KoBRA for low energy nuclear physics study at RISP

Y.K. Kwon and KOBRA Collaboration

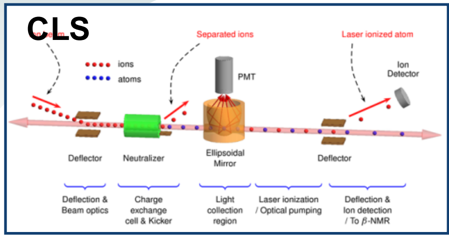
Experimental Systems Team
Rare Isotope Science Project
IBS, Korea

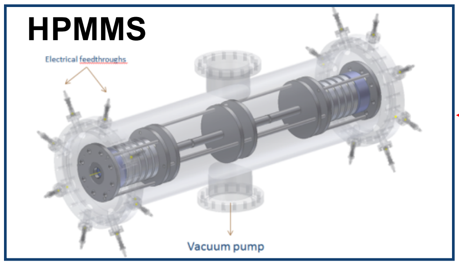
KoBRA
Korea Broad acceptance Recoil Spectrometer & Apparatus

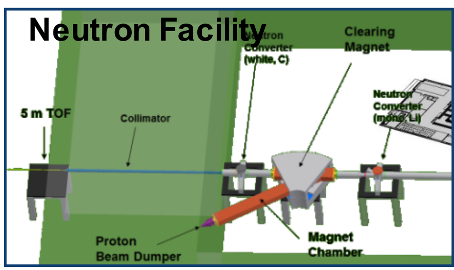
KPS 2015 fall meeting @ Gyeongju

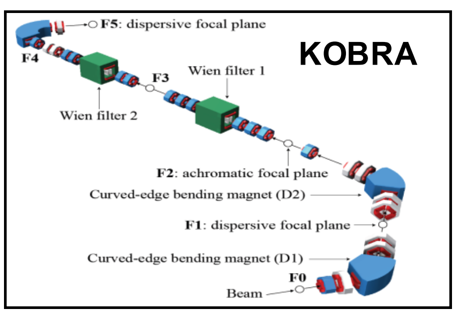
Experimental Systems at RAON

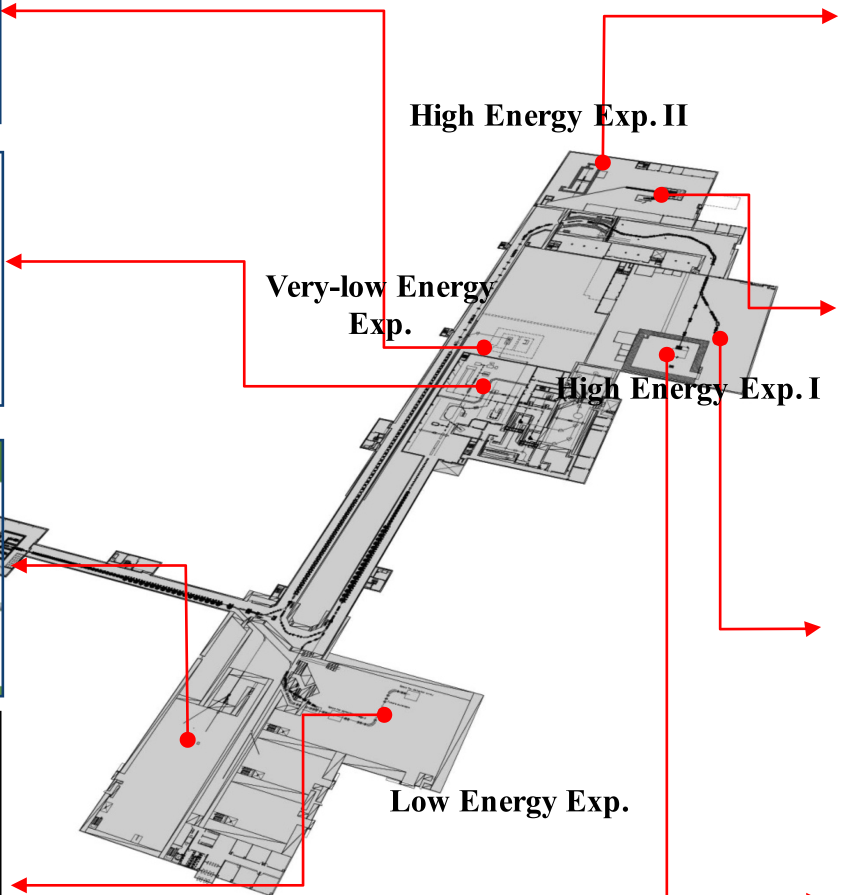
RAON

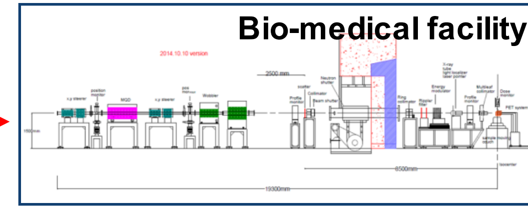


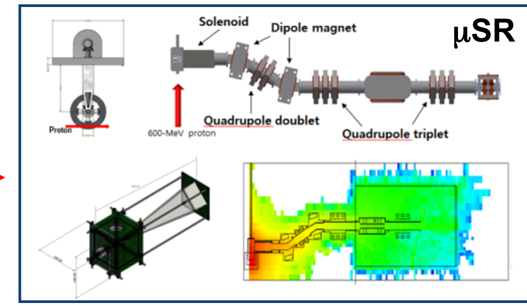


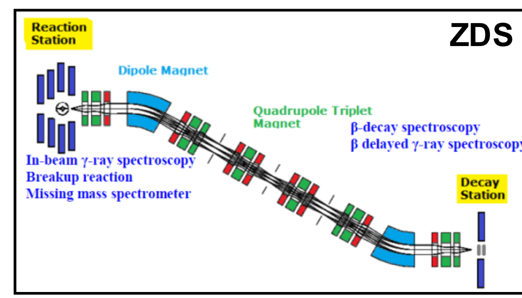


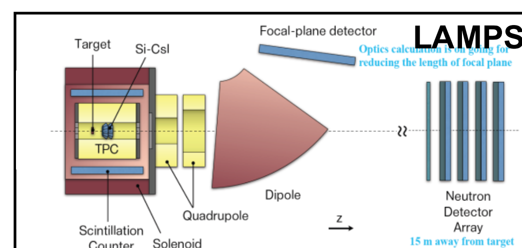




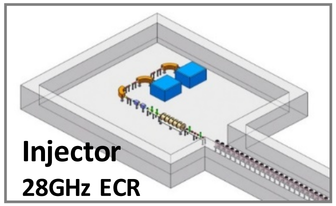


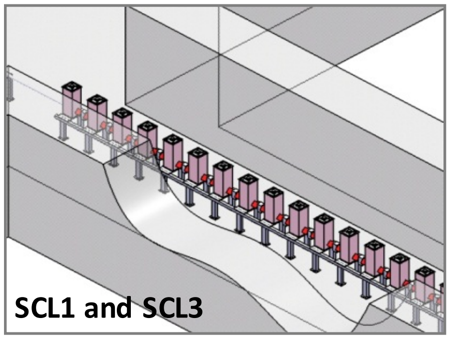




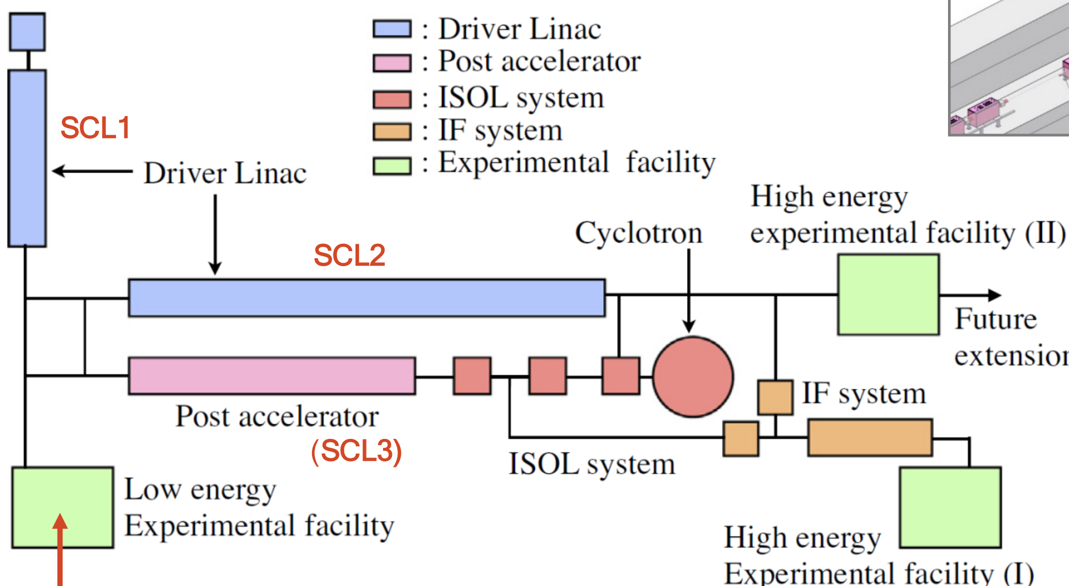


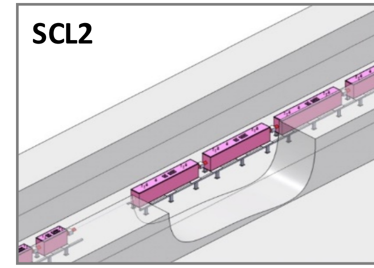
Overview of RAON and KoBRA





Schematic view of RAON taken from NIM B **317**, 242 (2013)



