# CONCEPTUAL DESIGN OF RECIRCULATOR RING FOR ELECTRON COOLING AT PETRA-P

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*Abstract*

Electron cooling is being discussed as a method to reduce the emittance of hadron beams in the PETRA pre-accelerator ring for HERA. In connection with a linac based cooler scheme,it is desirable to use a re-circulator for the electron bunches in order to reduce the average beam current,which must be delivered by the linac. A possible design for such a re-circulator ring with 50m long solenoid in the cooling section is presented in this paper.

## 1 INTRODUCTION

A few years ago a program was initiated to study the possibilities to increase the luminosity of the HERA e-p colider[1]. One proposal to improve the luminosity of HERA is to apply electron cooling[2]. During the last few years a scheme has been worked out to achieve a substantial increase in luminosity[3, 4]. An essential part of this scheme is an electron cooler for PETRA[5, 6]. Efficient cooling requires an electron beam of excellent quality - i.e. an electron beam with very small transverse emittances and a small energy spread - and a repetition rate of the linac of $10MHz$ . So in principle the repetition rate of the electron source - either a termionic or an rf gun - has to be $10MHz$ as well. Whether such a high repetition rate is feasible is questionable in case of the thermionic gun but is certainly not realisable in the case of rf gun.To lower the repetition rate the electron bunches are not only used once for cooling but several times. The electrons,therefore, have to be stored in a circular machine called recirculator for $100-1000$ turns. During the storage of the electrons one has to insure that the beam quality of the electrons is not spoiled which has strong implication for the design and layout of the recirculator. In the following sections the features of the magnetic lattice and the optics of the recirculator will be presented.

## 2 BASIC REQUIREMENTS AND FEATURES OF RECIRCULATOR RING

It is well known[7] that the presence of a longitudinal magnetic field in a cooling section leads to an essential growth of cooling rates. On other hand,the solenoidal magnetic field is necessary to counteract the destructive space charge forces of the electron beam. So the magnetic lattice of the recirculator ring has to be designed to satisfy the demands of round beam transportation optics (angular momentum conservation law-Bush's theorem,equal transverse emittances etc.). One can formulate the main requirements to the lattice design as follows:

1.The proton and electron beams should have similar transverse dimensions and angles in the cooling section so that the cooling proceed efficiently (that means the electron beam must have a transverse emittance of the order $10^{-6}mrad$ and beta values about ten's of meters).

2.The dispersion free cooling section to avoid the intra-beam scattering heating effect on transverse emittance [9].

3.A nearly isochronous magnetic lattice to avoid beam debunching.

The existing PETRA tunnel allows one to install a $50m$ long cooling section and short (about $1.5m$ long) arcs. The length of the machine has to be a multiple of the distance between proton bunches,and to fit in existing PETRA tunnel. There are three bunches orbitting in the ring simultaneously. As a first step we have chosen a simple magnetic lattice mainly consisting of solenoids that fullfils requirements (1) and (3) but doesn't fullfil requirement(2). This problem will be discussed in section (4).The design parameters of the recirculator ring are listed in Table 1 and a schematic layout is shown in Fig1.

Table 1: Design parameters of recirculator

| Parameter type | Unit | Value |
|---|---|---|
| Circumference | m | 97.89 |
| Cool.sect.length | m | 47.46 |
| Bend.radius | m | 0.25 |
| Magn.field in bends | T | 0.139 |
| Magn.field index(n) | - | 0.5 |
| Magn.field in solen. | T | 0.063 |
| Focus.quad.$k$ value | m$^{-2}$ | 1.69 |
| Defoc.quad.$k$ value | m$^{-2}$ | 1.32 |
| Drift section length (L1) | m | 1.2 |
| Drift section length (L2) | m | 2.155 |
| Quad.magnet length | m | 0.25 |

The ring has two $47.5m$ long straight sections,one is used for cooling and the other one for electron beam injection and extraction. Each arc consists of two 90-degree combine function bending magnets with bending radius $r = 0.25m$ and magnetic field index $n = 0.5$, and a $0.7m$ long solenoid. The bending magnets with $n = 0.5$ and the solenoids define an axial symmetric optical system. The quadrupole triplet located in the middle of the straight section provide two long drift sections $(L2 = 2.155m)$ for beam injection and extraction and serve also for beam fine tuning.The arrangement of the quadrupole magnets and the ratio of their gradients are taken according to the formula (in thin lens approximation)

