done)		
Degree 3	✓ (In progress)	✓ (In progress)		✓ (In progress)		

Done **In progress** **tomotok**

Tomotok: interoperability with another tomography library

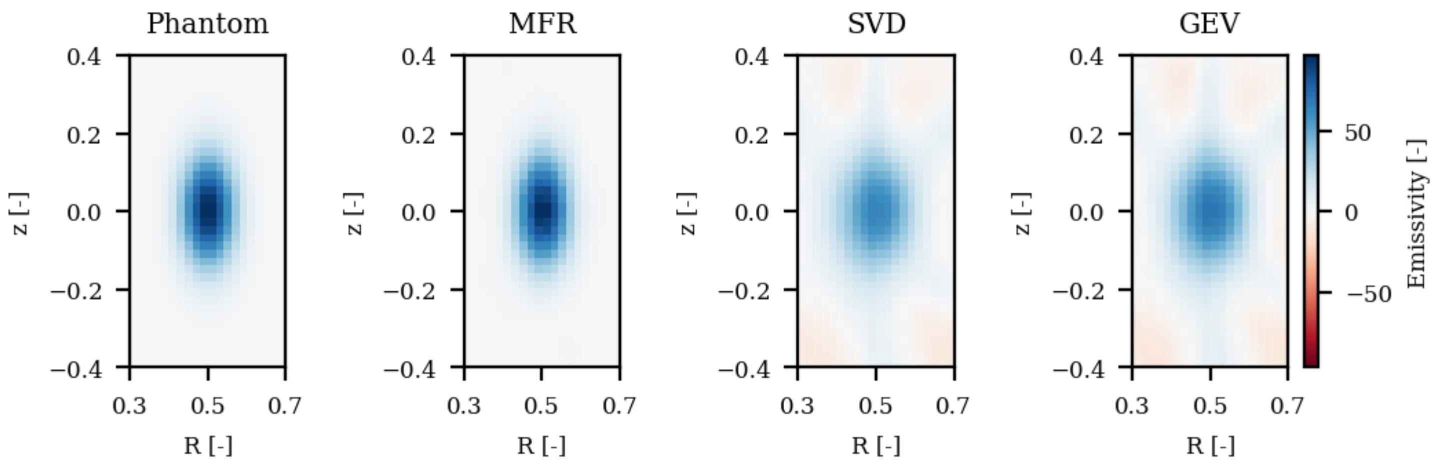
Coming (early 2022):

- Anisotropic smoothing



INTEROPERABILITY WITH OTHER LIBRARIES: TOMOTOK

- Open source (EUPL licence): https://github.com/tomotok
- Focused on discretiazation methods (input types numpy and scipy only)
- Regularised - Minimum Fisher Regularisation(MFR), Linear Algebraic Methods
- Not regularised – Biorthogonal basis decomposition
- Geometry matrix computation using single line of sight approximation
- Simple forward modelling framework
- Graphical user interface for visualization and post processing



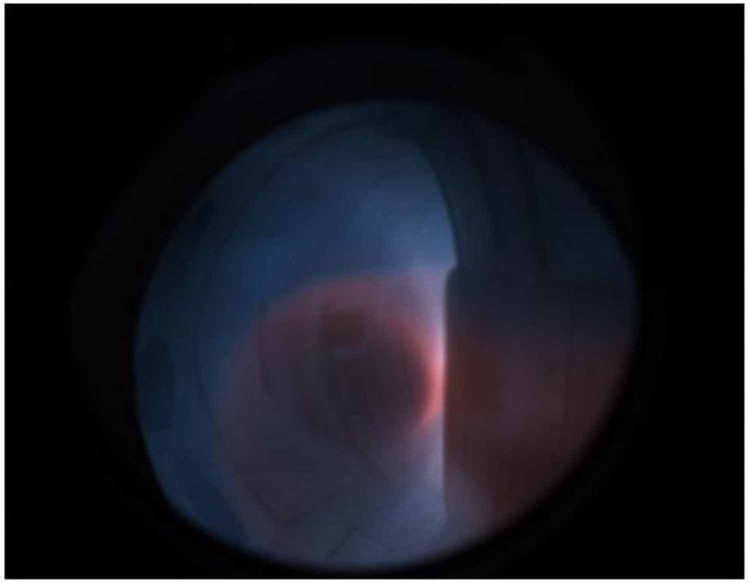
Example results of regularized methods used on a phantom model (SVD and GEV are linear algebraic methods)

