INVESTIGATIONS INTO THE USR "SHORT PULSE" OPERATION MODE

A.I. Papash#, Max Planck Institute for Nuclear Physics, Heidelberg, Germany and Joint Institute for Nuclear Research, Dubna, Russia (on leave)
C.P. Welsch, University of Liverpool, The Cockcroft Institute of Accelerator Science and Technology, UK

Abstract

One of the central goals of the Ultra-Low energy Storage Ring (USR) project within the future Facility for Low-energy Antiproton and Ion Research (FLAIR) is to provide very short bunches in the 1-2 nanosecond regime to pave the way for kinematically complete measurements of the collision dynamics of fundamental few-body quantum systems – for the first time on the level of differential cross sections.

The "short pulse" operation mode may be split up in two steps: First, the cooled coasting beam of low energy ions will be adiabatically captured by a high harmonic RF cavity (20 MHz) into ~50 ns buckets. Second, the beam will be compressed to very short pulses with a desired width of only 1-2 ns by an RF buncher located 2 m in front of the so-called reaction microscope. To efficiently limit the beam energy spread, RF decompression is then done at after the experiment to avoid beam losses. In this contribution, we present numerical investigations of this very particular operation mode.

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. A novel ultra-low energy storage ring (USR) [1] to be integrated at the proposed facility for low-energy antiproton and ion research (FLAIR) [2] 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, with possibility to decrease energy of stored beam to keV range.

To allow for kinematically complete investigations of a variety of different collision processes, a reaction microscope shall be integrated in the ring. For these collision experiments around 10^4 antiprotons are required per bunch. 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.

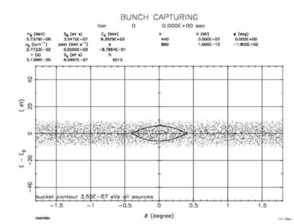
RF CAPTURE AT A HIGHER HARMONIC

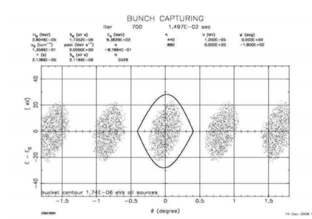
A preliminary study of the short pulse operation mode was presented by the authors in 2008 [3,4]. It was shown that an RF frequency of 20 MHz might be an optimum to start operation with short bunches. Short bunch operation has to start with a beam with an initial energy spread of $\Delta E/E=5\cdot 10^{-4}$ or $\Delta E= =\pm 10\ eV$ at an energy of 20 keV [5].

The computer code ESME [6] developed at FERMILAB was used for further simulations of the RF capture in the USR.

The revolution frequency of ions at the lowest energy of 20 keV in the USR is ~50 kHz. Therefore, an RF harmonic $h=440$ was used to simulate the capture process at $f_{RF}=20\ MHz$. A parabolic distribution of beam energy for the coasting beam and a random uniform population in the azimuth were considered to be a good representation of the beam after the electron cooling process, see Fig.1.

The RF capture efficiency was then checked against different parameters like the ramping time, initial and final amplitude of the RF voltage, etc. The capture efficiency of RF capture at 20 MHz is 98%.





a) *b)*

Figure 1: Iso-adiabatic capture of the coasting beam by a higher harmonic RF Cavity. The RF voltage $U=12\ V$ is sufficient to fully capture 20 keV pbars with an energy spread of $\Delta E/E=\pm 5\cdot 10^{-4}$ (ESME simulations): a)Energy spread of coasting beam is $\Delta E=\pm 10eV$, b)Energy spread of captured beam is $\Delta E=\pm 20eV$.

In order to realize a constant adiabatic degree and to avoid filamentation and blow up of phase space the ramping time should be larger than 1–2ms. The ramp time was varied from 0.5-50 ms. It was found that a 1-10 ms ramp time provides the best capture conditions, combined with an initial RF voltage of 0.5–1 V.

A minimum value of the final amplitude between 6 and 8 V is required to fully capture the electron cooled beam. An optimum amplitude of the RF voltage lies around 10 V. The resulting energy spread of a beam bunched by an RF voltage of 10 V is $\Delta E/E=10^{-3}$ i.e. $\Delta E=\pm 20\ eV$, *see* table 1. The distribution of beam intensity versus the azimuth before and after capture is shown in fig.2. One can see that pulses of 18 ns (FWHM) are available at 20 MHz. The results from the ESME simulations are presently being compared with MAD-X simulations and checked for consistency.

