SIMULATION OF BEAMS IN TARN II WITH A SOLID TARGET

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Summary

An employment of a solid target is proposed for nuclear physics experiments at TARN II. The electron cooling is used to provide beams of very small emittance. The characteristics of the circulating proton beams are investigated by a computer simulation. The proton energy is taken to be 200, 600 and 1000MeV. The rf acceleration is used to compensate the energy loss of the beams by the target. The energy resolution of the beam on the target is controlled by adjusting a target position and a beam collimator at an achromatic waist point in the ring. The present result shows that using 10^{8} protons in the ring at 1000 MeV, the luminosity $10^{30}cm^{-2}sec^{-1}$ for 0.2sec is obtained with Ni target($20\mu g/cm^{2}$) on the carbon backing($5\mu g/cm^{2}$) and 10^{29} $cm^{-2}sec^{-1}$ for 0.2sec with Pb target($10\mu g/cm^{2}$) on the same backing, while the beam momentum resolution on the target is kept within $2x10^{-4}$ range. Energy loss cooling plays an important role to obtain the good momentum resolution.

Introduction

On the basis of the study using a beam accumulator ring TARN[1] a heavy ion synchrotron-cooler ring TARN II is under construction at Institute for Nuclear Study (INS), University of Tokyo. TARN II is designed to accelerate protons from the SF cyclotron up to 1300MeV and light heavy ions with a charge to mass ratio of 1/2 up to 450 MeV/u (Synchrotoron mode). It is also aimed to cool the stored beam by an electron cooling as well as by a stochastic cooling (Cooler ring mode).

The electron cooling system at TARN II is used to cool down the emittance and the momentum spread of the circulating protons of 200MeV. It is to be noted that, since the thickness of the internal target tolerable in electron cooling is limited below several ten's ng/cm^{2}, some specific target techniques such as those for gas jet, fibers, liquid drops and micro particles have been considered and developed in cooler ring facilities. The micro particle target has been demonstrated to work at INS.

However, if a conventional solid target can be used as an internal target for cooler ring experiments, the scope of the experiment will be extremely expanded. This is clear, for instance, from the fact that an enriched isotope is not so easily handled in the specific target techniques mentioned above. Experiments with a relatively thick target have been proposed,[2] in which a possibility of high luminosity experiments is discussed. We propose, here, a method to employ a solid target in cooler ring experiments with a good momentum resolution. The energy loss of circulating beams caused by collisions with the target is compensated by means of the rf acceleration. In the present paper, the characteristics of the circulating beams are investigated by a computer simulation and several numerical numbers of importance for experiments are worked out.

Experimental Method

The target is prepared as shown in Fig.1. The left side of the frame is removed, which allows the beam to be steered without hitting the target frame. The target point is designed to have a high dispersion and low beta functions. The target is positioned off the central orbit so that the beam can be injected and accelerated without hitting the target. The beam cycle in the present method is shown in Fig.2. The beam is processed injection, acceleration to an optimum energy for cooling, cooling and second acceleration to the final energy. By virtue of electron cooling, the beam has a very small emittance even after the second acceleration. This small emittance of the beam is one of the very crusial points in the present method. At the end of the second acceleration, all the excitation currents of magnets is fixed at values corresponding to the momentum P(origin point O in Fig.1). On the other hand, the rf acceleration continues further until the beam has the momentum $P+\Delta P_1$(point C). The rf frequency is then slightly increased to match with the momentum $P+\Delta P$(point B), which induces a synchrotron oscillation. Without the target, the beam is driven horizontally like C - E - B - A - B in Fig.1 by synchrotron oscillation in conjuction with the high dispersion at the target position and small betatron oscillation of the cooled beam. The points A (corresponding to $P+\Delta Pmin$) and C($P+\Delta Pmax$) slightly shift depending on the starting position in the longitudinal phase space. The target is placed such that only the beams with the momentum higher than $P+\Delta Pt$ hit the target. Therefore the beam, getting energy , soon starts to hit the target. Since the target employed is so thin, the energy loss and the multiple scattering of the beam in the target do not change the global feature of the synchrotron oscillation. There occurs, however, a shrinkage of the longitudinal phase space area due to the energy loss . Details of the process are discussed below.

