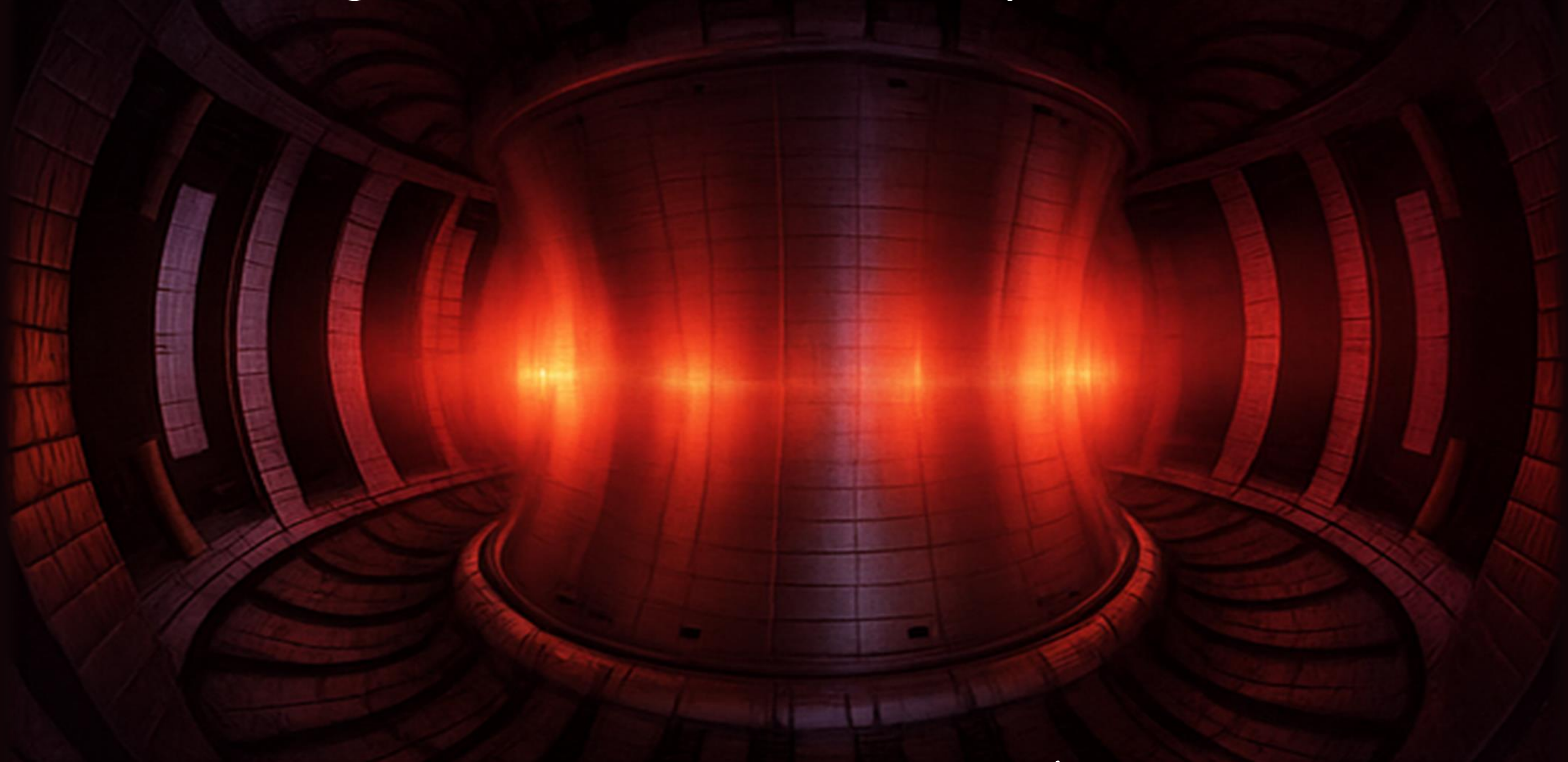
Use of integrated models to interpret measurements



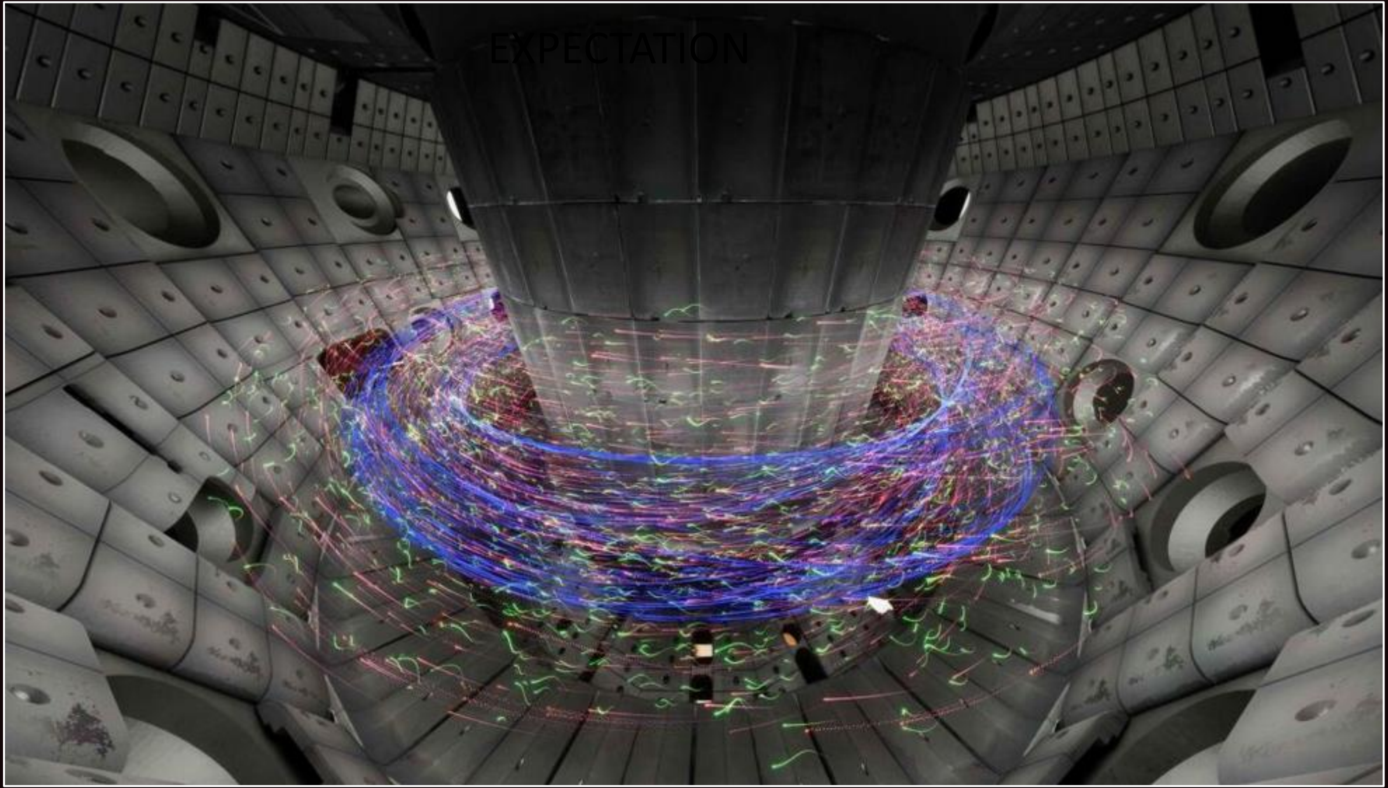
Anna Medvedeva Glasser – M2P2, Aix-Marseille University, École Centrale Méditerranée

ITER International School – Aix-en-Provence, 2025

Why interpretation of measurements matters

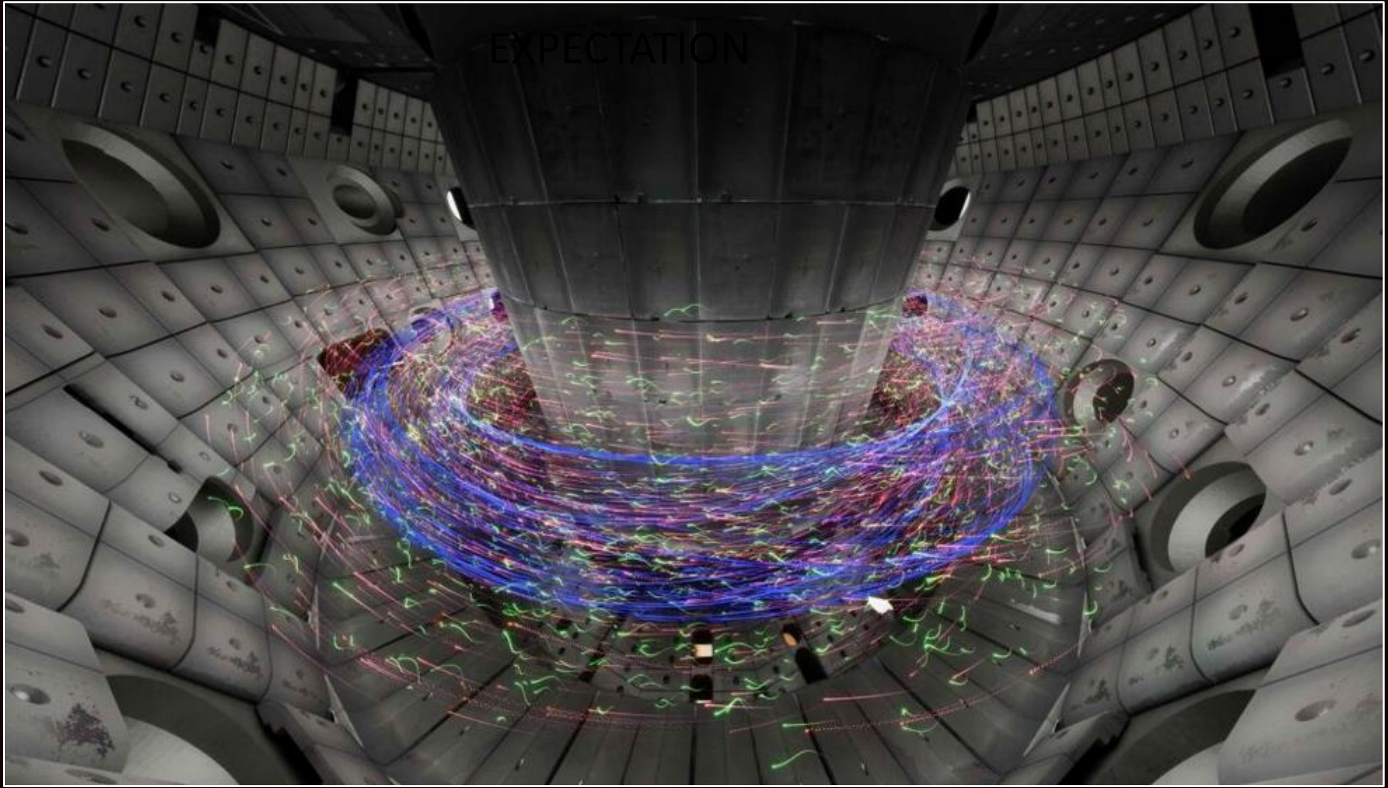
EXPECTATION

REALITY



Visualisation of plasma in a tokamak @2024 EPFL/Laboratory for Experimental Museology (EM+) – CC-BY-SA

