Muon Collider Note 209

Bunch Stacking Scheme for the Higgs Factory based on the Neutrino Factory Design

Yasuo Fukui, Alpher Garren, David Cline, Ping He (UCLA)
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Abstract

A scheme for a Higgs Factory is designed to generate a high intensity μ^+ bunch and μ^- bunch in order to create the high luminosity in a collider ring. Three modification need to be done to the Neutrino Factory Feasibility Study I(Fermilab) and II(BNL), (1) combine multiple primary proton bunches into one, (2) add a 6 dimensional ionization cooling ring, and (3) add two rings to stack muon mini-bunches transversely.

1 Introduction

The Higgs Factory will be the first $\mu^+\mu^-$ collider to be built. Compared to a Neutrino Factory where muons decay in a straight section of a storage ring, the Higgs Factory requires more 6 dimensional phase space cooling of the muon beam by a factor of 10^{4-5}. The Feasibility Studies I(Fermilab) and II(BNL) showed that those designs are feasible to build a neutrino Factory [3, 4].

In order to create the high luminosity in a collider, single high intensity μ^+/μ^- beam bunch will be transported into a collider where the many muon mini-bunch trains in the Neutrino Factory has to be combined into a single bunch.

The $\mu^+\mu^-$ collider has been under designing for several year, and many reports have been made by the Neutrino Factory and the Muon Collider Collaboration. [1, 2] The on-going BNL targetry experiment E951 will reveal the feasibility of the proposed mercury jet target with the input proton beam power of multi MW. Several R&D efforts on the components of the muon ionization cooling, 201 MHz and 805 MHz RF cavities, super conducting solenoid coils, and induction linac modules. Design of a cooling demonstration experiment is going on at Fermilab with the model of a cooling channel in a ring.

2 Goals

Table 1 shows the parameters of the general $\mu^+\mu^-$ colliders including a Higgs Factory which was given in Reference [2].

6 dimensional normalized emittance is 1.7 $\times 10^{-10}$ πmm-mrad and the RMS beam length is 9.4 cm, RMS $\Delta p/p$ is 0.01 % in a Higgs Factory with the center of mass energy of 100 GeV. The proton beam power is 4 MW, and the luminosity is 2.2 $\times$ 10^{31} $cm^{-2}s^{-1}$.

3 Steps from a Neutrino Factory to a Higgs factory

3.1 Proton Bunches

The requirement of the proton bunches is that a single proton bunch with the maximum available intensity hits target(s) within the γ times the life time of the muons so that single μ^+/μ^- bunch can be collided in a collider ring. Reducing the number of proton bunches in the proton driver will reduce the effort to combine the muon long bunches later on. In case of the Neutrino Factory, the number of primary proton bunches was not restricted, because the muons can be injected into the decay storage ring any time, and the only issue was the total number of the decays of the muons in the straight section.

The high power proton driver design is given in References [1, 2]. The primary proton power is estimated to be around 4 MW. Using the liquid metal target is the probable option to handle the severe energy deposition inside the target.

3.2 Ring Cooler

In order to add 6 dimensional phase space cooling to that in the neutrino Factory design, it is proposed to use a 6 dimensional ionization cooling ring which consists of cooling lattices, bending magnets, and wedge absorbers. The ionization cooling lattice is made of super conducting solenoid, RF cavities, and liquid Hydrogen absorber, The wedge absorbers are placed in high dispersion area so that $\Delta p/p$ in the longitudinal phase space is exchanged into the transverse phase space. The circumference of the ring is around 35 m. Depending on the initial normalized emittance of the muons, the cooling ring is expected to generate the 6 dimensional phase space cooling factor of 30-100. [5]

Figure 1 shows a schematic diagram of the components of the Higgs Factory. The additional cooling ring is placed after the phase rotation channel and bunching section and before the linear cooling channel.

3.3 Bunch Stacking Rings

Stacking muon mini-bunches coming out of the 201 MHz RF on top of each other naturally do the emittance exchange from the longitudinal phase space to the transverse phase space, besides the fact that getting a single muon bunch is the absolute must in the Higgs Factory.

Emittance exchange scheme by using transverse bunch stacking was first proposed by C. H. Kim [6]. The idea was then tested in a simulation by using a solenoid as a delay channel with pulse-by-pulse transverse bending which change the path length of beam bunches in the solenoid. Figure 2 shows a schematic diagram of the transverse bunch stacking in solenoid delay channels and in a bunch stacking ring. Figure 3 shows transverse(left plots) and longitudinal(right plots) phase space distribution before and after getting through the bunch stacking solenoid channel which was simulated by using ICOOL simulation code with a set of beam bunch parameters. In the Neutrino factory design, around 100 muon mini-bunches are created through the bunching channel and the ionization cooling channel with 201 MHz RF cavities.

