ADVANCED BEAM DIAGNOSTICS R&D WITHIN OPAC

C.P. Welsch[#]
Cockcroft Institute and the University of Liverpool, UK

Abstract

oPAC 'Optimization of Particle Accelerators' is a European research and training network that has received funding within the EU's 7th Framework Program. With a total budget of 6 M€ and 23 Fellows that are employed within the project, it is the largest Marie Curie network that was ever funded by the European Union. oPAC was started in 2011 and would usually come to an end at the end of 2015.

The network currently joins more than 30 partner institutions from all around the world, including research centers, universities and the private sector. One of the project's largest work packages addresses advanced R&D in beam diagnostics. This includes studies into advanced instrumentation for synchrotron light sources and medical accelerators, enhanced beam loss monitoring technologies, ultra-low emittance beam size diagnostics, beam diagnostics for high intensity beams, as well as the development of compact electronics for beam position monitors.

This paper presents the research outcomes of the diagnostics work package and discusses the demonstrated performance of each monitor. A summary of the various events the network has organized for the accelerator community is also given together with an outlook on future opportunities.

INTRODUCTION

An efficient optimization of particle accelerators and light sources requires close collaboration between beam dynamics experts, instrumentation specialists, along with powerful accelerator and electromagnetic field simulations tools. The oPAC network covers all these aspects in its different scientific work packages [1]. The project's Fellows carry out a broad yet closely interconnected R&D program in all these areas. The consortium consists of partners from industry, universities, as well as national and international research centers, such as ALBA, GSI and CERN. Selected associated and adjunct partners contribute to the research activities and complement the network's training program. The primary goals of oPAC are to provide the best possible training to its Fellows thus maximizing their career opportunities, as well as advancing knowledge through a cutting edge research program.

*This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289485.
#c.p.welsch@liverpool.ac.uk

BEAM DIAGNOSTICS R&D

A versatile beam diagnostics system is crucial for the successful operation and optimization of any particle accelerator or light source. Between 2011-2015 the DITANET consortium [2] set out to define improved training standards in this research area and the development of advanced beam diagnostics is also a key aspect in the oPAC project. Here, a summary of results from Fellows in beam diagnostics R&D is given.

Cavity BPM Electronics

In the last few years the number of projects and applications requiring sub-micrometer resolution for their beam position monitoring systems has increased dramatically. This trend is mainly driven by an increasing number of Free Electron Laser (FEL) projects and by specific applications such as inverse Compton scattering where the high resolution is required in the beam-laser interaction region. Depending on the characteristics of the beam, different cavities and resonant frequencies are used, ranging from single-bunch applications in high-Q cavities to low-Q for long bunch train cavities.

Because of the increased demand in these systems, the requirements for the readout electronics have been collected and extensive simulations run for different scenarios by oPAC Fellow Manuel Cargnelutti, based at Instrumentation Technologies. The idea is to develop a system flexible enough to deliver excellent performance over a broad range of cavities. The compact hard-/software platform on which this instrument will be developed is already in use for other applications [3,4], but several changes will now be introduced in the RF front-end: (1) Down-conversion: A PLL locked to an external reference is used to down-convert the cavity input signal from the cavity resonant frequency to a given intermediate value. (2) Variable attenuators: These are used to adjust the cavity input signal level to the ADC full-scale to maximize the signal-to-noise ratio. (3) ADC: The sampling rate is increased to 500 MS/s. This enables bunch-by-bunch position measurements for low-Q cavities, as well as bunch-train applications. The data acquired is processed by an FPGA of the Xilinx ZYNQ 7045 system-on-chip. Here, a special deconvolution filter and a parametrized time-domain processing of the input signal pulses enable to deliver the beam position for every electron bunch and with sub-micrometer resolution. Fig. 1 presents the simulation of the system position resolution where the internal attenuators setting is parametrized. The cavity used as reference for these simulations is the model BPM16 from the SwissFEL project [5].

