BEAM DYNAMICAL ISSUES OF THE KEK ALL-ION ACCELERATOR*

Ken Takayama, Toshikazu Adachi, Eiji Nakamura, and Hirohiko Someya, KEK, Tsukuba, Japan.

Abstract

Beam dynamical issues of an all-ion accelerator (AIA) [1], which is an injector-free induction synchrotron, are addressed. Extremely low energy injection in the KEK-AIA brings about various undesired features, such as electron capture by injected heavy ions and closed orbit distortion due to a relatively large amount of remnant magnetic fields and eddy current induced fields on the vacuum metal chamber. In addition, it is noted that a space-charge limited current and coupling impedances strongly depend on the injection b.

INTRODUCTION

R&D works to realize an all-ion accelerator (AIA) [1] capable of accelerating all species of ions with any possible charge state, based on the induction synchrotron concept, which was demonstrated using the KEK 12 GeV-PS in 2006 [2], are going on at KEK. The KEK AIA, which is realized by modifying the existing KEK 500 MeV Booster Ring of a rapid cycling synchrotron [3], which had dedicated as the injector for the 12 GeV-PS from 1975 to 2006, is an injector-free accelerator.

An ion beam from the high-voltage terminal of 200 kV is directly injected into the accelerator ring. Several key issues associated with the low energy injection must be addressed. Space-charge limited current is remarkably reduced due to a small relativistic β. Capture of residual electrons by a heavy ion should reduce the beam life-time at injection. Eddy-current induced magnetic fields associated with guide-fields ramping from a low field level become an additional source of the closed orbit distortion at the early stage of acceleration, as well as the remnant magnetic fields. Careful considerations on them suggest that the vacuum must be improved by a factor of 10 from the present level. However, additional COD sources seem to be tolerable using the present orbit correction system. At last achievable beam parameters will be given assuming the present parameters of the KEK AIA.

ACCELERATOR PARAMETERS OF THE KEK-AIA

Table 1 summarizes the machine parameters of the KEK-AIA. The lattice is that the 500 MeV booster ring of OFDF. It consists of 8 combined function-type magnets. A newly assumed injection energy is 200 keV for proton, since the existing 40 MeV Alvaretz linac is going to be replaced by the 200 kV high voltage terminal, where the ECR ion source [4] is embedded. At the early stage of the AIA study, acceleration of Ar ions is expected [5]. Whatever ion being accelerated may be, its injection energy is very low.

Table 1: KEK-AIA parameters for Ar^{18+}

Machine parameters		Value
Bending radius, ρ	(m)	3.3
Circumference, C_0	(m)	37.71
Maximum acceleration voltage	(kV)	3.24
Injection voltage	(kV)	200
Magnetic flux density, B_{min}	(T)	0.02916
Magnetic flux density, B_{max}	(T)	0.8583
Frequency of magnet ramping, f	(Hz)	10

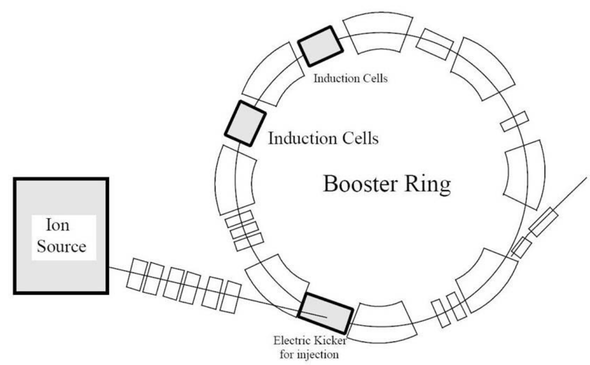


Figure 1: Schematic of the KEK-AIA

LOSS OF INJECTED HEAVY IONS AND VACUUM REQUIREMENT

It is known that the residual pressure in vacuum chambers of synchrotrons can cause severe losses of particles during acceleration. This loss is originated from electron capture or stripping as a result of collision with residual gas molecules. Two processes are fatal from a beam loss point of view, although other process, such as Moller scattering leading to the emittance blow-up, is likely to take place. Cross-sections of these physics process strongly depend on the velocity of ion and the achieved pressure. A simple estimation of beam intensity survival is described to help to locate a requirement in the vacuum system design. Here it is noted that the Ar^{+Z} is assumed to leave the 200 kV high voltage terminal with 200 (Z/A) keV/au, where A=40.

