3rd International Symposium on Nuclear Symmetry Energy (NuSYM13)
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22-26 July, 2013

Plan for the Nuclear Symmetry Energy Measurements at RAON, LAMPS Facility

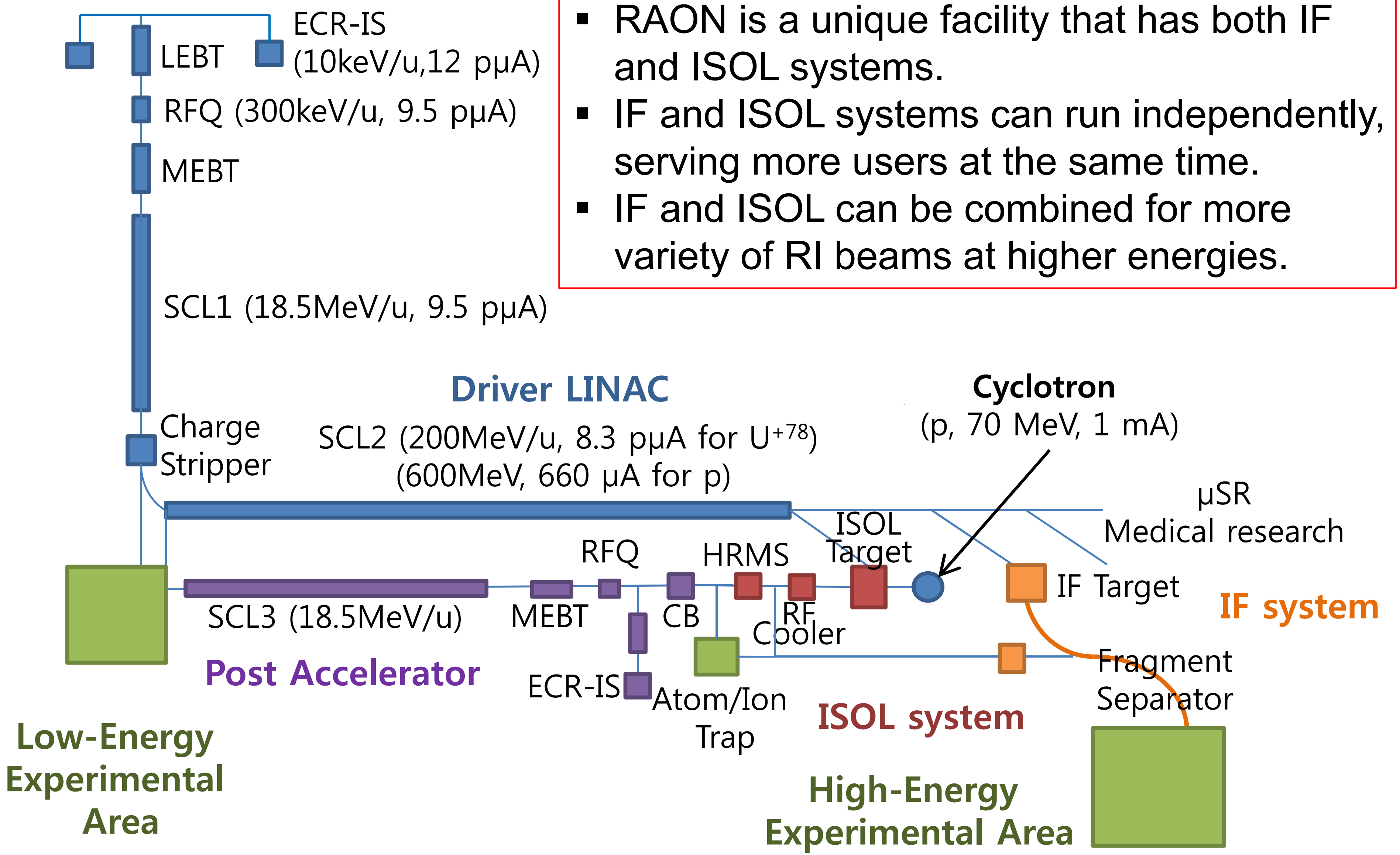
Byungsik Hong
(Korea University)

Outline

1. Introduction to RISP
   - Rare Isotope Science Project in Korea
   - RAON rare isotope beam facility
2. KOBRA
   - Broad acceptance recoil spectrometer at low-energy experimental area
3. LAMPS
   - Large-acceptance multipurpose spectrometer
   - A dedicated system for symmetry energy at high-energy experimental area
   - In addition, low-energy LAMPS will be also built and used at KOBRA for symmetry energy
4. Summary

RAON

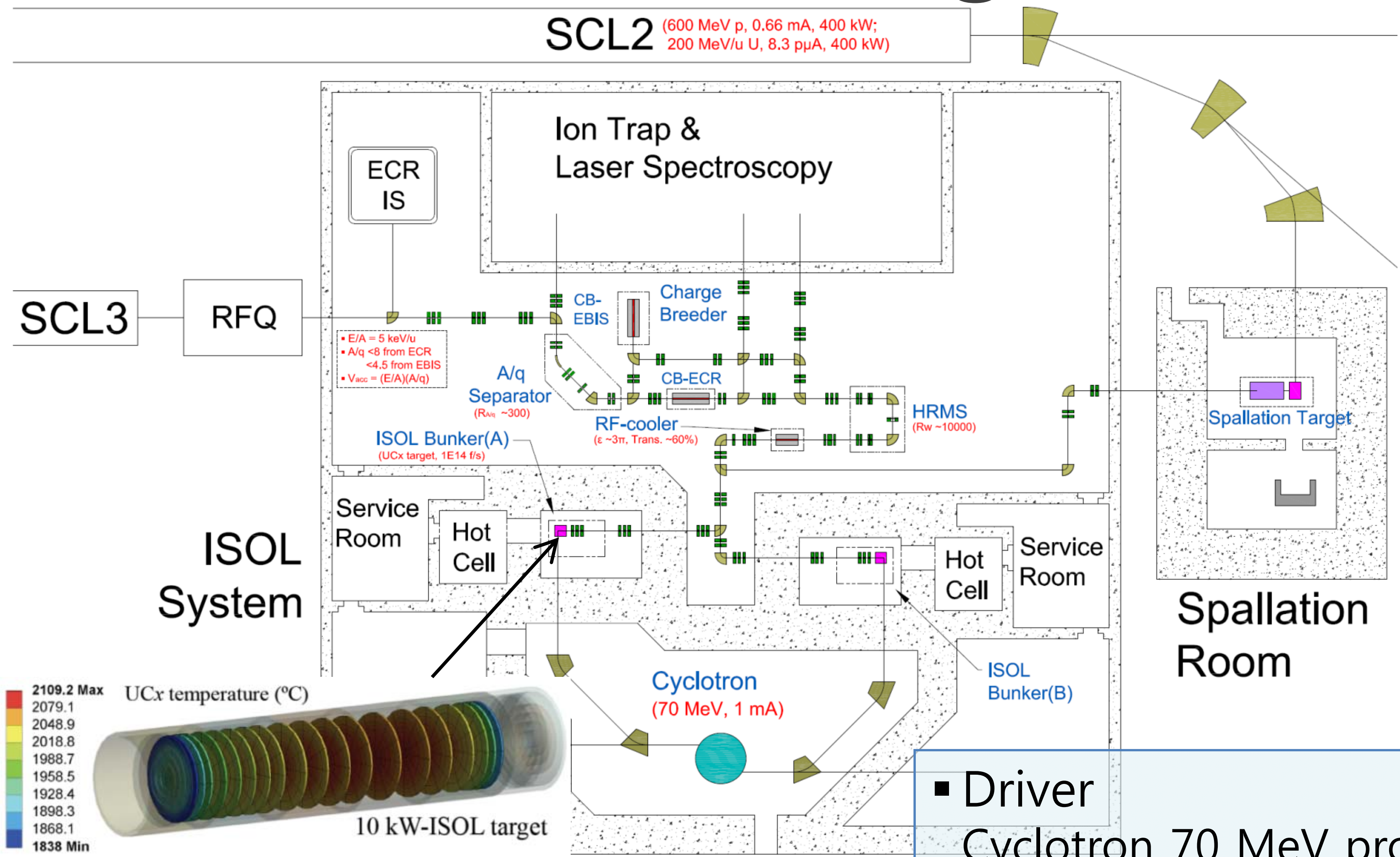
- RAON is a unique facility that has both IF and ISOL systems.
- IF and ISOL systems can run independently, serving more users at the same time.
- IF and ISOL can be combined for more variety of RI beams at higher energies.



Beam Parameters of RAON

	Driver Linac				Post Acc.	Cyclotron
Particle	H^{+}	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Beam energy (MeV/u)	600	320	251	200	18.5	70
Beam current (pμA)	660	78	11	8.3	-	1000
Power on target (kW)	>400	400	400	400	-	70

ISOL Design



low-density (2.5~5 g/cm³), porous, thin multi-disk UCx target

- Driver
  Cyclotron 70 MeV proton
  500 μA + 500 μA (2 ports)

RI Yield Estimation

$$Y_{\mathrm{ISOL}} = \Phi_{\mathrm{P}}\, \sigma_{\mathrm{f}}\, N_{\mathrm{target}}\, \varepsilon_{\mathrm{release}}\, \varepsilon_{\mathrm{ionization}}\, \varepsilon_{\mathrm{cooler}}\, \varepsilon_{\mathrm{transport}}\, \varepsilon_{\mathrm{charge\text{-}breeding}}\, \varepsilon_{\mathrm{acceleration.}}$$

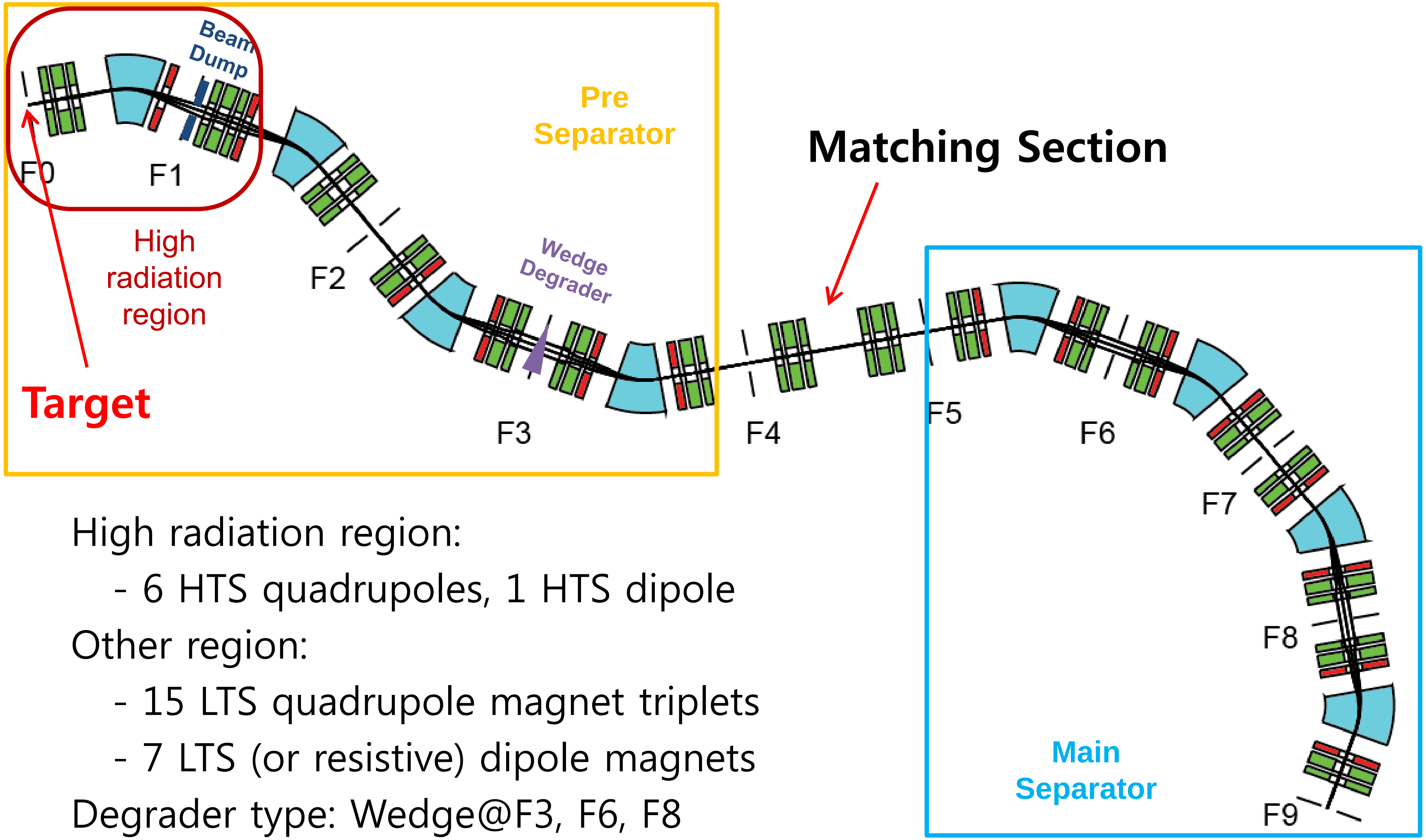
^{132}Sn intensities for 10 kW and 35 kW ISOL targets

