AB-Note-2008-035 (PS2)

RF Scenarios for Pb^{54+} Ions in the PS2

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Abstract

This note analyses some of the rf scenarios that are presently being considered for lead ions in the PS2. An earlier note principally concerning protons [1] highlighted the problem of the large revolution frequency swing of ions in the PS2 and the issue of bunching factor with direct injection from the LEIR machine. We present several solutions. One option is based on a 10 MHz system with a suitably large-tuning range, as in the present PS scheme. Another scheme assumes the 40 MHz principal rf system proposed for PS2 proton acceleration to have either a tuning range of more than an octave or, alternatively, to have switchable tuning ranges to cover the large frequency swing required. The 40 MHz route also requires an additional rf system in LEIR. More exotic approaches are also presented. The different scenarios are compared and the preferred variant is presented.

1. Introduction

This note analyses some of the rf scenarios that are presently being considered for lead ions in the PS2. With regards requirements, it is assumed that the PS2 will provide the so-called "nominal" Pb^{54+} ion beam [2] comprising four bunches spaced by 100 ns for the LHC. It is further assumed that ion beams for the PS2 will be supplied directly by the LEIR machine at a magnetic rigidity of 6.67 Tm, which will require an upgrade of LEIR main power converters and extraction elements. The main parameters of the "nominal" ion beam in the PS2 are summarized in Table 1 and compared to the present beam in the PS. Some of the parameters for the PS2 are dependent on the various schemes presented below.

Table 1: Nominal ion beam parameters in PS2 and PS.

"Nominal" Pb^{54+} ion beam	**Injection**		**Ejection**	
	PS2	**PS**	**PS2**	**PS**
Energy [MeV/n]	135	72	12320	5880
Magnetic rigidity [Tm]	6.67	4.8	169.9	86.7
Revolution frequency [kHz]	108.4	177.6	222.1	472.7
Harmonic number	scheme dep.	16	scheme dep.	169
Number of bunches	**k**	2	4	
Bunch spacing [ns]	scheme dep.	352	100	
Ions per bunch	9.0E8/**k**	4.5E8	1.2E8	
Total intensity	9.0E8		4.8E8	
Long. emittance [eVs/n/bunch]	scheme dep.	0.05	0.05	
Bunch length (total) [ns]	scheme dep.	200	4	
Emittance h,v (norm. rms) [$\pi\mu$m]	0.7,0.7		1.0,1.0	

We consider three different classes of solution:

- The 10 MHz route, similar to the present production scheme in the PS machine and based on a principal rf system in the PS2 covering the frequency range from 3.6 MHz to 10 MHz.
- The 40 MHz route, motivated by both the bunch patterns for LHC proton operation and by the SPL 40 MHz chopper and based on a principal rf system with either a tuning range of more than an octave or having switchable ranges to cover 18.6 MHz to 40.1 MHz. The LEIR machine will also have to be equipped with an additional rf system in this approach.
- More exotic schemes, like fixed-frequency acceleration similar to the SPS, operation of the old PS as a dedicated ion booster, or an alternative solution to the 10 MHz route based on a low-frequency tuneable system in the range 6.5 MHz to 13.3 MHz.

2. The 10 MHz route

Ion beams will be provided by the LEIR machine, which currently operates on harmonic h=1 or h=2. Since the circumference ratio of the two machines is 120/7, only a single bunch per LEIR cycle can be transferred in a straightforward manner into the PS2. However, h=34 (3.686 MHz) buckets in the PS2 are well adapted to receive the two bunches of today's nominal h=2 ion beam because the phase error of ±1.5° due to the circumference ratio (120/7 = 34.29/2) is insignificant.

Less rf voltage than for protons is required to get the nominal emittance of 0.05 eVs per nucleon through the acceptance bottleneck in the early part of acceleration. Protons define the 0.5 MV voltage specification of this rf system [1].

PS2 gymnastics are then directly analogous to the production of this beam in the existing PS machine [4]. After acceleration on h=34 to an intermediate plateau at B~0.3 T (cf., B=0.067 T at injection), there is enough frequency margin not only to perform a batch expansion from h=34 to h=24 (7.1→5 MHz), but also to split the bunches to h=48 (5→10 MHz). One further batch expansion step from h=48 to h=45 (10→9.375 MHz) gives the desired harmonic which, after final acceleration, yields four bunches in consecutive buckets 100 ns apart (9.995 MHz) on the flat top. The bunches are then shortened to 4 ns by an adiabatic step in voltage before ejection to fit them into 200 MHz buckets of the SPS.