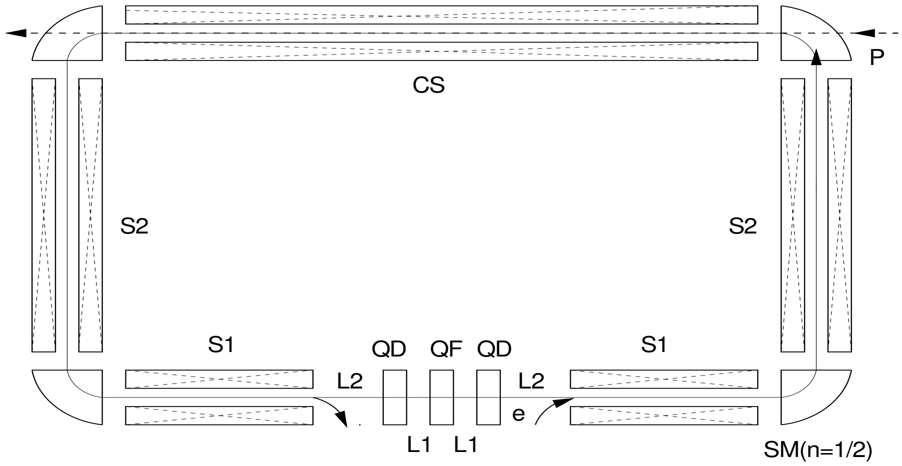


Figure 1: Schematic layout of Recirculator (not to scale).

$$(g_F/g_D)^2 = 2(1+a)/(1+2a) \qquad (1)$$

where $g_F$ and $g_D$ are focusing and defocusing quadrupole magnet gradients,respectively,and $a = L1/L2$. Eq.(1) guarantees perfect optical matching between both ends of the straight section. At the two ends of the bending magnets short drifts are foreseen for BPM's and correction magnets. Because of negligible radiation losses the ring doesn't contain any acceleration sections.

## 3 DETERMINATION OF OPTICAL PARAMETERS

As one can see from Fig.1 we have one superperiod of iso-magnetic lattice. In linear approximation the equation of motion in matrix form is

$$Y'(s) - A(s) \cdot Y(s) = \delta \cdot K(s) \qquad (2)$$

where $Y^T = (x, x', z, z')$ is the 4D particle state vector,describing betatron motion around the reference orbit, $x$ and $z$- are horizontal and vertical coordinates,respectively and the prime ($'$) denotes the derivative with the respect to the longitudinal coordinate $s$. The matrix $A(s)$ describes the magnetic element arrangement along the ring and its focusing properties (in linear approximation the box-shaped longitudinal magnetic field distribution for all magnets is considered). The 4D vector $K(s)$ on the right hand side of eq.(2) is $K^T = (0, R^{-1}, 0, 0)$ for the bending magnets and $K^T = (0)$ otherwise,$R$ is the radius of curvature in bends and $\delta$ is the momentum spread. To solve equation (2) we use a 4D matrix formalism. The optical parameters of the particle motion are calculated by a computer code (written on the basis of Maple) using Ripken's theory[8] of coupled motion. For the solenoids we use transfer matrices in hard edge approximation,which is justified because of the small ratio of solenoid diameter to length. To investigate the stability of the electron beam motion we solve the eigenvector problem for the one turn transfer matrix taken from eq.(2). The stability of motion depends on the two lattice parameters namely $k_F = eg/p$ and $k_S = eB/2p$. We found out that the stability depends more strongly on the field strength of the solenoids than on the field of the quadrupoles. The required accuracy of the solenoid field is $\Delta H/H \leq 10^{-3}$ while the required accuracy of the quadrupole gradient is $\Delta g/g \leq 10^{-2}$.

The working point $Q_I$= 5.63 and $Q_{II}$= 5.37 are chosen corresponding to the magnetic field value in solenoids $B_0$ = 633 Gs. For the beta-values in cooling section we have $\beta_{zI} = \beta_{xI} \approx 16m$, and $\beta_{zII} = \beta_{xII} \approx 20m$;and for the transverse emittances at the entrance of cooling section $\varepsilon_I \approx \varepsilon_{II} = 4\pi mmmrad$. We have a round electron beam of radius $r = 3mm$ entering the cooling section. In Fig.2 the projection of the 4D phase ellipsoid onto the $x{-}x'$ plane at the entrance of cooling section is plotted (the $z-z'$ projection is the same because of symmetry).The area of these ellipses in case of coupled motion is not an integral of motion but gives the value of transverse emittances at a given position.