- BERTINI-ORNL model for 2.5 g/cm^3 target
- Assuming overall efficiency of ~0.5 %

	10 kW	35 kW
Deposited power (kW)	5.1	32.2
In-target fission rate (s^{-1})	1.6 x 10^{13}	7.3 x 10^{13}
In-target ^{132}Sn production rate (s^{-1})	2.3 x 10^{9}	9.7 x 10^{9}
^{132}Sn release rate (s^{-1})	2.2 x 10^{9}	8.2 x 10^{9}
Experimental hall (s^{-1})	1.1 x 10^{7}	4.1 x 10^{7}

B.-H. Kang at RISP/IBS

IF Design



High radiation region:

- 6 HTS quadrupoles, 1 HTS dipole

Other region:

- 15 LTS quadrupole magnet triplets
- 7 LTS (or resistive) dipole magnets

Degrader type: Wedge@F3, F6, F8

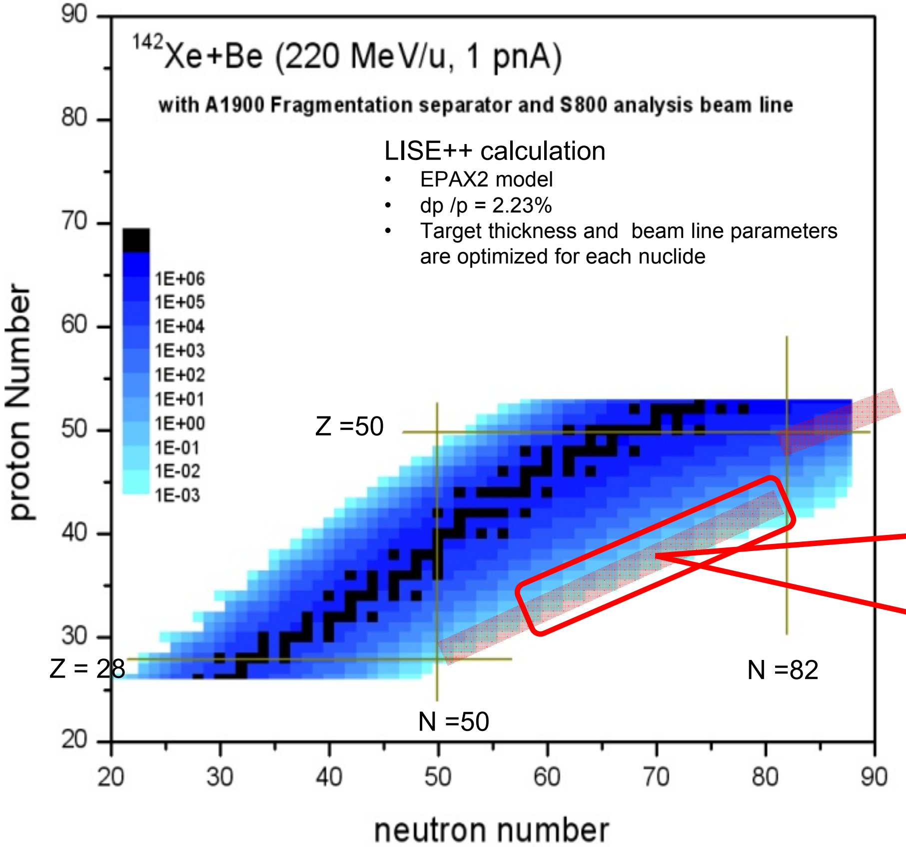
Production target at F0: Be, Graphite

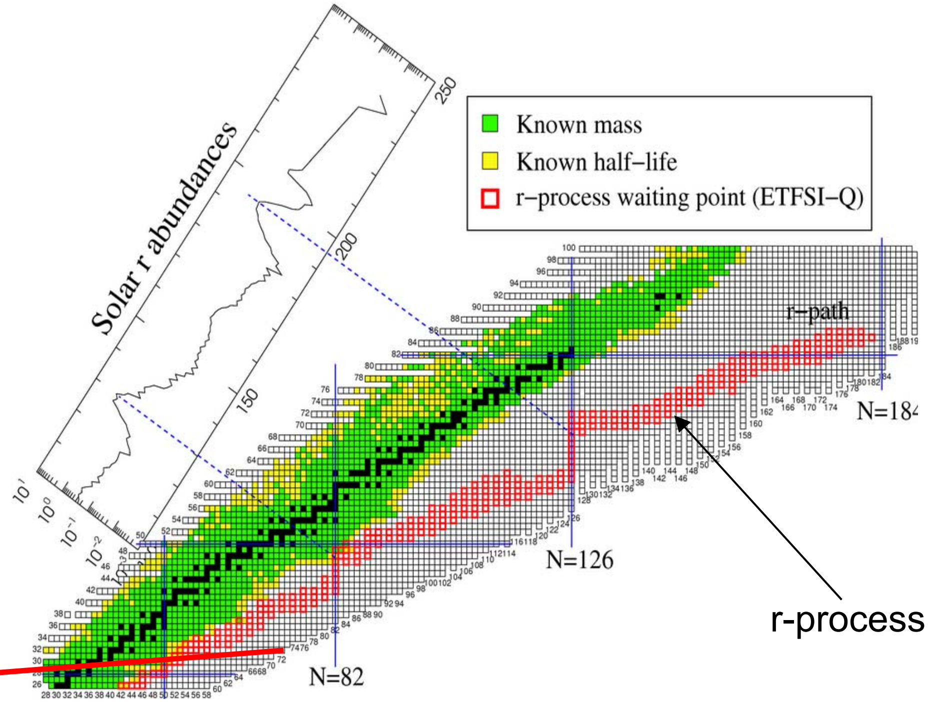
Main Parameters of IF Separator

C. C. Yun, RISP/IBS

Parameter	Design Goal
Angular acceptance	90 mrad (H), 100 mrad (V)
Momentum acceptance	8%
Maximum rigidity	10 Tm
Momentum dispersion	2.7 cm/% @F6 & F8
Resolving power (p/Δp)	1,350 @F6 & F8

Production of More Exotic RIB





RAON can reach new n-rich isotope with rates of 10^{-3} ~10 pps.

nuclide	Estimated Intensity (pps)
^{110}Y	1.8
^{110}Zr	1.8
^{114}Nb	1.1
^{116}Mo	3.8
^{118}Tc	1.4

^{142}Xe (ISOL) → post-accelerator → Driver Linac → IF target → Fragment separator → Experiment

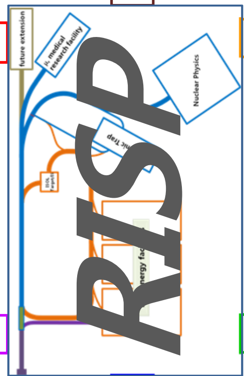
Note that ~10^3 times higher than ^{136}Xe (350 MeV/u, 10 pnA)+Be.

Research Topics

➢ **Nuclear Physics**
- Exotic nuclei near the neutron drip line
- Equation-of-state (EoS) of nuclear matter

➢ **Nuclear Astrophysics**
- Origin of nuclei
- Neutron stars and supernovae
- Nucleosynthesis Superheavies

➢ **Atomic/Particle Physics**
- Atomic trap
- Fundamental symmetries

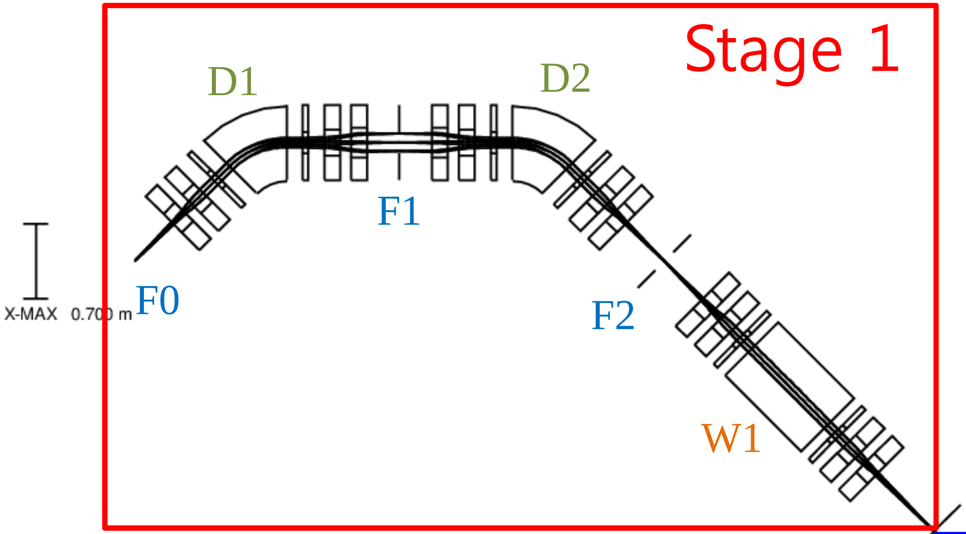


➢ **Medical & Biosciences**
- Advanced therapy technology
- Mutation of DNA
- New isotopes for imaging

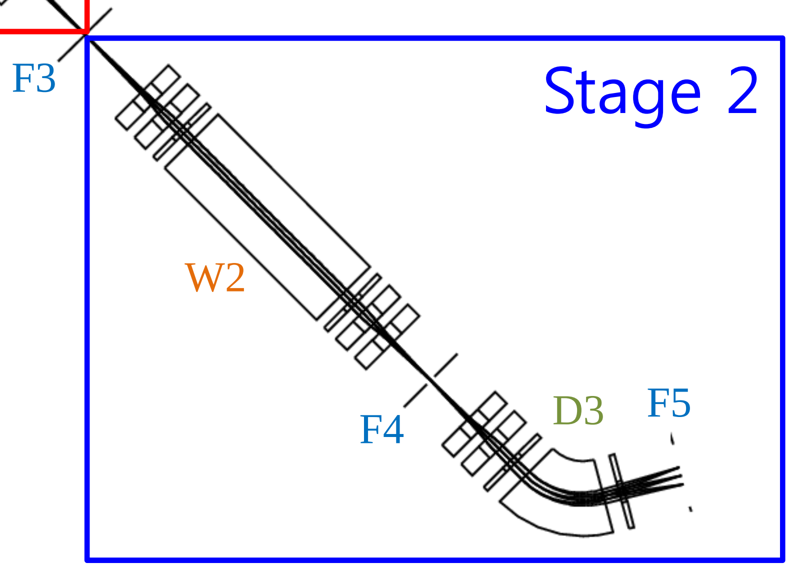
➢ **Nuclear data with fast neutrons**
- Basic nuclear reaction data for future nuclear energy
- Nuclear waste transmutation

➢ **Material science**
- Production & Characterization of new materials
- β-NMR / μSR

KOBRA

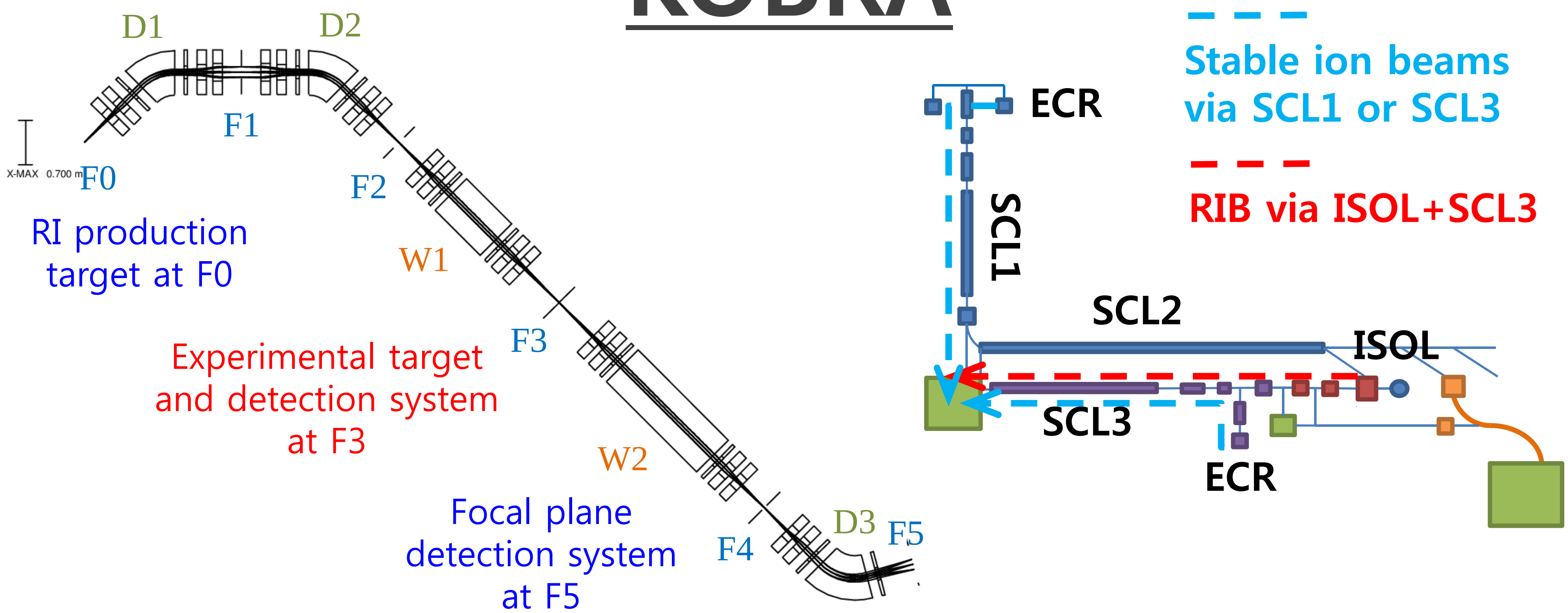


Korea Broad Acceptance Recoil Spectrometer and Apparatus at low-energy experimental area



