Cost and Feasibility Study of the Intensity Improvement for ASACUSA

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Summary

An electron cooling scheme for an antiproton beam confined into a $h = 1$ bucket in the CERN Antiproton Decelerator (AD) is proposed. The longitudinal beam density obtained this way is significantly higher than what can be achieved by cooling a coasting beam, allowing beam bunching with 202 MHz already in the AD ring, the frequency of the ASACUSA decelerating RF quadrupole (RFQD). The scheme requires installation of two 202 MHz cavities and a wall current monitor into the AD. With such a modest investment ASACUSA will gain a factor of 2-3 in intensity. In this paper a detailed list of the work needed in order to implement the proposal is compiled, as well as a first cost estimate.
An electron cooling scheme for an antiproton beam confined into a $h = 1$ bucket in the CERN Antiproton Decelerator (AD) is proposed. The longitudinal beam density obtained this way is significantly higher than what can be achieved by cooling a coasting beam, allowing beam bunching with 202 MHz already in the AD ring, the frequency of the ASACUSA decelerating RF quadrupole (RFQD). The scheme requires installation of two 202 MHz cavities and a wall current monitor into the AD. With such a modest investment ASACUSA will gain a factor of 2-3 in intensity. In this paper a detailed list of the work needed in order to implement the proposal is compiled, as well as a first cost estimate.

I. INTRODUCTION

Electron cooling of a coasting beam with a subsequent bunching is very different from directly cooling a bunched beam. The momentum spreads of a coasting beam and a bunched beam will be similar at the end of the cooling. However a coasting beam fills up the whole circumference of the ring, while a bunched beam is kept within a fraction. Therefore the longitudinal emittance is much smaller in the case of bunched beam cooling. A proposal [1] was made to use this principle in order to improve the efficiency of the RFQD by a factor 2-3.

Currently a coasting beam is first cooled, captured into a single bunch and then a bunch rotation before ejection is applied to shorten the bunch length. During the bunch rotation the momentum spread is increased to up to $10^{-3}$. The 202 MHz bunch structure needed for RFQD deceleration is created by a buncher cavity 6 m upstream of the RFQD located in the ejection line. This type of bunching limits the deceleration efficiency. In practice only 30% can be obtained at best. The AD C02 low level RF system uses a synchronization loop at ejection. This synchronization loop can not function properly if the electron cooling is also working at the same time, due to an unwanted interaction between the RF loops and the electron cooling.

In the proposed scheme the C02 cavity will be driven by a fixed frequency derived from the RF of the RFQD in open loop. The smaller longitudinal emittance obtained by the $h = 1$ bunched beam cooling will allow the 202 MHz bunching already in the AD ring. The improved 202 MHz structure will increase the deceleration efficiency of RFQD by a factor 2-3. The beam in the AD can not be compressed efficiently to fit inside the 10 degree phase acceptance of the RFQD [2] due to the low momentum acceptance of the 202 MHz capture process. The synchrotron tune is also unusually high at the end of the capture process. Therefore the buncher cavity is still needed to give an additional longitudinal focusing. However in this case only a much smaller part of beam is outside of the longitudinal acceptance of the RFQD, as the simulation results indicate in Fig.(1).

II. BUNCHED BEAM COOLING

Bunched beam cooling at 100 MeV/c with $h = 3$ has been successfully tested during an MD in 2009 [3]. The transverse profile measured was very similar to the profiles measured after coasting beam cooling. The horizontal emittance was about 0.3 $\pi$ mm mrad with 70 % of the beam inside the core. The vertical emittance was about 0.5 $\pi$ mm mrad with 80 % core.
The measured bunch length with $V_{rf} = 500V$ was dependent on the intensity. With $3.5 \times 10^7$ antiprotons 80 ns bunch length was measured. With $6 \times 10^6$ antiprotons the bunches were only 40 ns long. With such short bunches the bunch lengthening due to the longitudinal space charge force is significant. It is important to note that the upper frequency limitation of the AC beam transformer \cite{4} makes the measured bunch length appear longer than the reality.

Two types of bunched beam cooling have been tested so far, the barrier bucket cooling and the $h = 3$ cooling described above. The results of the barrier bucket cooling are published in \cite{1}. These tests strongly indicate that no problem should be expected with $h = 1$ bunched beam cooling. The $h = 1$ cooling will be tested as soon as the MD program of the AD allows it.