3. The 40 MHz Route

The 40 MHz route with direct injection from the LEIR machine immediately raises the issues of bunching factor and bunch length because of the limited length of the receiving PS2 bucket. The large revolution frequency swing of ions in the PS2 is also beyond the capabilities of conventional 40 MHz equipment.

3.1. Narrowband

Circumventing the 105% frequency swing of Pb^{54+} ions with only the sort of narrowband rf system that is typically available at 40 MHz would be problematic. Exploiting the fact that the LEIR rf system is a low-Q, finemet one, the two bunches must first be squeezed closer together in LEIR by the superposition [3] of an h=3 rf component to align with h=360 (39.03 MHz) buckets in the PS2, but the latter are simply too short to receive bunches of any reasonable longitudinal emittance. Consequently, the degraded bunching factor and increased direct space charge detuning rule out this option.

This makes somewhat academic the subsequent PS2 gymnastics of repeatedly accelerating and rebucketing such that the two bunches separated by 8 bucket lengths on h=360 are successively separated by 7 on h=315, 6 on h=270, 5 on h=225 and 4 (~100 ns) on h=180 (39.98 MHz at top energy). In principle, all this could be achieved on the fly provided transition does not interfere. The available percentage swing must still be greater than 100*(225/180 - 1) = 25% and only two bunches are produced instead of the four nominally required.

3.2. Wideband

To retain the 40MHz route implies pushing for an unprecedented tuning range and the introduction of a new rf system in LEIR.

The 120/7 circumference ratio immediately suggests filling 4 out of 7 LEIR buckets at transfer, but 8 out of 10 with 18.65 MHz buckets (h=172) waiting in the PS2 provides a much better filling factor with a penalty of only ~4° of phase error for the outermost bunches. This scheme sees four bunches accelerated with the existing rf system (frequency range ~0.36–5 MHz [3]) to an intermediate plateau in LEIR where a kicker gap is introduced (h=4→5) and the bunches are split (h=5→10) using the new rf system (~10 kV, ~10–19 MHz, see Fig. 1) before accelerating to extraction energy.

In the PS2 the beam is accelerated to an intermediate plateau at B~0.5 T (cf., B=0.067 T at injection) to double the revolution frequency and so permit merging (h=172→86) back to the four bunches required, then rebucketed (h=86→172) to fill every second bucket and provide the frequency margin to perform a batch expansion (h=172→154→138→124→112→100→90) in quasi-equal azimuthal steps to 100 ns bunch spacing before final acceleration to top energy (19.99 MHz). ESME simulations (see Figs. 2-5) show that all this can be achieved in about a quarter of a second.

This solution would require covering 18.6–37.3 MHz for ion operation, with the upper limit extended by the 39.3–40.1 MHz requirement for proton acceleration. Obviously, if more than an octave tuning range can be realized, it obviates the need for a fixed-frequency 20 MHz system to produce by merging the 50 ns proton variant for the LHC.

A less ambitious approach would be to aim for 50% tuning range, as the ion gymnastics above could be performed with cavities whose tuning range is switchable between 18.6 to ~27 MHz and ~26.5 to 40.1 MHz.

For proton operation all systems would work in the same range (~1.5 MV total voltage), while the ion gymnastics require significantly lower voltages so that it is possible to split the cavities into two groups with independent tuning.

