Possibility of High Brightness Micro-beam by a Combination of a Linac and an Ion Stretcher and Cooler Ring

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Abstract

Possibility of providing a micro-proton beam usable for elemental analysis by a combination of a ring and a linear accelerator is studied. The duty factor, repetition rate and brightness of the beam are expected to be ~100%, 180 Hz and 0.34 pA/(μm^2·mrad^2), respectively for *Stretcher Mode* and ~60%, 1 Hz and 0.11 pA/(μm^2·mrad^2), respectively for *Cooler Mode*.

I. INTRODUCTION

At Institute for Chemical Research, Kyoto University, an ion linear accelerator, which can accelerate protons up to 7 MeV, is operating from the beginning of 1992[1]. The pulse duration of the beam from the linac is 50 μsec and the repetition rate is 180 Hz at its maximum. So the maximum duty factor of the beam is only 0.9%, which imposes some restrictions on usage of the beam, because the detectors are anticipated to be choked by heavy background due to two-orders higher peak-intensity compared with the continuous beam of the same average current. In order to stretch the beam duration, addition of a ring is highly desirable. The ring is also to be used as a cooler ring with installation of an electron cooler which needs only 3.8 kV to cool 7 MeV protons. By application of the electron cooling, the phase space density is expected to be increased by the factors of 80, 60 and 30 in horizontal, vertical and longitudinal phase spaces, respectively. However, in order to utilize the cooled beam as a micro-beam for elemental analysis, the beam is required to be extracted from the ring. The extraction should necessarily be a slow extraction so as to attain the long beam spill time. This process usually utilizes resonance of betatron oscillation in the horizontal direction. So the horizontal beam emittance of the micro-beam is not determined by the emittance of the cooled beam, but by the one of the extracted beam, which largely depends on the extraction method. In the present paper, the combination of an Stretcher/Cooler ring with a linear accelerator is studied in the context of the brightness and duty factor of the beam.

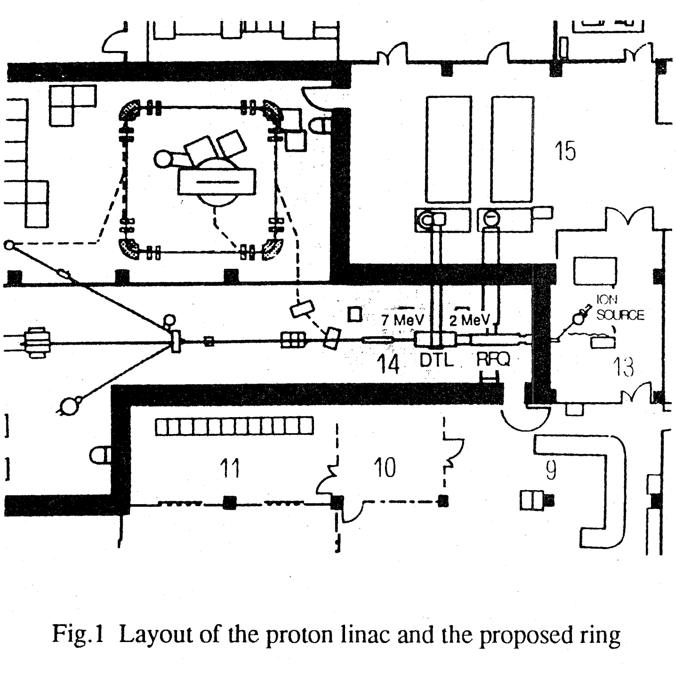

Fig.1 Layout of the proton linac and the proposed ring

II. ACCELERATOR SYSTEM

The layout of the combined system of the linac and the ring proposed here is shown in Fig. 1. As is known from the figure, the complex can be well installed in the existing radiation shielded area. As the purpose of the ring is only to stretch and/or cool down the beam and no acceleration is intended, the average radius of the ring is rather limited as 4.3 m. The radius of curvature of the bending magnet is 0.6 m and the dipole field is at the low level of the 6.4 kG for the 7 MeV proton beam. The length of the long straight section is chosen to be 3.8 m in order to keep necessary space for an electron cooler and injection and extraction equipments. In Table 1, the main parameters of the ring are given. The detailed lattice structure is shown in Fig. 2. The superperiodicity is chosen to be 4, while the mode with superperiod 2 is also to be provided so as to realize doubly achromatic straight sections. Betafunctions and dispersion

Table 1
Main parameters of the Stretcher/Cooler Ring;

