BEAM DIAGNOSTICS R&D WITHIN OPAC

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Abstract

Optimization of particle accelerators by combining research into beam physics, beam instrumentation, accelerator control systems and numerical simulation studies is the goal of the oPAC project. Supported with 6 Million Euros by the European Union, the network is one of the largest-ever Marie Curie Networks. During its four year duration 22 Fellows will be trained and a very broad international training program, consisting of Schools, topical Workshops and conferences will be organized by a consortium of currently more than 30 partner institutions. Here, we give an overview of oPAC's beam diagnostics R&D program, comprising instrumentation for synchrotron light sources, cyrogenic beam loss monitors, ultra-low emittance beam size diagnostics and development of compact electronics for beam position monitors. An overview of oPAC events is also given.

INTRODUCTION

The oPAC consortium combines studies into the physics and dynamics of particle beams, with an improvement of existing accelerator and field simulations tools, the development of beam instrumentation, and an R&D program into accelerator control and data acquisition systems. The network carries out a broad and closely interconnected experimental program that combines different scientific disciplines, such as for example physics, electronics, IT, material sciences, and medical applications. The presence of industry in the consortium ensures that spin-off developments are actively sought and that the training provides all ESRs with a skills set that will give them an excellent base for their future careers. All developments are closely linked to the much wider experimental programs at the different oPAC partner institutions. The network consists of 12 beneficiary partners (3 from industry, 3 universities and 6 research centers), as well as of 22 associated and adjunct partners, 7 of which are from industry [1].

BEAM DIAGNOSTICS R&D

A versatile beam diagnostics system is crucial for the successful operation and continuous optimization of any particle accelerator or light source. A few years ago, the DITANET consortium [2] set out to define improved training standards in this research area and the development of cutting edge beam diagnostics is also a key aspect in the oPAC project. Here, we give a summary of first research results from Fellows across the network.

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Beam Instrumentation for Light Sources

Synchrotron Light sources are accelerator facilities producing synchrotron radiation to perform experiments in many fields of science. ALBA is a third generation Synchrotron Light source, located close to Barcelona in Spain with a 3 GeV electron beam available for users since May 2012. The quality of the radiation used for the experiments directly depends from the longitudinal and transverse distribution of the electrons in the storage ring. Therefore these characteristics have to be continuously monitored with a non-invasive diagnostic system. To monitor the longitudinal charge distribution, the so-called filling pattern, different techniques were tested by oPAC Fellow Laura Torino at ALBA using analogue and electro-optical (EO) devices [3].

In the case of analogue devices, direct beam profile measurements were performed using a Fast Current Transformer (FCT) and the sum of the four buttons of a Beam Position Monitor (BPM), both located in the storage ring.

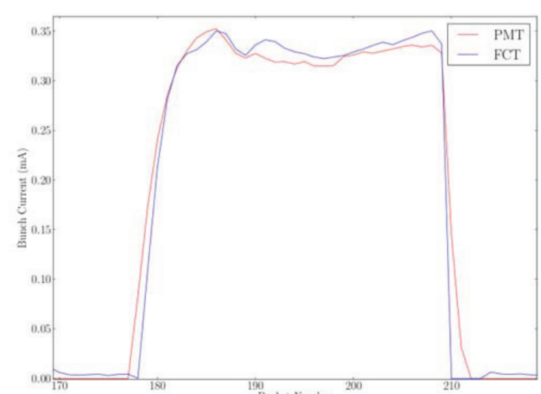

Figure 1: One train of the ALBA filling pattern measured with FCT (blue) and PMT (red). The FCT has a better time response, while the PMT is less affected by noise.

