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Transfer Line Between the Proton Driver Accumulator and Compressor Rings for the CERN Neutrino Factory

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Abstract

This note presents a possible design for the transfer line between the proton driver accumulator and compressor rings of the CERN Neutrino Factory. Based on the layout of the two rings presented in Ref. [1], a possible configuration for the transfer line is studied. The geometry and the optics of such a transport system are discussed in details.

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1 Introduction

The CERN reference scenario for the proton drivers of the Neutrino Factory is presented in Ref. [1]. The two rings, accumulator and compressor, are studied in details, in particular their geometrical layout and optics. Also, the beam dynamics is presented with particular emphasis to the accumulation and compression processes and beam instabilities.

However, the issue of the beam transfer between the two machines is not discussed. Two different options have to be considered:

- The proton drivers are stacked horizontally. This means that the two vacuum pipes intersect each other in eight points. The horizontal width of the ISR-tunnel allows to install the two rings in the same plane leaving also enough space for the transfer line between them. Hence, the transfer line lays in the plane of the two rings and only horizontal bending magnets are used. The critical point of this configuration is the impedance of the crossing and its effect on the beam dynamics.
- The proton drivers are stacked vertically. The two machines do not intersect anymore and the transfer line between them should have a rather complex geometry with both horizontal and vertical bending elements. With such a geometry, both horizontal and vertical dispersion is generated along the transfer line, thus making the matching of the optical parameters much more difficult to achieve.

By taking into account the pros and cons of both solutions, the decision has been taken to study the first option.

2 The Proton Drivers for the Neutrino Factory

For the sake of completeness, a number of key parameters, already reported in [1], are also summarised here. In Table 1, the main parameters of the proton beam delivered by the linac machine are listed.

Parameter	Unit	Value
Mean beam power	MW	4
Kinetic energy	GeV	2.2
Rep. rate	Hz	75
Pulse duration	ms	2.2
# of micro-bunch trains $\times$ turns		140×660
Pulse intensity		1.5×10^{14}
Train spacing	ns	22.7
# of micro-bunches/train		5
Micro-bunch spacing	ns	2.84
Micro-bunch intensity		3.3×10^{8}
Micro-bunch length	ns	0.5
Energy spread (2σ)	MeV	0.2
Energy jitter within pulse	MeV	± 0.2
Energy jitter between pulses	MeV	± 2
$\Delta p/p$ (2σ)		0.08×10^{-3}
ϵ_l	eVs	0.2×10^{-3}
$\epsilon^*_{h/v} = \beta\,\gamma\,\sigma^2_{h,v}/\beta_{h,v}$	μm	0.6

Table 1: Summary of linac output beam characteristics.

The accumulator ring, designed at RAL, is fed directly by the linac through a transfer line where beam collimation is also performed: 140 buckets out of 146 available are filled using an

H$^-$ injection scheme over 660 turns. Five linac micro-bunches, chopped from eight, are injected into each bucket. The ring is equipped with a 44 MHz RF system of the type developed for LHC in the CERN-PS [2]. The RF voltage is increased during beam accumulation to compensate continuously the longitudinal space charge.

The lattice of this machine, based on triplet cells, has an eight-fold symmetry. It has been designed to optimise the H$^-$ injection. In particular, the value of the dispersion function at the stripping foil has been adjusted to allow ease of painting. With respect to the version presented in [1], the magnetic elements near the crossing regions have been moved so to have enough room on both sides of the crossing.

The values of the optical parameters for half a super-period are shown in Fig. 1, while the corresponding layout is shown in Fig. 2.

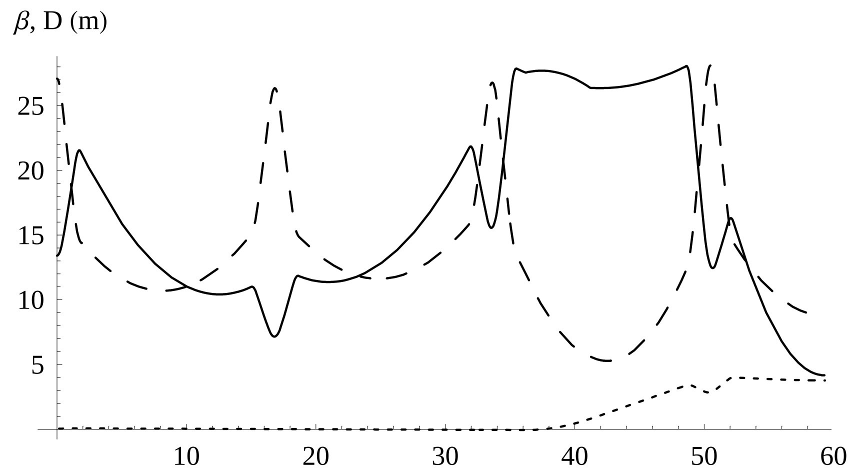

Figure 1: Optical parameters for half a super-period of the accumulator ring (β_h solid, β_v dashed, D_h dotted line).