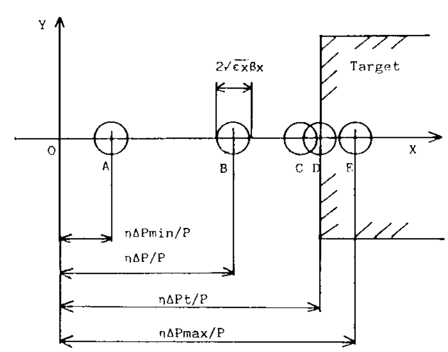

Fig.1 Geometry of the circulating beam and target. η represents the dispersion function at the target position. The beam momentum varies from $P+\Delta Pmin$ to $P+\Delta Pmax$ due to the synchrotron oscillation.

After a certain number of turns, an accumulation of the energy straggling and the multiple scattering of each turn grows to such an extent that the beam resolution and emittance becomes worse, althouth the energy resolution of the beam on the target stays almost constant. A collimator at other position with high beta and a low dispersion functions is used to stop the growing part of the beam in the emittance. When the number of partcles on the target decreases below a certain value, the rf frequency is again slightly increased so as to bring new particles to the target. The process continues until all particles are wasted.

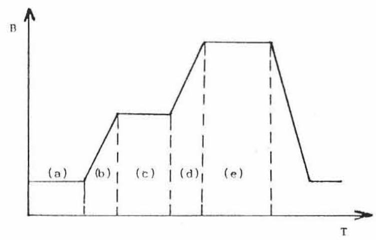

Fig.2 A schematic operation pattern of TARN II.
(a) injection (b) acceleration (c) cooling
(d) second acceleration (e) experiment

Simulation

The characteristics of the beam in this method is investigated by a computer simulation using FACOM M380R at the INS Computer Center. Some prescriptions and assumptions taken into this simulation are summarized below.

(1) The energy loss is described in terms of Vavilov distribution[3] This statistical process is simulated by Monte Carlo method.

(2) The multiple scattering is described as a sequence of a single collision process which is treated in a microscopic way. In the formalism, an approximation of a small angle scattering is taken and the relativistic kinematics and transformation between laboratory and center of mass system are properly considered[4] The Monte Carlo method is again used to give a scattering angle and a penetration length between two collisions.

(3) The closed orbit distortion caused by the limiting stability of the power supplies and higher order effect in ion optics are neglected.

(4) The field in the accelaration gap of the rf cavity has only the component parallel to the central orbit and the impulse acceleration is employed.

(5) The scattering effect by the resudial gas in the ring is neglected.

Parameters used in this simulation are summarized in Table 1.

Table 1 Parameters used in this simulation

Proton energy	200,600,1000MeV		
Number of protons	10^8		
Beam emittance		Hori.	Vert.
(mm•mrad)		0.1π	0.1π
Betatron tune value		1.75	1.25
Target	Pb, Ni, C		
Target position	51.3mm from the central orbit		
Beta function		1.46m	2.63m
Dispersion function		4.68m	0.0
Collimator aperture	10mmx50mm		
Beta function		36.4m	20.9m
Dispersion fuction		0.0	0.0
The rf voltage	1.0kV		
Synchronous phase	0 deg.		

Energy loss cooling

The shrinkage of the momentum spread of the beam due to the energy loss in the target - the energy loss cooling - is observed in the simulation as shown,in Fig.3. This is a trace of one proton in the longitudional phase space. The proton energy is 200MeV and the target is ^{208}Pb(10μg/cm^2) on the carbon backing (5μg/cm^2). The two beta functions βx, βy and the dispersion function η at the target are 1.46m, 2.67m and 4.68m, respectively. These are the design parameters for the Cooler ring mode of TARN II. The proton starts at point S in Fig.3 with no divergence angle. The rf peak voltage is 1kV. Without the target, the proton moves along the outermost curve of a normal synchrotron oscillation. With the target, the energy loss always works to bring the curve inward because the proton hits the target only when its momentum is higher than the average. Note that the multiple scattering does not change the general feature shown in the figure because the large angle scattering seldom occurs in such a thin target as the present one.

