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Analysis of RF Scenarios for the PS2

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Abstract

This note analyses the two main RF scenarios that are presently being considered for the PS2. One option is based on a wide-band 10 MHz system and, to a large extent, follows the approach already established in the existing PS machine. The other considers a 40 MHz system for the principal RF and is motivated by the possibility of chopping at up to 40 MHz as foreseen for the SPL, the proposed PS2 injector. The aim of the analysis is not only to estimate the hardware requirements – such as the number of different RF systems needed and their voltage specifications – but also to understand from the RF standpoint the interplay between machine performance and design – such as the dependence of cycle lengths on gamma at transition.

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1. Introduction

1.1. PS2 working range

The PS2 is proposed as a replacement for the ageing PS and will provide proton beams with kinetic energies up to 50 GeV [1]. The proton injection energy is determined by incoherent space charge considerations and will be ~4 GeV. The Low Power Superconducting Proton Linac (LP SPL) is the proposed injector [2, 3].

For ion operation it is assumed that the beams will be provided directly by LEIR, but at an increased energy corresponding to a magnetic rigidity of 6.67 Tm (cf., 4.8 Tm). This will require an upgrade of the LEIR main power converters, the extraction elements and some transfer line elements [4]. Nevertheless, the magnetic field in the PS2 at injection for ions will be significantly lower than that for protons resulting in a working range from 6.67 Tm to 169.9 Tm or a ratio of 25 in magnetic field.

The PS2 will provide beams with twice the energy available from the PS and it will be about twice the size. The exact circumference ratio has been chosen to be 15/7 – 15/77 with respect to the SPS – for two reasons. Firstly, the PS2 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 RFsynchronization [5].

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

	$B\rho$ [Tm]		**f_{rev} [kHz]**		**$100\cdot(f_{ej}/f_{inj} - 1)$**
	Inj	**Ej**	**Inj**	**Ej**	
Protons	16.2	169.9	218.6	222.6	1.8
Pb^{54+}	6.67	169.9	108.4	222.1	104.9

Table 1: Magnetic rigidity and revolution frequency range for proton and Pb^{54+} operation

1.2. Basic options for PS2 RF systems

The PS2 will have to provide many different beams (cf., the existing PS machine). For this reason, its RF system must be flexible enough to produce a wide variety of different bunch patterns.

An obvious choice is therefore to emulate the PS and use a tuneable 10 MHz system for acceleration. Such a system could have a tuning range of more than a factor of three, covering frequencies from 3 MHz up to 10 MHz [6]. From Table 1 it can be seen that the frequency change during the acceleration of protons is less than 2% and, consequently, proton beams could be accelerated on many different harmonic numbers. However, even the smallest bunch spacing that can be achieved with a 10 MHz system is incompatible with LHC requirements. Therefore additional RF systems and longitudinal gymnastics will be needed to produce the various LHC bunch patterns [7]. At the very least, additional 20 MHz and 40 MHz systems will be required to generate 50 ns and 25 ns bunch trains. Nevertheless, a clear advantage of the 10 MHz system is its large tuning range which accommodates the frequency swing of ions.

An alternative choice is to use a 40 MHz RF system for acceleration. This option is entirely motivated by the LP SPL [3], which offers an injected beam chopped at a frequency of up to 40 MHz [8]. With a 40 MHz RF system in the PS2, any bunch spacing of multiples of 25 ns can be achieved simply by filling only the corresponding buckets. In this way the different LHC beam variants could be produced without splitting (neglecting line density limitations for very high bunch intensities). However, a significant R&D effort would be needed to investigate the feasibility of such a system [9].

Whereas a small tuning range of 2% would be sufficient for proton operation, a factor of more than two is needed for a straightforward scheme for ions. Even if such a large tuning range proves possible, there are certain limits inherent with a higher frequency system. The bucket length will always be significantly shorter than for a lower frequency system and would not permit the acceleration of single high-intensity bunches like, for example, the present nTOF beam because of line density limitations [10].

