MAP Note 4304

Estimate of the Parameters for the Injection System into the Solenoid/Dipole Ring Cooler and the Heating of the Cooling Absorbers

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Abstract

We have recently finished a paper (to be published in NIMA) on the 6D cooling in the Solenoid/Dipole Ring. We now study the injection into this ring and the heating on the cooling wedges.

Contents

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1. Overview of the ring cooler performance

Six dimensional cooling of large emittance μ^+ and μ^- beams is required in order to obtain the desired luminosity for a muon collider. We propose to use a ring cooler that employs both dipoles and solenoids with the additional requirement that the arcs of the ring be achromatic. In Fig.1 to Fig. 6 and Table 1 to table 2, we describe the lattice and the beam dynamics of the proposed ring, and demonstrate that the lattice gives substantial cooling in all 6 phase space dimensions [1].

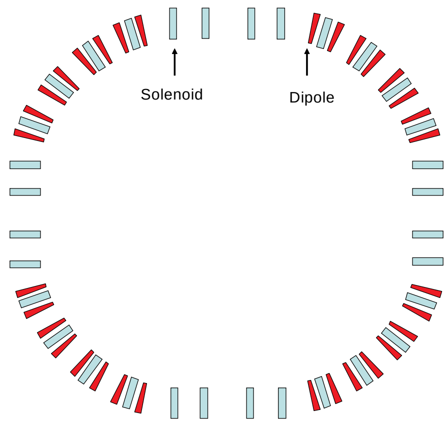


Fig. 1. Schematic drawing of the proposed four-sided ring utilizing dipoles and solenoids.

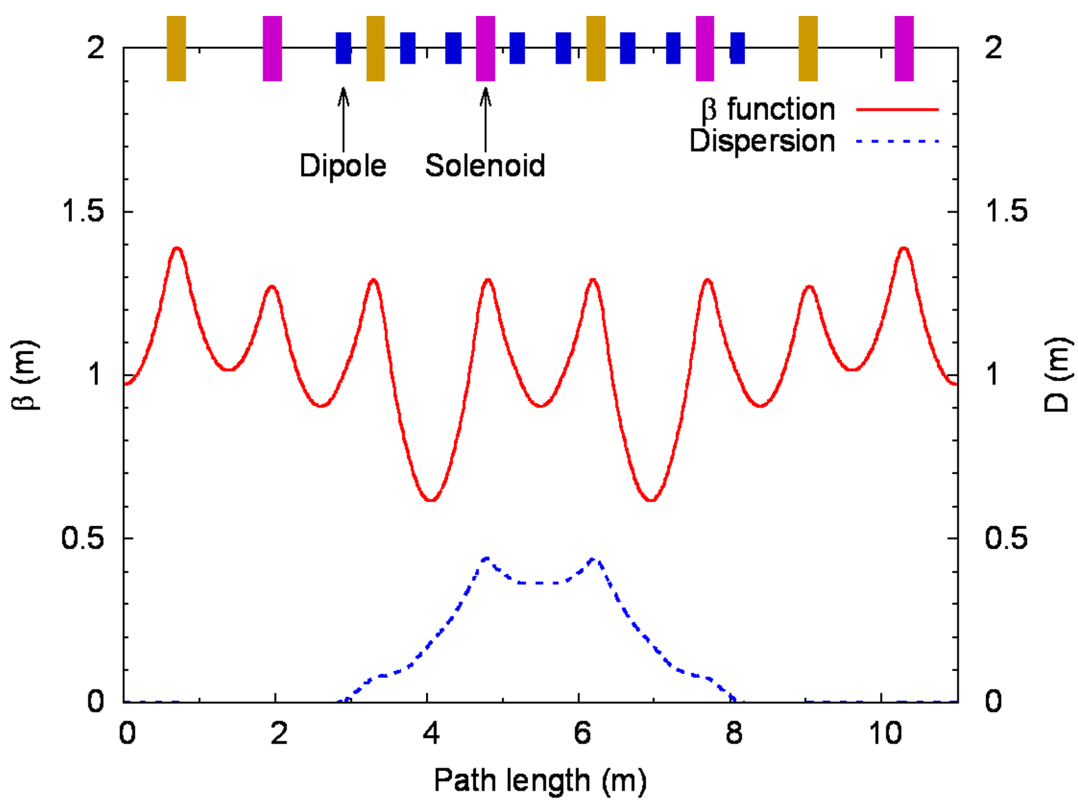


Fig. 2. Beta function and dispersion of the four-sided ring.

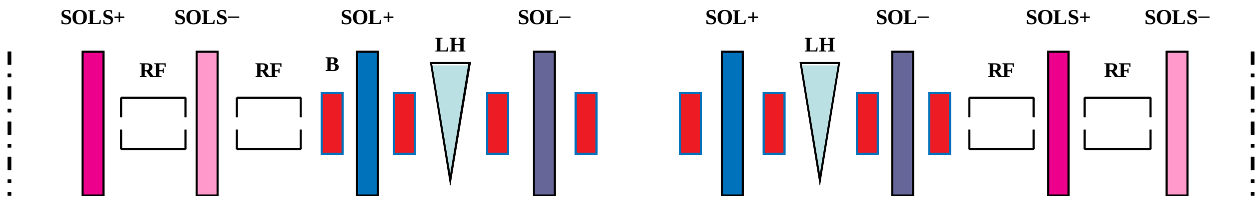


Fig. 3. Schematic drawing of the ring quadrant in the four-sided and achromatic ring cooler.

Table 1 Parameters of the four-sided and achromatic ring cooler

Momentum	220 MeV/c
Superperiods	4
Number of dipoles	32
Number of straight solenoids	16
Number of arc solenoids	16
Arc length	6 m
Straight section length	5 m
Dipole length & field	0.2 m, 0.72045 T
Dipole bend & edge angles	11.25^{O}, 2.8125^{O}
Arc solenoid length & field	0.25 m, 3.38290 T
Straight section solenoid length & field	0.25 m, 2.91555 T
Superperiod length & xytunes	11 m, 1.75
Circumference	44 m

