

DITANET - AN INTERNATIONAL NETWORK IN BEAM DIAGNOSTICS

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Abstract

Beam diagnostics systems are essential constituents of any particle accelerator; they reveal the properties of a beam and how it behaves in a machine. Without an appropriate set of diagnostic elements, it would simply be impossible to operate any accelerator complex, let alone optimize its performance. Beam diagnostics is also a rich field in which a great variety of physical effects are made use of and consequently provides a wide interdisciplinary base for the training of researchers. The DITANET consortium develops beyond state-of-the-art beam diagnostic techniques for hadron and electron accelerators and trained more than 20 researchers between 2008 and 2012. This contribution gives examples from the network's research outcomes in beam instrumentation and diagnostics.

INTRODUCTION

DITANET was funded by the European Union as an ITN in 2008, completing in May 2012. It was selected for funding amid high competition and achieved a budget of €4.16 million, making it the largest-ever researcher training initiative in beam instrumentation for accelerators. The Consortium consists of 10 beneficiary partners, all of whom employed researchers, and 12 associate partners who provided secondments and expertise within the Network. In addition, the Network gets support from 10 adjunct partners who joined and took part post-funding and throughout the lifetime of the project, adding an international element to the Network. DITANET has worked on developing diagnostics methods for a wide range of existing or future particle accelerators which was achieved through a cohesive approach, including promoting knowledge exchange between partners. With the aim to maximize employability of all fellows, and to provide them with an extremely broad skills set that shall serve them as a solid basis for their future careers, DITANET set out to define improved training standards for early career researchers.

SELECTED RESEARCH RESULTS

Research within DITANET was split over six thematic work packages: particle detection, beam current measurement, electronics, beam position determination, as well as transverse and longitudinal beam profile measurements. Although all fellows worked primarily on their individual research projects, very often in the frame of PhD studies, many links between projects were exploited during the four year project. This section

summarizes the research results from three selected research projects carried out by fellows based at CERN, the University of Seville/CNA and GSI.

LHC Longitudinal Density Monitor

The longitudinal density monitor (LDM) was developed by DITANET fellow Adam Jeff at CERN and is primarily intended for the measurement of the LHC particle population in nominally empty rf buckets. These so-called satellite or ghost bunches can cause problems for machine protection as well as influencing the luminosity calibration of the LHC. The high dynamic range of the system allows measurement of ghost bunches with as little as 0.01% of the main bunch population at the same time as characterization of the main bunches. The LDM is a single-photon counting system using visible synchrotron light. The photon detector is a silicon avalanche photodiode operated in Geiger mode, which allows the longitudinal distribution of the LHC beams to be measured with a resolution of 90 ps. The monitor allows for a precision measurement of the longitudinal density profile in the LHC [1].

Within this project it was shown that a photon-counting method can produce longitudinal profiles of the LHC beams with high dynamic range and good time resolution. Bunch-by-bunch measurement of all bunches in the machine is made simultaneously. Silicon APDs operated in Geiger mode are used for photon detection. The dynamic range of the system is largely limited by the response of these APDs, in particular by the dead time and by afterpulsing. Correction of the signal for these effects substantially increases the dynamic range.

A further improvement in dynamic range could be achieved if an optical gating could be applied to the signal, and a scheme is proposed to implement this using electro optic deflection. The small active area of the APDs causes difficulties with coupling stability and emittance dependence, but also opens the possibility of 3-dimensional bunch shape measurements by scanning the detector over the transverse plane.

The longitudinal density monitor has been proven against established instruments such as the beam current transformers and wall current monitors. The population of satellites close to the colliding bunches has also been confirmed by data from the experiments. The LDM is now widely used in LHC operation and plays an important part in the van der Meer scan procedure which is used for absolute luminosity calibration by the LHC experiments. The LDM is the primary tool for the quantification of ghost and satellite bunches, which can be measured with a dynamic range of 10^5 .

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Output Factor Determination for Dose Measurements in Axial and Perpendicular Planes using a Silicon Strip Detector

For a given photon beam at a given source to surface distance (SSD), the dose rate at a certain depth d in a phantom depends on the field size. The output factor (OF) is defined as the ratio of the dose for any field size $A \times A \text{ cm}^2$ to the dose for a reference field at the same source to surface distance, and at the same depth d in a slab phantom. Usually the reference field is a square field of $10 \times 10 \text{ cm}^2$ at an SSD of 100 cm; the larger the field size, the higher the dose. The OF is an intrinsic characteristic of the respective accelerator and is measured periodically to make sure that the accelerator is operating properly in order to treat patients.