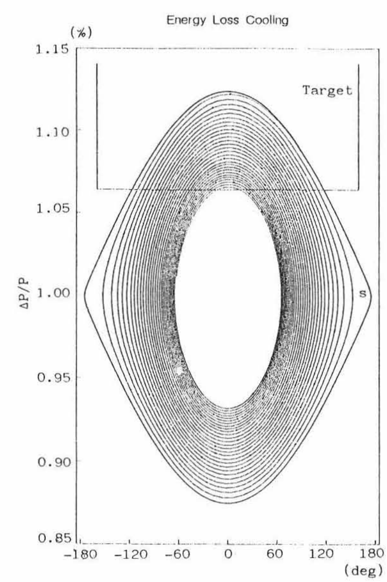

Fig.3 The shrinkage of momentum spread by the energy loss in a Pb target(10μg/cm^2) on the carbon backing(5μg/cm^2) for 200MeV proton circulating over 5x10^4 turns. The outermost curve shows the synchrotron oscillation without the target and the spiral one with the target.

Result

The momentum resolution and the luminosity attainable in the present method are worked out at proton energies of 200, 600 and 1000MeV for Pb target on the carbon backing(5μg/cm^2), for Ni target on the same backing and for self supporting C target. The 10^8 protons are assumed to have an emittance of 0.1π mm•mrad. The energy loss spectrum and angular distribution of a multiple scattering used in the simulation are shown in Fig.4 for the case of 1000MeV proton on the Ni target(20μg/cm^2), as an example.

The resolution and the peak momentum of the beam hitting the target , which are obtained by averaging over every 12000 turns, are plotted in Fig.5 for the Ni target at 1000MeV. Note that the horizontal numbers correspond to the elapsing time, but not the collision times. The vertical bars give the FWHM of the momentum resolutions of the hitting beams and the dots give the peak momenta. There is no drastic difference between results with and without a collimator. Fig.6 shows the collision rates as a function of elapsing time. This is one of the most important results of the present method, which means, collision rates do not change drastically over 120000 turns. The momentum spectra of the hitting beams are shown in Fig.7 for the 1st, 6th, and 12th 12000 turns. They correspond qualitatively to the product of two ordinates in Fig.5 and Fig.6 versus central momenta in Fig.6 . The closed circle curve gives the overall resolution of the hitting beams.

The results are summarized in Fig.8, in which the luminosity multiplied by beam life is plotted as a function of the experimental resolustion for the Pb,Ni and C targets. Simulation for other target thickness were aslo made, from which we found that the luminosity multiplied by beam life is rather independent of the target thickness as far as the experimental resolution is kept constant. From this fact we can select the target thickness from the view point of the counting rate, not from the experimental resolution.

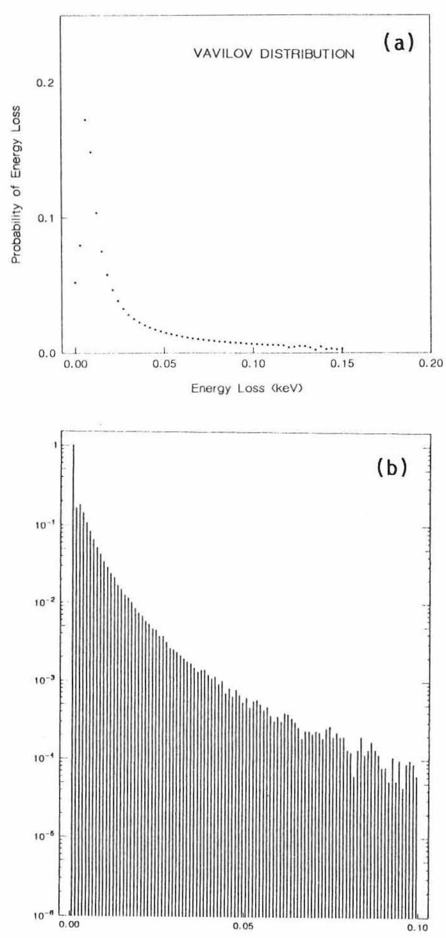

Fig.4 Collision of 1000MeV protons with Ni target of 20(μg/cm²) thickness, (a) Energy loss spectrum (b) Angular distribution of multiple scattering.

