ON THE POSSIBILITY OF REALIZING SHORTEST BUNCHES IN LOW-ENERGY STORAGE RINGS

A.I.Papash[a,e#] , A.A. Alzeanidi[d], M. El Ghazaly[d], K.-U. Kühnel[a], C.P.Welsch[a,b,c]

[a]Max Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany
[b]Kirchhoff Institute for Physics, University of Heidelberg, 69120 Heidelberg, Germany
[c]Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany
[d]KACST, 11442 Riyadh, Saudi Arabia
[e]Joint Institute for Nuclear Research, Dubna, Russia, on leave

Abstract

For some very interesting experiments in future low-energy storage rings it is highly desirable to realize ultra-short bunches in the nanosecond regime. These bunches could then be used for collision studies with atomic or molecular gas jet targets where the time structure of the bunches would be used as a trigger for the experiment. Thus, the control of the longitudinal time structure of the stored beam is of central importance since it directly determines the quality of the envisaged experiments. Since many years it has been a significant challenge for the storage ring accelerator-physics community to develop techniques to reduce the duration of bunches. Up to now, all methods that have been developed go along with various difficulties, which can include reduced stored-beam lifetimes. Thus, novel and innovative concepts for the manipulation and control of the longitudinal beam structure will have to be developed. In this paper, a possible approach to realize shortest bunches in an electrostatic storage ring is presented.

INTRODUCTION

Low-energy antiprotons are the ideal and perhaps the only tool to study in detail correlated quantum dynamics of few-electron systems in the sub-femtosecond time regime. Unfortunately cooled beams of antiprotons with the necessary beam quality and luminosity are not yet available and cannot be provided with present scientific infrastructures. In order to pave the way for a next-generation low-energy antiproton facility, challenging developments in both, storing and imaging techniques have been launched at the Max Planck Institute for Nuclear Physics (MPI-K). A novel ultra-low energy storage ring (USR) [1,2] to be integrated at the proposed facility for low-energy antiproton and ion research (FLAIR) [3,4] is being developed to provide electron-cooled beams of antiprotons and possibly highly charged ions in the energy range between 300 and 20 keV/q, maybe even approaching the sub keV regime.

To allow for kinematically complete investigations of a variety of different collision processes, a reaction microscope shall be integrated in the ring thus achieving unprecedented luminosities [1,5]. For these collision experiments around 10^4 antiprotons are required per bunch. This number is well below the space charge limit of the USR even at the lowest energies. However, the time structure of the pulses needs to be in the order of a few nanoseconds to allow its use as a trigger signal for the measurements. In this respect, an efficient control of the longitudinal time structure of the stored ion beam is of central importance since it directly determines the quality of the envisaged experiments.

GENERAL APPROACH TO SHORT PULSES OPERATION

It is technically possible to provide ultra-short pulses of 20 keV antiprotons by manipulation of the time structure of an extracted beam. The beam will interact with e.g. a gas jet only once per cycle which takes ~5 s in the case of the USR. This way a sufficiently high luminosity as required by the experiments cannot be reached.

We therefore consider the possibility of producing ultra-short pulses of a beam circulating in the USR [6]. 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.

An operation with ultra-short pulses for in-ring experiments might be realized by applying the sequence of the following procedures: Once the beam has been slowed down to 20 keV, the coasting beam of antiprotons is cooled down to a momentum spread of ~10^{-4} [7]. Then the cooled beam is adiabatically captured into τ~50 ns stationary buckets formed by a 20 MHz cavity operating at a high harmonic mode of the ring revolution frequency (h_{RF}=300-400) , see table 1.

The desired ultra-short pulses of ~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.

