Analysis of RF Scenarios for the PS2

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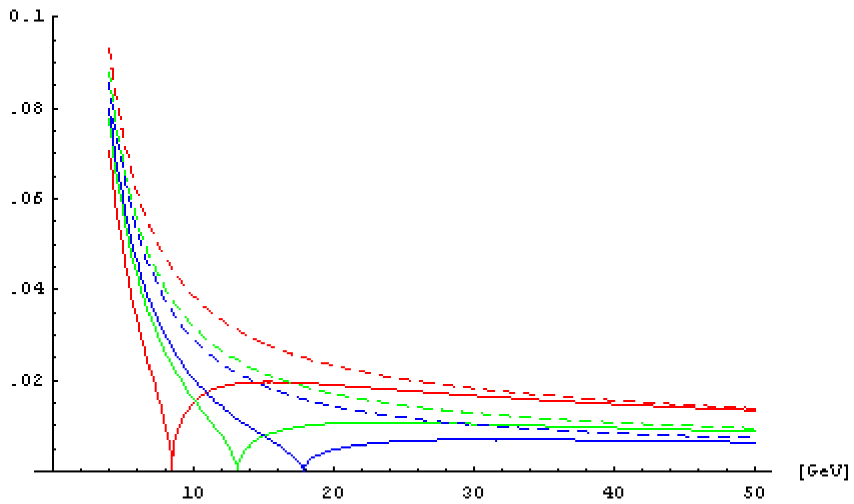
Introduction

The task of choosing a suitable rf system for the PS2 has followed two distinct routes. The first is based on a wide-band 10MHz system and is driven by the legacy of the large arsenal of beams supplied by the PS, which leads naturally to an emulation of the multiple rf systems of the existing machine. The second derives from the possibility of chopping at up to 40MHz as foreseen for the SPL, the proposed PS2 injector, and is based on a single 40MHz system.

Folded into this dichotomy is the choice of the value of gamma at transition.



Adiabaticity factor $\sqrt{(|\eta|/\gamma)}$ versus kinetic energy for protons in the PS2 for real (solid lines) and imaginary (dashed lines) values of γ_{tr} of 10 (red), 15 (green) and 20 (blue).

Beam Requirements (Protons, 10MHz)

The upgrade foreseen for the 25ns LHC variant doubles the brightness of today's "ultimate" beam. This means 3.4E11 protons per bunch at collision, or 4.0E11 at PS2 ejection with a 15% margin for losses in between. The 50ns LHC variant is based on 5.0E11 protons per bunch at collision.

A five-turn resonant island extraction will be used for the SPS fixed-target beam. The beam must be split and shortened in a manner similar to that for 25ns LHC beams in order for it to fit into the 200MHz buckets of the SPS.

	LHC 25ns Upgrade	**LHC 50ns Upgrade**	**SPS Fixed Target**
INJECTION			
Harmonic number	45	45	45
Number of bunches	42	42	32–42
Intensity per bunch	1.7E12	1.2E12	3.2E12
Long. emittance [eVs]	< 2.4	< 1.4	< 1.4
Total intensity	7.1E13	5.2E13	1 – 1.3E14
EJECTION			
Harmonic number	180	90	180
Number of bunches	168	84	128 – 168
Intensity per SPS bunch	4.0E11	5.9E11	1.5E11
Long. emittance [eVs]	0.6	0.7	0.35
Total intensity	6.7E13	4.9E13	1 – 1.3E14

Beam Requirements (Protons, 40MHz)

The intrinsic flexibility of the SPL chopper means that the requisite bunch trains can be established already at injection.

The 50ns LHC variant would require some 100kV at 20MHz to permit a merging gymnastic on the flat top.

	LHC 25ns Upgrade	LHC 50ns Upgrade	SPS Fixed Target
INJECTION			
Harmonic number	180	180	180
Number of bunches	168	168	128 – 168
Intensity per bunch	4.2E11	3.1E11	7.9E11
Long. emittance [eVs]	< 0.6	< 0.35	< 0.35
Total intensity	7.1E13	5.2E13	1 – 1.3E14
EJECTION			
Harmonic number	180	90	180
Number of bunches	168	84	128 – 168
Intensity per SPS bunch	4.0E11	5.9E11	1.5E11
Long. emittance [eVs]	0.6	0.7	0.35
Total intensity	6.7E13	4.9E13	1 – 1.3E14

Hardware Requirements (Protons)