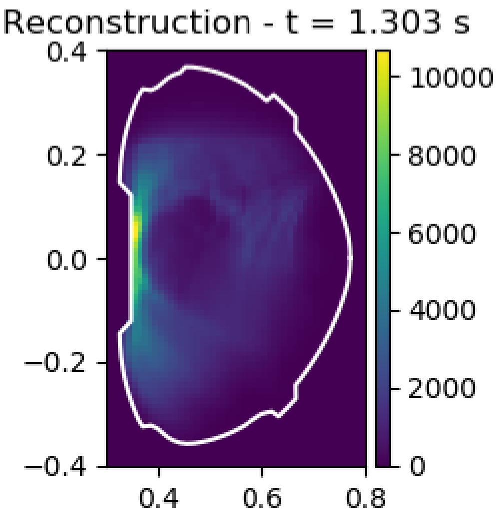
J. Svoboda, J.Cavalier, et al., *"Tomotok: python package for tokamak plasma tomography",* 4th ECPD conference, J. Inst. (Accepted Oct 2021, future DOI https://doi.org/10.1088/1748-0221/00/00/P00921)

INTEROPERABILITY WITH OTHER LIBRARIES: TOMOTOK

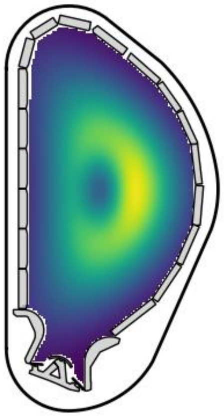
Biorthogonal basis decomposition used on experimental data of COMPASS tokamak (unregularized method - requires more lines of sights than reconstruction nodes)