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[#]Alexander.Papash@mpi-hd.mpg.de

Table 1: High harmonic mode of the USR

Parameter	8° + 37° + 37° + 8° deflectors	
	Injection	Extraction
Energy [keV]	300	20
Circumference [m]	42.984	42.984
$\beta = v/c$	$2.53 \cdot 10^{-2}$	$6.53 \cdot 10^{-3}$
Rotation period $T=L/\beta c$ [µs]	5.667	21.957
Rotation frequenc, F_{rot} [kHz]	176.46	45.5436
RF frequency F_{RF} [MHz]	20.1164	20.0392
RF harmonic number h_{RF}	114	440
Bucket RF width [ns]	49.71	49.9
Buncher drift space [cm]	200	200
Buncher voltage [kV]	21.5	0.37
Expected Pulse width [ns]	2	2
Momentum spread (before / after e-cooling)	$5 \cdot 10^{-3}$ $5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$
Achromatic mode dispersion D_{max} / D_{min} [m]	0.7 0	0.7 0
dP/P [%]	0.5	≤ 2
Transition factor γ_{tr}		2.2
Momentum compaction α		0.207
Frequency slip factor η		-0.8
Synchr. freq. Ω_S [kHz]		$1.7 \times V_{RF}^{1/2}$
Range of RF voltage change		10…2000
Momentum pc [MeV]	23.72	6.12
Time-of-flight τ_{ef} in the buncher gap 20mm [ns]	2.6 (19°)	10 (70°)
β - (at buncher location) [m]		5

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 [6].

While the original layout of the USR foresaw 90° bending elements in each of the ring's corner section [3,8], a modified design was proposed in 2006 [1]. This layout, however, is under reconsideration and the ring parameters for the short pulse operation mode are presented in the above table 1. The RF phase gymnastics will be applied to the antiproton beam at lowest energy.

LOW-ENERGY PHASE COMPRESSOR

The estimation of the parameters of the USR phase compressor as well as the expected pulse structure of the beam as presented in this paper are calculated with the computer code *Buncher_U400* [9]. We applied a sinusoidal voltage at 20 MHz to the phase compressor and assumed that the beam has already been pre-bunched to 25 ns pulses by adiabatic capture into RF buckets. We furthermore assumed that the high harmonic RF will keep
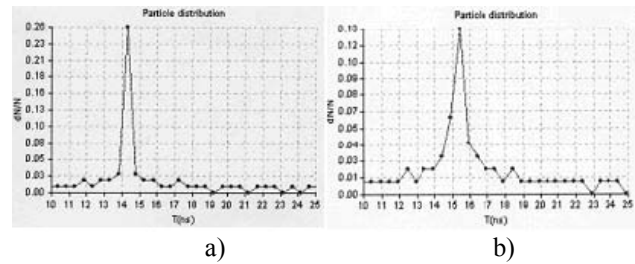

a) b)

Figure 1: a) Beam pulses at an RF frequency of $f_{RF}=20$ MHz. The amplitude of the buncher voltage is V=370 V b) Bunching of a beam with a momentum deviation of $\Delta p/p = 2$ %. The Pulse width increases to 1.7 ns

the beam captured in the buckets and that ion losses after the phase compressor are reasonably small. The code allows also addressing e.g. the gap crossing effect, influences from space charge, etc. The 2π phase band is divided into a number of intervals corresponding to a specific RF phase φ_i with an RF voltage amplitude proportional to $sin(\varphi_i)$. The beam density distribution is then calculated as the relative number of particles in each interval after crossing the drift distance between the buncher and its time focus.

At 1 MHz RF voltage the minimum available pulse width at the position of the reaction microscope will be at least 15 ns and the required amplitude of the buncher voltage exceeds 5-6 kV. The resulting energy spread caused by a 1 MHz phase compressor would thus lead to immediate loss of the beam. Increasing the RF frequency to 10 MHz leads to bunches with a pulse width of 2 ns in the time focus. In this case, a voltage of 715 V needs to be applied to the buncher. Finally, pulses of $\tau \approx 1$ ns will become available at an operation frequency of 20 MHz, see fig. 1a. It should be pointed out that the use of the here-proposed phase gymnastics would simply be impossible at a beam energy of *E=300 keV* where the amplitude of the buncher voltage would be 21.5 kV.

Because of the low beam energy and high RF frequency, time-of-flight effects during the passage of the electric field region between the buncher electrodes are of great importance. The minimum drift tube aperture is determined by the beam size before the electron cooling and cannot be reduced to less than 20 mm. At larger apertures there is an increased pulse width or even no bunching effect at all. Using the buncher at an RF frequency of more than 20 MHz is not possible due to fringe field effects.

