
RIKEN
NiSHiNA
CENTER

The Radioactive Ion Beam Factory: recent results, present status and perspectives

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紗糸　俳子

RIKEN NiSHiNA CENTER

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2010年12月10日

Outline

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- Introduction
  - RIKEN
  - RIKEN Nishina Center
  - RIBF (accelerators, BigRIPS, major instruments)
- DayOne, DayTwo, ... Experimental Campaigns
  - ^{238}U and ^{48}Ca primary beams
  - highlights
  - in-beam γ ray spectroscopy near “Island of Inversion”
- Next generation in-beam γ ray spectrometer
- Summary

RIKEN Nishina Center

RIKEN Institutes

- 7 campus locations
- over 17 institutes
- over 350 laboratory heads

▲RIKEN Wako Institute

▲Terahertz-wave Research Program

▲RIKEN Harima Institute

▲RIKEN Tsukuba Institute

▲RIKEN Yokohama Institute

▲RIKEN Kobe Institute

▲Bio-Mimetic Control Research Center

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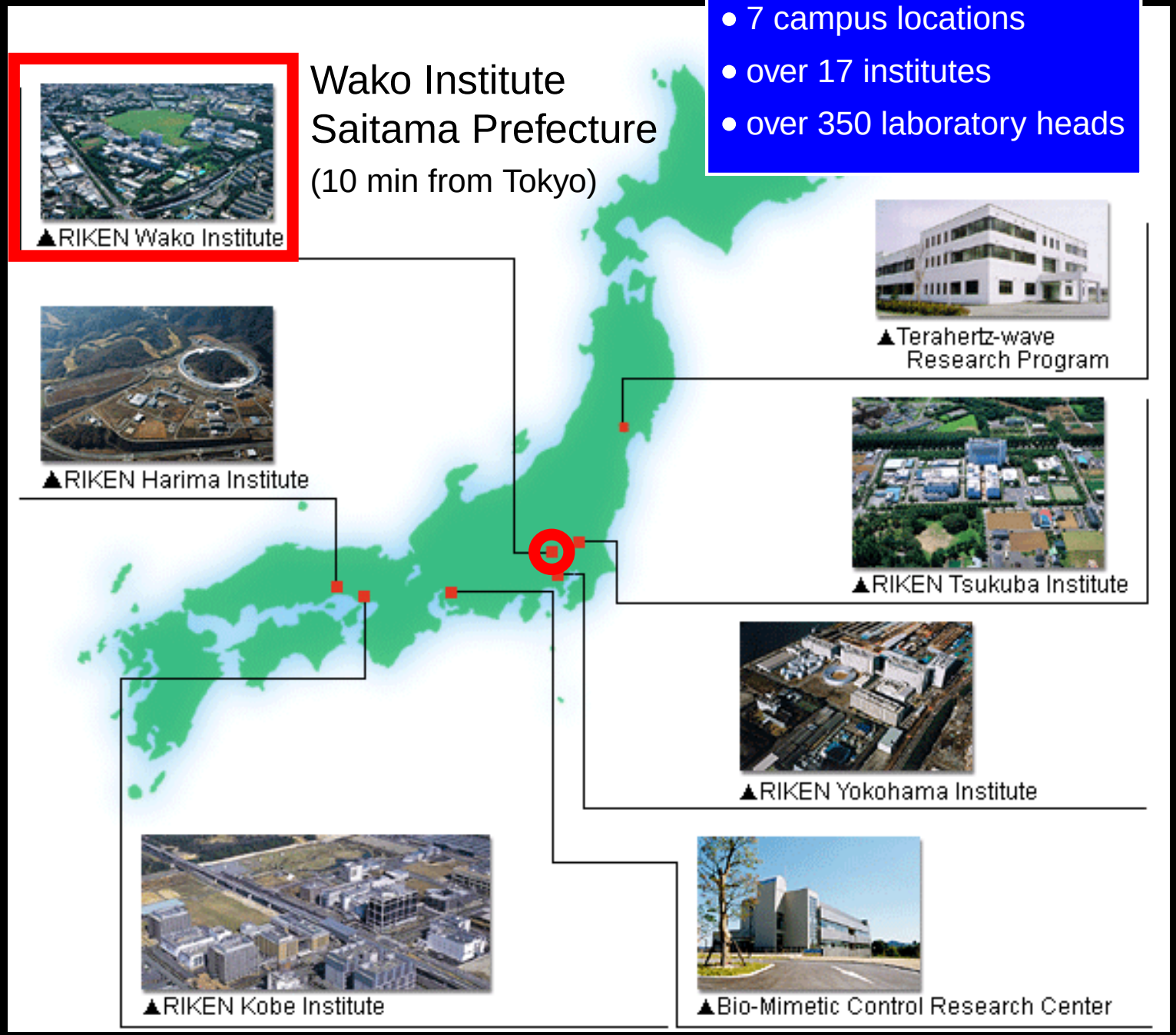


RIKEN Nishina Center

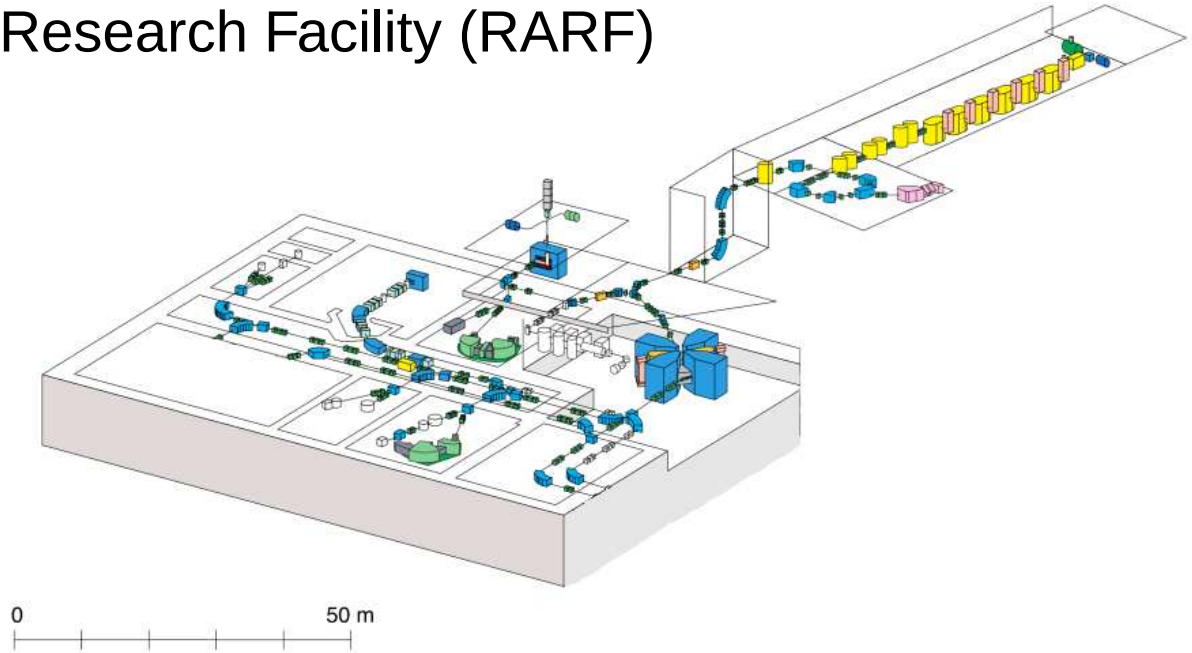
RIKEN Nishina Center

- located on the **RIKEN Wako campus**
- **founded** in **April 2006**, before: **RARF** + several separate institutes
- staff of 250 (140 permanent, ≈ 80 researchers),
  ≈ 700 guest researchers annually
- overall budget ~ 40 M\$, ~ 29 M\$ for RIBF (2008)
- external company workers partly responsible for accelerator operation

RIKEN Facility Overview

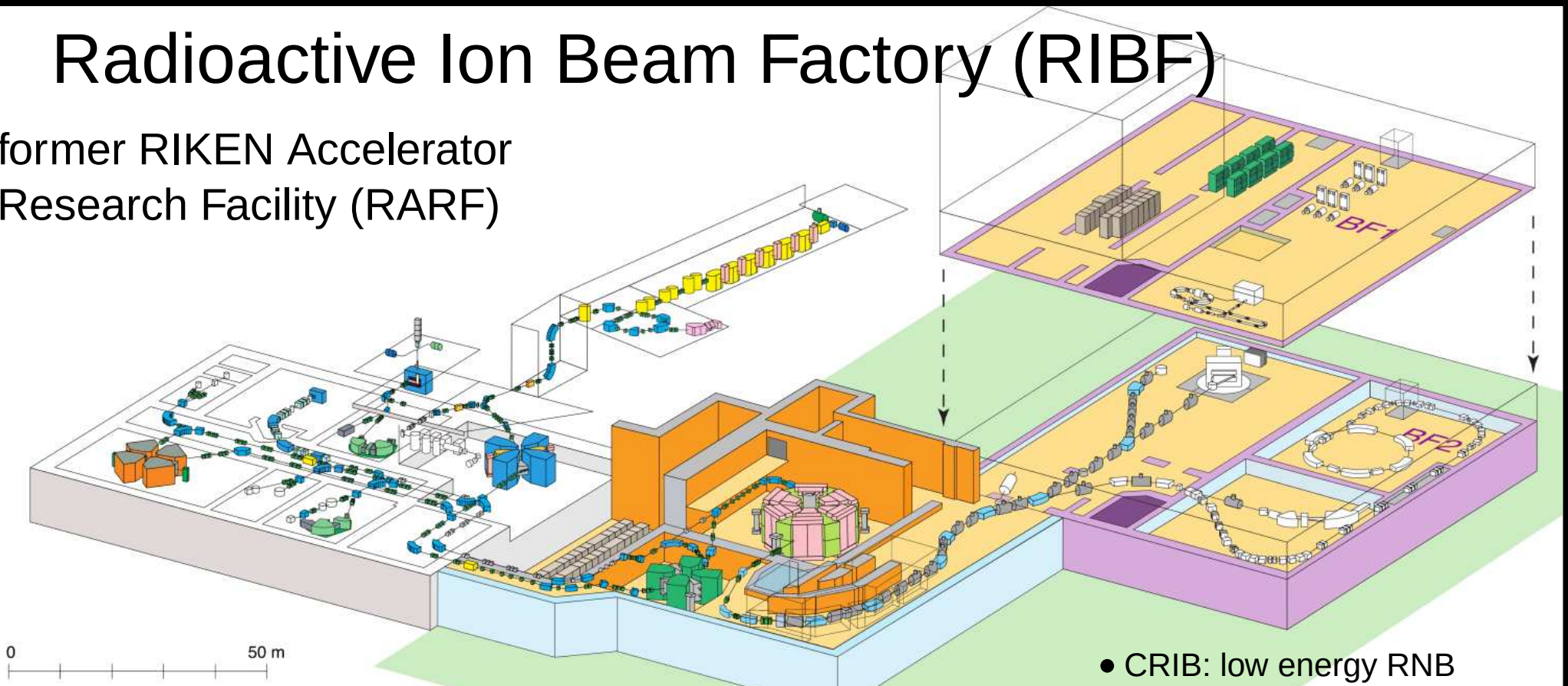
RARF and RIBF

former RIKEN Accelerator Research Facility (RARF)



Radioactive Ion Beam Factory (RIBF)

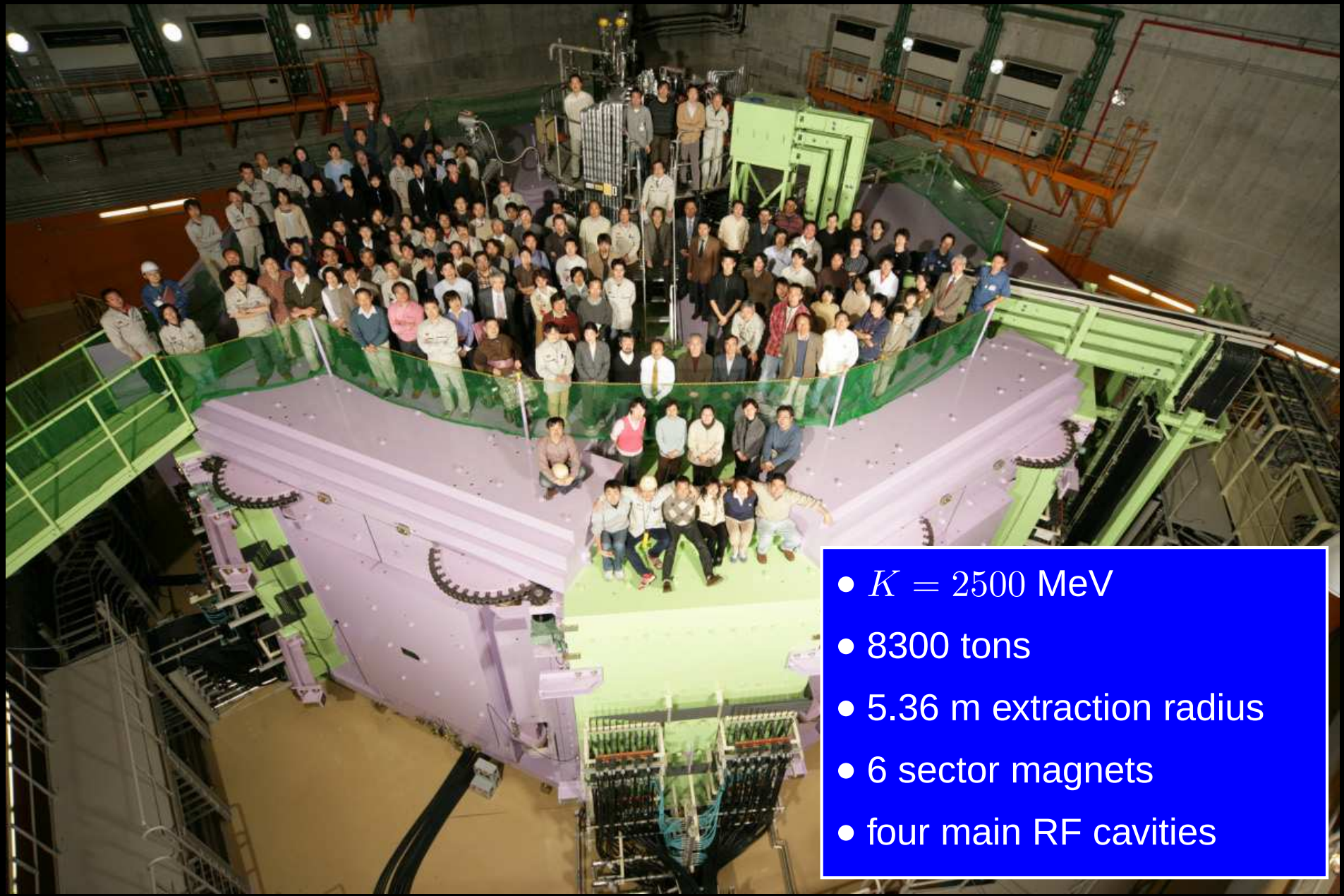
former RIKEN Accelerator Research Facility (RARF)



- new building (completed in 2005)
- 3 new cyclotrons (operational since 2006)
- intense (80 kW max.) HI beams (up to U) of 345 MeV/u
- fast RI beams by proj. fragmentation and U-fission

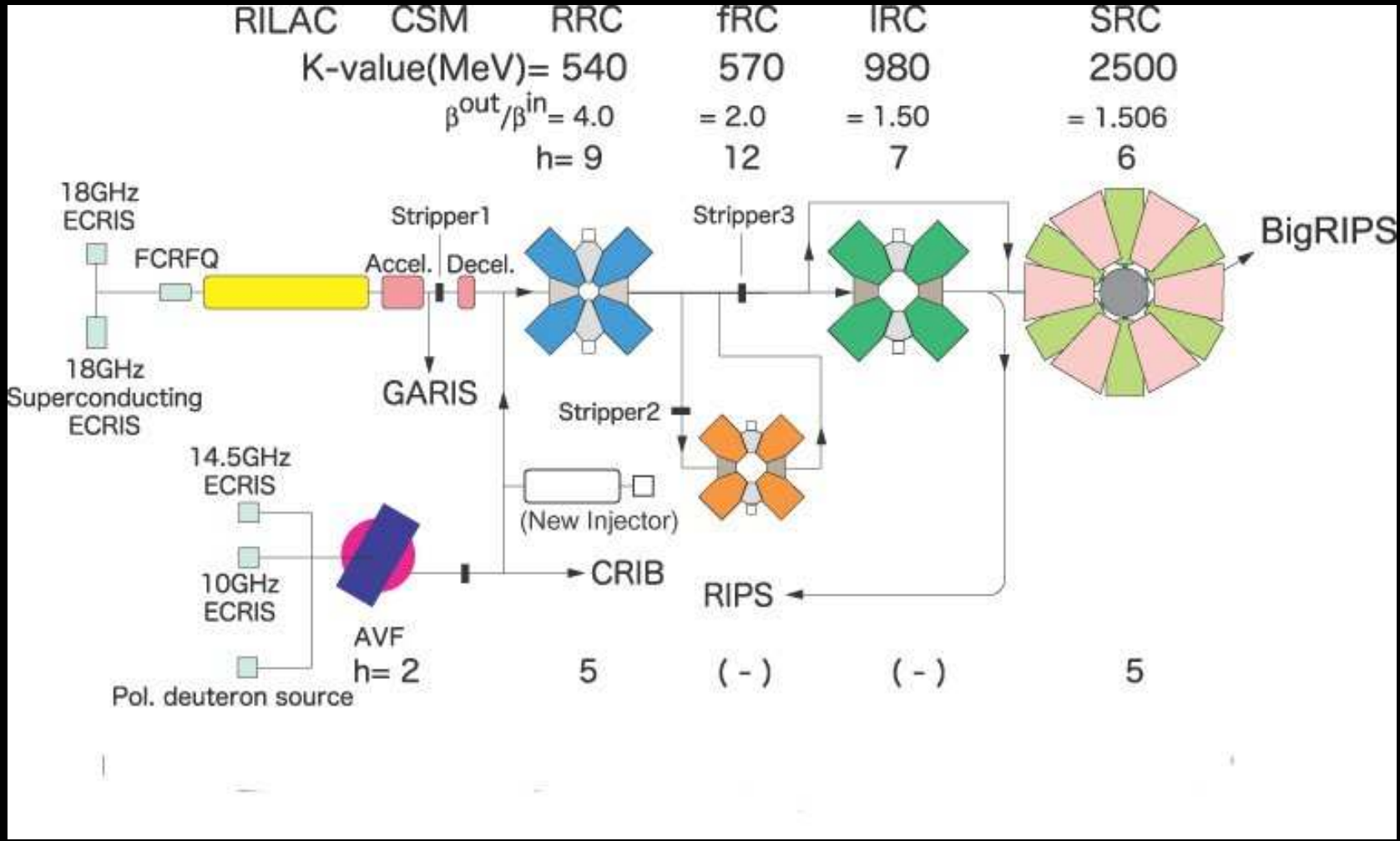
- CRIB: low energy RNB
- RIPS: fast RNB since 1990
- BigRIPS: since 2006
- RILAC2: from 2011
- GARIS: SHE program
- polarized d beam

Superconducting Ring Cyclotron (SRC)



- $K = 2500$ MeV
- 8300 tons
- 5.36 m extraction radius
- 6 sector magnets
- four main RF cavities

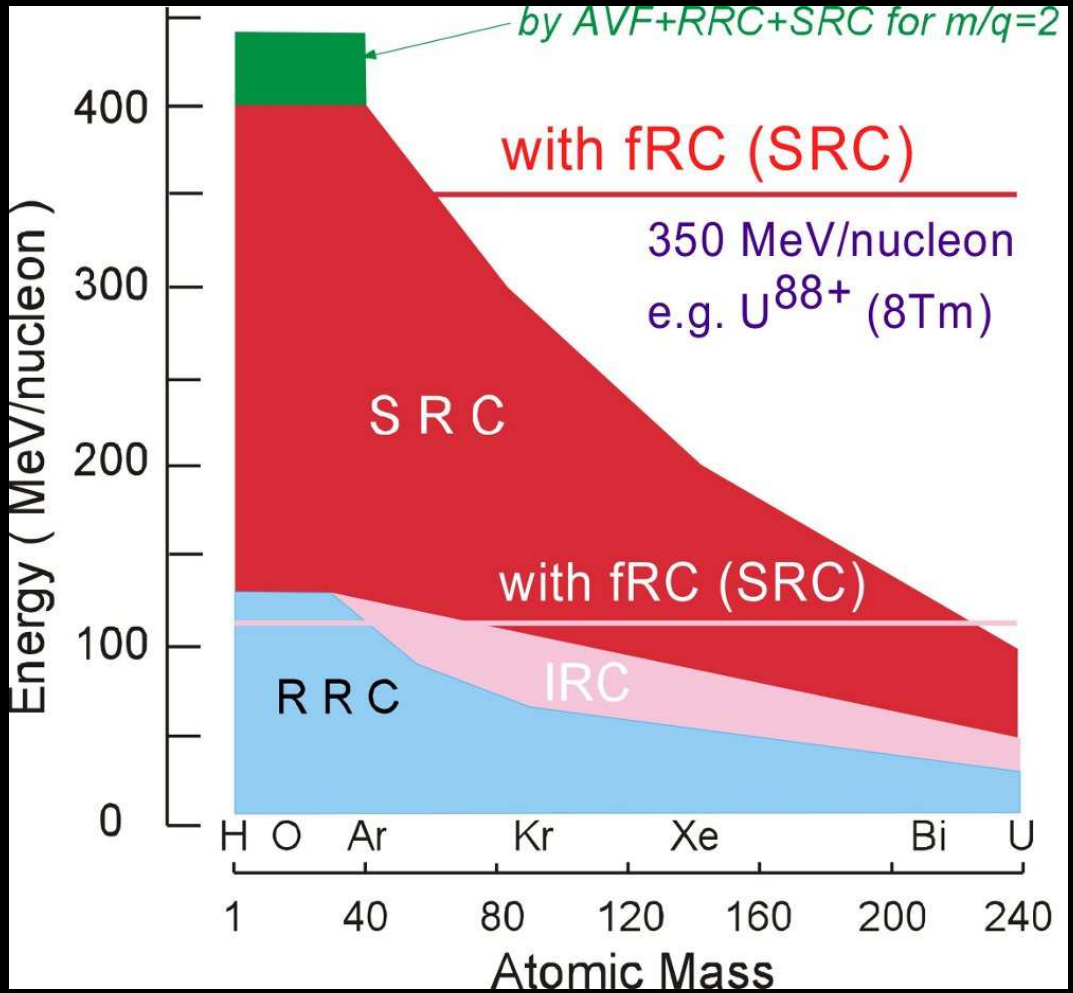
RIBF Acceleration Modes



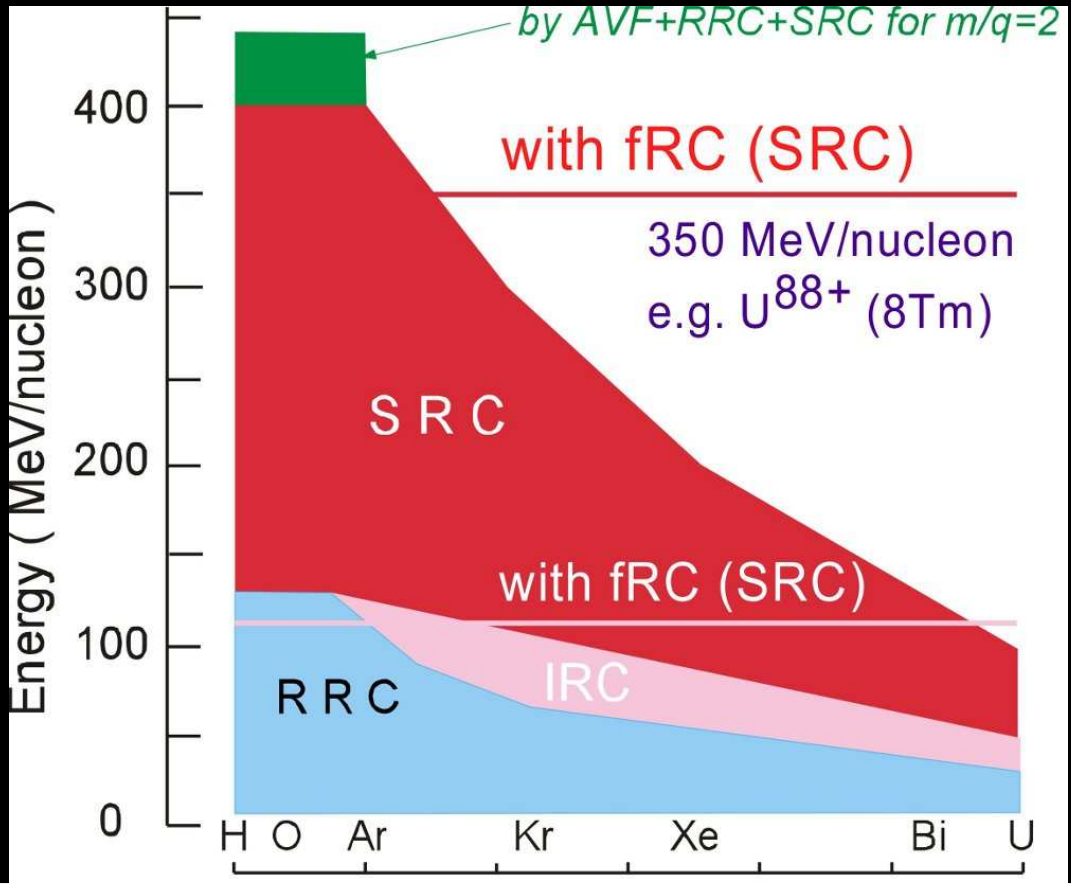
New:

- RILAC2 (commissioning starting Dec. 2010)
- GARIS2

RIBF Accelerator Operation



RIBF Accelerator Operation

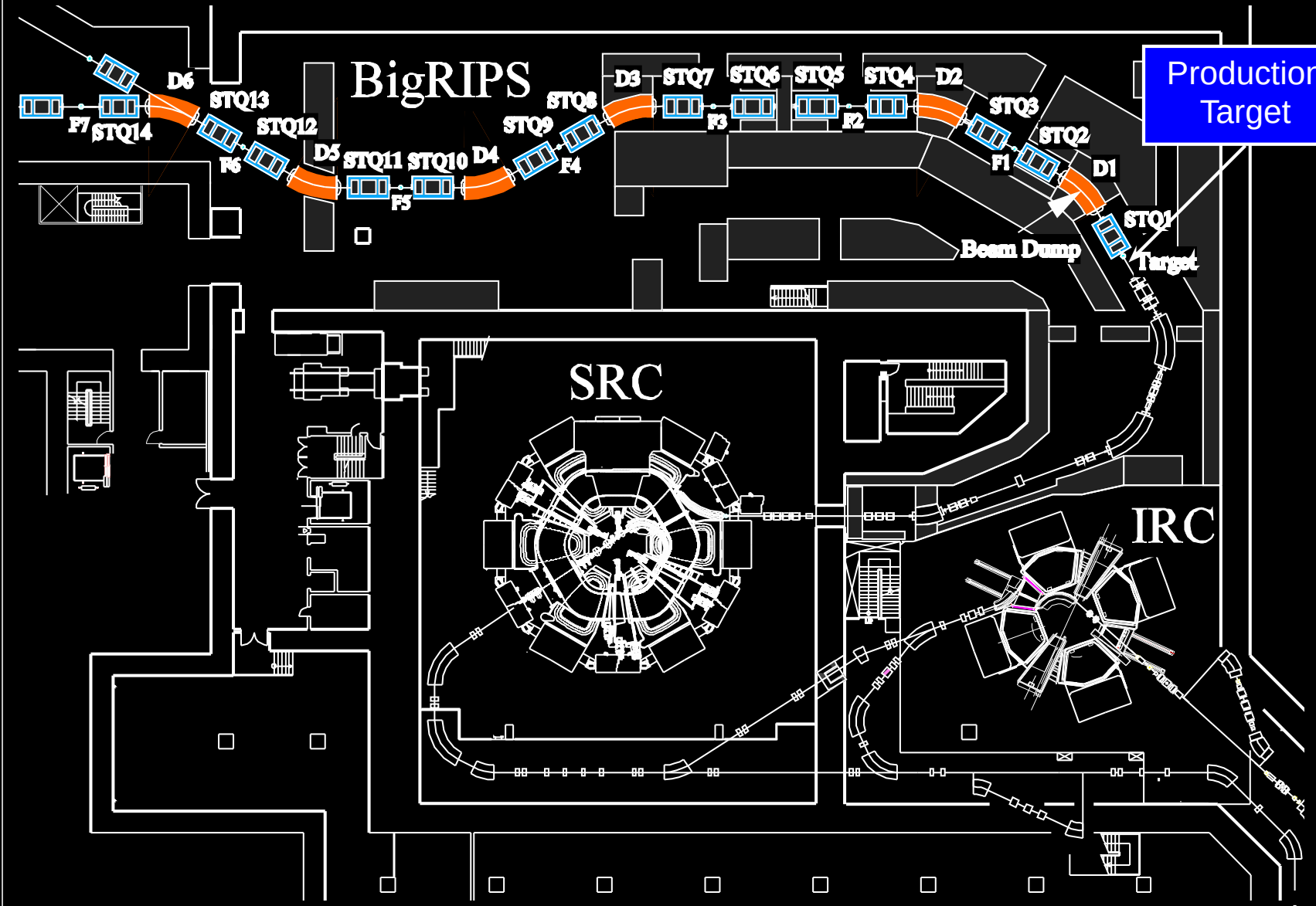


Intensities of 345 MeV/u beams from the SRC:

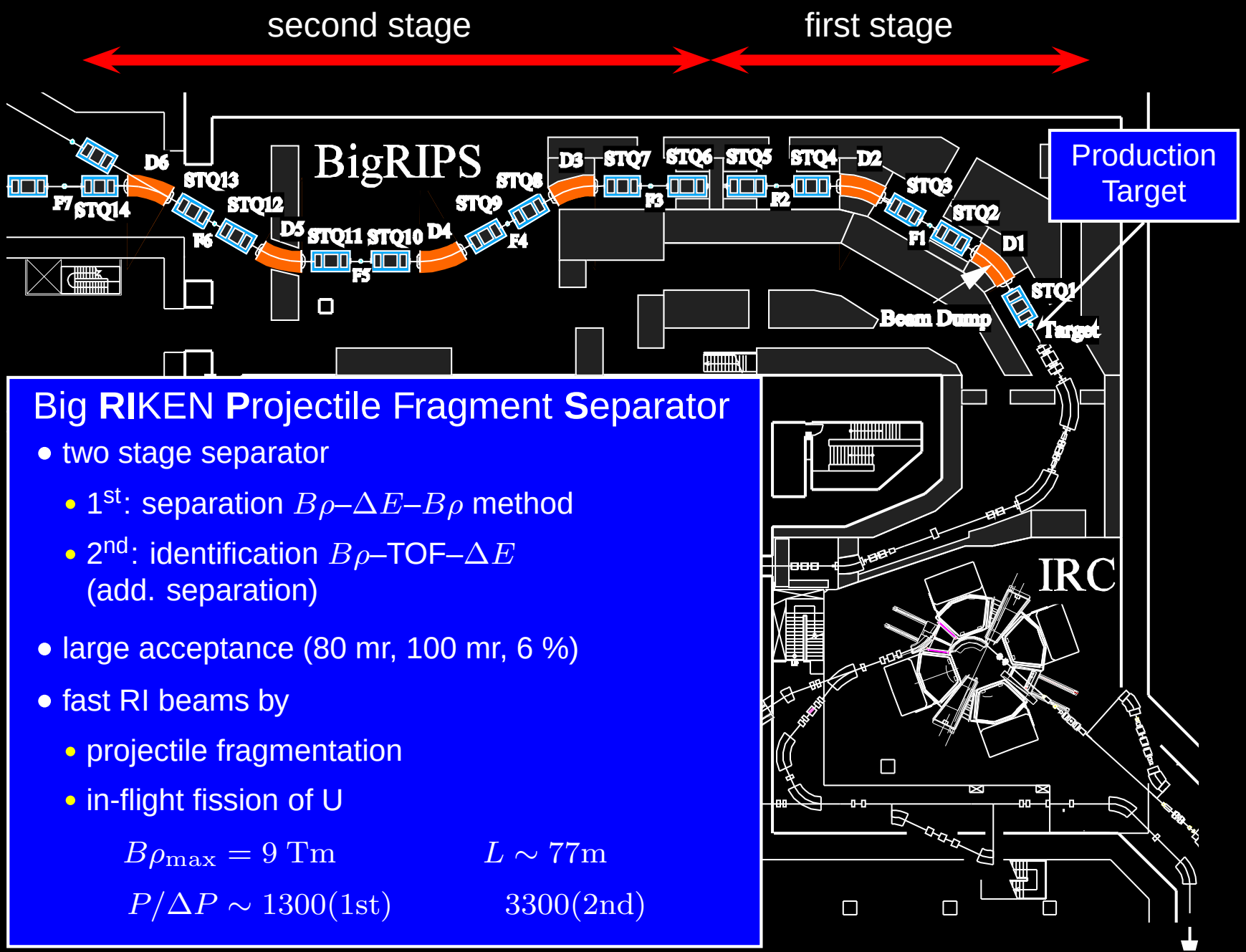
	Ca	Kr	Xe	^{238}U	
Intensity (pnA)	500			1000	final goal (4-5 years)
	200	50	10	5	expected 2009/10
	100	—	10	0.3	measured in 2008
	—	30	—	0.02	measured in 2007

BigRIPS

BigRIPS Overview



BigRIPS Overview



Big **RI**KEN **P**rojectile Fragment **S**eparator

- two stage separator
  - 1st: separation $B\rho$–ΔE–$B\rho$ method
  - 2nd: identification $B\rho$–TOF–ΔE (add. separation)
- large acceptance (80 mr, 100 mr, 6 %)
- fast RI beams by
  - projectile fragmentation
  - in-flight fission of U

$B\rho_{\max} = 9$ Tm $L \sim 77$m

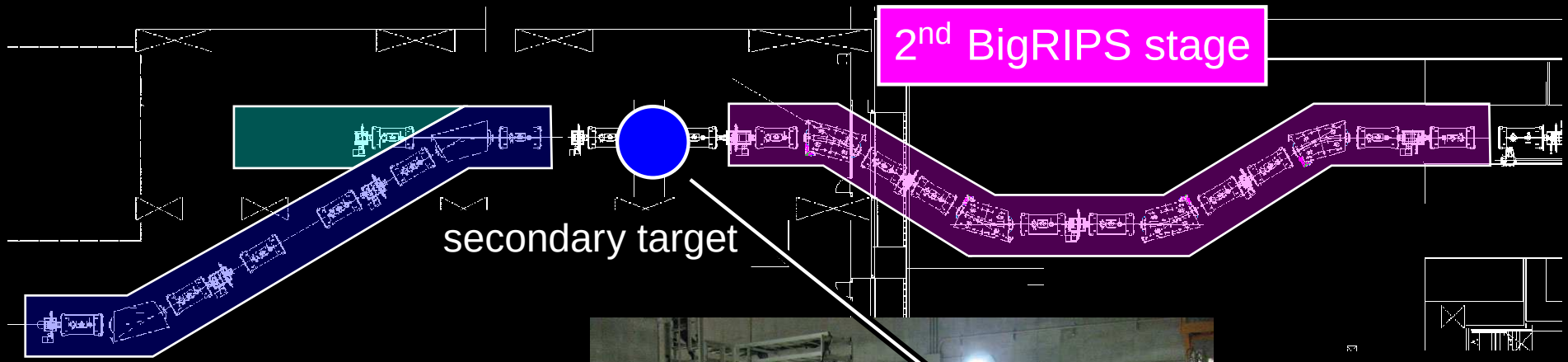
$P/\Delta P \sim 1300(1\text{st})$ $3300(2\text{nd})$

Instruments

Instruments Overview

Instrument	Description	status
ZeroDegree	general purpose spectrometer	complete
SHARAQ	high resol. spectrometer	complete
SAMURAI	high accept. spectrometer	funded
SCRIT	e^- RI scattering	funded
SLOWRI	stopped RI program	(funded)
RI Ring	mass measurement	(funded)
RI Spin Lab.	polarized RI beam	not funded
PALIS	“parasitic” slow RI beam	proposed
SHOGUN	next gen. γ ray spectrometer	proposed

ZeroDegree Spectrometer



0° Spectrometer ZeroDegree

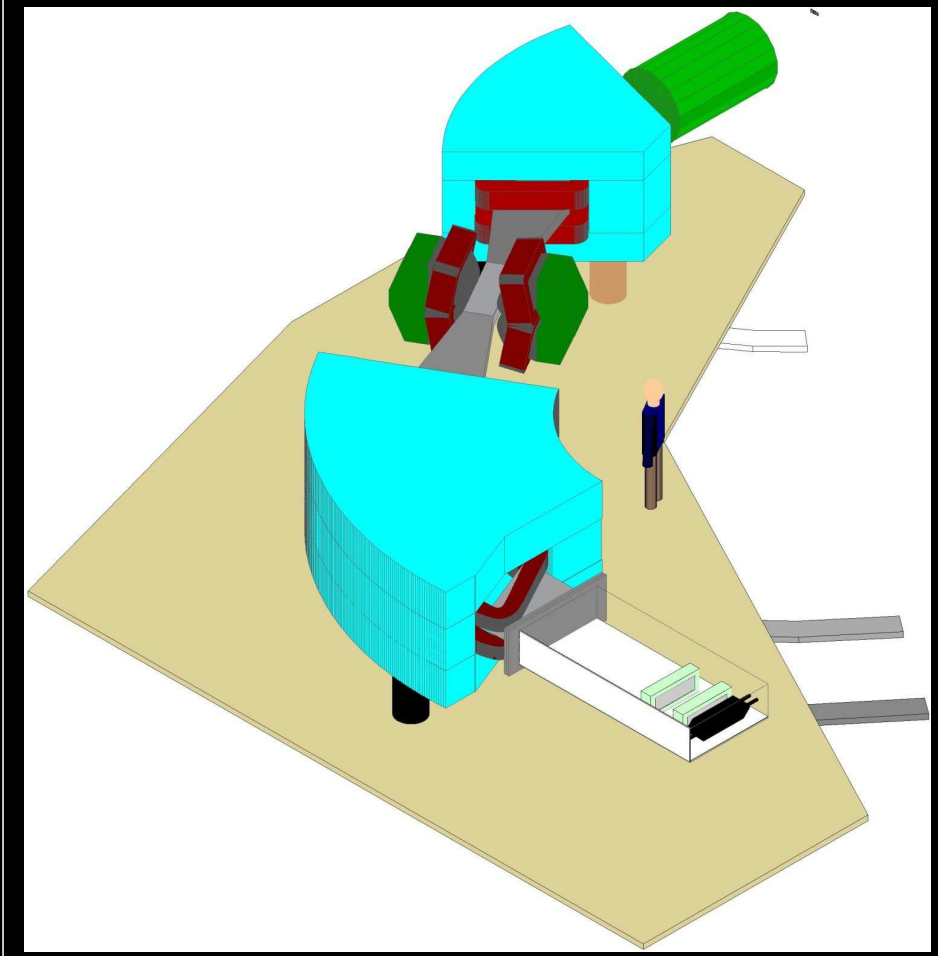
- **particle ID** after secondary target
- fragment momentum distribution
- various modes of operation

mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	1240	$\pm 3\%$	± 45 mrad(V) ± 30 mrad(H)
High res.(achrom)	2120	$\pm 3\%$	± 20 mrad(V) ± 30 mrad(H)
Dispersive	4130	$\pm 2\%$	± 20 mrad(V) ± 30 mrad(H)

~ 3 m between Q-poles

- DALI2 array (180 NaI(Tl))
- GRAPE HPGe array
- $E_{\mathrm{beam}} \sim 100 - 250$ MeV/u

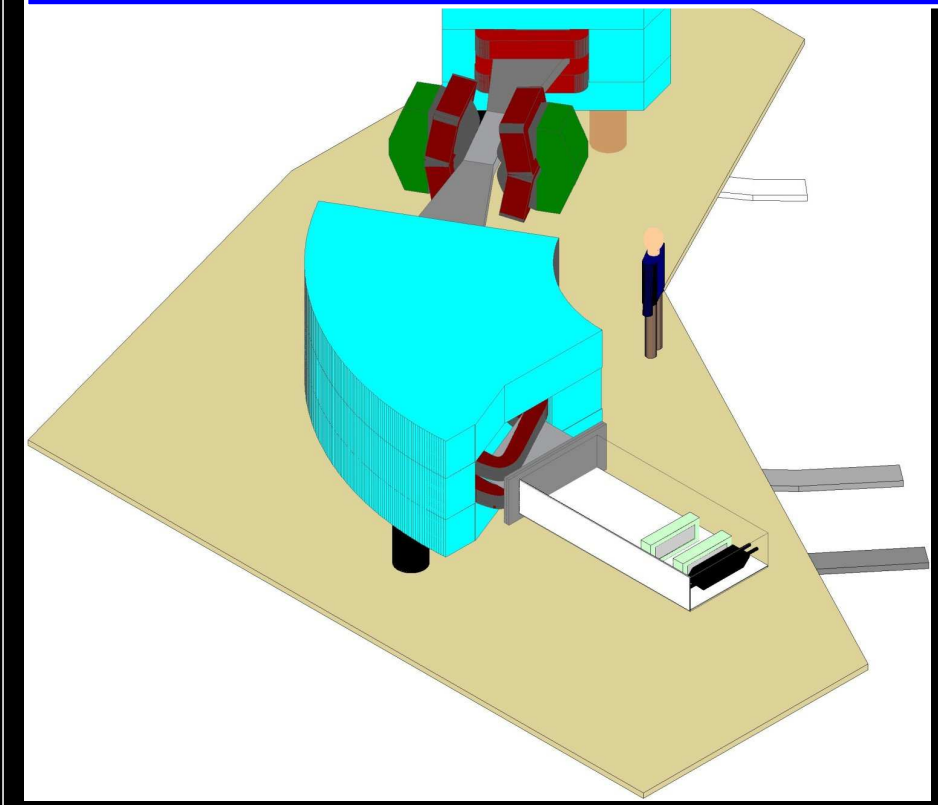
SHARAQ

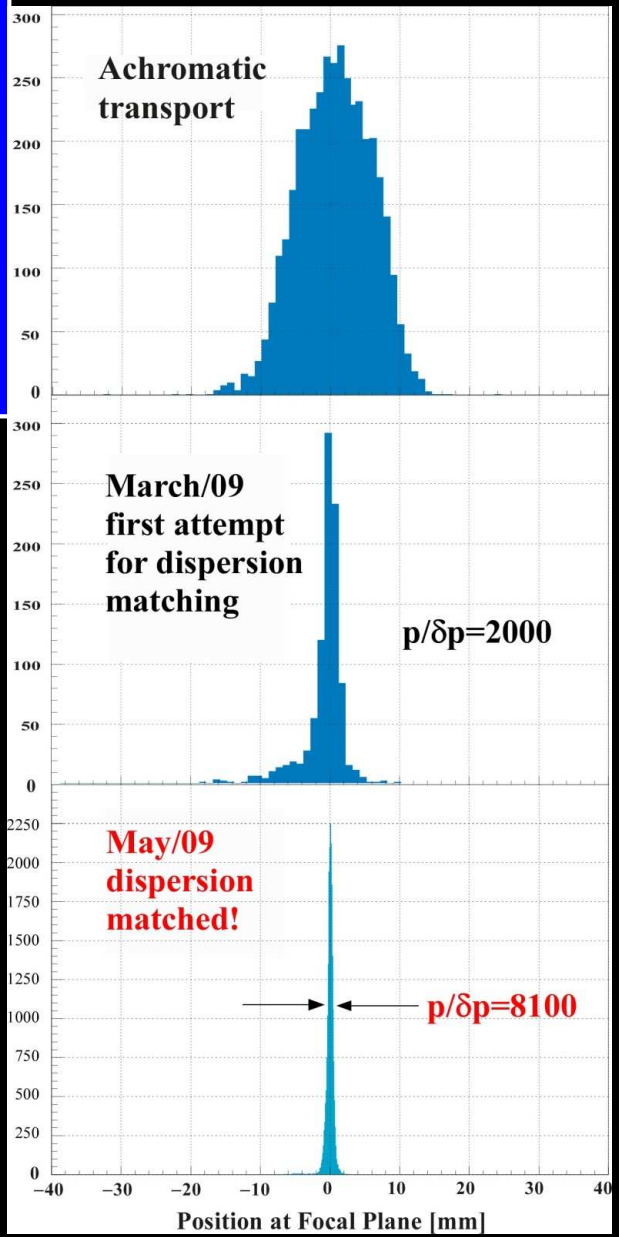


SHARAQ

SHARAQ CNS, Univ. of Tokyo

- high resolution spectrometer
- $p/\Delta p \sim 15,000$, $\Delta\theta < 1$ mrad, $B\rho = 6.8$ Tm
- **Missing mass spectroscopy** (standard kinematics)
- Double charge exchange: double GTR, IVSMR
- first beam: 23rd March 2009
- dispersion matching: May 2009
- first experiment using (t, ^{3}He) at 300 MeV/u: 2009



