11. SHARAQ Spectrometer

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(abstract)

Construction of a high resolution SHARAQ spectrometer with $p/\delta p=1.5\times10^4$ is proposed. Physics programs performed with the SHARAQ spectrometer are based on a new missing mass spectroscopy with an RI-beam used as a ``probe''. The properties of RI beams having a variety of isospin, internal energy, and spin, enable us to investigate the responses of multi-neutron systems and double Gamow-Teller states which have been hardly accessible with reactions induced by stable beams.

Designs of the SHARAQ spectrometer and the dispersion matched beam line are described.

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I. INTRODUCTION

1) Missing mass spectroscopy with RI beams at RIBF

Missing mass spectroscopy is a source of our knowledge on nuclear ground, bound excited, and continuum states. Bases of single-particle property of nuclei, correlation in nuclei, and so on have been established from the experimental data obtained through missing mass spectroscopy. Conventional missing mass spectroscopy uses light stable beams, such as proton, deuteron, and $^{3,\,4}$He, and high resolution detectors.

The proposed physics programs are based on **a new missing mass spectroscopy with an RI-beam used as a ``probe'' and with a high-resolution SHARAQ spectrometer.** RI beams can have a variety of isospin (T), internal energy (mass excess, ε), and spin (S), while light stable beams listed above have $T;\ S \leq 1$ and the minimum internal energies among isobars. With the properties of RI beams, it is possible to reach states which are hardly accessible via the stable-beam induced reactions. In this respect, a RI beam as a probe has in principle abilities that are not available to stable beams.

The energy range of RI beam produced in RIBF, 100–300 MeV per nucleon, is well suited for the spectroscopic study described above. At these energies, the nucleon-nucleon interaction is weakest. As a result of this, distortion effects, which may smear out signatures of interesting phenomena, should be smaller than at lower or higher energies. Additionally, the reaction mechanism becomes simpler at > 100MeV/A. Dominance of single- and two-step processes at these energies should facilitate a rather simpler interpretation of reaction data to deduce the nuclear structure information involved. Further advantage of the RIBF energies is that the spin-isospin interaction is strongest, relative to the spin-isospin independent interactions. The spin-isospin excited states can be clearly observed at the RIBF energies.

To take fully advantages of the unique properties of RI beams at RIBF, the construction of the high-resolution SHARAQ spectrometer and the development of a dispersion-matched beam-line are proposed.

2) Physics programs

Charge exchange reactions are a fundamental tool to probe nuclear systems. The reactions induced by light, stable nuclear beams have been proven to be effective to investigate excited states at low excitation energies. Exothermal charge exchange reactions induced by RI beams open new possibilities to probe higher excitation states with small momentum transfer. By using these reactions, we will be able to produce states which have been hardly observed so far, for example, multi-neutron systems, isovector spin monopole resonances, and double Gamow-Teller resonances.

a) Multi-neutron systems

Multi-neutron systems attract much attention for the understanding of few-nucleon systems and few-body forces which are to be compared with precise *ab initio* calculations based on realistic interactions. These systems are also interesting from the point of views of the limits of the nuclear system beyond the neutron dripline especially for correlations in multi-body scattering states. Missing mass spectroscopy of the multi-neutron system via exothermal double charge exchange reactions with minimum momentum transfers is a unique tool for experimental studies, which can be directly compared to theoretical predictions of the spectra by using realistic N-N interactions [2, 3]. This idea can be extended to the study of very neutron-rich ``superheavy'' hydrogen systems, ^{6,7}H, which are also unique multi-body scattering states.