ISBN 978-3-95450-176-2

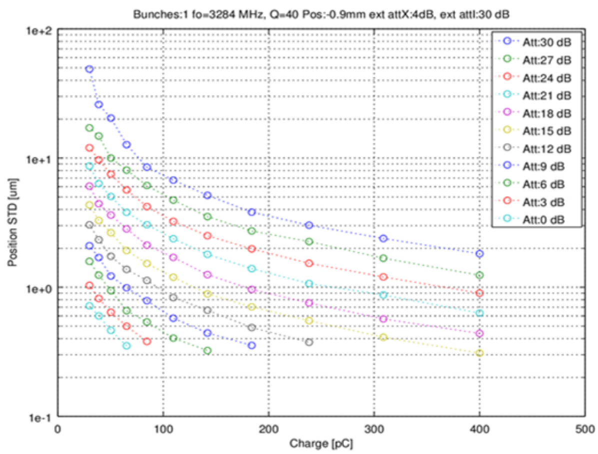

Figure 1: Position resolution for a single-bunch e- beam.

The project is currently in the high-level design phase. During this phase, a complete set of requirements is being collected to ensure that as many as possible use-cases are covered. Based on feedback from users the design will then be finalized and the implementation phase started.

Position Detection for Ultra-Low Intensity Heavy-Ion Beams

The Collector Ring (CR) at the Facility for Antiproton and Ion Research (FAIR) will mainly be used for collecting and pre-cooling high-intensity radioactive ion beams and antiprotons. It can also be used for isochronous mass spectrometry for neutron-rich or neutron-deficient exotic nuclei when it is tuned to a special ion-optical setting. The ultra-low intensity of these beams then imposes stringent sensitivity requirement on beam detection techniques. An RF cavity as a Schottky noise detector has proven to be an extremely sensitive beam diagnostic device with its ability to detect even single ions [6]. As an upgrade of the existing Schottky resonator installed in the Experimental Storage Ring (ESR) a position-resolving cavity has been proposed for the CR. This cavity, together with the intensity-sensitive one, will be able to distinguish the revolution orbits of stored ions for nuclear mass measurements. The measured positions will be used as a key input for subsequent analyses to correct for the anisochronism effect in the measurement and help improve the accuracy and precision of the evaluated atomic masses [7]. In contrast to a conventional cavity-based BPM the present design offsets the beam pipe to a side of the cavity and utilizes the resonant monopole mode [8]. Consequently, the shunt impedance, which is a measure of the coupling strength between the cavity and the beam exhibits an inclined trend over the aperture around a fairly high mean value. Having normalized the signal to a reference from the intensity cavity the position can be deduced by means of magnitude discrimination. In order to enhance the intensity sensitivity and position resolution of the cavity much effort has been devoted to the optimization of the cavity geometry so as to attain adequate mean value and slope of the shunt impedance. oPAC Fellow Xiangcheng Chen, based at GSI, carried out analytic and numerical studies into the design. First, the electric field inside the cavity was solved for a rectangular box and elliptic cylinder. The optimum dimensions were then selected in accordance with the experimental requirements. Second, an electromagnetic field solver was used to investigate changes in resonant frequency and shunt impedance taking into account realistic values for beam pipe and plunger. In order to verify the design two scaled prototypes have been manufactured and tested by Chen on a purpose-built benchtop. The electric fields inside the prototypes were measured by perturbation with a ceramic bead. The latter was held by a cotton thread while the cavity was moved by a motorized displacement unit. The resonant frequency was obtained from transmission measurements using a vector network analyzer. A dedicated Java application coordinates the movement-measurement cycle. In order to account for any temperature drift a reference measurement was taken before each perturbation measurement. The entire profiling process takes 5 hours and is fully automated. As an example the measured shunt impedance of the rectangular prototype is shown in Fig. 2. It is in very good agreement with the associated simulation studies.

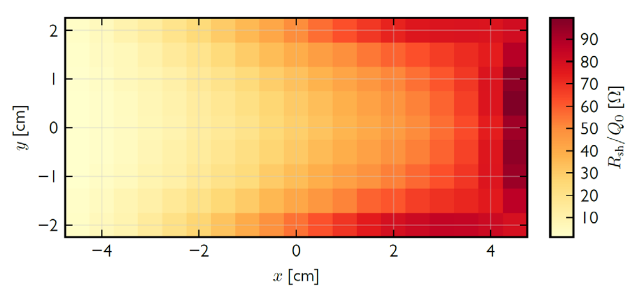

Figure 2: Measured shunt impedance of the rectangular Schottky monitor prototype.