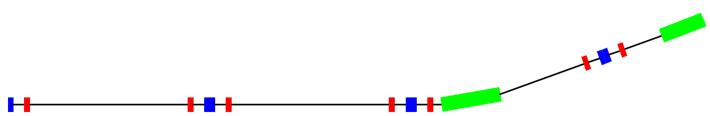

Figure 2: Geometry of half super-period of the accumulator ring. The triplet structure is clearly visible.

Once the accumulation process is over, the 140 macro-bunches are transferred to the compressor ring where their length is reduced by bunch rotation in less than 30 μs. For that purpose the compressor ring, designed at CERN, is equipped with four cavities at 44 MHz [2], providing a total voltage of 2 MV, and with one cavity at 88 MHz [3] delivering 350 kV. The compression process brings the bunches from the estimated initial r.m.s. length of 3.5 ns ($\Delta p/p$ is 1.5×10^{-3} at 2σ) to the final one of 1 ns ($\Delta p/p$ is 5.0×10^{-3} at 2σ).

The lattice of the compressor machine, based on doublet cells, has been designed to maximise the free space in the straight sections to allow the installation of the RF cavities. To this aim, the dispersion function is zero in the straight sections and special care has been taken to minimise the value of $\mathrm{D}_h^{\mathrm{max}}$ to reduce the transverse beam size of the rotated bunch. The values of the optical parameters for half a super-period are shown in Fig. 3, while the corresponding layout is shown in Fig. 4.

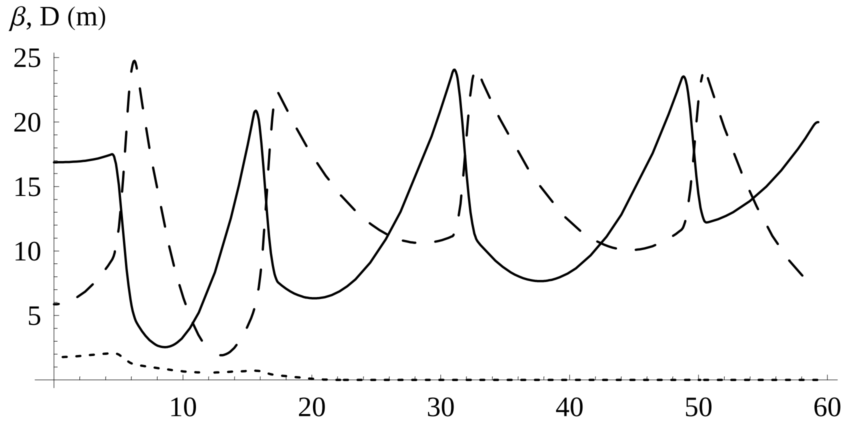

Figure 3: Optical parameters for half a super-period of the compressor ring (β_h solid, β_v dashed, D_h dotted line).

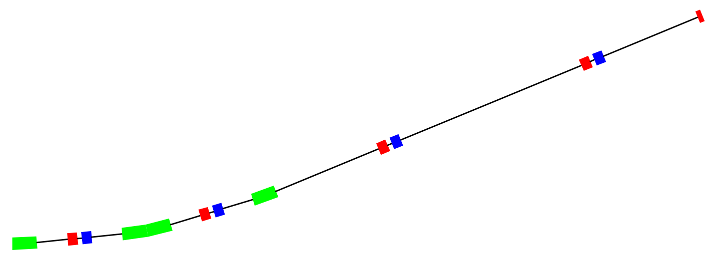

Figure 4: Geometry of half super-period of the compressor ring. The doublet structure is clearly visible.

The main lattice parameters are summarised in Table 2, while the beam parameters are listed in Table 3.

Parameter	Accumulator	Compressor
Radius (m)	151	151
Main dipole field (T)	0.69	0.49
γ_{tr}	14.837	15.089
η	-0.0848	-0.0849
${\beta_h}^{\max}/{\beta_v}^{\max}$ (m)	26.4/26.2	24.5/25.5
$\mathrm{D}_h^{\min}/\mathrm{D}_h^{\max}$ (m)	0.0/4.6	0.0/1.8
$\mathrm{Q}_h/\mathrm{Q}_v$	11.23/13.30	17.18/16.40
Super-symmetry	8	8
Vac. pipe half width (m)	0.09	0.09
Vac. pipe half height (m)	0.09	0.09
# of dip.-quad./super-period	$3-22$	$5-17$
Length of s.s./super-period (m)	73.4	86.2

Table 2: Summary of geometrical and optical parameters of the accumulator and compressor rings.