b) Spin Giant Resonances

Giant resonances which have been hardly within the reach of conventional probes can be effectively populated by RI-beams inducing single and double charge exchange reactions. They are isovector spin monopole resonance (IVSMR) and double Gamow-Teller resonance (DGTR). In order to establish the IVSMR, exothermal heavy-ion charge exchange reactions probing the spin-isospin strength at the nuclear surface around 250 MeV/nucleon are an excellent tool. Since the transition density of IVSMR changes its sign inside a nucleus, the surface sensitivity is an indispensable property of the probe to avoid undesirable cancellation of the strength. The (^{12}N, ^{12}C) and (^{12}B, ^{12}C) reactions for the $\beta^-$and β^+ directions, respectively, are excellent tools due to their large positive Q-values. The DGTR, which is of particular importance in relevance to double beta decay, is experimentally still unobserved, while other multi-phonon giant resonances, such as double isobaric analogue and double giant dipole resonances, have been observed via the (π^+,π^-) reaction. Attempts to find double Gamow-Teller strengths via heavy ion double charge exchange reactions have been conducted at GANIL, MSU and RCNP by using the (^{18}O, ^{18}Ne) and the (^{11}B,^{11}Li) reactions, respectively. No clear evidence has been found so far. The RI-beams inducing reaction, for example the (^{20}Mg, ^{20}Ne) reaction proposed here, are suitable tools to probe the double Gamow-Teller states in several respects. The energy required to excite the target nucleus, typically E_x ~ 20－30 MeV for the double Gamow-Teller resonance states, is provided by the internal energy of the ^{20}Mg nucleus of the beam. As a result, momentum-transfer can be kept to as small as ~ 5 MeV/c at 0 degree and at an incident energy of E/A = 300 MeV. This is in striking contrast to the (^{18}O, ^{18}Ne) and the (^{11}B, ^{11}Li) reactions where larger momentum transfers are unavoidable. It should also be emphasized that a continuum background is expected to be considerably suppressed in the (^{20}Mg, ^{20}Ne) reaction due to the condition of small recoil.

3) High resolution SHARAQ spectrometer

For spectroscopic purposes, it is necessary to measure both the projectile energy and the ejectile energy with high precision, with ΔE typically better than several hundred keV.[1)] Since RI-beams have total energies of 2~3 GeV (e.g. 2.4 GeV for 300MeV/A ^{8}He beam and 3 GeV for 150MeV/A ^{20}Mg beam), the beam energy spread $\Delta E/E$ should be less than about 10^{-4}.

The SHARAQ spectrometer is designed to achieve a resolving power $p/\delta p$ of 1.5×10^{4} to meet this requirement. High resolution and the precise reconstruction of the scattering angle from measurements in the focal plane are required for the separation of nuclear levels and the determination of the transfered angular momentum L=0, respectively. In addition the beam line will be fully dispersion matched to the spectrometer, involving spatial and angular dispersion matching and the focusing condition on target.[2)] As an alternative method the particle-by-particle tagging method will also be applied. Details of the design and operation modes of the beam line are still under investigation.

The spectrometer will rotate relative to the incoming beam in the range of −3° to +15°. The SHARAQ spectrometer will be a unique spectrometer at RIBF, with the capability of finite angle measurements. It will be possible to obtain angular distributions which are important in decomposing transferred orbital angular momentum. Note that finite angle measurements are also required in analyzing power measurements with polarized targets.

[1)] It is noted that typical level spaces among low-lying states in medium-heavy nuclei are around several hundred keV. The transition strengths in proposed exothermic reaction should be calibrated by the cross sections to the low-lying well-known states, where the proposed resolution is important.

[2)] The ion-optics of the spectrometer will be such so that the vertical component of the scattering angle can also be reconstructed.

II. SETUP

1) The SHARAQ Spectrometer

The SHARAQ spectrometer is designed to achieve a momentum resolving power p/Δp of 1.5×10^4 for particles with a maximum magnetic rigidity of $B\rho$ = 6.8 Tm, and a high angular resolution of $\delta\theta <$ 2 mrad. The magnetic rigidity corresponds to an orbital radius of 4.8 m of the central ray for a magnetic field strength of 1.42 T.

The SHARAQ spectrometer consists of three quadrupole and two dipole magnets as shown Fig. 1.

