ACCELERATOR R&D IN THE QUASAR GROUP

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Abstract

The QUASAR Group was founded in 2007 with an initial focus on the development and experimental exploitation of a novel electrostatic ultra-low energy storage ring (USR), part of the future facility for low-energy antiproton and ion research (FLAIR). The group's research activities have grown considerably over the past four years and now include also the development of beam diagnostic tools for accelerators and light sources, investigations into superconducting linear accelerators and medical applications, and, most recently, a broad R&D program into laser applications at accelerators. In this contribution, an overview of the QUASAR Group's research achievements to date is given.

LOW ENERGY ANTIMATTER RESEARCH

Cooled beams of low energy antiprotons open up numerous opportunities for fundamental research. At present, the Antiproton Decelerator (AD) [1] at CERN, Switzerland is the only place in the world where a physics program with these exotic particles is being carried out. It is presently focused on trapping antiprotons in Penning traps where antihydrogen is formed after recombination with positrons. The ultimate goal is to trap and perform spectroscopy on antihydrogene. In today's set-up, most (99.9%) of the antiprotons produced are lost by the use of degrader foils to decelerate from AD ejection energy down to around 5 keV, which is an energy suitable for trapping. By using a ring equipped with beam cooling, high deceleration efficiency and important increases in phase-space density can be obtained, resulting in an increased number of trapped antiprotons. At CERN, Exta Low ENergy Antiprotons (ELENA) at energies down to 100 keV will be provided in the future by a compact magnetic storage ring [2], whereas the electrostatic ultra-low energy storage ring (USR) [3,4] at the Facility for Low energy Antiproton and Ion Research (FLAIR) [5] will provide cooled beams of antiprotons in the energy range between 20-300 keV. In terms of the necessary beam dynamics studies and the beam diagnostics system both projects share many of their challenges. A third facility, the Antiproton Recycler ring [6], might be well placed to bridge the gap between the two rings and enable differential cross section measurements in antiproton-atom/molecule collisions, significantly before the USR will be commissioned. Here, the discussion will be limited to the USR.

Beam Dynamics Studies

A particular challenge in the initial layout of the USRs was that essentially all commonly used accelerator design codes, such as Mad-X or COSY Infinity, do not foresee the use of electrostatic elements for beam transport and modulation purposes. Therefore, new tools and methods had to be developed to study the USR beam dynamics in detail. In particular for the energies under consideration at the USR, where $\beta << 1$, the change in kinetic energy may be large enough to invalidate the paraxial approximation of constant velocity that many lattice codes make. Also, the intrinsic coupling between transverse and longitudinal motion in electrostatic deflectors is very often not correctly taken into account in existing codes. For the USR, a three-dimensional model of the ring was built up in the electromagnetic field simulation tool OPERA3D. This allowed for analyzing the non-linear parts of the electric field distribution and, by inputting this data into Mad-X for the purpose of beam tracking, for determining the dynamic aperture of the USR and how it is limited by the different ion optical elements [7].

In a next step, simulations of beam behavior, including non-linear terms in the equations of motion derived from a Fourier harmonic analysis of the electric field distribution in electrostatic deflectors were carried out. This included tracking ions in a computer model of an electrostatic storage ring, using relaxation electric field maps of all bending and focusing elements. Finally, transition processes, equilibrium conditions and long-term beam dynamics based on the kinetic equations were analyzed, and a consistent explanation of some of the effects observed so far in electrostatic storage rings was proposed [8].

Beam Diagnostics

Low energy beams as they will be provided in the USR are very important for many existing and future accelerator projects, but require optimization of new diagnostic methods as most of the standard high-energy techniques no longer work. The anticipated beam parameters demanded the development of a new set of high performance diagnostic tools for both, the initial commissioning of the storage ring with protons or H^- ions as well as for later operation of the USR and its transfer lines. The investigated and optimized instrumentation for low energy, low intensity beam diagnostics comprises scintillating screens, secondary emission monitors, Faraday cups, capacitive pick-ups and a flexible ionization monitor for least interceptive transverse beam profile measurements; the latter is described in detail in [9]. Although all the monitors were optimized for the

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USR, their use stretches well beyond this particular machine and they are also suited for other low energy storage rings and beam lines [10-12].

For beam profile measurements in the injection and extraction lines, a foil-based secondary emission monitor was designed. The detector consists of a grounded mesh and an aluminum foil on a negative potential, a chevron type MCP with a phosphor screen and a CCD camera registering the image. The design of the detector was made flexible to enable the use of two configurations, the foil-based SEM and a stand-alone MCP placed directly in the beam. The monitor in the first configuration was tested with 200 keV protons. The experiments revealed a high dynamic range of the SEM. It was demonstrated that beam currents of a few femotamperes can be observed, yet no detection limits were reached. A resolution of at least 2 mm was demonstrated, but the recorded images indicate that further tests may reveal a better performance.