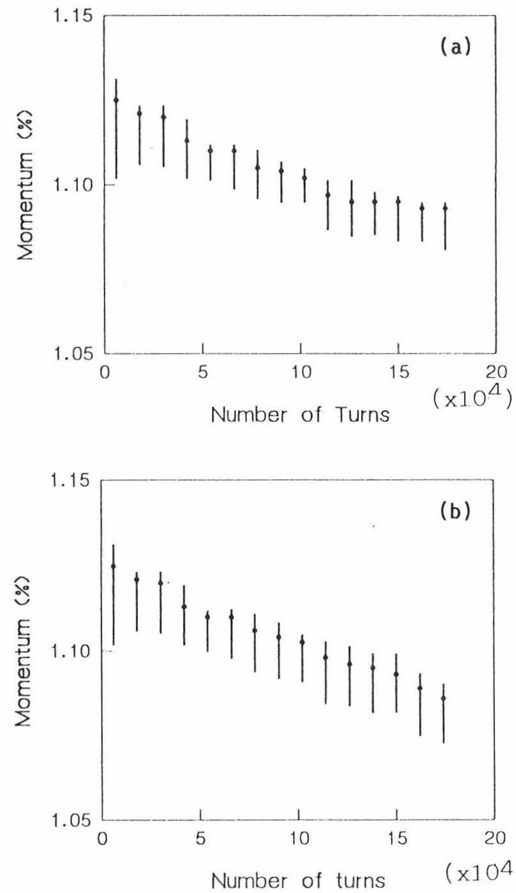

Fig.5 The momentum resolution of the beam hitting the target versus number of turns. Beams are 10^8 protons in the ring at 1000MeV and the target is Ni(20μg/cm²) on the carbon backing(5μg/cm²). This combination is also used in Fig.6 and Fig.7. Bars and points indicate the momentum resolutions(FWHM) and the peak momenta in the momentum distribution, respectively.
(a) with a collimator (b) without a collimator.

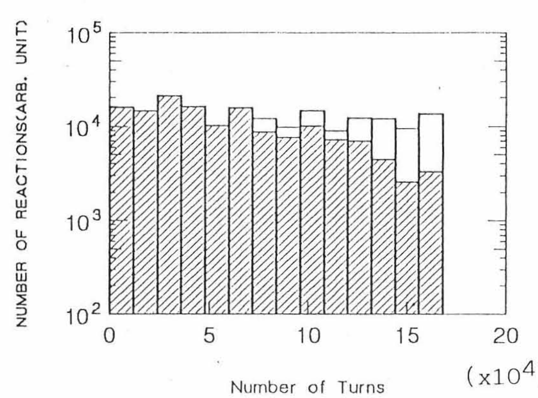

Fig.6 Collision rates with the target versus number of turns. The hatched histogram indicates the collision rate with a collimator and the blank one without a collimator.