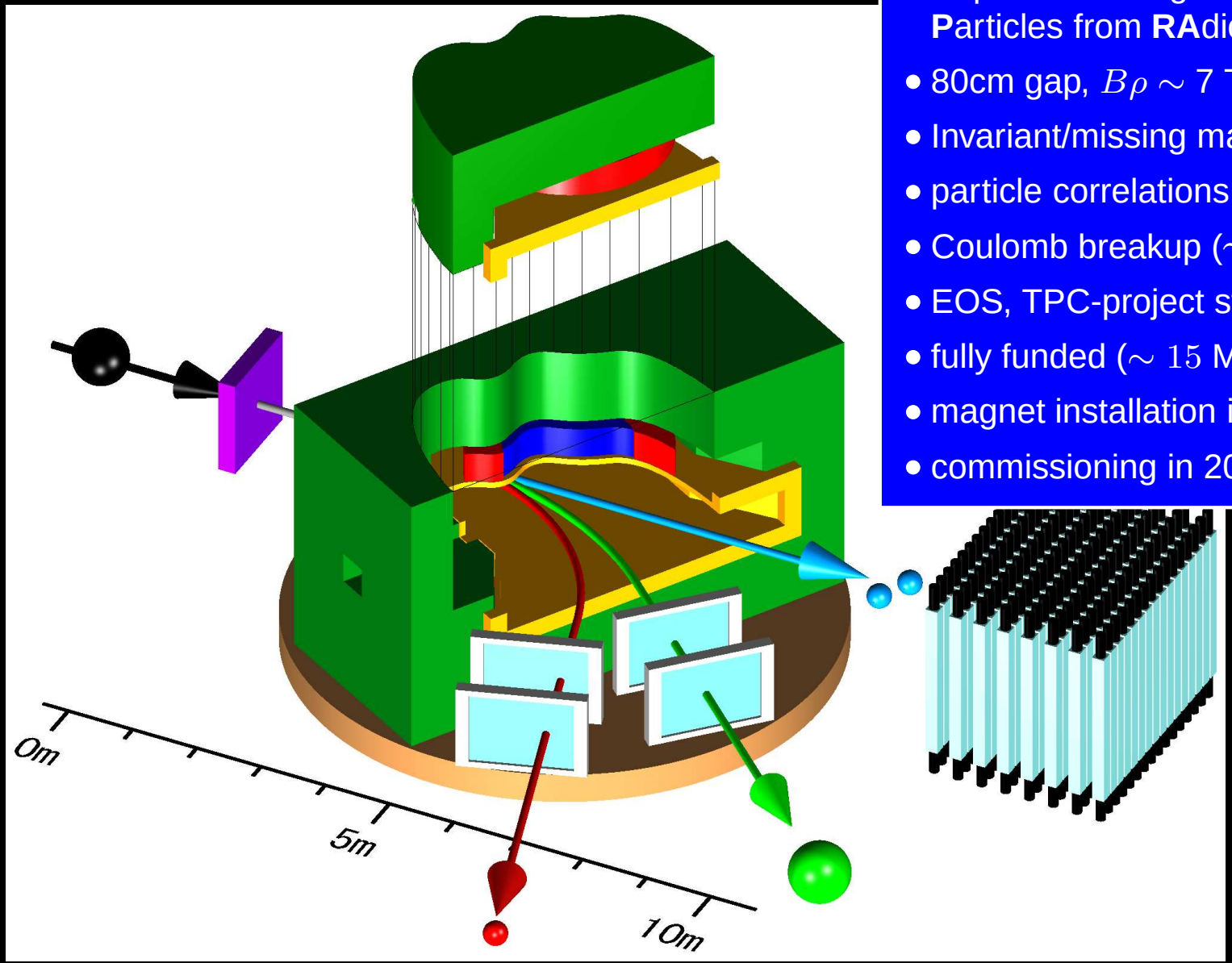


SHARAQ

SAMURAI

SAMURAI

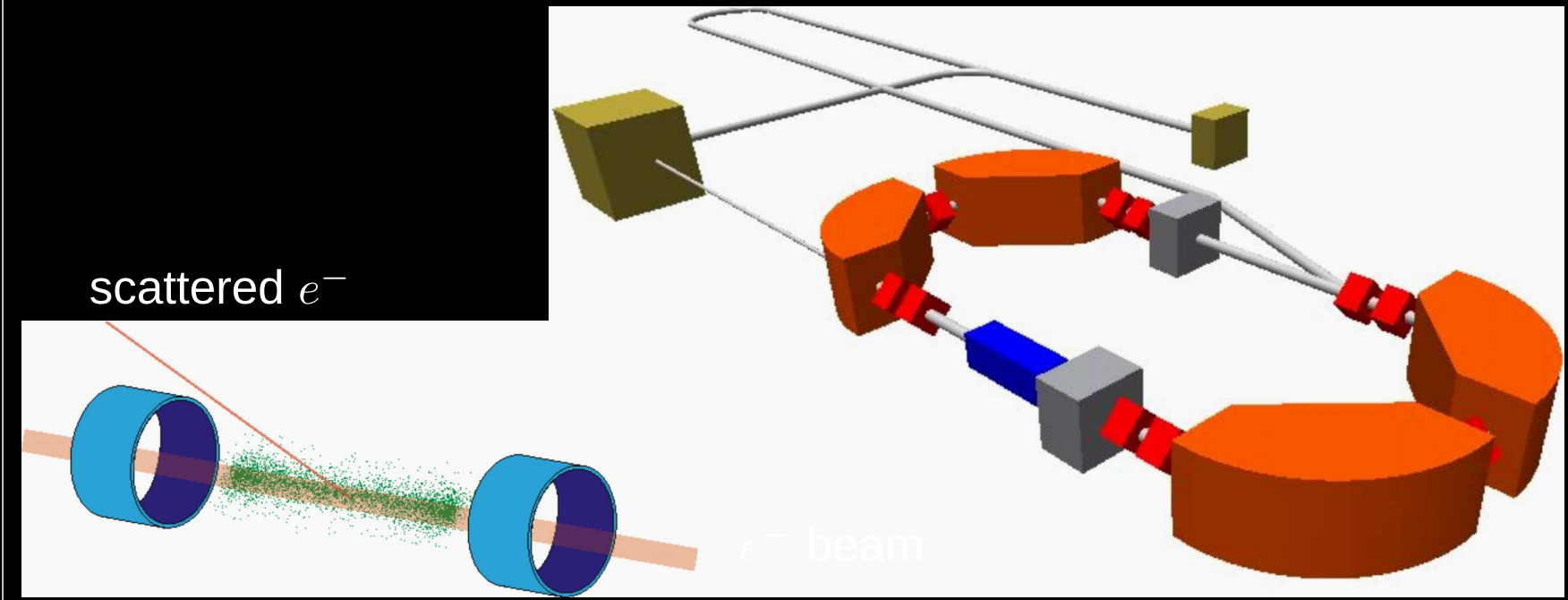
- **S**uperconducting **A**nalyzer for **MU**ltiple **P**articles from **RA**dioactive **I**sotope beams
- 80cm gap, $B\rho \sim 7$ Tm, $B_{max} = 3$ T
- Invariant/missing mass spectroscopy
- particle correlations (p,2p), (p,pn)
- Coulomb breakup (γ,n), (γ,p)
- EOS, TPC-project started
- fully funded (~ 15 M$)
- magnet installation in spring 2011
- commissioning in 2012



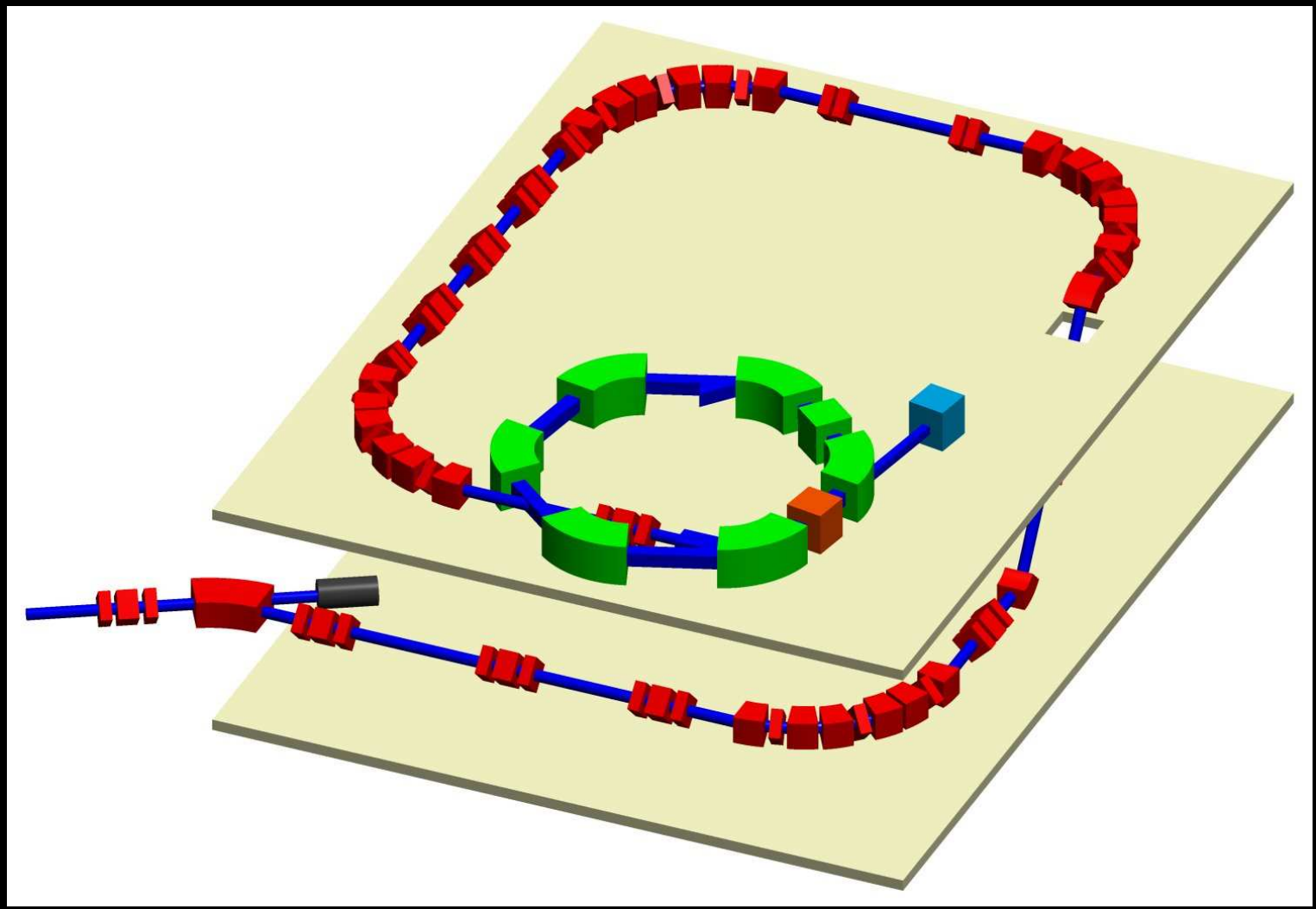
SCRIT

SCRIT — Wakasugi-san, Suda-san, 2012-

- **S**elf-**C**onfining **R**adioactive **I**on **T**arget system
- electron-ring for e-RI collisions
- proof of principle: Suda et al., Phys. Rev. Lett. 102, 102501 (2009)
- Microtron (150 MeV, ~ 1 kW) operational since 2009
  - injection into SCRIT storage ring
  - driver for RI production
- NB: completely independent from RIBF facility



Rare Radioactive Isotope Ring



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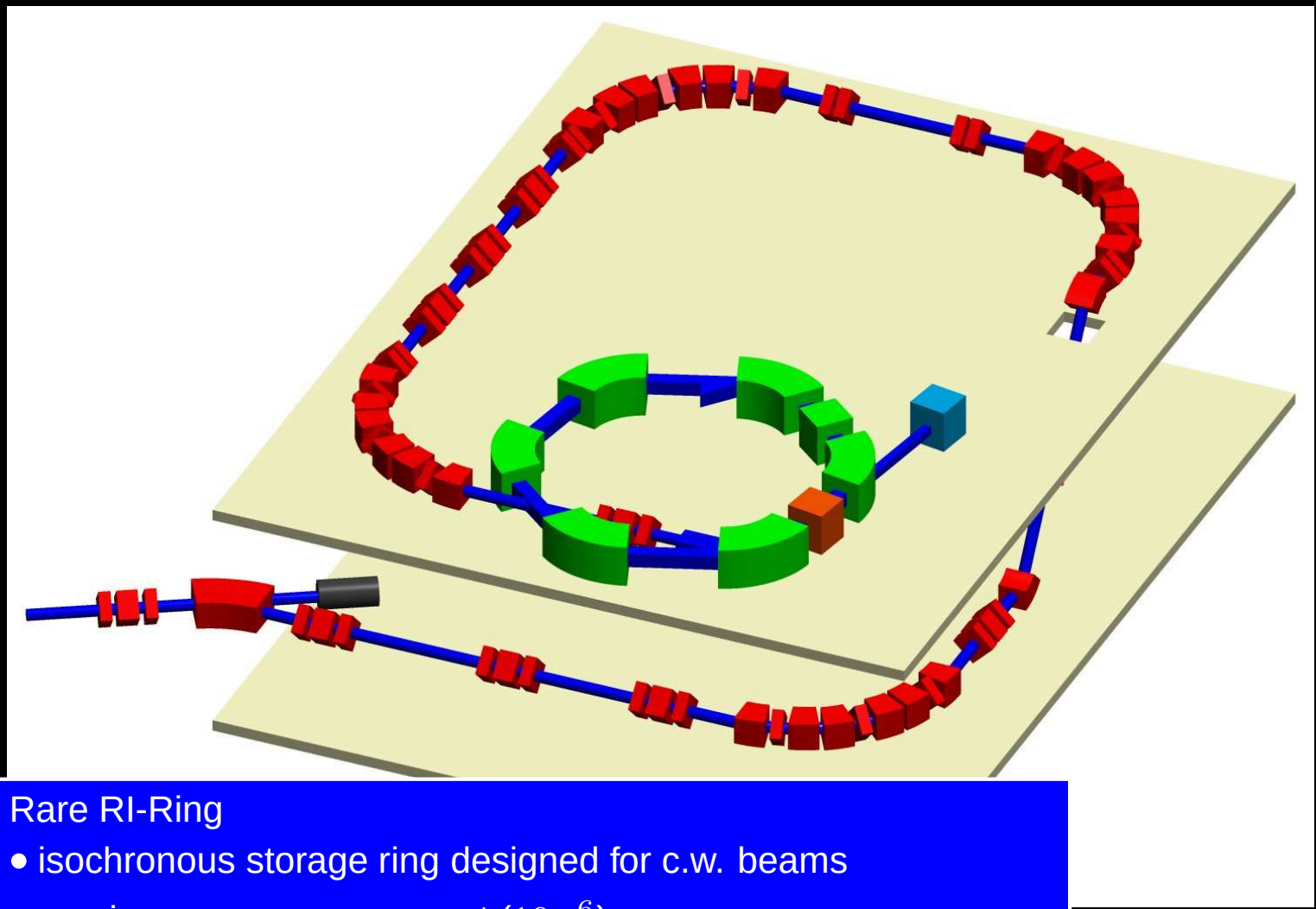
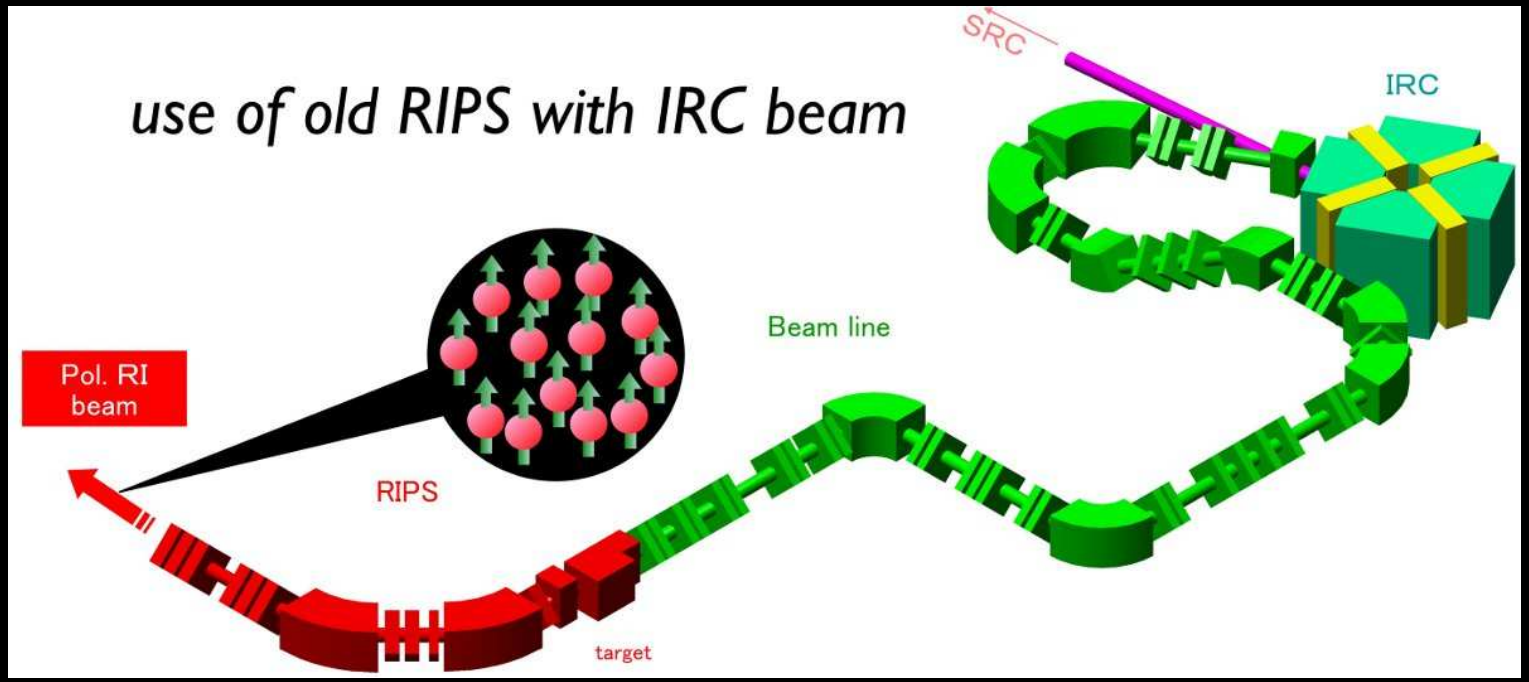


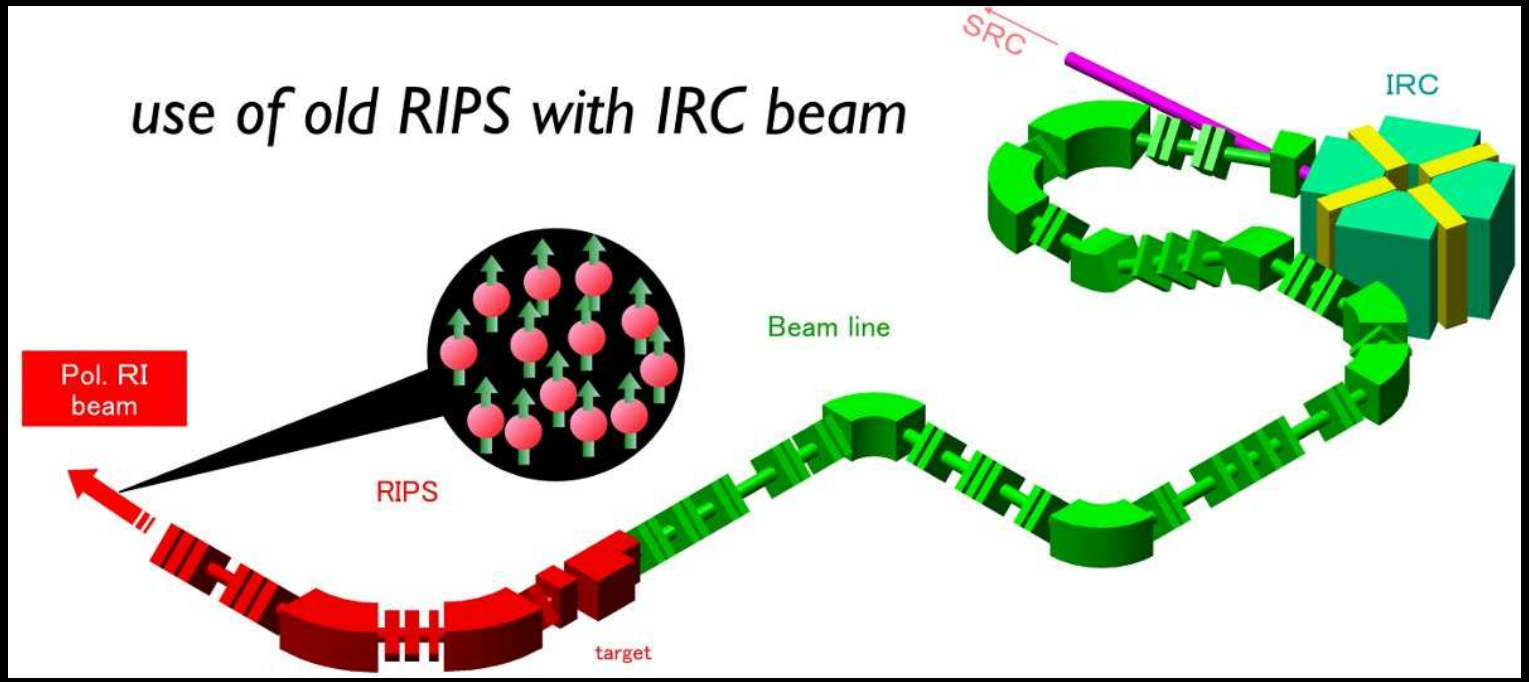
Rare RI-Ring

- isochronous storage ring designed for c.w. beams
- precise mass measurement (10^{-6})
- **individual injection/extraction**
- particle ID at injection/extraction
- Shell evolution and pairing correlation

