ACCELERATOR R&D IN THE QUASAR GROUP

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on behalf of the QUASAR Group

Abstract

The QUASAR Group is a pan-European research group based at the Cockcroft Institute in the UK. It carries out R&D into methods to decelerate and store very low energy antiproton and exotic ion beams, beam diagnostics developments for medical accelerators, including imaging and dosimetry, as well as opto-electronics and laser applications. This contribution presents the latest results of the Group's studies into low energy research facilities, novel least destructive beam profile monitors for medical and industry applications, beam dynamics studies into the optimization of medical accelerators, electron beam generation and new compact dielectric accelerators.

DEVELOPMENT OF LOW ENERGY RESEARCH INFRASTRUCTURES

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). Since then the group led the design of several other facilities with recent results highlighted in the following paragraphs.

Ultra-Low Energy Storage Ring (USR)

The USR design has been completely reconsidered since its initial layout in 2005. In order to match different requirements from a large variety of proposed experiments, several modes of operation are foreseen in the ring. The modified geometry of the USR ring is based on a four-fold symmetry split achromatic lattice with four 4 m long achromatic straight sections which gives the necessary flexibility to satisfy multiple boundary conditions. The linear machine lattice was developed using the MAD-X and Trace3D software and details about the storage ring design can be found in [1]. Over a circumference of 40 m the USR contains a gas jet target and other components of a so-called ‘reaction microscope’ for antiproton-atom collision studies, different RF systems for a dedicated short bunch operation mode, electron cooler, decelerating drift tube and elements for fast/slow extraction which are all located in the machine’s three straight sections. One of the straight sections is kept free for the possible inclusion of a merged positron ring. This way the beam characteristics can be varied over a wide range to operate the storage ring in various regimes in the tune diagram and specifically to achieve achromatic conditions in all four long straight sections. In addition, the USR can be set to a two-fold symmetry low-beta mode for operation of the reaction microscope.

In recent studies BETACOOL was used to find and optimize the parameters of the USR lattice and electron cooling system. The parameters of the antiproton beam are pre-defined by the previous chain of accelerators as well as by the efficiency of the antiproton production target. The energy of the antiprotons injected into the USR is fixed at 300 keV. It is anticipated that the emittance of the injected beam will be of the order of 5 π mm mrad (r.m.s.) and the initial momentum spread about $(\Delta p/p)_{in}=10^{-3}$ (r.m.s.). The intensity of the ions circulating in the USR can be varied widely between $N_0=10^4$ and $2 \cdot 10^7$ ions. In simulation studies it was found that electron cooling of ultra-low energy antiprotons will compensate for intra-beam scattering at high beam intensities as well as multiple scattering of ions on an internal target at high gas jet densities of up to $n_{tgt}=10^{12}$ cm^{-3}. We estimate that the number of useful ionization events might be as high as $1.5 \cdot 10^7$ counts during a 16 s operation cycle with an average count rate of about 20 events per turn. We also found that the beam life time will then be about τ_{life}~12 s [2].

Antiproton Recycler Ring

An injection line has been designed to transport and accelerate antiprotons from the MUSASHI trap at the Antiproton Decelerator (AD) at CERN to a small recycler ring, see Fig. 1 [3]. The line has been designed to accept a beam that originates from the center of the trap with an initial diameter of 1 mm and an extracted energy between 150 and 500 eV with an energy spread of ≤30 eV. The injector accelerates the particles to an energy of between 3 and 30 keV using a series of electrostatic electrodes and matches the phase of the beam to the ring using an electrostatic quadrupole quadruplet in the final part of the injector. A long electrostatic drift tube is used to shield the particles whilst changing the voltage reference to enable both the MUSASHI trap and the ring to be operated at ground potential.

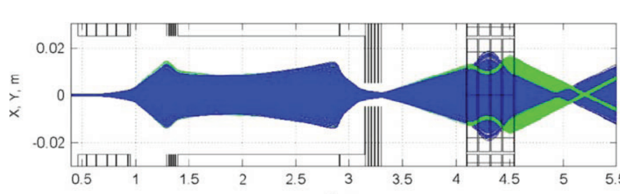

Figure 1: Particle trajectories from solenoid through acceleration section.

This injection beam line and antiproton recycler ring could offer, for the first time, access to measurement of

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fully differential cross sections in collisions between low energy antiprotons and various gas jet targets.

Electrostatic Ring at KACST

Based on studies into the USR and AD recycler ring the design of a low energy electrostatic storage ring that can store ions with energies of up to 30 keV/q was developed in close collaboration with experts at KACST [4]. This experimental facility shall consist of a double ring configuration in its final phase, allowing for a very broad and interdisciplinary research program. In a first step, a simpler, quicker to realize 'start version' was developed. Its lattice is based on four 7° electrostatic deflectors, in combination with two 166° cylinder deflectors and sets of quadrupole doublets. In design studies with the Simion program emphasis was put on an accurate simulation of the effects from non-linear fields.

BEAM DIAGNOSTICS

Beam diagnostic systems are essential constituents of any particle accelerator; they reveal the properties of a beam and how it behaves in a machine. The QUASAR Group has initiated and led the largest-ever training initiative in beam instrumentation, DITANET, since 2008 and carries out research into beam loss monitors, propagation and monitoring of beam halo, absolute beam current measurements, the exploitation of synchrotron radiation for beam profile measurements, gas jet-based beam profile monitors, very high resolution optical transition radiation (OTR), beam instrumentation for exotic ion beams and detectors for pulsed neutron beams [5]. Selected results are presented in the following sections.