For the purpose of verifying a detection system at the University of Seville/Centro Nacional de Aceleradores and its calibration, the dose given by various square fields was also measured in an in-house designed cylindrical phantom, normalized to the reference field. These measurements were carried out by Ziad Abou-Haidar at the Virgin Macarena University Hospital in Seville, where an electron linac, Siemens ONCORTM dual energy machine, is used to deliver radiotherapy treatment for cancer patients [2].

For these measurements the linac was operating in photon mode with a nominal energy of 6 MV. It is capable of generating high dose rate photons by colliding accelerated electrons on a tungsten target thus producing a bremsstrahlung effect. The different field sizes and shapes were obtained by using the collimation system provided within the accelerator head. It consists of a pair of jaws moving along the in-plane (longitudinal) direction and a multileaf collimator (MLC) moving along the cross-plane (transversal) direction. Longitudinal and transversal directions are related to the long and short dimensions of the treatment couch, respectively. The MLC incorporates 80 pairs of closely abutting tungsten leaves. Each leaf is individually motorized and controlled allowing the generation of irregular radiation fields. In our case, rectangular and square fields were used.

The dose that was measured is the dose deposited by the electrons that were accelerated by the photons hitting the phantom. The spectrum of these electrons depends on the field size. This was validated with a calibration using a reference field of $10 \times 10 \text{ cm}^2$ in earlier studies. Within DITANET the system was tested by using it to measure the output factor in order to make sure that the same calibration is maintained while using different electron spectra associated to various field sizes and shapes.

The spectrum of the electrons set in movement by the photons entering the phantom depends on the field size. The change in the spectrum for different fields would come into play through its possible effect in the dose calibration of the detector, which would be reflected in the output factor. Measurements proved that this change is not relevant and that the calibration of the detector performed with a standard field ($10 \times 10 \text{ cm}^2$) is also valid

for smaller ones that are usually employed for complex treatments. Based on a detailed validation, real treatments with any field size can then be measured and dose maps could be obtained by an in-house Radon transform based algorithm. As a follow on project, research is in progress to achieve a larger active area detector ($64 \times 64 \text{ mm}^2$) including 2D strips with smaller strip pitch (2 mm), more precise electronics, an improved rotating phantom, and a more user friendly data acquisition system.

Interpretation of Transverse tune Spectra in a Heavy-ion Synchrotron at High Intensities

Accurate measurements of the machine tune and the chromaticity are of importance for the operation of fast ramping, high intensity ion synchrotrons. In such machines the tune spread $\delta Q_{x,y}$ at injection energy due to space charge and chromaticity can reach values as large as 0.5. In order to limit the incoherent particle tunes to the resonance free region, the machine tune has to be controlled with a precision better than $\Delta Q \sim 10^{-3}$.

In the GSI Helmholtzzentrum für Schwerionenforschung heavy-ion synchrotron SIS-18 there are currently two betatron tune measurement systems installed. The frequency resolution requirements of the systems during acceleration are specified as 10^{-3} , but they provide much higher resolution (10^{-4}) on injection and extraction plateaus. The tune, orbit and position measurement system (TOPOS) is primarily a digital position measurement system which calculates the tune from the measured position. The baseband Q measurement system (BBQ) conceived at CERN performs a tune measurement based on the concept of diode based bunch envelope detection. The BBQ system provides higher measurement sensitivity than the TOPOS system.

These two complementary tune measurement systems were studied in detail by DITANET fellow Rahul Singh as part of his PhD work at GSI [3]. Analytical, as well as simulation models predict a characteristic modification of the tune spectra due to space charge and image current effects in intense bunches. The position of the synchrotron satellites corresponds to the head-tail tune shifts and depends on the incoherent and the coherent tune shifts. The modification of the tune spectra for different bunch intensities has been observed in the SIS-18 at injection energy, using the TOPOS and BBQ systems.

