# Electric Field Uniformity studies in the ESS LWU configuration for the NPM (ESS-0092070)Electric Field Uniformity studies in the ESS LWU configuration for the NPM

Cold NPM – Electric Field Uniformity

*CEA Saclay: CEA-ESS-DIA-RP-0019 v0.1*

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|---|---|---|
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| **Reviewer** | Cyrille Thomas | System Lead for the NPM system |
| **Approver** | | |

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# 1 INTRODUCTION

This report deals with the uniformity of the electric field for the Ionization Profile Monitors which will be installed in the cold part of the ESS accelerator.

## 1.1 Purpose

In this report, the electric field study done with Comsol software[1] for the IPM will be described. This later was done in the framework of the internship of Anna Vnuchenko started on March up to end of August 2016, defended at Orsay University on September 14th 2016.

## 1.2 Definitions, Acronyms and Abbreviations

| Short name | Definition |
|---|---|
| EF | Electric Field |
| FEM | Finite Element Method |
| IPM | Ionization Profile Monitor |
| LWU | Linac Warm Unit |
| NPM | Non-invasive Profile Monitor |
| wrt | with respect to |

# 2. PREREQUISITES

The uniformity of the electric inside an IPM is one of the main ingredients which contributes to the good reproducibility of the profile.

It as to be mentioned that the CDR of the vacuum chambers (LWU) design took place on June 21st 2016 at Lund freezing the geometry size of the LWU, 4 weeks earlier we had the kick-off meeting at Saclay for NPM (May 26th). During the Kick-off meeting, issues on the geometry of the LWU for the Cold Linac NPM has been raised and discussed. Proposal to modify the 5 chambers where NPMs will be installed has been transmitted to all parts. In spite of efforts, the committee of the CDR for the LWU rejected this proposal (see letter in annex). As a result, the raised issues, about the uniformity of the HV field and the potential limitation due to arcing, remain.

# 3. ELECTRIC FIELD STUDY

## 3.1 Why?

The uniformity of the EF is really important in an IPM since the ionization by-products (electrons or ions) drift under the EF influence from their beam interaction location to the

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[1] http://www.comsol.com/

read-out system. Thus, to get a good reproducibility of the profile, the drift paths followed by the particles have to be as parallel as possible wrt EF direction, otherwise the measured profile will be distorted.

Due to limited space available in the beam line, the design of beam profile measurement devices is developed without implementing magnetic field guidance. In order to mitigate the SC effect, the electric field applied on the IPM has to be as large as possible to minimize the impact of space charge. The shape of the vacuum chamber has to be taken into account since they are supposed to be grounded.

## 3.2 Geometry

IPMs have to be inserted in the cold part of the ESS accelerator, inside LWU (see Figure 1) which links two cryomodules. This Conceptual design drawing provided by ESS shows the different diagnostics: Beam Position Monitors (BPM), Wire scanner (WS), IPM, plus an optical system for a fluorescence profile monitor (FPM) on the vertical and horizontal viewports. The distance between two BPMs is 460 mm while the IPM vacuum chamber is 428 mm and 250 mm in diameter.

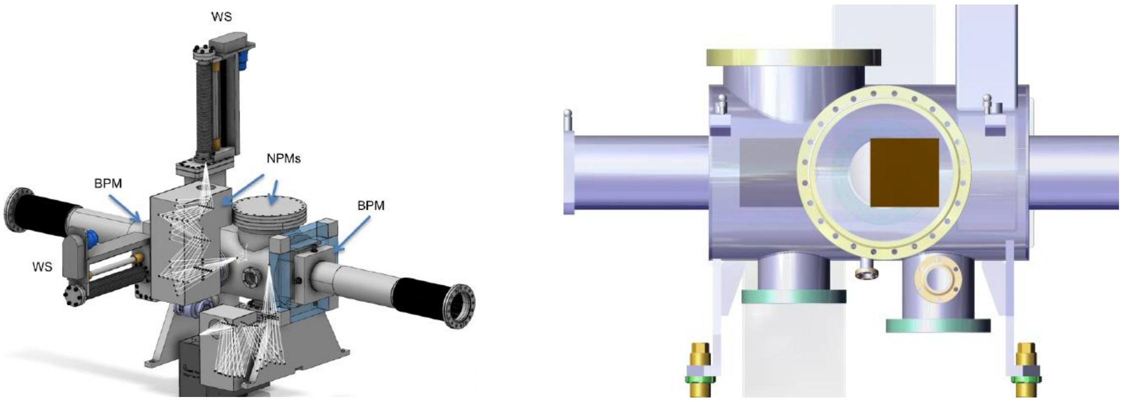

Figure 1: LWU without quadrupole (left) and detail showing the vacuum chamber devoted to the 2 IPM cages

