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NUMATRON PROJECT

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1. Introduction

An accelerator complex is planned at INS, University of Tokyo, which is named NUMATRON[1,2] and should provide heavy ions up to uranium in an energy range of 0.1 ∿ 1.3 GeV per nucleon.

The principal aim of the project is to open up new fields of nuclear physics. Looking back to the history of the entire developments and evolutional trends of nuclear physics, a future perspective in nuclear physics naturally opens before us.[3] Important developments will come out from the study of the extra-ordinary states of nuclear matter, which are expected to be realized inside stars. Various nobel features of nuclear matter will be disclosed in the laboratory by the use of the high-energy heavy-ion beam. In the past, we have engaged mainly in the study of nuclear matter at low temperatures and at low densities. While, the heavy-ion beams of high-energy will allow us to investigate the properties of nuclear matter at high temperatures and at high densities. The investigations in this direction have been already initiated by the Bevalac project at the Lawrence Berkeley Laboratory. The NUMATRON project has also been planned to extend nuclear physics in these evolutional trends with the use of heavier ions.

On the other hand, researches and applications in many other fields are also being considered. The applications of relatively light heavy-ions for radiation biology, radiation therapy and diagnostic radiology have been discussed intensively and a demand for a high-energy heavy-ion accelerator dedicated to such medical uses is growing up in our country. High peak intensity beams of heavy ion such as uranium have a possibility to give a pellet containing D-T mixture a peak energy sufficient for triggering the inertial fusion. The NUMATRON project will give new facilities not only for nuclear physics but also for many other sciences and applications.

In the following sections, the outline of the accelerator complex is described as well as major subsystems.

2. General Description

The proposed accelerator consists of Cockcroft-Walton generators, three Wideröe linacs, two Alvarez linacs and two synchrotrons (Fig.1).

Two identical preaccelerators are arranged symmetrically in order to be operated in parallel. Each preaccelerator installs a 500 kV high voltage generator and two ion source terminals. The acceleration voltage is adjustable in a wide range so that ions of various charge-to-mass ratios can be accelerated to a constant energy. After passing through the buncher section, ions are injected into a row of three Wideröe linacs, which have a resonant frequency of 25 MHz with π-3π mode for the first and the second, and π-π mode for the

Table 1. Numatron Parameters

A. Particle, Energy and Intensity

Particle	Max. Energy (GeV/A)	Intensity(pps)
U^{92+}	1.27	∿ 10^9
Kr^{36+}	1.47	∿ 10^{11}*
Ne^{10+}	1.81	∿ 10^{11}*

*Space Charge Limit

B. Injector

	T/A(MeV)	Freq. (MHz)	β(v/c)	ε(q/A)
Cockcroft-Walton (500 KV)	0.0147	—	0.006	0.029(U^{7+})
Wideröe (π-3π)	0.146	25	0.018	—
Wideröe (π-3π)	0.305	25	0.026	—
Stripping (Gas)	—	—	—	0.067(U^{16+})
Wideröe (π)	1.10	25	0.048	—
Alvarez	1.60	100	0.059	—
Stripping (Solid)	—	—	—	0.193(U^{46+})
Alvarez	10.0	100	0.146	—

C. 1st Synchrotron

Injection Energy	10 MeV/u
Maximum Energy	150 MeV/u
Repetition Rate of RF Stacking	50 Hz
Momentum Spread of Stacked Beam	± 2 %
Useful Aperture radial	18 cm
vertical	5 cm
Vacuum	1×10^{-10} torr
Space Charge Limit	2.9×10^{11} (U^{46+})
Number of Particles/sec	6.2×10^{11} (Ar^{13+})

D. 2nd Synchrotron

Guide Field (B_{max})	18.0 kG
Quadrupole Field $(dB/dr)_{max}$	1.38 kG/cm
Repetition Rate	1 Hz
Magnetic Radius	9.55 m
Average Radius	33.6 m
Circumference	211.2 m
Number of Normal Periods	24
Number of Long Straight Sections	8
Structure of Normal Periods	FODO
Useful Aperture radial	9 cm
vertical	3.5 cm
Number of Betatron Oscillations	6.25
Phase Advance per Normal Period	70°
Vacuum	1×10^{-9} torr

