Developments at the Interface between Accelerator Sciences and Atomic Physics within the QUASAR Group

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Particle accelerators have proven to be indispensable tools to understand nature at smaller and smaller scales. The QUASAR group started at the Max Planck Institute for Nuclear Physics in 2008 and combines developments in accelerator sciences with measurements on quantum systems, with a particular focus on antimatter research. The group's international structure and close collaboration with partners from around the world provides a fruitful ground for beyond state-of-the-art developments in a number of different fields.

THE ULTRA-LOW ENERGY STORAGE RING (USR)

Antiprotons stored and cooled at low energies in a storage ring or at rest in traps are highly desirable for the investigation of a large number of basic questions on fundamental interactions, on the static structure of exotic antiprotonic atomic systems or of (radioactive) nuclei as well as on the time-dependent quantum dynamics of correlated systems. In addition, low-energy antiprotons are the ideal and perhaps the only tool to study in detail correlated quantum dynamics of few-electron systems in the femto and sub-femtosecond time regime.

To enable the efficient investigation of these important questions, a novel electrostatic cooler synchrotron and a state-of-the-art in-ring spectrometer are under development in close collaboration between the QUASAR group, the Max-Planck Institute for Nuclear Physics, the GSI Atomic Physics Division, and groups from the University of Heidelberg with the aim of slowing down antiprotons as well as possibly highly charged ions (up to bare uranium) to low energies between 20 and 300 keV/q at FLAIR. This will provide world-wide unique conditions for both in-ring studies with an intensity of up to 10^{12} cooled and stored antiprotons or highly charged ions per second, as well as for experiments requiring extracted slow beams and will therefore push the limits in all fields concerned.

Ring Layout

In order to be adjustable to the different needs of the experimentalists, the storage ring has to be set to different operation modes. Apart from the basic cooling and deceleration schemes, internal experiments ask for short bunches in the ns-range while external experiments have to be provided with extracted beams of most different pulse duration.

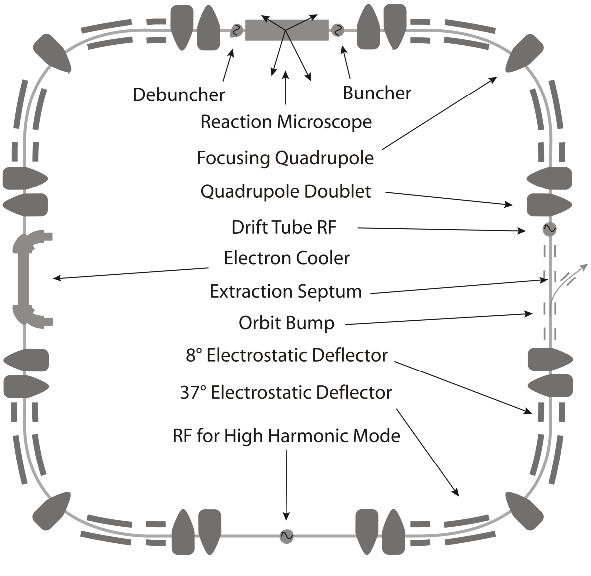

Figure 1: Layout of the ultra-low energy storage ring.

The synchrotron has been completely re-designed in 2008. The ring has a four-fold symmetry and an overall circumference of 42.6 m. The bending sections of the ring are designed in a novel "split-achromat" geometry. The total deflection of the beam by 90° in each of the corner section is realized by a combination of 8°-37°-37°-8° electrostatic cylinder deflectors. For the transverse modulation of the beam quadrupole doublets placed at the entrance and exit of every experimental straight section are used. An additional focusing quadrupole, placed in between the two 37° deflectors, is included to control the dispersion of the beam.

