Gamma at Transition in the Proposed PS2 Machine

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Abstract

The PS2 synchrotron is a normally conducting machine which is proposed as a replacement for the ageing PS to help meet the demand for brighter and more intense beams. In order to reprise the role of the PS, the new machine must be capable of a variety of beam manipulations. These impose constraints on the possible value of gamma at transition that can be considered.

BACKGROUND

The new PS2 machine is proposed to have double the mean radius of the existing PS, with a bending radius of 94.4 m and a maximum ramp rate of 1.5 Ts^{-1}. The proton injection and extraction (total) energies will almost double to 4.4 GeV and 50 GeV, respectively. Keeping the same 10 MHz upper frequency limit for the accelerating RF system means that all harmonic numbers will also be doubled.

The (zero-amplitude) synchrotron frequency at energy E in a machine of mean radius R with an rf voltage and harmonic of V_{RF} and h scales as

$$f_{\text{s}} \propto \frac{1}{R}\left(\frac{hV_{\text{RF}}\eta}{E}\right)^{1/2}$$

where the phase slip factor, η, is determined by the proximity to transition in terms of relativistic gamma.

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{\text{tr}}^2}$$

Taking into account all the factors of 2 between the original PS and the new machine, the old-to-new synchrotron frequency ratio reduces to

$$\frac{f_{\text{s}}^{(1)}}{f_{\text{s}}^{(2)}} \approx 2\left(\frac{V_{\text{RF}}^{(1)}}{V_{\text{RF}}^{(2)}}\right)^{1/2}\left(\frac{\eta^{(1)}}{\eta^{(2)}}\right)^{1/2}$$

Longitudinal acceptance scales as

$$A_{\text{L}} \propto \frac{R}{h}\left(\frac{V_{\text{RF}}E}{h\eta}\right)^{1/2}$$

so that its ratio reduces to

$$\frac{A_{\text{L}}^{(1)}}{A_{\text{L}}^{(2)}} \approx \left(\frac{V_{\text{RF}}^{(1)}}{V_{\text{RF}}^{(2)}}\right)^{1/2}\left(\frac{\eta^{(2)}}{\eta^{(1)}}\right)^{1/2}$$

Here, the role of the η-ratio is inversed, which means that some compromise between adiabaticity and acceptance is inevitable in the choice of γ_{tr}.

SOME CALCULATIONS FOR PROTONS

Consider the specific examples of triple splitting at low (injection) energy and the first double splitting at high (extraction) energy for the LHC beam with 25 ns bunch spacing. Taking the V_{RF}-ratio such that the initial bunch duration is exactly the same, i.e., ignoring the 7% increase in RF frequency at injection between the old and new machines (which means that the frequency swing of the new 10 MHz cavities will be slightly less), Figure 1 shows how the adiabaticity ratio (red curves) varies as functions of real and imaginary γ_{tr}. A value greater than unity means that adiabaticity is worse in the new machine and splitting will take longer, hence the label "penalty". The ratio of the rf voltages required to maintain bunch duration equality are also plotted (green curves). A value greater than unity means that more voltage is required in the new machine to achieve this. Bunch duration is important because it is difficult to split short bunches.

In the low-energy case, the RF voltage is considerably lower in the PS2 – particularly for real γ_{tr} because γ is already 4.7 at injection – and this leads to a very large adiabaticity penalty. Consequently, the situation is significantly improved by going to imaginary γ_{tr}. This also has the distinct advantage of eliminating transition crossing. In the high-energy case, the new extraction energy is so high that it makes little difference whether γ_{tr} is real or imaginary, at least for the plot range considered.

The triple splitting and flat-top gymnastics (including synchronization) for the 25 ns LHC beam currently take 30 and 300 ms, respectively. So a large adiabaticity penalty would be particularly undesirable at high energy.