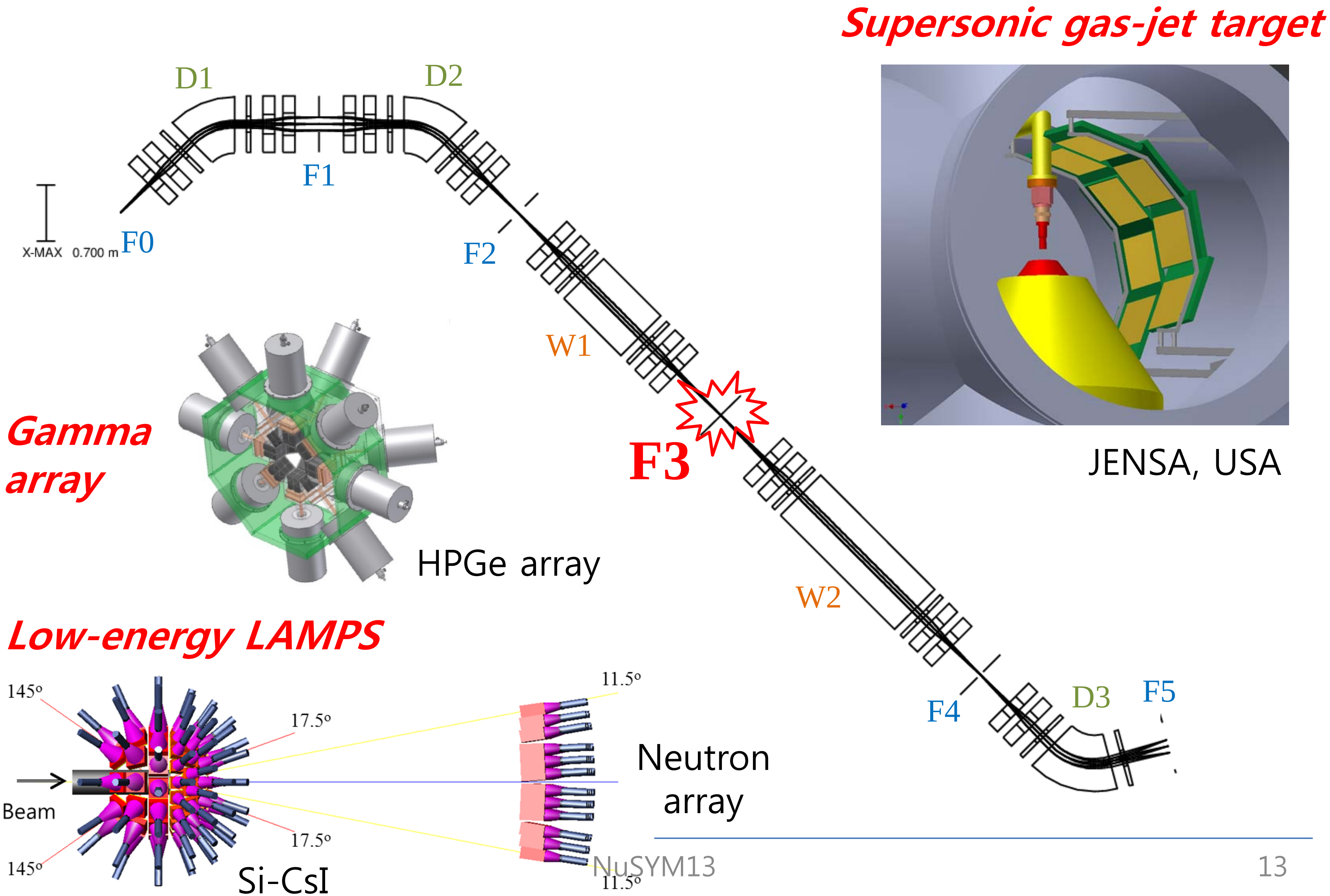
- High-performance spectrometer with detection systems
- Main experimental facility for nuclear physics with low-energy beams up to 18.5 MeV/u

KOBRA



- Stage 1 (F0~F3): Production and separation of RIBs by in-flight method with high-intensity stable ion beams from ECRs
- Experimental target at F3 (available space of ~3 m): In-beam γ-ray spectroscopy, Symmetry energy & charged particle spectroscopy, Spin dependence, etc.
- Stage 2 (F3~F5): Big-bite spectrometer with Wien filter

Target and Detection Systems for KOBRA

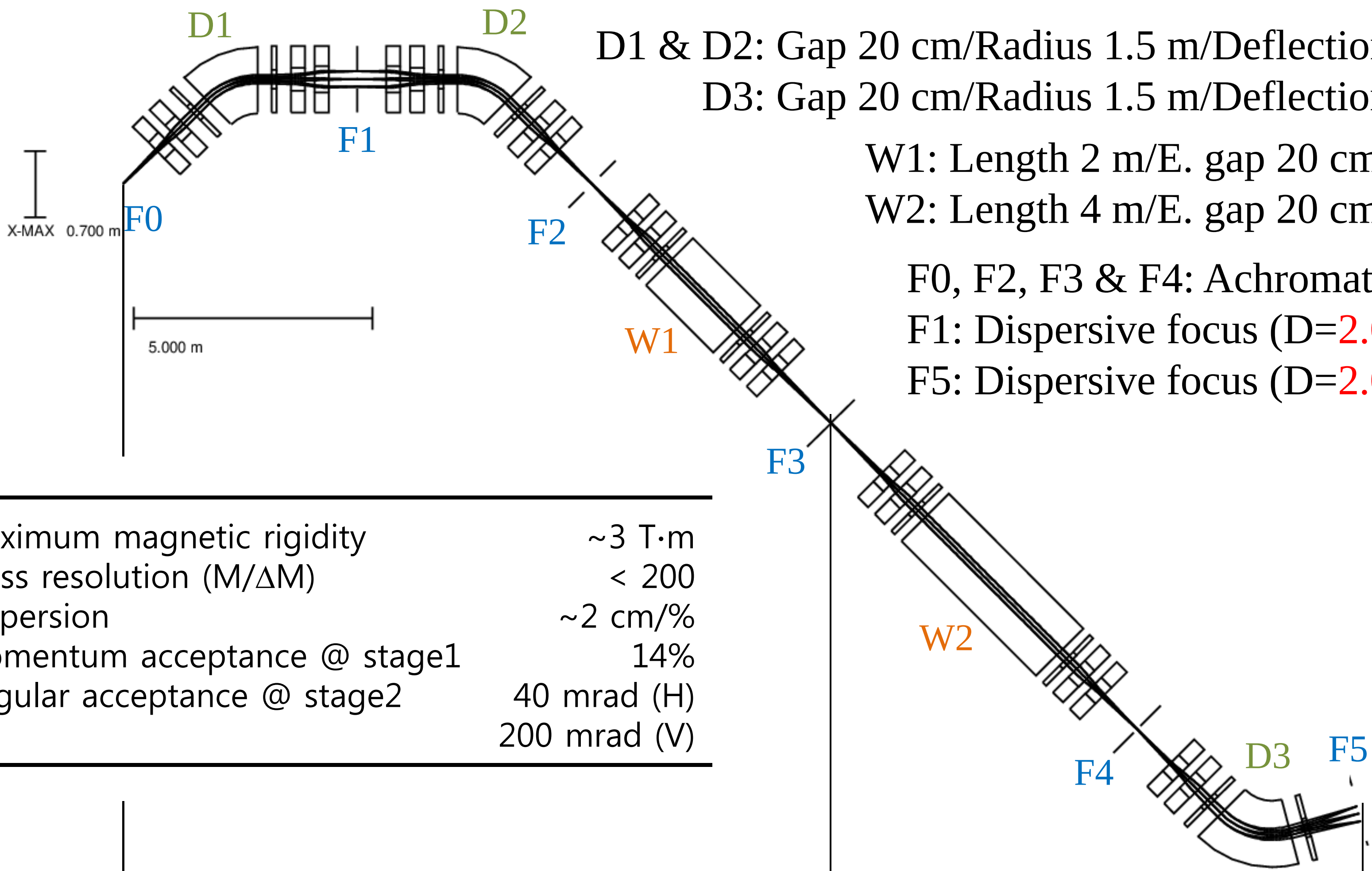


KOBRA

D1 & D2: Gap 20 cm/Radius 1.5 m/Deflection angle 45°
D3: Gap 20 cm/Radius 1.5 m/Deflection angle 60°

W1: Length 2 m/E. gap 20 cm/±300 kV
W2: Length 4 m/E. gap 20 cm/±300 kV

F0, F2, F3 & F4: Achromatic focusing
F1: Dispersive focus (D=2.03 cm/%)
F5: Dispersive focus (D=2.05 cm/%)



Maximum magnetic rigidity	~3 T·m
Mass resolution (M/ΔM)	< 200
Dispersion	~2 cm/%
Momentum acceptance @ stage1	14%
Angular acceptance @ stage2	40 mrad (H)
	200 mrad (V)

Stage 1: In-flight Separator
F0~F3
{QQDQQ-QQDQQ-QQWQQ}

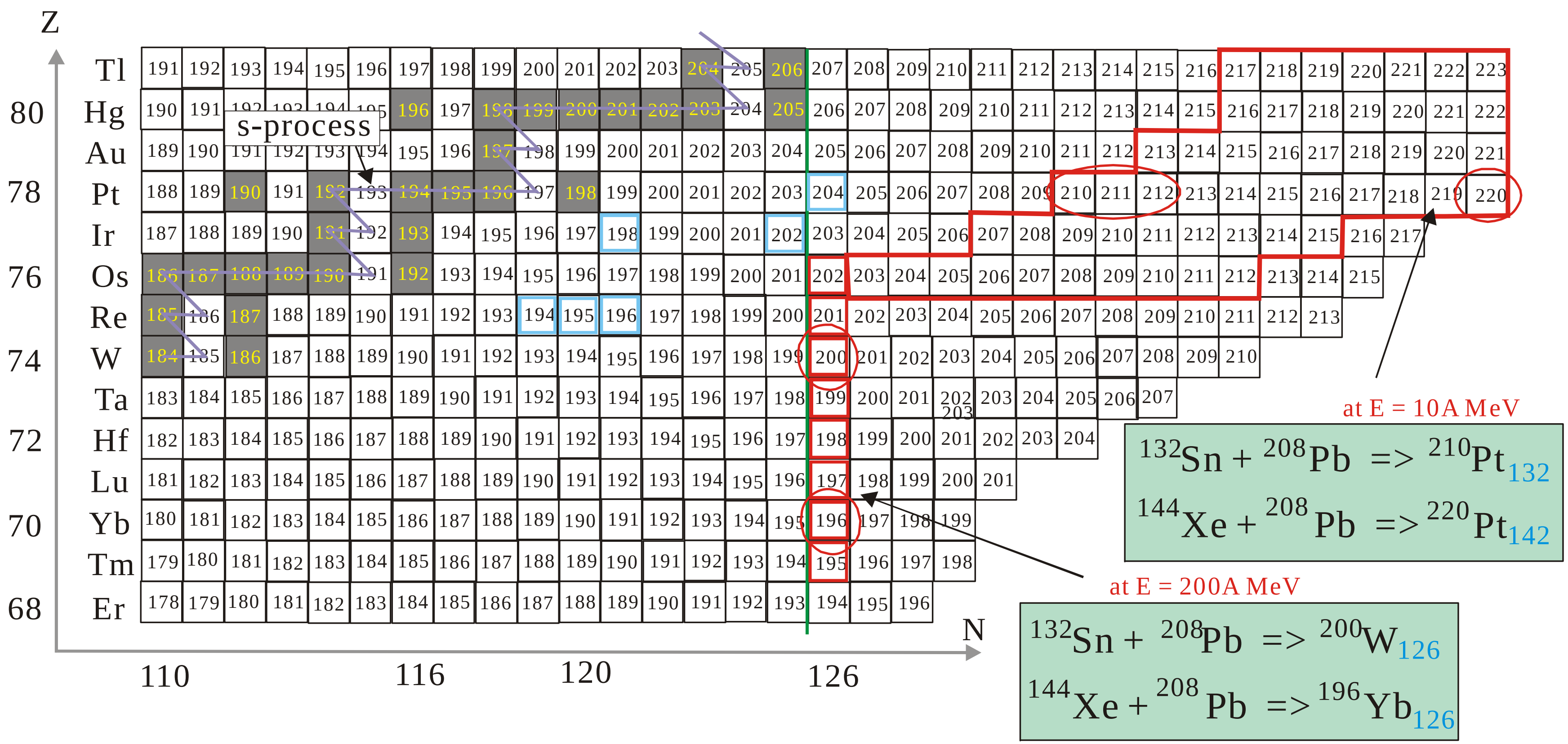
Stage 2: Large-Acceptance
Spectrometer F3~F5
{QQWQQ-QQD}