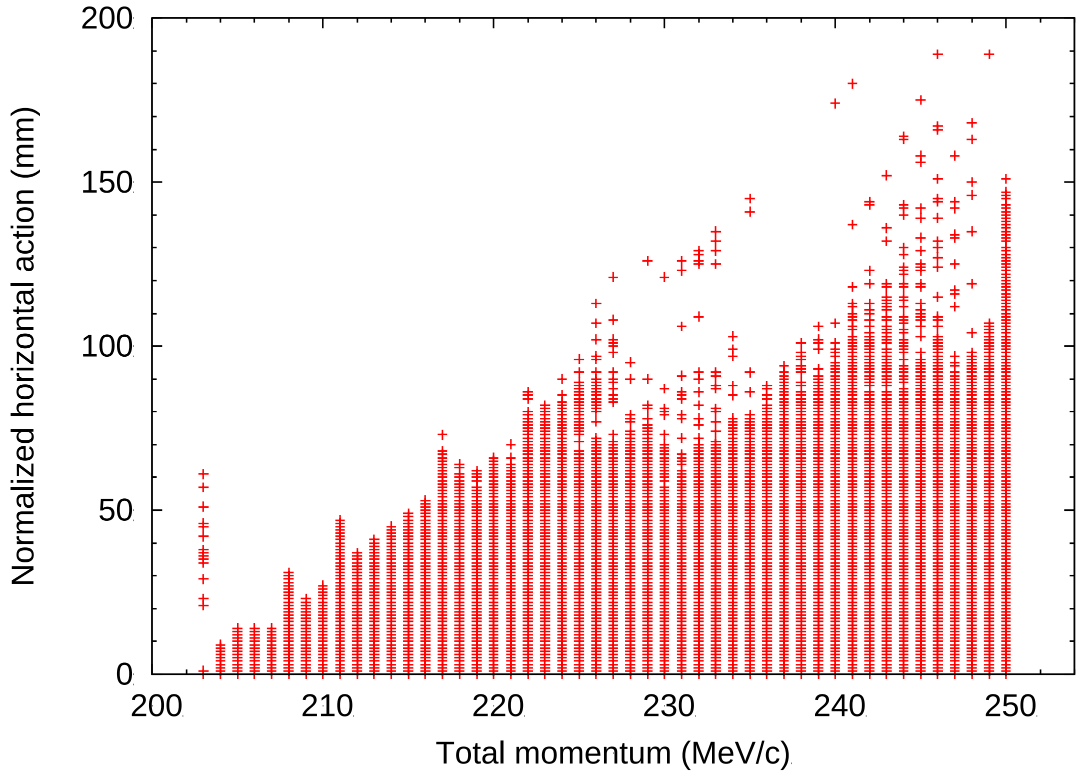


Fig. 4. Dynamic aperture for the four-sided ring cooler at working momentum of 220MeV/c. There is no dynamic aperture below 201 MeV/c or above 250 MeV/c due to integer and half-integer stopbands, respectively, arising from the dependence of the tune on momentum.

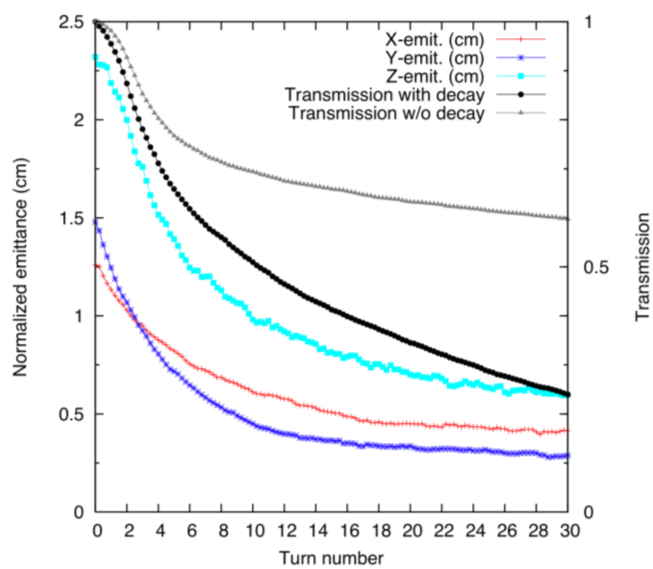


Fig. 5. Beam emittance and transmission as a function of full ring turns.

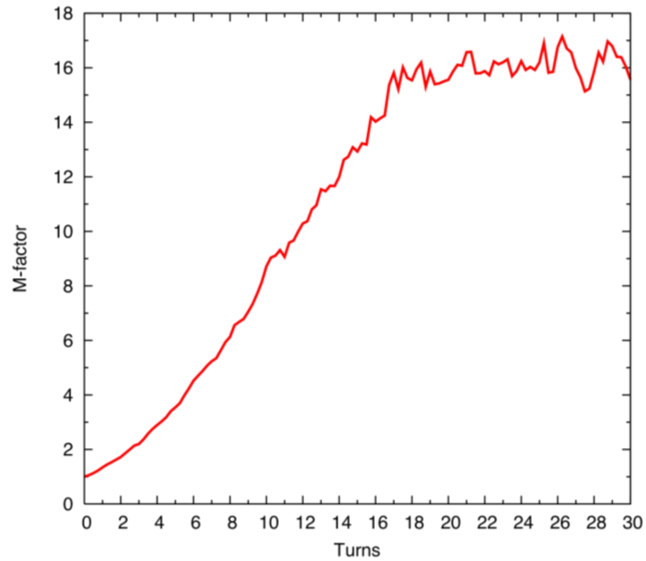


Fig. 6. The merit factor with muon decay considered.

Table 2 Beam parameters vs. number of turns

Number of turns	0	15
Normalized horizontal emittance (cm)	1.26	0.51
Normalized vertical emittance (cm)	1.48	0.36
Normalized longitudinal emittance (cm)	2.32	0.81
Transmission (%) w/o decay	100	65.9
Transmission (%) with decay	100	41.3

2. The concept of the injection into the cooling ring using a superconducting flux exclusion pipe

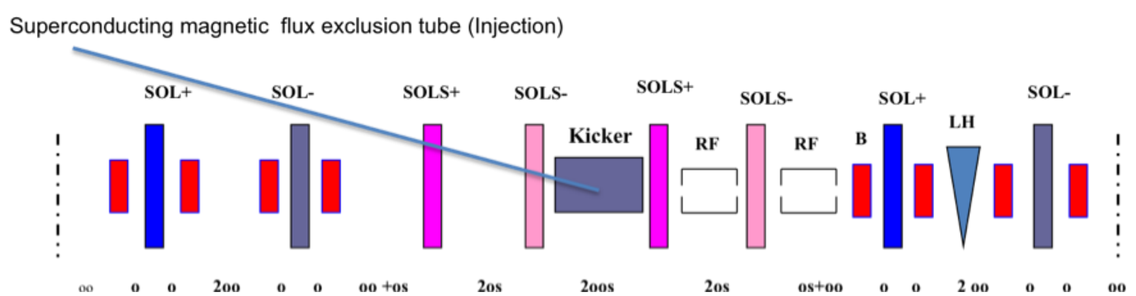


Fig. 7. Schematic diagram of injection system with superconducting flux pipe.

