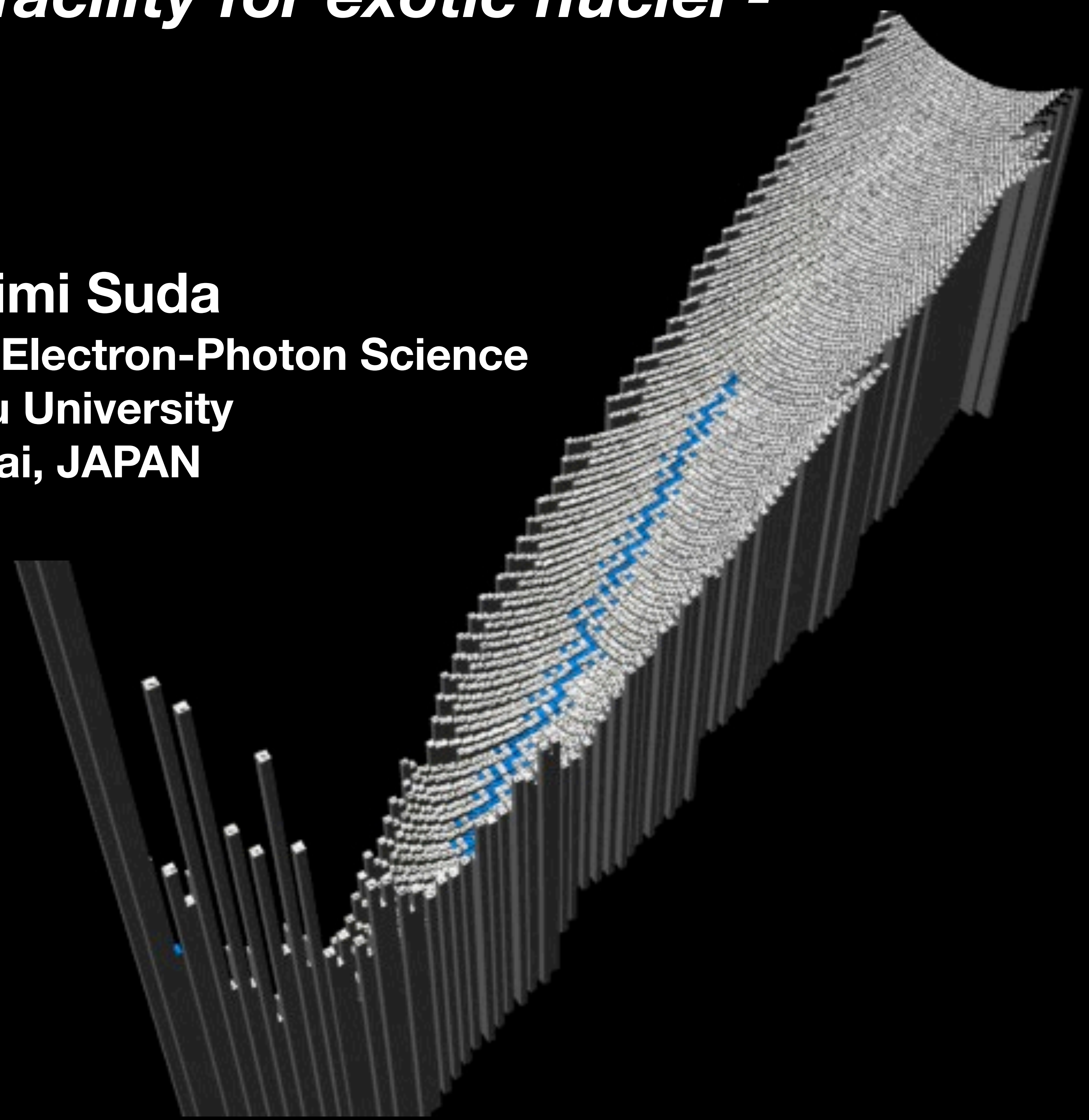
SCRIT Electron Scattering Facility

- world's first facility for exotic nuclei -



Toshimi Suda
Research Center for Electron-Photon Science
Tohoku University
Sendai, JAPAN

“The 11 Greatest Unanswered Question in Physics”

A list of the questions developed by
National Research Council’s Committee
on Physics of the Universe, US.

Q1. What is dark matter ?

Q2. What is dark energy ?

Q3. How are the heavy elements from iron to uranium made ?

Q4. Do neutrinos have mass ?

Q5. Where do ultrahigh-energy particles come from ?

Q6. Is a new theory for ultra high energy and high temperature ?

Q7. Are there new states of matter at ultrahigh temperature and densities ?

Q8. Are protons unstable ?

Q9. What is gravity ?

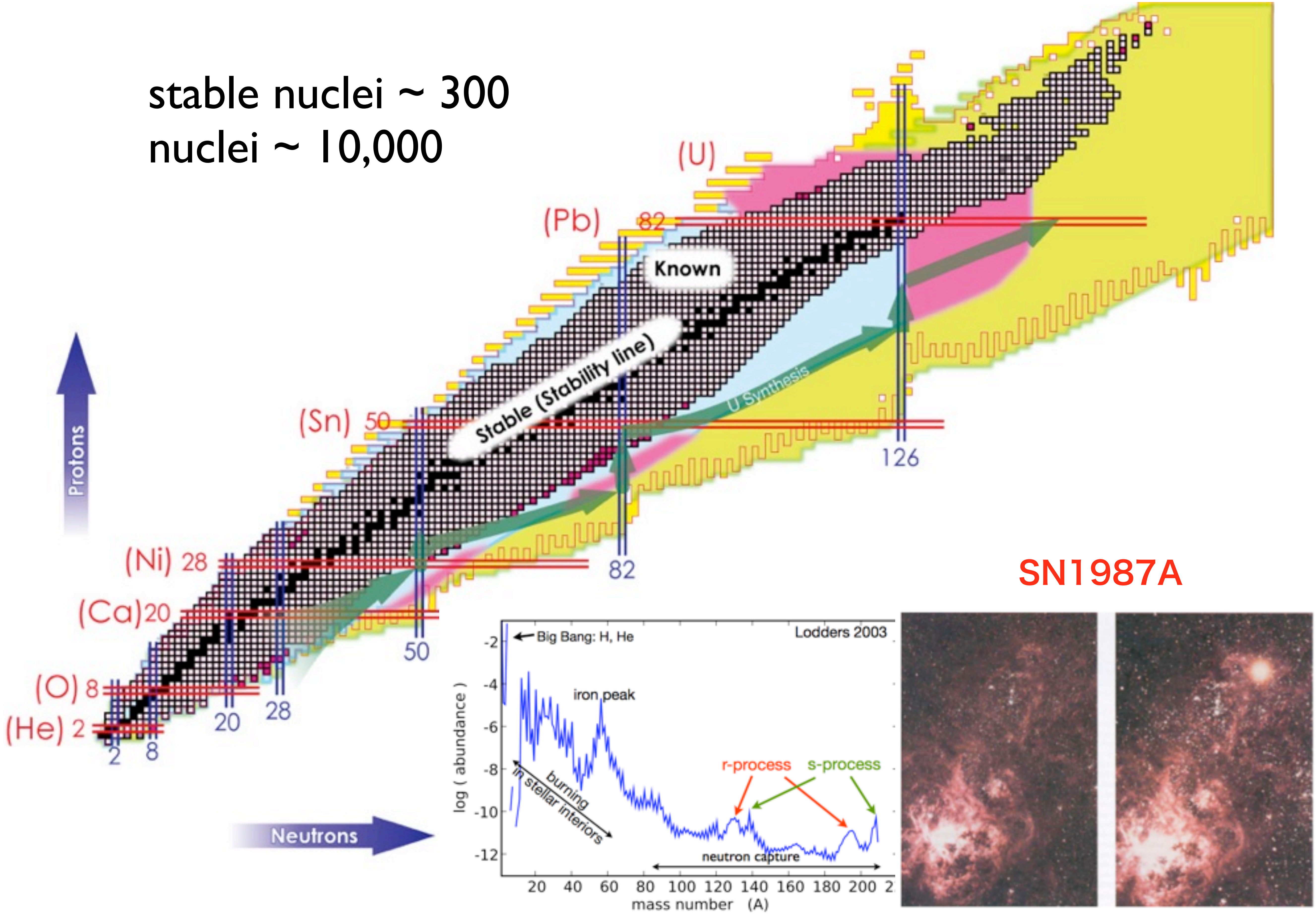
Q10. Are there additional dimensions ?

Q11. How did the universe begin ?

“Discover” 2002

Nuclear Chart

stable nuclei ~ 300
nuclei ~ 10,000



SN1987A

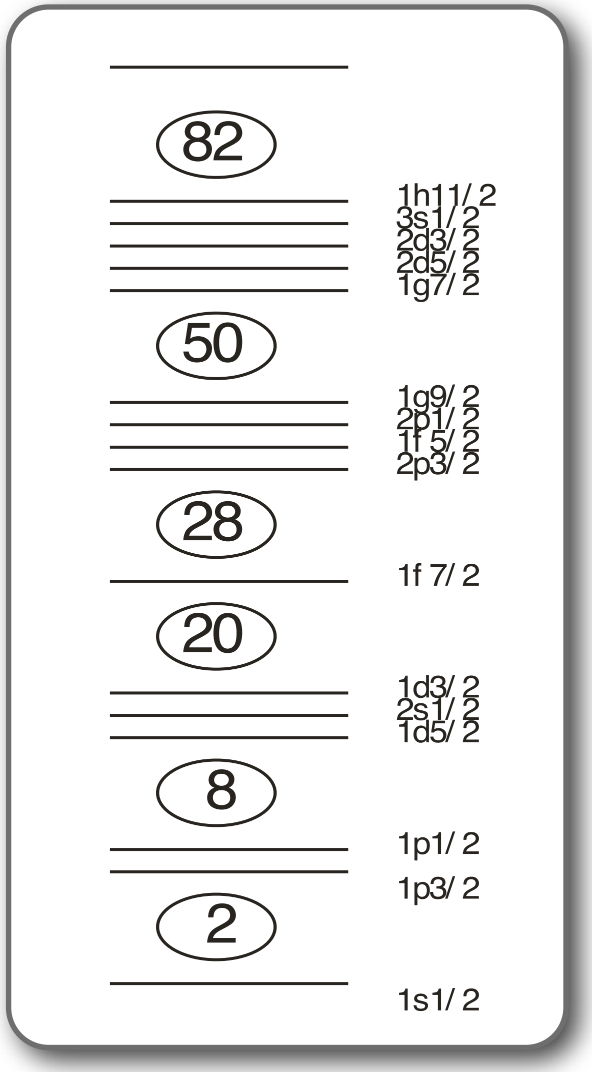
Structures of stable nuclei

Shell structure

magic numbers :
2, 8, 20, 28, 50, 82, 126
(for both proton and neutron)

⇨ stability

M.G.Mayer and J.Jensen
(Nobel prize : 1963)



Charge density distribution

"visualized" by elastic electron scattering (R. Hofstadter)

1) constant (saturated) density

2) clear surface despite a fully quantum system

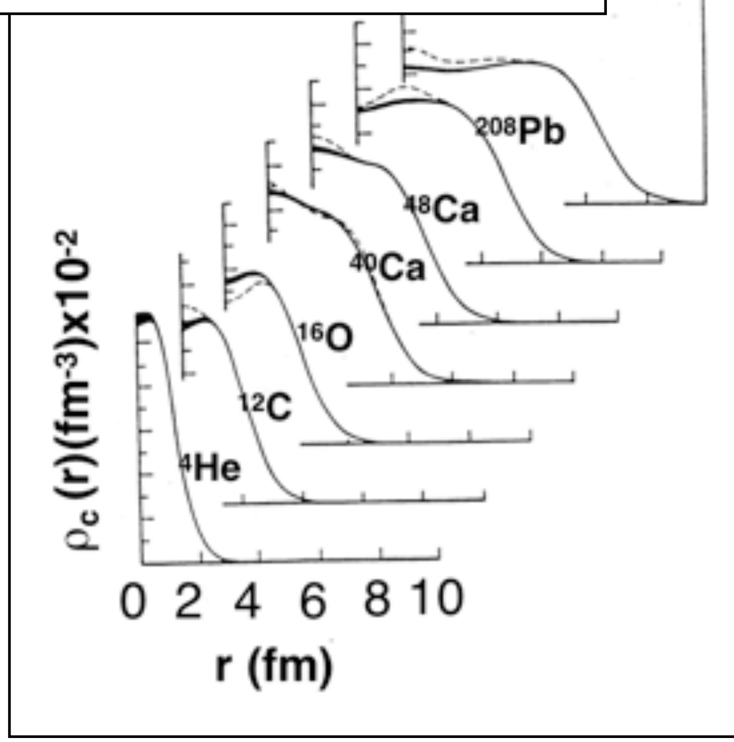
constant surface diffuseness

3) $A^{1/3}$ dependence of the radius

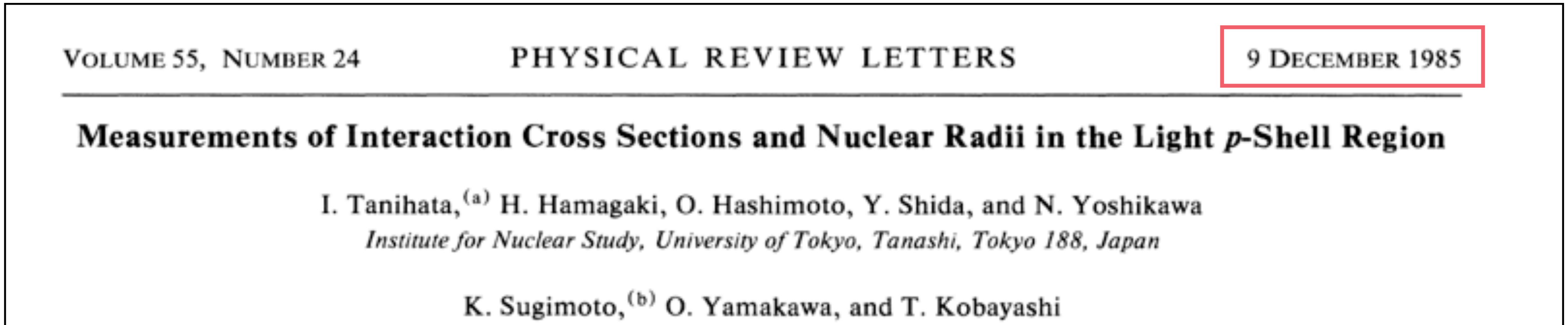
(A : mass number)

R. Hofstadter
(Nobel prize : 1961)

Charge density distributions by electron scattering



Ground-breaking discovery of neutron halo structure in ^{11}Li

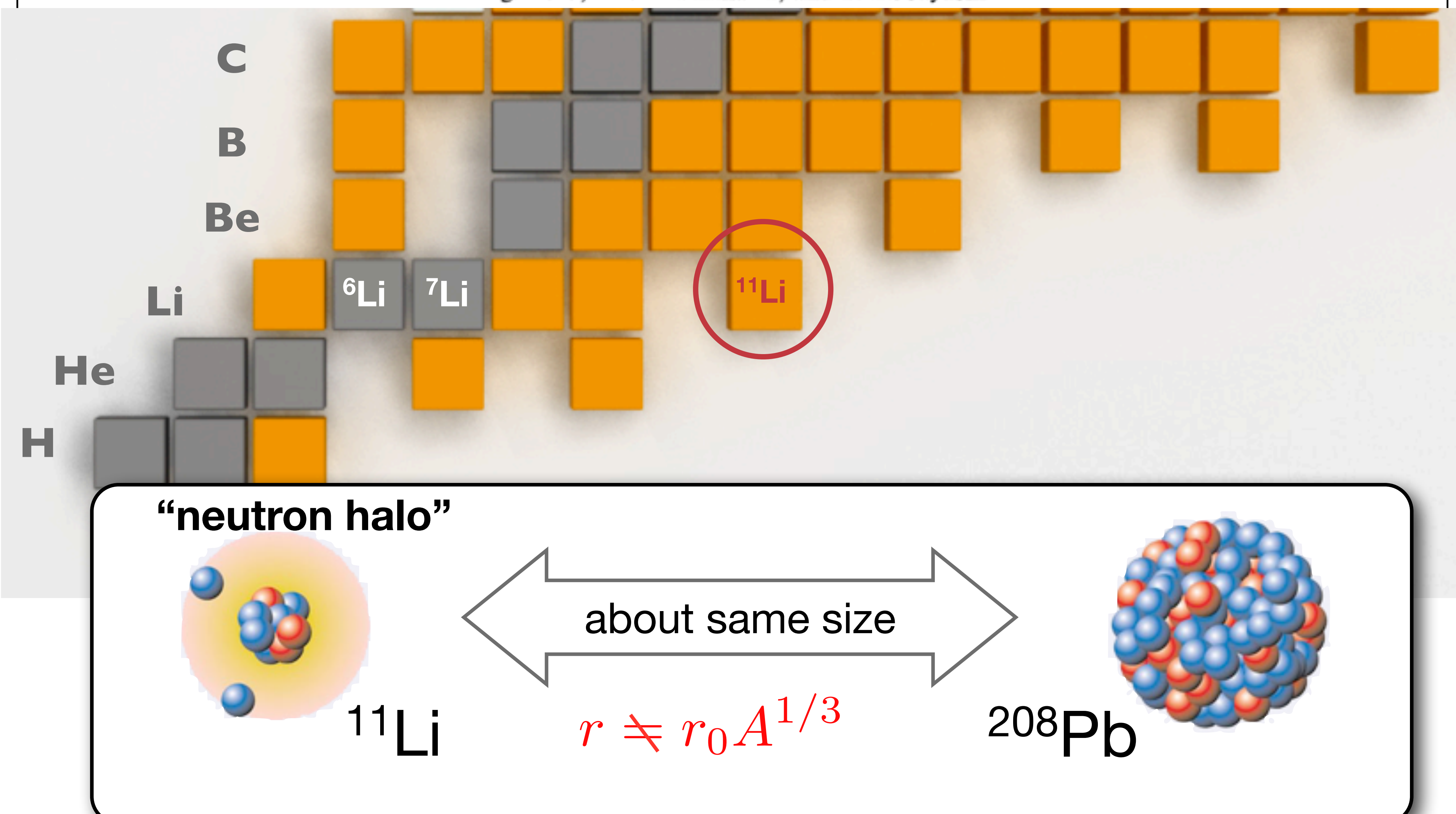


VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Measurements of Interaction Cross Sections and Nuclear Radii in the Light *p*-Shell Region