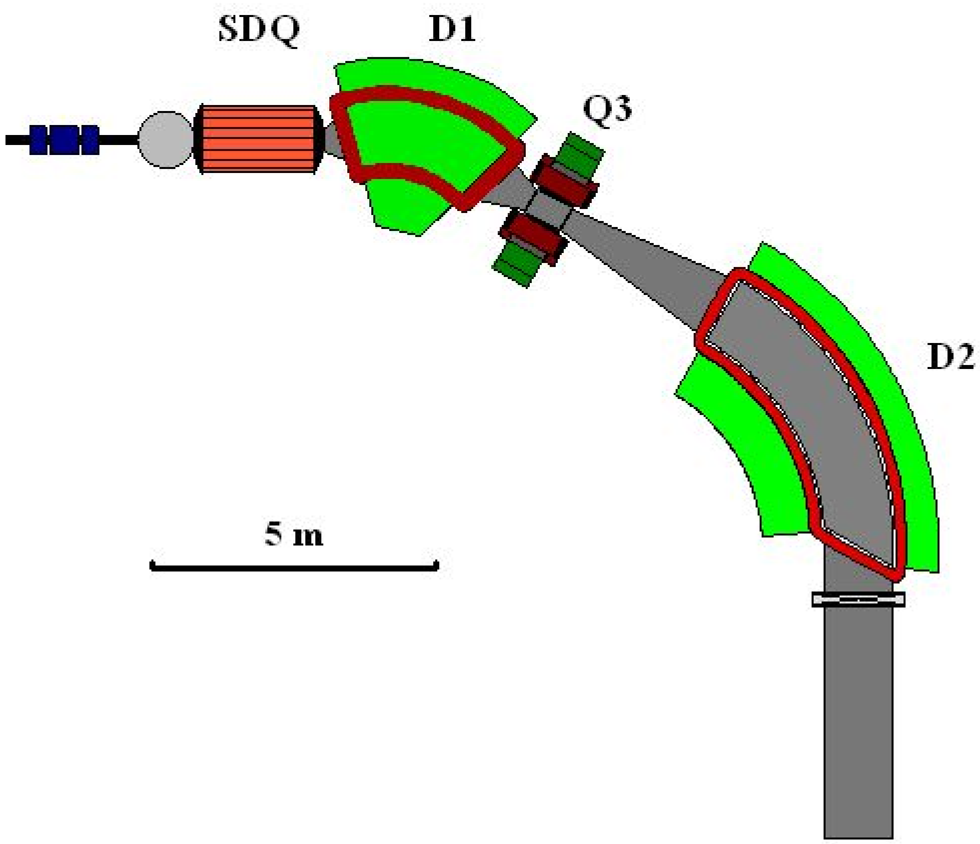

Fig. 1: Schematic drawing of the SHARAQ spectrometer.

The first doublet quadrupoles Q1, Q2 (SDQ) are superconducting magnets to provide the required large field gradient of > 10 T/m for a bore radius of 0.17 m. The design of the SDQ is similar to the design of the BigRIPS triplet quadrupole magnets (STQ). Modifications are made to the STQ vacuum chamber design. SDQ has a wide horizontal aperture in lozenge-shape of 340 mm in width and 230 mm in height, while the original BigRIPS STQ has a circular aperture with 240 mm in diameter. The wide horizontal bore provides large horizontal acceptances.

As the first dipole (D1) and the third quadrupole (Q3), we will use the existing magnets from the decommissioned SMART spectrograph of RARF. Dipole D1 of SMART was used as a 60-degree bending magnet for 3.4 Tm particles. In SHARAQ, which analyzes 6.8 Tm particles, the magnet is used as a 30-degree bending with 15-degree horizontally-focusing edges both at the entrance and the exit. The function of Q3 is to reduce the vertical magnification, which is necessary to provide the required angular resolution in vertical direction.

The specification of the magnets are tabulated in Table 1-3.

The second dipole magnet (D2) will be a new construction. The bending angle, total gap, and pole width are 60 degree, 200 mm, and 1400 mm, respectively. The exit has an edge angle of 30 degree for horizontal focusing. This horizontal focusing decreases the distance from the dipole exit to the focal plane by a factor of two, required for space considerations. A study is in progress to look for a possibility of smaller sized dipole magnet with higher field, which will provide better fit to the planed installation site and reduced costs.