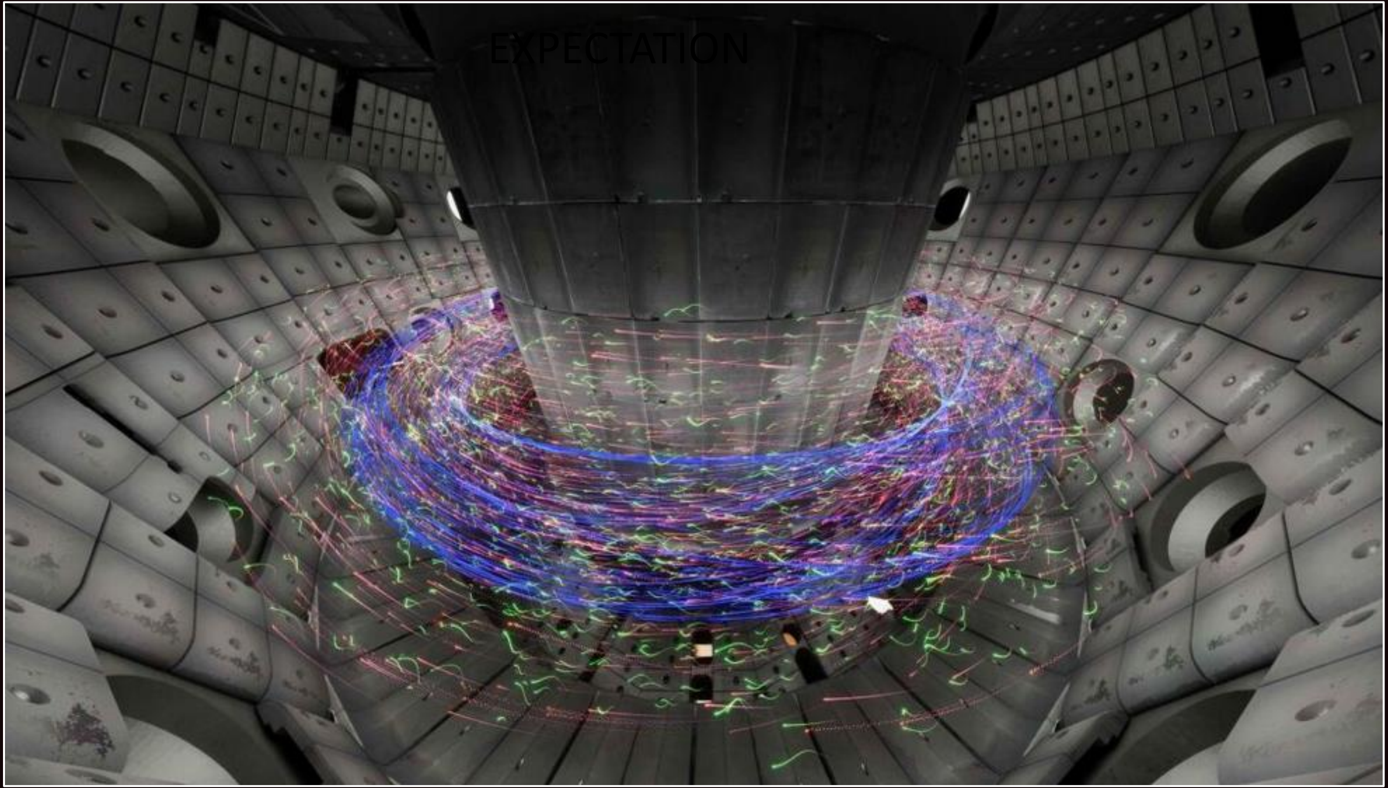
Why interpretation of measurements matters



Visualisation of plasma in a tokamak @2024 EPFL/Laboratory for Experimental Museology (EM+) – CC-BY-SA

JET pulse visible range camera image

Why interpretation of measurements matters

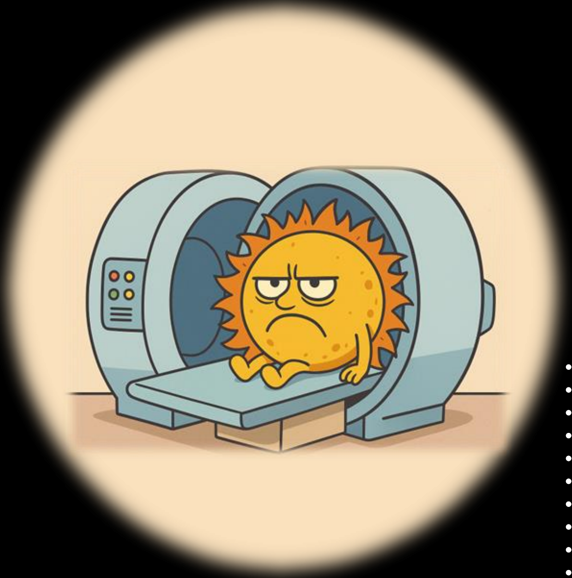


Visualisation of plasma in a tokamak @2024 EPFL/Laboratory for Experimental Museology (EM+) – CC-BY-SA

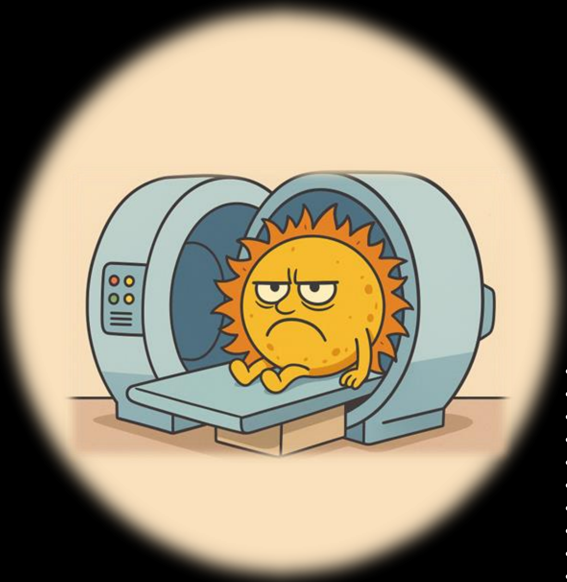
JET pulse visible range camera image

Experimental diagnostics, numerical models and theoretical understanding often diverge

Challenges in interpreting data



Challenges in interpreting data



CHALLENGE 1

Measurements are not direct

CHALLENGE 2

Fusion devices are not transparent

CHALLENGE 3

Plasma physics includes complex multi-scale coupled processes

Use of integrated models to interpret measurements

synthetic diagnostics

Use of integrated models to interpret measurements

synthetic diagnostics

1. Recognize the LIMITATIONS of experimental diagnostics

2. Learn what SYNTHETIC DIAGNOSTICS are

3. See how synthetic diagnostics help measurements INTERPRETATION

Use of integrated models to interpret measurements

1. Recognize the LIMITATIONS of experimental diagnostics

2. Learn what SYNTHETIC DIAGNOSTICS are

3. See how synthetic diagnostics help measurements INTERPRETATION

Use of integrated models to interpret measurements

LIMITATIONS

SYNTHETIC DIAGNOSTICS

INTERPRETATION

Diagnostics ecosystem: what they are…

Electromagnetic:

magnetic coils, flux loops, halo current sensors, interferometry, reflectometry, refractometry, polarimetry, electron cyclotron emission

Diagnostics ecosystem: what they are...

Electromagnetic:

magnetic coils, flux loops, halo current sensors, interferometry, reflectometry, refractometry, polarimetry, electron cyclotron emission

Optical:

spectroscopy (visible, UV, VUV, X-ray, CXRS, MSE), H-alpha monitors, visible & IR cameras, Thomson scattering, X-ray detectors

Diagnostics ecosystem: what they are…

Electromagnetic:

magnetic coils, flux loops, halo current sensors, interferometry, reflectometry, refractometry, polarimetry, electron cyclotron emission

Optical:

spectroscopy (visible, UV, VUV, X-ray, CXRS, MSE), H-alpha monitors, visible & IR cameras, Thomson scattering, X-ray detectors

Particle-based:

Langmuir probes, neutron detectors & cameras, gamma-ray detectors, neutral particle analyzers, fast ion loss detectors, residual gas analyzers

Diagnostics ecosystem: what they are…

Electromagnetic:

magnetic coils, flux loops, halo current sensors, interferometry, reflectometry, refractometry, polarimetry, electron cyclotron emission

Optical:

spectroscopy (visible, UV, VUV, X-ray, CXRS, MSE), H-alpha monitors, visible & IR cameras, Thomson scattering, X-ray detectors

Particle-based:

Langmuir probes, neutron detectors & cameras, gamma-ray detectors, neutral particle analyzers, fast ion loss detectors, residual gas analyzers

Calorimetric:

bolometry, calorimetry, thermocouples, calorimetric neutron monitors

Diagnostics ecosystem: …and what they tell us

Magnetic diagnostics (coils, loops,…)

Determine plasma equilibrium and current distribution

Used for real-time control of shape and position

Estimate stored magnetic energy

Diagnostics ecosystem: …and what they tell us

Magnetic diagnostics (coils, loops,…)

Determine plasma equilibrium and current distribution

Used for real-time control of shape and position

Estimate stored magnetic energy

Neutron & fusion product diagnostics (monitors, detectors)

Measure fusion power output

Diagnose fast ion behavior and losses

Diagnostics ecosystem: …and what they tell us

Magnetic diagnostics (coils, loops,…)

Determine plasma equilibrium and current distribution

Used for real-time control of shape and position

Estimate stored magnetic energy

Neutron & fusion product diagnostics (monitors, detectors)

Measure fusion power output

Diagnose fast ion behavior and losses

Plasma-Facing & operational diagnostics (Langmuir probes, IR, RGAs,...)