## 3.3 Software

Comsol is the software used for studying the uniformity of the EF. IPMs field boxes were designed based on FEM simulations of the electric extraction field. This numerical technique finds approximate solutions to boundary value problems for partial differential equations. The designed model provides the best possible electric field uniformity considering the limiting factors of the available space. The geometry in which the electric potentials have to be computed is meshed. Then, FEM solvers generate a mesh that is optimized for each particular geometry shape. To each point of the mesh that are non-uniformly distributed, a potential value can be assigned. Then, results can be extracted and are analysed with the famous Cern software Root[2].

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[2] Root, https://root.cern.ch/

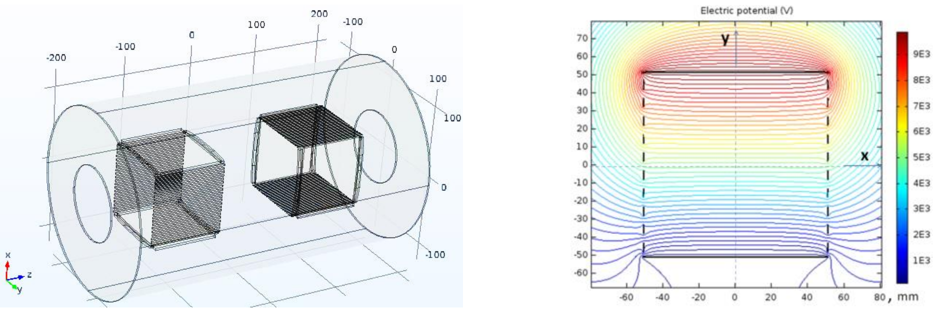

Figure 2: vacuum chamber with its 2 IPM (X & Y) cages geometry implemented in Comsol (left) and equipotential lines in 2D-model results (right) as examples of Comsol outputs.

The IPM geometry considered is the one presented on Figure 3. The aperture is 102×102 mm$^2$, a bit larger than the beam pipe dimeter (100 mm). The depth wrt the beam direction is 100 mm. It is made of 2 electrode plates (top and bottom), 20 degraders on each side in order to constrain the electric field equipotentials. The potential is uniformly decrease from HV applied on the HV electrode to a low voltage for the last one located near the grounded electrode.

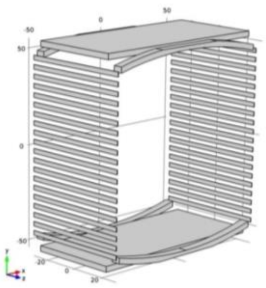

Figure 3: IPM cage.

Two pairs of curved electrodes are shown on top and bottom: their goals are to reinforce the field uniformity as it was done for LIPAc[3], but the simulation has demonstrated that they are useless in the ESS environment.

### 3.4 Electric Field Uniformity criterion

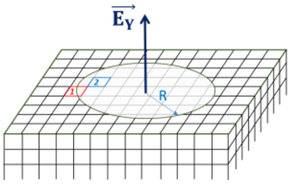

Figure 4: Comsol mesh

To quantify the uniformity of the EF, let assume a volume (Figure 4) divided in cubic cells in which a pure Y direction EF is applied $(\vec{E} = \overrightarrow{E_Y})$. The criterion is $\sigma = \frac{\sqrt{\sum_i^n \left(E_{X_i}\right)^2}}{n}$, calculated over the n cells of the volume by summing quadratically the X components of the EF. When the EF is perfect, all X components are null, and $\sigma = 0$.

Thus, the optimisation of the EF uniformity can be done by minimizing this criterion by changing parameters (position, size…).
In the next sections, $\sigma$ behaviour will be shown wrt the radius for instance. For low R values, the number of cells overlapping between inside and outside of the considered volume (like cell1 in Figure 4) are numerous compared to in-volume ones, generating fluctuations in $\sigma$ calculations.