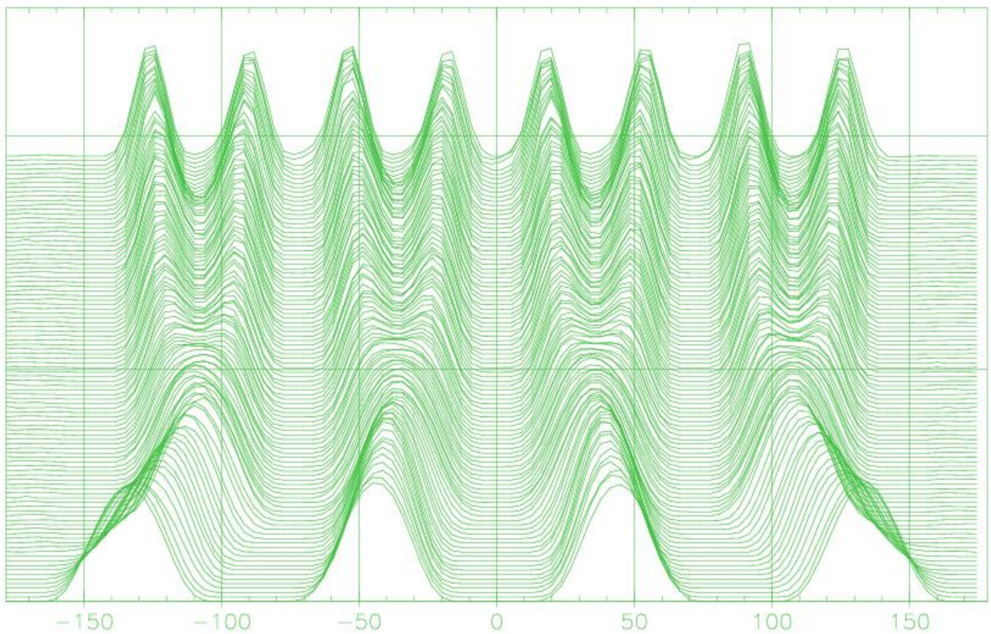

Figure 1: Simulated beam current profiles versus degrees of azimuth on an intermediate plateau in LEIR where a kicker gap is introduced (h=4→5) and the bunches are split (h=5→10) in order to adapt them to the constraints of a wideband rf system in the PS2. The duration of these gymnastics is 50 ms.

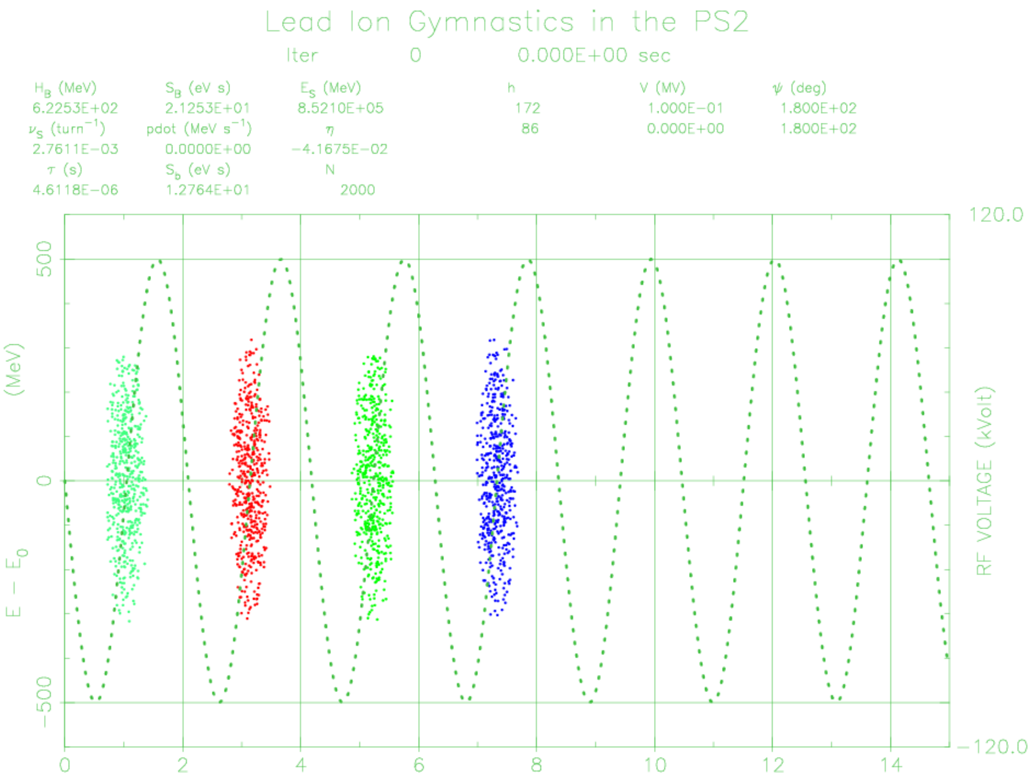

Figure 2: Phase space plot of half the resultant bunches of Fig. 1 on an intermediate plateau in the PS2 (h=172).

