HUN-REN Centre for Energy Research

Development of a Detachment Control Diagnostic for EU-DEMO

Dániel Dunai

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and contributors to EUROfusion WPDC

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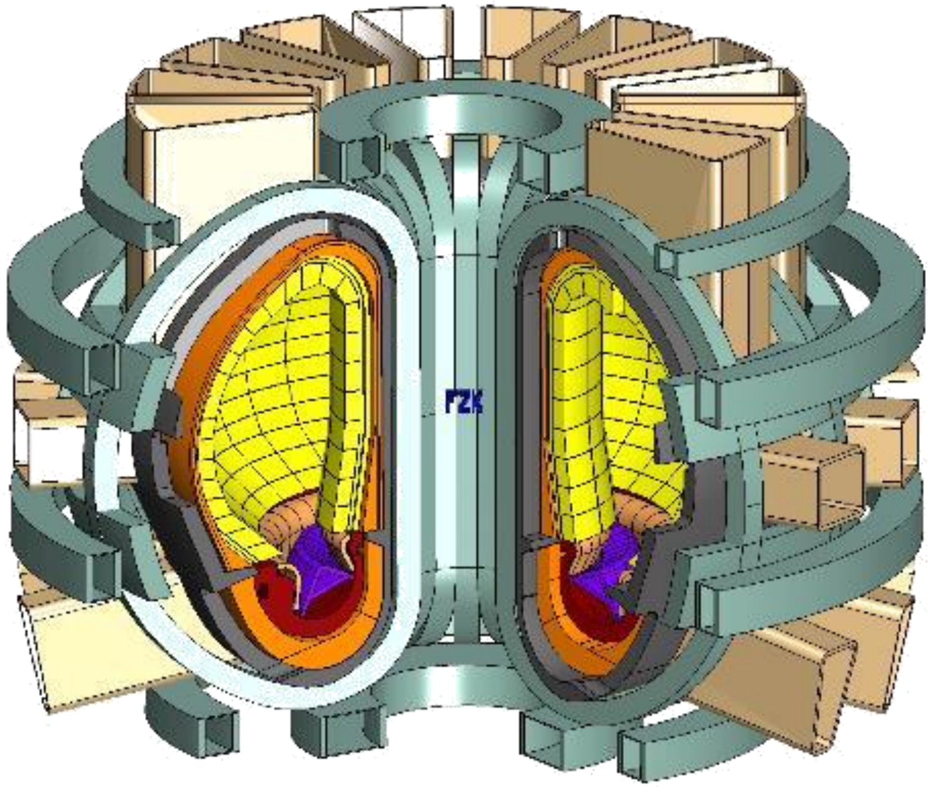
International Conference on
DIAGNOSTICS FOR FUSION REACTORS: THE BURNING PLASMA ERA

The conference will focus on **diagnostics systems**, related technologies, and control systems of ITER and **magnetically confined DT reactors** aimed at the production of fusion power.

Development of a Detachment Control Diagnostic for EU-DEMO

"Demonstration fusion power plant (DEMO) will be operational around 20 years after high power burning plasmas are demonstrated in ITER."



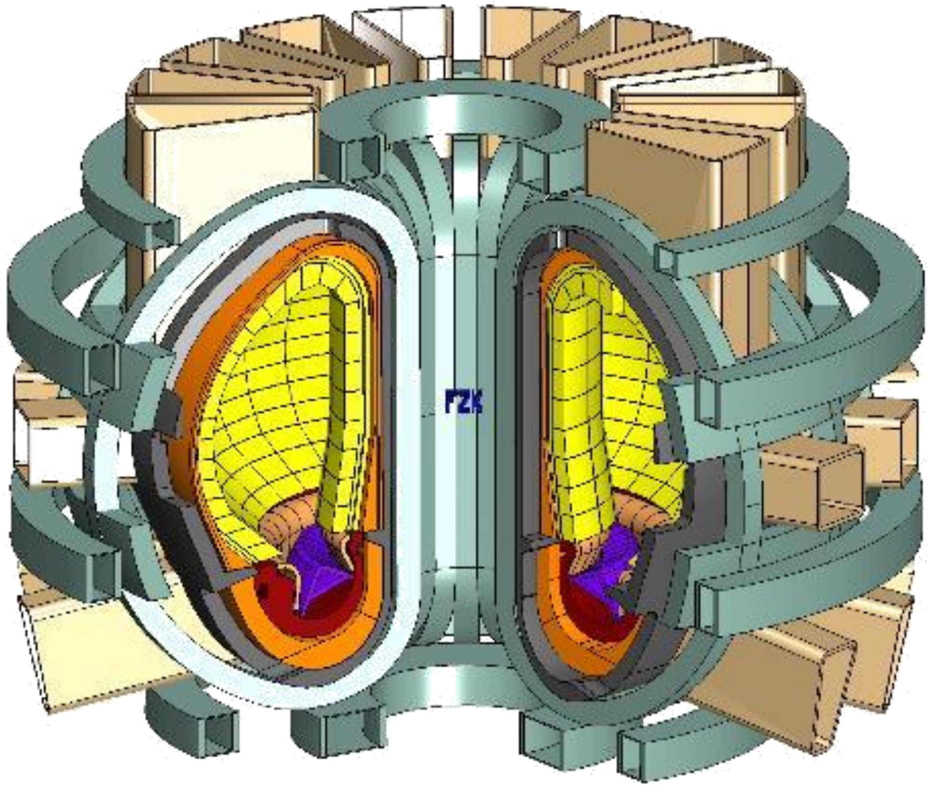
Main EU DEMO parameters:

- R_0, a ~ 9 m, 2.9 m
- B_0 ~ 5 T
- P_{therm} ~ 2 GW
- $P_{el,net}$ ~ 300…500 MW
- t_{pulse} > 2 h

European Research Roadmap to the Realisation of Fusion Energy - https://euro-fusion.org/eurofusion/roadmap/

"Demonstration fusion power plant (DEMO) will be operational around 20 years after high power burning plasmas are demonstrated in ITER."

- Pulsed DEMO tokamak as baseline
- Machine size ~ 1.5 times of ITER
- Lower Single Null Divertor
- High plasma density with fully detached divertor plasma operation



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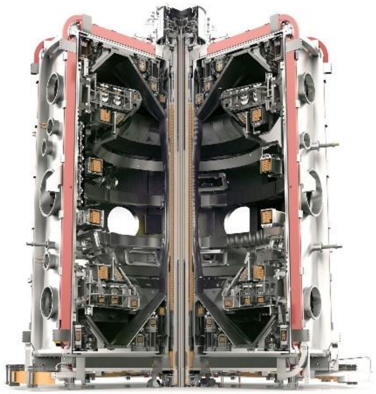
Fusion Power Plant

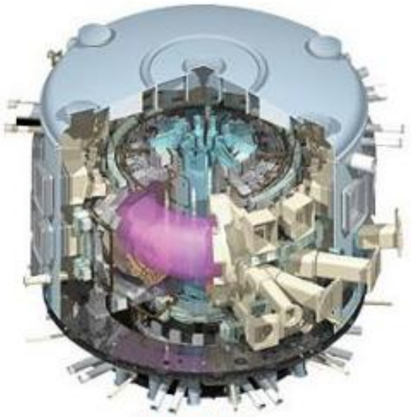
– Diagnostics are for control

W. Biel et al. Fusion Engineering and Design Volume 179, June 2022, 113122

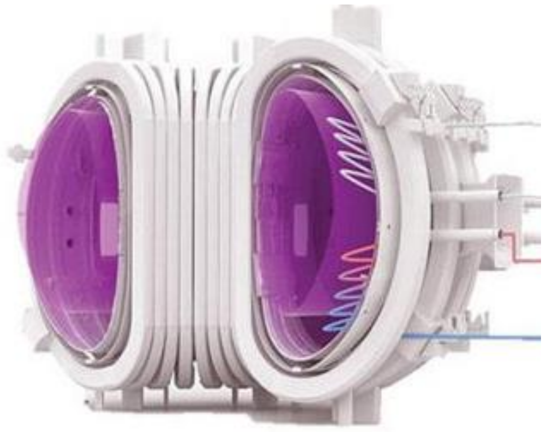
Diagnostics developments for various machines



MAST-U
8 m^3



ITER
800 m^3



DEMO
~1000 - 3500 m^3

	MAST-U	ITER	DEMO
Status	**Operational** **First plasma 2020** **(MAST – 2000 - 2013)**	**Under Construction** **First plasma 2034**	**Conceptual Design** **First plasma 20xx**
Diagnostics status	**Many advanced diagnostics and continuous development**	**From conceptual design, prototypes, manufacturing**	**Conceptual design (feasibility study)**
Personal Participation	**Turbulence imaging Beam Emission Spectroscopy - Physics**	**DMS Optical Pellet Diagnostics – Investment safety**	**Detachment Control – Machine Control**

