Design Study of a High Current Proton Beam Funneling Line

K. Bongardt
Kernforschungsanlage Juelich, D 5170 Juelich, Fed. Rep. of Germany

Abstract

The funneling line of the SNQ-project is described with all its restrictions and components. The line combines two beams, 180° out of phase, produced by identical 100 MHz RFQ's, into one 200 MHz Alvarez accelerator. Special emphasis is given to the beam dynamics of transporting a high current, bunched, unneutralized proton beam of 2 MeV over a length of about 15 m. Results of multiparticle calculations for the funneling line are presented.

Introduction

For the German Neutron Spallation Source SNQ project a combination of two proton beams is foreseen[1]. A funneling line will combine two 100 mA beams at 2 MeV, produced by two 100 MHz RFQ-structures, into one 200 MHz Alvarez accelerator. The reasons for chosing such an injector scheme are a reliable design of a 100 mA, 100 MHz RFQ[2] and the possibility of positioning a fast beam kicker (rise time: 10 nsec). Such a kicker is needed for the beam injection and extraction out of a compressor ring[1].

In this paper the main characteristics of the funneling line are described. Special emphasis is given to the emittance increase, caused by high space-charge forces of the low energy proton beam.

Description of the Funneling Line

The design of any funneling line must fulfill several tasks[3]:

- the two beam centers must be brought to a common axis and stay there,
- the longitudinal phase width has to be decreased by a factor 2 due to the frequency jump of the next accelerator,
- the beam has to be matched longitudinally and transversely into the following structure.

Due to the high space-charge forces of a low energy proton beam the focusing conditions are quite severe in that part of the line where the phase width has to be decreased.

We first discuss the position of the elements and the combination of the two beams. Afterwards numerical results, obtained from the fully 3 dimensional multiparticle simulation code MOTION[4] are given for the beam envelopes and especially for the emittance increase.

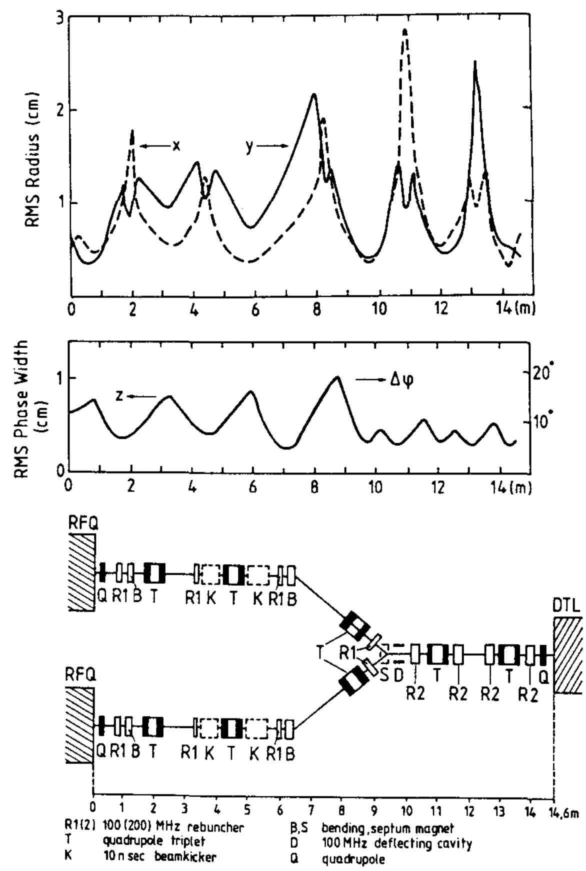

Fig. 1 rms radii along the funneling line

Combination of the Two Beams

The funneling line starts after two identical 100 MHz RFQ-structures, see fig. 1. The beam energy is 2 MeV, and the current is 100 mA. The two beams are 180° out of phase.

