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Read-Out systems for cold NPM (ESS-0092072)

Cold NPM – Read-Out systems for IPM

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1. INTRODUCTION

This report deals with the different Read-Out systems foreseen for the IPM that will be installed in the cold part of the ESS accelerator. These ROs have been down-selected so that they all fulfil the requirements and the measurement of profile and beam size to be provided, but also consideration of reliability, availability and maintenance are taken into account. Several RO are still to be selected since they all appear to satisfy the required performance criteria. As a consequence, it has been decided to build prototype of three of the down-selected ROs, and run a test and measurement campaign comparing them on the same bench and the measurement of the proton beam profile they report.

1.1 Purpose

In this report, we will review different Read-Out systems, which should be adapted to the signal provided by the ionization by-product of the gas-proton beam interaction in the HV cage. These systems will then be prototyped and installed on a bench test in order to check their ability to provide transverse beam profiles as requested. This test is a key in the finalisation of the detail design of the NPM for the Cold Linac. It will be decided at this stage, which RO will be used for the Cold Linac NPM.

1.2 Definitions, Acronyms and Abbreviations

Short name	Definition
BEE	Back-End Electronics
EF	Electric Field
FEE	Front End Electronics
FPM	Fluorescence Profile Monitor
IPM	Ionization Profile Monitor
LWU	Linac Warm Unit
MCP	Micro-Channel Plate
NPM	Non-invasive Profile Monitor
RO	Read-Out
SC	Space Charge
ToA	Time of Arrival
ToT	Time of Threshold
w.r.t	with respect to

2. PREREQUISITES

As already mentioned, 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 NPM kick-off meeting at Saclay (see Electric Field Uniformity report, for detailed information). This put an additional constraint to the design and eventually to the performance of the Cold Linac NPM.

There are 2 types of foreseen RO systems: either electronics or optics. Since there will be no flexibility on the viewport positions, the location of the IPMs is really dependent of the shapes and dimensions of the RO system.

3. IONIZATION SIGNAL

The estimates of e/ion pair production is reported on "Calculation of electron/ion pairs production", therefore here we have quoted on Table **1** the calculated the expected e/ions per pulse and per cm of active RO length and the ionization current which have of the most relevance for RO system choices. The gas mixture provided by ESS is H_2 (79%), CO (10%), CO_2 (10%) and N_2 (1%).

With the number of events to be detected in the range 10^4 to 10^5, it is clear that the RO has to be sensitive to single events.

Table 1: e/ion pair production per pulse and per cm of sensitive RO length for the ESS residual gas.

Energy (MeV)	Ions/Electrons per pulse	Charge/pulse (fC)	Current (pA)	Remark
90	105986	17	5.9	Spk
200	60159	9.6	3.4	MB
500	36622	5.9	2.0	end MB
1000	29463	4.7	1.7	mid HB
2000	27224	4.4	1.5	end HB

4. IONS VS ELECTRON DETECTION

Prior describing the foreseen RO systems, we would like to discuss about the detection of the ionization by-products, i.e. electrons or ions that presents specificities interesting to be emphasized.

4.1 Secondary electron emission

The impact of ions on electrodes may generate secondary electrons, which are accelerated at twice energy w.r.t electrons produced by ionization processes. Such undesired secondary electrons will be then detected efficiently by any RO types if the IPM is in electron mode working (Figure 1, right). When the IPM is switched to ion mode working (Figure 1, left), electrons will be generated by ions. These undesirable electrons will escape drifting w.r.t the electric field direction. They may induce signal for direct ROs (strips…) but they do not contribute to signal for RO based on MCP or Silicon detector. For strips, a Frisch grid may prevent against this contribution. Considering this effect, ion detection may be preferable.

