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J-PARC TEST OF ESS BEAM ON TARGET DIAGNOSTICS PROTOTYPES APERTURE MONITOR AND GRID

C.A. Thomas*, J. Etxeberria, J. Paulo-Martin, H. Kocevar, E. Donegani
T. Shea, European Spallation Source ERIC, Lund, Sweden
Shin-ichiro Meigo, Motoki Ooi, JAEA/J-PARC, Tokai-mura
Haihua Niu, Bin Zhang, IMP/CAS, Lanzhou
Anders Johansson, Markus Törmänen, Lund University, Lund

Abstract

The ESS high power beam will be delivered to the spallation target with high degree of control. To this end, we have designed a suite of instruments which provide measurement of the beam characteristics in a drift space a few meters from the target. We present in the paper two of these instruments, the APTerture Monitor (APTM) and the GRID. The APTM is designed to measure the fraction of beam that goes through the defined aperture, and covers the range of time from intra-pulse at µs sampling time to many pulses over seconds. The GRID measures the projected horizontal and vertical profiles. We have been designing a prototype of these two instruments and installed them in the 3NBT dump line of J-PARC. In this paper we present in a first part the prototypes design. They are designed to test functionality of these instruments in a similar radiation environment as ESS. The 3NBT Dump line at J-PARC presents such an environment: it takes a 50 mA beam pulse from 50 µs to 500 µs, at energies from 400 MeV to 3 GeV; the location of the instrument is in front of the dump, although at 12 m, and 30 cm downstream a thin Al-window, which generates secondary particles. In the second part of the paper we report the results and the measurements performed to test the prototypes. Before concluding we will discuss the results and propose improvements to the instruments final design.

INTRODUCTION

The ESS accelerator delivers a high power beam to the spallation target that is 30% below the material rupture. As a consequence, a beam in errant condition, i.e. not matching the nominal condition, may bring a risk to the target. Preventing any risk condition to occur during the phases of tuning and neutron production is critical. A suite of instruments has been designed to that end [1]. It will measure the beam properties of any pulse delivered to the target, and permit to abort the pulse within 10 µs after detection of any errant beam condition. The suite of instrument is composed of beam on target imaging, a harp and aperture monitoring. The beam on target imaging is a critical instrument that will provide the main 2D information on the beam properties. For each pulse it will measure the position of the beam, the edges of the beam distribution, and the flatness of the current density distribution [2], with respect to the centre of the target wheel sector on which the pulse must be delivered. The aperture monitoring is designed to detect any beam outside the nominal aperture. The harp is somehow redundant with the imaging, but it is complementary as it can detect the beam 1D profile within the pulse, thus detecting potential errant condition at the microsecond scale. In the following, we will focus on the harp and monitoring instrument. We will name the harp as the GRID, and the aperture monitoring as APTM.

APTM Functionality

The APTM is designed to detect small fraction of the proton beam that is outside a defined aperture. The detection account for charges corresponding to 0.1% of the nominal beam current from 5 µs to minutes. To covers such a time span, the design incorporates 2 detections schemes, one is a metallic blade, from which the proton induced current is sampled at 1MS/s, and the second one is a thermocouple, which senses the charge induced temperature. The sampling rate of the temperature is expected to be in the range of 100 S/s. The temperature sensor can detect small amount of charge that can't be seen by the blade, which can accumulate creating damage on the long term.

GRID Functionality

The GRID is designed to provide the 1D projected profile of the beam on orthogonal axis. While the pulse is been delivered to the target, it measures the edges of the beam distribution, the flat top of the current distribution, and the position of the beam. In addition, the rasterising of the beam can be detected. The design is based on a harp of wires, from which the proton induced current is measured.

