

# Removable samples for ITER – a feasibility and conceptual study

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## Abstract

The control of the radioactive inventory in the vacuum vessel of ITER is a main safety issue. Erosion of activated plasma-facing components (PFC) and co-deposition of tritiated dust on PFC and in areas below the divertor constitute the main sources of in-vessel radioactive inventory mobilisable in case of an accident and also during venting of the vessel. To trace the dust and tritium inventory in the machine, the use of collectors in form of removable samples was evaluated, beside other techniques, since it provides a reliable way to follow the history of the deposits and check critical areas.

Four types of removable probes and two optional active diagnostics were selected out of about 30 different options. For all four probes, a conceptual design was worked out and the feasibility was checked with preliminary estimations of thermal and electromagnetic loads, as well as remote handling (RH) paths. The highest temperature estimated for the front face of all probes lies in the range 300-500°C, which is tolerable. Installed in representative places, such removable samples may provide information about the dust and tritium distribution inside the vacuum vessel.

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NB Figures are left in the text for the convenience of the reviewers; they are all available with higher resolution.

## 1. Introduction

The control of the radioactive inventory in the vacuum vessel of ITER is a main safety issue. Erosion of activated plasma-facing components (PFC) and co-deposition of tritiated dust on those PFC and in areas below the divertor constitute the main sources of in-vessel radioactive inventory mobilisable in case of an accident and also during venting of the vessel. To trace the dust and tritium inventory in the machine, collectors in form of removable samples provide, beside other techniques, a reliable way to follow the history of the deposits and check critical areas, clearly in an averaged form over numerous discharges.

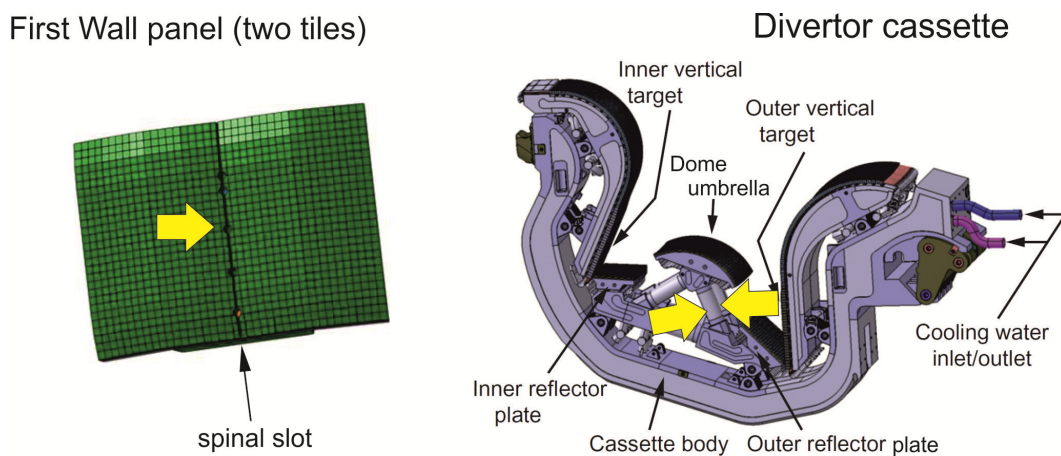
The present feasibility study intended to sort out a large number of possible options for a proper assessment of so-called removable samples that can be occasionally taken out of the torus or exchanged with remote handling. On the one side, the cost of such operations on the occasion of large maintenance shutdowns is obvious to the authors; on the other side, they cannot be avoided if the estimation of dust accumulation and of tritium inventory is to be refined by experimental undertaking. The removable samples come in addition to other methods which do not necessarily require operation of remote handling techniques and are nevertheless mentioned very shortly below. Deployment of a manipulator like the so-called MPD (Multi-Purpose Deployer) as presently known is a pre-requisite to the exchange of the probes selected in the frame of our investigation. Any other type of manipulator with similar performance is of course acceptable.

The selection of probe types was, to some extent, supported by modelling on the basis of given impinging particle fluxes and heat fluxes [1-3]. The accessibility with remote handling (RH) and the technical feasibility of the concepts played a major role in the screening. The surface temperature of the samples, for instance, may easily reach 300°C-600°C on the front face in spite of the proximity of active cooling lines. Many attractive items were dropped from the first list for reasons of necessary clearance in the course of installation. Others are still considered too demanding, as is the RH removal of actively cooled First Wall (FW) beryllium fingers to monitor the erosion and locally close deposition in the middle of the FW panels (esp. blanket modules of the inner wall). In such cases, the panels themselves were considered removable and the best samples that can be found, provided an adequate analysis of the deposition can be foreseen in the hot cells after removal.