Device	Experiments (W7-X, JT60SA, ….., ITER*)	Fusion Power Plant (EU-DEMO)
Relevance of Diagnostics	**Precise quantitative measurements** with high(est) resolution and accuracy (that the budget allows): - enhance the understanding of physics - inputs for detailed offline simulations - Maximum information for all discharges	**Control signal for actuators:** - Sufficient resolution and accuracy, but - High reliability (also in off-normal events) - Cost effective solution - Minimum number of diagnostics for reliable control

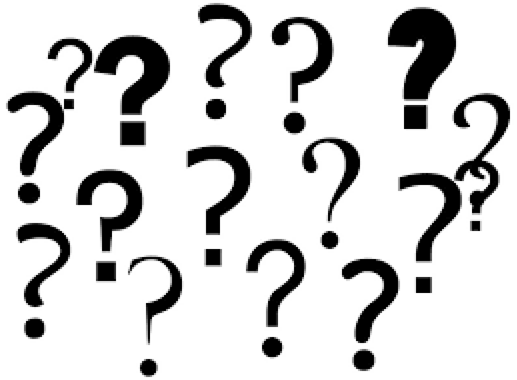
Control system: nuclear safety, investment protection and stable energy production

Diagnostics → Control system → Power plant

Diagnostics requirements for experiments and Fusion Power Plant

Device	Experiments (W7-X, MAST-U, JT-60SA, ….., ITER*)	Fusion Power Plant (EU-DEMO)
Diagnostics location	The vacuum vessel is full of ports, in-vessel diagnostics components, accessible all directions + special views for divertors	**Limited space allocation** for actuators and diagnostics – maximize the tritium breeding Integration – design driver
Maintenance and reliability	Accessible during campaigns (with restrictions) (*ITER no accessibility in nuclear operation) In case of core diagnostic failure → shut down	**Not accessible.** Remote handling compatibility. diagnostics port might be removed during shut down. **Redundancy for all actuators and diagnostics.**
Data analysis and modelling	Analysis is after the experiments. Checked against simulation results → virtual diagnostics	**Real time compatibility** → Real-time data analysis → Virtual diagnostics implemented in a flight simulator → Digital twin
Environmental constraints	Magnetic field, Vacuum, moderate radiation level (if any) (*ITER high neutron dose in D-T)	All previous + **Neutron and Gamma dose is primary design driver**

- DEMO is still in the early phase of the design (the baseline was changed in 2024/25)
- Limited information (incomplete CAD design, plasma modelling, irradiation data…)
- High level requirements based on physics considerations (like detect an ELM, or successful pellet launch)
- Diagnostic relevant requirements are deduced and compiled by the designers (signal, resolution,…..)
- Diagnostics design not final (by far) - Off normal events, ***maintenance***, cost effectivity, …. will be design drivers but the design cannot be optimized for all these yet.
- ***Control system design*** would need realistic inputs (even if it is incomplete)



What is the main goal of the design process?

1. Concentrate on DEMO (FPP) specific challenges.
2. Understand the physics requirements and deduce the diagnostics requirements
3. Identify missing bits: physics knowledge, simulation code, manufacturing technology, material choice
4. Setup a workflow where the **iterations** can be performed
5. Provide a conceptual design based on the actual EU-DEMO design and requirements

A conceptual design

from physics basics -> engineering design -> expected signal to the control system
(with large uncertainties, still better than only wait for more precise inputs)

Transferable solution between FPP variants

DEMO Divertor Monitoring Diagnostics – High level physics requirements

1. **Detachment control:** plasma near the strike-points. **Loss of detachment detection – 200ms**
   Measurement property: Occurrence of spectral lines which provide an unambiguous indication of the existence of a cold plasma region with significant neutral particle densities.
2. **Divertor local W-erosion:** inner and outer VT surface. Detection of spectral lines that indicate strong tungsten fluxes from the target into the divertor plasma.
   Measurement property: intensity of tungsten lines relative to lines from hydrogen isotopes
3. **Thermography on divertor wall, 500°C to 1200°C:** inner and outer VT surface.
   Measurement property: relative photon count between wavelengths.
4. **Plasma temperature near the divertor targets:** inner and outer VT parallel views.
   Measurement property: Doppler broadening and/or line intensity ratios (relative photon count between wavelengths).
5. **Detect MARFEs:** central divertor plasma near X-point.
   Measurement property: radial intensity distribution of spectral lines from impurities or from hydrogen isotopes.
6. **ELM detection**: DEMO should not exhibit ELMs, but in case ELMs occur, they have to be detected to protect the machine.

D. Dunai et al.: EFDA_D_2QES79

+1 **High resolution image** of the Vertical Targets to identify possible damages

Two different objectives – not independent

1. **An optical diagnostic system (with multiple line of sights) can fulfil the high-level requirements – identify the control signal**
   - Simulations, simplified virtual diagnostics

2. **Optical diagnostic system (meeting the requirements of 1. objective) can be realized in DEMO conditions.**
   - First mirror protection
   - Optics design
   - Opto-mechanics design
   - Material selection
   - Radiation doses – design is compatible with expected neutron and gamma flux

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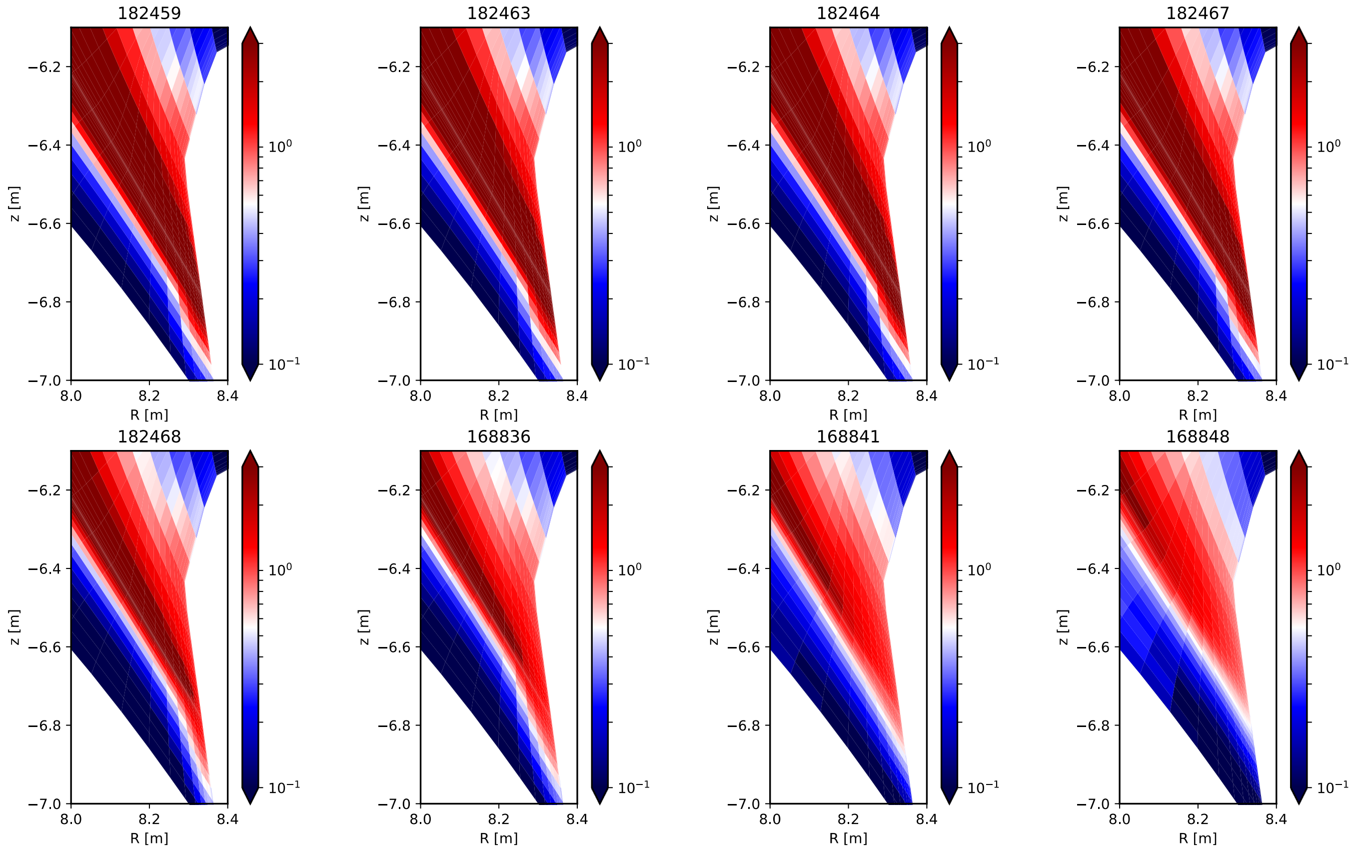
Loss of detachment defined as a temperature increase above 3 eV of the high-density plasma in front of the target



2D electron temperature at the outer divertor – colormap is top limited 3eV – Argon gas puff scan