Since the principal rf cavities in the 10MHz route cannot provide the appropriate bunch spacing for the LHC directly, additional cavities are required to perform splitting:

10MHz	Tunable	Acceleration
20MHz	Fixed-frequency	Splitting
40MHz	Fixed-frequency	Splitting + Bunch shortening
80MHz	Fixed-frequency	Bunch shortening

The 40MHz route would require only a modest additional rf system:

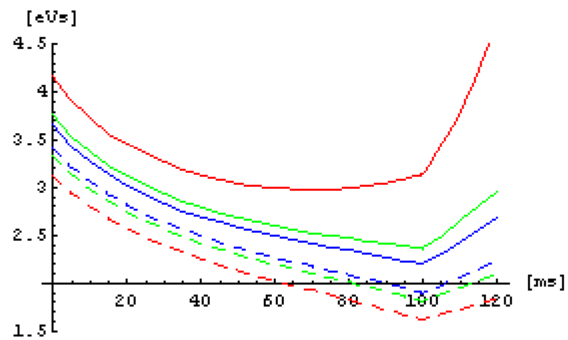
40MHz	Tunable	Acceleration + Bunch shortening
20MHz	Fixed-frequency	Merging

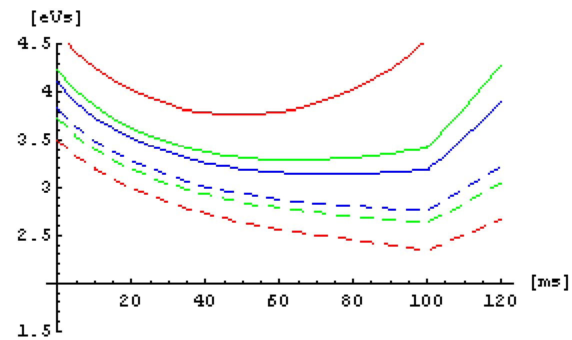
The entire tuning range for protons is less than 2%.

Voltage Requirements (Protons)

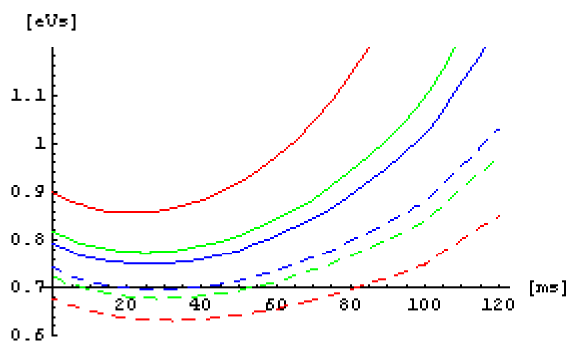
The rf voltage specification in both the 10 and 40MHz routes is fixed (to ~20%) by the acceptance requirements in the early part of acceleration.

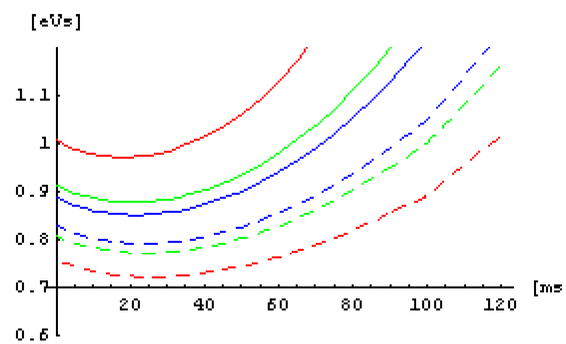
< 2.4eVs => 400-500kV @ 10MHz





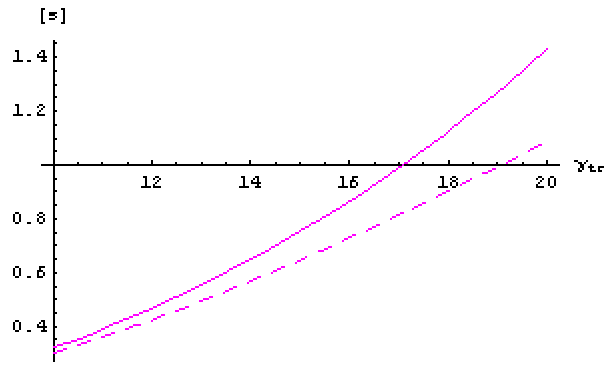
< 0.6eVs => 1.2-1.5MV @ 40MHz





High-energy Regime (Protons, 10MHz)

The gymnastics to produce the 25ns LHC variant cost time on the flat top.