EO measurements are based on the correlation between the longitudinal distribution of the electrons in the machine and the temporal distribution of the produced synchrotron radiation. To measure the filling pattern, the visible part of the radiation was detected at the ALBA optical beamline Xanadu using a Photomultiplier tube (PMT). Results were observed directly with an oscilloscope and analyzed later. The same PMT was then used to measure the filling pattern with Time Correlated Single Photon Counting (TCSPC). This technique consists of measuring the distribution of the time difference between a given trigger signal and the arrival time of a single photon from the beam to the detector. In

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all cases the quantitative information on the charge per bunch was achieved distributing the current read from the DCCT in the storage ring. A similar data analysis was applied to all acquired data to enable a comparison between different techniques. Results show that systematic errors induced by analogue or EO devices are different. This yields a good overall characterization of the filling pattern when combining the two techniques. Fig. 1 shows one train of the ALBA filling pattern measured with FCT and PMT. FCT (in blue) has a good time resolution but is affected by noise in the gaps. PMT (in red) has a slower decay time that makes identification of the last filled bunch of the train difficult, but gaps are not affected by noise at all. Currently the filling pattern is monitored online using mainly the FCT. Further developments of the TCSPC using a different detector are foreseen. To monitor the bunch by bunch transverse charge distribution interferometry is under development [4]. Preliminary measurements were performed at the ALBA optical beamline Xanadu where synchrotron radiation was selected, focused and guided through a double slit mask that produces an interference pattern. Data was then collected by means of a CCD camera and analyzed off-line. Good results were obtained for both, horizontal and vertical beam-size with limitations mainly coming from imperfection in the in-vacuum mirror used to extract the visible radiation from the vacuum chamber. Improvements are expected in December when a new mirror will be installed. In the future it is planned to replace the CCD camera by a Fast Gated Camera that can be synchronized with the general ALBA timing system. On-line data analysis will be implemented to provide real time bunch by bunch transverse beam size measurements.

Cryogenic Beam Loss Monitors for the LHC

The protection ability of the current Beam Loss Monitoring (BLM) system around the triplet magnets at the LHC interaction regions is not maintained for all loss scenarios for higher beam energies and intensities. The envisaged solution is to install particle detectors as close as possible to the superconducting coil, which means inside the cold mass of the magnets. This allows improved protection for the high-luminosity LHC. Prior to work carried out by oPAC Fellow Marcin Bartosik at CERN, no detector technology had proven to work under the conditions encountered at this location. Three detector technologies were selected for further investigation: silicon sensors, diamond detectors and a Liquid Helium (He_l) ionization chamber. Silicon detectors are widely in use for particle detection and possess promising properties at cryogenic temperatures [5]. Diamond detectors have the main advantages to generate significantly less leakage current at room temperature and to be more radiation hard compared to silicon material. The liquid helium chamber is a completely new in-house produced prototype. Its main advantage is to be insensitive to radiation damage. The downside is the extremely low charge mobility, which is 5 orders of magnitude lower than for diamond. Measurements in the laboratory with laser and alpha source allowed drawing a detailed picture of the charge carrier properties in the semiconductor detectors down to He_l temperatures. The setup for measurements with Minimum Ionizing Particles (MIP) is shown in Fig. 2. The silicon detector Full Width Half Maximum (FWHM) of the signal from a MIP is only 2.5 ± 0.7 ns. For the diamond detector the FWHM is 3.6 ± 0.8 ns, while the He_l chamber has a much longer charge collection time of 180 µs.

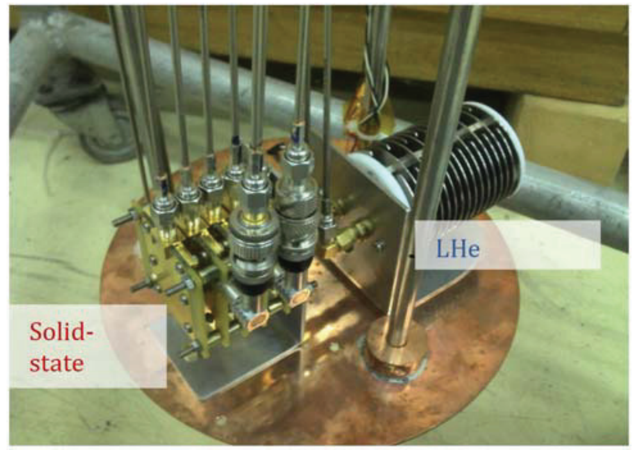

Figure 2: Detector installation for immersion in liquid helium and measurement in beam.