In using one of the transverse bunch stacking model, a numerical simulation was performed with a set of muon beam parameters. Figure 3 shows the transverse and longitudinal phase space of 10 muon mini-bunches before and after going through bunch by bunch delay channels inside a straight solenoid channel. Muon mini-bunches are simulated to have one 2π phase Larmor turn by using the ICOOL simulation code. [7] The transverse phase space, in position and angle, was enlarged and the longitudinal phase space in time was made smaller in this simulation.

We propose the transverse bunch stacking scheme by using an 1 GeV 320 m ring with Lithium lens for the transverse phase space cooling, which contain all the 100 muon mini-bunches. by using a Fast Pulsed kicker magnet/EM filed, we then inject each mini bunches into an 1 GeV 35 m smaller ring with Lithium lens element for the transverse cooling to stack the mini-bunches top on top each other so that we can get a single muon bunch. Figure 4 top plot shows the β_x, β_y, η, and the lattice component in the 320 m storage ring where a muon long bunch is contained with the 201 MHz RF structure. Figure 4 bottom plot shows the β_x, β_y, η, and the lattice component in the 35 m storage ring where a muon single bunch is generated which then transfered in to the subsequent accelerator section. SYNCH simulation code was used to design the synchrotron rings with 320 m and 35 m circumferences and to analyze beam orbits in those rings. [9] Although the exact beam injection/extraction have not been computer-simulated, injecting muon mini-bunches from the 320 m ring into the 35 m ring is a challenging task. [8]

Table 1: Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year $= 10^7$ s.

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch		2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch		2×10^{12}	2×10^{12}		4×10^{12}	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circum.	m	6000	1000		350	
Ave bending field	T	5.2	4.7		3	
Rms $\Delta p/p$	%	0.16	0.14	0.12	0.01	0.003
6-D $\epsilon_{6,N}$	$(\pi\mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n	π mm-mrad	50	50	85	195	290
β^*	cm	0.3	2.6	4.1	9.4	14.1
σ_z	cm	0.3	2.6	4.1	9.4	14.1
σ_r spot	μm	3.2	26	86	196	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1	2.1
Tune shift		0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)		785	700	450	450	450
Luminosity	cm^{-2}s^{-1}	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year				1.9×10^3	4×10^3	3.9×10^3

4 Conclusion

A scheme for a Higgs Factory has been designed by applying three major upgrades in the Neutrino Factory designs in the Feasibility studies I and II. The first is to use a single high intensity primary proton beams which are generated in a 4 MW proton driver. The second is to add the 6 dimensional ionization cooling ring in between the phase rotation/bunching channel and the straight ionization cooling channel. The third is the transverse muon mini-bunch stacking by using a 320m and 35 m synchrotron rings with Lithium lens for the transverse ionization cooling. A high intensity muon bunch will be generated there which then is accelerated and injected into a Higgs Collider storage ring. We need more detailed numerical simulation of the beam from the target to the collision point in the Higgs collider, where the goals are to obtain the high luminosity in the Higgs Factory.

