Transition energy crossing of polarized proton beam at NICA

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At an experiment on acceleration of a polarized proton beam up to an energy at 13 GeV, the possibility of crossing the transition energy at 5.7 GeV by a jump is considered. The scheme of crossing by a rapid change of transition energy, assumes the longitudinal movement of the beam near the zero value of the slip coefficient. The jump itself is carried out in the absence of an RF field. The paper presents the influence of the above features on the dynamics of a polarized beam.

1. TRANSITION ENERGY

Considering the longitudinal motion, the concept of the momentum compaction factor is introduced: [1]

$$\alpha_c = \frac{1}{R_0}\frac{dR}{\delta} = \alpha_0 + 2\alpha_1\delta + 3\alpha_2\delta^2 + \cdots \equiv \frac{1}{\gamma_{tr}^2} \tag{1}$$

and slip-factor:

$$\eta\left(\delta\right) = -\frac{1}{\omega_0}\frac{\Delta\omega}{\delta} = -\left(\eta_0 + \eta_1\delta + \eta_2\delta^2 + \cdots\right) \tag{2}$$

where δ – momentum spread, R_0, R – the averaged radius of the reference and deflected by δ particle, ω, ω_0 – corresponding frequencies, α_n, η_n – n-th expansion terms , γ_{tr} – transition energy. The coefficients can be related by the relations $\eta_0 = \alpha_0 - \frac{1}{\gamma_0^2}$, $\eta_1 = \alpha_1 - \frac{\eta_0}{\gamma_0^2} + \frac{3}{2}\frac{\beta^2}{\gamma^2}$. As

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can be seen at a certain energy of the reference particle – transition $\gamma = \gamma_{tr}$, the slip-factor takes a zero value $\eta = \eta_0 = 0$.

2. TRANSITION ENERGY JUMP SCHEME

2.1. LONGITUDINAL MOTION

To overcome the zero value of the slip-factor, the method of the transition energy jump is used. Thus, it is possible to maintain a stable beam motion in the phase space. This method has been used on many facilities and is described in [2, 3].

The necessity for a jump can be understood by considering the dependence on slip-factor $\eta(\delta) = \eta_0 + \eta_1\delta + \ldots$ of the longitudinal motion equations that describe the evolution of particles in phase space [4]:

$$\begin{aligned} \frac{d\tau}{dt} &= \eta(\delta) \cdot \frac{h \cdot \Delta E}{\beta^2 \cdot E_0} \\ \frac{d(\Delta E)}{dt} &= \frac{V(\tau)}{T_0} \end{aligned} \tag{3}$$

During acceleration, the value of the slip-factor η approaches zero for all particles. Thus, for particles that have already overcome the transition energy, the sign of the slip-factor changes. However, due to the non-zero momentum spread δ, the term $\eta_1\delta$ in Eq.2 becomes comparable to η_0 and plays an important role on the dynamics near the transition energy. For this reason, different particles overcome transition energy at different time. Based on Eq.3, it can be seen that the dynamic in the phase plane becomes unstable and leads to the beam losses.

The jump procedure allows, firstly, during the increasing of the transition energy, to keep the beam at a sufficient distance for all particles to have the same sign of the slip-factor. Secondly, to ensure a quick transition to a new state, where the slip-factor changes sign, but for all particles it again has the same sign. Stability is ensured by changing the polarity of the retaining RF barriers.

On the other hand for the momentum compaction factor, the expression can be obtained [5]:

$$\alpha = \frac{1}{C}\int_0^C \frac{D(s)}{\rho(s)}ds \tag{4}$$

where $D(s)$ – dispersion function, $1/\rho(s)$ – orbit curvature. For already build lattice the orbit curvature is constant. In this case, only a variation of the dispersion function achieves a change in the value of α, and, accordingly, η. An additional gradient in quadrupole lenses modulates the dispersion function and is considered as a modernization for NICA. Calculations shows that the change in the transition energy γ_{tr} can be carried out at a rate of $d\gamma_{tr}/\ dt\ =\ 8.5\ c^{-1}$ [6].