Central orbit radius	4.8 m
Bending angle	30 deg
Maximum Field	1.5 T
Pole gap	20 cm
Entrance Edge	15 deg(H-focus)
Exit Edge	15 deg(H-focus)
Weight	102 t
Power Consumption (max)	200 kW

Table 1: D1 Specification (Recycle of SMART PD1)

Central orbit radius	4.8 m
Bending angle	60 deg
Maximum Field	1.5 T
Pole gap	20 cm
Entrance Edge	0 deg
Exit Edge	30 deg(H-focus)
Weight	250 t
Power Consumption (max)	300 kW

Table 2: D2 Specification (to be constructed)

	Q1	Q2	Q3
Conductor	Super	Super	Normal
Maximum field gradient	14.1T/m	14.1 T/m	7.7 T/m
Length	1140 mm	640 mm	700 mm
Bore	170 mm(H) ×120 mm (V)	170 mm(H) ×120 mm (V)	135 mm
Weight	3.6 t	2.2 t	15.8 t
Power Consumption (max)	—	—	76 kW

Table 3: Specifications of Quadrupole Magnets. (Q1 and Q2 are now constructing)

・ Standard operation mode

In Fig. 2, ion optical calculations of SHARAQ in standard mode are shown. In the standard mode, target position is placed 1.2 m upstream from the entrance of Q1 to allow installation of gamma-ray and/or particle detectors around the target. Particle trajectories are drawn space for $\delta x = \pm 5$ mm, $\delta\theta = \pm 30$ and 0 mrad, $\delta p/p = \pm 1\%$, $\delta y = \pm 5$ mm, and $\delta\phi = \pm 40$ and 0 mr. Ion-optical properties of the SHARAQ spectrometer are shown in Table 2.

In dispersion matching operation, the horizontal angular acceptance decreases by a factor of about two. This is due to large beam spot size of 80 mm in horizontal direction.

To accommodate to a variety of measurement requirements, several operation modes other than the standard mode are needed to be investigated.

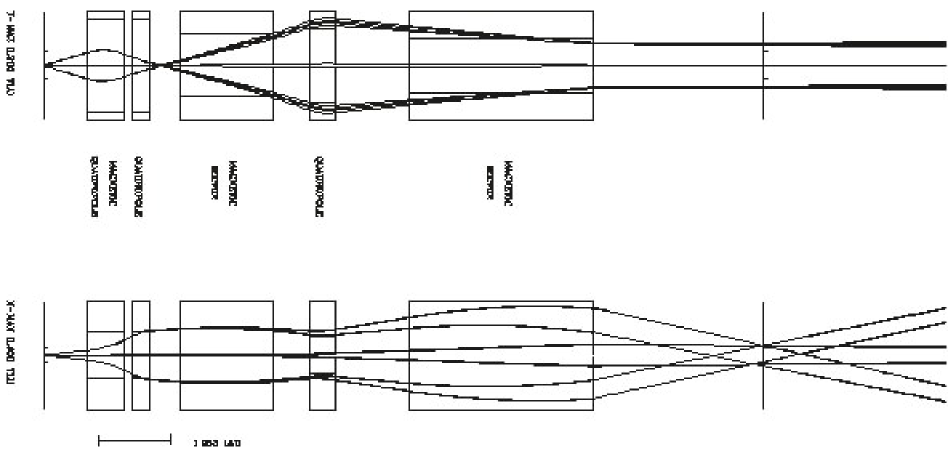

Fig. 2: Ion Optical Calculation in the standard operation mode.

Dispersion	6.8m
Magnification (horizontal)	˜0.45
Magnification (vertical)	˜0.3
Momentum resolution (Δx_{beam} of 1mm is assumed)	15200
Horizontal angular acceptance	±34 mrad (±17 mrad)
Vertical angular acceptance	±34 mrad
Solid angle	4.6msr (2.3msr)
Momentum acceptance	±1%

Table 4: Ion optical properties of SHARAQ spectrometer. Numbers in parentheses are those in dispersion matching mode.

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・ **High-resolution mode**

In the high-resolution mode, the target position is shifted downstream by 600 mm relative to the standard mode and the fields of Q1 and Q2 are changed by +25% and −10%, respectively. A resolving power of $p/\delta p = 2.1 \times 10^4$ can be achieved in this mode.

・ **Large-acceptance mode**

In the large-acceptance mode, the target position shift of 600 mm. Settings of quadrupole magnets are same as those in the standard mode. Large solid angle of 9.2 msr can be achieved in this mode.