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[3] Jan Egberts, IFMIF-LIPAc Beam Diagnostics: Profiling and Loss Monitoring System », PhD Thesis defended on September 25th 2012 (Orsay – CEA Saclay).

# 4. ELECTRIC FIELD UNIFORMITY RESULTS

All the following simulations are done with the IPM cage on which a large potential difference is applied, typically 30 to 60 kV over 10 cm. Moreover, when the IPM is located inside vacuum chamber, the wall of this chamber is set to V=0 V.

## 4.1 Uniformity inside the IPM cage

This study focusses on the EF uniformity inside the IPM cage, particularly on transversal planes wrt the beam direction. Uniformity was evaluated for transversal discs located along the z-axis. As expected, it is bad on the border but improved inside; quite good at z=±20 mm but for any reason getting worst between -12 to 12 mm. This is something that will be inquired for the design of the prototype, but uniformity remains below 1% in the interesting region (R<40 mm) where expected beam σ-radius is 3 mm.

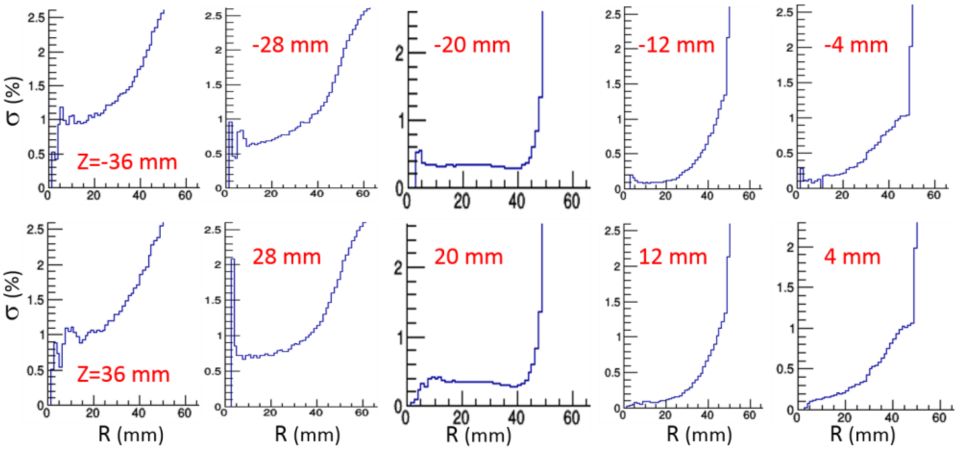

Figure 5: uniformity evolution along the z-axis.

Close to the sided degraders (R=50 mm), uniformity is completely bad as expected.

## 4.1 Length of the IPM cages

Since the dimension of the LWU vacuum chamber are already fixed, we have evaluated the possibility to decrease the depth (beam direction) of the cages. Vacuum chamber is shown on Figure 7 (or Figure 9 for more details) and the main dimensions are:

- length of vacuum chamber: 456 mm,
- radius of vacuum pipe: 100 mm,
- distance between cages: 90 mm,
- upstream wall chamber and 1st IPM: 126 mm,
- downstream 2nd IPM to exit wall is 40 mm.

Study was done with a cage of 60 mm depth and another one with 100 mm. The cage cross sections are the same for both of them, 102 × 102 mm$^2$. Cages were simulated with, and without, curved electrodes (see Figure 3) which are identify as “wires” on Figure 7 where results are presented. Simulation clearly shows that the longer the cages, the better the EF uniformity.

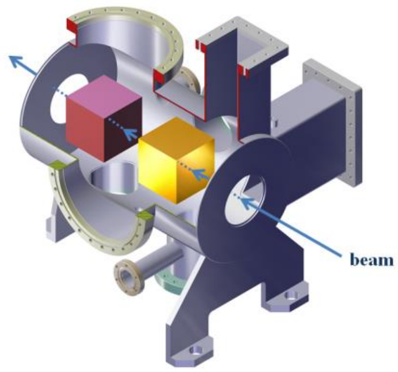

Figure 6: vacuum chamber with the 2 IPM cages.