III. 202 MHZ CAPTURE

A. Cavity locations

The 202 MHz capture process will take place at the 1160 harmonic of the revolution frequency, at 100 MeV/c. The longitudinal phase space ellipse is not standing straight at the cavities, but only half way between them. This is a consequence of the high harmonic number. Ideally the beam should arrive at the RFQD buncher cavity with the ellipse in longitudinal phase space standing straight. This can not be achieved precisely since there are only a few suitable locations for the 202 MHz cavities, but the penalty of having a slightly longer than ideal distance to the RFQD buncher is very small. In order to maximize the momentum acceptance, the distance between the two cavities should be approximately half of the AD ring circumference. Taking into account these requirements and the space available, the cavities will be best placed in sections 16 and 44.

In order to make space for the first 202 MHz cavity, the length of the horizontal damper kicker marked as “B” in Fig(2) has to be reduced. The cavity will be installed at a position of 50.6 meters (gap centre, MAD \cite{5} coordinate). A modification of the damper space ellipse is not standing straight at the cavities, but only half way between them. This is a consequence of the high harmonic number. Ideally the beam should arrive at the RFQD buncher cavity with the ellipse in longitudinal phase space standing straight. This can not be achieved precisely since there are only a few suitable locations for the 202 MHz cavities, but the penalty of having a slightly longer than ideal distance to the RFQD buncher is very small. In order to maximize the momentum acceptance, the distance between the two cavities should be approximately half of the AD ring circumference. Taking into account these requirements and the space available, the cavities will be best placed in sections 16 and 44.

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B. Cavity design modifications

The design of the existing PS 200 MHz cavities has been used as starting point for the new 202 MHz bunching cavities. Since the relativistic $\beta$ of the antiproton beam is only 0.106, the transit time factor would be very low with the original design. In order to increase it, both the gap distance and the gap aperture have to be reduced. The lowest possible gap diameter is determined by the acceptance of the AD machine and the optical functions at the location of the cavities. The horizontal plane is more demanding. The following discussion refers to the horizontal plane. At injection the acceptance must be at least $220\pi$ mm mrad \cite{6}. With the high energy optics, the $\beta$ function is less than 8.2 m at the locations of the cavities. Taking into account $\pm 5$ mm for orbit excursions, 47.5 mm is obtained as minimum gap radius. As the horizontal dispersion at the locations of the cavities is 0.042, and the momentum acceptance is $\pm 3\%$, another 1.3 mm is added. The minimum gap radius becomes 48.8 mm. At low energies a different optics is used. Calculating with the low energy optics...
and 48.8 mm cavity aperture, a value higher than 220π mm mrad is obtained for the acceptance. Less than 1 m away from the 202 MHz cavity in the section 16, there is already an aperture limitation of 36.7 mm, due to the horizontal damper kicker. The cavities will not have any effect on the machine acceptance.

The same estimation applies to the second cavity to be installed in section 44, where the \( \beta \) function is even smaller than 8.2 meters in both planes, while the dispersion is similarly small.

Since the existing 200 MHz cavities will be kept as spares for the PS, two new cavities have to be developed and built for the AD. As shown in Fig(4), only the accelerating gap region is under vacuum, the rest of the cavity can be in air, which significantly simplifies its construction. The body and the support of the cavity can be built in the CERN workshop. It is made of aluminium, a good compromise between electrical resistivity, thermal conductivity and price. The gap region with the ceramic insertion is available, as well as the special RF fingers to contact it with the cavity body. The gap distance and diameter will be reduced by inserting two metallic cones inside, significantly improving the transit time factor. The cost of the cavities will be dominated by the manpower required for manufacturing. The tuning of the cavity to keep it on resonance does not need to be fast, a simple motorized tuning plunger in air can be used. The design for the tuners and the electronics to drive its stepping motor are available, but it has be built [7].