2.2. MAIN STAGES

At jump procedure, there are five main states of longitudinal dynamics based on the change in the transition energy γ_{tr} (Figure 1):

1. Acceleration from injection energy E_{inj} with a stationary value γ_{tr}^{stat};
2. Smooth increase of γ_{tr} parallel to the particle energy up to the peak value, the slip-factor η_0 acquires the minimum possible value, approaching the zero value;
3. The transition through the stationary value of the transition energy, while η_0 crosses the zero value for all particles;
4. Smooth recovery of γ_{tr} up to a stationary value, also parallel to the particle energy;
5. Acceleration to the energy of the experiment with a stationary value of the trasition energy γ_{tr}^{stat}.

States 2-3-4 define the procedure for overcoming γ_{tr} by a jump. A change in magneto-optics leads to a dependence of γ_{tr} corresponding to the displacement of the working point $\nu_{x,y}$ (Figure 2), as well as higher orders of momentum compaction factor α_1, α_2.

3. TRACKING

The most dangerous from the point of view of beam destruction are states 2-3-4, at which the accelerator parameters change. From the point of view of dynamics, states 2 and 4 are symmetric.

The beam profile in the longitudinal plane is uniform, and the energy spread is Gaussian. States 2 and 4 are characterized by the fact that the slip coefficient for an equilibrium particle

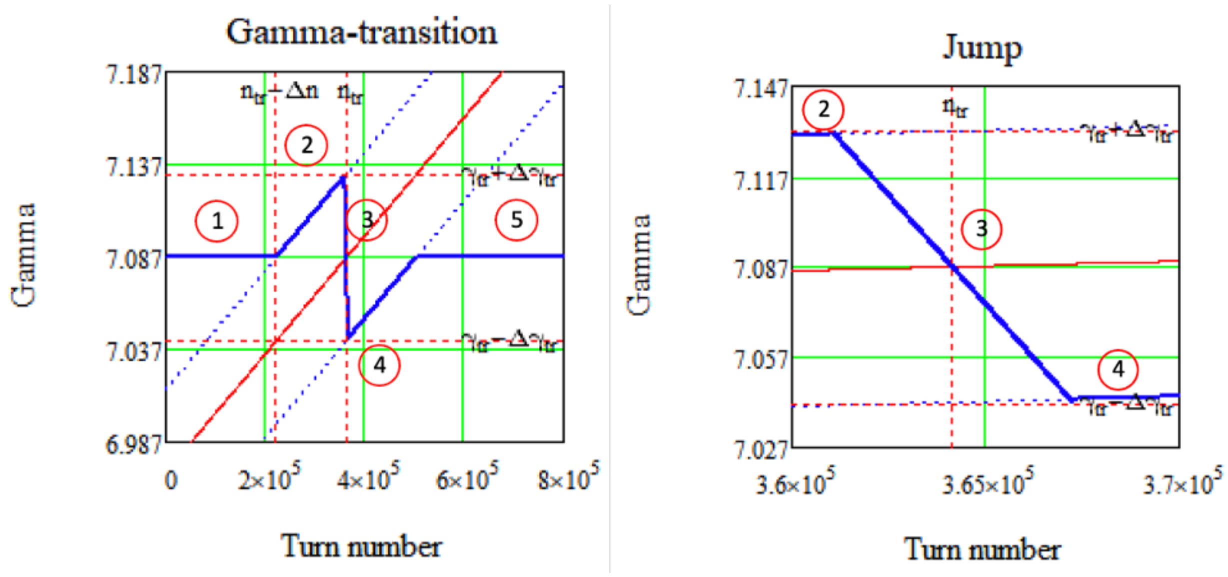

Figure 1. Transition energy jump scheme. The blue line is the actual transition energy of the accelerator γ_{tr}, the red line is the energy of the reference particle.