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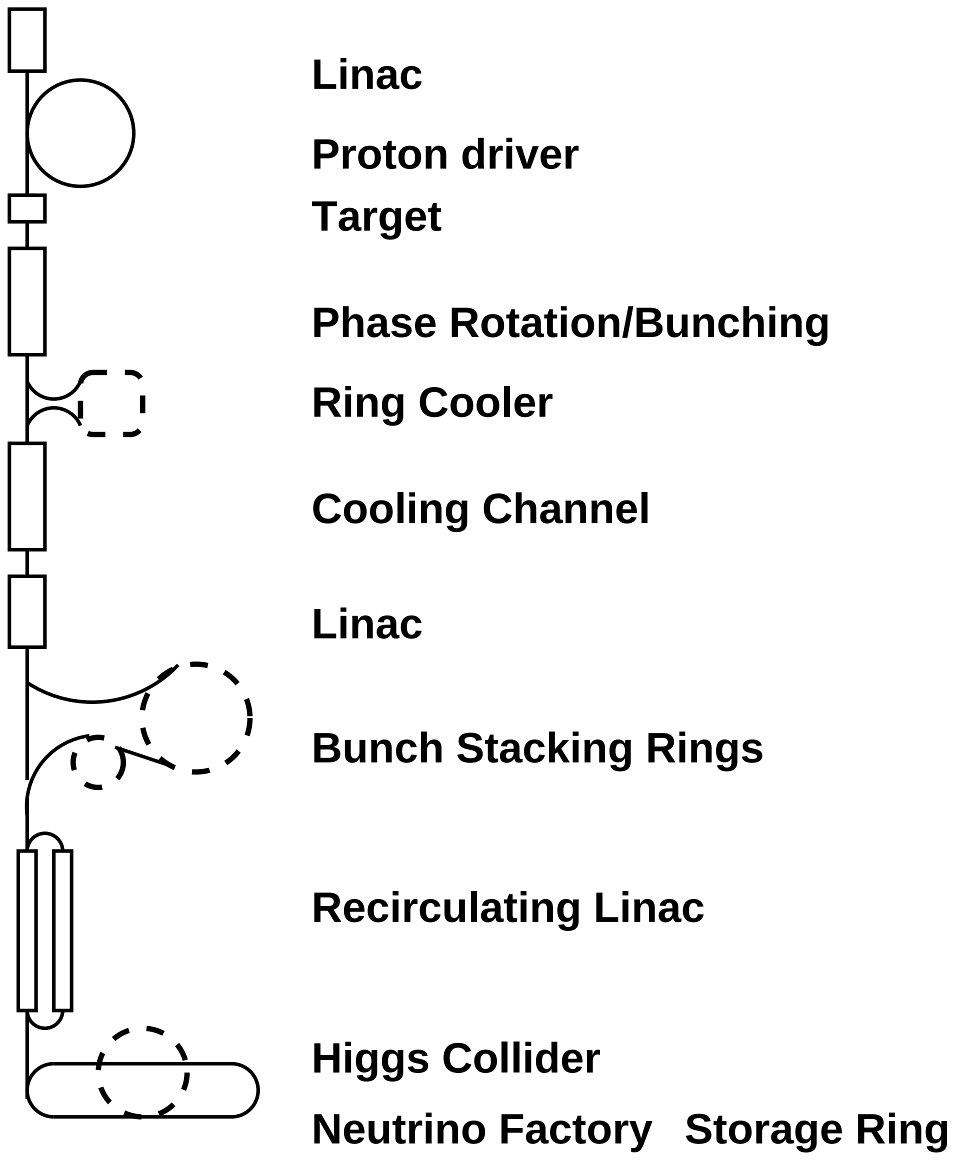

