Spectroscopy with High-resolution Analyzer & RadioActive Quantum beams

SHARAQ Project

~ New Spin-Isopin Modes in Nuclei ~

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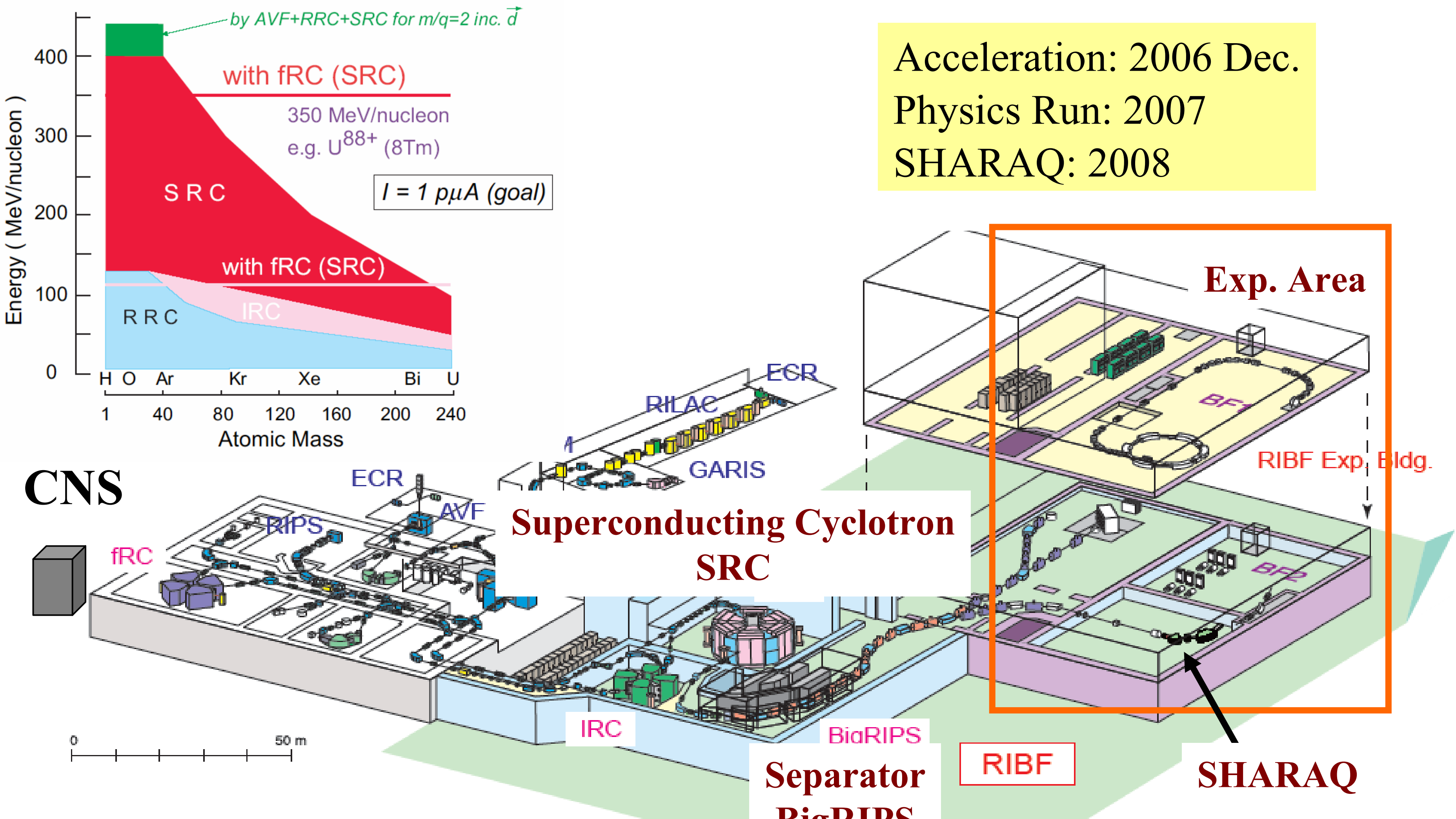
RI Beam Facility @ RIKEN

Acceleration: 2006 Dec.
Physics Run: 2007
SHARAQ: 2008

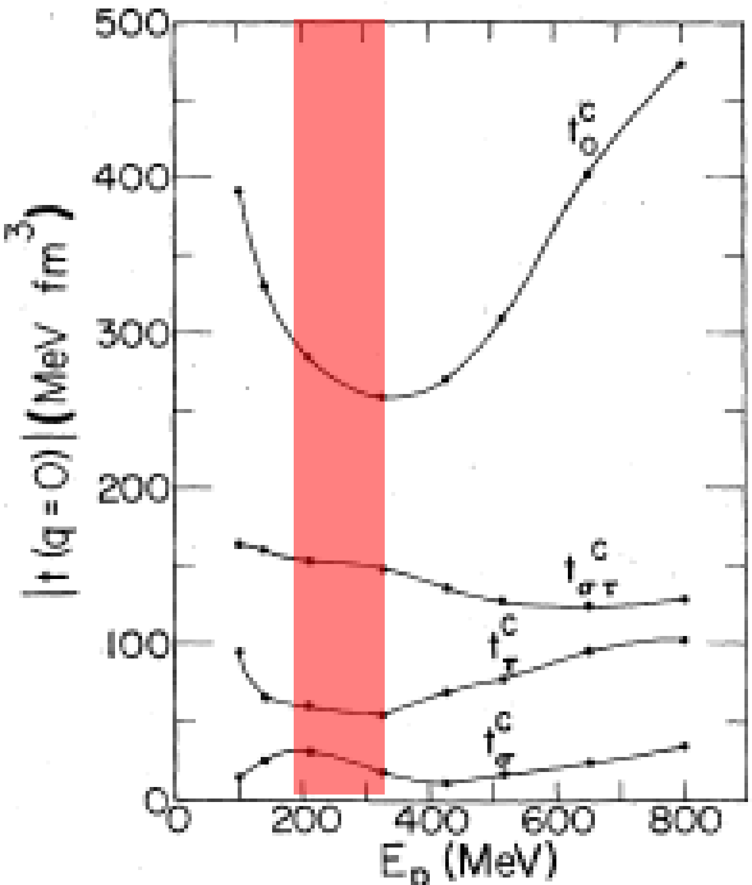


RIBF RI beam generator
featuring superconducting ring cyclotron (SRC)
and projectile fragment separator (BigRIPS)
will be commissioned late in 2006.

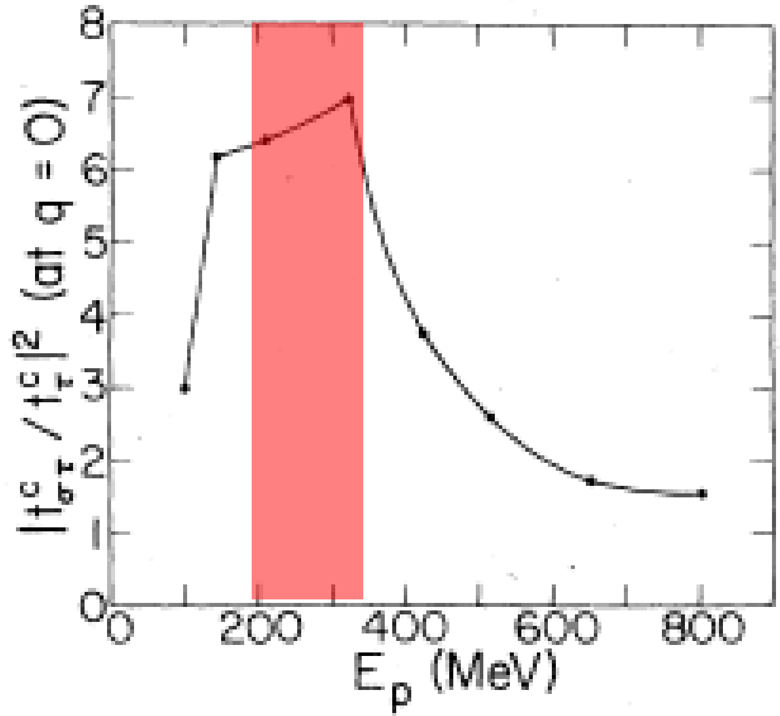
RIBF RI beam experiments
will be started in 2007,
with colored experimental installations.

