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TRANSITION ENERGY CROSSING IN THE FUTURE FAIR SIS-100 FOR PROTON OPERATION

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Abstract

The FAIR project foresees to deliver an intense single bunch beam with 2e13 protons of 50ns duration to the experiments. Besides the original γ_t-shift scenario, an alternative RF proton cycle has been recently studied: the transition energy is crossed with possibly a gamma transition jump. The flexibility of the lattice allowing to change the value of γ_t, a transition crossing has been considered for two possible energies. This challenging scenario is limited by several constraints such as space charge, a small momentum acceptance and by the required RF manipulations aiming to produce the final single bunch beam in the proposed SIS-100. This paper focuses on how the high intensity beam would suffer of the mismatch in bunch length at transition and new sets of beam parameter are defined for the proton beam. The jump quadrupole system is also presented. The applicability of the foreseen longitudinal feedback system to cure quadrupolar oscillations is also discussed in this paper.

PROTON CYCLE FOR SIS-100

The future SIS-100 is a 1 km circumference synchrotron, receiving various ions species and proton beams from its injector the SIS-18. A part of the duty cycle foresees to deliver an single bunch beam with 2×10^{13} protons to the experiments. Originally the production of this beam was aimed as described in Fig. 1: 4 bunches are injected into the SIS-100 and via successively batch compressions and bunch merging, the harmonic is reduced from 10 to 5 and only one bunch is obtained at the end. The beam is then accelerated and the optics is changed during the ramp to produce a γ_t-shift in order to always stay below transition energy. However issues came out of the γ_t-shift scenario and the question of the possibility for SIS-100 to cross transition energy arose. The γ_t-shift scenario is still under study and is described in Ref. [1]

In a synchrotron, a relative momentum error $\Delta p/p$ can be related to a relative change in the revolution frequency $\Delta f/f$ by $\Delta f/f = \eta \Delta p/p$, except at transition energy where the slip factor factor η goes to zero since

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \tag{1}$$

with γ is the Lorentz energy factor and γ_t the value of γ at transition energy, given by the machine optics. While the beam is accelerated, it can meet the energy $\gamma = \gamma_t$, η goes to zero and the synchrotron motion is considered frozen. Once this energy is crossed, the motion slowly starts again. Another parameter, the *nonadiabatic time*, T_c can be defined as [2],

$$T_c = \left(\frac{\beta^2 E_0 \gamma_t^4}{4\pi f_0^2 \dot{\gamma} h e V_{rf} |\cos \phi_s|} \right)^{1/3} \quad \text{and} \quad \omega_s^2 = \frac{|t|}{T_c^3} \tag{2}$$

with ω_s the synchrotron frequency, V_{rf} the total voltage, h the RF harmonic number, $\dot{\gamma}$ is $d\gamma/dt$, f_0 the revolution frequency. Let consider the time t with $t = 0$ being the transition energy. For $|t| < T_c$, the synchrotron motion is considered frozen and is namely *nonadiabatic*: the particle motion will not follow a change of the bucket shape. One can see that the nonadiabatic time strongly increases with the transition energy.

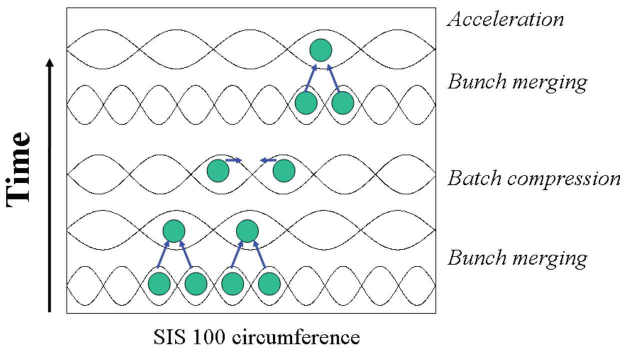

Figure 1: Original RF cycle at injection energy in the SIS-100 [3].

BUNCH SHAPE AT TRANSITION

Let suppose that all RF manipulations are performed at injection energy. The beam is accelerated at harmonic $h = 5$ with the original intensity foreseen for the single bunch beam. No longitudinal dilution is assumed. A table of beam parameters is presented in Tab. 1.

The longitudinal equation of motion for the zero intensity case is then written as [2]

$$\frac{d}{dx}\left(\frac{1}{x}\frac{d\Delta\phi}{dx}\right) + \Delta\phi = 0 \tag{3}$$

where $x = t/T_c$ and is a time in units of T_c. This equation can be solved analytically as described in Ref [2]: the bunch length shrinks before transition energy to reach a minimum at $\gamma = \gamma_t$, and therefore, because of the conservation of the phase space, the energy spread reaches a maximum: the beam ellipse appears to be tilted in the longitudinal phase space. As consequence, the momentum acceptance has to be check at transition energy to avoid beam