1.3. Specific aspects for ion operation

Ion beams will be provided directly 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.

An important aspect that must not be forgotten is the bunch length that can be accepted by the PS2. A narrow-band 40 MHz system, whilst well-suited to protons from the SPL, would present a target of only 25 ns at injection, whereas the current bunch length at extraction from LEIR approaches 200 ns in the “nominal” LHC scheme for Pb^{54+} ions [11]. The cost in acceptance of such a large shortfall in bucket length is insurmountable without envisaging a brand new RF system in LEIR or a dedicated booster machine for ions between LEIR and the PS2. Indeed, today’s ion schemes are only possible because the 10 MHz principal RF system of the existing PS machine is tuneable down to 2.8 MHz.

By contrast, in the 10 MHz route, an h=34 (3.686MHz) bucket in the PS2 is well adapted to receive the two bunches of the nominal ion beam from LEIR. The phase error of ±1.5° due to the circumference ratio (120/7 = 34.29/2) is insignificant. PS2 gymnastics are then directly analogous to the production of this beam in the existing PS machine. 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→5MHz); but also to split the bunches to h=48 (5→10MHz). One further batch expansion step from h=48 to h=45 (10→9.375MHz) gives the desired harmonic which, after final acceleration yields four bunches in consecutive buckets 100ns apart (9.995MHz) on the flat top.

Still more exotic schemes have been considered for ions. These will be the subject of a separate report [12].

1.4. Strategy for the analysis of RF scenarios

One of the most important lattice parameters from the RF standpoint is the momentum compaction factor and hence gamma at transition. It impinges directly on the voltage needed to create a given bucket area and on synchrotron frequency within that bucket. Adiabaticity is governed by the latter, so it further influences the time needed for longitudinal processes like bunch splitting, for example. Another related aspect is whether transition has to be crossed during acceleration or whether this can be avoided by a negative momentum compaction factor. For these reasons, several lattices with both real and imaginary gamma at transition are being studied.

For a classical FODO lattice assuming average beta-functions of ~20 m, the typical tunes of a machine the size of the PS2 will be around $Q \approx 10$. Gamma at transition will then be real with a similar value, $\gamma_{tr} \approx 10$. However, the situation is very different for lattices with negative momentum compaction and imaginary gamma at transition. The optics and tuneability of the machine improve strongly with higher absolute values of gamma at transition, so magnitudes of this parameter in the range 10 to 20 have been studied to better highlight trends.

The analysis presented in this document was made to compare the competing RF options and to quantify the influence of gamma at transition with particular focus on the following:

- Number of different RF systems and their frequency and voltage specifications.
- Performance aspects, such as adiabaticity and its impact on the duration of certain RF manipulations.
- Operational aspects like flexibility and complexity.

Aspects like cost, feasibility of high-power hardware, space requirements and impact on machine impedance have not yet been studied for the different scenarios. These items will be addressed in a future document.

2. Beam parameters

The design of the PS2 is driven by the requirements of the LHC and in particular the so-called "LHC upgrade beam" with twice the brightness of the "ultimate" LHC beam and 15% intensity reserve for beam losses in the downstream accelerators. This translates into an intensity requirement of 4.0×10^{11} protons per bunch (with 25 ns spacing) at PS2 ejection instead of 1.7×10^{11} for the "ultimate" beam at LHC collision energy. The 25 ns bunch spacing corresponds to a harmonic number h=180 in the PS2 and 168 buckets will be filled leaving a kicker gap of ~300 ns. Alternatively, the PS2 should be capable of producing a bunch train with 50 ns spacing and an intensity of 5.0×10^{11} protons per bunch at LHC collision energy, resulting in an intensity requirement of 5.9×10^{11} protons per bunch at PS2 ejection.