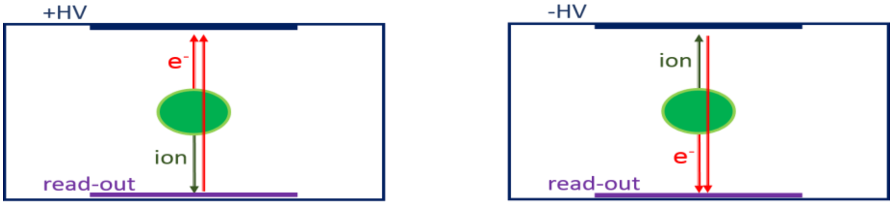

Figure 1: IPM in mode "ion detection" (left) and mode "electron detection" (right).

4.2 Beam particles energy transfer to ionization by-products

In the report "Space Charge based model of an IPM - ESS-0092068", the energy distribution transferred by the beam of protons to the electrons escaping from the residual gas molecules, follows the distribution depicted in Figure 2. The exponential shapes are calculated for the residual gas encountered in ESS beam pipe, but at various pressures. A factor 100 is shown for electron energy going from 0 to 50 eV. If we consider the residual gas molecules at rest (the most probable energy is 12.4 meV at 15°C) and if we neglect the binding energy, therefore the momentum conservation between the electron and the ion applies like $\overrightarrow{\mathrm{P_{ion}}} = -\overrightarrow{\mathrm{P_{electron}}}$. The kinetic energy obeys to $\mathrm{K_{electron}/K_{ion} = M_{ion}/M_{electron}}$, where $\mathrm{M_{ion}/M_{electon}} = 3671$ for $\mathrm{H_2^+}$ ions. For instance, when an electron is emitted with a kinetic energy of 10 eV, the $\mathrm{H_2^+}$ ion one is only 2.7 meV.

Such considerations may explain a larger beam profile spread when measured with electrons than ions as noticed in[1] and mentioned by a Ganil IPM specialist[2]. We have also seen similar behavior during a profile beam test with an IPM done at GSI in 2010[3].

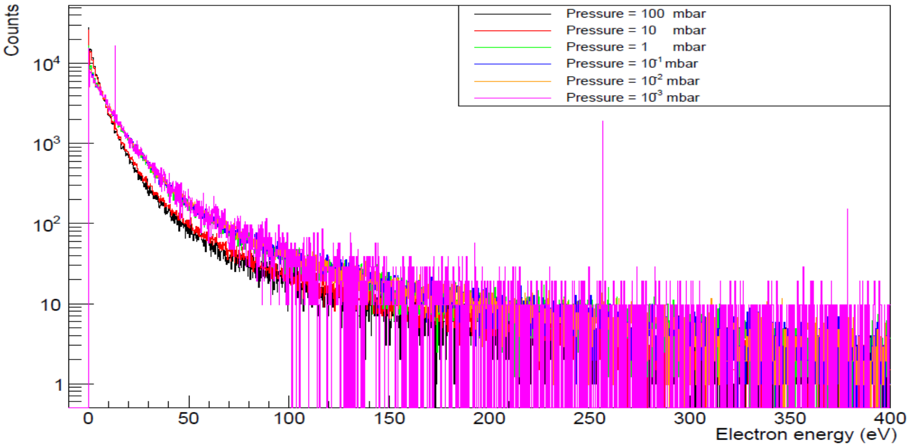

Figure 2: transferred 2 GeV proton to electrons coming from residual gas ionization molecules.

4.1 Space Charge effect

Referring once again to Space Charge report, the study shows clearly that the effect is much less pronounced for ions than for electrons. Moreover, the profile shape may often be

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[1] G. Cuttone et al., "LOW INTENSITY BEAM DIAGNOSTICS WITH MICROCHANNEL PLATE DETECTORS", PAC 1997.

[2] Jean-Luc Vignet, private discussion, 2011.