## 2. Expected fluxes and loads

The expected fluxes for different plasma scenarios were summarised in several articles [4-6]. To make things simple, impinging particle fluxes (deuterium) of about  $1.25 \times 10^{23} \text{ s}^{-1}$  and  $0.15\text{-}1.0 \times 10^{25} \text{ m}^{-2}\text{s}^{-1}$  at the first wall and in the divertor, respectively, were assumed throughout this study as more precise variations of the fluxes with the plasma conditions were deemed insignificant for our purpose.

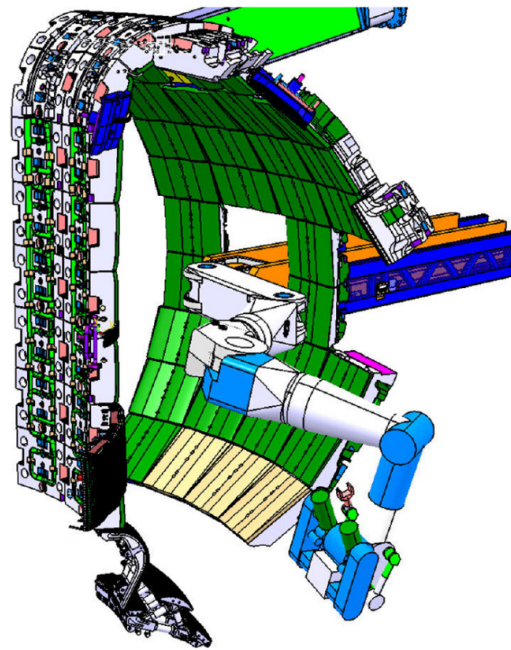
Similarly, heat fluxes in the order of  $0.4 \text{ MW/m}^2$  and  $0.3 \text{ MW/m}^2$  were taken as a valid ansatz for the envisaged positions respectively on the FW and in the divertor. These values account for the radiative loads and the bombardment by charge exchange neutrals at the considered locations both for the FW and divertor cases (see below). Note that an average flux of  $q=0.4 \text{ MW/m}^2$  is assumed for the slits and gaps within or between FW panels as a worst case scenario for radiative and CX-induced loads, sometimes embracing the local volume heating by neutrons for thin probes close to the last closed flux surface (LCFS). But on the panels themselves, loads of  $2.0 \text{ MW/m}^2$  to about  $4 \text{ MW/m}^2$  are expected, depending on the poloidal position. Those highly loaded positions were not considered for the installation of removable probes, as already mentioned. The divertor value of  $0.3 \text{ MW/m}^2$  was assumed for any position between the dome legs i.e., poloidally, between the dome umbrella and the reflector plates since the probes would be dominantly subjected to radiative loads and bombardment by neutrals. The [semi-] detached plasmas that are planned, if only for a sufficient reduction of the loads on targets, may be considered equivalent to a radiating tube close to the height of the dome as the origin of photonic loads. These are as defined in ref. [7]. The envisaged positions are summarised in Fig. 1.



**Fig. 1** FW panel and Divertor: the arrows point to considered locations

### 3. Accessibility with remote handling

From several manipulators that were considered, at least initially, the MPD (Multi-Purpose Deployer) is the sole selection for the present study. Absence of this manipulator or, of course, of a similar one would obviously render the concepts of removable samples useless. The current model of the MPD allowed a dynamic check of the accessibility of the foreseen divertor probes on the dome legs and between the dome legs. Other regions in the divertor were not considered with respect to an RH access. Moreover, the two arms of the front end effector can be configured in such a way that positioning and fixing is ensured. A picture from the study is presented in Fig. 2.