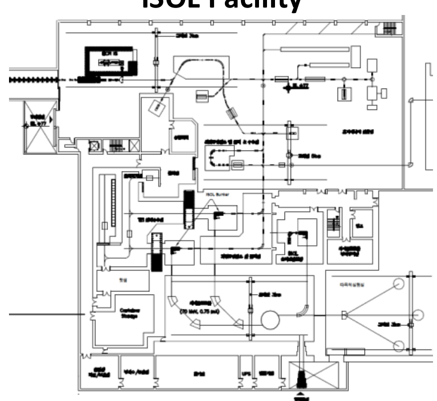


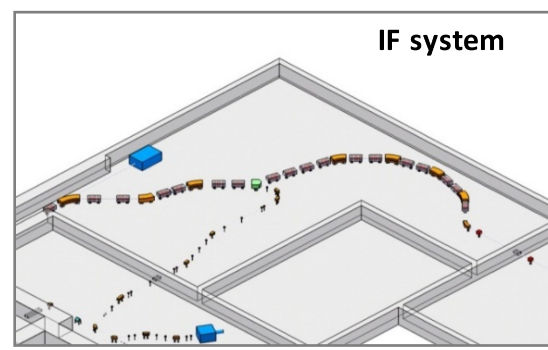
KoBRA

Korea Broad acceptance Recoil spectrometer and Apparatus

- Nuclear astrophysics
- Nuclear structure
- Rare event study

ISOL Facility





KoBRA
Korea Broad acceptance Recoil Spectrometer & Apparatus

Scientific Program at KOBRA

- Nuclear Structure

  - Study of shell evolution in proton- and neutron-rich nuclei:
    Measurements of excitation energy and angular distribution
    Determination of nucleon occupancy in single particle orbit
    (inelastic scattering, (d,p) reaction, nucleon removal reaction, and so on)

  - Study of soft dipole and Pygmy dipole resonances using nuclear probe, e.g., α, Ca and Pb:
    Measurements of excitation energy and angular distribution
    (Bound state: ϒ ray spectroscopy, unbound state: missing mass method)

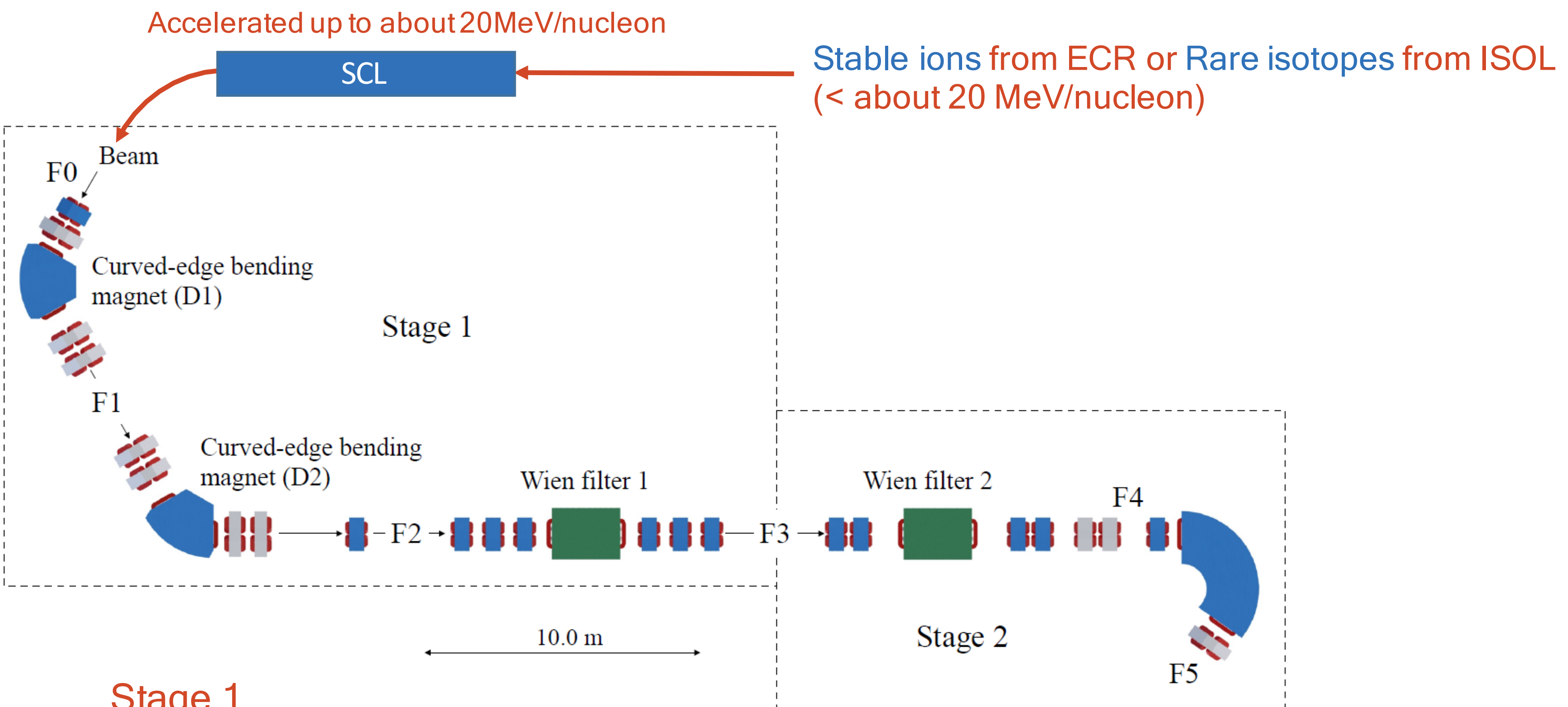
  - Study of shape coexistence
  - Cluster structure
  - And others …

- Nuclear Astrophysics

  - Direct measurement of charged-particle capture cross section, e.g., for ^{65}As(p, ϒ) and ^{15}O(α, ϒ) reactions at < ~1 MeV/nucleon

  - Indirect measurement of radiative capture cross section, e.g., for (d,p) reaction at a few MeV/nucleon

Overview of KoBRA



Stage 1

- RI beam production at a few MeV/nucleon and about 20 MeV/nucleon (**production mode**)
  - Reaction: (p,n), (d,p), (d,n), and (3He,n) at a few MeV/nucleon
  - <u>multi-nucleon transfer reactions at about 20 MeV/nucleon</u>
- Recoil mass separator at about 1 MeV/nucleon (**radiative capture mode**)

Stage 1 + Stage 2

- Recoil mass separator at about 1 MeV/nucleon
- High-resolution separator at a few MeV/nucleon (**dispersion matching mode**)

Optical design for **Production mode** in Stage 1

Stable beam or RI beam at about **20 MeV/u**

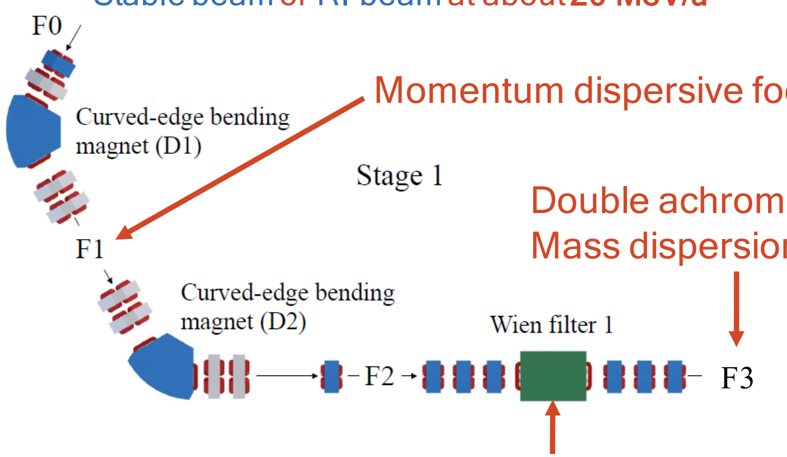


Table 1: Optical design parameters of KOBRA stage 1 for the production mode at an energy of ~20 MeV/nucleon. The magnifications in horizontal and vertical directions and momentum dispersion are listed for each focal plane, F1, F2, and F3.