#Alexander.Papash@quasar-group.org

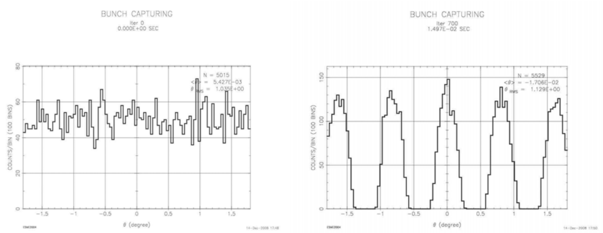

a) b)

Figure 2: Distribution of the beam intensity as a function of the azimuth: a) random uniform distribution in θ of the coasting beam, b) bunches of 18 ns pulse width (FWHM) after RF capture.

Table 1: Multiple Split of RF Frequency

Transition Mode	Iso-adiabatic RF capture		Iso-adiabatic Bunch Split		
F_{RF}, *[MHz]*	DC to 20	DC to 40	20 to 40	40 to 80	80 to 160
h_{RF}	440	880	440 880	880 1760	1760 3520
τ_{FWHM}, *[ns]*	DC→ 18	DC→ 12	12→ 6	6 → 4	4 2
Capt.Effic.	97%	97.7%	95%	83%	38 %
Initial Beam Distri-bution	θ - Rand E-Parab	θ - Rand E-Parab	Bi-Gauss (95%)	Bi-Gauss 95%	Bi-Gauss (95%)
Number of Particles	500 000	500 000	100 000	100 000	100 000
Total Effic. Capture + Split	**DC – 4 ns 75%**				**DC – 2 ns 30%**
U1(in–fin), *[V]*	0.5 -12	1 – 8	12 – 1	12 – 0	6 – 0
U2(in–fin), *[V]*	0	0	1–10	1–6	0– 4
Split time, *[ms]*	10	5	10	10	10
observation time, *[ms]*	150	220	40	200	400
INITIAL ΔE *[eV]*	±10 95%	±10 95%	±20 95%	±16 95%	±8 95%
FINAL ΔE *[eV]*	±20 95%	±14 95%	±16 95%	±8 95%	±4 95%
F_{rot} *[kHZ]*	46.755				
T_{rot} *[µs]*	21.388				
ν_S = F_S / Frot	0.136	0.157	0.175	0.192	0.22
F_S *[kHz]*	6.08	7.3	8.2	9	10.3

ISOADIABATIC RF SPLIT

The resulting bunches at 20 MHz may be further reduced to the required 2 ns by higher RF harmonics, table 1. It can be seen that the adiabatic split from 40 to 80 MHz provides 4 ns bunches. The total efficiency of the capture process and subsequent splits to 4 ns bunches is 75%. It is expected that the overall efficiency for the realization of 2 ns bunches will be in the order of 30%, see fig.4.

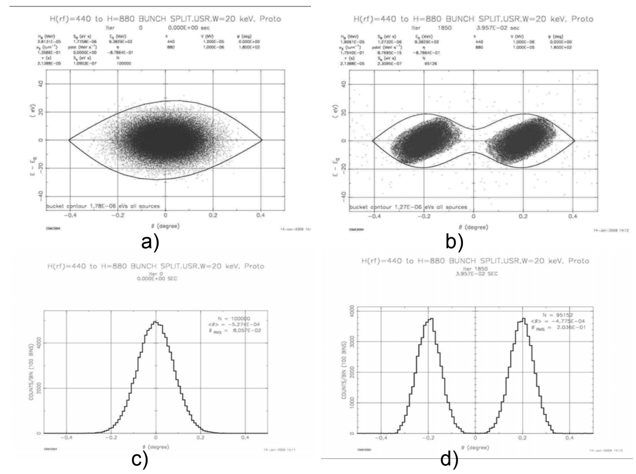


Figure 3: Iso-adiabatic split with RF frequency changed from 20 to 40 MHz (h_{RF}*=440* to h_{RF}*=880*). Initial beam distribution is bi-Gaussian in E and θ : a) before split, b) after split, c) pulse width (FWHM) before split is12 ns, d) after split – 6 ns.

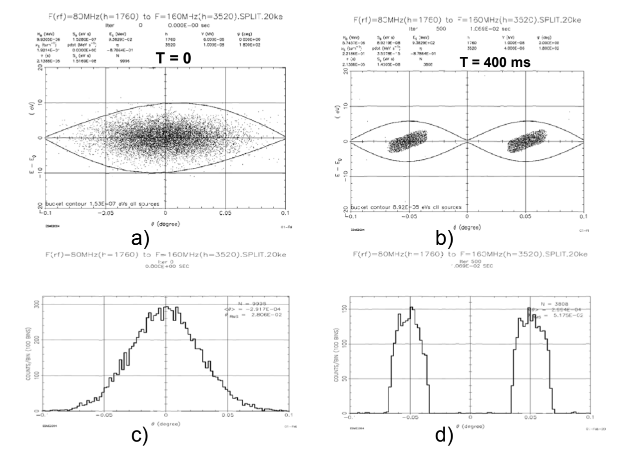


Figure 4: Iso-adiabatic split with RF frequency changed from 80 to 160 MHz (h_{RF}*=1760* to h_{RF}*=3520*). Initial beam distribution is bi-Gaussian in E and θ : a) before split, b) pulses stable after split, c) pulse width (FWHM) before split is 4 ns, d) after split – 2 ns.