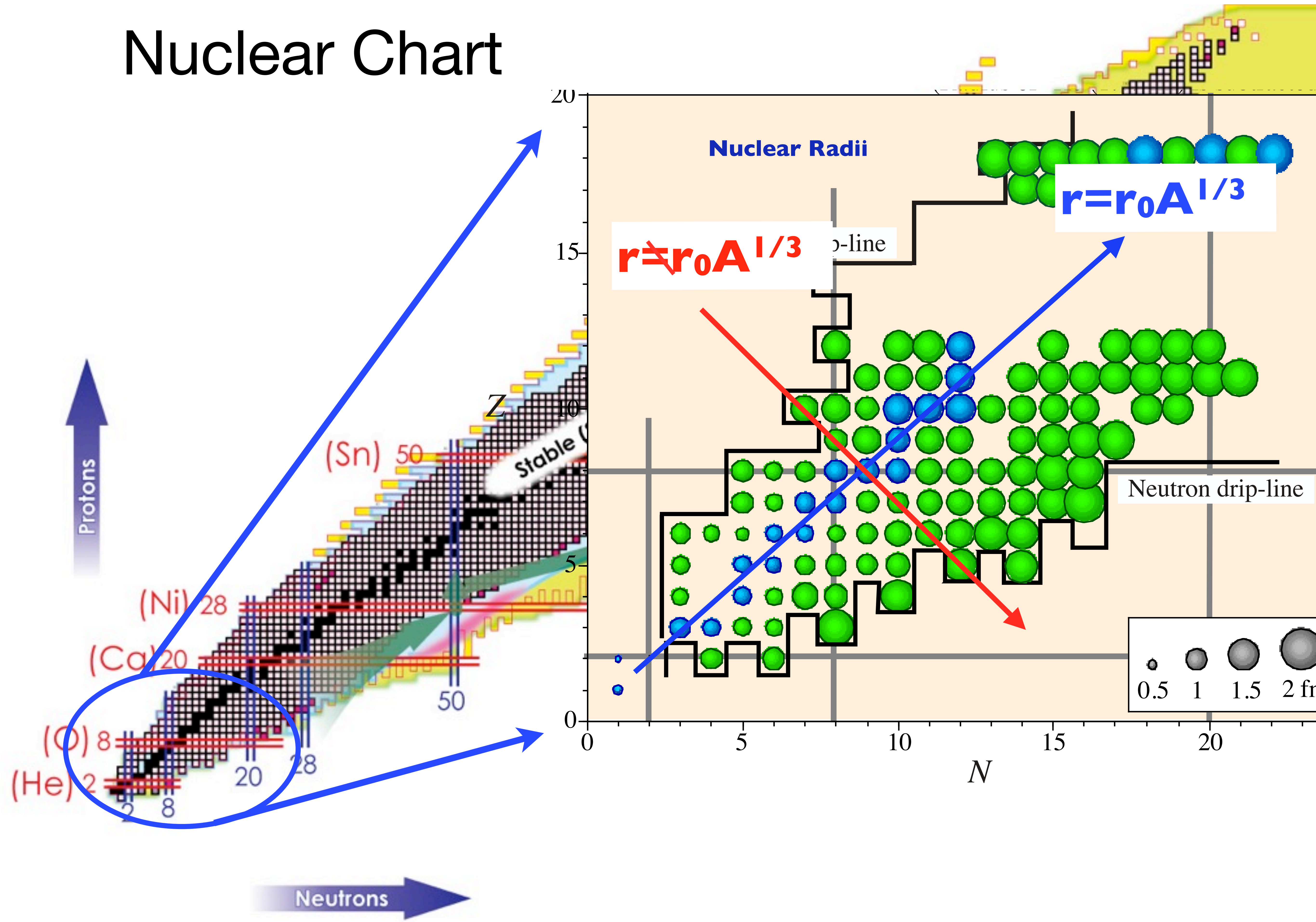
I. Tanihata,[a] H. Hamagaki, O. Hashimoto, Y. Shida, and N. Yoshikawa
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

K. Sugimoto,[b] O. Yamakawa, and T. Kobayashi



our understanding of nuclear properties : limited to nuclei near the stability ??

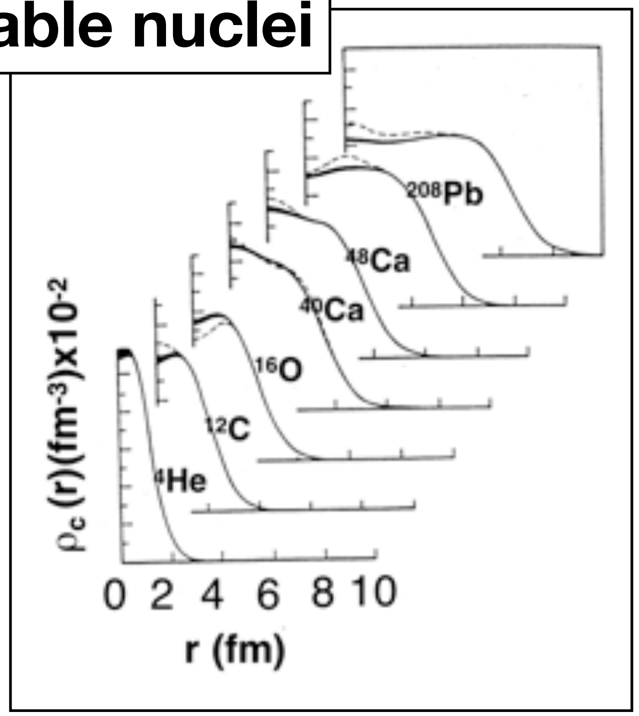
Nuclear Chart



Basic properties of nuclei far from stability

nucleon density distributions

stable nuclei



	stable nuclei	exotic nuclei
radius	$\propto A^{1/3}$	$\not\propto A^{1/3}$
surface diffuseness	const.	ex. halo
saturation	~0.17 /fm^3	??

magic numbers

well-established numbers for stable nuclei

2,~~8~~,~~20~~,28,50,82, 126 16, 34 ...

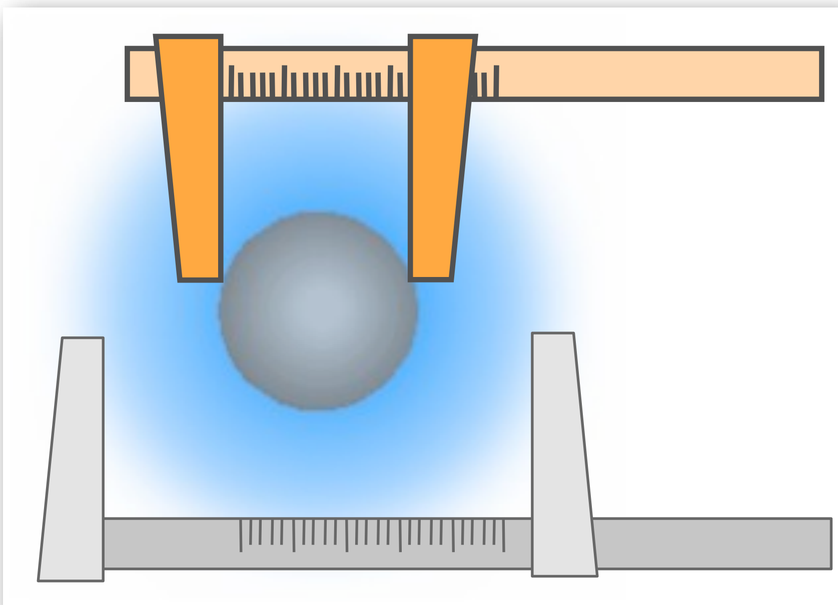
LETTER Nature 502, 207 (2013) 34 doi:10.1038/nature12522

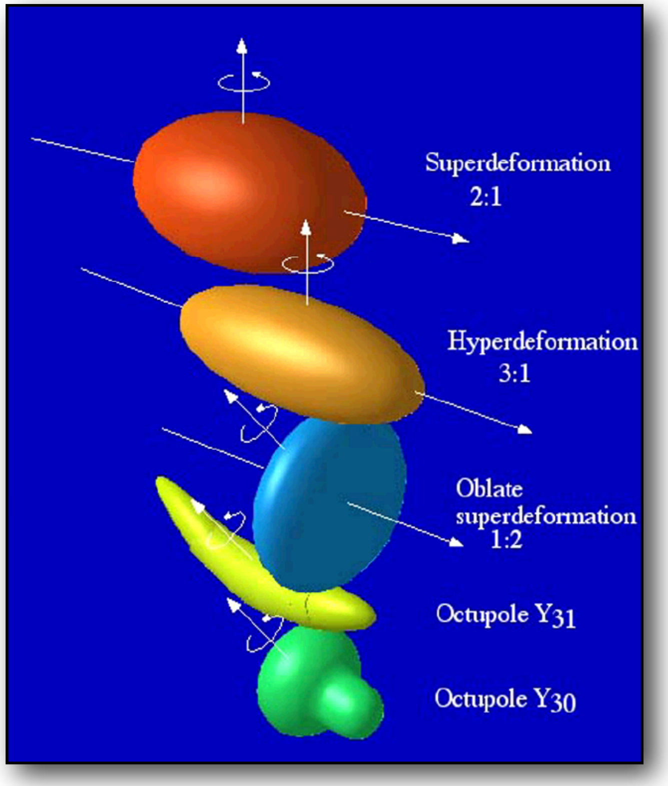
Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

Ground-state properties of exotic nuclei

such as mass, size and shape, lifetime ...





1) establish "better" nuclear structure model

2) exploit the limit of existence

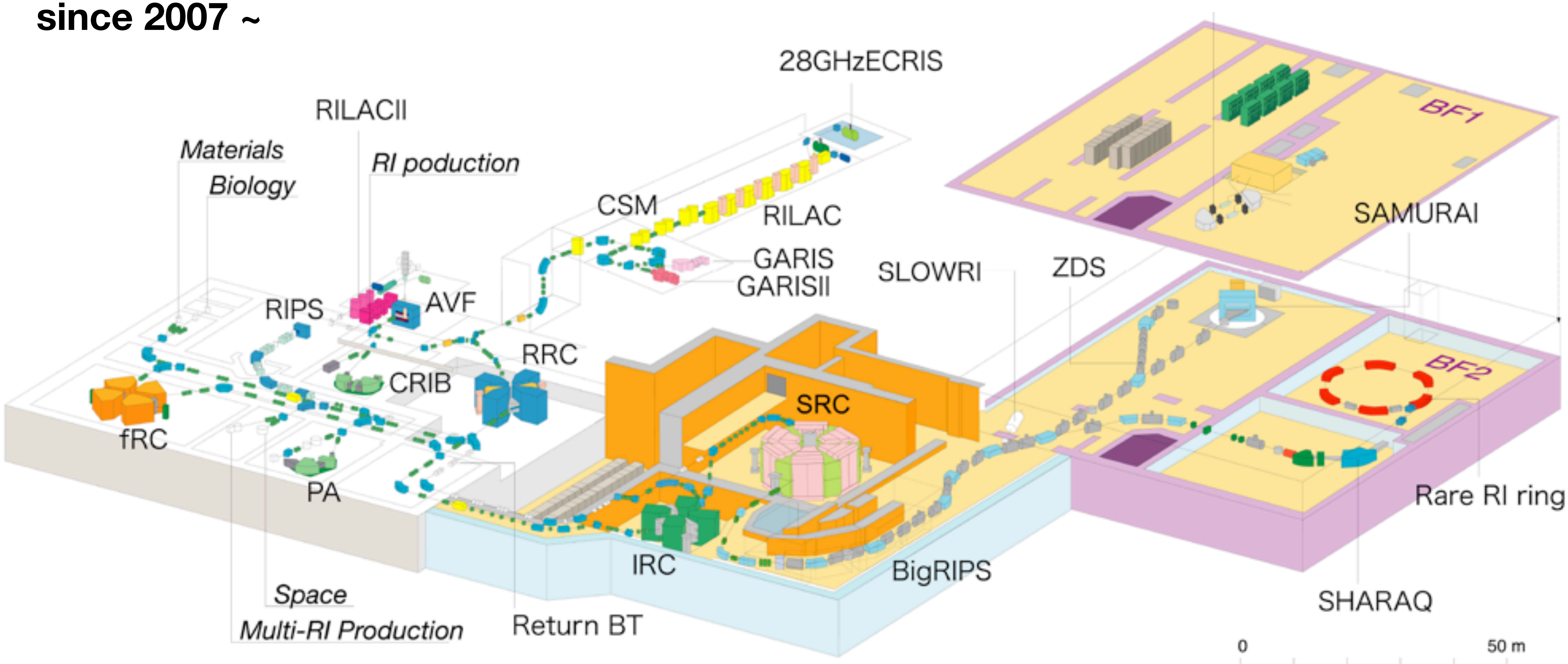
3) understand nucleosynthesis in the universe

RIKEN RI Beam Factory (Japan)

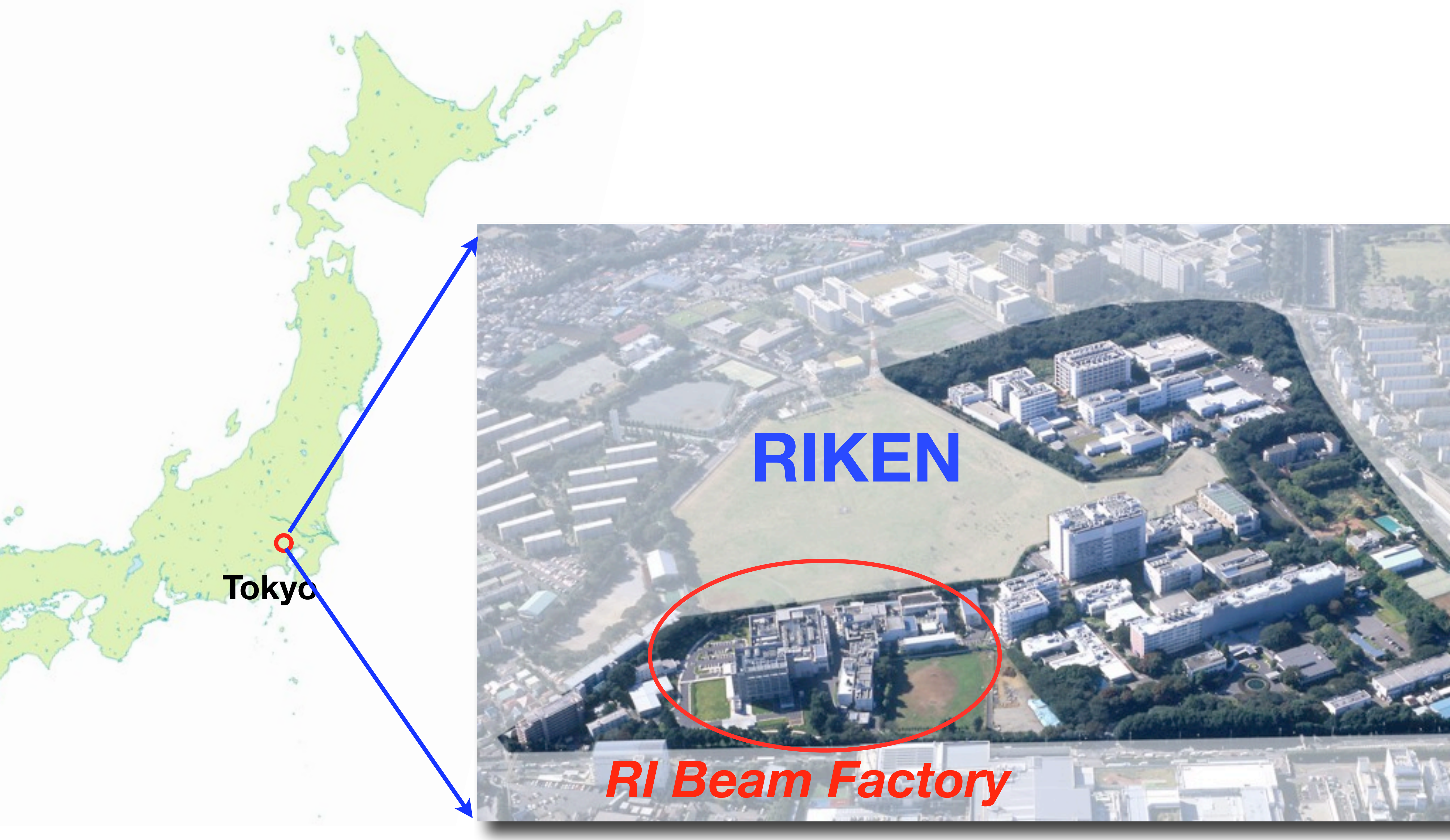
Primary beam : p - U (350 MeV/u, 1 pμA)

Radioactive Isotope (RI) beam :
projectile fragmentation + in-flight fission
$\beta \sim 0.6$

since 2007 ~



Where is RIKEN RI Beam Factory ?



"Nature" **"Science"**

Often he is asked what he has done with the roughly $350,000 in Nobel Prize money, an enormous sum in a country where experienced researchers are being promised 30,000 rubles ($1150) a month by 2008. He says that he has put the money away for the college educations of his two great-grandchildren, a twin boy and girl living in Princeton, New Jersey.

He sold his country house to help pay for medical treatment and likens his fate to that of two great Soviet physicists, Igor Y. Tamm and Lev D. Landau, both Nobel laureates with whom he worked. (Like Tamm, Ginzburg was recruited to help design the first Soviet nuclear bombs, but by a stroke of luck, he says in his Nobel autobiography, his low security rating kept him in Moscow, away from the Arzamas-16 military site.) Although he is proud to have followed in the footsteps of Tamm and Landau as a physicist, he says he is reluctant to be following "their path [to the grave]." He recounts their deaths in an essay on the Web site of a magazine for which he is editor, *Uspekhi Fiziki*, or *Advances in Physics*, which has been in existence since 1918.

Tamm, who suffered from amyotrophic

NUCLEAR PHYSICS

Japan Gets Head Start in Race to Build Exotic Isotope Accelerators

A new facility begins to explore the structure of the nucleus as Europe awaits two machines and the United States revises its plans

WAKO, JAPAN, AND ROSEMONT, ILLINOIS— Sometime this month, a warning siren will clear personnel out of the bowels of a massive concrete building in Wako, a city just east of Tokyo. Then, the world's most powerful cyclotron will propel a stream of uranium ions at a carbon target. The resulting smashup will produce radioactive nuclei that have never existed outside a supernova. Such fleeting exotic bits of matter should help unify a fragmented theory of the nucleus, reveal the origins of the heavier elements, and provide clues to why the universe contains so much more matter than antimatter.

Data from the $380 million Radioactive Isotope Beam Factory (RIBF) at the Institute of Physical and Chemical Research (RIKEN) in Wako "will allow us to form a new framework for nuclear physics," says Hiroyoshi Sakurai, chief nuclear physicist at RIKEN's Nishina Center for Accelerator-Based Science, which built and will operate the machine. Richard Casten, a nuclear physicist at Yale University, agrees that knowledge sifted from the atomic shards "will be transformational in our understanding of nuclei."

But Japanese physicists aren't the only ones staking a claim to this fertile turf. RIBF is the first in a new generation of exotic isotope accelerators. Researchers in Germany and France hope to have machines ready to power up in 2010 and 2011, respectively.

Meanwhile, a U.S. National Research Council (NRC) report released last week makes the case for building the most powerful machine of all. U.S. researchers hope the report will jump-start a project, once known as the Rare Isotope Accelerator (RIA), that stalled last year after the U.S. Department of Energy (DOE) ordered researchers to cut in half the projected $1 billion cost. "This report helps get the project unstuck by more clearly defining the science that can be done with it and the international situation," says Michael Turner, a cosmologist at the University of Chicago and chief scientist at DOE's Argonne National Laboratory in Illinois, one of two institutions vying for the machine.

Accounting for more than 99.9% of an atom's mass and less than a billionth of its volume, the nucleus is a knot of protons and neutrons. Nature provides 260 stable nuclei, and researchers have glimpsed 10 times that number of unstable ones. But machines that produce even more would provide new insights into the structure of the nucleus.