	$(x\|x)$	$(x\|\delta)$	$(y\|y)$
F1	0.9	4.0 cm/%	−5.3
F2	−3.2	0.0	3.0
F3	3.4	0.0	4.6
Momentum acceptance		$\Delta p/p = \pm 4\%$	
Angular acceptances		$\theta_x \approx \pm 40$ mrad, $\theta_y \approx \pm 100$ mrad	

- Selection of rays of a 5th order optics calculation (COSY infinity)

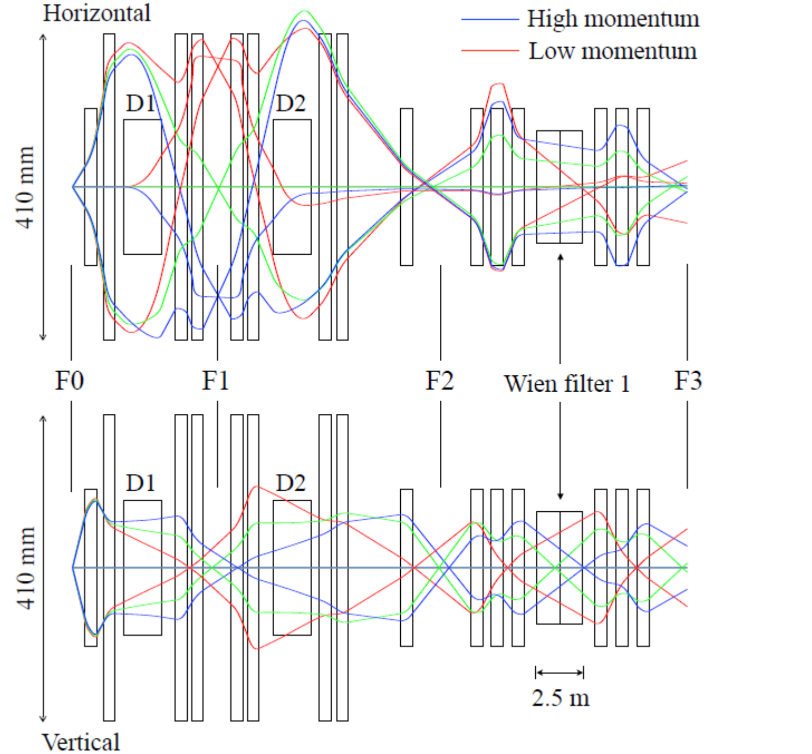


Figure 2: (Color online.) Horizontal and vertical rays of KOBRA stage 1 for the production mode from the 5th order ion-optics calculation with switched-off Wien filter. Beam trajectories with an angular spreads of ±40 mrad (±100 mrad) in horizontal (vertical) plane are shown. The blue-, green- and red-solid lines correspond to the trajectories with $\Delta p/p = +4\%$, 0% and −4%, respectively.

Momentum resolving power: $D_p/(2x_0M) = 2200$

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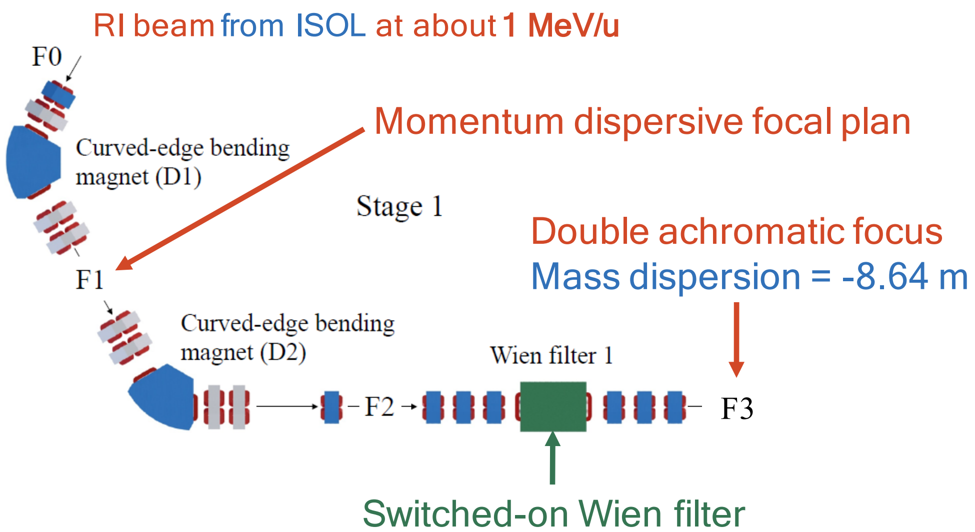
Optical design for **Radiative Capture mode** in Stage 1



- Selection of rays of a 1st order optics calculation (COSY infinity)

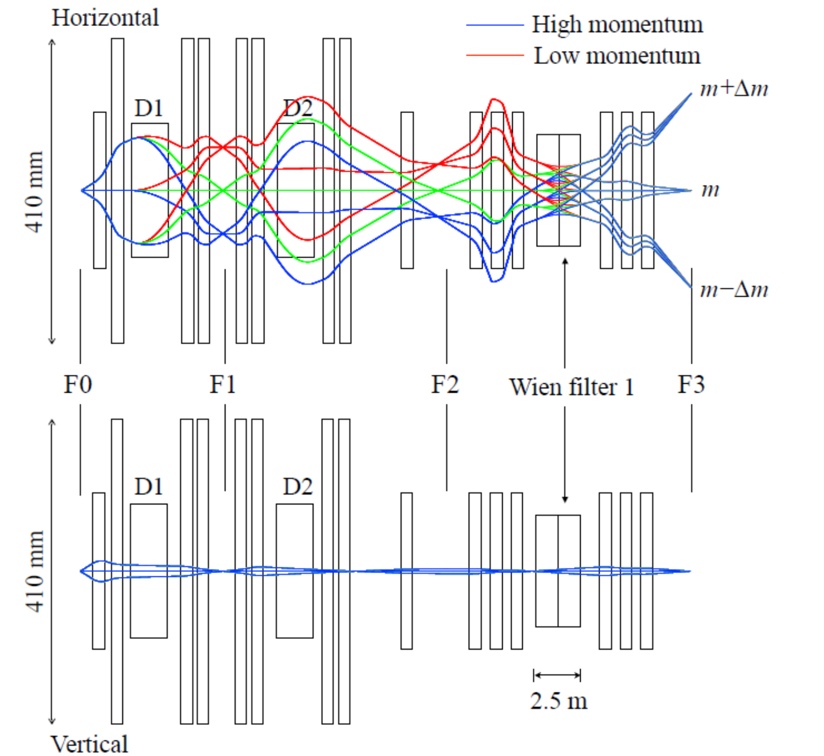


Figure 3: (Color online.) 1 MeV/nucleon $^{66}Se^{19+}$ rays of KOBRA stage 1 for the radiative capture mode from the first order ion-optics calculation. Beam trajectories with an angular spreads of ±15 mrad (±15 mrad) in horizontal (vertical) plane are shown. The blue-, green- and red-solid lines correspond to the trajectories with $\Delta p/p = +1.5\%$, 0% and -1.5%, respectively, where $\Delta m/m$ is ±1/66.

