DTT 2024 THM-DIA Conceptual Design Review Meeting

Tomography and Imaging

G. M. Apruzzese (PL) and team

ENEA, CNR, RFX, INFN, UniMiB,UniRoma2

June 10 – 12, 2024 - Bruno Brunelli Hall, ENEA Frascati

DTT-THM-DIA Conceptual Design Review Meeting

Tomography and Imaging: Task and diagnostics allocation

Subtask	Diagnostic	DTT phase	Contact person
DBO	Bolometry	1 & 2	G. M. Apruzzese
DXT	SXR Tomography • CVD	1	F. Bombarda
DXI	SXR Imaging	1	V. De Leo/ D. Pacella
DXT	SXR Tomography • GEM	1 & 2 (?)	V. De Leo/ D. Pacella

DTT Allocation

	Sector	Port	In-Vessel
DBO	15 1,5 and 10	**1**, 2, 3, 4 **1**	bolometers
DXT • CVD • GEM	15	**1**, 2, 3, 4 **1**,3	diamond
DXI	8	3	

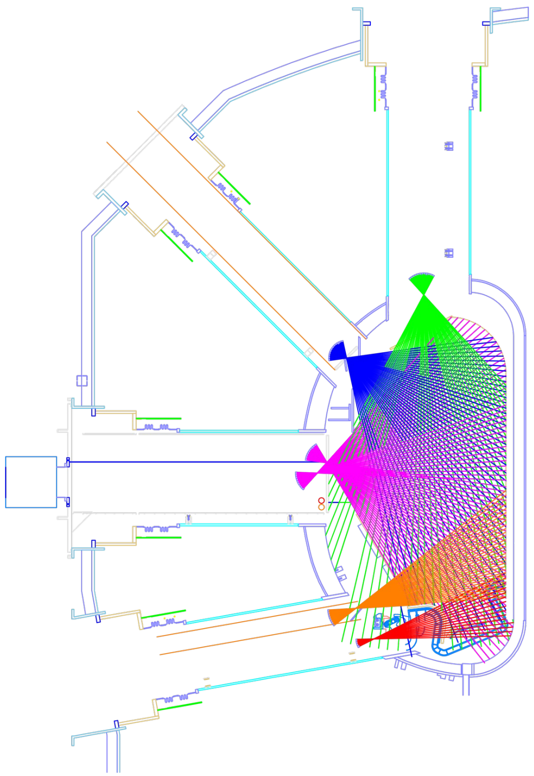
Bolometer Diagnostic : Sectors and Ports

Measurement of the plasma radiated power

- Sector 15
- aperture of pinhole around 5 mm for a LoS aperture of 4-5 cm

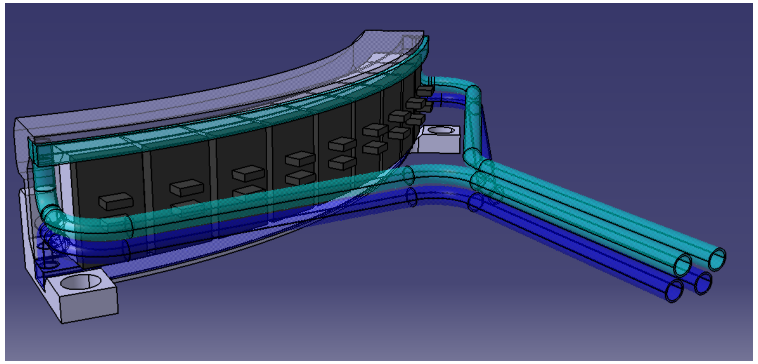
Port Array Name	P1	P2	P3 1	P3 2	P4	P4 div
Distance slit-sensor [mm]	200	160	200	200	260	160
Number of LoS	48	48	36	36	32	16
Total aperture [deg]	67,2	86,4	50,4	50,4	35,2	28,8

DTT Sectors 1, 5 and 10
Port 1 16 LOS for sector
(for studying the asymmetries in the plasma radiation emission)



Sectors far from gas valves and therefore their influence is not expected to play a role

Detectors assembled along the circle

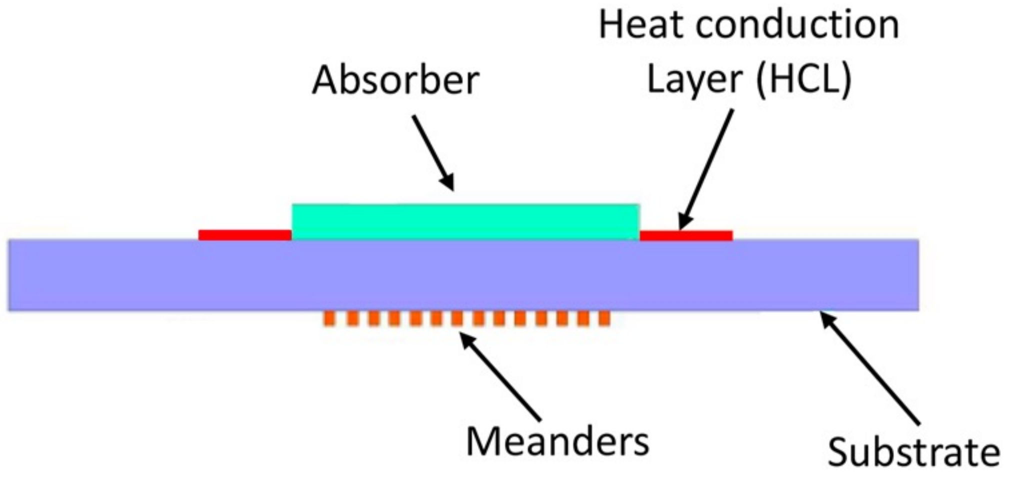


Both the current and a reduced PHASE 1 layout can be upgraded by simple mechanical modifications. The cooling system under development is also designed to meet this requirement.

Bolometer type

Foil based bolometer

- Standard (IPT)
  - Gold layer absorber/ Pt resistor
  - Energy range 5 eV – 12.5 keV (4μm)
  - Absorber tickness can be customized.
  - Working temperature < 180 °C
  - The limit, in the operational temperature, for this sensor is just the sensor holder (contact pins)
- For ITER (under investigation)
  - Gold absorber(20μm) with different membranes.
  - Absorber tickness can be customized.
  - Resistive to high neutron and γ flux
  - High operational temperature 350 °C
  - bolometer sensor holder with different contacts



In case of mixed configuration (IPT and ITER) the absorber tickness can be customized.
The thicker the absorber, the higher the upper limit of the energy range that can be measured.

Bolometer Diagnostic : Critical issues

ECRH issues

Bolometer shielding from EC stray radiation (170 GHz). Not negligible the contribution of thermal load due to the microwaves (0.7 meV). A metallic grid in front of bolometer has to be mounted (see W-7X, 140 GHz, ϕ=90 μm and w=0.24 mm)

Cooling

Bolometer cooling system to prevent increasing temperature:
Max temperature of Kapton-based film is around 180 °C.
For DTT baking (expected values)

- 165 °C for Port Plug
- 200 °C for First Wall

Cooling system available
ECRH @ 8 bar
DTT @ 40 bar

Long discharge (100 s) effects on the thermal shift

First result (not considered in the report) by LT-Calcoli for bolometric cooling system 1/2