[3] J. Marroncle et al., Workshop on "Non-Invasive beam Size Measurement for High Brightness Proton and Heavy Ion accelerators", Cern April 15-18 2010, https://indico.cern.ch/event/229959/timetable/#20130415

distorted for electrons, which should avoid any possibility to a software correction. However for ions, SC affects the profile by an enlargement, which should be negligible for beam size larger than 3 mm.

To conclude this paragraph, working with ions would be preferable considering these three reasons. Yet, for the IPM, the level of the signal provided by ions has to be checked for each of the selected ROs.

5. READ-OUT SYSTEM FOR IPM

In this section, four RO systems possibilities are described. We plan to test all of them with beam on a same test bench in order to compare their performances.

5.1 TimePix3

5.1.1 TimePix3 chip

TimePix3 is a Hybrid pixel detector, which consists of a pixelated silicon sensor bonded to a pixelated RO chip. By removing the surface deposit, it has been shown that the pixel detector may be sensitive to electrons of 3.6 eV. This detector was developed at Cern in the framework of the Medipix Collaboration R&D program. The silicon matrix is made of 256×256 pixels of 55 μm^2 size each, mounted on a chip of 14×14 mm^2.

TimePix3 can operate in 3 measuring modes:

- Time of Arrival (ToA) and Time over Threshold (ToT): The time of arrival of a particle is measured with a 1.56 ns precision. The Time of Threshold is also recorded, ToT is related to the particle energy.
- Only ToA: Same as above except that ToT counting is skipped.
- Event count & ToT: In this mode, TimePix3 measures the ToT and the amount of particles which hit a pixel.

These measuring modes operate without dead time if hit rate is below 70MHits/s/chip.

TimePix3 transfers the data through 1 up to 8 serial links at 640 MHz max (5.12 GB/s Band-Width max). This can be done with 2 different ways:

- Data driven mode: TimePix3 send data only for pixels where hits are detected.
- Frame based mode: TimePix3 are also able to send entire column of pixels. The maximum framerate is about 1300 fps for the full matrix (at the maximum of BW).

5.1.2 TimePix3 used as NPM readout for CERN PS

The development and the use of TimePix3 for a non-intrusive profile monitor is in progress at Cern[4]. They have designed a RO system using 4 TimePix3 chips set aside and transversely

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[4] D. Bodart et al., « Development of an IPM based on a pixel detector for the Cern Proton Synchrotron », IBIC 2015, Melbourne, Australia.

to the beam direction. A similar RO is high radiation tolerant since it was still working above 4.6 MGy.

We have met this Cern's team in October 2016, and we have decided to collaborate in order to implement this tricky RO system on our IPM. We have checked that bonding should be made at Saclay but specific tools need to be developed to do it in a clean manner to cope with a 10^{-9} mbar vacuum requirements.

5.1.3 TimePix3 for ESS NPM

To evaluate the implementation of such a RO, we have to adapt the IPM cage design to fit with ESS vacuum chamber. A liquid cooling system has to be considered for the BEE since heat can only be extracted by radiation in vacuum.

Also CERN Team uses CERN devices to drive and acquire TimePix3 which may not fit the ESS device interface requirements therefore it must be investigated (ESS, CEA). For test bench another possibility is to use a much simpler solution, which is commercially available: FitPix. However, with this solution, the test will be limited to one or two TimePix3. If tests are successful then we will develop a custom FEE.

To summarize, NPM based on TimePix3 will be highly sensitive, fast and reliable solution. However, it raises many technological challenges as seen above.

5.2 Conductive strips

5.2.1 General considerations

As quoted on Table **1**, the ionization current expected at the RO location vary between 1 to 6 pA. In order to measure accurately the beam profile, we can propose to use an insulated plate on to which 32 conductive strips will be printed (with narrower strip in the centre). Since ESS facility should have a high reliability, we propose to measure the independent strip currents by integrating numerous pulses. That should be done with specific electronic boards based on transimpedance chips devoted to low current measurements, consisting in:

1) integrating current + noise along the beam pulse duration on a 1st integrator channel,
2) integrating noise between 2 pulses (68.6 ms) on a 2nd integrator channel

then, subtract the later (noise) to the former (signal + noise).