Ion optical properties of the three operation modes are shown in Table 5 together with those of ZDS at RIBF, S800 at MSU, and Grand-Raiden at RCNP.

Table 2 Comparison of Spectrometers

	SHARAQ			ZDS			S800	Grand Raiden
Configuration	QQDQD			Q^3DQ^3 Q^3Q^3 Q^3DQ^3			QQDD	QSQDMD
Modes	Standard	High resolution	Large acceptance	Achromatic		Dispersive (III)		
				(I) FB&FC	(II) FB&FC			
Maximum Rigidigy [Tm]	6.8	6.8	6.8	7.3	9	9	4	5.41
Dispersion (D) [m]	6.76	6.76	6.76	2.24	2.12	4.13	9.5	15.4
Horizontal Magnification (M_x)	−0.45	−0.3	−0.54				0.74	−0.41
D/M_x [m]	15.2	20.9	12.5	1.24	2.12	4.13	12.8	37
Momentum resolution (object size : 1mm)	15200	20900	12500	1240	2120	4130	20000	37076
Vertical Magnification (M_y)	0.3	0.3	0.3				0	6.0
Horizontal angular resolution (mrad)	~1	~1	~1				2	2
Vertical angular resolution (mrad)	~1	~1	~1				2	3 − 5
Momentum acceptance	+/−1%	+/−1%	+/−1%	+/−3 %	+/− 3 %	+/− 2 %	+/−3%	+/− 2.5
Horizontal angular acceptance (mrad)	+/−17	+/−34	+/−34	45	20	20		+/− 20
Vertical angular acceptance (mrad)	+/−34	+/−34	+/−136	30	30	30		+/− 40
Flight Path length (m)	20.1	19.5		37			13.1	
Dispersion Matching	x & θ	x & θ		—	—	—	x	x & θ

2) Dispersion Matching Beam Line and Beam Line Detectors

A dispersion matching technique and/or an event-by-event tagging of the beam momentum will be introduced for the purpose to compensate the energy spread of the RI beam. Effectiveness of two methods depends on the beam intensity. In addition to momentum dispersion matching, angular dispersion matching condition should be fulfilled in the beam-line design. High angular resolution of SHARAQ spectrometer can be fully facilitated with the (momentum-) dispersion and angular-dispersion matched beam-line.

The configuration of the beam-line should be considered to have a large dispersion at the SHARAQ target. In this respect, the beam-line should have more than four 30°-bending magnets from the F3 focus point to the SHARAQ target. A singlet quadrupole magnet will be placed between the last two beam-line STQ for ease in tuning of the matching condition.

Calculations of beam-line optics to realize the matching conditions are being made for several sites proposed for the SHARAQ spectrometer. The present proposal of the location and a solution of the transport calculation starting from F3 are shown in Figs. 3 and 4, respectively.