Wien filter 1 specification

- Effective length: 2.5 m
- Full gap between electrodes: 15 cm
- Maximum electric field: 2.7 kV/mm (±200 kV)
- Maximum magnetic field: 0.3 T

Mass resolving power: $D_m/(2x_0M)$ = 720 for $^{66}Se^{19+}$ at 1 MeV/nucleon

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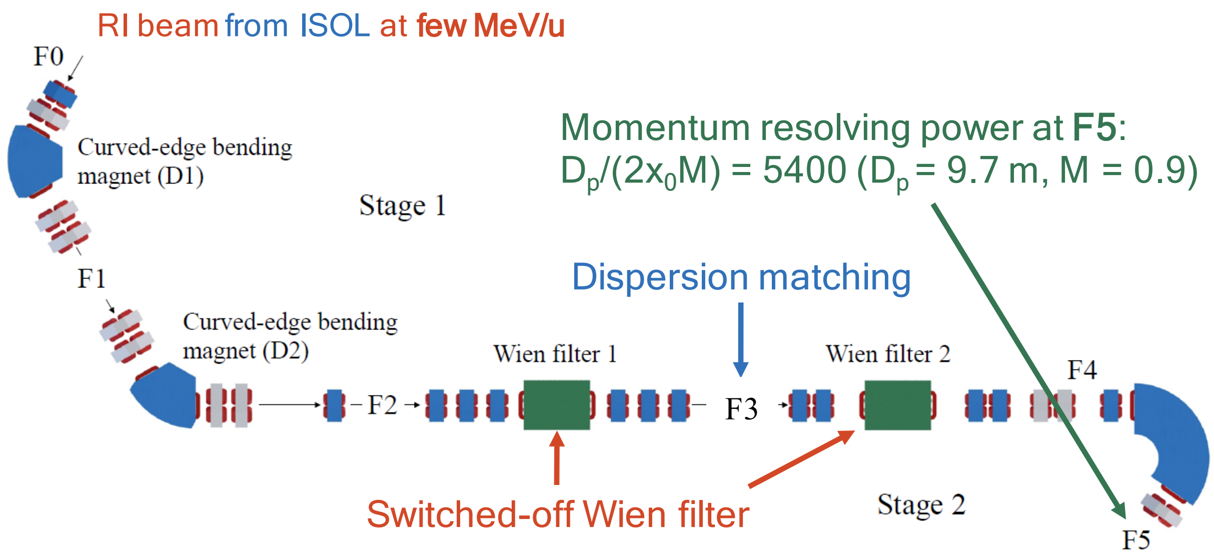
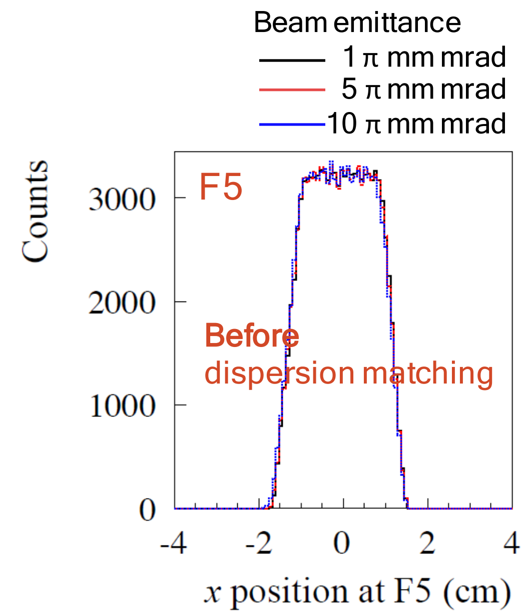
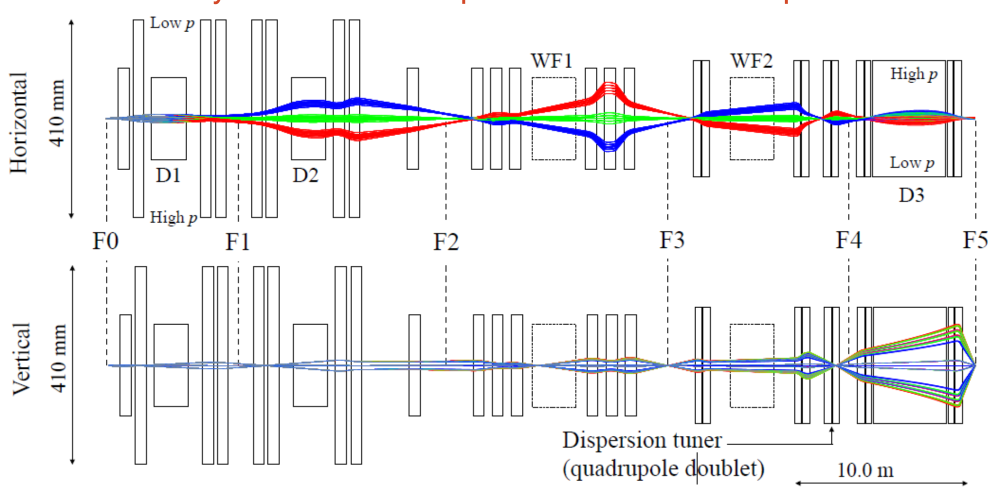
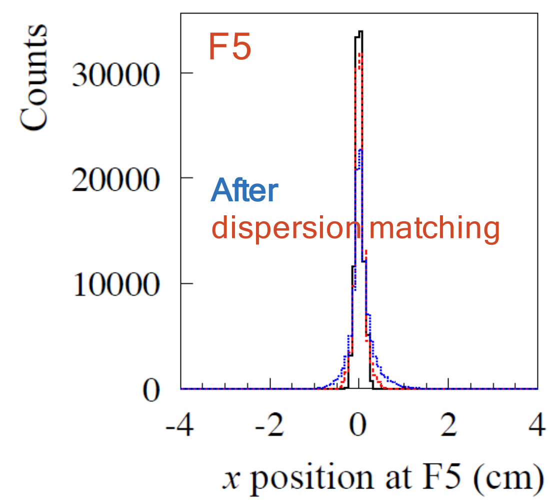
Optical design for **Dispersion matching mode**





- Selection of rays of a 5th order optics calculation for dispersion matching mode





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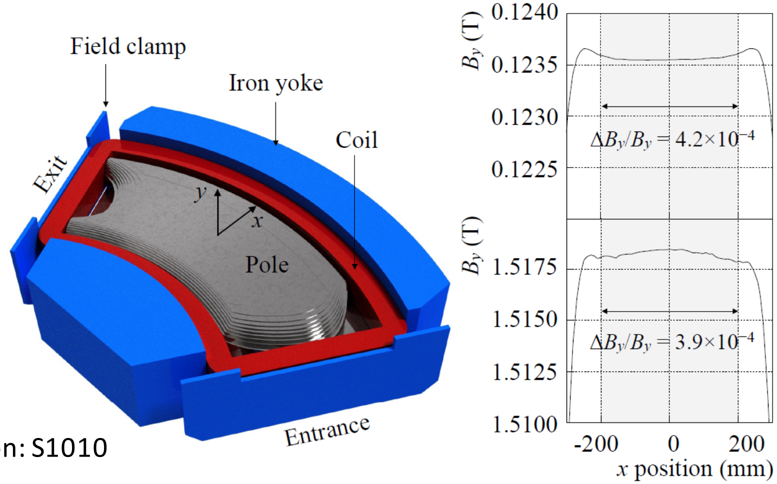
Magnet design

- Curved-edge bending magnet (bending radius: 2 m, bending angle: 60°)

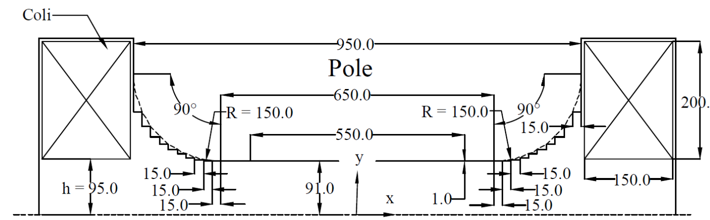


Iron: S1010

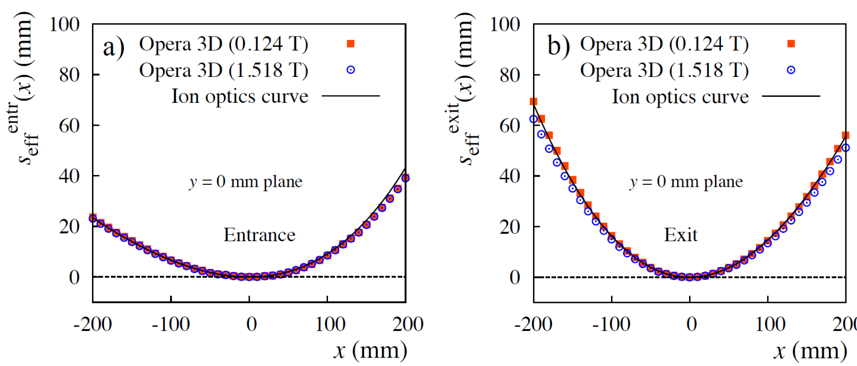
Figure 4: (Color online.) Layout of the curved-edge bending magnet D1. The center field distributions in the midplane ($y = 0$) for low ($B = 0.12$ T) and high ($B = 1.52$ T) field strengths are shown as calculated using the finite-element code OPERA 3D.

