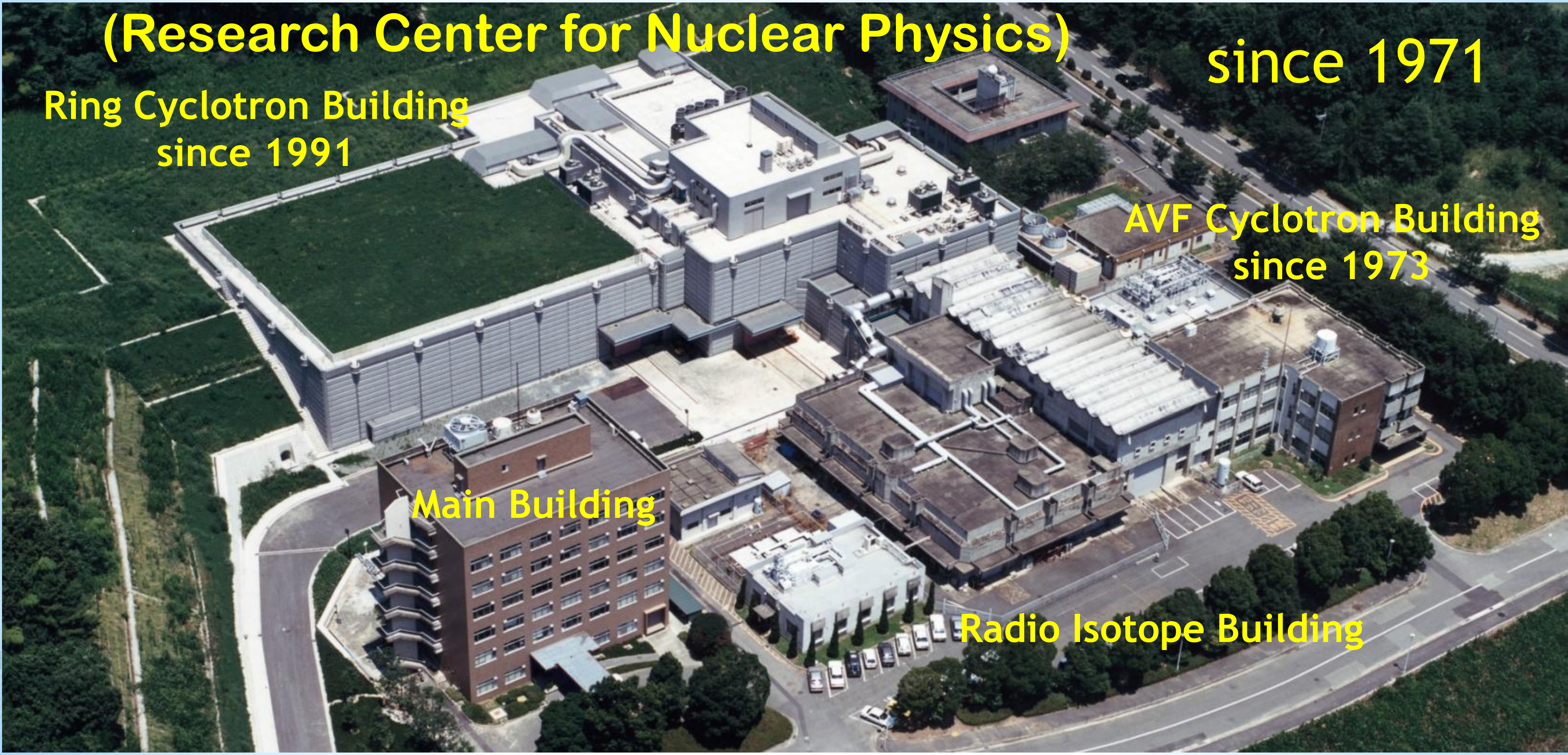
7th Italy-Japan Symposium
on Nuclear Physics

November 20 to 23, 2012
Milan, Italy

*RCNP Cyclotron Facility



Mitsuhiro FUKUDA
RCNP, Osaka University

OSAKA UNIVERSITY

RCNP

* Contents

1. Overview of the RCNP cyclotron facility

Research programs

- **Nuclear Physics**

  Few nucleon system
  Medium modification of the interaction
  Spin isospin excitations
  Giant resonance
  Heavy ion physics with radioactive isotopes
  . . .