For high-intensity fixed-target beams delivered to the SPS, a five-turn resonant island extraction is foreseen. To minimize beam losses, a kicker gap (for PS2 extraction and SPS injection, but also for SPS ejection if required) will be built into the beam already at PS2 injection. The fixed-target beam will be extracted from the PS2 as a 40 MHz train, with the bunches shortened before extraction to fit into the 200 MHz buckets of the SPS. Thus the high-intensity fixed-target beam will be produced in a similar fashion (from the longitudinal viewpoint) to the 25 ns LHC beam.

For fixed-target physics supplied directly from the PS2, a beam similar to the SPS fixed-target one can be used. The main differences are that bunch shortening and five-turn extraction will not be required. Instead, either a fast extraction or a slow extraction with debunching will be used.

The longitudinal emittance requirements of the LHC and high-intensity fixed-target beams at PS2 ejection are dictated by SPS stability criteria. From measurements it is known that an LHC-type bunch with an intensity of 1.5×10^{11} protons and a longitudinal emittance of 0.35 eVs is at the limit of longitudinal stability. In order for a higher intensity bunch to be stable, the longitudinal emittance should scale as the square root of the intensity ratio [13], i.e., $\varepsilon_l(I_2) = \varepsilon_l(I_1)\ \sqrt{(I_2/I_1)}$.

2.1. Proton beam parameters for the 10 MHz route

The main parameters for the LHC upgrade beams with 25 ns and 50 ns spacing and for the high-intensity fixed-target beam in the 10 MHz scenario are summarized in Table 2. The higher bunch intensity for the fixed-target beam is possible because of the larger transverse emittances with respect to the LHC beam. The 10 MHz principal RF system is operated at the highest possible harmonic, h=45, during injection and acceleration. Additional RF systems are needed to fabricate the 25 ns and 50 ns bunch trains on the flat top before ejection. These can be fixed-frequency 20 MHz and 40 MHz systems to perform one (50 ns) or two (25 ns) double splittings.

For the special case of a single high-intensity bunch of the style of the nTOF beam, the 10 MHz system is operated at the lowest possible harmonic, h=15 (assuming a tuning range of at least a factor of three). In this case, the longitudinal emittance will be determined by PS2 stability arguments.

	LHC 25 ns upgrade	LHC 50 ns upgrade	SPS / PS2 fixed target	nTOF
INJECTION				
Harmonic number	45	45	45	15
Number of bunches	42	42	32–42	1
Intensity per bunch	1.7E12	1.2E12	3.2E12	9.5E12
Long. emittance [eVs]	< 2.4	< 1.4	< 1.4	~2.5
Total intensity	7.1E13	5.2E13	1 – 1.3E14	9.5E12
EJECTION				
Harmonic number	180	90	180	15
Number of bunches	168	84	128 – 168	1
Intensity per bunch	4.0E11	5.9E11	7.5E11	9.0E12
Intensity per SPS bunch	4.0E11	5.9E11	1.5E11	-
Long. emittance [eVs]	0.6	0.7	0.35	~2.5
Total intensity	6.7E13	4.9E13	1 – 1.3E14	9.0E12

Table 2: Main parameters for LHC and fixed target beams for the 10 MHz option

2.2. Proton beam parameters for the 40 MHz route

The main parameters for the LHC upgrade beams with 25 ns and 50 ns spacing and for the high-intensity fixed-target beam in the 40 MHz scenario are summarized in Table 3. The higher bunch intensity for the fixed-target beam is possible because of the larger transverse emittances with respect to the LHC beam.

	LHC 25 ns upgrade	LHC 50 ns upgrade	SPS / PS2 fixed target	nTOF
INJECTION				
Harmonic number	180	180	180	180
Number of bunches	168	168	128 – 168	2
Intensity per bunch	4.2E11	3.1E11	7.9E11	7.9E11
Long. emittance [eVs]	< 0.6	< 0.35	< 0.35	~0.35
Total intensity	7.1E13	5.2E13	1 – 1.3E14	1.6E12
EJECTION				
Harmonic number	180	90	180	90
Number of bunches	168	84	128 – 168	1
Intensity per bunch	4.0E11	5.9E11	7.5E11	1.5E12
Intensity per SPS bunch	4.0E11	5.9E11	1.5E11	-
Long. emittance [eVs]	0.6	0.7	0.35	~0.7
Total intensity	6.7E13	4.9E13	1 – 1.3E14	1.5E12