F. Subba et al 2021 Nucl. Fusion 61 106013

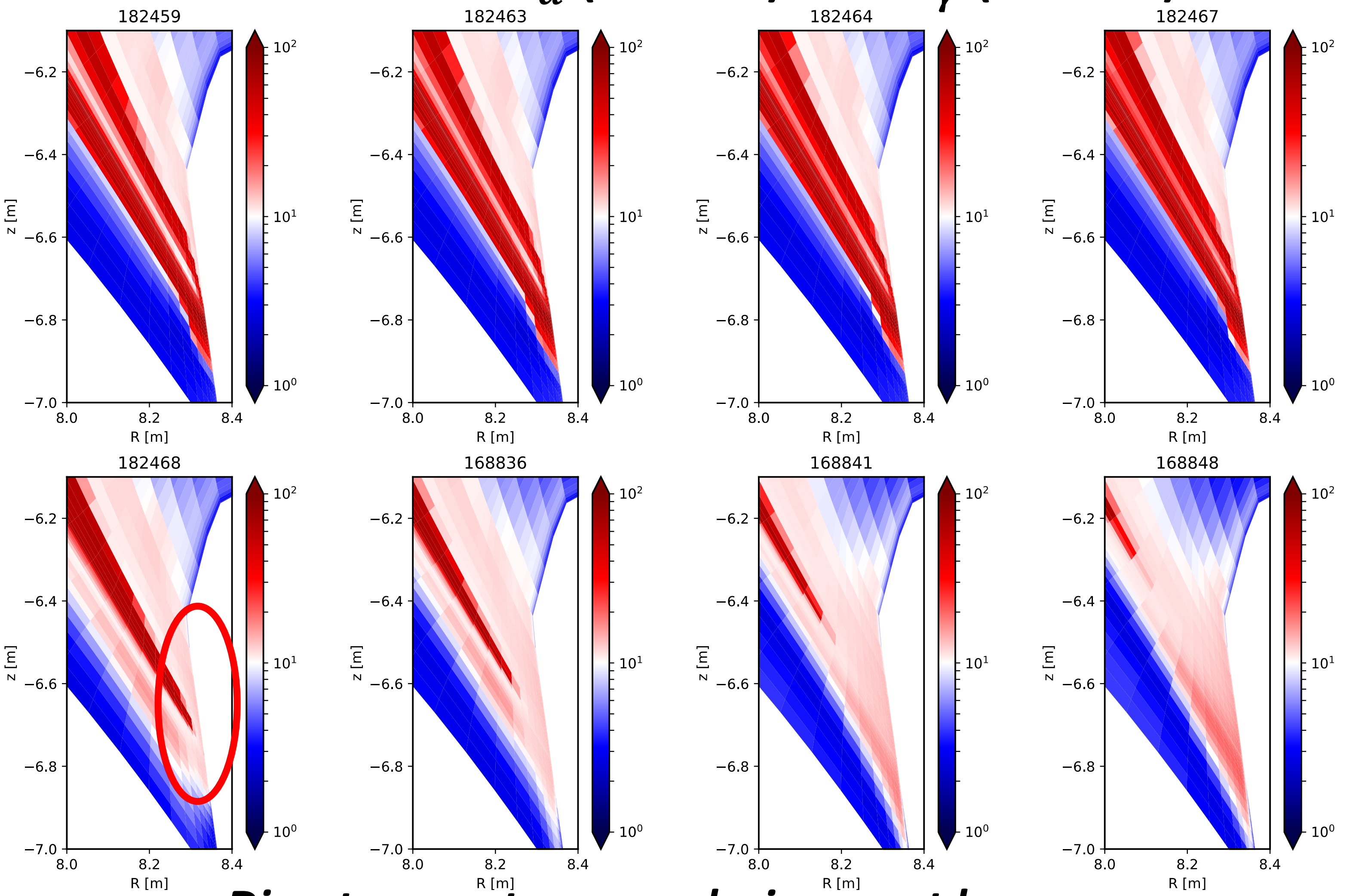
Dedicated SOLPS-ITER modelling of detached plasmas
Injected gas puff scan Deuterium and Argon

$\Gamma_A = 2.0 \cdot 10^{20} s^{-1}$ to $\Gamma_A = 3.5 \cdot 10^{21} s^{-1}$
$\Gamma_D = 1.0 \cdot 10^{24} s^{-1}$ is fixed

Simulation results are used to identify the plasma volume, where a detached plasma reaches T_e < 3 eV and provide information on the required spatial resolution.

Simulation analysis is performed by Marco Cavedon - *University of Milano-Bicocca*

Emission ratio of D_α (656 nm) and D_γ (434 nm)



Light emission depends on the local plasma parameters and the detachment can be observed from the measured spectra

Simulation results are also used to calculate the intensity of various emission lines to determine the sensitivity in detachment conditions

Which emission lines?

- Only VIS and near UV emission lines are considered
- Hydrogen and Helium lines
- Brightest lines were considered – easier detection

Balmer line ratio as found to be a great tool for monitoring $T_e < 3\ eV$

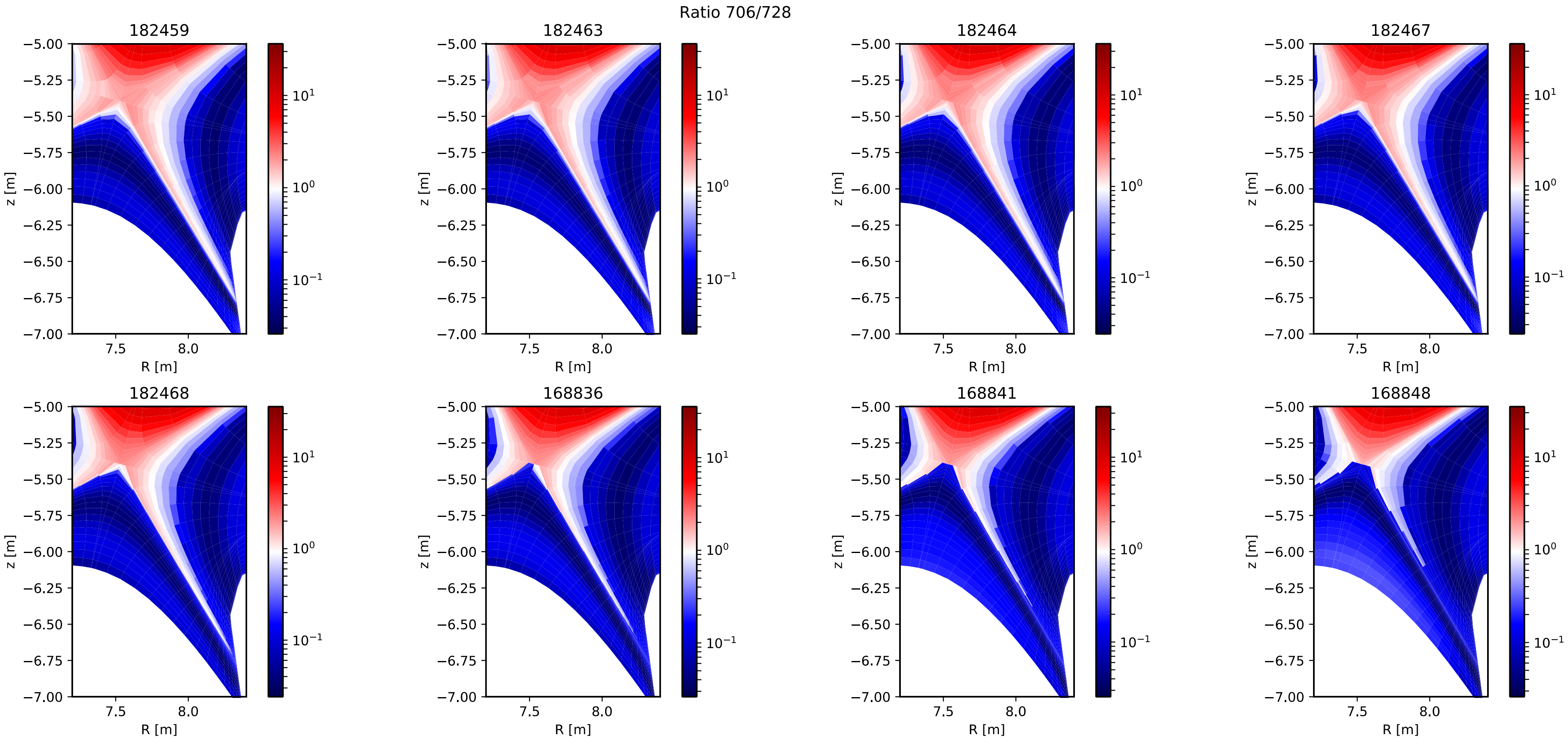
A.G. Meigs: Journal of Nuclear Materials Volume 438, Supplement, July 2013, Pages S607-S611

*K Verhaegh et al 2019 Plasma Phys. Control. Fusion **61** 125018*

Divertor spectroscopy design must be capable to resolve relatively small volumes

Emission ratio of He 706 nm and He 728 nm

He 706 nm and 728 nm line ratio is highly sensitive to the electron temperature, making it a very good indicator for $T_e < 3\ eV$