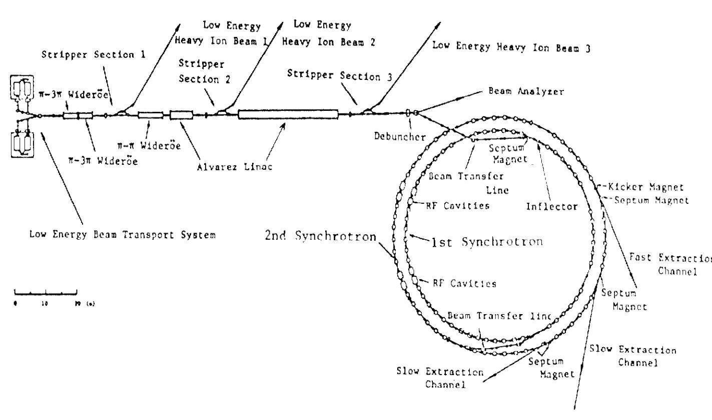

Fig.1 Layout of NUMATRON

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third linacs. The last Wideröe linac is followed by an Alvarez linac with a resonant frequency of 100 MHz at the energy of 1 MeV/u. Two stripper sections with achromatic charge analyzing systems are installed at the specific energies of 0.3 and 1.6 MeV/u in order to obtain an efficient acceleration in the linac.

Final stage of the accelerator complex is composed of two synchrotrons. The first synchrotron has a capability of beam accumulation for obtaining heavy ions of high intensity. A combination of multiturn injection and RF stacking methods is applied to the injection scheme to the first ring.[4] The beam is accelerated up to the energy of 150 MeV/u and is extracted by a one turn ejection method. After passing through the final stripper section in the beam transport line between the first and the second synchrotrons, ions completely stripped are injected into the second ring, where uranium is accelerated up to the maximum energy of 1270 MeV/u. A transition energy of the second synchrotron is 4.33 GeV and any ions are not accelerated through the transition energy.

The required vacuum in the first ring is 1×10^{-10} torr for a survival rate of 90 % after an injection period of 1 sec, whereas in the second ring, the pressure of 1×10^{-9} torr suffices the above survival rate because of its high energy operation. The output intensity of uranium is typically estimated at 10^9 particles per second, whereas for the ions lighter than $Z \simeq 20$, it may be 10^{11} particles per second, which is limited by space charge effects. The main parameters of the accelerator complex are given in Table 1 and the operation scheme of the linac and two synchrotrons is illustrated in Fig.2.

3. Injector Systems and Charge Stripping Stages

It is reported that some new types of ion sources such as EBIS and ECRIS are favorable for the synchrotron with a slow repetition rate, because they could produce heavy ions of high charge state and of high peak current. At the present design of the accelerator, however, a well known PIG type ion source is assumed, considering a present stage of new type ion sources. Preinjector is a Cockcroft-Walton generator with a rather low maximum voltage of 500 kV because of its reliability and accessibility for developments and maintenances of the ion source. For U^{7+} (charge to mass ratio of 0.029) this voltage gives a β (= v/c) value of 0.006, which is kept constant also for other ions by tuning the voltage.

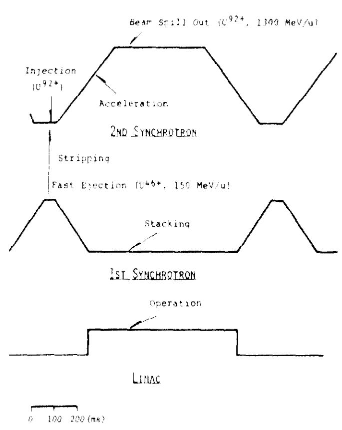

Fig.2 Operation Scheme of the Accelerator Complex

The optimum number and positions of charge stripping stages were determined to attain a minimum acceleration voltages in the linac and their specific energies are 0.3 and 1.6 MeV/u. The first stripper is a helically revolving drum equipped with carbon foils.

The first linac should be Wideröe type which is operated in π-3π mode because of low velocities of ions. A coaxial type Wideröe linac is adopted considering its simpler power feeding system for quadrupole magnets than that of the resonant twin-line type Wideröe linac. The resonant characteristics of the linac are analyzed as a transmission-line resonator loaded with drift tubes based upon the results of the model cavity measurements at GSI,[5] LBL[6] and INS.[7]

In Fig.3 gap voltage distribution in the first Wideröe tank is shown with its cross sectional view.

