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ACCELERATION OF DEUTERON BEAM IN THE KEK PROTON SYNCHROTRON

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(abstract)

Deuteron beam acceleration in the KEK 12-GeV proton synchrotron (KEK PS) has been tried. In the preliminary experimnet, the beam was accelerated up to the energy of 7.2GeV (3.6GeV/u) and the beam intensity of 4x 10^{11} ppp was achieved at this energy.

Introduction

Acceleration of heavy ion beams in the KEK PS was discussed about more than 8 years ago. However, the project was stopped by several reasons and heavy ion acceleration in the KEK PS has not been realized so far. One of the reasons why heavy ion acceleration at that time was difficult was attributable to somewhat complication of the proposed acceleration scheme.[1] In the previously proposed scheme, the injection beam energy to the main ring(MR) from the booster was chosen to be relatively low. Therefore, several flat porches had to be settled in the magnetic field pattern of the main ring to debunch and rebunch the beam during acceleration because the frequency changing range of the RF cavity in the MR was limited to fext/ finj< 2.

Very recently, as one of the possible candidates among the future plans of the KEK PS, the PS-Collider, which aims to accelerate and collide heavy ion beams with the beam energy of up tp 7GeV/u for a gold beam, has been proposed.[2] The PS-Collider is designed to use the present KEK PS as its injector, therefore a much more simple scheme compared with the previous one for accelerating heavy ions in the PS has been examined carefully for ease of operation. Simultaneously, possibility of a polarized deuteron beam acceleration in the PS has been also studied.[3]

In November of 1990, the PAC(Programme Advisory Committee) of the KEK PS has conditionally approved an experiment using a high energy deuteron beams of 2 ~ 5 GeV. According to the request from the PAC, a task force for aiming deuteron beam acceleration in the PS has been initiated in the accelerator department . Until March of 1991, a simulation study with proton beams has been carried out and and from May of 1991, a real acceleration study with deuteron beams based on the newly proposed scheme has started after a permission of deuteron beam acceleration concerning to radiation safety was received from the Agency of Science and Technology. On July 19 in 1991, deuteron beam has been successfully accelerated in the KEK PS up to the energy of 7.2GeV(3.6GeV/u), which was corresponding to the beam energy of 8GeV for proton and the beam intensity was about 4 x 10^{11} ppp.

Acceleration scheme

There were some changes in the PS after the first proposal for heavy ion acceleration was made. The linear accelerator(linac) was upgraded from its original energy of 20 MeV for proton to 40 MeV by adding another RF structure(TANK 2). This was actually fortunate for heavy ion beam acceleration. The velocity of the beam at the booster injection increases by 40 % more than before and it reduces the RF frequency changing range of the booster. The ratio of the RF frequency in the booster between beam extraction and injection, f_{ext} / f_{inj} , becomes slightly larger than 3.5 when a harmonic number of the ring is chosen to be 1 and this seems to be acceptable for the present RF system by making small modifications. Earnest studies of examining the beam behaviors in deuteron acceleration according to the newly proposed scheme has been carried out for each part of the KEK PS. Some components of the accelerator were replaced or modified for this purpose.

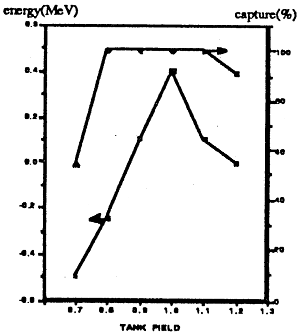

Fig.1 Variations of the beam capture efficiency and beam energy as a function of the average electric field in the TANK-2 of the linac.

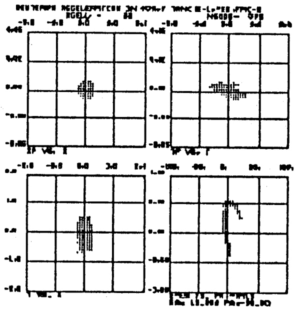

Fig.2 Calculated beam emittances at the exit of the TANK2 of the linac.