Monitor wall and divertor temperatures, erosion, and tritium retention

Aid in machine protection and safe operation

Diagnostics ecosystem: …and what they tell us

Bolometric systems

Measure radiated power from plasma and walls

Sensitive to impurity content and detachment behavior

Diagnostics ecosystem: …and what they tell us

Bolometric systems

Measure radiated power from plasma and walls

Sensitive to impurity content and detachment behavior

Spectroscopy & Neutral Particle Analysis (NPA)

Assess impurity composition and plasma fueling

Measure ion temperature, plasma rotation and current density

Track particle fluxes, ionization, and edge emissions

Diagnostics ecosystem: ...and what they tell us

Bolometric systems

Measure radiated power from plasma and walls

Sensitive to impurity content and detachment behavior

Spectroscopy & Neutral Particle Analysis (NPA)

Assess impurity composition and plasma fueling

Measure ion temperature, plasma rotation and current density

Track particle fluxes, ionization, and edge emissions

Microwave diagnostics

Electron temperature profiles (ECE) and density profiles (reflectometry)

Contribute to plasma position and transport studies

From echoes and shadows: diagnostics limitations

Indirect:

Diagnostics measure consequences (light, particles), not direct plasma state

Plasma and machine geometry restrict access and distort signals

Integrated:

Many measurements are line- or volume-integrated

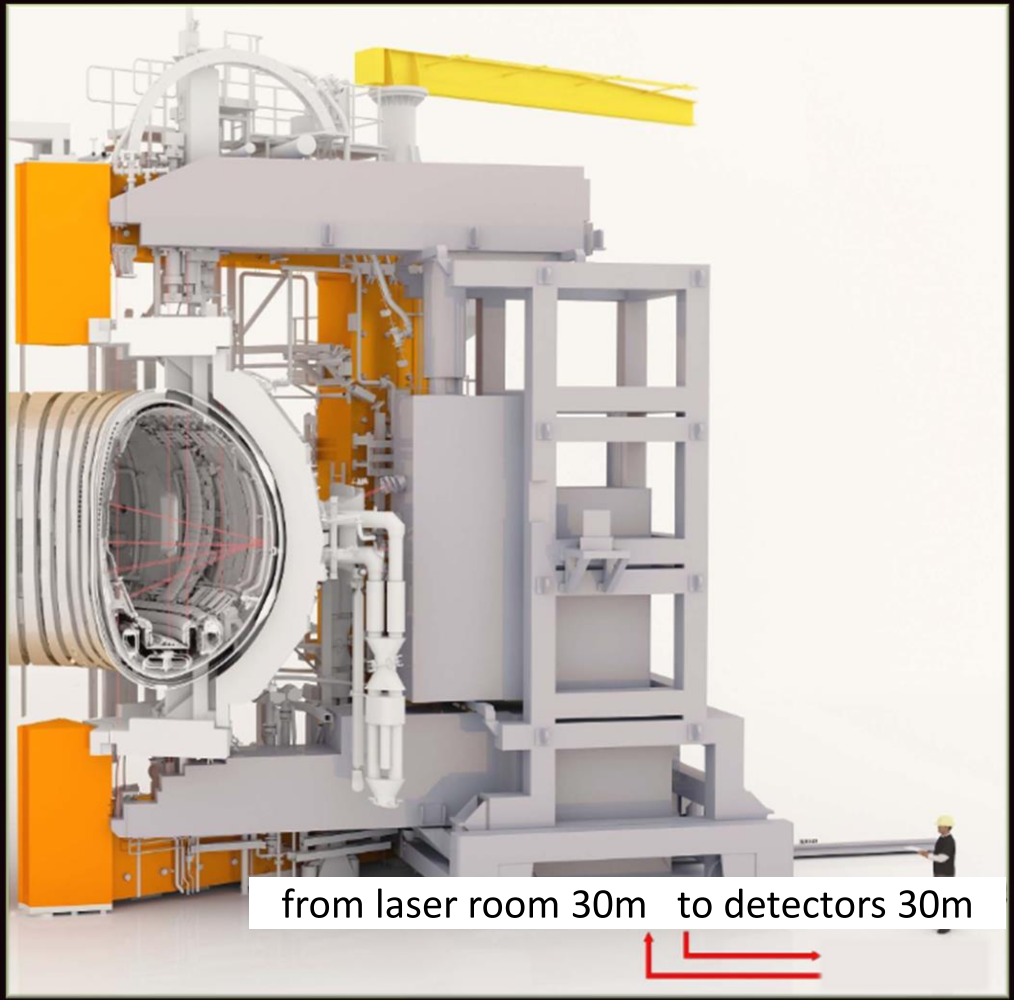
Inferred:

Diagnostic interpretation relies on simplified or idealized models

Phase shifted truths

Interferometry limitations:

- Measures line-integrated electron density → requires inversion and assumptions for profiles
- Sensitive to density fluctuations, path-integrated turbulence
- Assumes known geometry and refractive index model (cold plasma approximation)

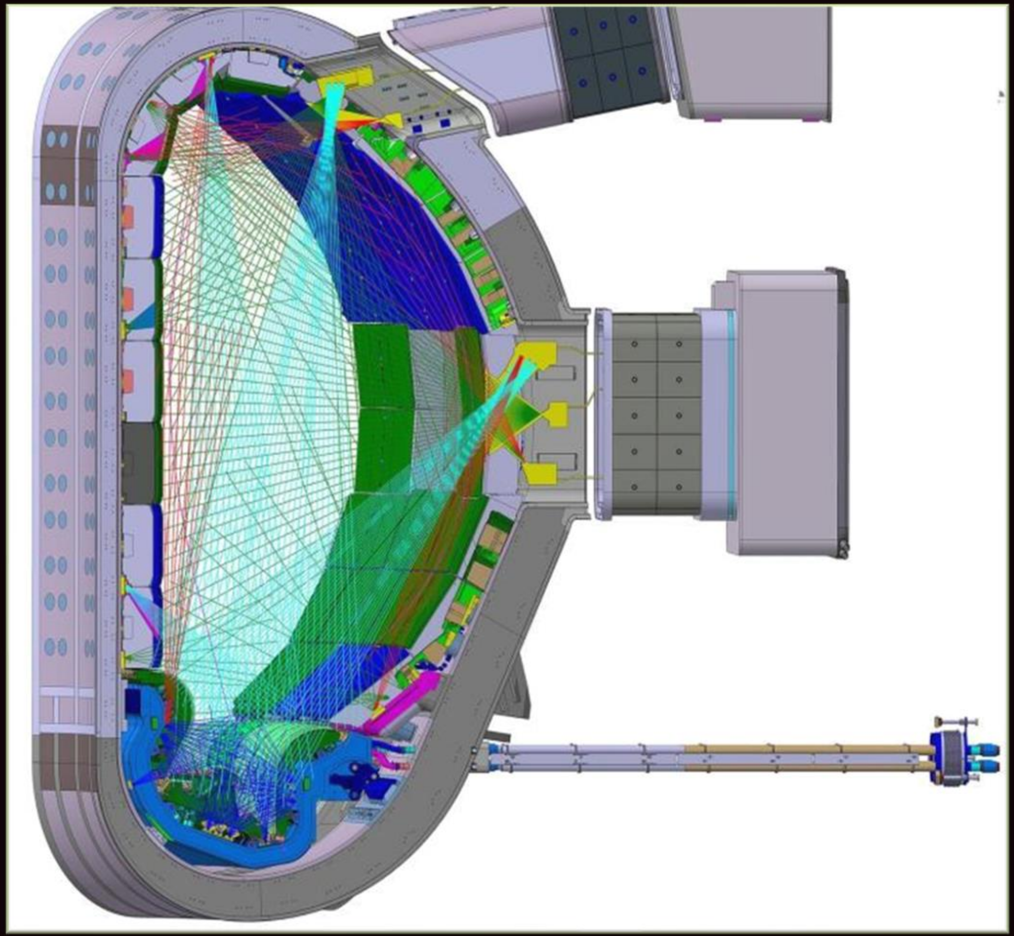


JET far IR interferometer, Boboc 2024 PPCF

Untangling the radiation web

Bolometry limitations:

- Line-integrated radiated power instead of local emissivity
- Interpretation depends on:
  - View geometry
  - Assumptions (for tomography) on emission distribution
  - Detector spectral sensitivity
- Multiple emitters (impurity species, bremsstrahlung, reflections)