PROTOTYPE DESIGN

The location of these instruments in the close target region imposes some additional constraint, mainly due to the high radiation environment, that must be understood and taken into account. This is addressed by the choice of the materials, and by additional features to the current or temperature sensing. By this, we need to address the sensitivity of the instrument in radiation environment; the perturbation of the signal by radiation and general environment brought by pulsed high power beam, RF parasitic signals and charged secondary particles; the resistance of the instrument to any errant beam condition, in particular the most extreme where all the beam power is deposited on the instrument. This is addresses primarily by modelisation of the instrument in

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* cyrille.thomas@esss.se

its environment. However, modelisation cannot reproduce with high fidelity all aspects of the reality associated with this specific environment. In order to probe part of this, and complement the design, we have been designing a prototype to be installed in a facility that offers a comparable environment to the ESS target, i.e. the 3NBT dump at J-PARC. It is near to a target (the dump, although far compared to ESS case), its vacuum is separated from the accelerator one by a Aluminium thin Proton Beam Window, and the vacuum pressure is 1 mbar.

The design of the prototype of the APTM and GRID was driven by several objectives. The first one was to test and compare the signal from silicon carbide (SiC) and tungsten (W) wires. Indeed, we have had some experience with the W wires, but studies showed a large probability that the target environment becomes corrosive. In this case the lifetime of the W wires would be significantly reduced. Therefore we have been looking and selected another material which is SiC, that is in use at J-PARC, and at ISIS. So we decided to build the GRID with both wires.

The first analysis we carried out was to evaluate which maximal wire diameter would sustain the J-PARC beam delivered from the Linac, i.e. 400 MeV, and 50 mA peak, and at the Dump the beam size will be set to be around 2 mm. We developed a model of the wire temperature. The model takes into account the beam parameters, the material properties such as stopping power for proton, the heat capacity, the wire diameter. Looking into off-the-shelf catalogues, we found SiC and W wires 110 μm and 50 μm diameter respectively. For the full beam power at J-PARC, the SiC wire temperature reaches 1170 K. The same analysis shows the W wire would reach 850 K. In both cases, the wires are expected to work fine with no damage in the 3NBT Dump and in the above beam conditions.

The evaluation of the current is calculated so far by means of the Sternglass expression [3]. Using this formula we could estimate the order of magnitude of the induced current and specify the appropriate current sampling ADC card. The expected signal using the above J-PARC beam parameters is 160 μA, and 110 μA for the selected SiC and W wires respectively.

The ESS nominal beam is 62,5 mA, 2.86 μs pulse, repeting at 14 Hz. In addition, the beam will be rastered in front of the target, at 39 kHz and 29 kHz in horizontal and vertical planes respectively. The peak current expected for the GRID at ESS is in the 5 μA range. Taking into account the required 1 MS/s sampling speed, and the ESS selected μTCA, we chose the AMC-PICO-8 which is an eight channel picoammeter AMC board in MTCA.4 format[1]. The inner core of the channels is connected to the wires, so when electrons are ejected from the wire, a positive current is measured. Conversely, if electrons are collected by the wire, a negative current is measured.

The access to the vacuum chamber of the 3NBT dump can be done through a unique port that is 38 mm diameter. In addition, the pipe diameter is 600mm diameter, and the port is above stairs. The mechanical assembly has 2 actuators which support the APTM and Grid. They are shown in the Fig. 1. The front one is the GRID, composed of 2 sets of wires. The orientation of the head is horizontal, so the horizontal (vertical) wires will probe the vertical (horizontal) beam distribution. The horizontal has 8 W wires and the vertical has 6 W wires and 1 SiC. The reason is only practical and mainly due to assembling issues. More SiC wires were planned initially, but one remains for comparison. The SiC wire is the first vertical wire from the right on the Fig. 1.

The APTM is composed of 3 Ni blades, and 2 type-K thermocouples. The induced current in the blades is sampled by the AMC-PICO8. The thermocouple is attached to a metallic part, so when particles are deposited in it, the temperature increases. It is read by a EL3314-0002 analog input terminal from Beckoff[2].

