EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - SL DIVISION

SL/Note 92-56 (EA)

MOMENTUM LOSSES IN LHC:

THE SPECIAL CASE OF RF UNCAPTURED PROTONS

AT INJECTION

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Abstract

After injection in LHC, The protons which are not captured by the radio-frequency are lost in a flash a moment after the beginning of the acceleration ramp. A quench will occur if adequate tools and controls are not implemented. A simple solution is discussed and quantified but some remaining difficulties are outlined. This paper is also a call for new ideas.

Geneva, 9 October, 1992

1. INTRODUCTION

At the beginning of the acceleration ramp, the protons which were not captured by the RF are not accelerated, while the magnetic field B is growing at the rate of $\dot{B}/B = 1.34\ 10^{-2}$ which is the nominal ramping speed [1]. The nominal central momentum is the one of the accelerated protons. The dp/p of the uncaptured protons will be more and more negative while the dispersion D is positive. Therefore the uncaptured protons will drift towards the inside of the ring. If nothing is done, they will hit the vacuum chamber after a time

$$\Delta t = \frac{r}{D_{max} \cdot \dot{u}} = 0.8s$$

where r = 20 mm is the radius of the vacuum chamber, D_{max} = 1.86m is the maximum dispersion and u = dp/p is the central momentum of the uncaptured protons, such that $\dot{u} = -\dot{B}/B$. The duration of the flash of losses around Δt will be

$$\delta t = 2\,\sigma_u / \dot{u} = 0.08s$$

where $\sigma_u = \sigma_E/E = 5\ 10^{-4}$ is the energy spread of the beam at 450GeV (see Appendix 1 of [1]). The duration of the flash δt might be longer, up to $\delta t' = (\Delta p/\sigma_p)\delta t = 2.6\delta t$ if the uncaptured protons occupy the full bucket area $2\Delta p$. This factor 2.6 does not modify the arguments which follow.

The transverse amplitude will increase at each turn by $\delta x = D_{max} \cdot u / f_r = 2.2\ \mu m$, with the frequency of rotation of the beam $f_r = 10^4$ Hz. δx is such small that losses will be located on one (or a few) location, where by misalignment or closed orbit distortion the aperture is most limited. Therefore, even if the uncaptured fraction of the injected beam is small, say 1% of $N_p = 4.7\ 10^{14}$ [1], $N = 5\ 10^{12}$ protons would touch the vacuum chamber in one location in a fraction of a second, while at 450GeV a quench occur at $N_q \approx 3\ 10^8$ p/s [2]. A drastically different approach must be explored, which allows for filling this gap of four to five orders of magnitude between the rate of losses and the quench level.

2. COLLIMATION AND RAMPING SPEED

2.1 Collimation

An obvious way to improve the situation described in section 1 is to use collimators. A two-stage collimation system was studied at 8 Tev [1,2]. A notional efficiency was estimated, but large uncertainties remain and further studies are needed. A similar calculation remains to be done at 450 GeV. We use here a somewhat arbitrary efficiency of $\eta = 10^3$, which is defined as the flux falling on the primary collimator divided by the flux leaking out of the secondary one(s). Then the product $\dot{n}_c = \eta \cdot N_q$ is the maximum allowed rate of losses on the primary collimator , where N_q is the quench thresh ld at a single location. At 450GeV , $N_q = 3\ 10^8$ p/s, and therefore $\dot{n}_c = 3\ 10^{11}$ proton/s.

2.2 Ramping speed

From past experience at the SPS colider, a fraction f of uncaptured protons of several percent was common, and it was sometimes larger than 10%. Of course, special care (what 'special care' means remains to be specified) shall be taken at LHC in order to limit f at most, but we do the present estimations with f = 0.1. More optimistic scenarios can then simply extrapolated.

The number of uncaptured protons is expressed by $N = f \cdot N_p = 4.7\ 10^{13}$. The allowed loss rate $\dot{n}_c = 3\ 10^{11}$ p/s is a few hundred times smaller than $N/\Delta t$, if $\Delta t < 1$s, as discussed in Section 1, even with the two-stage collimation system able to provide an efficiency of $\eta = 10^3$.

Unless a better idea is found, the duration Δt of the loss must therefore be enlarged, until $N/\Delta t < \dot{n}_c$. In practice, an initial very slow ramping speed must be used, until the last uncaptured proton is eliminated. Afterwards, the nominal ramping speed (see Section 1) can be used. The time needed to eliminate all the uncaptured protons is computed in two steps.