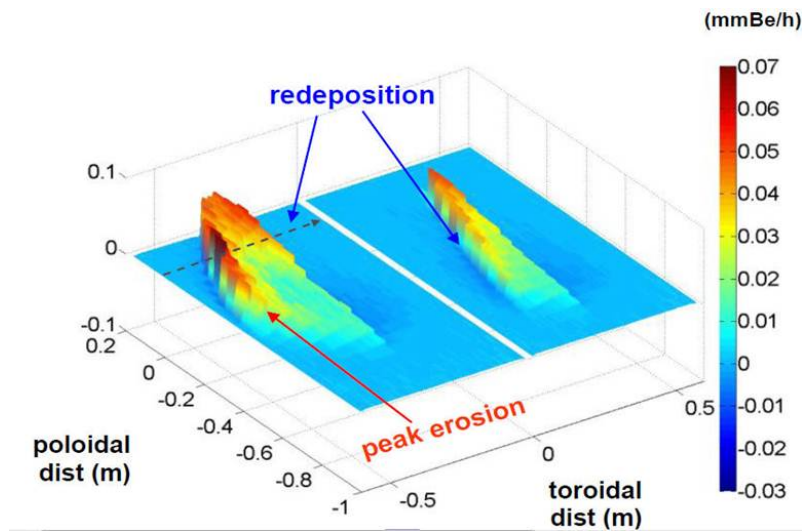


**Fig. 2** A model of the Multi-Purpose Deployer was used to check accessibility in the divertor region [8]

### 4. Modelling of erosion and deposition

It appears that even a tentative probe design is not only quite dependent on the hardware environment and constraints but also on the location where high erosion or deposition is expected. The physics studies, mainly analyses of the adequate probe locations, were reduced to a minimum as several data sets may already be available. Still, a sound re-estimation was of great help – especially in the case of the divertor.

As for the wall, known studies [9, 10] predict the main erosion zone close to the middle of any FW tile (Fig 3), hence it cannot really be captured by removable samples except if a limited section of one –actively cooled– beryllium finger is made removable. Remarkably, the highest deposition is very close to the eroded domain and is therefore located on the hardly accessible main part of the tile as well. It was deliberately decided to restrain from designing a removable section in a FW finger to avoid a large use of resources in the present frame and later in the development of FW panels: owing to the active cooling of the beryllium ‘fingers’, this position was considered too complex to provide a sensible removable probe concept. Quite the contrary, the narrow slit between the wings (tiles) in the spinal part of a FW element looks quite attractive as already shown in Fig. 1.



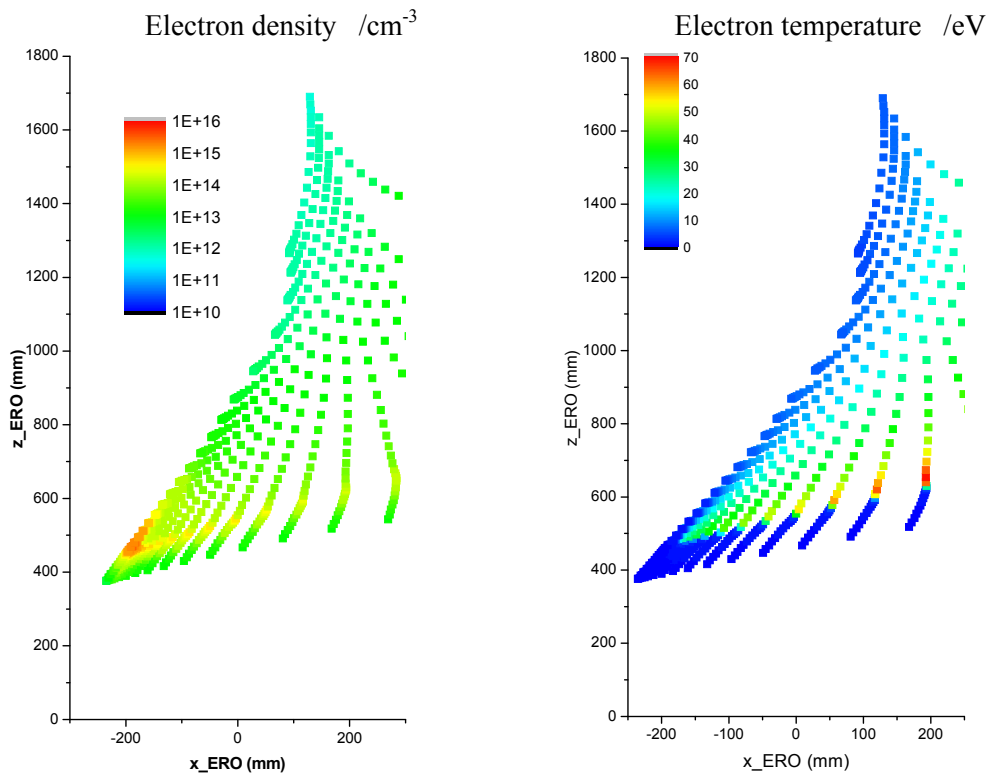
**Fig. 3** Typical erosion and deposition on a FW panel [9, 10].