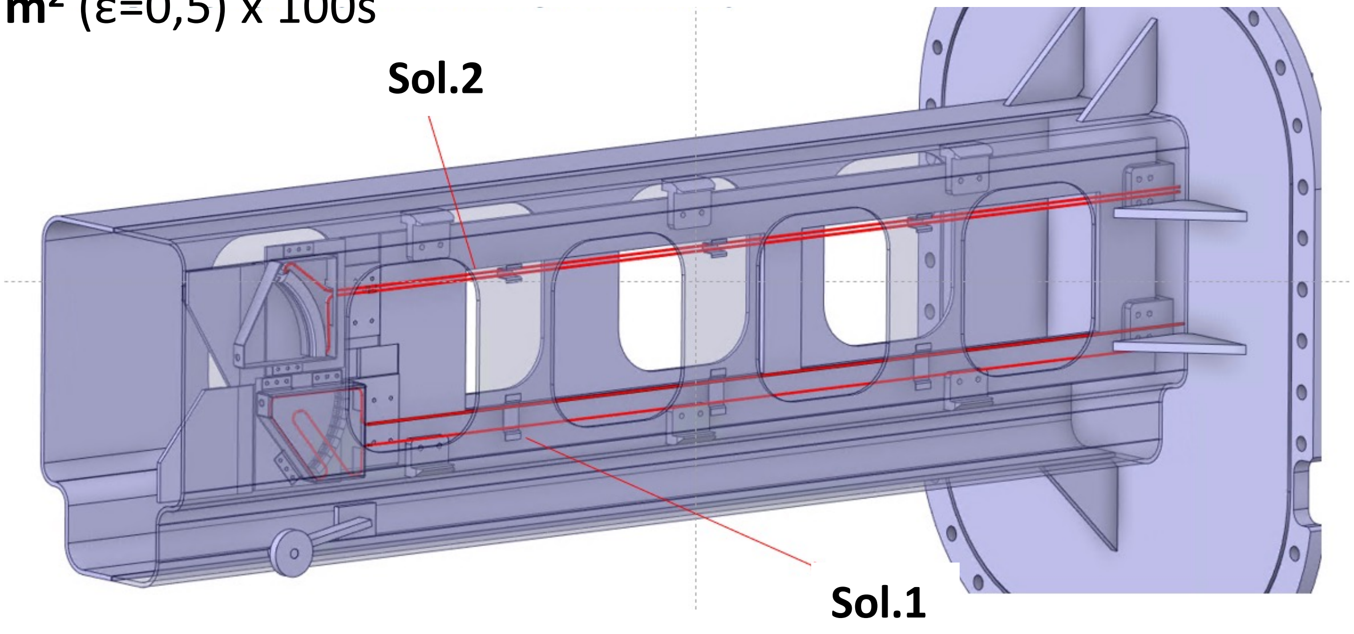
Two solution has been tested:

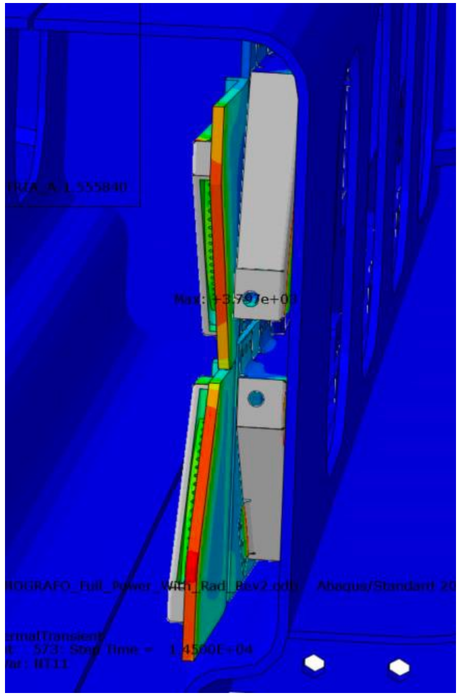
- Cooling of the box (Sol 1)
- Cooling on a structure that integrate the bolometer (Sol 2)

Tests performed:

- Baking: 250 °C
- Discharge : **0.5 MW/m²** (ε=1) x 100s
- Discharge : **0.25 MW/m²** (ε=0,5) x 100s

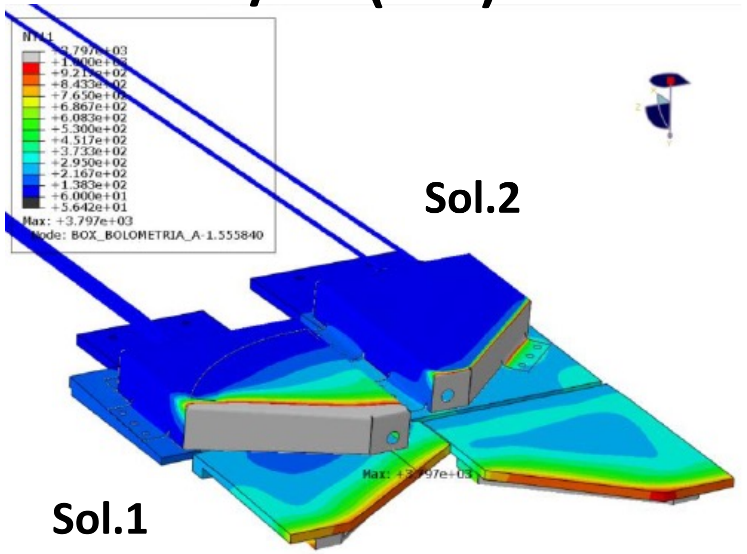
Water: 40 bar – 60°C





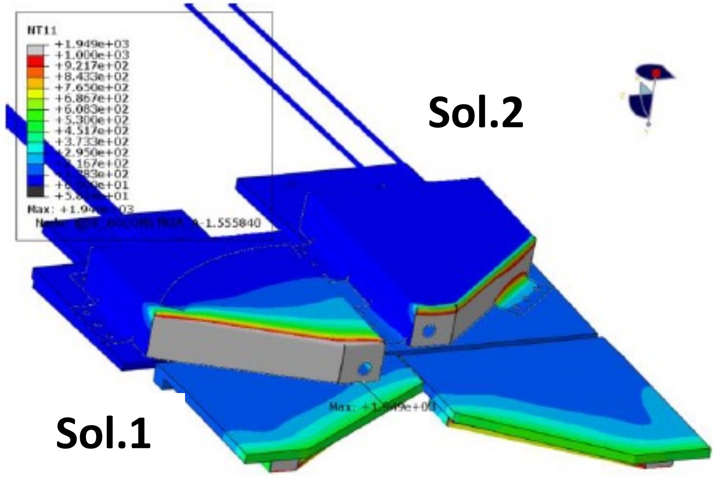
First result (not considered in the report) by LT-Calcoli for bolometric cooling system 2/2

0.5 MW/m² (ε=1) x 100s



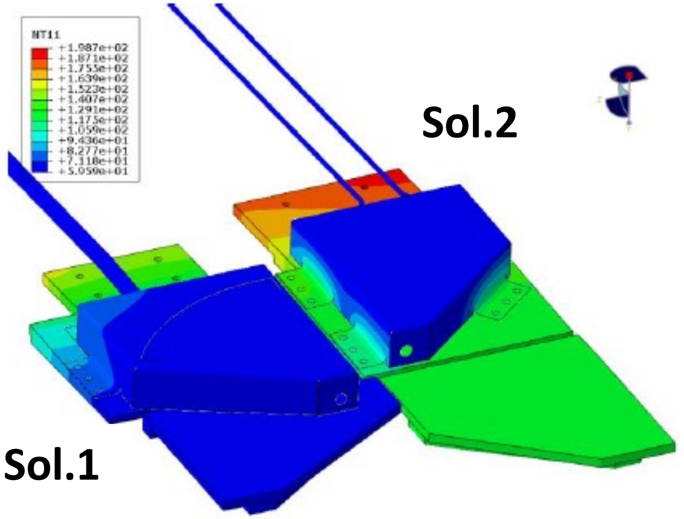
	Box	Bolometer
Sol.1	**3797**	**420**
Sol.2	**3797**	**185**

0.25 MW/m² (ε=0,5) x 100s



	Box	Bolometer
Sol.1	**1949**	**251**
Sol.2	**1949**	**124**

Baking



	Box	Bolometer
Sol.1	**71**	**147**
Sol.2	**71**	**61**

In the report are shown:

- for CVD the results by LT-Calcoli, obtained by considering a semi-closed port plug facing the plasma;
- for Bolometers no data were available so only rough estimates have been considered

Electronic systems for bolometric diagnostic

- Complete Analogic System based on lock-in @20 kHz (IPT-Albrecht.de).
- Digital System based on FPGA (Field-Programmable Gate Array)

    - Developed at MAST_U since 2016.
        - D-TACQ
        - Systems on MAST-U, JET, TCV, DIII-D, PPPL

    - Developed at FTU, 2019 based on a Hardware PXI platform of NI (National Instrument). It is programmed using LabVIEW.