RI-spin Laboratory



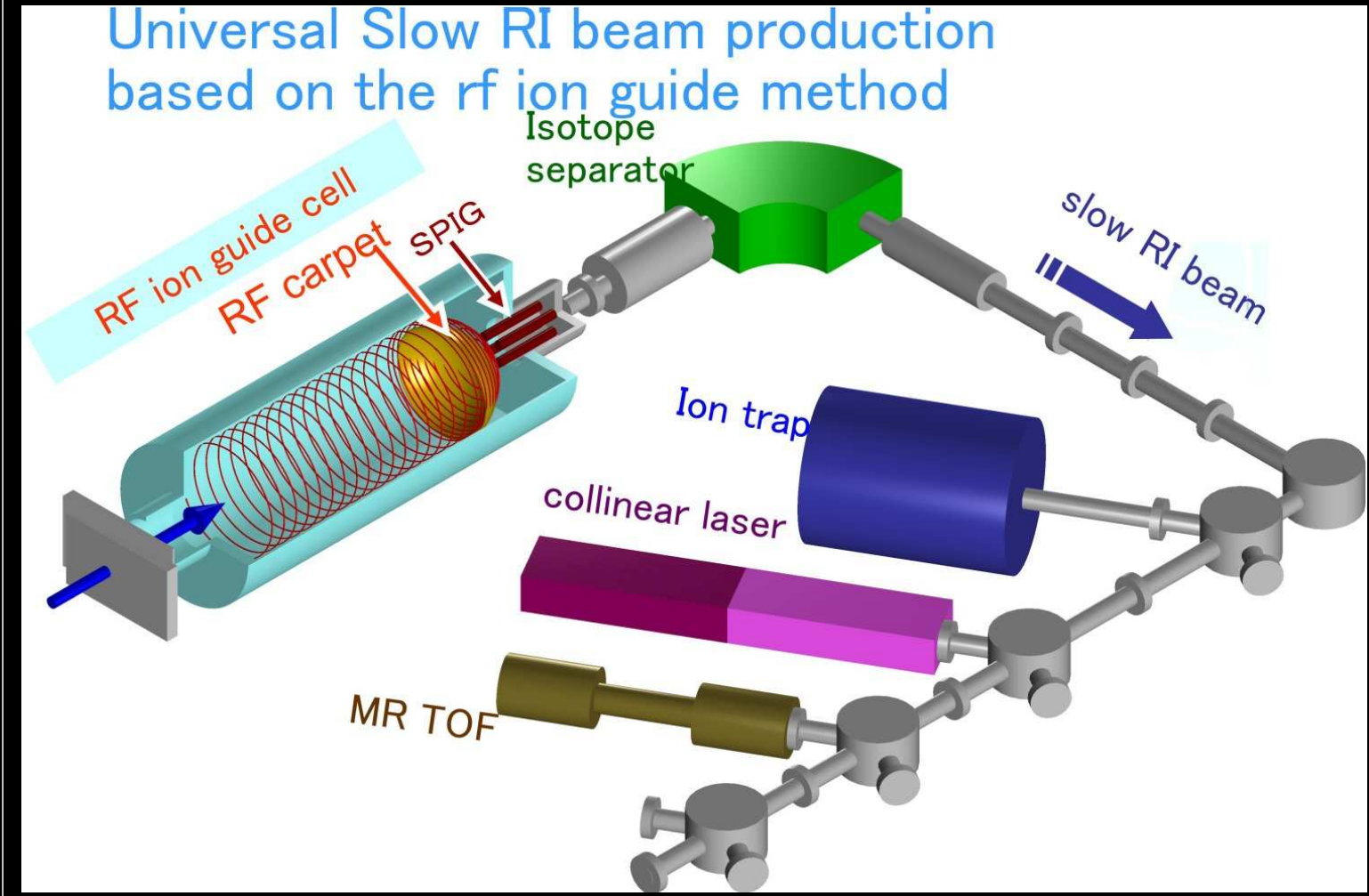
RI-spin Laboratory



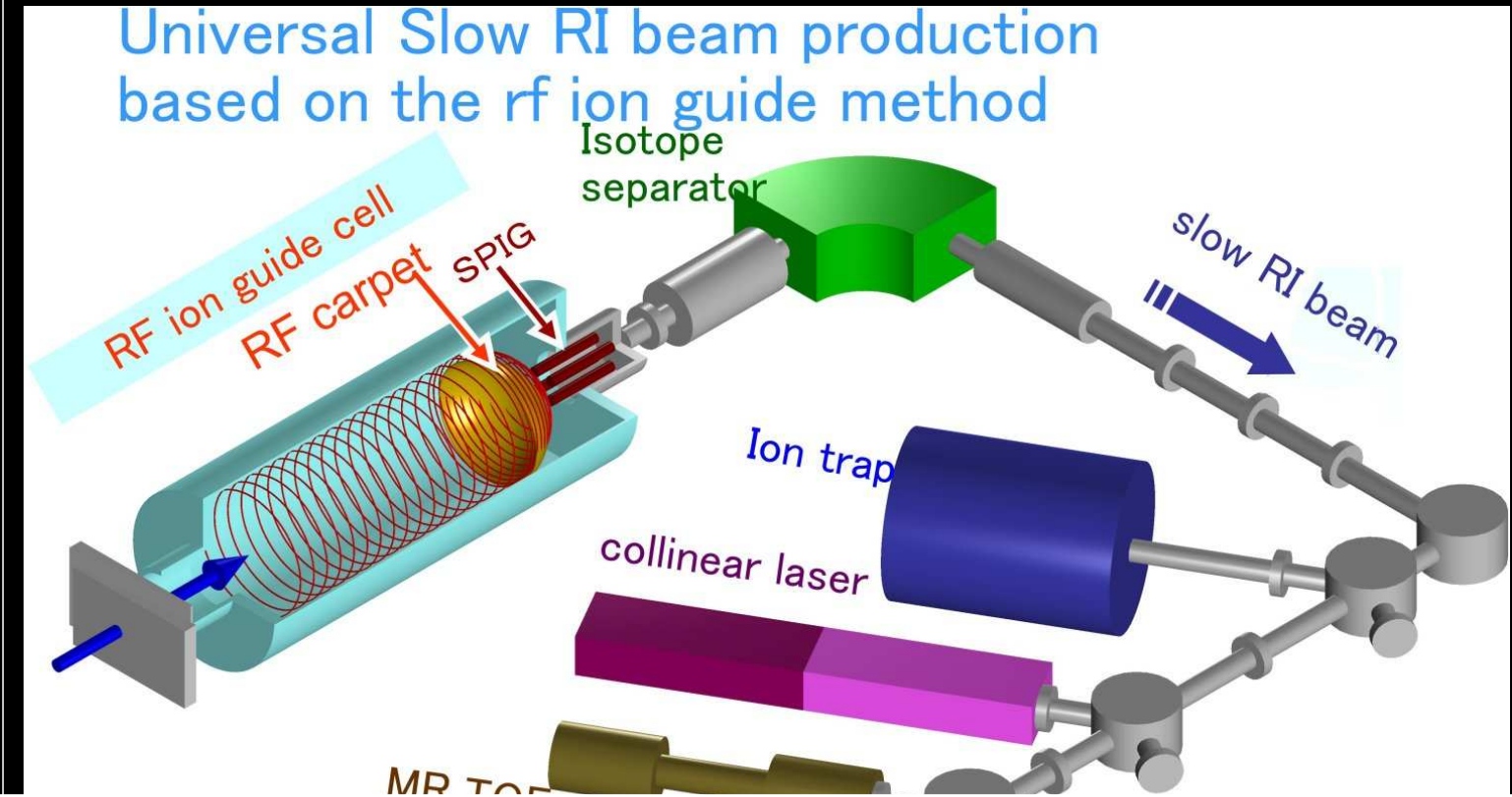
Spin polarized RI beam

- use of (old) RIPS with IRC beams
- dedicated setup to produce spin aligned or polarized beams
- IRC-based production
- nuclear moment,
- condensed matter physics

SLOWRI



SLOWRI



SLOWRI

- production of high-purity and slow RI beam with an rf-ion guide system
- Wide Range of Nuclides, No Chemical Processes in Production & Separation
- High Purity, no Isobar, no Isotone Contamination
- Small Emittance
- Mass spectroscopy (10-5) via MR-TOF system, co-linear laser spectroscopy, trap...
- “Super ISOLDE”

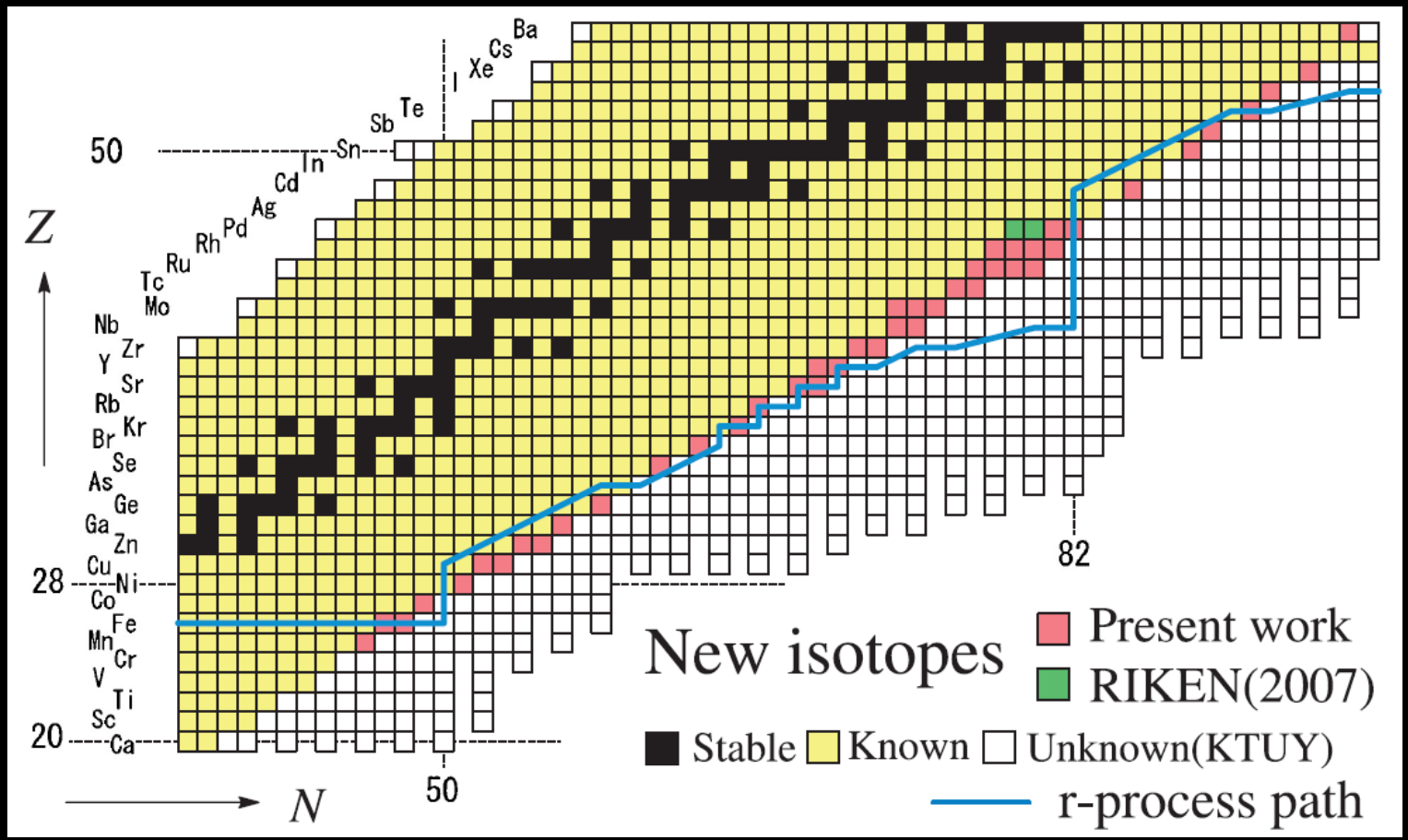
Other

- GARIS II separator operational
- new injector RILAC II for RIBF
  - independent operation of RIBF and GARIS (I/II)
- new 28 GHz ion source: more intense U beam

Highlights

45 New Isotopes

345 MeV/u ^{238}U beam ~ 0.2 pnA



T. Kubo, T. Ohnishi
T. Ohnishi *et al.*, JPSJ 79 (10) 073201

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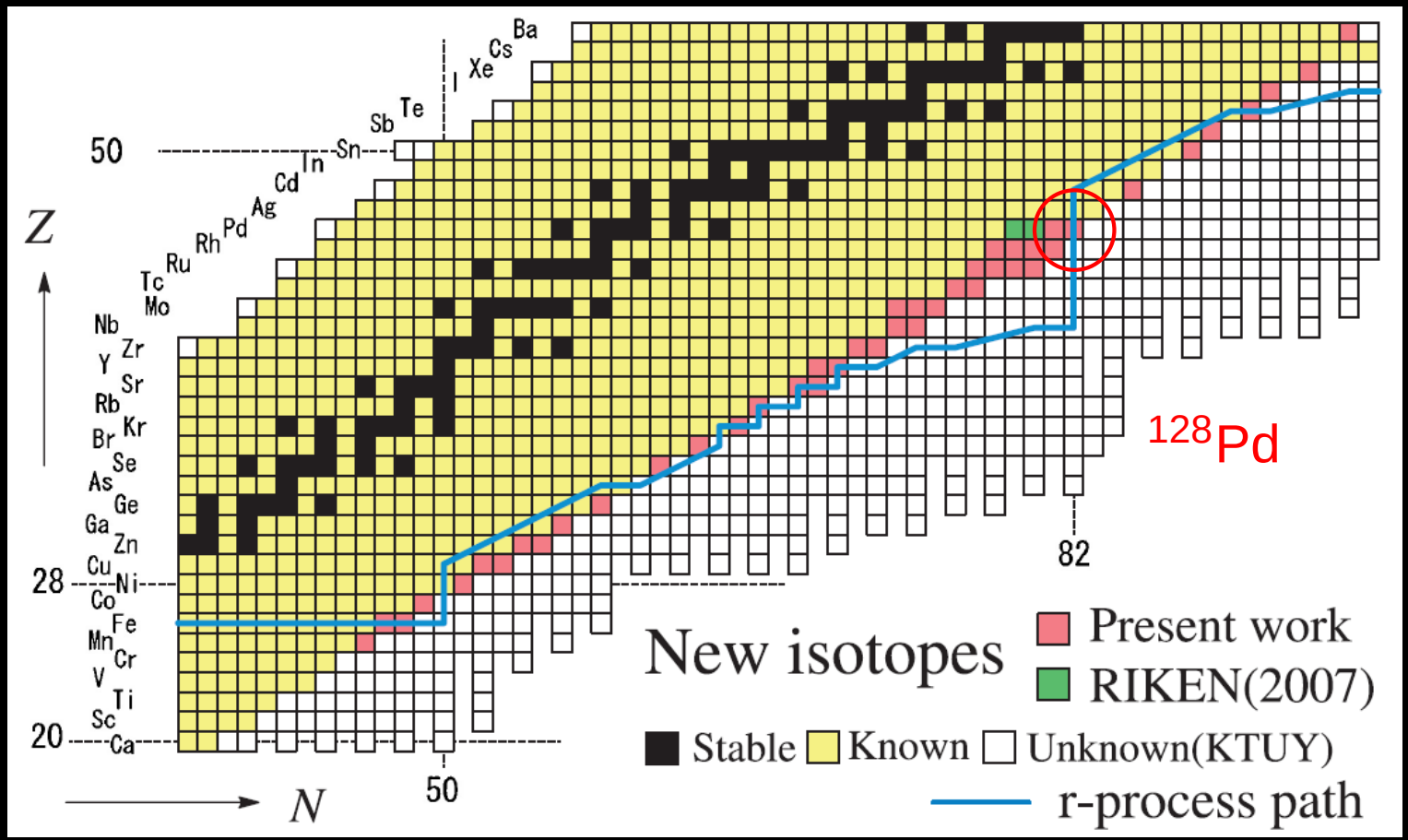
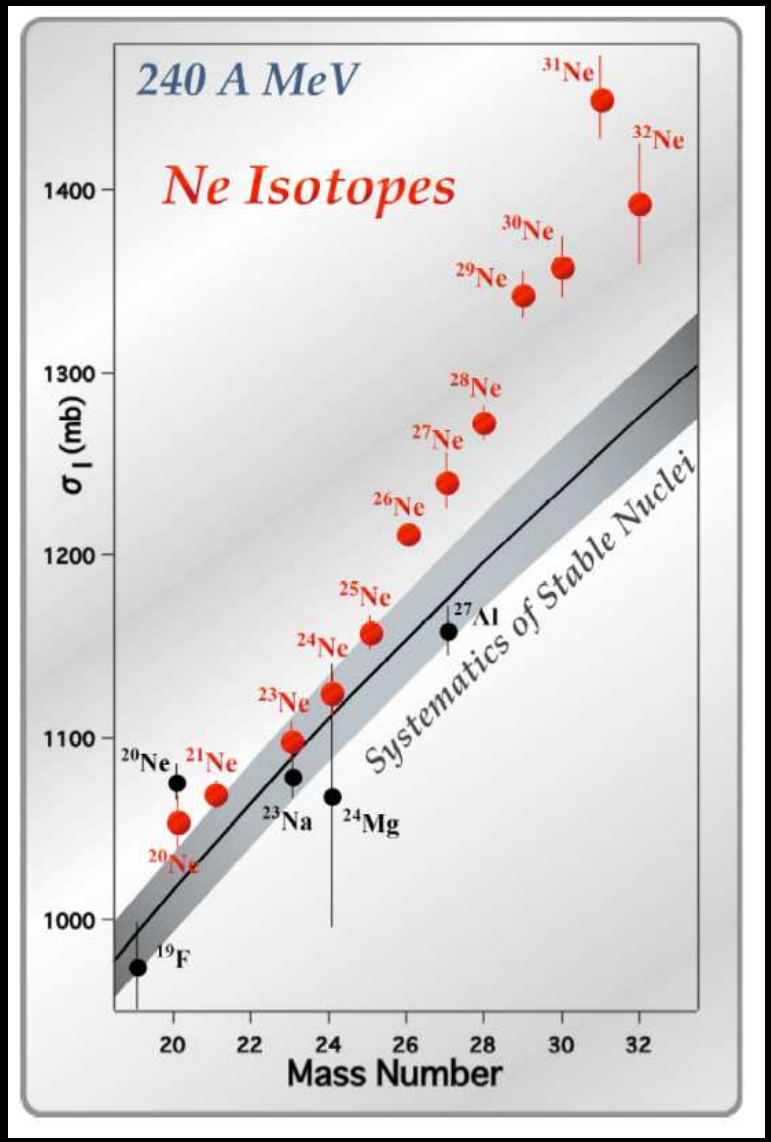


T. Kubo, T. Ohnishi
T. Ohnishi *et al.*, JPSJ 79 (10) 073201

Interaction Cross Section



- increasing cross section with neutron-number
- cross section “jumps” at ^{29,31}Ne
- Takechi, Otsubo *et al.*

Coulomb Breakup of Halo-candidate Nuclei ^{22}C and ^{31}Ne

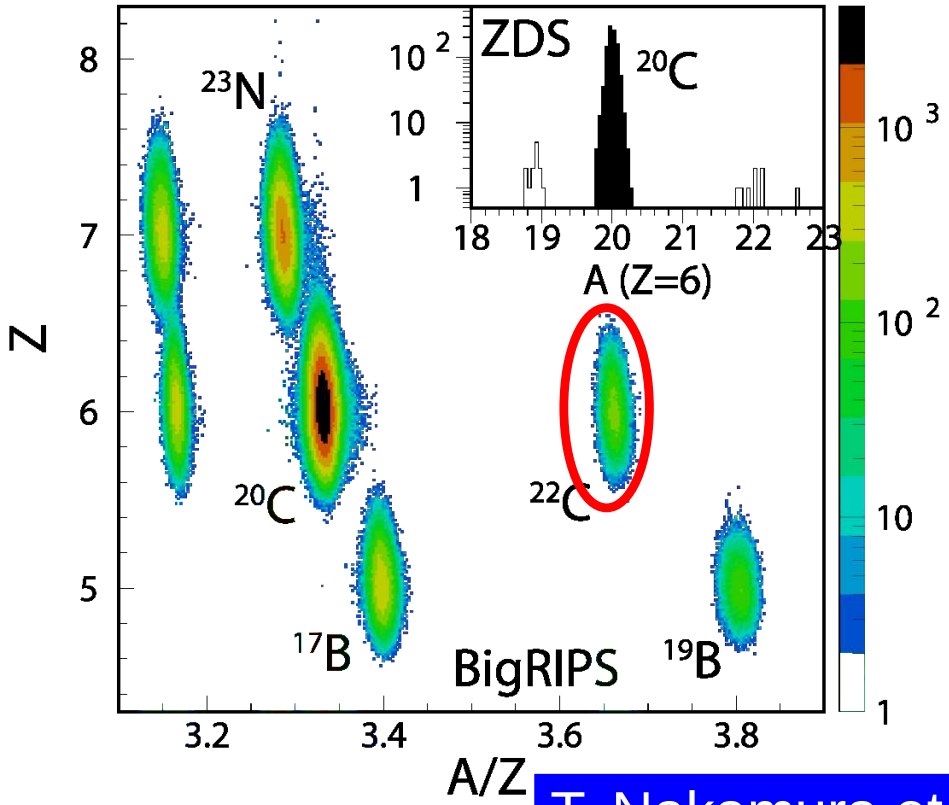
Spokesperson Takashi Nakamura

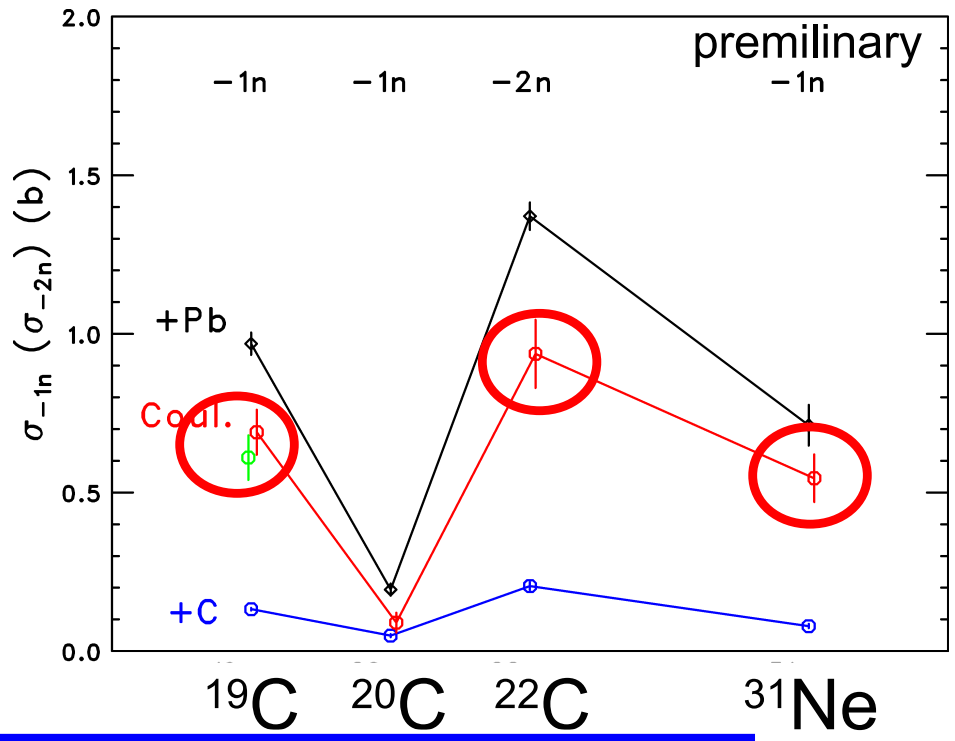
S_{2n}=0.42(94) S_n=0.29(1.65)

@230MeV/nucleon

Halo Nuclei→ Large Coulomb Breakup cross section of 0.5-1b

Halo/Non Halo can be distinguished by inclusive CB cross section!





T. Nakamura et al., PRL 103, 262501 (2009)

^{22}C ~ 6cps

^{31}Ne ~ 5cps

(c.f. ^{31}Ne -- 4 counts/day @RIPS H.Sakurai et al.PRC54,2802R(1996).)