For example, since the 1940s, physicists have known that nuclei with certain "magic" numbers of protons or neutrons appear to be more stable than might otherwise be expected. However, recent findings suggest that the known magic numbers—2, 8, 20, 28, 50, 82, and 126—may not apply to nuclei with an extreme excess or deficiency of

Published by AAAS

Japan speeds up nuclear physics

No particle accelerator in the world is strong enough to create a usable beam of uranium ions. But that will change next month, when Japan switches on a huge facility of connected accelerators, to produce the world's most powerful beams of heavy radioactive isotopes.

Radioisotopes are forms of elements that are unstable because they contain either more or fewer neutrons than usual, and so undergo radioactive decay. Nuclear physicists are studying rare short-lived isotopes to understand their properties and how they are formed. The RIKEN research institute in Saitama, Japan, already has accelerators that can create the world's strongest radioisotope beams, but even these are only powerful enough to produce usable beams for the lighter elements.

But next month, RIKEN will switch on a major upgrade. The ¥44-billion (US$378 million) Radioactive Isotope Beam Factory will add two more ring cyclotrons and the world's first superconducting ring cyclotron to the existing linear accelerator and ring cyclotron. It will then be able to accelerate beams of any element up to uranium at 70% of the speed of light. The accelerated beams are smashed into a target such as beryllium to knock out neutrons and protons and create the desired radioisotopes.

The facility should open a new realm of astrophysics. "With this new facility, scientists at RIKEN have the opportunity to study nuclear isotopes that exist only in the hottest stars of the Universe," says John Schiffer, a senior scientist at the Argonne National Laboratory in Chicago, Illinois.

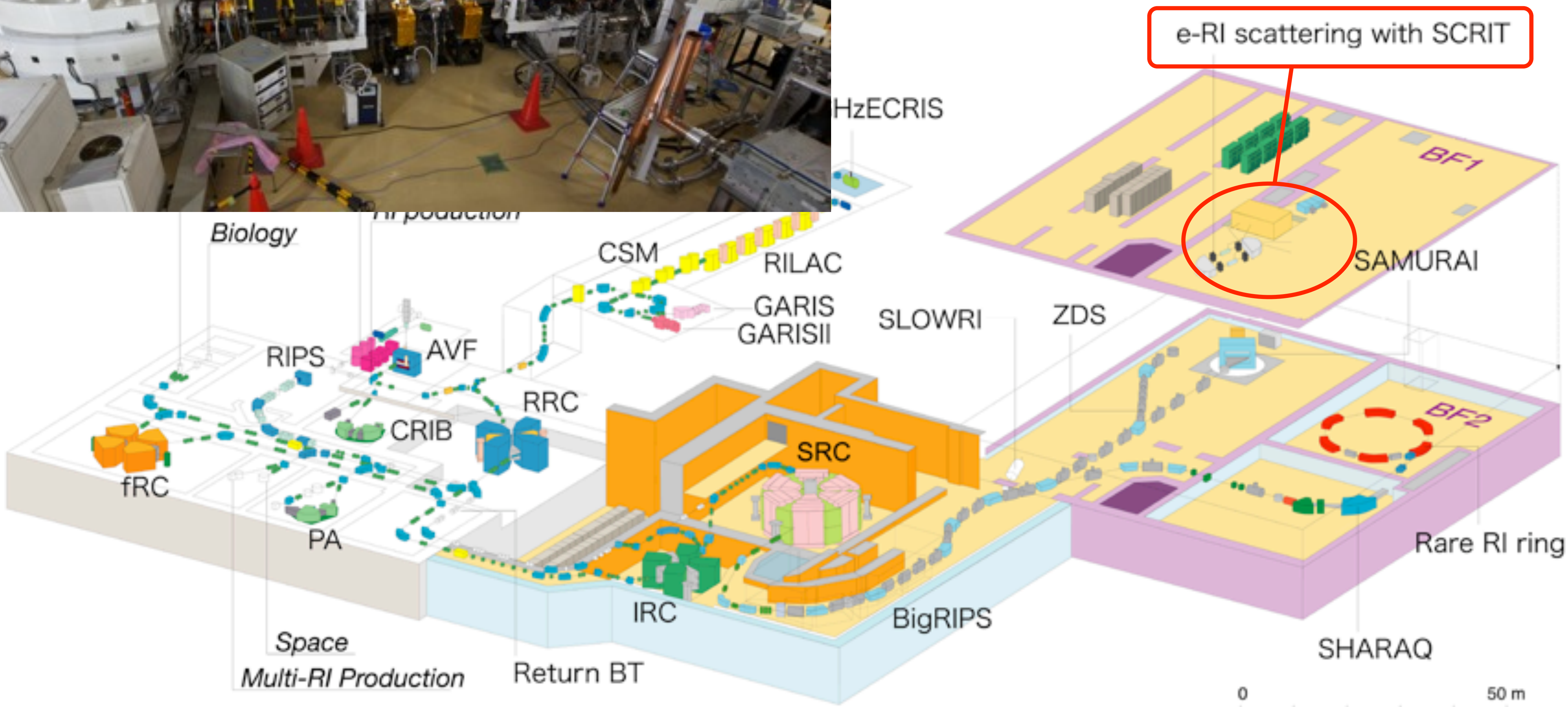
> "Scientists will be able to study nuclear isotopes that exist only in the hottest stars."

As well as exploring the formation of uranium, RIKEN plans to measure the properties of various very short-lived nuclei, as well as looking for 'magic numbers' of neutrons and protons that allow heavy nuclei to be surprisingly stable. These experiments will start from next year, with full operation scheduled for 2011. The facility makes Japan the world leader in the field, says Ysushige Yano, director of the RIKEN Nishina centre for accelerator-based science, adding that Japan's other big physics facilities have just been upgrades of US and European versions. "But this time it is different," he boasts. "This time, Japanese scientists are leading the way."

Rivals aim not to let Japan savour its victory for long. A US plan for a superconducting linear accelerator called the Rare Isotope Accelerator has stalled, at a proposed cost of $1 billion. But France is expected to complete construction of its new radioisotope facilities, including experiments, by around 2012 and Germany by 2014. "In five or six years, Japan may lose the number one position," says Sydney Gales, director of the French heavy-ion accelerator GANIL in Caen. ■

Ichiko Fuyuno

SCRIT Electron Scattering Facility

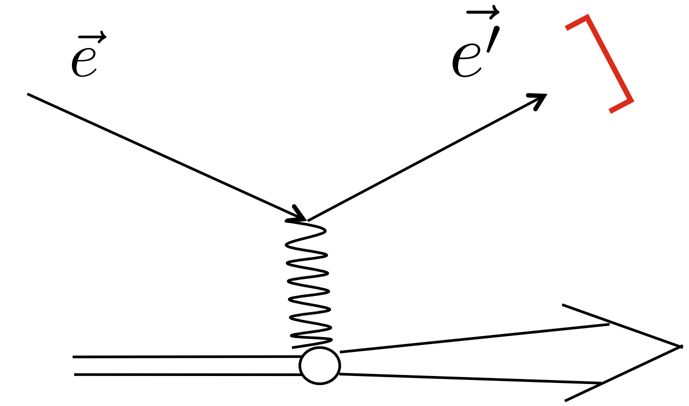


*The **world's first** and **only** electron scattering facility dedicated for exotic nuclei is nearly completed in RIKEN RI Beam Factory, JAPAN.*

The first electron scattering off an exotic nucleus will take place in 2014 !!

Electron scattering

Electron Scattering



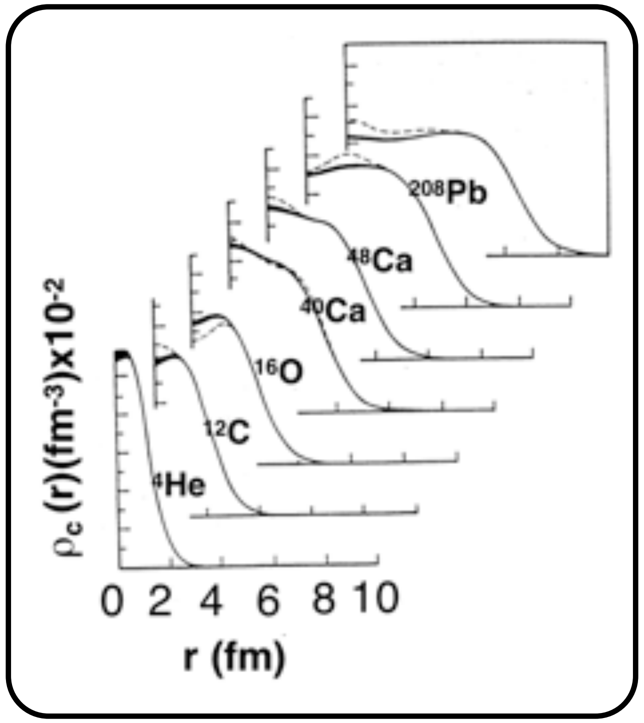
Electron scattering provides direct and unambiguous structure information of atomic nuclei

$$\omega = e - e'$$
$$\vec{q} = \vec{e} - \vec{e'}$$

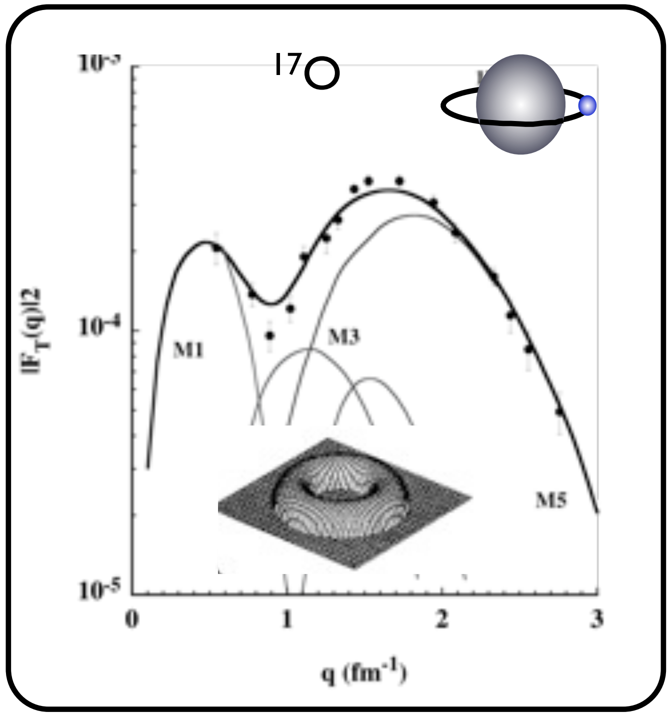
1. *point particle*
2. *electromagnetic interaction*
   - *i) coupling : charge and current => el.mag. structure*
   - *ii) "weak" -> probing whole volume*
     perturbation theory
   - *iii) exp. data => structure information*
3. *variable q for fixed ω*

Electron scattering for stable nuclei

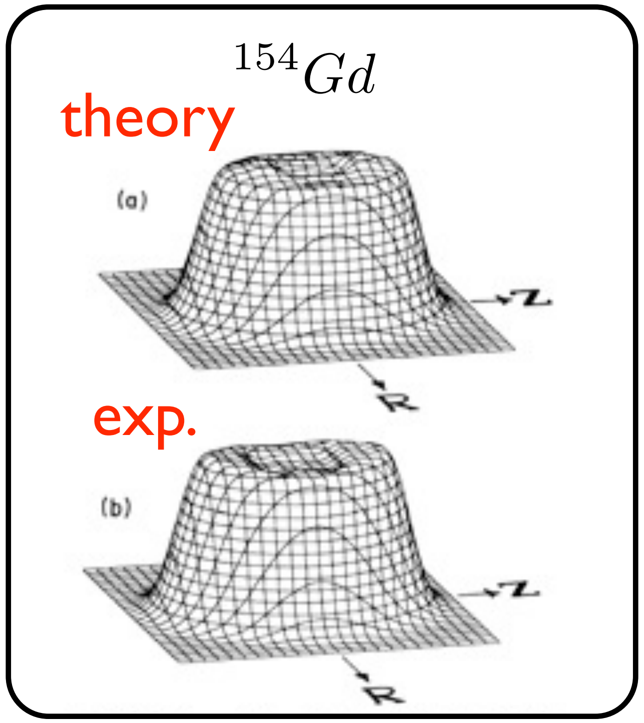
charge distribution



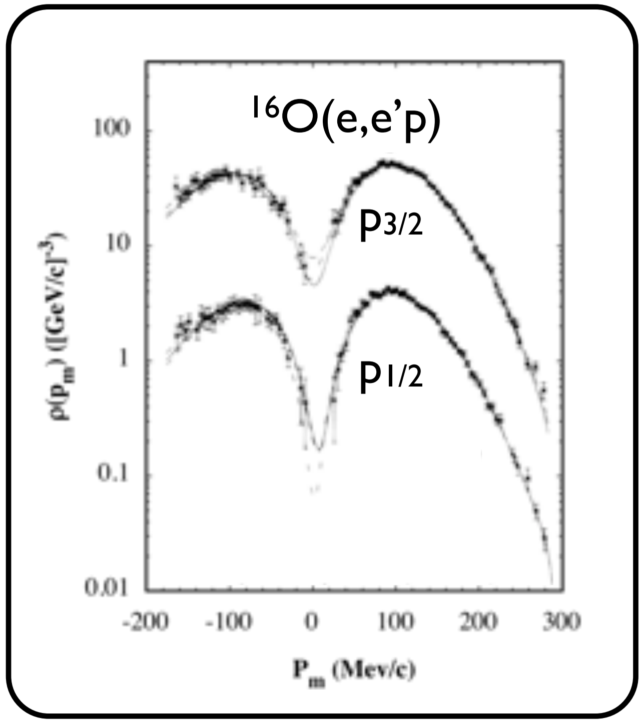
valence neutron



deformation

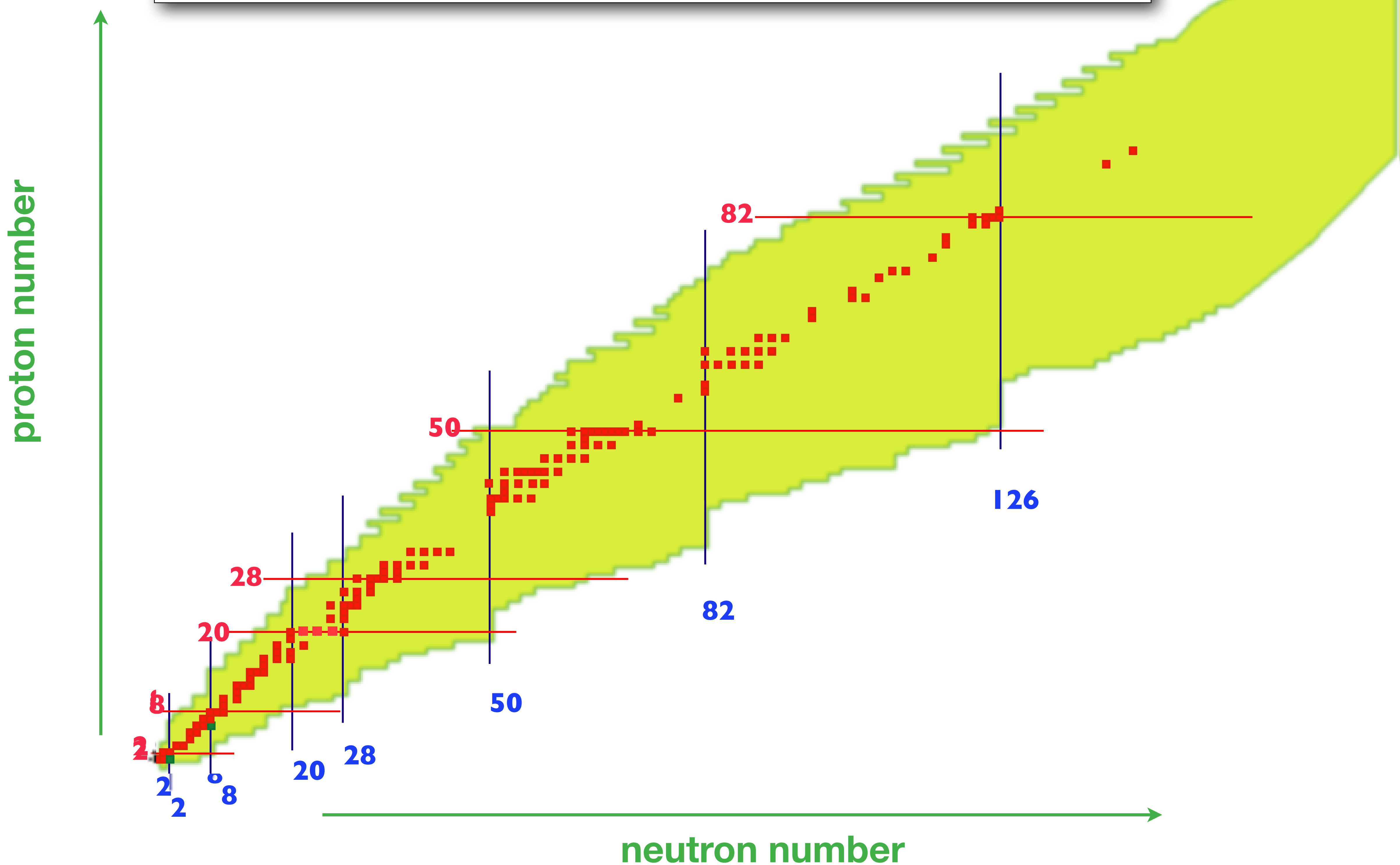


$|\Phi(p)|^2$, S-factor



Nuclei so far studied by electron scattering

- Most of stable nuclei (except noble gases such as Kr, Xe)
- some example for unstable nuclei such as ^{3}H, ^{14}C, ^{41}Ca etc…



Hofstadter's experiments for exotic nuclei

low production rate, and short half lives ⇨ no "thick" target

expected low luminosity ⇨ elastic scattering (largest σ)