- The ongoing work of F4E for ITER diagnostics (*under development*) will be considered when information will be available

Main Cost for 1 channel (1 LoS)

Hardware	Euro	
Sensor (IPT-Albrecth) Prototype for ITER	1800 No data available	The cost of the ITER detectors cannot yet be estimated and it is not yet possible to assess whether they will be commercialised (private communication).
Cables (in and ex-vessel)	1640	
Electronic System: 1. Digital 2. Analogue (IPT-Albrecth) 3. F4E	 670 5000 Monitoring phase	The electronic systems (1. and 2.) are completely different. Estimates are based on quotes already received. Risk due to planning or development for 3.
DAC	No evaluation	Standard DTT acquisition system. No custom system is required (CODAS)

General considerations 1/2

- The final choice of bolometer type depends on:
  1. The actual possibility of overcoming the technical difficulties of placing commercial bolometers in the divertor region (aiming also at increasing the coverage of both sides of the divertor), including cooling, i.e. once thermal load estimates are available for the final layout;
  2. the actual planning for the release of the diagnostic, in order to maximize the possibility to use the ITER prototypes;

     2a. It is even possible that such prototypes will not be commercilized (private communication with H. Meister) and therefore will not be available;
  3. Considering 1. and 2. the final choice will take into account the time required for the procurement and the installation. At the moment it is expected to take place in 2027.
  4. In case of a mixed configuration (commercial and ITER prototypes) the same thickness of the absorber will be chosen

- Cost reduction:
  1. Efforts are currently being made to design a reduced layout (around 130 channels).
  2. In order to improve the coverage of the divertor area, technical difficulties have to be overcome and possible solutions are being considered.

General considerations 2/2

- DTT phases
  1. All considerations shown and reported are related to Phase 1 and Phase 2 for which at the moment no requirement about an eventual upper divertor installation has to take into consideration. Eventually a further layout can be designed.

  2. Phase 1:
     1. Reduced layout to provide estimates of the radiated total power and emissivity profiles (related to the equilibrium, i.e with a spatial resolution of the order of the cm) eventually including tomographic reconstructions

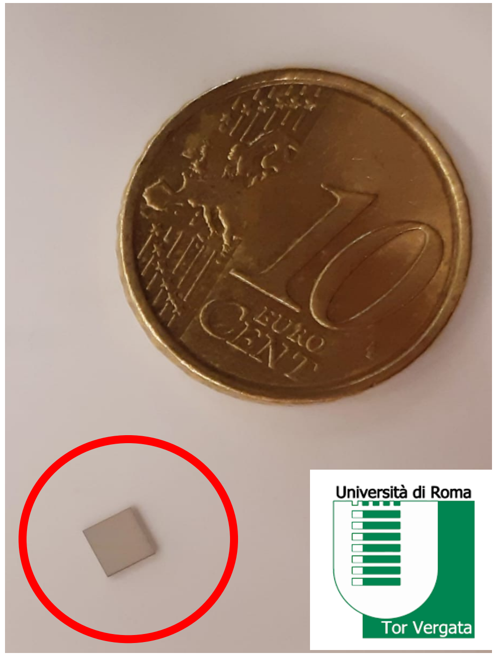
  3. Phase2:
     1. Tomographic reconstructions from the final layout of the bolometry

CVD Diamond diagnostic

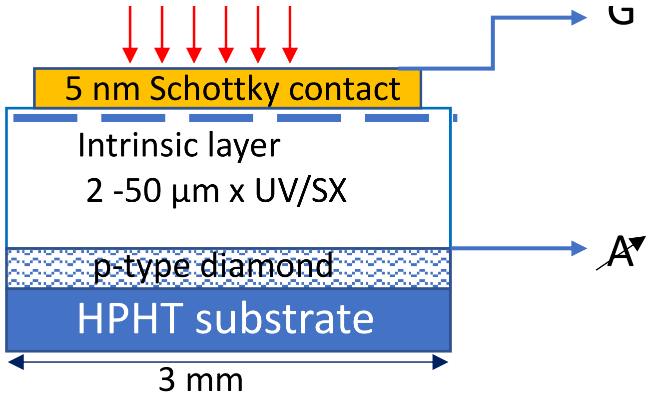
CVD Diamonds for UV and SX photon detection
Developed and custom grown at “Tor Vergata” University in Rome

Chemical Vapour Deposition (CVD) single crystal diamonds exhibit excellent photon detection properties:

- Wide band gap (5.5.eV) → low leakage current at room temperature
- Sensitivity to photon **λ < 225 nm = 5.5 eV** <u>(visible & ECH blind)</u>
- High carrier mobility → fast time response (< 1 ns)
- High thermal and mechanical resistance
- **Good radiation hardness > Si photodiodes**; measured at FNG up to 2×10^{18} (14 MeV n/m^2) with no appreciable degradation
- High Vacuum compatible → No Be windows required → Full plasma coverage



Multilayer Planar Configuration



What is the effects of stray ECH on diamonds? Is shielding required?

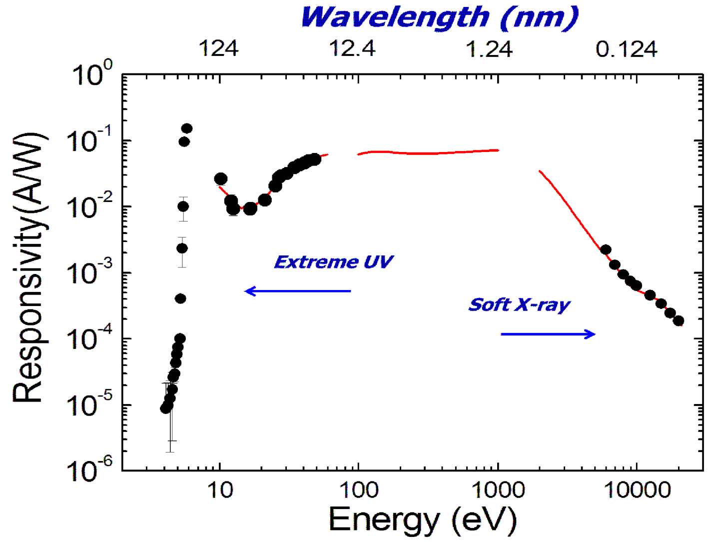
- Shielding is planned for the electrical noise on the (Kapton coated?) cables in-vessel; it is not expected to be a problem for the additional thermal load (to be checked) nor spurious signal