Both beams are then transported over the first 9 m in two separated, but identical transport lines. Here diagnostic equipment is located for measuring the beam quality coming out of the RFQ. The transverse and longitudinal emittances are measured in a separated beam line which starts at the bending magnet located at 1.2 m.

At 3.5 m, fast beam kickers (rise time: 10 nsec) are positioned. The 10 nsec rise time corresponds to one period of the chosen accelerating frequency of 100 MHz for the previous RFQ structure. In the kicker elements, the beams are only separated in phase-space, but not in real space.

If we apply a voltage $\pm U$ to the kicker plates and we use an aperture twice as the beam radius, then for separating the beams the product U·L is given by[5]:

$$U \cdot L = 2 \cdot E^{nor} \cdot \beta \cdot \frac{mc^2}{q}$$

L : length of the kicker

E^{nor} : total normalized emittance

For the design value of $E^{nor} = 4\ \pi$ mm mrad, β = 6.52 % (E_{kin} = 2 MeV), we obtain

$$U \cdot L = 490\ V \cdot m$$

As the voltage gain is limited to about $100 \frac{V}{nsec}$ [6], we only can get about 1 kV in 10 nsec. Therefore the length of the beam kicker is at least 0.5 m.

In the actual design of the funneling line about 1.6 m total length are foreseen. Not shown is the needed collector. This element should be placed around 6 m between the rebunching cavity and the bending magnet. This part of the line is not optimized as yet.

After 6.2 m, both beams are bent to the common axis by 30° bending magnets. At 9 m, the beams are then so close to each other that from this point on we only have one common line for both beams.

The beam displacement from the common axis is further reduced by a 20° septum magnet.[3] Then by two rf-deflecting cavities[3] both beams are brought to a common axis and stay there. These rf-cavities operate at 100 MHz, their length is $\frac{\beta\lambda}{2}$ = 10 cm. They have a sinusoidal deflecting field strength, the peak deflecting gradient is 5 MV/m. The field changes its sign from bunch to bunch if the bunches are 180° out of phase. The cavities itself are phased in such a way that each beam sees one full half cycle of the sinusoidal field strength. With such a phasing we get the maximum deflecting effect and only second order transverse-longitudinal coupling effects are present[3]. With two rf-deflecting cavities, we obtain a deflecting angle of 160 mrad. A design of such a cavity is given in Ref. 7.

After combining the two beams together within 1.2 m, the beam is now transported to the entrance of the 200 MHz Alvarez accelerator. In this part of the linac we have to use 200 MHz rebunching cavities instead of the previous 100 MHz ones. At 12 m, 50 cm space is foreseen for diagnostic equipment[8]. The matching into the Alvarez structure is transversely done by the last single quadrupole, longitudinally we use the last rebunching cavity.

Along the whole funneling line, the beam is transversely focused by triplets which have a magnetic field gradient about 5-7 T/m. These triplets consists of 10 and 20 cm long quadrupoles, separated by 10 cm drift space.

The rebunching cavities have a field strength E_0T of about 2 MV/m (for 100 MHz) or 1 MV/m (200 MHz). The length of these elements are 10 cm or 30 cm respectively.

Beam Envelopes

In fig. 1, the transverse and the longitudinal rms radii are given together with the position of the elements. All numerical results are obtained with the fully 3 dimensional multiparticle simulation code MOTION[4].