Similar with that of D2 of the high resolution SHARAQ spectrometer

Cross section of bending magnet

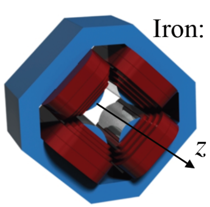


Effective field boundary curves



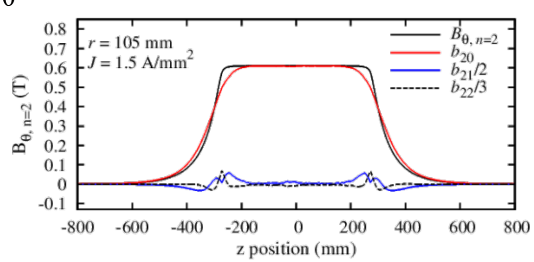
- Qaudrupole magnets

Small quadrupole magnet

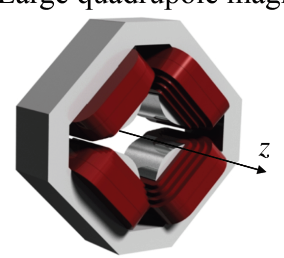


Iron: S1010

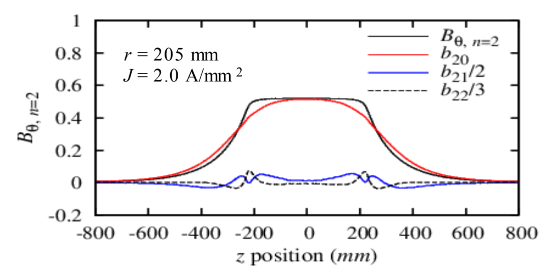
Aperture radius: 105 mm
Field gradient: 7.6 T/m



Large quadrupole magnet



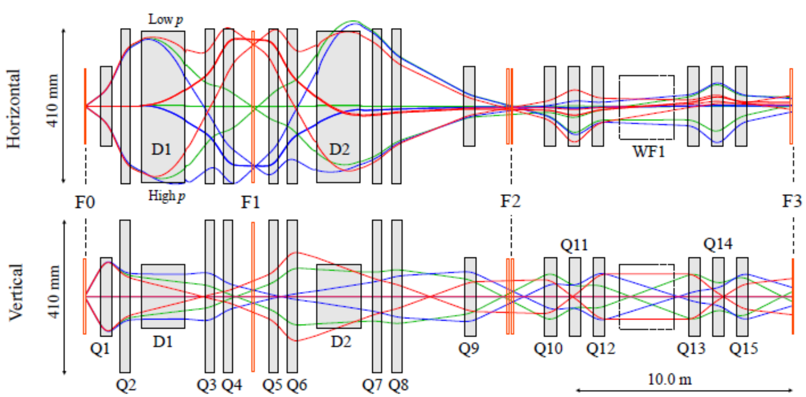
Aperture radius: 205 mm
Field gradient: 3.4 T/m



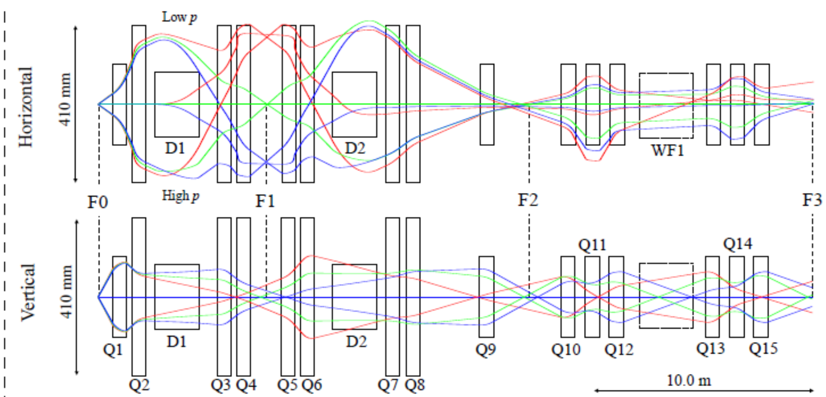
Development of a ray tracing code

- A ray-tracing code has been developed taking into account beam profile, geometry, magnetic field distributions, energy losses, multiple scatterings in materials, detector resolutions, and charge distribution.

Beam: ± 40 and ±100 mrad in horizontal and vertical directions with $\Delta p/p = \pm 4\%$

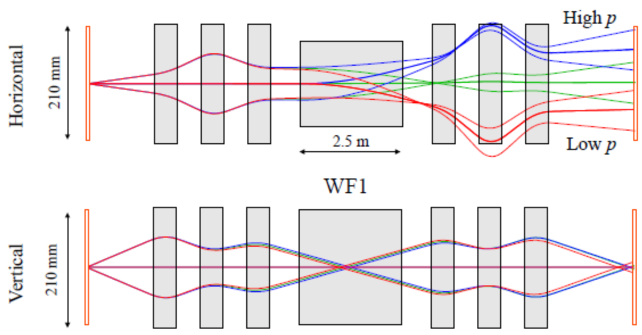


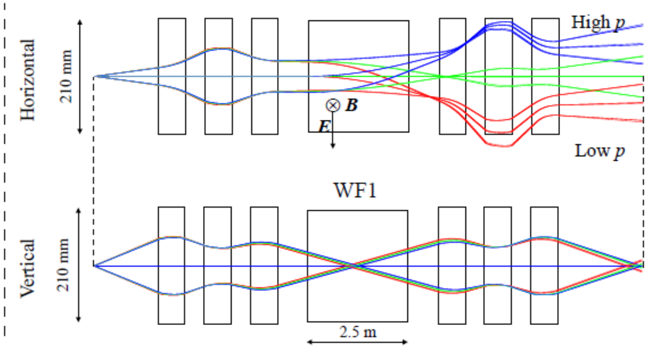
Selection of rays of Ray Tracing calculation



Selection of rays of 5th order ion optics calculation

Beam: $^{8}B^{3+}$ at 0.11 MeV/nucleon, $\theta_x = \pm 10$ mrad, $\theta_y = \pm 30$ mrad, $\Delta p/p = \pm 2\%$





Wien filter: $B = 0.06$ T, $E = 0.28$ kV/mm (near hard edge fringing field distribution)

We have confirmed that the first order transfer matrix elements extracted from the ray tracing code are consistent with those of the calculation using COSY infinity.

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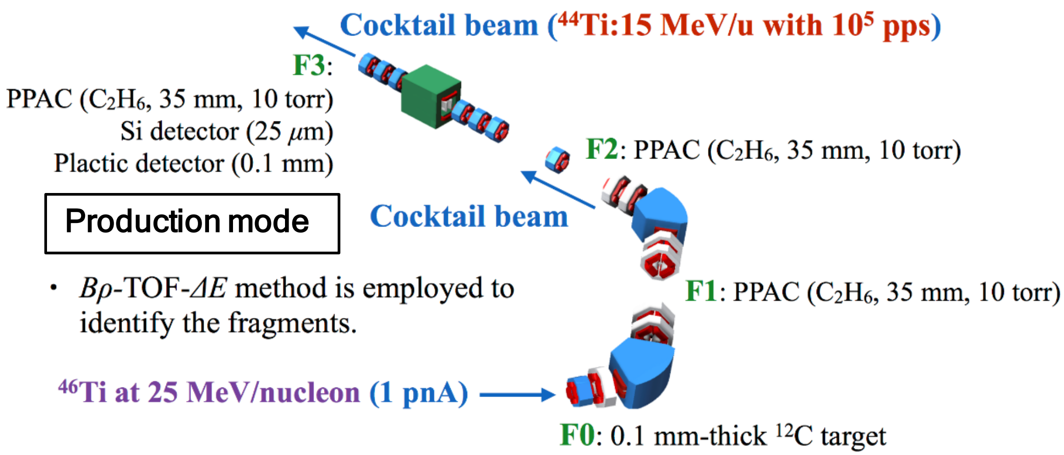
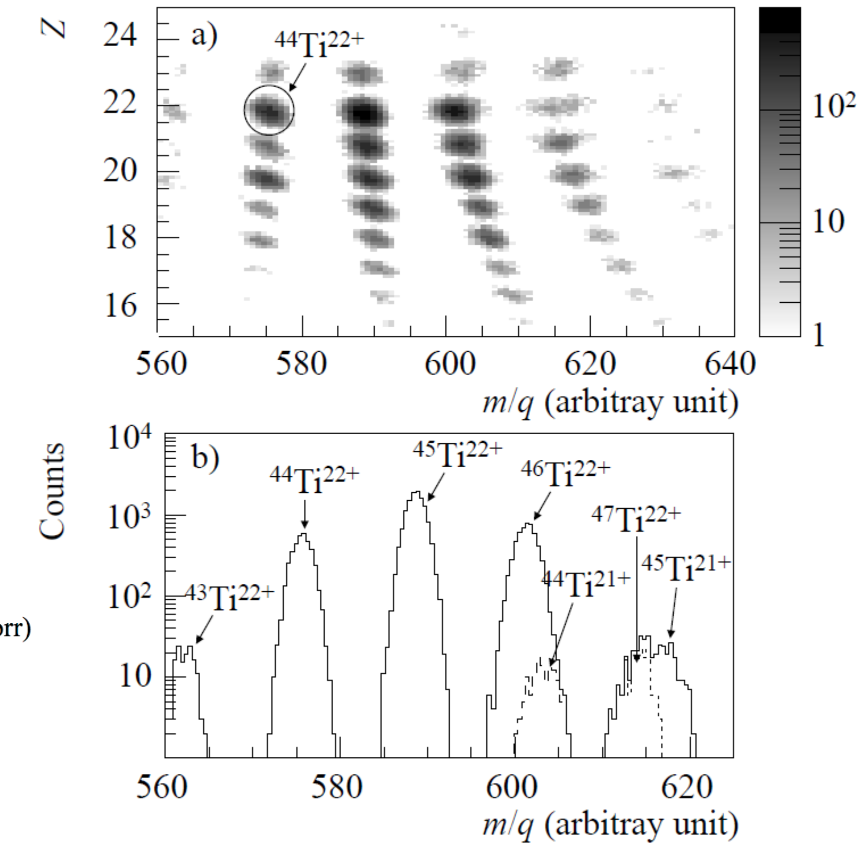
Production of ^{44}Ti at 25 MeV/nucleon (example)

