MUSES PROJECT AT RI BEAM FACTORY

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1 INTRODUCTION

At RIKEN, Radio Isotpe beam factory project is proposed as an expanding facility of the existing high current heavy ion accelerators of an ECR ion source, a frequency variable linac and a ring cyclotron [1]. A new type of experimental facility, MUSES (Multi-USe Experimental Storage rings), is planed for this RI beam factory. It consists of an Accumulator Cooler Ring(ACR), a Booster Synchrotron Ring (BSR) and Double Storage Rings (DSR). This MUSES will be installed downstream from the Superconducting Ring Cyclotron (SRC) and RI separator, Big RIPS (Fig.1). The DSR permits various types of unique colliding experiments; ion-ion merging or head-on collisions; collisions of electron and ion (stable or RI) beams and collisions of RI beams with high brilliant X-ray from an undulator. On the other hand, the ACR functions for the accumulation and cooling of RI beams and for the atomic and molecular physics with cooler electron beams. The BSR works solely for the acceleration of ion and electron beams. In the present paper, the outline of MUSES accelerator will be given while the details of each accelerator are described in other papers presented in this conference.

2 ACCUMULATOR COOLER RING(ACR)

In Table 1, the main parameters of ACR are listed [2]. Taking the accumulation and cooling of an extremely neutron-rich ^{132}Sn^{50+} (a double-magic nucleus of 40 s in half-life) beam of 200 MeV/nucleon as an example, we give some specifications of the ACR. This RI beam is produced via projectile fragmentation of a primary beam of ^{136}Xe ions with a peak current of 100 pμA. Typical beam characteristics are estimated as follows: the production rate is nearly 5×10^8 particles per second; the momentum spread is $\pm 0.5\%$; the phase width relative to RF frequency is ± 5 degrees; and the transverse emittance is 4.5π mm·mrad in both horizontal and vertical directions. This beam is transported from the target point to the injection point of ACR along the length of 70 m. At the end point of transport line, a debuncher system with 8MV voltage and harmonics number 6, will be installed to reduce the momentum spread to $\pm 0.1\%$. Firstly, the RI beam is stored in the ACR with the conventional multi-turn injection method in the horizontal phase plane. About 5×10^2 particles are injected for each one turn revolution, because the orbit frequency is nearly 1 MHz. Provided that the acceptance of horizontal phase space of the ACR is designed to be 125 π mm·mrad, and that the dilution factor during the multiturn injection, is 1.25, the emittance of the stored beam becomes as large as the full acceptance after 22 turns injection. At this moment, the number of stored particles increases up to 1×10^4 particles. Secondly, the stored particles are RF-stacked [3]: The RF voltage of 24 kV is applied, and the frequency is swept from 30.30 MHz (corresponding to 200 MeV/nucleon) to 30.62 MHz. This frequency sweep brings about changes in the beam momentum and average radius by 1.8 % and 17 mm, respectively. This multi-turn-injection plus RF-stacking process is repeated at 10 Hz (1/τ_{cool}) where τ_{cool} is a longitudinal stochastic or electron cooling times. During this process the stacked beam continuously undergoes the stochastic or electron cooling at the stacked top energy. Typical parameters of the stochastic cooling and electron cooler are tabulated in Tables 2 and 3. The longitudinal cooling time by the stochastic method is estimated to be as short as 0.1 s while the cooling time of electron cooler is several seconds [4]. After a sufficiently longer period than the intrinsic half-life, the number of coasting particles accumulated in the ACR amounts up to the equilibrium value of 5×10^6. The momentum spread and emittance of the cooled stacked beams, become less than 0.15 % and nearly 1 π mm·mrad, respectively. This high-quality stored beam is adiabatically bunched with RF field. They are fast extracted, and is injected into the BSR by one turn injection method.

Table 1: Main Parameters of Accumulator Cooler Ring.

Circumference(m)	C=168.4836
Max. Magnetic Rigidity(Tm)	Bρ=7.244
Max. Beam Energy(MeV/u)	T$_{max}$=500(q/A=0.5)
Transition Gamma	γ_{tr}=4.987
Betatron Tune Values	Q$_x$/Q$_y$=4.555/3.540
Natural Chromaticity	Q$_x$'/Q$_y$'=-5.058/-6.571
Beam Acceptance(mm.mrad)	125π
Momentum Acceptance(%)	ΔP/P=$\pm$2.5
Injection Method	Multiturn injection +RF stacking
Beam Cooling Method	Stochstic+Electron Cooling

Table 2: Parameters of the Stochastic Cooler.