Figure 1: Schematic Diagram of the Higgs Factory and the Neutrino Factory

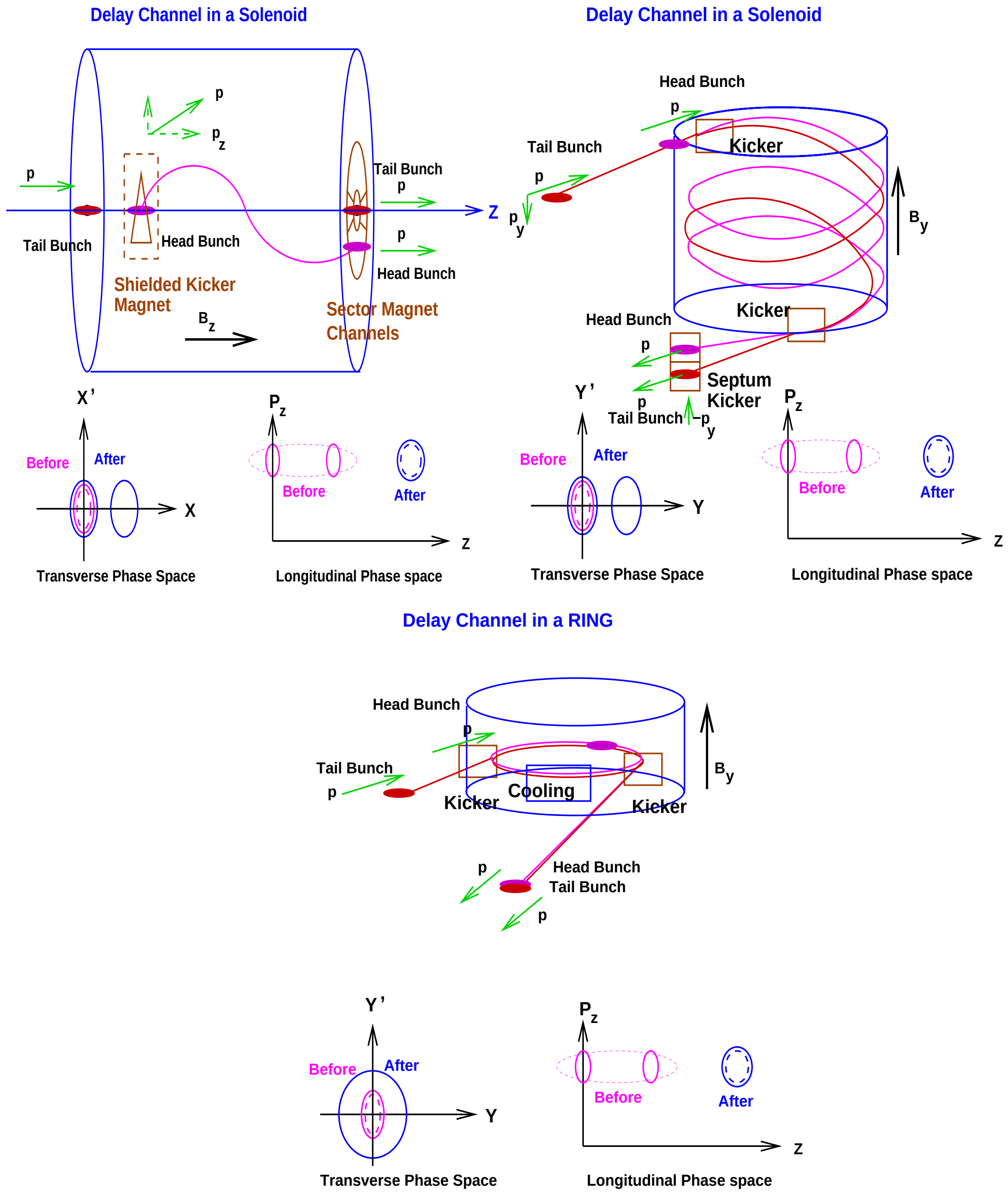

Figure 2: Schematic Diagram of the transverse bunch stacking in solenoid delay channels and in a bunch stacking ring

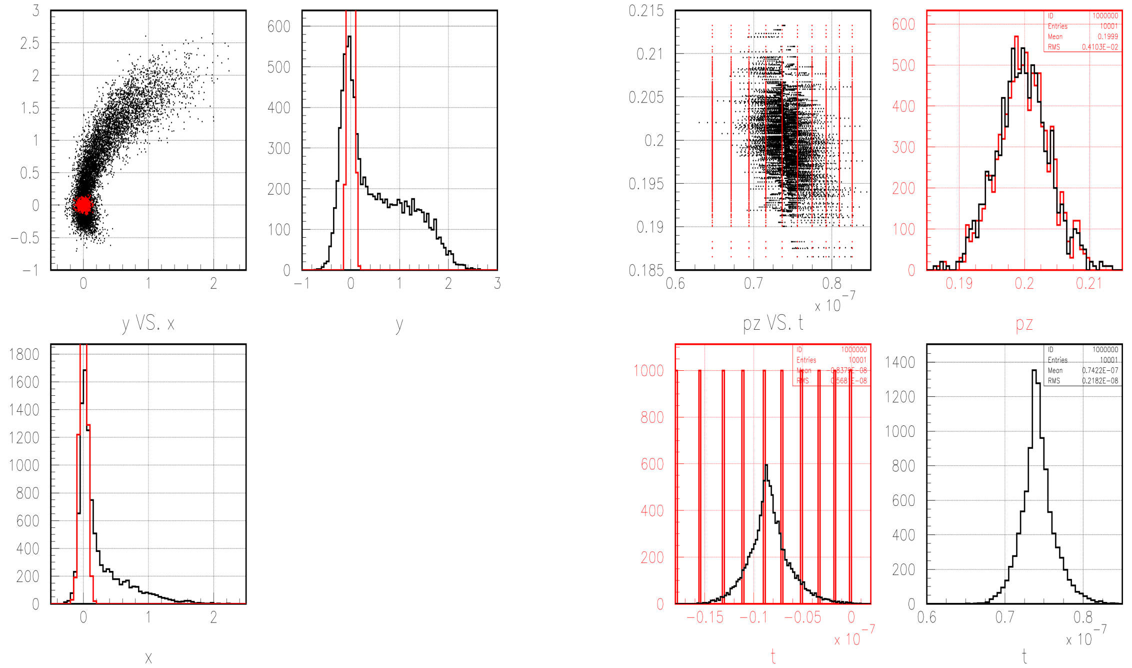

Figure 3: Transverse and longitudinal phase space (ICOOL simulation) on 10 bunch stacking