Table 3: Main parameters for LHC and fixed target beams for the 40 MHz option

The narrow frequency range available from a 40 MHz system has consequences for the production of the 50 ns LHC upgrade beam. Since a tuning range of only 2% is required for proton acceleration, all beams are accelerated on harmonic h=180 corresponding to 25 ns bunch spacing at ejection. To generate a spacing of 50 ns, an additional RF system is needed to merge adjacent bunches into 20 MHz (h=90) buckets. This could be a dedicated 20 MHz system or it might be possible to switch some of the 40 MHz cavities down to half their normal frequency on the flat top.

It should be noted that, in the 40 MHz scenario, single-bunch beams of the nTOF type would be severely limited in intensity.

3. The 10 MHz route

A first estimate of the scale of the RF voltage needed at 10 MHz may be obtained from the usual rule of thumb that the stable phase angle should not exceed 30 degrees during acceleration. This gives a figure of around 400 kV. The PS2 will be 15/7 times longer than the PS machine while the acceleration rate will be roughly the same at ~150 Tm/s, so the factor of two with respect to the 200 kV installed in the existing machine comes as no surprise. However, the rule of thumb ignores longitudinal acceptance and there is invariably an acceptance bottleneck at low energy (see Figure 1).

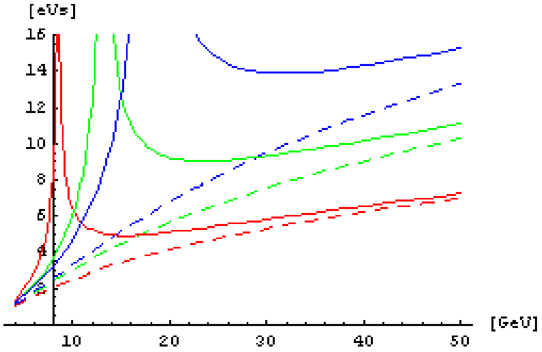

Figure 1: 10 MHz (h=45) acceptance versus kinetic energy in the PS2 for a 400 kV RF system at the maximum ramp rate of 1.5 T/s for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

3.1. Injection

Space charge dictates that bunches must be maintained long during the multi-turn injection process from the SPL. Figure 2a shows the 10 MHz RF voltage required to achieve this for the two values of longitudinal emittance of the LHC upgrade, which are essentially the extrema of Table 2.

Since the duration of the multi-turn injection will be of the order of 100 turns, Figure 2b shows that the transverse painting that is envisaged cannot be supplemented by painting in the longitudinal plane without modulating the energy at the exit of the SPL. This means that some form of controlled longitudinal blow-up should be considered in order to establish the emittance values required and, in turn, that the largest of these need not be digested right from injection.

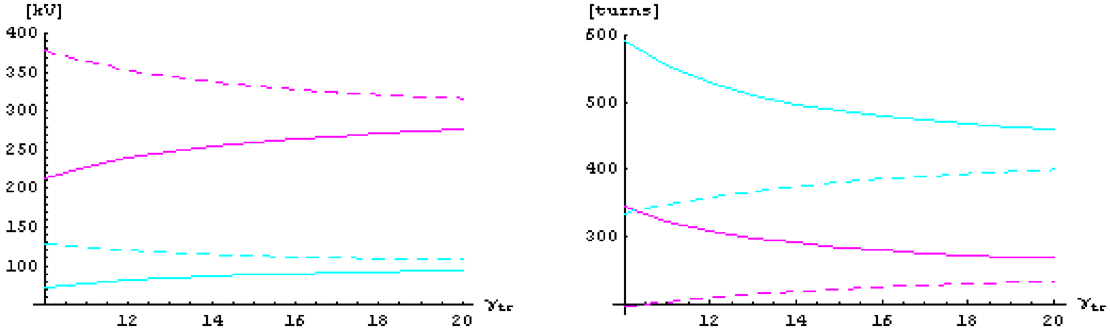

Figure 2: (a) 10 MHz RF voltage (left) at which bunches of 1.4 eVs (cyan) and 2.4 eVs (magenta) occupy 80% of a stationary bucket at PS2 injection energy; (b) corresponding synchrotron period (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

