

# DEVELOPMENT OF LONGITUDINAL BEAM PROFILE DIAGNOSTICS WITHIN DITANET\*

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## Abstract

The exact determination of the time structure of ever shorter bunches in accelerators and light sources such as for example the X-FEL, the ILC or CLIC is of high importance for the successful operation of these next-generation machines. It is also a key to the optimization of existing scientific infrastructures. The exact measurement of the time structure poses a number of challenges to the beam diagnostics system: The monitors should be non-destructive, easy to maintain and provide time resolutions down to the femtosecond regime.

Several DITANET partners are active in this field. This contribution gives examples of the network's research activities in this area with a focus on the LHC longitudinal density monitor, beam profile monitoring using electro-optics techniques and the exploitation of diffraction radiation for non-invasive diagnostics.

## INTRODUCTION

The DITANET project started on 1.6.2008. It is a Marie Curie Initial Training Network that brings together ten network beneficiary partners and presently 18 associated and adjunct partners. The main aim of the network is to provide research training to its internationally recruited early stage (ESR) and experienced (ER) researchers. Participation of industry partners is an integral part of this training with smooth integration of industry not only in the individual research projects, but also in the overall training of the DITANET trainees. The network thereby strives to improve the career perspectives of the next generation of researchers in this field.

## RESEARCH RESULTS

Many partners from the DITANET consortium are carrying out research into longitudinal beam profile measurements. This includes for example DESY, INFN, Berkeley or Fermilab. The following sections summarize some of the recent research outcomes with an emphasis on projects realized by DITANET trainees. Full details can be found on the network's homepage [1].

### *LHC Longitudinal Density Monitor*

Synchrotron Radiation (SR) is an excellent tool for particle beam diagnostics as it is non-disruptive and carries information on both the transverse and longitudinal particle distribution. The Longitudinal Density Monitor (LDM) for the LHC uses single-photon counting to overcome the problem of low light intensity

\*Work supported by the EU under contract PITN-GA-2008-215080.

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and achieve a high dynamic range. Within the ESR project of A. Jeff at CERN, the synchrotron light for the LDM is exploited from two different sources: A dipole with a maximum field of 3.9 T emits visible SR at beam energies above 1.5 TeV, but produces only infra-red radiation at LHC injection energy of 0.45 TeV. To fill this gap a superconducting undulator with two 28-cm periods and a peak field of 5 T was installed upstream of the dipole. The undulator produces visible light from 0.45-1.5 TeV before moving into the ultraviolet above 1.5 TeV. Visible light is thus available across the whole energy range, with a minimum in intensity at the crossover of the two sources around 1.2 TeV [2].

The detector used for the LDM is the Photon Detection Module (PDM) from Micro Photon Devices [3]. This is a silicon avalanche photodiode (APD) operated in the Geiger mode [4]. Its detection efficiency is ~35% averaged over the visible range and its time resolution is 50 ps FWHM. Measurements were taken with the LDM during both proton and ion runs. In the case of lead ions, the lower relativistic  $\gamma$  means that the SR is almost entirely in the infra-red at injection, and measurements with the LDM were only possible above 900 GeV proton-equivalent energy.

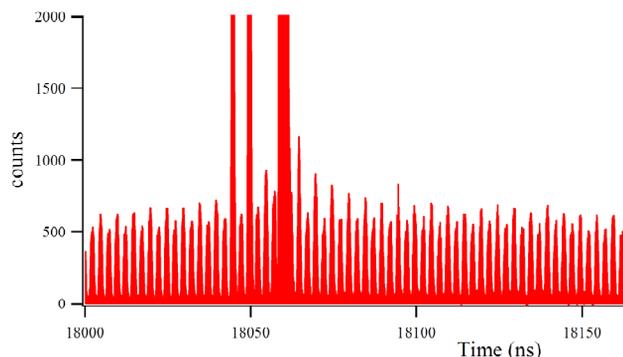


Figure 1: Measured longitudinal profile of heavy ion beam in the LHC with 500 ns bunch spacing. The main bunch arrives at  $t=18,060$  ns and is preceded by two satellites; ghost bunches spaced at 2.5 ns are present around the ring.

A measured beam profile is shown in Fig. 1. Ghost bunches can be distinguished down to a peak of 50 counts, compared to the main bunch with a peak of  $1.4 \times 10^6$  counts, corresponding to a dynamic range of better than  $10^4$ . Small ghost bunches spaced at 2.5 ns (i.e. occupying the LHC RF buckets) spread around the ring with population slowly decreasing far from the full bunches. Larger satellites near to the full bunch have 5 ns

spacing and are thought to originate in the LHC injectors where a lower RF frequency is used. This pattern of satellites, with the largest occurring 10 and 15 ns before the main bunch, was reproduced in most ion fills.