Finally, irradiation measurements at cryogenic temperatures were performed. The measured radiation induced signal degradation over 20 years (2 MGy) of LHC operation is of a factor 25 ± 5 for silicon detectors, while it is of 14 ± 3 for the diamond devices. With silicon and diamond sensors a fast detection system can be designed allowing bunch by bunch resolution. The He_l chamber on the other hand is an elegant solution due to its insensitivity to radiation damage. The results hence motivate to combine the advantages, by using solid-state detectors for a fast protection system, while the He_l chamber can be used in parallel for calibration and for protection from steady state losses. Further measurements, models, simulations and the installation of first CryoBLM prototypes during the first long shutdown will allow additional conclusions.

Ultra-low Emittance Beam Size Measurement

Transverse electron beam diagnostics is crucial for stable and reliable operation of the future electron-positron linear colliders such as CLIC or Higgs Factory. The-state-of-the-art in transverse beam diagnostics is based on the laser-wire technology. However, it requires a high power laser significantly increases the cost of the laser-wire system. Therefore, a simpler and relatively inexpensive method is required. A beam profile monitor based on Optical Transition Radiation (OTR) is very promising. The resolution of a conventional OTR monitor is defined by the root-mean-square of the so-called Point Spread Function (PSF) which describes the response of an

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optical system to a source distribution generated by a single charge. In the optical wavelength range the resolution is diffraction limited down to a few micrometers. The best resolution achieved so far by conventional OTR monitors is around a few micrometers [6]. However, in [7] it was demonstrated that the OTR PSF differs from a conventional PSF of an optical system. While the vertical polarization component of the OTR has a two-lobe structure which can be used to monitor the vertical beam size with sub-micrometer resolution. On the other hand if the beam is flat, which is true for linear colliders, the horizontal projection of the distribution represents a direct measurement of the horizontal beam size which gives an opportunity to measure the electron beam size in two directions in a single shot. Transverse beam size measurements were recently carried out at the ATF facility in Japan showing that it is possible to achieve a sub-μm resolution, see Fig. 3 [8].

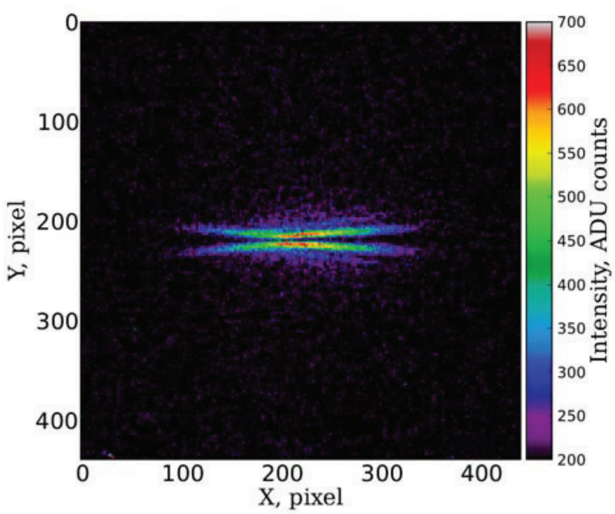

Figure 3: Typical image of the OTR spot taken with linear polarizer and 550±20 nm optical filter.

The minimum measured vertical beam size was 0.7541±0.034 μm which is approximately 5 times better than the resolution of conventional OTR monitors. In order to further improve the resolution of the monitor, effects significantly influencing on the PSF width need to be reduced. One way is to use a special simulation tools for optical calculations to better understand of the PSF behavior. It was shown in [9] that using such tools lead to results which are in a good agreement with real experimental data and can be used for very accurate simulations of the optical system to achieve the best resolution. Another way would be to use reflective instead of refractive optics. For example using an off-axis parabolic mirror could reduce chromatic aberration effects. However, using such mirror in a real experiment becomes challenging because of mirror alignment. Even small deflection of an incidence angle leads to significant image distortion. The idea of using reflective elements for OTR beam profile measurements and its influence on the resolution are subject to further studies.