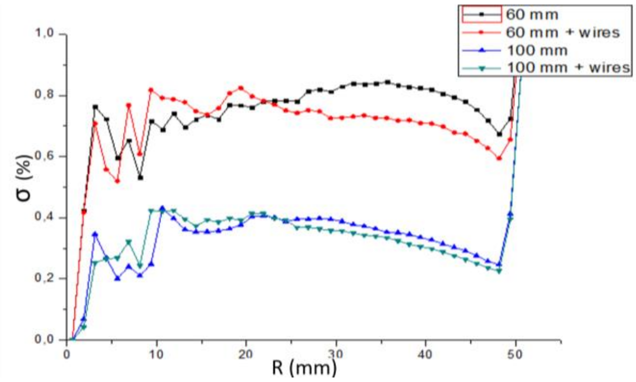

Figure 7: 60 and 100 mm IPM cages uniformity (in the legend, "wires" means curved electrode).

## 4.2 Interferences between the two IPM cages

We have simulated the insertion of an open conductive disc as shown on Figure 8. The aperture diameter is 10 cm and it is grounded as well as the entrance and exit wall of the chamber. In the centre is plotted the absolute uniformity (σ.$E_X$) for 30, 40 and 50 kV while the right picture shows that the relative uniformity (σ) is the same for all applied potentials. In both cases and for each HV, simulation was done with and without the central disc.

This later shows clearly that the central disc is useless since it degrades the EF uniformity.

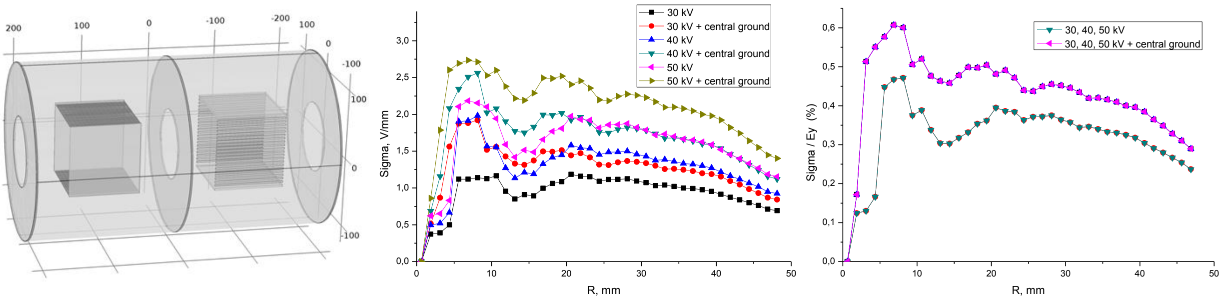

Figure 8: vacuum chamber with a disc separating the 2 IPMs (left), σ$E_X$ for 3 HVs applied on both IPMs (centre) and the normalized σ giving the same relative contribution for all HVs (right).

The right picture exhibit a scaling which is interesting since it guaranties a reasonable EF behaviour at high voltage, which should be very interesting to reduce the profile distortion due to the space effect but limited to sparks.

## 4.3 Electric Field uniformity inside the LWU Vacuum chamber

Finally the EF uniformity was studied for the 2 IPM cages inserted in the LWU Vacuum chamber. The vacuum chamber inner volume can be seen on Figure 9 with all dimensions, particularly the gap between the cages. On the right-hand side, there is a 126 mm gap for allowing the wire scanner insertion into the vacuum chamber. Both IPM cages have 100 mm depth for 102×102 $mm^2$ cross section. The gap between IPM cages is 90 mm to mitigate the EF interferences or/and influences of both IPMs. Only 40 mm remains between the exit window and the downstream IPM cage; such little gap may generate sparks leading to reduce the IPM HV.

Using this geometry, the EF uniformity was simulated and the result calculated over a 40 mm disc diameter is on shown on Figure 10. It appears that the uniformity can be about 0.5% for both cages. This calculation need to be improved in order to find an inner location in the centre of the cages.

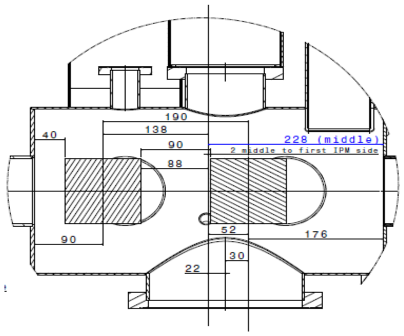

Figure 9: vacuum chamber inner volume, with the 2 IPM cages

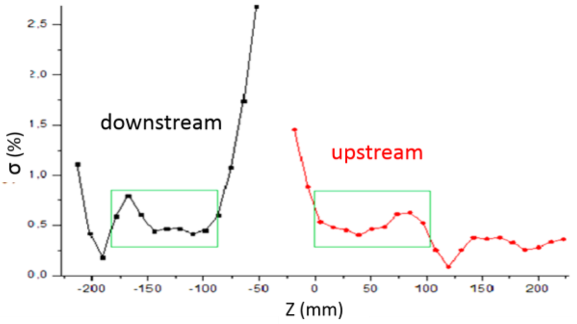

Figure 10: EF uniformity versus z-axis (beam direction) and the locations of both IPM cages (green rectangles).