RIBF Energy

Minimum Nuclear Absorption



Maximum Sensitivity to Isovector Spin-Flip Transitions

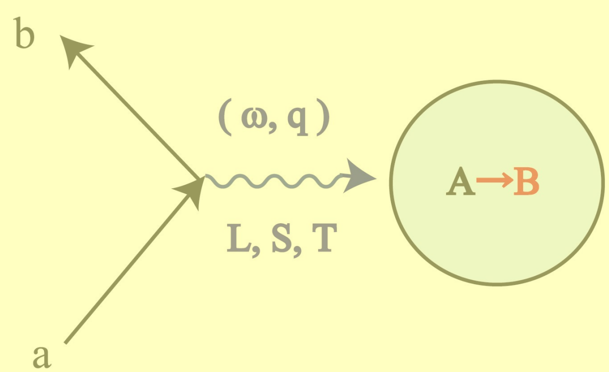


W. G. Love and M. A. Franey, Phys. Rev. C **24**, 1073 (1981).

Best Energy to Investigate Spin-Isopsin Excitation Modes

Spin-Isospin Responses of Nuclei

Extensive charge exchange studies were performed in past.



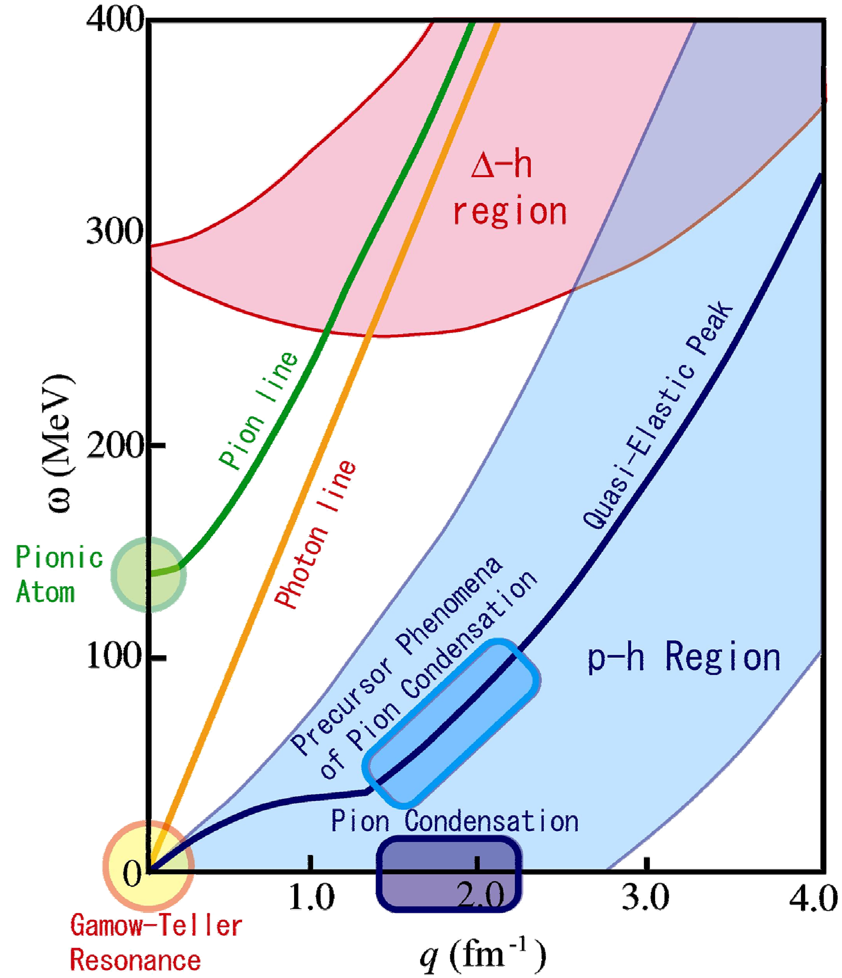
GT resonance

$q \sim 0$, $\omega \sim$ several MeV

Pion condensation

$q \sim m_\pi$

M.Ichimura, H. Sakai, and T. Wakasa, Prog. Part. Nucl. Phys. **56**, 446 (2006).

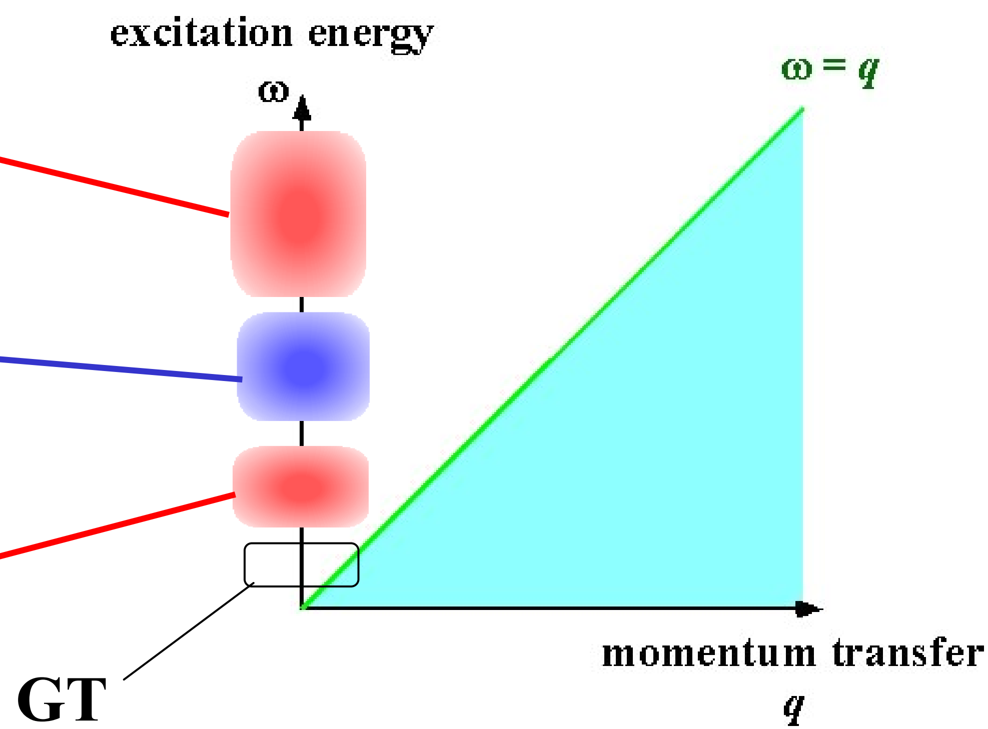


New Modes at Large ω & Small q

Isovector Spin
Monopole Resonances
$\omega = 30 – 40$ MeV

Multi-neutron states
$\omega \sim 30$ MeV

Double Gamow-Teller
resonance
$\omega = 20 – 25$ MeV



Can we study these interesting states
with conventional charge exchange reactions?

Probing ω > q Region

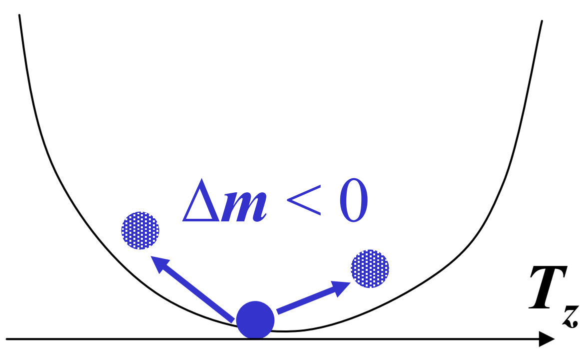
The answer is "NO".
Charge exchange reaction with a stable beam can probe only $\omega < q$,
while the region of interest locates $\omega > q$.

