Digital twin of edge tokamak diagnostics for heat exhaust prediction

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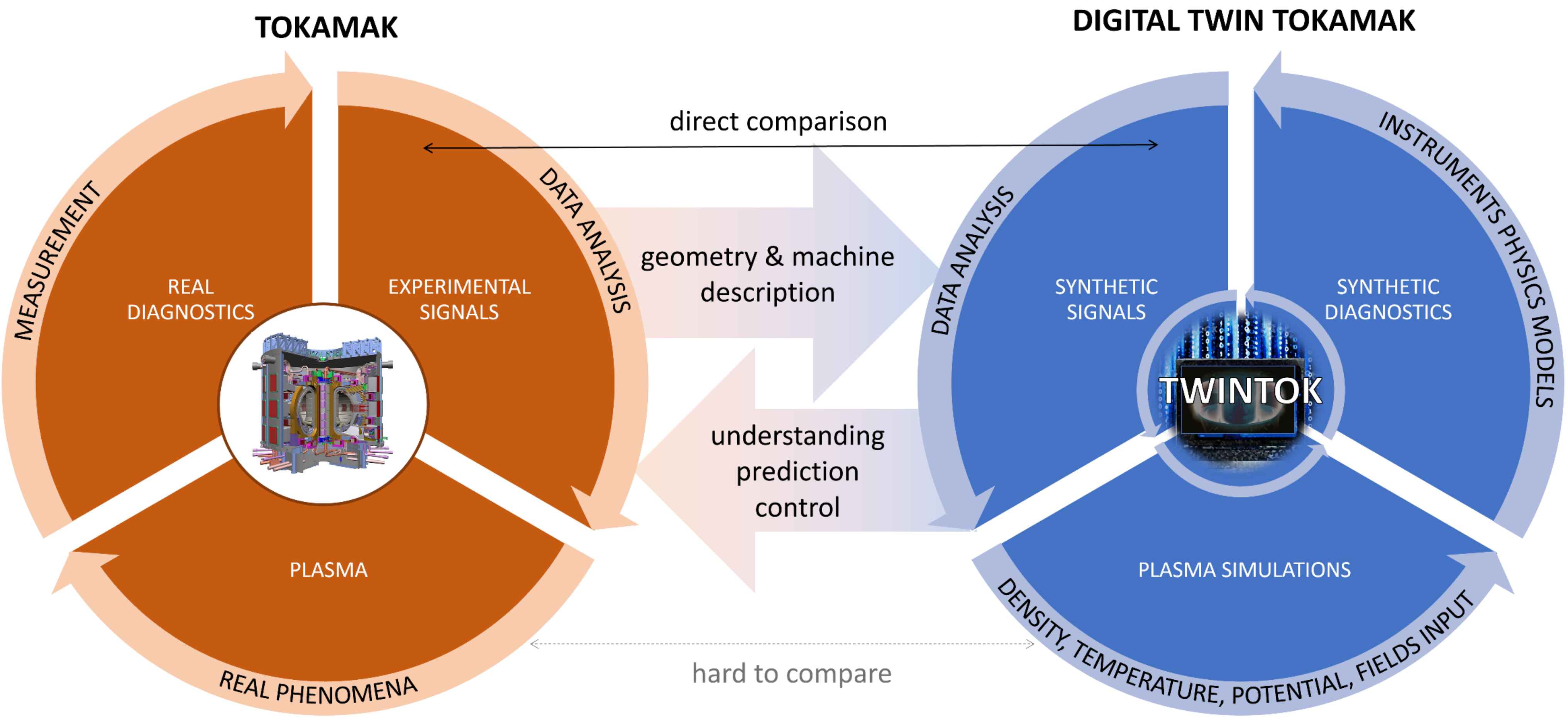
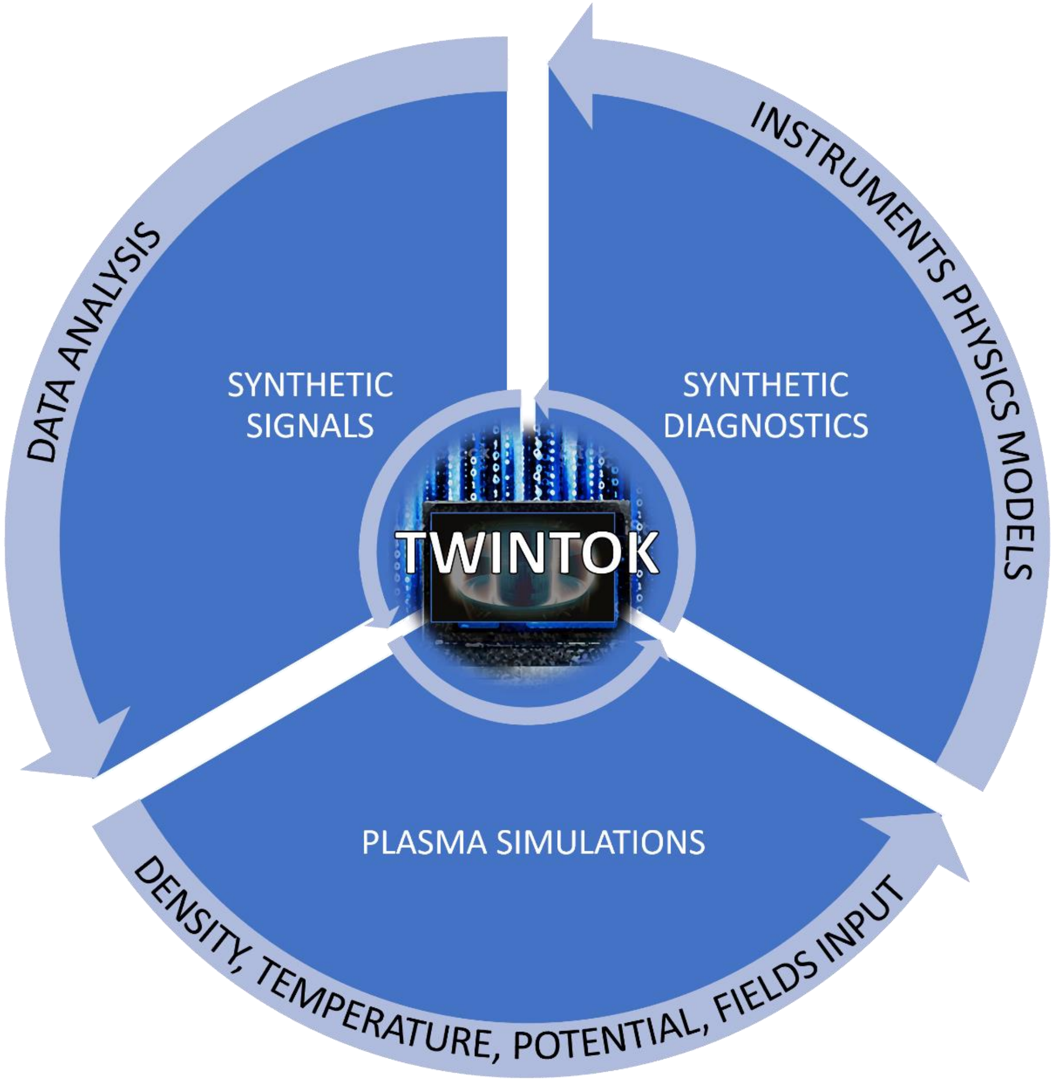
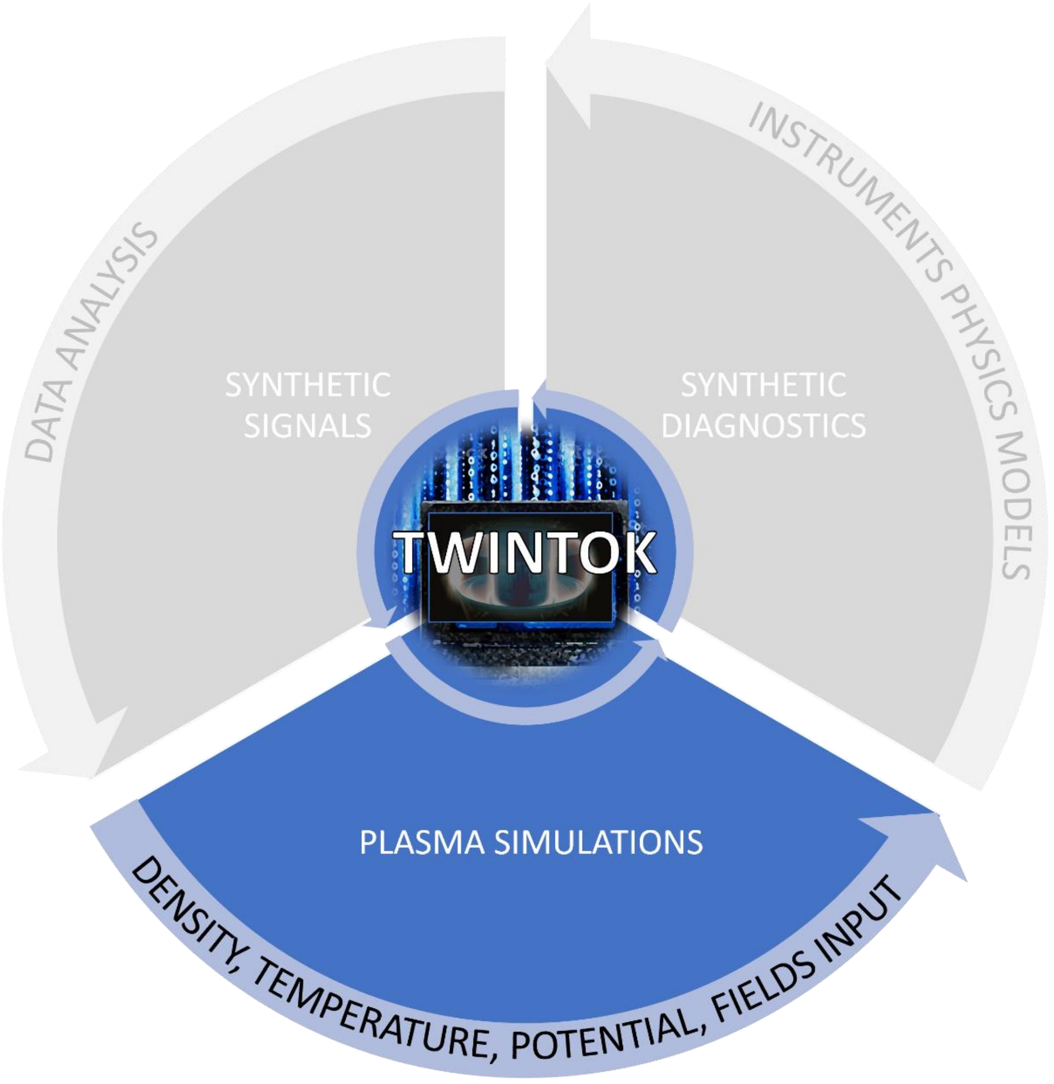
Advancing heat exhaust prediction through digital twin technology



