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A 40-80 MHz system for phase rotation and cooling

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Introduction

In this note a scheme for the collection, phase rotation and cooling of muons for a neutrino factory is reported. The scheme is sufficiently generic to be site independent also if some particular choices are influenced by the CERN design. The system discussed in this note is worked on as a possible alternative to the induction linac scheme [1]. The results presented assume the following overall set-up: the proton driver is constituted by a 2.2 GeV superconducting linac [2] followed by an accumulator and compressor ring [3]; the muon re-circulator and decay ring are assumed as described in PJK scenario [4].

Layout

The pions are let decay in a 30m long channel focussed by a 1.8 Tesla solenoid. At the end of the decay channel the particles with kinetic energy in the range 100-300 MeV are captured in a series of 44 MHz cavities and their energy spread reduced of a factor two. At this point a first cooling stage, employing the same RF cavities, reduces the transverse emittance in each plane by a factor 0.7 while keeping the average energy constant. After the first cooling stage the beam is accelerated to an average energy of 300 MeV. The beam phase extend as well as the reduced physical dimensions of the beam allow to employ at this point a 88 MHz cavity cooling system. In this second cooling system rematching cells are periodically inserted to control the longitudinal dynamics. At the end of the second cooling stage the emittance is reduced by a factor 4 in each transverse plane. The system is continued at 88 MHz, and 176MHz until the final energy of 2 GeV -suitable for injection in a µRLA- is reached. The system works also with 40 MHz, 80 MHz, 200 MHz. The general layout is presented in Table1

Table1
Components of the 40-80 MHz scheme and their characteristics

	Decay	Rotation	Cooling I	Accel.	Cooling II	Accel
Length [m]	30	30	46	32	112	≈450
Diameter [cm]	60	60	60	60	30	20
B-field [T]	1.8	1.8	2.0	2.0	2.6	2.6
Frequency [MHz]	-	40	40	40	80	80-200
Gradient [MV/m]		2	2	2	4	4-10
Kin Energy [MeV]		200		280	300	2000

Beam dynamics for each section

A pion beam was generated (program FLUKA) from a 2.2 GeV proton beam (dp/p= 1.2 10^{-2},emittx=50µm) instantly impinging on a 26 mm mercury target immersed in a 20 Tesla solenoid. The data were extrapolated (linearly) to a 260mm long target. These particles were used for all the simulations presented in this paper also if further optimisation of the target and the subsequent focussing system have advanced.

The beam dynamics of pions-muons system from the decay channel until the injection in the µRLA was studied with the program PATH (CERN version).

All the particles produced from the target were tracked through the system, cuts in longitudinal phase space have been made at the interface of each section for the sake of clarity in the presentation.

The decay channel input and output longitudinal and transverse phase space are reported in figure 1. Notice the transverse emittance increase due to decay. No attempt has been yet made to control this increase.

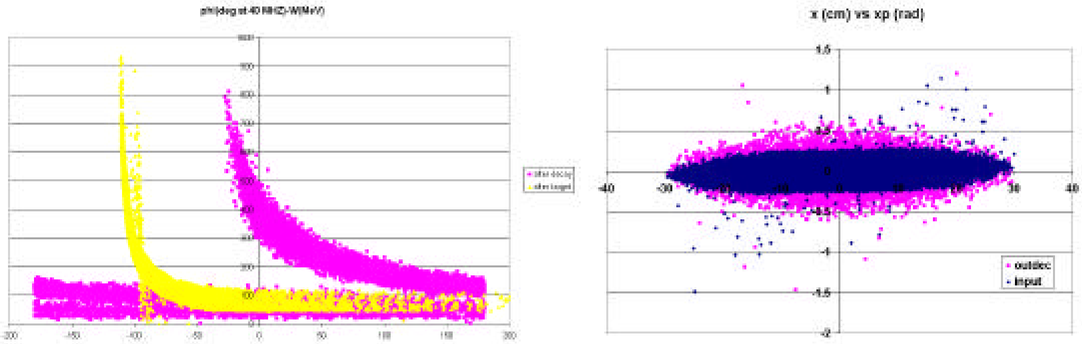
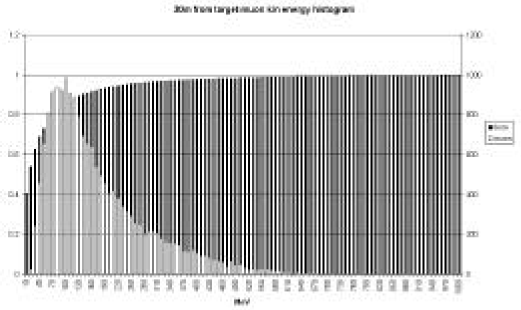