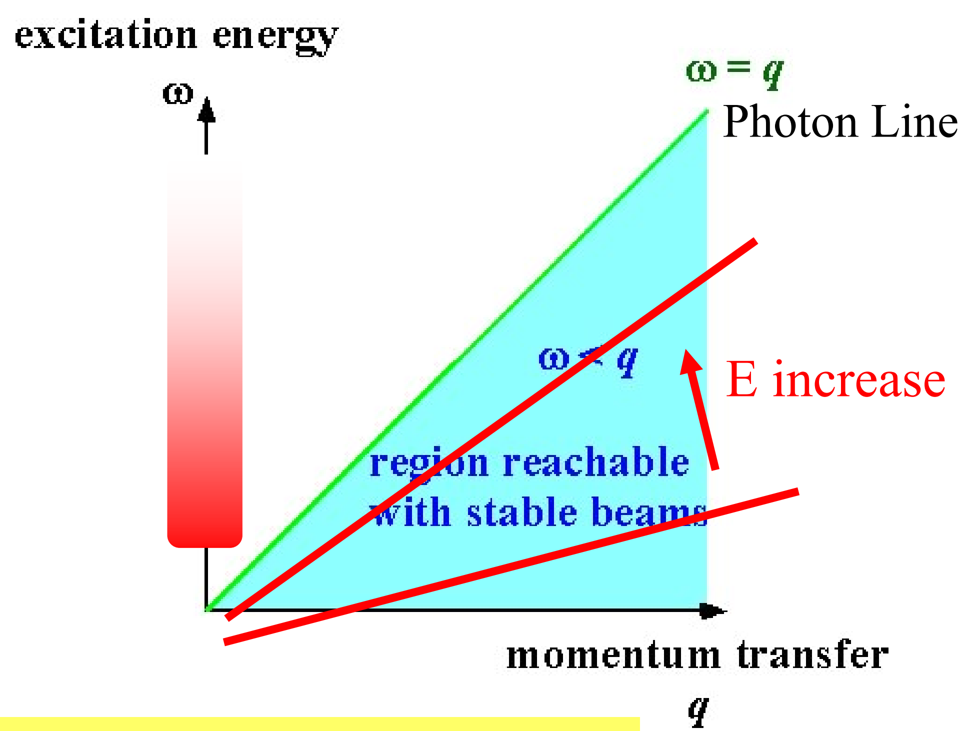
$$\omega \approx \frac{m_1 - m_3}{\gamma} + \beta q$$

Stable nucleus has the smallest mass among its isobars.

$$\Delta m = m_1 - m_3 \leqq 0$$

in stable beam induced reactions.



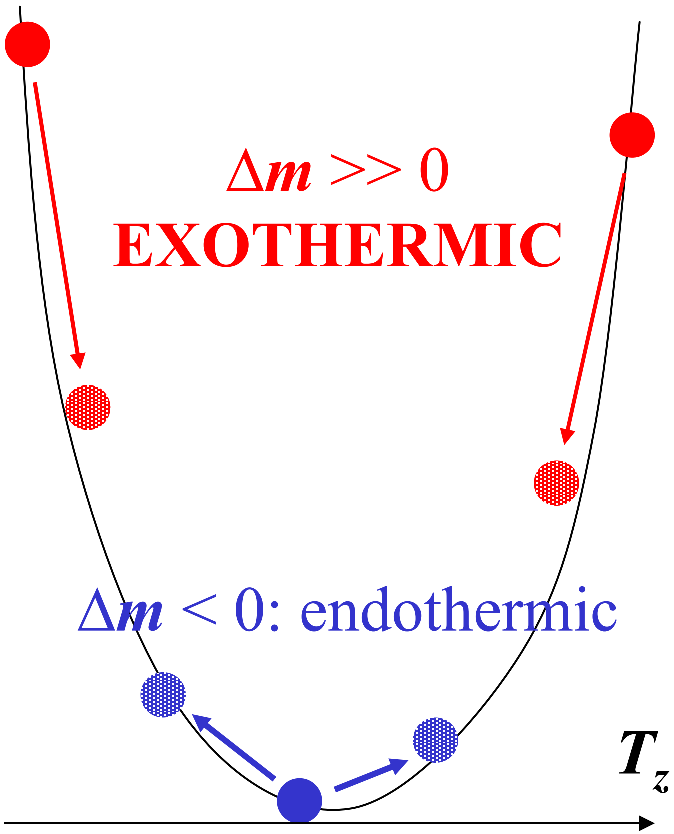


We need a new idea to probe the ω > q region.

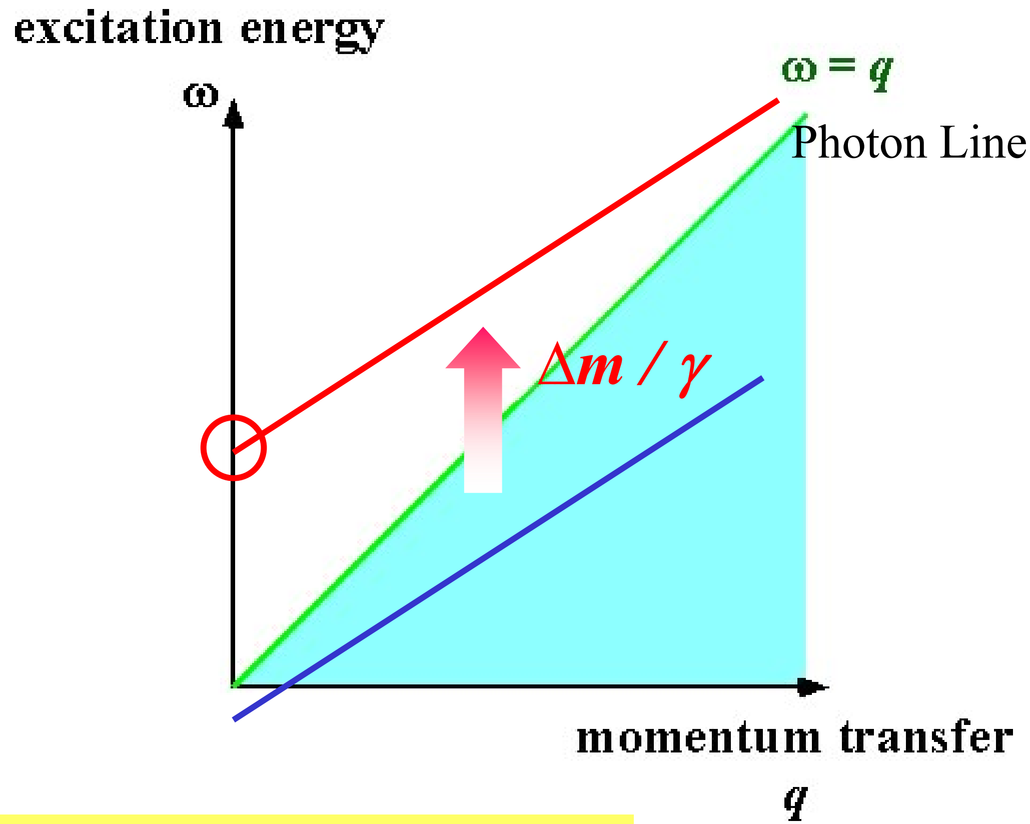
New Idea to Use Unstable Nuclei

With stable beam

With unstable beam



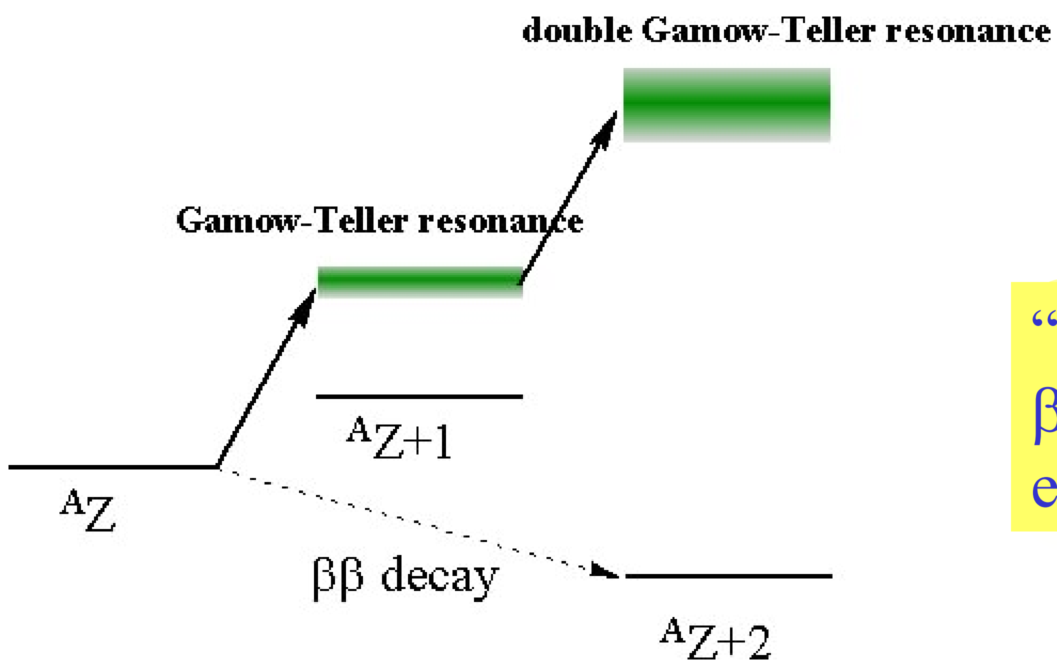
$$\omega \,\square\, \frac{m_1 - m_3}{\gamma} + \beta q$$



RI beam is capable to probe the ω > q region.