Low Energy Beams

A set of diagnostic instrumentation for low-energy, low-intensity charged particle beams was developed and tested with beams of keV energies and femtoampere range currents [6]. The detectors include beam-profile monitors based on scintillating screens and secondary electron emission, a sensitive Faraday cup, and a capacitive pickup. Although the devices were primarily developed for the USR at FAIR, they can find application at other low-energy, low-intensity accelerators, storage rings, and beam lines. For beam-profile measurements in the injection and extraction lines, a foil-based secondary emission monitor was designed. It was demonstrated that beam currents of a few femotamperes can be observed, yet no detection limits were reached.

Images of 2 mm holes yielded higher spatial resolution than predicted in theoretical estimates. Alternatively, CsI:Tl screens 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. Additionally, 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 was developed and tested. The prototype equipped with a commercial amplifier with a gain of 10^{12} V=A and a bandwidth of 0.1 Hz yielded the peak-to-peak noise of 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 nondestructive beam position/closed-orbit measurements at the USR, capacitive pickups will be used. Diagonally cut electrodes guarantee linear response of the system to beam displacements within the required range of up to 40 mm. It was demonstrated that the nonlinear effects caused by low beam velocities are not a problem in the USR as long as bunching frequencies f_{rf} are low and a narrowband signal processing is used.

Beam Halo Monitoring

A new high dynamic range method to image beam halo using a digital micro mirror device (DMD) has been developed in collaboration with CERN and the University of Maryland over the past few years. This technique can readily be applied to any accelerator or light source and provides a new, enabling technology for the study of halos and beam dynamics. Recently measurements have been carried using the UMER electron beam and a dynamic range of ~10^5 of the imaging system was successfully demonstrated, see Fig. 2 [7]. It was shown that (1) the DMD has excellent extinction; (2) the quality of the beam image reflected from the DMD is unaffected by the diffraction effects produced by the DMD itself; and (3) the resolution of the DMD optics is equivalent to that of comparable system in which a mirror replaces the DMD.

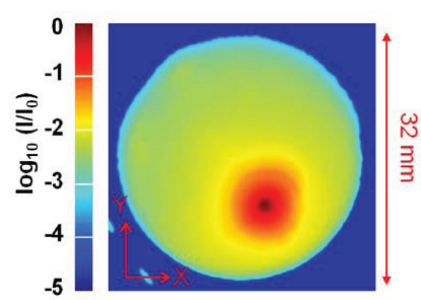

Figure 2: Reconstructed UMER beam profile.

Also, the ability of a DMD to create adaptive optical masks to block out the beam core, thus allowing the halo of the electron beam to be observed at UMER was demonstrated in this study. It turned out to be a very flexible method for masking the beam core with different shapes and observing halo formation. Further halo studies at UMER and other accelerator facilities using upgrades to the current imaging system are already planned and will further improve the dynamic range and quality of the beam images obtained with this unique monitor.

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BEAM PHYSICS

Medical Accelerators

Quadrupole variation scans were performed at the Clatterbridge Cancer Centre cyclotron beam line [8]. Proton beam orientation in phase space was determined to find an adequate beam line model and simulate the beam dynamics. It was the first time measurements had been carried out for the treatment beam line since its commissioning. The calculated beam parameters are essential for a detailed modeling of the proton beam transport through the scattering foils for both medical physics models and future measurements of the beam 'halo' with the VELO detector as a non-invasive beam current monitor. Also, discussions are being carried out to look into possible optimization and, therefore, efficiency improvement of the treatment beam line.

Compact Fiber Optics Accelerators

Photonic crystals are a promising way to realize an on-chip electron beam source for fundamental radiation biology. Currently, there are three different candidates for photonic crystal accelerator structures: the dual-grating structure, photonic crystal fibres and the woodpile structure. The QUASAR Group has recently started studies into a new dual-grating structure [9]. Optimum pillar height and vacuum channel gap were determined in simulation runs. For electric field calculation CST Microwave Studio was used. A laser wavelength of 1,550 nm and silicon as material was chosen for all simulations, see Fig. 3 for an example of the resulting field distribution in a dual-grating structure.

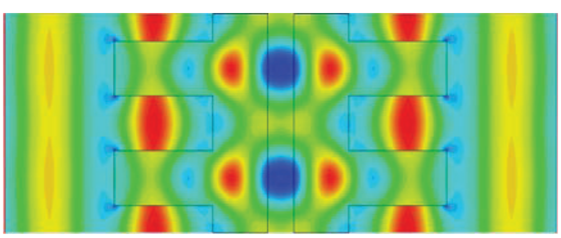

Figure 3: z-component of the electric field distribution in dual-gratings structure.

This work allowed the maximum acceleration field gradient to be determined as a function of pillar height, vacuum channel gap and laser wavelength. Future studies will focus on ways to accelerate low energy particles requiring adjustment of structure dimensions to decrease phase velocity.

NEW INITIATIVES

The QUASAR Group has coordinated the international DITANET project since 2008 [10]. Based on the network's training ideas and vision two new initiatives, oPAC [11] and LA³NET [12] were recently selected for funding by the European Union. With budgets of 6 M€ and 4.6 M€ these networks are some of the largest Marie Curie projects ever funded by the EC and will allow training of 40 early stage researchers over the projects' four year duration.

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