Beam Energy	Proton 7 MeV
Average Radius	4.3 m
Circumference	27 m
Radius of curvature of dipole magnet	0.6 m
Magnetic Field of dipole	6.4 kG
Focusing Structure	OFDBDFO
Length of long straight section	3.8 m
Superperiodicity	4 or 2
Betatron Tune	
Horizontal	2.75
Vertical	0.80
Repetition Rate	180 Hz(Stretcher Mode) 1 Hz (Cooler Mode)
Revolution Period	741 ns

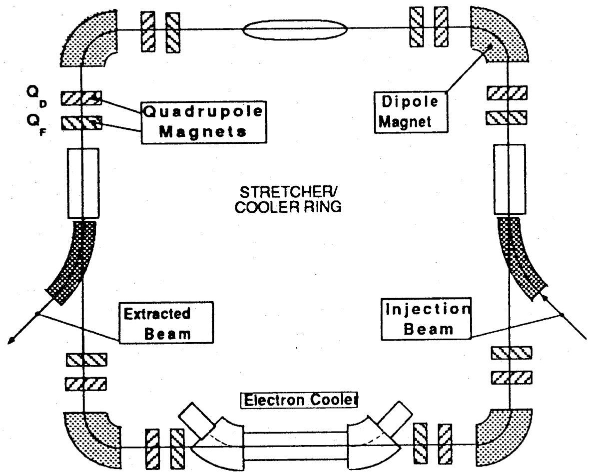

Fig. 2 Layout of the Arrangement of the stretcher/cooler ring

function for one quadrant are shown in Fig. 3(a) and (b), respectively for the operating point of $(Q_H, Q_V)=(2.75, 0.8)$.

Utilizing a stretcher ring, the duty factor of the beam is almost 100 times enlarged and the counting rate of the detector is largely reduced for the same average current, which itself is quite a benefit of the addition of a ring.

III. LIMIT OF THE BEAM COOLING

If an electron cooler is utilized, the phase space density can be increased although the compression factor in the horizontal transverse phase space is to be lost in the process of slow beam extraction from the ring.

A. Beam from the Linac

The energy spread of the 7 MeV proton beam is measured to be ±0.2 MeV [2]. The beam emittance of the 2 MeV beam between the RFQ and DTL is measured to be 42 πmm·mrad and 30 πmm·mrad in horizontal and vertical directions, respectively[3], which is considered not so much increased by the DTL.

B. Space Charge Limit in the Ring

The space charge limit which can be injected into a ring is estimated by the formula,

$$N = \frac{\Delta\nu\sqrt{\varepsilon_H\varepsilon_V}\,\beta^2\gamma^3}{r_p},$$

where β and γ are relativistic factors; ε_H and ε_V are emittances in horizontal and vertical directions, respectively; r_p is a classical radius of proton and $\Delta\nu$ is tune shift due to space charge repulsion. For the present case of 7 MeV proton, β and γ are 0.121 and 1.007, respectively and using the above values of measured emittances of the injected beam, the space charge limit is estimated to be 3.5×10^{10}, where tolerable $\Delta\nu$ is estimated to be 0.10. This intensity can be reached if 7.5 mA (peak current) beam from the linac is injected by single-turn injection. So if the beam from the linac is to be only stretched and used without cooling, the repetition rate of 180 Hz can be attained with duty factor of almost 100 %.

Experimental data tell us the momentum spread of the cooled beam is ~5×10^{-4} for the above beam intensity[4] although it largely depends on the experimental condition. The equilibrium emittance of the cooled beam is estimated to be 0.5 πmm·mrad from the experimental result at TSR[5]. Thus the phase space density is compressed by factors of 30 and 60 in longitudinal and vertical transverse phase spaces, respectively.

C. Cooling time of the Electron Cooling

The energy of the electron which has the same velocity as the 7 MeV proton is as low as 3.8 keV and the current density of the electrons cannot be increased so much in order to suppress the transverse gradient of the longitudinal electron velocities. So the electron current density is estimated to be 0.01 A/cm^2 [6].

The cooling time can be estimated by the formula[7]