Double Gamow-Teller Resonance

GT resonance laid on GT resonance has never been observed.



$E_{DGTR} = 2\,E_{GTR}$?
$\Gamma_{DGTR} = \sqrt{2}\;\Gamma_{GTR}$?

"Calibration standard" of ββ-decay nuclear matrix element.

Heavy-ion double charge exchange reactions
(^{18}O,^{18}Ne), (^{11}B, ^{11}Li) → No successful results

Momentum Transfer in DGT Study

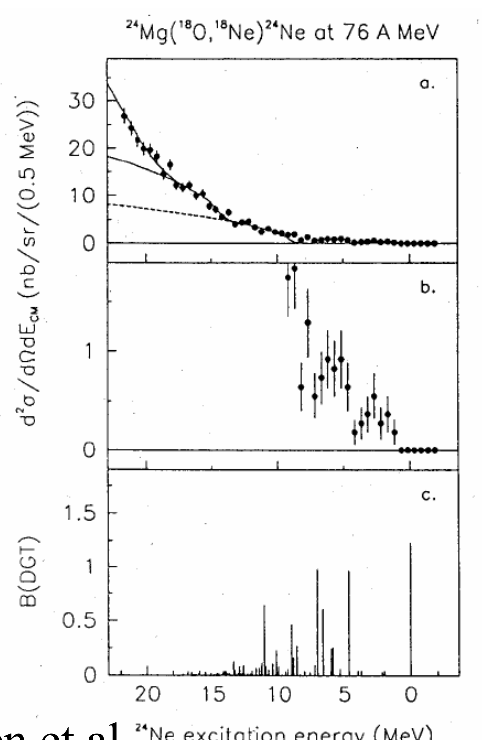
$\theta = 0$ deg, $\omega = 20$ MeV

^{24}Mg(^{18}O,^{18}Ne) @76 MeV/A, GANIL

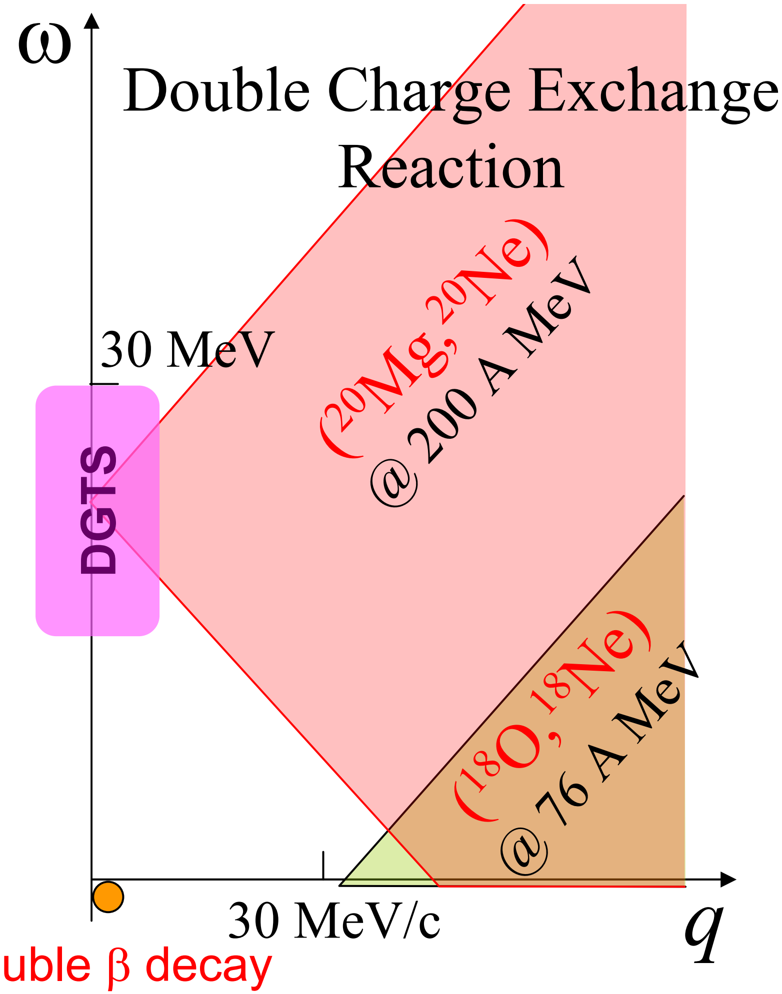
$\rightarrow$ $q = 85$ MeV/c

^{24}Mg(^{11}B, ^{11}Li) @69 MeV/A, RCNP

$\rightarrow$ $q = 161$ MeV/c



J. Blomgren et al., Phys. Lett. B **362** (1995) 34.



^{24}Mg(^{20}Mg,^{20}Ne) @200MeV/A , RIBF

$\rightarrow$ $q = 7$ MeV/c

Most promising reaction

Isovector Spin Monopole Resonance

Breathing (compressive) mode: $\hat{O}_{IVGMR} = \sum r_i^2 \sigma_i \tau_i$

Spin-isospin density ($\langle\sigma\tau\rangle$) oscillation.

⇔ "Spin-Isospin Compressibility"

Propagation velocity of "spin-isospin sound"

Sensitivity to the neutron skin thickness through the sum rule

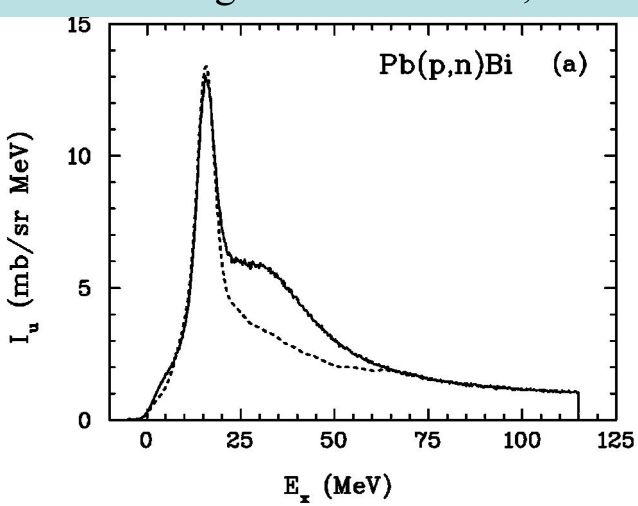
Some indications have been reported in the β^- type reactions.

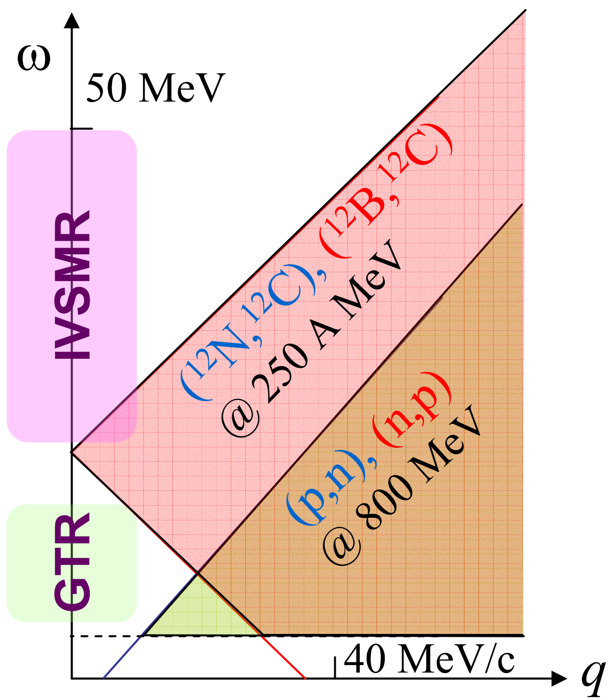
^{208}Pb(*p*,*n*) @ 795MeV (LAMPF)

D.L. Prout et al., PRC **63**, 014603 (2000).

(^{3}He,t) @ 150 MeV/u (RCNP)

R. G. T. Zegers et al. PRL **90**, 202501 (2003).





RI beam induced reaction is promising.