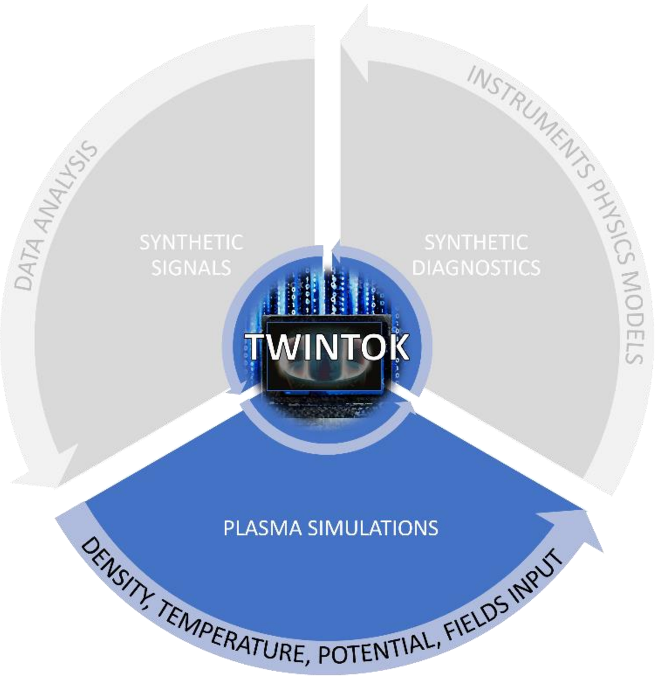
Outline


DATA ANALYSIS
INSTRUMENTS PHYSICS MODELS
SYNTHETIC SIGNALS
SYNTHETIC DIAGNOSTICS
TWINTOK
PLASMA SIMULATIONS
DENSITY, TEMPERATURE, POTENTIAL, FIELDS INPUT

Enhancing operational designs with high-fidelity plasma simulation



Core-edge full discharge with SolEdge3X-HDG to follow heat & particle flux evolution

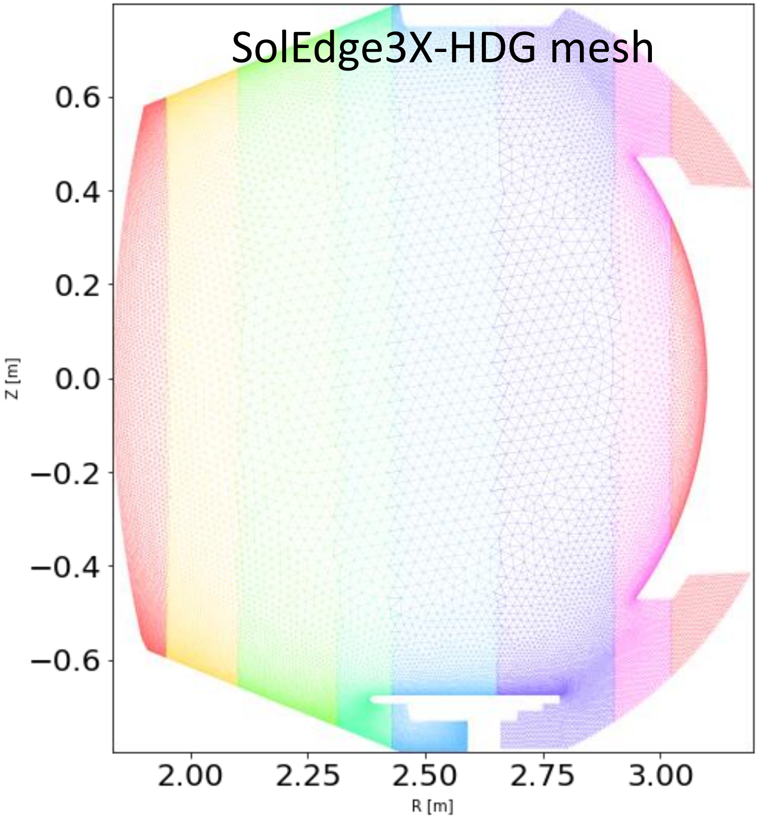


Through IMAS database or code's output

TWINTOK can use various simulation inputs:

METIS	[Artaud NF 2018]
JINTRAC	[Militello IAEA FEC 2021]
SOLPS	[Wiesen JNM 2015]
SolEdge3X(-HDG)	[Giorgiani JCP 2018]
GYSELA	[Dif-Pradalier CP 2022]

…



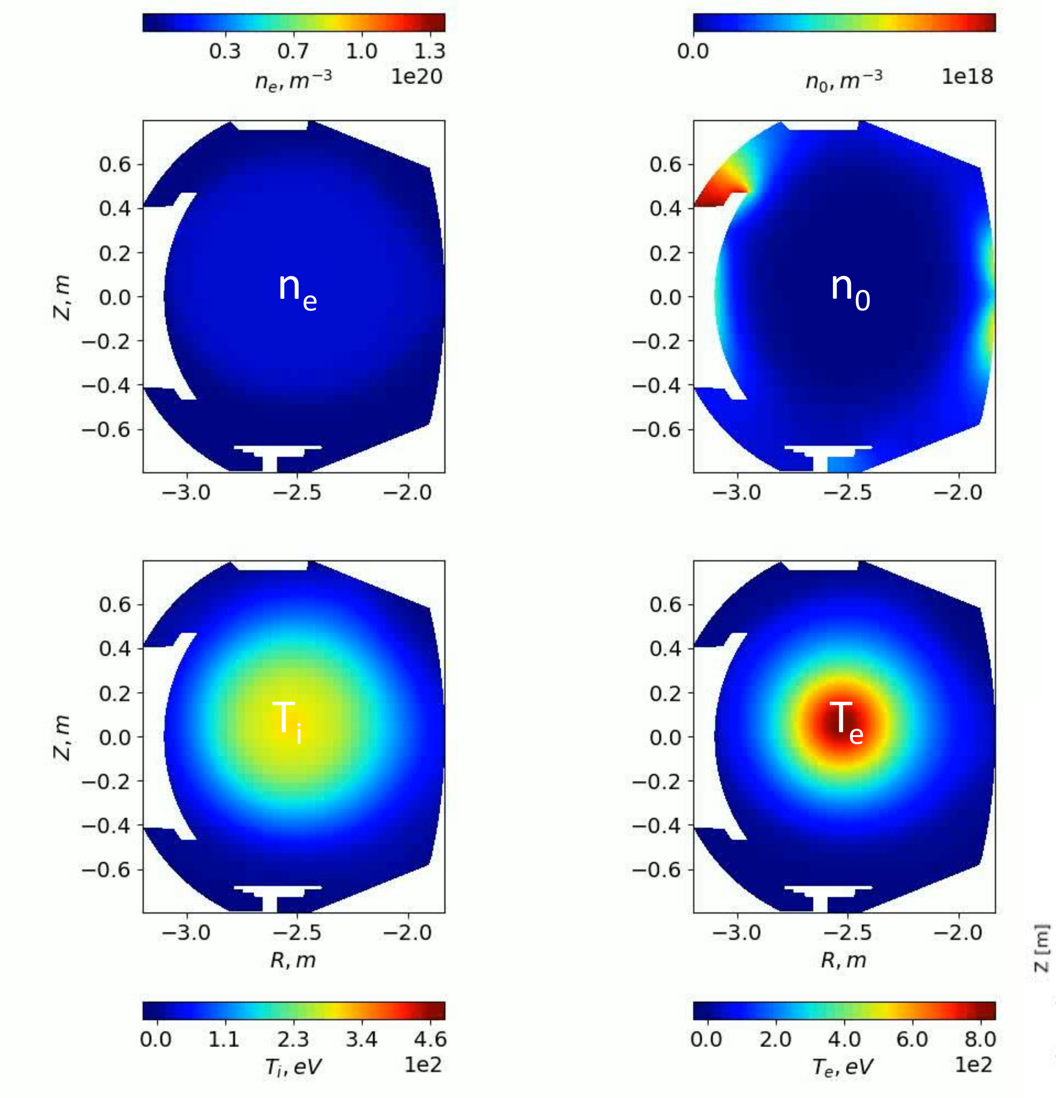
To study evolution of heat and particle fluxes at the PFC during the full discharge

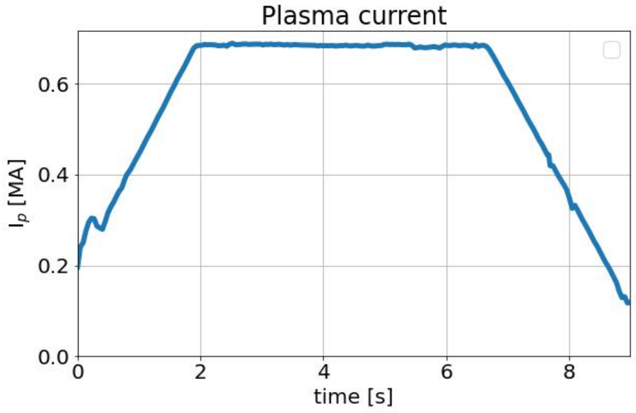
→ core-edge full discharge simulation

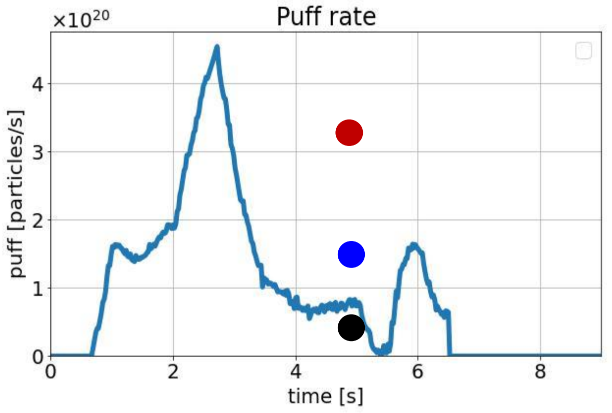
✅ **SolEdge3X-HDG** hybridized discontinuous Galerkin fluid transport code

- k-(ε) self-consistent transport model
- advanced fluid neutral model with non-constant diffusion