ADCs should have to be integrated on the Front-End Electronics really close to the IPM to transport the digitized signal toward the control system. Dose rates have to be inquired in order to define a compliant radiation location (close to the ground for instance…).

This solution needs to be inquired since IPM with conductive strips is a robust system, with no peculiar long term expected degradation for material inside vacuum chamber. Therefore, this later is a good candidate when reliability and maintenance minimisation are relevant parameters in a User facility like ESS.

5.2.2 Preliminary hardware study

We have identified an electronic board[5], which is able to measure very small currents. Moreover, in our case we have to measure very low charge too. Considering only 32 strips (2 cm long) with different widths optimized for a σ_{beam} = 3 mm at 2 GeV, imposes to measure about 0.25 fC.
We have already initiated few tests in order to handle this electronic board for further use (see next section).
We have tested this board by injected very low currents through a reference potential V_{ref} = 0.1 V attenuated by 50 dB and a resistor of 10 MΩ integrated over Δt = 2.6 ms.
Therefore, we get the following formulae giving the injected charge w.r.t the applied current:
$Q = \frac{V_{ref}\,\Delta t}{10^{50/10}\,R}$, meaning for instance Q=82.2 fC for a 31.6 pA injected current.
On Figure 3 are plotted the DDC264[6] board response where we observe a good linearity down to 50 fC. Below the noise will dominate meaning that such a measure can't be done with this board.

With this card, we can measure both positive and negative signals. In particular for measuring negative currents, a constant bias positive current is injected into all analogic DDC's inputs.

For this purpose, we foresee to investigate the Caramel board[7] developed at LPC Caen[8]. The card consists in 32 channels, each of them is a current-input analogic to digital converter (2 x DDC316), inserted in the VITA57 format board. Caramel card can be associated with the SYROCO-AMC[9] modular digital acquisition system in the µTCA system.

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[5] DDC264-64 channels, from Texas Instrument company, http://www.ti.com/lit/ds/symlink/ddc264.pdf
[6] **DDC316:** DDC316-16 channels, from Texas Instrument company, http://www.ti.com/lit/ds/sbas370a/sbas370a.pdf
[7] CARAMEL: http://faster.in2p3.fr/
[8] LPC Caen: http://caeinfo.in2p3.fr/
[9] SYROCO_AMC: http://faster.in2p3.fr/index.php/introduction/hardware/mother-boards/20-syroco-amc