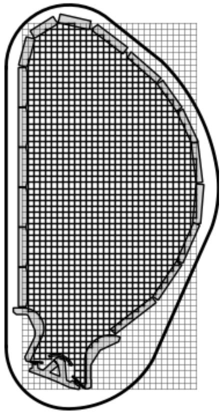
#16693 - Frame 1761

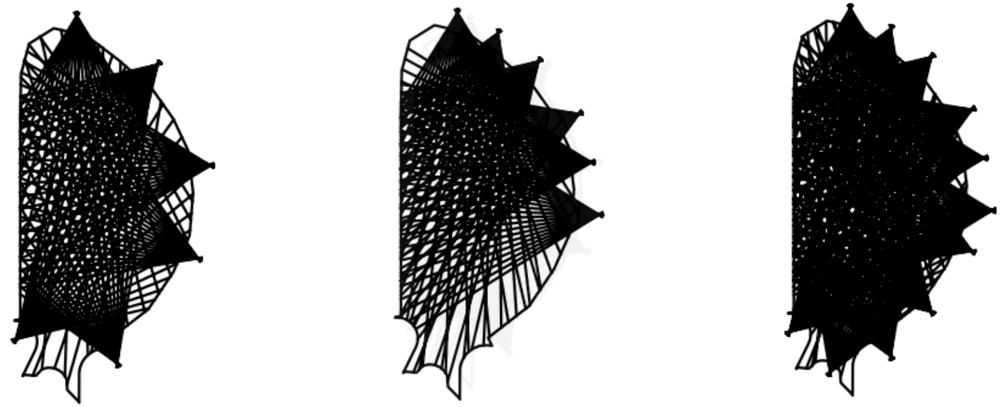




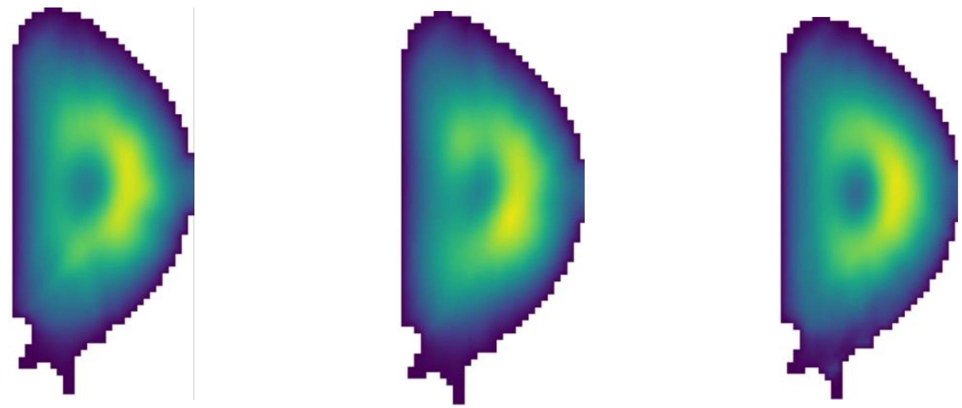
J. Svoboda, J.Cavalier, et al., *“Tomotok: python package for tokamak plasma tomography”,* 4th ECPD conference, J. Inst. (Accepted Oct 2021, future DOI https://doi.org/10.1088/1748-0221/00/00/P00921)