Beam Profile Monitors for High Intensity Beams

The European Spallation Source (ESS) [9], currently under construction, consists of a partly superconducting linac which will deliver a 2 GeV, 5 MW proton beam to a rotating tungsten target. Two different types of devices are currently been designed for the ESS linac to monitor the beam profile, an invasive and a non-invasive one, which will both be located in the same module. The invasive device will be a wire scanner and will be used during the commissioning at low beam current and short pulse. Because this invasive system would get damaged by the beam under nominal conditions the development of an additional non-invasive device became necessary.

The Non-invasive Profile Monitor (NPM) chosen for ESS are based on the interaction of the beam with the residual gas. Two different devices are being developed by Charlotte Roose and colleagues to meet the ESS constraints: a Beam Induced Fluorescence monitor (BIF) [10] and an Ionization Profile Monitor (IPM) [11]. The BIF monitor is based on the fluorescence emission of the excited residual gas. In the warm linac, the main constraint is the 10 cm available space for the NPM. This compact monitor is a good answer to that issue as both horizontal and vertical profile measurements can be performed at the same place. Furthermore, its design is rather simple and can be easily changed since all the device components, except for the beam pipe viewport, are outside the beam pipe.

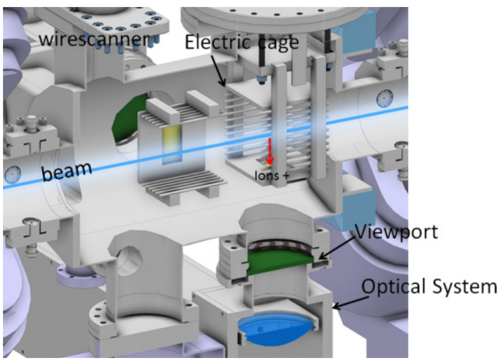

Figure 3: ESS IPM - current model.

The IPM uses charged particles produced during the interaction of the beam with the residual gas to obtain the profile. Fig. 3 shows the current model of the ESS IPM. The electric field created by the IPM cage has two purposes: First, it guides secondary ions to a screen. Second, it decreases the space charge effect [12] of the beam which would otherwise disturb the ion trajectories and hence distort the profile. Due to the anticipated high dose rate in the cold linac a scintillator screen is used to collect the secondary ions. This is then imaged by a conventional camera system placed outside the vacuum.

Cryogenic Beam Loss Monitors

Beam Loss Monitors (BLMs) close to the interaction points of the Large Hadron Collider (LHC) are currently located outside the cryostat, far from the superconducting (SC) coils of the magnets. In addition to their sensitivity to lost beam particles they also detect particles coming from the experimental collisions which do not contribute significantly to the heat deposition in the SC coils. In the future, with beams of higher energy and brightness resulting in higher luminosity, distinguishing between these interaction products and dangerous quench-provoking beam losses from the primary proton beams will be challenging. The system can be optimized by locating BLMs as close as possible to the SC coils, inside the cold mass in a superfluid helium environment at 1.9 K. The dose then measured by cryogenic BLMs would more precisely correspond to the real dose deposited in the coil. The candidates under investigation for such detectors are based on p+-n-n+ silicon and single crystal Chemical Vapour Deposition (scCVD) diamond, of which several have now been mounted on the outside of the cold mass of the SC coil in the cryostat of the LHC magnets. The cryogenic BLM specifications represent a completely new and demanding set of criteria that have never been investigated in such a form before. A certain knowledge about radiation hardness of particle detectors is available for the temperature of outer space (2.7 K), i.e. from the requirements of space-based experiments, but little is known for detectors below this temperature. The main unknown was the combination of the cold environment with a total ionizing radiation dose of 2 MGy. This is why the first radiation-hardness test of the diamond and the silicon detectors in liquid helium environment were recently performed at CERN.