In a next step, we investigated the phase compression as a function of the beam energy spread. Simulations were performed with a well-defined deviation from the design beam energy of 20 keV, while keeping the same amplitude of the buncher voltage as for the design energy. Particles with a large momentum spread of up to $\Delta p/p = \pm 2\%$ were tracked through the buncher, tuned for nominal

beam energy. In this case the pulse width increased to 1.7 ns, see fig. 1b.

ENERGY COMPRESSOR AND HIGH HARMONIC RF CAVITY

The evolution of a beam bunch is shown in the following fig. 2. The longitudinal emittance of the coasting beam at E=20 keV, the total bucket area and the required amplitude of the RF voltage depend on the initial energy spread of the beam and are summarized in table 2.
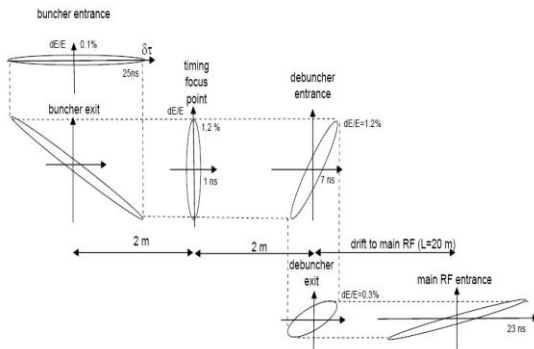

Figure 2: Sketch of the evolution of the phase space ellipse in the short pulse operation mode

The RF voltage which has to be applied to fully capture the un-cooled coasting beam is ~80 V, while it is only ~1 V for a cooled beam.

Table 2: Coasting beam emittance and total bucket area

Energy spread [dE/E]	$5 \cdot 10^{-4}$	$5 \cdot 10^{-3}$	$2 \cdot 10^{-2}$
Longitudinal emittance of coasting beam [keV·ns]	220	2200	8800
RF harmonic	440	440	440
Voltage to capture beam [V]	0.8	82	1370

The energy spread during the passage of the buncher/de-buncher combination is expected to be reduced from $\Delta E/E$ =1.2% in the time focus to $\Delta E/E$ = $3 \cdot 10^{-3}$ after the energy compressor. At a revolution period of ~20 μs the bunch with a 2ns pulse width will expand to 23 ns. The beam is then captured by the RF cavity for the next cycle. The bucket area must follow the growing beam emittance. For that purpose one has to provide a dynamic increase of the RF voltage amplitude in phase with increasing energy spread. The dynamic range of the RF cavity thus needs to cover variations of the voltage

Table 3. Full bucket area for an E=20 keV beam

V_{RF} [V]	$\Delta P/P$	$2\Delta E$ eV	$2\Delta E/E_k$
2	$5.6 \cdot 10^{-4}$	24	10^{-3}
40	$2.5 \cdot 10^{-3}$	108	$5.3 \cdot 10^{-3}$
200	$5.6 \cdot 10^{-3}$	240	$1.2 \cdot 10^{-2}$
500	$9 \cdot 10^{-3}$	380	$1.9 \cdot 10^{-2}$
1000	$1.3 \cdot 10^{-2}$	540	$2.7 \cdot 10^{-2}$

amplitude from a few Volts to roughly 2 kV, see table 3.

Computer simulations to build up a complete model of the USR ring short pulse operation mode are underway.

SUMMARY

The future ultra-low energy storage ring at the facility for low-energy antiproton and ion research will provide antiprotons and possibly highly charged ions with unprecedented beam quality and luminosities in the energy range of 300 down to 20 keV/q.

For these experiments, shortest beam pulses in the range of 1-2 nanoseconds at lowest beam energies are necessary. Given the natural dispersion of the beam and the coupling between transverse and longitudinal motion in an electrostatic cylinder deflector, such pulses are very difficult to realize. In this paper, we present the results of a preliminary study describing a possible beam bunching scenario in the USR. The simulations indicate that even shortest pulses might be realizable if an adequate beam forming scheme is applied.

The next step will now be to extend these simulations and to build up a full model, where the beam dynamics in longitudinal and transverse phase space will be investigated in detail [10].

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