- Production model (multi-nucleon transfer):
  Deep Inelastic Transfer (DITm) + GEMINI

DITm: L. Tassan-Got and C. Stefan, Nucl. Phys. A524, 121 (1991).
G. A. Souliotis et al., Phys. Rev. Lett. 91, 022701 (2003).
M. Veselsky and G. A. Souliotis, Nucl. Phys. A 765, 252 (2006).
GEMINI (statistical model): R. Charity et al., Nucl. Phys. A 483, 371 (1991).



- $B\rho$-TOF-ΔE method is employed to identify the fragments.

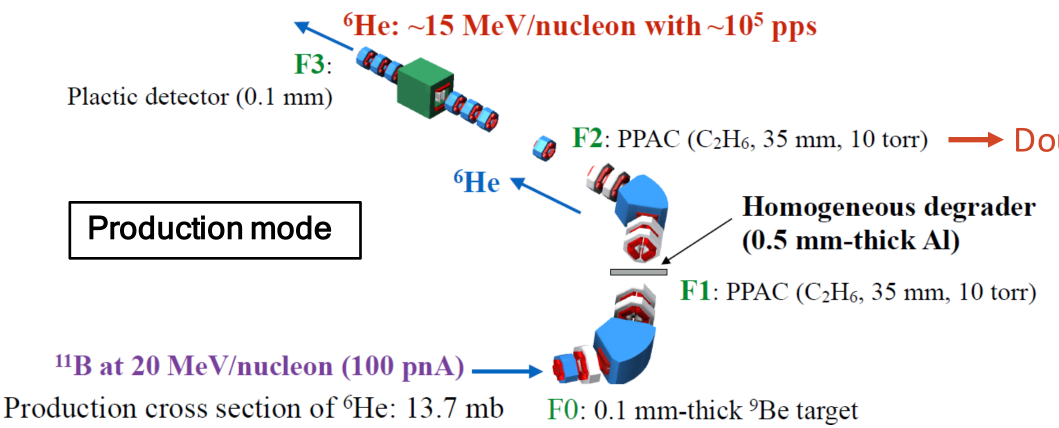


- Intensity of ^{44}Ti and Cocktail Beam for 1 pnA ^{46}Ti primary beam

Target	Cocktail beam at F1	Cocktail beam at F2	Cocktail beam at F3	^{44}Ti at F3	Energy of ^{44}Ti at F3
^{12}C (0.1mm)	2.5 × 10^6 pps	1.7 × 10^6 pps	1.6× 10^6 pps	**1.4 × 10^5 pps**	14.61 MeV/u

Production of ^{6}He at 20 MeV/nucleon (example)

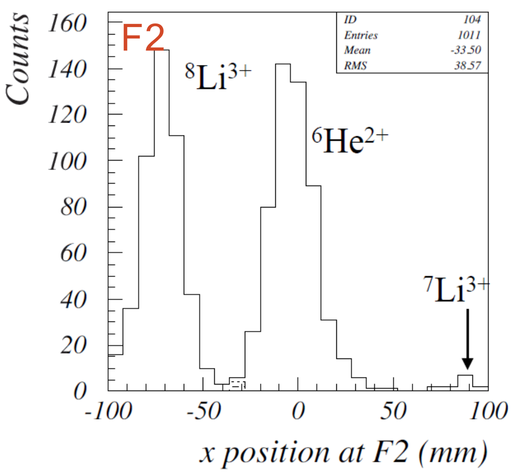
- Production model (multi-nucleon transfer):
  Deep Inelastic Transfer (DITm) + GEMINI

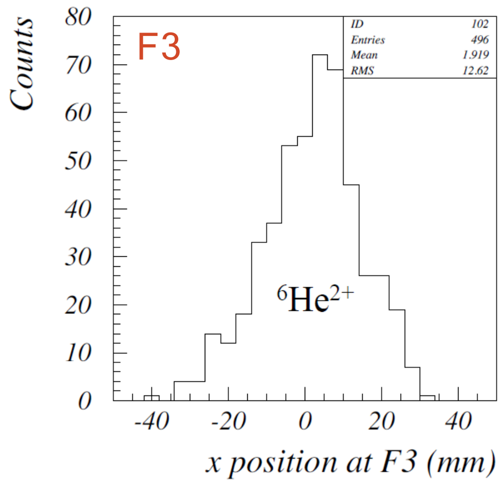


Double achromatic condition for homogeneous degrader:

$$(\theta|x)_{F2-F1} + \left(1-\frac{d}{R}\right)^{-1}\frac{(\theta|\delta)_{F2-F1}}{(x|\delta)_{F1-F0}} = 0$$

d: thickness of degrader
R: Range of ^{6}He in degrader

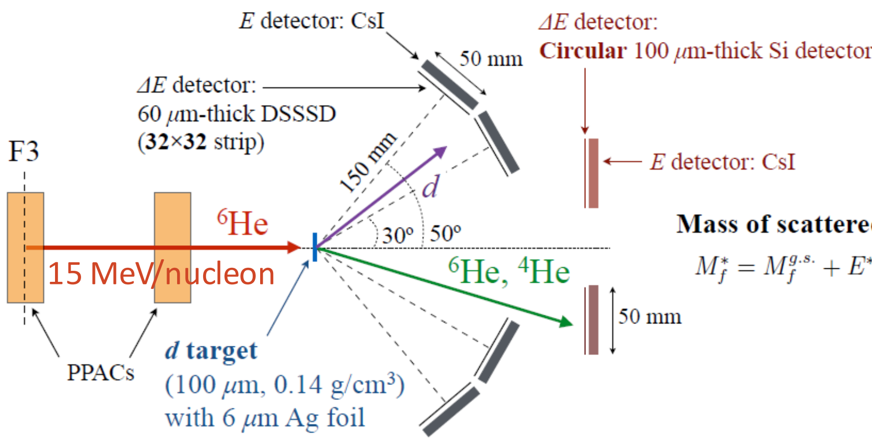




- ^{6}He secondary beam can be physically separated by employing the flat degrader after optical tuning.

Measurement of Isoscalar Soft dipole Resonance for ^{6}He(d,d') ^{6}He* (example)

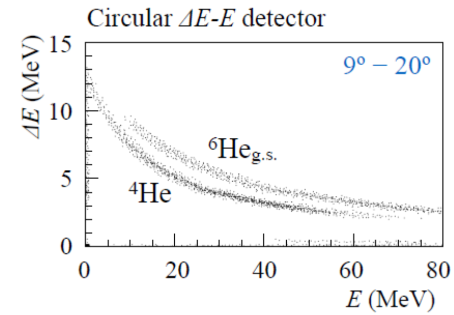
- Isoscalar Soft Dipole Resonance (ISDR) can be strongly excited by isoscalar probe, e.g., (d,d') and (α,α').
- Very recently, evidence for excitation of ISDR was obtained in an inelastic scattering of ^{11}Li with a deuteron target.
  L.V. Chulkov et al., Eur. Phys. J. A (2015) **51**: 97
  R. Kanungo et al., Phys. Rev. Lett. 114, 192502 (2015)
- The evidence for ISDR in ^{6}He has been no observed so far.