Longitudinal Cooling Time	
(Number of Ions 1×10^7) (sec)	
U^{92+}(150 MeV/u)	0.06
C^{6+} (400 MeV/u)	0.01
Band Width (MHz)	2000
Ambient Temperature (K)	18
Atmospheric Temperature (K)	80
Amplifier Gain/Gain$_{opt}$	0.2
Total Microwave Power (kW)	10
Longitudinal Pickup Sensitivity (Ohm)	300

Table 3: Parameters of the Electron Cooler.

Maximum Electron Energy (keV)	300
Maximum Cooled Ion Energy (MeV/nucleon)	500
Maximum Electron Current (A)	10
Cathode Diameter (mm)	8.0
Max. Electron Current Density(A/cm^2)	0.25
Electron Diameter at Cooling Section (mm)	50
Maximum Solenoid Field	
at Cooling Section (kG)	1.2
Length of Cooling Section (m)	3.6
Cooling Time (s) for 200-MeV/nucleon $^{132}Sn^{50+}$,	
initial Δp/p=0.5%	
and emittance ϵ =125π mm·mrad	5.4

3 BOOSTER SYNCHROTRON RING (BSR)

The Booster Synchrotron Ring (BSR) serves as a synchrotron to accelerate ion beams transferred from the ACR [5]. The main parameters are given in Table 4. The maximum Bρ of the BSR is designed at 14.6 Tm which is matched with the DSR. The accelerated ion beams will be fast extracted and one turn injected into the DSR, and also slowly extracted for the experiments. The electrons from a 0.3 GeV linac will be also accelerated in BSR up to 2.5 GeV. At the initial energy of 0.3 GeV the damping times are estimated to be 0.5 s for the transverse direction and 0.26 s for the longitudinal direction, which are short enough for the accumulation of electrons. The acceleration up to 2.5 GeV is done within 1 s. This top- energy electron beam is fast extracted and injected into the DSR by one turn injection method.

4 DOUBLE STORAGE RINGS

The DSR consists of vertically stacked two rings of the same specifications as shown in Table 5. Each lattice structure takes the form of a racetrack to accommodate two long straight sections. These straight sections of one ring vertically intersect those of the other ring at two colliding points. The ring circumference is 258.336 m, which is

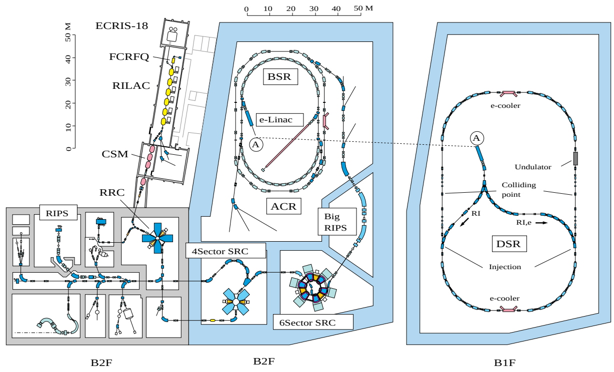

Figure 1: Preliminary layout of the MUSES. The accelerators are housed in the 2-story building.

46/6 times the extraction circumference of the Superconducting Ring Cyclotron (SRC), 5.363m. It means that the harmonic number of DSR is 46 while that of SRC is 6. The maximum Bρ-value becomes 14.6 Tm when a dipole field strength is 1.5 T at the maximum. The maximum energy is then, for example, 3.5 GeV for protons; 1.4 GeV/nucleon for light ions of q/A=0.5; and 1.0 GeV/nucleon for U^{92+} ions. For electrons the BSR boosts them up to the maximum energy of 2.5 GeV from 300 MeV injector linac, and they are stored in the DSR. In the present lattice structure, the betatron tune values are 14.653 (horizontal) and 16.283 (vertical). The operating ion-beam energy is kept to be under the transition energy, since the transition gamma is as high as 24.44. At the colliding points the beta-function amplitudes are 0.02 m for both directions. This small values are required from the point of view of luminosity [6] and beam-beam effects [7]. At the collision of electron beam and RI beam, the bunch length of electron is 2.2cm and that of ion is 50 cm. The optimized beta values at the collision point is 0.02 m which is the same value of electron bunch length. The linear tune shift by the beam-beam effects is limitted as low as 0.005 for ion beams. The field-free section near the colliding points where experimental detector systems are installed, is 3.0 m in length. These two long

Table 4: Main Parameters of Booster Synchrotron Ring.