The properties of the 202 MHz cavity with the reduced 20 mm gap distance and 50 mm radius were estimated and optimized with the code Superfish [8]. Table I summarizes the relevant parameters, including the RF power required to produce an effective (including the transit time factor) accelerating voltage of \( V_{\text{acc}} = 10 \text{kV} \). With

\[
\begin{array}{ll}
\text{Resonance frequency} & 202 \text{ MHz} \\
\text{Shunt impedance, } R_s & 105 \Omega \\
\text{Unloaded quality factor, } Q & 10700 \\
\text{Transit time factor (at } \beta = 0.106) & 0.357 \\
\text{Power required for } V_{\text{acc}} = 10 \text{kV} & 0.95 \text{kW}
\end{array}
\]

TABLE I: Parameters of the 202 MHz bunching cavity.

20 mm gap width the maximum electric field at 10 kV accelerating voltage is well below breakdown limits.

In the PS accelerator PIN diode switches are used to reduce the shunt impedance and thus the beam induced voltage of the 200 MHz cavities when not in use. Due to the very low beam intensity in AD such a set-up is not required. However the possibility of adding a mechanical relay (instead of the PIN diode) should be kept for safety.

C. 202 MHz RF amplifiers

Two solid state amplifiers will be constructed at CERN. There are 400 W pallet amplifiers available from several companies for VHF TV transmitters, they cost less than 2 kCHF including the driver stage. The amplifiers with interlocks and diagnostics will be built around these pallets. Three pallets connected to a combiner will give the required power. The amplifiers must be protected against reflected power by circulators.

D. Cost and manpower

<table>
<thead>
<tr>
<th>cost [kCHF]</th>
<th>manpower [m.m.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of the cavity</td>
<td>0</td>
</tr>
<tr>
<td>2 x cavity body</td>
<td>20</td>
</tr>
<tr>
<td>2 x tuner</td>
<td>50</td>
</tr>
<tr>
<td>2 x cav. support</td>
<td>10</td>
</tr>
<tr>
<td>2 x 1 kW amplifiers</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>130</td>
</tr>
</tbody>
</table>

TABLE II: Cost and manpower for the 202 MHz cavities.

IV. LOW LEVEL RF

A. Overview

The block diagram of the RF system necessary for the proposal is shown in Fig(5). The oscillator of the RFQD will be the master. It will determine the 202 MHz capture frequency directly. Since the \( h = 1 \) bucket and the
202 MHz capture need to be synchronized, the revolution frequency in the AD during the flattop FT4B will also be determined by the RFQD. This will be achieved by dividing the 202 MHz signal of the RFQD and using it to drive the C02 cavity. The phases of the 202 MHz cavities respect to the RFQD have to be adjusted. The phases of the 202 MHz cavities in the ring also need to be adjustable respect to each other by a second phase shifter. The 202 MHz voltage function will be generated by a CVORG function generator. The C02 voltage function is generated by the existing GFAS.

B. RFQD frequency stabilization

Keeping the RFQD at its optimum performance requires a driving frequency close to the resonance. Presently the RFQD has no frequency regulation loop. It can have a long term drift due to external temperature changes up to 100 kHz. It is pulsed regularly every 2.4 seconds for monitoring. Since 100 kHz frequency drift would correspond to an offset in \( \Delta \frac{p}{p} = 5 \times 10^{-4} \), the RFQD needs frequency stabilization. This will be most likely a simple loop which changes the amplitude of the monitoring pulses. Controlling the dissipated heat on the RFQD structure, the resonance frequency can be kept close to 1160 times of the nominal revolution frequency of the AD. The analog and digital inputs for the amplitude control are available [9].

C. Cost and manpower

The cost of the low level RF system will be dominated by electronics developments needed. Similar equipment in the PS is obsolete and can not be easily rebuilt.

<table>
<thead>
<tr>
<th>Cost [kCHF]</th>
<th>Manpower [m.m.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics development</td>
<td>120</td>
</tr>
<tr>
<td>RFQD stabilization</td>
<td>10</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>140</strong></td>
</tr>
</tbody>
</table>

TABLE III: Cost and manpower for the low level RF. The item ‘Other’ includes phase shifters and a VME crate if needed.

V. WALL CURRENT MONITOR

Currently it is difficult to observe a 202 MHz longitudinal structure in the AD ring. The longitudinal pickup has much lower cut-off frequency. A wall current monitor (WCM) needs to be installed. WCMs can work up to several GHz. In our case 1 GHz upper frequency will be sufficient. The lower cut off frequency is not critical. The main difficulty will be the low intensity in the AD, the peak current will be only about 50 µA. Due to the very low signal level, the WCM should not be too close to the 202 MHz cavity. The WCM will be installed in section 13, about 8 m away from the cavity. The WCM will be similar to the new PS design [10], shown in Fig(6). The signal will be amplified and connected to the ACR. The impedance of the WCM is about 6 Ω. This increase in
the longitudinal impedance of the machine is negligible.