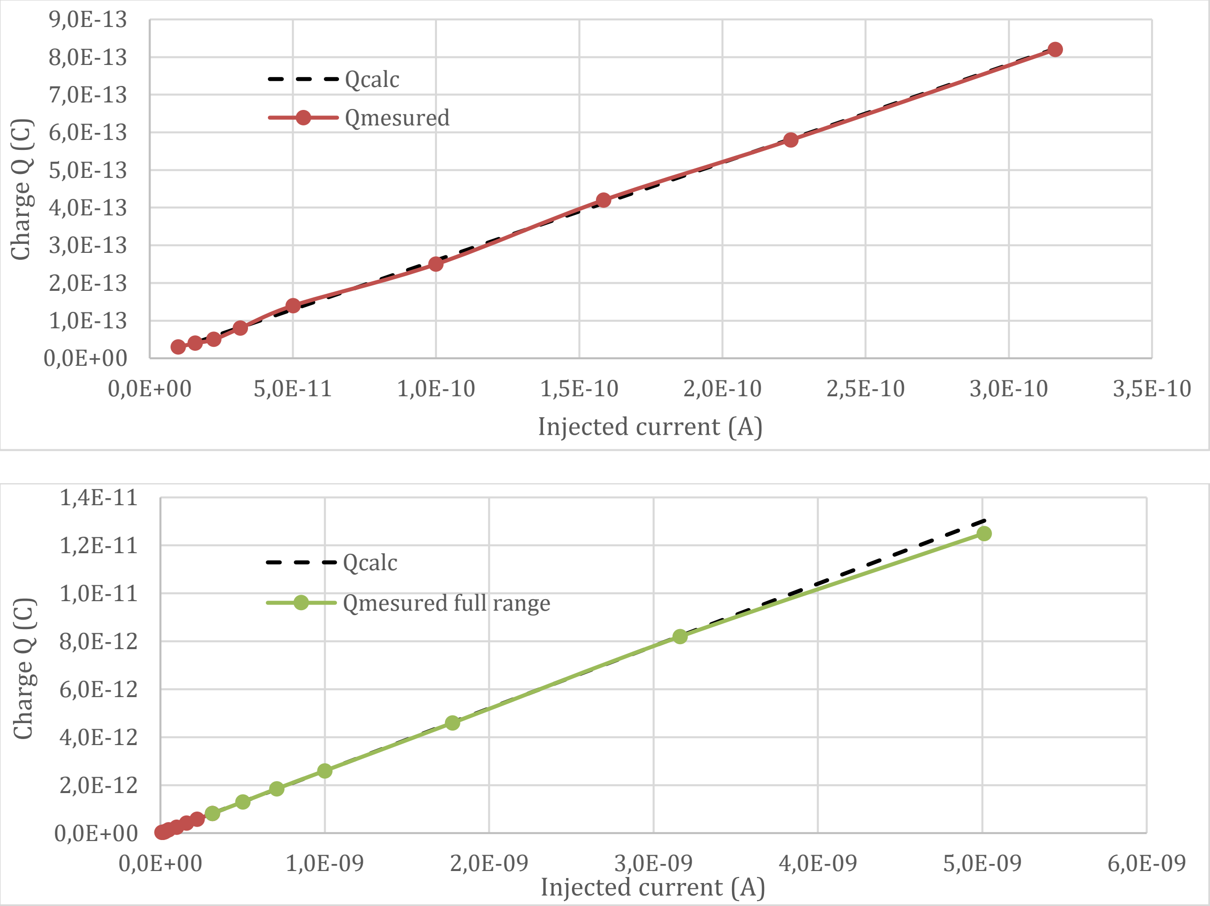

Figure 3: Measured and calculated charge with DDC264 versus injected current integrated over 2.6 ms. Top picture shows the low charge current (30 to 820 fC) while the bottom one concerns the whole measurement where saturation appeared for the upper point.

5.3 MCP + conductive strips

A MCP with chevron layers can be set upstream to the RO for amplifying the ionization current (Figure 4). Due to their high gain, MCP may generate a high amount of electrons and greatly increasing signals for each conductive strip set on an insulated plate, as the one depicted in the previous paragraph. Gain of a double stacked MCP is about 10^5 to 10^7. With a MCP quoted with MGO, IPM may be used to detect ions with a negligible contribution of secondary electron production (see paragraph 4.1), avoiding Frisch grid screening. However, An MCP is undergoes through ageing degradation, which is proportional to the total charge it delivers. A typical number shows the effective MCP gain to drop by a few percent for a total charge of 0.1C/cm^2. Therefore a calibration system is foreseen, for monitoring its efficiency, compensate for the gain and manage maintenance periods.

As discussed above strip read-outs might be done by DDC264 with a MCP gain of about 500, and enabling single event detection. Such a low gain may insure a longer MCP lifetime, increasing the reliability and the availability of the system.