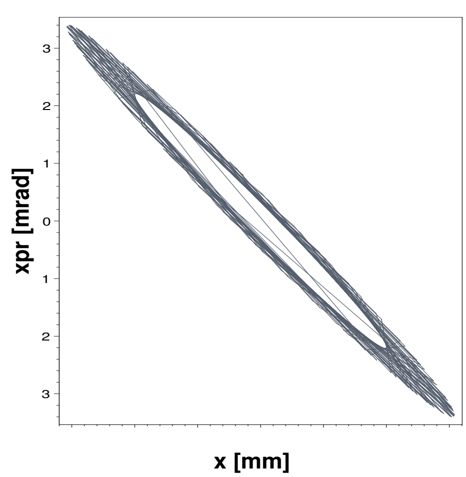


Figure 2: Phase ellipsoid projection onto x-x'plane

The calculated values of the momentum compaction factor is $\alpha = 0.017$ so gamma transition is $\gamma_{tr} \approx 7$. This value is small enough, so that debunching of the electron beam is no problem. To calculate the chromaticity the following formula [8] is used

$$\xi_{I,II} = -1/2\pi \cdot \int_0^C ds \cdot \vec{V}_k^+(s) \cdot \underline{S} \cdot B(s) \cdot \vec{V}_k(s) \quad (3)$$

where $\vec{V}_k, (k = I, II)$ are eigenvectors of the transfer matrix in case of stable motion, $\underline{S}$ is the unit symplectic matrix. We obtain a chromaticity of $\xi_I$=$\xi_{II} \approx 17.9$ for both modes and the corresponding tune shifts are $\Delta Q_I = \Delta Q_{II} = 0.0089$ which are tolerable. The fact that the chromaticity is positive is due to solenoids.

## 4 DISPERSION CANCELLATION

The preliminary magnetic lattice has one disadvantage namely the cooling section is not dispersion free. The maximal value of the horizontal periodical dispersion in cooling section is $D_{xmax} = 5m$ and the average value is $< D_x >= 3m$.

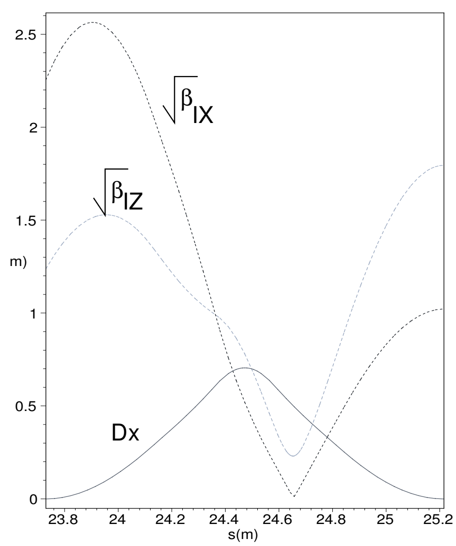


Figure 3: Lattice functions of the arc

In order to get no dispersion in the cooling section the solenoid (S2) in the arc is replaced by a quadrupole triplet. The arc is then turned into a linear achromat. The main parameters of the quadrupole triplet are listed in Table 2. The lattice functions ($\beta_{xI}$,$\beta_{xII}$ and $D_x$) of the arc are plotted in fig.3. Unfortunately a quadrupole triplet in the arcs doesn't satisfy condition (1) and so we have slightly disturbed the axial symmetry of the lattice.

To restore the axial symmetry in the cooling section additional quadrupole magnets have to be installed at both ends of cooling section.

The Matlab based computer code has been extended to investigate nonlinear beam dynamics and space charge effects. Taking into account the possibility of dispersion cooling [9] as well as the first results of nonlinear simulations we conclude that the preliminary version of the recirculator with small dispersion in the cooling section can lead to appreciable cooling rates.

Table 2: Arc triplet parameters

| Parameter | Length | Gradient |
|---|---|---|
| Focusing quadrupole | 0.2m | 4.82m$^{-2}$ |
| Defocus. quadrupole | 0.15m | 2.09m$^{-2}$ |
| Drift L3 | 0.07m | - |
| Drift L4 | 0.03m | - |

## 5 CONCLUSION

We found a recirculator design incorporating the cooling section. It is suitable for e-cooling of protons in PETRA in the energy region $18 - 20GeV$. The lattice consists of solenoids,drifts and combined function bending magnets thus providing tranquil electron motion inside the cooling section. The problem of electron beam injection and extraction and the study of nonlinear and space charge effects are under ongoing investigation.

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