- **Fundamental Symmetry**

  Ultra Cold Neutron

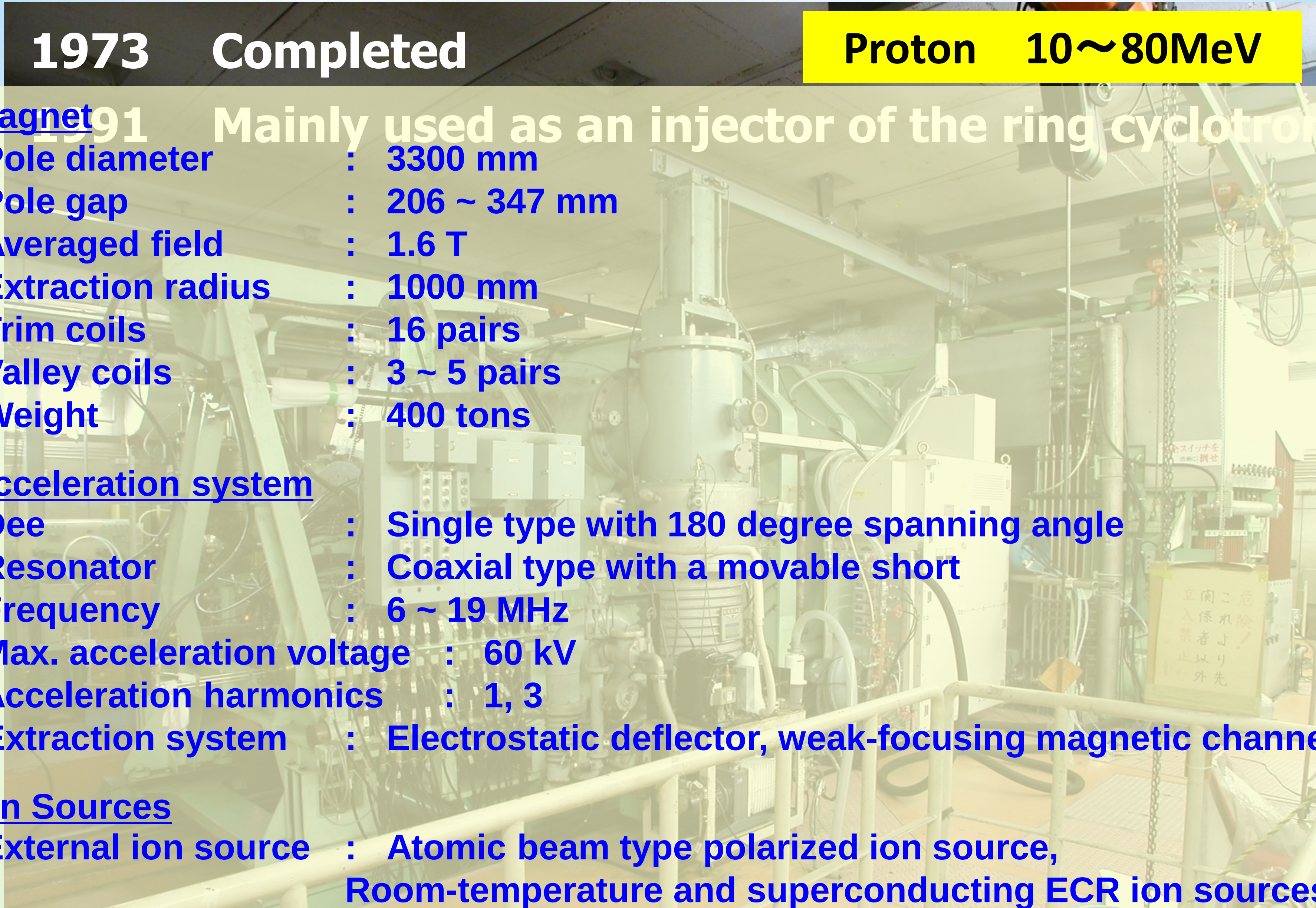
- **Interdisciplinary Researches**

  Nuclear chemistry
  Nuclear medicine
  Biological science
  Materials science
  Radiation damage of semiconductor devices

* RCNP Cyclotron Facility

Odahara-san and Aoi-san talks

* RCNP K140 AVF Cyclotron



1973 Completed

Proton 10～80MeV

1991 Mainly used as an injector of the ring cyclotron

Magnet
- Pole diameter : 3300 mm
- Pole gap : 206 ~ 347 mm
- Averaged field : 1.6 T
- Extraction radius : 1000 mm
- Trim coils : 16 pairs
- Valley coils : 3 ~ 5 pairs
- Weight : 400 tons