From the measured spectra the coherent and incoherent tune shift for bunched beams in SIS-18 at injection energies were obtained experimentally using the analytic expression for the head-tail tune shifts. Head-tail modes were individually excited and identified in time domain and correlated with the spectral information. A novel method for determination of chromaticity based on gated excitation of individual head-tail mode is shown. The dependence of the relative amplitudes of various head-tail modes on chromaticity is also studied. The systems were compared against each other as well as with different kinds of excitation mechanisms and their respective

powers. These measurements give a clear interpretation of tune spectra at all stages during acceleration under typical operating conditions. The understanding of tune spectra provides an important input to new developments related to foreseen transverse feedback systems for SIS-18 and SIS-100. The measurement systems also open new possibilities for detailed beam investigations as demonstrated in [3].

TRAINING AND OUTREACH

In addition to the local training provided by the host institutions, DITANET organized a number of network-wide events, such as Diagnostics Schools, Topical Workshops and a conference that were also open to the wider diagnostics community.

International Schools

The network organized two international schools on beam diagnostics. The first took place March 30th-April 3rd 2009 at Royal Holloway, University of London, UK. It started with an introduction to accelerator physics and the definition of particle beams, before basic beam instrumentation such as, for example, beam energy, beam current or transverse beam profile measurement were covered. Later the week more advanced topics, such as the monitoring of the machine tune or electron cloud diagnostics were presented. An excursion to Rutherford Appleton Laboratory including visits to ISIS and DIAMOND, as well as two tutorials and one poster session complemented the broad program.

An advanced DITANET School took place in Stockholm, Sweden March 7th-11th 2011. The event was hosted by Manne Siegbahn Laboratory. This school joined around 100 researchers and started with a recap of some of the key concepts introduced during the first school back in 2009. During the week, beam instrumentation for specific applications, such as low energy accelerators, light sources, colliders or high intensity accelerators were presented in detail. The intense lecture program was complemented by dedicated Question & Answer sessions, as well as focused tutorials. In addition, participants were given the opportunity to present their own work in this interdisciplinary field in a poster session that triggered many discussions.

Topical Workshops

Altogether, DITANET has organized nine Topical Workshops on special areas of beam instrumentation and diagnostics to date: Beam Position Monitors at CERN, 16th - 18th January 2012; Beam Loss Monitoring at DESY, Germany, 5th - 7th December 2011; Detection Techniques at University of Seville/CNA, Seville, Spain, 7th - 8th November 2011; Technology Transfer at Instrumentation Technologies, Solkan, Slovenia, 29th - 30th September 2011; Beam Intensity Measurements at CEA, France, 26th - 27th September 2011; Ultra-High Brightness Electron Sources at Cockcroft Institute/University of Liverpool, UK, 29th June - 1st July 2011; Longitudinal Beam Profile

Measurements at Cockcroft Institute/University of Liverpool, UK, 12th - 13th July 2010; Diagnostics of Low Energy Low Intensity Ion Beams at Hirschberg-Großsachsen, Germany, 24th - 25th November 2009 and most recently on non-invasive beam profile monitoring at CERN, 15th - 18th April 2013. All presentations can be found in CERN indicio, via the project homepage [4].

Conference and Symposium

In its final year, the consortium held a three day international conference on diagnostic techniques for particle accelerators and beam instrumentation in Seville, Spain between 9th and 11th November 2011. The conference was hosted by DITANET partner Centro Nacional de Aceleradores (CNA)/ University of Seville and brought together all beneficiary, associate and adjunct partners from the consortium. It was also open to participants from the world-wide diagnostics community, in particular to researchers in their early career stage. The latest developments and trends in this research area were presented in both oral and poster sessions. Invited talks given by research leaders from around the world formed the core of this interdisciplinary event. They were complemented by talks that were selected from all contributors to the conference. The scientific program of this conference reflected the extremely broad research program that is being carried out by the DITANET partners and covered all essential aspects of state-of-the-art beam diagnostics R&D. An international symposium on researcher training, beam diagnostics and antimatter research completed the training program and was held at the Cockcroft Institute in May 2012.

CONCLUSION

Within DITANET more than twenty early career researchers have been trained and many of them have completed their PhD studies in the frame of this project. Selected examples of research results were presented in this paper and an outline of the network's international training program was given. Based on the DITANET research and training concept and vision, two new initiatives, the oPAC and LA³NET projects, were recently selected for funding by the European Union. Both projects started at the end of 2011 and have a duration of 4 years.

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