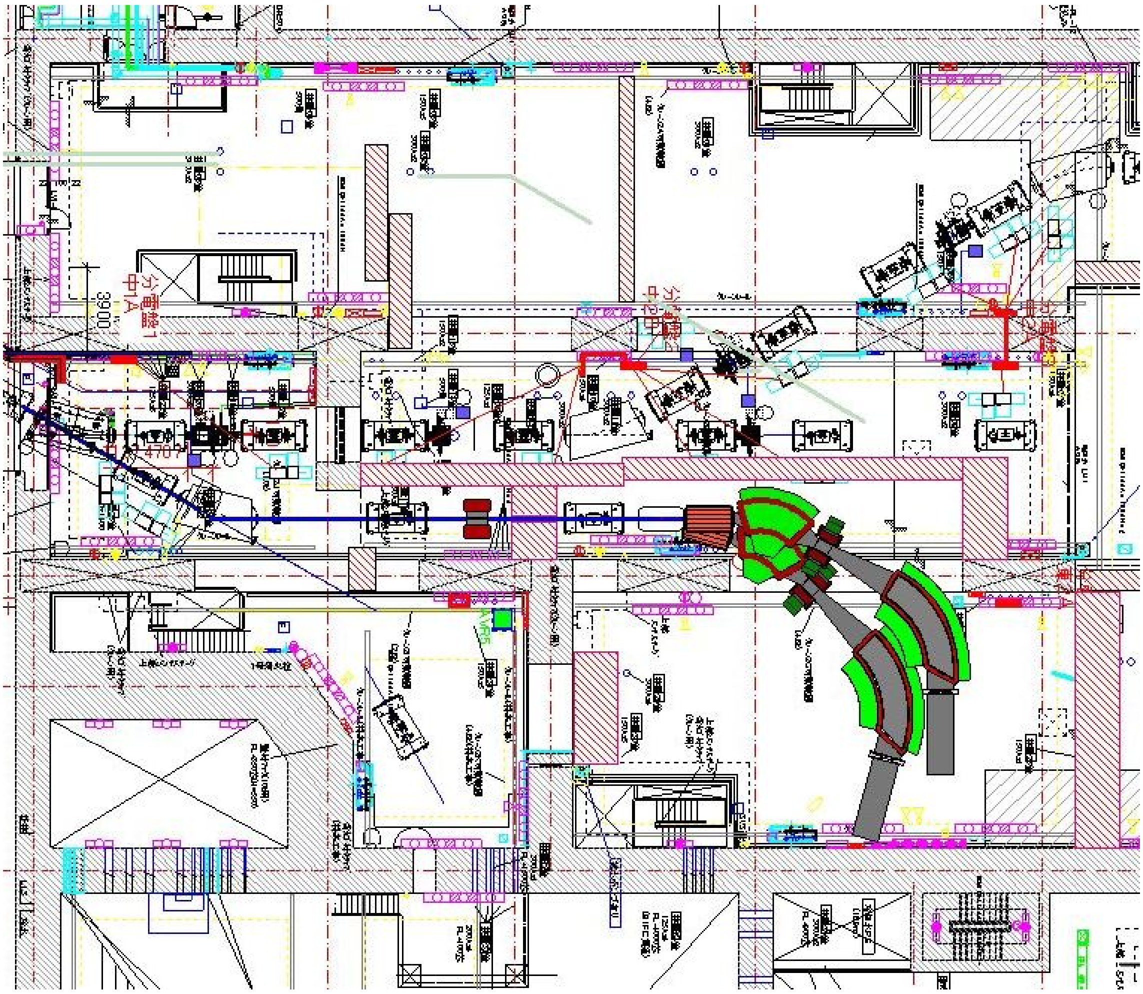
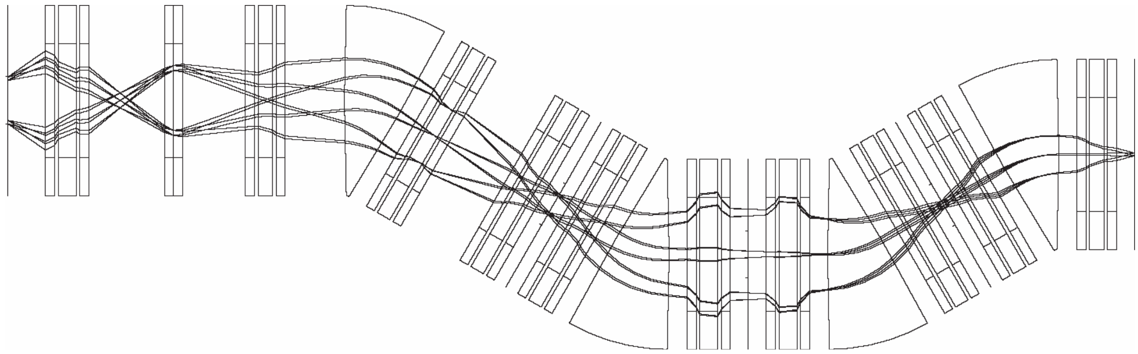


Fig. 3. Planned installation site of the SHARAQ spectrometer.