Figure 1-Longitudinal and transverse phase planes at the input and output of the decay channel.

Only a subset of the muons surviving at the end of the decay channel can be captured in a RF structure because of the enormous energy spread. Assuming a realistic gradient of few MV/m, and in order to keep the phase rotation section within a length of approximately 50 m only the particles within and energy spread of 100 MeV can be successfully captured. The slow muons (kinetic energy lower than 100 MeV) don't have a structure on a 44 MHz time-scale and can't be considered for this scheme..



energy spread average energy (MeV)	±50 MeV	±100MeV
150	4.7°	12.7°
250	1.4°	3.3°
350	0.6°	1.4°

Figure 2- Left: muon energy histogram at the end of decay and corresponding beta. Right: de-bunching per meter (in degrees at 44 MHz) vs. energy

In figure 2 the terms of the trade-off are schematised: the higher the energy the smaller the variation of beta (de-bunching not too severe), the lower the energy the higher the density of muons

In this note we have chosen to collect around an energy of 200 MeV (kinetic). More than 50% of the muons arriving at the end of the decay fit in the energy acceptance of the phase rotation system. This fraction can't be improved -unless a first phase rotation on the pions is applied-as the enormous energy spread comes from production.

A set-up composed of 30 1m long 44 MHz closed cavity at 2 MV/m and an aperture radius of 30 cm with a solenoid around the vacuum chamber has been employed, giving the results reported in figure 3. The rotation is very slow (3 degrees per cell, thus containing the transverse emittance increase to some 10%).

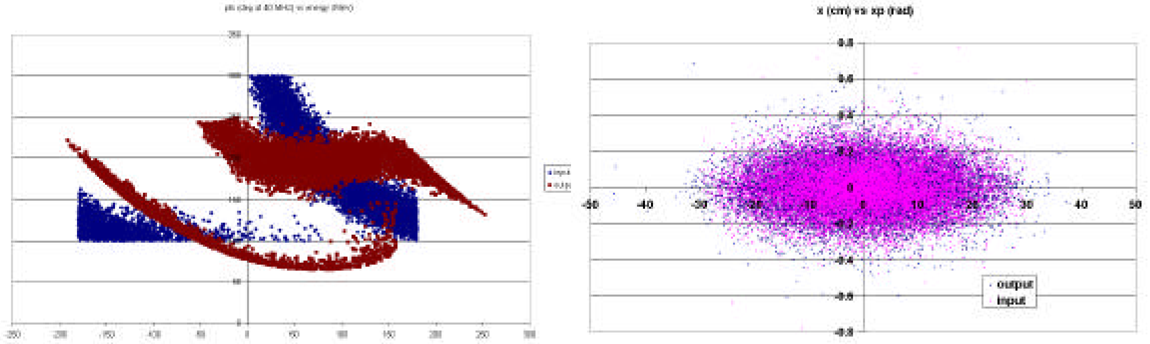


Figure 3-Longitudinal and transverse phase planes at the input and output of the phase rotation system

Notice that the system would work also 1)with a gradient of 1 MV/m (twice the length), 2) if the solenoid can't be fitted around the cavity and the RF cavity and the solenoid are put one after the other (section of 1m cavity + 1 m solenoid).