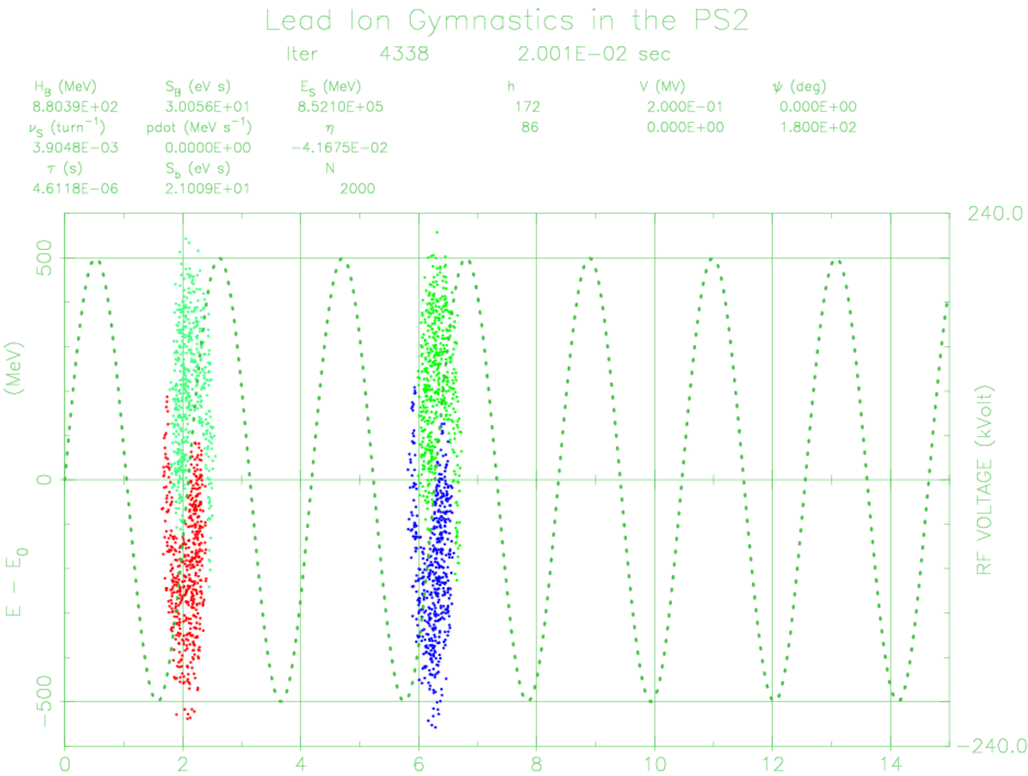

Figure 3: Phase space plot of the bunches of Fig. 2 after merging (h=172→86) and rebucketing (h=86→172).