### EO Techniques for Femtosecond Diagnostics

Electro-optic (EO) and related techniques have shown themselves to be extremely promising for the measurement of electron beam longitudinal profiles where the ultra-short electron bunches have structure in the range from picoseconds down to tens of femtoseconds (and indeed below). Within DITANET, the group of W.A. Gillespie at the University of Dundee has led many groundbreaking experiments in this area in the past. The ESR R. Pan at CERN is closely collaborating with this group and ASTeC, UK. He is presently working on further improvements on the resolution limits.

The principle of electro-optic longitudinal diagnostics is to accurately measure the temporal profile of the Coulomb field of the extreme relativistic electron beam, without intercepting the beam itself, through optical nonlinearities induced in an electro-optic crystal within the electron beam line. The crystal is placed adjacent to the electron beam, but the beam does not traverse the crystal, making this a completely non-intercepting technique. The Coulomb field sweeping through the appropriately chosen crystal renders the material birefringent during the field transit; this birefringence is probed by a chirped (or sometimes ultra-short) optical probe laser pulse that is passed through the crystal parallel to the electron beam axis, and in synchronism with the electron bunch.

Once the probe laser beam has interacted with the electron bunch, it is extracted from the beam line and the resulting time-varying rotation of the polarization of the optical pulse can be sensitively detected using all-optical techniques to yield a temporal (or longitudinal) evolution of the Coulomb field, which itself is a measure of the charge density longitudinal profile within the bunch.

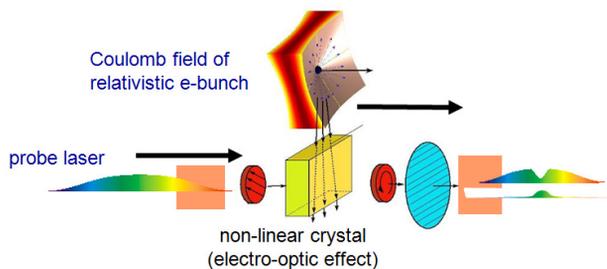


Figure 2: Principle of operation of EO detection.

Three techniques of EO longitudinal diagnostics have been demonstrated in accelerator experiments, spectral decoding [5], temporal decoding [6] and spectral upconversion [7]. Of these, SD and TD have been most extensively developed and demonstrated.

In all techniques, the encoding of the bunch profile is via the Coulomb field at a radially offset distance, which introduces a time resolution limit through the relativistic

angular spread of the Coulomb field [6, 7]. This limit can be ignored for multi-GeV and TeV electron beams.

In spectral upconversion, the encoding is realized in terms of optical sideband generation via sum and difference frequency mixing of the optical and terahertz fields in the crystal. The aim here is to directly measure the Fourier spectrum of the electron bunch, accepting the loss of phase and explicit time information compared with temporal decoding, but gaining as a result the potential for determining information on even shorter structures within the bunch, potentially below 10 fs. Since this technique uses a long-pulse (picosecond) laser probe, there is a considerable gain in measurement simplicity, and laser transport in optical fiber becomes relatively trivial. Note that the long probe pulse is converted (upshifted) to the optical replica, and that this method can measure non-propagating long wavelength components, not accessible to radiative techniques such as CSR, CTR, CDR and Smith-Purcell. Current extensions of this work include investigations of multiple crystal arrangements, and new materials with enhanced optical bandwidth including thin metal-dielectric films and “metamaterials”. These techniques will now be used at the CTF3 test facility at CERN, as part of a project to measure the bunch profile of the CLIC Main Beam. The requirement is to measure the detailed longitudinal profile of the 44  $\mu\text{m}$  (150 fs) rms bunch with a resolution of 20  $\mu\text{m}$  (20 fs) rms at high charge density.

### Coherent Diffraction Radiation Monitor

The recent installation of a second target at one of the beam profile monitors at CTF3 required in depth studies of a two-target configuration. The first target is located upstream of the setup, the beam is propagating from it a second target. The DITANET ESR K. Lekomtsev at Royal Holloway University of London has investigated into the generation of Coherent Diffraction Radiation (CDR) from these two targets. The main goal of his work is to obtain a single electron spectrum which can then be utilized for bunch profile reconstruction.

