AN RF SCENARIO FOR PROTONS AND IONS IN THE PS2

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Abstract

The PS2 is proposed as a replacement for the ageing PS and will provide proton beams with kinetic energies up to 50 GeV. It must also deliver Pb^{54+} ions, for which the revolution frequency swing will be more than a factor of two. The favoured rf scenario considers a 40 MHz accelerating system and is motivated by the possibility of chopping at up to 40 MHz in the LPSPL, the proposed proton injector. Using the same principal rf system for ions implies pushing for an unprecedented tuning range and the introduction of a new rf system in LEIR, the existing ion source. We present a solution to the disparate requirements of protons and ions based on a 40 MHz rf system with switchable tuning ranges to cover the large frequency swing required.

INTRODUCTION

The PS2 will provide beams with twice the energy available from the PS and it will be about twice the size [1]. The exact PS2 circumference has been chosen to be 15/7 the one of the PS and, thus, 15/77 the one of the SPS, for two reasons. Firstly, the PS2 circumference should approach 1/5 of the SPS, to permit complete filling of the latter by five-turn extraction and, secondly, the ratio of the two machines has to be compatible with RF synchronization [2]. The proton injection energy is determined by incoherent transverse space charge considerations and will be ~4 GeV. The Low Power Superconducting Proton Linac (LPSPL) is the proposed injector [3,4].

For ion operation it is assumed that the PS2 will provide the so-called "nominal" Pb^{54+} ion beam [5] comprising four bunches spaced by 100 ns for the LHC. The ions will be provided directly by LEIR, but at an increased energy corresponding to a magnetic rigidity of 6.67 Tm (cf., 4.8 Tm at present). This will require an upgrade of the LEIR main power converters, the extraction elements and some transfer line elements [6]. Nevertheless, the dipole magnetic field in the PS2 at injection for ions will be significantly lower than for protons (16.2 Tm), resulting in a working range from 6.67 Tm to 169.9 Tm or a ratio of ~25.

Table 1 summarizes the revolution frequencies for protons and Pb^{54+} ions at injection and ejection in the PS2 machine. The frequency range required for proton acceleration is just below 2%, while it is slightly more than a factor of two for Pb^{54+} ions.

Table 1: Proton and Pb^{54+} revolution frequency swings

	Revolution frequency [kHz]		Swing [%]
	injection	ejection	$100\cdot(f_{ej}/f_{inj}-1)$
Protons	218.6	222.6	1.8
Pb^{54+} ions	108.4	222.1	104.9

BASIC CONSIDERATIONS

The PS2 will have to provide many different beams and its rf system should be flexible enough to produce a wide variety of different bunch patterns. For both protons and ions for the LHC, the final bunch pattern must be established already at PS2 ejection. The high-intensity fixed-target (FT) beam will likewise be transferred into the 200 MHz rf buckets of the SPS.

Two possible rf scenarios for the PS2 have been analysed based on a principal accelerating system operating at either 10 MHz or 40 MHz, with the latter option being preferred [7]. This preference is motivated by the LPSPL, which offers a beam chopped at a frequency of up to 40 MHz [8]. Any bunch spacing of multiples of 25 ns can then be achieved simply by filling only the corresponding buckets. In this way the different LHC beam variants can be produced without bunch splitting (neglecting line density limitations for very high bunch intensities), avoiding the additional rf systems that are needed in the PS today [9]. However, it should be noted that the bucket length will always be significantly shorter than for a lower frequency system and will not permit the acceleration of single high-intensity bunches like, for example, the present nTOF beam due to line density limitations [10].

The challenge for a 40 MHz system stems from the required frequency swing of more than an octave for ions. An R&D programme is being launched for the development of a system based on ferrites with perpendicular bias [11], to circumvent the problem of high hysteresis losses inherent to parallel biased systems in this frequency range.

Alternatively, one could aim for reduced tuning ranges, as the longitudinal gymnastics for ions could be performed with overlapping systems with switchable ranges.

The work presented here aimed at investigating the parameter space of a 40 MHz RF system for proton and ion operation in PS2 and its dependency on lattice parameters e.g. transition energy, as well as the common impact on operation aspects e.g. longitudinal gymnastics.

PROTON BEAM PARAMETERS

The main parameters for the most demanding PS2 proton beams are summarized in Table 2. LHC 50 ns denotes an LHC beam variant with 50 ns bunch spacing and a brightness (intensity) higher than the one possible in a single 40 MHz bucket and a bunch spacing of 50 ns at PS2 injection. The longitudinal emittances at PS2 extraction are dictated by SPS stability considerations [12]. For the high intensity FT beam the longitudinal emittance can be kept small to allow for faster acceleration in the SPS, since the beam current provided to the SPS is divided by five by the extraction method.