Target discharge simulation: Ohmic plasma in WEST with varied gas puff rates

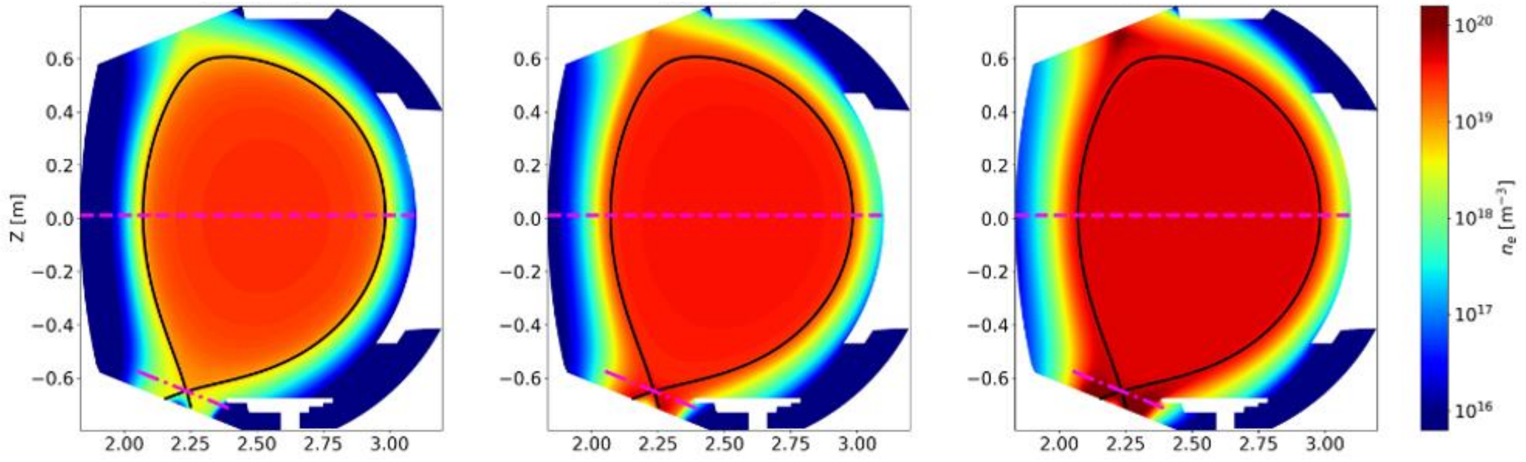




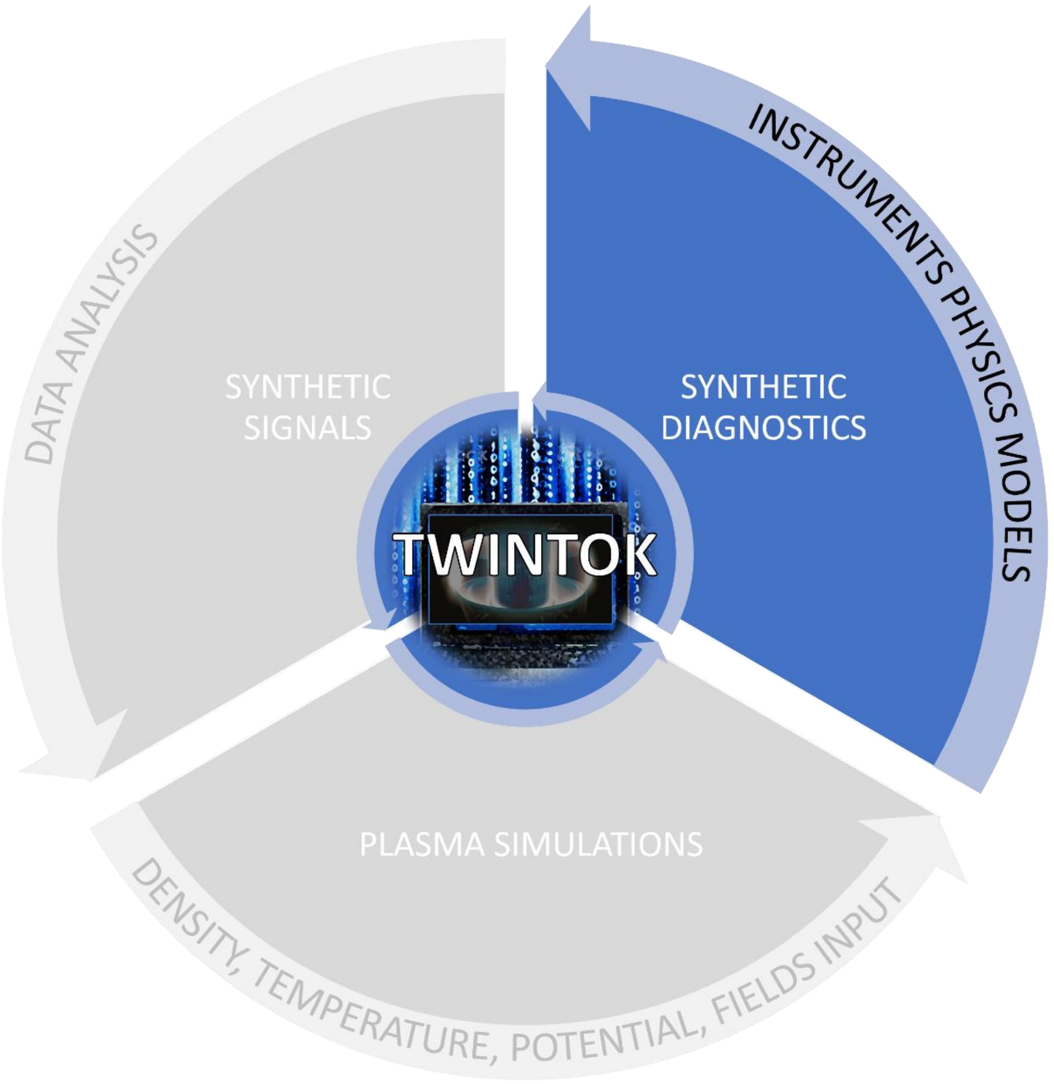


- Target discharge WEST#54487: Ohmic plasma with a current ramp up and a varied gas puff rate
- SolEdge3X-HDG allows to simulate alternative heat flux organization regimes at t=4.73s

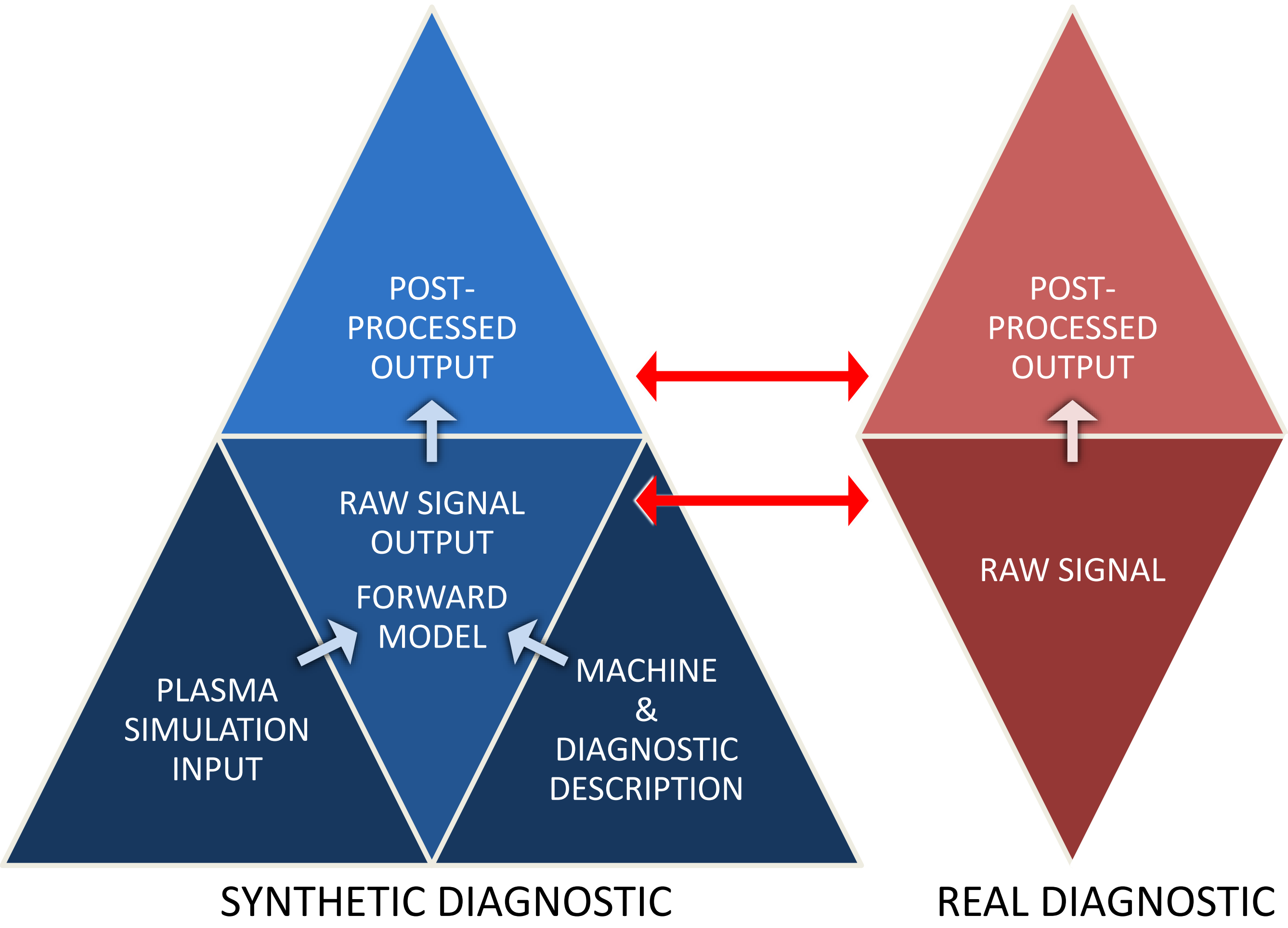
sheath-limited ● 0.3×10^{20} s^{-1} | high recycling ● 1.5×10^{20} s^{-1} | detached ● 3.25×10^{20} s^{-1}



TWINTOK forward models and universal architecture within IMAS



Universal SD architecture within IMAS enabling multi-machine application



ITER Integrated Modelling & Analysis Suite (**IMAS**)