The Alvarez type linacs accelerate heavy ions from 1.1 to 1.6 and from 1.6 to 10 MeV/u. The overall specifications of the injector linac are given in Table 2.

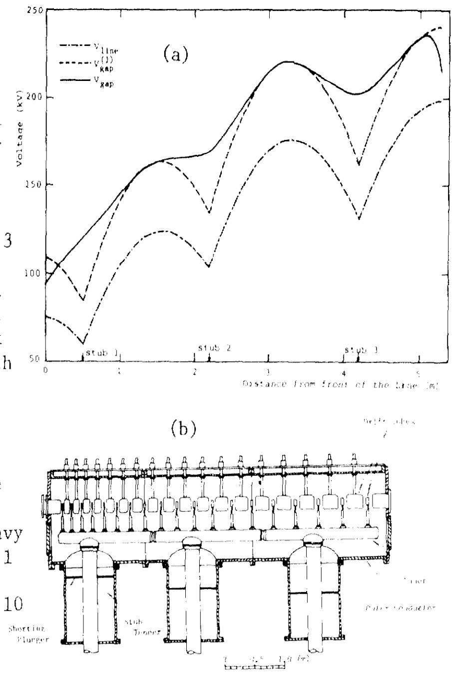

Fig.3 (a) Gap voltage distributions and (b) Cross sectional view of the Wideröe tank 1.

4. Synchrotrons

Two synchrotrons are provided in order to obtain a heavy ion beam of high-intensity and to attain an efficient acceleration. They are planned to be constructed in a tunnel. The diameters of the first and second rings are 58.8 and 67.2 m, respectively. The harmonic numbers of the first and second rings are determined at 7 and 8, respectively, for the synchronized transfer of the bunched beam.

A combination of multiturn injection and RF stacking method is applied to the accumulation of beams in the first ring, and the intensity is estimated to increase 1900 times compared with the single turn injection method. Details of the injection scheme are given in another report to this conference.[8] In the first ring, the momentum spread and radial beam size at the injection energy is ± 2 % and 150 mm, respectively. At the ejection energy of 150 MeV/u, however, these values reduce to ± 0.3 % and 40 mm due to the adiabatic damping. The ejected beam from the first ring can be also used for the experiments in the medium energy region (50 ∿ 150 MeV/u).

4-1. Magnetic Focusing System

Each of two rings consists of 24 normal cells with a FODO structure and eight long straight sections which are prepared for the injection, extractions, RF accelerating sections and for other equipments.

Superperiodicity of both rings is eight and the number of betatron oscillations per revolution both in radial and vertical directions is 6.25, as they are far from the third order sector resonances. The widths of stop bands due to random errors of field gradients and rotations of axis of the quadrupole magnets are estimated at 0.005 and 0.021, respectively, while systematic deviations of field gradients bring about ν shifts of 0.05 over the range of useful aperture.

The field strength of the dipole magnet increases from 2.82 to 11.32 kG as U^{46+} is accelerated from 10 to 150 MeV/u.

On the other hand, the charge state of ion is raised up to 92 for uranium by passing through the stripper section, then the magnetic fields of the bending magnet in the second ring are 4.98 at the injection and 18.0 kG at the maximum energies, respectively.

The bending system of each ring consists of 48 uniform-field magnets of modified window frame type, and the magnet lengths in the first and second synchrotrons are determined by adding 2 cm space to the useful beam aperture for the wall of vacuum chamber and baking elements. The pole width and gap height of magnets in the second ring are determined as 110 mm and 55 mm, respectively, whereas at the first ring, the horizontal aperture is designed considering spaces necessary for the multiturn injected and RF stacked beams. The pole width and gap are determined as 200 mm and 70 mm, respectively.