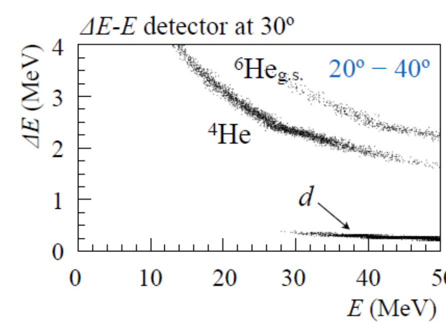


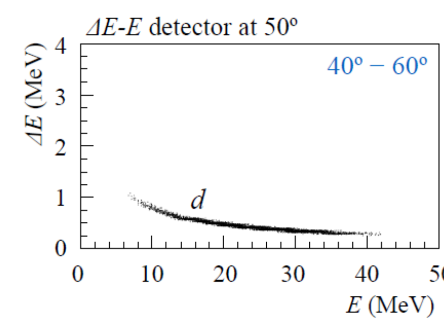
- Reaction channel:
  ^{6}He(d,d')^{6}He$_{g.s.}$
  ^{6}He(d,d')^{6}He$^* \rightarrow$ ^{4}He + 2n
  (S_{2n} = 0.98 MeV, ^{5}He: unbound)

Mass of scattered ^{6}He (missing mass method):

$$M_f^* = M_f^{g.s.} + E^* = \sqrt{(E_{\rm beam} - E_d + m_d)^2 - (\mathrm{p_{beam}} - \mathrm{p}_d)^2}$$

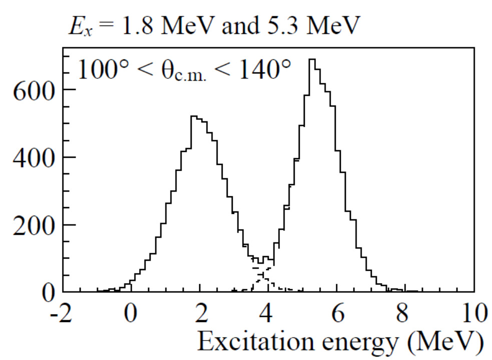




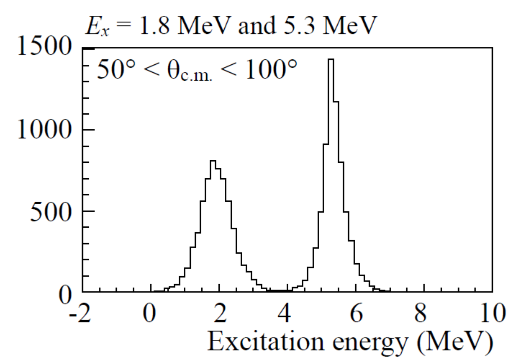


Momenta of d and ^{6}He are isotropically generated in the center of momentum system of d + ^{6}He*.
Momenta of ^{4}He + 2n are generated in uniform phase space using Dalitz plot, in the center of momentum system of ^{6}He*.

Assuming zero resonance widths



Energy resolution (FWHM) ≈ $2.2 - 0.1E_x$ in MeV



Energy resolution (FWHM) ≈ $1.3 - 0.1E_x$ in MeV

Ref. for excitation energies in ^{6}He:
X. Mougeot et al., Phy. Lett. B 718 (2012) 441–446

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Calculations of intensity of secondary beam using stable beam

- Production model (multi-nucleon transfer): Deep Inelastic Transfer (DITm) + GEMINI

Z	A	Production Cross section (mb)	Angular acceptance < +/-50 mrad	Energy acceptance F1 slit (+/-10 cm): dE=+/- 4%	losses by q distribution No losses	Primary beam 1 pnA B11(30 MeV/u)	Traget 0.1 mm-Be9	F0 Energy	F3 Intensity	F3 Energy
						pps	atoms/cm2	MeV/nucleon	pps	MeV/nucleon
H	3	141.4	0.036	0.079	1	6.25E+09	1.23E+21	24.66	3.09E+03	24.34
He	8	0.1	0.105	0.141	1	6.25E+09	1.23E+21	23.35	1.14E+01	22.84
Li	11	0.08	0.305	0.166	1	6.25E+09	1.23E+21	22.53	3.11E+01	21.66
Be	12	0.62	0.709	0.231	1	6.25E+09	1.23E+21	21.21	7.81E+02	19.71
B	13	0.56	0.688	0.421	1	6.25E+09	1.23E+21	22.1	1.25E+03	19.98

RIPS: 300 pnA

Z	A	Production Cross section (mb)	Angular acceptance < +/-50 mrad	Energy acceptance F1 slit (+/-10 cm): dE=+/- 4%	losses by q distribution No losses	Primary beam 1 pnA C12(30 MeV/u)	Traget 0.1 mm-Be9	F0 Energy	F3 Intensity	F3 Energy
						pps	atoms/cm2	MeV/nucleon	pps	MeV/nucleon
H	3	90.95	0.041	0.081	1	6.25E+09	1.23E+21	24.69	2.32E+03	24.37
Li	9	2.63	0.159	0.185	1	6.25E+09	1.23E+21	22.9	5.95E+02	21.85
Be	12	0.31	0.716	0.205	1	6.25E+09	1.23E+21	21.16	3.50E+02	19.65
B	13	0.82	0.565	0.226	1	6.25E+09	1.23E+21	21.5	8.05E+02	19.32
B	8	0.23	0.178	0.114	1	6.25E+09	1.23E+21	22.63	3.59E+01	19.17
C	9	0.032	0.482	0.161	1	6.25E+09	1.23E+21	24.04	1.91E+01	19.77
N	12	0.2	0.608	0.224	1	6.25E+09	1.23E+21	22.65	2.09E+02	18.02

RIPS: 400 pnA

Z	A	Production Cross section (mb)	Angular acceptance < +/-50 mrad	Energy acceptance F1 slit (+/-10 cm): dE=+/- 4%	losses by q distribution No losses	Primary beam 1 pnA O18 (30 MeV/u)	Traget 0.1 mm-Be9	F0 Energy	F3 Intensity	F3 Energy
						pps	atoms/cm2	MeV/nucleon	pps	MeV/nucleon
Li	9	6.08	0.121	0.2	1	6.25E+09	1.23E+21	25.86	1.13E+03	24.91
Be	12	1.74	0.142	0.24	1	6.25E+09	1.23E+21	25.43	4.56E+02	24.14
B	15	0.43	0.225	0.23	1	6.25E+09	1.23E+21	24.75	1.71E+02	23.09
C	17	0.2	0.448	0.324	1	6.25E+09	1.23E+21	26.12	2.23E+02	24.09
N	19	0.25	0.597	0.402	1	6.25E+09	1.23E+21	26.14	4.61E+02	24.65
O	20	0.33	0.808	0.901	1	6.25E+09	1.23E+21	27.27	1.85E+03	24.27

RIPS: 500 pnA

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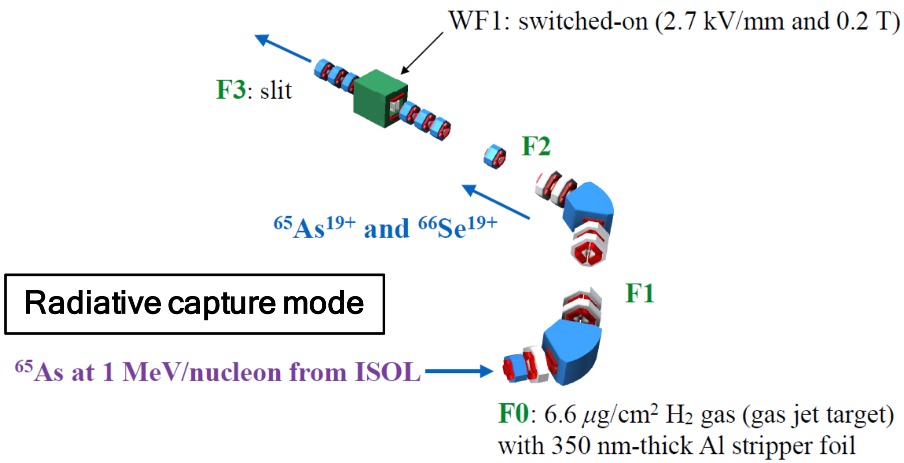
Primary beam intensity at RIPS were taken from http://www.nishina.riken.go.jp/RIBF/RIPS/intensity.html

Beam rejection for p(^{65}As,^{66}Se)γ at 1 MeV/nucleon (example)

- Radiative-capture (p,ϒ) reaction on ^{65}As in inverse kinematics

Since the magnetic rigidity difference between ^{65}As and ^{66}Se is only about 10^{-4} for the same charge state of ~20+, i.e. too small for a separation, the Wien filter is utilized to separate ^{66}Se from ^{65}As on the basis of their mass differences.