The asymmetric behaviour can be due to the fact that the distance between IPM cages and vacuum chamber window set at 0 V is larger for upstream than for downstream cages.

## 5. FUTURE

In the development plan of the cold NPM, it is foreseen to design a test bench with few viewports for read-out comparisons. A preliminary design study is displayed on Figure 11. Mounted read-outs on the viewport will measure the "same" profile projection and will be compared. IPM vacuum chamber geometry will be duplicated on one test bench end to check that distances to wall or window chamber will be compliant to high HV!

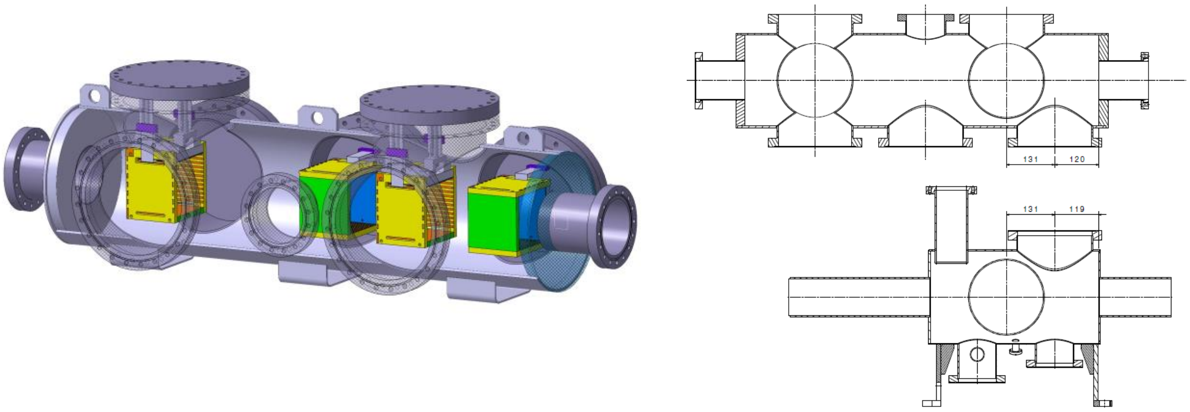

Figure 11: test bench with viewports on which different read-outs can be attached (left), test bench presenting at one end the same geometry as the IPM vacuum chamber (right).

In such a way, sparking, EF interferences and homogeneity, space charge effect, read-out signals, profile comparison… can be checked with redundancy.

## 6. CONCLUSION

The preliminary electric field uniformity gave us confidence in the ability for achieving results compliant to parallel electric field line. Indeed, uniformity in the interesting area of the IPM cages is better to 0.5%.

Nevertheless it is necessary to improve these results by changing the size and the position of the cages, the degrader numbers… before to design the bench test. Few tasks need to be addressed as:

- EF uniformity (σ) oscillations in the center part of the IPM,
- Understand the EF uniformity versus the depth of the IPM cages
- How to improve σ inside IPM cages when they are inserted in the vacuum chamber?
- Optimization of the IPM cage locations inside the constraint vacuum chamber without degrading the EF uniformity?
- Etc.

The EF uniformity must be fixed and understood for the bench test design, in order to tackle other difficult topics like space effects, read-outs…

# ANNEX

Hereunder is the letter emailed to Tom Shea and Cyrille Thomas, about our request for moving one viewport of the LWU devoted to IPM implantation.

Saclay, June 7th 2016

## Vacuum chamber interface with Ionization Profile Monitor (IPM)

IPM group of CEA Saclay

The vacuum chambers, which are supposed to integrate our IPMs on the cold linac part of ESS, is about to freeze the design, since its Critical Design Review is scheduled for mid-June 2016. Therefore, we would like to withdraw attention on this design, which should not fit the insertion of our IPMs (up to now, it may concern only 5 of these chambers).