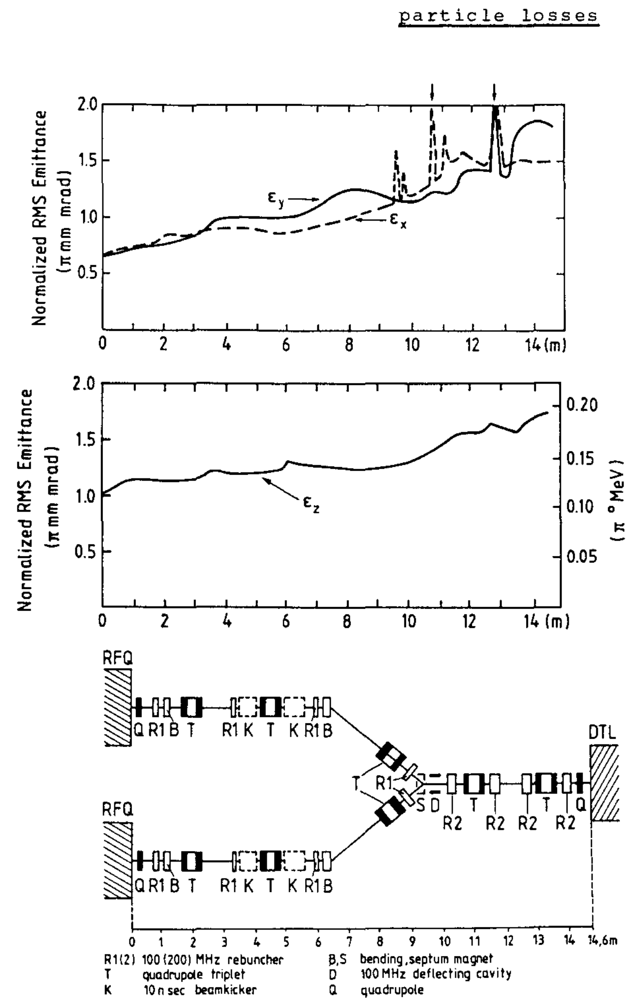

Fig. 2: rms emittances along the funneling line

In order to avoid nonlinear fields in the rebunching elements, the total phase width should not exceed $\pm$ 35°. A very similar relation is valid for the transverse radius. Here the $I_0\left(\frac{2\pi}{\beta\gamma\lambda} \cdot r\right)$ function causes this radius dependence of the rebunching field. In the 100 MHz rebunching cavities, the total radius should not exceed 2 cm, whereas this limit is 1 cm in the 200 MHz cavities. In order to stay below these limits simultaneously, a triplet focusing scheme was chosen. With such a scheme we almost get a round beam inside the rebunching cavities.

In the actual design, the longitudinal rms phase width stays below $\pm$ 20°, the transverse rms radii stay below 1 cm in the 100 MHz rebunching cavities. With these values we almost see no emittance increase. In the 200 MHz rebunching cavities, due to the high space-charge forces it was not possible to keep the transverse rms radii below 0.5 cm. Here the rms radii change from 0.8 to 0.5 cm which causes some emittance increase.

At the end of the funneling line we have a quite well matched beam in all 3 directions for the following Alvarez structure[8].

	Z = 0.0 m	Z = 8.7 m $\hat{=}$ 45 $\beta\lambda$			Z = 14.6 m $\hat{=}$ 75 $\beta\lambda$		
	ε	ε	μ	$(\overline{\frac{\mu}{\mu_o}})$	ε	μ	$(\overline{\frac{\mu}{\mu_o}})$
x	0.66	1.0	155	0.48	1.48	366	0.6
y	0.66	1.23	91	0.3	1.64	273	0.43
z	1.0	1.21	490	0.64	1.68	1340	0.9

ε : normalized rms emittance / π mm mrad

μ : phase advance / °

$(\overline{\frac{\mu}{\mu_o}})$: average phase advance depression

Table 1 emittances and phase advance at certain positions along the funneling line

Emittance Increase

In fig. 2, the normalized transverse and longitudinal rms emittances are plotted. The calculations are made with two independent waterbag distributions of the particles, one for the transverse and one for the longitudinal direction.

In table 1, the rms emittances are listed at the beginning, after 8.7 m, and at the end. Also given[9] are the values for the phase advance and for the average phase advance depression. In a nonperiodic transport line the phase advance describes how fast the particles oscillate whereas the phase advance depression determines the importance of the space-charge forces.