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Table 1

SIS-100 circumference	1083.6 m
Transition energy γ_t	8.9
Total RF voltage	280 kV
Harmonic h	5
Revolution frequency f_0	275 kHz
Stable RF phase ϕ_s	54deg
Nonadiabatic time T_c	4.8 ms
Full bunch area at injection S	2.4 eV.s
Number of proton N_b in the final single bunch	2×10^{13}
Momentum acceptance	0.005
Q_x, Q_y	10.4,10.3
Dispersion D_{max}	6.8
$\Delta\gamma_t$	2 in 500μs

losses. Eq.3 is solved for the beam parameters of Tab. 1 and the bunch shape at transition ($x = t/T_c = 0$) is [4] $\tau(x = 0) = 36.85$ ns$, \delta_{max} = 0.0058$. Without any collective effects taken into account into the calculations, the momentum spread might reached the momentum acceptance, causing beam losses. However, the longitudinal dynamics at transition can be strongly impacted by the longitudinal space charge forces, causing lengthening and shortening of the bunch length at transition energy.

In the machines as such the CERN PS [5] or AGS [2], a wide experience exists of operating high intensity beams through transition. One of the first intensity effects that can be studied is the longitudinal space charge force [6] which distorted the RF potential well in such a way that the force is defocusing below transition, the bunch length is longer than the zero intensity case. Above γ_t, the force is focusing, the bunch length is shorter than the zero intensity case. As a consequence, the longitudinal space charge induces a mismatch in bunch length with respect to transition energy, leading to an increase of the longitudinal emittance.

As for the zero intensity case, a longitudinal beam envelop equation describes the behavior of the half bunch length with longitudinal space charge, here for a parabolic bunch and a linear bucket [2],

$$\frac{d}{dx}\left(\frac{1}{x}\frac{d\hat{\Delta\phi}}{dx}\right) + sgn(x)\hat{\Delta\phi} + \frac{\kappa^l_{sc}}{\hat{\Delta\phi}^2} - x\frac{(Sn/\pi)^2}{\hat{\Delta\phi}^3} = 0 \qquad (4)$$

with the longitudinal perveance term,

$$\eta_{sc} = \frac{\kappa^l_{sc}}{\hat{\Delta\phi}^3} \quad \text{and} \quad \kappa^l_{sc} = \frac{3\pi N_b r_p E_{rest} g_0 h^2 Sgn(\eta)}{R\gamma^2 eV|\cos\phi_s|} \qquad (5)$$

The last term of the longitudinal beam envelop equation is the emittance term. The area is converted in normalized dimensionless bunch area S_n to transform the bunch ellipse to as circle. S_n is related to the full bunch area S in eVs by [2]

$$S_n = \frac{2h^2\omega_0^2\dot{\gamma}T_c^2}{\beta^2\gamma^4 E_{rest}} S \qquad (6)$$

The solution of Eq. 4, solved by below and by above transition, shows a large bunch length mismatch in Fig. 2. Even if the longitudinal space charge helps to produce smaller momentum spread before transition, the momentum acceptance can be reached after transition due to the mismatch Fig 3. Moreover some margin in longitudinal dilution has to be considered (currently a factor 3 dilution in SIS-18). If no special optics is applied, and for the case of the single bunch in $h = 5$, the tolerable dilution is 1.5 where the momentum acceptance is reached at transition.

In machines such the CERN PS, a γ_t-jump $\Delta\gamma_t$ is used to overcome the problem of longitudinal space charge [5, 8]. The principle is to change the optics (therefore γ_t) to catch rapidly the same bunch length after transition. Usually, the jump start well before $x = -1$,n because the beam ellipse is already tilted in the longitudinal phase space. However as shown in Fig. 2, even with a γ_t-jump and without dilution, the same bunch length cannot be catch up after the jump, because the longitudinal space charge focuses strongly the bunch length. A mismatch remains. However, if the residual bunch length oscillation is not too large, an adapted longitudinal feedback system could damped the oscillations. In our study, we choose a jump starting at $x = -2$, which allows a tolerable dilution of a factor 2 before reaching the momentum acceptance below transition. In this case, the γ_t-jump without residual mismatch is possible within a $\Delta\gamma_t$ of 2.

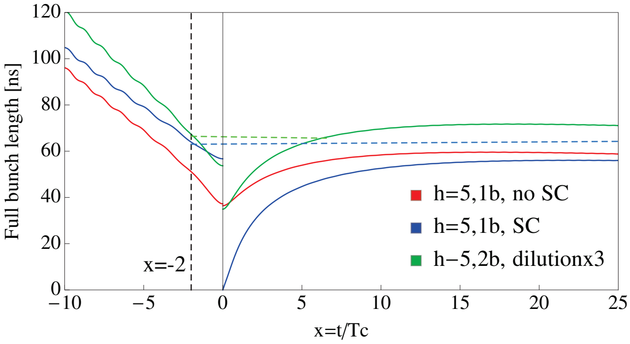

Figure 2: Bunch length as a function of time through transition crossing in the non-dynamical case for different configurations: in red, the original RF cycle with one bunch, no space charge, in blue, the original RF cycle with one bunch, with space charge, in green, 2 bunches are accelerated in $h = 5$ with space charge with a bunch area of 1.2 eVs diluted by a factor 3.