KOBRA: Physics Program

1. Nuclear structure
   - Comparison of the nuclear structures for the isobaric mirror nuclei at drip lines (charge symmetry and/or independence)
   - Resonant conditions of unbound nuclear states
   - Spin dependence of basic properties
2. Nuclear astrophysics
   - Capture reactions: (p,γ), (α,γ), (n,γ)
   - Transfer reactions: (d,p), (α,p), etc.
   - Resonant scattering: p and α resonant elastic scattering
3. Rare events
   - Super-heavy elements
   - Decay spectroscopy
4. Nuclear symmetry energy
   - Charged particle and neutron productions in central collisions
   - Electric dipole excitations

New Neutron-Rich Heavy Nuclei

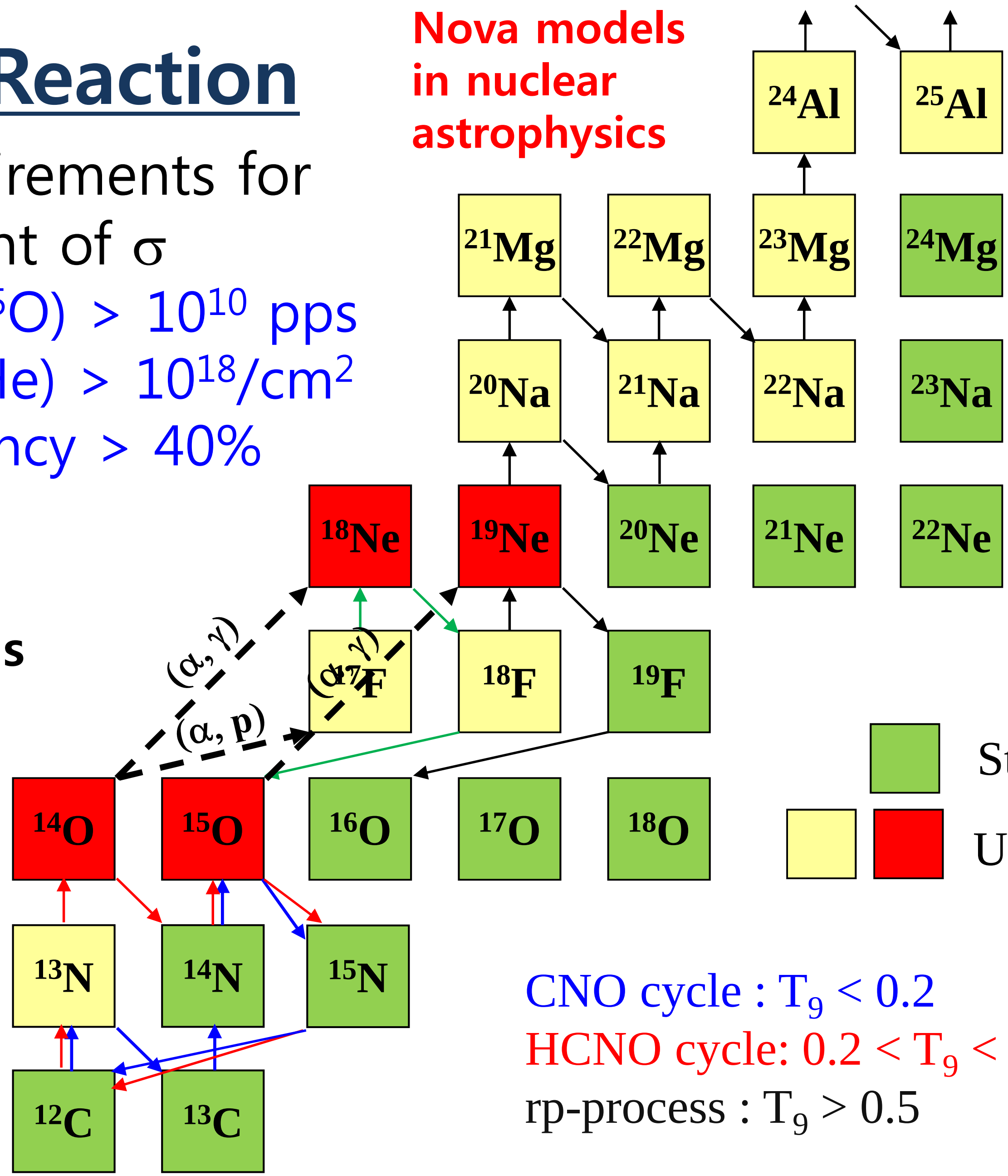
"High Intensity Stable Beams in Europe"
NUPECC Report (July 2007)



$^{15}O(\alpha,\gamma)^{19}Ne$ Reaction

- Experimental requirements for direct measurement of σ
  - Beam intensity (^{15}O) > 10^{10} pps
  - Target density (^{4}He) > $10^{18}/cm^2$
  - Recoil det. efficiency > 40%
  - ⇒ >1 Count/hr

Nova models in nuclear astrophysics



Breakout paths to rp-process

rp-process
Hot-CNO II
Hot-CNO I
CNO cycle

Stable
Unstable

CNO cycle : $T_9 < 0.2$
HCNO cycle: $0.2 < T_9 < 0.5$
rp-process : $T_9 > 0.5$

$^{44}Ti(\alpha,p)^{47}V$ Reaction

INTEGRAL

Gamma Ray Emission from Cassiopeia A

29 Sep 2006

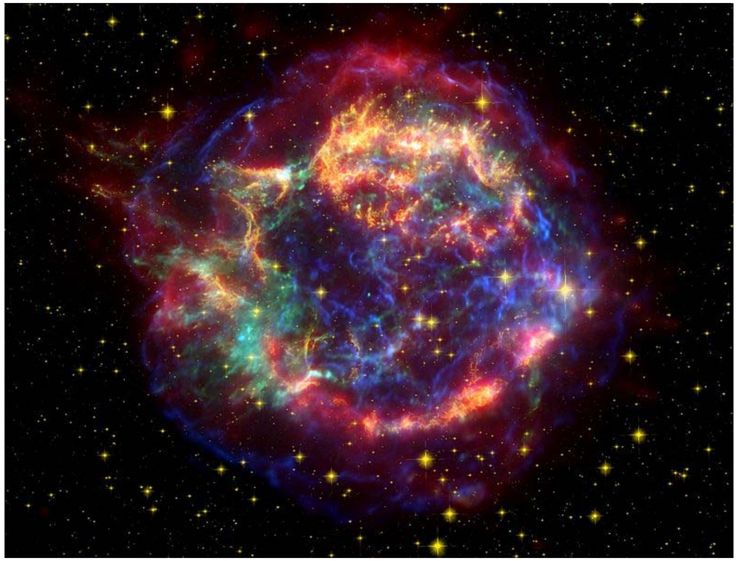
Supernovae and their remnants are the main galactic nucleosynthesis sites. Few radioactive isotopes are accessible to gamma-ray astronomy for probing these stellar explosions. Among them, ^{44}Ti is a key isotope for the investigation of the inner regions of supernovae and their young remnants.

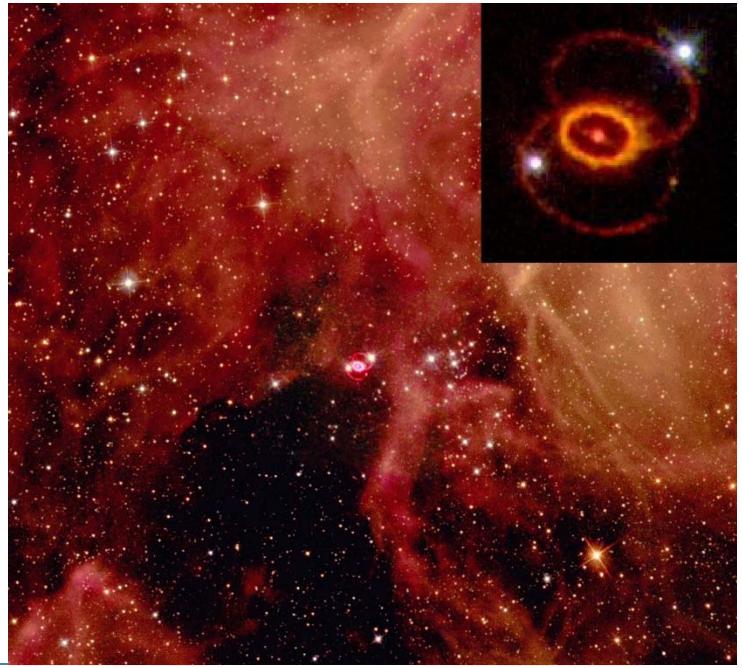
INTEGRAL

INTEGRAL finds titanium in supernova remnant 1987A

17 Oct 2012

Astronomers using INTEGRAL have detected the first direct signature of titanium-44 in the remnant of the nearby supernova 1987A. The discovery reveals a large amount of this key isotope in the remnant, equivalent to 0.03 per cent the mass of the Sun. This value is close to upper bounds from theoretical predictions and exceeds the amount of titanium-44 observed in Cassiopeia A - the only other supernova remnant where this isotope has been found. The amount of titanium-44 found in SNR 1987A demonstrates that its radioactive decay has been powering the source for the past 22 years.





$^{44}Ti(\alpha,p)^{47}V$ Reaction

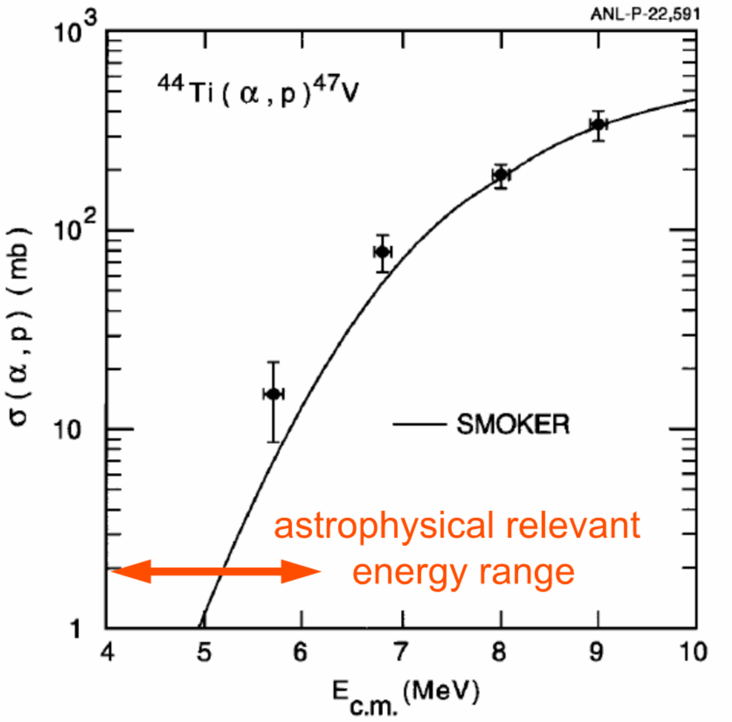
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$

Reaction Rate Multiplied by 1/100		Reaction Rate Multiplied by 100	
Reaction	^{44}Ti Change (percent)	Reaction	^{44}Ti Change (percent)
$^{44}Ti(\alpha, p)^{47}V$	+173	$^{45}V(p, \gamma)^{46}Cr$	−98
$\alpha(2\alpha, \gamma)^{12}C$	−100	$\alpha(2\alpha, \gamma)^{12}C$	+67
$^{40}Ca(\alpha, \gamma)^{44}Ti$	−72	$^{44}Ti(\alpha, p)^{47}V$	−89
$^{45}V(p, \gamma)^{46}Cr$	+57	$^{44}Ti(\alpha, \gamma)^{48}Cr$	−61
$^{57}Ni(p, \gamma)^{58}Cu$	−47	$^{57}Co(p, n)^{57}Ni$	+25
$^{57}Co(p, n)^{57}Ni$	−33	$^{40}Ca(\alpha, \gamma)^{44}Ti$	+22
$^{13}N(p, \gamma)^{14}O$	−16	$^{57}Ni(n, \gamma)^{58}Ni$	+10
$^{58}Cu(p, \gamma)^{59}Zn$	−14	$^{54}Fe(\alpha, n)^{57}Ni$	+9.4
$^{36}Ar(\alpha, p)^{39}K$	−11	$^{36}Ar(\alpha, p)^{39}K$	+5.5
$^{12}C(\alpha, \gamma)^{16}O$	+3.5	$^{36}Ar(\alpha, \gamma)^{40}Ca$	+5.3

The *et al*., *Astrophys. J.* 504 (1998)

- Presently, TRIUMF, CERN, CNS CRIB are working on this reaction.
- At RISP, the direct measurement will be possible with an active target in the IF mode of KOBRA.