The probability of capturing one electron is given by the cross-section sc and for loss of electron by sl. There are governed by a velocity dependence of different kinds. From suitable literature, one usually can get a good figure of

$$\sigma_c, \sigma_l \sim Z^p \beta^q \text{ with } p \sim 2, q \sim \begin{cases} -2 \text{ for loss cross - section} \\ -4 \text{ or } 5 \text{ for capture depending on} \beta \end{cases}$$

, where Z is the charge state of ion, β is the relativistic

*Work supported by Kakenhi 15GS0217
takayama@post.kek.jp

beta. To simplify calculations, it is generally admitted that

$$\sigma_c \sim Z^2 \beta^{-5}$$
$$\sigma_l \sim Z^{-2} \beta^{-2} \qquad (1)$$

It is obviously practical and useful to take actual experimental results, where nitrogen is assumed as a residual gas. From Fig. 2, a major source of loss is known to be capture below a few MeV/au and stripping beyond that. The survival ratio at time *t* from injection is given by

$$S = \frac{n(t)}{n(0)} = \exp\left[-2.12 \times 10^{27} \cdot P_{torr} \cdot \int_0^t \sigma_{tot} \beta \cdot dt\right] \qquad (2),$$

where $\sigma_{tot} = \sigma_c + \sigma_l$ and β changes with acceleration and is determined from the filed ramping pattern. From (1), $\sigma_l = \sigma_{l0}[\beta(0)/\beta(t)]^2$, $\sigma_c = \sigma_{c0}[\beta(0)/\beta(t)]^5$, where σ_{l0} and σ_{c0} are obtained from Fig.2.

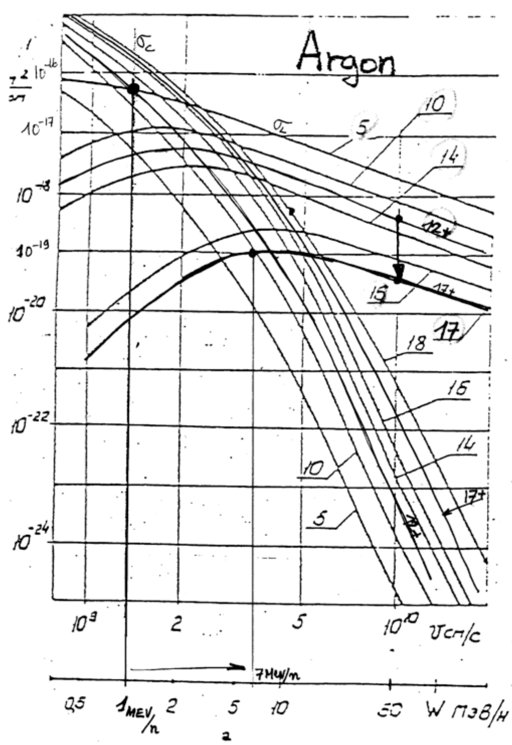


Figure 2: Cross-sections for electron capture and stripping of Ar ion [6]

As a function of vacuum pressure P_{torr} and repetition rate *f*, the survival rate *S* at the end of acceleration is shown in Table 2.

Table 2 Survival ratio

Numerical values in parenthesis include the effects due to electron capture

P_{torr}	1 Hz	5 Hz	10 Hz	20 Hz
10^{-11}	0.993	0.998	0.999	0.999
10^{-10}	0.928	0.985	0.993(0.983)	0.996
10^{-9}	0.472	0.861	0.927(0.844)	0.963
2×10^{-9}	0.223	0.741	0.861(0.715)	0.928
5×10^{-9}	0.023	0.472	0.687(0.431)	0.828
10^{-8}	0.0004	0.223	0.472(0.186)	0.687

We know that the vacuum pressure of 10^{-9} Torr is required in order to achieve the survival rate more than 90%. To realize this requirement, a drastic improvement of the present evacuation system of the KEK Booster is inevitable. The evacuation capability must be enhanced with additional evacuation pumps. An evacuated volume-size along the circulating orbit must be reduced to its limit. Bump magnets, which are located in the large size vacuum tanks, must be removed in air and ceramic ducts will be employed instead of the large size SUS tanks.