The picture corresponds to the panel shown in Fig. 1.

In order to assess the adequacy of the probe positions in the divertor, first simulations of the expected erosion and deposition was performed with the ERO code [11]. They are based on an input by A. Kukushkin [12] of the plasma parameters for steady state operation conditions simulated with B2-EIRENE as shown in Fig. 4. The deuterium impinging flux calculated from electron temperature and density has a maximum in the strike point of  $\Gamma_D \sim 1.5 \times 10^{24} \text{ m}^{-2} \text{ s}^{-1}$ .

ERO simulations have been carried out for carbon targets applying physical sputtering and chemical erosion. The assumed physical sputtering yield for the release of carbon atoms from the target under bombardment by deuterium ions  $D^+$  (and 1% carbon impurities  $C^{2+}$ ) is

$Y_{D_{onC}} \sim 0.2\%$  ( $Y_{C_{onC}} \sim 0.6\%$ ) at target location, where the electron temperature has its maximum of about 7 eV – the sputtering yields become even smaller at other locations as the electron temperature and thus the ion impact energy is smaller. Chemical erosion is considered assuming the formation of methane ( $CD_4$ ) with an erosion yield according to the Roth formula [13]. The surface temperature profile has been calculated from the impact power flux, scaled to a maximum temperature in the strike point of about 550°C. This results in a chemical erosion yield of about 0.024% in the strike point and larger yields up to 1.2% within the scrape-off-layer. Reflection of atomic carbon on plasma-facing surfaces has been taken into account with