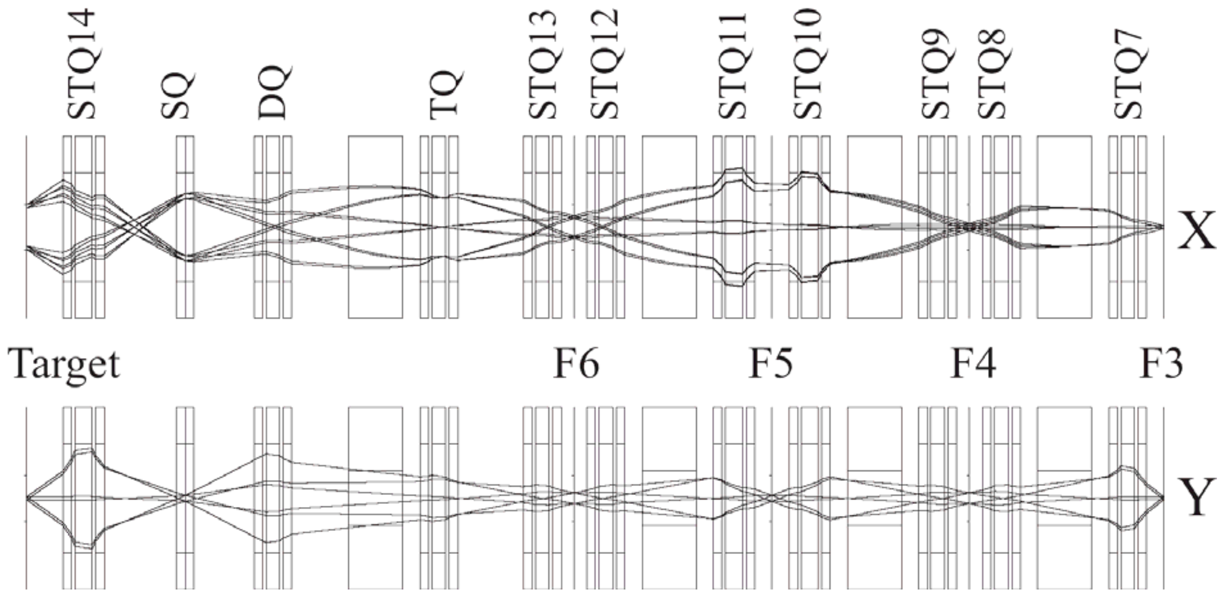


Fig. 4: Ion Optical Calculation of dispersion matching transport from F3**.** Beam comes from right to left.

The tracking detectors in the beam line are used for tuning the dispersion matching transport. From F0 to F6, the standard BigRIPS detector system consisting of position sensitive parallel plate avalanche counters (PPAC) and plastic scintillators will be used. For the tuning at each focus, only the corresponding detectors will be installed.

For the tracking at the SHARAQ target, a set of multi-wire drift chambers (MWDC) are being developed. Considering that the MWPC will be used for particle-by-particle measurement of beam, the specifications are decided to be position resolution of <0.3 mm (FWHM), total efficiency of >95 %, energy-loss of < 1 MeV, multiple-scattering less of < 1mrad, and counting rate of a few times 10^6/sec. In the present design, the MWDC has cell sizes of 5 mm square and strip cathodes of 5 mm width with the delay-line readout developed in the readout of the PPAC [6]. The prototype is being constructed, which will be tested for its performance.

3) Focal Plane Detectors

Cathode-readout drift chambers will be constructed.

III. R&D ISSUES

The construction of the SHARAQ spectrometer and the dispersion-matched beam line is an analytical extension of the well-established technique. The development of the tracking detector is also based on a conventional technique.