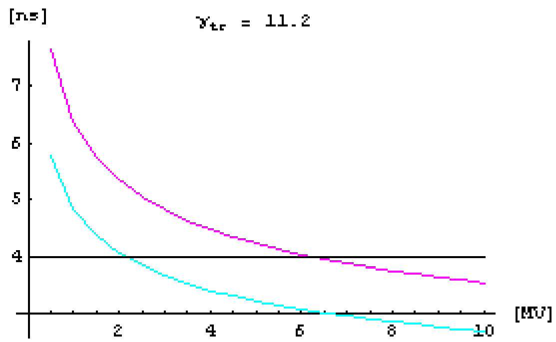
Quadruple bunch splitting duration for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

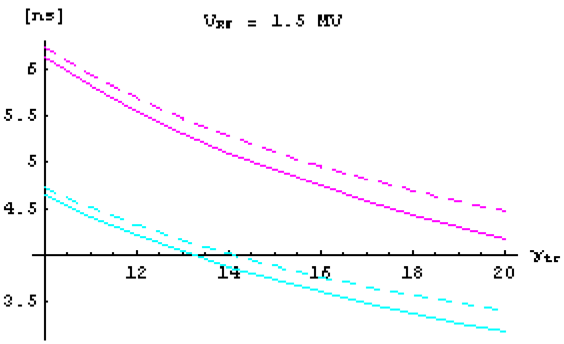
There is a clear preference for lower magnitudes of gamma at transition. Adiabaticity issues mean that the single splitting step in the 50ns case will not take less time.

ESME simulations confirm the timescale needed and demonstrate that the voltage requirements of the additional 20, 40 and 80MHz fixed-frequency rf systems are unchanged from those of the existing hardware.

High-energy Regime (Protons, 40MHz)

Although short, matched bunches cannot be bought at a reasonable cost in rf voltage, this can by overcome by accepting a slight mismatch.





Bunch length for matched bunches of 0.35eVs (cyan) and 0.6eVs (magenta) for real (solid lines) and imaginary (dashed lines) values of γ_{tr}.

Even with just the 1.5MV sufficient for acceleration, the corresponding bucket filling factor is rather small so that shortening the bunches by means of a non-adiabatic voltage step is simply not an issue.

LEIR Upgrade

If the PS2 is to replace completely the existing PS machine, then there are consequences for LEIR.

- Increasing the transfer energy to its maximum ($B\rho = 4.8 \rightarrow 6.67$Tm) partially compensates the increase in incoherent space charge tune shift in the larger machine ($\beta\gamma^2$ is raised by a factor of 1.48 for Pb^{54+} ions, cf., 15/7 = 2.14). There is also something to be gained in bunching factor over today's nominal ion scheme.

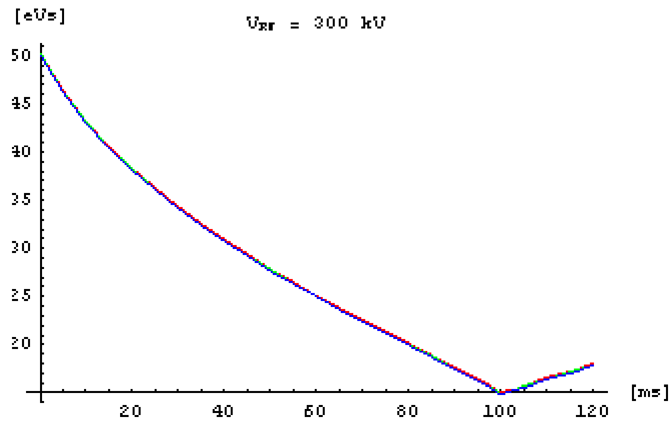
- This increases the magnetic field at PS2 injection (to 670Gauss for Pb^{54+} ions), although it remains significantly lower than for protons (1620Gauss).

- It requires an upgrade of the main power converter, ejection equipment and possibly of some elements in the transfer line. However, ramp rate could be an issue.

Nevertheless, this does not constitute a major development (cf., superconducting dipoles).

RF Gymnastics (Pb^{54+} Ions, 10MHz)

An h=34 (3.686MHz) bucket in the PS2 is well adapted to receive two bunches from LEIR. The phase error of ±1.5º due to the circumference ratio (120/7 = 34.29/2) is insignificant. Less rf voltage than for protons is required to get 10.4eVs through the acceptance bottleneck in the early part of acceleration.