Beam Extraction

As different types of experiments using antiproton beams are planned within the FLAIR project, the extraction scheme of the USR needs to be highly flexible. Experiments requiring single short pulses per deceleration cycle, like e.g. trap experiments, a fast extraction scheme needs to be provided while nuclear-physics type experiments require a continuous beam during one machine cycle and thus slow extraction. For fast extraction the beam will be moved adiabatically towards the electrostatic septum, located in one of the straight sections, by a local orbit bump. To allow for high flexibility during this process, the bump is created by four dedicated electrostatic deflectors, located symmetrical around the electrostatic extraction septum. As soon as the beam moves along the orbit bump, an additional "kicking voltage" is applied to one of the bump electrodes, pushing the beam over the septum wall into the extraction transfer line in a single turn. Simulations with SIMION showed that the required electrode potentials are below +/- 800 V, which can be easily realized. Slow extraction on the other hand requires a resonant extraction scheme using a third order resonance. To drive this resonance, a dedicated sextupole will be installed, working on the $3 \cdot Q = 8$ resonance. This leads to a distortion of the stable elliptical trajectories (in un-normalized phase-space) and the available phase-space is split into stable and unstable regions by the separatrices that define the stable triangle. It should be pointed out that this is the first time ever such a combined fast/slow extraction scheme has been designed for an electrostatic storage ring.

Short Bunches

In order to reach a high resolution in the envisaged experiments with the novel in-ring reaction microscope, presently being developed in the QUASAR group in collaboration with the Ullrich group at MPIK, ultra-short pulses of 20 keV antiprotons with a time structure of only a few nanoseconds have to be provided. It is clearly impossible to create ultra-short bunches of a few ns duration in one step from a coasting beam: With a revolution period of 20 µs the required buncher voltage to provide a 2 ns time focus would exceed 10 kV and thus the induced energy spread by the phase compression would simply destroy the beam circulating in the ring.

The following procedure was developed in 2008 to provide ultra-short bunches: Once the beam has been slowed down to 20 keV, the coasting beam of antiprotons is cooled down to a momentum spread of $\sim 10^4$. Then the cooled beam is adiabatically captured into $\tau \sim 50$ ns stationary buckets formed by a 20 MHz cavity operating at a high harmonic mode of the ring revolution frequency h_{RF}=400-500. The desired ultra-short pulses of τ=2ns duration will then be formed in the symmetry point of the straight section where the reaction microscope is located. The focus will be provided by an additional $3\beta\lambda/2$ double drift buncher, placed at the beginning of the straight section. Once the experimental section is crossed, a debuncher will provide phase decompression and limit the growth of the equilibrium momentum spread. Otherwise the increasing energy spread introduced by the phase compressor would cause a beam blow up in the bending sections of the ring.

As it was already pointed out, the phase compression will lead to an additional energy spread. This requires that any manipulation of the beam towards short pulses needs to be limited to the straight sections of the ring, where the dispersion function needs to be zero. To allow for this special operation mode, the USR lattice was recently modified substantially, as described in the previous section.

Beam Diagnostics

The USR puts very high demands on the beam instrumentation as most conventional techniques will not work. Ultra-short bunches (1-2 ns) on the one hand and a quasi-DC beam structure on the other, together with a variable very low beam energy, ultra-low currents (from 1 µA down to 1 nA, or even less for a non-circulating beam) require the development of new diagnostic methods. A set of diagnostics devices, ranging from fully destructive monitors to non-perturbing ones, is under development for the USR. This includes a highly sensitive resonant beam position monitor based on capacitive pick-ups, Shottky pick-ups, specially adapted Farraday cups, and different kinds of beam profile monitors.

In addition, a neutral supersonic gas jet target shaped into a thin curtain combined with bi-dimensional imaging of the gas ions created by impact with the projectiles is being developed as an interesting alternative to profile monitors based on secondary electron emission and/or luminescent screens. A study of the intrinsic sensitivity and resolution of the monitor depending on its geometrical design has been carried out, and optimisation of it proposed, therewith highlighting the importance of the curtain geometric width.

We identified as relevant variables to be monitored the first maximum Mach number in the expansion and its coordinates, the maximum Mach number in a plane further away from the skimmer (and in particular at 70% distance in our simulation domain), and finally the geometry of the curtain itself.

By in-detail analysis of the simulation results, we achieved a powerful optimization method for highly variable gas jets. A test vacuum chamber has been designed and optimized for testing the validity of the numerical simulation on the behaviour of the jet curtain and will be built up in 2009.

RF ACCELERATORS

Benchmarking OPERA/SOPRANO

Rebunching cavities are today routinely used for matching a beam of charged particles between different accelerator structures, and thus optimizing the overall transmission and beam quality. At low resonance frequencies, unnecessary large dimensions of these cavities can be avoided by using spiral-loaded cavities. The optimization of these structures is a complicated process in which a wide range of different parameters have to be modified essentially in parallel. We investigated in detail the characteristics of a model structure with the 3D code OPERA/SOPRANO. This includes the optimization of the structure in terms of the spiral geometry for a given resonance frequency, the investigation of power losses on the inner surfaces, and the possibility of cavity tuning by means of a tuning cylinder.