At the end of the phase rotation the beam has still a structure on 44 MHz and it can be cooled without previous bunching. The fundamental cooling cell (figure 4) is composed of four 44 MHz cells and 24 cm of hydrogen; the solenoid is fitted around the gap of the RF cavity and covers almost uniformly the cell. Preliminary SuperFish runs confirm the feasibility of this structure. The distortion in the longitudinal phase space caused by sinusoidal variation of the RF can be tolerated as the field gradient is small compared to the energy spread.

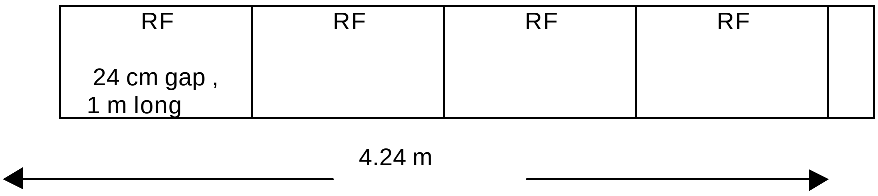


Figure 4-Cooling cell at 44 MHz

The energy loss/gain per cell is 5.6 MV. The process is applied 11 times and the emittance is reduced of a factor 0.7 in each transverse plane. The beam is then accelerated to an average energy of 280 MeV by the same set-up (without absorbers): this accelerating section provides also some re-bunching and matching to the next cooling section. A good fraction of the beam (65% at the moment-can be improved) at the end of the first stage of acceleration fits in a 88-MHz bucket. The cooling process can be continued with 88 MHz cavities 0.5m long at 4 MV/m and 15 cm aperture radius. The advantages of operating at 88 MHz are: 1)that the cooling per metre increases; 2) that the 88 MHz cavities have an acceptable field also if the bore is not closed with a window. The 88 MHz fundamental cooling cell (reported in figure 5) is composed of eight 50cm long 88 MHz cells and a 40 cm long Hydrogen absorber; a solenoid is fitted around the bore of each cavity. The longitudinal beam phase space along the 88 MHz cooling channel is reported in fig 6. The final beam phase space is reported in fig 7. The fraction of muons within the 6D re-circulator acceptance meets the specification of the neutrino factory as reported in the next section.

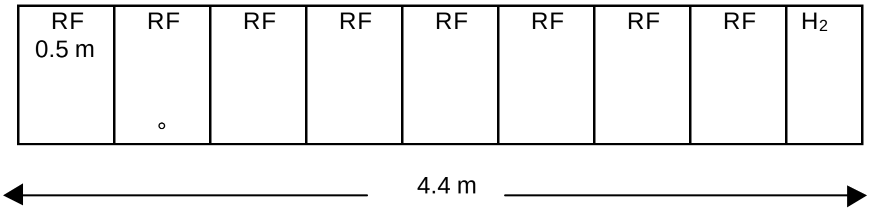


Figure 5- Fundamental 88 MHz cooling cell

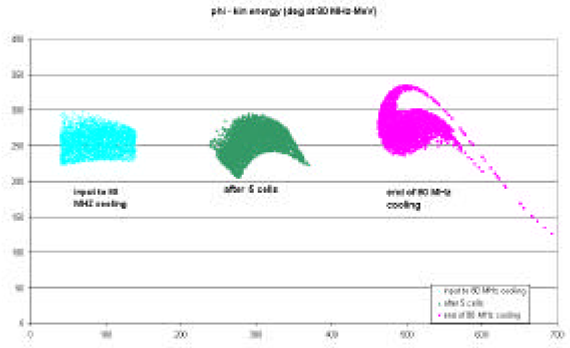


Figure 6 - Longitudinal beam phase space along the 88 MHz channel.