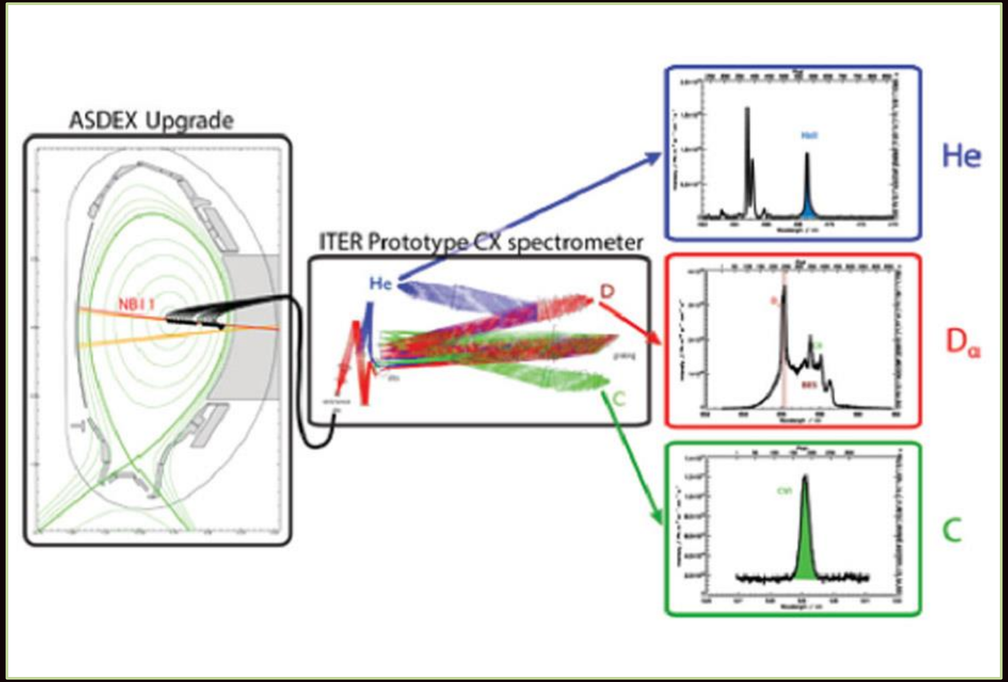


ITER bolometry system ©Adam Pataki IPP

Line of sight, layers of assumptions

Spectroscopy limitations:

- Sensitive to:
  - Instrument function (spectral/spatial resolution)
  - Atomic models (excitation, ionization rates)
  - Viewing geometry
- Often assumes coronal equilibrium, may not hold
- Emission often integrated along complex lines of sight

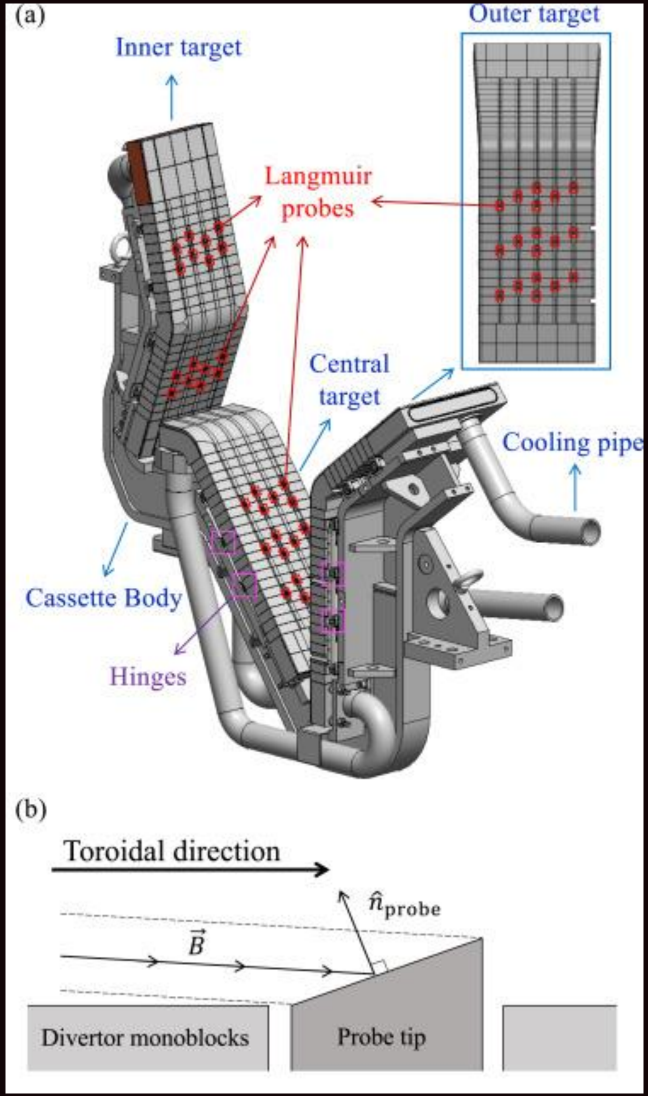


ASDEX Upgrade CXRS system ©Athina Kappatou IPP

Direct contact, distorted truth

Langmuir probes limitations:

- Perturbs local plasma (especially in high-temperature regions)
- Interpreted via Debye sheath theory, assumes:
  - Maxwellian electrons
  - Collisionless sheaths
- Mostly used in edge/SOL where assumptions are already strained



Lim Fusion Engineering and Design 2024

KSTAR Langmuir probes

Fragmented measurements → coherent understanding

Experimental data: indirect, integrated, inferred

Diagnostic signals require:

- Modeling of diagnostic response
- Inversion to retrieve physical quantities
- Cross-validation across diagnostics

Direct interpretation can mislead
without careful analysis

➞ This is where synthetic diagnostics
become essential

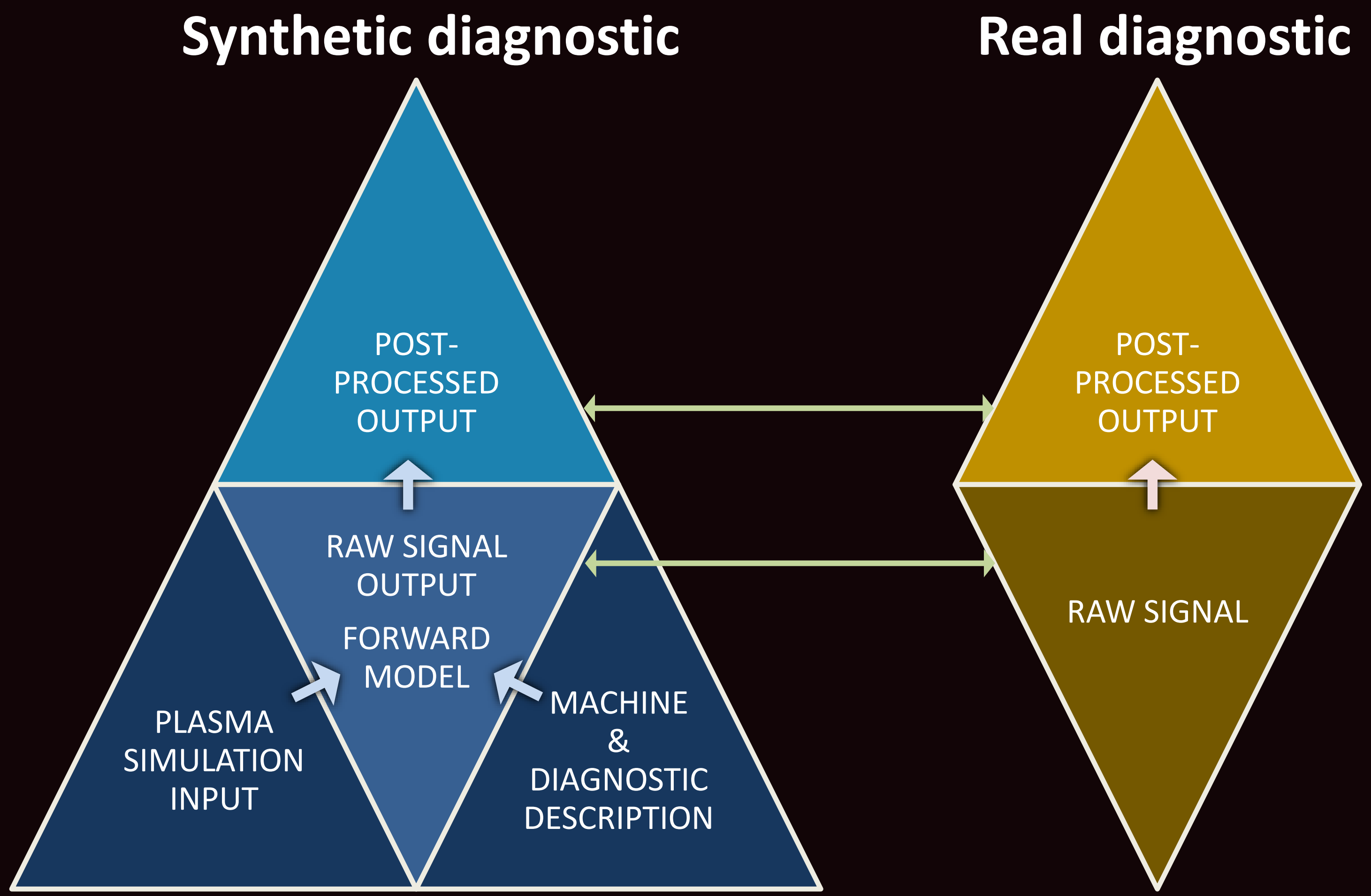
Use of integrated models to interpret measurements