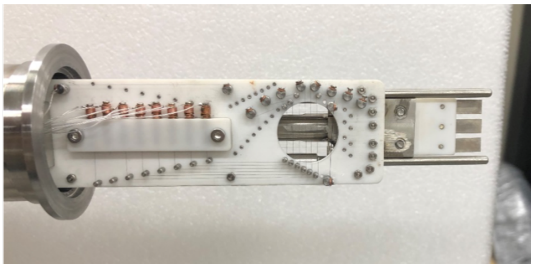

Figure 1: Photo of the prototype of of the APTM and Grid.

To support the head and put it in the beam path, it is supported by 2 actuators that are mounted on a rigid mechanical assembly design to be installed over the stairs. Fig. 2 shows the installed assembly.

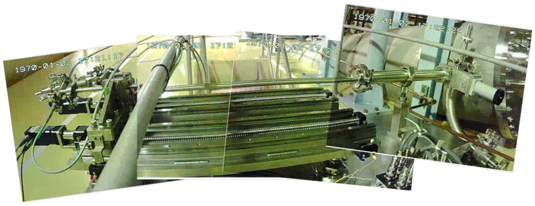

Figure 2: Photo of the prototype of the APTM and Grid mechanical assembly installed on the 3NBT dump vessel.

EXPERIMENTAL DATA

The data presented here are extrated from 2 shifts performed at J-PARC on the 3NBT dump. During the first shift, pulses at 400 MeV, 50mA current, and varying the pulse length to 50, 300, 500 μs have been delivered in single shots to the GRID and APTM. Then pulses from various energies, 800 MeV, 1, 2, 3 GeV, composed of 2 short 160 ns bunches separated by 600 ns, and with a peak current estimated to be of the order of 1-10A, however not measured, have been

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[1] from CAEN ELS, `https://www.caenels.com/products/amc-pico-8/`

[2] `https://www.beckhoff.com/`

delivered to the instrument. In the second shift only the first part of the first shift has been repeated with 400 MeV beam, but this time, a voltage bias has been added to the middle APTM blade. In the following, summarised results from the 2 shifts are reported and discussed.

APTM Results

The APTM is located downstream from the GRID. However, it is possible to extend the position of the blade beyond the GRID. In this position, the APTM can be exposed directly to the beam. An example of the current sampled when the beam is expected to heat the blade is shown in Fig. 3. The beam seems to hit part of the top blade. Almost no current is in the second blade which is not biased, and the third one sees a negative current. The beam charge delivered by the J-PARC Linac is of the order of 25 µC, and remain almost the same after acceleration and compression in the RCS[3]. The peak current read by the top blade is 4 orders of magnitude larger than the noise floor of the instrument. So it is expected the APTM detects charges in the range of a few nC. The requirement for the instrument is to detect 0.1% of the beam charge in 10 µs. The detection level of the APTM as designed in the prototype is 2 to 3 orders of magnitude lower.

The beam size is expected to be between 6mm. So a large current should be read in all blades. However, the blades are partially behind the GRID, so we should expect a large amount of electrons generated by the proton beam and other scattered particles into the support structure of the instrument. Monte Carlo simulation have been done to study the instrument, but the ceramic and the many small metallic supports for the wires have not been taken into account. However, we may expect a non-centered beam to produce such a response as shown in the Fig. 3, but we cannot fully understand it yet. Further model and Monte Carlo simulation is necessary.

Long pulses have been sent to the APTM, but in this case, the signal is not as clear, almost all the time dominated by electrons, generating a negative signal. This is critical for the design of the APTM. The final design of the instrument will have to take this into account.

The thermocouple has shown to be sensitive to the beam. For instance, in the Fig. 3, the top thermocouple senses a higher temperature than in the lower one. However, the data is not exploitable, as increase the temperature is associated with energy deposition and doesn't distinguish between particles. Therefore we were not able to calibrate the temperature increase with the proton beam.