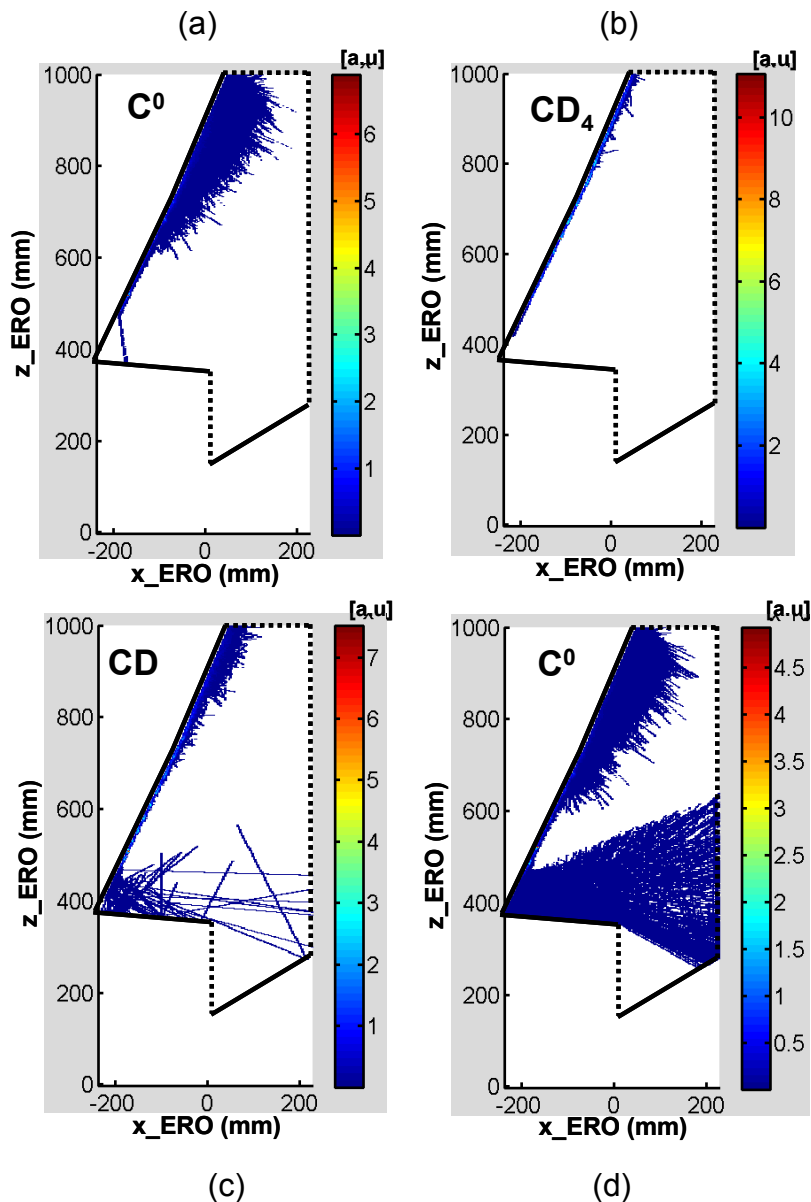


**Fig. 4** Density and temperature provided by IO for the ERO calculations

reflection coefficients  $R_C$  according to Molecular Dynamics (MD) simulations,  $R_C$  ranging between 0.2 and 0.5 for impact energies under consideration. For hydrocarbon species from chemical erosion, reflection coefficients of  $R_{ion}=0.1$  for charged and  $R_N=1$  for neutral species have been assumed.

In case of chemical erosion significant re-deposition outside the target plates occurs only at the “far end of the dome leg structure” with deposition rates about  $1 \cdot 10^{18}$  atoms/m<sup>2</sup>s. With a typical density for a-C:H layers of  $6.5 \cdot 10^{28}$  atoms/m<sup>3</sup> this results in a deposition rate of about

0.02 nm/s. For physical sputtering, deposition rates outside the target plates are much smaller, around  $10^7$  atoms/m<sup>2</sup>s – the resulting layer formation thus can be neglected. The simulations suggest that particles reaching the far end of the dome leg, leading to deposition, originate from locations at the lower end of the vertical target. Whereas in case of chemical erosion there is still a significant erosion flux at these locations, the electron temperature is too low there for physical sputtering. Figure 5 illustrates this phenomenon by means of simulated traces (2D densities, integrated in toroidal direction) of eroded particles.



**Fig. 5** Traces of eroded particles.  
 (a) Carbon atoms from physical sputtering, (b) Methane from chemical erosion,  
 (c) CD from chemical erosion and (d) Carbon atoms from chemical erosion.

For a tungsten based divertor, the layer formation from W sputtering in the inner divertor can most probably be neglected even if sputtering due to seeding impurities is considered. However, it can be expected that the inner divertor target (vertical plate) could be covered with a beryllium layer resulting from Be influx from the first wall, which can be further eroded. As for carbon, one most probably cannot expect significant net Be deposition at the divertor leg from physical sputtering. Nevertheless, chemical erosion via the formation of BeD molecules as observed in PISCES-B and MD calculations [14, 15] could lead to net deposition at the divertor leg similar to the case shown for the chemical erosion of carbon.

A consequence of these first estimations is that collecting samples, removable or not, may have to be located higher on the dome legs than initially intended for technical reasons, among others accessibility with RH. If at all, deposition could occur at these locations.

## 5. Results: selected probe concepts

### 5.1 At the First Wall

The only position selected on the first wall is the spinal gap between the tiles of a panel. A conceptual view of such a removable sample is shown in Fig. 6.