Measurement at FMA at Argonne Nat. Lab.
^{44}Ti intensity of ~5 x 10^5 s^{-1}



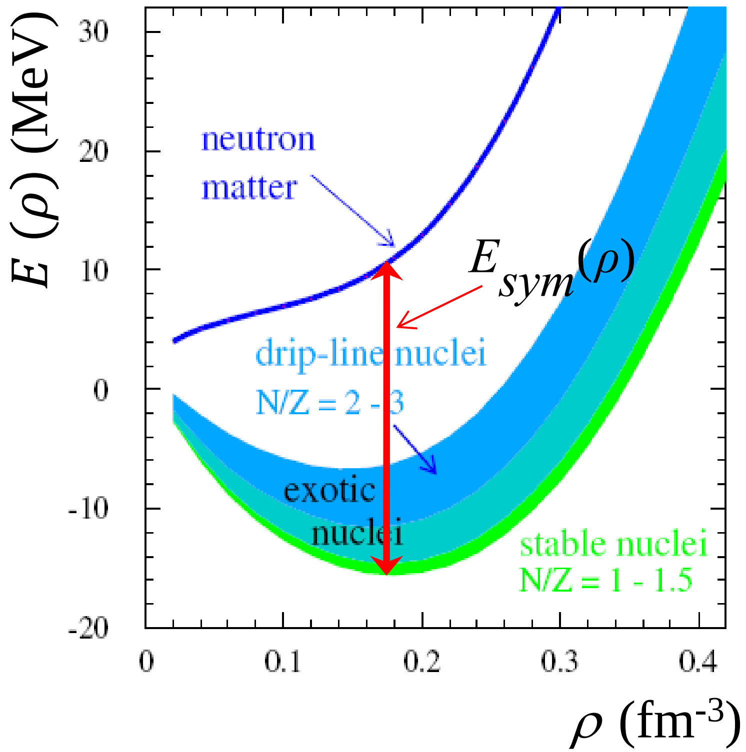
Sonzogni *et al*., *Phys. Rev. Lett.* 84 (2000)

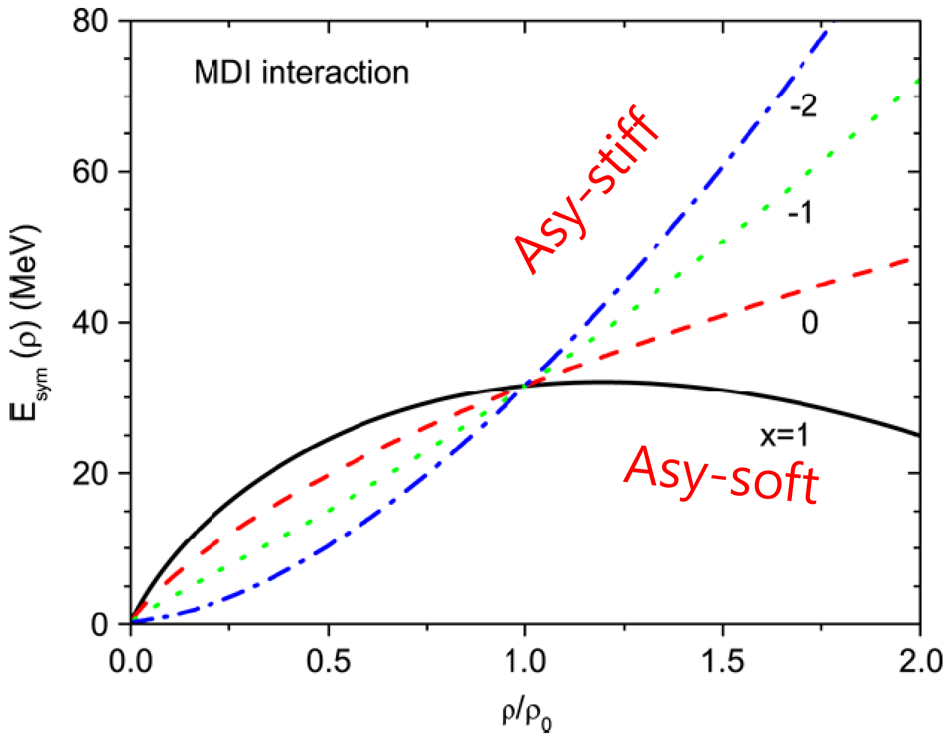
EOS & Symmetry Energy

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

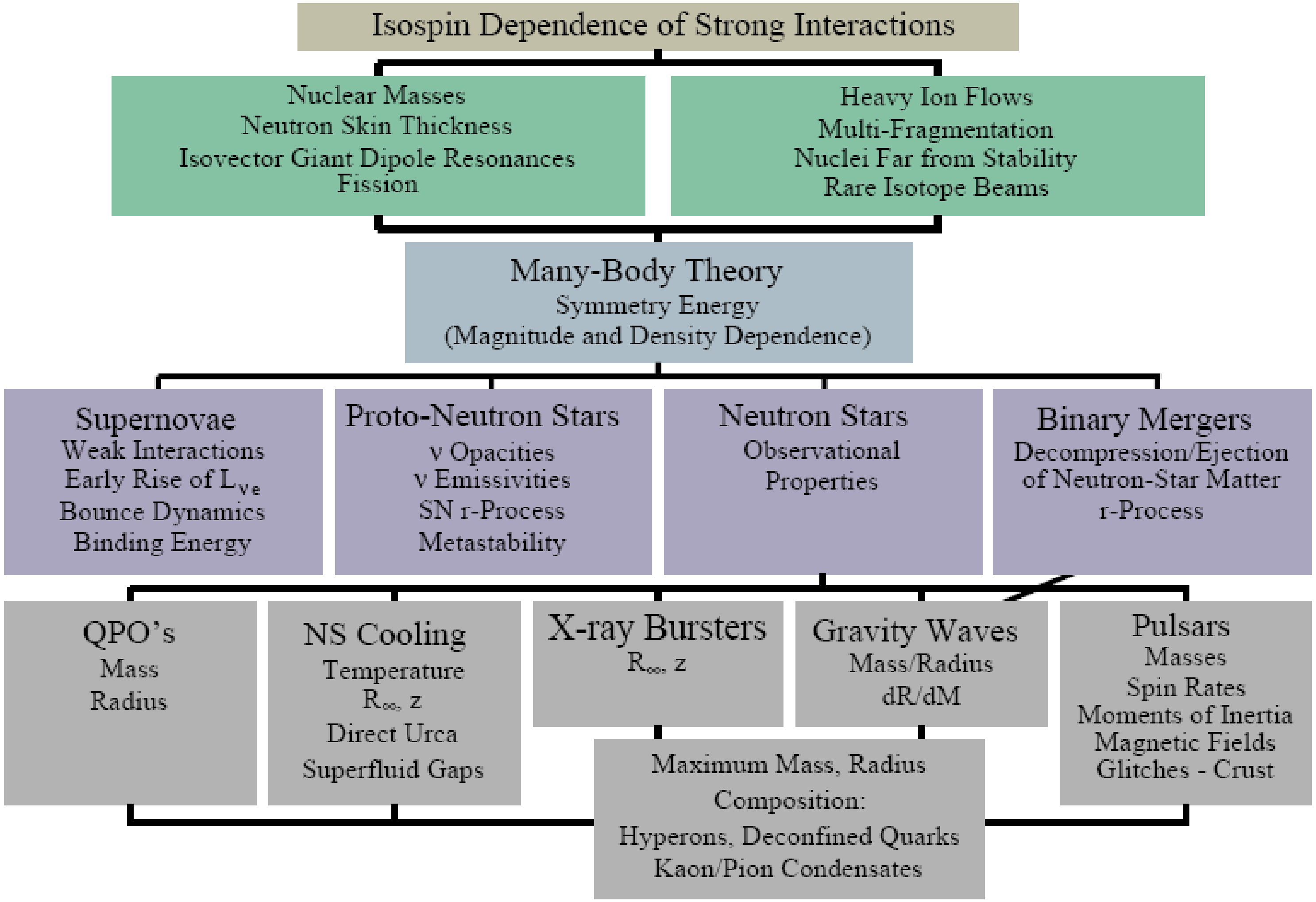
where $\rho = \rho_n + \rho_p$ and $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$

L.W. Chen et al.,
PRL 94, 032701 (2005)





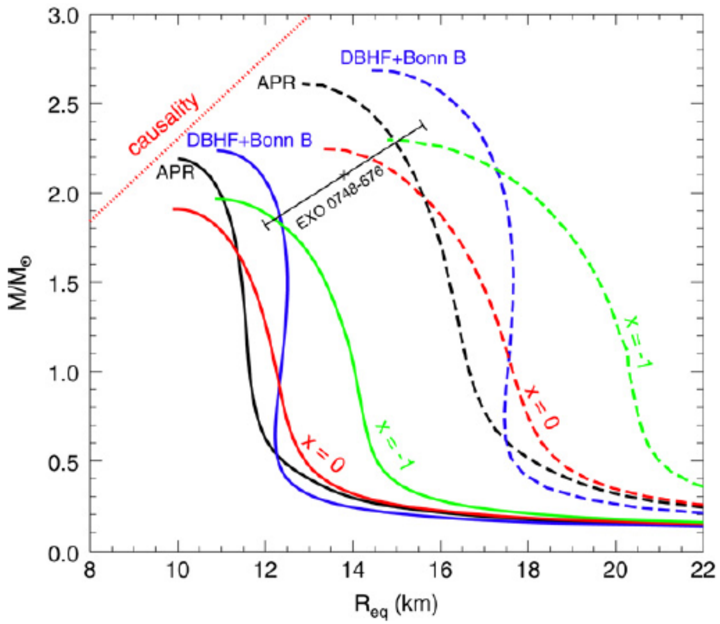
Symmetry Energy



- A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)

Symmetry Energy & Neutron Stars

- Neutron star stability against gravitational collapse
- Determine stellar density profile and internal structure
- Observational consequences
  - Cooling rates of proto-neutron stars
  - Stellar masses, radii & moment of inertia from temperatures & luminosities of X-ray bursters
- M vs. R relationship
  - Uncertainty of softness of EOS and influence of E_{sym}
- Need to provide additional laboratory constraints at specific densities



