Muon front-end chicane and acceleration

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Abstract. A muon front-end system is described which includes an initial pion to muon decay channel, a reverse phase slip bending chicane and a 190-400 MeV, 88 MHz muon linac. A chicane is preferred to a phase rotation system as it leads to a more linear acceleration of the muons in a shielded, 88 MHz linac. The design proposed is compatible with the linac-compressor ring option for the proton driver of the CERN neutrino factory scheme.

1. Introduction

In the decay channel, the large energy spread of the pion-muon bunches causes a shearing in longitudinal phase space. An initial 1 ns rms bunch extends by $\sim$ 70 % in a 30 m channel for muon energies of 190 $\pm$ 70 MeV. The shearing may be reversed, and the initial beam orientation in longitudinal phase space almost restored, by transit through a special bending chicane. The non-linearities in the subsequent acceleration are then reduced.

Comparisons may be made with linac phase rotation systems. The bunch frequency of the protons on target and the emerging pions is 44 MHz and a harmonic of this may be chosen for both phase rotation and acceleration. Use of a sinusoidal 88 MHz rotation field results in an increase of bunch area after filamentation. The effect is enhanced for a 44 MHz field due to its reduced focusing and the return of non-linearity when the frequency is raised for linac acceleration. A linear phase rotation, using a multi-harmonic system or an induction linac, is not considered as the high bunch frequency leads to added cost and complexity. A chicane, followed by an 88 MHz linac, is the preferred solution, resulting in longitudinal bunch areas of $\sim$0.5 eV sec.

Regular solenoid focusing is used before and after the chicane and the total system length is $\sim$130 m, for no transverse cooling. There is, however, an initial 20 T solenoid in the decay channel, followed by a few adjustable solenoids, to optimize the muon distribution from the chicane. Aperture radii are 0.1 m in the 20 T unit, 0.3 m in the following solenoids, then 0.25 m, 0.2 m and finally 0.15 m at the end of the channel and in the muon linac. The aperture reduction provides some energy and betatron selection. Chicanes may take μ^+ or μ^- but the design is for μ^+.

The required reverse phase slip in the 17 m chicane is obtained by the choice of a magnet lattice with a gamma-transition of 1.68, which is below the muon γ range. In addition, the lattice transverse focusing is set for approximate input and output matching and for achromatism at the centre and end point.

2. Chicane lattice

The chicane lattice consists of twelve combined function magnets arranged in four groups of three, as indicated in Figure 1.

In each group, the three magnets bend the muon beam successively either by 64°, -27° and 64° or by equal and opposite amounts. By this means, the first two groups introduce a total horizontal bend of 202° and the next two, -202°. The axis of the downstream linac is then well displaced from that of the decay channel so that it may be appropriately shielded. Strong transverse focusing is obtained using magnets of large input and output edge angles and small bending radii, but of low gradient, FFAG, pole profiles. The end field extent and symmetry are important parameters due to the small bending radii. Two magnet types are involved, B1 units for 64° bends, B2 for 27°, providing a symmetrical B1-B2-B1 triplet.

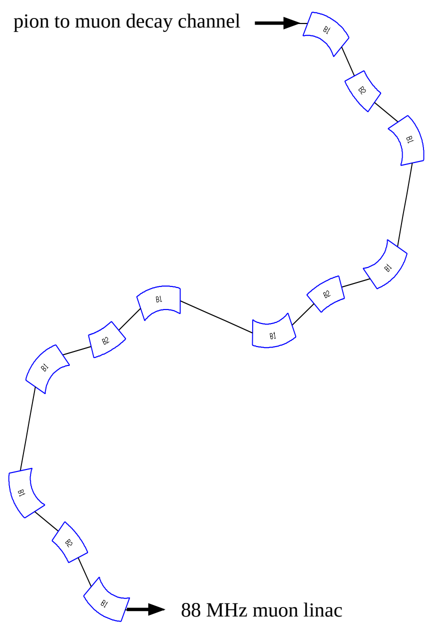

Figure 1. Muon chicane.

In the lattice design, the magnet lengths, bend angles, edge angles, separations and pole profiles have been varied to obtain the required features. These include a γ_t value of 1.68 for a 17 m total chicane length, a horizontal betatron phase shift of 180° for the basic triplet group, and maximum lattice parameters of < 1.8 m (α_p) and < 2.0 m (peak β), 1.5 m (input β). For these maximum values, it is assumed there is no input dispersion and vertical betatron motion is matched, with the horizontal and vertical input β-values assumed equal (for a round beam).

The horizontal-betatron, phase-shift choice provides both for achromatism at the chicane centre and end points and for periodic horizontal β-values over the four triplet groups. In addition, symmetry for the magnet end fields results in symmetry of the triplet β-functions, as shown in Figure 2, which also shows the effect of the reverse bends on the dispersion. Only half of the chicane is displayed, but the β-functions are repeated in the second half, while the dispersion is inverted. Similar lattice functions are also obtained with a different triplet, which has the advantage of a zero gradient B1 magnet, but with the disadvantage of a narrower pole on its inner radius.

