# ACCELERATOR OPTIMIZATION THROUGH BEAM DIAGNOSTICS

C.P. Welsch#, Cockcroft Institute and The University of Liverpool, UK
on behalf of the oPAC Consortium

*Abstract*

A comprehensive set of beam diagnostics is key to the successful operation and optimization of essentially any accelerator. The oPAC project received 6 M€ of funding within the EU's 7th Framework Programme. This has allowed to successfully train 23 Fellows since 2011. The network joins more than 40 institutions from all around the world, including research centers, universities and private companies. One of the project's largest work packages covers research in beam diagnostics. This includes advanced instrumentation for synchrotron light sources and medical accelerators, enhanced beam loss monitoring technologies, ultra-low emittance beam size diagnostics, diagnostics for high intensity beams, as well as the development of electronics for beam position monitors. This paper presents an overview of the research outcomes from the diagnostics work package and the demonstrated performance of each monitor. It also shows how collaborative research helps achieving beyond state-of-the-art solutions and acts as an ideal basis for researcher training. Finally, an overview of the scientific events the network has been organizing for the wider accelerator community is given.

## INTRODUCTION

The optimization of the performance of particle accelerators was the goal of the Marie Curie Initial Training Network (ITN) oPAC [1]. The project received 6 M€ of funding from the European Union within the 7$^{th}$ Framework Programme, making it the largest-ever ITN. It successfully trained 23 Fellows across 4 scientific work packages (WPs) and allowed them to develop expert knowledge in a number of different fields, such as engineering, physics, electronics, IT and material sciences. Training through network-wide events including schools and topical workshop, participation in international conferences, and secondments for specific skill-building has allowed them to carry out cutting edge research whilst providing them with a broad set of skills that is expected to be an excellent basis for their future careers.

## RESEARCH

The results from the oPAC Fellows' research have resulted in more than 100 contributions to international conferences and workshops. More than 30 papers have already been published in peer-reviewed journals and several more are currently in preparation as results from research projects are being analyzed and Fellows are finalizing their doctoral theses. The following sections present the results from three selected research projects that all formed part of the beam diagnostics work package.

The developments in this WP received additional support by a dedicated hands-on training day in beam instrumentation hosted by Bergoz in June 2013. This familiarized all Fellows in the first year of their project with the particular challenges in carrying out measurements of the detailed characteristics of charged particle beams and allowed them to discuss progress in all sub projects. Of particular importance for instrumentation development is that no single monitor has yet been developed that is able to monitor all properties of a beam, i.e. several different technologies usually need to be combined to get a full understanding of the beam inside its vacuum chamber. Most oPAC projects initially targeted the development of a single detector (prototype) for a specialized purpose. Information from this monitor was then combined with other detectors and linked to the accelerator control and data acquisition system to obtain a full understanding about the beam.

### *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.

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#c.p.welsch@liverpool.ac.uk

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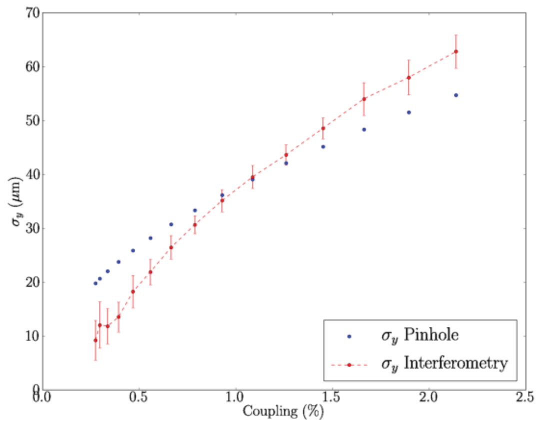


Figure 1: Vertical beam size measurements $\sigma_y$ from the pinhole (blue) and the interferometer (red).

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. 1. Further details are given in [2].

### *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 [3]. 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 [4]. 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 [5]. 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.