Table 2: Proton beam parameters for 40 MHz operation

Parameter	LHC 25	LHC 50	FT SPS
Harmonic injection/ejection	180	180/90	180
Bunches injection/ejection	168	168/84	128-168
Bunch intensity injection	4.2×10^{11}	3.1×10^{11}	6.2×10^{11}
Bunch intensity ejection	4.0×10^{11}	5.9×10^{11}	6.0×10^{11}
Total intensity ejection	6.7×10^{13}	5.0×10^{13}	1.0×10^{14}
Long. emittance inj. [eVs]	<0.4	<0.3	<0.4
Long. emittance ej. [eVs]	0.6	0.7	<0.6

The 50 ns variant of the LHC beam can be produced by exploiting the tuning range required for ions, either by merging before extraction or by direct painting into 20 MHz rf buckets already at injection.

PROTON OPERATION

An installed rf voltage of about 1.5 MV is needed for proton operation. Fig. 1 shows the acceptance that such an RF system would provide.

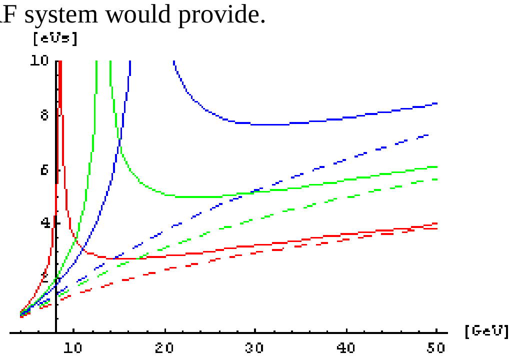

Figure 1: 40 MHz (h=180) acceptance versus kinetic energy in the PS2 for a 1.5 MV RF system at the maximum ramp rate of 1.5 T/s for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

Proton Injection

Fig. 2 shows the 40 MHz rf voltage required to maintain long bunches during the multi-turn injection process and the corresponding synchrotron period for longitudinal emittances of 0.35 eVs and 0.6 eVs.

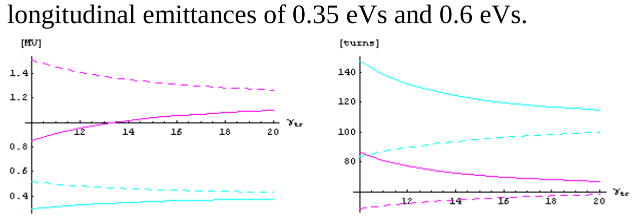

Figure 2: 40 MHz RF voltage (left) at which bunches of 0.35 eVs (cyan) and 0.6 eVs (magenta) occupy 80% of a stationary bucket at PS2 injection energy; corresponding synchrotron period (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

Even though the synchrotron period is of the order of the injection duration (100–300 turns), longitudinal painting schemes using synchrotron motion and chopping with fixed energy offsets of the injected beam show promising results for the more favourable larger emittances [13], but will be refined and extended also to smaller emittances.

Proton Acceleration

Fig. 3 assumes a parabolic increase in dipole magnetic field taking 100 ms to rise from a ramp rate of zero to a maximum of 1.5 T/s. 1.5 MV is sufficient to digest the largest emittance in all scenarios, but it is not overly generous as any reduction in RF voltage rapidly decreases the acceptance available during early acceleration.

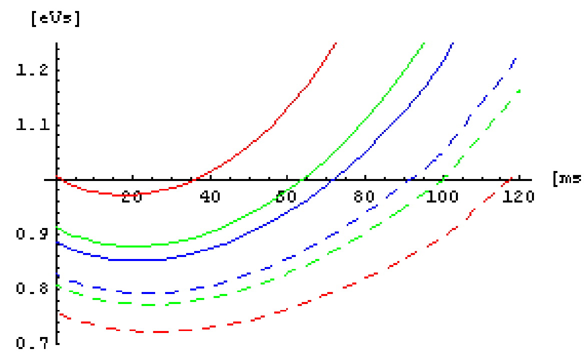

Figure 3: 40 MHz acceptance during early acceleration for 1.5 MV for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

Bunch Shortening at Ejection

Although a 40 MHz voltage of 1.5 MV is entirely sufficient at injection and during acceleration, matched bunches of 4 ns compatible with the 200 MHz system of the SPS cannot in all cases be produced at top energy (see Fig. 4). However, since the corresponding bucket filling factor is rather small, shortening the bunches non-adiabatically to the required duration could be achieved without much degradation in bunch shape. This is confirmed by ESME simulations. Since non-adiabatic bunch shortening can be performed in ~1 ms or less in all cases, this has no bearing on the choice of gamma transition in the range considered here.