The biggest challenges in our Dipole/Solenoid ring cooler and the similar RFOFO cooling ring [2] have been injection and extraction. Because of little space in the basic lattice cell, an extremely powerful kicker is expected. Our proposed ring has a long straight section of 0.9 m in its cell structure (The length of solenoids in straight section is modified from 0.25 m to 0.5 m for less hard edge focusing to the beam), it is still not enough to separate the injected beam having magnetic rigidity of 0.73 Tm away from the cooling orbit in single straight section that a kicker is located. Therefore, the injected beam has to go through one or more solenoids before it can be merged into the closing orbit. We must also insert a device to create a field-free path inside those solenoids that the beam will go through before merging.

In the 1970s SLAC built a superconducting flux exclusion pipe, which is being used to create a field-free path through a transverse magnetic field of 1.5 T in an experiment at SLAC. The flux exclusion tube itself is made of Nb3Sn tape bonded with lead-tin solder to form a rigid tube of laminated superconducting material, approximately four meters long and 6 to 25 mm in diameter. The transverse magnetic field shielded exceeds 1.5 T [3].

In our injection system, we can use this idea with a superconducting flux exclusion pipe to make the beam go through the solenoids and using one or more induction kickers to merge the beam into the cooling orbit.

3. The parameters of the kicker system

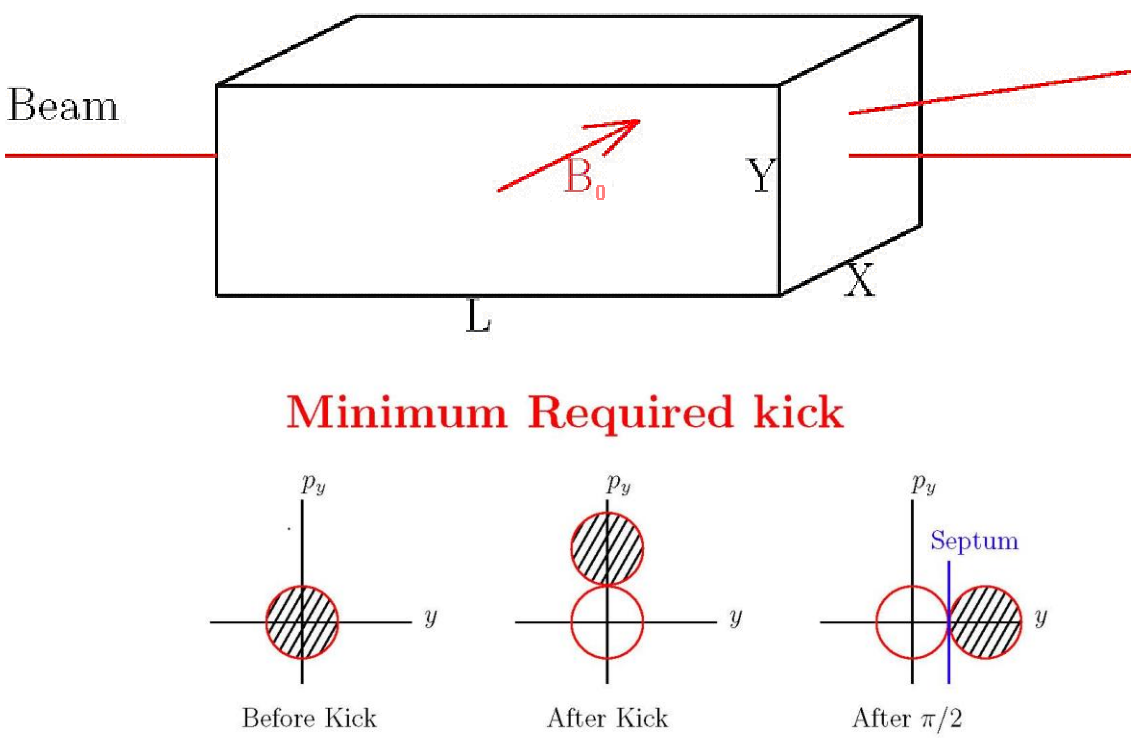


Fig. 8. Schematic diagram for estimation of the kicker system [4].

Consider a kicker with horizontal field B_0, length L, height Y, and depth X (see Fig. 8) and define f_Φ so that the total flux $\Phi=f_\Phi B_0 LY$ to allow for leakage flux, and $f\mu$ so that $\int Bdl/\mu=f_\mu B_0 X$ to allow for finite μ's in the flux return. With the transverse twiss parameter in the kick direction $\beta_\perp$ (assumed equal in x and y), relativistic parameter $\beta\gamma$, normalized emittance ε_n (also assumed equal in x and y), the half acceptances in sigma's

4.

f_σ, the muon mass m_μ in Volts, the velocity of light c, the field rise time t_{rise}, we have the formulae below to determine the transverse dimensions of X and Y, strength of kick, flux, current, and the voltage required to change the field in the rise time for the kicker system needed 90 degrees away in betatron phase to make the beam follow the central orbit [4]:

$$\Delta p_y = B_x L c = m_\mu 2 f_\sigma \sqrt{\frac{\varepsilon_n \beta\gamma}{\beta_\perp}}$$

$$X = 2 f_\sigma \sqrt{\frac{\varepsilon_n \beta_\perp}{\beta\gamma}}$$

$$\frac{Y}{X} \approx (1 + \frac{L}{2\beta_\perp})$$

$$\Phi = f_\Phi B_0 L Y$$

$$I = \frac{f_\mu B_0 X}{\mu_0} = \frac{f_\mu 4 f_\sigma^2 m_\mu}{\mu_0 c} \frac{\varepsilon_n}{L}$$

$$V = \frac{\Phi}{t_{rise}} = \frac{f_\Phi B_0 Y L}{t_{rise}} = \frac{f_\Phi 4 f_\sigma^2 m_\mu R}{c} \frac{\varepsilon_n}{t_{rise}}$$

Table 3 lists our calculated results. In the table, we consider the initial normalized emittanc of 12.4 mm, momentum of 220 MeV/c and beta function of 1.2 m. In addition, the rotation time in each turn (circumference of 44 m) is about 163 nsec and this must be divided between the length of bunch train and the rise or fall time of the kicker pulse. Because there is a bunch train of 12 muon bunches with about 5 nsec (201.25 MHz) bunch spacing during each injection/extraction, the length of bunch train is then about 55 nsec. Therefore, we set the field rise time to be 108 nsec.

Table 3 The parameters of the kicker system (based on 3 sigma acceptance)

Name	Unit	Value
Momentum	MeV/c	220
Normalized emittance	π mm	12.4/π ≈ 4
Beta function	m	1.2
fΦ/ fμ/ fσ		1.05/1.05/3
Transverse dimension (X)	m	0.286
Transverse dimension (Y)	m	0.382
Length of magnet	m	0.80
Field	T	0.22
Flux	W	0.07
Field rise time	ns	108
Current	kA	52
Voltage	kV	645

4.