3.2. Acceleration

The early part of Figure 1 is pessimistic in that the full ramp rate is taken right from injection. Figure 3 addresses this in more detail by considering a parabolic increase in dipole magnetic field of 100 ms duration between a ramp rate of zero and the maximum of 1.5 T/s. Although the constant RF voltage is unrealistic – in practice it would be tailored according to bunch length and acceptance margin constraints – it permits the minimum acceptance to be identified and a straightforward comparison to be made of the values of gamma at transition.

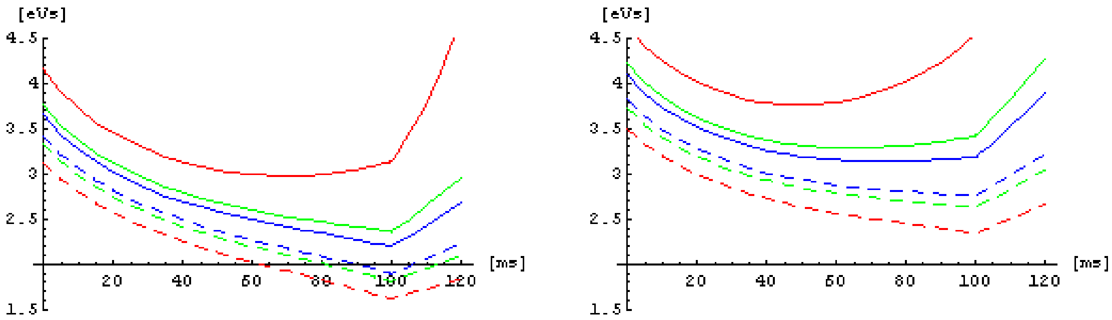

Figure 3: 10 MHz acceptance during early acceleration for (a) 400 kV (left) and (b) 500 kV (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

Depending on the emittance budget allocated to acceleration (and, possibly, transition crossing) and to the subsequent RF gymnastics, the maximum which must pass at low energy will be significantly less than 2.4 eVs. However, even if all uncontrolled dilution is retained as acceptance margin, the largest emittance can be digested in all scenarios by a modest increase in 10 MHz voltage to 500 kV (see Figure 3b). Increasing the RF voltage is more "cost effective" than slowing down the ramp rate because it directly increases the acceptance as well as reducing the accelerating phase.

Figure 3b suggests that the value of gamma at transition is unconstrained by considerations at low energy, particularly as the intrinsic flexibility of the SPL chopper circumvents the need for any RF gymnastics like triple splitting so that adiabaticity [14] is not an issue. However, if the value is too low, the time to reach transition may limit how much controlled longitudinal blow-up can be achieved on the fly.

3.3. Ejection

3.3.1. Bunch splitting

In the existing LHC 25 ns case, the PS 10 MHz voltage is first reduced such that the bunch occupies some 60% of the bucket length (splitting short bunches is difficult due to the precision with which the relative phase between harmonic components can be controlled) and the entire quadruple splitting takes 130 ms or roughly ten times the synchrotron period under these initial conditions. Following these same guidelines, Figure 4 shows the duration of this RF gymnastic for the case of the LHC 25 ns upgrade.

There is a clear preference for lower magnitudes of gamma at transition. Adiabaticity issues mean that the single splitting in the 50ns case will not take less time.

