THE ADVANCE TECHNOLOGY EXTRACTION FOR THERAPY IONS BEAM FROM CARBON STORAGE RING WITH ELECTRON COOLING

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Abstract

The electron cooling because of increasing the 6D phase space density of ion beams is the path for development compact accelerator ions beam therapy. The aperture magnets for the main synchrotron, the transport lines and the moveable ion gantry can be decreased very fundamentally. The systems for the extraction ions will operate with the smaller aperture and the low fields that improves reliability of dose control. The first experiments made at Landzow Institute of Modern Physics with cooling carbon beam on the energy 200 and 400 MeV/u increased enthusiasm of authors this report at these sort therapy systems.

INTRODUCTION

At Institute Modern Physics the electron cooling systems was install at the main ring CSRm and at experimental ring CSRe. In the treatment phase the stripping injection of carbon beam with few repeated cycles accumulation by e-cooling (7 MeV/u) to insure the current and stability of slow-extracted carbon beam with energy range 150 to 250 MeV/u [1]. But using the electron cooling directly at the energy treatment will open high perspective for shrinking the ion beam diameters. The reasons connected with the space charge limitation of the intensive ion beam. The transverse beam emittance limited so called the tune shift at the range of values $\delta\nu \leq 0.1-0.2$ as follow from equation:

$$\varepsilon_{\perp} = \frac{r_i N_i g}{2\pi\delta\nu\beta^2\gamma^3}, \quad (1)$$

with the classical ion radius $r_i = (Z_i e)^2 / M_i c^2$, the relativistic quantities β, γ, g is the bunch factor or the ratio the peak current of the ion beam to average current. As was showed at many experiments the electron cooling [2,3] effectively cooled the ions beam up to this limits and increasing energy will inverse proportional decrease the ion beam emittance. The carbon beam on energy 7 MeV/u at the storage ring with betafunction 20m and intensity $N_i = 10^{10}$ have the ion beam diameter (for $\delta\nu = 0.1$) 2 cm but on 400 MeV/u only 2 mm..

ELECTRON COOLING RESULTS OF THE CARBON BEAM IN CSRE

For illustration we can used results the first electron cooling experiments with 400 MeV/u the carbon ion beam in CSRe. After injection from CSRm ring the ion beam cooled as show fig. 1 at the momentum spread.

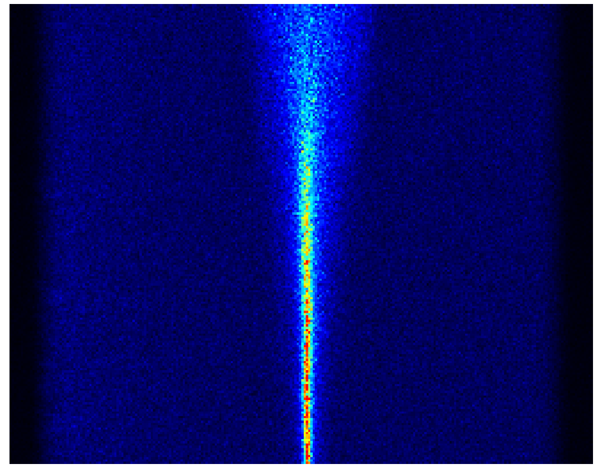

Fig. 1. The signal of Schottky signal after new injection.

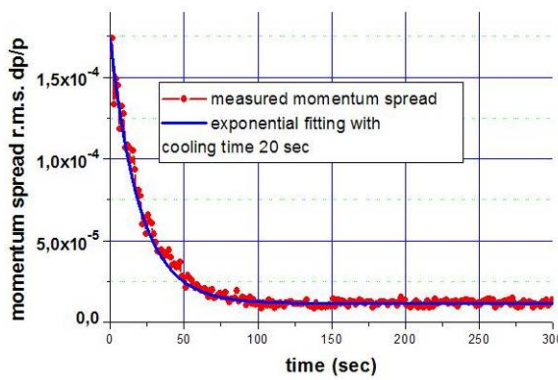

Fig. 2. The momentum spread at process electron cooling versus time.