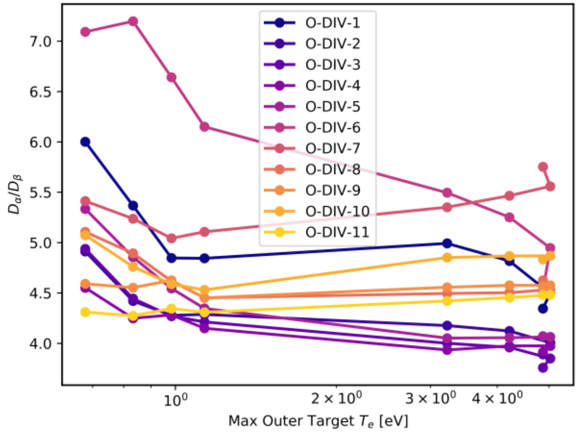


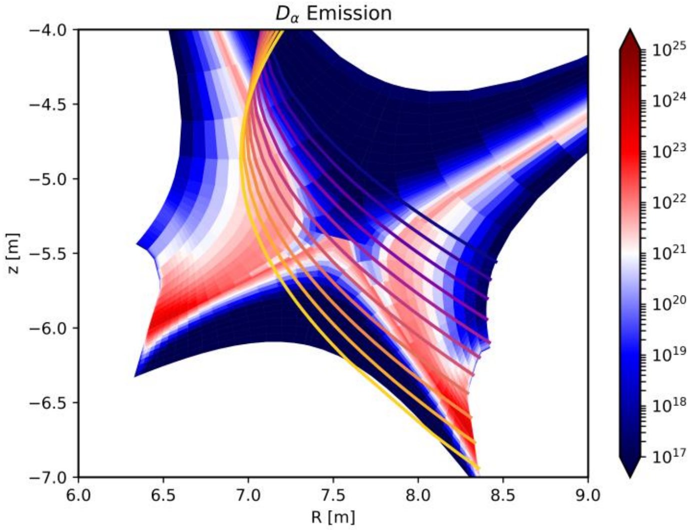
D. Dunai et al.: EFDA_D_2QES79

Selection of optimal line of sight is an important for the measurable line ratio signal

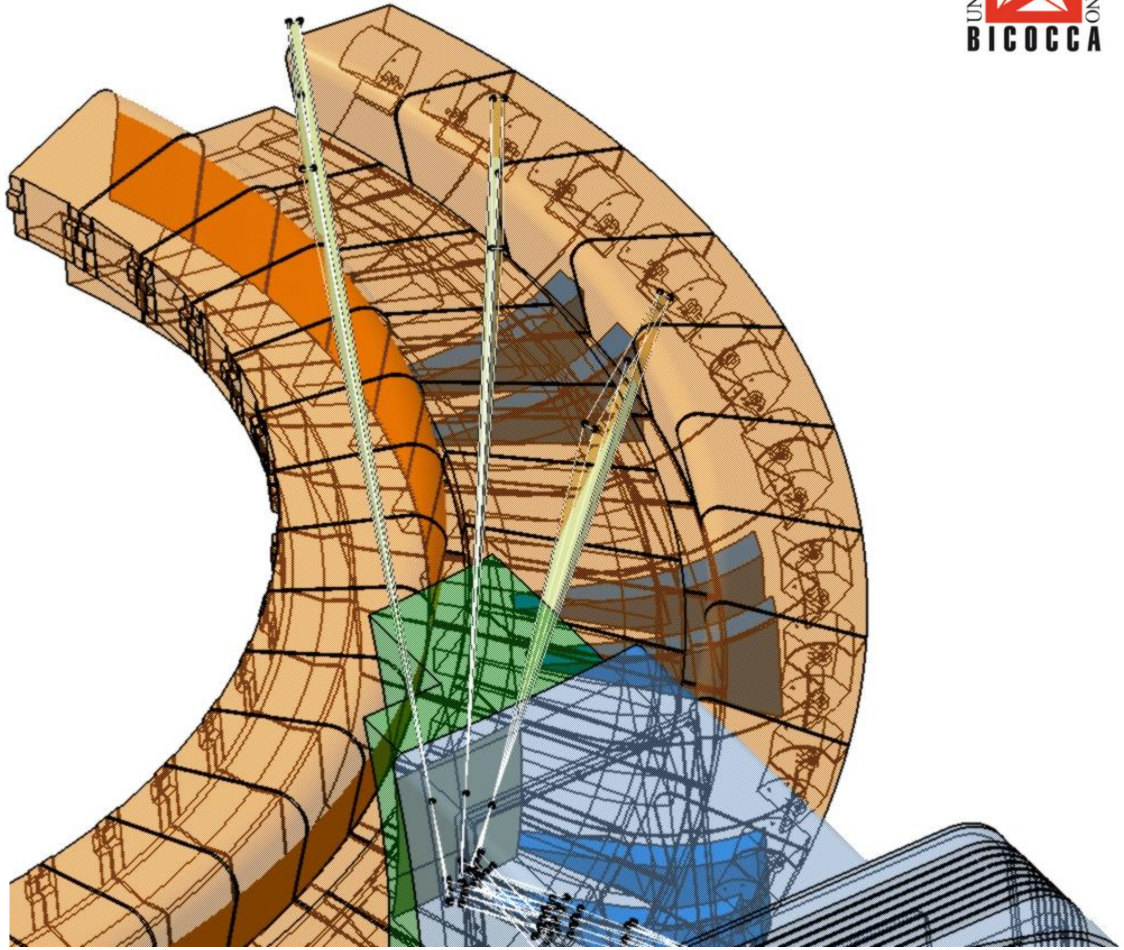
- The diagnostic provides a line integrated measurement
- The achievable spatial resolution is limited by the line integration
- Avoid plasma volumes of high visible emission

Line ratio as control signal





Line of sight integration



Future plans

⇒ Consider opacity for both Helium and Hydrogen lines

⇒ Consider reflections

⇒ Consider strike point sweeps

Two different objectives – not independent

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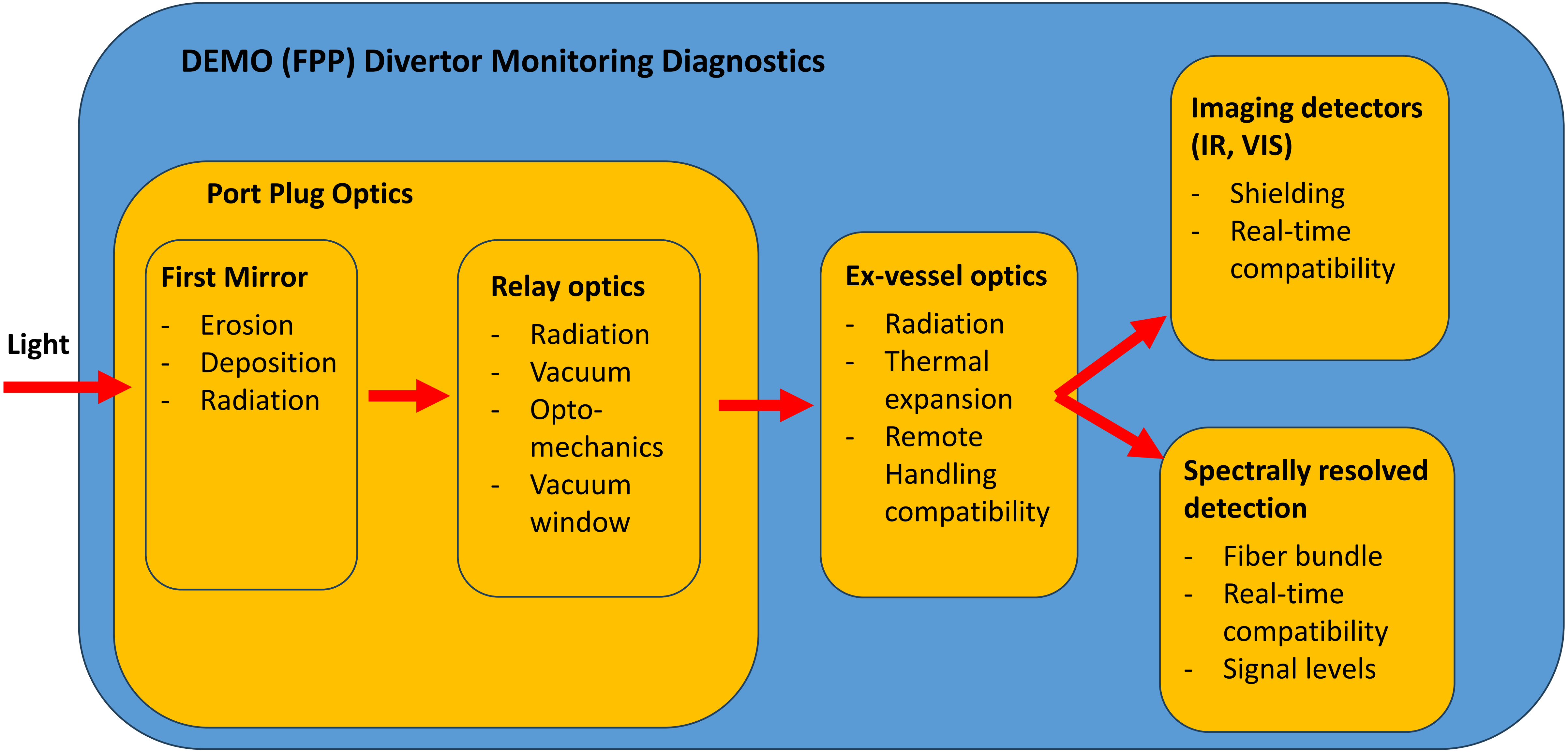
Diagnostics schematics – Divertor Monitoring diagnostics

