NOVEL SLOW EXTRACTION SCHEME FOR PROTON ACCELERATORS USING PULSED DIPOLE CORRECTORS AND CRYSTALS*

V. Shiltsev#, FNAL, Batavia, IL 60510, USA

Abstract

Slow extraction of protons beams from circular accelerators is currently widely used for a variety of beam-based experiments. The method has some deficiencies including limited efficiency of extraction, radiation induced due to scattering on the electrostatic septa and limited beam pipe aperture, beam dynamics effects of space charge forces and magnet power supplies ripple. Here we present a novel slow extraction scheme employing a number of non-standard accelerator elements, such as Silicone crystal strips and pulsed strip-line dipole correctors, and illustrate practicality of these examples at the 8 GeV proton Recycler Ring at Fermilab.

INTRODUCTION

Many high energy physics experiments demand extended extraction of an intense particle beam from a circular accelerator – so called "slow extraction". Among the most critical requirements for the extraction are uniformity of the extracted beam intensity over the duration of the spill (ideally, under 10% or less), high overall efficiency of extraction (above 95-98%), low activation of the accelerator components (e.g., electrostatic septa) and, often, a limited average extraction rate. The most widely used method of resonant slow extraction (see, e.g. in Ref.[1]) employs non-linear magnetic elements to excite large amplitude betatron motion of particles when they are tuned on an appropriate resonance (usually, near tunes equal to one-third or half-integer). The large amplitude particles are intercepted by an electrostatic septum which further deflects them and forces them to leave the ring aperture into an extraction beamline.

However, there are intrinsic problems with the method which become of utmost importance when applied to very high average intensity beams of protons. First of all, the losses at the extraction septum – which are determined by the ratio of the septum grid width and the extraction step size (particle position increment after 3 turns) – are of very serious concern even at the level of 2% of the total beam intensity. One of the advantages of the third-order resonance is that the step size is growing with the betatron amplitude and can be made large far from the non-linear resonance separatix [2,3]. At the same time, the maximum step size is limited by the machine acceptance. Moreover, the space-charge and chromatic effects interfere with the resonant beam dynamics and make slow resonant extraction less efficient for high intensity beams [3,4]. Below we discuss a method to overcome these limitations and deliver particles beyond the septum in one step, with no or minimal losses on the septum and no additional aperture required beyond the septum to accommodate large step size.

* Work supported by the U.S. Department of Energy under contract No. DE-AC02-07CH11359
#shiltsev@fnal.gov

THE METHOD

The proposed technique is non-resonant and employs two new elements: a bent Si crystal which provides large transverse (say, horizontal) kick to any particle going through it and an orbit corrector that moves the whole beam onto the crystal until complete extinction – see Fig.1.

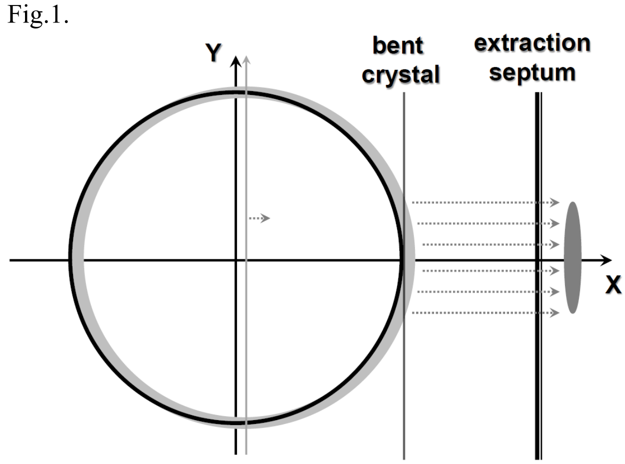

Figure 1: Schematics of the slow extraction with use of bent crystals and pulsed dipole deflectors (orbit correctors).

The angular beam deflection by the crystal – see Fig.2 – must be large enough to send the particles beyond the septum in a single passage (single turn).