COD DUE TO REMNANT FIELDS

Remnant fields in the main magnets (MM) are of our concern, because the injection flux density is extremely low and about 200-300 Gauss. The remnant fields have been measured at limited positions in the pole gap of all magnets along the circulating orbit. On the other hand, the remnant fields of the monitoring magnet, which is employed for the field feedback correction, have been measured on three points (outer edge, middle, and inner edge) along the center axis of F sector and D sector. Both results seem to be consistent. According to the preliminary measurements, there is the dipole component of 5 Gauss with a maximum 18% dispersion along the center orbit.

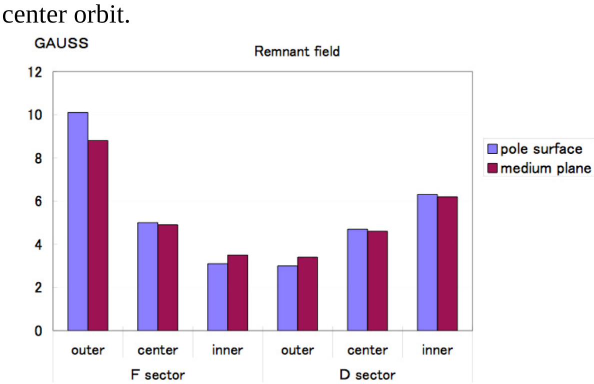


Figure 3: Remnant fields of the monitor magnet

This filed error induces a closed orbit distortion. Calculations show that its possible amplitude is about 1cm, as shown in Fig.5a . COD correction calculations (see Fig.5b) tell us that the magnitude can be reduced to 0.5 cm by the optimized excitation of two sets of the existing 8-figure back-leg coil shown in Fig.4, which wind two poles of the adjacent MMs so as to cancel the induced voltage associated with excitation. This size of COD amplitude may be tolerable just for the demonstration of the KEK-AIA.

EDDY CURRENT INDUCED FIELDS

It is an intrinsic nature that an all-ion accelerator is operated in a wide range from a low field to the saturation field of the guiding magnets. It is well known that a rapid change in the magnetic flux generates eddy currents on metal surface penetrated by the magnetic flux. The eddy