<u>(a) Ion source</u> The ion source which has been used at the KEK PS is a plasma-sputter type of negative hydrogen ion source. It generates more than 20 mA negative hydrogen ion beam with the 90% normalized emittance of 1.5 mm.mrad.[4] This type of ion source can be converted to produce negative deuterium ions by changing a gas species from hydrogen to deuterium. The negative deuterium ion beam extracted from the ion source is accelerated by the Cockcroft-Walton preinjector and injected into the linac. The acceleration energy is 375keV, which is a half of that for proton acceleration, because the linac is operated in 4π mode acceleration for deuteron acceleration. It has been also pointed out that not only the beam energy of 375 keV but of 540keV could be acceptable for the linac.[5][6]

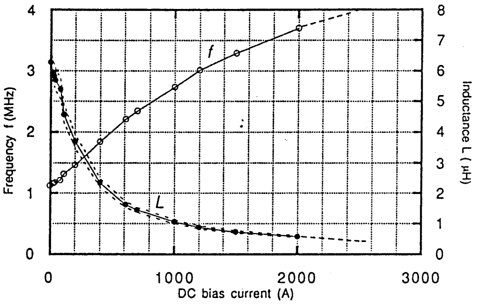

Fig.3. Variations of measured inductance and tuned frequency of the RF cavity in the booster as a function of the ferrite DC bias current.

<u>(b)Linac</u> In order to accelerate heavy ions whose Q/A = 0.5 in an Alvaretz type of proton linac, 4π mode acceleration can be used. The energy gain in each cell of the drift tubes in the linac can be expressed in the following equation.

$$\Delta W = e E_0 T L \cos\phi_s . \qquad (1)$$

Here, T is the transit time factor, ϕs the accelerating phase, E_0 the average electric field and L the cell length, respectively. When deuteron acceleration is performed in 4π mode, the energy gain in each cell should be half of that for proton. Thus,

$$\Delta W_d = m_p/m_d \times \Delta W_p = 1/2\Delta W_p , \qquad (2)$$

where m_p and m_d are the masses of proton and deuteron , respectively. Since the transit time factor of each cell for 4π mode acceleration is almost a half of that for 2π mode acceleration, the energy gain calculated from eq.(1) can satisfy the condition of eq.(2). Beam behaviors of deuteron acceleration in the linac have been examined in detail using the PARMILA code. Figures 1 and 2 are the results of beam simulations. In Fig. 1, variations of the beam capture efficiency and energy at the exit of the linac are shown as a function of the average electric field in the TANK 2 of the linac, which is normalized to a design field of proton beam acceleration. Figure 2 presents the calculated beam emittance at the exit of the TANK2.

<u>(c) Booster</u> Beam parameters of deuteron acceleration in the booster is summarized in Table 1.

Table 1 Beam parameters of deuteron acceleration in the booster

	injection	extraction
Energy(MeV)	19.28	293.8
Bρ(Tm)	0.8994	3.636
βγ	0.1438	0.5812
β	0.1423	0.5025
harmonic number	1	
RF frequency(MHz)	1.132	3.996
RF voltage(max. kV)	~25	
emittance(πmm.mrad)		
horizontal	90	22
vertical	40	10
δP/P	+-0.5%	+-0.4%
bunch width(nsec)		100

There are two RF cavities in the booster at the moment. In deuteron acceleration, the RF frequency at the beam injection is 1.132MHz, which is almost a half of that for proton acceleration. The capacitance of each RF cavity is about 1000pF and the maximum inductance of each RF cavity is about 6 μH when the ferrite DC bias current is zero, respectively. Therefore, another capacitance of about 2000pF should be added for each RF cavity so as to tune the injection RF frequency to 1.132MHz. Practically, this can be made by attaching a vacuum capacitor to the accelerating gap of each cavity. Figure 3 shows measured variations of inductance and tuned frequency as a function of the ferrite DC bias current of the cavity, when the vacuum capacitor of 2000pF was attached to the RF cavity. The inductance was changed for more than 13 times. This might be enough for deuteron acceleration. The shunt impedance of the cavity was also measured. The shunt impedance was about 400 Ω at the beam injection, which was approximately 40 % of the minimum shunt impedance for proton acceleration. However, since the RF voltage at the beam injection has to keep small to raise a longitudinal capture efficiency by an adiabatic process, the power loss in the ferrite of the cavity due to the low shunt impedance can be eliminated.

