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DEVELOPMENT OF THE ELECTRON BEAM PROBE FOR HADRON SYNCHROTRONS*

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Abstract

Non-invasive diagnostics is essential to get important information about intense hadron beams, e.g. the transverse beam profile, which is indispensable in order to attain high brilliance and luminosity for upgrades on present machines and for future projects. Furthermore, it can be used to optimise parameter settings in environment of the running machine.

An electron beam probe (EBP) is a beam diagnostics instrument which scans a low energy, low current electron beam through a hadron beam and obtains information from the detected response. The electrons are shot perpendicular through the hadron beam to be examined, which causes deflection in the beam potential of the intense hadron bunch, that needs to be detected and further analysed.

We propose to build the EBP scanning apparatus for synchrotrons under ultra-high vacuum condition. The results of multi particle simulations evaluating limitations the expected measurement potential and limitations are presented. This work will be performed in collaboration with CERN.

INTRODUCTION

CERN operates two large ring accelerators used for high energy physics (HEP) experiments, the Super Proton Synchrotron (SPS) with beam energies up to 450 GeV/c, and the Large Hadron Collider (LHC) operating at 7 TeV/c per beam. Furthermore, a Future Circular Collider (FCC-hh), currently under study at CERN [1], can have energies up to 50 TeV/c per hadron beam. To maximize the luminosity

$$\mathcal{L} = \frac{n_1 n_2 f_{rev} N_b}{4\pi\sigma_x\sigma_y}$$

at the interaction points (IP) of a particle collider, the beam intensity of both colliding beams needs to be maximized: n_1, n_2 being the number of particles per bunch in each beam, N_b the number of colliding bunches; while their transverse beam size needs to be minimized: σ_x, σ_y being the RMS size of the Gaussian horizontal and vertical cross-section beam profiles respectively.

The measurement of the transverse beam profile is particularly challenging in such high energy, high intensity machines. The instrument of choice for accurate measurements is a wire-scanner, where a thin wire some tens of microns in diameter is scanned through the beam with time evolution of the secondary shower created during the scan used to measure the profile. Unfortunately, due to the high power in the stored beam, this wire-scanner method is limited to a few percent of the nominal LHC beam intensity due to wire over-heating and superconducting magnet quench effects caused by the secondary shower [2]. Other transverse beam profile measurement methods exist for these high energies, including using synchrotron radiation, i.e. imaging the synchrotron light as the high energy hadron beam passes through a dipole or dedicated undulator [3]. However, due to a variety of effects, including imaging beyond the diffraction limit, changing synchrotron radiation source points, RF heating of the light extraction mirror, mechanical tolerances, etc., cross calibration with the wire-scanner is still required to give accurate results. Several other non or minimally invasive beam profile monitoring methods are currently being tested or investigated [4], all with their individual strong points and disadvantages.

The electron beam probe is another possible technique that has already been shown to be an asset for very high intensity hadron machines [5, 6] and for relativistic electron beams [7]. However, all of them are dependent on a particular case, specific conditions (bunch length, dimensions, particle density, scanning time) and the tasks to be fulfilled.

At IAP, we focus our effort on research, development and testing of the advanced concepts and techniques for the EBP, which can be used for the accelerators at CERN. The possibilities of the production modulated electron beamlets, their detection and experimental phase space analysis will be examined. Experiments at test bench and comparison with simulations are planned to test various concepts (sheet beam, rapid and slow scanning procedure, modulation) and their limitations.

In this contribution we investigate the use of a non-invasive coulomb scattering method between the high-power hadron beam and a scanning low power electron beam, following on from the successful operational of such a device at both for the collector ring of the spallation neutron source (SNS, US) [5] and more recently the main ring injector at Fermilab, US [6]. We discuss the general layout of the EBP, first simulations and the experimental setups at IAP, which will be used in the framework of the project.

EBP FUNCTIONAL PRINCIPLE

Figure 1 shows the principle behind a scanning EPB. The projected trace after coulomb scattering with the hadron beam is proportional to the integrated transverse beam profile (Fig. 2). A low energy (E < 20 keV), low current (I ~ 1 mA) electron beam is shot transversally through the circulating high energy hadron beams. An electrostatic de-

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flector is used to scan a small area (1cm x 1cm) of the passing hadron bunch with electrons. The electrons will be deflected by the positive hadron beam potential, with this deflection mapped at a detector surface, e.g. a camera. The detected signals can then be used to calculate properties (dimensions, beam potential, position, density [6]) of the passing hadron beam.

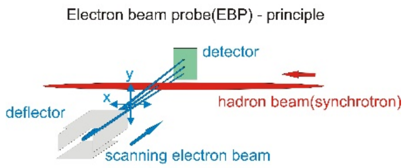

Figure 1: Layout of the electron beam probe (EBP).