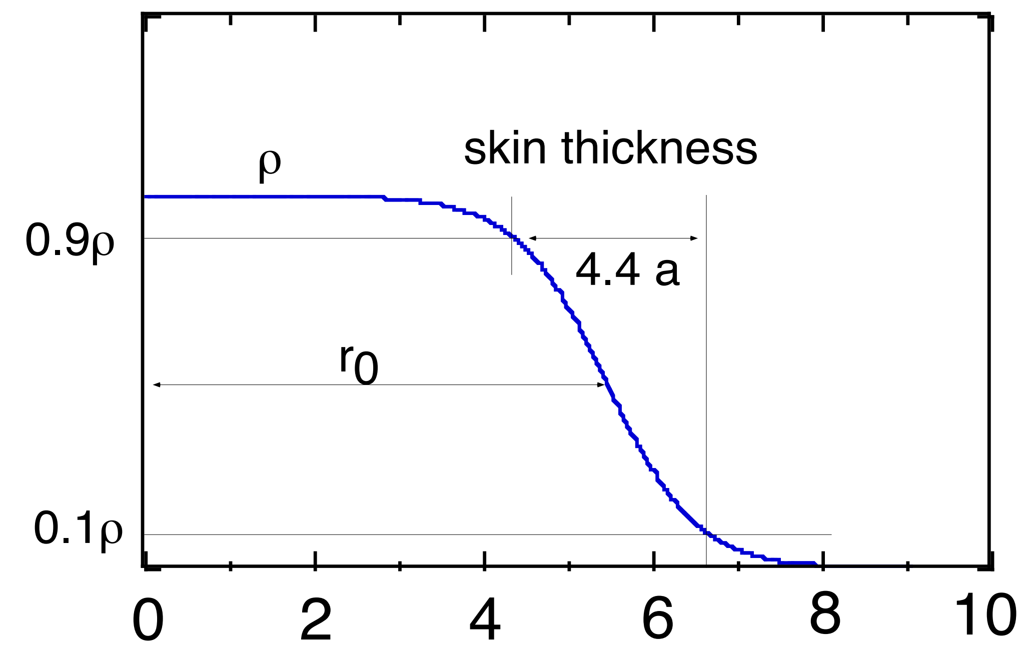
Elastic Electron Scattering

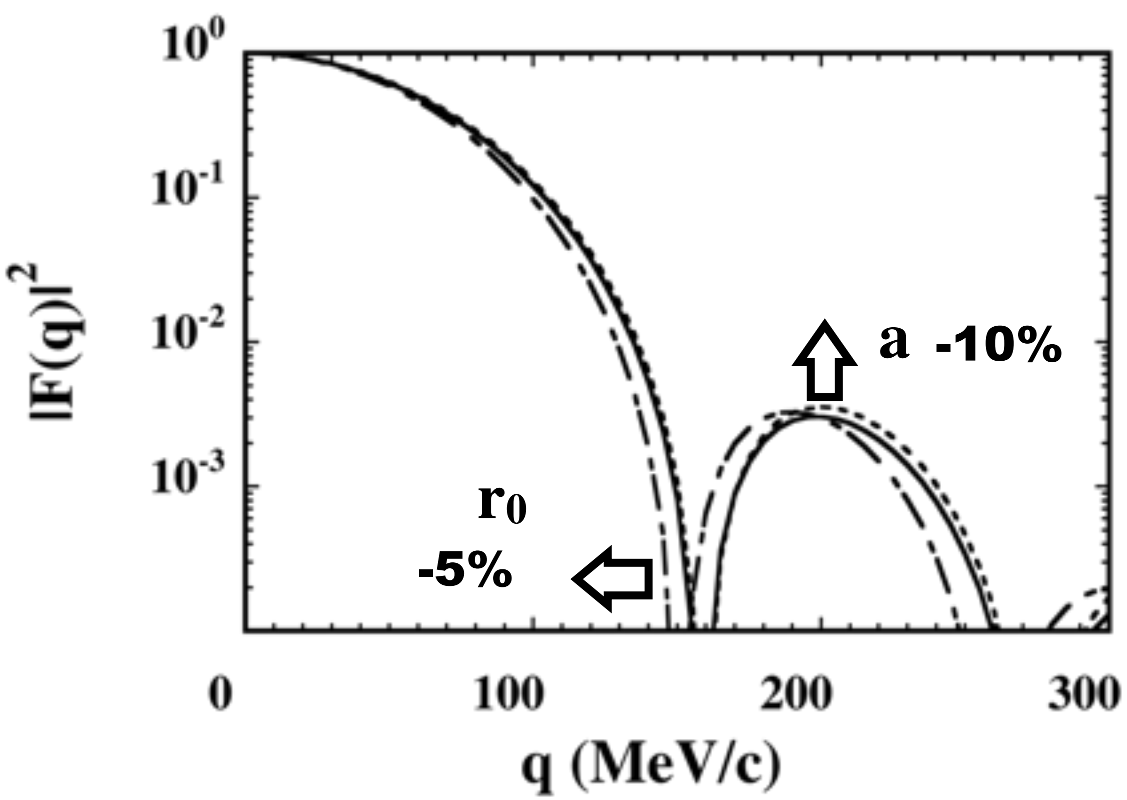
$$\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{Mott}|F_c(q)|^2$$

$$\frac{d\sigma_{Mott}}{d\Omega} = \frac{z^2\alpha^2 cos^2(\frac{\theta}{2})}{4e^2 sin^4(\frac{\theta}{2})}$$

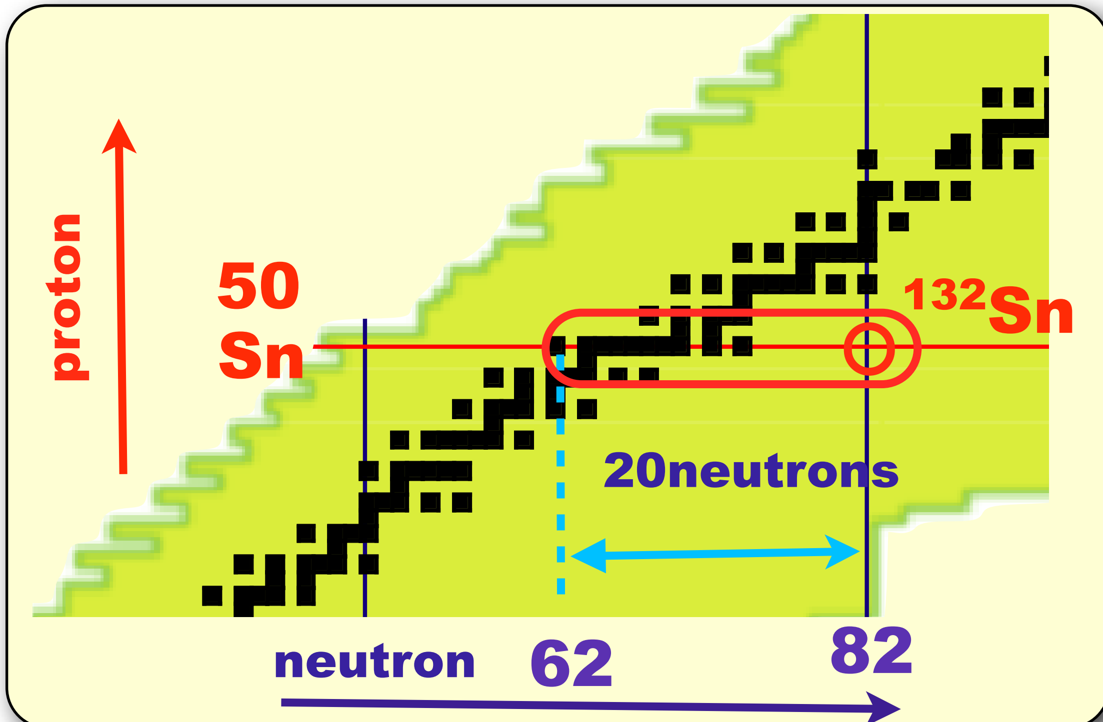
$$F_c(q) = \int \rho_c(\vec{r})e^{i\vec{q}\vec{r}}d\vec{r}$$

$$\rho_c(\vec{r}) = \sum_{i=1}^{Z} |\psi_i(\vec{r})|^2$$





One example : unstable Sn including ^{132}Sn (doubly magic)



$^{112-124}$Sn : stable

$^{126-132}$Sn : unstable

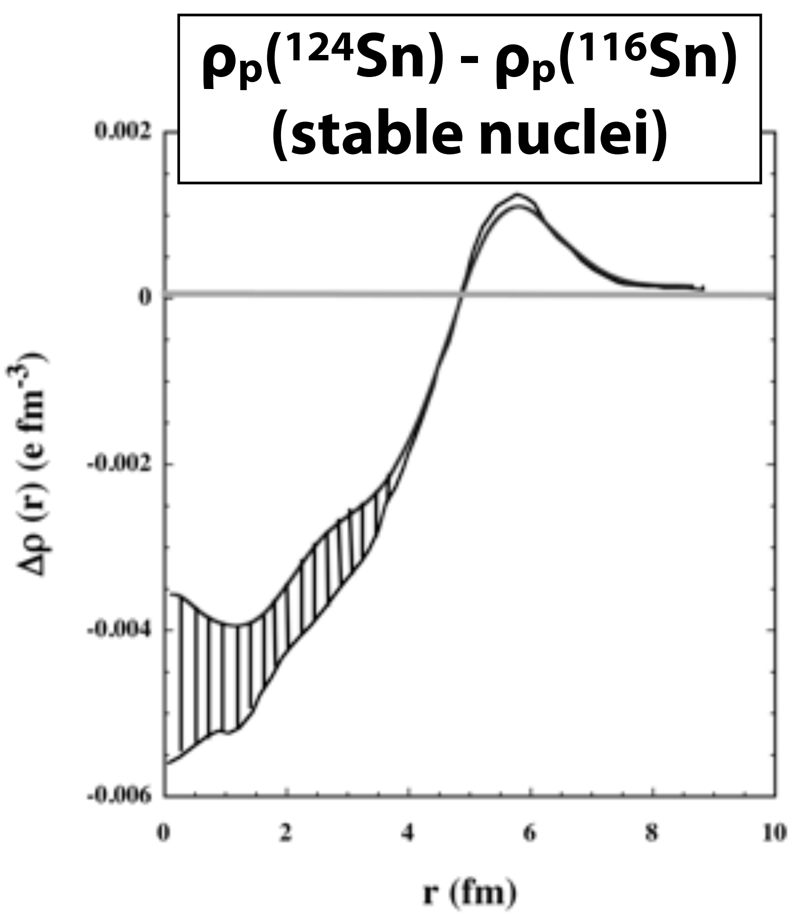
^{126}Sn : 10^5 year

^{128}Sn : 59m

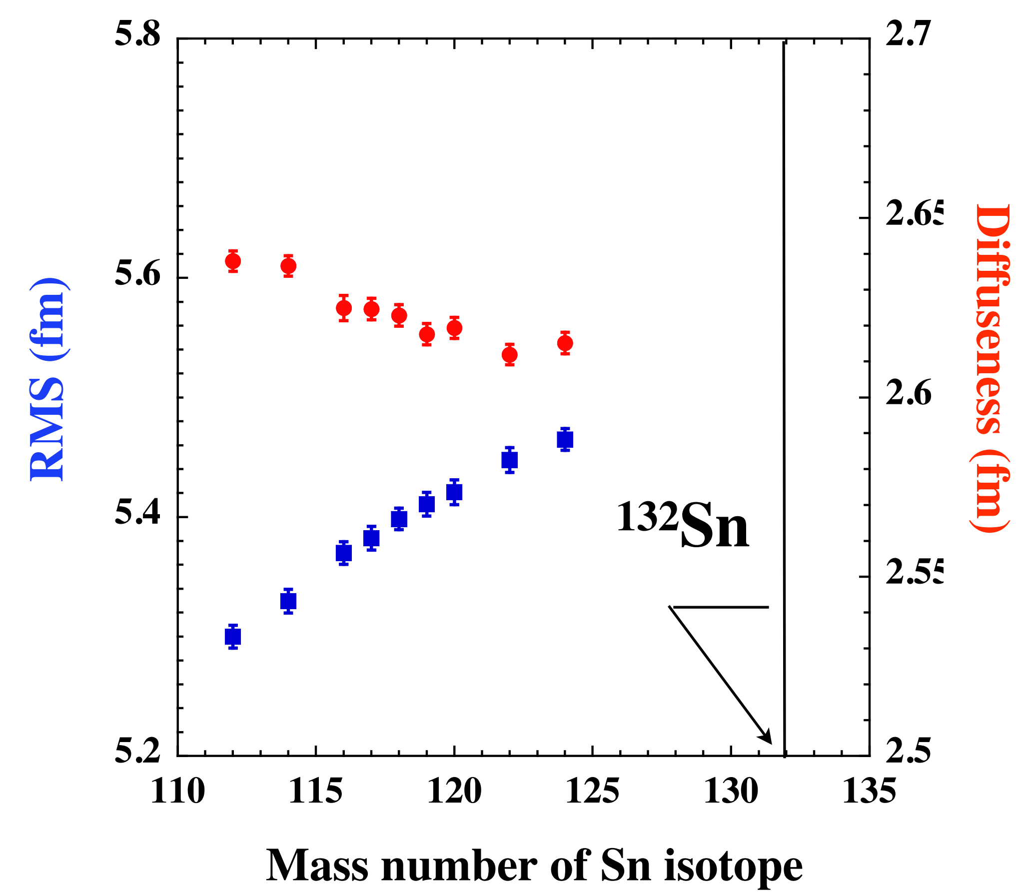
^{130}Sn : 3.7m

^{132}Sn : 39s

^{134}Sn : 1.2s

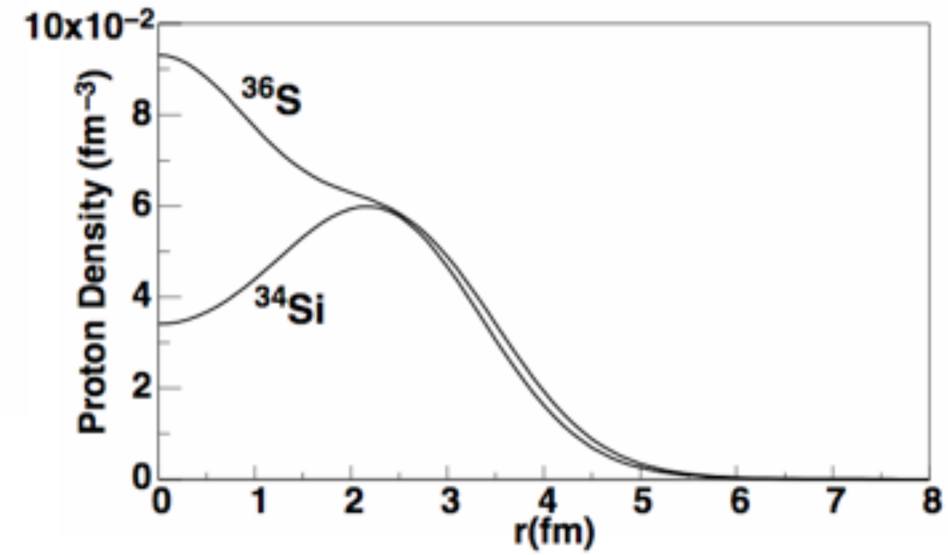


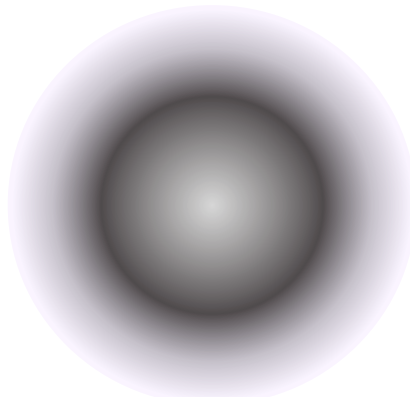
charge radius and diffuseness of Sn isotopes

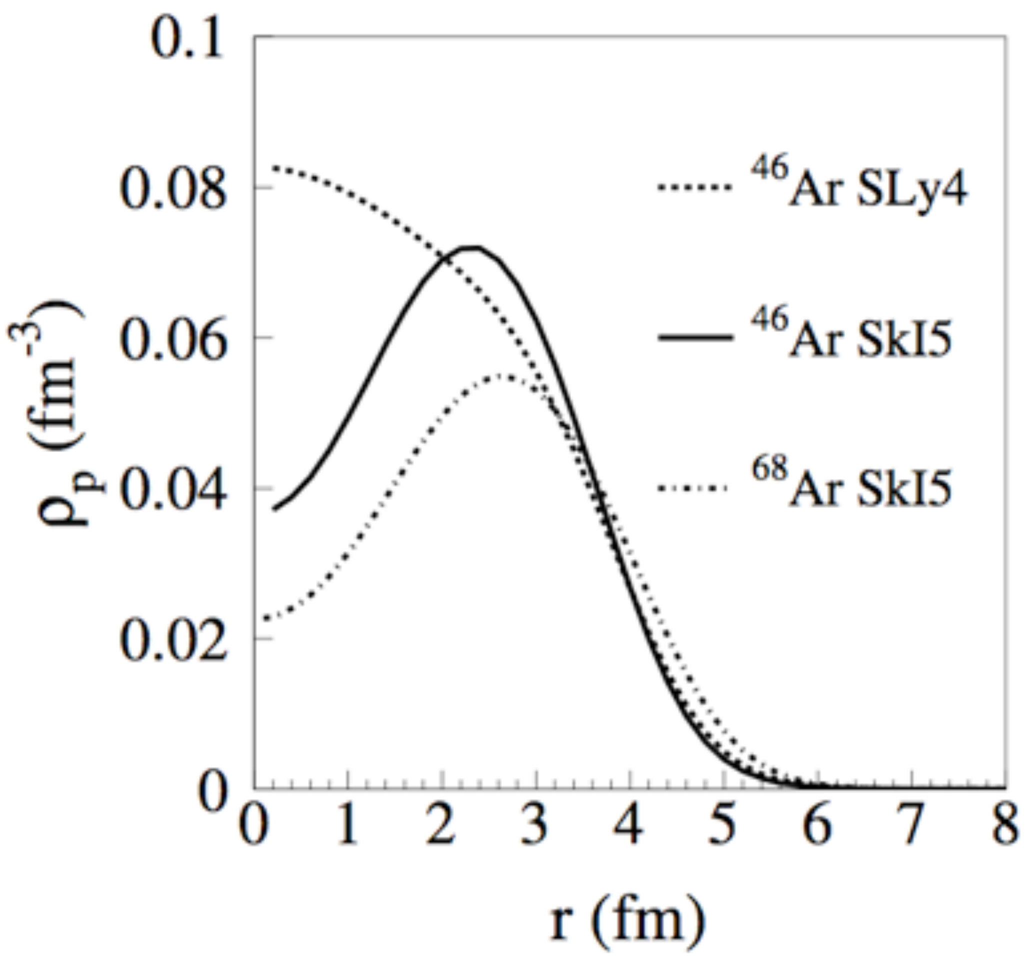


Proton bubble nucleus ??

