DESIGN OF ACCUMULATOR AND COMPRESSOR RINGS FOR THE PROJECT-X BASED PROTON DRIVER*

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Abstract

A Muon Collider (MC) and a Neutrino Factory (NF) - which may be considered as a step towards a MC - both require a high-power (~4 MW) proton driver providing short (<1 m r.m.s. length) bunches for muon production. However, the driver repetition rates required for these two machines are different: ~15 Hz for MC and ~60 Hz for NF. This difference suggests employing two separate rings: one for accumulation of the proton beam from the Project-X linac in a few (e.g. 4) long bunches, the other for bunch compression - one by one for NF or all at a time for MC with simultaneous delivery to the target. The lattice requirements for these two rings are different: the momentum compaction factor in the accumulator ring should be large (and possibly negative) to avoid the microwave instability, while the compressor ring can be nearly isochronous in order to limit the required RF voltage and reduce the dispersion contribution to the beam size. In the present report we consider ring lattice designs which achieve these goals.

INTRODUCTION

Simulations predict that the maximum muon yield per unit beam power is achieved at about 8 GeV proton energy [1] (though the fall-off with energy is rather slow, ~15% at 24 GeV). With 8 GeV energy, a very large number of protons per pulse, $2.1{\cdot}10^{14}$, is required to achieve the goal of 4 MW average proton beam power with a 15 Hz repetition rate set for a high-luminosity Muon Collider (MC) [2]. Space-charge forces in a bunch with r.m.s. length ≤ 1 m and such intensity would be prohibitive. A solution was proposed to pack the required number of protons in a few bunches and deliver them simultaneously onto the pion production target [3].

In contrast to MC, the Neutrino Factory (NF) baseline design calls for a higher proton driver repetition rate – 60 Hz – but at the same average power of 4 MW. This suggests the proton driver configuration which resembles the one proposed for the Fermilab mu2e experiment [4]: 8 GeV beam from a linac or a Rapid Cycling Synchrotron is accumulated in a number of bunches in an Accumulator Ring (AR) at 15 Hz rep rate which are then transferred to a Compressor Ring (CR) – one a time for NF or all together for MC – for compression to ≤ 1 m r.m.s. bunch length. In the case of MC, for simultaneous delivery of all bunches from CR onto the target a special transport system called a “trombone” can be used [3].

Here we consider the basic requirements of the Accumulator and Compressor rings and propose two options for their lattices, using either FODO or Flexible Momentum Compaction (FMC) arc cells.

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BASIC PARAMETERS

We assume that the proton beam will be provided by the Fermilab Project X linacs [5]. The first stage of the project envisages a 3 GeV CW linac with bunch frequency 162.5 MHz and average H^- current upgradable to 5 mA. The most likely solution for the second stage is a pulsed 3 → 8 GeV linac. To accumulate $2.1{\cdot}10^{14}$ protons at 5 mA injection current 6.7 ms is required. To reduce the longitudinal emittance in the accumulated beam and to facilitate its compression it is possible to “pre-chop” the linac beam so that it consists of bunch trains with 10 mA average current and gaps of equal duration. The expected rms momentum spread in the H^- beam is $\sigma_p/p = 4.2{\cdot}10^{-4}$.

The ring parameters must ensure beam stability against coherent effects, most notably the longitudinal microwave instability:

$$eI_{peak}\left|\frac{Z_n}{n}\right| \le 2\pi|\eta|\beta\ pc\left(\frac{\sigma_p}{p}\right)^2 F \qquad (1)$$

where F is a form factor depending on the longitudinal distribution and the slippage factor

$$\eta = \alpha_p - \frac{1}{\gamma^2} \qquad (2)$$

For sufficiently smooth distributions $F \sim 1$ if $\eta > 0$ and can be a factor of 2 to 3 or more larger below transition ($\eta < 0$) making lattices with negative momentum compaction, $\alpha_p < 0$, particularly attractive. A large $|\eta|$ is beneficial for beam stability and it also allows some adiabatic compression in the AR by increasing the synchrotron tune. In the Compressor Ring, small $|\eta|$ reduces the required RF voltage. To avoid fast blowup due to space charge impedance the slippage factor must be negative. Instability due to the real (active) part of the impedance should not present a danger since the energy spread significantly increases in a few hundred turns.

The proposed set of basic parameters for both FMC rings is presented in Table 1. The circumference is 8×21 times the bunch spacing at 162.5 MHz so that to form four bunches in AR the linac beam may consist of trains of 21 bunches with gaps of equal length.

LATTICES

We consider two types of lattices for both rings: a FODO-cell lattice and a Flexible Momentum Compaction (FMC) lattice. In the FODO lattice α_p is determined by the focusing strength, while in the FMC lattice α_p can be varied over a wide range while keeping the phase advances fixed.