VI. TIMING

A. Overview

The timings need to be added to the existing ones:

- Start for the CVORG, generator of the 202 MHz capture function;
- Start for the ejection kicker and all related timings;
- 202 MHz cavity tuning.

The CVORG should start about 100 turns before the ejection, the duration of the 202 MHz capture function. The counter for this timing can be clocked by the revolution frequency.

The timings for the 202 MHz capture and the ejection kicker need to be synchronized with the revolution frequency. The ejection kicker timing needs a finer resolution in time, its clock will be derived from the 202 MHz signal.

The ejection timings for the bunched beam cooling will work in parallel with the current ejection scheme. To generate the different timings needed, a new VME crate will be installed next to DADETIM (Building: 193 S-0310 Rack: CY03). This VME crate can also be used to progressively renovate DADETIM with new timing receivers. The cost of the new VME crate and the related cabling (Ethernet, etc.) will be covered by the controls renovation project (ACCOR).

VII. SUMMARY OF COST AND MANPOWER

The total cost and manpower requirement of the proposal is summarized in Table V.

<table>
<thead>
<tr>
<th>cost [kCHF]</th>
<th>manpower [m.m.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and test</td>
<td>0</td>
</tr>
<tr>
<td>Construction</td>
<td>0</td>
</tr>
<tr>
<td>Materiel</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
</tr>
</tbody>
</table>

TABLE IV: Cost and manpower for the WCM.

<table>
<thead>
<tr>
<th>cost [kCHF]</th>
<th>manpower [m.m.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>202 MHz cavities and ampl.</td>
<td>130</td>
</tr>
<tr>
<td>Low level RF</td>
<td>140</td>
</tr>
<tr>
<td>Wall current monitor</td>
<td>20</td>
</tr>
<tr>
<td>Timing</td>
<td>0</td>
</tr>
<tr>
<td>Cabling</td>
<td>10</td>
</tr>
<tr>
<td>Drawings</td>
<td>17.2</td>
</tr>
<tr>
<td>Vacuum modifications</td>
<td>25</td>
</tr>
<tr>
<td>Bake out of 2 AD sectors</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>367.2</td>
</tr>
</tbody>
</table>

TABLE V: Summary of cost and manpower.

VIII. RISK ASSESSMENT

The possible risks of the modifications in the AD ring have been evaluated from three points of view: vacuum, aperture limitations and impedances.

There will be no material inserted into the AD vacuum, which has not been already proven to be appropriate in an accelerator. The WCM design will respect the AD vacuum requirements. The 202 MHz cavities have only their gap regions in vacuum, the body is in air. The other modifications concerning the vacuum are only rearrangements of the existing equipment.

From the aperture limitation point of view, most care has to be taken with the 202 MHz cavities. As described earlier the gap diameter is calculated such that the acceptance limitation due to the cavities is at least \( 220 \pi \text{ mm mrad} \) in both planes. Equipments with smaller aperture are already installed close to the cavities, the transverse damper kickers and pickups. The other modifications are not critical.

The insertion of the 202 MHz cavities will add a narrow band longitudinal impedance. As described earlier, due to the very low beam current this is not expected to be a problem. The insertion of the WCM will increase the longitudinal impedance by only 6 \( \Omega \), which is negligible.
IX. CONCLUSIONS

A new scheme is proposed to improve the ASACUSA RFQD deceleration efficiency by a factor of 2-3. The two key elements of the proposal are the electron cooling of the antiproton beam confined longitudinally and the 202 MHz capture in the AD ring at 100 MeV/c. A detailed description of the feasibility of the scheme with cost and manpower estimate is given. No direct showstopper has been identified so far. The proposed modifications do not introduce any significant risk for the AD operation. The equipments necessary for the proposal are mostly independent from existing systems, therefore the commissioning will have little impact on the normal operation of the AD. The very significant improvement offered for a modest cost and effort makes this proposal a good investment.

X. ACKNOWLEDGMENTS

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