LIMITATIONS

SYNTHETIC DIAGNOSTICS

INTERPRETATION

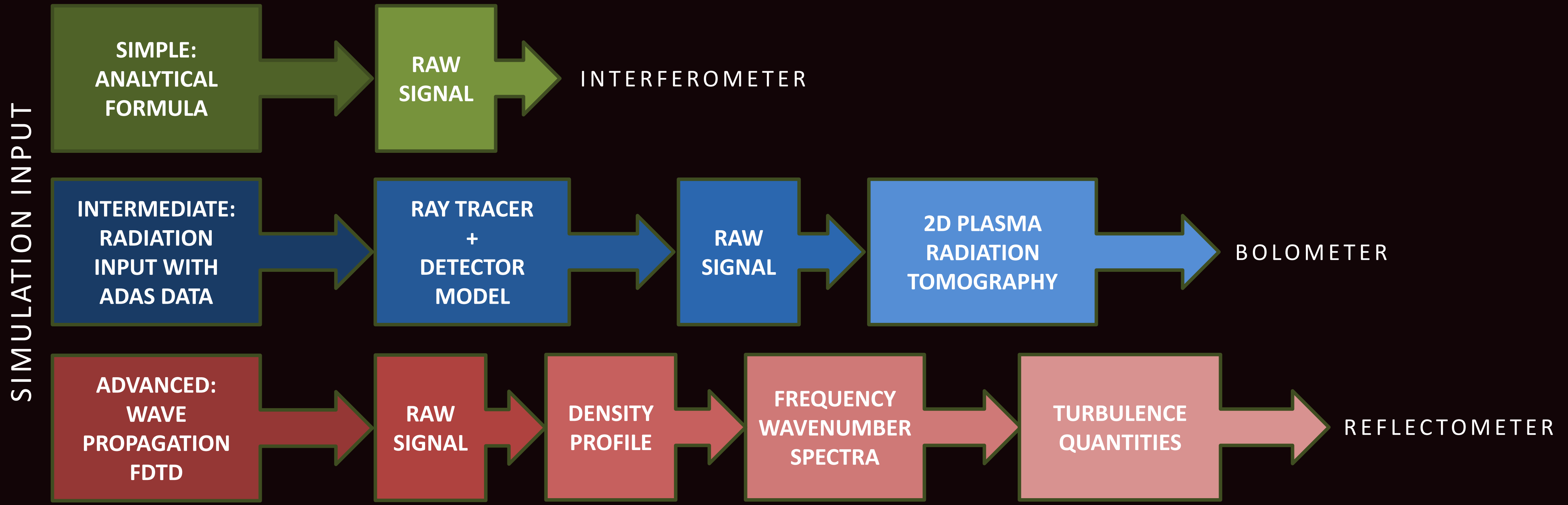
What are synthetic diagnostics?



Using SD to build, guide and understand

- Build: to optimize the design and performance of the diagnostics
- Guide: to support the development of control algorithms needed for the plasma control system design
- Understand: to support the physics interpretation and analysis, e.g. to predict the diagnostic performance in specific scenario contexts or validate a theoretical assumption

The spectrum of synthetic diagnostic complexity



Challenges of synthetic diagnostics

- ⏱ Temporal limitations
- 🧮 High computational cost
- 📐 Spatial constraints
- ⚛ Incomplete physics of simulation input
- 🧩 Simplified models
- 🔁 Lack of self-consistency
- 📉 Scenario specificity

Use of integrated models to interpret measurements

LIMITATIONS

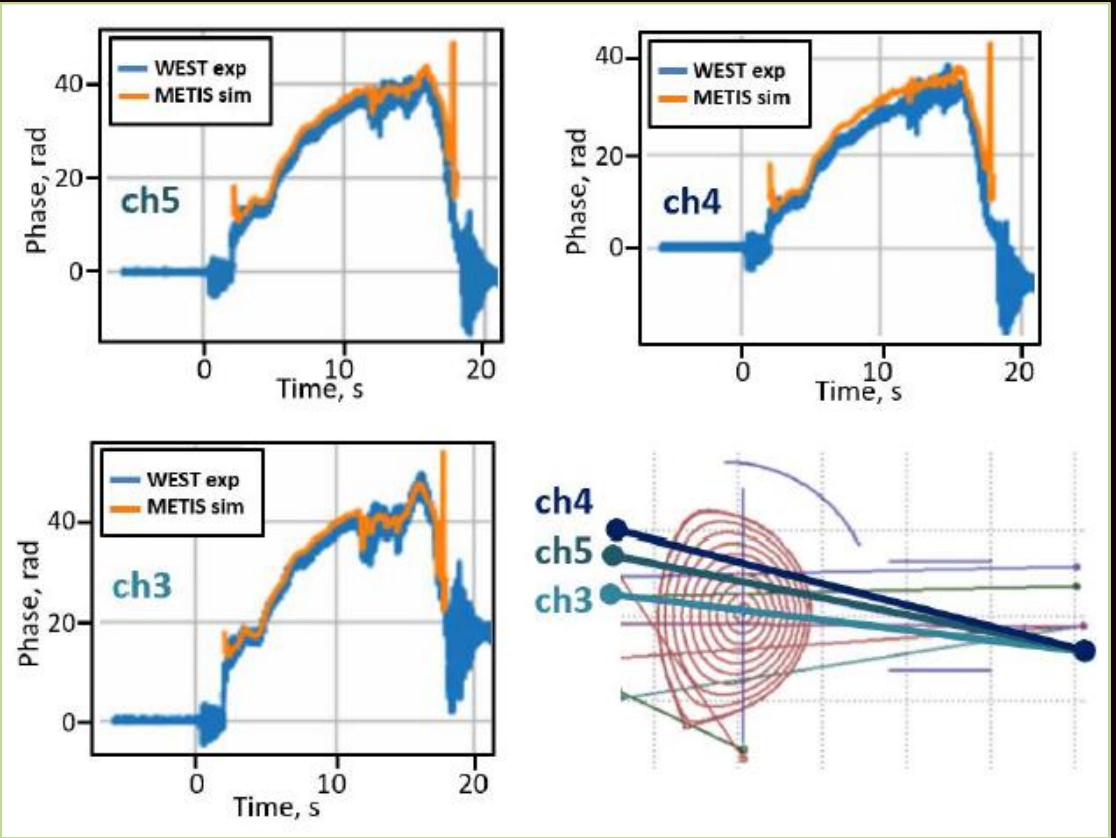
SYNTHETIC DIAGNOSTICS

INTERPRETATION

Lesson from a 'simple' diagnostic

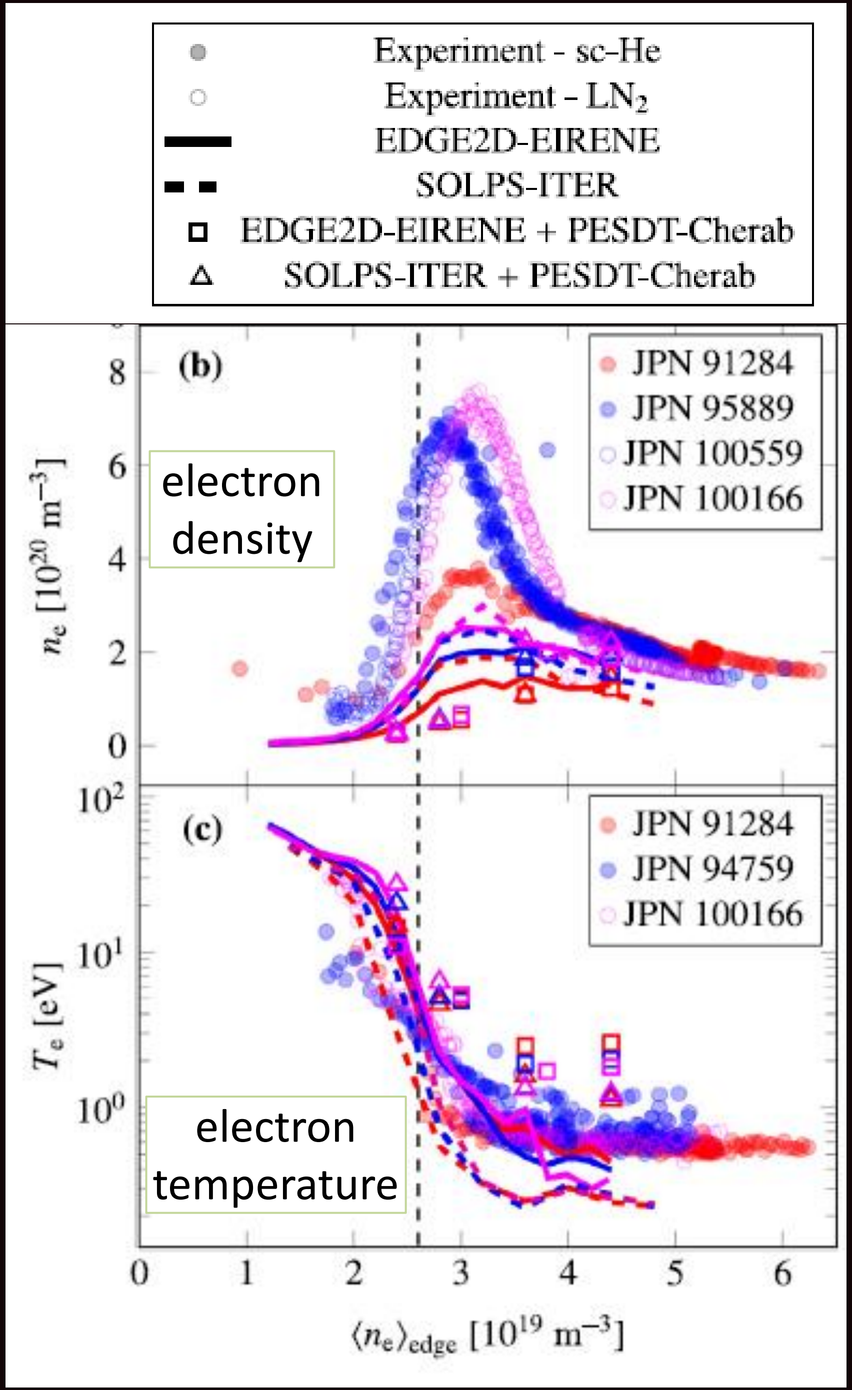
- TIP synthetic interferometer: developed for ITER, adapted to WEST via IMAS
- TIP integrates electron density along lines of sight with relativistic corrections
- Good match between METIS-based (0D transport, 1D current diffusion, 2D equilibrium) synthetic signals and WEST measurements
- Edge discrepancies due to optical path and SOL density, not modeled

→ question your models!