The heating in the liquid hydrogen absorber

Using a ring for ionization cooling causes the beam bunches to pass through a given absorber many times. This results in the thermal load on the absorber in a ring being much larger than for the same absorber used in a linear channel. Consider the absorber material is liquid hydrogen (LH_2). The density of LH_2 is approximately 0.071 g/cm^3. The energy loss, as given by the Bethe-Bloch formula with a mean excitation energy of 21.9 eV, is 4.6 MeV*cm^2/g. The muons lose 6.2 MeV in the LH_2 absorber with length of 19 cm (or energy loss rate of 0.32 MeV/cm). Consider the example shown in Table 4, which uses a 1 MW beam with similar parameters to FS2 [4]. We estimate the maximum power dissipation per absorber to be about 300 W, dominated by the ionization energy loss of the muons.

Table 4 Absorber heating example

Muons/bunch	$2*10^{12}$
Bunch rep. rate (Hz)	12
Absorber length (cm	19
Energy deposit/bunch (J)	24
Average beam radius (cm)	4
Temperature rise/bunch (^{0}C)	0.08
Average power dissipated (kW)	0.288

5. Simulation of injection through the flux pipe

First, we study the behavior of a single muon particle in the long straight section of our four-sided ring for extraction [5]. As shown in Fig. 9, we increase the length of solenoids in the straight section of original lattice in Fig. 1 from 0.25 m to 0.5 m. This will keep the circumference and the 6D cooling behavior no change. But it can reduce the hard edge focusing of solenoids and make the larger deflected beam by the kicker go through this solenoid without being lost. In Fig. 10, we see there is no any separation between the particle and circulating (cooling) orbit in front of the first solenoid of Sol1 if only one kicker (K1) is used and its strength is varied from 0.1 T to 0.6T, We can have a separation in the 0.4, 0.5 and 0.6T case in front of the second solenoid of Sol2. In addition, we see the particles in these cases will go into the closing orbit again downstream of second solenoid of Sol2 due to its focusing. To extract the particle, we must create enough separation just in front of the Sol2 and insert a device to create a field-free path inside the Sol2 to let the beam go through. We show this scheme in the case that the second of K2 (0.5T) are used at the same time to obtain more separation in front of the Sol2. By turning off Sol2, we see the particle will separate further inside and downstream of Slo2. Moreover, if an extraction beam is taken to replace the single particle in simulation and we assume it has the same size with the circulating beam, we see the extracted beam size can’t be more than 60/2=30 cm if we want to separate them in front of the Sol2.

Second, we simulate the real beam, not single particle, for extraction. This beam comes from our previous 6D cooling study with normalized horizontal emittance of 1.26 cm and vertical emittance of 1.48 cm and its plot of X-Y and Px-Py at the beginning of first straight section before the K1 is shown in Fig. 11. Our simulation (see Fig. 12) shows we can't obtain necessary separation in front of the Sol2 if this entire initial beam is launched. In our lattice, a 90 degrees in betatron phase is already designed for some point in the straight section in front of the Sol2 relative to the middle point of the kicker.

We found the high horizontial momentum is harmful for the separation between the extracted beam and circulating orbit. By limiting the Px to 0.03 GeV/c to pick out the remaining 85% from the entire initial beam, we found a clear separation between this beam and the circulating orbit. Fig. 13 show this simulating result and we see this selected beam can be tracked and arrive at the location in 100% just before the second solenoid with a clear separation for inserting the flux tube. By the way, we found the strength of 1st kicker (K1) can be neither too high nor too low. If too low, the deflection is not enough for separation in the following straight section. If too high, the solenoids will bring some beam to center axis in negative slope in the following straight section. Our best value of K1 and K2 in the beam case is around 0.28 T and 0.65T, respectively.

Because a solenoid will rotate the median plane and give the beam a tilt, the r-z plot in Fig. 13 can't exactly reflect the real beam separation between the injected/extracted beam and closed orbit. We must use x-y plot to directly see if the beam is separated or not in space. Fig. 14 is a x-y plot at the end of K2. We see the beam has already enough separation using only strength of 0.3 T for each of K1 and K2.

In conclusion, we have simulated the extraction process with both single particle and the beam. We find two kickers and a superconducting flux exclusion tube are required in our extraction system. At this stage, our simulation shows a clear separation can be created in front of the Sol2 between the extracted beam from 85% of the entire initial beam for 6D cooling and the circulating orbit. The injection is exactly a reverse of extraction process. So we can envision the beam can be injected from the right to left inside this flux exclusion tube, go through the Sol2 with field-free path and then merged into the cooling orbit utilizing two kickers.

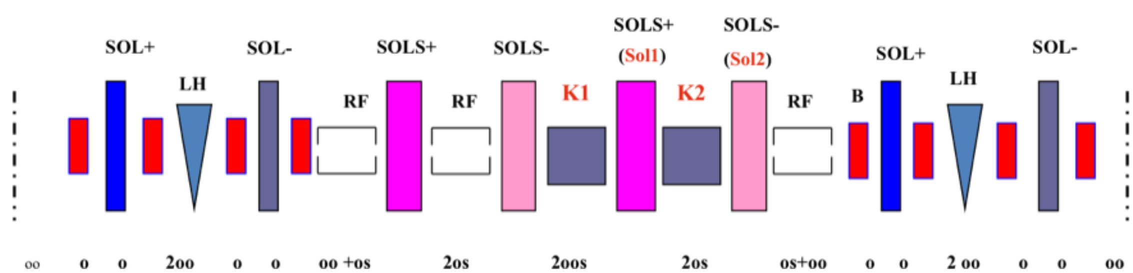
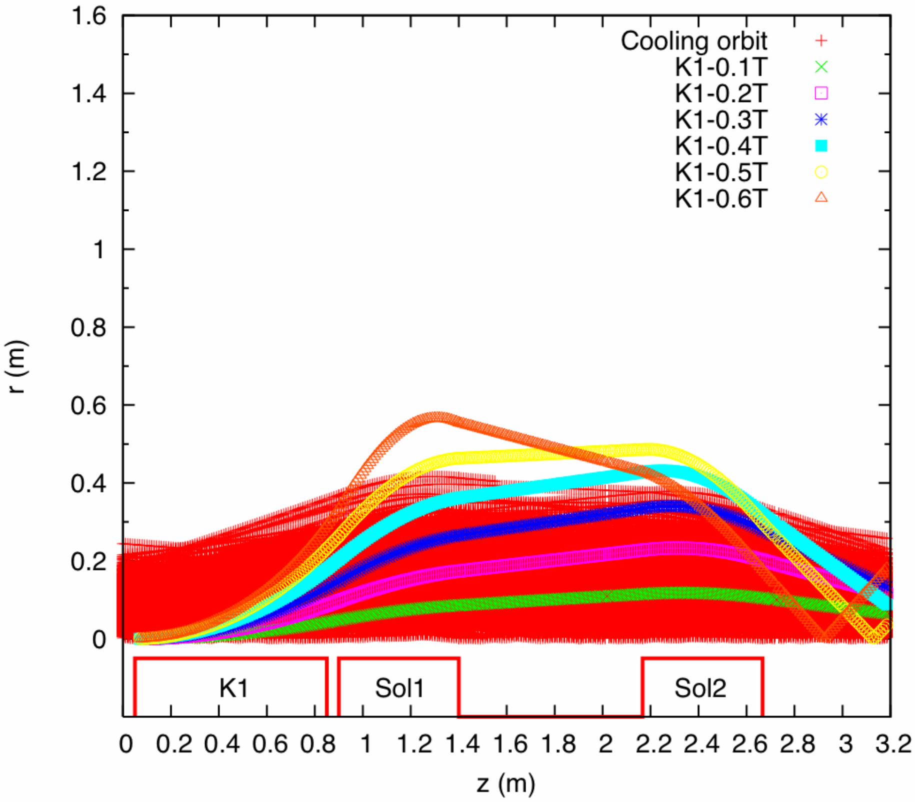