Parameter	Unit	Value
Pulse duration	μs	3.3
RF frequency	MHz	44.02
# of bunches/h		$140/146$
Bunch intensity	protons	1.1×10^{12}
ϵ_l	eVs	0.1
$\epsilon^*_{h/v} = \beta\,\gamma\,\sigma^2_{h,v}/\beta_{h,v}$	μm	50

Table 3: Summary of output beam characteristics common to accumulator and compressor rings.

3 The Transfer Line

3.1 Geometry

The beam is extracted from the accumulator ring using the standard approach based on kicker and septum magnets. Some attempts have been made to avoid using the septum, but the large aperture needed to reduce the beam losses, makes it impossible to design a kicker magnet fast enough and capable of generating the deflection angle needed to separate the circulating beam from the extracted one. In the present design, the kicker magnet provides a deflection angle of 16.4 mrad, while the septum generates an angle of 100 mrad. Using these values, the two magnets seem to be within the reach of present technologies [4, 5].

The topology of the accumulator and compressor rings, together with the size of the ISR-tunnel, would make it possible to design a straight transfer line connecting the two machines. However, to achieve a perfect matching of the dispersion function and its derivative, a bending magnet is introduced in the middle of the transfer line to vary the dispersion invariant along the line. In the final layout, it generates a deflection angle of 192.7 mrad.

The injection section of the compressor ring is designed using the same principle, i.e. a couple of kicker and septum magnets. The deflection angles are not exactly the same as those for the extraction from the accumulator ring: in this case the angle generated by the septum magnet is again 100 mrad but the kicker provides a deflection of 17.3 mrad.

The geometry of the proposed transfer line together with the two rings and the walls of the ISR-tunnel is shown in Fig. 5. The key parameters are summarised in Table 4. The total length of the transfer line is 63.6 m.

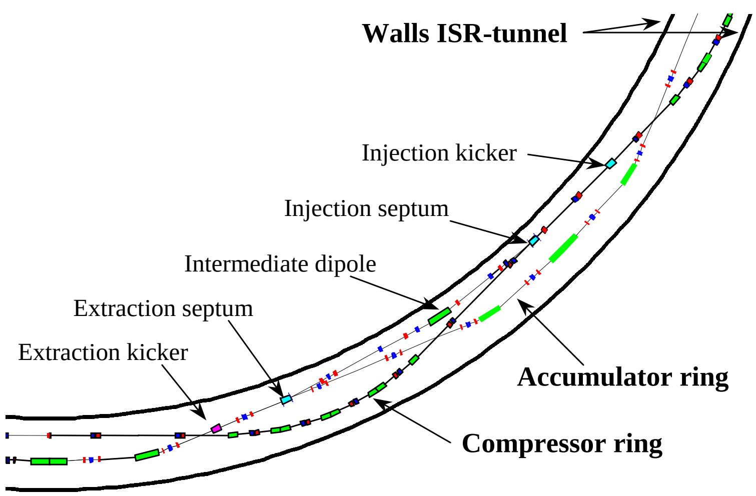

Figure 5: Geometry of the transfer line from the accumulator's extraction point (on the left side) to the compressor's injection point (on the right side). The walls of the ISR-tunnel are also shown.

3.2 Optics

The optical structures used in the two rings are not the same. The accumulator is based on triplet cells, while the compressor ring is made of doublet structures. The transfer line accounts for the transition between them. To this aim, ten quadrupoles, each 0.8 m long, are used to obtain a perfect matching of the optical parameters (Twiss, dispersion and its derivative). Special care has been taken to decrease the value of the beta-function in both planes to reduce the mechanical aperture needed to avoid beam losses. The optical parameters along the transfer line, from the accumulator's extraction point to the injection in the compressor ring, are shown in Fig. 6. The computation of the transfer line optics has been carried out using the *MAD* [6] and *BeamOptics* [7] programs.