For understanding the emittance increase, the funneling line can be divided into two parts. Along the first 8.7 m the initial particle distribution has adapted almost itself under the influence of the strong space-charge forces to an equilibrium distribution[9]. This can be seen either by looking at the ε_z or ε_y emittances or by looking at ratios between the total and the rms emittances (not shown). In z-direction, where we have the smallest emittance increase up to 8.7 m, the phase advance is high[9] and the average phase advance depression is small. A high phase advance means a small beam radius. The length of 8.7 m corresponds to 45 $\beta\lambda$, where $\beta\lambda$ is the 'natural' scale of a bunched beam.

Now the beam could be transported furthermore without emittance increase if only linear external forces would be present[9]. But this is not the case in the following rebunching and deflecting elements.

Due to the sinusoidal deflecting field strength E_x, the rf-deflectors cause some emittance increase in x-direction. The deflectors are located at 9.5 m. More severe are the following 200 MHz rebunching cavities, positioned after 10 m. Particles which had acceptable phase width before, will now cause emittance increase due to the frequency jump from 100 to 200 MHz.

Most of the emittance increase from 8.7 m on, especially the wild oscillations of the transverse emittances after 10 m, are due to these nonlinearities and not due to space-charge forces. Therefore we see in table 1, that from 8.7 m on we have much more emittance increase although the average phase advance depression is less.

At the end of the funneling line the obtained emittances can be handled by the following Alvarez structure[8]. About 1 % of the particles are lost.

The obtained adaption of the bunched beam to a self-consistent distribution[9] is very similar to the results seen by transporting an unbunched beam in a periodic channel[10]. Specially the fact that the emittance increase depends on the phase advance depression (for a nonperiodic transport line) or on the tune depression (for a periodic channel).

The obtained emittance increase might not be true because the calculations were made with a waterbag distribution. But the particle distribution produced by the RFQ structure in front of the funneling line is certainly not a waterbag distribution[2]. Calculations are going on to transport the outcoming beam of the RFQ through the funneling line.

Summary

A design study was made for a 2 MeV, 100 mA proton beam funneling line. The emittance behaviour can be understood as the adaption of the beam to a self-consistent distribution over the first 8.7 m. Then furthermore nonlinear rebunching and deflecting fields cause emittance increase. However at the end of this line, we have a matched beam for the following Alvarez accelerator with acceptable emittances.

Acknowledgement

The author thanks H.G. Hereward and M. Pabst for numerous stimulating discussions. He appreciates all the help from U. Funk and M. Wagner in doing the numerical calculations. He thanks M. Reiser, University of Maryland, for pointing out the importance of the phase advance depression.

References

1. C. Zettler, Proc. 1984 Linear Accelerator Conf., Darmstadt, 1984
2. R. Lehmann, Proc. 1984 LAC
3. K. Bongardt, D. Sanitz, "Funneling of Heavy Ion Beams", Proc. of the Symp. on Accelerator Aspects of Heavy Ion Fusion 1982, GSI-Report 82-8, Ed. D. Böhne
4. K. Mittag, D. Sanitz, "MOTION - A Versatile Multiparticle Simulation Code", Proc. 1981 Linear Accelerator Conf., Santa Fe 1981.
5. G. Schaffer, "Rapid Beam Switching Techniques", Proc. ICANS-Meeting 1981, Karlsruhe 1981
6. J.S. Lunsford, R.A. Hardekopf, "Pulsed Beam Chopper for the PSR at LAMPF", Proc. Particle Accelerator Conf. 1983, Santa Fe 1983
7. J. Schelten, internal SNQ/ABT-note 9/84, KFA Juelich 1984
8. M. Pabst, Proc. 1984 LAC
9. K. Bongardt, "Emittance Growth of High Current Beams in Transport Lines", Proc. 1983 PAC
10. for example: J. Struckmeier, J. Klabunde, M. Reiser, Proc. 1984 LAC