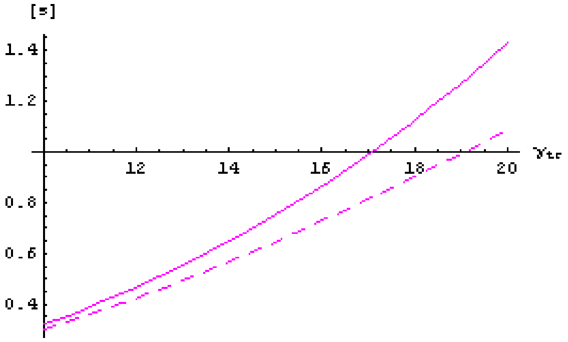

Figure 4: Quadruple bunch splitting duration at PS2 ejection energy for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

ESME simulations confirm the timescale needed and demonstrate that the voltage requirements of the additional 20 and 40 MHz RF systems for splitting are unchanged from those of the existing hardware. This puts the specification at 20 MHz in the order of a very modest 20 kV.

3.3.2. Bunch shortening

Continuing to emulate the existing PS machine, the final step in the production of LHC beams is a non-adiabatic bunch shortening involving 40 and 80 MHz systems. ESME simulations again show that the voltage requirements of these additional PS2 RF systems are unchanged from those of the existing hardware. This puts the specification at 40 MHz and 80 MHz in the order of 300 and 600 kV, respectively.

Since the bunch splitting takes more than two orders of magnitude longer than non-adiabatic bunch shortening in all cases, the duration of the latter has no bearing on the choice of gamma at transition in the range considered here.

4. 40 MHz route

The RF voltage needed at 40 MHz may be estimated by scaling from the 10 MHz scenario. The factor of 4 in frequency reduces the acceptance per bucket by a factor of 8. However, no splittings would be required to produce LHC beams so the emittance during acceleration is reduced by a factor of, for example, 4 in the most demanding case of 25 ns spacing. To regain the missing factor of 2, the 40MHz voltage must be 4 times that proposed at 10MHz. These simple arguments (which are only strictly true at zero ramp rate) give a ball-park figure of 1.5 MV. Figure 5 shows the acceptance that such an RF system would provide.

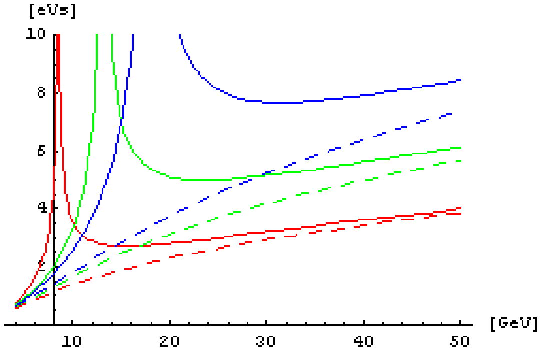

Figure 5: 40 MHz (h=180) acceptance versus kinetic energy in the PS2 for a 1.5 MV RF system at the maximum ramp rate of 1.5 T/s for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

4.1. Injection

Figure 6 shows the 40 MHz RF voltage required to maintain long bunches during the multi-turn injection process and the corresponding synchrotron period for the two values of longitudinal emittance of the LHC upgrade, which are the extrema of Table 3. As found in the 10 MHz scenario, controlled longitudinal blow-up should be considered because longitudinal painting using synchrotron motion alone is excluded.