P. Krastev, B.A. Li, and A. Worley, Astrophys. J. 676, 1170 (2008)

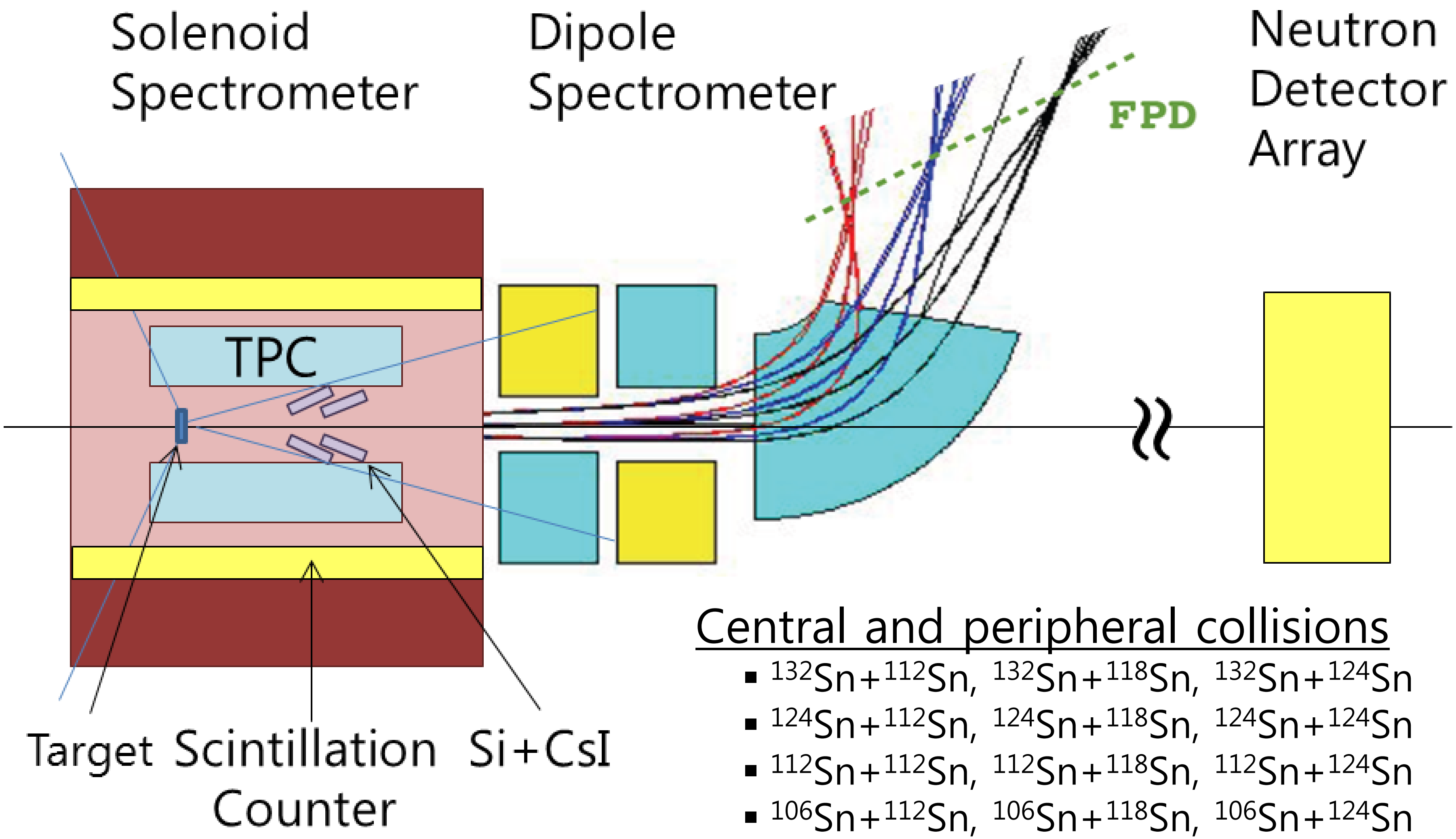
Experimental Observables

1. Particle ratios of mirror nuclei and pions
   - n/p, $^{3}H/^{3}He$, $^{7}Li/^{7}Be$, π^{-}/π^{+}, etc.
2. Collective flow
   - Directed (or sideward) and elliptic flow parameters of n, p, and heavier fragments
3. Various isospin-dependent phenomena
   - Isoscaling in nuclear multifragmentation
   - Isospin transport/diffusion
4. Electric dipole resonances
   - Energy spectra of the excitation energy and/or gammas
   - PDR~the size of n-skin for unstable nuclei

Experimental Requirements

1. We need to accommodate
   - Large acceptance
   - Precise measurement of momentum (or energy) for variety of particle species, including $\pi^{+/-}$ and neutrons, with high efficiency
   - Gamma detection for electric dipole resonances
   - Keep flexibility for other physics topics
2. This leads to the design of **LAMPS**
   - Large-acceptance Multipurpose Spectrometer
   - Low-energy LAMPS at F3 of KOBRA
   - High-energy LAMPS

LAMPS

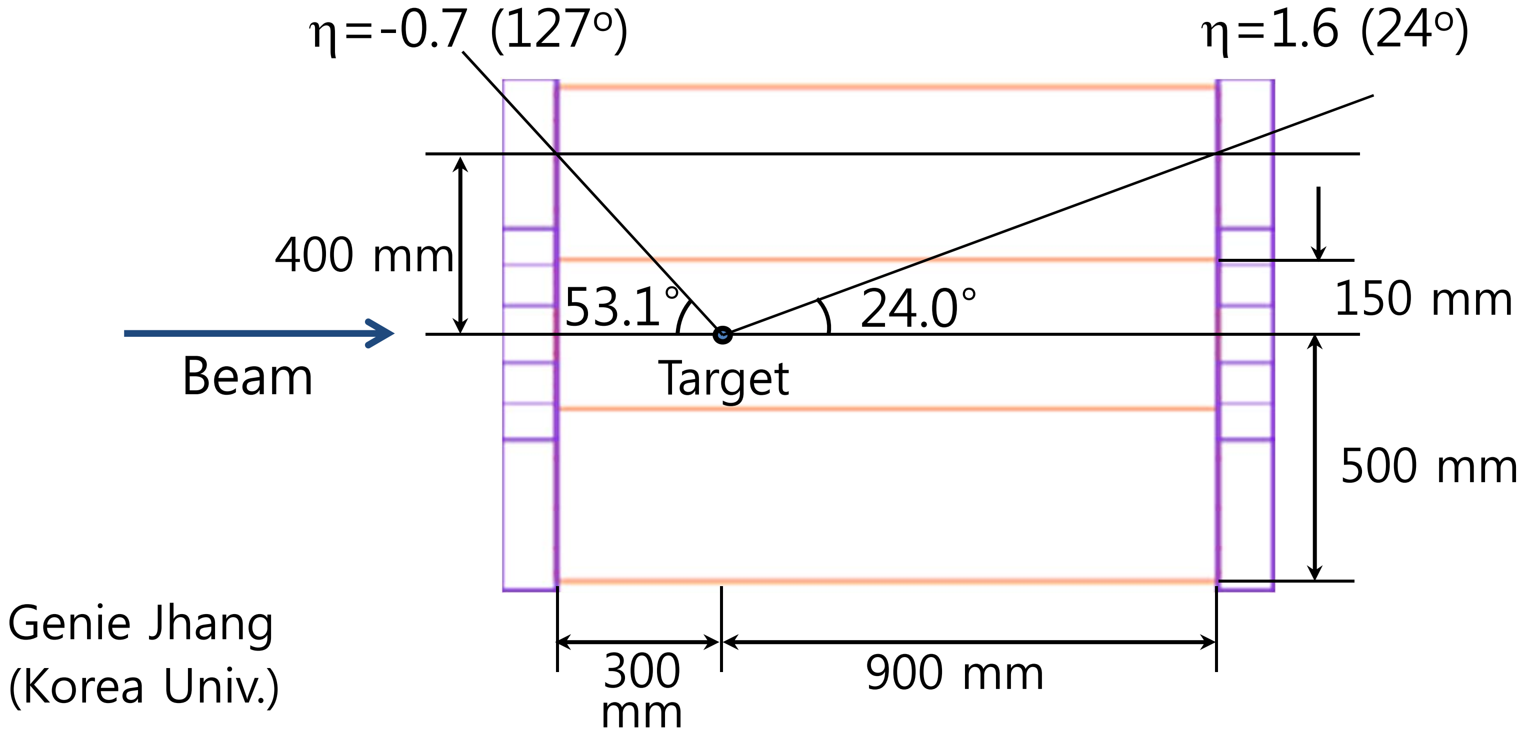


Central and peripheral collisions

- $^{132}Sn+^{112}Sn$, $^{132}Sn+^{118}Sn$, $^{132}Sn+^{124}Sn$
- $^{124}Sn+^{112}Sn$, $^{124}Sn+^{118}Sn$, $^{124}Sn+^{124}Sn$
- $^{112}Sn+^{112}Sn$, $^{112}Sn+^{118}Sn$, $^{112}Sn+^{124}Sn$
- $^{106}Sn+^{112}Sn$, $^{106}Sn+^{118}Sn$, $^{106}Sn+^{124}Sn$

  etc.

Time Projection Chamber

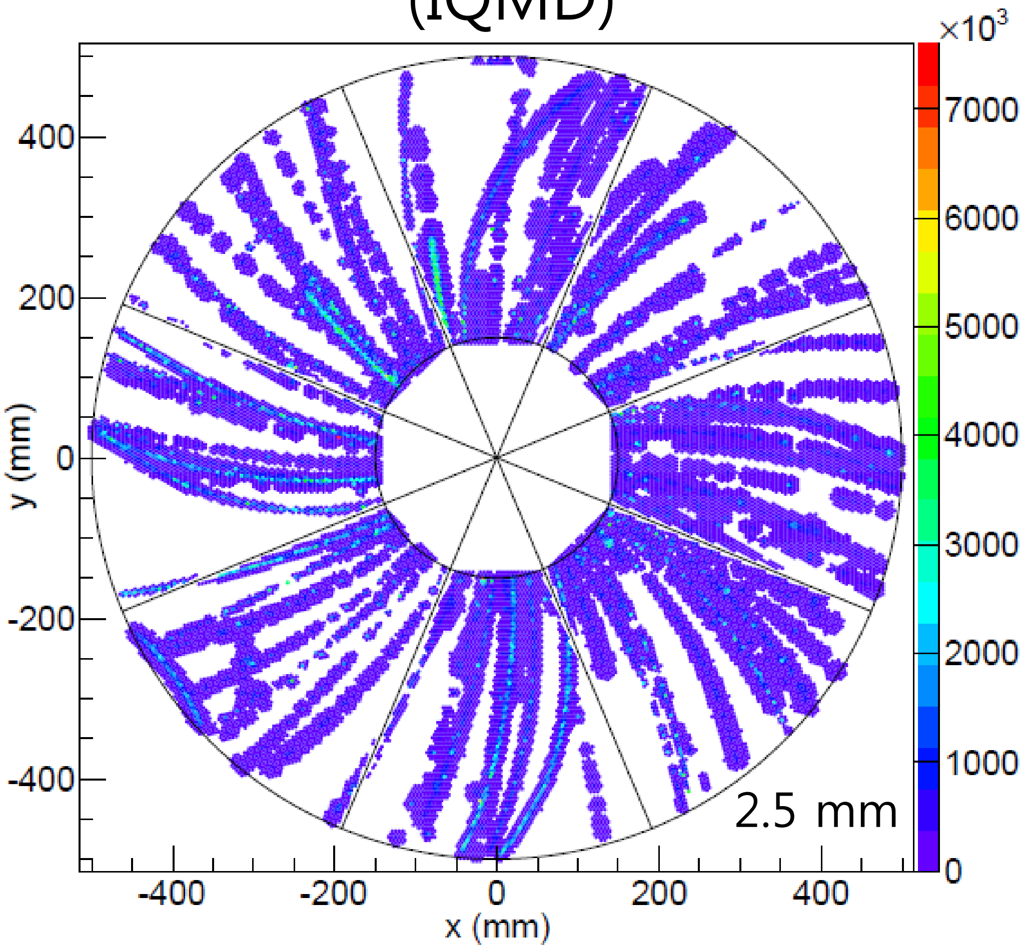


- Simulation with triple GEM readouts at both ends by Garfield++
  - Gas mixture: Ar 90%+CO_2 10%, Voltage for each foil: 450 V
  - <Gain>~1.4×10^6, <Drift velocity>~50 mm/μs
  - <Dispersion> after 60 cm (maximum drift distance) < 3 mm

Time Projection Chamber

Genie Jhang (Korea Univ.)

Central Au+Au at 250 AMeV (IQMD)



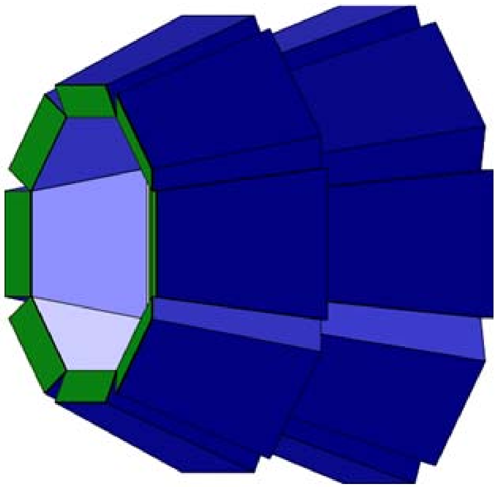
Color scale: the number of electrons in each pad

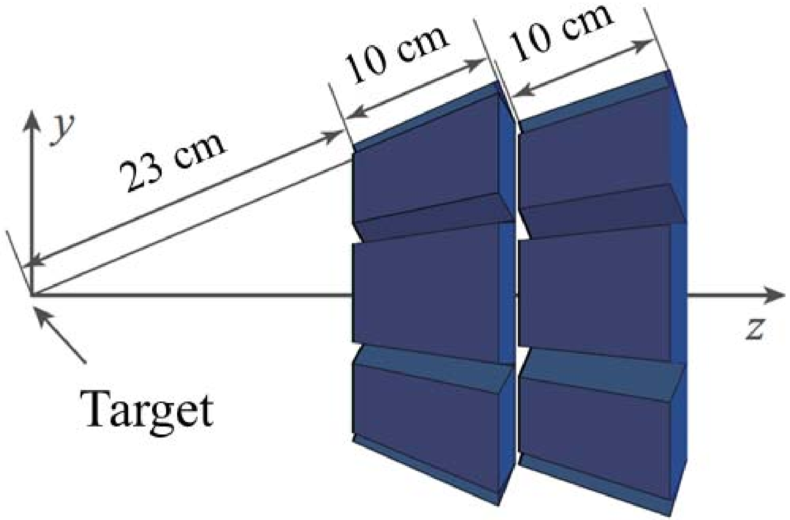
- Pad
  - Shape: hexagonal
  - Total number
    90,000 for 2.5 mm
    20,000 for 5 mm
- Signal processing
  - GET: General Electronics for TPC