A linear lattice code has been used for the initial design, assuming hard edge magnets, but correcting for end fields. Effects found due to the extent and asymmetry of the end fields have been confirmed by muon tracking studies using the Parmila linac simulation code. The B1-B2-B1 triplet was then modelled using the magnet code, Opera-3d, as reported in [1], and the fields have been entered in a new code, Muonplayer [2], which includes pion decays and tracks target pions and decay muons through both the decay channel and the chicane. The code uses accurate expansions for the solenoid end fields. The two sets of cell parameters are given in Table 1.

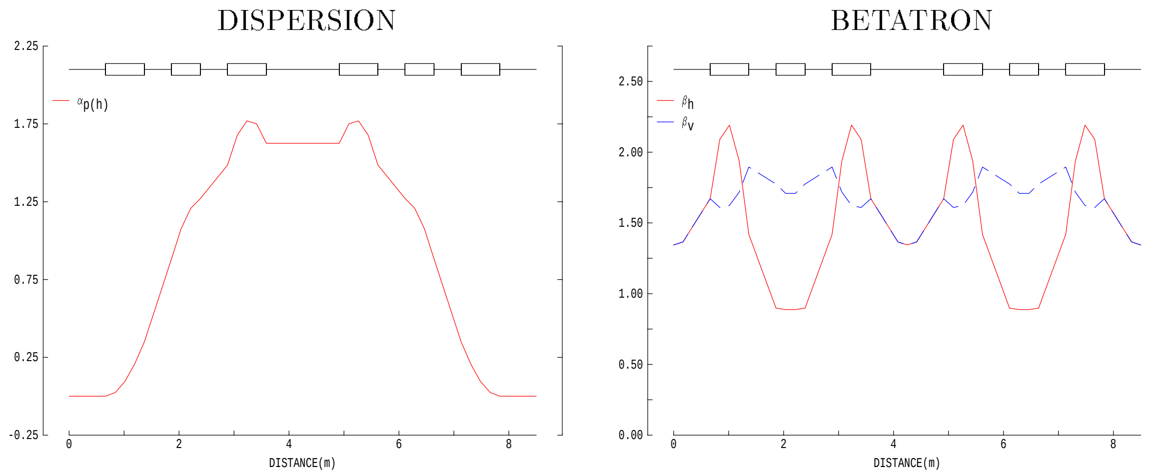

Figure 2. Chicane lattice parameters.

Table 1. Chicane cell parameters.

Unit	Length (m)	Angle (°)	Gradient (m^{-2})
B1	0.176	16.0	-0.39010
B2	0.176	-9.0	-0.27678
B1, B2 end	0.330	0.0	0.0
B1E edge	0.000	21.275	0.0
B2E edge	0.000	13.5	0.0
O1	0.4935	0.0	0.0
O2	0.170	0.0	0.0
B1	0.176	16.0	0.0
B2	0.176	-9.0	-0.13222
B1, B2 end	0.330	0.0	0.0
B1E edge	0.000	15.25	0.0
B2E edge	0.000	13.5	0.0
O1	0.4713	0.0	0.0
O2	0.2144	0.0	0.0

Cell C1:	O1,	B1E,	4*B1,	B1E,	O1:
Cell C2:	B2E,	B2,	B2,	B2,	B2E:

Cell structure: 2*(O2, C1, C2, C1, O2),2*(O2,-C1,-C2,-C1, O2)

Lattice studies are still continuing, in conjunction with tracking evaluations. The points at issue are the following: motion of muons along the inner and outer off-momentum orbits (shown in Figure 3), end field symmetry and curtailment, the choice between the two lattice solutions found, and the required modifications of the FFAG pole profiles. Adjustments for the magnet pole profiles are needed to preserve achromatism for the far off-momentum orbits.