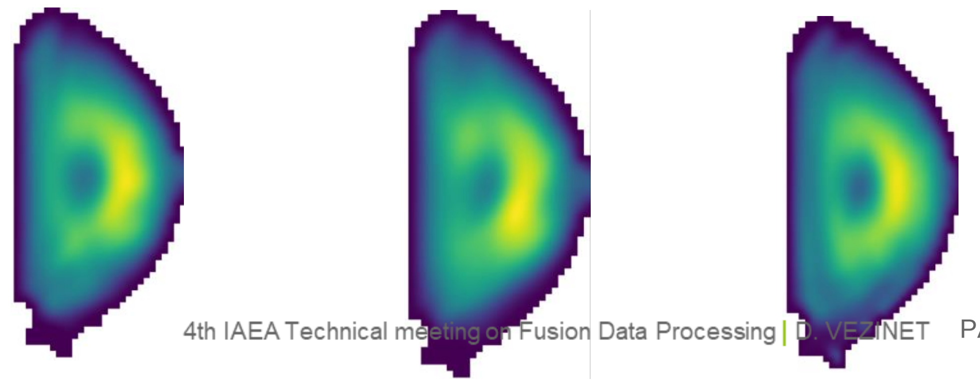




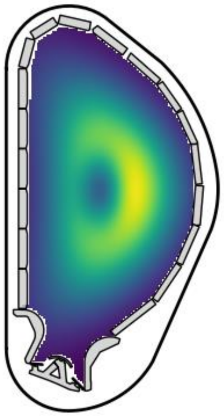
$||\nabla\epsilon||^2$

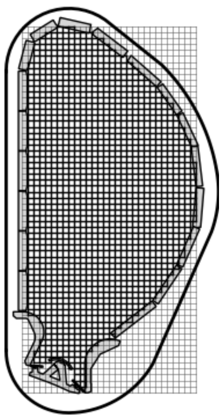


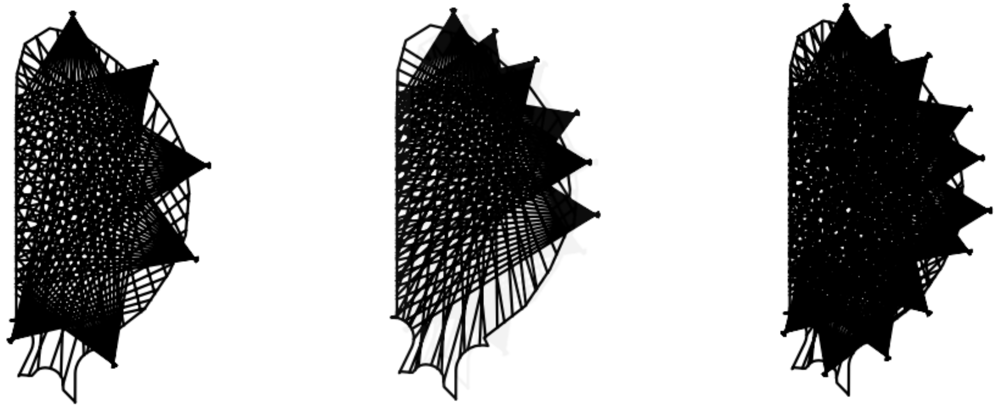
$||\Delta\epsilon||^2$



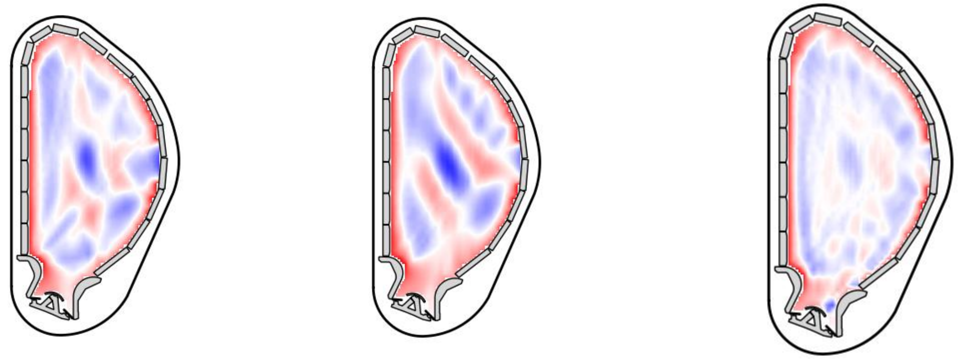
INVERSIONS - EXAMPLES



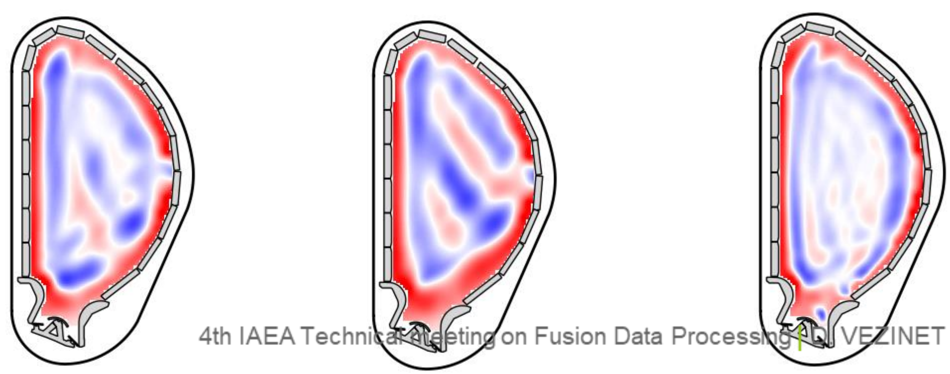




$||\nabla\epsilon||^2$



$||\Delta\epsilon||^2$



OUTLINE

- Why is it relevant for data processing, validation and analysis?
  - Open-source
  - Quality standards
- What it does:
  - Tokamak and diagnostic modelling and synthetic diagnostics
  - Inversions (priority of 2021-2022)
- **Perspectives**

PERSPECTIVES: SYSTEMATIC ERRORS, THINGS WE THINK WE KNOW BUT WE DON'T

All the above relies on implicit assumptions (possible sources of **systematic errors**)

- Is the **geometry of the diagnostic** properly modelled / known ?

  How many diagnostics underwent a proper in-situ metrology campaign?

  Which level of accuracy?

A fraction of a degree in camera orientation can result in significant worse / better inversion quality !