SHARAQ Project

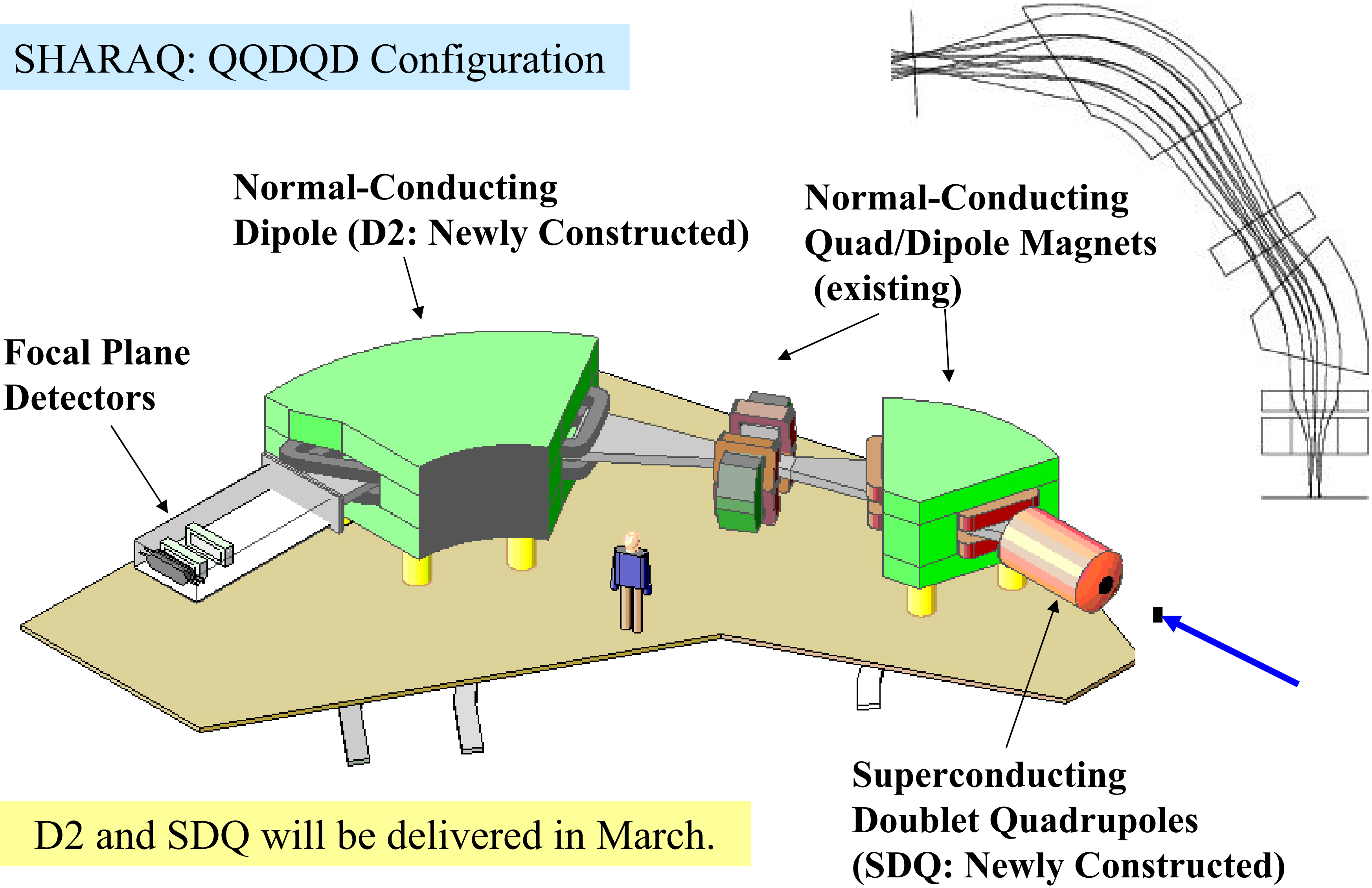
We have launched the SHARAQ project
to construct a high resolution spectrometer aiming at ....

- ✓ Missing mass spectroscopy with RI beams
  - Spin-isospin excitation via RI-beam induced EXOTHERMIC reaction.
    Probe highly excited states of stale nuclei with extremely small momentum transfer.
    ex. DGTR, IVSMR, tetra neutron spectroscopy
  - Elastic scattering experiments.

- ✓ High resolution analysis of reaction products
  - Inelastic, breakup, knockout reactions
  - Combined with γ-ray and/or decay-particles measurements
  - Particle identification
  - Q value measurement
  - Momentum distribution of reaction products

SHARAQ Spectrometer

SHARAQ: QQDQD Configuration



D2 and SDQ will be delivered in March.

Design Concepts

- ✓ Configuration: QQDQD
  - – Good angular resolution ($\Delta\theta \sim 1$ mr)
  - – Good momentum resolution ($\Delta P/P \sim 1/15{,}000$)
- ✓ Normal conducting magnets except for Q doublet
  - – Minimization of higher order aberration by pole-edge shaping.
- ✓ Superconducting Q doublet
  - – Reasonable acceptance ($\Delta\Omega \sim 5$ mSr)
  - – Minor modification of the triplet Q in BigRIPS
- ✓ Rotatable (–2deg to +15deg)
  - – Unique rotatable spectrometer at RIBF
- ✓ Full use of existing resources (magnets, R&D. . .)

Specifications

Dispersion (D)	5.86 m
Horizontal magnification (M_x)	0.40
D/M_x	14.7 m
Momentum resolution (image size 1mm)	1/14700
Vertical magnification (M_y)	0.0
Angular resolution	< 1 mrad
Vertical acceptance	± 3deg

for spot size 60mm × 10mm (in dispersion matching operation)

Horizontal acceptance	± 1deg
Solid angle	2.7msr

for spot size of 10mm × 10mm

Solid angle	4.8 msr

High Resolution Measurement with RI Beam

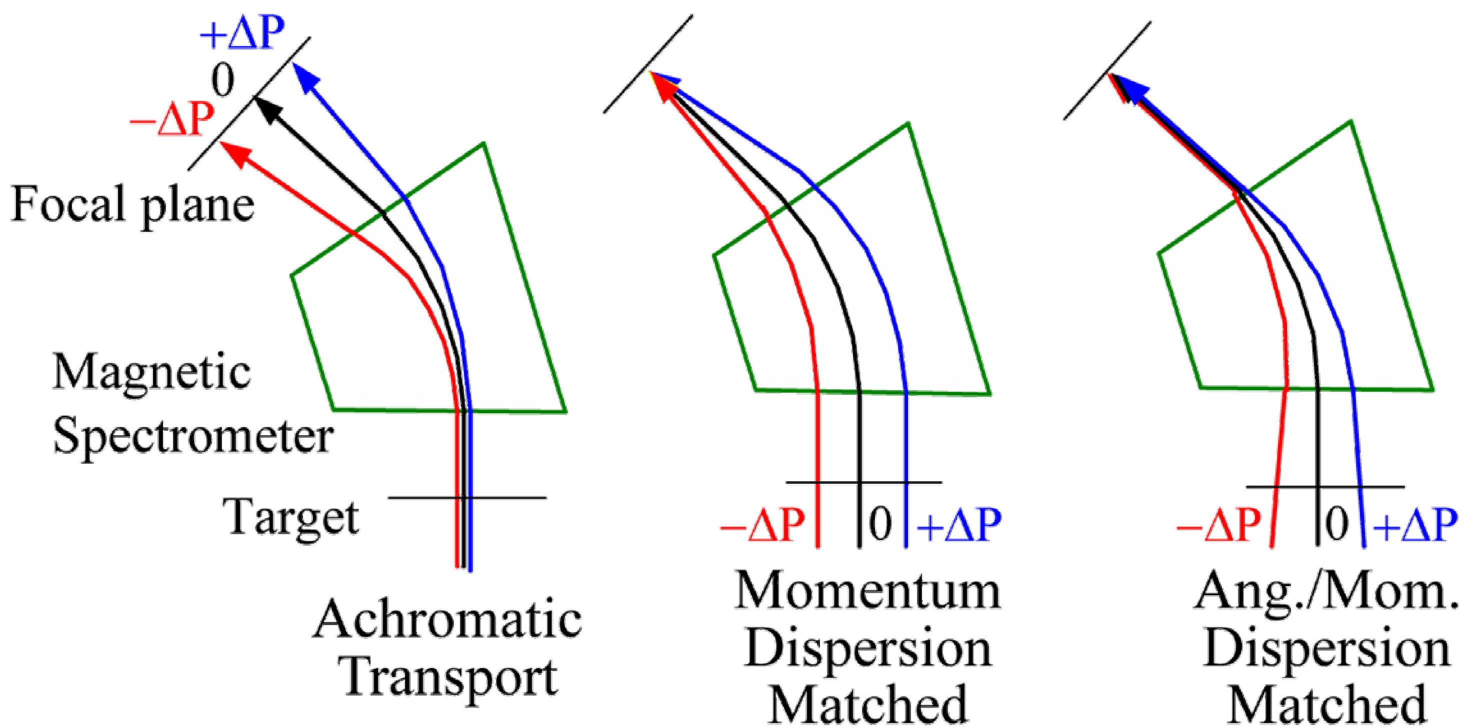
Large momentum spread of RI beam

200 MeV/A ^{12}N beam with $\Delta p/p = \pm 0.3\%$

$\Delta E \sim 30$ MeV

→ Need cancellation of the momentum spread

Dispersion Matching Technique



Dispersion Matching Condition

B_{ij}: Transport Matrix for Beam Line, s_{ij}: Transport Matrix for the Spectrometer