Medvedeva 49th EPS 2023, Artaud NF 2018

Spectrometry on JET

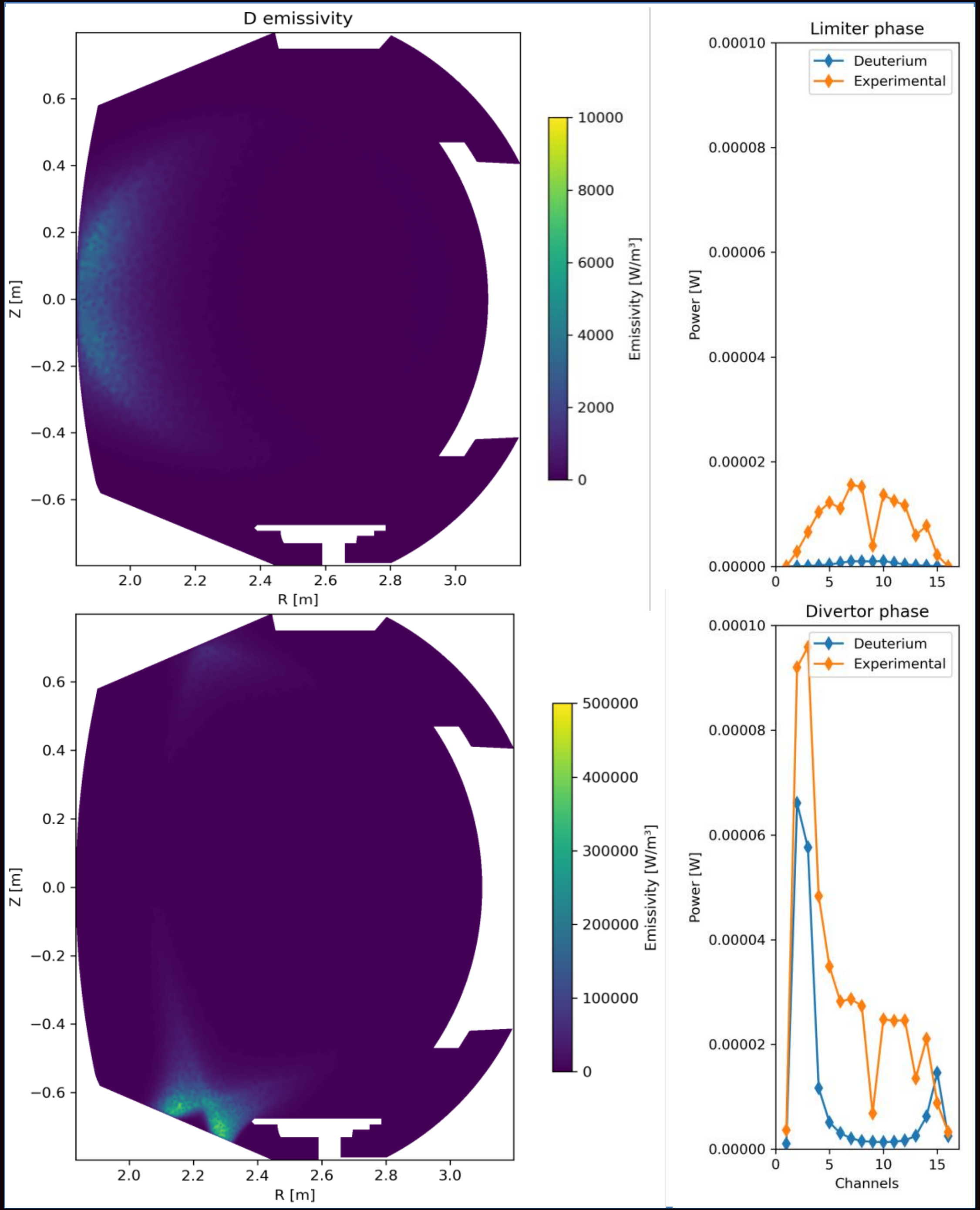


Horsten NME 2025, Radford CPP 1996, Wiesen JNM 2015

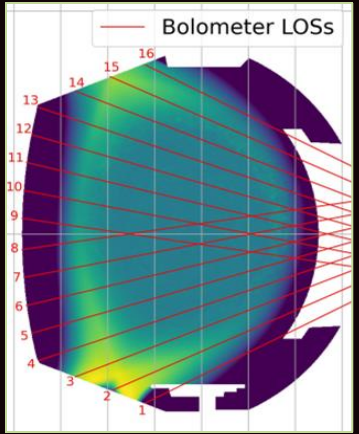
- To follow detachment, electron density and temperature are measured at the strike-point on the LFS divertor target
- Direct values from EDGE2D or SOLPS simulations ≠ line-averaged quantities inferred from spectroscopy
- A better comparison:
  via SD based on Cherab that calculates
  - line-averaged density
  (Balmer-δ Stark broadening)
  - line-averaged temperature
  (Balmer continuum)

Cherab: V Neverov PPCF 2020, M Carr 44th EPS 2017
https://www.cherab.info/ https://www.raysect.org/

Bolometry on WEST

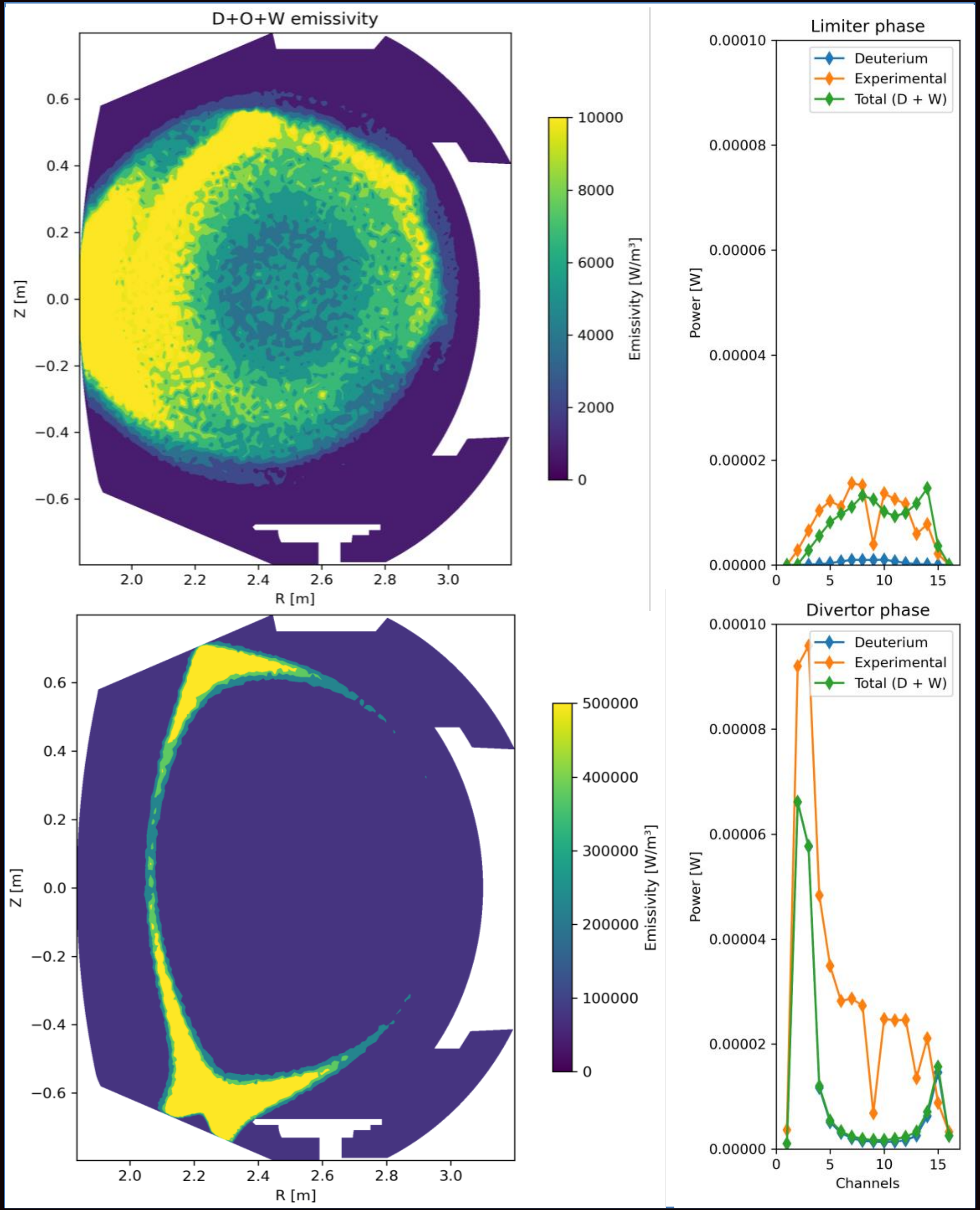


- WEST full discharge is simulated by 2D fluid transport integrated model SOLEDGE3X-HDG for D plasma
- Synthetic bolometer signals (Cherab) don’t match WEST experimental data
- Missing impurity physics (no W, no O) leads to underestimation of radiation and poor agreement with experiments!