GRID Results

The signal from the GRID is composed of 15 sampled signals at 1 MS/s of the 7 horizontal and 8 vertical wires. A typical trace on one of the wires is shown in the Fig. 4. The duration of the pulses larger than 1 µs are measurable. The peak current in this wire, in the 100 µA, is well over the noise of the instrument, which is typically in the 0.1 µA range level. One may note the large oscillations in the signal. The main frequency found is 26 kHz, with a typical amplitude measured with FFT of the signal is about 10 µA/$\sqrt{\text{kHz}}$. This signal appeared only after the instrument has been installed on the 3NBT. It seems this is a parasitic signal, and the source hasn't been located so far. A further step in the design will be focused on better isolating the electrical signal from the GRID wires.

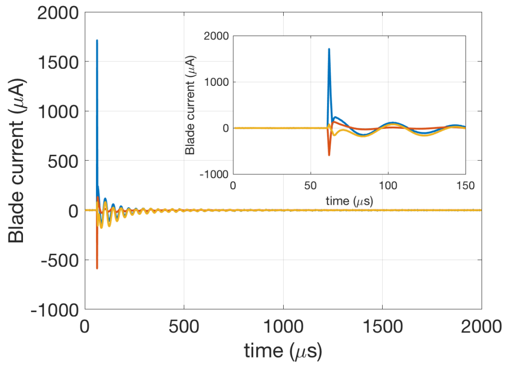

Figure 3: APTM Blades signal. The beam is 3GeV, 160ns pulses. The peak current values are 1905, 64, −650 µA for top, middle and bottom blades.

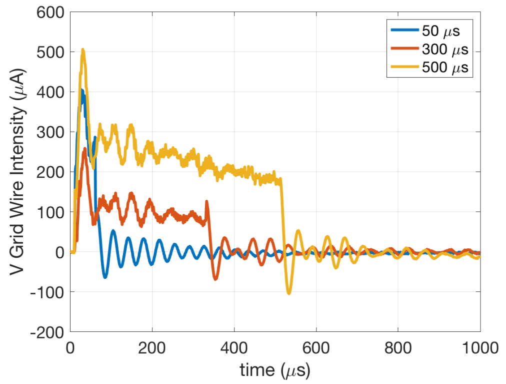

Figure 4: Current signal in one of the vertical wires for 50, 300, 500 µs pulses, 400 MeV, 50 mA. The position of the Grid is in nominal position at 554 mm, and the APTM is retracted 25 mm from the GRID, in its shadow. The APTM is biased at -30V.

The typical trace with the vertical wires is shown in the Fig. 5. The pulse is 500 µs, sent in single shots. one may read a distribution of peak current. The highest instensity measured here is of the order of 400 µA. In comparison with the expected current from [3] it is 2.5 larger.

From the signals recorded in Fig. 5, the charge in each wire can be integrated and the profile of the beam can be measured. Figure 6 returns the result of the integration of the signal. The profile can be fit with a Gaussian function. The beam position and width corresponds to the Gaussian

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[3] Rapid Cycling Synchrotron

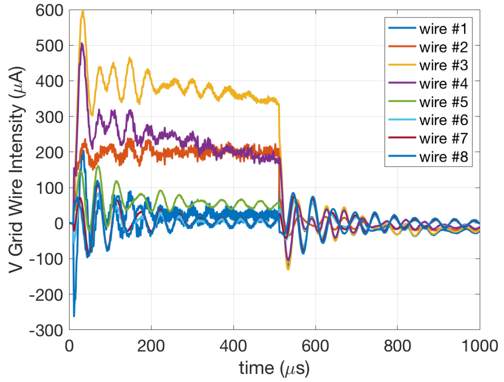

Figure 5: Current signal in the vertical wires for a 500 µs pulse, 400 MeV, 50 mA. The position of the Grid is 554 mm, and the APTM is 530 mm. The APTM is biased at −30 V.

returned fit parameters. In the example shown, the width is 2 mm, which is close within % from the predicted beam size.