It is now planned to develop a fully parameterized model where the simulation and evaluation is automated using OPERA's internal script environment.

Power Dissipation in Higher Order Modes

In pulsed high power superconducting H^- linacs different resonances can be triggered by the beam pulses. To ensure machine operation even at high currents the influence of Higher Order Modes (HOM) on beam motion has to be understood in detail. If HOM were triggered next to one of the resonances frequencies, high voltages might be induced, leading to additional power dissipation and negative impact on beam stability.

In order to estimate the additional power consumption from HOMs for the superconducting proton linac (SPL) at CERN, simulation studies with rescaled cavities at different operation frequencies (704 Mhz and 1408 MHz) and beta values were started. On the basis of these results HOM damping requirements will be defined to efficiently limit the power dissipation to a few watts per cavity.

MEDICAL ACCELERATORS

Therapy-synchrotrons, like the HIT-facility, operate in a fast pulse-to-pulse mode, where beam energy and intensity are switched in every new cycle. Furthermore, efficient tumor treatment requires a high precision of both, the beam position and the spill structure.

Hysteresis effects or eddy currents that occur in fast ramped synchrotron dipole and quadrupole magnets are in contradiction to those requirements. The standard (current-based) magnet control cannot handle these effects, demands additional time and increases the overall energy consumption. A field-based magnet control, however, could. This requires, among others, an improved magnetic field measurement with an accuracy of 10^{-4}.

It was decided to first measure the magnetic field with a Hallsensor at injection level (50-100 mT) of each synchrotron cycle. As the HIT-synchrotron is operated in 24/7 mode and thus not accessible for systematic studies, an external test bench for tests and measurements was installed. It consists of a former GSI dipole magnet and the corresponding power supply to simulate the field of interest. In addition, the lattice design of the HIT synchrotron and in particular its extraction mechanism has been studied in detail.

HIGH DYNAMIC RANGE BEAM PROFILE MEASUREMENTS

A thorough understanding of halo formation and its possible control is highly desirable for essentially all particle accelerators. Limiting the number of particles in the halo region of a beam would allow for minimizing beam losses and maximizing beam transmission, i.e. the experimental output. Measurements based on either optical transition radiation (OTR), synchrotron radiation (SR) or on light from luminescent screens at low energy accelerators like the USR provide an interesting opportunity for high dynamic range measurements of the transverse beam profile, since the signal is linear with the beam charge. In order to approximate a typical beam distribution as it is found in an accelerator we use a conventional laser beam in a small lab setup. Its profile was then analyzed by a charge injection device (CID) camera system. By covering at least five orders of magnitude in dynamic range, the CID-camera is the perfect tool for said measurements. Another option under investigation in parallel is the so-called "core masking technique". If it were possible to blank out the intense light from the beam core, a normal camera could be used to monitor the halo without saturation and overexposure. A strong limitation in earlier tests at CERN with the core masking technique was the fixed shape of the mask itself. In our setup, we thus aim for realizing a flexible mask by using a Micro-Mirror-Array (MMA). A test setup was built up and we are currently automating the overall process: profile acquisition - mask definition - reacquisition of halo profile.

DITANET

Beam diagnostics is a rich field in which a great variety of physical effects are made use of and consequently provides a wide and solid base for the

training of young researchers. Moreover, the principles that are used in any beam monitor or detector enter readily into industrial applications or the medical sector which guarantees that training of young researchers in this field is of relevance far beyond the pure field of particle accelerators. Without an appropriate set of diagnostic elements, it would simply be impossible to operate any accelerator complex let alone optimize its performance. DITANET - **DI**agnostic **T**echniques for particle **A**ccelerators - a European **NET**work" - covers the development of advanced beam diagnostic methods for a wide range of existing or future accelerators, both for electrons and ions. DITANET is the largest ever coordinated EU education action for PhD students in the field of beam diagnostic techniques for future particle accelerators with a total budget of 4.2 M€. The network was initiated and is coordinated by the QUASAR group.

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