Fig. 9. Layout of K1, K2, Sol1 and Sol2 for injection/extraction (Modified lattice with 0.5m of solenoids in straight section).



Cooling orbit
K1-0.1T
K1-0.2T
K1-0.3T
K1-0.4T
K1-0.5T
K1-0.6T
r (m)
z (m)
K1
Sol1
Sol2

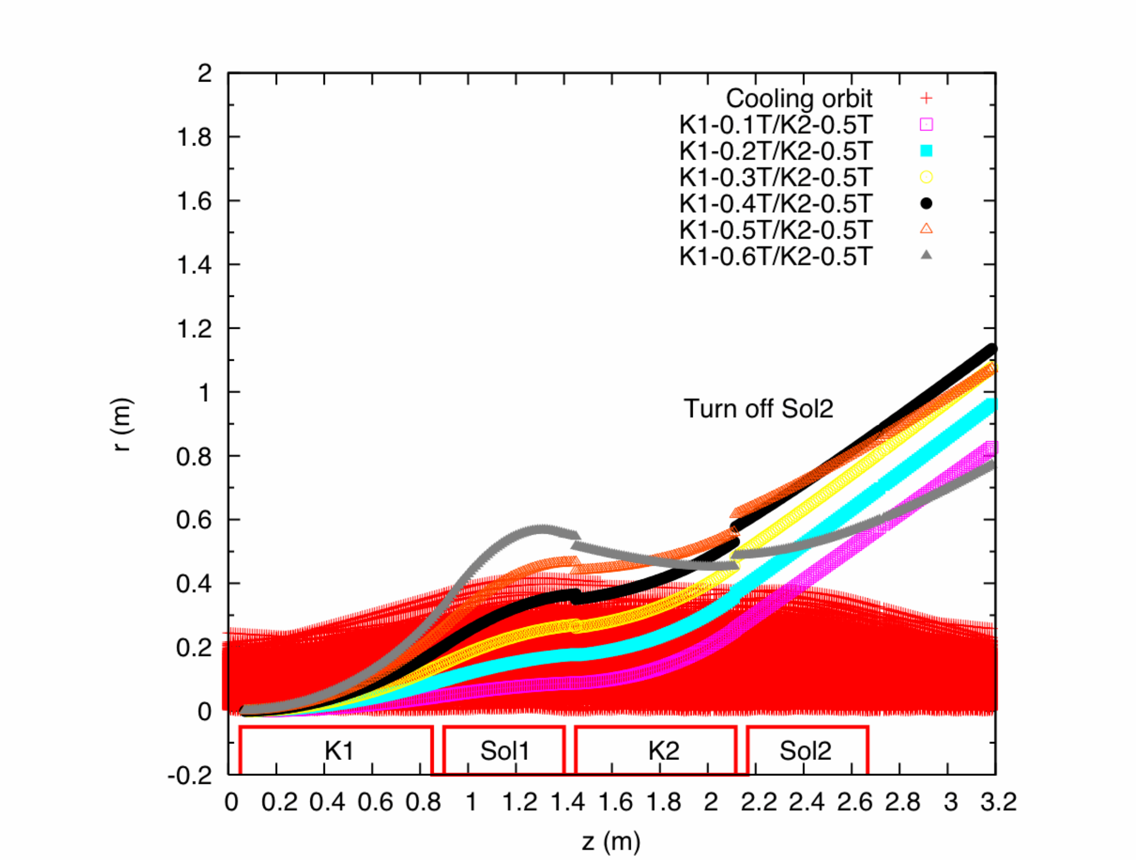
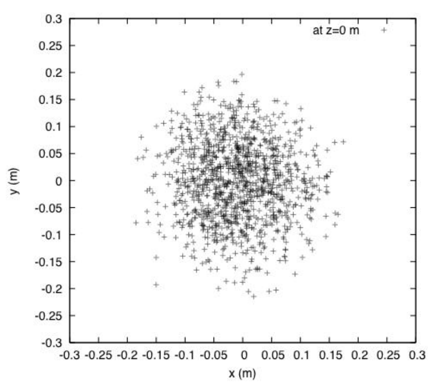


Fig. 10. Simulation of single particle for injection/extraction with only K1 used (top) and both K1 and K2 used (bottom) (using flux exclusion tube to create a field free region inside the Sol2 is equivalent to turn off sol2 here).



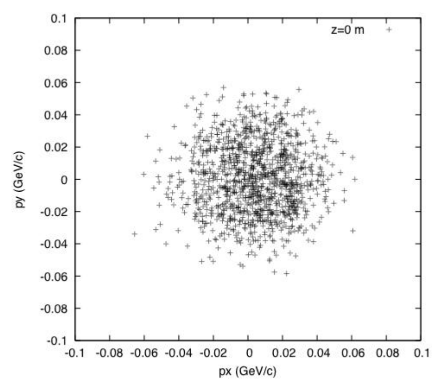


Fig.11. Plot of X-Y and Px-Py with initial beam found in the 6D cooling study.