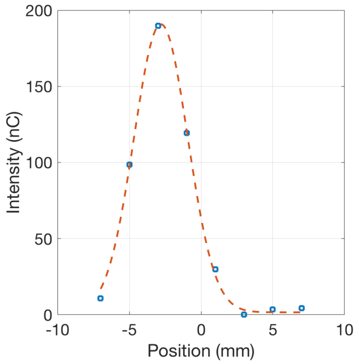

Figure 6: Profile of the beam exracted from the wires signal shown in Fig. 5.

The current sampled from the SiC wire is shown in Fig. 7. The pulse is 300 µs, 50 mA, 2 mm r.m.s width, delivered in single shot. On the figure, three APTM bias conditions are shown. In the case of a -30V bias, the shape of the pulse resembles the expected square shape. Compared to the prediction from Sternglass formula, the peak current measured is more than 4 times larger. With 0 V, the droop of the pulse is noticeable. It is expected that some of the electrons produced by the beam and scattered particles impinge on the wires. So the droop of the pulse shape in attributed to electrons hitting the wire. The droop is varied between 10% and 40%. This can be partially explained by a first order approximation of the number of electrons created by the Proton Beam Window, by the ionised gas, and by the electrons from the GRID. However, a detailed model is needed so that the experimental data is fully understood.

The case of +30 V is even more stricking. A reverse pulse shape can be seen, and the peak amplitude is 6 times larger than for the positive signal. It looks like all the electrons created in the environment of the APTM are attracted by the wire. As mentioned above, we have not studied this in details, so we cannot explain the results shown here.

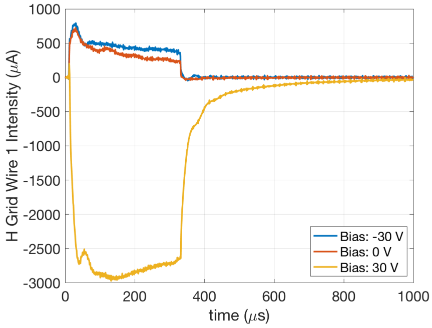

Figure 7: Current signal in the horizontal SiC wire for a 300 µs pulse, 400 MeV, 50 mA. The position of the Grid is 554 mm, and the APTM is 530 mm.

CONCLUDING REMARKS

In order to test and validate concepts for the APTM and the GRID, instruments dedicated to beam on target, we have design and produced a prototype to be installed in the 3NBT dump at J-PARC. The location presents an environment and beam properties similar to the ESS target and therefore the behaviour of the prototype provides rich return experience for the design of the APTM and GRID at ESS. It has been shown that the ATPM can be sensitive to the required fraction of the beam. However, it is also sensitive to other charged particles and in particular the large amount of electrons that has been observed during the prototype tests. The GRID has been shown to produce a larger current than expected from theoretical prediction. This is not a new results. We haven't discuss this in details as the aim of the prototype was to measure the yield for this specific design. With this information, the design of the ESS GRID will benefit by levering some uncertainty. The profiles measured seem to be trustworthy. However, some parasitic signal has been caught in the prototype. It would be beneficial to eliminate external sources of noise in the ESS GRID design. In addition, a bias field in the level of 50V should be sufficient to screen most of the electrons susceptible to perturb the GRID signal. A specific schematic to implement such a screen shield will be subject to an upgrade of the existing prototype. A new GRID has been designed and produced and is expected to be installed on this prototype assembly. Finally, designing and producing the prototype gave a significant experience returned to the final design of the APTM and GRID, in the choice of the materials, and how to implement the concepts successfully. The design of the instruments will proceed in its main lines. However, the implementation of the bias field and the isolation of the electronic circuit will have to be proved before the final design can be delivered.

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