The experiments with cooling the bunch beam (with RF on) demonstrated that the cooling was continued up to the compensations the RF field the own space charge field. At this case the longitudinal shape of the ion beam bunch are close to parabolic but the longitudinal potential well becomes very flat. There is correspond low synchrotron frequency for individual ions and the momentum spread demonstrated its self as the small tails near edges of the ion bunch. This phenomena was the subject of PD theses dissertation S.Negaitsev many years ago. At this regime the momentum spread at many times less estimation from the bunch length according single particle oscillation at RF field. This phenomena's interesting for using at ion-ion colliders but increased problems for stochastic cooling the bunches beam.

The same shrinking the transverse the ion beam size was measured with scanning the ion beam aperture with moveable collimator.

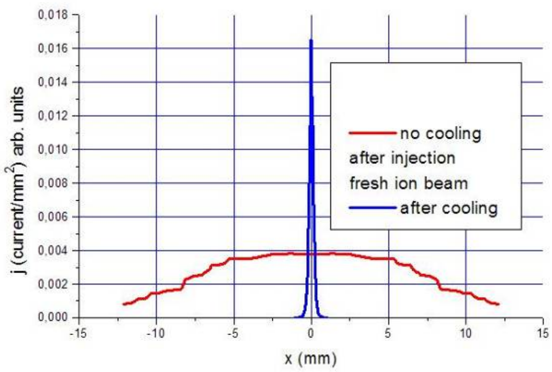

Fig. 3. The transverse profile of the carbon ion beam (700 µA ($N_i = 0.44*10^9$) measured at CSRe.

Before cooling r.m.s. radius ion beam is σ=8 mm, after cooling σ=0.15 mm, according equation 1 for this conditions tune shift is equal to $\delta\upsilon = 0.08$.

This experiments was made with electron beam current 0.75 A. Carefully extraction so cooled ion beam will help to have very precise irradiation dose control and the low aperture transport lines.

3-ORDER RESONANCE EXTRACTION WITH COOLING

The common use of slow resonant extraction from a synchrotron extends the beam spill time sufficiently to perform on-line dosimetry at the patient and to switch the ion beam on and off according to the dose required. Usually used the slow extraction ion beam system based on the third-integer resonance [2]. The present at the storage ring the local sextuple divided betatron phase space on the stable region with almost linear betatron oscillation, separatice and zone with the spirals increasing amplitude zone as show fig. 4.

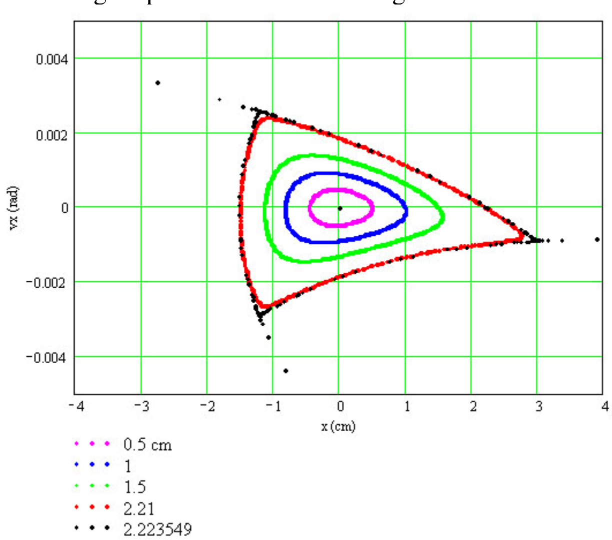

Fig. 4. The computer simulation the horizontal phase plane motion of ions for different initial amplitude with: tune $\nu_x = 0.36$, the sextupole value $\delta = 2*10^{-4}cm^{-2}$ that introduce nonlinear additional focusing proportional $1/F = \delta * x$.