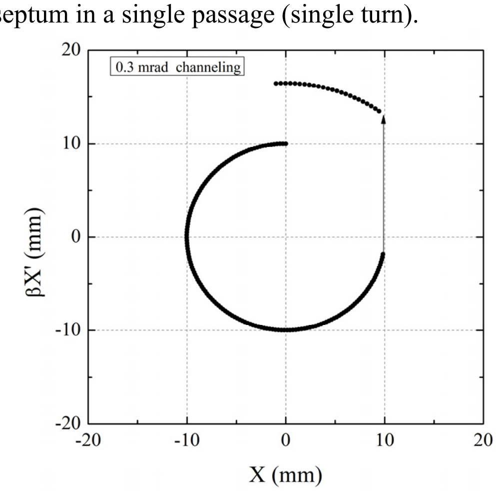

Figure 2: Horizontal phase space trajectory of a particle deflected by a 0.3 mrad bent crystal.

ISBN 978-3-95450-115-1

There are two possibilities to generate the required deflection of the order of a (big fraction of) milliradian – either via channelling or volume reflection processes [5]. Both have been successfully tested with in the Tevatron with 980 GeV proton beams [6,7], and are considered to be applicable to much lower energies [8]. In the process of channeling, the particles follow the crystal axes and bent by the full crystal bend angle of θ_d if they have fit within the angular acceptance of the critical angle +-θ_c. In the "volume reflection" regime, particles are bent off the crystal surface planes by some (1.5-2)×θ_c if their incident angles are within the full crystal bend angle of θ_d. The critical angle is θ_c=0.07 mrad/$(E/8\text{GeV})^{1/2}$ for protons trapped in the (110) planes of Si while crystal bend angles of about θ_d =0.2-1 mrad are quite practical.

There are several challenges with the proposed scheme: firstly, the crystals should have high efficiency (>90%) of the channeling or the volume reflection; secondly, the scattering of the uncaptured particles inside the crystal should be small – that usually means shorter crystals as the scattering angle of about 0.2mrad×d[mm]$^{1/2}$/[E/8GeV] grows with the material thickness d; and, thirdly, in some cases (e.g. as in the example of the Mu2e experiment presented below) it may be required to extract slowly not the entire beam circulating in the machine, but only out of smaller portions, one after another. Fig.3 illustrates how it can be done if two fast deflectors are used to move only a part of the beam (say, only a train of 20 bunches) onto the bent crystal. The modern pulsed HV technologies are quite capable generating 3 kV peak, 200 ns width pulses at the repetition rate of 90 kHz or more, needed to feed a strip-line deflectors, as confirmed experimentally in [9].

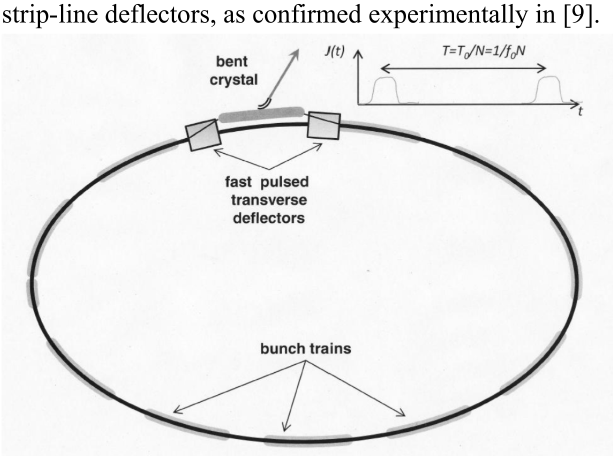

Figure 3: Scheme of selective slow non-resonant extraction: a pair of the fast pulsed deflectors moves the orbit of only one bunch train out of many circulating in the machine; after that train is extracted, the deflector timing is changed to operate on another bunch train, etc.

MODELING FOR THE 8 GEV RECYCLER

Below we present results of computer modelling of the non-resonant slow crystal assisted extraction of a 8 GeV proton beam from the Fermilab Recycler ring which could be considered as a simple alternative scheme for the muon to electron conversion experiment Mu2e, which calls for extracted beam consisting of less than 200 ns pulses every 1.6 microsecond [10]. In simulations we modelled uncoupled horizontal motion of particles at the initial 10 mm amplitude in the tune Q_x=0.465 lattice. A bent crystal is set 10 mm away from the beampipe center. After the beam is moved by 0.01 mm as a whole by deflectors onto the crystal, then any particle which gets into the channeling acceptance of +-0.1 mrad gets 0.3 mrad deflection and leaves the aperture (septum set at 20 mm) in one turn – as shown in Fig.4.