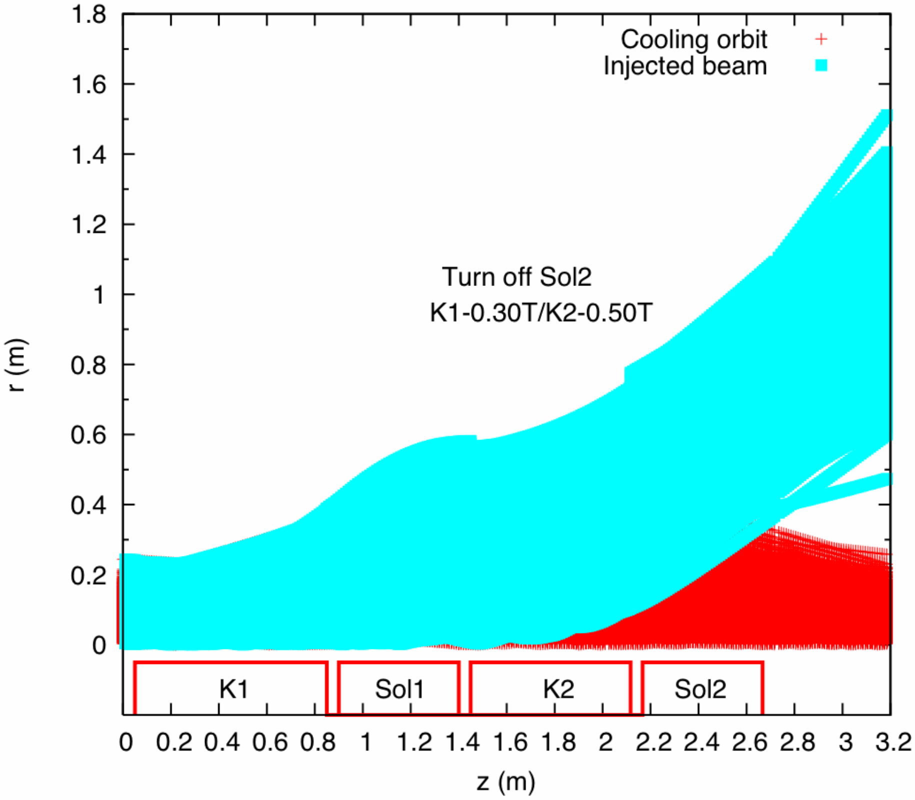


Fig. 12. Simulation of the initial entire beam for injection/extraction.

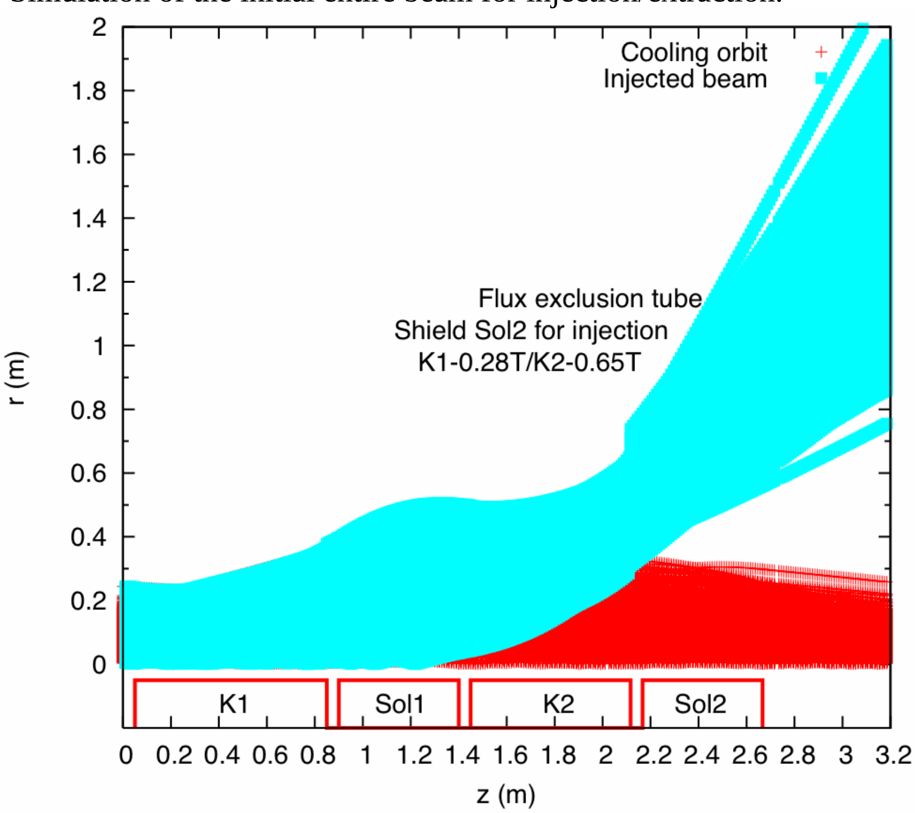


Fig. 13. Simulation of 85% of the initial entire beam for injection/extraction (r-z plot).

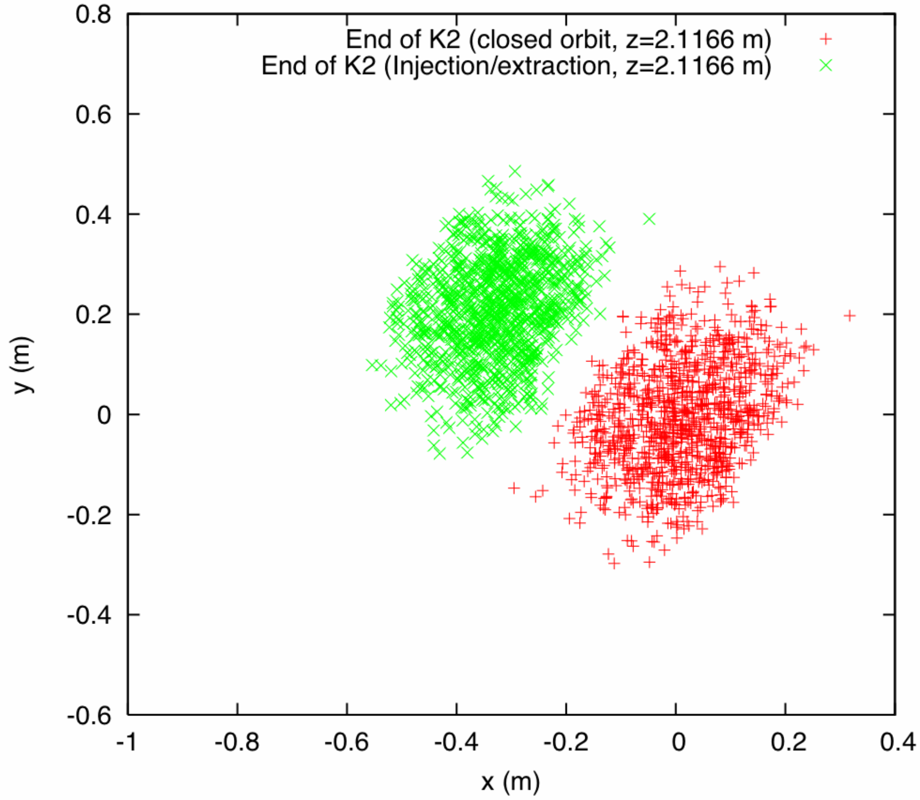


Fig. 14. Simulation of 85% of the initial entire beam for injection/extraction (x-y plot).