When the horizontal tune are moved slowly to 1/3 the separatice are go to the 0 amplitude and all the ions of the beam kick out the position electrostatic septum knife as demonstrated at figure 5.

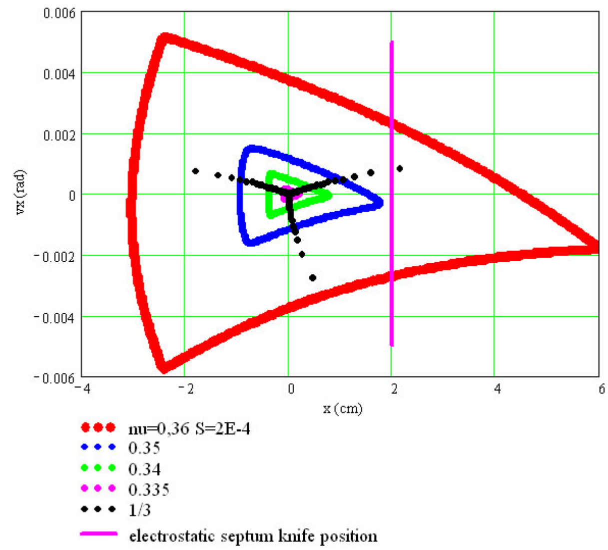

Fig. 5. The profile of separatrice for different horizontal tune.

The electron cooling shrink the ion beam at center of separatrix and for extraction we should have extremely small separatrix that decreased emitance extracted ion.

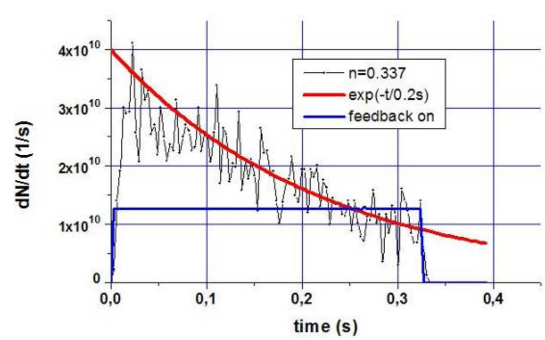

Fig. 6. The computer simulation the electron cooled carbon beam with constant tune and with the feedback for constant extract ion current by modulation the tune storage ion beam..

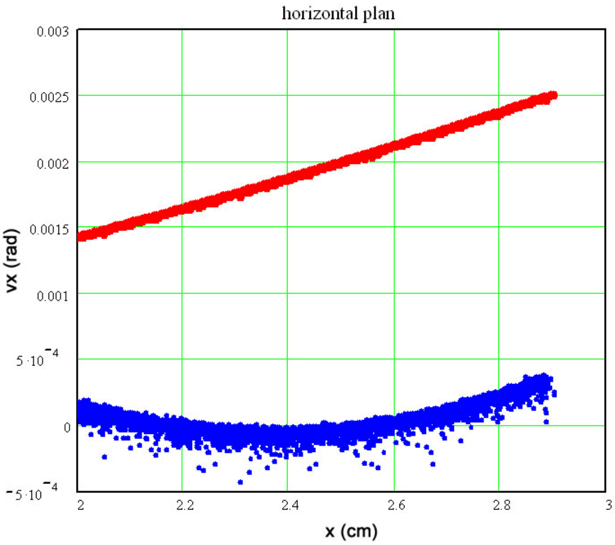

Fig. 7. The horizontal phase plane extracted ion beam. The blue points after pass the focusing lengths at extraction line (vertical scale increased at 10 times).