Interface Data Structure (**IDS**)

example of SD architecture

```
class tip:
    init_static(interferometer_MD, param_file)
```
Reads diagnostic's geometry and parameters
```
    init_dynamic(equilibrium)
```
Reads flux quantities, interpolates on the LOS
```
    evaluate(core_pofiles)
```
Evaluates density and temperature on the LOS
```
    fill_in_output_ids(self)
```
Saves the output into an IDS

```
spectrometer:
    world = World()
    plasma = sim.create_plasma(world)
    plasma.atomic_data = OpenADAS()
    plasma.models=[Bremsstrahlung(),..]
```
Creates a plasma object in the scene
```
    DVIS2 = FibreOpticGroup(parent=world)
    DVIS2.observe()
```
Creates an observer and calculates the signal

https://git.iter.org/

Cherab/Raysect approach for emission diagnostics: wall description

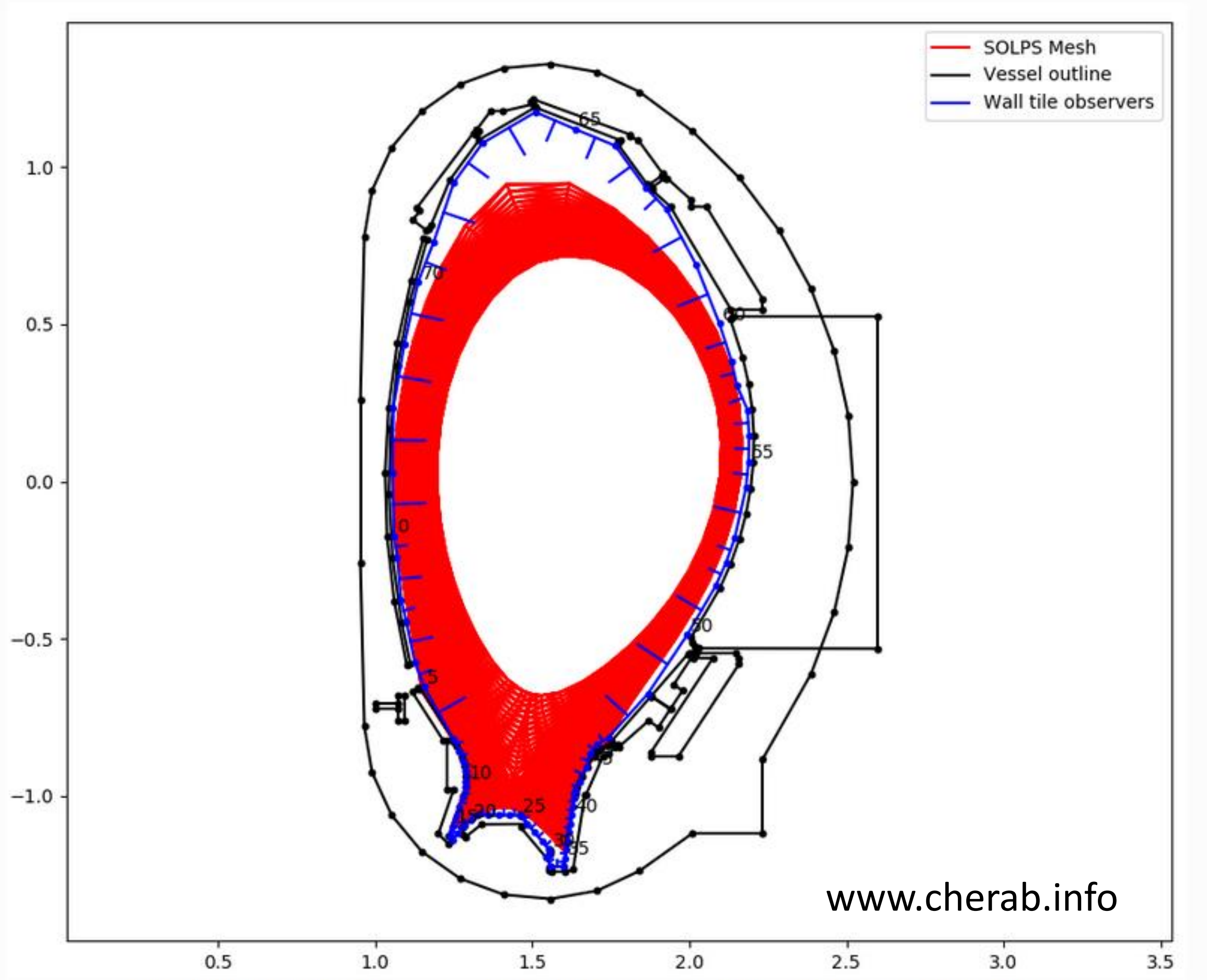
Wall description from CAD

```
for mesh_path in FULL_MESH:
    directory, filename = os.path.split(mesh_path)
    mesh_name, ext = filename.split('.')
    if ext == 'rsm':
        Mesh.from_file(mesh_path, parent=world,
        material=material, name=mesh_name)
WALL_OUTLINE = np.array([
  [1.670482, -0.9978656, 1.6668, -0.9992], …])
WALL_POLYGON_BOUNDARY = [
  Point2D(1.0566, -0.072559), …]
```

↓

import_tcv_mesh

(TCV, AUG, MASTU, JET, Compass, WEST, ITER)



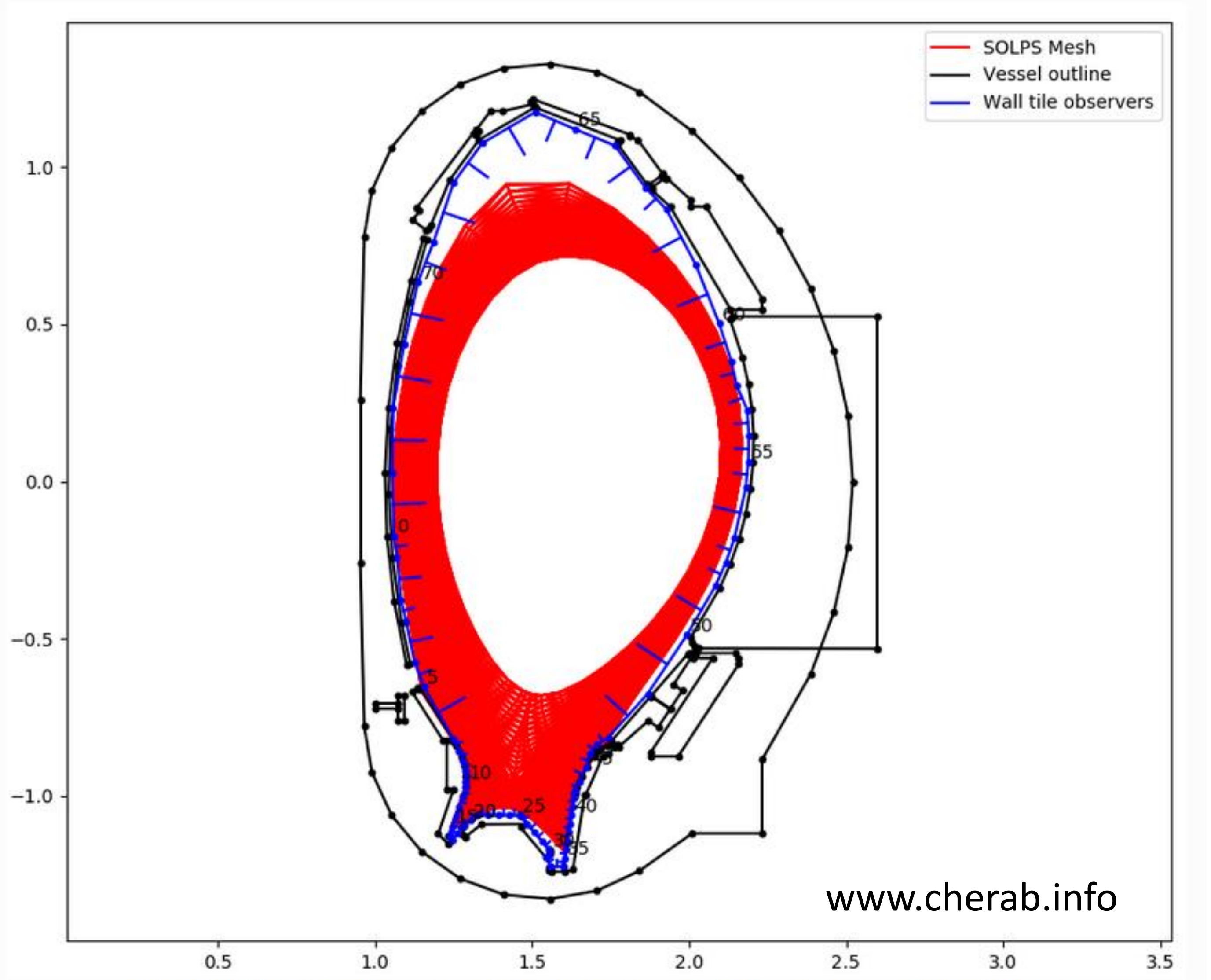
Example wall observation geometry for AUG shown in blue. Surface normals indicated.

Cherab/Raysect approach for emission diagnostics: wall elements as PFC

Wall elements as detectors

(detector index, xwidth, ywidth, centre_point, normal_vector, y_vector)

```
wall_detectors = [
   (0, 0.01, 0.2027, Point3D(1.0566, 0.0, -0.072559),
    Vector3D(0.99958, 0.0, 0.028904),
    Vector3D(0.028904, 0.0, -0.99958)), ...
   ]
```



Example wall observation geometry for AUG shown in blue. Surface normals indicated.

Load the grid vertices

for vertex_id in range(num_vertices):

vertex_coords[vertex_id, :] = (
edge_profiles.grid_ggd[index].**space**[0].**objects_per_dimension**[0].**object**[vertex_id].geometry[:])

Initialize the plasma

plasma = Plasma(parent=parent, ...)

plasma.b_field = VectorAxisymmetricMapper(**equilibrium.b_field**)

te = **edge_profiles.ggd**[index].**electrons.temperature**[0].values

ne = **edge_profiles.ggd**[index].**electrons.density**[0].values

for ion_species in **edge_profiles.ggd**[index].**ion**:

ti = ion_species.temperature[0].values

ni = ion_species.density[0].values

for neutral_species in **edge_profiles.ggd**[index].**neutral**:

n0 = neutral_species.density[0].values

Cherab/Raysect approach for emission diagnostics

Create plasma emission model

plasma.atomic_data = OpenADAS(permit_extrapolation=True)

Define emission lines

d_alpha = Line(deuterium, 0, (3,2))

...

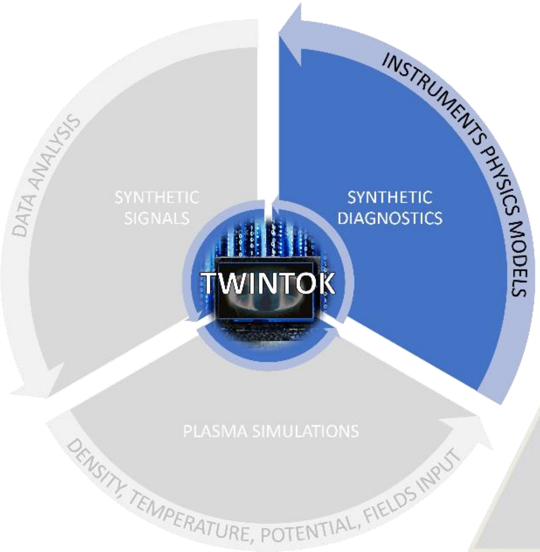
Add emission lines to plasma

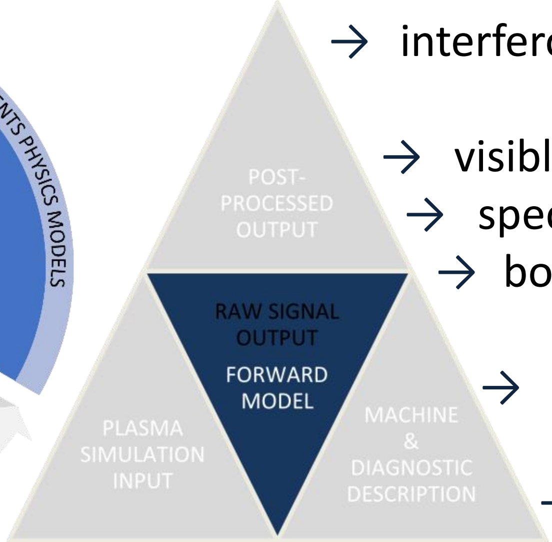
```
plasma.models = [
   Bremsstrahlung(),
   ExcitationLine(d_alpha),
   RecombinationLine(d_beta), ...
]
```