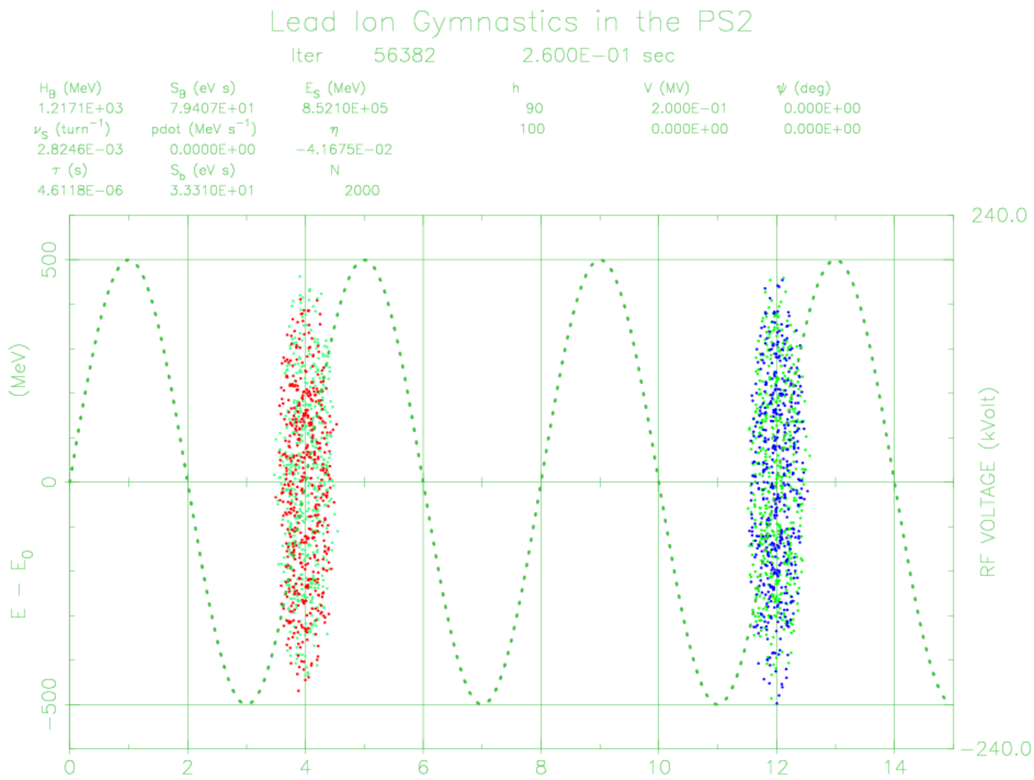

Figure 4: Batch expansion (h=172→…→90) yields bunches 100 ns apart (corresponding to 8 degrees of azimuth).

4. Other schemes

4.1. 13 MHz in the PS2

Ion acceleration in the PS2 requires an rf system that can handle a large frequency swing. A dedicated system covering roughly 6.5–13.3 MHz could be envisaged as an alternative to the 10 MHz route.

In this scenario the two bunches must first be pushed further apart in LEIR by the superposition [3] of an h=3 rf component to align with h=60 (6.505 MHz) buckets in the PS2 with one empty bucket between them. After acceleration on h=60 to an intermediate plateau at B~0.5 T (cf., B=0.067 T at injection), they are rebucketed on h=30 (13→6.5 MHz) and split back to h=60 (6.5→13 MHz). There are now four bunches in consecutive buckets 75 ns apart. Batch expansion in steps of 5 from h=60 to h=45 (13→9.75 MHz) gives the desired harmonic which, after final acceleration yields four bunches in consecutive buckets 100 ns apart (9.995 MHz) on the flat top.

However, compared with the 10 MHz and 40 MHz wideband routes, this scheme goes in entirely the wrong direction for bunching factor and thus direct space charge detuning could be an issue.

4.2. Fixed-frequency acceleration in the PS2

If the filling time of the PS2 cavities is short enough, ions could be accelerated using the fixed-frequency method established in the SPS [5].

4.3. PS as a dedicated ion booster

The PS machine could be reborn as a dedicated booster for ions. It would be a low-energy machine only, operating without pole-face windings and with no transition crossing and a scaled-down main power supply just to cater for the bulk of the frequency swing. No upgrade of LEIR would be necessary.

5. Comparison of the options and conclusions

The 10 MHz route follows closely the present production scheme of the PS. Consequently, no rf hardware R&D is necessary to realise this scheme for the PS2. Another advantage is that no modifications are needed in the LEIR machine other than raising the extraction energy. The drawbacks of the scheme are that several additional rf systems are needed in the PS2 for gymnastics and bunch shortening before ejection, and that the 10 MHz system is incompatible with the preferred variant for proton operation based on 40 MHz.

The 40 MHz narrowband option is ruled out because it does not provide buckets that are large enough to digest the beam from LEIR.

The 40 MHz wideband solution requires R&D for the principal rf system, aiming either at a tuning range from 18.6 to 40.1 MHz, or to cover this in two switchable steps each of a factor ~1.5 in frequency. Both options are fully compatible with 40 MHz proton operation. Furthermore, the large tuning range allows the production of the 50 ns LHC proton variant by merging. A new ~10–19 MHz rf system is needed in LEIR to produce more and shorter bunches to overcome the problem of bunching factor and bunch length at injection to the PS2.

None of the more exotic schemes offer any particular advantages. The 6.5–13.3 MHz option is similar to the 10 MHz route but has a lower bunching factor. The operational parameters of a fixed-frequency-acceleration system in the PS2 will be more demanding than those of the SPS since the revolution period is shorter and the time for cavity filling is reduced accordingly. Keeping the PS machine as an ion booster has the obvious drawback of operating and maintaining one more accelerator.

All the schemes considered here are of course tailored for lead ions. Other ion species would require a complete re-assessment of the production scheme.

Finally then, the two most interesting options are the 10 MHz route based on the PS experience and the wideband 40 MHz route. The latter is preferred because of its synergy with proton operation, even though it requires an additional rf system in LEIR.

6. References

[1] M. Benedikt and S. Hancock, *Analysis of RF scenarios for the PS2*, CERN-AB-Note-2008-028-OP (2008).

[2] M. Chanel et al., *LEIR: towards the nominal lead ion beam*, Proceedings of the 4th Asian Particle Accelerator Conference, India, 2007

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