The main aim of the cryogenic irradiation test was to investigate the radiation hardness of ionizing radiation detectors in liquid helium at 1.9 K. After careful preparations, the irradiation experiment was performed in the IRRAD facility at CERN. At the end of the cryogenic irradiation a total integrated fluence of $1.22 \cdot 10^{16}$ protons/cm^2 was reached, corresponding to an integrated dose of about 3.26 MGy for the silicon and 3.42 MGy for the diamond detectors.

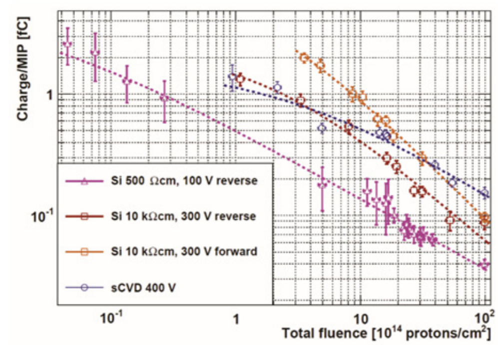

Figure 4: Degradation curves of scCVD diamond detector at 400 V compared with a 10 kΩcm silicon detector at 300 V and 500 Ωcm silicon at 100 V reverse as reference curve (courtesy of C. Kurfuerst).

It can be seen that the silicon has a larger signal than the diamond at the beginning of irradiation, but the situation changes rapidly, see Fig. 4. The reduction in signal corresponding to 20 years of LHC operation (2 MGy) is of a factor of 52 ± 11 for the silicon device at 300 V and of a factor of 14 ± 3 for the diamond detector at 400 V. As a safety critical system, the long term stability of the BLM is a high priority criterion. During Long Shut-down 1 of the LHC four cryogenic radiation detectors were mounted on the outside of the cold mass containing the SC coils in the cryostat of two LHC dipole magnets. These four detectors consisted of one 500 µm scCVD diamond detector, one 100 µm silicon detector and two 300 µm silicon detectors. Once the interconnection between the two magnets where the detectors were located was closed and the cryostat was under vacuum a Current-Voltage (IV) curve measurement of the detectors was performed [13]. The results show that the leakage current is at a reasonably low level which should allow

ISBN 978-3-95450-176-2

the measurement of beam losses with a high signal to noise ratio. These first cryogenic radiation detectors installed in operational SC magnets will not only allow the behavior of the detectors to be tested under realistic conditions, but also determine the validity of the integration in a setup at 1.9 K, in a magnetic field and under vacuum. First results with beam are expected in September 2015.

Beam Size Measurements at ALBA using Interferometry

Synchrotron radiation interferometry is now a reliable method to measure the horizontal and vertical beam size at the ALBA storage ring in Barcelona, Spain. The technique, developed by T. Mitsuhashi, allows determining the beam size by measuring the visibility of the interferogram, obtained by making the visible part of the synchrotron radiation interfere using a double slit interferometer. Due to the layout of the ALBA diagnostic beam line Xanadu interferometry measurements were not completely straight forward. Fellow Laura Torino introduced several enhancements to the existing set-up to overcome existing limitations, in particular: The light selected by a photon shutter cuts the light horizontally whilst the first extraction mirror selects only the upper lobe of the produced radiation. This generates a final footprint that is dominated by Fraunhofer diffraction. The use of a double slit system allows the selection of several different fringes of the footprint. Fringes generated by Fraunhofer diffraction don't have necessarily the same phase. This might provoke a loss of contrast affecting the visibility measurements. To reduce this effect the slits were substituted by pinholes to select a more compact region of the footprint and consequently, a reduced number of fringes. Furthermore, the 7 mirrors guiding the light up to the Xanadu optical table are "in-air". The air turbulence in the tunnel or in the beam line can provoke vibrations of the optical elements that are converted in a rigid displacement of the centroid of the interferogram image on the CCD sensor.