Table 1: FMC Accumulator and Compressor Parameters

Parameters	AR	CR
Circumference, m	308.23	308.23
Momentum compaction	-0.052	0.001
Slippage factor	-0.063	-0.01
RF frequency, MHz	3.87	3.87
RF voltage, kV	10	240
Synchrotron tune	$2.1{\cdot}10^{-4}$	$4.2{\cdot}10^{-4}$
Peak current, A	100	1040
Final r.m.s. bunch length, ns	29.2	3.2
Final r.m.s. energy spread	$5.2{\cdot}10^{-4}$	$6.9{\cdot}10^{-3}$
Threshold impedance, Ohm	20	$3 \rightarrow 53$
R.m.s. emittance, μm	5	5
Space charge tuneshift, h/v	0.02/0.02	0.14/0.16
Betatron tunes, h/v	7.94/6.91	6.76/8.44

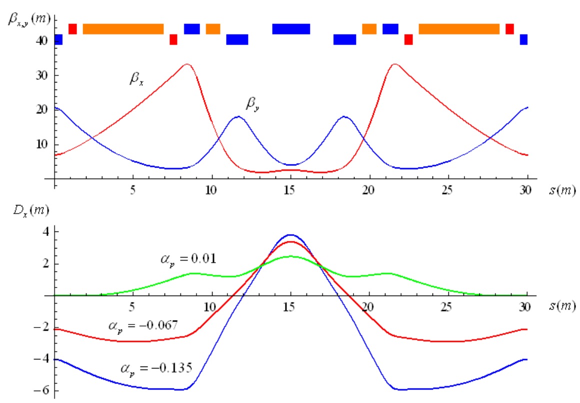

Figure 1: AR arc cell layout and optics functions. The rectangles at the top depict bends (orange), quads (blue) and sextupoles (red). α_p is varied by changing the central quad strength.

The FMC arc cell design is similar to that previously proposed for a Rapid Cycling Synchrotron [6]. The bending field is 1.9 T, quad gradients are limited by 11 T/m, 0.4 m spaces are inserted between all elements. The AR cell layout and beta functions for $\alpha_p = -0.067$ are shown in Fig. 1 (top). The phase advance per cell $\mu = 270°$ is chosen for both planes. With α_p changing from -0.135 to $+0.01$ there is little change in the β-functions and all quad gradients remain within specified limits. However, the dispersion function varies significantly (Fig. 1 bottom).

The ring includes 8 such cells and two straights for injection and extraction, optics functions in a half straight (together with the preceding arc cell) are shown in Fig. 2. At the symmetry point (right side) the beam sizes at extraction are σ_x=3.2 mm, σ_y=5.6 mm. For a $10\sigma_y$ vertical orbit deflection there the extraction kicker (shown in green) must provide just a 4 mrad angle.

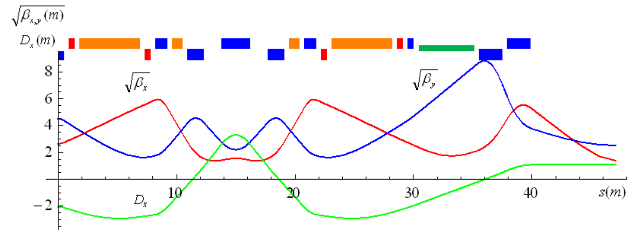

Figure 2: Optics functions in the last AR arc cell and half of straight section.

Since the energy spread in AR remains small, straight sections do not need to be dispersion-free. The systematic synchro-betatron coupling with RF can be eliminated by arranging the RF cavities in pairs separated by 3π in betatron phase, using empty spaces in the arc cells. Tracking predicts that the effect of coupling is negligible. The momentum compaction factor in the whole ring is $\alpha_p = -0.052$.

Compressor Ring

The small slippage factor and the large (final) energy spread in the CR makes the effect of α_p variation with momentum important. The FMC arc cell allows effective control of α_p' with a sextupole placed in the cell center (Fig. 3). An integrated gradient of 43 T/m is needed to change the default value of α_p'= 0.25 to -0.03, rendering η'= 0.

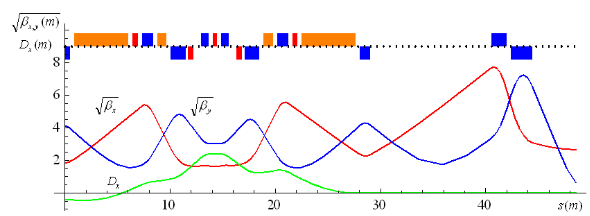

Figure 3: Optics functions in the last (irregular) CR arc cell and half of straight section.

Another difference is the relocation of the sextupoles for vertical chromaticity control closer to larger dispersion. As a result the arc cells are shorter – 28.5 m against 30 m in AR – and the straight sections are correspondingly longer, providing an ample space for kickers and RF cavities. They are dispersion-free to facilitate extraction and eliminate systematic synchro-betatron coupling if the RF cavities are placed there.