Responsivity 1/2

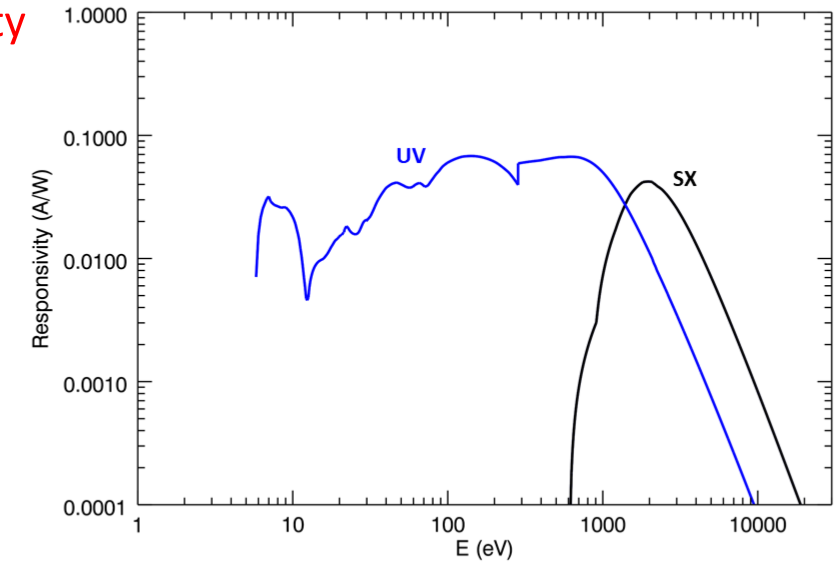
- Bandwidth (0.5 eV-30 kV) seems too large. Kapton could be incompatible with stray ECH. Have you foreseen to protect it?
- If a filter is introduced to reduce the spectral range of the CVD detectors the effect of stray ECH on it must be considered?
- commercial diodes costs much less. It must be evaluated the cost of beryllium windows and shielding from stray ECH.

Experimentally validated CVD diamond responsivity curve

The spectral response of the detector (A/W) as a function of the photon energy in the range 2-60 eV (EUV) and 6–20 keV (SXR). The measured responsivity values (black dot circles) were also simulated taking into account absorption losses in the Schottky metal electrode and charge collection processes of photogenerated carriers in diamond (solid red lines).



Ciancaglioni et al., J. of Appl. Physics **110**, 054513 (2011).



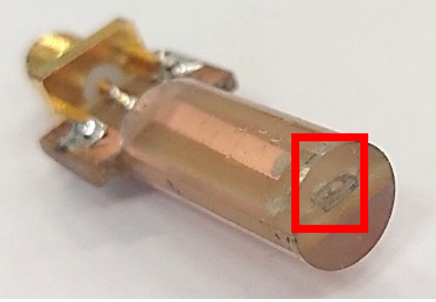
Calculated responsivity curves for the actual geometry of the detectors used on FTU; the calculation includes the Pt and Cr 5 nm contact layers, and the 6 mm Mylar filter for the SX detector.

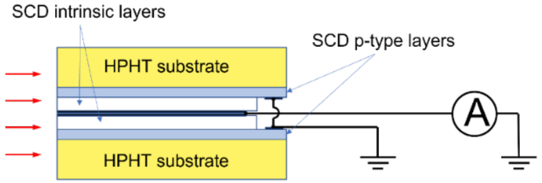
F. Bombarda et al., Nucl. Fusion **61** (2021) 116004

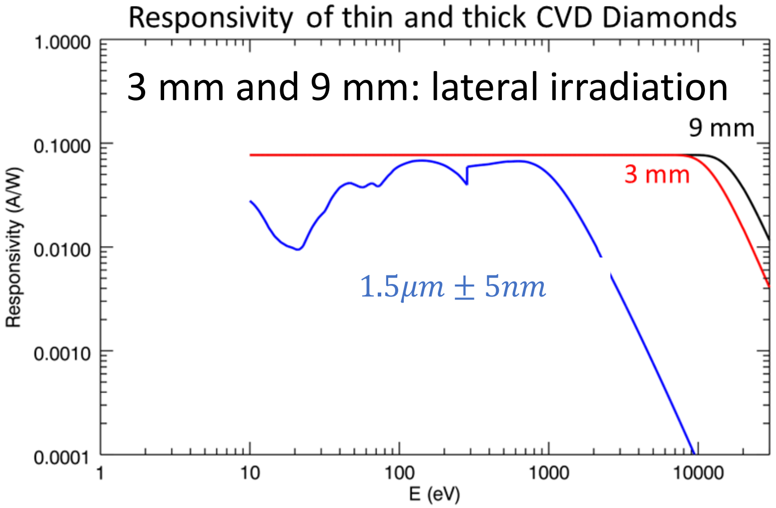
- Bandwidth:
  5.5 eV-30 keV
- Mylar filters are certainly not suitable for DTT
- Aluminized Kapton is being considered for SPARC; compatibility with ECH to be checked

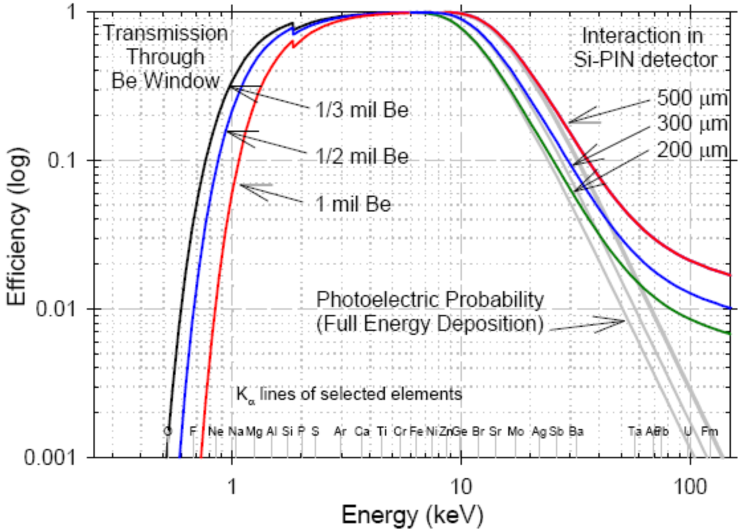
Responsivity 2/2

- Bandwidth (0.5 eV-30 kV) seems too large. Kapton could be incompatible with stray ECH. Have you foreseen to protect it?
- If a filter is introduced to reduce the spectral range of the CVD detectors the effect of stray ECH on it must be considered
- Commercial diodes costs much less. It must be evaluated the cost of beryllium windows and shielding from stray ECH.







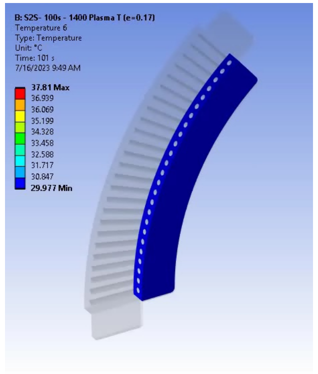


The LAT configuration (=lateral irradiation) extends the spectral range to about 30 keV. This layout needs to be further validated and will not require filters to cut off the low energy part of the plasma emission.

- Si diodes have similar high energy limit and are bigger;
- They are cheaper but will die faster

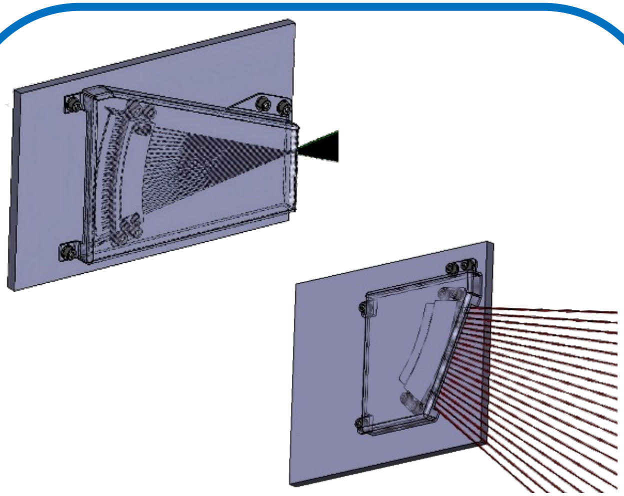
CVD Diamond Tomography : Preliminary heat flux estimates

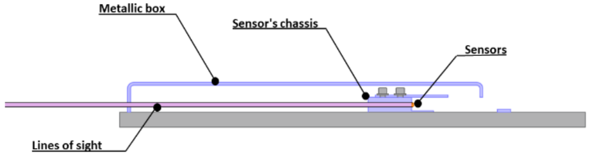
- Preliminary calculations, considering the shield on PP facing the plasma, indicate that the support will reach temperatures not requiring active cooling of the sensors
- More recent calculations have been performed by LT-Calcoli ("unofficially" delivered mid-May)



A layout that minimize the aperture on the Port FW is recommended, in order to reduce radiation and stray ECH on the detectors.