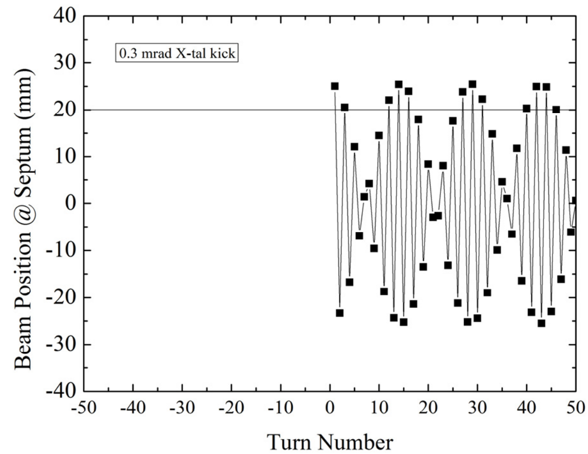

Figure 4: Horizontal oscillations induced by 0.3 mrad crystal deflection (see in text), if a septum is set at 20 mm, then the extraction takes place at the very 1st turn.

Alternatively, if the particle has not been deflected by channeling (or volume reflection) then it will experience random 0.1 mrad rms scattering every time it passes through the crystal and will get to very large amplitudes in hundred(s) turns – see Fig.5.

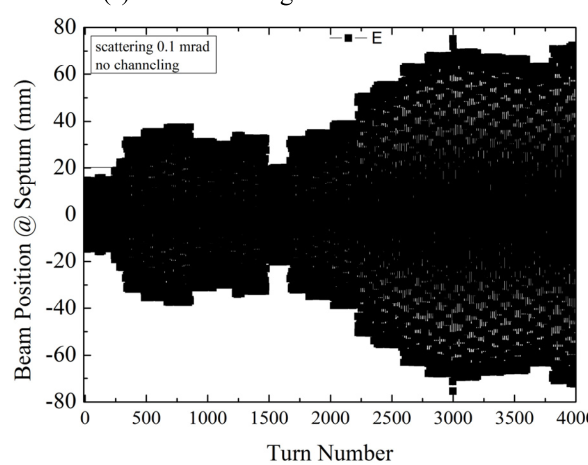

Figure 5: Betatron oscillations excited by random scattering in 0.3 mm thick piece of Si (no channelling).

Of course, in the reality, the efficiency of the channelling/volume reflection is less than 100% and one should expect a combination of these two processes. Fig. 6 shows results of simulation of horizontal motion of 10,000 macro particles with the initial betatron amplitude of 10 mm which were uniformly distributed over the

ISBN 978-3-95450-115-1

betatron phase. The modelling starts with a 0.01 mm deflection of the beam orbit onto a 0.3mm long crystal which can provide 0.3mrad deflection for any particle which enters it within +-0.1mrad incident angle. Thickness of the crystal (dimension across the beam) is 0.5mm. Fig.6 a shows that in the case of the 100% crystal extraction efficiency, all the particles get deflected beyond the septum (placed 50 m downstream the crystal at *X*=20 mm), in the interval of coordinates between 23mm and 27 mm. The whole process of extraction takes less than 30 turns as shown in Fig.6 d. If the single-turn crystal extraction efficiency is 90%, the overall extraction efficiency is still very high and close to 100% as particles get "the second" and "the third" and so on chances to get into the crystal acceptance. Of course, the ineffective passage through the crystal is accompanied by scattering. Now the spread of the amplitudes at the exit is larger (from 20 mm to 30 mm), but most importantly, only very small fraction <1% hits the septum at 20 mm – see Fig.6 b. Though more than 97% of the particles get out in 60 turns or less, there is a long tail, showing that the last exits occur after 500 turns or so – see Fig. 6 e. Finally, Figs. 6 c and 6 f demonstrate that if there is no effective channelling or volume reflection by the crystal, then most of the extracted particles either fall onto the septum or within 6 mm of it, and the whole process of the extraction by diffusion takes more than 1000 turns. The latter variant obviously cannot be considered as acceptable.