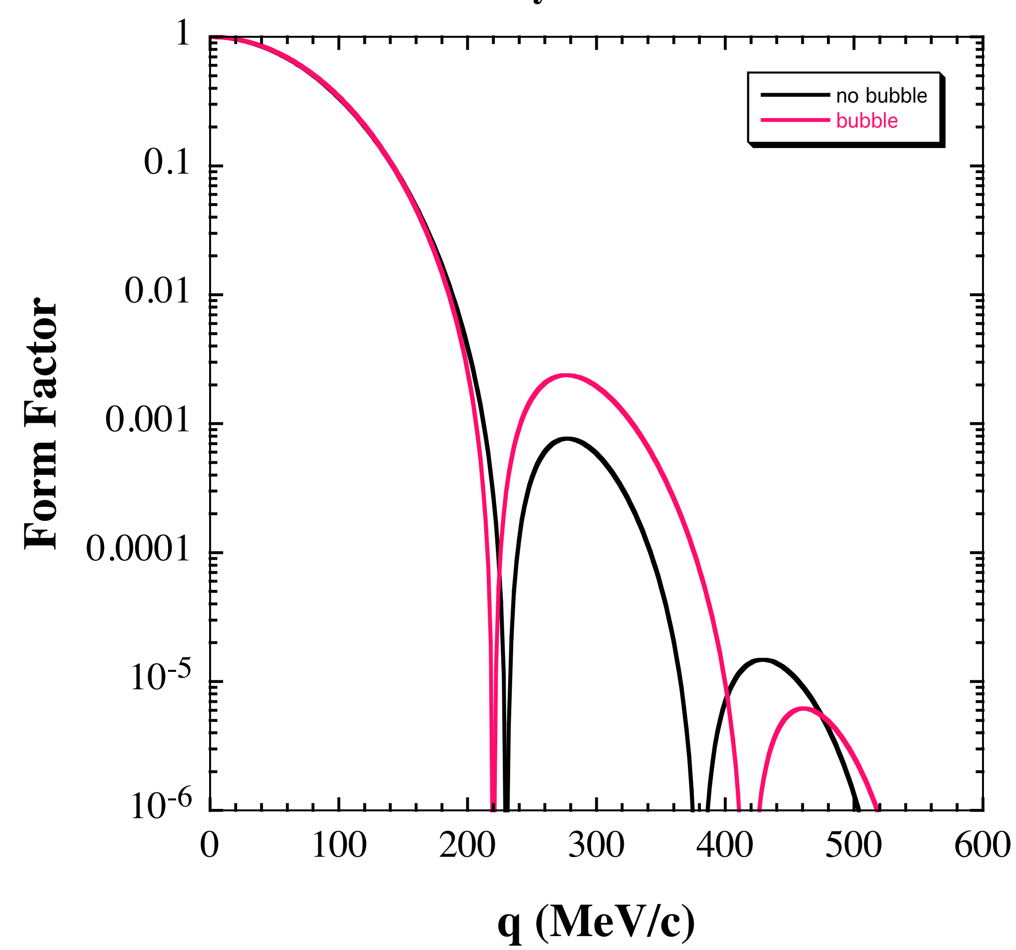
other candidate ^{34}Si (2.8s)







Orsay calculation

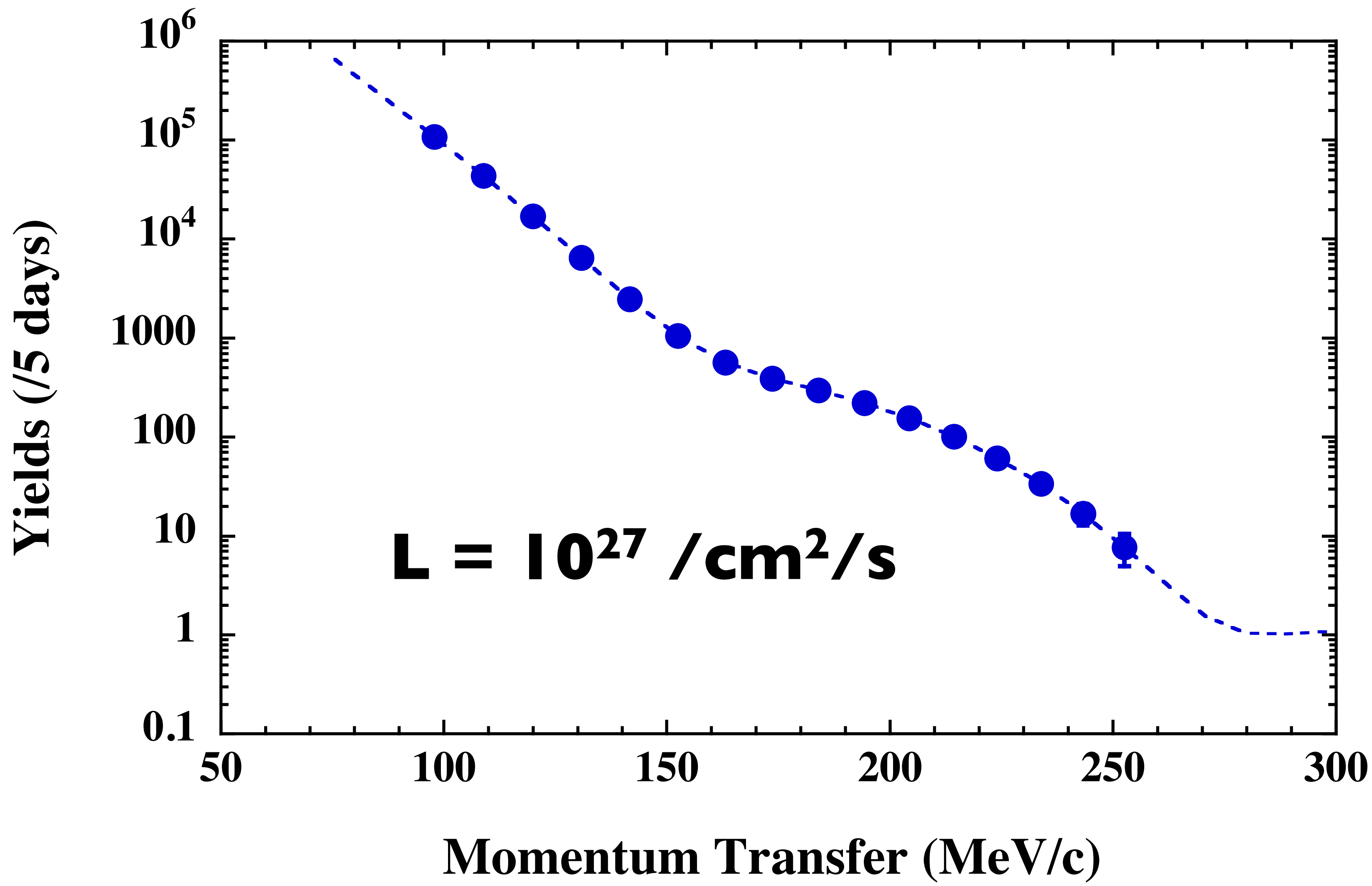


E. Khan et al.
Nucl. Phys. A800 (2008)37.

Minimum required luminosity for electron scattering

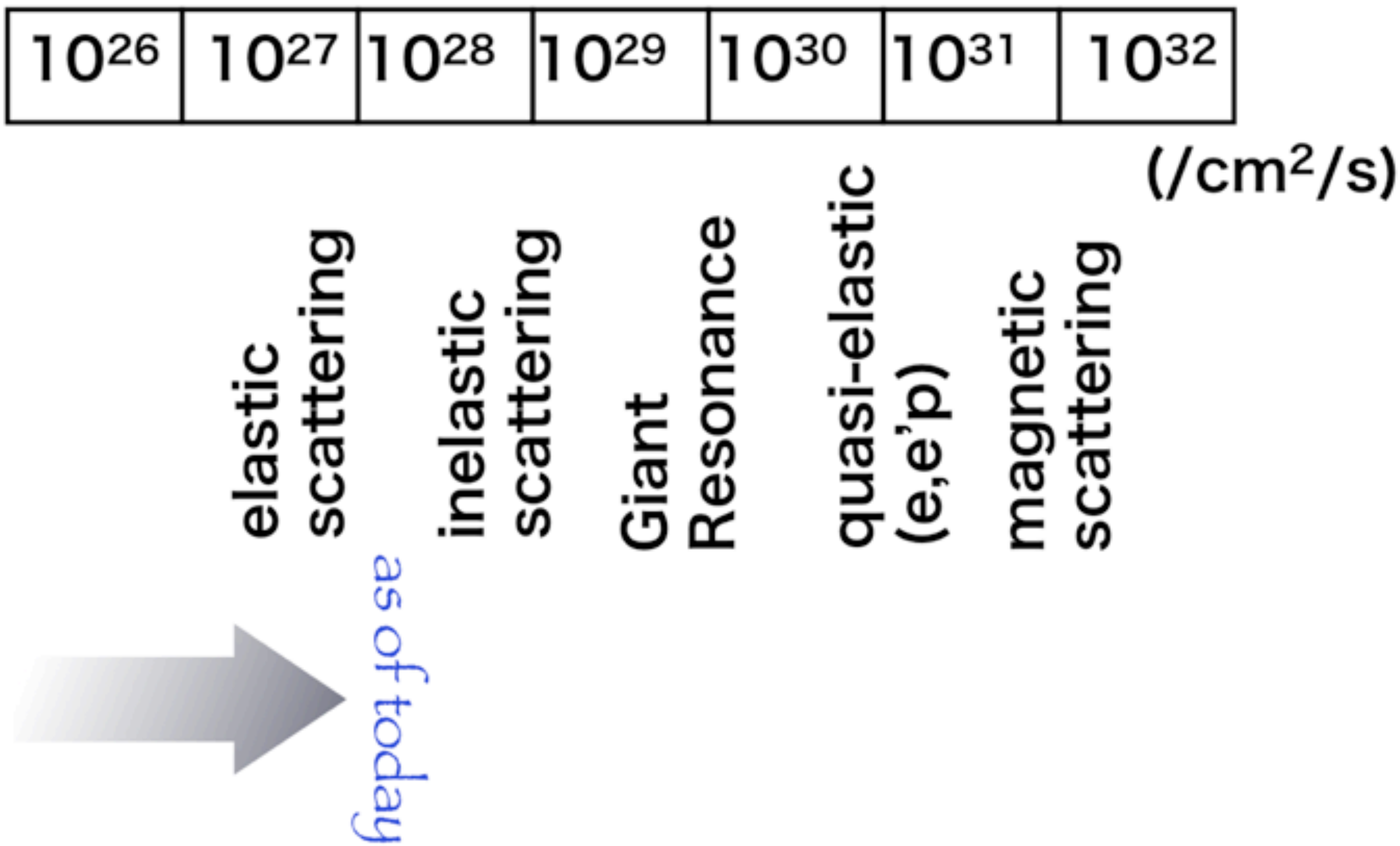
Electron energy :   Ee = 150 - 300 MeV

e+^{132}Sn : 5 days



a few % accuracy for radius and surface diffuseness

Beyond elastic (charge) scattering



elastic ⇨ **charge density distribution** ***(deformation, neutron orbit)***

inelastic ⇨ **transition density**

quasi-elastic ⇨ **momentum density distribution, S- factor.....**

towards higher luminosity with limited number of target exotic nuclei

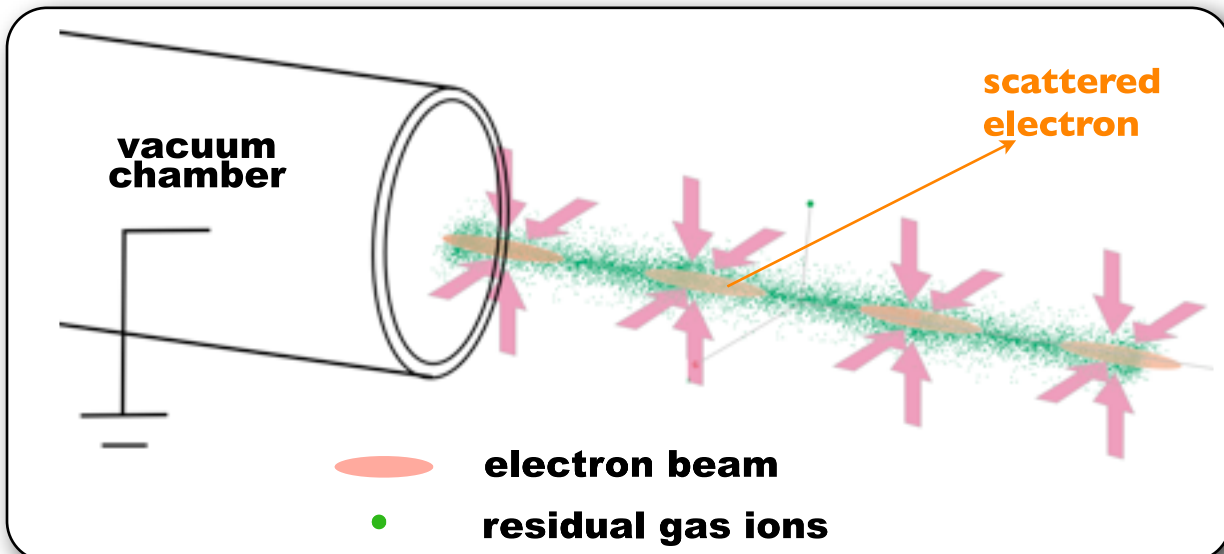
The SCRIT electron scattering facility

A novel experimental technique : SCRIT (Self-Confining RI Target)

Idea

Problematic ion trapping phenomena
@
electron storage ring

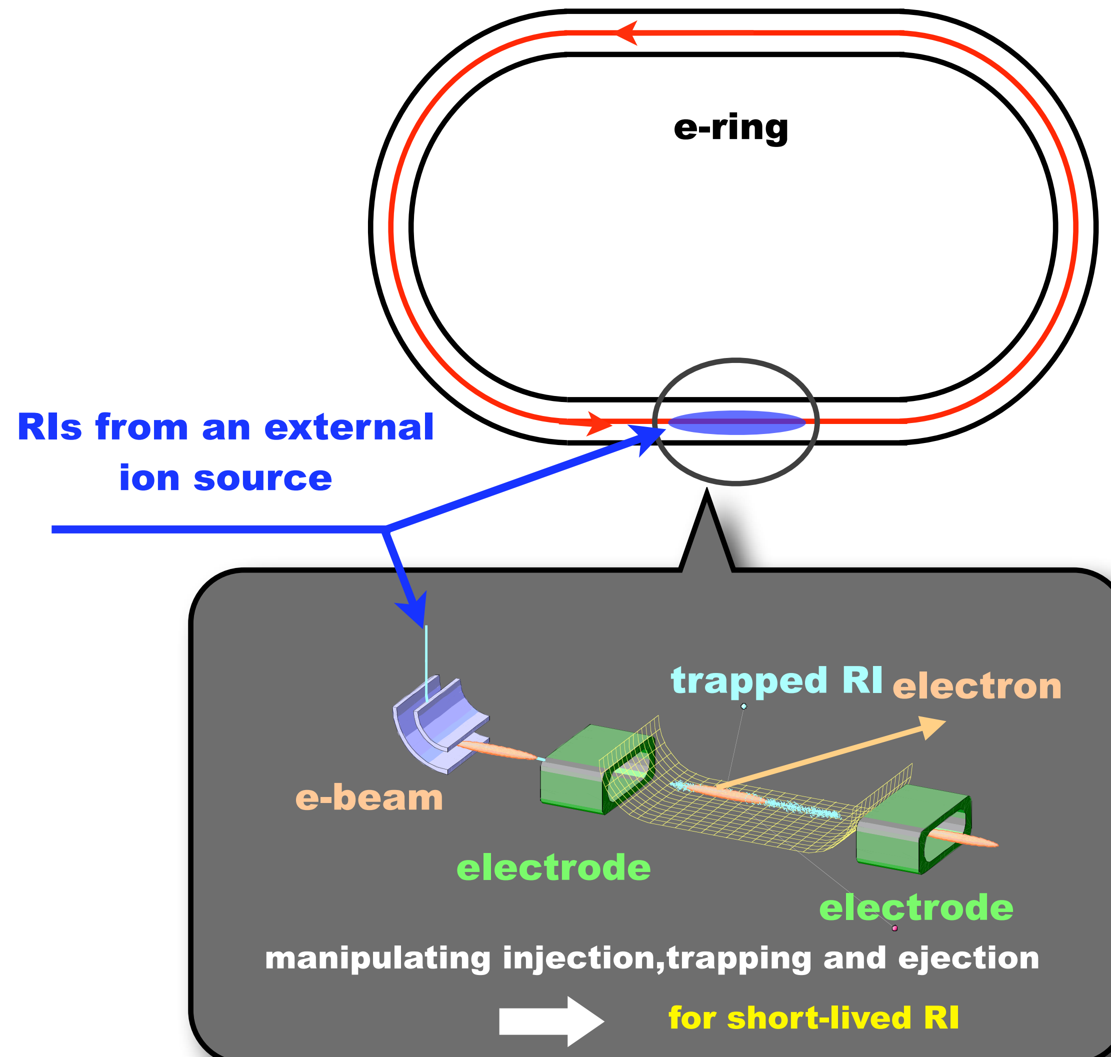
ionized residual gases are trapped
by the circulating electron beam



ill problem of e-storage ring

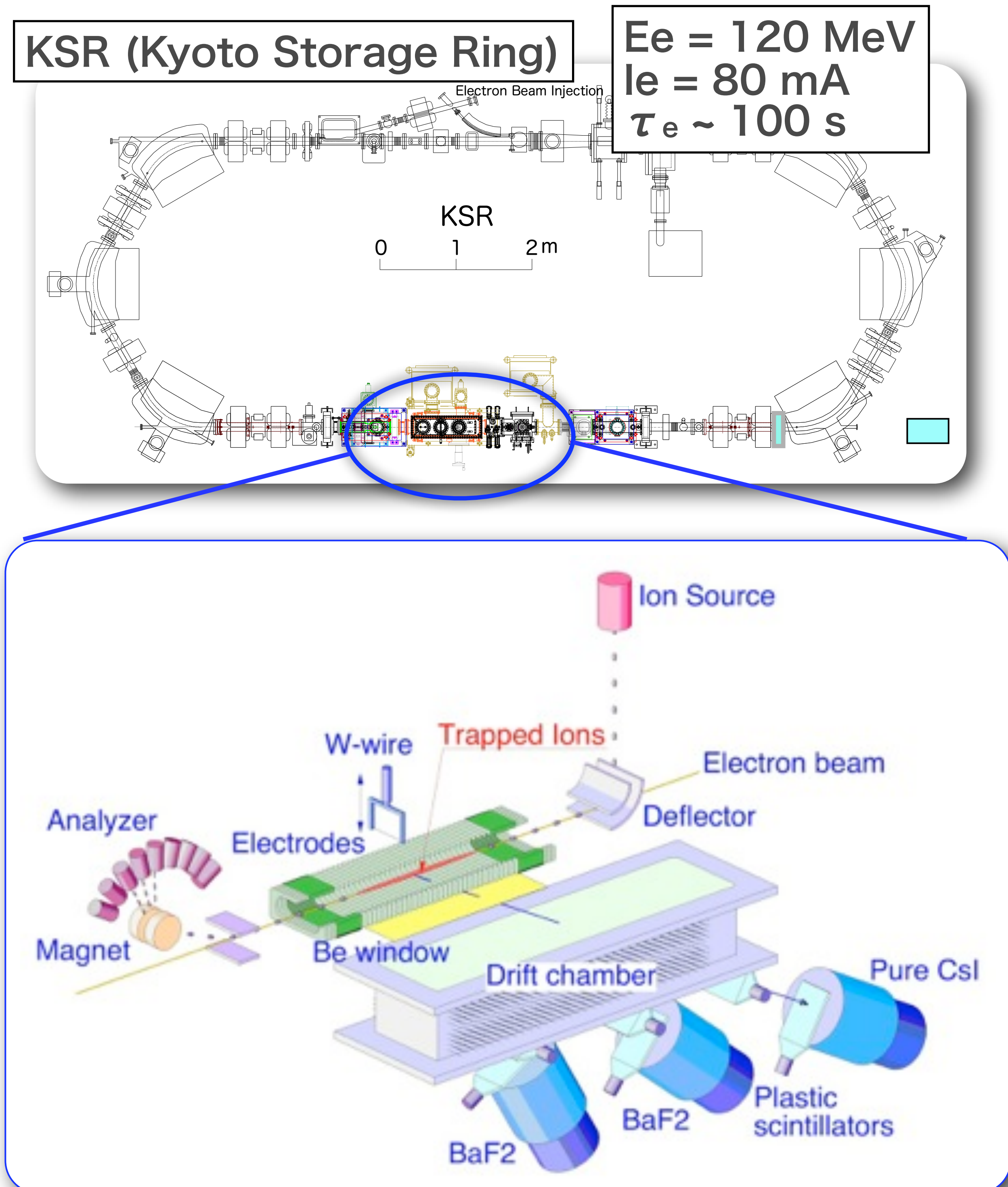
new ion trap for e-RI scattering

trapping RIs on electron beam
(automatic e-scattering off trapped RIs)