- Heat loads on the CVD diamonds increase the dark current but not compromise measurements. Tests up to 625 K carried out on thicker samples (M. Angelone et al., *et al., Nucl. Instrum. & Meth. In Phys. Res.*, **A 943**, 162493 (2019)).
- Tests are ongoing for the SPARC system and so far weldings seems to hold fine to baking temperatures (main concern)
- The additional heat flux associated with ECH will be evaluated





Different types of support are being considered to minimize the heat flux from the plasma and the divergence of the individual LoS, while still providing the best coverage of the plasma cross section

CVD Personnel and other issues

Regarding the CVD diagnostic, the University of Tor Vergata:

- has the capability of producing that number of detectors in due time (standard yearly production ~1000 pcs)
- can guide the design of the supports but not manufacture them, just as ENEA; will select and calibrate each diode; will realize the mounting of the diamonds and their in-vessel wiring;
- CANNOT take care of the installation on the machine, cabling, set up of the DAS and analysis software: this is the area where ENEA has to increase the professional resources.

Installation:

- The progressive installation (during PHASE1) can be done in two ways:
- i) installing all the supports carrying only half the detectors: this would allow for proper tomographic inversion at lower resolution, and leave room to introduce additional detectors with different characteristics at a later time;
- ii) installing only few supports, giving up the possibility of tomographic reconstruction, and leave room to change the support geometry.

- A design for a support carrying commercial diodes can be done, eventually, but it would be unpractical to design one compatible for both, given the considerable differences in dimensions of the detectors

Test on other devices

- Contacts have started for the installation of an 8-10 ch prototype on TCV in 2025

GEM - based SXT and Imaging

SXR Imaging and tomography based on GEM detector

Complete reconstruction of X-ray plasma emissivity (2-30 keV) by:

- One GEM X-ray camera with one-dimensional view of the plasma with a low tangential angle (Imaging)
- One X-ray spectrometer at high energy resolution with a silicon SDD detector with active shutter and collimator

Conceptual design for the PHASE 1

- Two one-dimensional X-ray cameras based on Gas Electron Multipliers (GEM) in a tomography configuration (one vertical, one horizontal)

Feasibility study

- Each GEM camera has 128 lines of sight and works in energy range of 2 – 30 KeV or even higher and an energy resolution of 25 %
- SDD detector allows X-ray measurements until 30 KeV with energy resolution of 4 % and temporal resolution of 5 ms. It operates along one l.o.s.

Each detector has to be installed outside of the port: no particular issues, just a pinhole with Be window is necessary for the GEM cameras

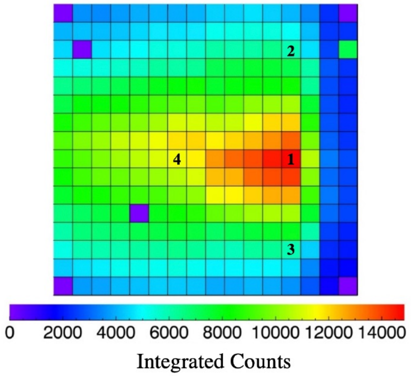
Triple Gas Electron Multiplier (GEM) detector for Soft X-ray detection

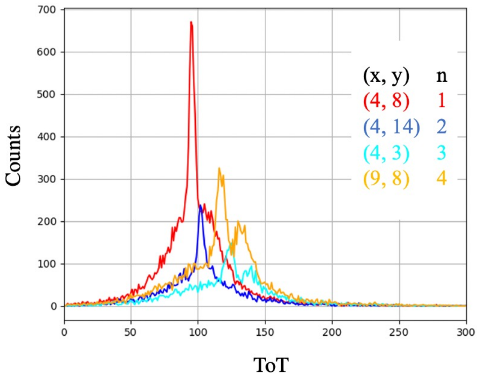
Fully assembled GEM detector with double FPGA acquisition board and front-end electronics (GEMINI chips).

Active area of 10×10 cm²

- New front-end electronics offer flexibility for:

- Recording X, Y position, energy (ToT), and time of arrival of each detected photon (ToA)
- Post-process spatial and temporal integrations without loss of information





Complementarity GEM- diodes

SXR GEM camera

- Frequenza: 10kHz
- High detection efficiency
- Mainly Core
- Optical flexibility
- Energy discrimination
- Post-process resolution
- Limited view of the plasma
- Lower energy cut-off at 1-2keV

SXR diodes

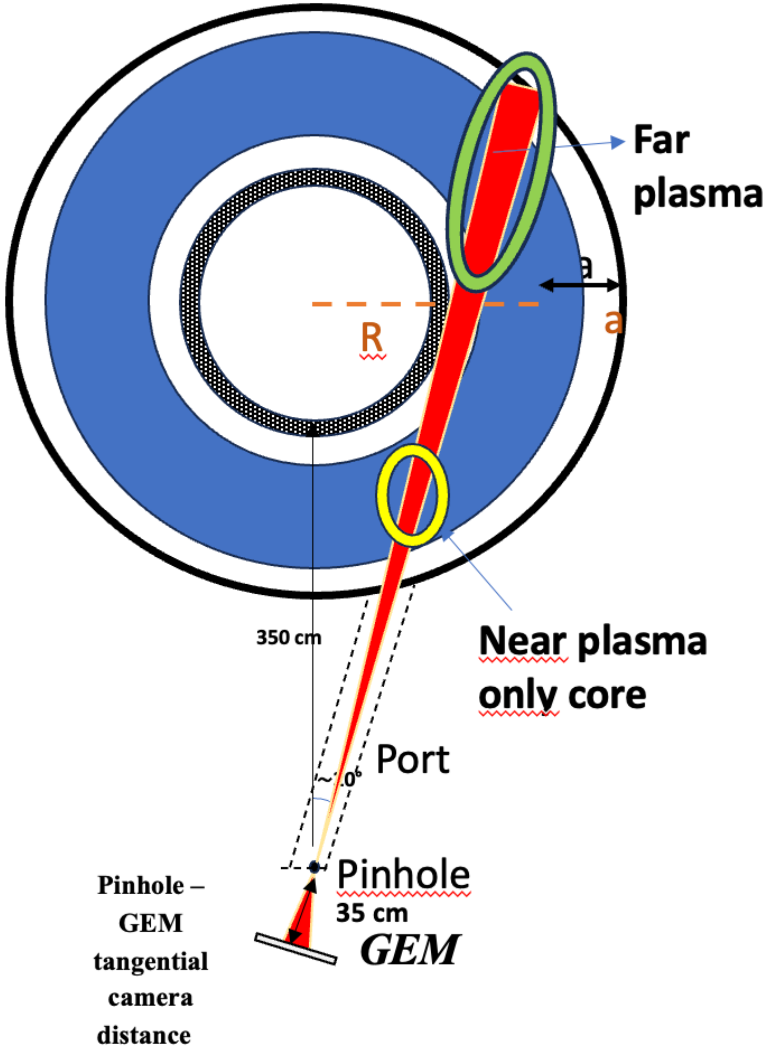
- Frequency: 1 MHz
- Low detection efficiency
- Core + edge
- Fixed geometry
- Energy integration
- Pre-process resolution
- Wide view of the plasma
- Extended to EUV-VUV

Contribution to plasma physics:

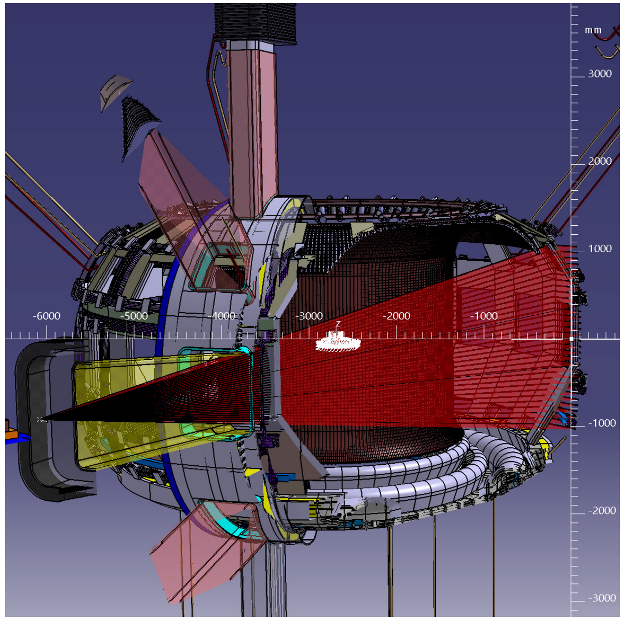
- Reconstruction of magnetic configuration in the core
- Slow (kHz) core MHD instabilities (s.t., m1, m2..)
- Impurity dynamics in the core
- Localized effects of heatings
- Detection of magnetic island
- Energy and particle transport

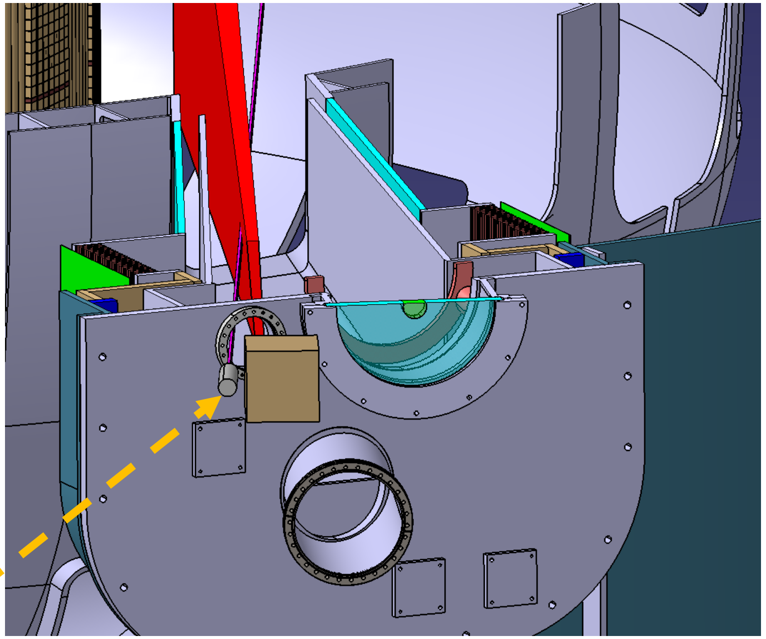
Tangential Imaging Conceptual design (PHASE 1)

- 1-D GEM camera with 128 lines of sight, pixels of 0.8 mm and a vertical spatial resolution of approximately 10 mm on the plasma.



X-RAY GEM TANGENTIAL IMAGING



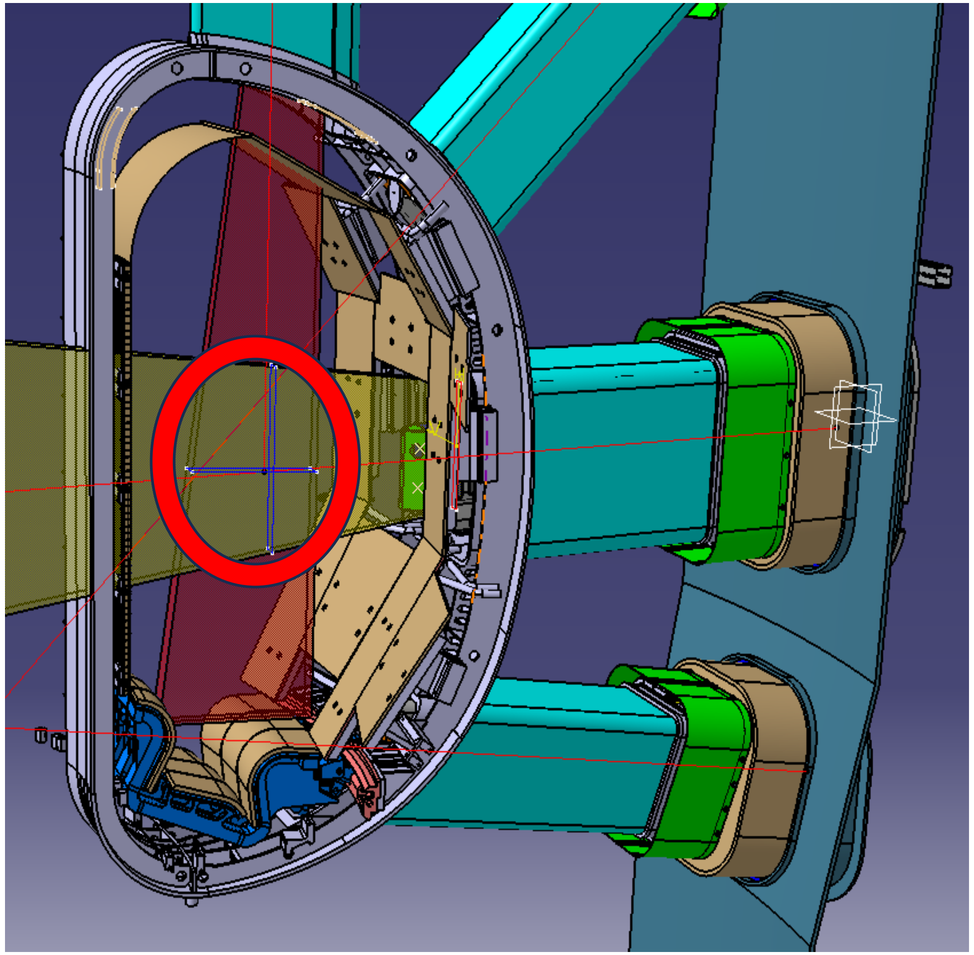


Tangential GEM detector (included in the shielding box) and the high resolution SDD spectrometer updated layout (DTT Sector 8 port 3).

Construction of an asymmetric GEM camera conceived to allow its positioning

The tangential camera provides access to different regions of the plasma (core and outer) but strongly spatially and spectrally integrated → Data deconvolution of the GEM tangential camera would be possible with the support of the tomography system.

PROPOSAL OF CORE SXR ENERGY RESOLVED ACTIVE X-RAY GEM TOMOGRAPHY



- SXR Tomography system was proposed as composed by two 1-D GEM cameras, oriented horizontally and vertically, each equipped with 128 lines of sight and **high spatial resolution** of 10 mm.
- **Energy resolution** (25 %), tuning on impurity emissions and continuum as well
- **unprecedented performances** due to the detection of each single photon with its energy and time of arrival, providing **high time resolution (μs)**

NO SUITABLE PORT FOR THIS TOMOGRAPHY HAS BEEN FOUND

Answers to Comments 1/2

- The angular aperture of tomographic cameras seems too small to provide any further information respect to the standard tomography
- <u>Answer</u>: **In our proposal the angular coverage was sufficient for performing the core tomography**

- The imaging system requires the other two cameras (not available in phase1) to provide useful information. Having different spectral range of CVD tomography, also this system cannot be used for the GEM data deconvolution, so it seems appropriate to **move it to phase 2** diagnostics.