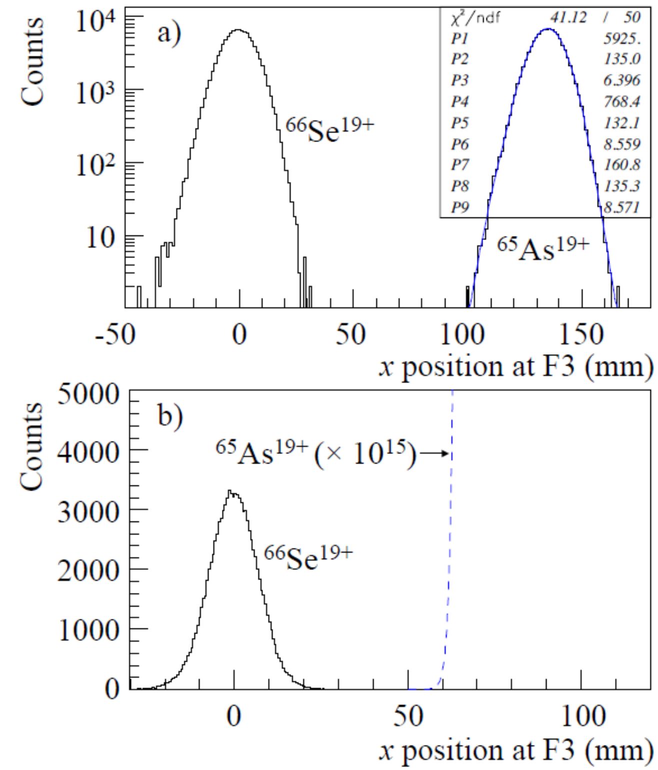


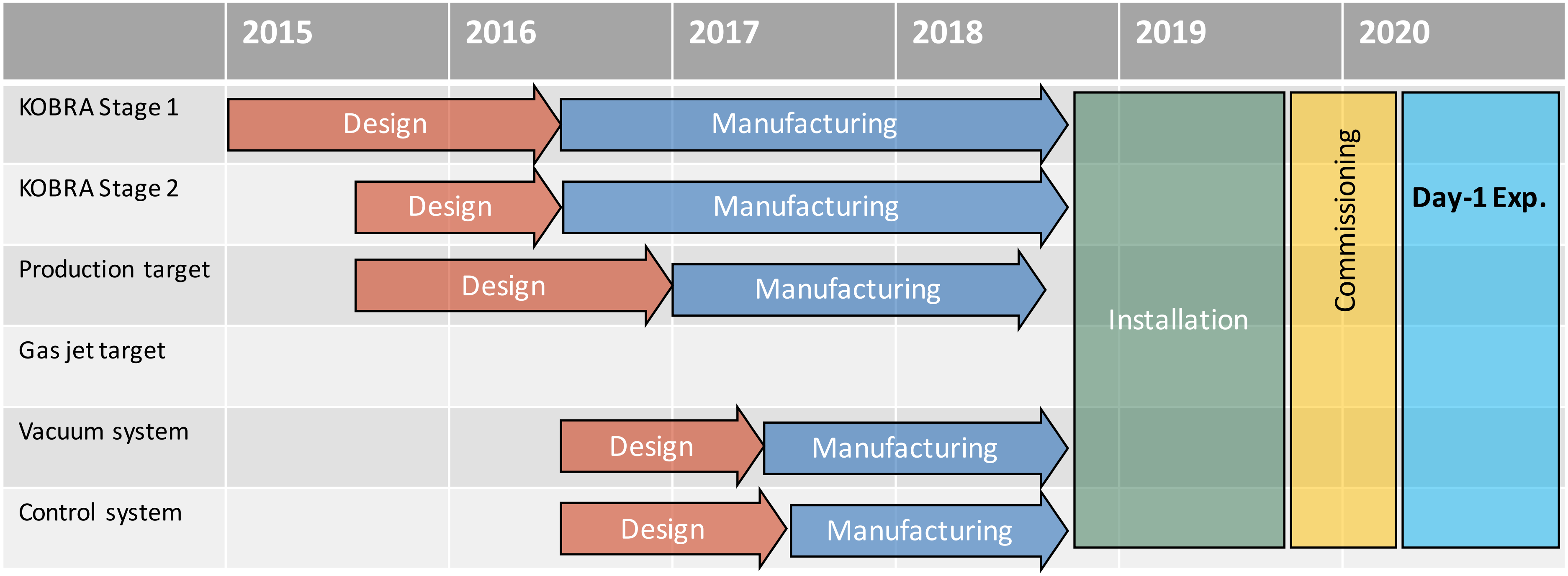
Figure 6: (Color online.) (a) Simulated position distributions of ^{65}As and ^{66}Se at F3 for the $p(^{65}As,^{66}Se)\gamma$ reaction at an energy of 1 MeV/nucleon. The blue-solid line represents the best fit result obtained using a linear combination of three Gaussian functions. (b) Tail of the fitted distribution of ^{65}As (blue-dashed line) and the position distribution of ^{66}Se, assuming that the yield of ^{65}As is higher then that of ^{66}Se by 15 order of magnitudes (see text).

- Beam size, angular spread, and momentum spread of ^{65}As at F0 are represented by Gaussian distributions with σ = 1 mm, 1 mrad, and 0.1%, respectively.

- If we can neglect the non-Gaussian tail of the beam and other background sources like scattering and charge exchange on residual gas and vacuum chamber walls.
- The separation can be further improved by utilizing the second Wien filter of KOBRA stage 2.

Planning and Man power for KoBRA

- Planning



- Present man-power

	KOBRA group (RISP)	Other group (RISP)	Collaboration
Stage 1 design	Dr. K. Tshoo Mr. J. Park (student) Mr. H. Chae (student)	Mr. Z. Aziz	S. Kubono (RIKEN) S. Kato (Yamagata Univ.) G. Souliotis (Univ. of Athens) G.P.A. Berg (Univ. of Notre Dame) N. Iwasa (Tohoku Univ.) H. Yamaguchi (CNS) K. I. Hahn (Ewha), K. Chae (SKKU), S. Choi (SNU) C.S. Lee (CAU), C-.B. Moon (Hoseo) Y.K. Kim (Hanyang)
Stage 2 design	Dr. T. Hashimoto Dr. Y. Satou	Mr. Z. Aziz	
Production target		Dr. H.J. Woo	

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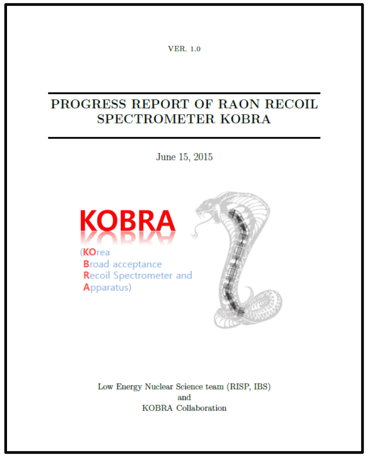
Summary

- The KOBRA facility is being designed for the RI beam production using multi-nucleon transfer reaction at an energy of 20 MeV/nucleon and for high background rejection for direct measurements of radiative-capture cross sections in the astrophysical energy range.
- We have performed a Monte Carlo simulation of ^{44}Ti and ^{6}He productions, as examples, showing clear separation.
- The simulated position distributions of ^{65}As and ^{66}Se for the p(^{65}As,^{66}Se) reaction at an energy of 1 MeV/nucleon are indicative of a possibility of high rejection of the beam in KOBRA.
- We expect that KOBRA will give the opportunity to study the nuclear structure of exotic nuclei in the energy range of 10 - 20 MeV/nucleon, as well as a variety of astrophysically interesting reactions.
- Construction of KOBRA facility will be completed in early of 2020, and Day-1 experiment will be performed in 2020.

More information…


VER. 1.0

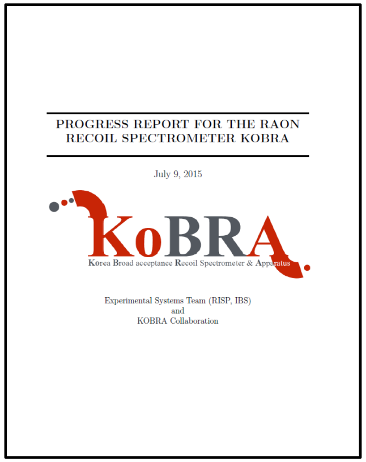
PROGRESS REPORT OF RAON RECOIL SPECTROMETER KOBRA

June 15, 2015

KOBRA
(KOrea
Broad acceptance
Recoil Spectrometer and
Apparatus)

Low Energy Nuclear Science team (RISP, IBS)
and
KOBRA Collaboration

KOBRA progress report 2014


PROGRESS REPORT FOR THE RAON RECOIL SPECTROMETER KOBRA

July 9, 2015

KoBRA
Korea Broad acceptance Recoil Spectrometer & Apparatus

Experimental Systems Team (RISP, IBS)
and
KOBRA Collaboration

KOBRA progress report 2015

KOBRA indico page http://indico.risp.re.kr/indico/index.py (needs to register)

contact : Young Kwan Kwon (ykkwon@ibs.re.kr) , Kyung Ho Tshoo (tshoo@ibs.re.kr)

Thank you for your attention !

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