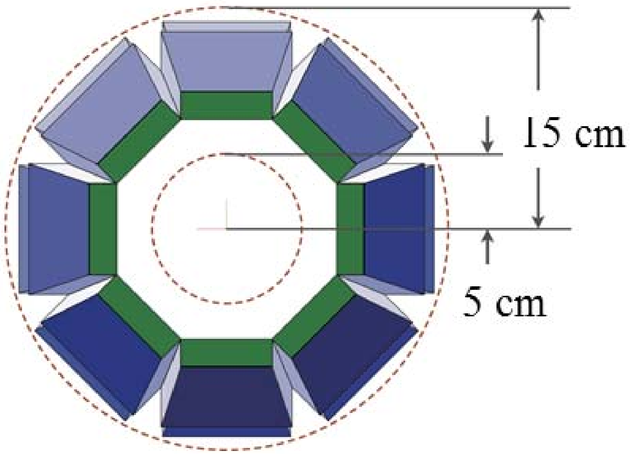
Si-CsI

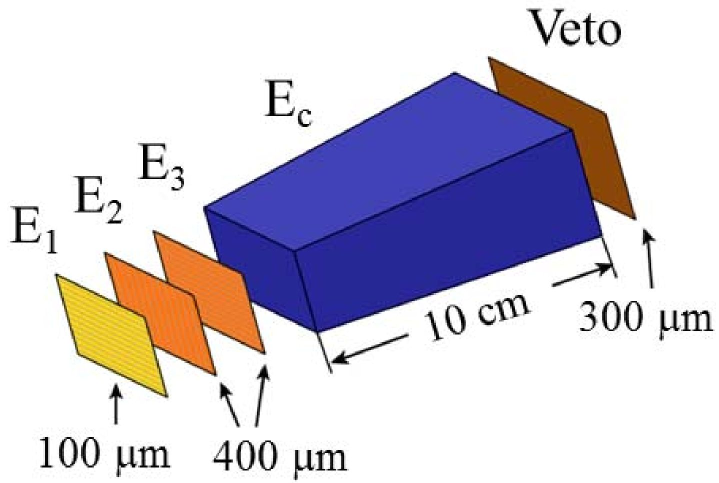
$1.6 < \eta < 2.1$
$(14^{o} < \theta_{Lab} < 24^{o})$

Suhyun & Songkyo Lee
(Korea Univ.)



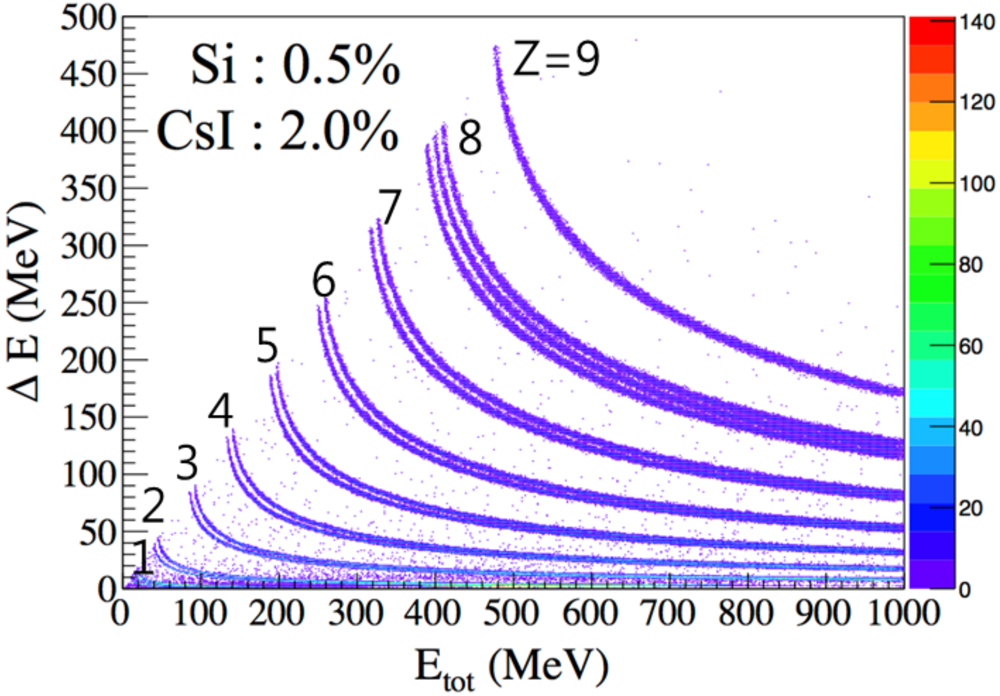






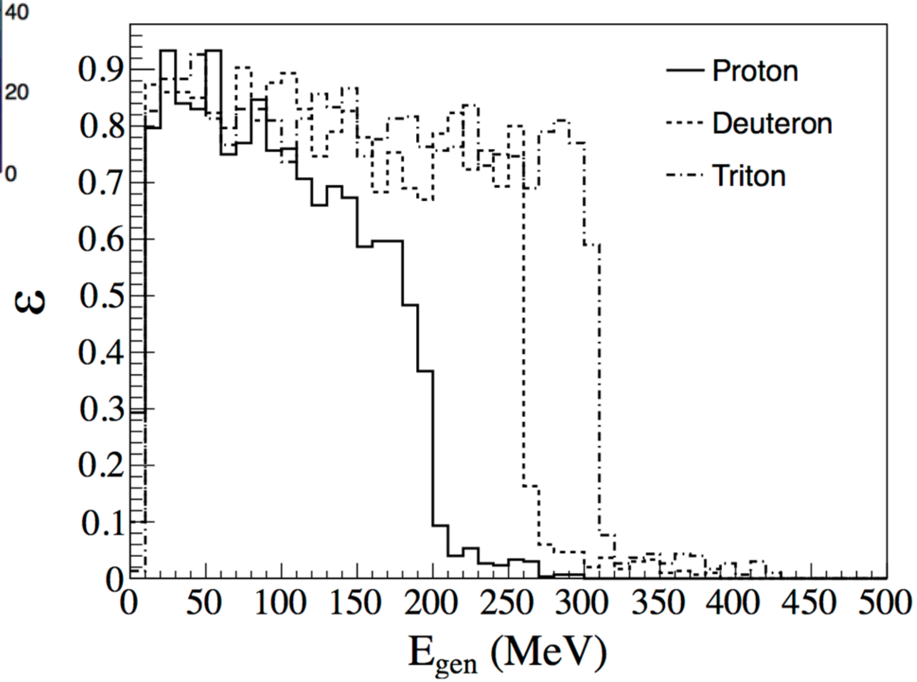
Si-CsI

Suhyun & Songkyo Lee
(Korea Univ.)



$\Delta E = E_1 + E_2 + E_3$

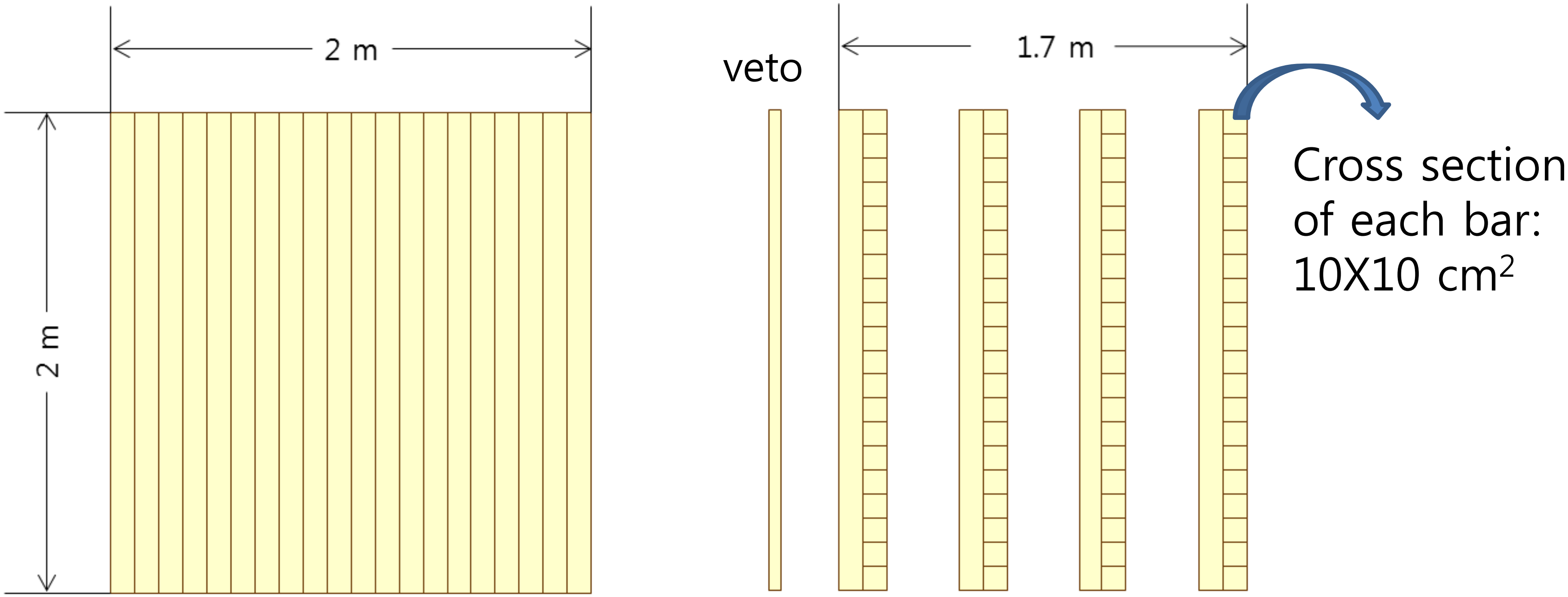
$E_{tot} = \Delta E + E_c$



- $\Delta E = E_1 + E_2 + E_3$ is preferred at high energies
- $\Delta E = E_1$ is preferred at low energies

Neutron Detector Array

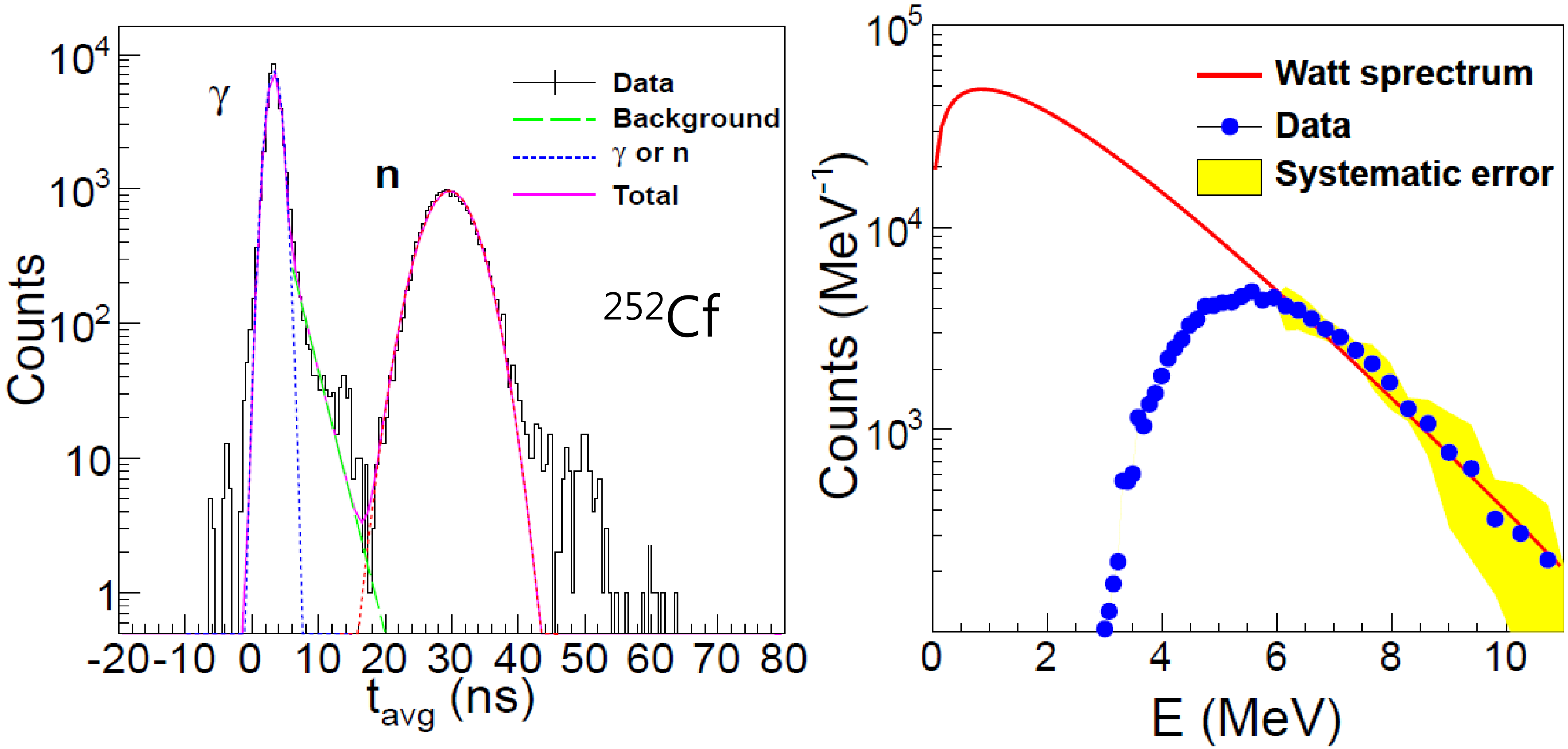
Kisoo Lee & Eunah Joo (Korea Univ.)