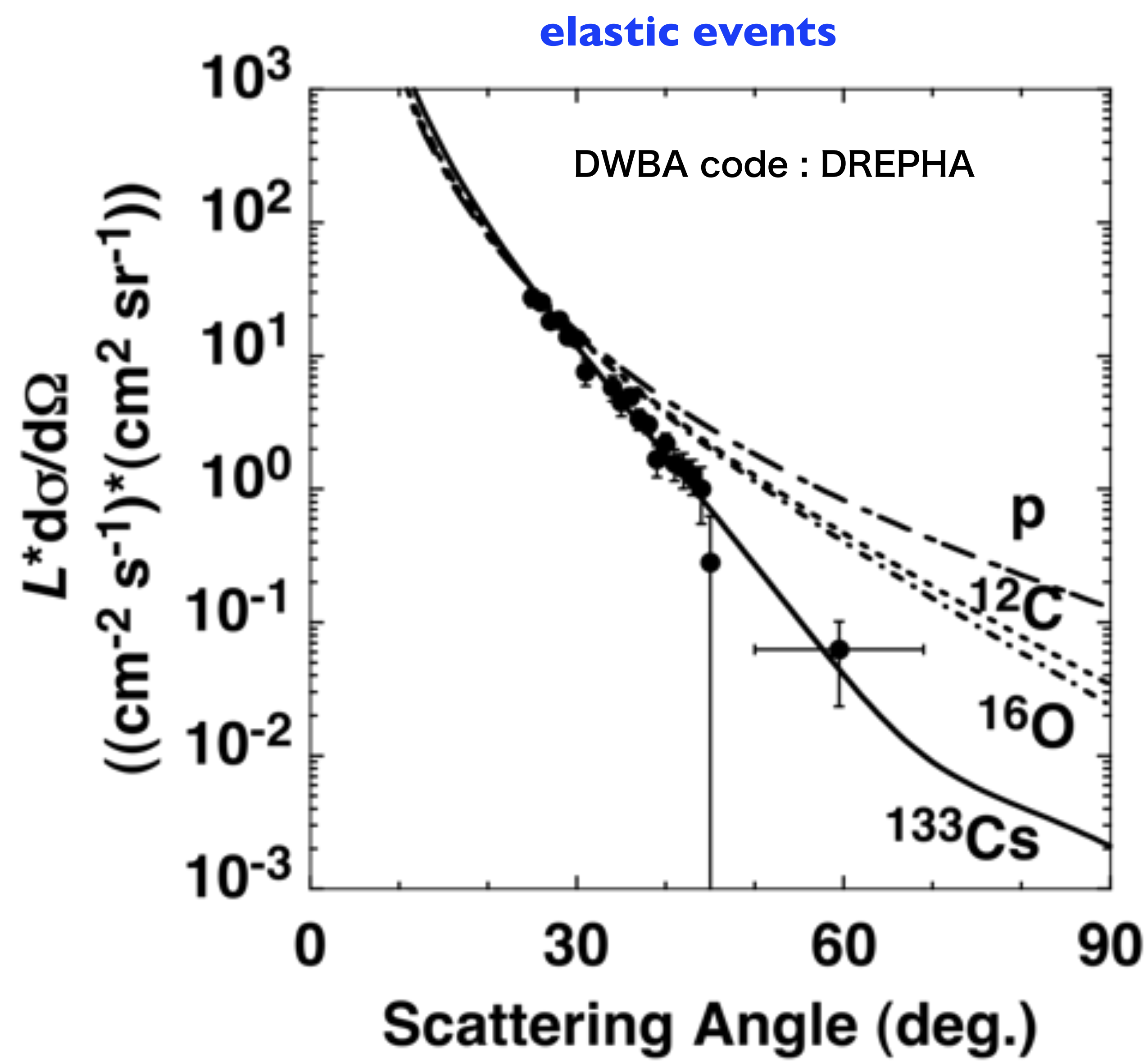


Nucl. Instrum. Methods A532 (2004) 216.

Proof-of-principle study of the SCRIT scheme



- stable nuclei : ^{133}Cs
- trapping time 50 ms :
- $L = 10^{26}$ /cm^2/s with 10^6 trapped ions

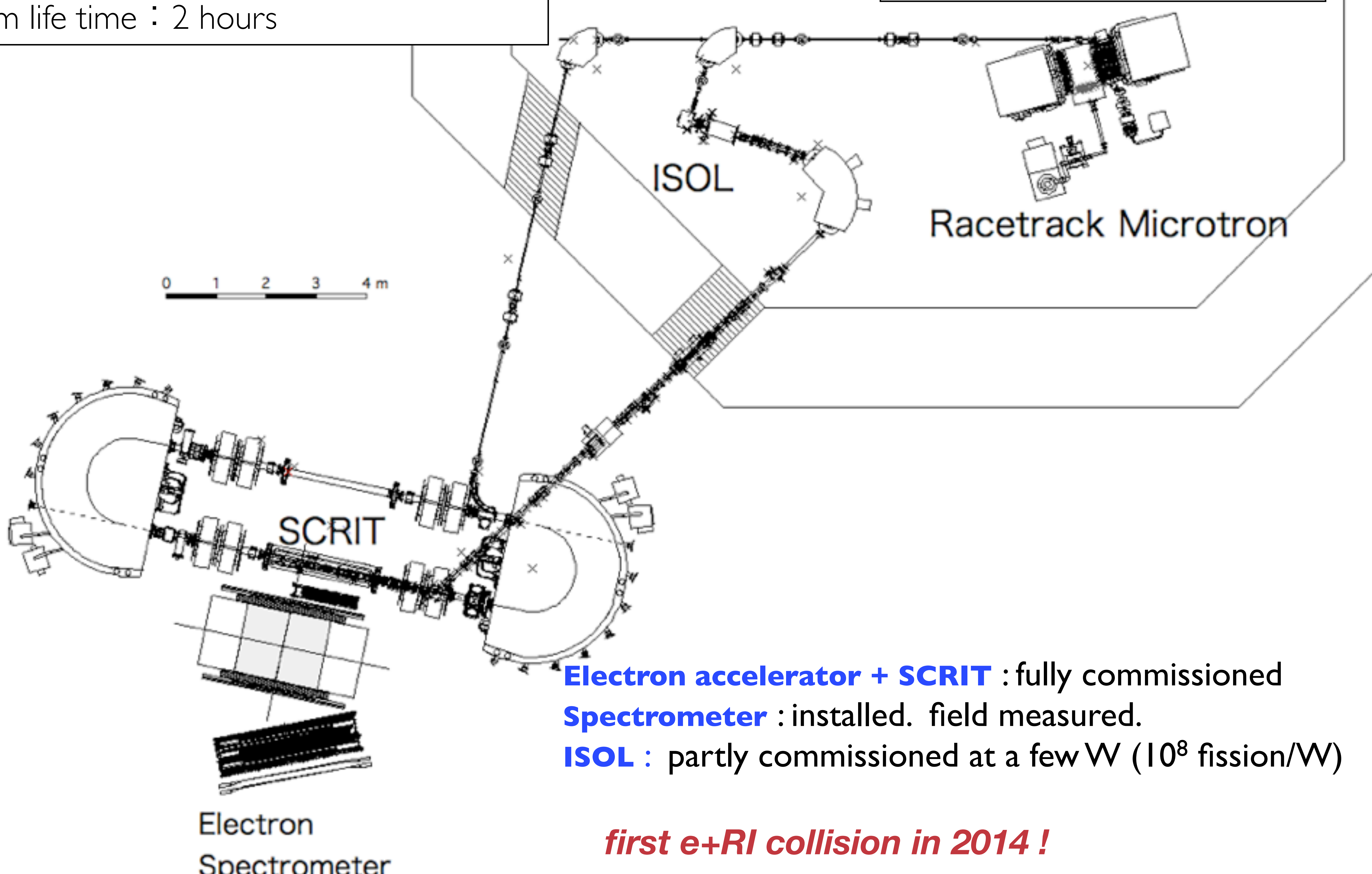


Phys. Rev. Lett. 100 (2008) 164801
Phys. Rev. Lett. 102 (2009) 102501

SCRIT electron scattering facility

Electron energy : 150 - 700 MeV
stored current : 300 mA (as of today)
beam life time : 2 hours

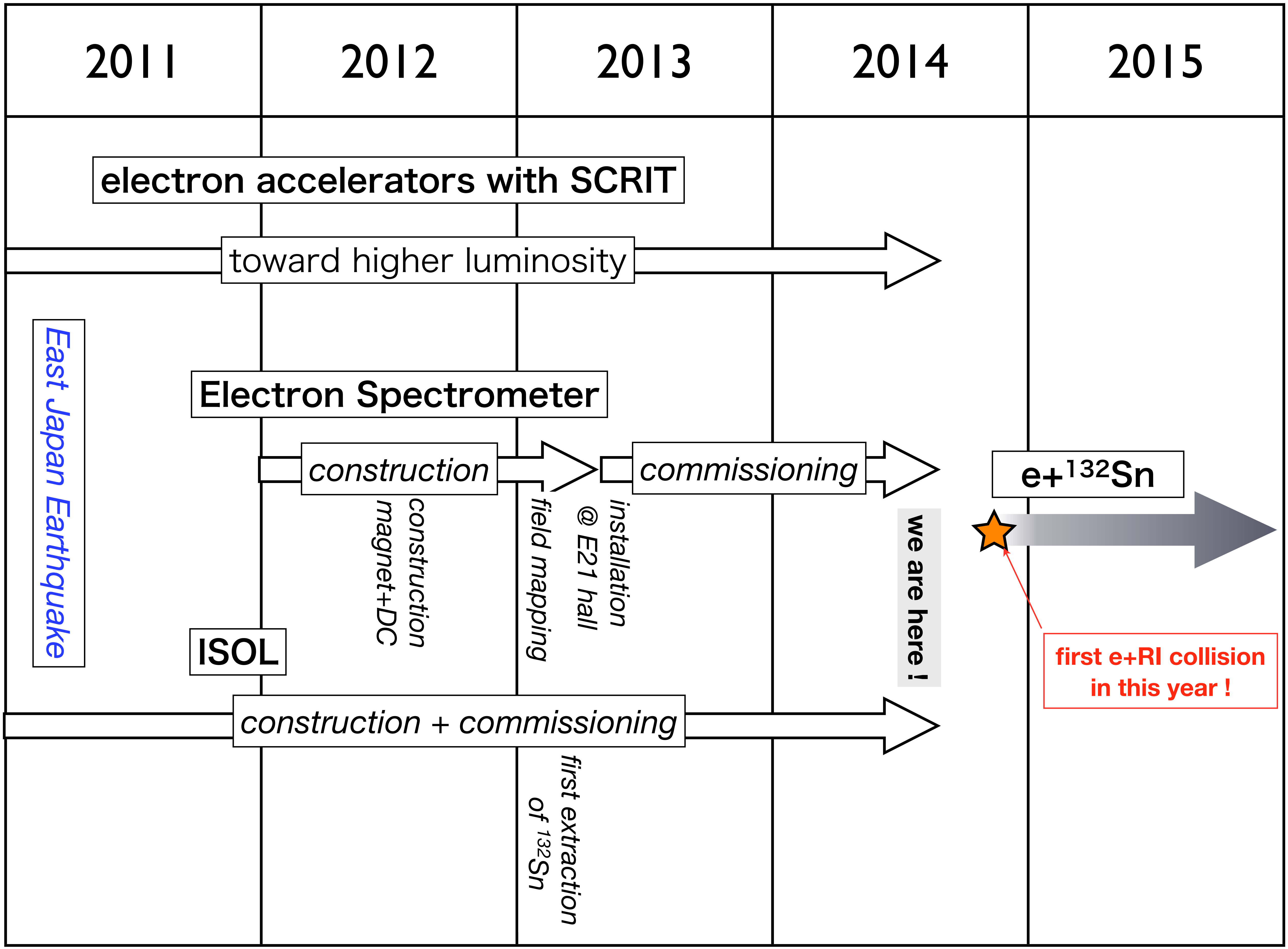
RTM : Race Track Microtron
injector + ISOL driver
150MeV/0.5 mA peak/2 μs pulse

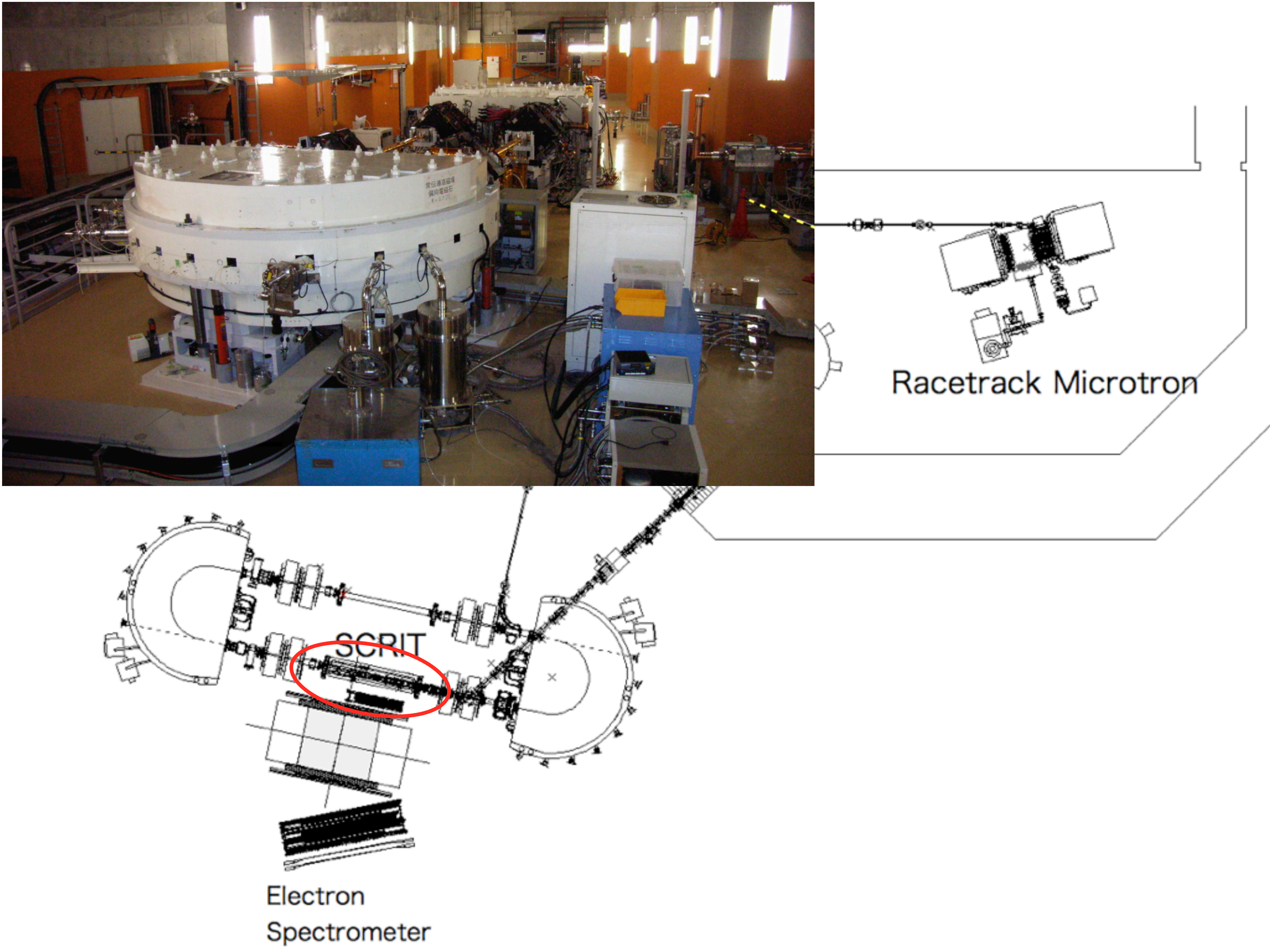


Electron accelerator + SCRIT : fully commissioned
Spectrometer : installed. field measured.
ISOL : partly commissioned at a few W (10^8 fission/W)

first e+RI collision in 2014 !

Schedule

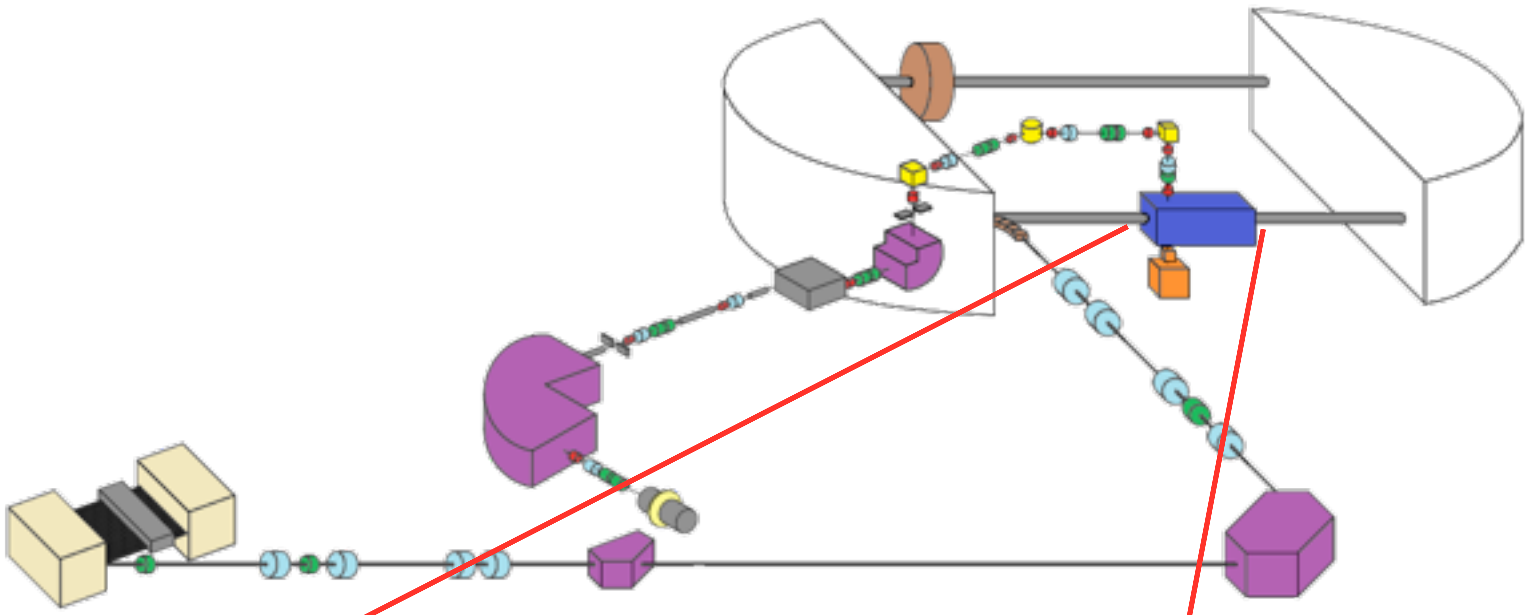

2011
2012
2013
2014
2015
electron accelerators with SCRIT
toward higher luminosity
East Japan Earthquake
Electron Spectrometer
construction
commissioning
construction magnet+DC
field mapping
installation @ E21 hall
we are here !
e+^{132}Sn
first e+RI collision in this year !
ISOL
construction + commissioning
first extraction of ^{132}Sn