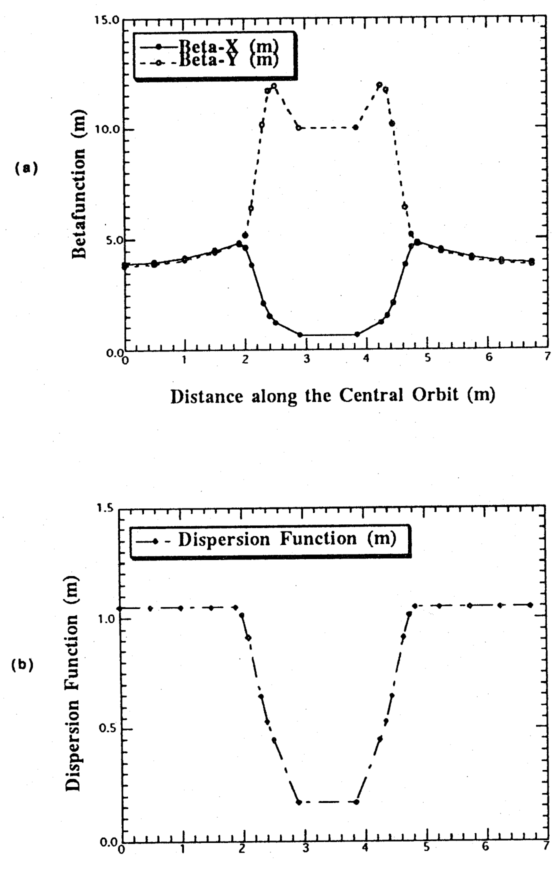

Fig. 3 Betafunctions (a) and dispersion function (b) in a quadrant of the ring.

$$\tau_e = k\frac{\beta^4\gamma^5 e(\theta_e^{\ 2}+\theta_i^{\ 2})^{3/2}}{r_p r_e \eta L_c j},$$

where β and γ are as above; θe, θi are transverse divergences of electron and ion, respectively; r_p and r_e are classical radii of proton and electron, respectively, η is the length ratio between the cooling section and the circumference; L_c is the Coulomb logarithm and j(A/m^2)is the current density of the electron beam and k is the constant to be 0.6 for spherical Maxwellian electron velocity distribution and 0.16 for a flattened distribution[8]. The cooling time is estimated to be 0.35 sec. for the flattened distribution, where 2.7 mrad, 2/27 and 0.01 A/cm^2 are used as values of θi (θe≤θi), η and j, respectively. Thus the injected beam is e-cooled in 0.4 sec. and then slowly extracted with spill time of 0.6 sec. realizing the beam duty factor of 60 % with repetition rate of 1 Hz. In Table 2, main parameters of the electron cooling system are given.

IV. SLOW BEAM EXTRACTION

In order to realize a micro-beam, very small emittance is required. The slow extraction utilizes the resonance of betatron oscillation and the usual method, which drives the operating point closer to the resonance as the extraction proceeds, results in a rather larger time-integrated beam emittance. Recently a new scheme of resonant extraction keeping the separatrix size to be constant is proposed[9,10] in order to realize a small emittance of extracted beam and this scheme has already been partially tested experimentally with success[11]. By the application of this method, the extracted beam emittance of 0.1 πmm·mrad is expected[12].

V.QUALITY OF THE AVAILABLE BEAM

Addition of a ring to the existing linac of 7 MeV proton makes two possibilities; one is a *Stretcher Mode* where the phase space density is not changed and only the duty factor of the beam is increased to almost 100 %. The other is a *Cooler Mode* which apply cooling to the injected beam although the repetition rate and duty factor are reduced to 1 Hz and 60%, respectively reflecting the fact the cooling time is rather long.

A. Stretcher Mode

With this mode, beams with the intensity of 3.5×10^{10} are injected into the ring with 180 Hz. As the beam is single turn injected, the beam emittance from the linac is kept into the ring. The horizontal beam emittance of the extracted beam is determined by the slow extraction process and is estimated to be 0.1 πmm·mrad. Thus 1μA beam is delivered into the emittance size of 0.1 πmm·mrad and 30πmm·mrad. in horizontal and vertical directions, respectively, which results in a beam brightness of the size of 0.34 pA/(μm^2·$mrad^2$). This value is comparable with the micro-beam utilized for the PIXE at Max-Planck-Institut for Kernphysik, Heidelberg [13], although the vertical beam emittance is not small enough to focus the beam into μm size.

B. Cooler Mode

With this mode, the repetition rate and duty factor are reduced to 1 Hz and ~60 %, respectively owing to a rather long cooling time of the electron cooling. The circulating beam emittance is expected to be reduced to 0.5 πmm·mrad, while the horizontal emittance of the extracted beam is 0.1 πmm·mrad. In this case 3.5×10^{10} protons are delivered to the target in every second, so the brightness of the beam is 0.11 pA/(μm^2·$mrad^2$), which is a little smaller compared with the *Stretcher Mode*. This is due to the lower repetition rate, although the beam emittance is cooled down to a small value.

Table 2
Main Parameters of the Electron Cooler

Electron Energy	3.8 keV
Electron Current	0.05 A
Electron Current Density	0.01 A/cm^2
Electron Beam Size	2.6 cmφ
Length of cooling section	2 m
Cooling Time	0.35 sec

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