ALTERNATIVE RF CYCLE

The initial RF cycle of the single bunch created at injection and accelerated in $h = 5$ suffers of a lake of margin with respect to the momentum acceptance if the beam is longitudinally blew up. Nevertheless to be able to produce

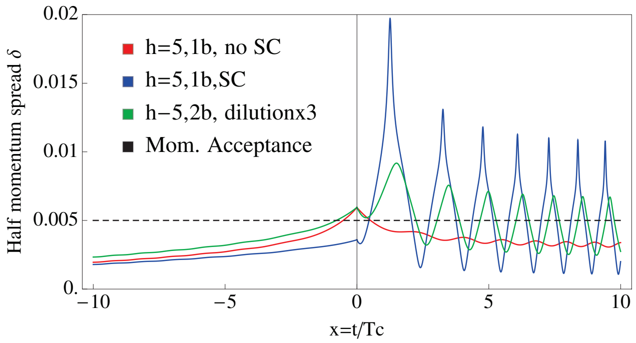

Figure 3: Half momentum spread as a function of time.

a γ_t-jump without residual mismatch, a dilution of 2 has to be applied, but the momentum acceptance is then reached. The RF cycle must be reshuffled and a possible scenario is to postponed the last bunch merging to higher energy and accelerate 2 bunches in $h = 5$ with a bunch area of 1.2 eV.s with some longitudinal dilution of 3, see Fig. 2 and Fig 3. This gives more margin for the momentum spread and the γ_t-jump without residual mismatch is possible within a $\Delta\gamma_t$ of 2. The clear disadvantage is the synchrotron motion which is much slower at high energy to perform the last step of the single bunch creation.

TRANSITION LATTICE

SIS-100 is a superconducting machine optimized for the operation with low charge state heavy ions [7]. Its lattice is designed to allow the confinement of ions lost through charge exchange reactions on dedicated ion catchers in the arcs. These ion catchers, though not actually required for proton operation, limit the momentum acceptance for the proton transition jump scheme.

The transition jump scheme for SIS-100 is realized by introducing six doublets of fast pulsed normal conducting quadrupoles separated by π in horizontal phase advance and by an integer number of lattice cells. Since the jump quadrupoles have to be integrated into a cryostat operated at liquid helium temperature, it is important to minimize their strength and, correspondingly, their AC losses. Under the given premises, the strength is minimized for a given $\Delta\gamma_t$ by maximizing $D_1^2 - D_2^2$, where D_1 and D_2 are the values of the horizontal dispersion at the location of the two jump quadrupoles, and by implementing a bipolar jump scheme [8].

The SIS-100 lattice being fixed, the only parameters to be chosen are the working point and the location the jump quadrupoles, with the additional objective of minimizing the jump quadrupole strength. Two tight constraints are posed by the available momentum acceptance, which must be large enough to accommodate the increasing momentum spread of the beam near transition, and the necessity to correct chromaticity to positive values above transition to ensure transverse beam stability. Furthermore, since the proton beam will have to undergo RF manipulations on the flattop, a maximization of the synchrotron oscillation frequency is desirable, favouring a small value of γ_t.

Since SIS-100 has 84 lattice cells, the horizontal tune has to be chosen close to $Q_h = 84/(2n)$ for n integer. Taking into account constraints on the available strength of the main quadrupole and chromaticity magnets and the physical aperture, only $n = 3,4$ are feasible, corresponding to $Q_h = 14, 10.5$. These two options lead to momentum acceptances during the transition crossing of 8.5×10^{-3} and 5×10^{-3}, respectively. On the other hand, for $Q_h \approx 14$ the required jump quadrupole strength for $\Delta\gamma_t = 2$ is about five times larger. Since the longitudinal scheme presented above respects the momentum acceptance of 5×10^{-3}, the working point for the transition scheme was set to $Q_h = 10.4$.

CONSIDERATIONS ABOUT THE LONGITUDINAL FEEDBACK SYSTEM

A bunch-by-bunch longitudinal feedback system [9] with two dedicated broadband cavities providing 12 kV (about 6% of the total available gap voltage) is foreseen, to damp hardly predictable, minor mismatches of single bunches, i.e. <10° phase offset and <10% deviation in bunch length. Due to the limited available correction voltage, the system is neither able nor designed to cure the strong distortion of >50% in bunch length described below. In parallel to the γ_t-jump scenario, however, the longitudinal feedback system can provide damping to minor dipolar and quadrupolar oscillations of single bunches, e.g. due to sightly varying phase space populations.

CONCLUSION

A scenario with transition crossing was proposed as alternative to the γ_t-shift. The main part of the RF manipulations is foreseen at injection and 2 bunches in $h = 5$ are accelerated through γ_t with a γ_t-jump with some margin on the tolerable dilution and a feedback system could damp minor oscillations. However further studies are needed to confirm that this scenario fulfils the requirements in term of beam quality. Simulations are on going to model the full scenario of transition crossing with longitudinal space charge and the longitudinal impedance.

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