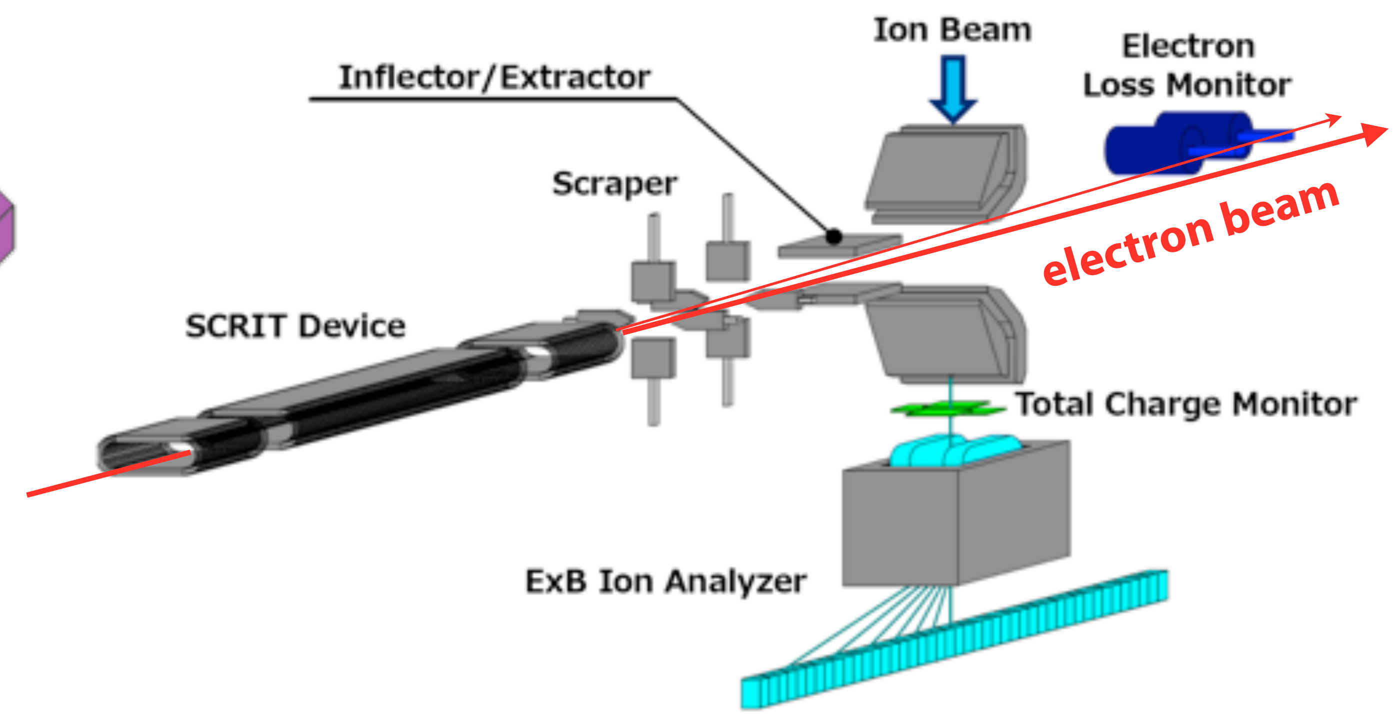

Racetrack Microtron
SCRIT
Electron
Spectrometer

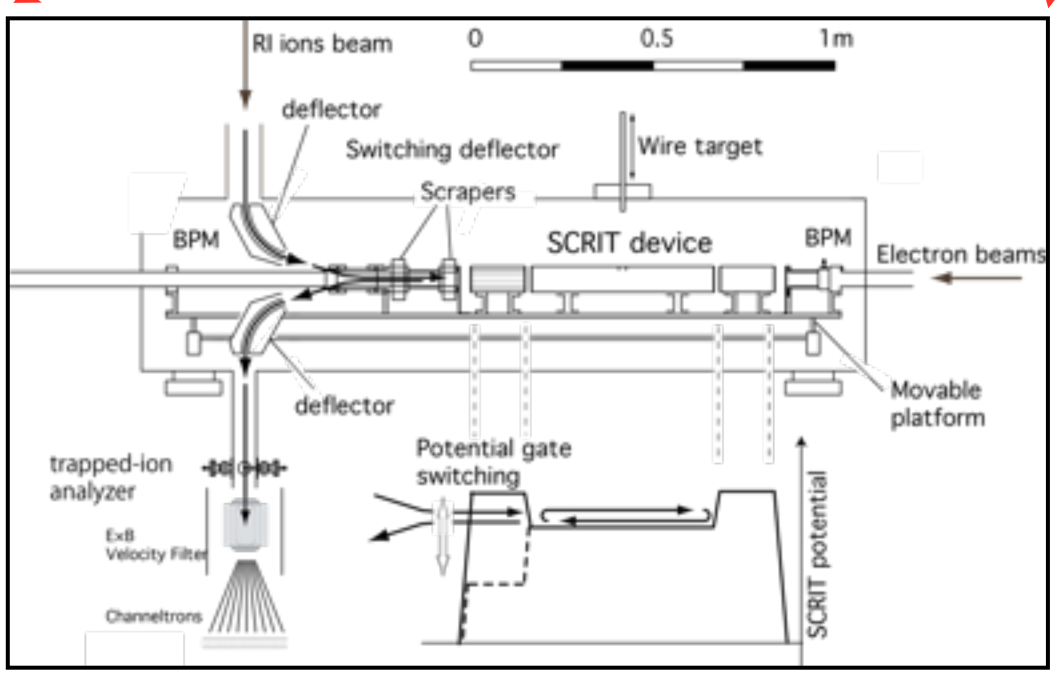
SCRIT and electron storage ring + SCRIT

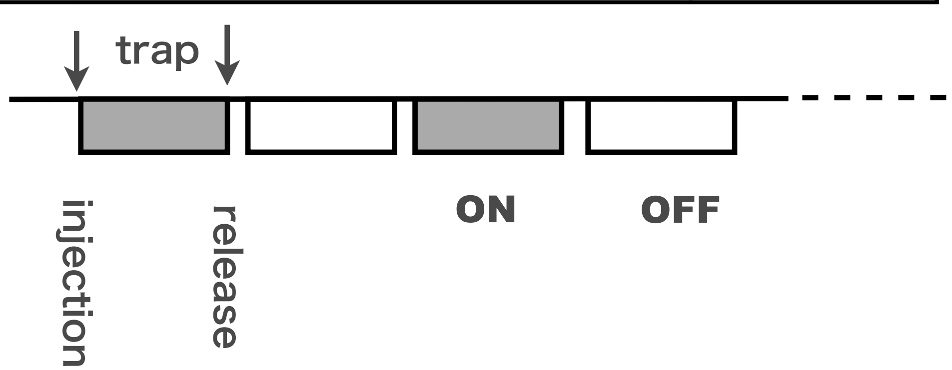
M. Wakasugi

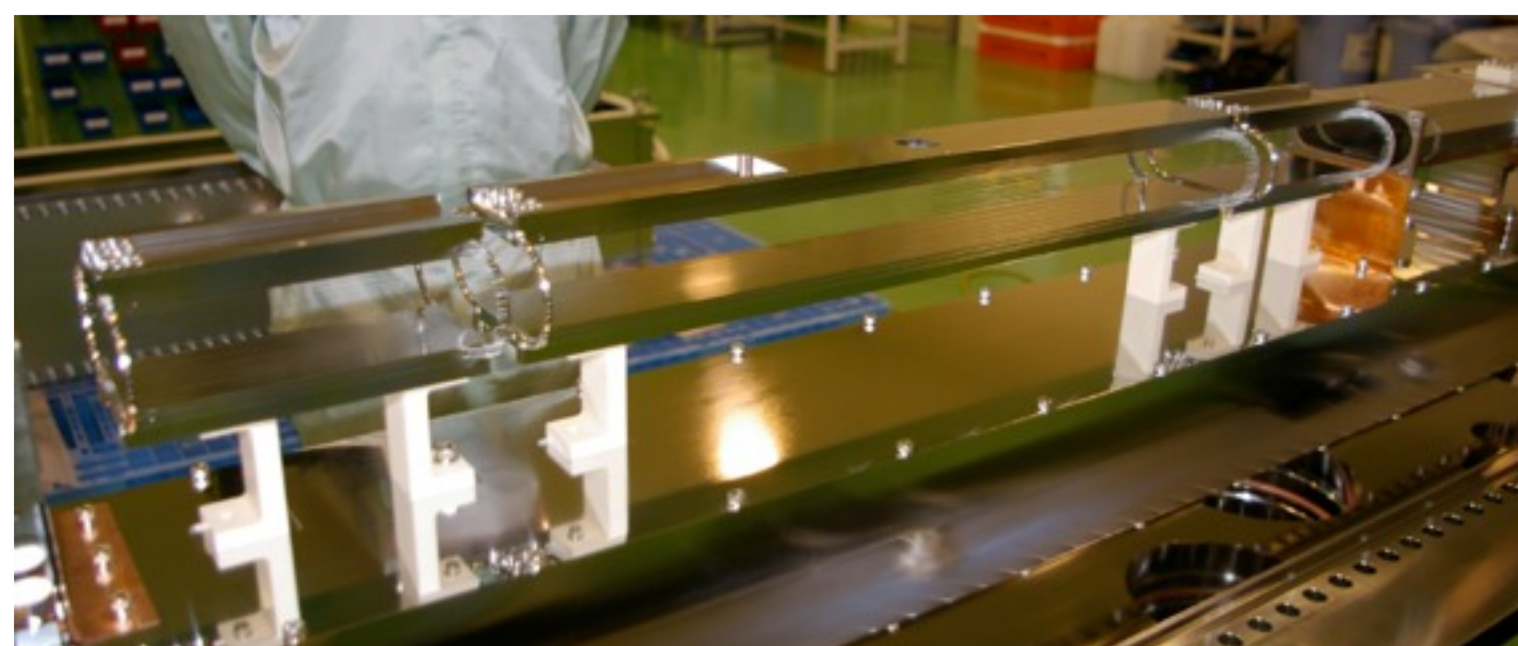
NIM B317 (2013) 668.





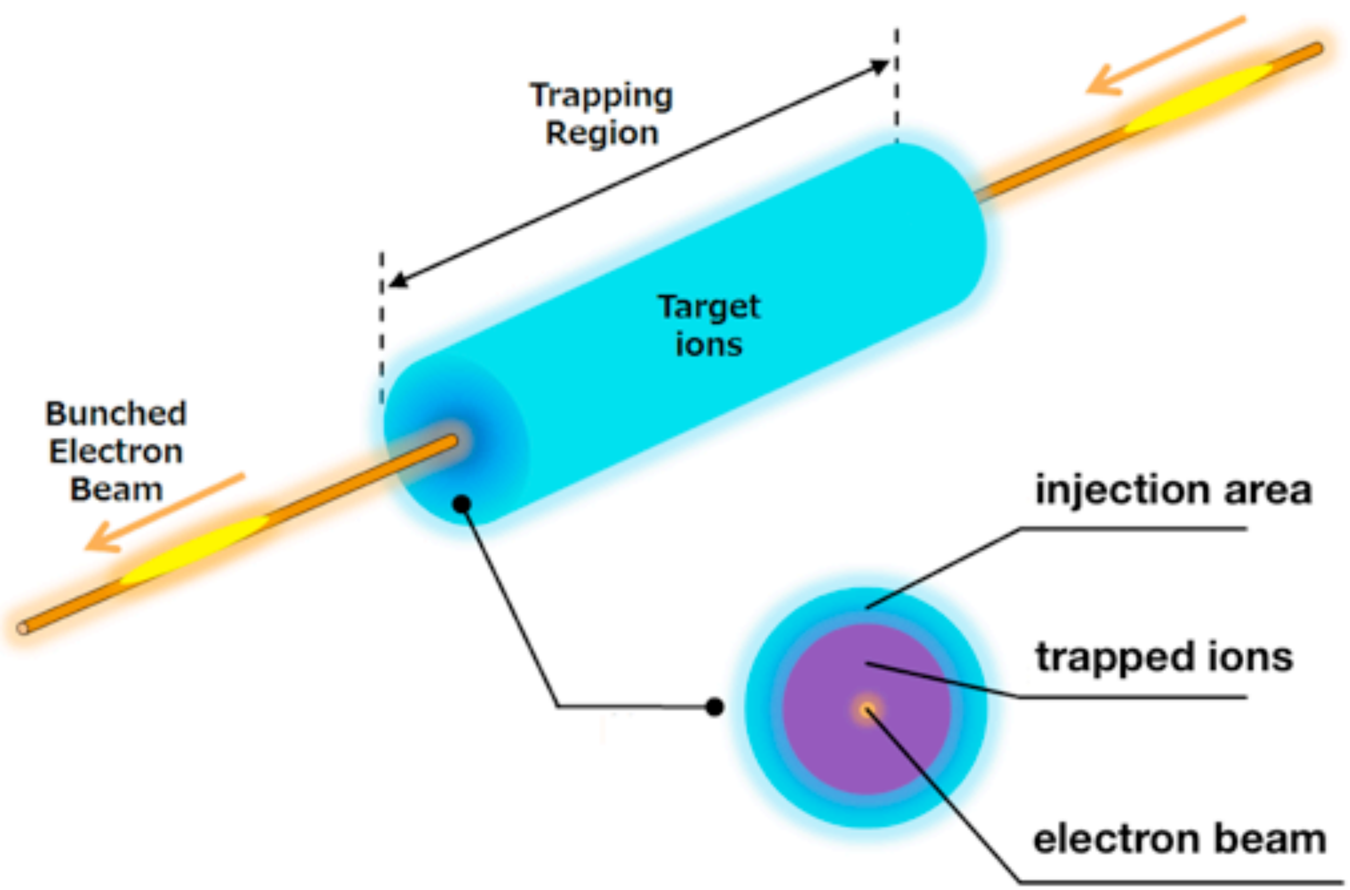


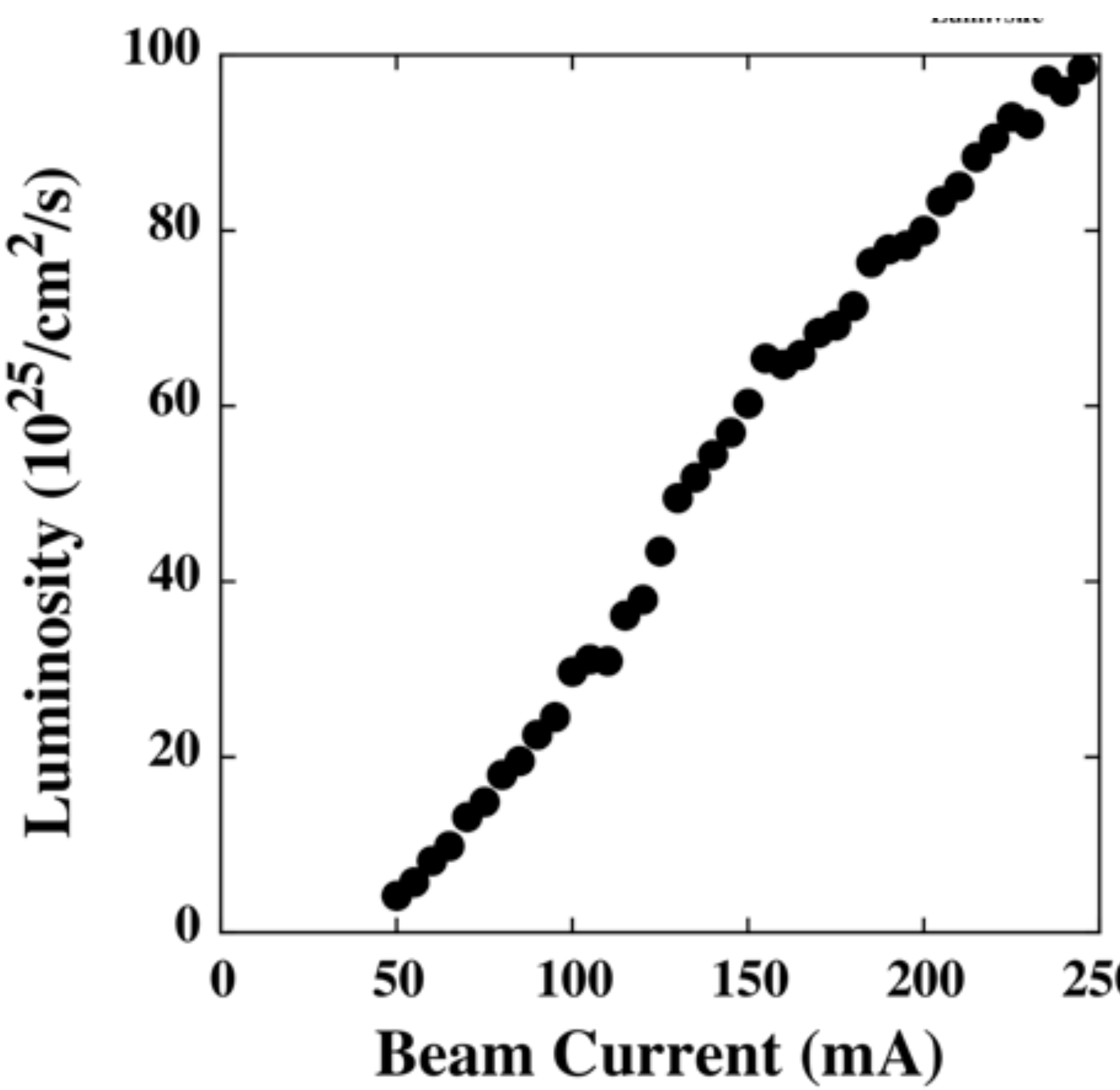




Luminosity, ion trapping efficiency

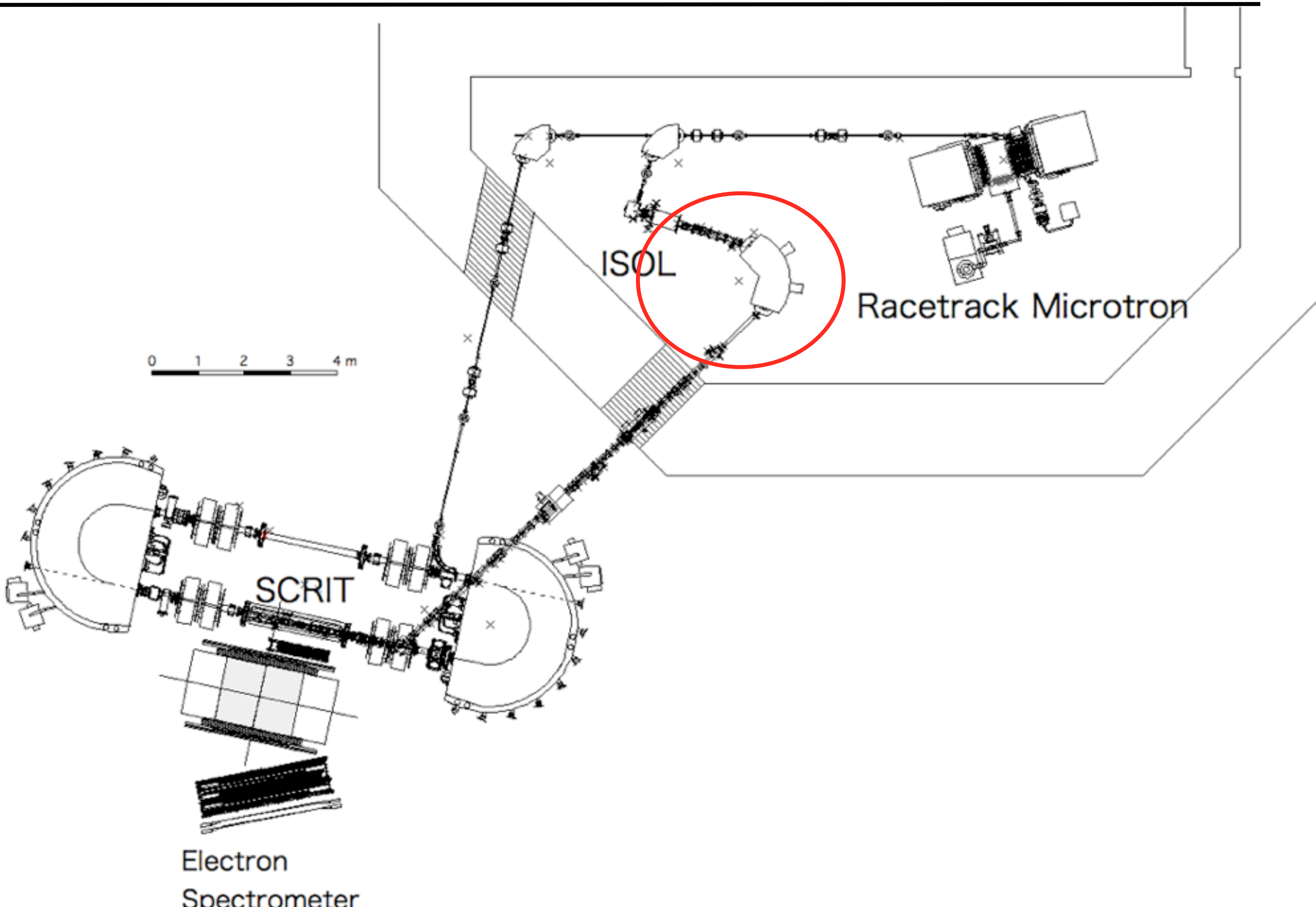
R. Ogawara
NIM B317 (2013) 674.