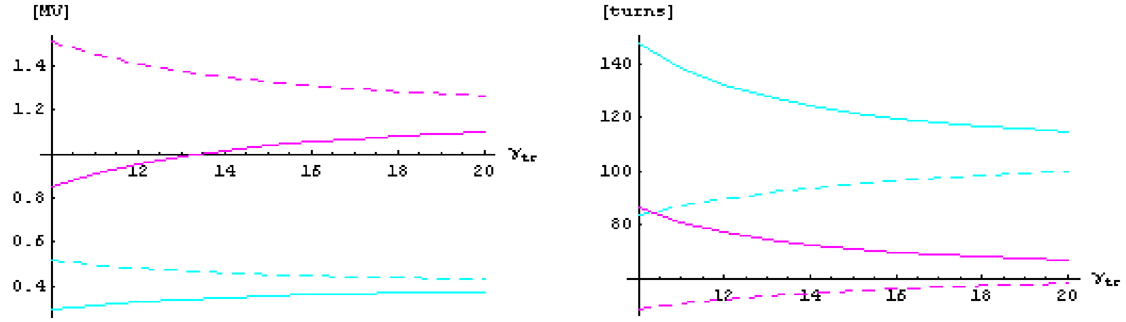

Figure 6: (a) 40 MHz RF voltage (left) at which bunches of 0.35 eVs (cyan) and 0.6 eVs (magenta) occupy 80% of a stationary bucket at PS2 injection energy; (b) corresponding synchrotron period (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

4.2. Acceleration

Figure 7 considers a parabolic increase in dipole magnetic field lasting 100 ms between a ramp rate of zero and the maximum of 1.5 T/s. 1.5 MV is sufficient to digest the largest emittance (see Table 3) in all scenarios, but it is not overly generous as any reduction in RF voltage rapidly decreases the acceptance available during acceleration.

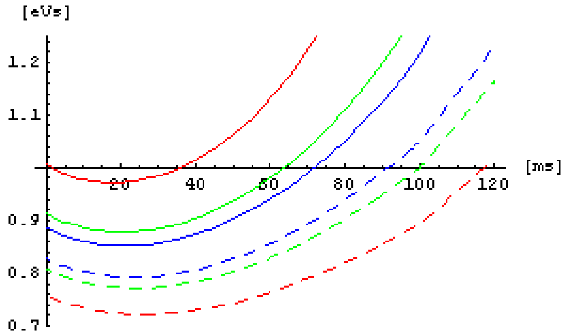

Figure 7: 40 MHz acceptance during early acceleration for 1.5 MV for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

4.3. Ejection

4.3.1. *Bunch shortening*

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 always be produced at top energy (see Figure 8a). However, since the corresponding bucket filling factor (Figure 8b) 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.

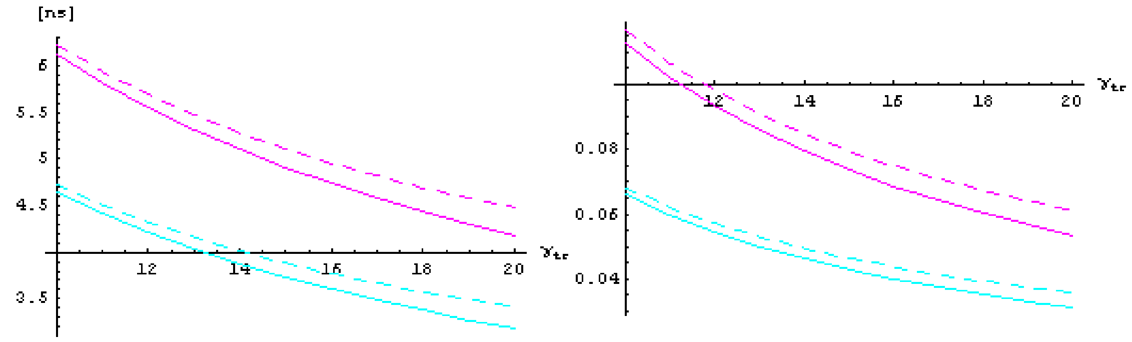

Figure 8: (a) Bunch length (left) for matched bunches of 0.35 eVs (cyan) and 0.6 eVs (magenta) in a 1.5 MV 40 MHz stationary bucket at PS2 ejection energy; (b) corresponding bucket filling factor (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

Since non-adiabatic bunch shortening can be performed in the order of 1 ms or less in all cases, this has no bearing on the choice of gamma at transition in the range considered here.