The emittance of extracted beam are:

$\varepsilon x := \sqrt{x2 \cdot vx2 - vxx^2}$ $\varepsilon x = 2.498\times 10^{-6}$ cm

$\varepsilon y := \sqrt{y2 \cdot vy2 - vyy^2}$ $\varepsilon y = 5.722\times 10^{-6}$ cm

So low ion beam emittance help to made low aperture line for ion beam. For example: interlock switcher for ion beam can have collimator slot with size 1 mm on distance 10 m and the electrostatic kicker with storage energy only 10^{-6} J for 100% modulation intensity.

SPLITING THE ION BEAM AT MOMENTUM SPACE

The electron cooling effectively concentrated the ion beam at point of momentum space where the ion beam and electron beam have the same velocity.

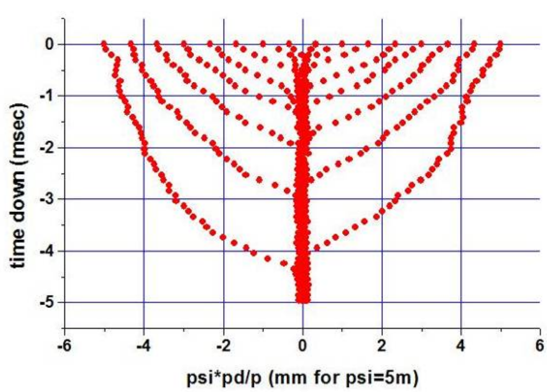

Fig. 8. The computer simulation of initially injected beam cooling (momentum): electron current 0.5 A, electron energy 16 kV, time range arrow is shown from up to down in milliseconds.

The presence of electron cooling in the synchrotron provides a small size and energy spread of the cooled beam thus enabling the realization of the original beam extraction scheme by small precisely dosed portions, the so-called pellet extraction. Electron cooling allows concentrating a portion of the ion beam in a given place of the phase space and then getting the ion beam low density in the neighboring regions for decreasing the "tails" of the distribution and losses at the extraction septum. The operation scheme is the following. Upon the ion beam acceleration up to the required energy, RF voltage is off and the beam is de-bunched. In the period of 50-200 ms (depending on the extraction energy) the beam is cooled down to the relevant equilibrium state. Then the beam is prepared for its extraction, for example, by scanning the electron beam energy with respect to the mean energy of the ion beam we produce the flat distribution of ions with $\Delta p / p = \pm 2 \div 2.5 \cdot 10^{-3}$. Then it is necessary to separate a portion of particles with energy deviation from the main beam. The portion intensity should be controlled in the range of N = $10^6 \div 10^7$ particles. The neighbouring ions are concentrated under the friction force action. The intensity of obtained portion is controlled by the time of storage and de-tuning of the electron beam energy from the distribution edge. By placing the kicker at the azimuth of the ion orbit where the dispersion is sufficient to separate the main beam from the portion the single turn extraction of the portion is realized. It is clear that ions concentrate in a portion but close to the storage portion region there are many ions nearing the ion cooling region, which will be bombarded the septum knife. In order to improve the extraction efficiency, it is necessary to clean the septum knife region. One of simplest solutions is to use the betatron core for accelerating the ion beam and "separating" the main beam from the region where the beam is prepared for its extraction. The magnet field in the core slowly increases so that the energy of the ion beam also increases on every turn moving the beam aside the septum. In this case, the maximum electron cooling force should be sufficient for the confinement and cooling the ions in the extraction region (Fig.9). It is seen that the main beam is moving away from the storage region and the left side portion is concentrated in the extraction area. Such an ion energy swiping accelerates noticeably the beam preparation for its extraction and cleans the "knife" region from the lost particles.

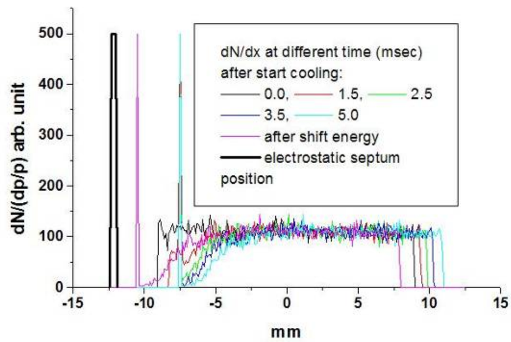

Fig. 9. The 5 msec cycle of carbon ions extraction with electron cooling.