BUNCH ROTATION

The multiple iso-adiabatic split leads to a separation between pulses of 20 keV antiprotons of only 7 ns. This needs to be compared to the standard electronics of existing reaction microscopes (RM) which normally register coincidence events if the time between bunches is no less than 200 ns. Thus a different scheme where 25 ns bunches are rotated in phase space in one of the dispersion-free straight sections of the USR was proposed to overcome problems with the multiple split mode [3, 4]. The evolution of longitudinal phase space is shown in fig.5. The drift distance between RF cavity 2 (RF2) and the RM is 2 m. RF1 provides short (25 ns) pulses which are then further compressed by RF2 to 2 ns. A debuncher then reduces the energy spread to allow for the beam to be captured by RF1 for the next turn.

This mode was investigated in more detail with the computer code MAD-X [8]. 500 particles randomly populated in E and θ space were tracked over 1000 turns including the main RF to benchmark the code, fig. 6a. It can be seen that most of the particles are kept inside the bucket. In a next step the phase space ellipse matched to the RF acceptance was introduced and simulations were run again.

The effects of the buncher (RF2) and debuncher (RF3) were simulated by applying sinusoidal voltages at the location of both elements. The bucket area and the initially matched phase space ellipse at the position of RF1 as well as the orientation and shape of the phase space ellipses at the position of RF2, RM, and RF3 are shown in fig. 7a. It can be seen that a voltage of 370 V is enough to reduce the pulse width from 25 to 1 ns at the RM location, fig.7b. The energy spread introduced by the buncher exceeds 350 eV in this case.

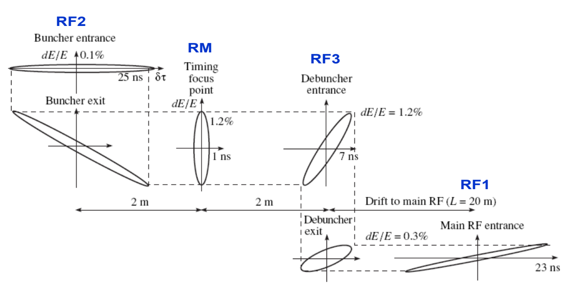


Figure 5: Evolution of the longitudinal phase space during bunch rotation in the USR. The location of all rf systems and the reaction microscope are indicated.

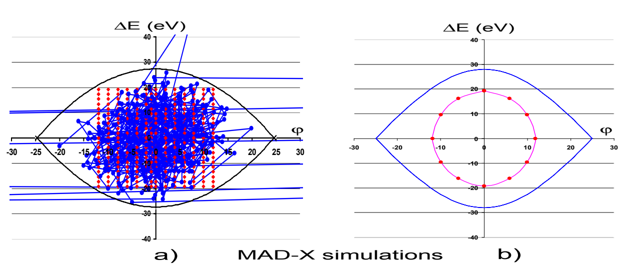


Figure 6: Beam distribution in longitudinal phase space. a) Stationary bucket filled with 500 particles randomly populated in phase space: red points – initial distribution, blue points – after 1000 turns, b) Initial ellipse matched to the RF acceptance.

RF3 is located at a distance of 2 m downstream of RM and reduces the energy spread to an acceptable level. A strong filamentation of phase space can be restricted by applying of saw tooth field to the buncher and debuncher.

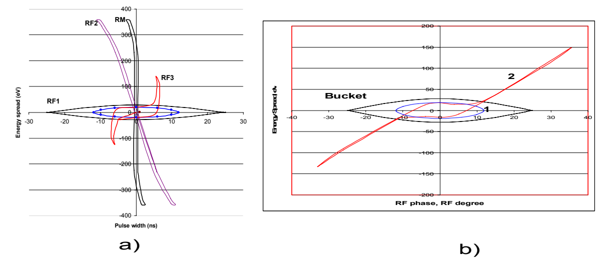


Figure 7: Change of phase space ellipse during bunch rotation in the USR.

SUMMARY

In-ring collision studies with a reaction microscope are of particular importance since they directly address one of the most fundamental yet unanswered problems in physics – the few-body Coulomb problem and in particular the question whether or not correlation effects are important for a full understanding and possibly even control of this process.

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 storage ring, such pulses are very difficult to realize. In this paper, we present the results of computer simulations of 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.

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