  <u>Answer</u>: a tomographic reconstruction will be provided by the CVD diamond array which works in the 5.5-30 keV range and is therefore suitable for the deconvolution of the tangential GEM. In any case, given the absence of other X-ray diagnostics and its features such as high sensitivity, adjustable spatial (5-10 mm on plasma) and temporal resolution (sub-microsecond in macrozones), post-processing flexibility, a wide dynamic range, energy discrimination and immunity from noise , **we reaffirm its validity**.

- A system for the measurements of the SXR spectrum (as the SDD proposed) would provide more information that the tomographic and imaging system.

  <u>Answer</u>: SDD it is a slow, expensive and complex system suitable for working along a single line of sight. It has a limit of 500 kHz, in fact it features an active shutter and collimator. It is complementary with tangential imaging

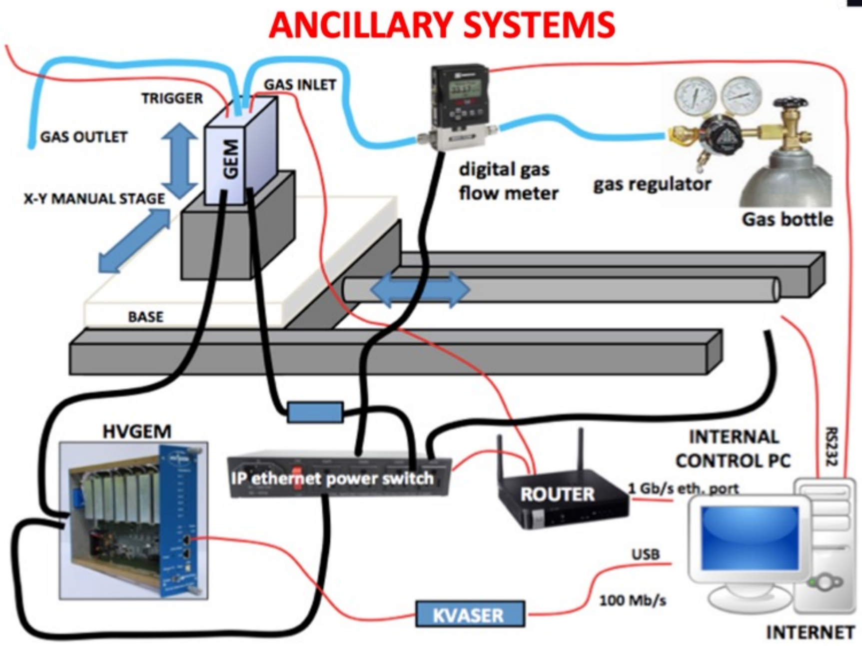
Answers to Comments 2/2

- Systems are neutron sensitive. No studies of the neutron shield have been presented for the phase1 diagnostics. Has it been evaluated (size and weight, supporting mechanics, cost,…) and integrated into CAD of DTT?

- **Answer:** Resistance of GEM detectors to high neutron flux has been proved and box dimensions, supports
- and costs were evaluated in DTT CAD drawings, without neutron shielding.

Costs & Resources

Imaging diagnostic components	Cost (k€)	Total (k€)
2D GEM detector	20	
1D GEM detector	15	
Box supports and movements	5	
Data acquisition system	15	
Gas system	5	
Window, pinhole	2	
SDD spectrometer with collimator and shutter	20	
Software development	8	
Calibration and tests	10	
		100



Tomography system components	Cost (k€)	Total (k€)
2D GEM detector	40	
Box supports and movements	10	
Data acquisition system	20	
Gas system	3	
Window, pinhole	2	
Spare Detector	10	
Software development	10	
Calibration and tests	10	
		105

Institution	Task	Estimated pm
ENEA	DXI-GEM	5
INFN	DXI-GEM	2
CNR-ISTP	DXI-GEM	1
UniMiB	DXI-GEM	1
ENEA	DXT-GEM	5
INFN	DXT-GEM	2
CNR-ISTP	DXT-GEM	1
UniMiB	DXT-GEM	1

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Tomography and Imaging

G. M. Apruzzese and team

Enea, CNR, RFX, INFN,

UniMiB, UniRoma2

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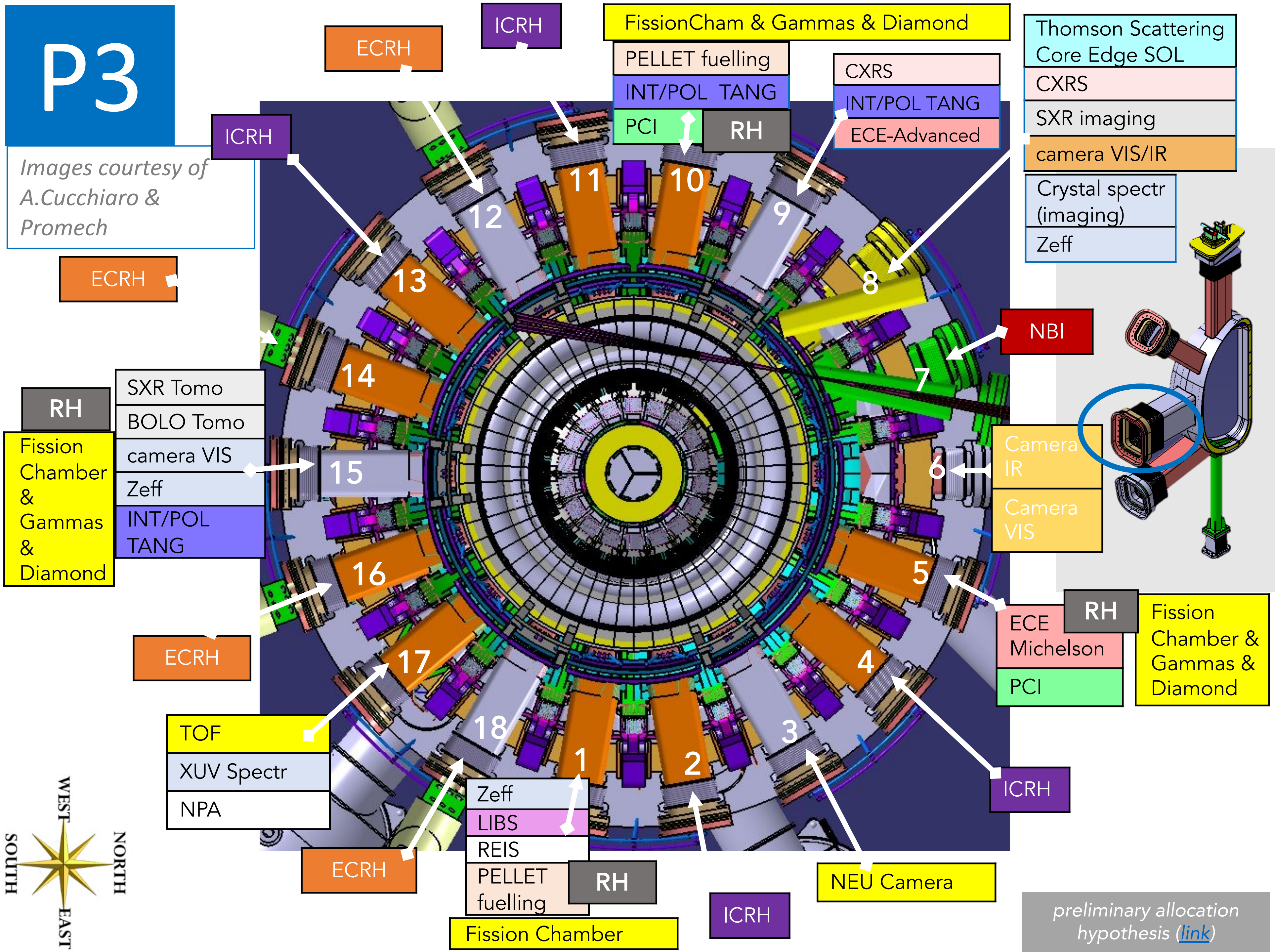
Thank you for attention