For these calculations, the classical theory of Diffraction Radiation (DR) was used [8]. Each point of the target surface can then be represented as an elementary source. The two polarization components of DR from two targets can then be written as:

$$E_{\xi,\eta} = \frac{ik}{8\pi^3} \iint_{r_1, r_2} E_1(r_1) \frac{\exp[i(\varphi_1 + \varphi_2)]}{a} dr_1 dr_2 + \frac{1}{4\pi^2} \int_{r_2} E_2(r_2) \frac{\exp[i\varphi_2 + ikd/\beta]}{a} dr_2. \quad (1)$$

where  $r_1$  and  $r_2$  are the coordinates of the particle field at the second and at the first target correspondingly;  $E_1$  and  $E_2$  give amplitudes of arbitrary elementary sources positioned at  $r_1$  and  $r_2$  on the targets;  $\varphi_1$  defines the phase advance of the photons propagating from the first target to

the second one;  $\varphi_2$  defines the phase advance of the photons propagating from the second target to the observation plane,  $d$  is the distance between the targets,  $a$  is the distance from the second target to the observation plane  $(O, \xi, \eta)$ .

### Diffraction Radiation Spatial Distribution

Once two radiation components in (1) are obtained one can derive the DR distribution from two targets [8]:

$$\frac{d^2 W_{x,y}^{DR}}{d\omega d\Omega} = 4\pi^2 k^2 a^2 \left[ \left| \text{Re} E_{\xi,\eta} \right|^2 + \left| \text{Im} E_{\xi,\eta} \right|^2 \right], \quad (2)$$

where  $E_{\xi,\eta}$  defines the amplitude of the particle field interacted with the two target system. By integrating the DR spatial distribution over the detector aperture  $(\xi, \eta)$ , the single electron spectrum can be obtained, Fig. 3.

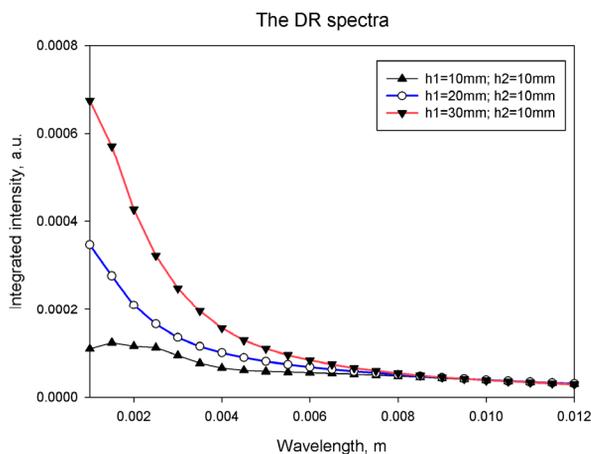


Figure 3: The DR spectra for three configurations of the experimental setup.

The figure shows the spectra for three different configurations of the system, when the upstream target is gradually lifted upwards and the DR spectrum converts itself while the influence of the second target becomes negligible. These single electron spectrum calculations will now be utilized for bunch profile reconstruction in the CDR experiment at CTF3.

## DITANET WORKSHOP

The DITANET consortium organized a two day workshop at the Cockcroft Institute, UK on July 12<sup>th</sup>/13<sup>th</sup> 2010. The workshop brought together around 30 experts from the international beam diagnostics community to provide a forum for knowledge exchange, allow for a review of the state of the art, and discuss future developments and challenges.

Participants discussed the use of electro-optic techniques, coherent diffraction radiation, streak camera technology and rf deflectors to characterize the longitudinal beam structure in a wide range of particle

accelerators, such as the LHC and CTF3, third and fourth generation light sources such as DIAMOND, ANKA and LCLS, as well as the US facilities SPEAR3 and ALS.

This workshop is part of the DITANET workshop series. All presentation from the workshop can be found at [9].

## SUMMARY

Within DITANET, the development of new technologies and techniques for measuring the longitudinal beam profile with highest temporal and spatial resolution is one of the key research areas. For the first time, synchrotron radiation from lead ion beams was used for monitoring the LHC longitudinal density profile. Good time resolution and high dynamic range were successfully demonstrated. Electro-optic techniques are presently one of the most promising means to measure ultra short beam pulses in the femtosecond range and a summary of the present work at U Dundee/ASTeC and CERN was given. In addition, new ways of measuring the longitudinal beam profile at CTF3 by means of CDR from two targets are presently under development. In addition to its extensive internal secondment program, the network has been promoting knowledge exchange in longitudinal beam tdiagnostics through a Topical Workshop in 2010.

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