Create an observer and calculate the signal

```
DVIS2 = FibreOpticGroup(parent=world)
DVIS2.observe()
```

TWINTOK: unveiling synthetic diagnostics for holistic power exhaust investigation



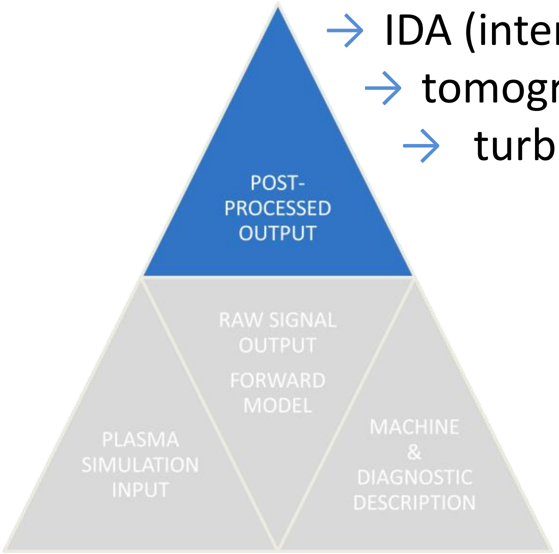


→ interferometer — LOS integration **TIP** [Medvedeva 5th AAPPS DPP 2021]

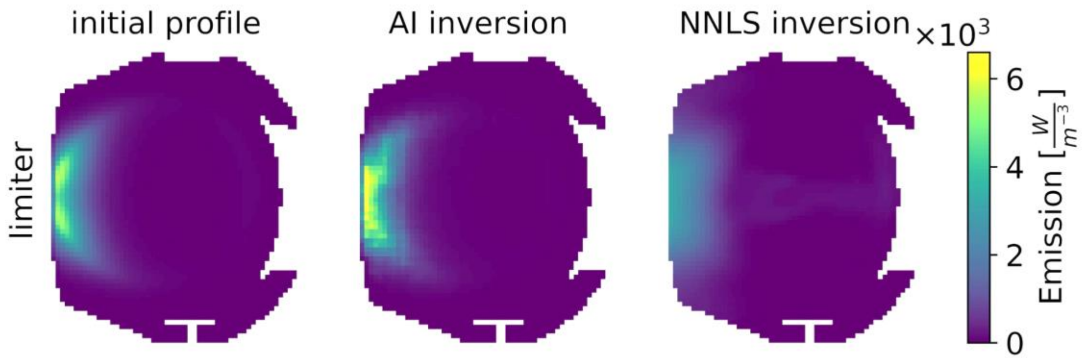
→ visible camera
→ spectroscopy — **Cherab+Raysect** [Neverov PPCF 2020, Carr 44th EPS 2017]
→ bolometry

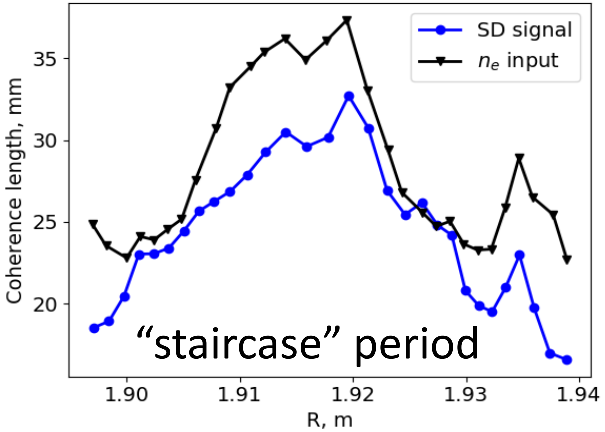
→ reflectometry — 2D FDTD full wave **FeDoT** [Medvedeva 15th IRW 2022]

→ Langmuir probes — 2D PIC simulator – ongoing

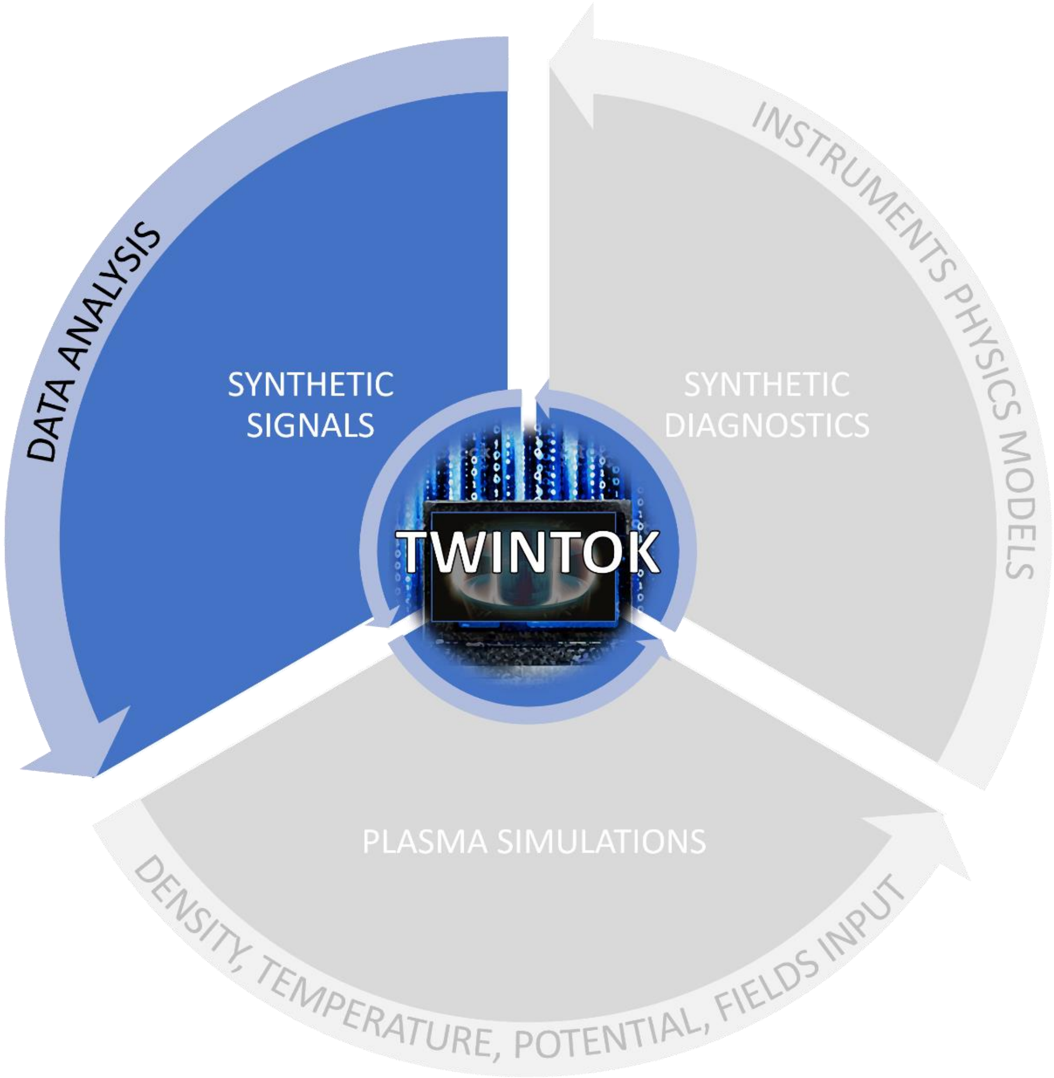


→ IDA (interferometry + ECE + reflectometry + …) [Fischer FST 2010]
→ tomography (bolometry) [Kudashev ICFDT6 2022]
→ turbulent transport analysis (reflectometry) [Medvedeva 15th IRW 2022]

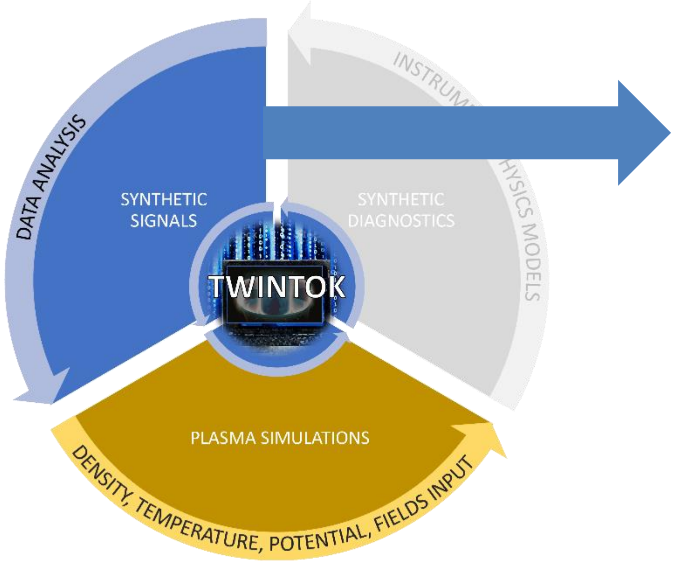


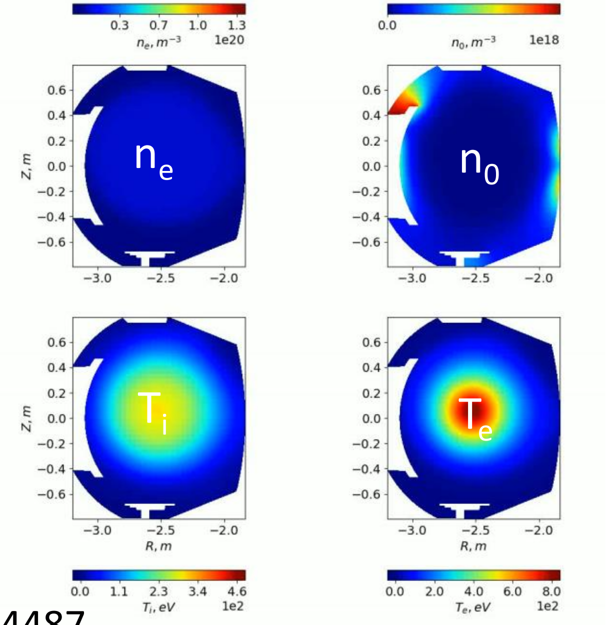


Support experiment interpretation and code validation with TWINTOK



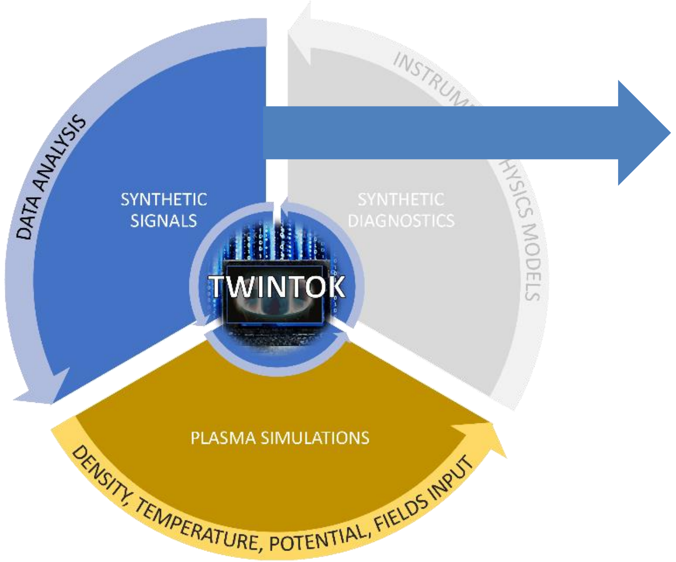
Extensive coverage by TWINTOK allows a thorough validation of simulation results