Spare Slides

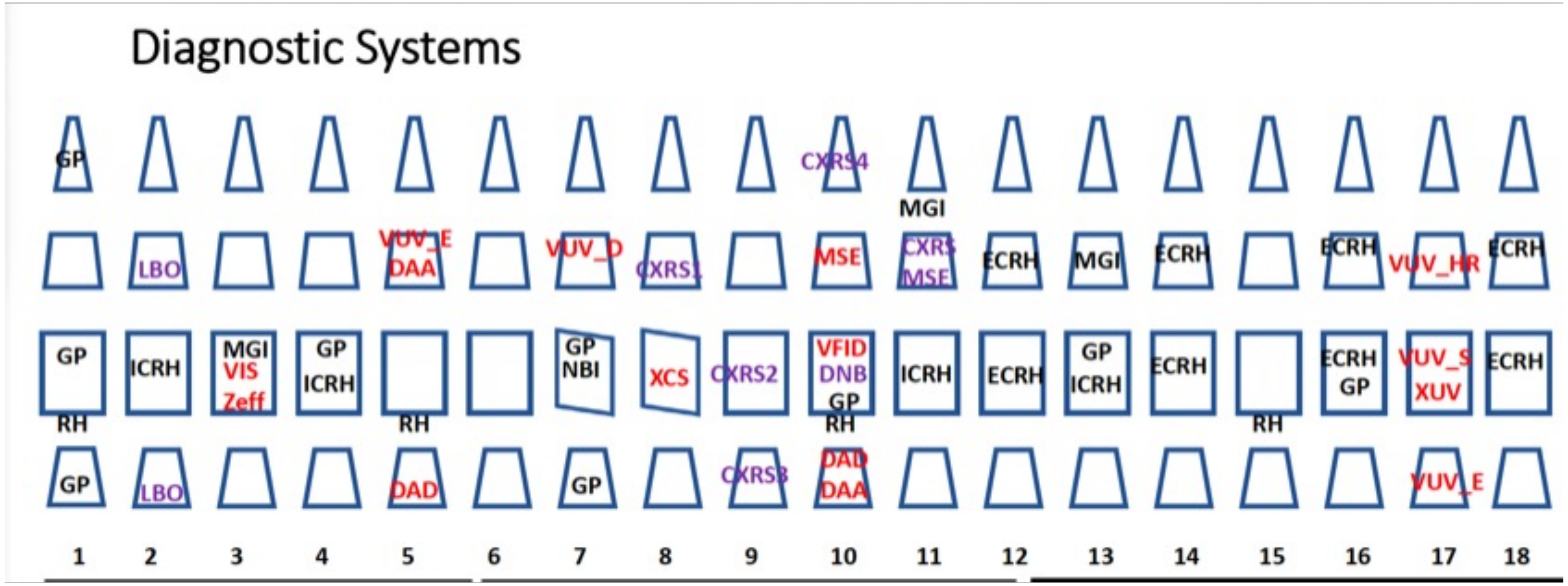
P3

Images courtesy of A.Cucchiaro & Promech



preliminary allocation hypothesis (link)

DTT Ports


Diagnostic Systems
GP
CXRS4
MGI
LBO
VUV_E
DAA
VUV_D
CXRS1
MSE
CXRS
MSE
ECRH
MGI
ECRH
ECRH
VUV_HR
ECRH
GP
ICRH
MGI
VIS
Zeff
GP
ICRH
GP
NBI
XCS
CXRS2
VFID
DNB
GP
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VUV_S
XUV
ECRH
RH
RH
RH
RH
GP
LBO
DAD
GP
CXRS3
DAD
DAA
VUV_E
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DBO - Bolometer Diagnostic

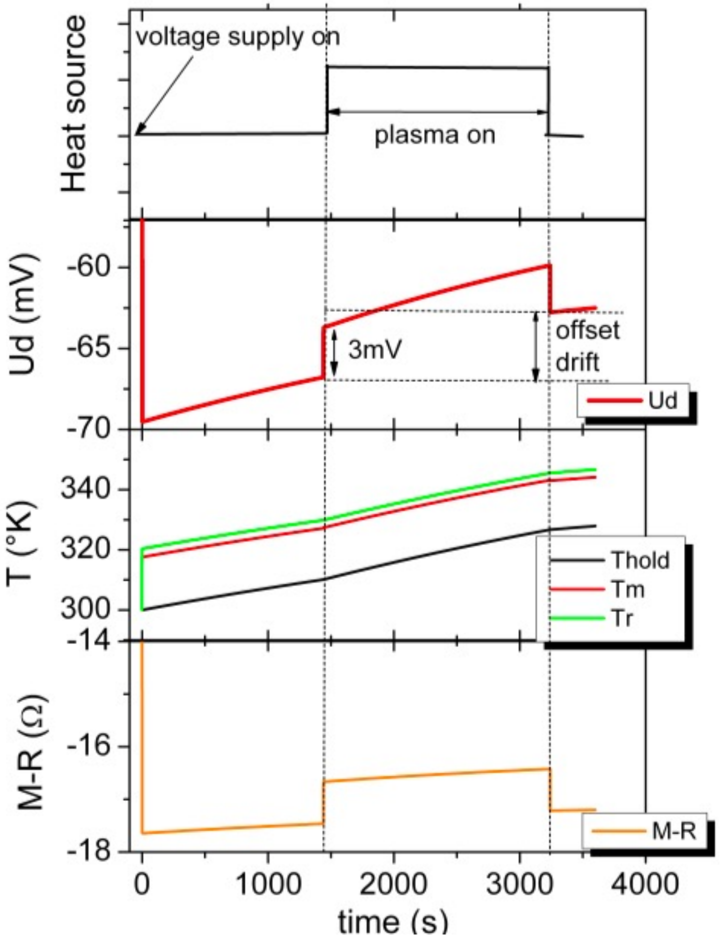
Equation for Tm,Tr and Tholder

$\eta = R_0/M_0$

$$U_{offset} = U_0 \frac{1+\alpha\Delta T_m - \eta(1+\alpha\Delta T_r)}{1+\alpha\Delta T_m + \eta(1+\alpha\Delta T_r)},$$

Thermal shift = 10^{-4} V/°C

η	1.02
β	$\eta\,(\tau_r/\tau_m)/(C_r/C_m)$
R_0	1200
α	0.0034 K^{-1}
U_0	10



Holder (heat sink) temperature change = Offset Drift = Thermal drift

$$U'_{offset} = \frac{2U_0\alpha^2(\Delta T_r - \Delta T_m)}{\eta + \eta^{-1} + 2\alpha(\Delta T_r + \Delta T_m + \Delta T_r\eta + \Delta T_m/\eta)}.$$

Long discharge (100 s) effects on the thermal shift

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$$U_{offset} = U_0 \frac{1+\alpha\Delta T_m - \eta(1+\alpha\Delta T_r)}{1+\alpha\Delta T_m + \eta(1+\alpha\Delta T_r)},$$

Thermal shift = 10^{-4} V/°C

Holder (heat sink) temperature change = Offset Drift = Thermal drift

$$U'_{offset} = \frac{2U_0\alpha^2(\Delta T_r - \Delta T_m)}{\eta+\eta^{-1}+2\alpha(\Delta T_r + \Delta T_m + \Delta T_r\eta + \Delta T_m/\eta)}.$$

η	R_0/M_o	1.02
β	$\eta\ (\tau_r/\tau_m)/(C_r/C_m)$	0.05
R_0		1200
α	0.0034 K^{-1}	
U_0		10
C_r	135 μJ/K	
U'_{offset}		120 μV/K

Long discharge (100 s) effect on the thermal shift