IV. COSTS and SCHEDULE

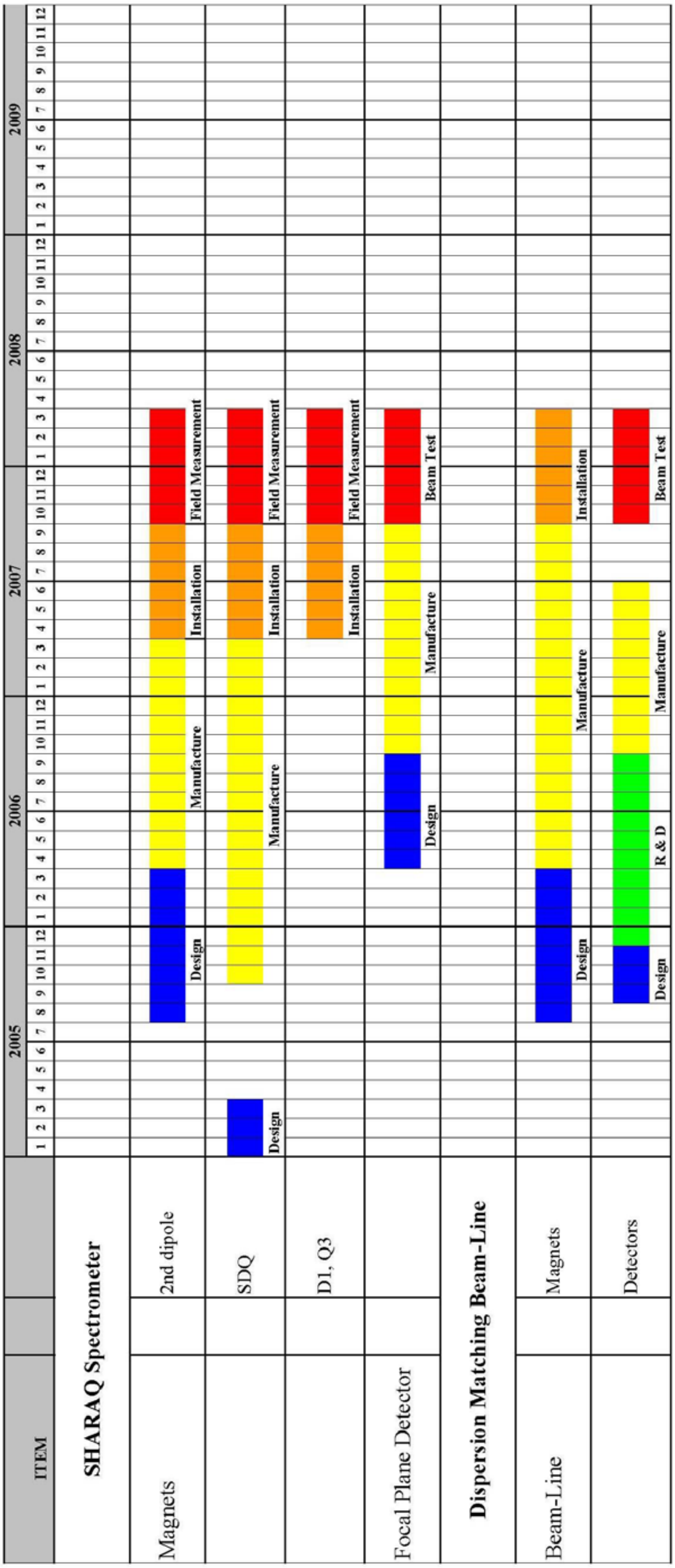
Costs

D1 and Q3 are recycled from an existing spectrograph, SMART, at RIKEN.

● Superconducting Q magnets	90 M yen	(CNS)
● Dipole magnet (D2)	300 M yen	(Grant-in-Aid of MEXT)
● Rotating Device	30 M yen	(Grant-in-Aid of MEXT)
● Power Supply	50 M yen	(Grant-in-Aid of MEXT[D2] / CNS [others])
● Vacuum Apparatus	50 M yen	(CNS)
● Focal Plane & Beam Line Detectors	60 M yen	(Grant-in-Aid of MEXT)
● Beam-line elements	200 M yen	(RIKEN)
TOTAL	**780 M yen**	

Manpower for construction

● Spectrometer	4	(CNS/UT)
[Design, Magnets, Vacuum, Control, Field measurement, Infrastructure]		
● Beam line magnets	2	(RIKEN)
● Beam line detectors	2	(CNS)
● Focal plane detectors	2	(CNS)


ITEM
2005
2006
2007
2008
2009
1 2 3 4 5 6 7 8 9 10 11 12
SHARAQ Spectrometer
Magnets
2nd dipole
SDQ
D1, Q3
Focal Plane Detector
Dispersion Matching Beam-Line
Beam-Line
Magnets
Detectors
Design
Manufacture
Installation
Field Measurement
Beam Test
R & D

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