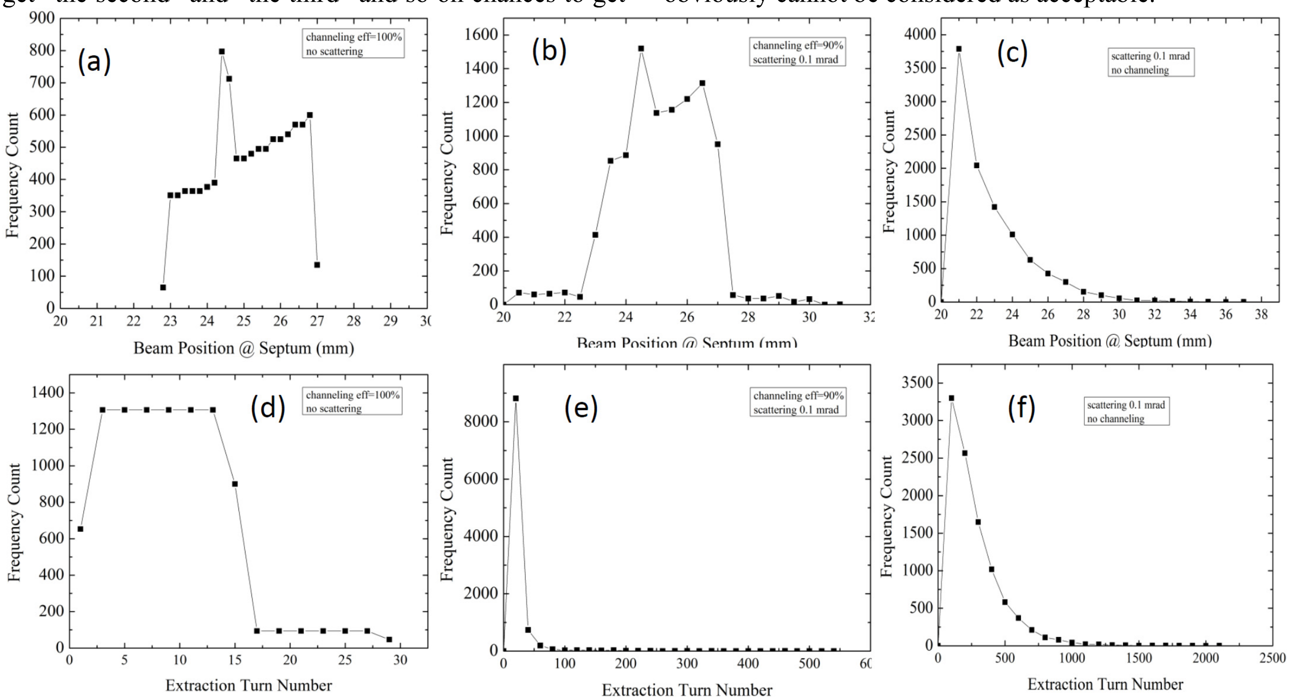

Figure 6: (a to f, left to right, top to bottom): the position of the extracted particles (top row) and speed of the extraction (bottom) under various crystal conditions (see text).

DISCUSSION AND SUMMARY

The proposed method of non-resonant slow extraction of protons by bent crystals in combination with orbit fast deflectors shows great promise in simulations. We propose to initiate an R&D program in the Fermilab 8 GeV Recycler to address the key issues of the method : a) feasibility of very short crystals – from few mm down to 0.2 mm [11]; b) their efficiency in the channelling and volume reflection regimes; c) practical aspects of the fast deflectors.

I would like to thank N.Mokhov, V.Nagaslaev, D.Wildman, A.Drozhdin, E.Prebys and R.Madrak for useful discussions on the subject of the paper.

REFERENCES

[1] D.Edwards, M.Syphers, *An Introduction to the Physics of High Energy Accelerators* (1993), pp.108-143.
[2] L.Michelotti, J.Johnsotone, Fermilab-FN-0842 (2009).
[3] V.Nagaslaev, et al., Fermilab-Conf-10-395 (2010)
[4] C.Park, et al., Proc. IEEE PAC11 (New York), p.1645.
[5] V.Biryukov,Y.Chesnokov, V.Kotov, *Crystal Chan-neling and Its Application at High Energy Accelerators* (Springer–Verlag, 1997).
[6] V.Shiltsev, et al., Proc. IPAC10 (Kyoto), p.1243.
[7] V.Zvoda, et al., Proc. IEEE PAC11 (New York), p.73.
[8] S.Belucci, V.Biryukov, PRSTAB **10**, 013501 (2007).
[9] D.Wildman, R.Madrak, FNAL *beams-doc-4121*(2011).
[10] Mu2e doc-388v1, at http://mu2e-docdb.fnal.gov/
[11] I.Yazynin, Y.Chesnokov, private communication.