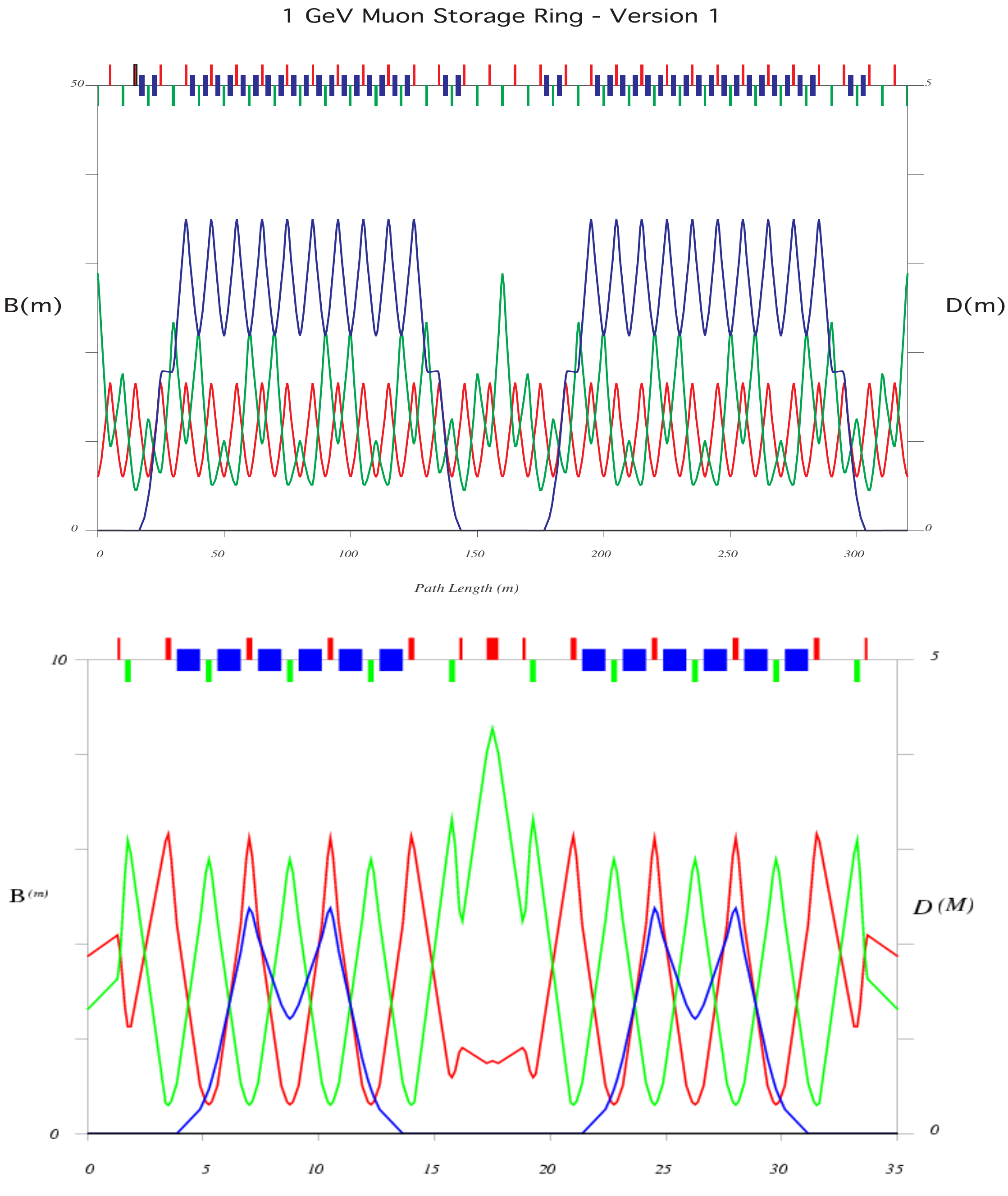

Figure 4: β_x, β_y, η, and the lattice component in 320 m ring(top) and in the 35 m ring(bottom)