Evidence for 2n Halo in ^{22}C

1n Halo in ^{31}Ne

c.f. ^{19}C (known halo)

Other Highlights

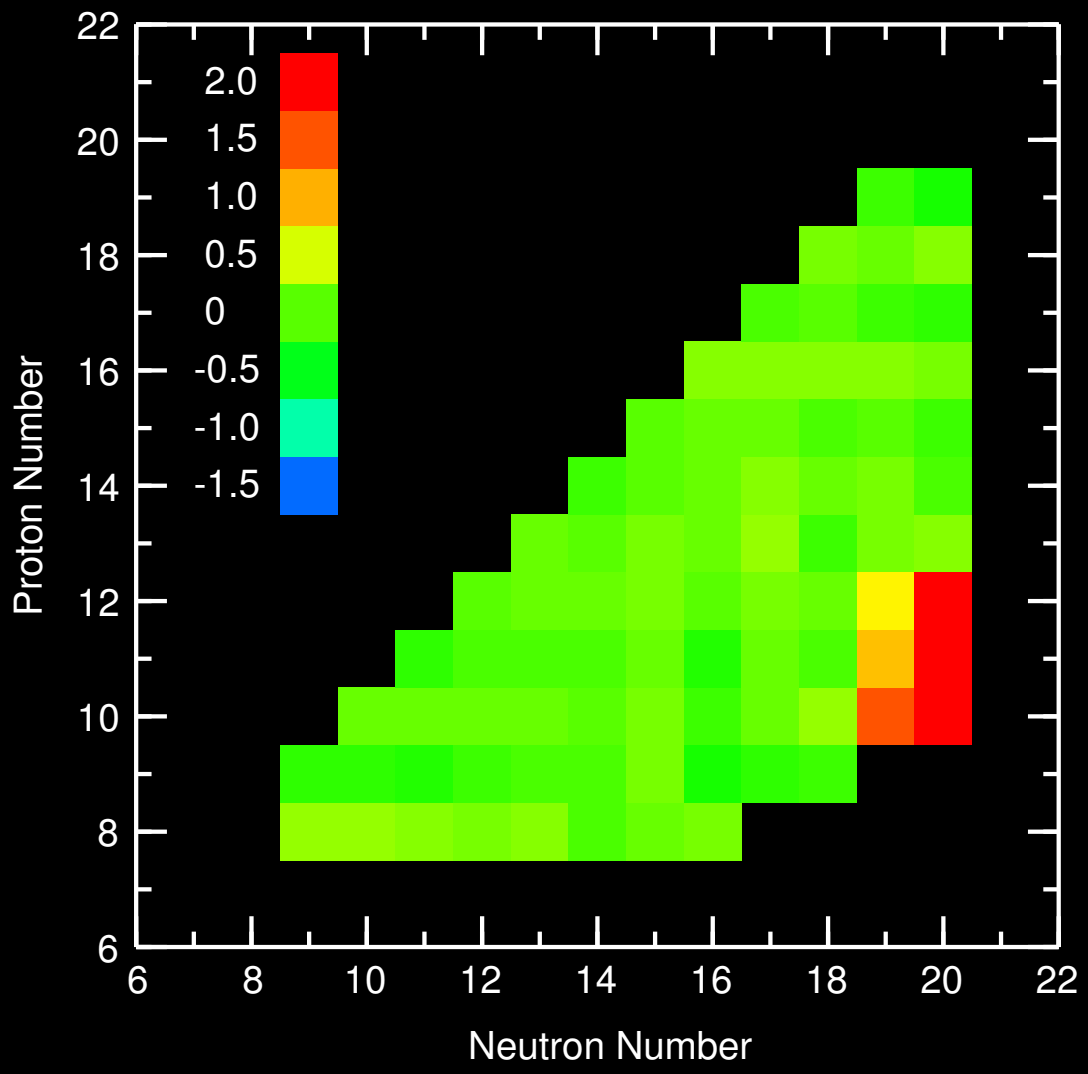
- beta-decay half-lives and isomer search
  - $A \sim 110$ region (Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc)
  - 18 isotopes are measured for the first time
  - despite poor beam conditions (0.1-0.2 pnA U)
  - new isomers
  - Nishimura, Sumikama, Watanabe *et al.*
- MUST2 campaign
  - study of $N = 16$ magic number in O-isotopes
  - search for (unbound) exited states in ^{24}O
  - missing mass spectroscopy (p, p')
  - Lapoux, Otsu *et al.*

Outlook

- Spring 2011: ^{124}Xe (~ 10 pnA expected)
- Fall 2011: U, Xe
- operation budget
  - so far only for 5 months (backlog of > 200 days)
  - soon 7-8 months

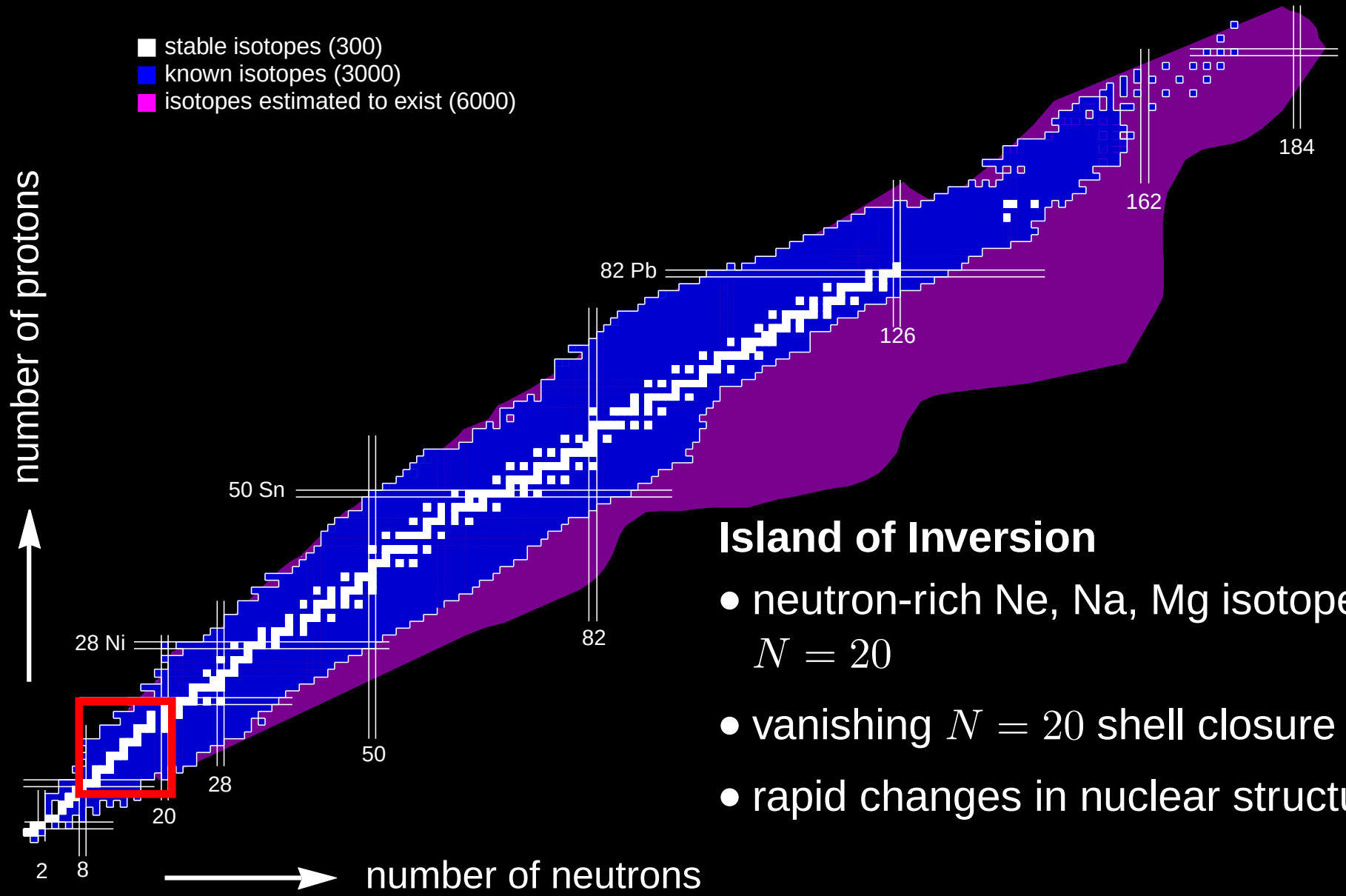
Island of Inversion Region

Universal sd Interaction Vers. B (USDB)



B.A. Brown and W.A. Richter, PRC 74 (2006)

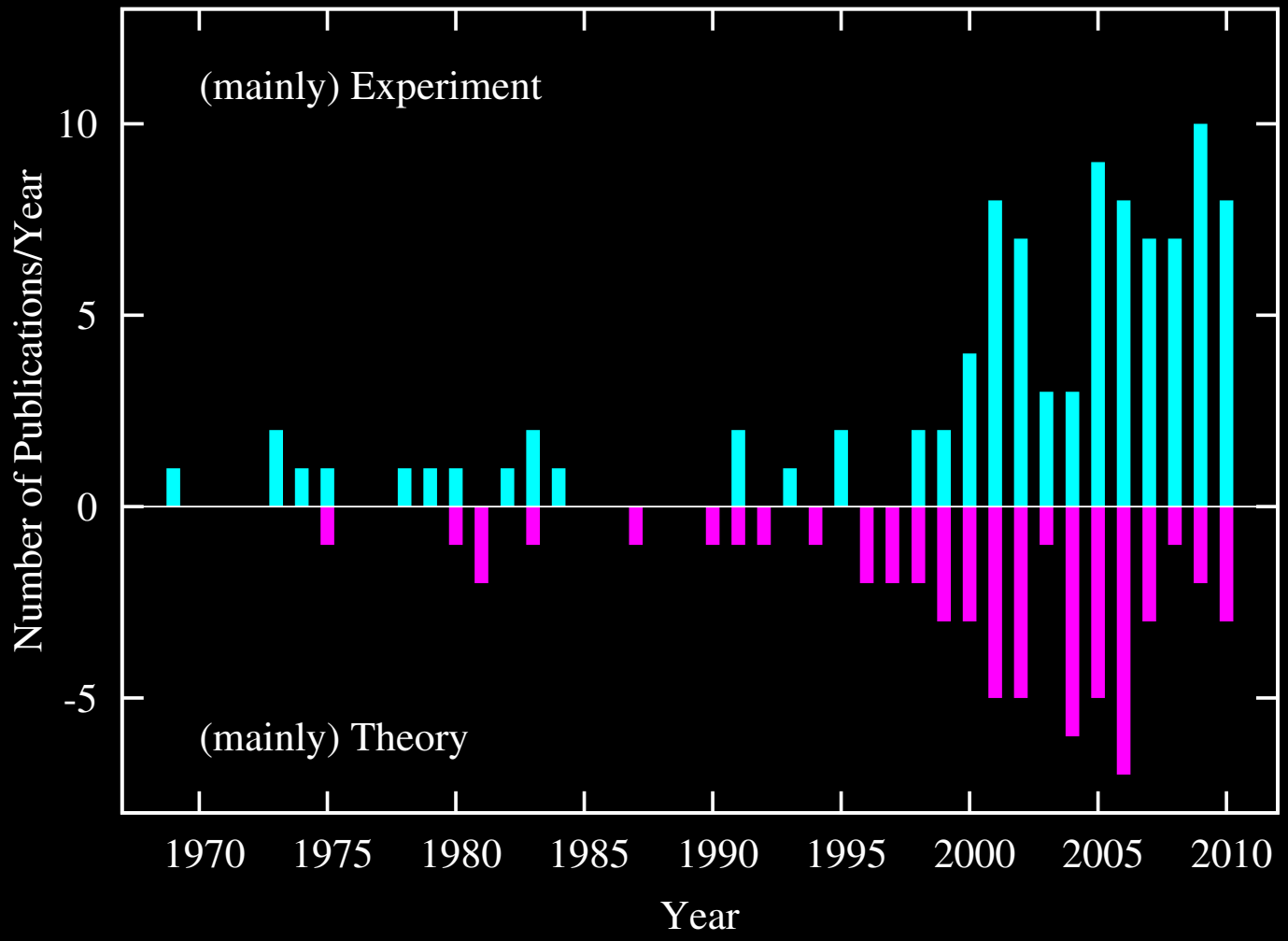
Nuclear Chart



Island of Inversion

- neutron-rich Ne, Na, Mg isotopes near $N = 20$
- vanishing $N = 20$ shell closure
- rapid changes in nuclear structure

Number of publications

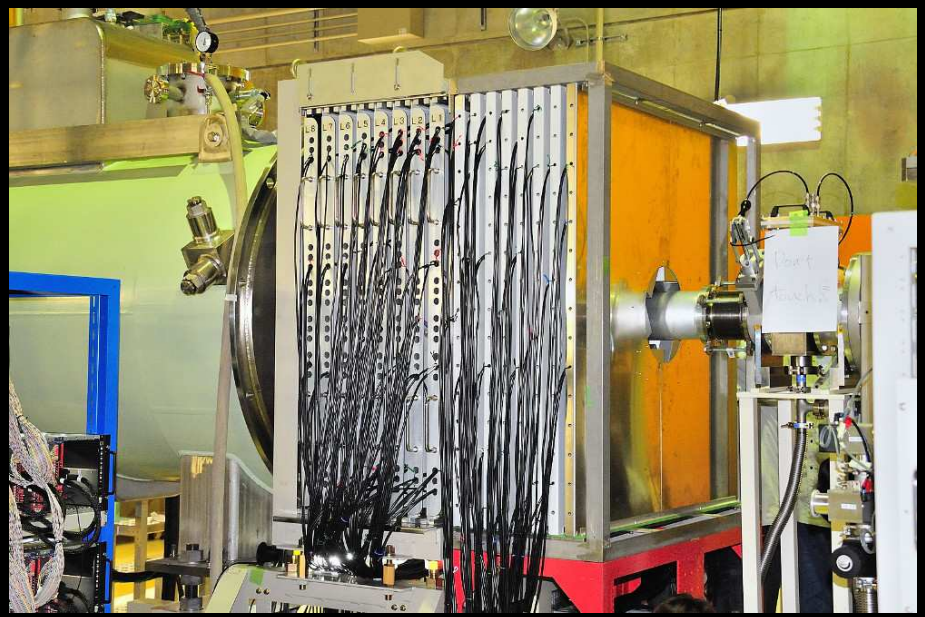


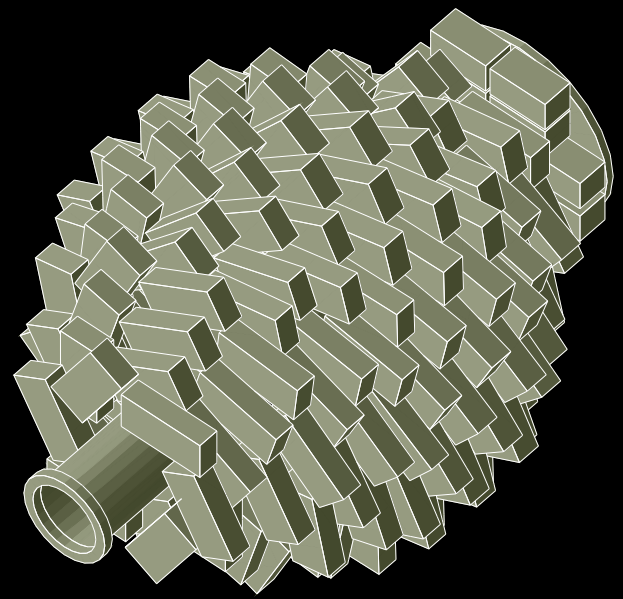
- only recently
  - improved experimental access
  - new theoretical developments

In-beam gamma Experiments at the RIBF

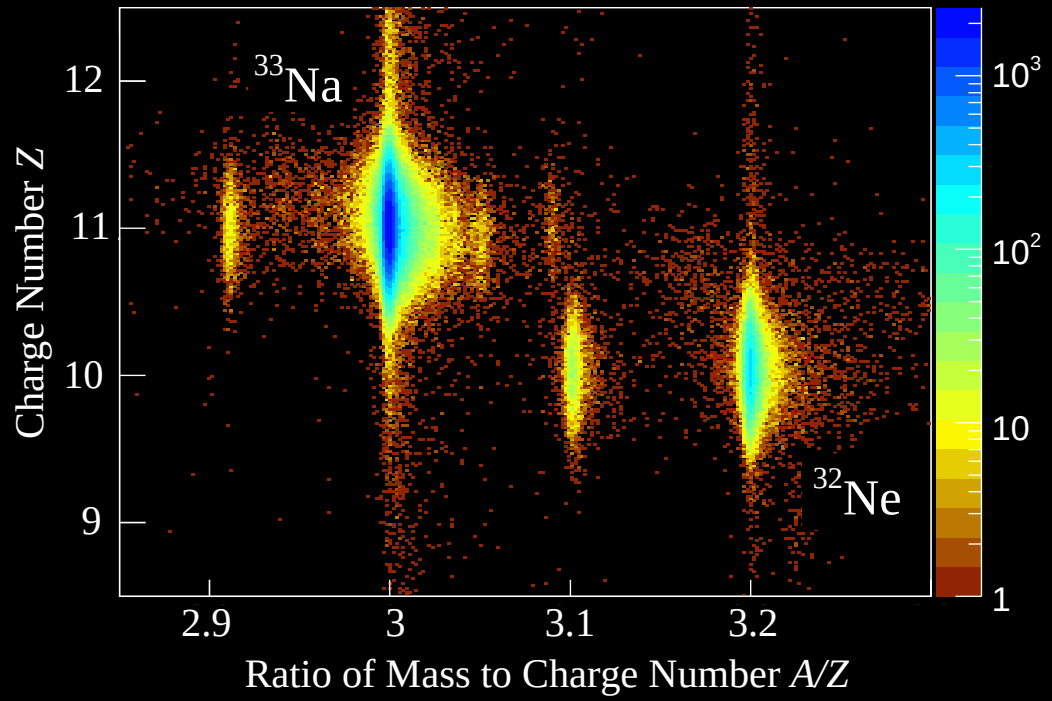
DALI2

- 182 NaI(Tl) detectors
- θ coverage: 11°–165°
- $\epsilon_\gamma \approx 20\%$
- $\Delta E/E = 6\%$ (1 MeV) $\quad 11\%$ ($\beta = 0.6$)
- target: 2.54 g/cm^2 C
- S. Takeuchi *et al.*, RIKEN Prog. Rep. 36, 148 (2003)



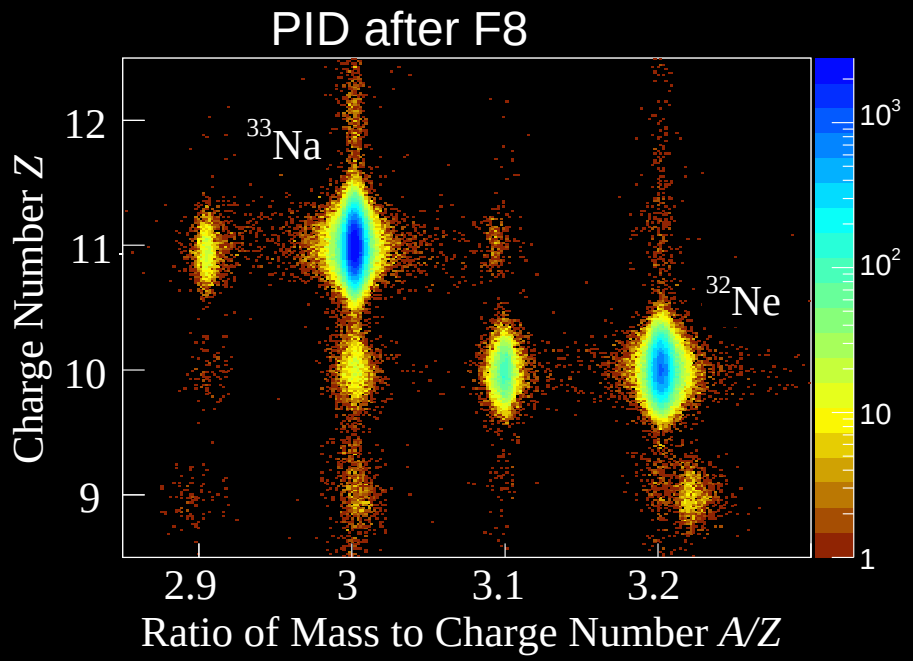


PID Before Secondary Target



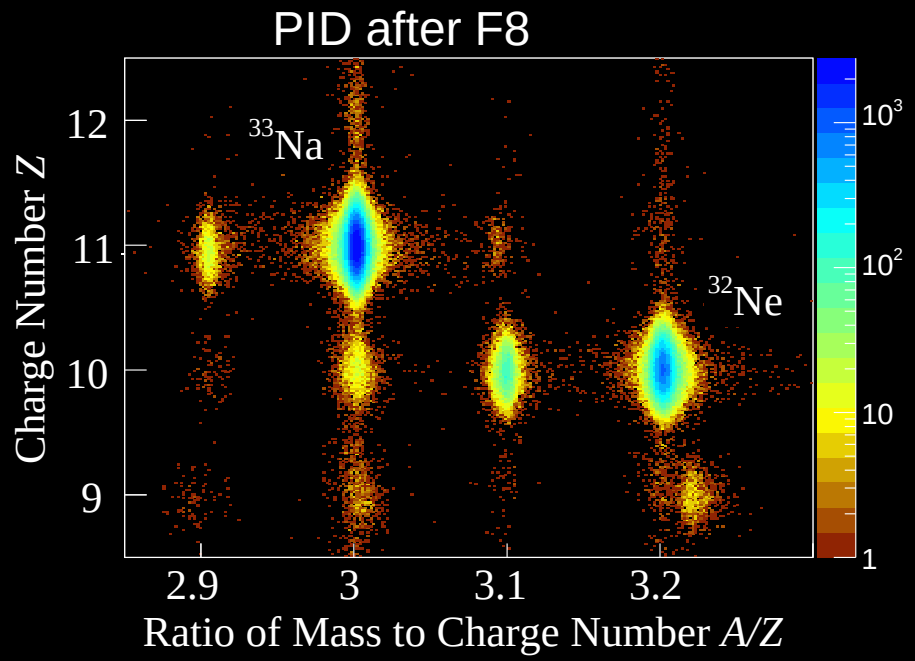
- ΔE–$B\rho$–TOF method
  - $Z \propto \Delta E$ $\Delta Z = 0.5$ (FWHM)
  - $A/Q \propto$ TOF $\Delta A = 0.06$ (FWHM)
- ^{32}Ne: 5/s $E \approx 230$ MeV$/u$
- ^{33}Na: 30/s

PID After Target and γ ray Spectra



- C(^{32}Ne,^{32}Ne*), C(^{33}Na,^{32}Ne*)
- ^{32}Ne: 5/s, 225 MeV/u
- F8 target: $^{nat.}$C (2.54 g/cm^2)
- DALI2 array: 182 NaI(Tl) detectors
- total data taking: 7 hours