Circumfernce(m)	C=134.787
	Racetrack shape
Magnetic Rigidity(Tm)	Bρ=14.6
Max. Repetition(Hz)	1
Transition Gamma	γ_{tr}=4.684
Betatron Tune Values	Q_x/Q_y=5.640/4.615
Natural Chromaticity	Q_x'/Q_y'=-7.526/-8.066
Max. Betatron Amplitude(m)	β_x/β_y=20.461
Max. Dispersion(m)	D_x/D_y=2.918/0.0
RF Frequency Range(MHz)	25-55
Max. RF Voltage(kV)	50

straight sections are dispersion-free in horizontal and vertical directions.

One of the key researches planned at the DSR is the colliding experiment of an electron beam with an RI beam: 2.5 GeV electrons accumulated in one ring of the DSR collide with an RI beam stored in the other ring. The scientific aim of this experiment is to determine the charge and current distribution in the neutron- or proton-rich radio- active nuclei. To keep a sufficiently long Touchek lifetime, the RF voltage of 2.0 MV is applied to the electron beam. The detailed specifications of stored electron beams in the DSR are given in Table 6. The number of stored electrons amounts up to 2.7×10^{12} particles which is limited due to the longitudinal coupled bunch instability. The typical colliding luminosity for the electrons and RI ions is estimated to be 5.6×10^{26} cm^2/s, provided that 1×10^7 particles of RI ions are stored and synchronously collide with electron bunches. In order to further improve the luminosity, the installation of a powerful pulsed heavy-ion source, e.g. a laser ion source or a metal-vapor ion source, should be installed instead of ECR ion sources.

Another envisaged experiment is the isotope shift of X-ray absorption by the Li-like or H-like unstable nuclei [8]. To produce the short wavelength X-ray from 20-1000 eV energy, an undulator will be inserted in an electron ring. To obtain the high flux mono-energetic X-ray, the emittance of stored electron beam should be as small as around 10 nano m.rad. The lattice structure of DSR is designed so as to give such a low emittance electron beam [9]. Other experiments such as ion-ion merging collisions at small angles are also envisaged. The luminosity is expected to be around 1×10^{26} cm^2/s when the number of stored ions is assumed to be the space charge limit of 4×10^{12} particles and the colliding angle is 10 degrees.

Table 5: Main parameters of the DSR.

Circumference C (m)	258.336
Max. Bρ (Tm)	14.60
Average Radius R (m)	41.12
Radius of Curvature ρ (m)	9.733
Max. Stored Beam Energy	
proton (GeV)	3.55
ion (q/A = 0.5) (GeV/nucleon)	1.45
ion (q/A = 0.387) (GeV/nucleon)	1.00
Betatron Tune Values (Q_x/Q_y)	14.653/16.283
Momentum Compaction	0.00167
Transition γ	24.444
Max. Betatron Amplitude (β_x/β_y, m)	22.0/13.5
Max. Dispersion Function (D_x/D_y, m)	0.727/0.569
Betatron Amplitude	
at Interaction Point (β_x^*/β_y^*, m)	0.020/0.020

Table 6: Parameters of the Stored Electron Beam.

Max. Stored Beam Energy E_{max} (GeV)	2.5
Max. Stored Beam Current I (A)	0.5
Max. Stored No. of Electrons N	2.7×10^{12}
Injection Energy E_i (GeV)	2.5
Beam Emittance at 2.5 GeV (ϵ_x/ϵ_y) (nm·rad)	8.54/25.5
Energy Spread ΔE/E	6.8×10^{-4}
Bunch Length σ (cm)	0.50
RF Voltage V_{RF} (MV)	2.0
Revolution Frequency f_{rev} (MHz)	1.159
RF Frequency f_{RF} (MHz)	500.688
Harmonic No. h	432
Touschek Lifetime at 2.5 GeV (s)	3.0×10^4
Synchrotron Radiation Loss	
at 2.5 GeV (keV/turn)	371.7

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