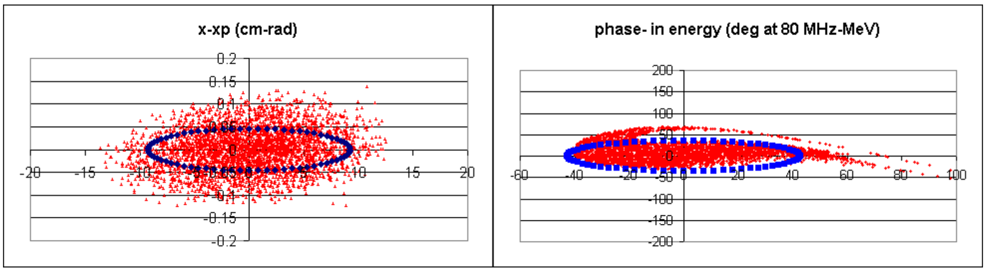


Figure 7-The transverse and longitudinal phase space at the end of cooling. The ellipse area are 1.5π cm rad for the transverse and 150 π mm dp/p (normalised)for the longitudinal [4]

After the beam is cooled, the system is continued with 88 MHz cavity of the same type until the beam has reached 1 GeV when a transition to 176 MHz is possible.

Particle budget

The particle budget as calculated by PATH is reported in figure 8. The calculation presented does not yet include: the effect of the hydrogen vessel, the effect of the RF windows to close the RF cavities nor the losses due to muon decay (The latter have been estimated after the conference : no sensible effect of 150µm thick berillium windows and 20% losses due to decay till 2GeV)

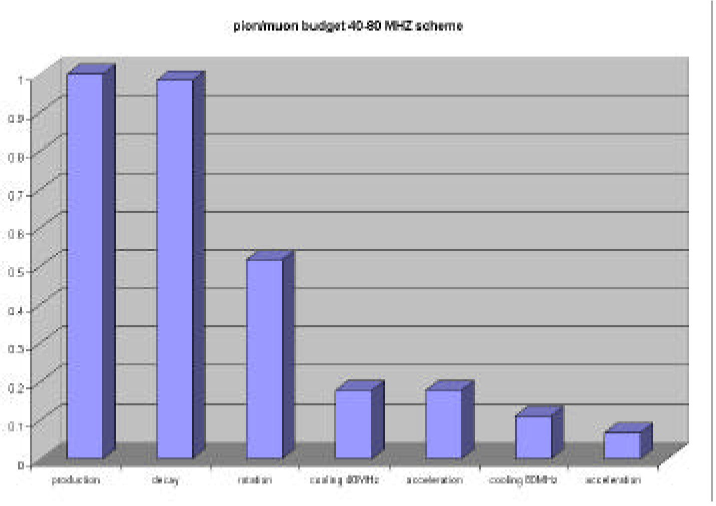
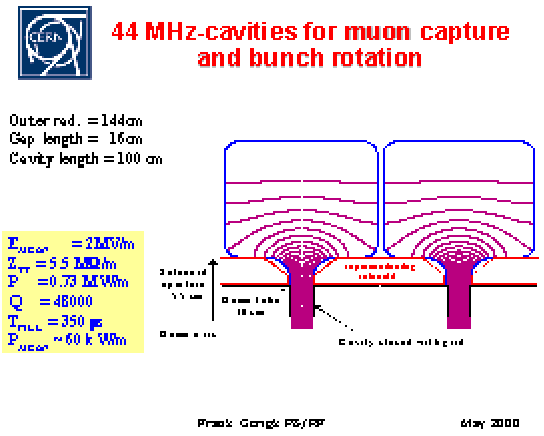


Figure 8-Pions -muons budget along the channel

Assuming the particle production as predicted by FLUKA (0.2 π^+/proton at 2.2GeV) the yield of the system is 0.42 % μ^+/protGeV. Assuming the proton flux of the CERN Superconducting linac and accumulator ring this would result in some 10^{21} µ/year (1 year = 10^7 sec) delivered into the acceptance of the muon re-circulator.