4.3.2. *Bunch merging to 20 MHz and shortening*

The 50 ns LHC upgrade variant would 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 depending on the magnitude of gamma at transition. The non-adiabitic shortening process would then have more to do (see Figure 9a), but more phase space (Figure 9b) in which to do it. Consequently, the final product of the bunch rotation seen with ESME is very clean and the 4 ns bunch length specification is readily met.

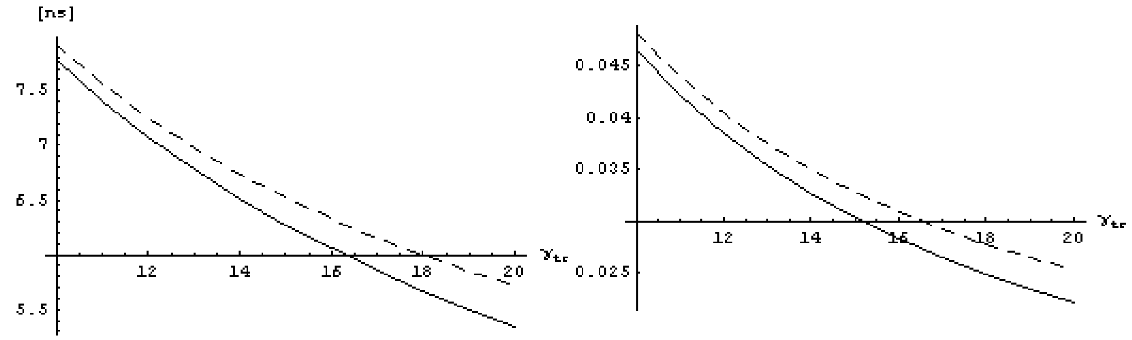

Figure 9: (a) Bunch length (left) for a matched bunch of 0.7 eVs in a 1.5 MV 20 MHz stationary bucket at PS2 ejection energy; (b) corresponding bucket filling factor (right) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

Instead of switching the (narrow band) frequency between 40 MHz and 20 MHz, merging could be achieved with a dedicated fixed-frequency 20 MHz system and the resultant beam rebucketed and then shortened using the principal RF cavities which remain tuned at 40 MHz. ESME simulations show that such an approach requires the additional 20 MHz system to deliver ~100 kV.

5. Summary and Conclusions

The intrinsic flexibility of the SPL chopper removes concerns about adiabaticity at low energy, so RF considerations in this energy regime do not impinge on the choice of gamma at transition. However, the maximum RF voltage requirement (see Table 4) for both the 10 and 40 MHz routes is determined by acceptance constraints during the early part of acceleration. Also, some form of controlled longitudinal blow-up is essential.

At high energy, there is little difference in adiabaticity between real and imaginary values of gamma at transition of the same magnitude. Consequently, the choice between the two is dominated solely by the desire to avoid transition crossing itself. One adiabaticity constraint does remain: in the high-energy regime of the 10 MHz route there is a strong preference for low magnitudes of gamma at transition in order to reduce cycle length, but this goes in the opposite direction to the demand from optics considerations.

Bunch shortening in order to fit the 5 ns bucket length of the SPS must be non-adiabatic in all cases.

	10 MHz Route			**40 MHz Route**		
	h, f_{min} [MHz]	**h, f_{max} [MHz]**	**V_{max} [MV]**	**h, f_{min} [MHz]**	**h, f_{max} [MHz]**	**V_{max} [MV]**
Protons	45, 9.837	45, 10.02	0.5	180, 39.35	180, 40.07	1.5
Pb^{54+} Ions	34, 3.686	45, 9.995	0.3	-	-	-

Table 4: Principal RF parameters constrained by LHC-type beams for proton and Pb^{54+} operation.

The 40 MHz route offers no immediate solution for ions nor for "legacy" beams of the nTOF type. To retain this scenario as an option would require pushing for a factor of more than two in continuous tuning range – down to below 20 MHz – in order to accommodate the frequency swing of Pb^{54+} ions. Taking the 10 MHz route results in the same high multiplicity of RF systems that has been historically accumulated in the existing PS. Thus, neither route is entirely satisfactory.

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