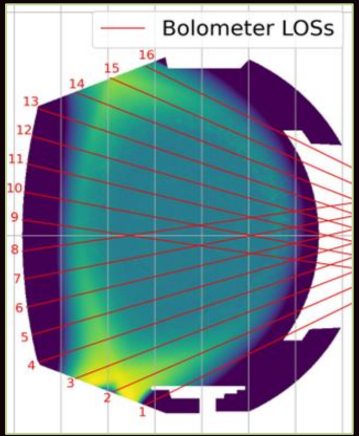


Giorgiani NME 2019
Romazanov Phys. Scr. 2017
Kudashev AS 2022, JINST 2023

Bolometry on WEST



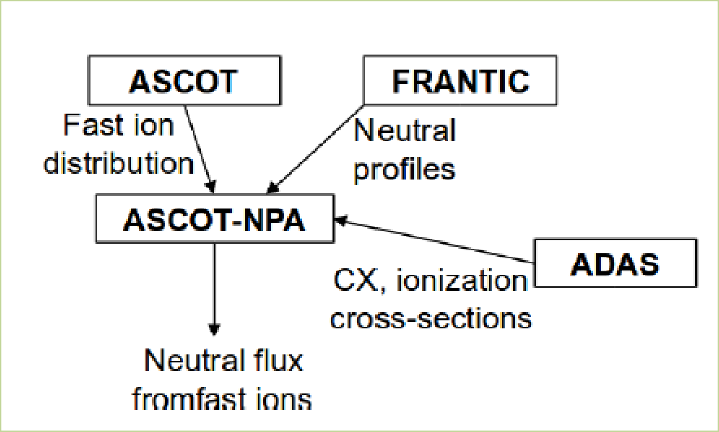
- W transport added by coupling SOLEDGE-HDG + ERO2.0 (+O trace fraction to mimic W cooling physics)
- Synthetic signals now closely match experimental measurements
- To reproduce diagnostic signals reliably, simulations must include all relevant physics

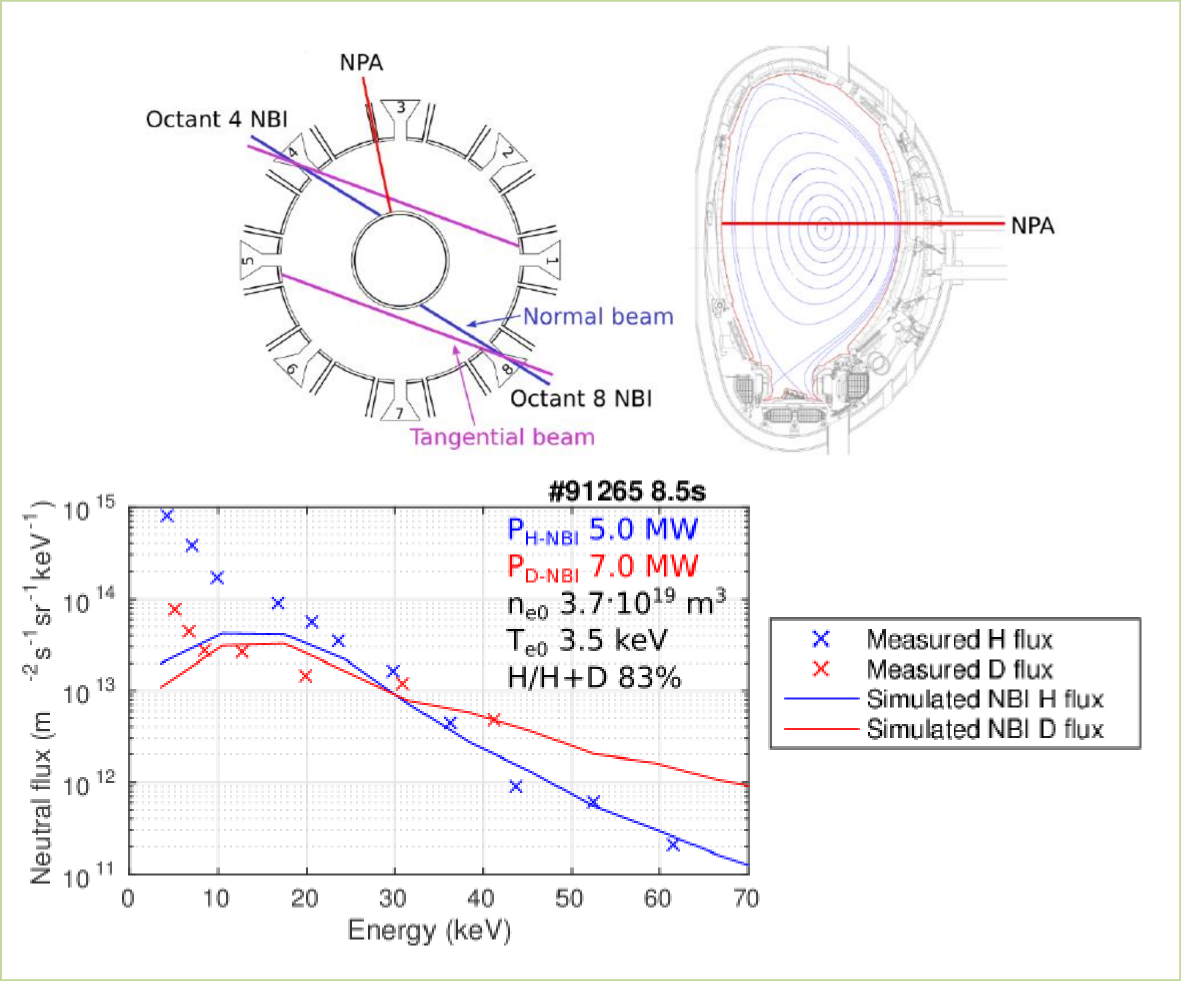


Giorgiani NME 2019
Romazanov Phys. Scr. 2017
Kudashev AS 2022, JINST 2023

Interpret fast ion behavior on JET

- Neutral Particle Analysis detects charge-exchanged neutrals escaping from the plasma and measures fluxes and energy spectra
- Combining integrated modeling with synthetic diagnostic allows to bridge simulation and measurement with high confidence

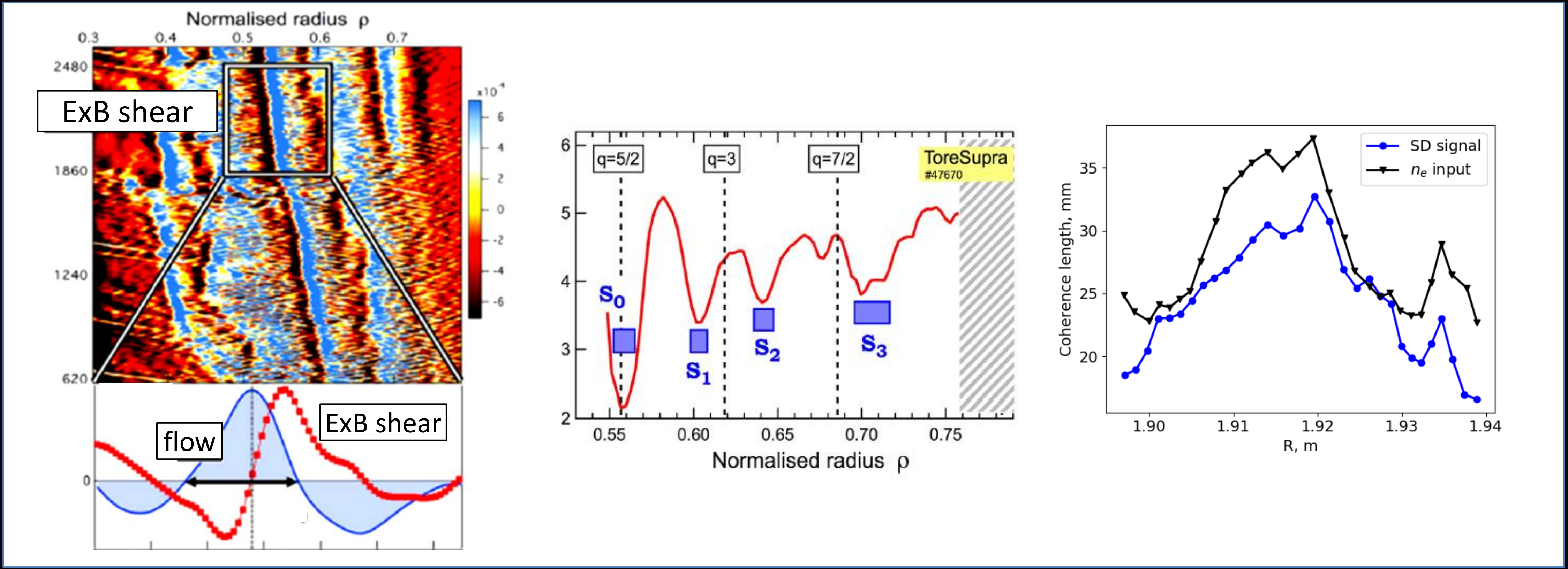




Varje JINST 2017

Validating turbulence signatures with FeDoT synthetic reflectometry

GYSELA simulation | UFSR measurement (Tore Supra) | FeDoT synthetic diagnostic validation