Of course, the initial bunch lengths are not written in stone and some improvement would be possible at higher RF voltage provided the bunch is not made too short. However, for LHC-type beams, raising the 10 MHz voltage at the start of the high-energy flat-top would have consequences for all the high-frequency RF systems involved in the subsequent gymnastics. Indeed, in order to be able to re-use these systems without a mark-up in voltage performance implies that the V_{RF}-ratio at high energy should be kept near unity. A similar set of plots to those of Fig. 1 are shown in Fig. 2, but this time for exactly the same initial RF voltage in both machines.

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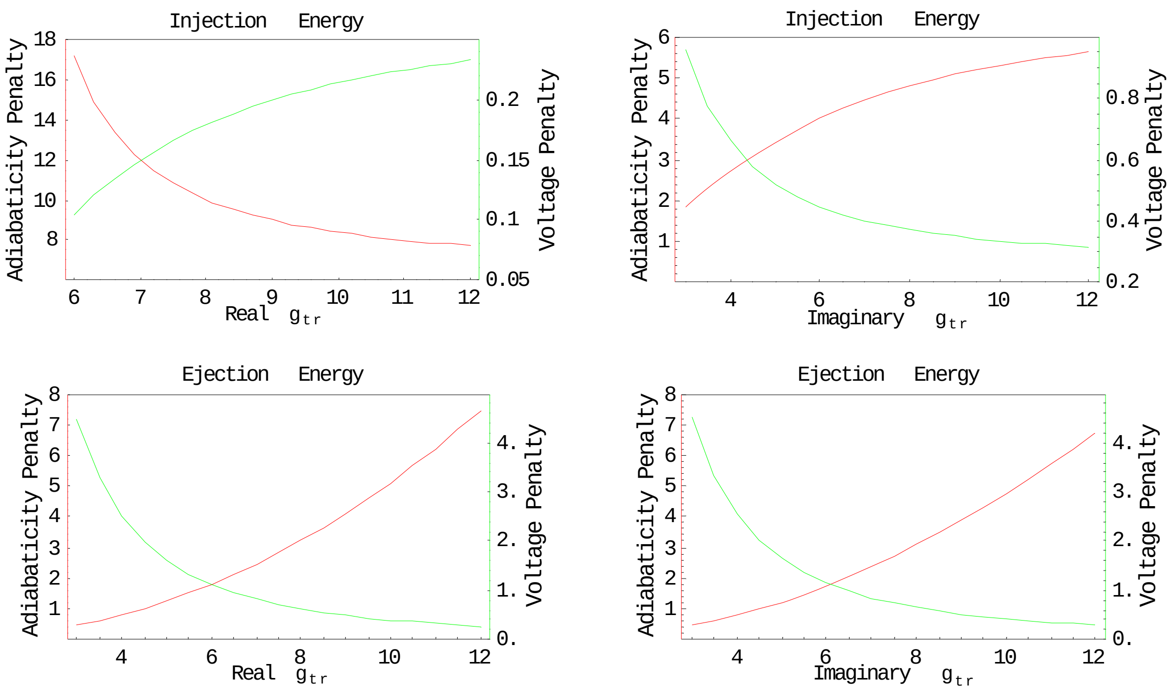

Figure 1: PS-to-PS2 synchrotron frequency ratio (red curves) and PS2-to-PS RF voltage ratio (green curves) as functions of γ_{tr} for the same bunch duration prior to splitting at low and high energy.

The corresponding longitudinal acceptance ratios are also plotted (blue curves). An acceptance penalty greater than unity means that less acceptance is available in the new machine, so that a bunch of given emittance will be longer.