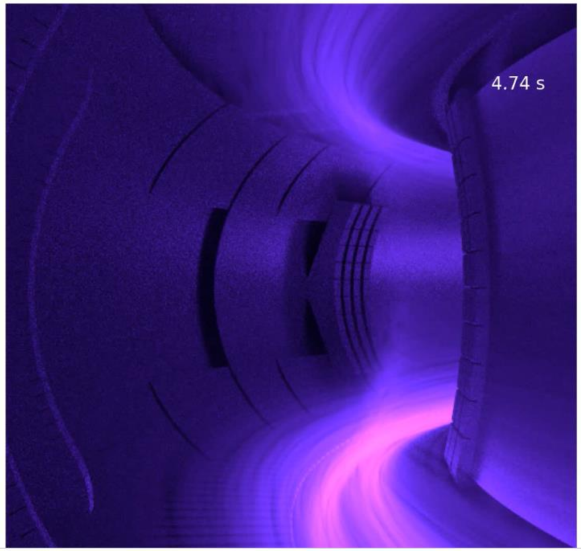




Digital twin of visible camera for WEST#54487

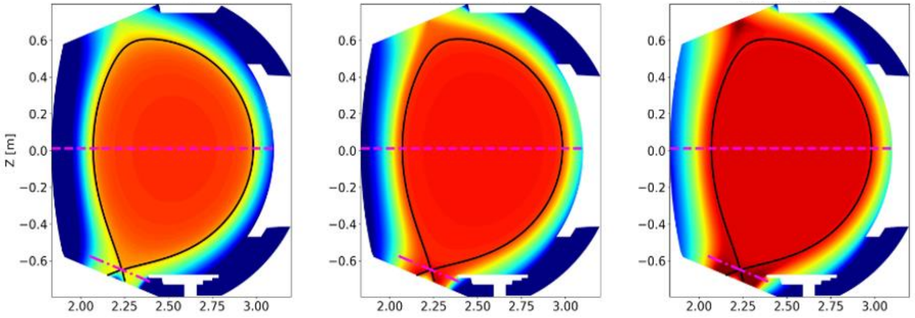
Extensive coverage by TWINTOK allows a thorough validation of simulation results

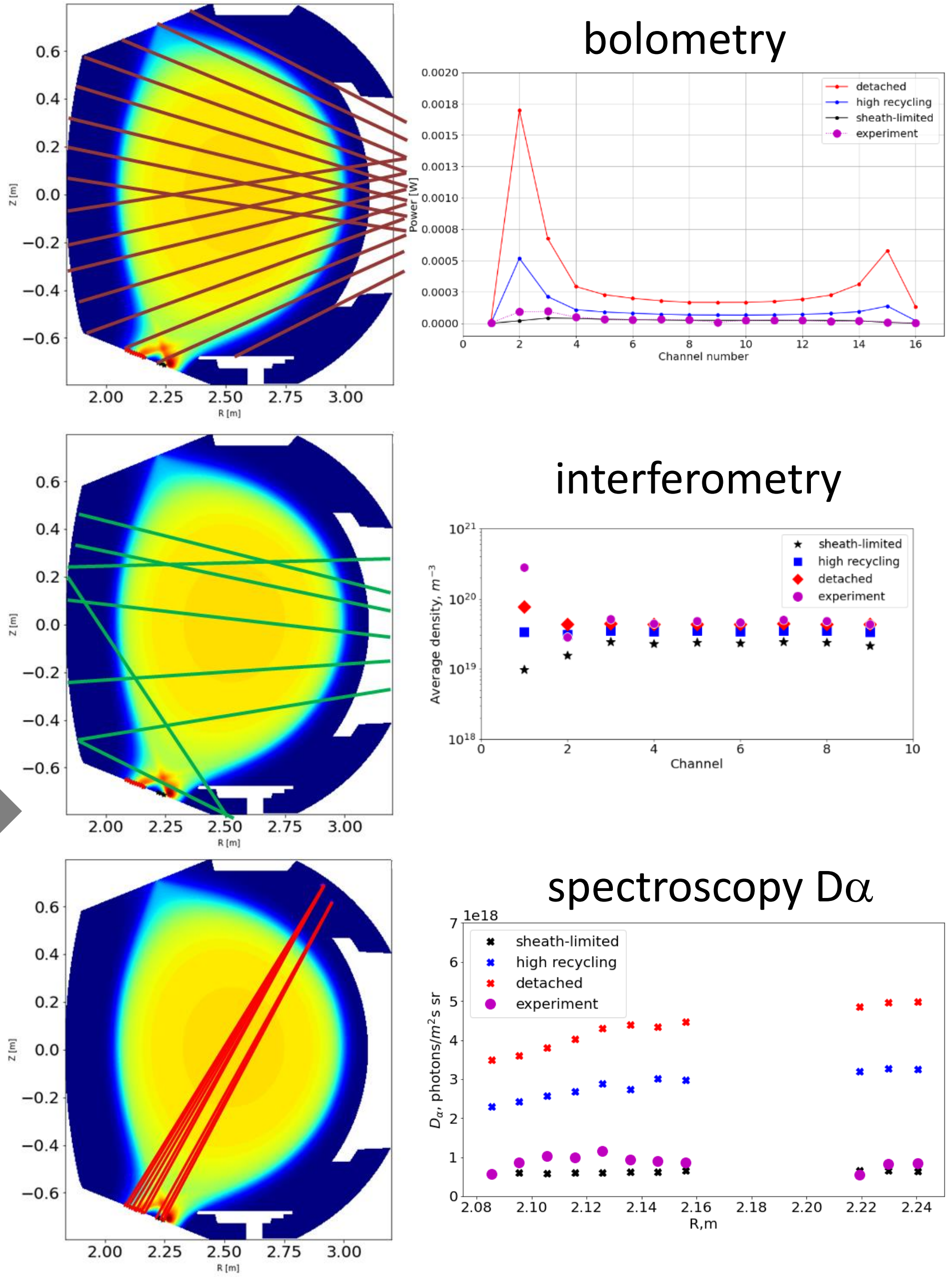




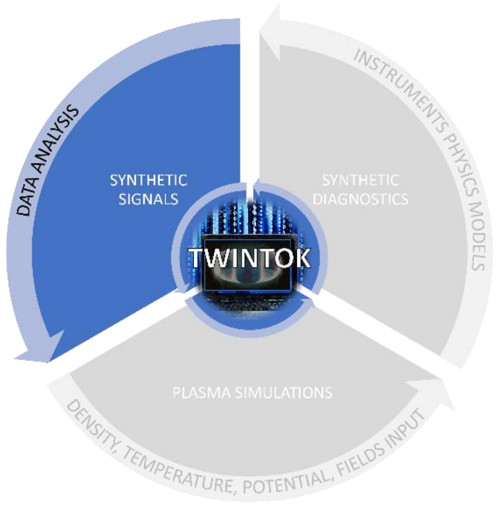
Digital twin of visible camera for WEST#54487

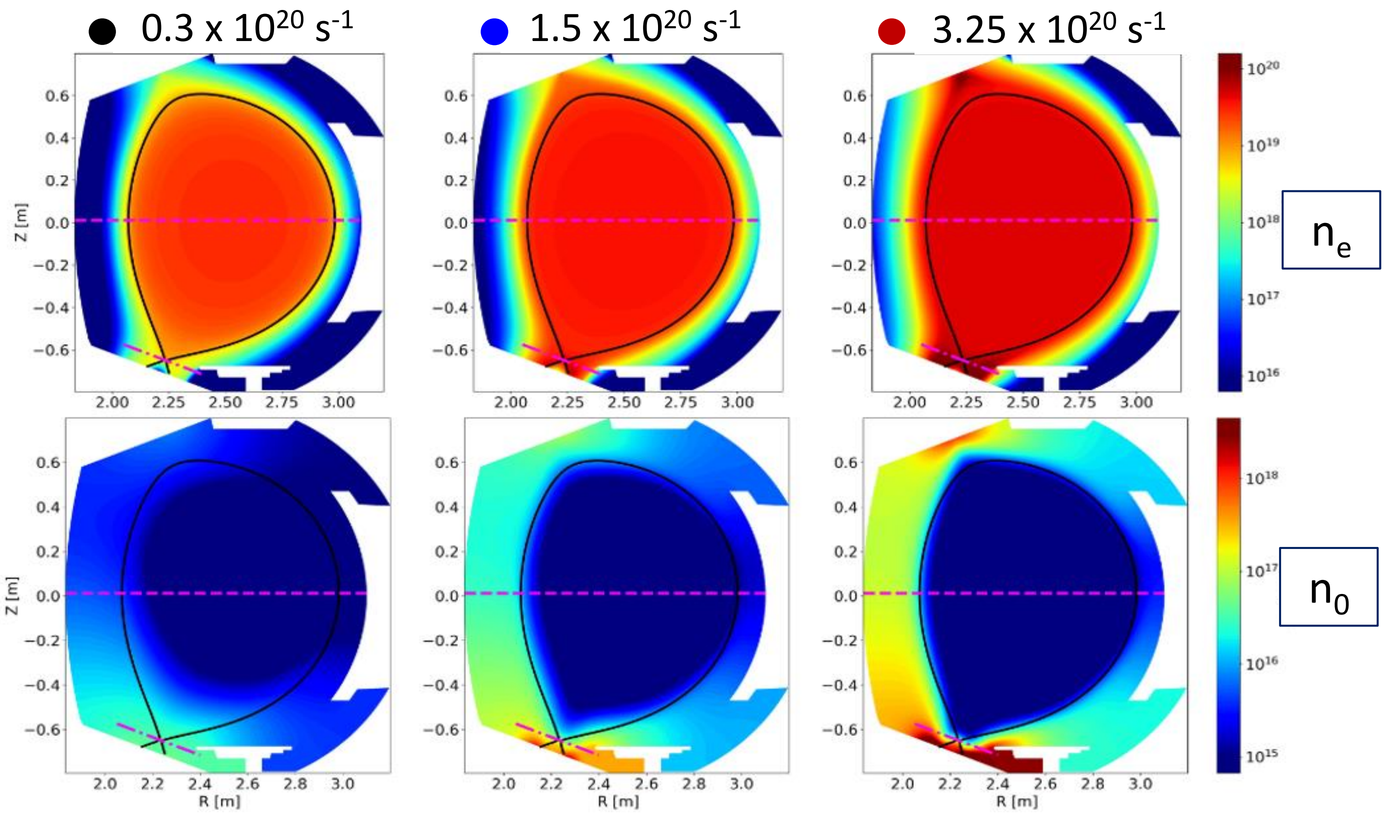
● 0.3 x 10^{20} s^{-1} ● 1.5 x 10^{20} s^{-1} ● 3.25 x 10^{20} s^{-1}