PID After Target and γ ray Spectra



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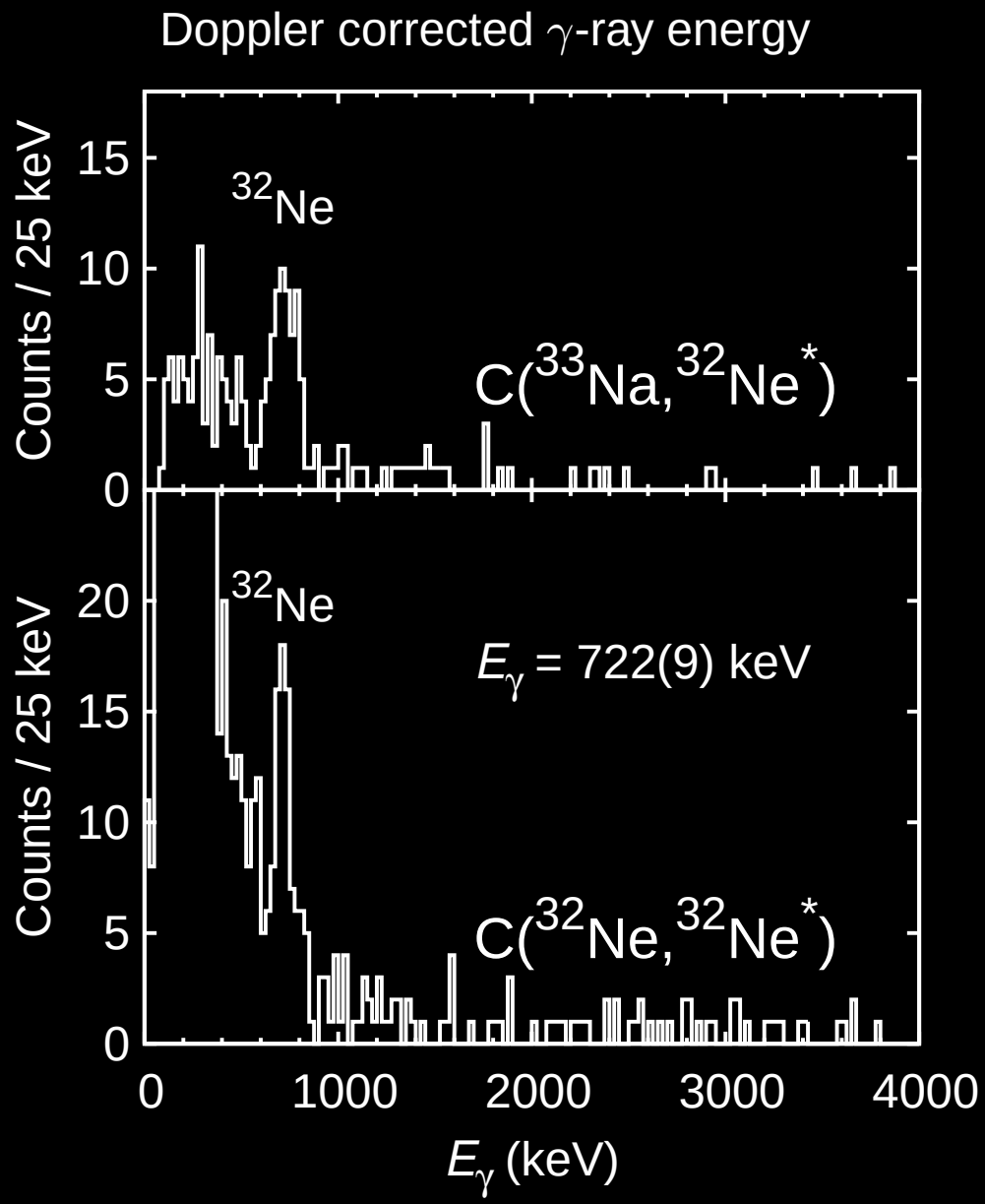
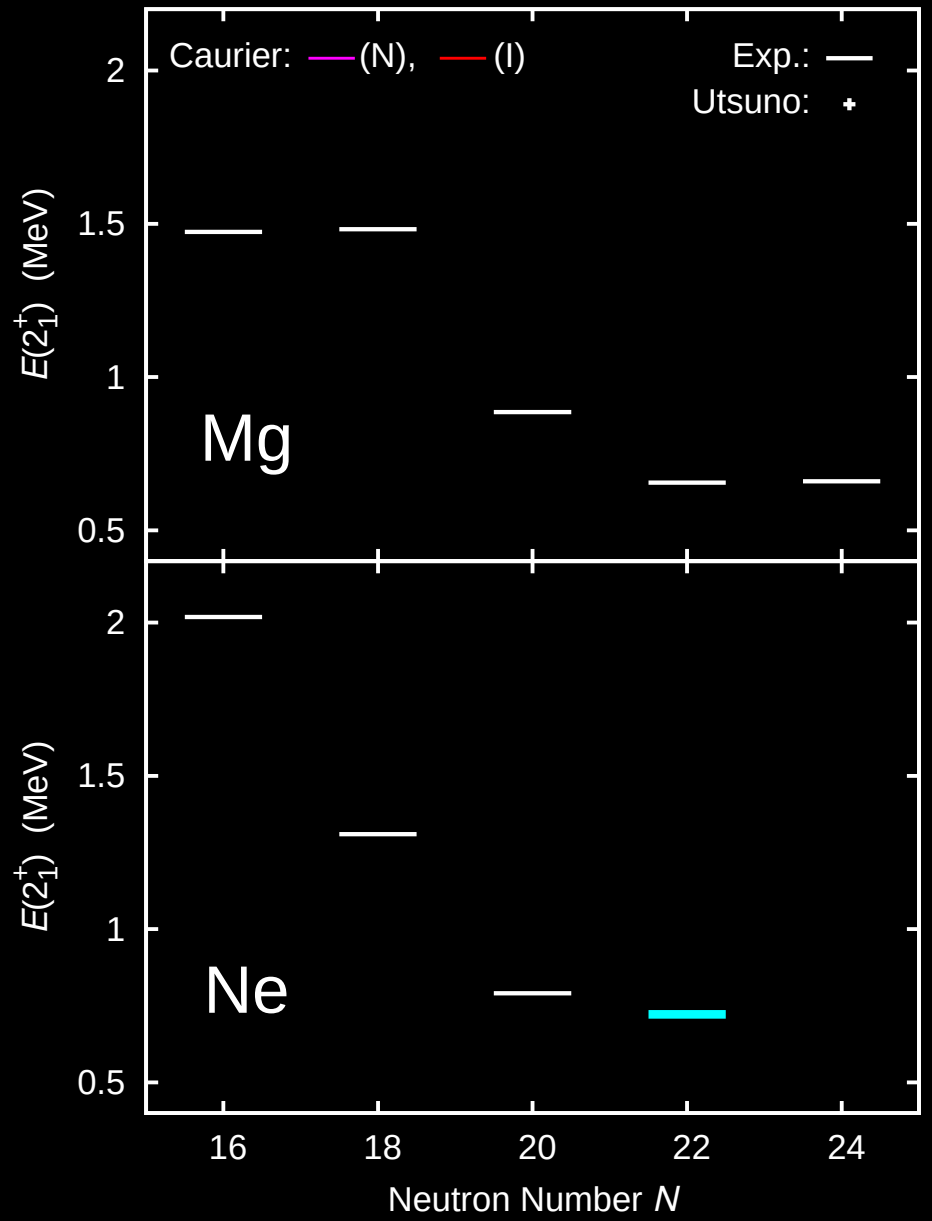


$E(2^+)$ as Function of N

- lowest $E(2^+)$ of Ne isotopes



P. Doornenbal, H. Scheit *et al.*
Phys. Rev. Lett. 103, 032501 (2009)

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- very good agreement with Utsuno et al., PRC 60, 054315 (1999)

P. Doornenbal, H. Scheit *et al.*
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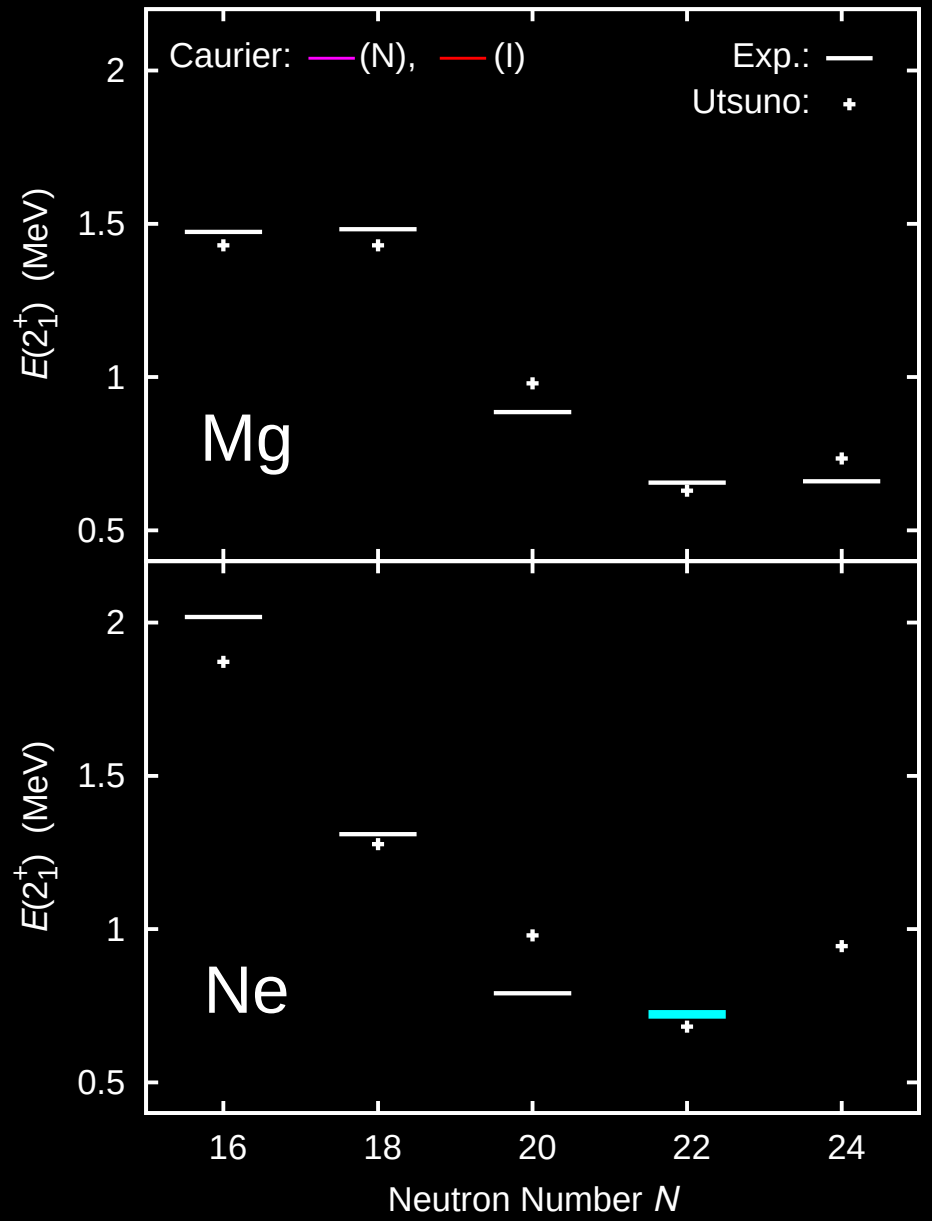

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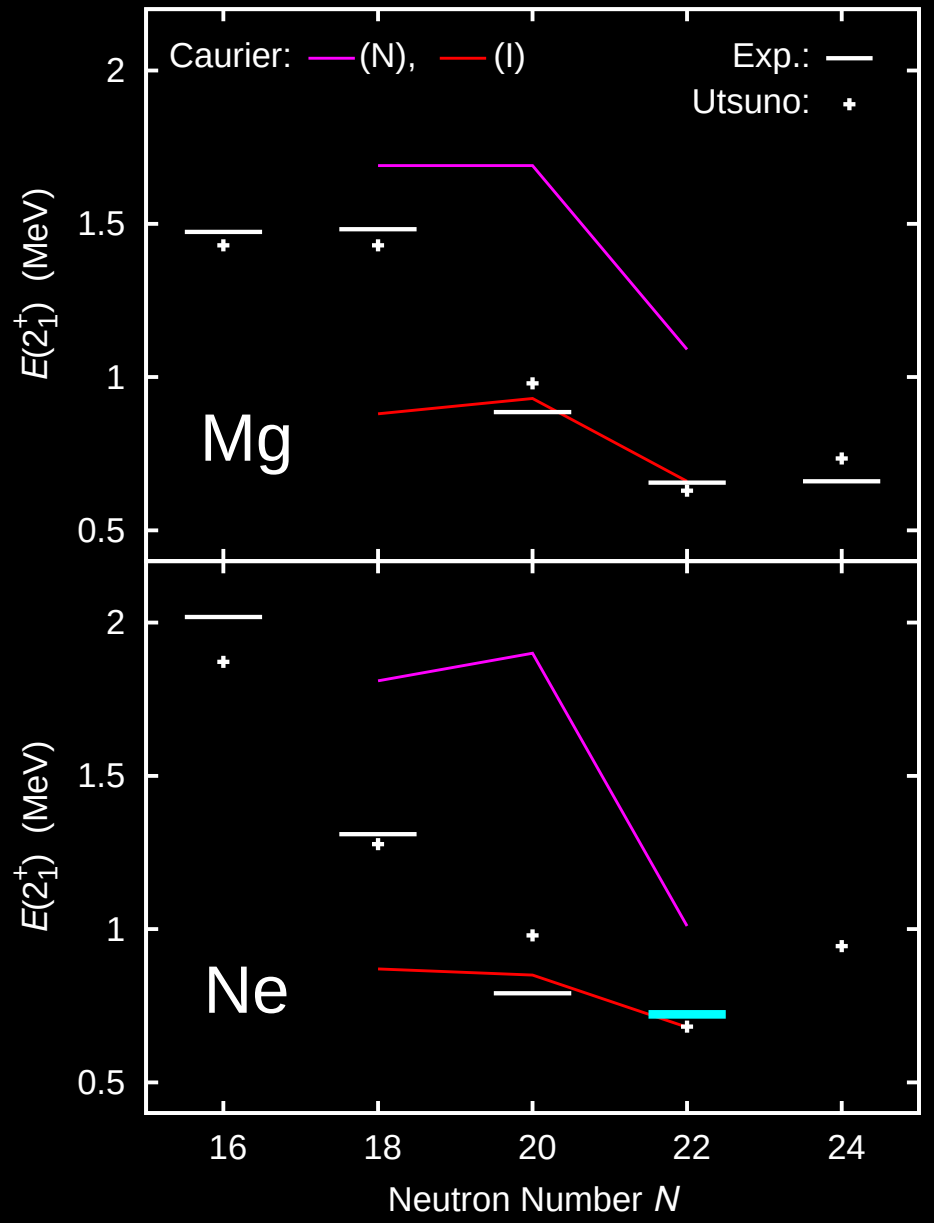
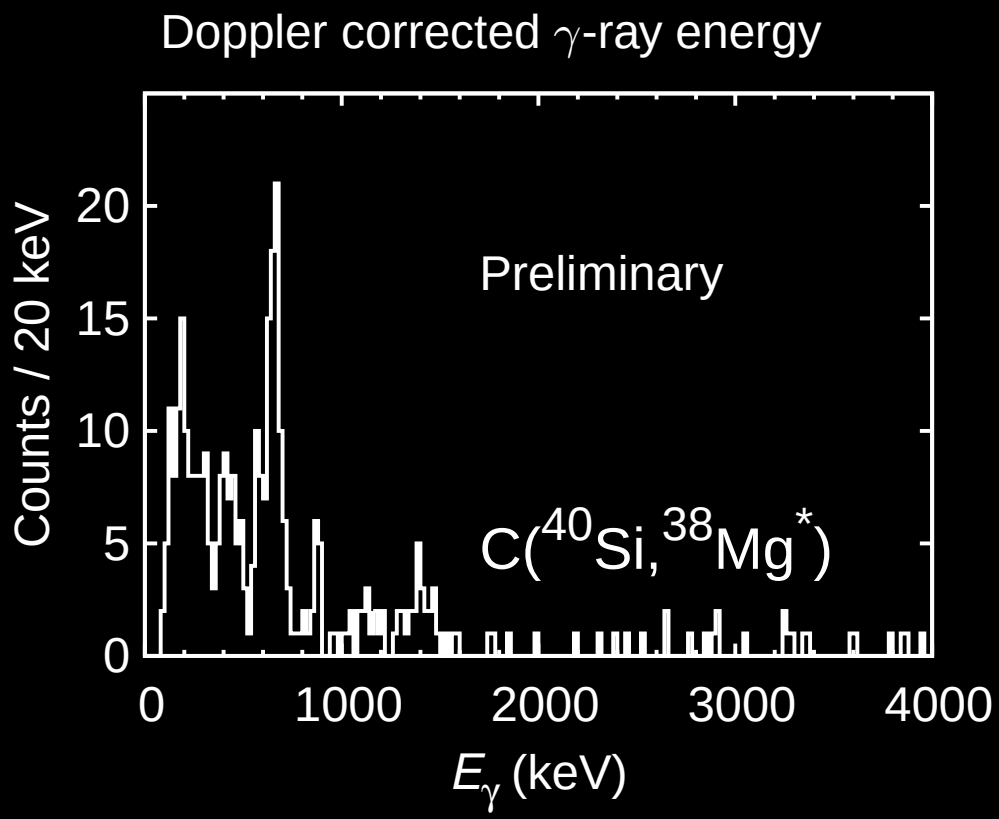
- very good agreement with Utsuno et al., PRC 60, 054315 (1999)
- very good agreement with Intruder calculation of Caurier et al., NPA 693, 374 (2001)
- ^{32}Ne belongs to the "Island of Inversion"

P. Doornenbal, H. Scheit *et al.*
Phys. Rev. Lett. 103, 032501 (2009)

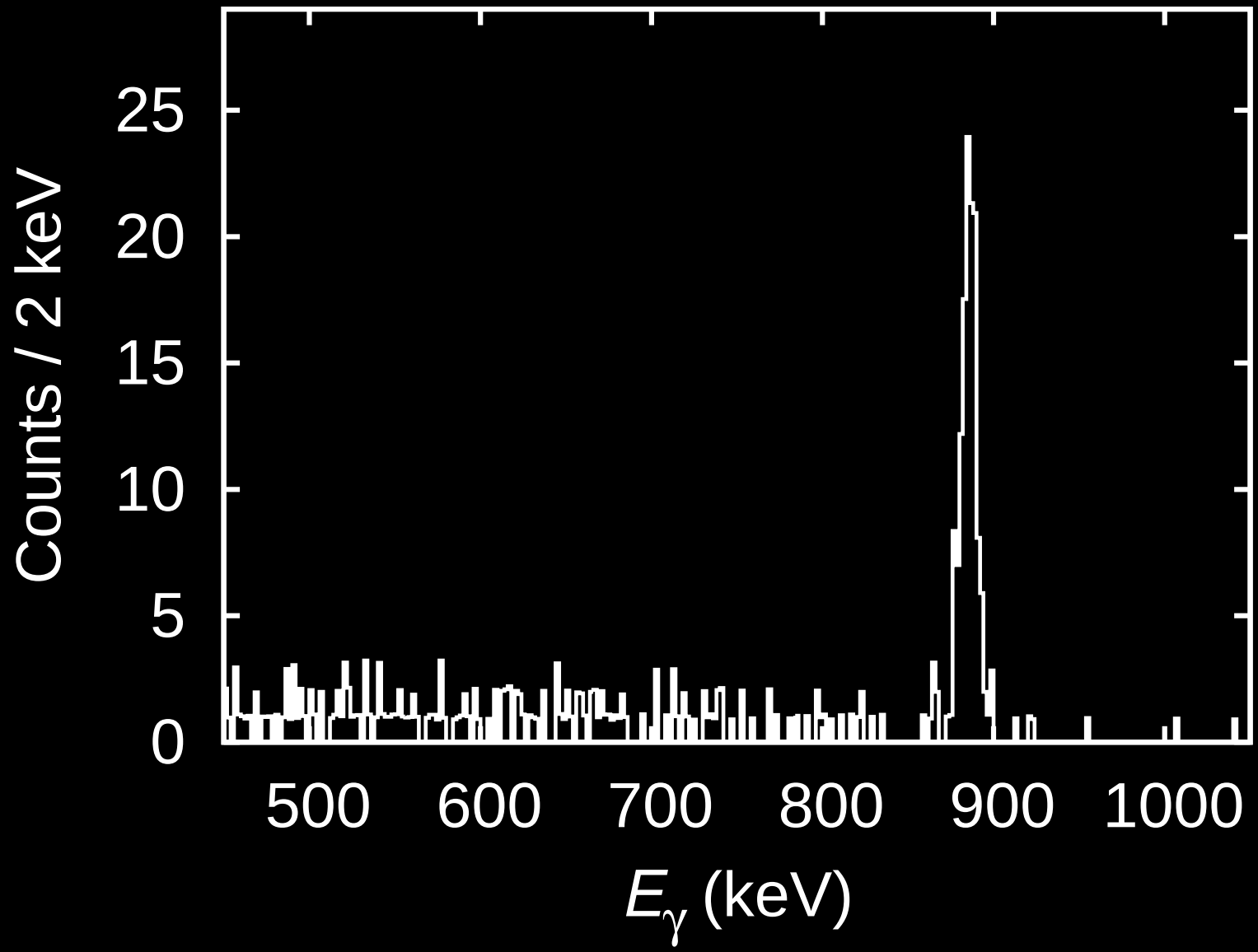


$E(2^+)$ of ^{38}Mg

- C(^{40}Si,^{38}Mg*)
- ^{40}Si: 3000/s, $\sim$ 220 MeV/u
- F8 target: $^{nat.}$C (2.54 g/cm^2)
- DALI2 array: 182 NaI(Tl) detectors
- total data taking: 16 hours
- **online spectrum; measured last week!**



Coulomb Excitation of ^{32}Mg at REX-ISOLDE



Next Generation γ ray Spectrometer for Fast Beams at the RIBF

SHOGUN

S cintillator based
H igh-res**O**lution
O
G amma-ray spectrometer for
U nstable
N uclei

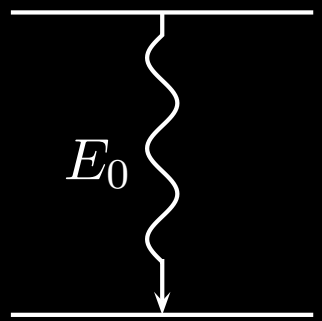
- γ ray spectrometer optimized for **in-beam** γ ray spectroscopy at **RIBF beam energies**
- Construction proposal accepted by NP-PAC (Dec. 2009)
  (no funding)

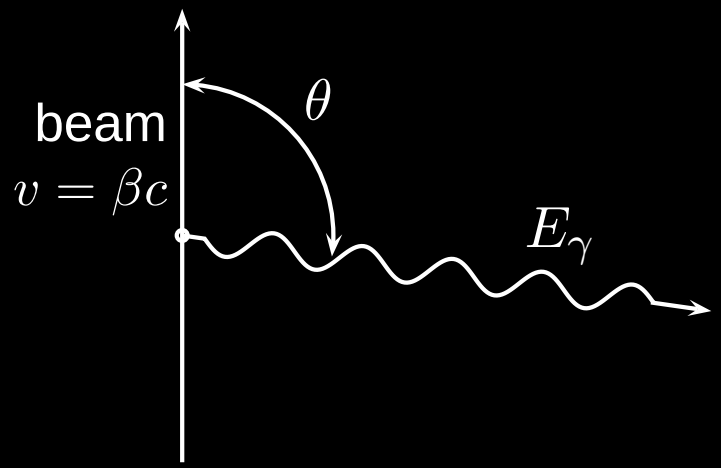
Doppler Shift

- Lorentz transformation of 4-momenta between laboratory frame and frame of emitting nucleus