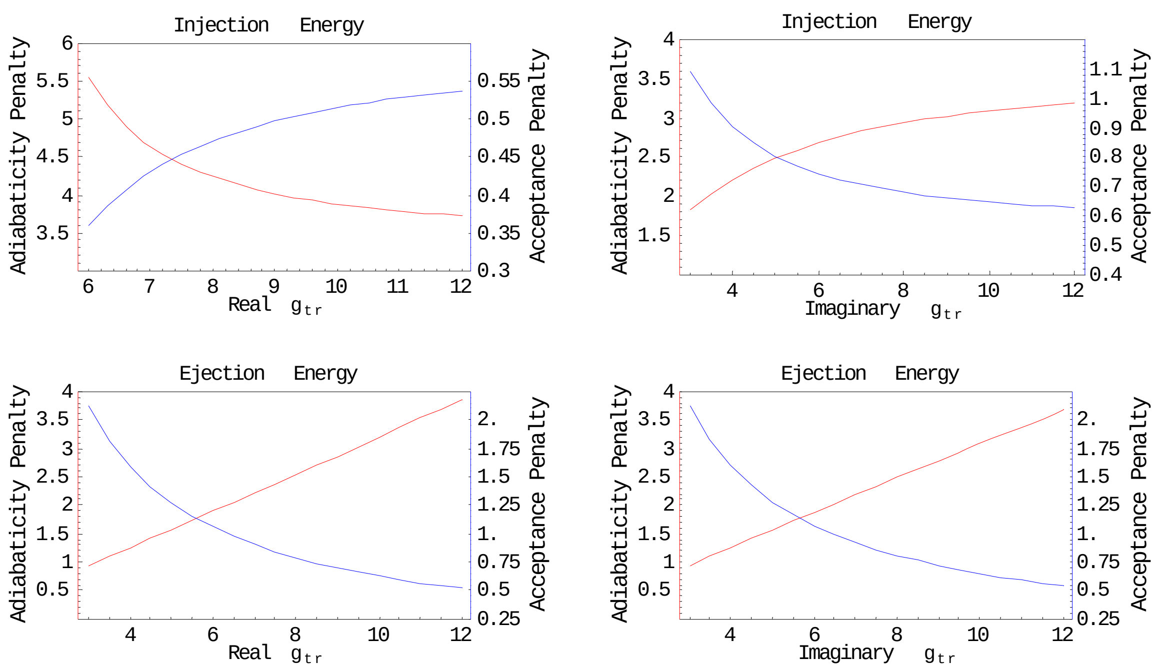

Figure 2: PS-to-PS2 synchrotron frequency ratio (red curves) and PS-to-PS2 acceptance ratio (blue curves) as functions of γ_{tr} for the same RF voltage prior to splitting at low and high energy.

Choosing $\gamma_{tr} = 6.4\sqrt{-1}$ yields an A_L-ratio of unity in the last plot of Fig. 2, so that bunches will have the same length for the same RF voltage. Consequently, for this value of γ_{tr}, the corresponding plot of Fig. 1 shows a voltage penalty of unity. Furthermore (see Section 1), the η-ratio is also near unity and the adiabaticity penalty is close to two. This is confirmed by detailed tracking simulations which show that the current performance of LHC flat-top gymnastics can then be achieved in the PS2 machine with the same voltage programmes on all cavities (10, 13/20, 40, 80 MHz) provided those programmes are played out at half-speed.

Again, in the high-energy case, it makes little difference whether γ_{tr} is real or imaginary and $\gamma_{tr} = 6.3$ also yields an A_L-ratio of unity. However, the deciding factor is at low energy, where such a value of real γ_{tr} incurs a prohibitively large adiabaticity penalty.

CONCLUSIONS

The goal of re-using the existing PS high-frequency rf cavities without increasing the voltage they deliver severely restricts the range of γ_{tr} values that can be considered for the PS2 machine. Real γ_{tr} would appear to be excluded or, at least, would result in much longer magnetic cycles.

The consequences are less compelling if RF gymnastics can be avoided at low energy in the PS2. For example, building a linear machine to reach the 3.5 GeV (kinetic) injection energy would radically change the fabrication of all beams. Or even perhaps, in an interim period, the old PS could provide LHC-type beams that are already split before injection into the new one.