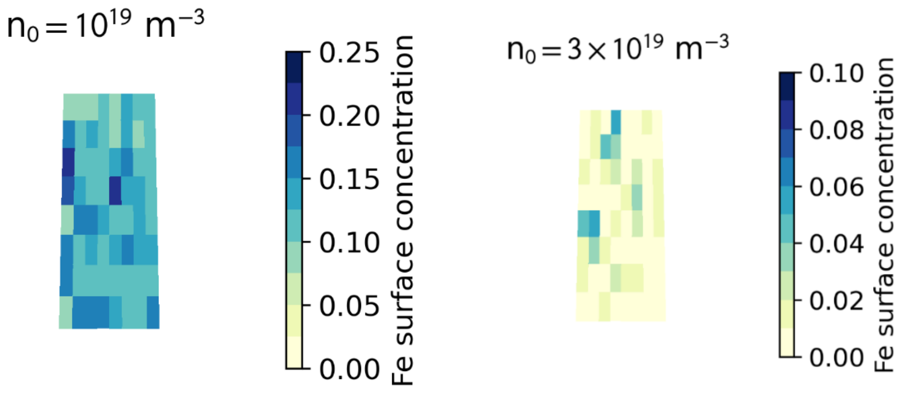


First mirrors are subject to erosion and deposition fluxes from the plasma side – gas target can protect the surface

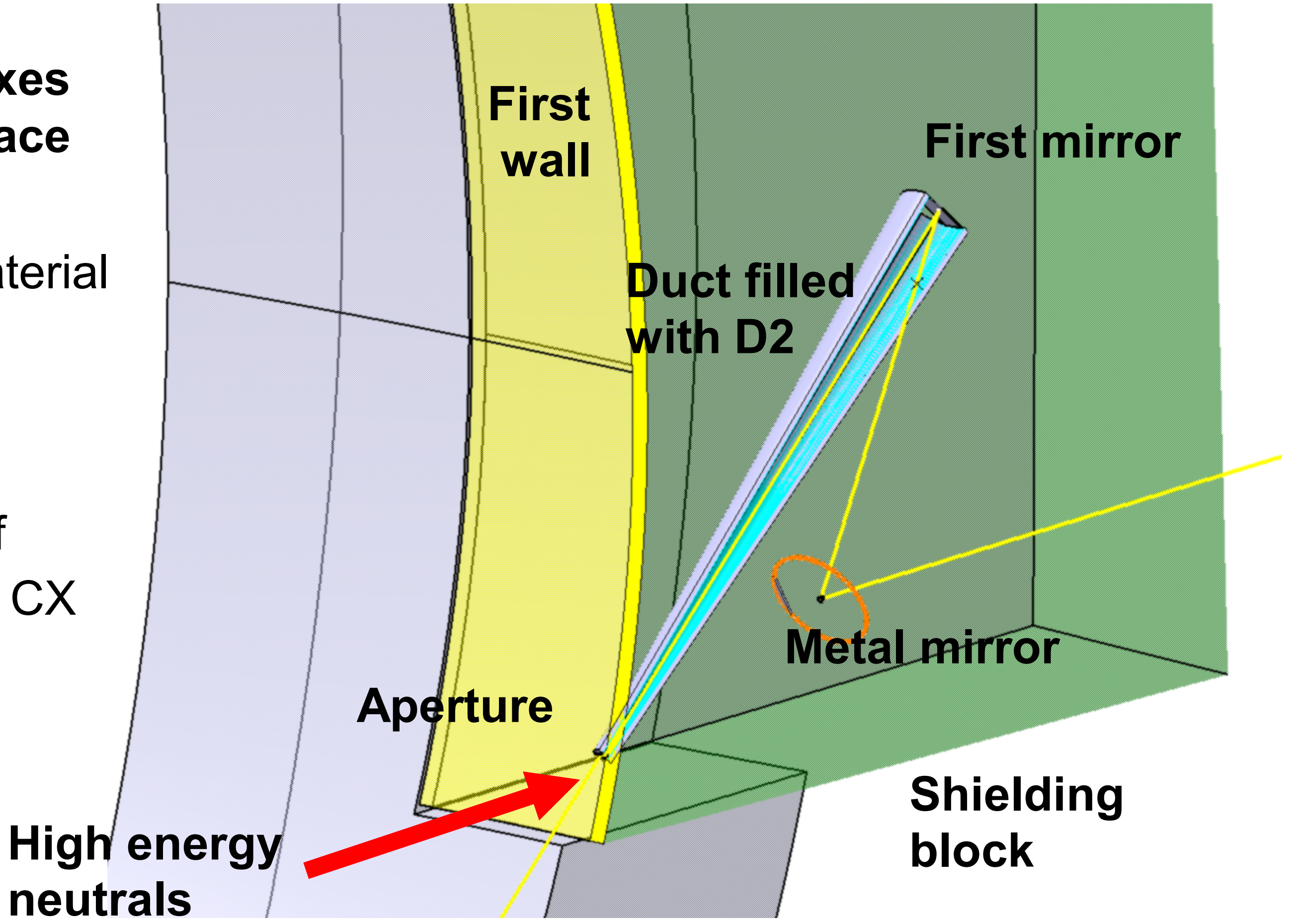
M. Z. Tokar, Nucl. Fusion 58, 096007 (2018)

- Single crystal Rhodium / Molybdenum as first mirror material
- D=30 mm, L=2000m cone shaped duct in simulation
- Mirror size was maximized at 180x60mm
- D_2 background densities (n_0 = 1x10^{19} m^{-3}, 3x10^{19} m^{-3}).
- ERO 2.0 was use for the simulation, includes release of sputtered particles from the duct wall. Only the effect of CX neutrals from plasma is taken into account.