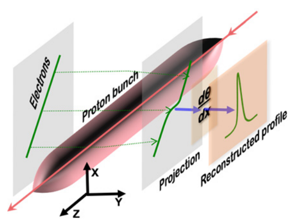

Figure 2: Transverse beam profile measurement with a tilted sheet of coulomb scattered electrons (W. Blokland).

Demanding issues include the design of the electron beam optics, as well as high temporal and lateral resolutions of the detector.

SIMULATIONS

Beam dynamics studies are initiated to evaluate the performance and limitations of the proposed diagnostics system.

A dedicated multi-specie 3D Particle-in-cell simulation (PIC) code was developed at IAP for this purpose. The particle motion is integrated in the time coordinate utilizing a symplectic method of the second order. The space charge forces are calculated by a Poisson solver based on the iterative Bi-CGSTAB method [8] and a sparse matrix formalism. The algorithm is parallelised and is running on the FUCHS – CSC cluster of the Goethe University Frankfurt [9]. Up to 10^7 macro-particles of the different species running on 50 nodes can be used in one simulation run.

In the first stage, an approximation of the non-relativistic electron beam and the electrostatic potential of the homogenous proton bunch with cylindrical symmetry (radius of the bunch $r_b = 2\,mm$, proton beam density $n_p = 5 \cdot 10^{15} m^{-3}$) were assumed. The electron source was placed transversally, at a distance of 0.27 m from the proton beam axis, while a negligible beam current was applied. Different initial electron energies (E_e = 20, 10, 5, 2 keV) were simulated with adjusted time steps. A corresponding constant spacial step of Δz = 0.42 mm was chosen for all energies. 10 x10 beamlets were generated through the variation of the transversal momenta.

An example of the simulation results in a distance of z = 0.5 m behind the electron source and for the electron energy E_e = 5 keV are depicted in Fig. 2 and Fig. 3. The grey points are electron beamlets detected in free space, while blue points represents electrons deflected by the proton beam potential.

The focusing effect of the electron beamlets in a beam potential in Y-direction (vertical plane) can be identified and is affirmed through the overall size reduction of the ensemble (Fig. 2). Due to the symmetry of the assumed beam potential, such effect is missing in the X-direction.

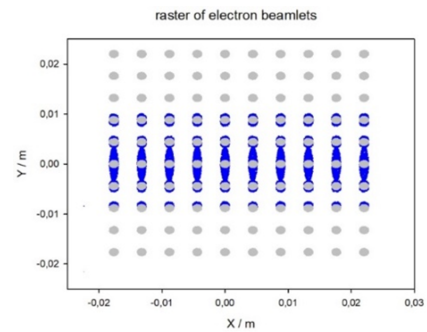

Figure 3: Detector signal (X – Y) at 0.5 m from the electron source (E_e = 5 keV). Grey – simulation without, blue – simulation with proton beam potential.

This focusing effect on the beamlets is more obvious in the Y -Y′ phase space, as depicted in Fig. 4. Moreover, a non-linear behaviour of the focusing strength can be identified for different beamlets. It originates from the form of the beam potential and will be important when optimizing the settings of the source – detector distance for a particular application. For example, “beamlet 0” is propagating through the center of the proton bunch, still the distribution of the beamlet at the detector is already strong over focused. The signals of beamlets overlap in the X -Y plane and their detection is expected to be challenging to achieve the required spatial resolution.

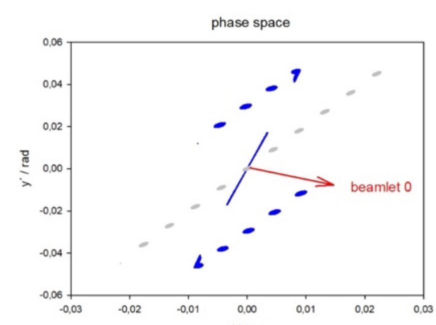

Figure 4: Detector signal in phase space (Y – Y′) at 0.5 m from the electron source (E_e = 5 keV). Grey – simulation without, blue – simulation with proton beam potential.

A similar behaviour can be observed also for other proved simulations at different electron energies. However, the focusing strength changes with an electron energy, so this could be used as an additional parameter for a bunch diagnostic.

The next steps will include an implementation of an ellipsoidal bunch potential, the implementation of the various proton bunch distributions, and simulations under dy-

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namical (moving proton bunch) and full space charge conditions. An investigation of the relativistic effects and comparison with previous simulations are planned at a later stage.