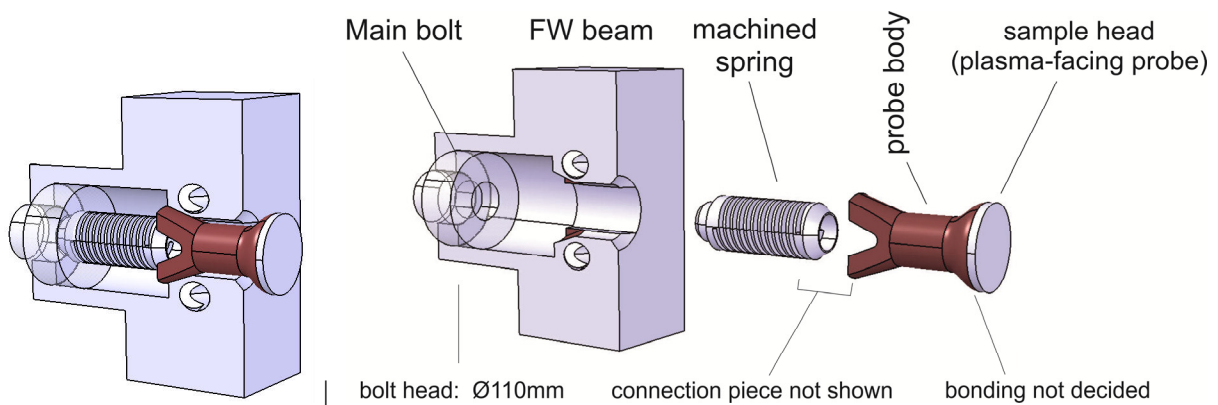


Fig. 6 Removable probe in position and exploded view of the assembly in front of the mounting hole

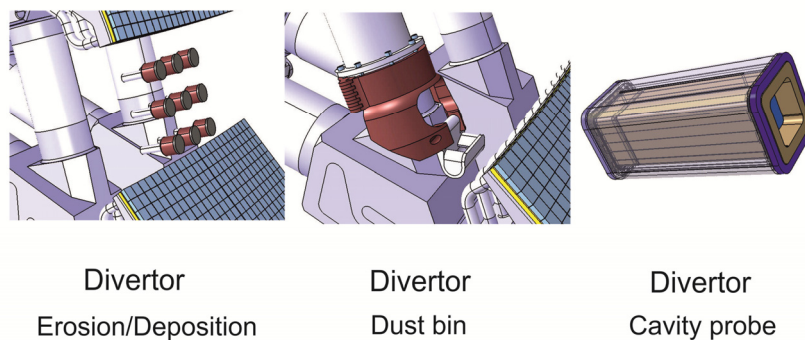
If installed in front of the main bolt, it even protects the bolt head from overheating by radiation and CX-neutrals. The collector disk in front can become quite hot. In order not to exceed a surface temperature of about 500°C and risk the corresponding desorption of the

collected material if any, the diameter of the disk ranges from Ø30 mm to an upper limit of about Ø80 mm and the probe should be installed close to cooling channels (section shown on the picture). Moreover, the body is made of a material with high heat conductivity, for instance a tungsten “alloy” and the machined spring must guarantee a force of  $F_{spring} \geq 2.5$  kN for a contact pressure to the massive supporting beam of  $p_{therm-contact} = 2-5$  MPa. The force is evidently limited by the allowable torsional stress and the minimal length  $l_{spring}$  is defined by the distance of the bolt head to the conical fin during installation, i.e. during rotation until the bayonet snaps into place. Note that we expect this kind of arrangement to be an erosion probe under the flux of CX-neutrals. It is recommended to install an array of probes in one or two sections of the torus to record the poloidal distribution in the highest possible number of blanket rows.

Other probe locations were rejected because they were hardly accessible while maintaining the required clearance to and between the closest wall elements, or because they would easily become too hot, that is reach the 500-600°C limit we have imposed. This is the case for positions between the upper FW rows 8-9 and close to the so-called Diagnostic First Wall (DFW) around the upper port plugs.

### 5.2 In the divertor region

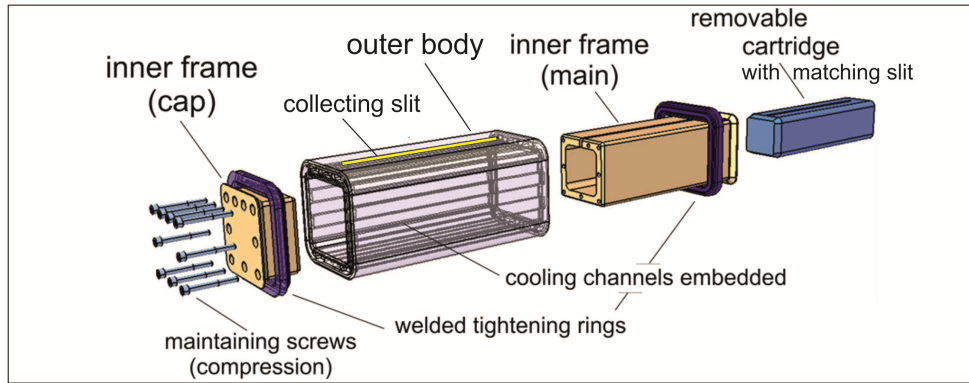
Three different types of samples were kept for the divertor region (Fig. 7): simple cylindrical erosion/deposition samples which can be installed as a matrix on a supporting frame (not shown), dust bins that can be installed on the dome legs after assembly by the integrator (IO) of the divertor cassette, and so-called cavity probes.