Acknowledgments

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References

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[4] R. B. Palmer, L. Reginato, D. Summers. “An introduction Kicker for Muon Cooling Rings and Other Applications Needing Very Large Apertures”.
http://www.fnal.gov/projects/muon_collider/eexchange/Meetings/Kickers/agenda.htm

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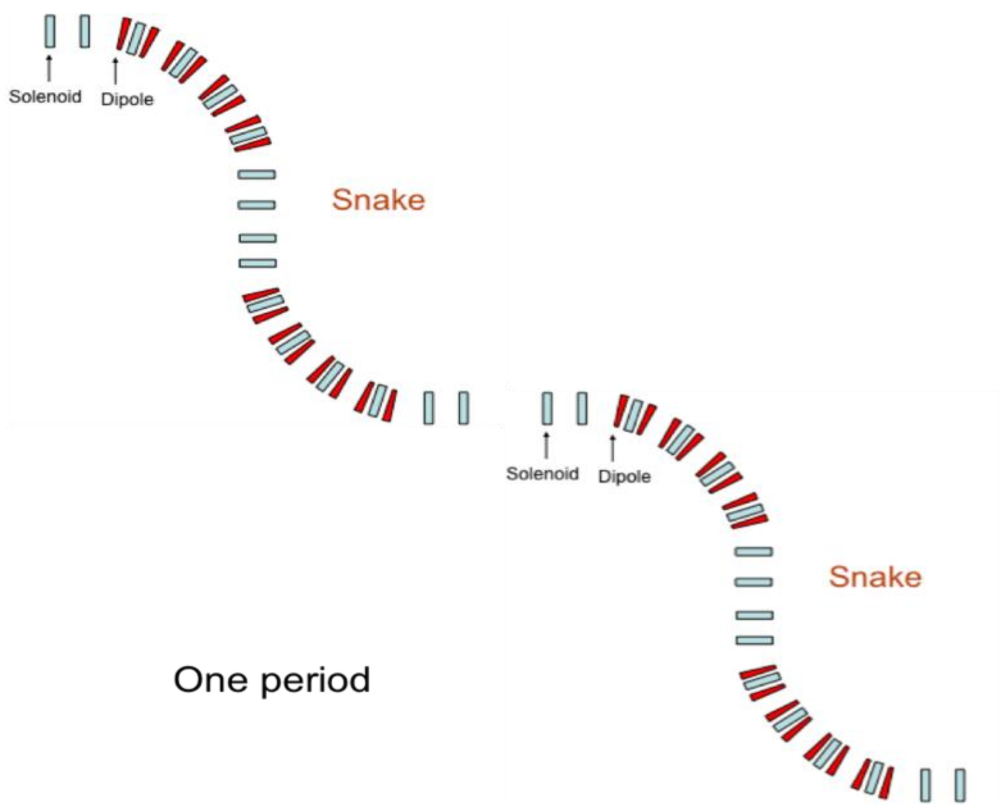
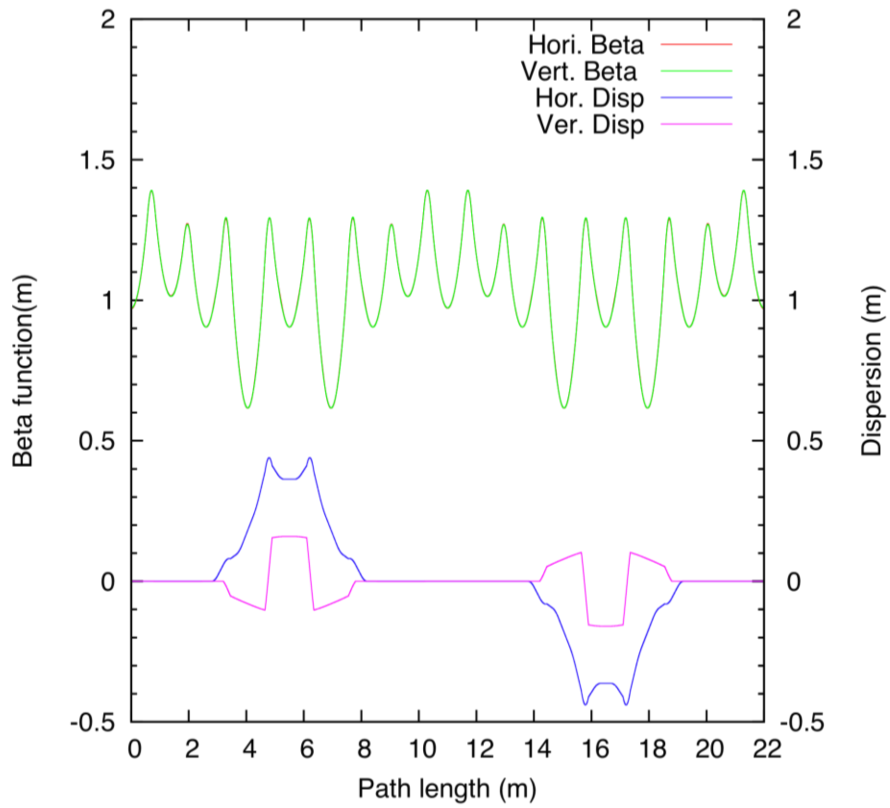
Appendix: Injection into a snake cooler

We are recently studying also a snake cooler. The following figures show some our beam dynamic simulations for this snake. We can see the beam can be easily injected into this snake without requiring a kicker system.