Upon completion of the extracted portion storage and cooling, the betatron core exchanges polarity rapidly enough and the stored portion is rapidly moving to the kicker and the main beam distribution tail returns again in the cooling region for storing a new portion. In the scheme of using swiping, the extraction efficiency is much higher for the system repetition frequency up to 500 Hz. In the region of 1-2 kHz, the losses are still high 20-30 % for the septum knife with thickness 0.5 mm.

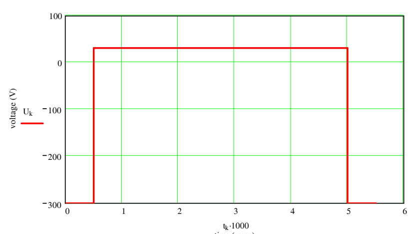

Fig. 10. The voltage on betatron core versus time at cycle.

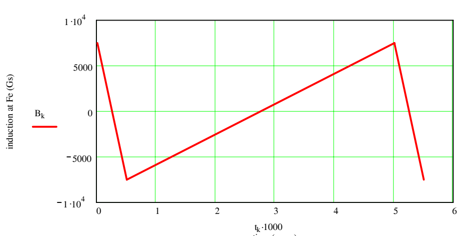

Fig. 11. The voltage on betatron core versus time at cycle.

For the beam extraction the fast kicker, electrostatic septum and permanent septum of the Lambertson type are used. Since the dispersion function at the kicker azimuth and electrostatic septum has the maximum value of 4.3 m, the main beam orbit and portions are separated by $\Delta X \approx$ 10 mm. After kick, the portion reaches the electrostatic septum aperture and acquiring an additional deflection along radius reaching the aperture of the Lambertson-type septum magnet, by which it is extracted vertically at the angle $\varphi_y = 13.5°$ with respect to the equilibrium orbit. The beam deflection angle corresponds to the ΔX =10 mm beam drop to the electrostatic septum aperture and, correspondingly, the electrostatic septum drops the beam into the septum magnet at the value of ΔX = 14 mm. The kicker kicks the beam by purely electric field and has the pulse duration of 80 ns with the fronts about 10 ns by order of magnitude. The presence of the cut in the inner plate causes the stray field and field non-uniformity inside the kicker aperture. With the separation of orbits by 10 mm, the main beam perturbation is $\Delta\varphi \le 5 \cdot 10^{-6}$.

Fig. 12 shows the 10 cycles of extraction when main beam during each 200 Hz cycles linearly moved to right and just before extraction jumped to the left (the time of the magnetic field polarity exchange). Slow moving to the left is connected with action of the cooling force which shifts the main beam to extraction zone.

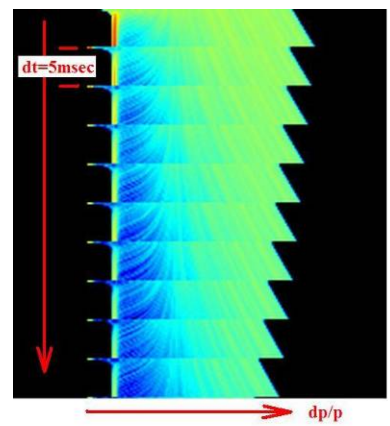

Fig. 12. The computer simulation of 10 cycles of extraction with period 5 msec (full time 50 msec.), initial momentum spread $\Delta p/p = \pm 0.001$.