Acceleration system
- Dee : Single type with 180 degree spanning angle
- Resonator : Coaxial type with a movable short
- Frequency : 6 ~ 19 MHz
- Max. acceleration voltage : 60 kV
- Acceleration harmonics : 1, 3
- Extraction system : Electrostatic deflector, weak-focusing magnetic channel

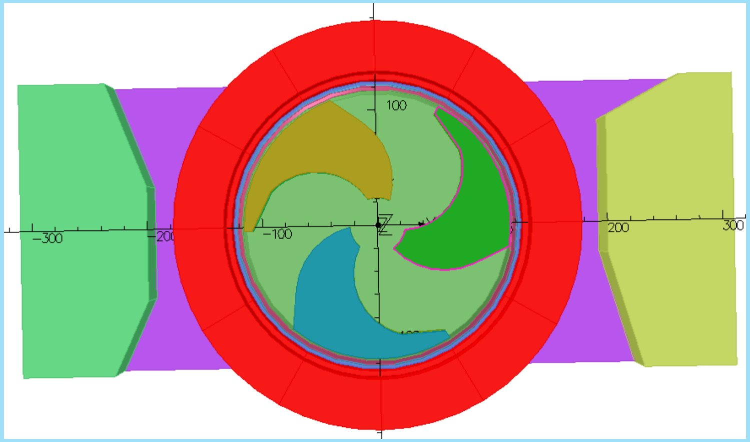
Ion Sources
- External ion source : Atomic beam type polarized ion source, Room-temperature and superconducting ECR ion sources

Operation Parameters of K140 AVF Cyclotron

【Specifications】

- Energy of ions with $M/Q \leqq 5$
  - proton $\leqq$ 80 MeV
  - D^+, $^4He^{2+}$ $\leqq$ 35 MeV/n
  - $^3He^{2+}$ $\leqq$ 180 MeV
  - Heavy Ion $\leqq 140 \times (Q/A)^2$
- RF 6〜19 MHz
- Acc. harmonics 1, 3
- Average field $\leqq$ 1.7 T