We are sorry for this really late letter but the kick-off meeting of the In Kind agreement for IPM, part of the Non invasive Profile Monitor (NPM) took place at Saclay last month, May 26th 2016. Therefore, we would like to warn for preventing our project against space availability risks.

The Preliminary Design Review (PDR) of IPM is foreseen in March 2017, with a Go no Go gate since this technics is quite challenging for this ESS beam line part. Challenges for our subject are related to Space Charge effect (SC), which will have an impact on the measured profiles since electric field distort the drift pass of ionized by-product resulting in an artificially profile enlargement. In order to counteract or mitigate this effect, high electric fields must be applied in the IPM boxes (horizontal & vertical, see figures). To summarize, electric field uniformity is of the upmost importance.

Unfortunately, we have just begun the study and can’t provide numbers and design, but the recipe to achieve such a goal is to have a large depth box (between 60 to 100 mm wrt beam direction) and to have large free space between boxes for avoiding electric field interferences between their components!

Figure 1 represents the vacuum chamber foreseen for IPMs. On figure 2 is sketched the vacuum chamber as it is design up to now (without downstream and upstream flanges, plus holes for very HV and signal feedthroughs), where we have inserted the 2 IPM boxes. It is clearly seen that the horizontal viewport is not enough shifted toward upstream for the IPM read-out. That should be even worse if we choose an optical option.

On figure 3, it is a configuration of the IPM boxes with the horizontal viewport upstream shifted as much as we can, but leaving free space for the grid monitor insertion. Seems to be ok at first sight for a read-out system, at least manageable even if it should not be very easy.

A mitigated solution should be to leave 5 such vacuum chambers ready to be modified following the NPM PDR conclusions.

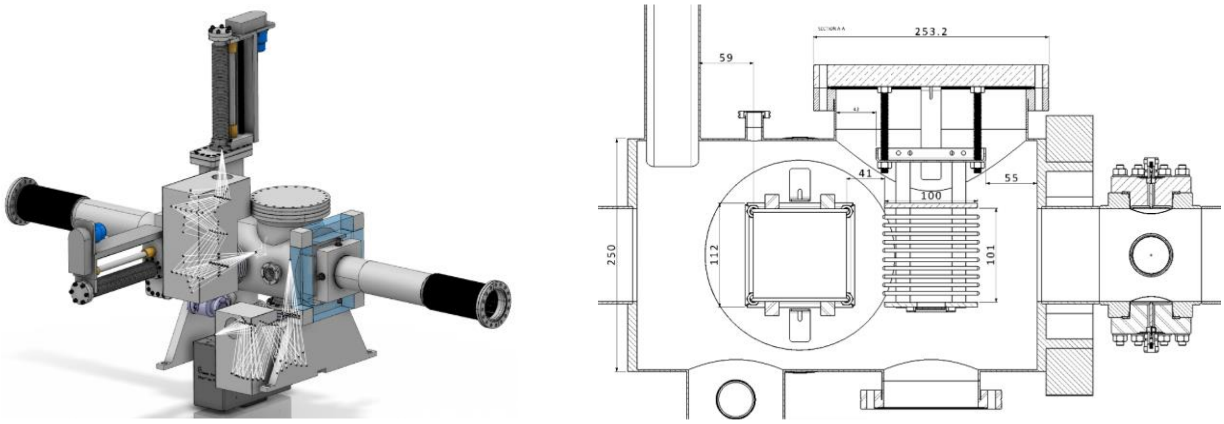

Figure 1: foreseen vacuum chamber (ESS)

See Figures 2 and 3 on next page.