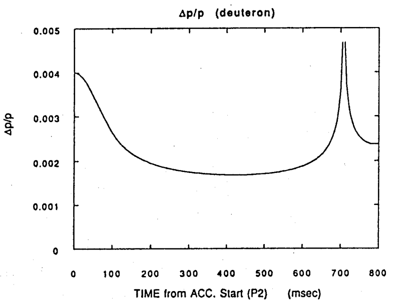

Fig.4 Longitudinal motions in the main ring.

Bucket height of the longitudinal motion in the synchrotron for heavy ion beams is expressed in the following equation.[7]

$$\frac{\Delta p}{p} = \sqrt{\frac{Q c_s V_{rf}}{A \pi \beta 2 \gamma} \cdot f(\phi_s)} \qquad (3)$$

Here, Vrf is the RF voltage and f(ϕs) the function determined by the synchrotron phase ϕs, respectively. It is found that the bucket height at the beam injection is relatively large for deuteron acceleration compared with proton acceleration. This is caused by the fact that the velocity of the deuteron beam at injection is a half of that for proton acceleration.

(d)Main ring Beam parameters for deuteron acceleration in the main ring are summarized in Table 2.

In deuteron acceleration in the main ring, the RF frequency range is as follows: finj = 3.996MHz, fext = 7.869 MHz and fext / finj = 1.97. For proton acceleration, finj = 6.027 MHz. The RF frequency can be lowered by adding extra capacitance to the accelerating gap of each RF cavity used in the main ring. Since the maximum inductance of the present RF cavity is approximately 6μH, the total capacitance of about 260 pF is required for deuteron acceleration. The present total capacitance of each cavity is about 110 pF, so another 150 pF should be added. The variations of the RF frequency as a function of the ferrite DC bias current were measured when the vacuum capacitor of 150 pF was attached to the accelerating of the RF cavity. It was observed that the frequency increased up to 7.9MHz when the ferrite DC bias current was raised to 1100A. The variations of the shunt impedance were also measured carefully and no serious power loss in the ferrite of the cavity due to the shunt impedance reduction was not observed. Details of the results in these measurements are also presented in this symposium.[8] The calculated longitudinal motions in the main ring for deuteron acceleration are shown in Fig. 4.

Table 2 Beam parameters in the main ring

	injection	extraction
Energy(GeV)	0.294	11.2
Bρ(Tm)	3.636	43.04
βγ	0.5812	6.879
β	0.1423	0.9895
harmonic number	9	
RF frequency(MHz)	3.996	7.869
RF voltage(max. kV)	~92	
emittance(πmm.mrad)		
horizontal	22	-
vertical	10	-
δP/P	+-0.4%	+-0.35%
bunch width(nsec)	100	

Beam acceleration test

The first trial for deuteron acceleration in the main ring of the KEK PS has been performed from July 17 in 1991 and on July 19, the deuteron beam was successfully accelerated in the main ring up to the energy of 7.2GeV(3.6GeV/u). The beam intensity was 4 x 10^{11}ppp at the maximum. Characteristics and performance of each part of the accelerator in the deuteron acceleration test are briefly described in the following.