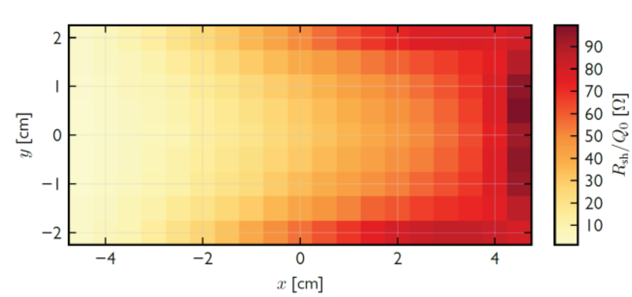


Figure 2: Measured shunt impedance of the rectangular Schottky monitor prototype.



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### *Cryogenic Current Comparator for Low Energy Antiproton Beams*

A Cryogenic Current Comparator (CCC) monitor optimized for the AD and ELENA rings at CERN has been developed by M. Fernandes, based at CERN, and first measurements with beam have been carried out, see Fig. 3 [6]. These are the first CCC beam current measurements performed in a synchrotron using both, coasting and short-bunched beams.

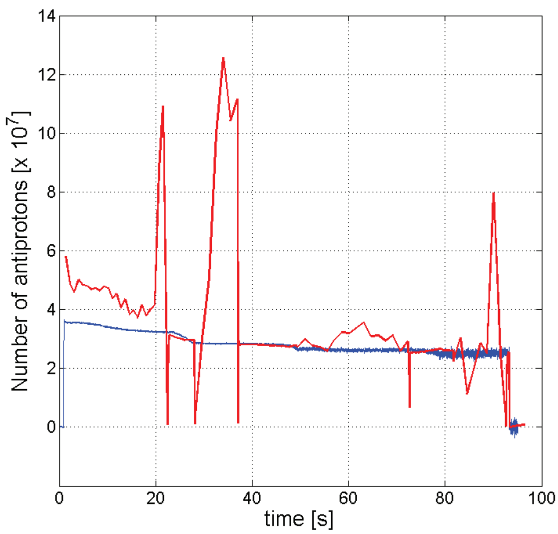


Figure 3: Comparison between measurement with Schottky noise based monitor (in red) and CCC (blue).

The CCC is currently the only device able to measure non-perturbatively very low-beam intensities. A particular improvement is the possibility of absolute calibration of the experiments receiving the particle beam using data from the CCC, as well as cross-calibration of other intensity monitors for which no simple calibration method is available. A current intensity resolution of 30 nA was successfully demonstrated after low-pass filtering with a cut-off frequency at 10 Hz. The system was able to cope with a beam current signal slew-rate exceeding 8 kA/s maintaining the SQUID/FLL stability. A new cryostat mechanical design provided for an excellent decoupling of mechanical perturbations, enabling the CCC monitor to attain this performance even when the connected cryocooler unit was operating.

## TRAINING EVENTS

Training within oPAC was provided to all Fellows 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 7$^{th}$-11$^{th}$ 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 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 27$^{th}$/28$^{th}$ 2013 [7], a workshop on Beam Diagnostics hosted by CIVIDEC [8] 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 [9]. This was a special event for the network

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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. In 2016, the Fellows were invited to a careers workshop held in June in Krakow, Poland. A Topical Workshop on Beam Loss Monitors, organized immediately after this IBIC conference, was the final event to date [10].

### *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 [11]. Finally, the network has organized a 3-day international conference on accelerator optimization in Seville, Spain [12].

## SUMMARY

oPAC has successfully trained 23 early stage researchers between 2012 and 2015. The network has also organized a large number of international schools and topical workshops that have benefited the world-wide accelerator community. On the basis of the extremely positive feedback that was received from the community, the consortium has recently organized a Fellow reunion and careers workshop, as well as a Topical Workshop on Beam Loss Monitors [13] that follows after this IBIC conference. Additional future events will be considered based on the demand and input from the wider beam instrumentation community.

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