The technical challenges and an estimate of the RF power needed

The underlying motivation for this set-up is to propose a solution that makes use of existing technology or a little extrapolation of it. The starting value for the gradient of the 44 MHz cavities came from the performance of the existing PS-40MHz cavity [5]. Some exploratory SFH runs have been made [6] on a 44 MHz normal conducting cavity with a bore radius of 30 cm and the results are encouraging (1.6 MW power required for 2 MV/m). This cavity could accommodate a solenoid around the chamber (fig.9). Some preliminary estimation of the power losses, for 2MV/m at 44 MHz and 4 Mv/m at 88 MHz gives a figure of 10 MW for the entire phase rotation and cooling system, assuming that the system is pulsed at 75 Hz.



44 MHz-cavities for muon capture
and bunch rotation

Outer rad. = 144cm
Gap length = 16cm
Cavity length = 100 cm

E_{accel} = 2MV/m
Z_{TT} = 5.5 MΩ/m
P = 0.73 MW/m
Q = 48000
T_{fill} = 350 μs
P_{accel} ~ 60 kW/m

Frank Gerigk PS/RF May 2000

Figure 9- Possible design of the 40 MHz cavity

The dependence on the proton beam time duration design

As the building block of the RF scheme is to make use of the pions beam microstructure to avoid re-bunching before cooling, the impinging proton beam longitudinal structure has an influence on the overall performance. We can see from fig 1 that the intrinsic spread due to decay and path length through the solenoid is of the order of naseconds so a proton beam bunch length below that value would not help. In table 2 the relative performances at the end of cooling for a square and for a gaussian proton pulse are reported. An rms bunch length of 1 nsec (3nsec total) would be welcome. This value is achievable [7] as the number of microbunches is virtually unlimited and the space charge per bunch can thus be lowered to allow such a tight compression.

Table 2
Muon yield vs. proton bunch length for a square and for a gaussian pulse

proton pulse total length(nsec) (square pulse)	μ/year (10^21)
0	1.6
1	1.5
2	1.4
3	1.3
4	1.2
5	1.1
6	1.1
7	1.0
8	0.98
9	0.97
10	0.93

proton pulse rms length(nsec) (gaussian pulse)	relative yield
0	100
1	89
2	80
3	73

Conclusions and future work

A study of a RF phase rotation and cooling scheme that meets the muon flux required by a neutrino factory has been started. Preliminary results are encouraging. The advantages of this scheme are: the use of moderate gradient, the use of RF cavity similar to examples already working and the better match to the CERN proton driver capabilities.

Future optimisation work includes: the optimisation of the transition between sections, in particular a smoother longitudinal dynamics between phase rotation and the first cooling section; the completion of the design of the final acceleration; and a more thorough tuning of the parameters of each section.

References

[1] R. Scrivens, 'Example Beam Dynamic Designs for a Neutrino Capture and Phase Rotation Line using 50m, 100m and 200m Long Induction Linacs',CERN-NUFACT-note14 , http://nicewww.cern.ch/~molat/neutrino/nf14.pdf

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http://muonstoragerings.cern.ch/Welcome.html/Events/Neutrino/Vretenar/splannex.html

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[4] R.B. Palmer, C. Johnson, E. Keil, 'A Cost-Effective design for a Neutrino Factory', CERN-NUFACT-note09, http://nicewww.cern.ch/~molat/neutrino/nf09.pdf

[5] R. Garoby, D. Grier, E. Jensen, CERN. A. Mitra, R.L. Poirier, TRIUMF, The PS 40 MHz Bunching Cavity,1997 Particle Accelerator Conference, 12-16.5.97, Vancouver, B.C., Canada.

[6] F. Gerigk, R. Garoby

[7] R. Cappi, H. Schoenauer, these proceedings.