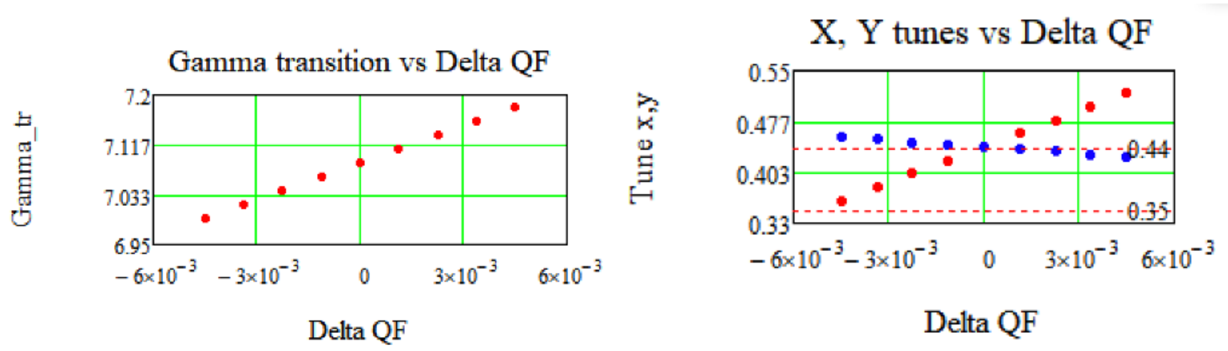

Figure 2. The dependence of the transition energy and the working point on the perturbation of the quadrupole gradient lenses.

remains unchanged, and the critical energy changes synchronously with the beam energy for about 2×10^5 revolutions. Thus, the retention of the beam at a stationary value of the critical energy is equivalent to the accelerated movement of the beam in a structure with changing parameters. As can be seen in Figures 8, the beam profile shifts to the left barrier, this is due to the fact that for particles with positive $\delta > 0$, the slip coefficient $\eta_{+\delta}$ is greater than for particles with negative $\delta < 0$ $\eta_{-\delta} : \eta_{+\delta} > \eta_{-\delta}$. This can be seen from Equation (2) and the fact that $\eta_1 < 0$.

State 3 – rapid parameter change within 6×10^3 revolutions (10 ms). RF barriers are turned off so as not to destroy the beam. The influence of the spatial charge is most important