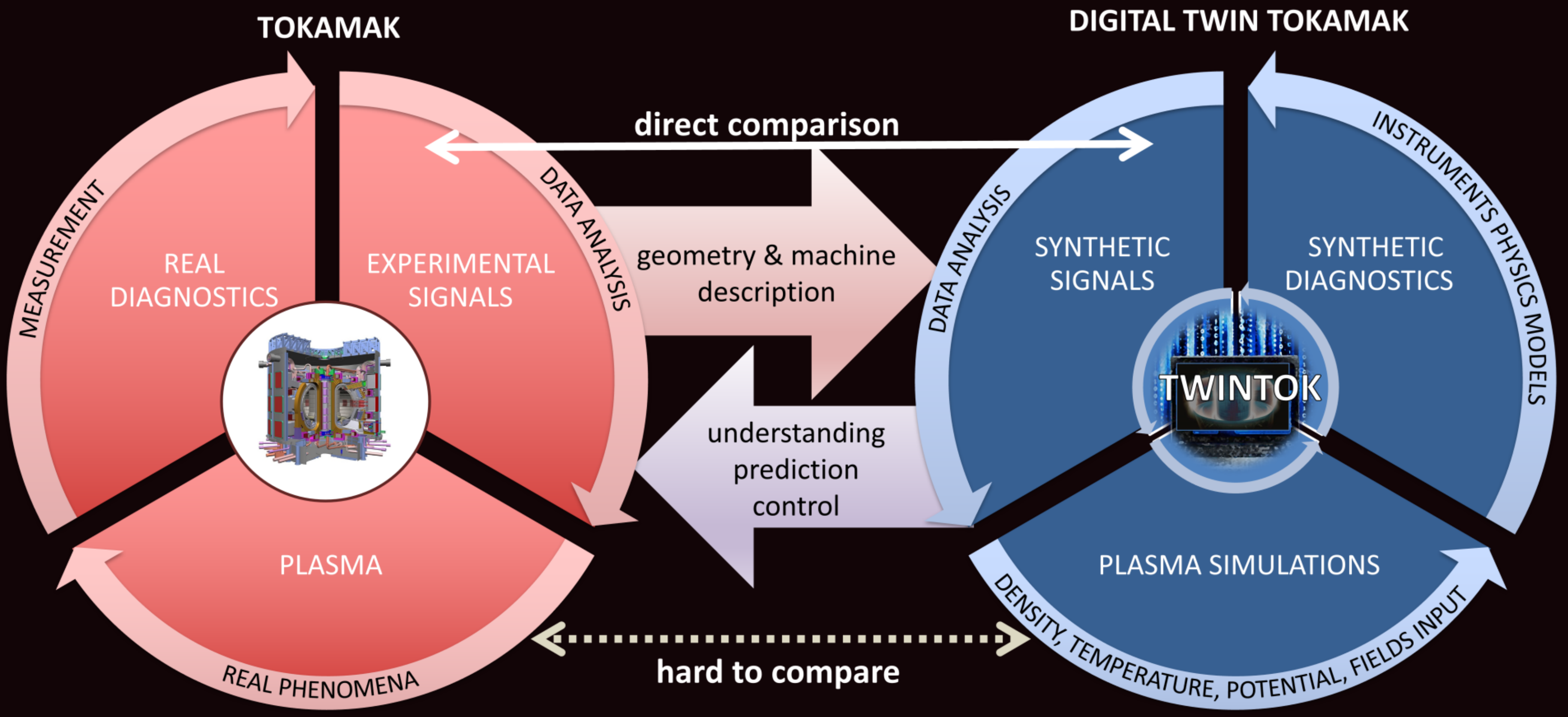


Spontaneous organisation
of weak transport barriers: ExB staircase

Dif-Pradalier NF 2017, Hornung NF 2017, Glasser PPCF 2025

Precise turbulence modeling can unlock new diagnostic insights

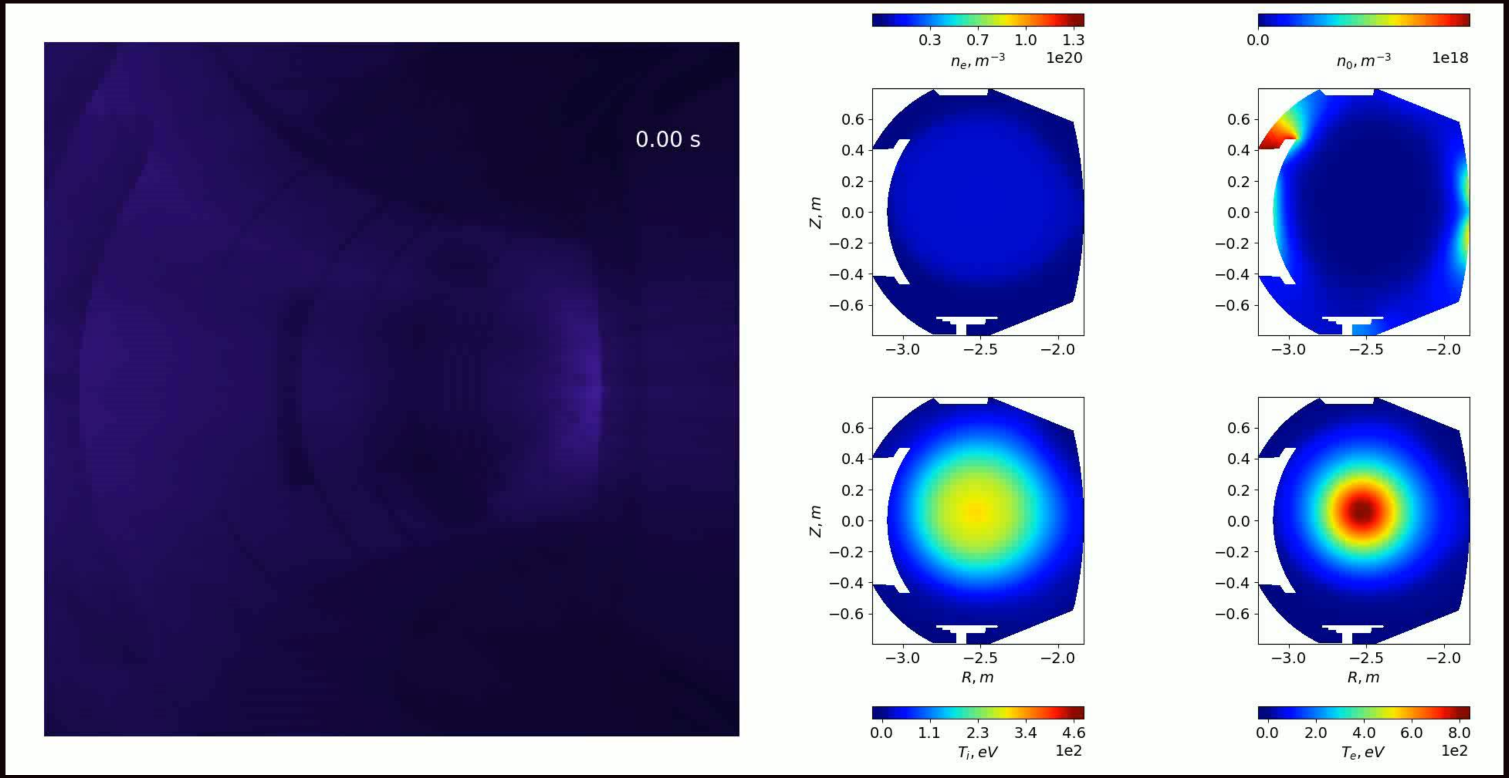
Toward a real-time digital twin

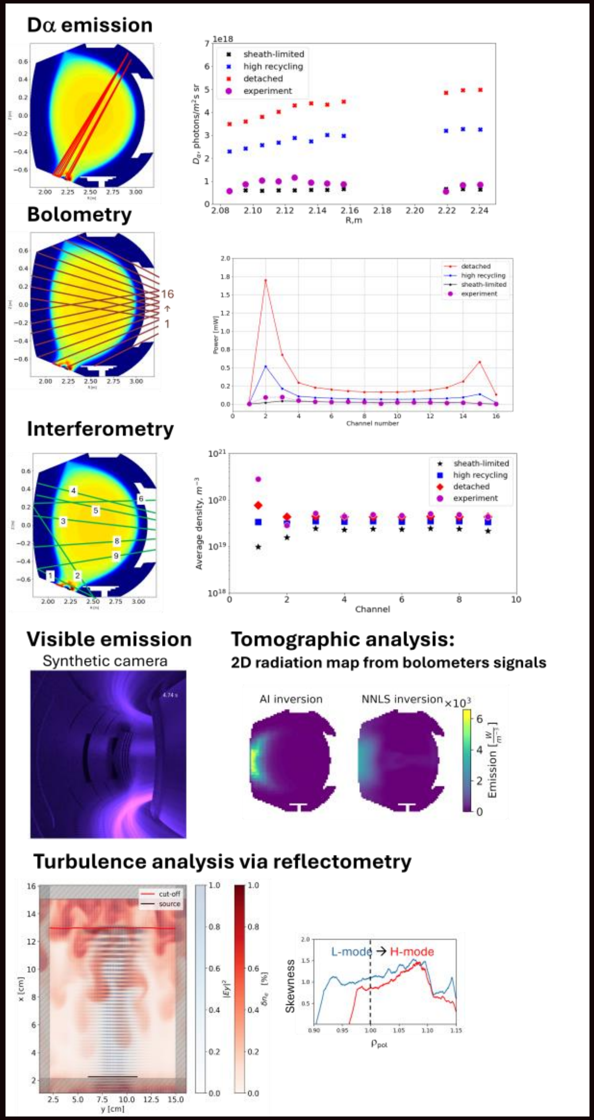


Medvedeva 49th EPS 2023

Generate synthetic signals from integrated simulations to validate models, interpret data and move toward real-time plasma control

SOLEDGE-HDG + TWINTOK: full-discharge synthetic view





Courtesy I. Kudashev, F. Schwander, E. Serre, D. Zarzoso, M. Scotto D'Abusco, G. Ciraolo, F. Clairet, G. Dif-Pradalier, N. Fedorczak, P. Ghendrih, S. Hacquin, A. Jamann, P. Abreu, M. Schneider, ITER, SOLEDGE and WEST teams

Join TWINTOK team: anna.medvedeva@univ-amu.fr

Broader perspectives

Advanced uncertainty quantification

→ propagating model and diagnostic uncertainties consistently

Riva PhD Thesis 2017, Ricci PoP 2011, Coster NME 2022

Data fusion across diagnostics

→ combining signals in Integrated Data Analysis (IDA) frameworks

Fischer FST 2010

Synthetic design studies for future machines

→ predicting diagnostic performance in future scenarios (e.g., ITER, DEMO)

Walsh IEEE 2011, Kajita PFR 2019, Meister SOFE 2023

Machine learning integration

→ synthetic datasets support training of AI for interpretation and control

Citrin NF 2015, Brunet FED 2023, Pavone PPCF 2023

Takeaway messages

- Integrated modeling is essential to understand plasma measurements

Takeaway messages

- Integrated modeling is essential to understand plasma measurements
  - We don't measure plasma
  - Measurements are indirect, integrated and inferred

Takeaway messages

- Integrated modeling is essential to understand plasma measurements
  - We don't measure plasma
  - Measurements are indirect, integrated and inferred
- Synthetic diagnostics connect model predictions with experimental signals

Takeaway messages

- Integrated modeling is essential to understand plasma measurements
  - We don’t measure plasma
  - Measurements are indirect, integrated and inferred
- Synthetic diagnostics connect model predictions with experimental signals
  - Synthetic diagnostics help to compare apples to apples

Takeaway messages

- Integrated modeling is essential to understand plasma measurements
  - We don’t measure plasma
  - Measurements are indirect, integrated and inferred
- Synthetic diagnostics connect model predictions with experimental signals
  - Synthetic diagnostics help to compare apples to apples
- They bridge theory and reality, improve validation and guide ITER-era fusion

Takeaway messages

- Integrated modeling is essential to understand plasma measurements
  - We don’t measure plasma
  - Measurements are indirect, integrated and inferred
- Synthetic diagnostics connect model predictions with experimental signals
  - Synthetic diagnostics help to compare apples to apples
- They bridge theory and reality, improve validation and guide ITER-era fusion
  - This is actually true