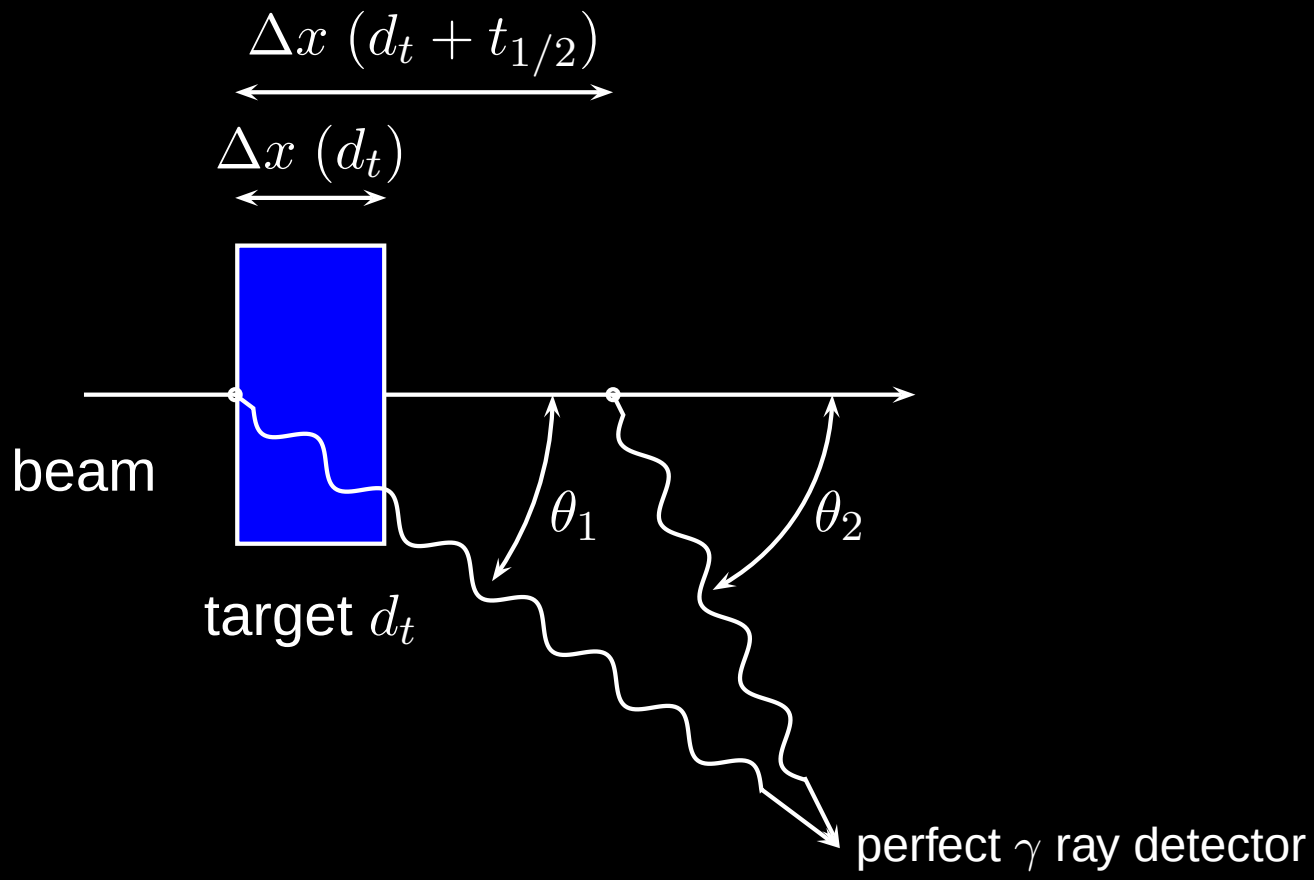
$$E_\gamma = \frac{E_0}{\gamma(1-\beta\cos\theta)} \qquad d\Omega_0 = \left(\frac{E_\gamma}{E_0}\right)^2 d\Omega$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$





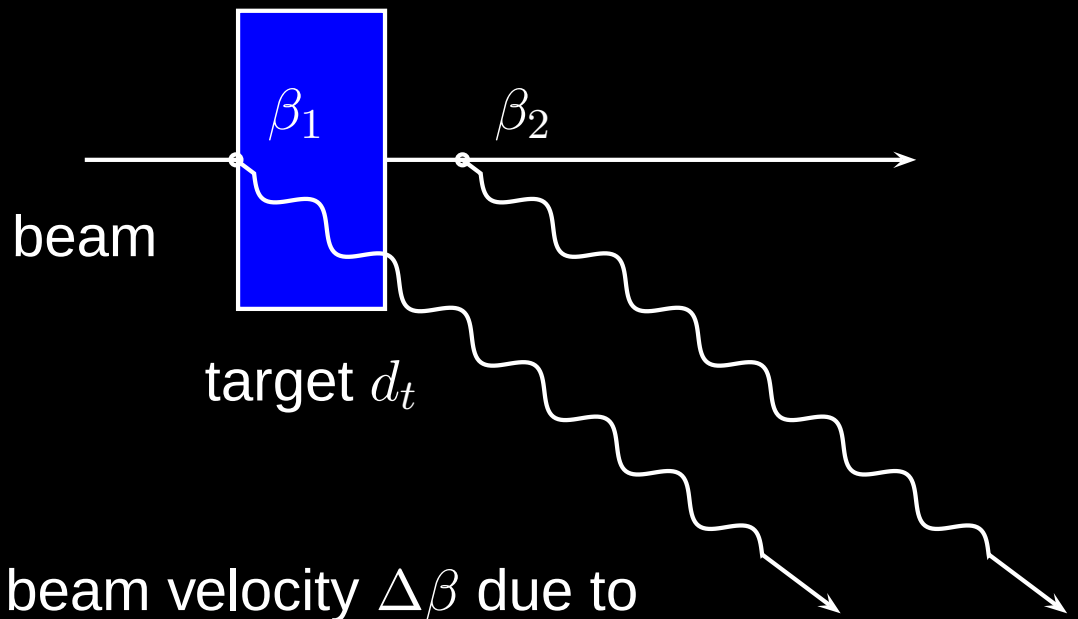
Doppler Broadening: Emission Angle



Uncertainty Δx of point of γ emission due to

- target thickness: $d_t \sim 1 \ldots 20$ mm
- γ decay in-flight: 100 ps ➡ 15 mm

Doppler Broadening: Velocity



Uncertainty in beam velocity $\Delta\beta$ due to

- energy loss in the target: $\Delta E \sim 10$–20%

$$\frac{\Delta\beta}{\beta} \sim \begin{cases} 5\text{–}10\% & \text{if } \gamma\beta t_{1/2} < d_t \\ \text{small} & \text{if } \gamma\beta t_{1/2} > d_t \end{cases}$$

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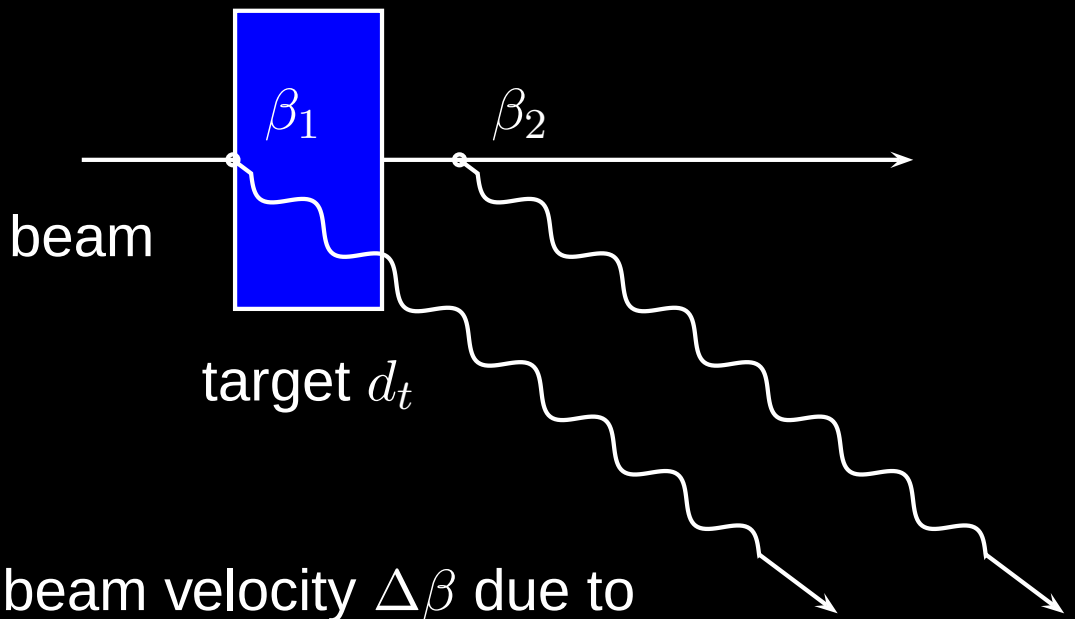

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- very small uncertainty in beam velocity vector $\vec{\beta}_2$
  - beam mom. spread and reaction mech. do not contribute to $\Delta\beta$

Doppler Broadening

Due to:

- uncertainty of θ
- uncertainty of β

$$\Delta E^2 = \left(\frac{\partial E}{\partial \beta}\right)^2 \Delta\beta^2 + \left(\frac{\partial E}{\partial \theta}\right)^2 \Delta\theta^2$$

$$\frac{1}{E}\frac{\partial E}{\partial \beta} = \frac{\cos(\theta)}{1-\beta\cos(\theta)} - \beta\gamma^2$$

$$\frac{1}{E}\frac{\partial E}{\partial \theta} = \frac{\beta\sin(\theta)}{1-\beta\cos(\theta)}$$

Boundary Conditions at RIBF

for in-beam γ ray spectroscopy at the RIBF:

- beam energy: 200 MeV/u $\quad v/c = \beta = 0.5$

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- beam energy: 200 MeV/u $\quad v/c = \beta = 0.5$
- target thickness: $d_\mathrm{t} \sim 1 \ldots 20$ mm
- γ decay in-flight: 100 ps ➡ 15 mm
- achievable angular resolution: $\Delta\theta = 3^\circ = 50$ mrad
  (assuming a detector distance of 25 cm)
- 10–20% energy loss in target: $\Delta\beta = 5$–10%
- NB: $\Delta\theta$ does not include detector contributions

Angular and Velocity Uncertainties

for in-beam γ ray spectroscopy at the RIBF:

Angular and Velocity Uncertainties

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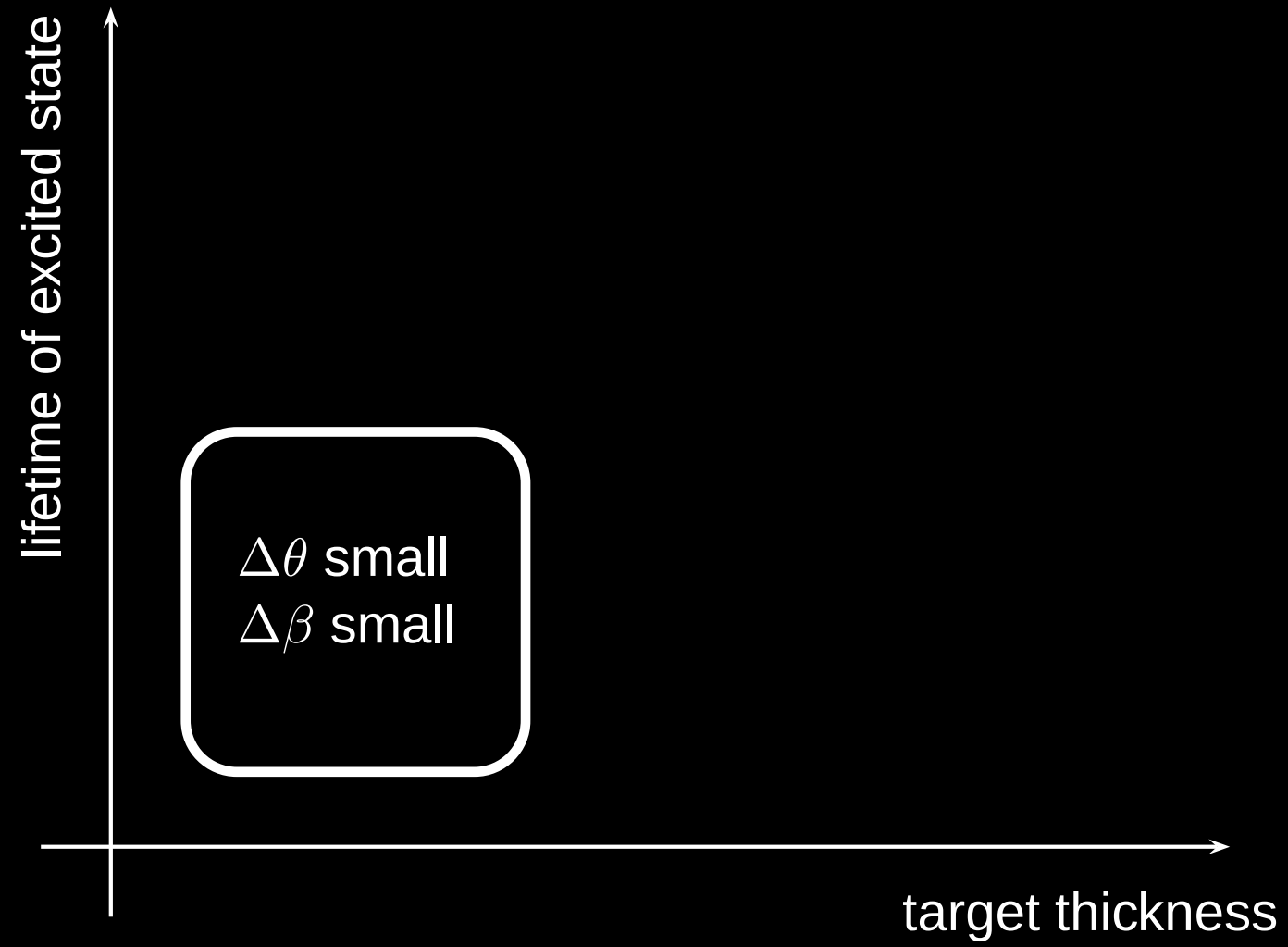

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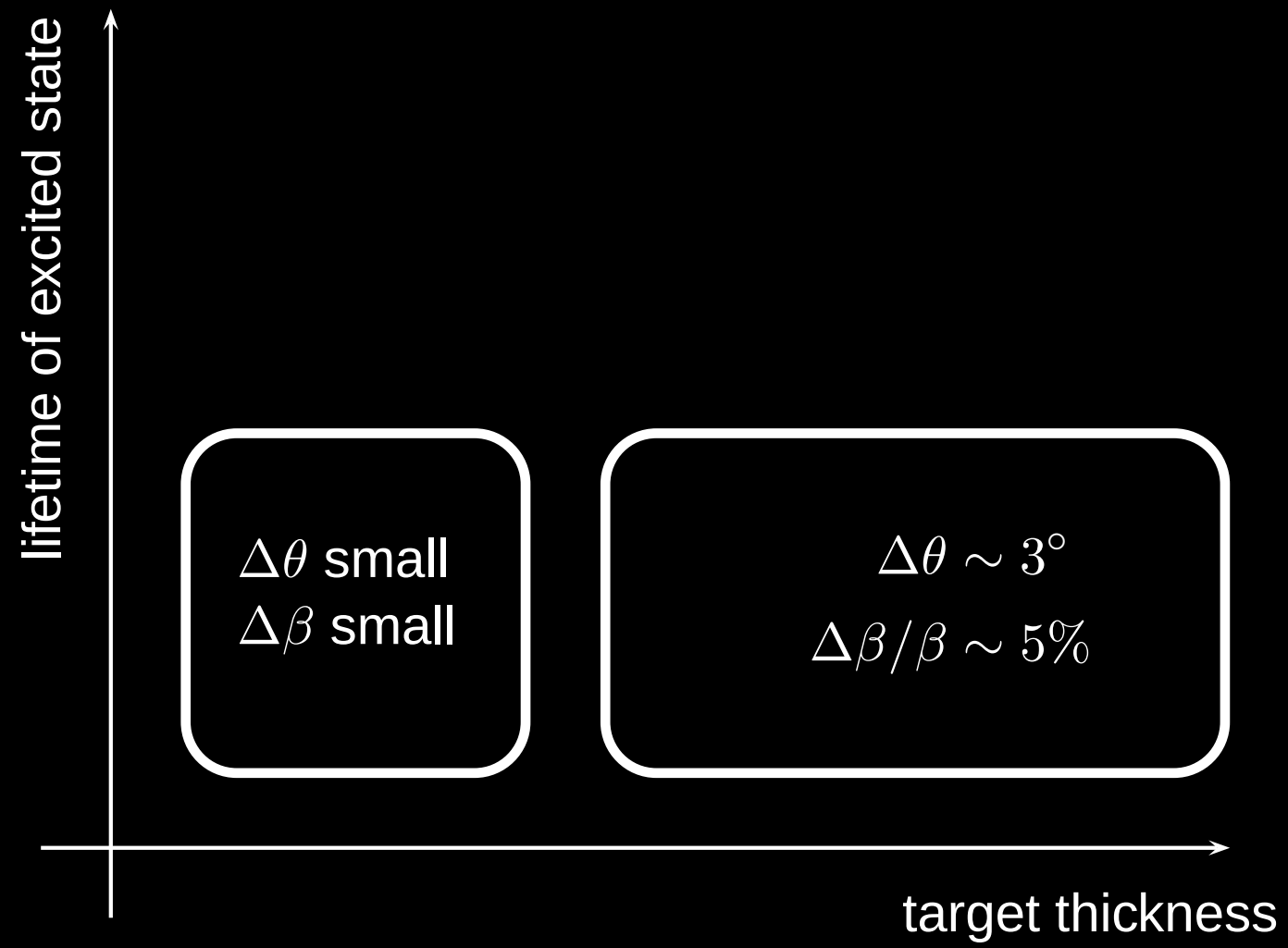

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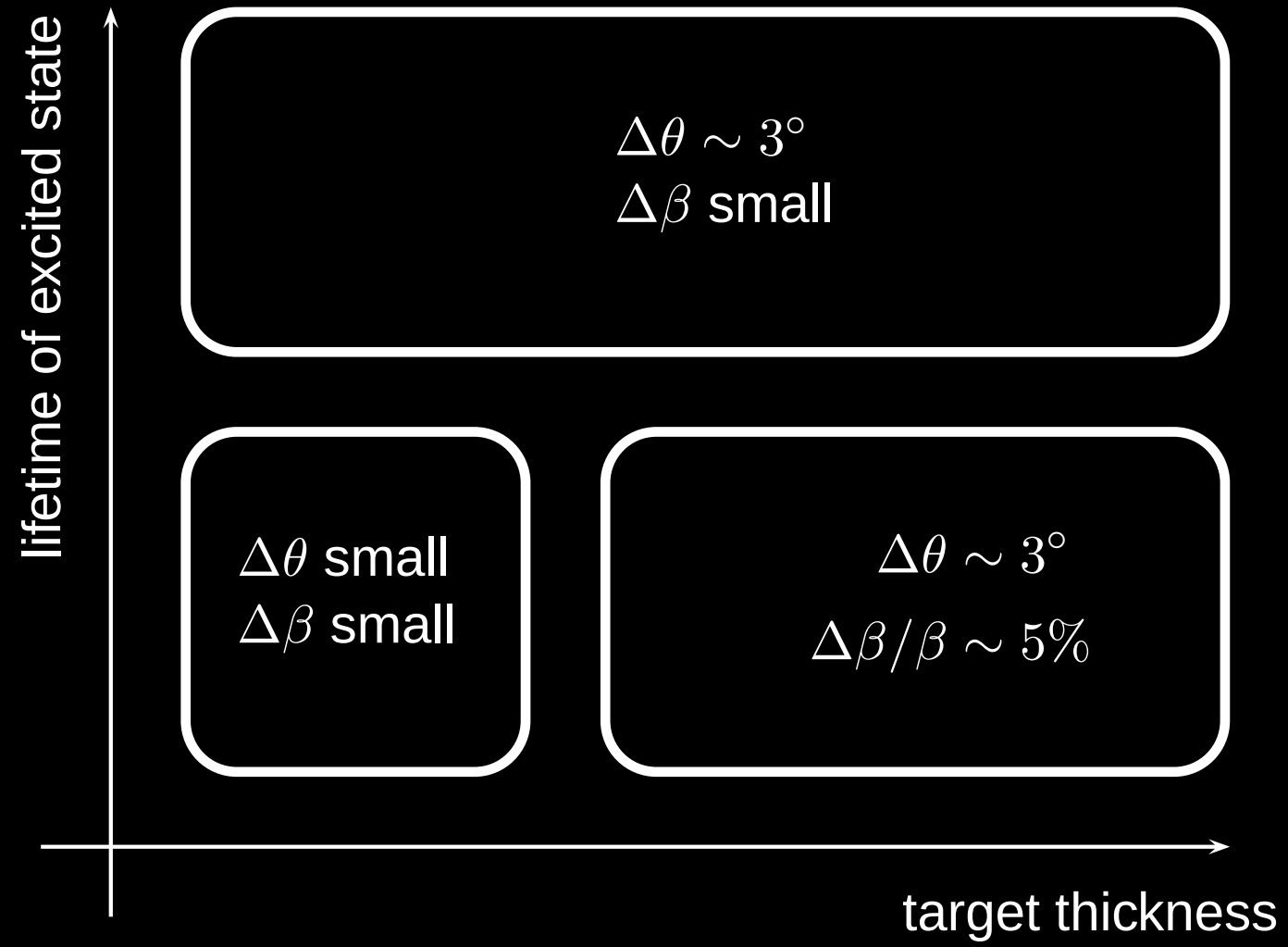