$$\begin{pmatrix} x_{\rm fp} \\ \theta_{\rm fp} \\ \delta_{\rm fp} \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ \delta_0 \end{pmatrix}$$

$$\begin{aligned} x_{\rm fp} = &\left(s_{11}b_{11} + s_{12}b_{21}\right)x_0 \\ &+\left(s_{11}b_{12} + s_{12}b_{22}\right)\theta_0 \\ &+\left(s_{11}b_{13} + s_{12}b_{23} + s_{13}\right)\delta_0 \end{aligned}$$

$$\begin{aligned} \theta_{\rm fp} = &\left(s_{21}b_{11} + s_{22}b_{21}\right)x_0 \\ &+\left(s_{21}b_{12} + s_{22}b_{22}\right)\theta_0 \\ &+\left(s_{21}b_{13} + s_{22}b_{23} + s_{23}\right)\delta_0 \end{aligned}$$

Dispersion Matching Condition

$$s_{11}b_{13} + s_{12}b_{23} + s_{13} = 0$$

Angular Matching Condition

$$s_{21}b_{13} + s_{22}b_{23} + s_{23} = 0$$

SHARAQ Spectrometer

$s_{11} = 0.397$ $s_{12} = 0.000$ $s_{13} = 5.858$

$s_{21} = 0.773$ $s_{22} = 2.516$ $s_{23} = -0.661$

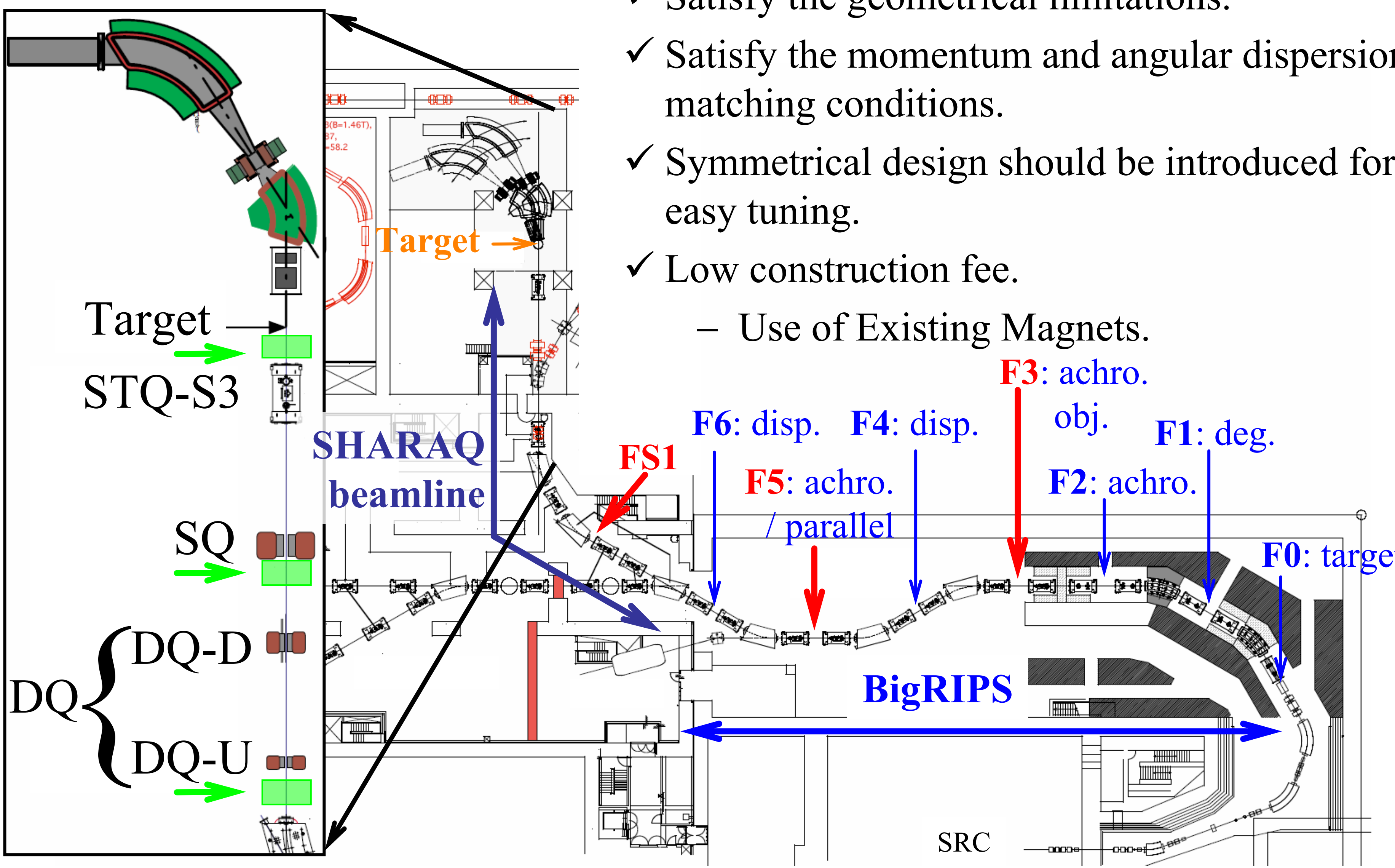
Matching Condition

$b_{13} = -14.76$

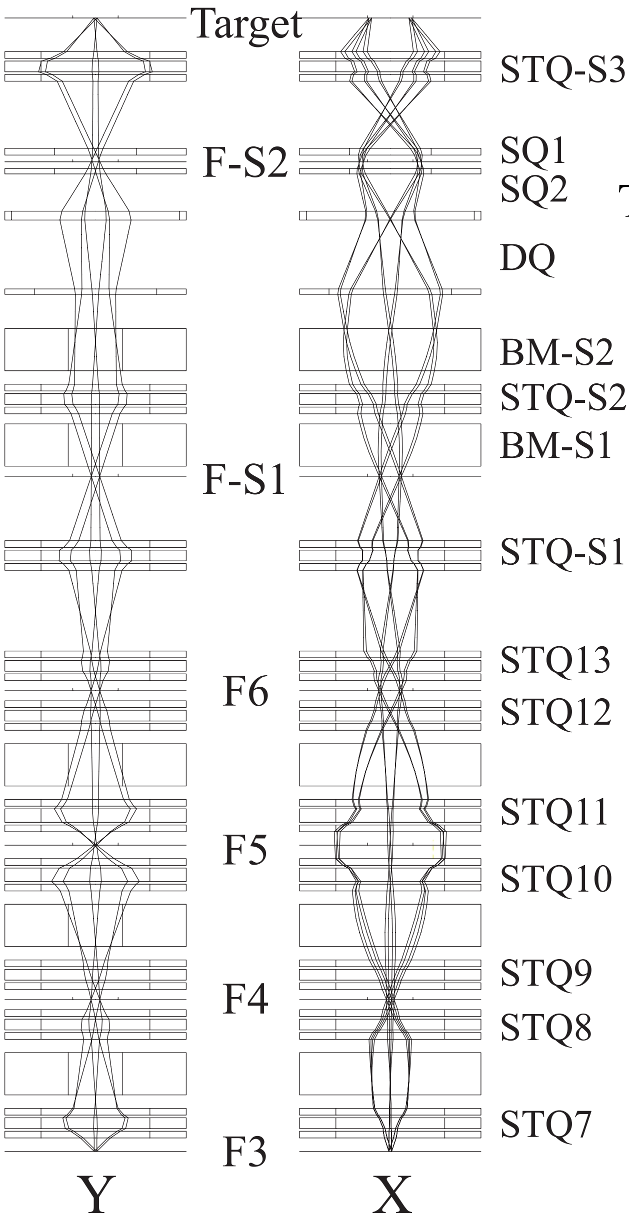
$b_{23} = 4.79$

BigRIPS & SHARAQ beamline

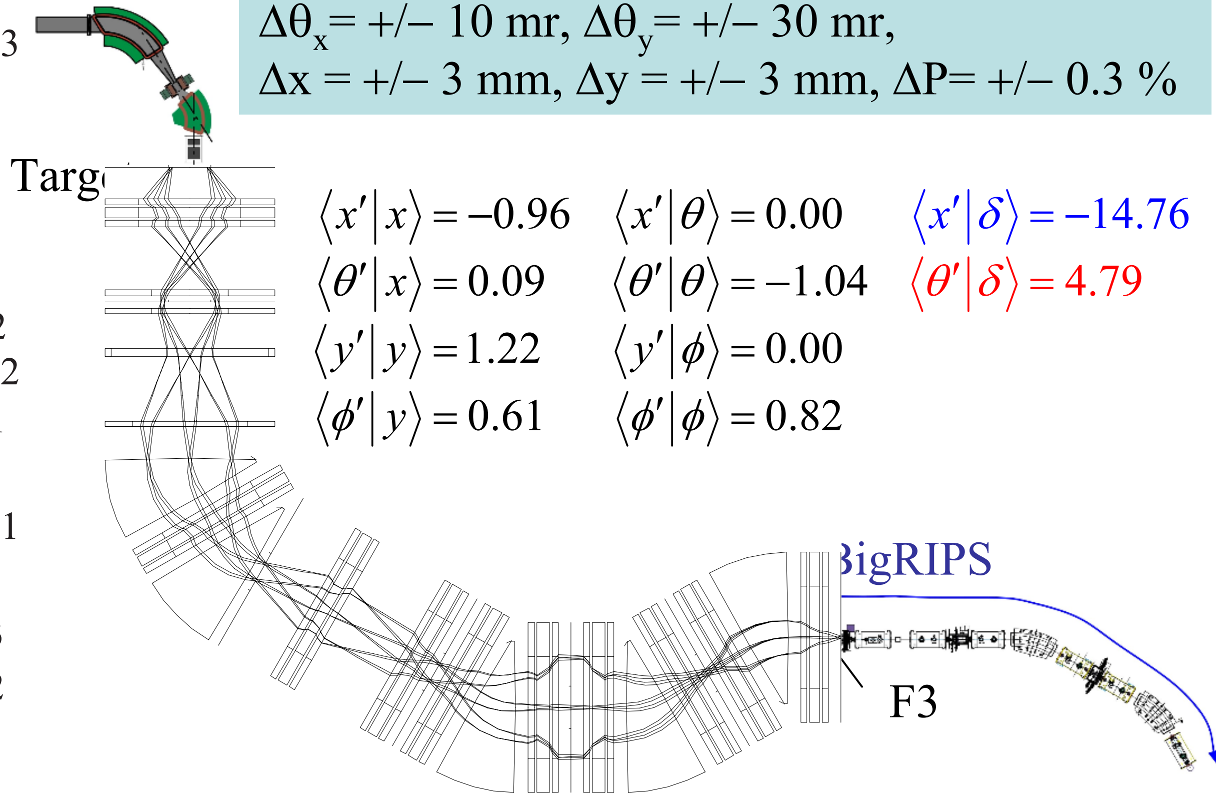
- ✓ Satisfy the geometrical limitations.