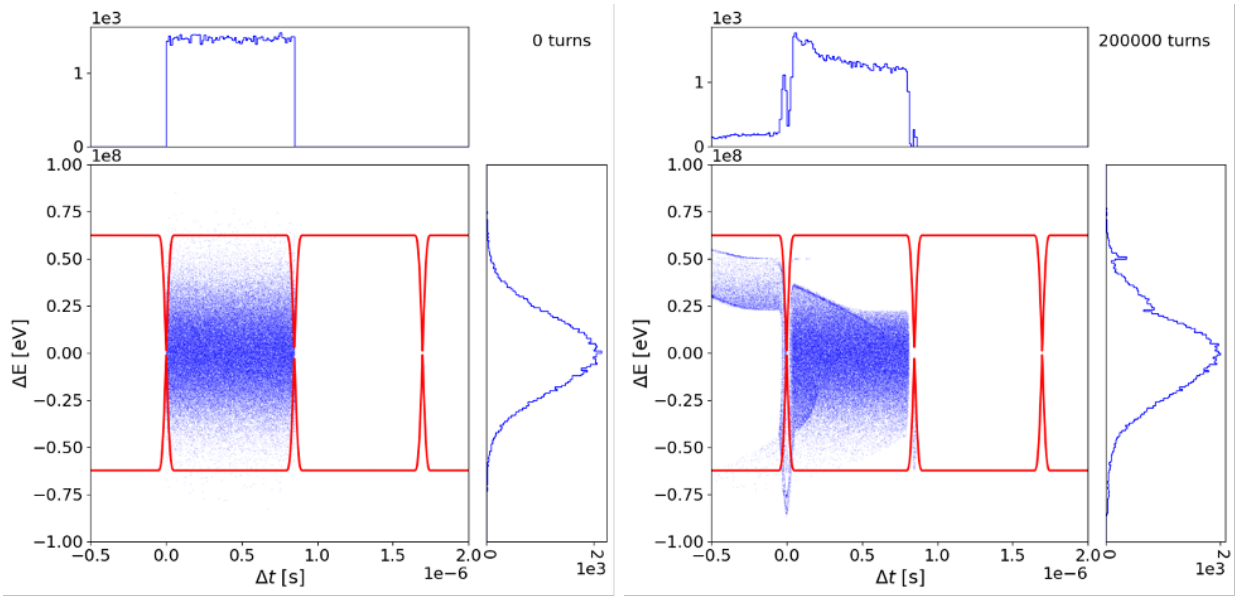

Figure 3. The phase plane, the beam is held inside the Barrier Bucket RF. On the left is the initial distribution, on the right is the distribution after 2×10^5 revolutions.

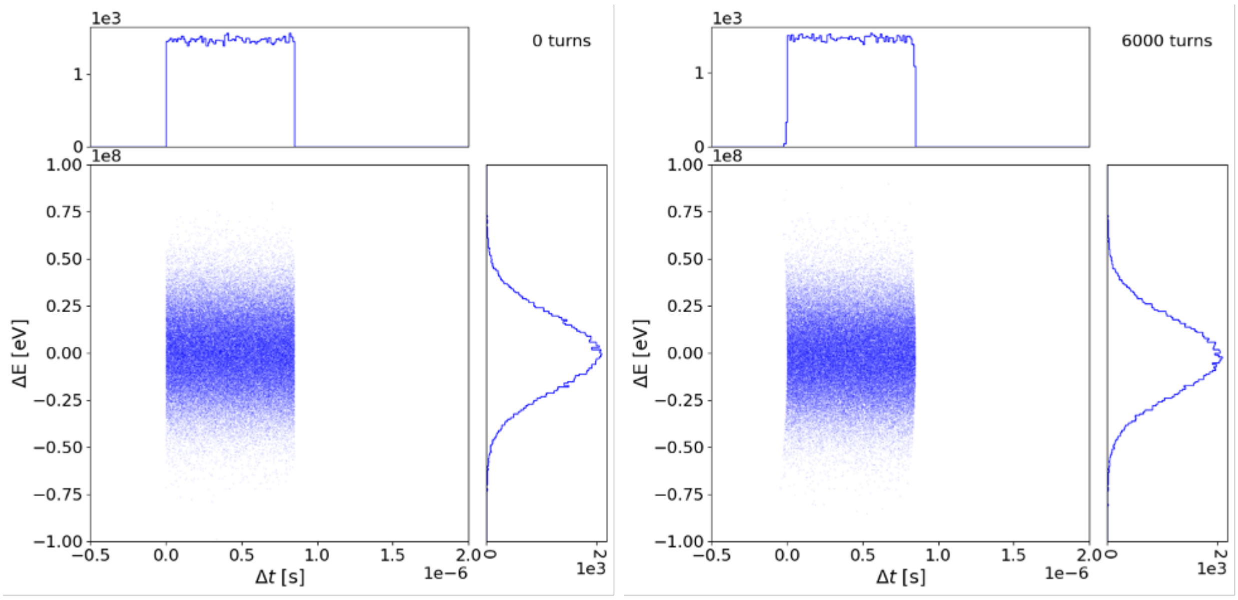

Figure 4. Phase plane during the jump, Barrier Bucket RF are disabled. On the left is the initial distribution, on the right is the distribution after 6×10^3 revolutions.

in the absence of barriers, since there is no external holding force. Tracking is done taking into account the spatial charge impedance described above.

There was no significant change in the beam profile during the jump. Modeling was performed in the BLonD environment [12-13].

4. POLARIZATION

5. CONCLUSION

The dynamics of longitudinal motion near the critical energy in barrier-type RF is studied, taking into account the spatial charge impedance. The procedure of abrupt change of accelerator parameters is an affordable option to overcome the critical energy.

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