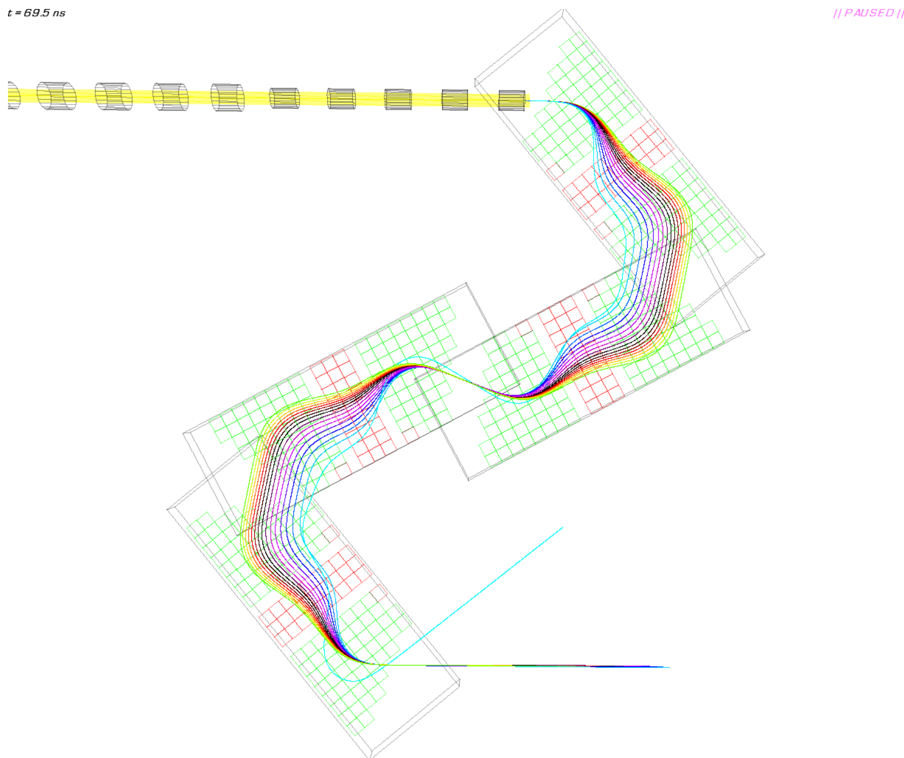

Figure 3. Off-energy orbits.

3. Solenoid focusing

Regular solenoid focusing is used downstream and just upstream of the chicane but there is an initial 20 T solenoid in the decay channel, followed by lower field units. These are set at the field levels found by an optimizer in Muonplayer, which seeks a maximum transmission of muons after the chicane. Betatron matching into and out of the chicane is not feasible over the entire muon energy range from 120 to 270 MeV. Instead, the mis-matching is limited for the full energy range, as far as is practical.

The solenoids in the 81 m muon linac have an aperture radius of 0.15 m while those in the 30 m decay channel have 0.1 m in the 20 T unit, 0.3 m in the following units, then 0.25 m, 0.2 m and finally 0.15 m. Some momentum and transverse collimation is obtained due to the progressive aperture reduction ahead of the chicane. The adjustable solenoids have to be set differently for an optimum transmission from the target to the chicane output, in place of its input.

4. Muon linac

The 88 MHz linac for accelerating muons from 190 to 400 MeV uses the cavity design of the CERN front-end scheme. This is a single cell unit, with a 0.15 m bore radius, a 0.9 m length and it includes a 0.4 m superconducting solenoid within the inner nose cone. There are ninety such units in an overall 81 m length. If cooling is added, every fifth cavity in the cooling interval is replaced by an ionizing unit, but the focusing pattern is retained. The use of 0.4 m solenoids at intervals of 0.9 m is also adopted in the decay channel.

An accelerating field gradient of 4 MV/m is proposed ($E_0LT = 3.6\,\mathrm{MV}$) for each cavity, but the synchronous phase varies smoothly from -66° at 190 MeV to -39° at 400 MeV. On leaving the chicane, the beam has an upright distribution in longitudinal phase space and there is acceptable non-linearity during acceleration for the parameters chosen. The energy at which to change to a higher accelerating frequency has yet to be decided.

5. Simulation results

Pion and muon tracking studies with the Muonplayer code were initially made for the decay channel. After lengthy optimizing of the solenoids, a transmission efficiency of $\sim$7% μ^+ per π^+ was obtained from a 10 mm radius, tantalum target, with normalised rms transverse emittances of $\sim$6500 (π) mm mr for the 120 to 270 MeV μ^+. This translates to $\sim$0.67% μ^+ per (proton GeV) for the 2.2 GeV protons on target.

Tracking of muons was then extended into the chicane and 400 MeV linac. At first, simulations were made with the Parmila linac code, using hard edged models for both the chicane magnets and the linac solenoids. The optimized figure of merit found for muon yields was $\sim$0.51% μ^+ per (proton GeV). More accurate simulations, however, with the Muonplayer code, using field maps from the Opera-3d magnet models, indicate that the yields are reduced to $\sim$0.25% μ^+ per (proton GeV).

Studies have now been re-directed to the design of a racetrack cooling ring in which the two long straight sections have solenoid focusing and the two arcs are formed from 180^0 chicane units, each formed from two, B1-B2-B1 triplet sets with bending angles (64^0, -38^0, 64^0). The muon front end has the 30 m decay channel, as before, but this is followed by a 44 MHz rf phase rotation channel, which reduces the muon energy range to 180 $\pm$ 35 MeV for injection into the cooling ring.

References

[1] M.R. Harold, Magnets for a muon front end chicane, Proceedings of this conference, NuFact02.
[2] S.J. Brooks, Muonplayer tracking code, Rutherford Appleton laboratory.