- ✓ Satisfy the momentum and angular dispersion matching conditions.
- ✓ Symmetrical design should be introduced for easy tuning.
- ✓ Low construction fee.
  - – Use of Existing Magnets.



Ion Optical Calculation



$\Delta\theta_x$ = +/– 10 mr, $\Delta\theta_y$ = +/– 30 mr,
Δx = +/– 3 mm, Δy = +/– 3 mm, ΔP= +/– 0.3 %



$\langle x'|x\rangle = -0.96$ $\langle x'|\theta\rangle = 0.00$ $\langle x'|\delta\rangle = -14.76$

$\langle \theta'|x\rangle = 0.09$ $\langle \theta'|\theta\rangle = -1.04$ $\langle \theta'|\delta\rangle = 4.79$

$\langle y'|y\rangle = 1.22$ $\langle y'|\phi\rangle = 0.00$

$\langle \phi'|y\rangle = 0.61$ $\langle \phi'|\phi\rangle = 0.82$

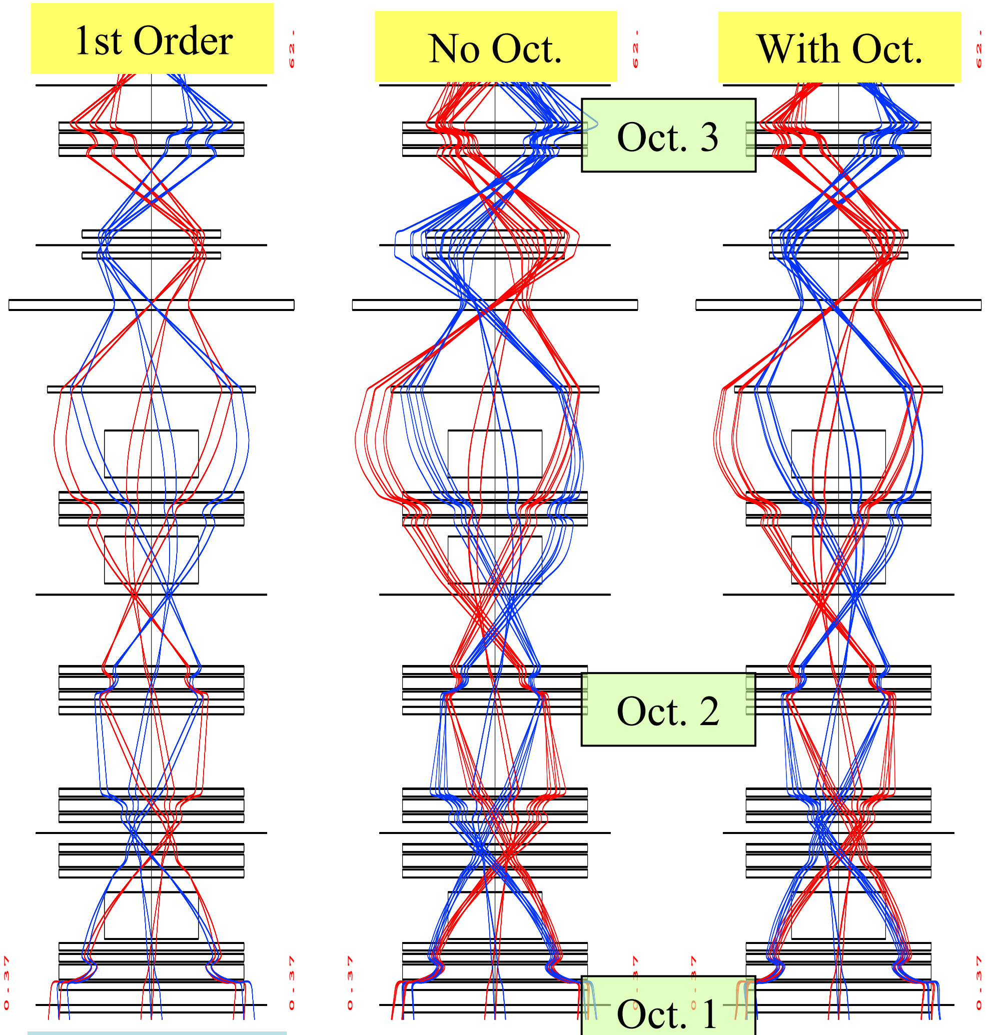
Matching conditions are satisfied.

Symmetric design is introduced.

STQ10-11, STQ8-12, STQ13-S1 are symmetric.
19 DOFs for 34 Quadrupoles.

Higher Order Aberration

$\Delta\theta_x$= +/– 10 mr, $\Delta\theta_y$= +/– 30 mr, Δx = +/– 3 mm, Δy = +/– 3 mm, ΔP= +/– 0.3 %

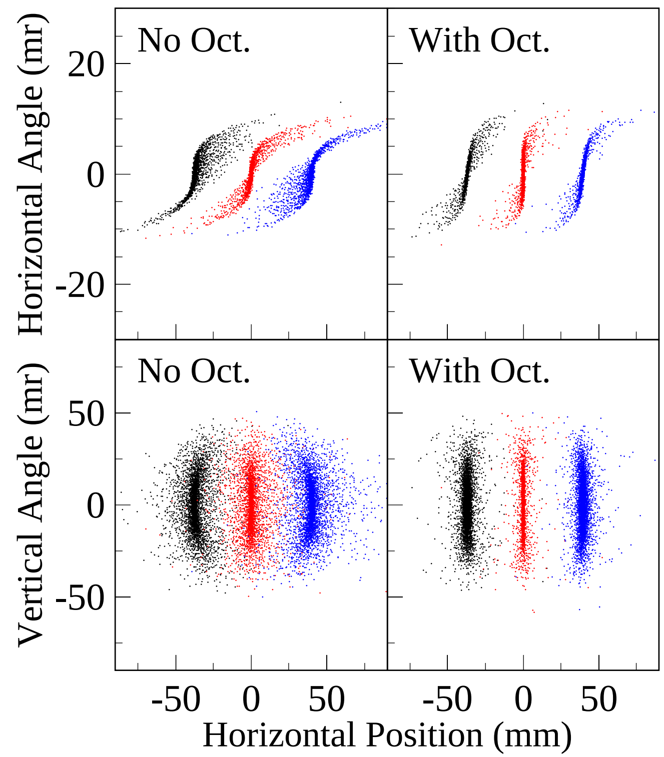


$$\sum \left| A(x^i \theta^j y^k \phi^l) \right|$$
$$(i + j + k + l = 3)$$

41.3.