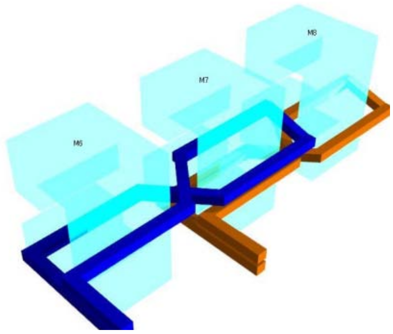


Figure 4: 8-figure back-leg coils

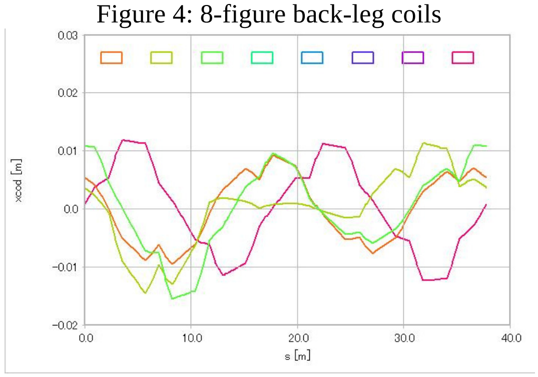


Figure 5a: COD generated by the remnant fields

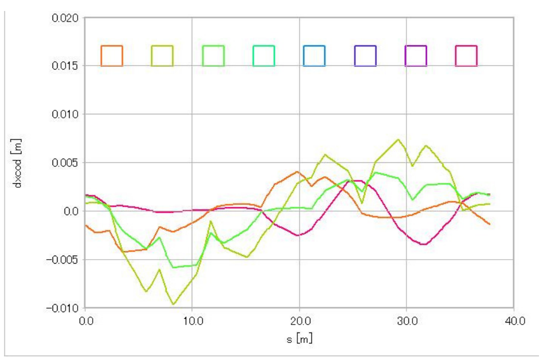
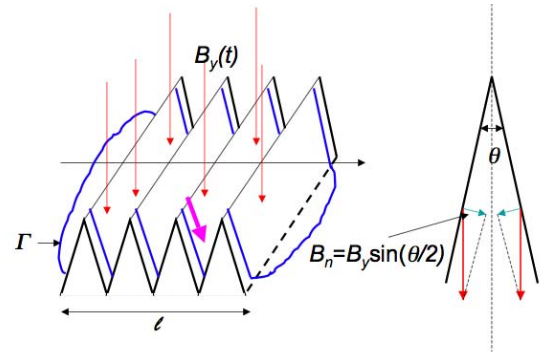


Figure 5b: Corrected COD

current simply depends on a ramping rate of guiding-fields, thickness and conductivity of metal, and physical geometry of the metal chamber. This suggests that any perturbing fields generated by this eddy current may become significant to affect on the motion of ion. The eddy current induced magnetic fields has been estimated in a simple approximation under the actual situation of the KEK-AIA, where the vacuum chamber is not flat metal but it has thin convolutions on its SUS surface so as to mitigate the eddy current. In an idealized rectangular shape (g x $2x_{max}$) SUS chamber with convolution of thickness h, conductivity σ, and angle θ, as shown below



the magnetic field generated by the eddy currents induced on the upper and lower surfaces is written by

$$\Delta B_y(x) = -\frac{\mu_0 h(1-\cos\theta)\sigma \dot{B}_y}{2g}\cdot\left[x_{max}^2 - x^2\right]$$

$$\dot{B}_y = \omega\cdot\left(\frac{B_{max}-B_{min}}{2}\right)\cdot\sin(\omega\cdot t) \qquad (3a).$$

Obviously, this error field is a sextupole field with its maximum at the center. On the other hand, the magnetic field by the eddy currents induced on the side wall is written by

$$\Delta B_y = -\frac{\mu_0\cdot h\cdot\sigma\cdot\sin(\theta/2)\cdot x_{max}\cdot d\cdot\dot{B}_y}{g} \qquad (3b),$$

where d is the vertical height of side wall and close to g. Substituting the parameters of $f(\omega/2\pi)$=10 Hz, h=0.15 mm, θ=40 degree, σ=1.38x10^6 /Ωm, x_{max}=7.5 cm, g=8 cm, d=6 cm into (3a) and (3b), we have their maximum values of 0.54 Gauss and 1.35 Gauss, respectively. They seem to be sufficiently tolerable.

SPACE-CHARGE LIMITED CURRENT

It is well known that the space-charge limited particle number N_{limit} is proportional to $(A/Z^2)\beta^2\gamma^3$, where Z and A are a charge state and mass number, respectively. At the injection of the KEK-AIA, γ is almost unity and β is proportional to $(VZ/A)^{1/2}$, where V is the voltage of the ion source terminal. Thus, we have N_{limit} ~ (V/Z). For Ar+8, which will be obtained at first, N_{limit} ~ 4.3x10^{9}ppp is estimated.

SUMMARY

As addressed in the discussions, the vacuum pressure is most significant. A task to improve the vacuum is urgent. Until the end of this year, we will be able to achieve sufficient vacuum for the demonstration of the KEK-AIA.

REFERENCES

[1] K. Takayama , Y. Arakida, T. Iwashita, Y. Shimosaki, T. Dixit , and K. Torikai , *J. Appl. Phys.* 101 (2007) p. 063304.

[2] K. Takayama, Y. Arakida, T. Dixit, *et al.*, *Phys. Rev. Lett.* **98** (2007) p. 054801.

[3] E.Nakamura, *et a.l*, Proceedings of PAC07, Albuquerque, NM USA, p1490.

[4] H. Suzuki *et al*., in this conference, MOPC156.

[5] T.Dixit *et al*., in this conference, WEPP129.

[6] D.Jean-Michel Lagniel (GANIL) has pointed out the importance of the residual gas in a low energy ion accelerator and informed valuable data obtained by I.S.Dmitriev.(2007).