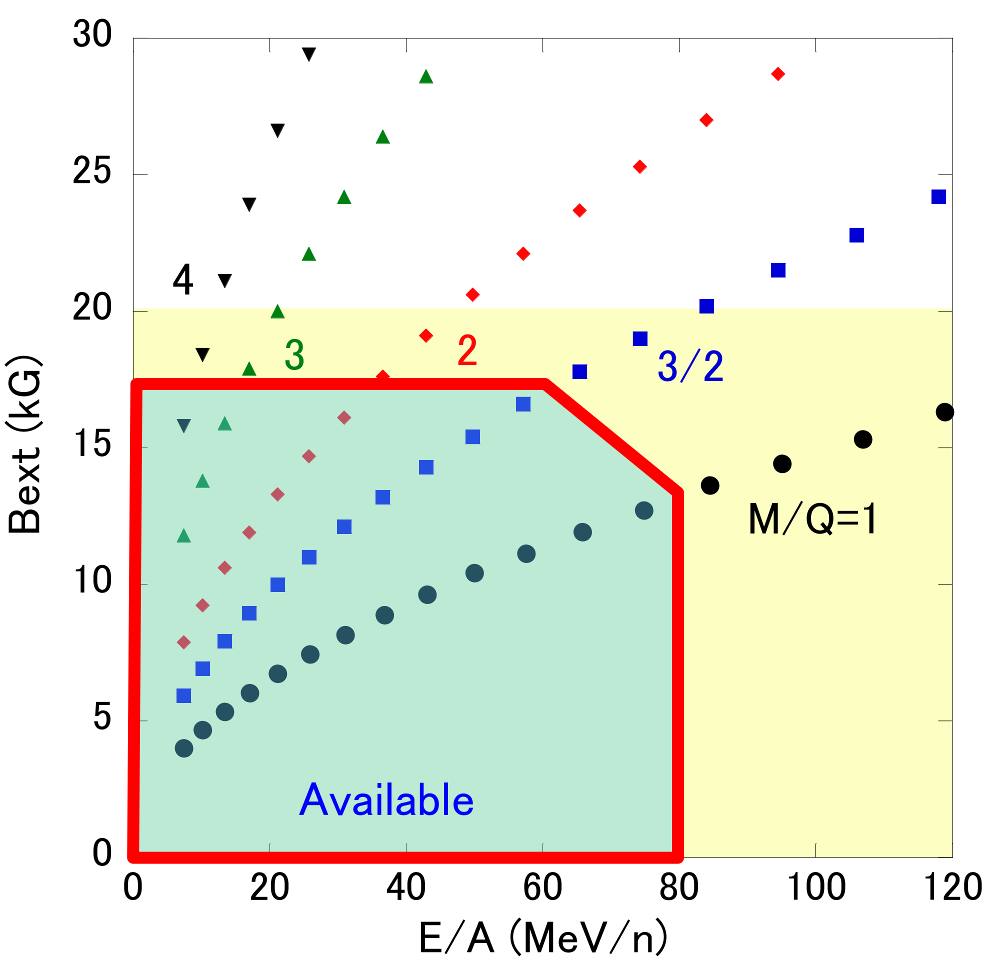
Magnet of 3-sector type



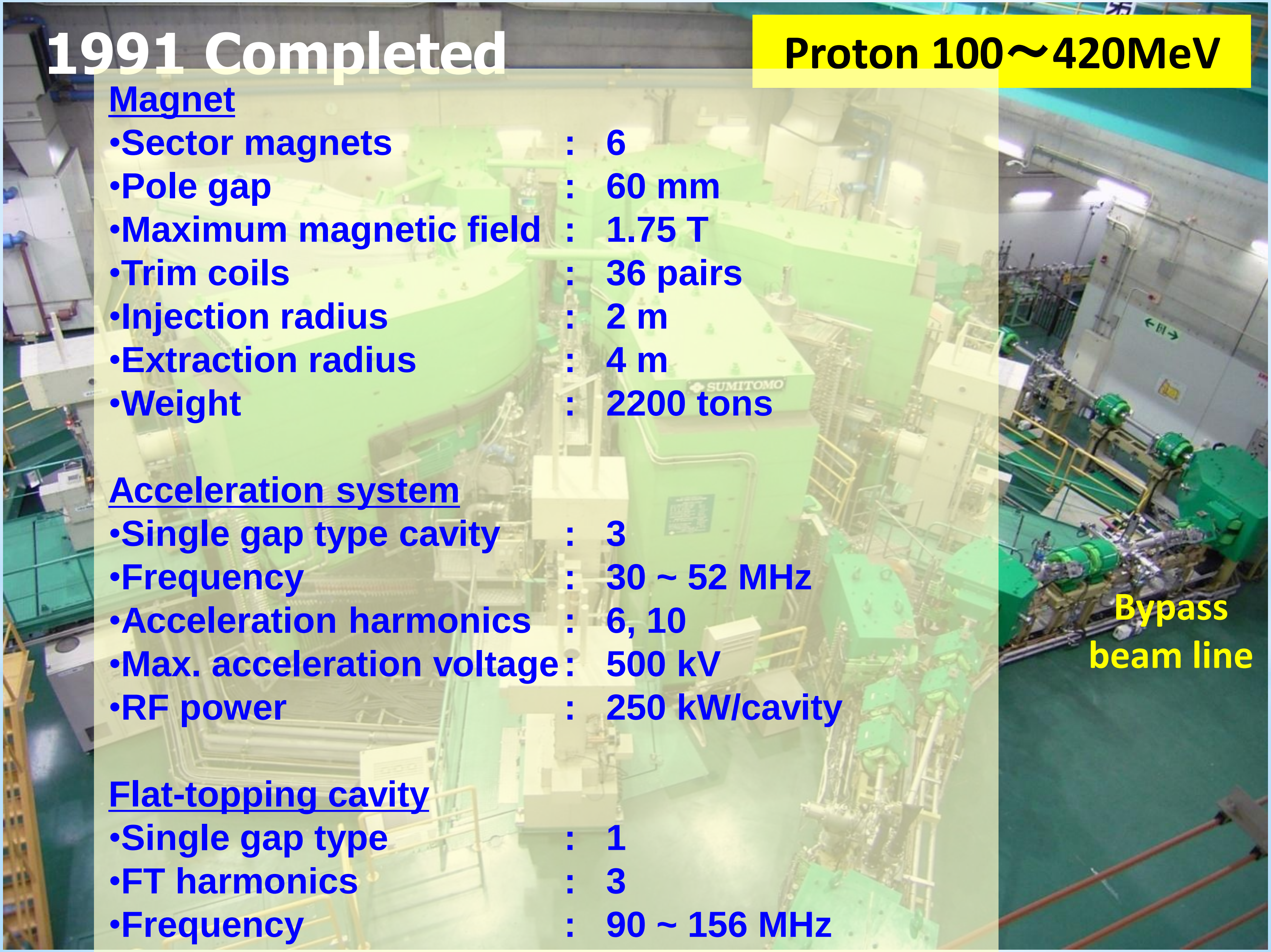
● Characteristics

– Variable energy and multi-particle

– Operation mode : injector of the ring cyclotron and stand-alone mode



RCNP K400 Ring Cyclotron



1991 Completed

Proton 100～420MeV

Magnet

•Sector magnets	:	6
•Pole gap	:	60 mm
•Maximum magnetic field	:	1.75 T
•Trim coils	:	36 pairs
•Injection radius	:	2 m
•Extraction radius	:	4 m
•Weight	:	2200 tons