FODO lattices

FODO lattices were designed for both AR and CR. Both of these are racetrack lattices with dispersion-free straight sections. The AR lattice has 11.2m cells (72°/cell) and γ_t=4.5. The CR lattice is more demanding since its momentum compaction factor must be small enough to leave $\eta < 0$. The design shown in Fig. 4 provides $\alpha_p = 0.0079$ (γ_t=11.1) and $\eta = -0.0031$. Since the opti-

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mum RF voltage for bunch rotation is proportional to $|\eta|$, such small value of the slippage factor makes the compression process quite slow (~2000 turns), which reduces the rf voltage requirement but leaves the beam more exposed to the adverse effects of self-fields.

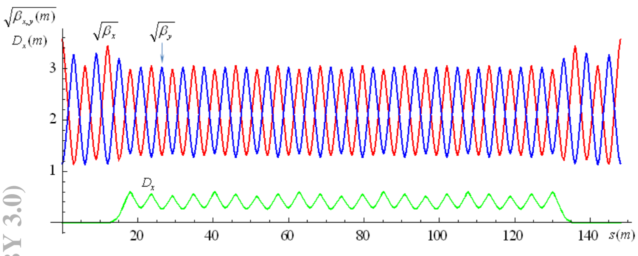

Figure 4: Optics functions in half the CR FODO lattice.

In a FODO lattice it is problematic to increase $|\eta|$ while keeping $\eta < 0$: it would require even larger number of magnets (the total number of cells in the present design is 52) and/or higher integrated strength of quadrupoles and sextupoles which is already ~ twice as large as the FMC lattice. On the other hand, the beam sizes in the arcs are ~40% smaller making it possible to achieve the required gradients with conventional magnets. Also, in a FODO lattice with compensated chromaticity, the α_p variation with momentum is naturally quite small (α_p'=0.015), so no special correction is required.

LONGITUDINAL DYNAMICS

As mentioned earlier we assume the injected beam to consist of trains of 21 bunches with gaps of equal length. The total duration of the beam accumulation is 6.7 ms. With a 60 Hz NF operation this leaves up to 10 ms before the first bunch transfer to CR which can be used for adiabatic compression.

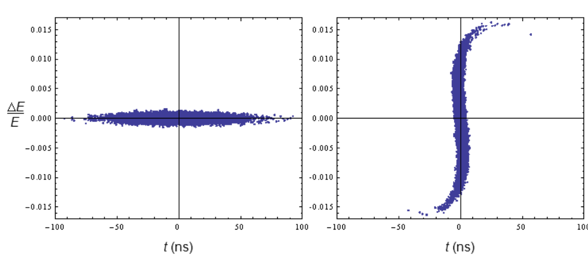

Figure 5: Longitudinal bunch rotation in the CR.

If the RF field in CR were linear, the bunch rotation would be described by the formula:

$$\sigma_t^{(final)} = \frac{C}{c}\sqrt{\frac{|\eta|E}{2\pi\, h\, eV}}\frac{\sigma_p^{(initial)}}{p} \qquad (3)$$

where C is the circumference and V is the RF amplitude, which shows that the preliminary compression in AR increases the final bunch length since $\sigma_p^{(\mathrm{initial})} \sim 1/\sigma_t^{(\mathrm{initial})}$. However, a larger $\sigma_p^{(\mathrm{initial})}$ improves instability thresholds and the smaller $\sigma_{t.initial}$ can be helpful in reducing the RF field nonlinearity.. The optimum ratio of adiabatic compression in AR and bunch rotation in CR should be studied in detailed simulations. Here we assume that RF voltage in AR increases linearly from 5 kV at the start of accumulation to 10 kV in 16 ms. The resulting longitudinal phase space distribution is shown in Fig. 5 and the r.m.s. values are cited in Table 1.

The final distribution after 646 turn bunch rotation in CR is shown in Fig. 5. The nonlinear "arms" significantly increase the final bunch length. The longitudinal phase space dilution as well as the required RF voltage can be reduced with the addition of higher harmonic RF.

The values of space-charge tune shifts and the threshold values of $|Z_n|/n$ are computed with simulated distributions (and F =2) and displayed in Table 1. As noted before, the initially small threshold value of $|Z_n|/n$ in CR should not present a danger since it rapidly increases during bunch rotation to ≈ 53 Ohms.

SUMMARY

We have shown that a two-ring scheme opens the way for using the upgrade Project-X beam to meet the difficult requirements for the Muon Collider and Neutrino Factory proton driver. Both FODO and FMC lattice designs enable the stated goals using warm iron magnets. The important issues of coherent beam instabilities and beam loading, as well as beam stability with magnet errors, will be addressed in the future. We also will consider scenarios in which the accumulation and compression may be obtained in the same ring.

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