Should a simpler, cheaper and more robust solution be used for beam profile measurements in the injection and extraction lines, CsI:Tl screens can be used. They offer sufficiently high sensitivity to low energy, low intensity beams. It was demonstrated that it is possible to measure currents even in the fA range corresponding to about 10^4 particles per second at 200 keV. For 50 keV beams, the sensitivity drops down and is about 4 times lower for CsI:Tl. Furthermore, an absolute light yield calibration technique can be applied to estimate the beam current of the impinging proton beams.

For measuring intensities of injected and extracted beams, a sensitive Faraday cup will be used. A purpose-built cup was tested with keV protons and beam currents in the femtoampere range. With a gain of 10^{12} V/A and a bandwidth of 0.1 Hz, the peak-to-peak noise was about 40 fA and further averaging over 20 seconds was applied. It was demonstrated that beam currents as low as 5.0 fA ± 0.3 fA can be measured in a reproducible manner.

For non-destructive beam position/closed-orbit measurements at the USR, four capacitive pick-ups will be installed in the ring. The diagonally cut electrodes will provide a linear response of the system to beam displacements within the required range of ±40 mm.

Finally, for non-destructive acquisition of transverse profiles with sub-mm resolution, a supersonic gas jet screen based monitor will be used [13].

SUPERCONDUCTING ACCELERATORS

The QUASAR Group has been contributing to an international effort in optimizing superconducting cavities for future high gradient accelerators. Recently, investigations into the surface characteristics of different commonly used superconducting materials have been completed.

SC Materials for High Gradient Cavities

Currently, two different methods for manufacturing niobium RF cavities are used. They are either made of bulk niobium or a micrometer thin niobium film is deposited on the inner surface of a copper cavity. It has been shown that interface tunnel exchange (ITE) acting between surface oxides and the adjacent superconducting material can give rise to losses on niobium film surfaces, while these losses are negligible for well prepared bulk niobium surfaces [14]. Results from surface resistance, UFM and XPS measurements on a bulk niobium and a niobium film on a copper substrate sample were presented elsewhere at this conference [15].

MEDICAL APPLICATIONS

A non-invasive beam current monitor based on the multi-strip LHCb VELO silicon detector has been developed at the Cockcroft Institute/University of Liverpool and first tests will soon be carried out at the treatment beam line at the Clatterbridge Centre for Oncology (CCO), UK. Originally, this detector was designed to track vertices in the LHCb experiment at CERN, but first feasibility tests performed at the CCO treatment beam line in 2010 demonstrated the possibility of non–intrusive beam monitoring. The initial measurements consisted of data taken at several points along the beam line and gave high count rate, high resolution results. Over the past year, the VELO detector was developed into a stand-alone device with local cooling and several positioning stage. This setup allows to integrate the monitor into almost any beam line and will be used to study the beam halo - dose relationship at CCO in detail. The detector will be complemented by a purpose-built Faraday Cup for absolute current measurements and a multi-leaf Faraday Cup for energy spread measurements. Full details about the design of the monitor are included in [16]

BEAM DIAGNOSTICS

In addition to the research program linked to low energy antiproton facilities presented in the first section of this contribution and the instrumentation for medical accelerators, the QUASAR Group also carries out an intense R&D program into beam diagnostics for low and high energy accelerators. Results from some selected projects are presented below. In addition, the group is also coordinating the Marie Curie research and training network DITANET [17].

LHC Longitudinal Density Monitor

The longitudinal density monitor (LDM) is primarily intended for the measurement of the 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

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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 and has become a highly valued tool for LHC operation and optimization in a very short time. Full details about recent results from the LDM are presented in [18, 19], including a proposed method for constructing a 3-dimensional beam density map by scanning the LDM sensor in the transverse plane. There, a scheme to improve the sensitivity of the system by using an optical switching technique is also presented.

HIE-ISOLDE Instrumentation

In the framework of the High Intensity and Energy (HIE)-ISOLDE project at CERN, a beam instrumentation R&D program is on-going for the superconducting upgrade of the REX-ISOLDE heavy-ion post-accelerator. An overview of the foreseen beam diagnostics system is presented elsewhere at this conference [20], focusing on the specifications required by the HIE-ISOLDE linac. Due to the low beam intensities, the diagnostic instrumentation will be based on high-sensitivity intercepting devices. The project includes intensity and transverse profile monitors to be implemented in the very narrow longitudinal space that is available for beam diagnostics in the regions between the superconducting cryomodules. A longitudinal profile monitor is foreseen downstream the linac to measure the energy and time beam distributions and to allow for a fast phase tuning of the superconducting cavities. A custom made emittance meter will finally provide transverse emittance measurements based on a phase space sampling technique.

NEW INITIATIVES

The DITANET research and training concepts and vision have been strongly supported by the community. Based on this project two new initiatives, oPAC [20] and LA³NET [21] were proposed to the EC in 2011 and selected for funding . With budgets of 6 M€ and 4.6 M€ these networks are some of the largest Marie Curie projects ever funded by the EC. They will guarantee that the DITANET concepts will continue to benefit the international accelerator community.

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