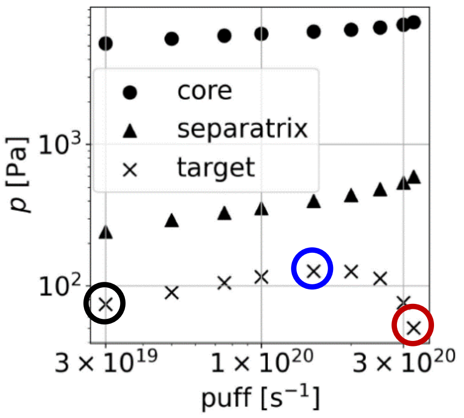


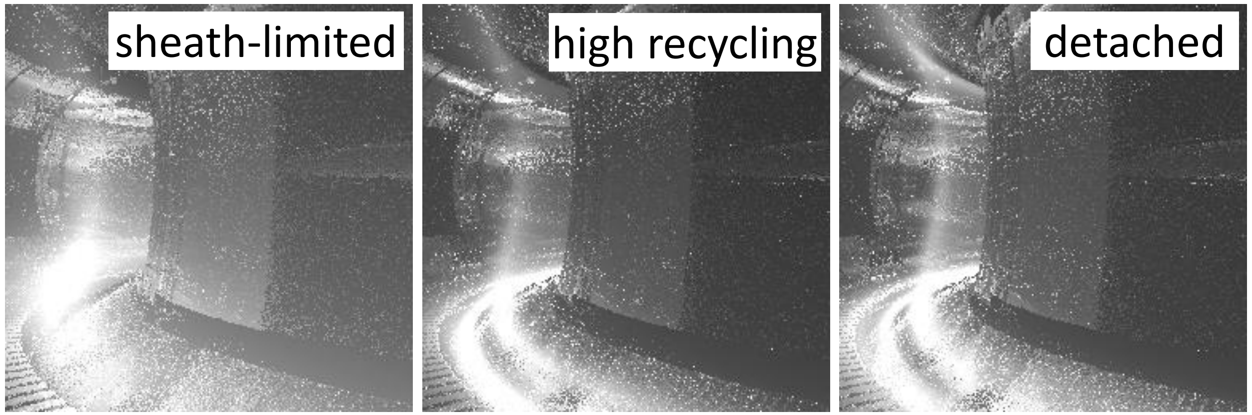


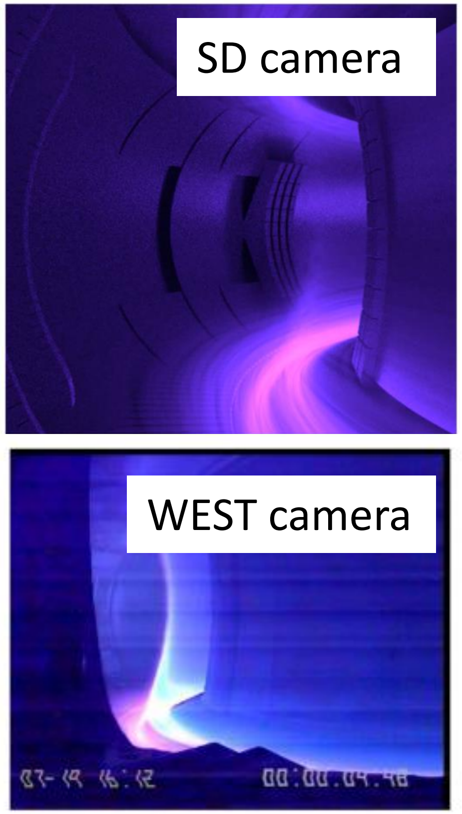
Understanding of plasma composition and configuration through visible emission





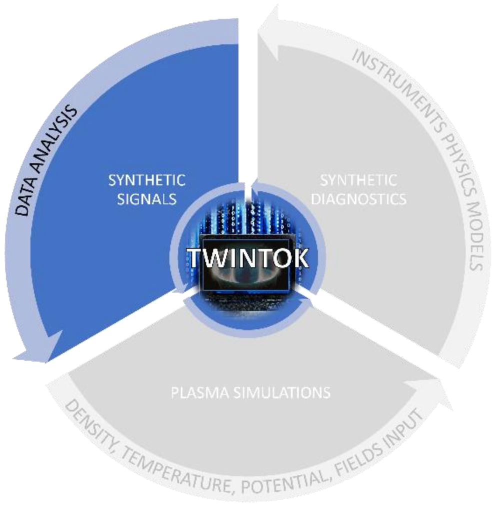


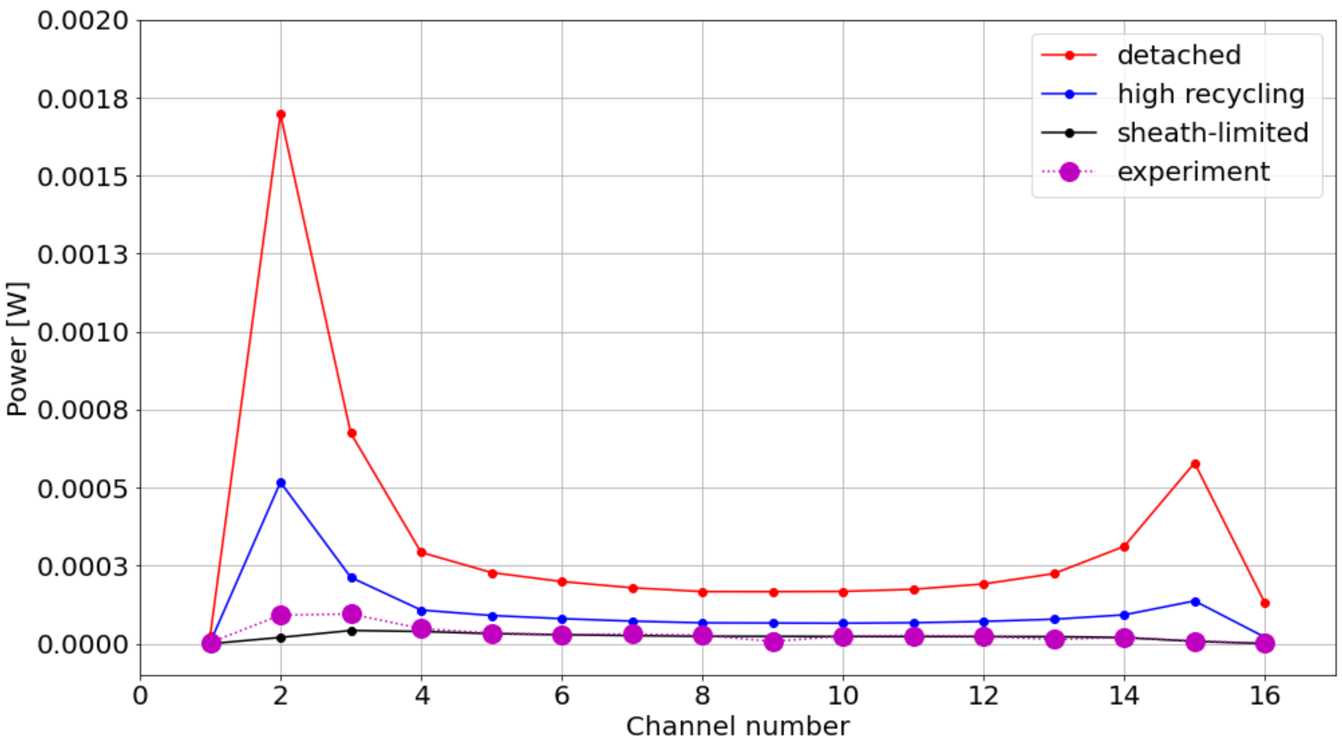


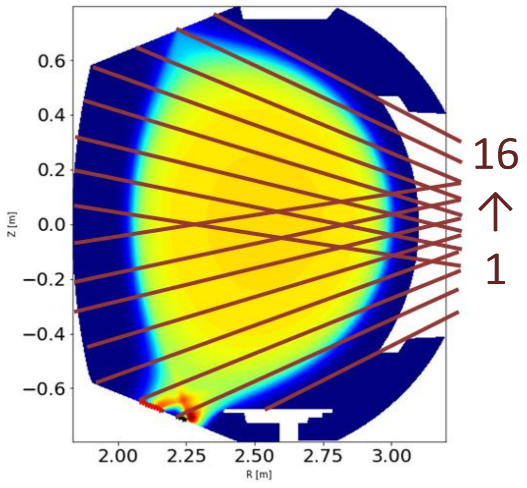


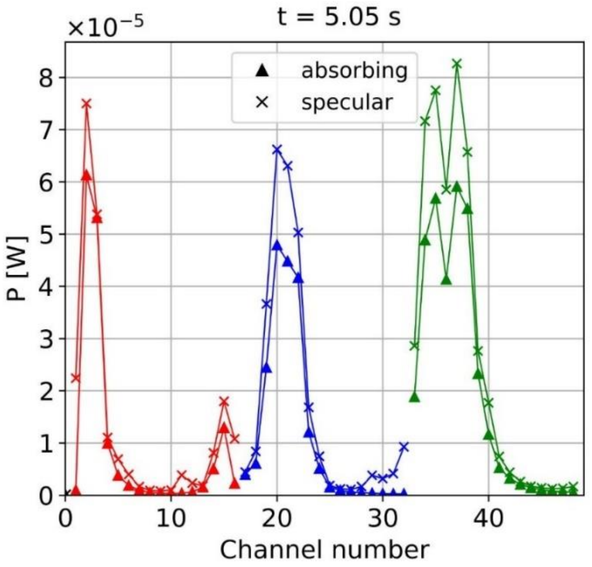
[Kudashev Applied Sciences 2022]