Hori. Beta
Vert. Beta
Hor. Disp
Ver. Disp
Beta function(m)
Dispersion (m)
Path length (m)
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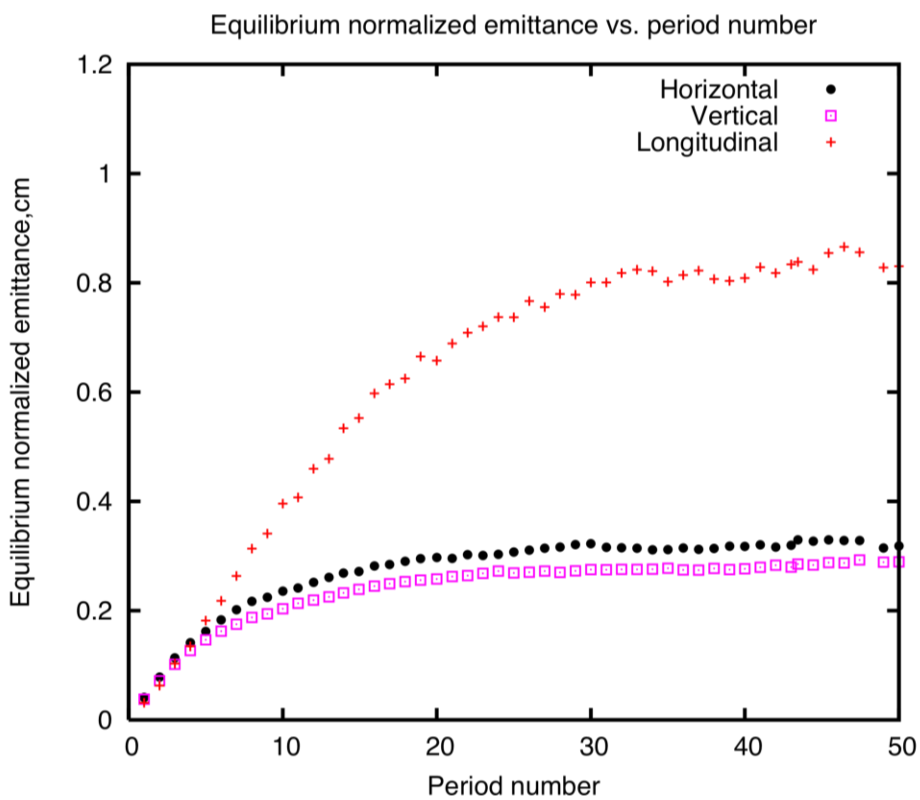
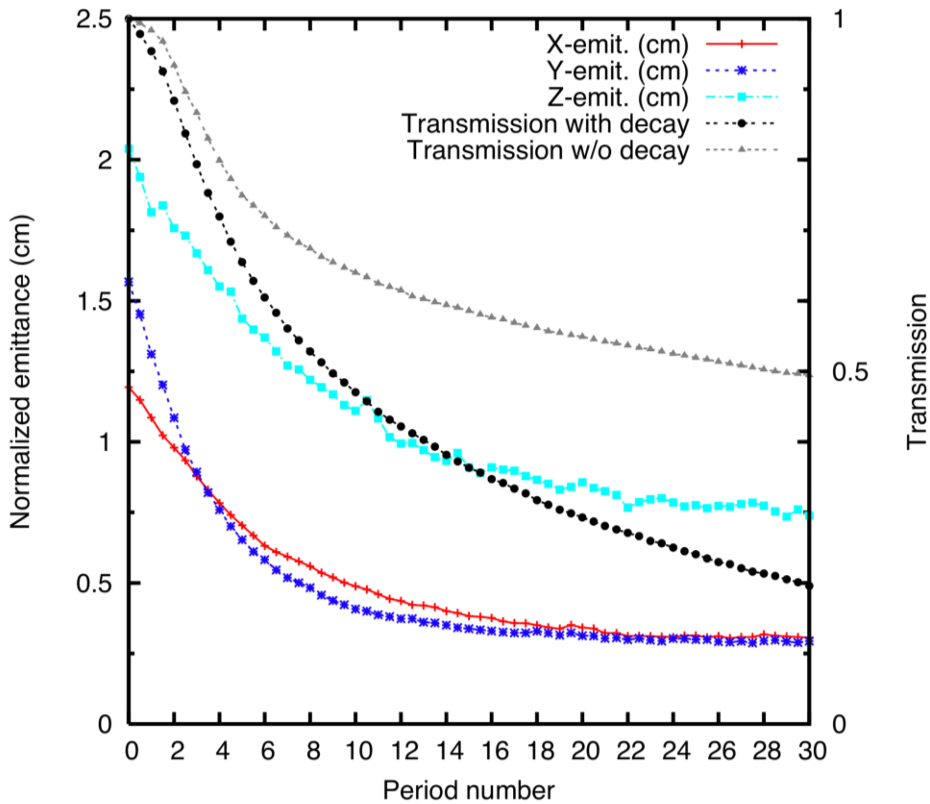

Equilibrium normalized emittance vs. period number
Horizontal
Vertical
Longitudinal
Equilibrium normalized emittance,cm
Period number
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50


X-emit. (cm)
Y-emit. (cm)
Z-emit. (cm)
Transmission with decay
Transmission w/o decay
Normalized emittance (cm)
Transmission
Period number
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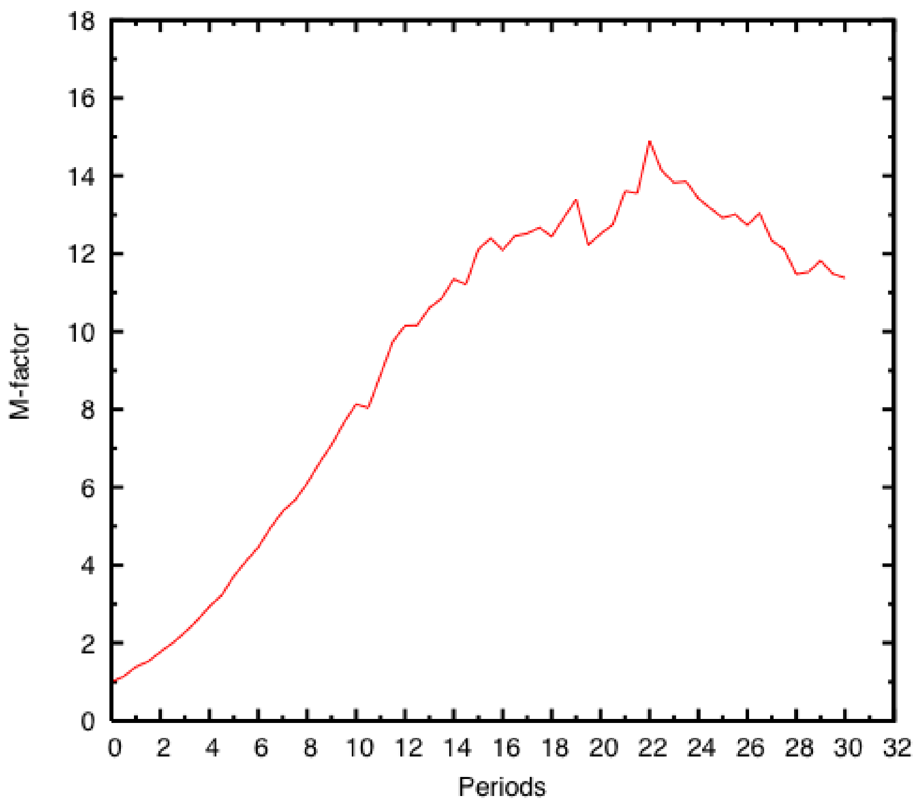
M-factor
Periods
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