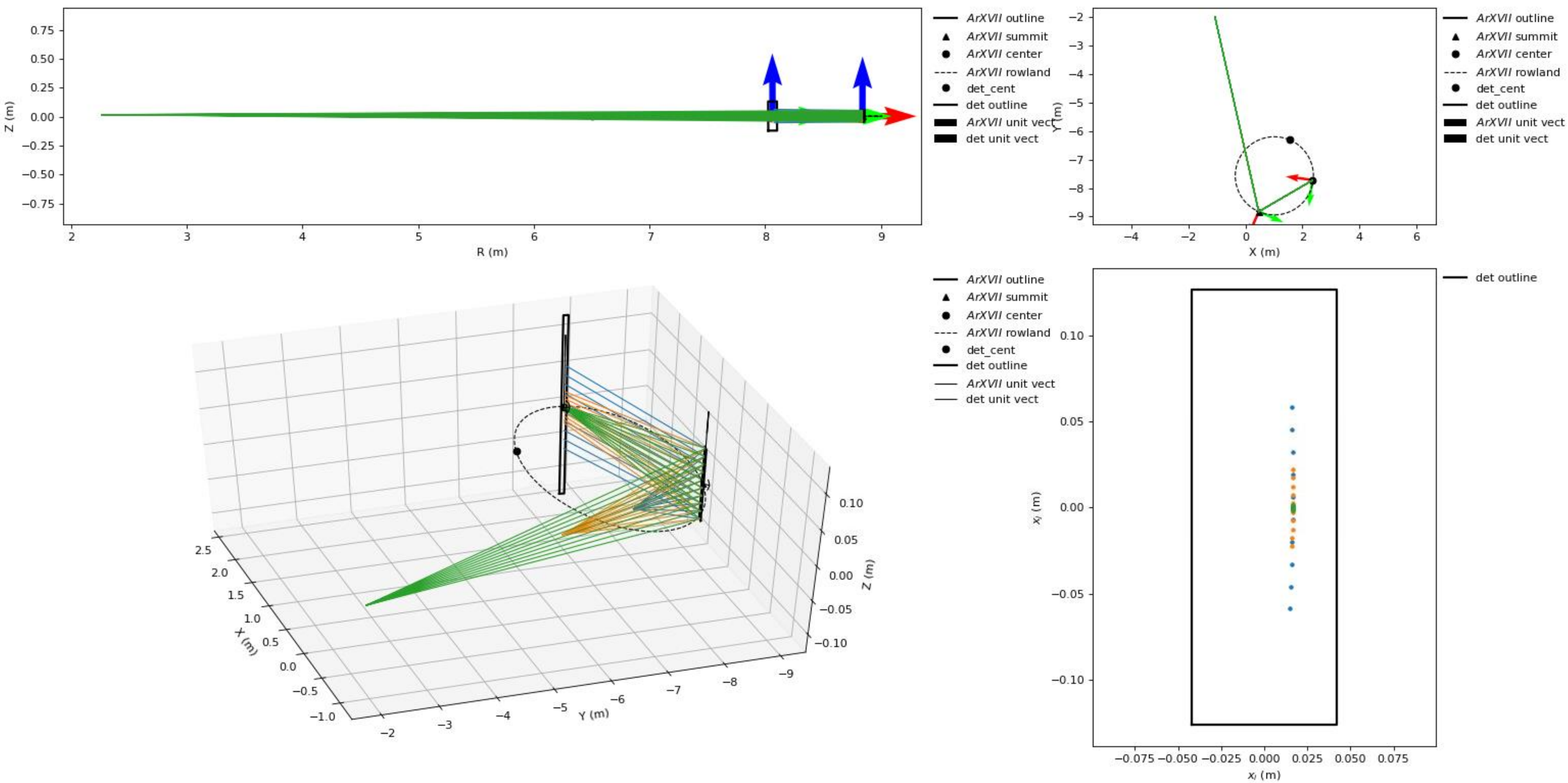
=> ideally, the geometry should be part of the unknowns (iterated over)

PERSPECTIVES: Mutualize numerical tools with X-ray spectrometers

X-Ray spectrometers

Geometry modelling & ray-tracing + inversions

(ongoing)



Perspectives: Algorithms

Philipps-Tikhonov regularization **(ongoing)**

Gaussian process Regressions **(next main approach to be implemented)**

Particularly interesting for error bars and bayesian approach

Possible interoperability with existing libraries?

Neural networks and AI for fast reconstructions

Questions on the training set!

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint Paul Lez Durance Cedex
T. +33 (0)4 42 25 46 59 | F. +33 (0)4 42 25 64 21

DSM
IRFM
West Project

Philipps-Tikhonov regularization

Geometry matrix

Regularization operator

$$\Phi_{t_n}(\underline{\epsilon}^{\eta}) = \|\underline{\underline{T}}\,\underline{\epsilon}^{\eta} - \underline{f}(t_n)\|_2^2 + \alpha H(\underline{\epsilon}^{\eta})$$

Measurements

Regularization parameter (scalar)

- **Discrepancy principle**
- **Generalized cross-validation**
- L-curve
- Akaike information criterion
- …