**Fig. 7** Various probe types, with different purposes, for the divertor region

A selection of properties of those concepts are

- for the cylindrical probes, the tensile pre-load in the bolt and its conservation under exposure to the high heat fluxes are the main parameters of the design (long threads and a high tightening torque in the order of 100 N.m for an Inconel alloy 718). If the contact is properly maintained, the heat transfer can be input to the thermal calculations. The highest temperature on the front face is estimated to  $T_{surf} \leq 310^\circ\text{C}$  under the present assumptions.
- the dust bin requires an active cooling too. As the diagnostics in a divertor cassette are close to the coolant outlet, the temperature is closer to the upper limit of about  $120^\circ\text{C}$  than to the inlet at  $70^\circ\text{C}$ . With a contact pressure of the clamping half-shells  $p_{ctc} = 2 \times F_{clamp} / (\pi \times d_F)$  of about 12 MPa, a front temperature below  $500^\circ\text{C}$  can be achieved if coolant flows through the hinge axis. An improvement with respect to the original design at  $\sim 3000^\circ\text{C}$  without active cooling other than the umbrella legs. All parts underwent a structural analysis.
- the third proposal, the cavity probe, would be inserted from the low field side (LFS) to collect dust and impurities from the inner divertor region. A similar positioning of probes could be dug out, namely for cavity probes in JET [y]. To monitor the deposited particles regularly in a two dimensional manner, a cooled housing needs to be designed in order to contain a removable part which provides the surface for deposition. A long slit is foreseen as the main feature in the housing to enable particles to enter the allocated volume. *Vis-à-vis* to the slit, a collecting surface where the particles can stick on is needed. We have decided for a flat collection area. During a shutdown the removable part should be exchanged by MPD or by a similar manipulator and investigated to get the amount and distribution of the sticking particles on the surface. Both the enclosure and the inner removable cartridge have a square cross section. Fixings to the dome legs or to the divertor cassette were not developed: they belong to a detailed design and have little influence on the properties and characteristics discussed below. Approximate dimensions are  $380 \times 160^2 \text{ mm}^3$ . Fig. 8 gives an exploded view where all parts can be seen.



**Fig. 8** Exploded view of the proposed cavity probe concept

### 5.3 Other concepts

Other concepts were considered less important or were not removable samples *stricto sensu*. While that is the reason for not having studied them in detail, they may become relevant at a later stage. It is the case for the following items, which are on top of the priority list of remaining developments:

- dust collectors in the form of bins located below the (9 mm) gap between reflectors and targets in the outer divertor leg. They could not be removed without high risks of damaging the target plates or other divertor elements but the collected material could be (i) analysed in the hot cells when the divertor cassette is taken out or (ii) evaporated with an installed heater and possibly detected with quadrupole mass spectrometry through a sensor in the nearby pump duct;
- membrane, “Baratron”-like dust detectors [17-18] usually suffer from the inhospitable tokamak environment if electronics is on board or from noise caught on long electric lines laid in-vessel. We suggest to couple such a membrane to a microwave guide with generator outside the torus, behind the port plug interspace if necessary;
- laser methods like laser-induced ablation spectroscopy (LIAS), desorption spectroscopy (LIDS) or, possible even better laser-induced breakdown (LIBS) which can be used between plasma pulses since the excitation of the released atoms and molecules by the tokamak plasma is not needed [19-20].

## 6. Summary and conclusions

A strong filtering has taken place to select, out of the initial ~30 proposed concepts, robust types of probes which are expected to imply a reasonable effort for development and chances of surviving the phase of detailing down to design reviews and manufacturing drawings. The probe intended for the first wall panels is now moving to the development phase. The removable samples for the divertor are under consideration for possible detailing.

A conceptual design was worked out for all of them and the feasibility was checked with preliminary estimations of thermal and electromagnetic loads, as well as RH paths. The highest temperature estimated for all probes lies in the range 300-500°C. Installed in representative places, the removable samples may provide information on the dust and tritium distribution inside the vacuum vessel and contribute to the control of their inventory.

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