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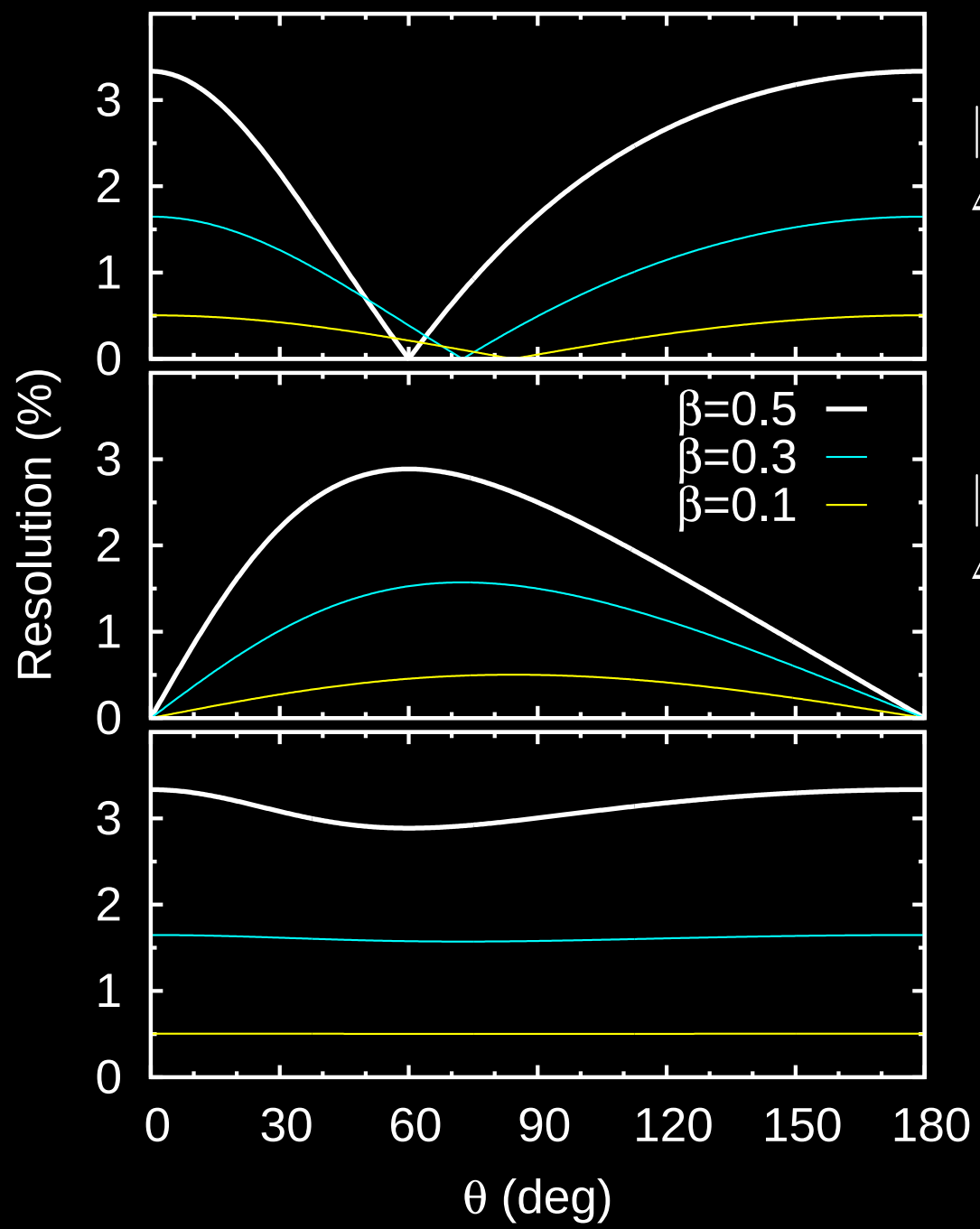
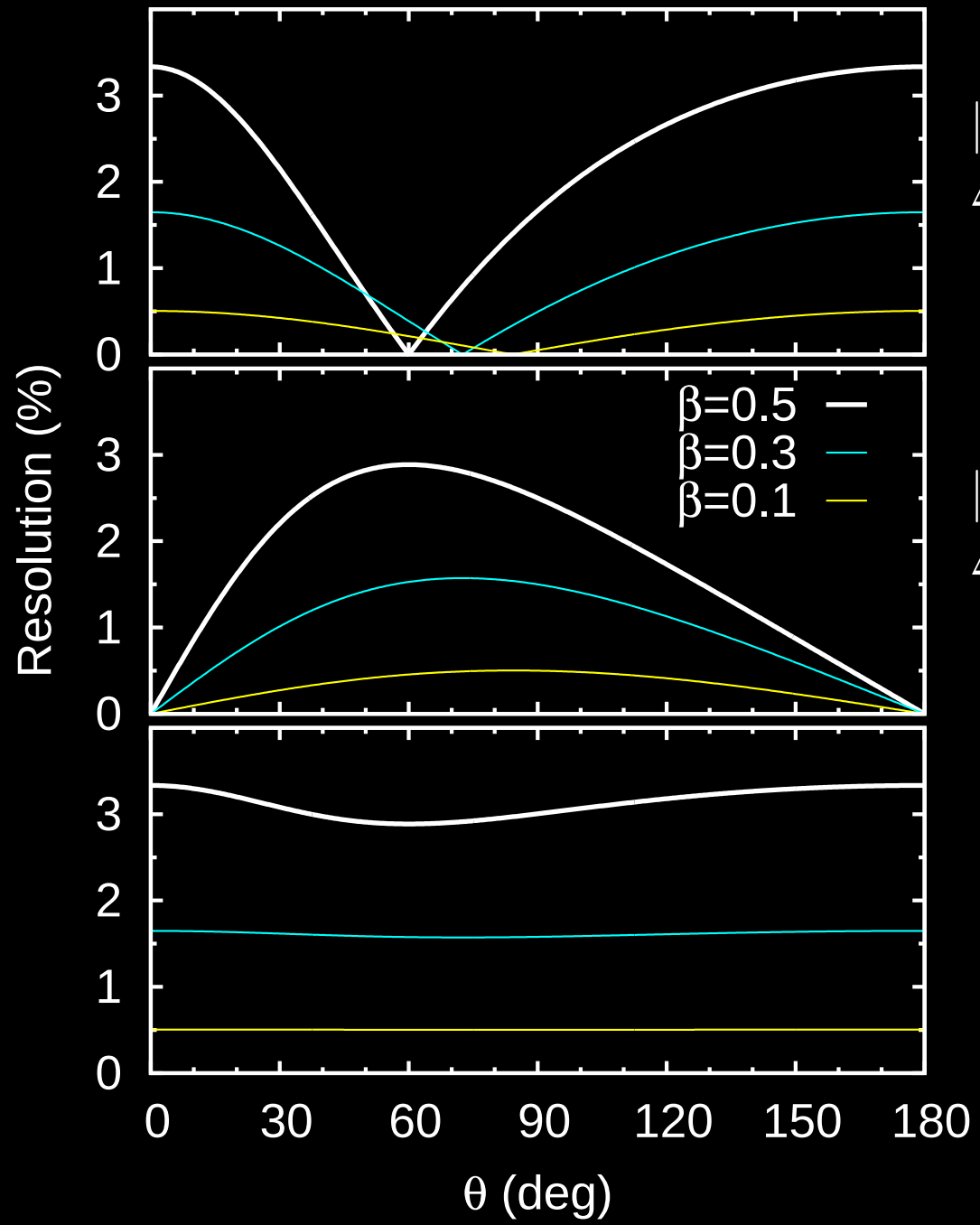


$|\partial E/\partial\beta| \cdot \Delta\beta$
$\Delta\beta/\beta = 5\%$

$|\partial E/\partial\theta| \cdot \Delta\theta$
$\Delta\theta = 50$ mrad

Doppler Broadening



$|\partial E/\partial\beta| \cdot \Delta\beta$
$\Delta\beta/\beta = 5\%$

$|\partial E/\partial\theta| \cdot \Delta\theta$
$\Delta\theta = 50$ mrad

achievable
energy resolution:

3%

Which detector should be used?

RIKEN CNS GRAPE **OR** DALI2

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RIKEN	CNS GRAPE	**OR**	DALI2
MSU	SeGA	**OR**	CAESAR/APEX

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(good) resolution **OR** good efficiency

Which detector?

$LaBr_3$(Ce) based detectors!

$LaBr_3$(Ce)

- new scintillation crystal invented in 2001 by Delft University, Netherlands; licensed to Saint-Gobain
- marketed under name: Bril**La**n**Ce** 380

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- most remarkable property:
  - energy resolution of **2.6%** at 662 keV
  - compare to NaI(Tl): 6.5%
- but, until recently no large(ish) crystals
  - strong anisotropic thermal expansion (a-axis: 22 ppm/K; c-axis: 8 ppm/K)
    - prone to cracking during cooling after growth
- now: “127 mm ingots . . . are routine” (Saint-Gobain)

Properties of $LaBr_3(Ce)$

- comparison to common scintillators:

	NaI(Tl)	BaF_2	$LaBr_3(Ce)$
Light Output (1/keV)	38	2 10	$>$**71**
Decay Time (ns)	250	.7 630	**16**
Z	11, 53	56, 9	57, 35
Density (g/cm^3)	3.67	4.88	**5.1**
Temp. Coef. (%/K)	-0.3	0 1.1	**0.0**
Max. Sc. Wavel. (nm)	415	220 310	380
Energy Res. (%)	7	12	**2.5**
Time Res. (ns)	2.5	0.2	**0.2**
Linearity	low	low	**very high**
Hygroscopic	yes	no	yes

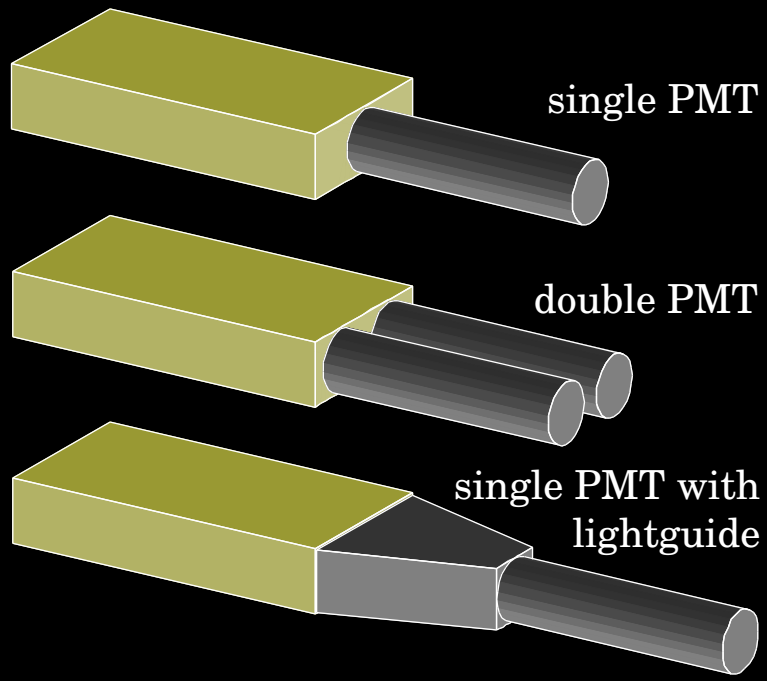
- for same detector volume

$$\epsilon_{FEP} \propto \rho^{1.5} \times Z^{3.5}$$

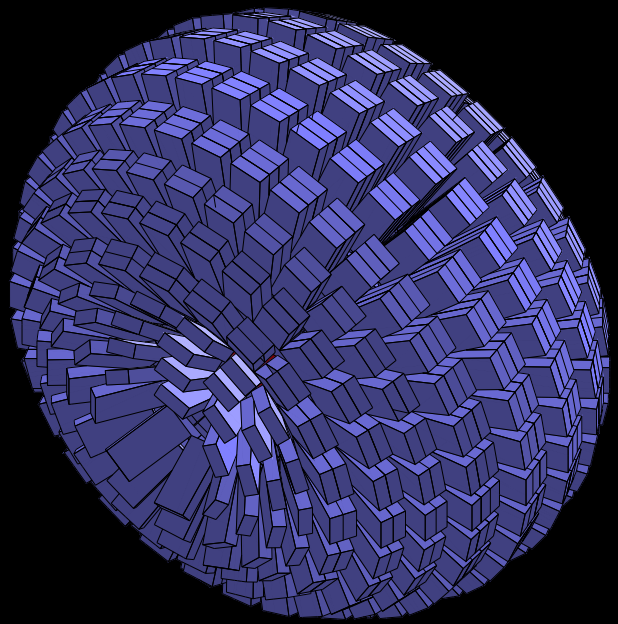
SHOGUN array

SHOGUN Detector Shape

- only one detector shape to reduce detector design/development cost
- possibly place 2–3 detector in one housing, to reduce inactive material
- cuboid: 1.5 cm $\times$ 4 cm $\times$ 8 cm

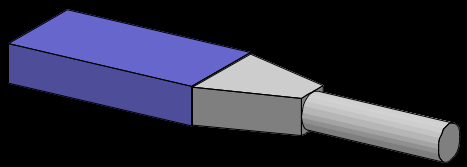


SHOGUN Configurations

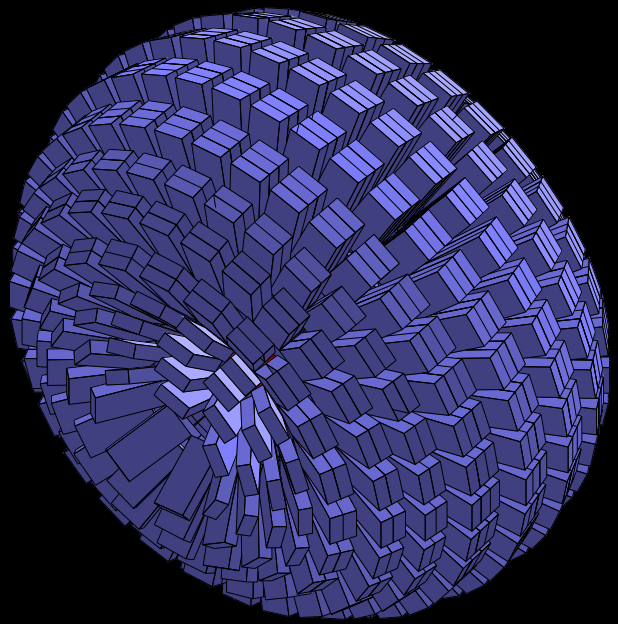


fast beam setup ($v = 0.6c$)			
	$\frac{\Delta E}{E}$ (%)	ϵ_γ (%)	$\epsilon_{\gamma\gamma}$ (%)
NaI(Tl) DALI2	10.0	23.5	5.5
RISING	1.9	2.8	0.08
SHOGUN 1000	**3.2**	**35.0**	**12.2**

$8 \times 4 \times 1.5$ cm^3



SHOGUN Configurations



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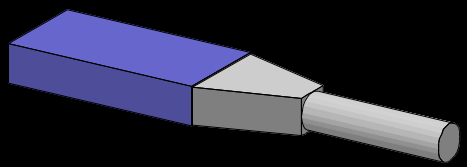
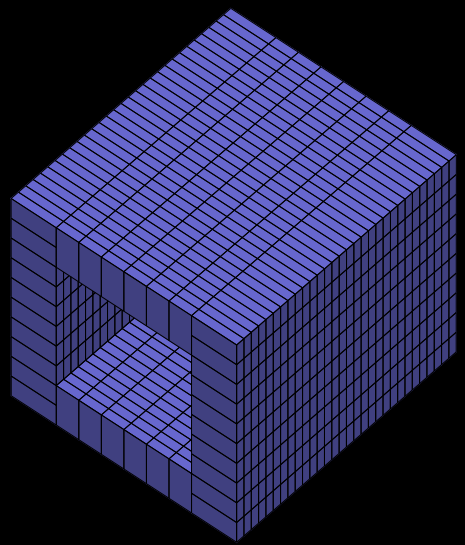
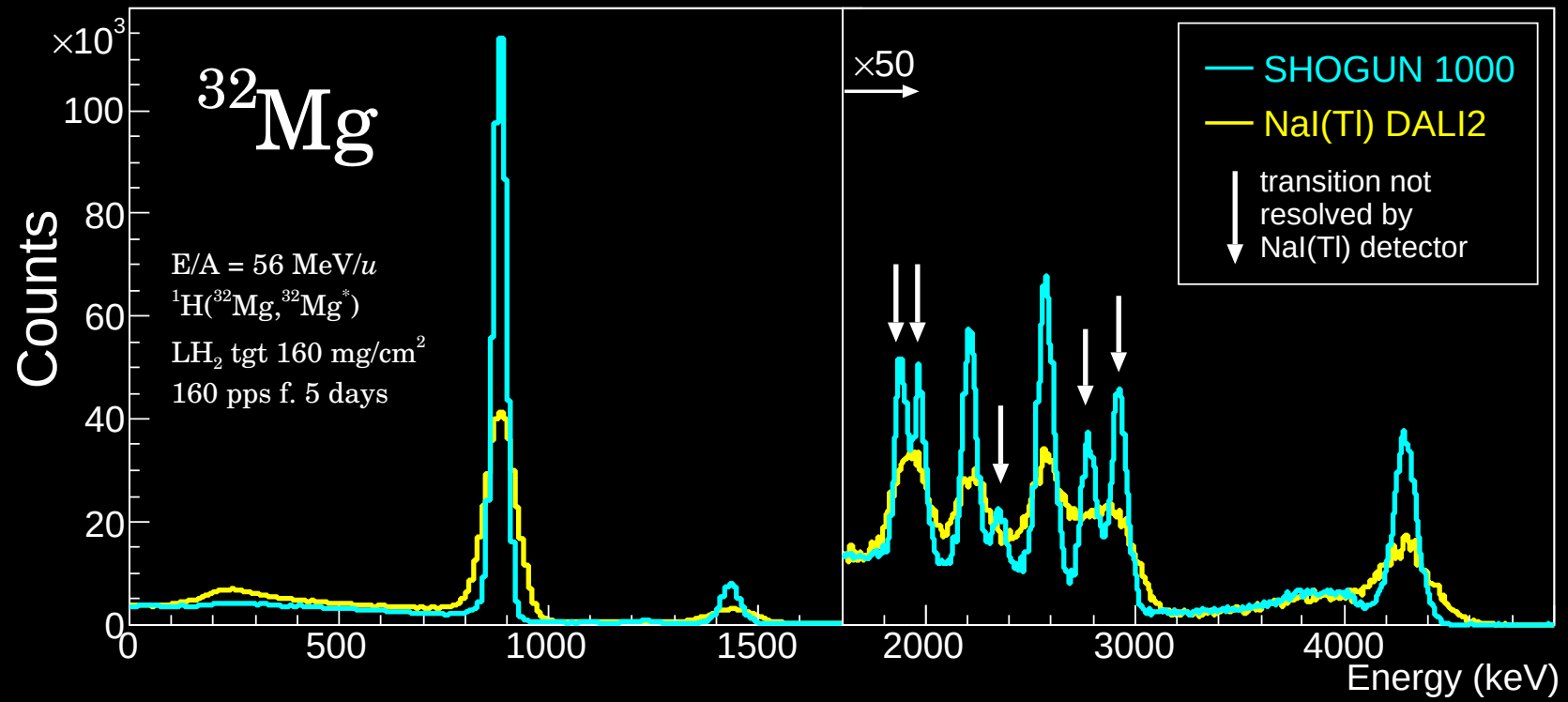




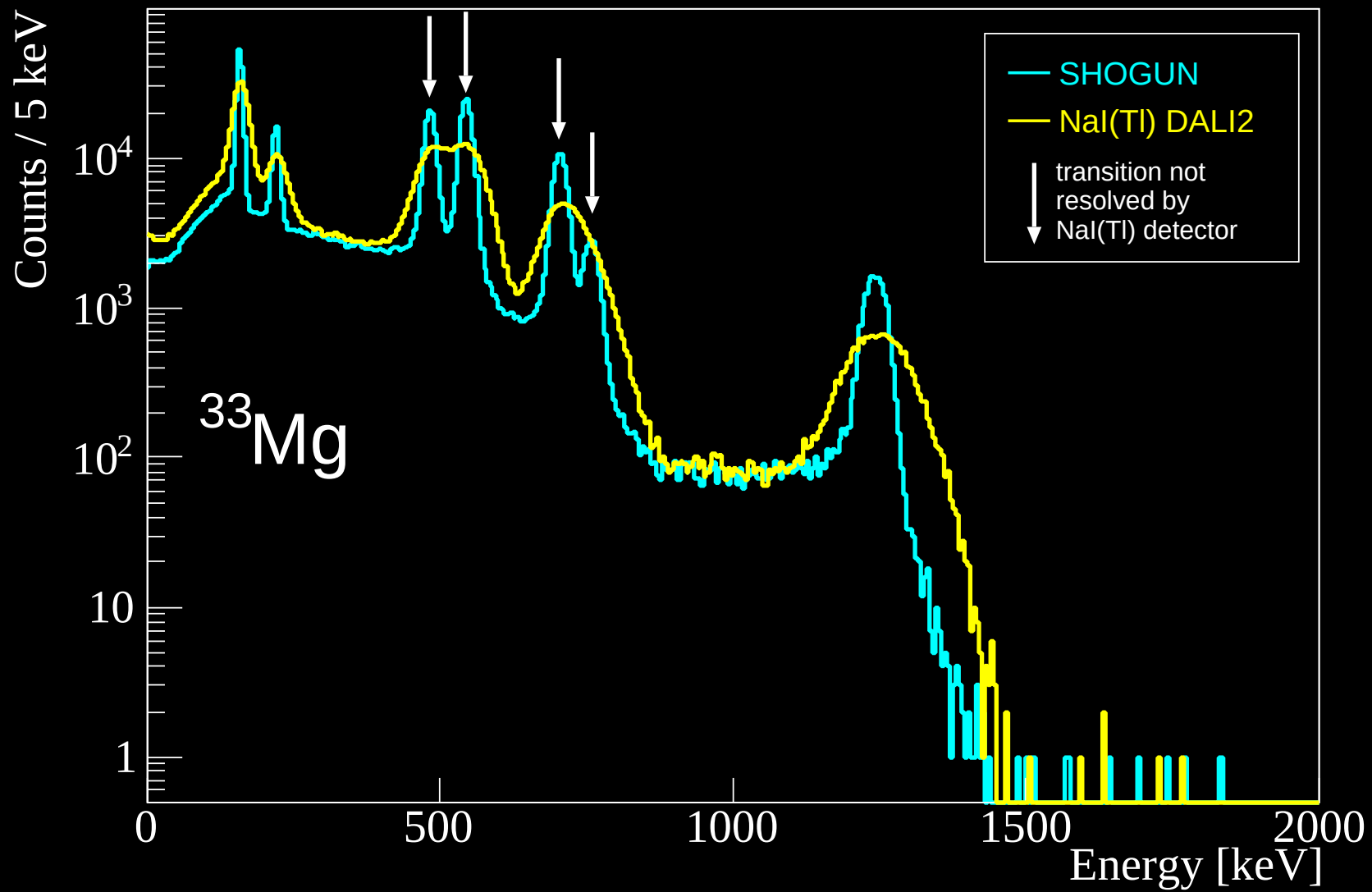
slow/stopped beam setup			
	$\frac{\Delta E}{E}$ (%)	ϵ_γ (%)	$\epsilon_{\gamma\gamma}$ (%)
RISING	0.2	15.0	2.25
SHOGUN 1000	2.4	**56.0**	**31.3**

Simulation: SHOGUN 1000 and DALI2



Simulation by P. Doornenbal
based on experimental data of
S. Takeuchi *et al.*, PRC 79, 054319 (2009)

Simulation: SHOGUN 1000 and DALI2



- E/A = 250 MeV/u
- 1n-removal from ^{34}Mg

SHOGUN Workshop

- February 4-5, 2011
- at RIKEN
- announcement will be sent soon

Summary

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  - 45 new isotopes with $Z = 25 - 52$
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  - 45 new isotopes with $Z = 25 - 52$
  - inclusive Coulomb breakup, interaction cross section
  - β decay studies, many others
- new devices/facilities going online soon (2012)
  - SCRIT, SAMURAI
  - others in planning stage: SLOWRI, RI ring, RI spin laboratory, PALIS, SHOGUN
- SHOGUN, a next generation γ ray spectrometer for fast beams at the RIBF

DayOne Collaboration

N. Aoi, H. Baba, D. Bazin, S. Deguchi, **P. Doornenbal**, N. Fukuda, H. Geissel, R. Gernhäuser, J. Gibelin, I. Hachiuma, Y. Hara, C. Hinke, N. Inabe, K. Itahashi, S. Itoh, D. Kameda, S. Kanno, Y. Kawada, N. Kobayashi, Y. Kondo, R. Krücken, **T. Kubo**, T. Kuboki, K. Kusaka, M. Lantz, K. Li, S. Michimasa, T. Motobayashi, K. Namihira T. Nakamura, T. Nakao, S. Nishimura, T. Ohnishi, M. Ohtake, N. Orr, H. Otsu, K. Ozeki, H. Sakurai, Y. Satou, H. Scheit, S. Shimoura, T. Sumikama, H. Takeda, E. Takeshita, **S. Takeuchi**, M. Takechi, K. N. Tanaka, K. Tanaka, Y. Togano, H. Wang, M. Winkler, Y. Yanagisawa, K. Yoneda, A. Yoshida, K. Yoshida