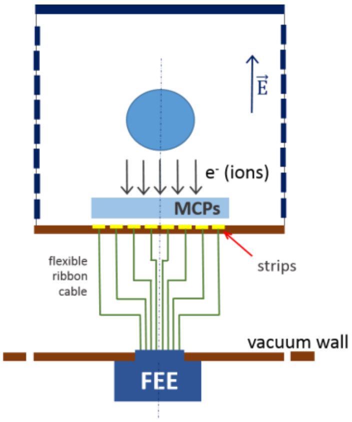

Figure 4: IPM read-out using MCP and conductive strips, these later connected the FEE through flexible ribbon cable

5.4 MCP + Optics + CCD camera

The last one is an entire optical RO as sketched on Figure 5. A double chevron MCP integrating a phosphor layer allows to convert the numerous electrons produced by the MCP into light. This one will enlighten partly a CCD camera with a lens system to optimize the photon collection.

A blackened cylinder (conical shape) should have to screen the sensitive CCD camera against external background photon source. Here also a Frisch grid is not mandatory for avoiding secondary electron background effect. However as seen above, MCP but also phosphor screen are sensitive to radiation and therefore to ageing.

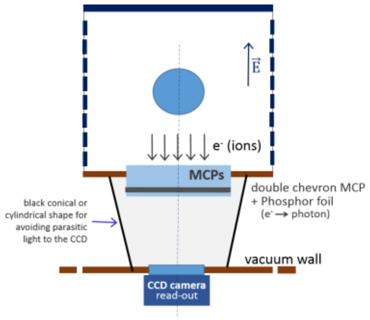

Figure 5: entire optical read-out

The concept for imaging the profiles described in Figure 5, having an optical system imaging onto a camera just outside the vacuum chamber applies on the prototype only. For the ESS NPM, the camera will have to be in a shielded area. This area is planned to be in the Stubs, which provide 5 orders magnitude of shielding. In the detail design phase, a coherent fibre bundle will transport the image from an intermediate image of the MCP to the camera, shielded into the Stub. In this configuration and with an optimised optical system, the coupling efficiency, the gain of the MCP and the high conversion efficiency of the luminescent material, an image at full pulse length and nominal current would bring to the camera 10^{10} visible photons. This gives at least 3 orders of magnitude margin to perform a descent image of the beam profile.

6. OPTICAL CALIBRATION

MCPs are known to have ageing sensitivity reduction or even damaging. Similarly, scintillators also degrade with radiation dose. We propose to monitor the response of the system – MCP+strips or MCP+optics – in order firstly to correct remotely the MCP response by software and secondly to alert maintenance services before MCP is going to die. This can be done with a UV source and dedicated optical system, which illuminates uniformly the MCP. The system can be designed in such a way that it can be installed during short maintenance time, without breaking the vacuum. After measurement of the signal from the IPM with uniform illumination, a calibration factor can be stored in software, in order to provide a correction coefficient for each of the pixels of the IPM profile.

The concept for the illumination system is illustrated in the Figure 6. A Fiber Optics Plate (FOP) can be used to illuminate the MCPs area uniformly. The FOP is also a feedthrough, and the light coupling can be done by means of a second optical system that couples a uniform image into the FOP. This optical system is outside vacuum and can be removed from radiation area when not used. The monitoring of the FOP can be done by metallic coating small area of the FOP on the inside face, forming reflective zones. In this way the transmission of the FOP can be characterized. With this system, one can monitor the IPM with a calibrated uniform signal.

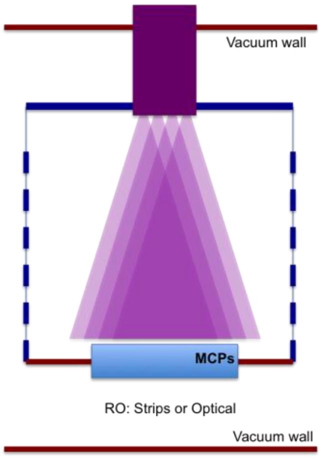

Figure 6: Illumination system

7. TEST BENCH

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 7. Mounted read-outs on the viewport will measure the “same” profile projection and will be compared. It is planned to install 2 CCD cameras for X and Y profile measurement based on fluorescence induced by the beam to use it as a reference. 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!