Mirror deposition after 1 year of DEMO operation



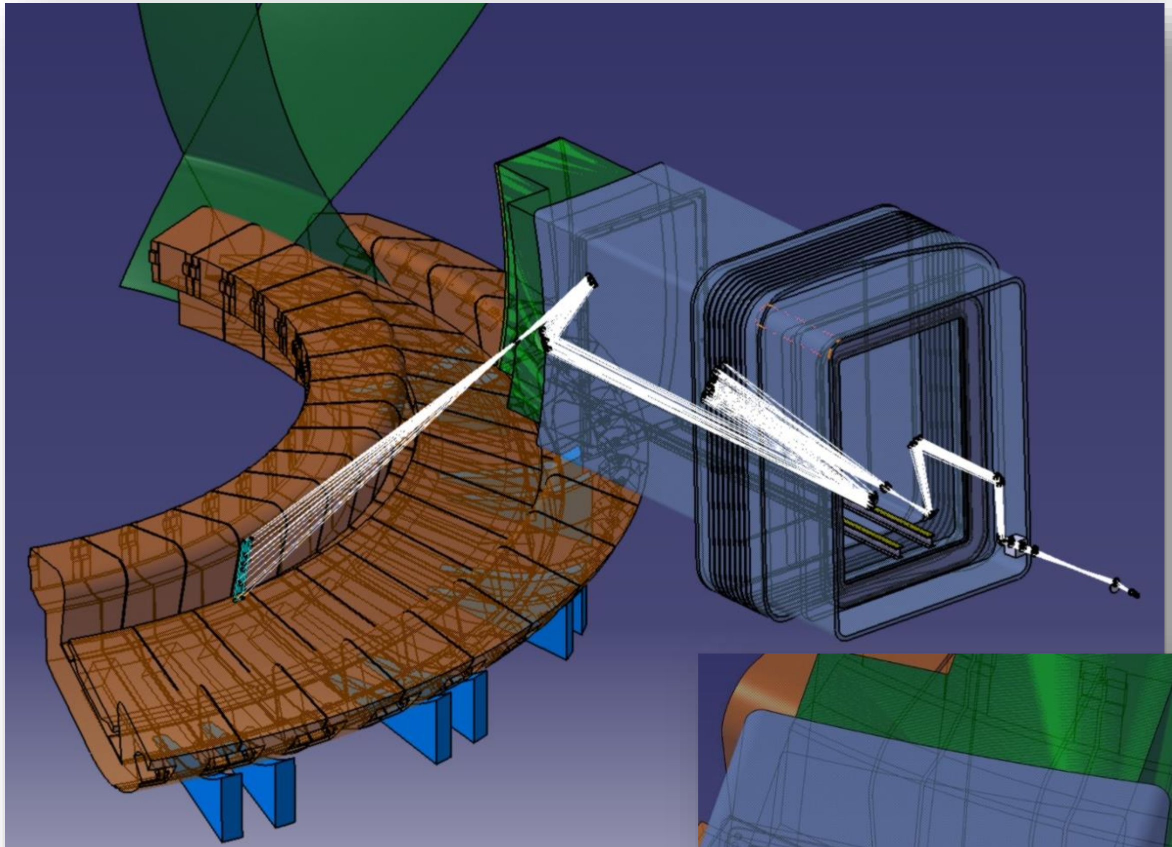
C. Baumann: EFDA_D_2RF7UX

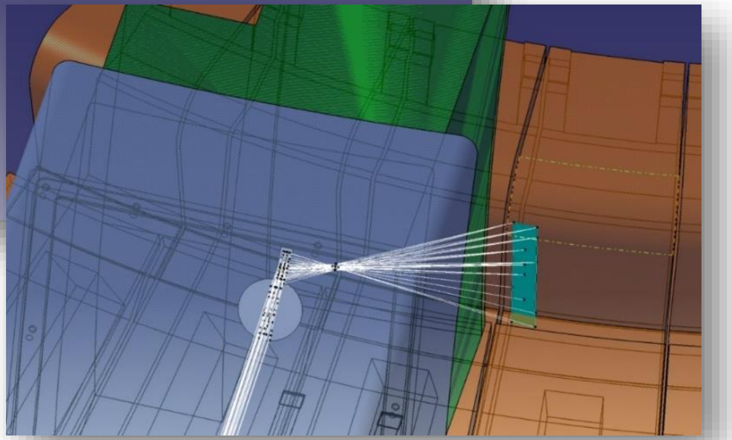


Molybdenum and Rhodium are both acceptable as first mirror material

Mirror deposition after 1 year of DEMO operation:

averaged Fe surface concentration in the interaction layer 1.4%





Field of View : 120x900mm

Aperture D=30mm

Aperture distance – 2000mm

First mirror - 60x180mm flat mirror

Distance of object: ~ 7500mm

D. Dunai et al.: EFDA_D_2QES79

Optics design was performed in ZEMAX

- Only metal mirrors in the port in relay optics (aluminium substrate with silver coating)

- Fused silica double vacuum window

- Radiation hard glass outside of bio-shield

- Flat first mirror

Maximize FOV with the given first mirror constraints

- **Visible imaging - 500-700nm**
- **IR imaging - λ=2-3μm**

Achieved Spatial resolution :

- **~0.5 mm for visible imaging**
- **~1 mm for Infra-red imaging**
- **~10 mm for the detachment control**

Additional design parameters

- Remote Handling compatibility to be able replace the Vacuum window
- Bioshield width 2m
- Imaging Detectors behind the bio-shield in a neutron shielded box.
- Thermal expansion must be compensated

Opto-mechanical design

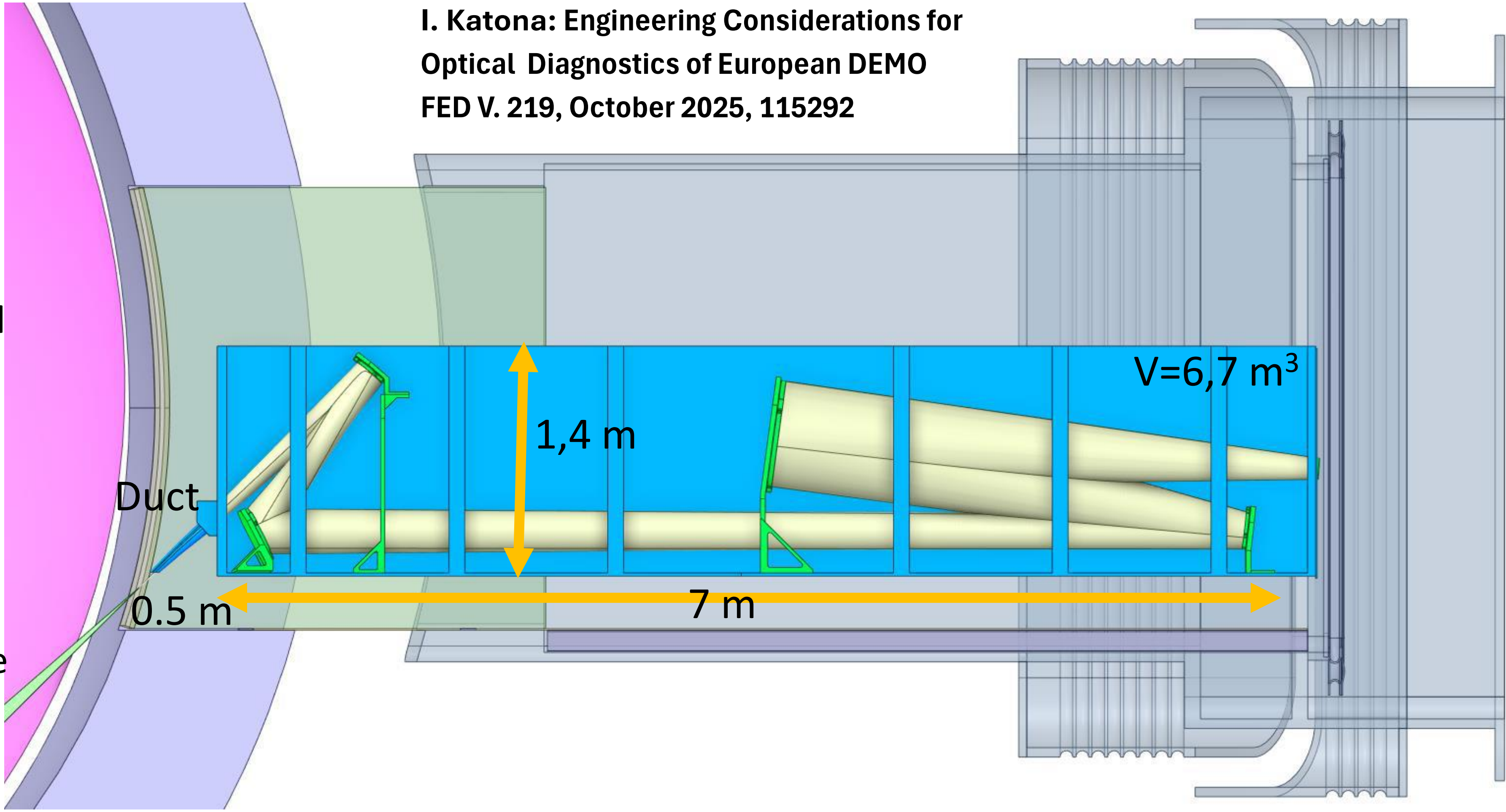
New Challenge :
Integration of gas filled duct
- **Open aperture**
- **Optical path free**

Continuous flow to the Vacuum Vessel
Multiple options were considered.
The optics is installed in a box

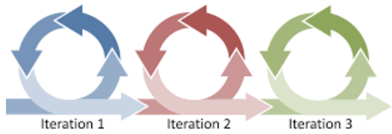
Box-mounted version advantages:
- Simplest, and robust optomechanical design
- Vacuum Window is RH maintainable
- Easier to integrate multiple opical diagnostics into one larger box
- Easier to incorporate the shielding

Box-mounted version disadvantages:
- Large, uncontrolled gas volume
- Large space requirement