1) <u>Relate the loss rate to the ramping speed</u>

The uncaptured beam has an initial momentum distribution equal to the captured one, i.e. approximately gaussian with an r.m.s momentum width $\sigma_u = \sigma_p/p = \sigma_E/E = 5\ 10^{-4}$ [1]. The distribution is normalised to the amount of amount of uncaptured protons fN_p . The peak density is therefore

$$\frac{dn}{du}(u{=}0) = \frac{f\,N_p}{\sqrt{2\pi}\,\sigma_u} \qquad (1)$$

The ramping speed $\dot{u} = du/dt$ must be adjusted such that the loss rate is equal to $\dot{n}_c$.

$$\frac{dn}{du}(u{=}0) \cdot \dot{u}_c = \dot{n}_c = \eta \cdot N_q \qquad (2)$$

The critical ramping speed $\dot{u}_c$ is obtained by replacing (1) in(2).

$$\dot{u}_c = \frac{\sqrt{2\pi}\,\sigma_u\,\eta\,N_q}{f\,N_p} = 8\ 10^{-10}\,\eta/f = 8\ 10^{-6}\ s^{-1} \qquad (3)$$

2) Define the position of the primary collimator

To avoid any unwanted correlation between betatronic and momentum collimation, the jaw of the momentum collimator must be placed at $\approx 10\sigma_\beta$ from the the beam axis (the betatronic collimator must do a cut at $\approx 6\sigma_\beta$). If β = 100m and D = D_{max}, then the uncaptured protons will touch the jaw at a relative momentum

$$(\frac{dp}{p})_{coll} = u_{coll} = \frac{10\sigma_\beta}{D} = \frac{9}{1860} = 4.8\ 10^{-3}$$

The uncaptured protons are not submitted to synchrotron oscillations. Therefore, the momentum of each proton relative to the central one shall be constant during the time needed to evacuate them. The density distribution in momentum can be considered to be low enough at $u \approx 3\sigma_u$. The last dangerous proton will then be exhausted after

$$\Delta t = \frac{u_{coll} + 3\sigma_u}{\dot{u}_c} \qquad (4)$$

Using (3),

$$\Delta t = 7.9\ 10^6 \frac{f}{\eta} = 790s$$

After the time Δt the nominal ramping speed can replace the slow $\dot{u}_c$.

2.3 Consequences of a slow ramping speed

Apart from the increasing duration of the injection process, some problems might be related to the very low value of the ramping speed $\dot{u}_c = 8\ 10^{-6}\ s^{-1}$, which is equal to the current rise $\dot{I}/I$ of the main power supply.

- The RF power necessary for this very slow acceleration must be of the order of $\delta E = \dot{u}_c E$ = 3.6 MeV/s = 330 eV/turn. According to D. Boussard [3], while substantial fluctuations can affect this very low power in a turn by turn basis, the average value over time can be well controlled. The uncaptured particles are not accelerated, and therefore cannot be affected by the RF noise. This effect shall not affect the smoothness of the losses. It remains to see if nothing harmful happens to the accelerated protons.

- Persistant currents in the magnets might be more difficult to handle with a slow ramp and a larger overall time at low field.

- The control of the current rise of the main power supplies might be a more serious problem. With $\dot{I}/I = 8\ 10^{-6}\,s^{-1}$ at $I = I(450GeV)$, the current rise normalised to $I_{max} = I(7700GeV)$ is

$$\dot{I}/I_{max} = 4.6\ 10^{-7}\,s^{-1}$$

According to J.Pett, even by envisaging the use of a new technology (presently under evaluation) for the control of the current, a practical ramp speed smaller than $\dot{I}/I_{max} = 10^{-6}\,s^{-1}$ should not be envisaged. This limit corresponds to the level of the residual noise after filtering. It does not include systematic offsets and absolute control of the ramp speed, which are thought to be corrected when adjusting the machine.

The conclusion is here that a factor 10-20 must be found elsewhere to be in a somewhat safe situation.

3. WHERE TO GAIN

3.1 At the source

If the uncaptured fraction is smaller, the gain is linear with f, which could be made smaller by :

- Improving the RF control between the different machines (to avoid a large phase mismatch, as a trivial exemple).
- Detecting excessive f values at each injection. If a measurement of f could be invented, a threshold might be set, above which a dump action is initiated. The threshold value shall be set at ~1% to be useful.

3.2 Improve the efficiency of the collimation

This implies first to compute a realistic value of the efficiency of a two-step collimation system at 450 GeV and compare it to the somewhat arbitrary value used here ($\eta = 10^3$).

4. SUMMARY

The control and the elimination of RF uncaptured protons after injection in LHC is a non-trivial problem. Severe hardware controls shall maintain the uncaptured fraction to the smallest possible level. A strong momentum collimation scheme is needed at injection, associated to a safe beam loss monitoring. The critical parameter is the ramping speed which must be very slow in the scheme envisaged here.

A measurement of the fraction of uncaptured protons would strongly help to master the problem.

A more elaborated scenario than the basic one exposed here to eliminate the uncaptured protons would be welcome.

Acknowledgements

I had the benefit of the expertise of D. Boussard, L. Burnod and J. Pett while tackling with this quite unexplored subject.

References

1) The 'Pink Book', CERN 91-03, May 1991.

2) L. Burnod and J.B. Jeanneret, CERN/SL 91-39 (EA), LHC Note 167, 25.9.1991.

3) D. Boussard, private communication, September 1992.

4) J. Pett, private communication, September 1992.