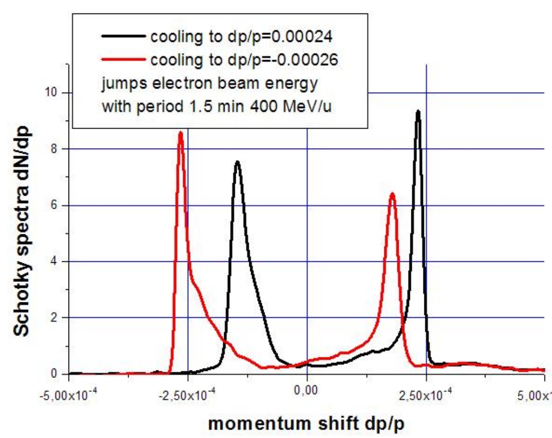

Fig. 13. CSRe momentum spectra of 400 Mev/u carbon beam after procedure of cyclic jump the electron beam energy.

The experiments with splitting the ion beam at CSRe ring was made at 2009 for prove the idea of this sort extraction by manipulation of the electron beam energy (fig.13). Practically its correspond existing the two electron beam with different energy, and the ion beam can be distributed to the each momentums by changing duty factor for each energy of electron beam.

SLOW EXTRACTION BY RECOMBINATION

The project of the storage ring for the cancer therapy proposed by BINP team proposes using recombination reaction C^{+6}+e->C^{+5} for the extraction of the ion beam. The charge states C^{+6} and C^{+5} have difference 20% in momentum, so it is possible to organize the strong shift between primary and extracted beam by the proper choice of the dispersion with very low ion density in the gap between these two orbits. So, the flow of the particles on the septum elements can be low according the extraction scheme. It leads to small leakage of the particles during extraction and liberalizes the requirement to the power supply of the storage ring because the ripple of the magnetic field doesn't produce the interference of the primary and extraction beam in the space. The ion beam after cooling on high energy 100-400 MeV/u have very small diameter (see Fig.6) and after recombination diameter extracted beam will be small. For example, fig. 14 show photo of nuclear emulsion after exposition at hydrogen beam on distance 10 m from the electron cooler NAP-M.


490 VI. Электронное охлаждение

Рис. 4. Фотография ядерной фотоэмульсии, экспонированной пучком быстрых атомов водорода ($v/c = 0{,}35$), возникающих при рекомбинации протонного и электронного пучков на участке охлаждения

Фотоэмульсия расположена на расстоянии 10 м от участка взаимодействия. Метки нанесены через 1 мм. Размер изображения соответствует диаметру протонного пучка 0,5 мм и угловой расходимости $3\cdot 10^{-5}$ рад

Fig. 14. The first photo of hydrogen atoms beam after recombination at NAP-M cooler [6], distance between mark points 1 mm.

The recombination coefficient is proportional to electron density. This enables to operate by the dose of the extraction beam. The electron gun as an electron tube can modulate the electron current in the megahertz frequency range. This frequency is certainly enough for any regime of the tumor scanning. The presence of the diagnostic of the extraction dose enables to have a feedback for the stabilization dose in the tumor. Moreover the recombination extraction is more safety because it is very difficult to have breakdown extraction of all stored ion beam during very short time. Protection system can quickly switch off the electron current and stop the extraction. The main disadvantage of the recombination extraction is relatively small rate of the extraction namely 10^7 /s at the number of the ions in the storage ring 10^{10} and the electron density 10^8 1/cm^3 in the cooling section. But this value is enough for the treatment of the small cancer tumor. For example, the tumor with diameter 30 mm should be irradiated ions those have the rest kinetic energy near 50 MeV/u. For accumulation doze of 5 Gy with ion flux 10^7/s required exposition time is near 1 min.

CONCLUSION

The carbon ion beam system is based on a few approved key innovations historically came from BINP (Novosibirsk) such as: electron cooling, using negative ions for stripping injection, storage rings. Electron cooling helps to make operation of the system easier by decreasing the beam emittance which results in stable ions energy and easy extraction. Example of CSRm operation shows that electron cooler can stable operates many months without switching off.

ACKNOWLEDGMENTS

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