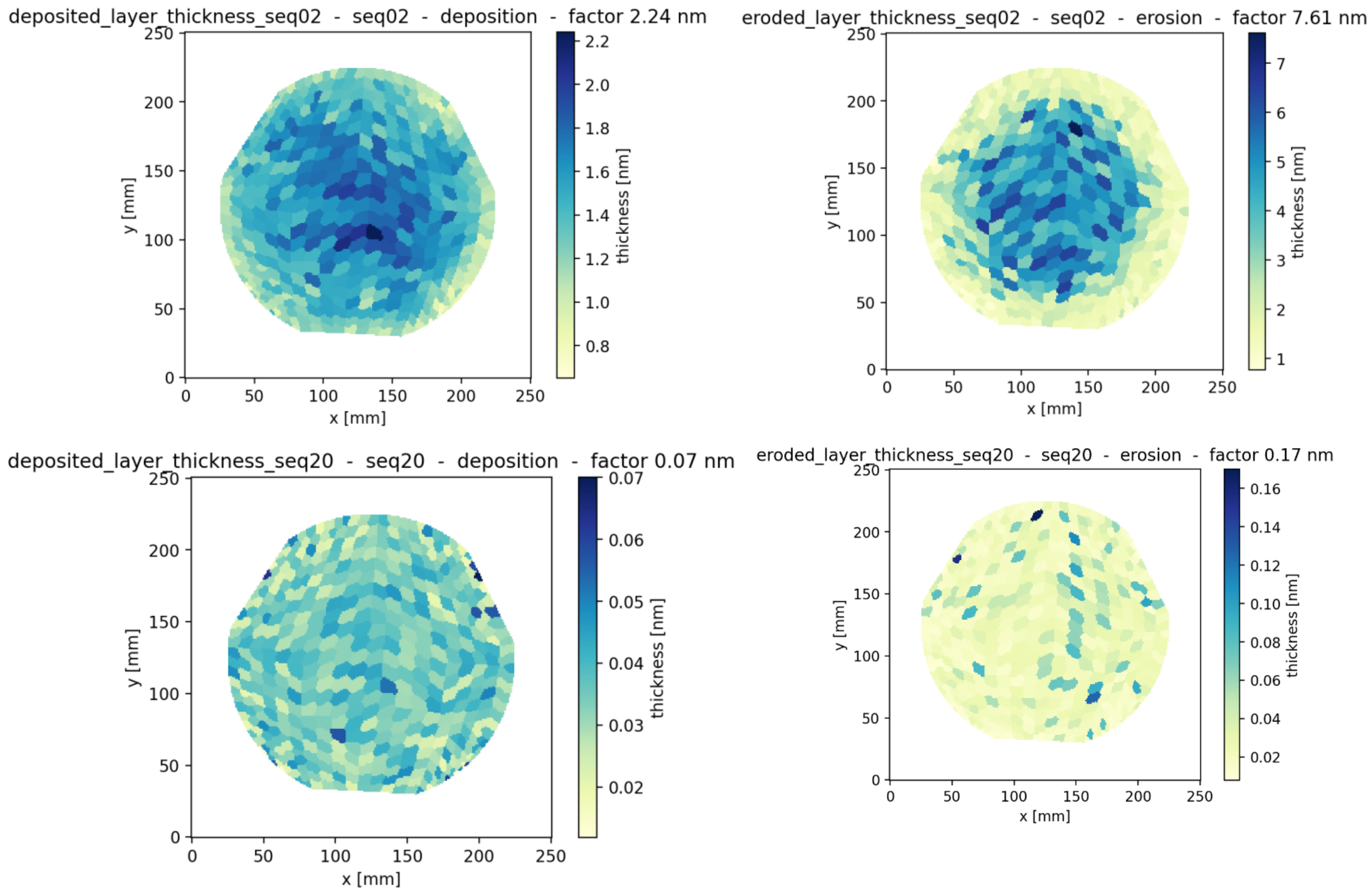
I. Katona: Engineering Considerations for Optical Diagnostics of European DEMO FED V. 219, October 2025, 115292



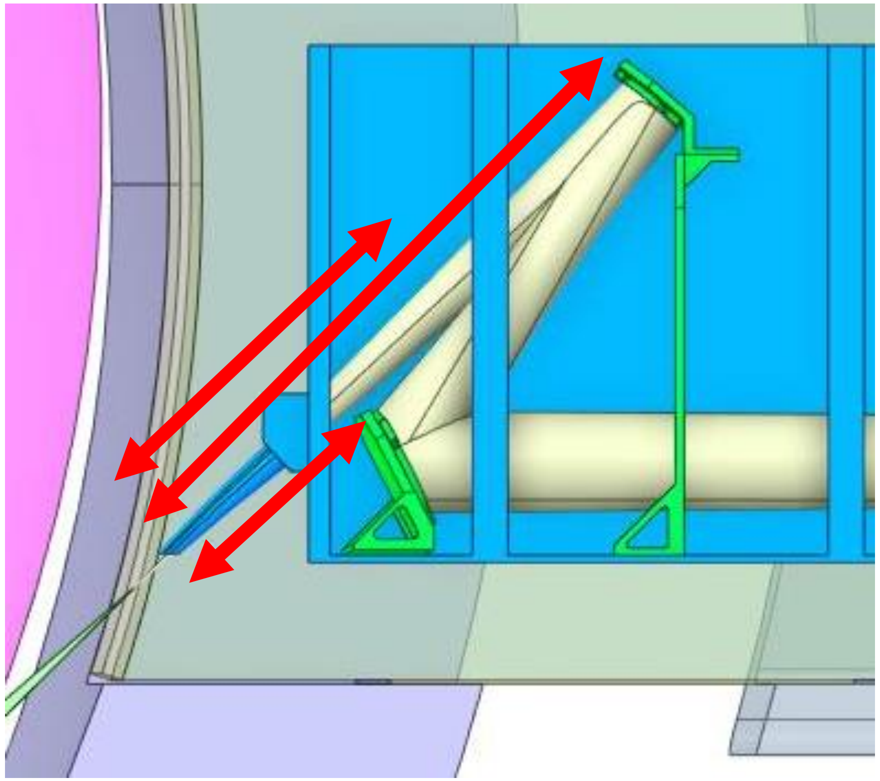
The duct is only 0.5m in this solution, and the Fe sputtering and erosion is expected to be reduced - ERO 2.0 simulations are running in 2025
- **Smaller aperture and first mirror – Changes the optics design**
- **Lower duct gas density – operation advantage**



3 different aperture sizes * 3 different mirror positions



Christoph Baumann – FZ Jülich



In the simulations the observed erosion / deposition changes a factor of 100 between the two extreme cases

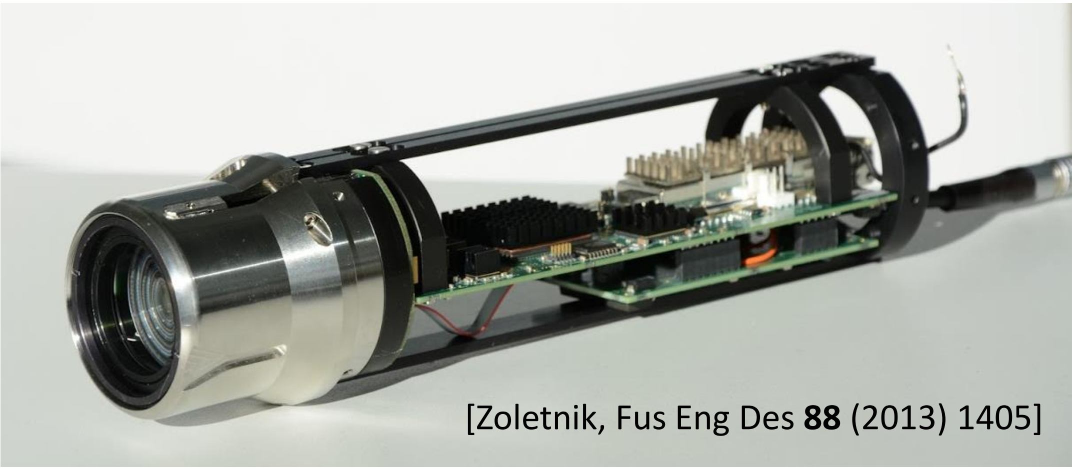
The real question is how the imaging properties are changed if the eroded mirror surface is introduced to Zemax

Imaging vs Light collection

The detector technology will develop, but could be solved with present technology

Imaging cameras – Visible and Infra-red cameras

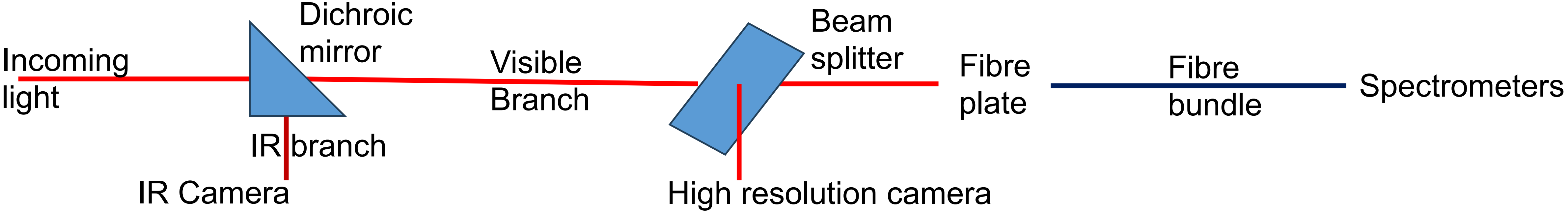
- Relatively simple visible camera is sufficient with real-time capabilities EDICAM development is a good candidate
- ~500x500 pixel IR camera is sufficient, and would be available
- Installed relatively close to the bioshield utilizing additional shielding