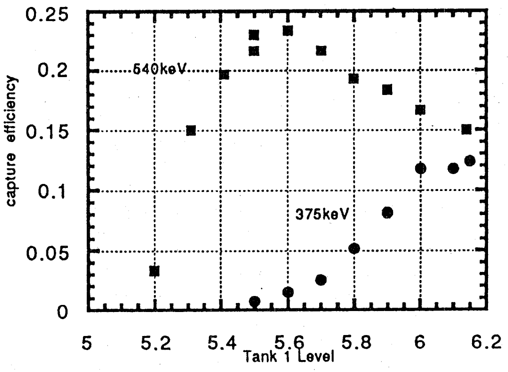

Fig. 5 Variations of the beam transmission in the linac

The ion source has produced negative deuterium ions by feeding a deuterium gas instead of a hydrogen gas. More than 12 mA negative deuterium ion beam from the ion source was accelerated by the Cockcroft-Walton preinjector and 10mA negative deuterium beam was injected into the linac. One of the most different operating parameters of the ion source compared with proton beam operation was a cesium consumption rate. The cesium consumption rate was relatively large for negative deuterium ion beam operation. In this type of ion source, negative ions are generated on the cesium covered molybdenum surface by ion sputtering in the plasma. Thus, the large cesium consumption was probably caused by a mass effect of sputtering ions.

In 4π mode acceleration of deuteron in the linac, the possible injection energy is not only 375 keV, which is a just half of that for proton. A relatively high energy of 540keV is also possible. Variations of beam transmission in the linac as a function of the RF field strength of the TANK 1 are shown in Figs. 5-a and b for 375keV and 540 kev injections, respectively. It was found from these results that the required RF field strength in the TANK 1 was almost 30% less than that for 540 keV injection compared with 375 keV injection. The transit time factor for 4π mode acceleration is substantially small at the first several cells in the TANK 1 and it becomes less than a half of that for 2 π mode acceleration. The higher injection energy could help somewhat this situation. In this acceleration test, 540keV injection was chosen and the optimized beam capture efficiency in the linac was reached to more than 20 %.

The injected beam momentum of the booster for deuteron acceleration is about 3% less than that for proton acceleration. Not only the magnetic field of the booster at beam injection was decreased but the beam transport elements between the linac and

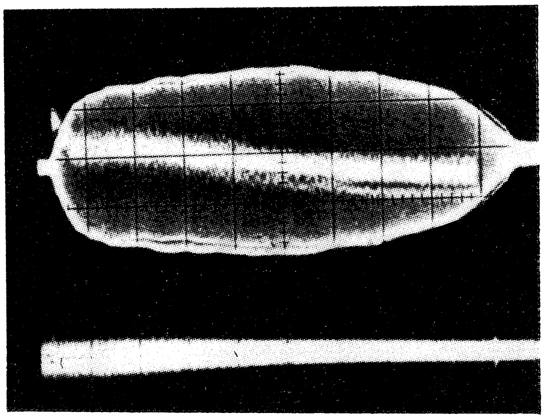

Fig.6 Accelerated deuteron beam intensity in the booster.

the booster were re-tuned to match the deuteron beam momentum. By tuning them carefully, almost 90 % injection efficiency was achieved in the booster. In Fig. 6, accelerated deuteron beam intensity in the booster is simultaneously shown with the RF voltage during acceleration. Figure 7 presents the measured beam surviving rates during acceleration (=intensity at extraction / intensity at injection) for various RF voltages. Clearly seen from the figure, the total RF voltage of about 20 kV was at least necessary for accelerating the deuteron beam without any serious beam loss. More than 95 % of the beam was extracted from the booster and transported to the main ring.