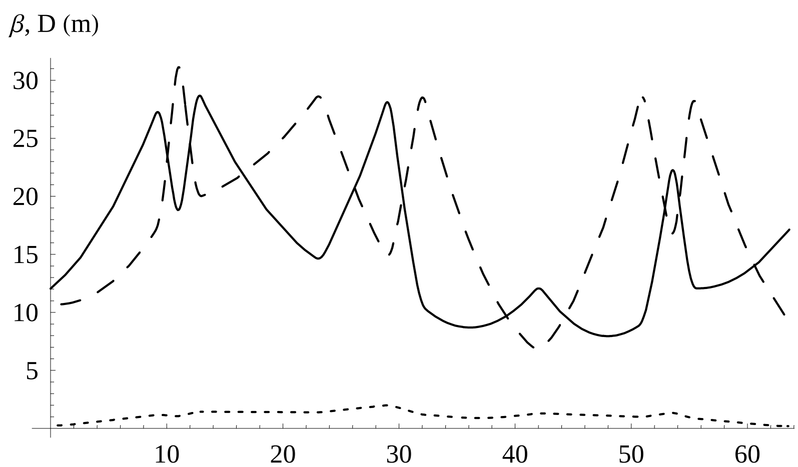

Figure 6: Optical parameters for the transfer line between the accumulator and compressor rings (β_h solid, β_v dashed, D_h dotted line).

While in both machines $\beta_{h,v}^{\max}$ is always smaller than 26.5 m, the maximum value of the beta-function slightly exceeds 30 m in the transfer line. This is due to the quadrupole spacing at both ends of the transfer line. This parameter can be used as an additional degree of freedom during the matching process: a large spacing increases $\beta^{\max}$ in the line, but it makes more room in the injection/extraction regions to ease the installation of magnetic elements. On the other hand, a smaller spacing reduces $\beta^{\max}$, but the price to pay is a tighter packing of hardware elements. The value used here represents the best compromise between the two extreme situations. In Fig. 7 the evolution of the horizontal and vertical beam envelope along a super-period of the accumulator, the transfer line and a super-period of the compressor ring is shown. The beam envelope is computed at 4σ using a linear addition of the betatronic and dispersion contributions.

The values of the gradients of the ten quadrupoles needed to generate the optical parameters shown in Fig. 6 are listed in Table 4.

4 Conclusions

In this note, a possible layout for the transfer line between the accumulator and compressor rings of the CERN Neutrino Factory scenario is presented. It is based on the assumption that the two rings lay in the same plane and the vacuum pipes intersect eight times along the circumference. Under this hypothesis, the transfer line is horizontal and is located in the inner side of the ISR-tunnel.

The solution proposed is technically feasible. However, further investigations are needed to estimate the value of the impedance due to the crossing sections of the vacuum pipes, to confirm the assumption made that such an impedance does not drive any beam instability.

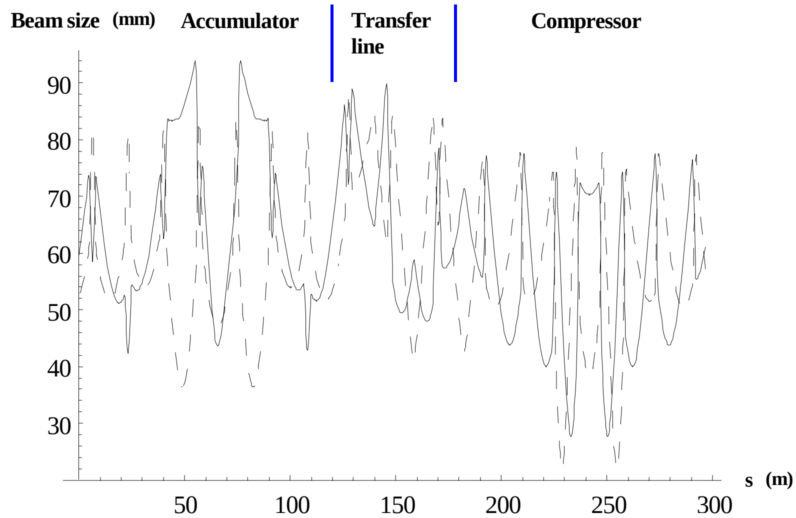

Figure 7: Beam envelope (radius at 4σ) along a super-period of the accumulator, the transfer line, and a super-period of the compressor ring (horizontal solid, vertical dashed).

Parameter	Unit	Value	Quad #	Strength (T/m)
Length ext. kicker	m	2.000	1	2.27
Field ext. kicker	T	0.082	2	-4.08
Length ext. septum	m	3.000	3	2.30
Field ext. septum	T	0.334	4	-1.00
Length dipole	m	5.000	5	2.58
Field dipole	T	0.386	6	-2.28
Length inj. septum	m	3.000	7	1.41
Field inj. septum	T	0.334	8	-2.27
Length inj. kicker	m	2.000	9	4.36
Field inj. kicker	T	0.086	10	-2.97

Table 4: Summary of properties of transfer line elements.

Acknowledgements

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References

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