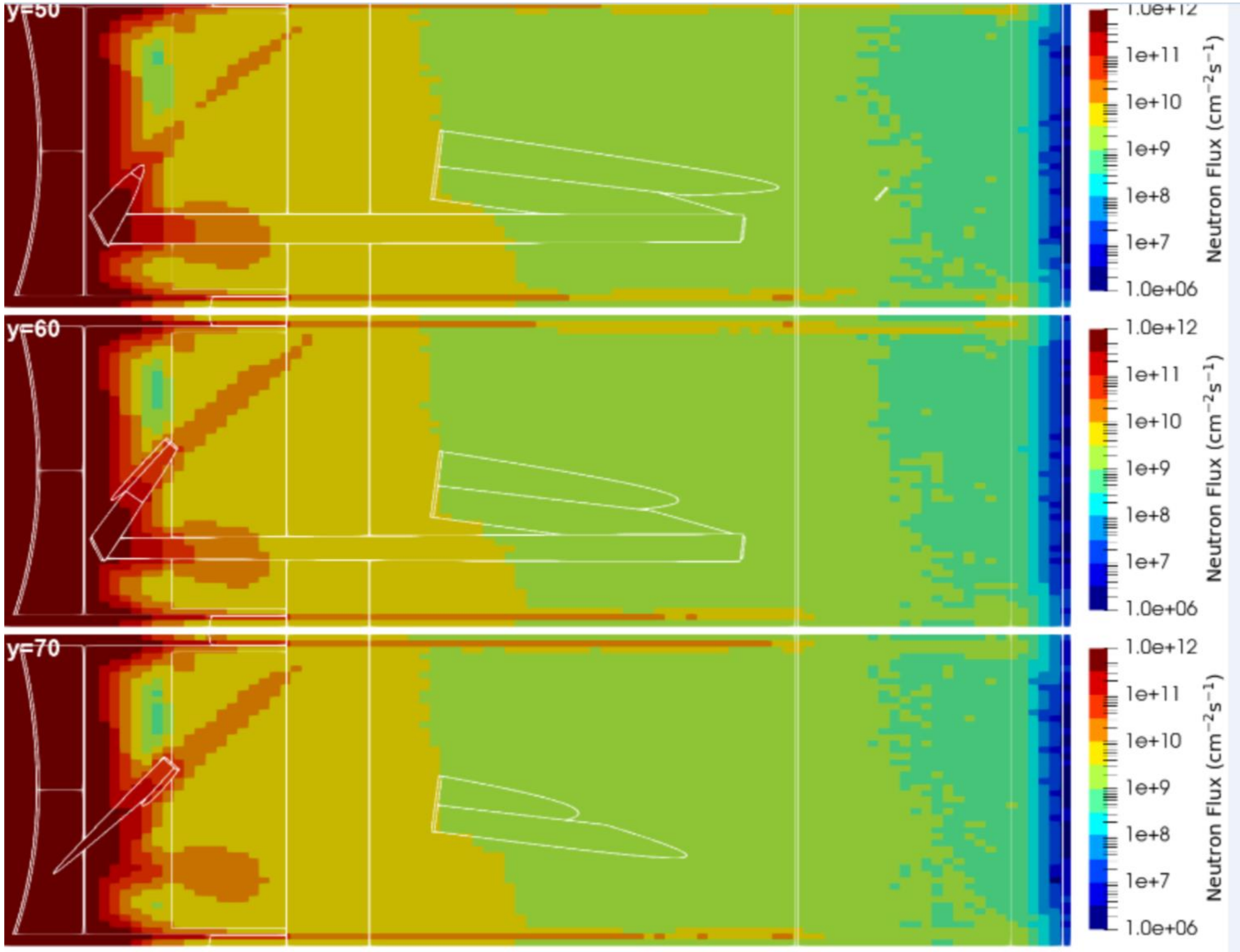


[Zoletnik, Fus Eng Des **88** (2013) 1405]

Other detectors

- The detachment control and W erosion diagnostic -> high-resolution spectrometers for calibration and filtered single detector solutions (real-time capabilities)
- Spectrometers in a diagnostics cubicle,
- The light would be transmitted by fiber bundle – no reliable fiber bundle technology for DEMO





R. Luís et al. Neutronics Simulations for DEMO Diagnostics. Sensors 2023, 23, 5104.

Preliminary neutronics simulations:

- **Increased radiation originated from tubular optical path**
- **Additional doglegs in the shielding block can decrease flux**
- **The applicable neutron shielding is limited due to weight restrictions**
- **The sensitive electronics (high resolution camera, IR camera) outside the bioshield needs additional protection – size limitations**
- **The spectrometers are planned to be installed in diagnostics cubicles 100+ meters**

Diagnostic design activity for DEMO is possible with limitations

1. **Concentrate on DEMO (FPP) specific challenges.**
   - *First mirror protection*
   - *Gas filled optics container*
   - *Mirror based port-plug optics*
2. **Understand the physics requirements and deduce the diagnostics requirements**
   - *Simulation of various line intensities*
   - *Line of sight optimization*
3. **Identify missing bits: physics knowledge, simulation code, technology, material**
   - More detailed detachment modelling
   - Opacity and Reflections
   - Irradiation material information (IR- optics, mirrors, etc…)
   - General DEMO design and requirements, …

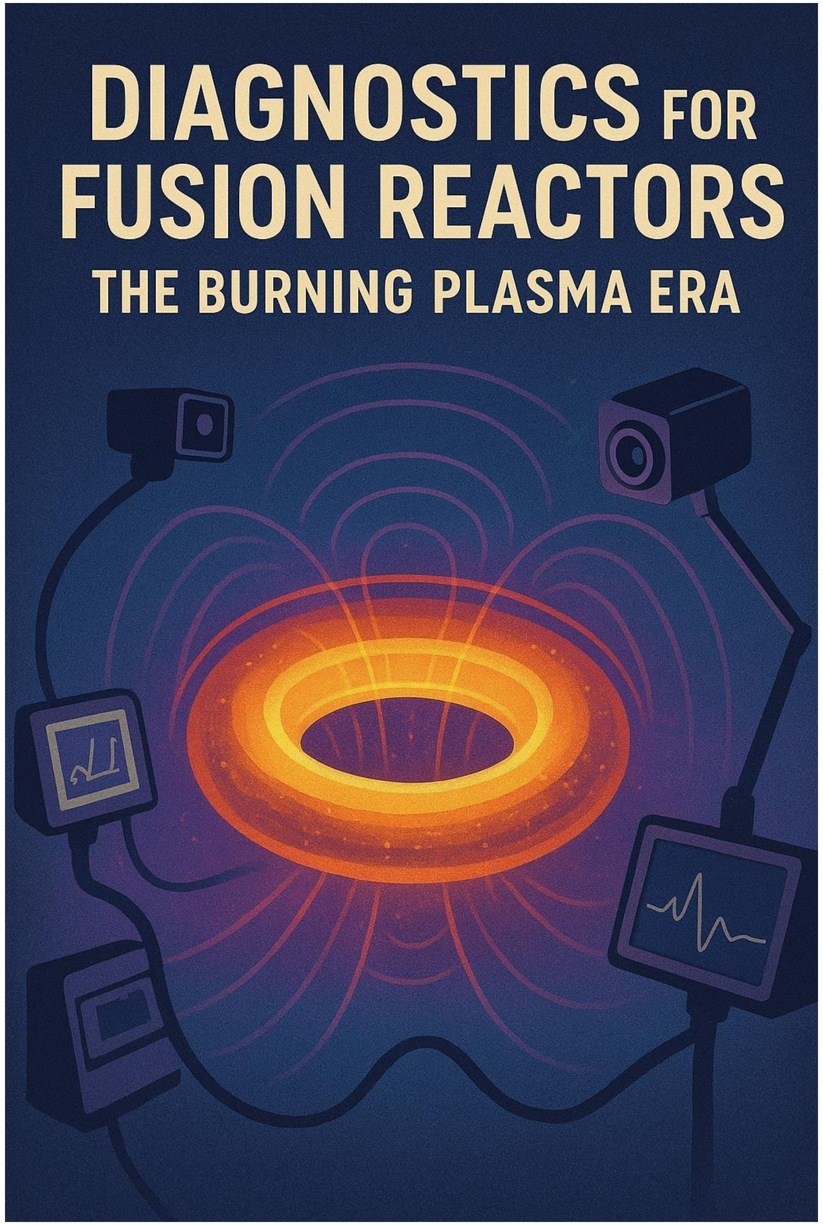
Transferable results and expertise between DEMO variants and FPP designs

Test the developed diagnostic and control techniques on present day and near future devices – **Eurofusion Feasibility study to JT-60SA - 2025**

The concept could also be tested on ITER, BEST, KSTAR…

HUN-REN Centre for Energy Research

Thank you for your attention!


DIAGNOSTICS FOR
FUSION REACTORS
THE BURNING PLASMA ERA

Beam Emission Spectroscopy Diagnostic – MAST-U

Beam Emission Spectroscopy diagnostic

- Collisionally-excited, Doppler-shifted neutral beam fluorescence (visible range , ~660 nm)
- ~cm spatial and ~µsec temporal resolution
- **$I = n_{plasma} * n_{beam} * \sigma$**

intensity fluctuations ~ density fluctuations

MAST-U BES installed on the South-South Heating beam

-2D turbulence imaging – ***8*8 pixels (poloidal-radial resolution)***

-In the plasma ~2cm pixel pitch : $k_{r,\vartheta} \leq 1.6\ \text{cm}^{-1}$ ($k_{\perp}\rho_i < 1$)

-***The observation range can be changed from 0<r/a<1***

-Temporal resolution up to 4MHz sampling,

- 500 kHz analogue bandwidth
- $>10^{11}$ photons/sec, SNR up to 300
- Temperature controlled interference filter – optimize background

2D BES can characterize turbulence, fast transient events, and mean and fluctuating poloidal flows