In this acceleration test, only one RF cavity of the main ring was available in accelerating deuteron beam. There was just only one ferrite bias power supply which was capable to swing its current up to 1100 A. Therefore, the maximally attainable RF voltage in this test was about 23 kV. The RF voltage of at least 50 kV is necessary for beam acceleration in the main ring when a field ramping rate of the bending magnets (dB/dt) equals to 3.17 T/sec as used in normal proton acceleration. Therefore, in this acceleration test, we have reduced dB/dT to one third of the normal value, although the attainable deuteron beam energy was somewhat decreased to 7.2GeV(3.6GeV/u). The low RF voltage also leads a beam loss at injection because of the small bucket height. The measured capture efficiency at the beam injection in the main ring was only 40 %, when the booster extraction RF voltage was 10.5kV. The measured momentum spread of the extracted beam from the booster was about $\Delta p/p$ = +- 0.31% at this booster RF voltage. The momentum spread of the extracted beam from the booster was estimated by measuring a debunching time in the main ring. Since the calculated bucket height of the main ring for the RF voltage of 23 kV was less than +- 0.2%, such a large beam loss was happened at the beam injection. In order to avoid this problem, the momentum spread of the beam extracted from the booster was reduced as small as possible by decreasing the booster RF voltage at beam extraction. When the booster RF voltage at beam extraction was decreased to 5.7kV, the beam capture was increased to 77 %. The measured momentum spread of the injected beam in this case was +- 0.15%.

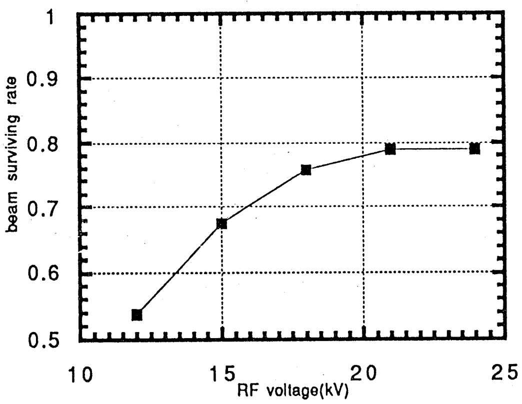

Fig.7 Measured beam surviving rates during acceleration in the booster for various RF voltages.

In Fig. 8, the accelerated deuteron beam intensity in the main ring is simultaneously shown with a magnetic field pattern. The maximum accelerated deuteron beam intensity in the main ring was 4 x 10^{11}ppp. It was rather difficult to increase the beam intensity more than this because the RF voltage in the main ring was too small for compensating a large beam loading. We are now preparing the two ferrite bias power supplies for the main ring RF cavities, which can swing their currents up to 1200A, respectively. Totally three RF cavities will be available for deuteron acceleration in near future and, hopefully, accelerated deuteron beam intensity of 1 x 10^{12}ppp at the maximum energy of 11.6GeV (5.8GeV/u) is expected in the KEK PS.

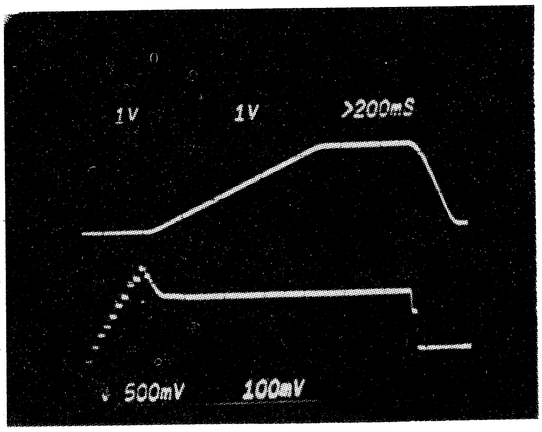

Fig. 9 Accelerated deuteron beam intensity in the main ring

Conclusion

A preliminary test for deuteron acceleration in the KEK PS has been done. The accelerated beam intensities and energies at each part of the accelerator are summarized as follows.

Ion source	15mA	0.54MeV(0.27MeV/u)
Linac	2.5mA	20MeV(5MeV/u)
Booster	5 x 10^{11}ppp	294MeV(147MeV/u)
Main ring	4 x 10^{11}ppp	7.2GeV(3.6GeV/u)

Only one RF cavity in the main ring was used for this acceleration test. After another two RF cavities are available in near future, it is hoped that the deuteron beam can be accelerated up to the maximum energy of 11.6 GeV (5.8GeV/u) and the beam intensity reaches to 1x 10^{12}ppp.

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