Table 2. The Injector Linac Specifications

	Wideröe 1	Wideröe 2	Wideröe 3	Alvarez 1	Alvarez 2
Operation Mode	$\pi-3\pi$, 38 gaps	$\pi-3\pi$, 20 gaps	$\pi-\pi$, 36 gaps	2π, 46 gaps	2π, 108 gaps
Synchrotron Phase (deg.)	-30.0	-30.0	-30.0	-25.84	-25.84
T/A (MeV/u)	0.015 - 0.146	0.146 - 0.305	0.305 - 1.102	1.102 - 1.603	1.600 - 10.023
v/c (%)	0.562 - 1.768	1.768 - 2.557	2.557 - 4.861	4.861 - 5.859	5.854 - 14.553
ϵ	0.0294 (U^{7+})	0.0294 (U^{7+})	0.0672 (U^{16+})	0.0672 (U^{16+})	0.193 (U^{46+})
L (m)	5.5	5.4	8.0	7.5	32.1
$\Delta T/(L\cdot\epsilon)$ (MeV/m)	0.85	1.00	1.49	0.988	1.36
Z_{eff} (MΩ/m)	67.8	36.0	47.6	41.8 - 43.4	43.3 - 31.6
Power Loss (MW)	0.076	0.215	0.494	0.206	1.903
Q-magnet Sequence	FDFD	FDFD	FFDD	FFDD	FFDD
G (kG/cm)	10.0 - 3.18	3.18 - 2.20	3.50 - 1.83	4.00 - 3.30	3.30 - 1.33
$\cos\mu$	0.849	0.849	0.572	0.906	0.906
Aperture (mmϕ)	20, 25, 30	30	35	40	40
Admittance (mm mrad)	114 π	88.7 π	127 π	248 π	203 π

4-2. RF System

The RF systems in the rings have two functions, one of which is for RF stacking and the other is to accelerate the beam to the extraction energy. The former is fully described in other reports[8] and only the latter is presented in this paper.

Sweep range of RF frequency in the first ring is 1.88 ∿ 6.58 MHz and in the second ring it is 6.58 ∿ 9.89 MHz. At the present design the magnetic fields of two synchrotrons vary linearly with time, $\dot{B}$ = 65.5 kG/s, and then the required RF peak voltage is around 22 kV for the synchronous phase angle of 30°. On the other hand, the energy spread of the accumulated beam in the first ring is 425 keV for the stacked number of 100, and the required peak RF voltage is determined so that the separatrix well cover the energy spread of the beam, namely 140 kV.

The total accelerating voltage is supplied by four cavities at the two long straight sections. Each cavity is composed of two $\lambda/4$ coaxial resonators with 50 cm in diameter and 100 cm long. The cavity is ferrite loaded in order to change the resonant frequency, where the ferrites are saturated with 4 turn windings of the bias current of 0 to 750 A. The average flux density in the ferrite is 120 G at the maximum accelerating voltage of 35 kV/gap. The total ferrite loss in a cavity is 40 kW, and the shunt impedance of the cavity is 10 kΩ.

4-3. Vacuum

The required pressure for the synchrotron should be lower than 10^{-10} torr due to the charge exchange reactions between ions and residual gas molecules assuming a cross section of the reactions as 2×10^{-17} cm^2.

The vacuum chambers of the rings have circumferential length about 200 m, which are divided into eight major bending sections and eight straight sections by gate valves. Each bending section has six pumping units.

Eight turbo-molecular pumps are used for roughing down the chambers and for pumping during the bakeout. The chambers are pumped down by 64 sputter-ion pumps, and also 64 titanium-getter pumps are used as the auxiliary pumps at high vacuum region.

4-4. Ejection

At the present proposal, one fast ejection channel and two slow ejection channels are provided to answer the various needs for high energy heavy ion beams. Even at the final stage of the acceleration, the beam size is rather large and it is important that the ejection system is safe for the beam blow up. From this point of view, we adopt the third integer resonance, although in this extraction mode, the arrangements of non-linear magnets will largely affect the emittance, spill time and the size of stable region.

Third integer resonance is excited by a sextupole magnet after the radial ν-value is tuned to 6.30 and the closed orbit at this moment is distorted so that the beam clears the resonance orbit.

The growth rate of the amplitude is found to be 0.71 cm per turn at the position of the first septum. When the septum with the thickness of 1 mm is used, the ejection efficiency in this process is expected to be 86 %. The emittance of the ejected beam is estimated at 2.3 π mm·mrad.

The test accumulation ring for the NUMATRON project, TARN, is now under construction at INS for the preparatory study of the project. Details of the TARN are presented at this conference. The construction of NUMATRON is expected to start in a few years.

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