trapping efficiency ~ 100 %
overlapping efficiency ~ 17 %

ISOL (Isotope Separator On-Line)



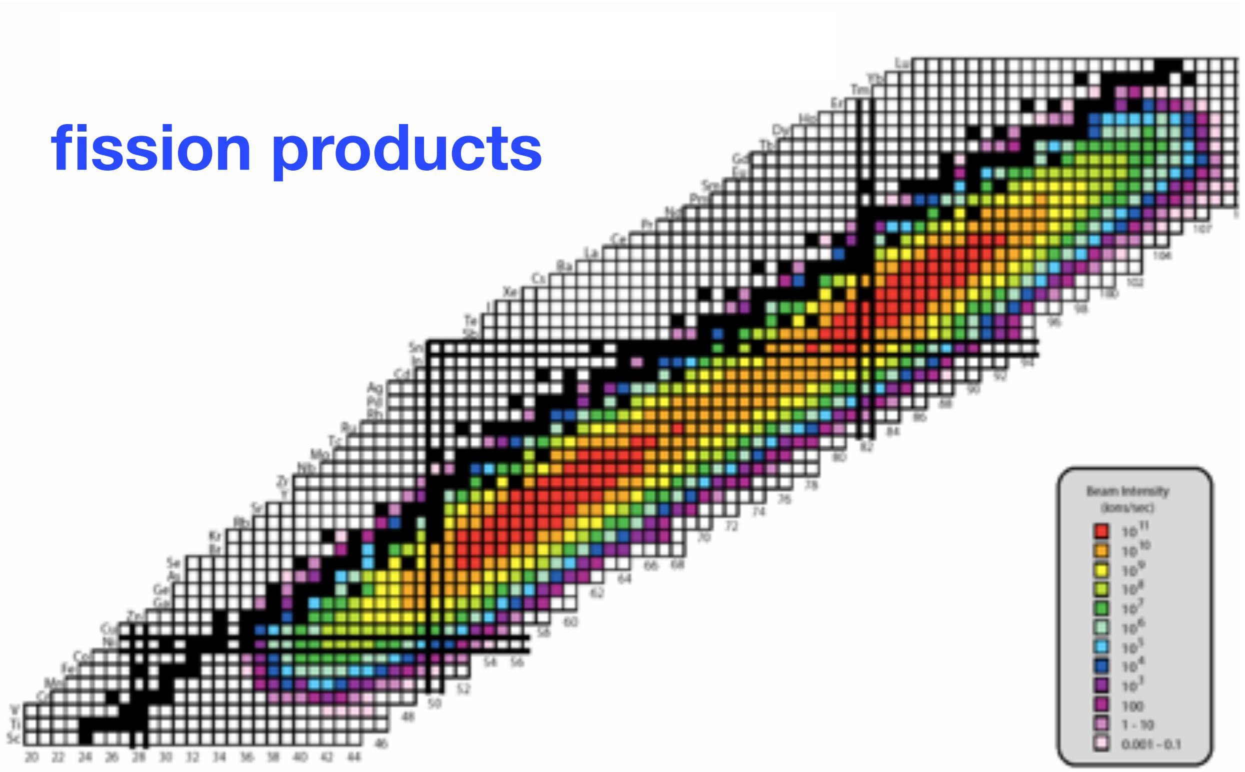
ISOL (Isotope Separator On-Line)

T. Ohnishi

NIM B317 (2013) 357.

Reaction : photo- (electro-) fission of ^{238}U.
Target : house-made UCx
Driver : Race Track Microtron (Ee=150 MeV)
Ion Source : FEBIAD type

fission products



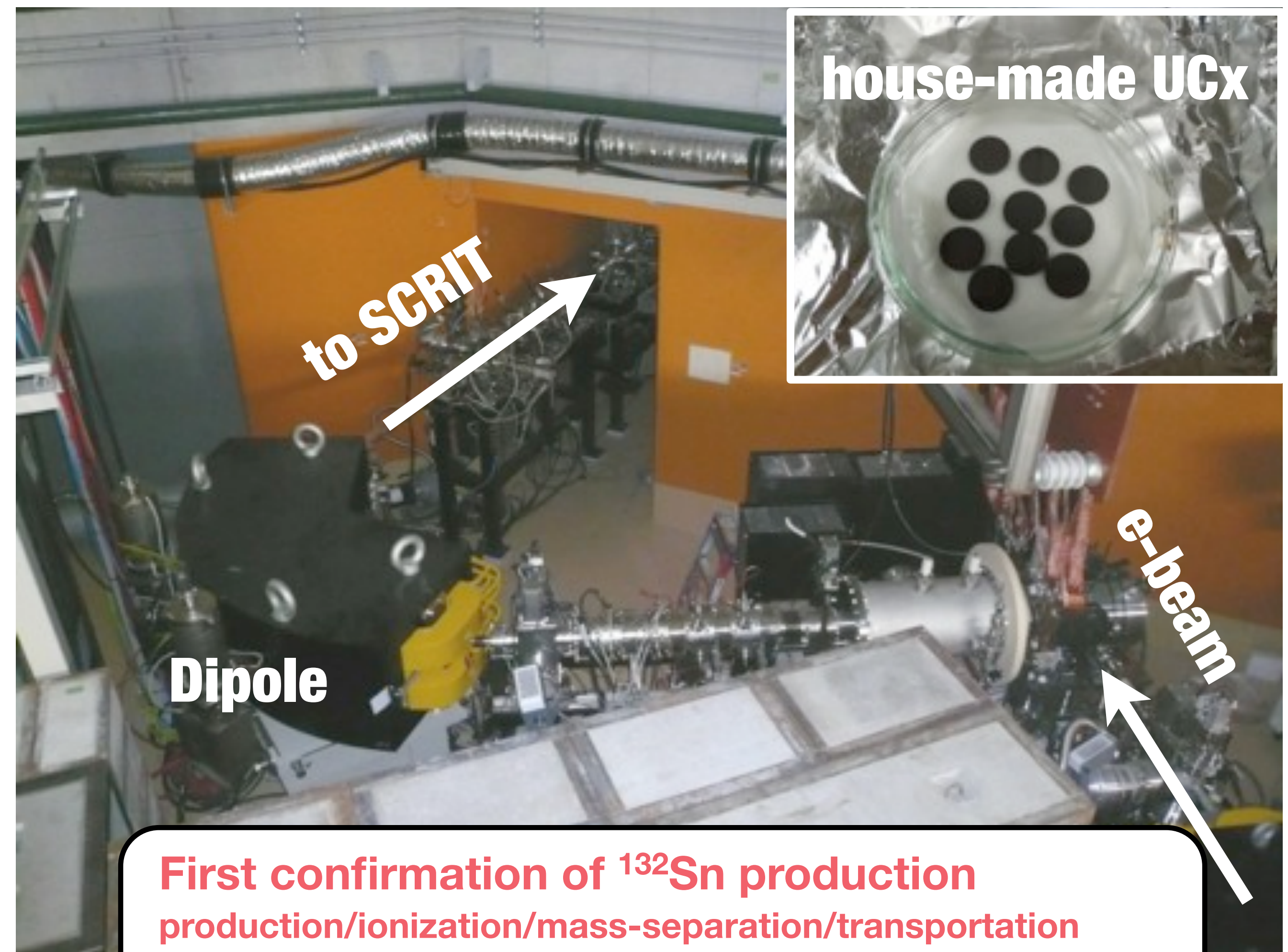
Production Rate

$N_{fission}$ ~ 10^8 /watt

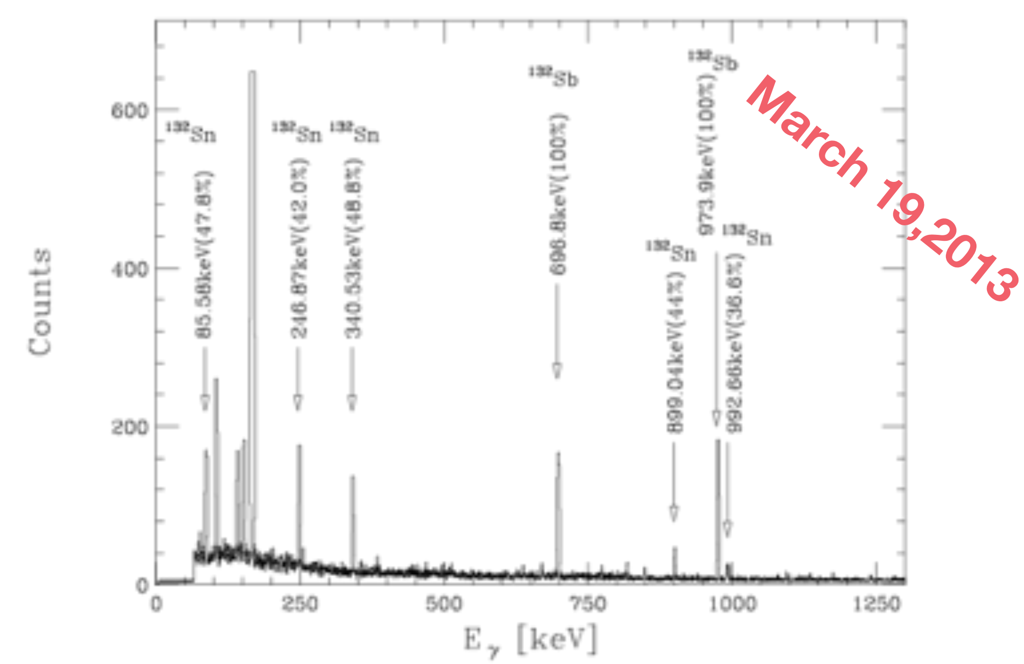
$N_{^{132}Sn}$ ~ 10^6 / watt * 1% ($\varepsilon_{trans.}$)

beam power : ~ 10W in operation

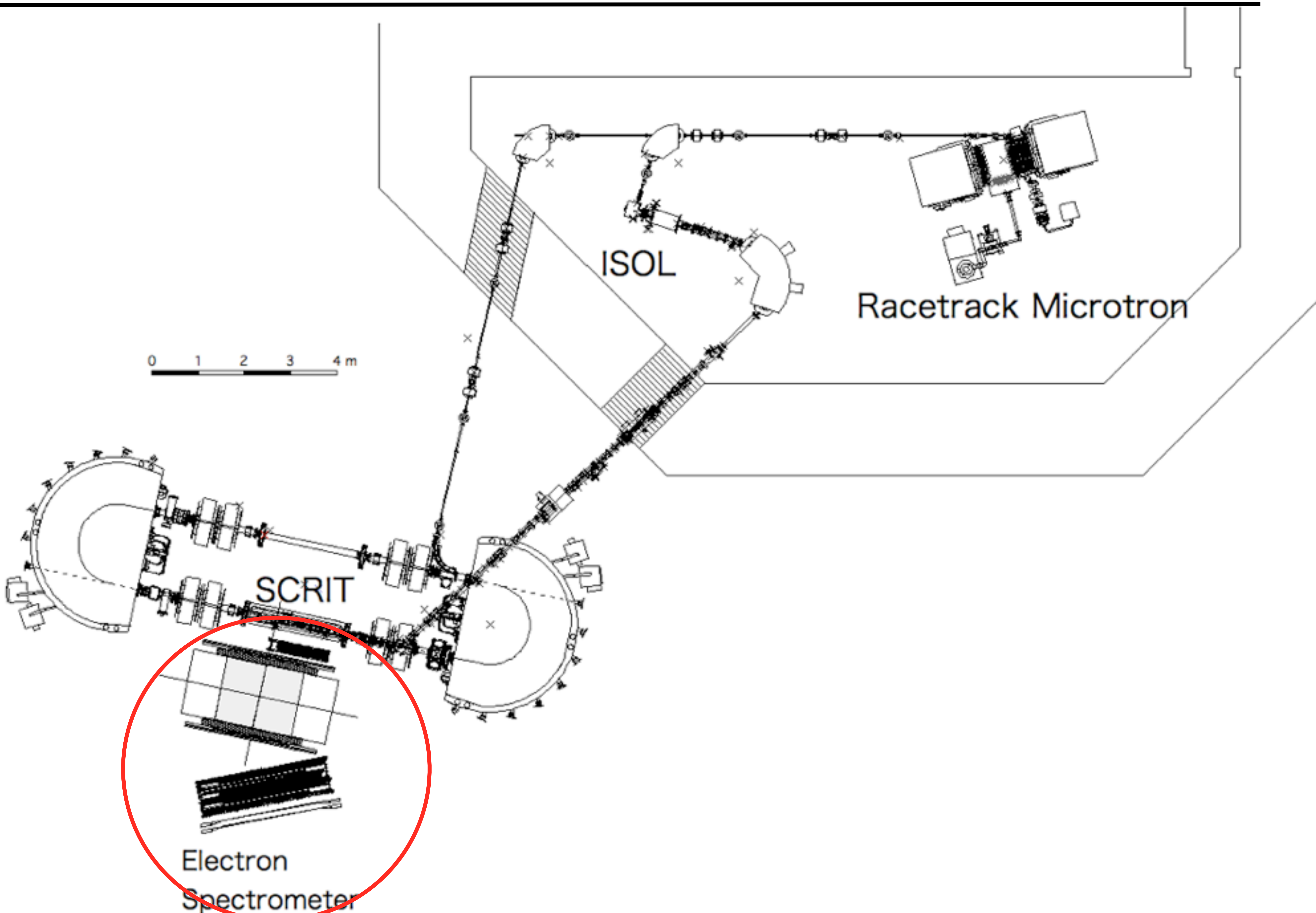
~ 1 kW the goal



First confirmation of ^{132}Sn production
production/ionization/mass-separation/transportation



SCRIT electron spectrometer

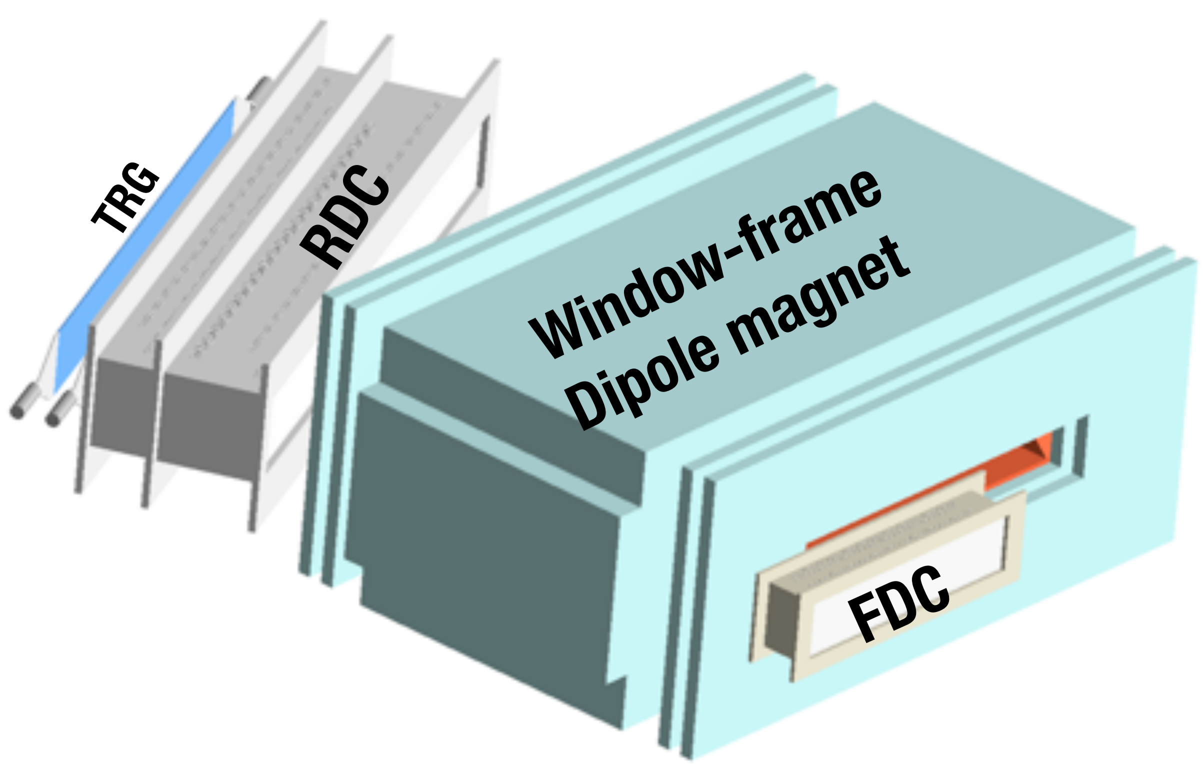


SCRIT electron spectrometer

A high-resolution electron spectrometer for identifying elastic scattering events is now ready. It consists of a window-frame type dipole magnet (0.8 T), sandwiched by two sets of large drift chambers.

- **$\Delta p/p \leq 10^{-3}$ (ΔE<300keV@300MeV)**
- **$\Delta\theta$ = 30° (45±15°)**
- **$\Delta\Omega$~ 100 msr**
- **long target acceptance (40cm)**
- **field leakage at e-beam : a few G**

- **field measurement done & installed**



Conclusions

RIKEN RI Beam Factory (RIBF) in Japan is the new generation exotic-beam facility, and provides the world’s most intense exotic beam for the study of their internal structure and reaction.

１．**SCRIT electron scattering facility is the world’s first facility for exotic nuclei.**

２．**Electron accelerator + SCRIT system : commissioned. Req. Luminosity achieved.**

３，**first electron scattering off exotic nucleus (^{132}Sn) in 2014 !!**