Bolometry synthetic diagnostic: investigating plasma detachment on WEST





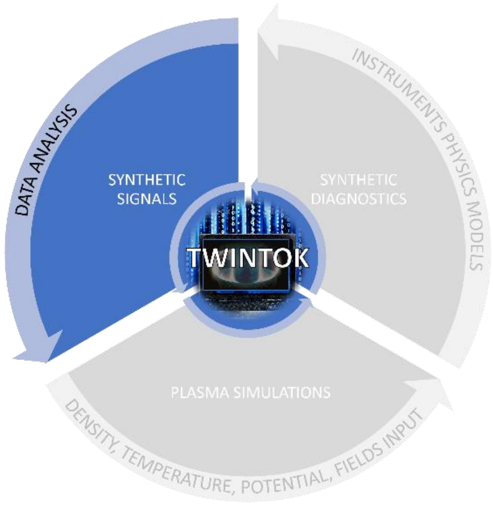


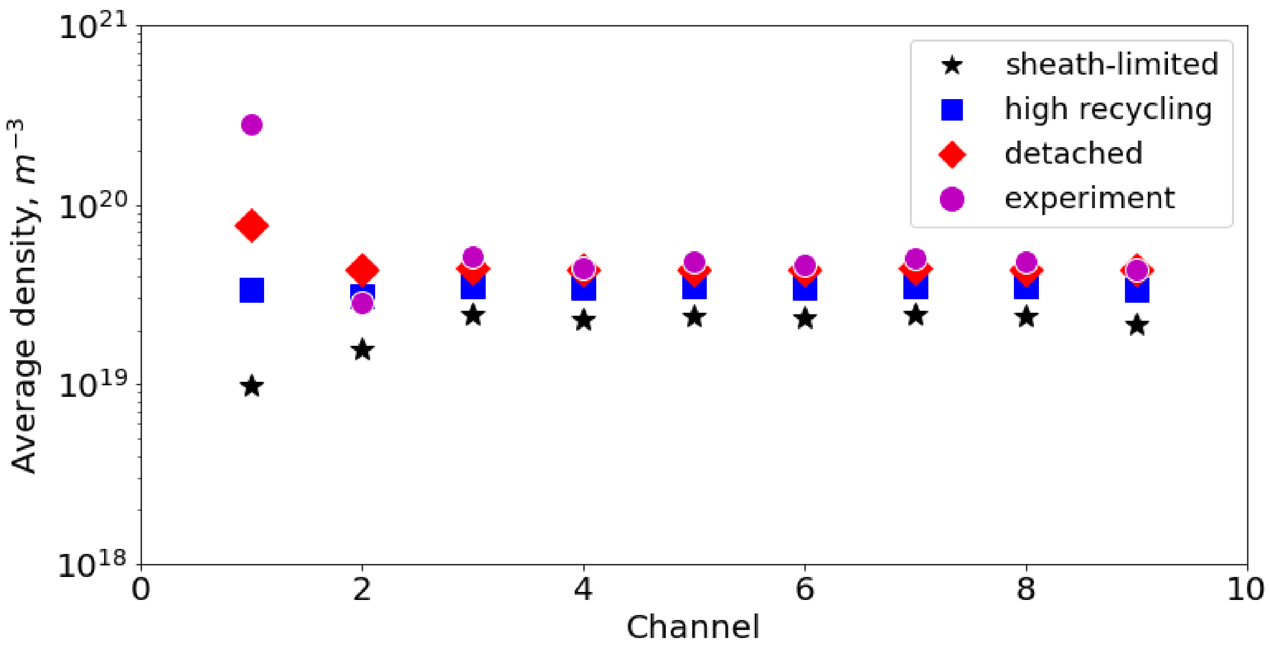


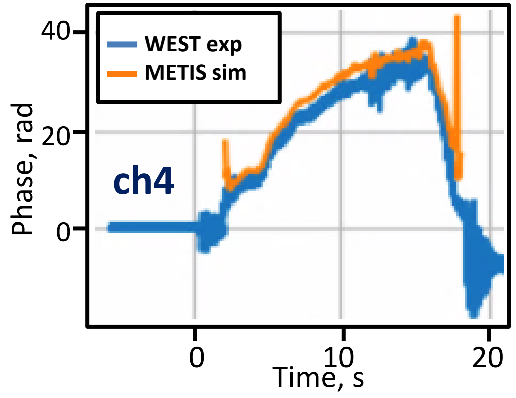
[Kudashev AS 2022]

- Impurities contribution assessed using HDG+ERO2.0 simulation [Scotto d’Abusco NF 2022, Di Genova NF 2021]
- Different wall surface models have strong impact on the signals
- SD participates in the design of the ITER bolometry system [Meister SOFE 2023]

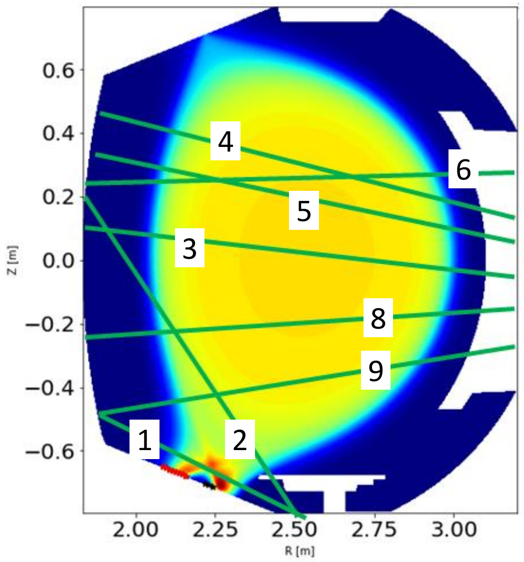
Interferometer synthetic diagnostic TIP confronting real data to simulation





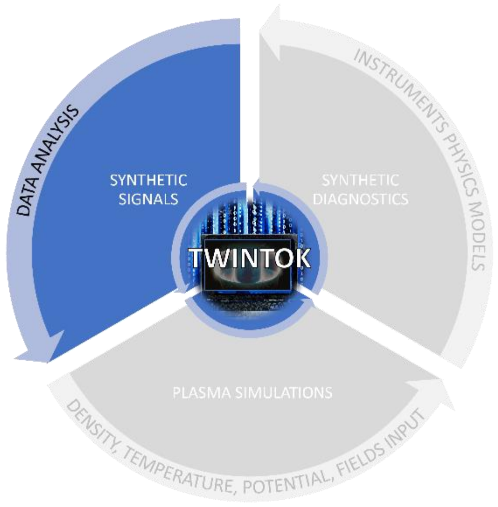


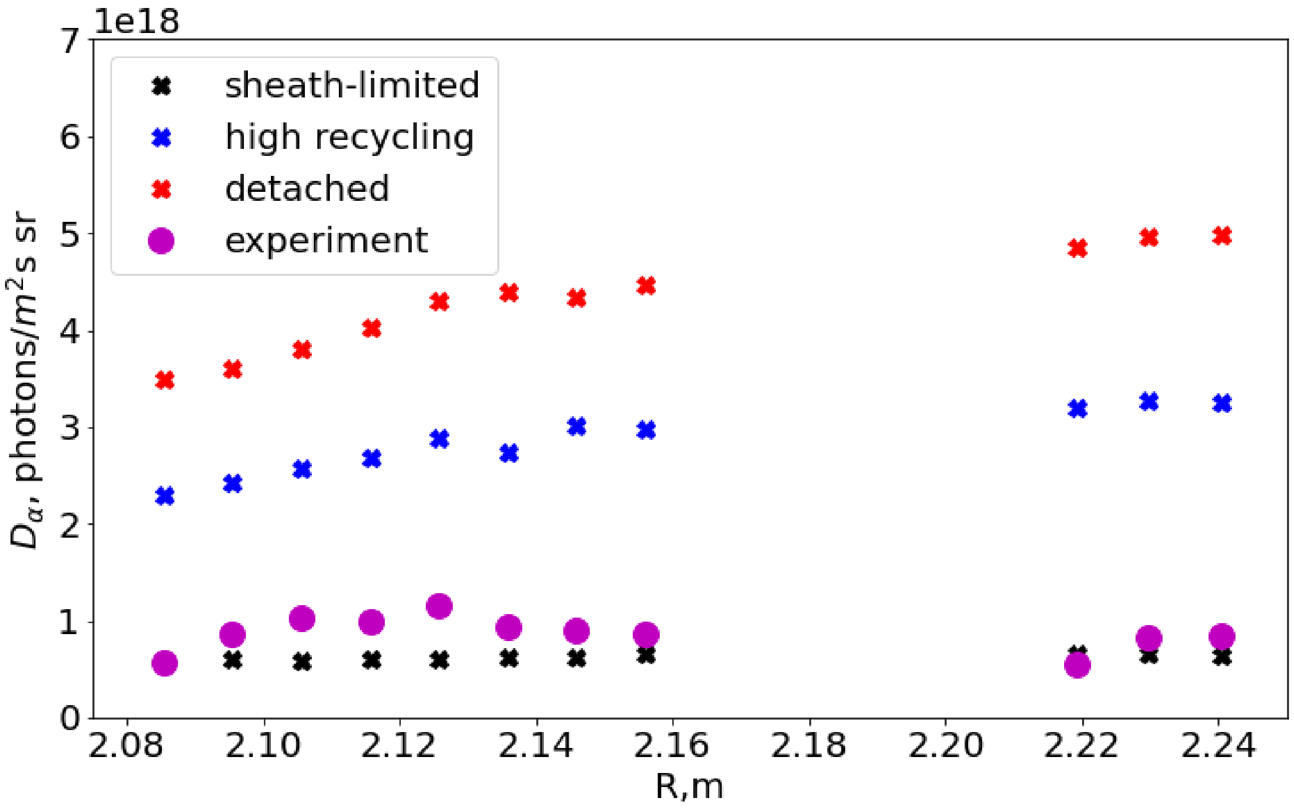
[Medvedeva 49th EPS]

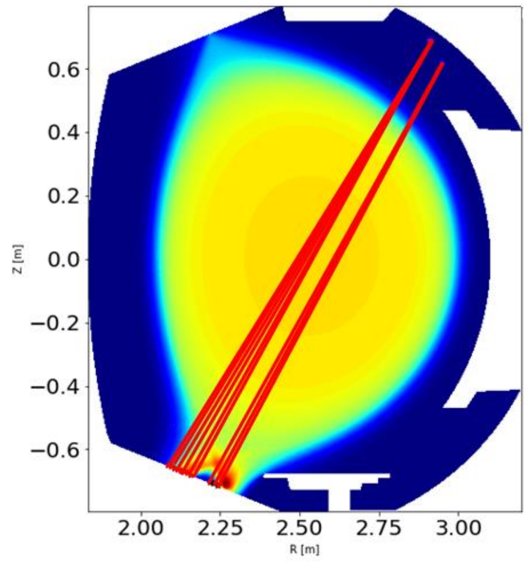


- TIP previously validated METIS+TIP on WEST experimental signals
- 3 different gas puff simulations approach interferometer data
- Discrepancies due to the variation of the optical path and SOL density contribution

Dα synthetic diagnostic's high-fidelity reproducing of experimental signals







- Synthetic signals along the divertor targets are calculated considering WEST geometry and wall reflections
- Experimental signal falls between the sheath-limited and high recycling simulations level of Dα radiation, aiding in regime determination

Concluding remarks

- By combining experimental data with synthetic diagnostic signals generated by TWINTOK, we gain a deeper understanding of diagnostics measurements and plasma behavior.

- Universal synthetic diagnostic **architecture within IMAS** offers a standardized approach for integrating various measurement systems.

- Achieving the best operation scenarios with reduced heat fluxes and improved confinement demands **high-fidelity plasma simulations** → SolEdge3X-HDG is under development.

- **TWINTOK forward models** will offer the necessary coverage for measurement interpretation, models validation and operation prediction.