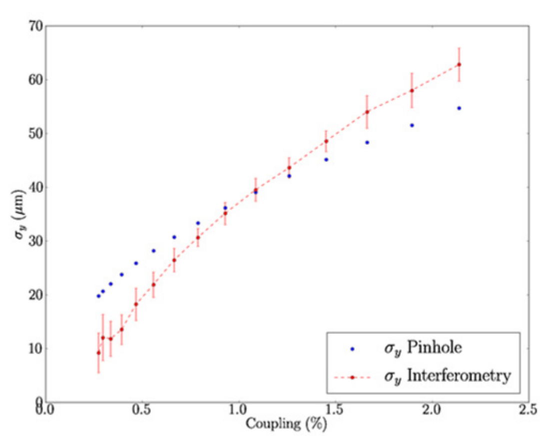

Figure 5: Vertical beam size measurements σ_y from the pinhole (blue) and the interferometer (red).

The incoherent sum of artificially displaced images also produces a loss of contrast in the visibility measurements. Reducing the CCD exposure time is an intuitive and efficient way to solve this problem, but also causes a reduction in intensity of the image which leads to an impossibility in the visibility measure, due to the reduced dynamic range of the CCD camera. To overcome this problem a matching algorithm was developed to superimpose low exposure time images (0.1 ms) and improve the contrast and the dynamic range of the interferogram. The reliability of these measurements, both for horizontal and vertical beam size, was verified in several ways. It was possible to study depth of field effects on the horizontal beam size by performing measurements for different distances between the pinholes. In addition, the effectiveness of vertical beam size measurements was verified by performing so-called coupling scans: By changing the emittance coupling using skew magnets the vertical beam size also varies. The results obtained with the interferometer follows the ones obtained with the x-ray pinhole. The x-rays used for pinhole measurements, and the visible light for the interferometry come from two consecutive bending magnets at slightly different locations. For this reason the measurements do not exactly coincide, but the trend is nicely confirmed, as shown in Fig. 5. Further details are given in [14].

TRAINING EVENTS

Training within oPAC is provided locally by the host institute, primarily through cutting edge research, specialized lectures and seminars, as well as network-wide training offered by the whole consortium. In addition, oPAC has organized a series of Topical Workshops and Schools for its Fellows which were also open to the wider accelerator community.

International Schools

At the start of their training all oPAC Fellows participated in either the established CERN Accelerator School or the Joint Universities Accelerator School. This provided them a sound training basis as they took on their projects within the Network. Both Schools included lectures and tutorials covering accelerator physics, relativity and electro-magnetism, particle optics, longitudinal and transverse beam dynamics, synchrotron radiation, linear accelerators, cyclotrons and general accelerator design. An oPAC School on Accelerator Optimization was then organized by the consortium between 7th-11th July 2014 at Royal Holloway University of London, UK. It covered advanced techniques for the optimization of particle accelerator performance - in particular the combination of different fundamental techniques to push the limits of accelerators ever further.

All Fellows initially met for a dedicated researcher skills School in Liverpool, UK in June 2013. During the week-long School they were provided with subject-specific training in addition to generic topics, including

ISBN 978-3-95450-176-2

project management, scientific writing, problem solving techniques and building bridges between academia and industry. The Fellows were asked to present a short summary of their projects as part of presentation skills training and also to develop a detailed project plan of their oPAC projects. Towards the end of their projects all Fellows followed a 4-day advanced researcher skills workshop which brought them again to Liverpool. The transition to permanent employment from postgraduate research is a challenging prospect in an ever more competitive job market. The workshop provided dedicated and practical support to help the Fellows in their future careers. External and internal trainers provided an extremely broad training throughout the week. This included support in career planning by providing practical and specific advice on CV writing and interview skills, writing competitive grant applications and science communication and networking. The university's business gateway team and Dr. Marco Palumbo, IPS Fellow in the physics department, contributed dedicated sessions on intellectual property rights, commercialization and entrepreneurship that were very positively received by the course participants.