CHARACTERISATION OF THE ELECTRON SOURCE

A commercial electron source is investigated, expected to deliver the required performance for the EBP. A dedicated vacuum recipient is used for the investigation. It is equipped with a Faraday cup and a retarding field spectrometer to estimate the energy distribution. Furthermore, a vacuum window enables the possibility to measure the electron beam profile by the use of a CCD-camera and the (Beam Induced Fluorescence) BIF-method. In a first step, the emission current was measured as a function of cathode heat power and the electron beam energy given by the maximum extraction voltage at the source (Fig. 5). Later the electron beam will undergo a post acceleration and the beam energy will be adjustable between 0.5 and 20 keV.

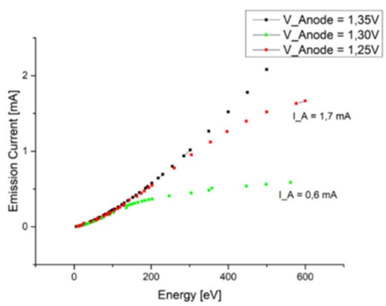

Figure 5: Measured electron beam current as a function of different cathode heat power and beam energy.

During the conditioning of the electron source, no significant vacuum degradation was observed. In a second step, the extraction grid of the source was used to modulate the electron beam to create a time structure with different pulse lengths and repetition rates. The modulation can be useful for time dependent measurements of fill and extraction cycles of the synchrotron. Numerical simulation of electron extraction and beamlet forming were performed based on the first experimental results (Fig. 6).

EBP TEST BENCH

The experimental environment (Fig. 7) was designed to enable sufficient flexibility, combined with the requirements of a EBP later to be used in a synchrotron, especially the extreme ultra-high vacuum. After the finalization of performance tests, the electron source will be integrated in the first section of the test bench. This section is equipped with an electrostatic Einzel-lens for the beam focusing and a deflector, providing the scanning with a high spatial resolution. This part is connected to the interaction section by the use of a bellow to adjust different angels between the geometric axes of the first section and the passing ion beam.

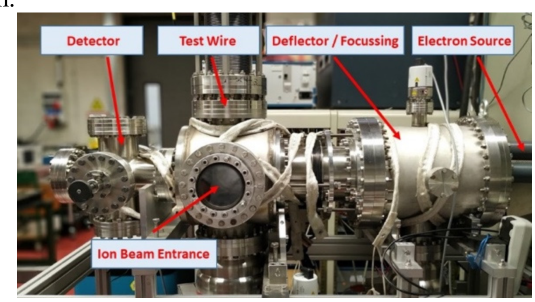

Figure 7: Image of the EBP test bench at Goethe-University after assembling, before applying the bake-out procedure.

It is planned to run the first experiments with a wire as a proxy for the synchrotron beam. The wire is mounted on a movable feed through and can be biased on high voltage in the kV range. Furthermore, tungsten wires with different diameters can be used to evaluate the spatial resolution of the designed EBP. Downstream the interaction region the detector will be installed. It is foreseen to use a micro-channel plate (MCP) combined with a CCD-camera for the initial tests. Based on the simulation and experimental results the beam optics and the deflector system will be designed and integrated within the EBP test bench.

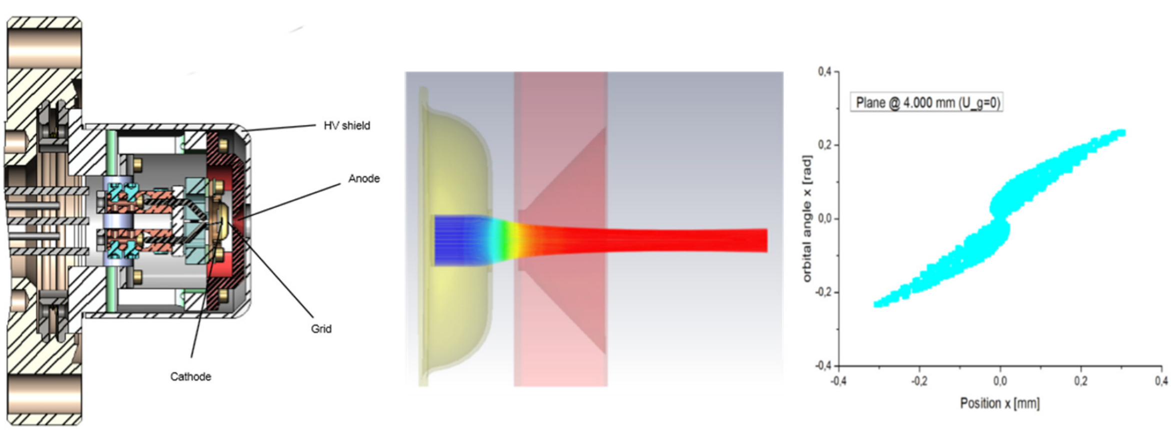

Figure 6: Technical layout of the electron source (left) and simulated electron extraction, beamlet formation (middle) and phase space distribution of electron beamlet 4.0 mm behind extraction grid (right).

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