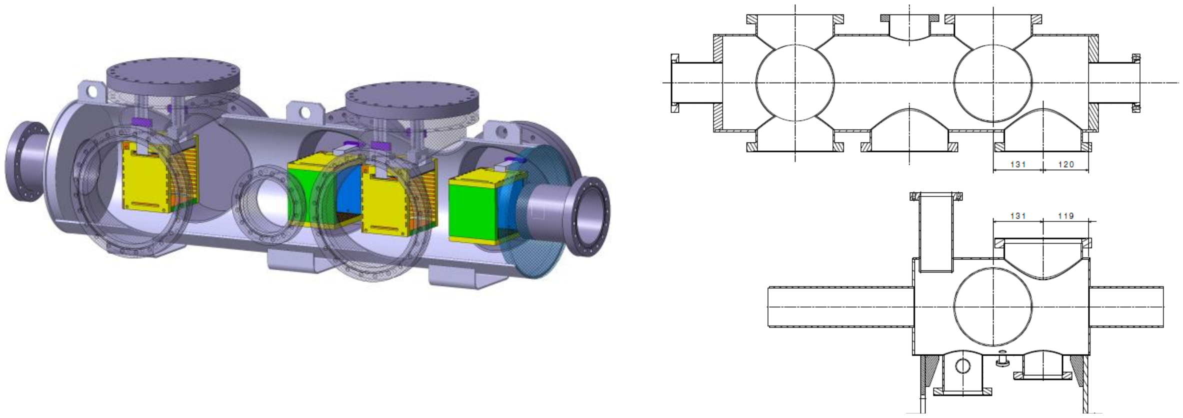

Figure 7: test bench with viewports on which different read-outs can be attached (left), test bench (right-top) presenting at one end the same geometry as the IPM vacuum chamber or LWU (right-bottom).

This test bench will be conveniently suited to check the following hot topics:

- Spark effects: the upstream end of the bench is at the same scale of the vacuum chamber (see Figure 7-right); therefore increasing HV will give us limits for avoiding sparking
- HV uniformity: comparisons between measured traverse profiles and the one obtained with FPM insensitive to HV will give feed backs about electric field uniformity
- HV interferences or influences will be studied by varying IPM HV and following the profile evolution
- Space charge effect: tinkering either with HV, either with beam conditions before to compare with SC calculation should be a good way to check this later.
- electron / ion detection: both will be tested by HV polarity switching. Signal strength, as well as supposed ion degradations will be inquired.
- Profile comparisons for evaluating the cons / pros of the different RO
- Improvements which should have to bring to the final version, particularly concerning the FEE (digitization…), mechanical supports, radiation ageing…

Using redundancies provided by these ROs would allow checking these tabulated topics and probably more than that, and of course make a valuable choice in terms of reliability and profile measurement resolution.

We plan firstly to install this test bench at Saclay, on Iphi accelerator (proto, 100 mA, 3 MeV) in order to set and fix all systems for optimizing their functioning with the help of our on–site colleagues specialized in different topics (electronics, mechanics, vacuum, CS…). Once ready, this bench will be installed on a machine working in the energy range of ESS like Cosy from Jülich in Germany.

8. CONCLUSION

Several Read-Out systems have been considered to exploit the tiny ionization signal expected in an IPM and were briefly described.

Table 2: The different types of readout in short

Parameter\System	**Strips**	**MCP + Strips**	**MCP + Optics**	**TimePix3**
Global reliability[10]	++	-	--	+
Signal	--	+	+	++
Rapidity	--	+	+	++

We propose to make test beams to check them in a bench which should have to be designed based on a preliminary study shown here. Many developments have to be done, but few of them have been already began. The goal is to test them in same conditions for checking their ability to fulfil the requirements and select one based on reliability and profile measurement accuracy for the ESS IPMs.

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[10] Global reliability includes radiations hardness, ageing of readout.