Topical Workshops

oPAC also organized a whole series of Topical Workshops. This included expert training days on 'Simulation Tools' (CST, Germany) and 'Beam Diagnostics' (Bergoz, France), a 2-day Topical Workshop on the Grand Challenges in Accelerator Optimization at CERN, Switzerland on June 27th/28th 2013 [15], a workshop on Beam Diagnostics hosted by CIVIDEC [16] and one on Libera Technology at Instrumentation Technologies. Most recently, a workshop on Computer-Aided Optimization of Accelerators (CAoPAC) was held at the GSI Centre for Heavy Ion Research in Darmstadt, Germany from 10 – 13 March 2015 [17]. This was a special event for the network as it was organized by the Fellows of the network, providing them with the opportunity to take charge of a whole event from scratch, with a limited time-frame, limited resources, and the challenge of offering an interesting event to attract a good number of participants.

Accelerator Symposium and Conference on Accelerator Optimization

An international Symposium on Lasers and Accelerators for Science & Society took place on the 26th of June in the Liverpool Arena Convention Centre. The event was a sell out with delegates comprising 100 researchers from across Europe and 150 local A-level students and teachers. The aim was to inspire youngsters about science and the application of lasers and accelerators in particular. It is now possible to share the enthusiasm of the accelerator experts through online presentations [18]. Finally, the network will organize a 3-day international conference on accelerator optimization which will be hosted by CNA in Seville, Spain.

SUMMARY

An overview of the beam diagnostics R&D results within the oPAC project was given in this paper. The network has successfully trained 23 early stage researchers and achieved all of its scientific deliverables. The project's Steering Committee has recently decided that the network will continue to organize events for the accelerator community and disseminate research results from its Fellows. Despite the enormous success and impact that oPAC has had, there remains a considerable shortage of skilled accelerator experts to meet the demand of the most advanced accelerator-based research facilities. The consortium plans to propose additional training initiatives in the future to help overcome this problem.

REFERENCES

[1] http://www.opac-project.eu

[2] http://www.liv.ac.uk/ditanet

[3] G. Jug, M. Cargnelutti, B. K. Scheidt, "Development of Compact Electronics Dedicated to Beam Position Monitors in Injectors and Boosters", Proc. IBIC, Oxford, UK (2013).

[4] M. Znidarcic, E. Janezic, M. Cargnelutti, "Compact Single Pass BPM", Proc. IPAC, Richmond, USA (2015).

[5] B. Keil, "Cavity BPM Pickups for SwissFEL", DEELS Workshop 2014.

[6] F. Nolden, et al., "A fast and sensitive resonant Schottky pick-up for heavy ion storage rings". Nucl. Instrum. Meth. A 659 (2011) 69.

[7] X. Chen, et al., "Accuracy Improvement in the Isochronous Mass Measurement Using a Cavity Doublet." Hyperfine Interact., (in press, 2015).

[8] M.S. Sanjari, et al., "Conceptual Design of Elliptical Cavities for Intensity and Position Sensitive Beam Measurements in Storage Rings." Phys. Scr., (in press, 2015).

[9] S. Peggs et al., "ESS Technical Design Report", Lund, Sweden (2013).

[10] F. Becker, "Non-destructive Profile Measurement of Intensive Heavy Ion Beams", PhD Diss., Darmstadt, Germany (2010).

[11] T. Giacomini et al., "IPM@GSI", Proc. DIPAC2011, Hamburg, Germany (2011).

[12] C. Roose et al., "Methods for Measuring the Transverse Beam Profile in the ESS High Intensity Beam", Proc. IBIC, Monterey, USA (2014).

[13] M.R. Bartosik, et al., 'Cryogenic Beam Loss Monitors for the Superconducting Magnets of the LHC', Proc. IBIC, Melbourne, Australia (2015).

[14] L. Torino et al. "Limitations and Solutions of Beam Size Measurements via Interferometry at ALBA", Proc. IBIC, Melbourne, Australia (2015).

[15] indico.cern.ch/conferenceDisplay.py?confId=243336

[16] indico.cern.ch/conferenceDisplay.py?confId=293158

[17] indico.cern.ch/conferenceDisplay.py?confId=333414

[18] indico.cern.ch/conferenceDisplay.py?confId=368273

[19] indico.cern.ch/conferenceDisplay.py?confId=380975

ISBN 978-3-95450-176-2