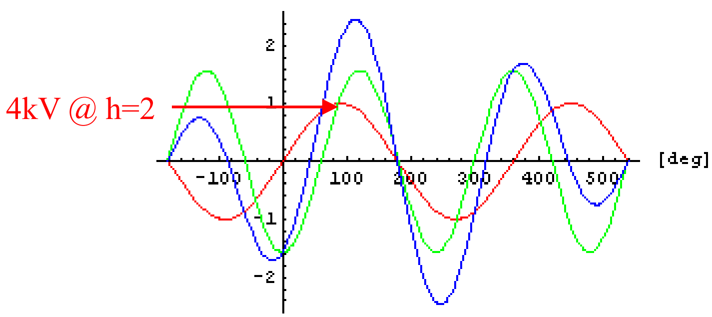


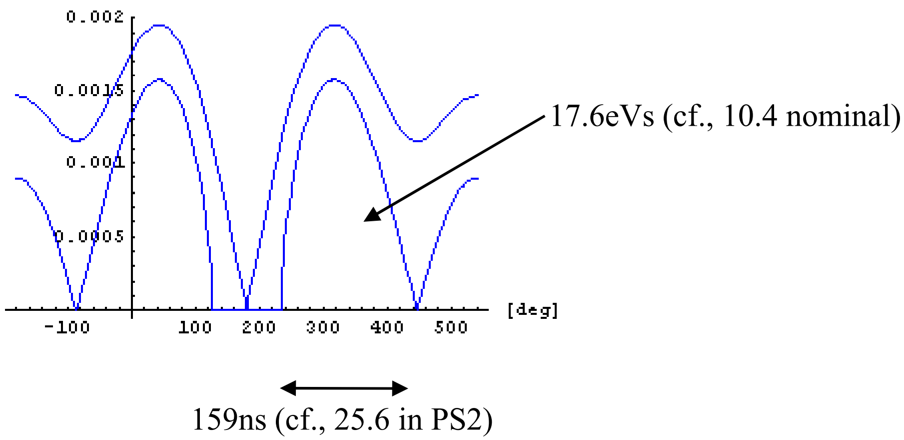
PS2 gymnastics are then acceleration on h=34 to an intermediate plateau; batch expansion from h=34 to h=24 (7.1→5MHz); splitting to h=48 (5→10MHz); and further batch expansion from h=48 to h=45 (10→9.375MHz). Final acceleration yields four bunches in consecutive buckets 100ns apart (9.995MHz).

All this is directly analogous to the production of today's nominal ion beam and both exploit the large tuning range available at 10MHz.

RF Gymnastics (Pb^{54+} Ions, 40MHz)

Circumventing the 105% frequency swing of ions is problematic. The two bunches must be squeezed together in LEIR to align with h=360 (39.03MHz) buckets in the PS2, but the latter are simply too short to receive bunches of any reasonable emittance.





This (plus the poor bunching factor!) 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 (~100ns) on h=180 (39.98MHz 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%.

Wide-band 40MHz

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 (unless the size of LEIR is increased!), but 8 out of 10 with 18.65MHz buckets (h=172) waiting in the PS2 provides a much better filling factor with a penalty of only ~4^{o} of phase error for the outermost bunches. This scheme sees 4 bunches accelerated 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 (~10kV, ~10-20MHz) before accelerating to extraction energy. In the PS2 the beam is accelerated to an intermediate plateau to provide the frequency margin to merge (h=172→86) back to the 4 bunches required, then rebucketed (h=86→172) to fill every second bucket and provide the frequency margin to perform a batch expansion (h=172→90 in several steps) to 100ns bunch spacing before final acceleration to top energy (19.99MHz).

Obviously, if more than an octave can be realized at 40MHz, it obviates the need for a fixed-frequency 20MHz system to produce by merging the 50ns proton variant for the LHC.

Conclusions

The intrinsic flexibility of the SPL chopper removes concerns about adiabaticity at low energy. So, given enough rf voltage, there are no constraints on gamma at transition in this energy regime.

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 10MHz 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 5ns bucket length of the SPS must be non-adiabatic.

The 10MHz route involves multiple additional rf systems, but it is compatible with ions thanks to the possibility of a factor of 3 in tuning range.

The 40MHz route requires a significant R&D effort in order to cope with the large frequency swing of ions.

Bottom Line

	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	172, 18.65	172, < 40	0.5