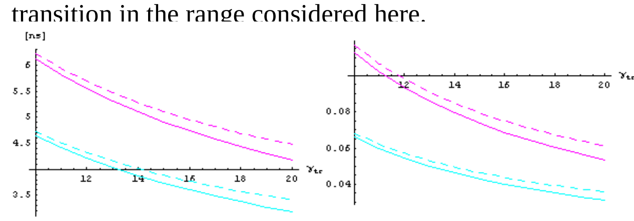

Figure 4: Bunch length (left) for matched bunches of 0.35 eVs (cyan) and 0.6 eVs (magenta) in a 1.5 MV 40 MHz stationary bucket at PS2 ejection energy; corresponding bucket filling factor (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}

Bunch Merging to 20 MHz and Shortening

The 50 ns LHC beam variant could be achieved by bunch pair merging into 20 MHz buckets. Assuming that comparable rf voltage is available when the 40 MHz cavities are retuned (switched) to 20 MHz, ESME simulations demonstrate that the merging can be done in the order of 100 to 200 ms. The final product of the bunch rotation seen with ESME is very clean and the 4 ns bunch length specification is readily met.

ION OPERATION

The 120/7 circumference ratio of PS2 and LEIR 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 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 [14]) to an intermediate plateau in LEIR where a kicker gap is introduced (h=4→5) and the bunches are split (h=5→10) using a new rf system (~10 kV, ~10–19 MHz, see Fig. 5) before accelerating to extraction energy.

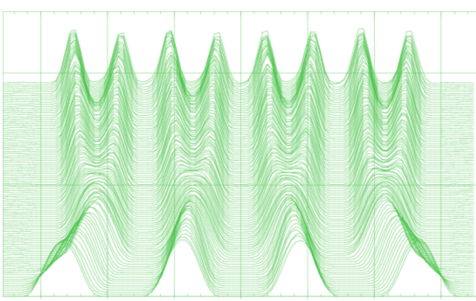

Figure 5: Simulated beam current profiles versus degrees of azimuth on an intermediate plateau in LEIR where a kicker gap is introduced (h=4→5) and the bunches are split (h=5→10) in order to adapt them to the constraints of a wideband rf system in the PS2. The duration of these gymnastics is 50 ms.

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 show that all this can be achieved in about a quarter of a second. It should be noted that this scheme cannot be easily extended to light ions. This latter case, if required for future physics programmes, may require additional rf systems in the PS2.

The proposed solution requires a PS2 RF system covering 18.6–37.3 MHz for Pb^{54+} operation, with the upper limit extended by the 39.3–40.1 MHz requirement for proton acceleration. 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.

SUMMARY AND CONCLUSIONS

The 40 MHz rf concept for PS2 is based on LPSPL chopping and makes straightforward the fabrication of any bunch patterns >25 ns for LHC operation without requiring additional rf systems in the PS2 for splitting.

The fact that no longitudinal gymnastics will be needed at ejection removes adiabaticity issues at high energy and opens the way to higher (absolute) values of transition energy. This eases the design of lattices with imaginary transition gamma and reduces the rf voltage needed.

If the tuning range of slightly more than an octave can be achieved, the 40 MHz system also enables production of the nominal Pb^{54+} ion beam for LHC. An additional rf system will however be required in LEIR.

REFERENCES

[1] M. Benedikt, *PS2 Design optimisation*, this conf.

[2] R. Garoby, *RF constraints on the size of PS2*, CERN-AB-Note-2007-020 (2007).

[3] R. Garoby et al., *Comparison of options for the injector of PS2*, CERN-AB-2007-014-PAF (2007).

[4] F. Gerigk (ed.), *Conceptual design of the SPL II: A high-power superconducting H^- linac at CERN*, CERN-2006-006 (2006).

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

[6] C. Carli, *private communication*.

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

[8] T. Kroyer, F. Caspers, E. Mahner, *The CERN SPL chopper structure*, CERN-AB-2007-004 (2007).

[9] R. Garoby, *Multiple splitting in the PS: results and alternative filling schemes*, Proc. 11th LHC Workshop Chamonix, CERN-SL-2001-003 (2001).

[10] R. Cappi, M. Giovannozzi, G. Métral, *The proton beams for the new time-of-flight neutron facility at the CERN-PS*, CERN-PS-2000-009-AE (2000).

[11] R.L. Poirier, *Perpendicular Biased Ferrite-Tuned Cavities*, PAC'93, Washington (1993).

[12] E. Chapochnikova, *private communication*.

[13] M. Benedikt et al., *Longitudinal painting schemes for H- charge-exchange injection into the PS2*, this conference.

[14] R. Garoby et al., *The LEIR RF system*, Proc. 2005 Particle Accelerator Conference, Knoxville, CERN LHC Project Report 818 (2005).