Compact Electronics for BPMs

Electronics for BPMs have been focused in the past on storage rings and their requirements, where the beam stability needs to be as good as it can be. Precise measurements of beam position and fast data delivery rates are then provided. For boosters such performance is not required: usually the beam position resolution ranges from tens of microns to millimeters, and the operator needs to access such information on demand. As a consequence, the complexity of the design can be reduced while other aspects could be improved. The idea behind a new development in which oPAC Fellow Manuel Cargnelutti is involved through Instrumentation Technologies is to provide an instrument optimized for both, booster and injector applications. This will support beam position data with micrometer resolution, provided for the whole acceleration cycle, digital-down-conversion (DDC) feature with mean average filter (MAF) functionality to optimize measurements at different fill patterns, zero maintenance and passive cooling and Power-over-Ethernet (PoE) supply. To combine all these features, a new platform was required and a device was developed that would be able to cover more than one booster application. Special effort was spent in optimizing the balance between flexibility and high performance in special focus areas. A big novelty in the design is in the System on Chip (SoC) – Xilinx Zynq 7020 – that hosts both field programmable gate array (FPGA) and central processing unit (CPU). Since the memory is shared between the two parts, no data transfer protocols are needed any more. Another advantage is a consequence of fans removal and adoption of passive cooling: the system can be powered through Power-over-Ethernet (PoE). The interface with the instrument is based on the Standard Commands for Programmable Instrument (SCPI) and provides an easy way to integrate the instrument into the control system.

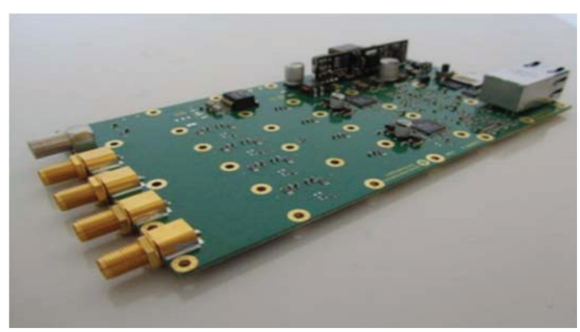

Figure 4: Photograph of prototype board.

The development of the instrument is on the way with first prototypes produced, see Fig. 4. First measurements are underway using the already implemented software and FPGA logics. Initial results are within expectations. Confirmation of the design and implementation is expected to be tested on the development prototype in the end of October 2013 at ESRF [10].

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TRAINING EVENTS

Training within oPAC is provided locally at the respective host institute, primarily through cutting edge research, local lecture and seminar series, as well as network-wide training offered by the whole consortium. In addition, the network also organizes a series of Topical Workshops and international Schools for its Fellows which are also open to the wider accelerator community.

International Schools

At the start of their training all oPAC Fellows participated in either the CERN Accelerator School or the Joint Universities Accelerator School. This provided them a sound training basis as they take 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 will be organized by the consortium between 7th-11th July 2014 at Royal Holloway University of London, UK. It will cover 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 met already 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. A second complementary skills School in the project's final year will allow the Fellows to build on project management with an advanced course in addition to covering topics relevant to their future employment, such as CV writing and job applications, as well as an introduction to the careers market and writing competitive grant applications.

Topical Workshops

oPAC will also organize a series of Workshops; most will be open to external participants. Two expert training days on 'Simulation Tools' (CST, Germany) and 'Beam Diagnostics' (Bergoz, France) were already held for all Fellows on June 25/26 . This was followed by a 2-day Topical Workshop on the Grand Challenges in Accelerator Optimization at CERN, Switzerland on June 27/28th 2013. This event provided an overview of the current state of the art in beam physics, numerical simulations and beam instrumentation and highlighted existing limitations. Full details and all presentations can be found on the Workshop web site [11].

A Workshop on 'Beam Instrumentation' focusing on beam profile and position monitoring will take place in Vienna, Austria on 8th /9th May 2014 and many more are in the planning. All events will be announced via the oPAC web page [1] and in the project's quarterly newsletter and Facebook page.

Conference on Accelerator Optimization

In the final year of oPAC, a 3-day international conference on accelerator optimization will be organized, with a focus on the methods developed within the network. This event will also serve as a career platform for the network's trainees who will get the opportunity to present the outcomes of their research projects. In addition, a Symposium open to the general public will be held in Liverpool on 26th June 2015 to promote the research outcomes beyond the scientific community.

SUMMARY

An overview of the beam diagnostics R&D program within the recently approved oPAC project was given. The network is one of the largest initial training networks ever funded by the European Union and will train 22 early stage researchers over the next four years. The consortium consists of universities, research centers and industry partners and will also organize a rather large number of training events. This includes Schools, Topical Workshops and an international conference which will all be open also for participants from outside the project.

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