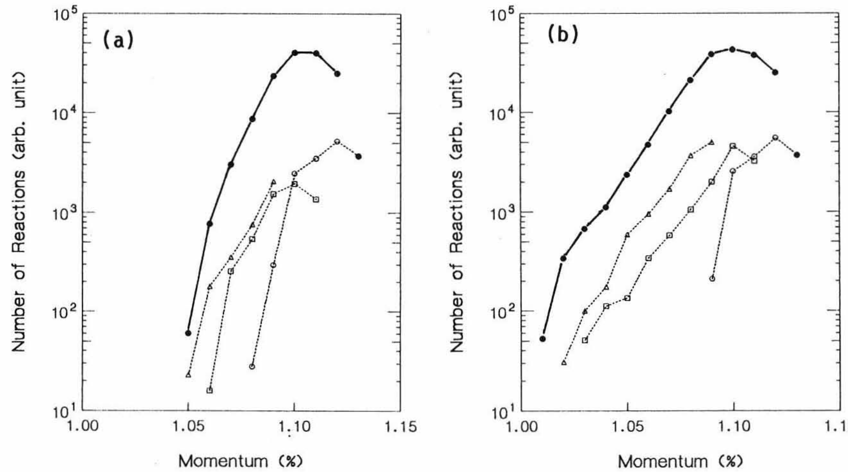

Fig.7 The momentum distribution of the beam hitting the target.
The closed circle line indicates overall resolution of protons circulating 1.8×10^5 turns.
o : during 0-12000 turns.
□ : during 72000-84000 turns.
△ : during 156000-168000 turns.
(a) with a collimator
(b) without a collimator

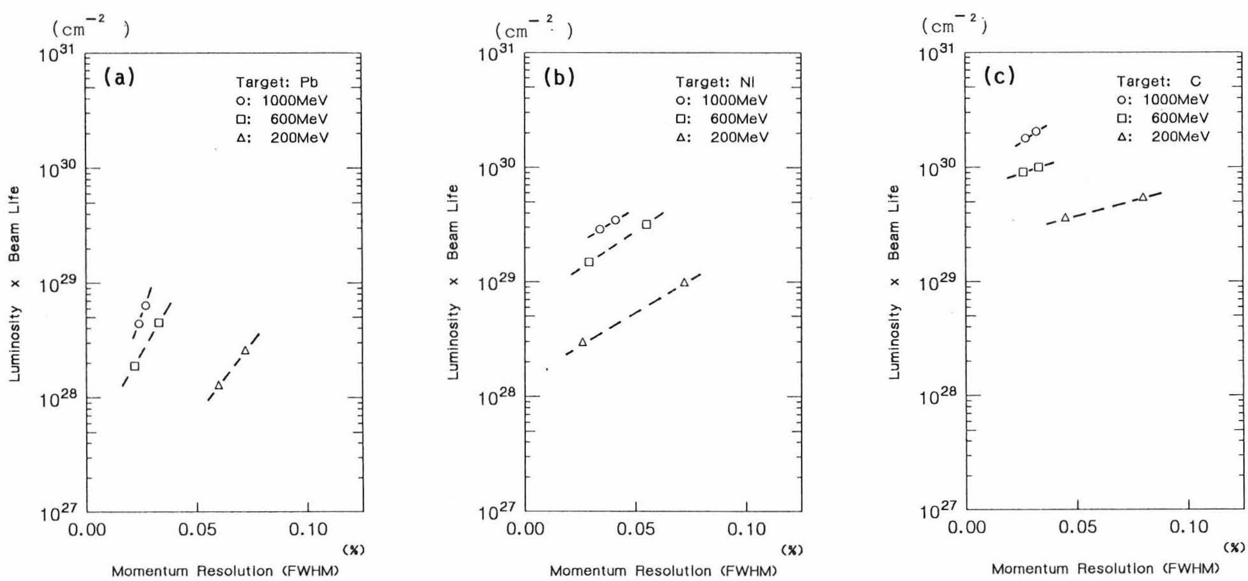

Fig.8 The product of the luminosity and beam life time versus the momentum resolution (FWHM).
(a) ^{208}Pb target(5μg/cm^2 for 200MeV proton beams, 10μg/cm^2 for 600 and 1000MeV) on a carbon backing of 5μg/cm^2 in thickness.
(b) ^{60}Ni target(10μg/cm^{2}for 200MeV,20μg/cm^2 for 600 and 1000MeV) on the same carbon backing.
(c) Self supporting ^{12}C target(20μg/cm^2 for 200,600 and 1000MeV).

Acknowledgement

The authors would like to thank Dr. N. Sakamoto for providing us a program on multiple scattering, Dr. K. Sato for helpful discussions on rf, Mr. I. Sugai for discussions on thin targets and construction members of TARN II for their warmful support for this work. One of the authors(I. K.) is appreciating the discussion with Prof. O. Schult on a foil target in cooler experiments.

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