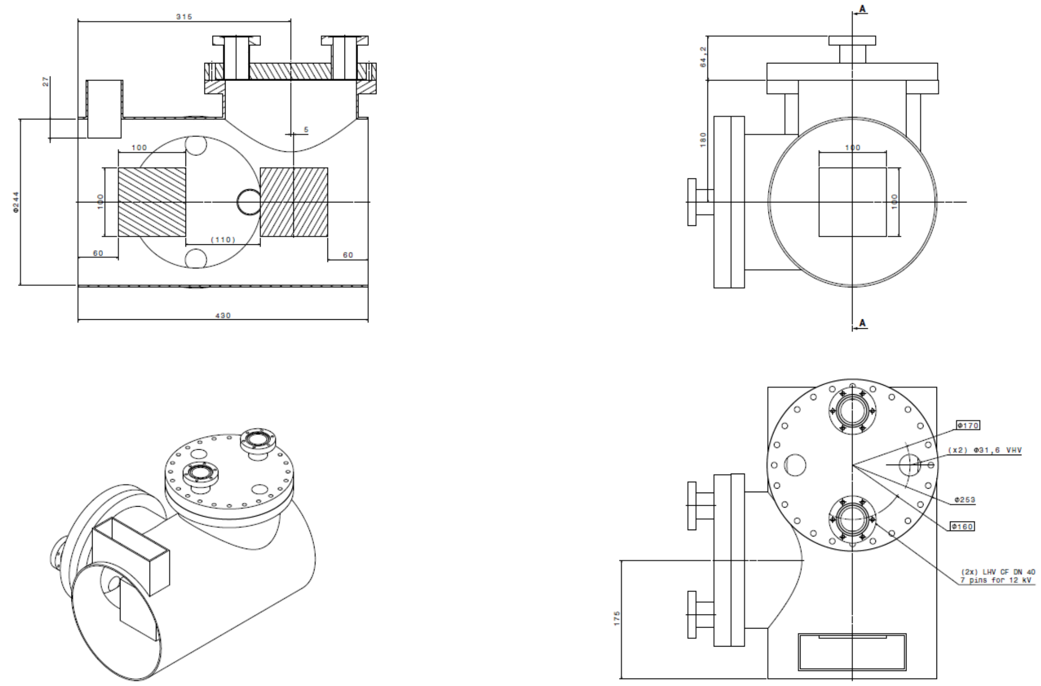

Figure 2: IPM boxes inserted in the vacuum chamber as it is foreseen. It clearly appears that the read-out of the upstream box is far from its axis.

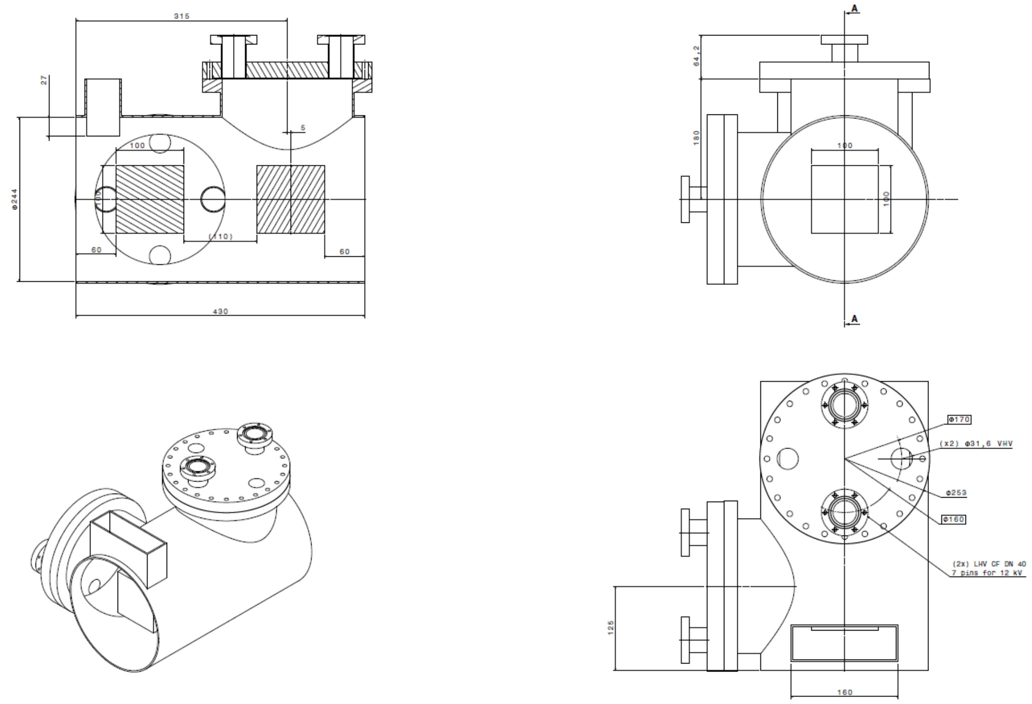

Figure 3: the upstream IPM box can be now in a location allowing read-out system