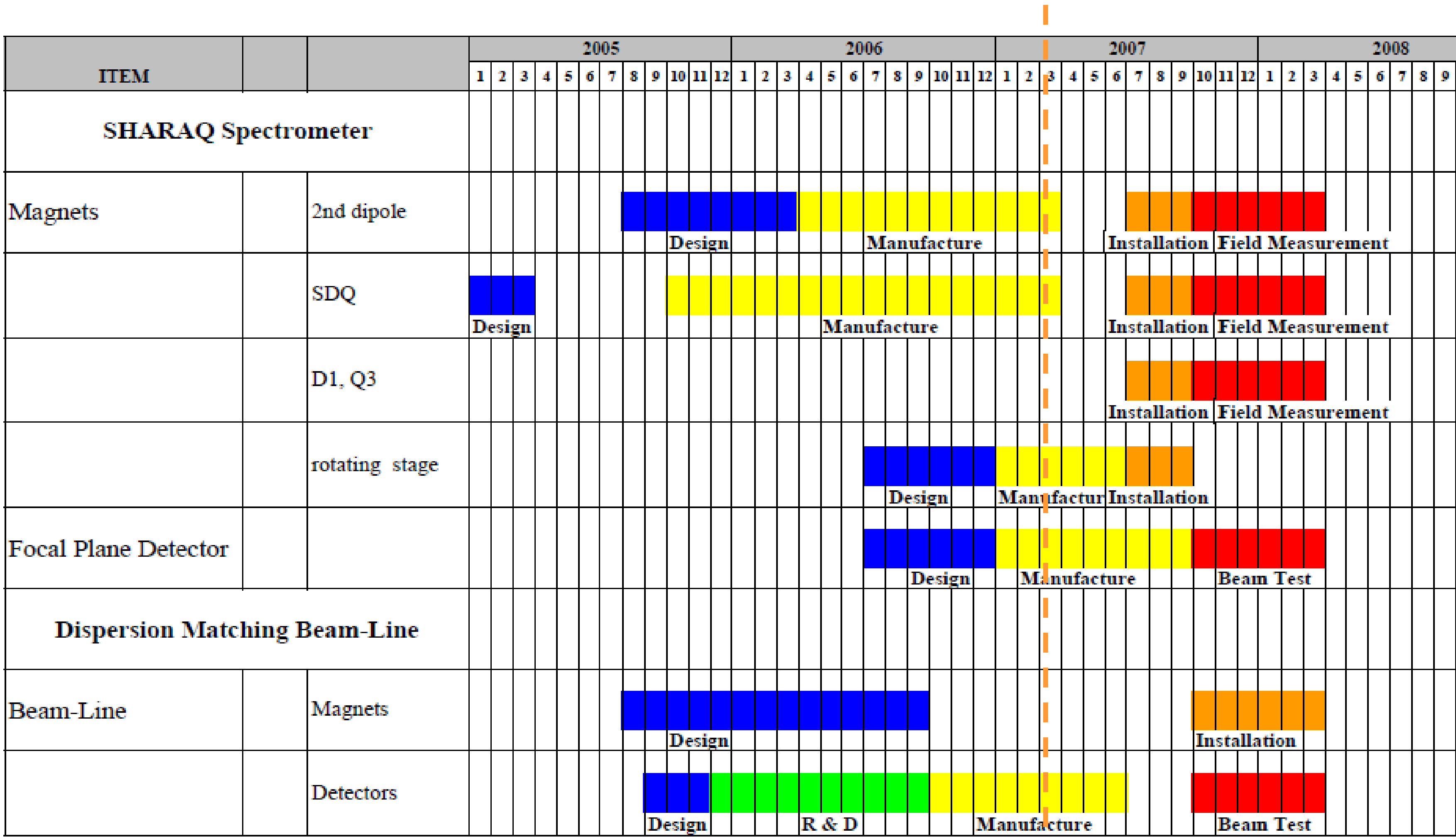
8.3

δ = +0.3%, 0%, –0.3%

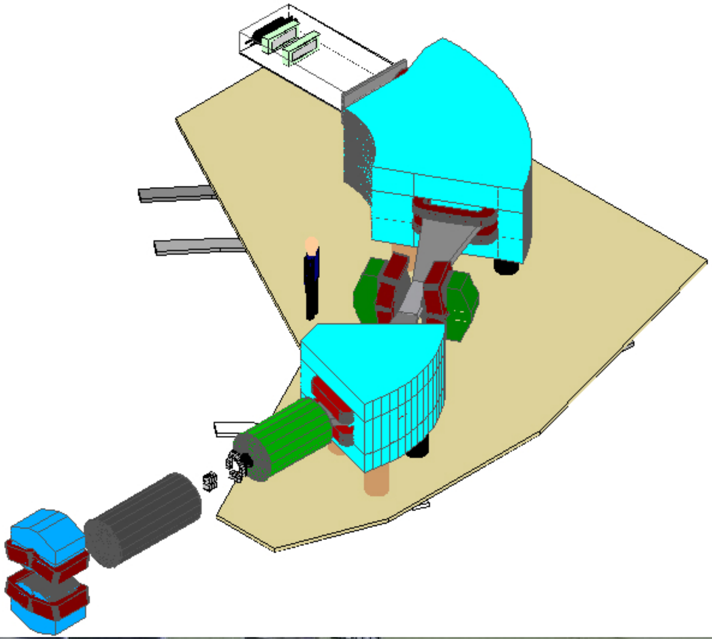


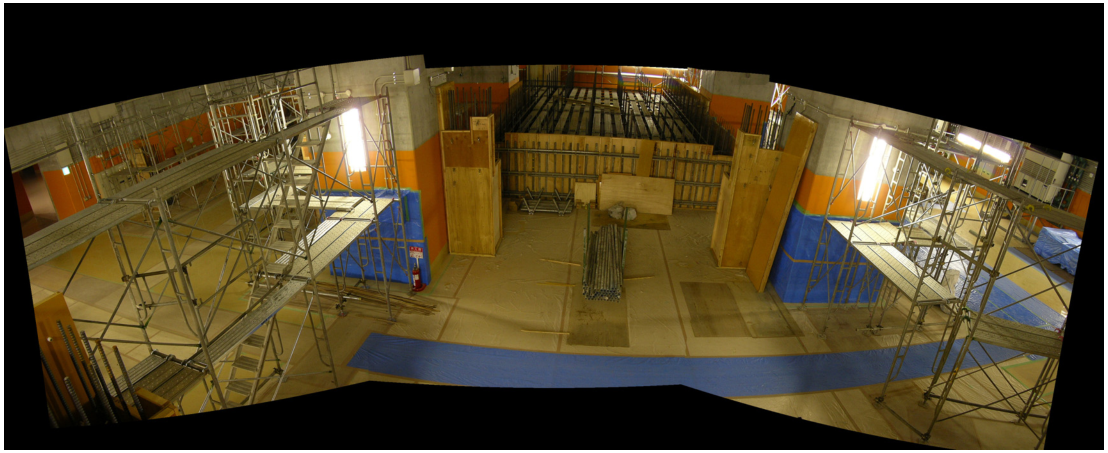
Three oct. mags. significantly improve the aberration.

Schedule


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

Current Status





Summary

- ✓ RIBF@RIKEN is now under commissioning. First beam from SRC has been extracted in Dec. 2006.
- ✓ RI-beam induced reactions provide a very promising probe to investigate new spin-isospin modes.
- ✓ SHARAQ spectrometer and dispersion-matched beam line for the high-resolution measurement is under construction.
- ✓ The physics program will state in FY2008.
- ✓ We are pleased to start collaboration for the BEST use of the spectrometer.