- Construction of the prototype and test with radiation sources
  - Dimension: 0.1X0.1X1.0 m^3
  - Sources: ^{60}Co and ^{252}Cf
  - Time resolution: 488 ps, Position resolution: ~8 cm for CFD

Neutron Detector Array

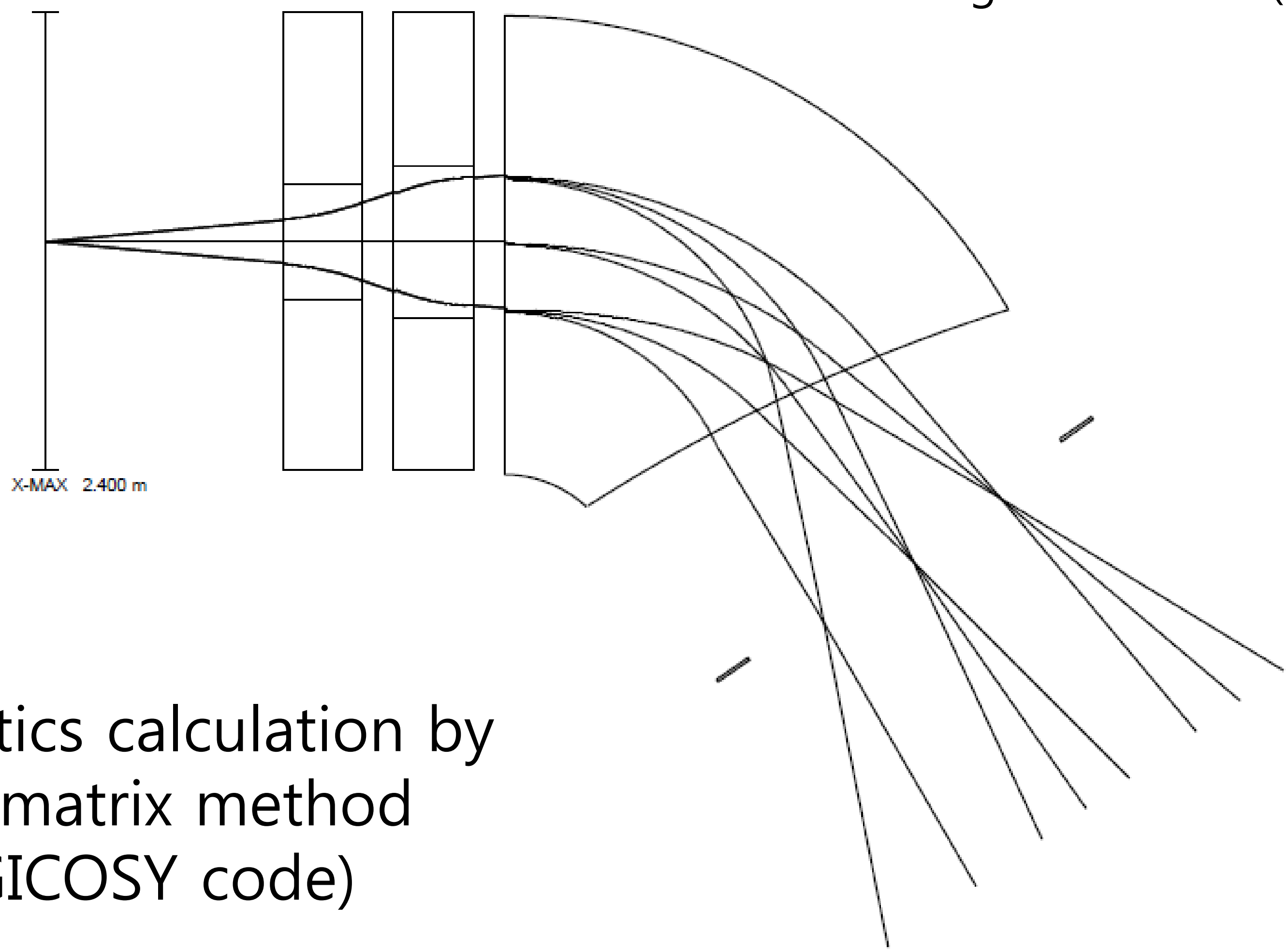
Kisoo Lee & Benard Mulilo (Korea Univ.)



- Watt spectrum: ${dN}/{dE} \propto e^{-aE} \sinh\sqrt{bE}$
  with a=0.88 MeV^{-1} and b=2.0 MeV^{-1}
  Ref) B. Watt, Physical Review 87, 1037 (1952)

Dipole Spectrometer

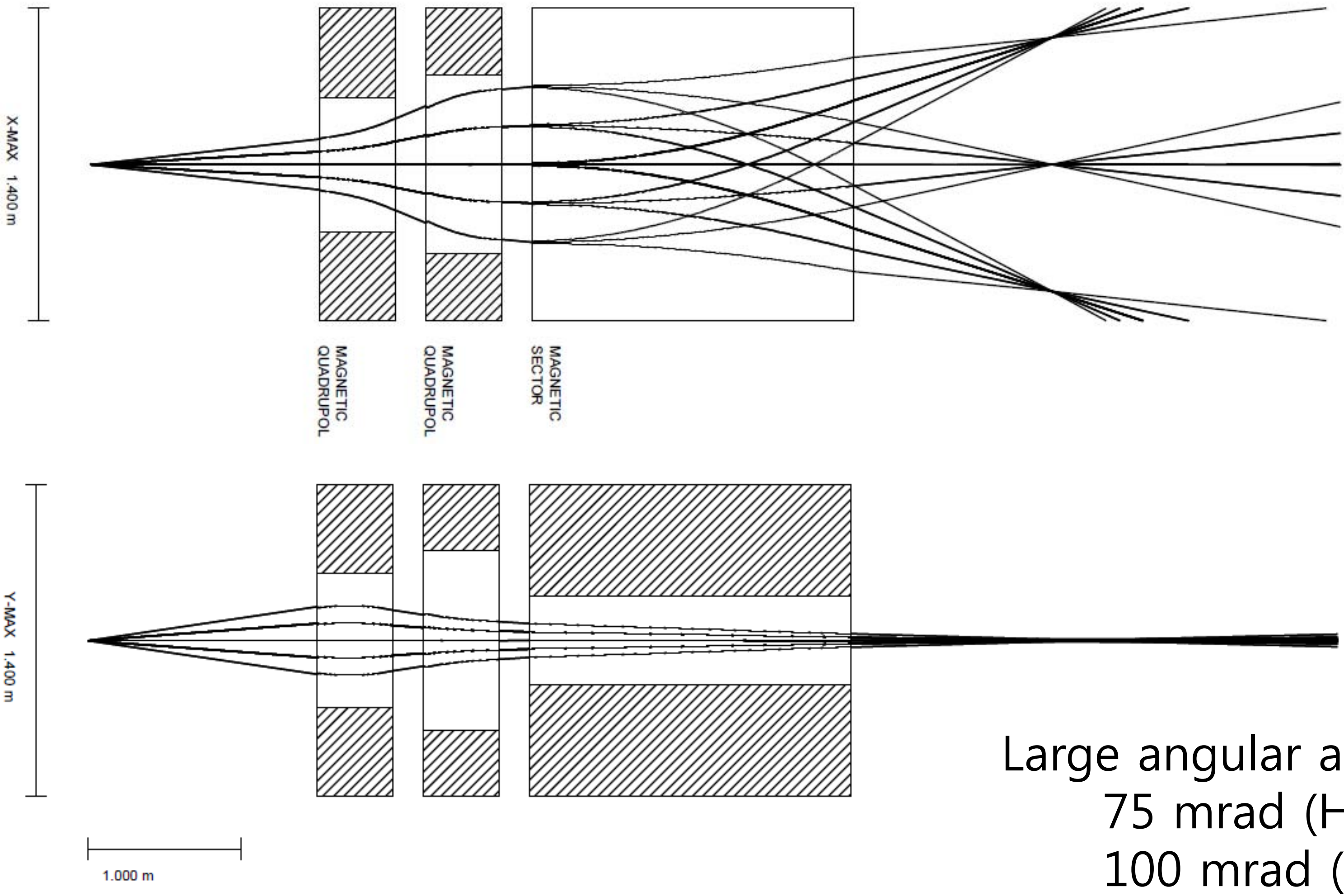
Songkyo Lee (Korea Univ.)
Chong Cheoul Yun (RISP/IBS)



Ion optics calculation by the matrix method (GICOSY code)

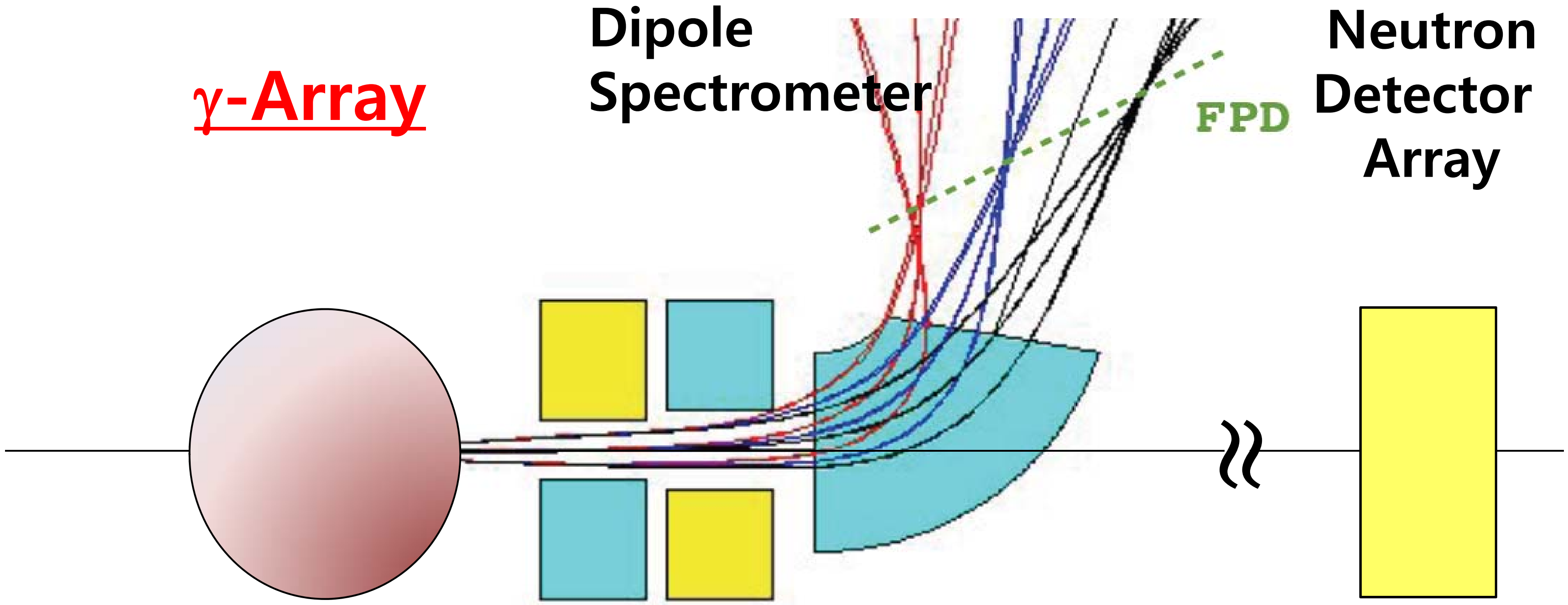
Dipole Spectrometer

Songkyo Lee (Korea Univ.) & Chong Cheoul Yun (RISP/IBS)



Large angular acceptance
75 mrad (H)
100 mrad (V)

Coulomb Breakup & Transfer Reactions



- Photoabsorption measurements
  - PDR/GDR measurements via $^{124,130,132}Sn+^{208}Pb$, $^{68,70,72}Ni+^{208}Pb$, $^{50,54,60}Ca+^{208}Pb$, etc.
  - 1n and 2n removal cross sections for unstable nuclei
  - Measuring E* from beam fragment, n's, and γ's
- For example, 2n transfer reaction is important for the structure

Summary

1. RAON
   – First large-scale facility for nuclear physics in Korea
2. KOBRA
   – Broad acceptance recoil spectrometer at low-energy experimental area
   – To cover nuclear structure, nuclear astrophysics, super-heavy elements, and nuclear symmetry energy
3. LAMPS
   – Large-acceptance multipurpose spectrometer at high-energy experimental area
     (Low-energy version of LAMPS at KOBRA)
   – Primary purpose is to measure the nuclear symmetry energy at sub- and supra-saturation densities
   – Useful also to study various photoabsorption processes and transfer reactions