Acceleration system

•Single gap type cavity	:	3
•Frequency	:	30 ~ 52 MHz
•Acceleration harmonics	:	6, 10
•Max. acceleration voltage	:	500 kV
•RF power	:	250 kW/cavity

Flat-topping cavity

•Single gap type	:	1
•FT harmonics	:	3
•Frequency	:	90 ~ 156 MHz

* RCNP K400 Ring Cyclotron

【Specifications】

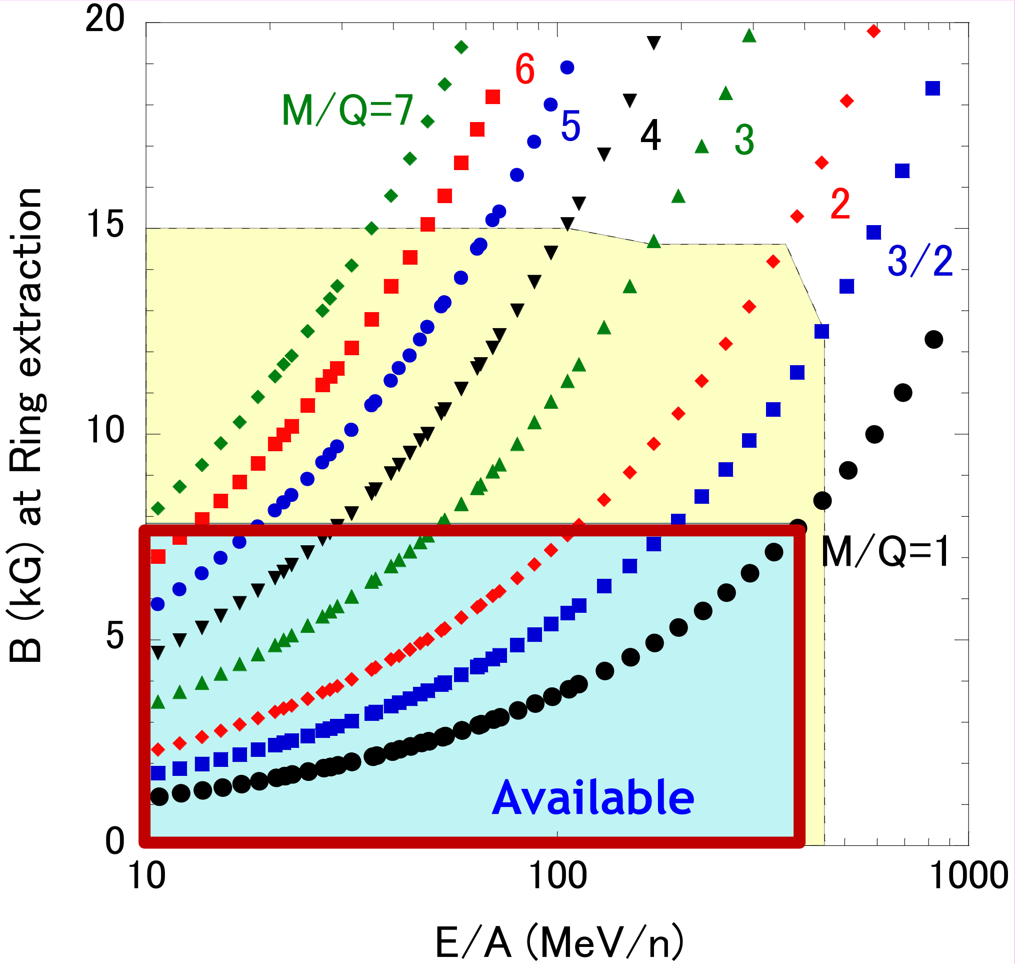
- Energy Designed for light ions with $M/Q \leqq 3$

proton	$\leqq$ 420 MeV
D^+, $^4He^{2+}$	$\leqq$ 100 MeV/n
$^3He^{2+}$	$\leqq$ 170 MeV/n
Heavy Ion	$\leqq 400 \times (Q/A)^2$

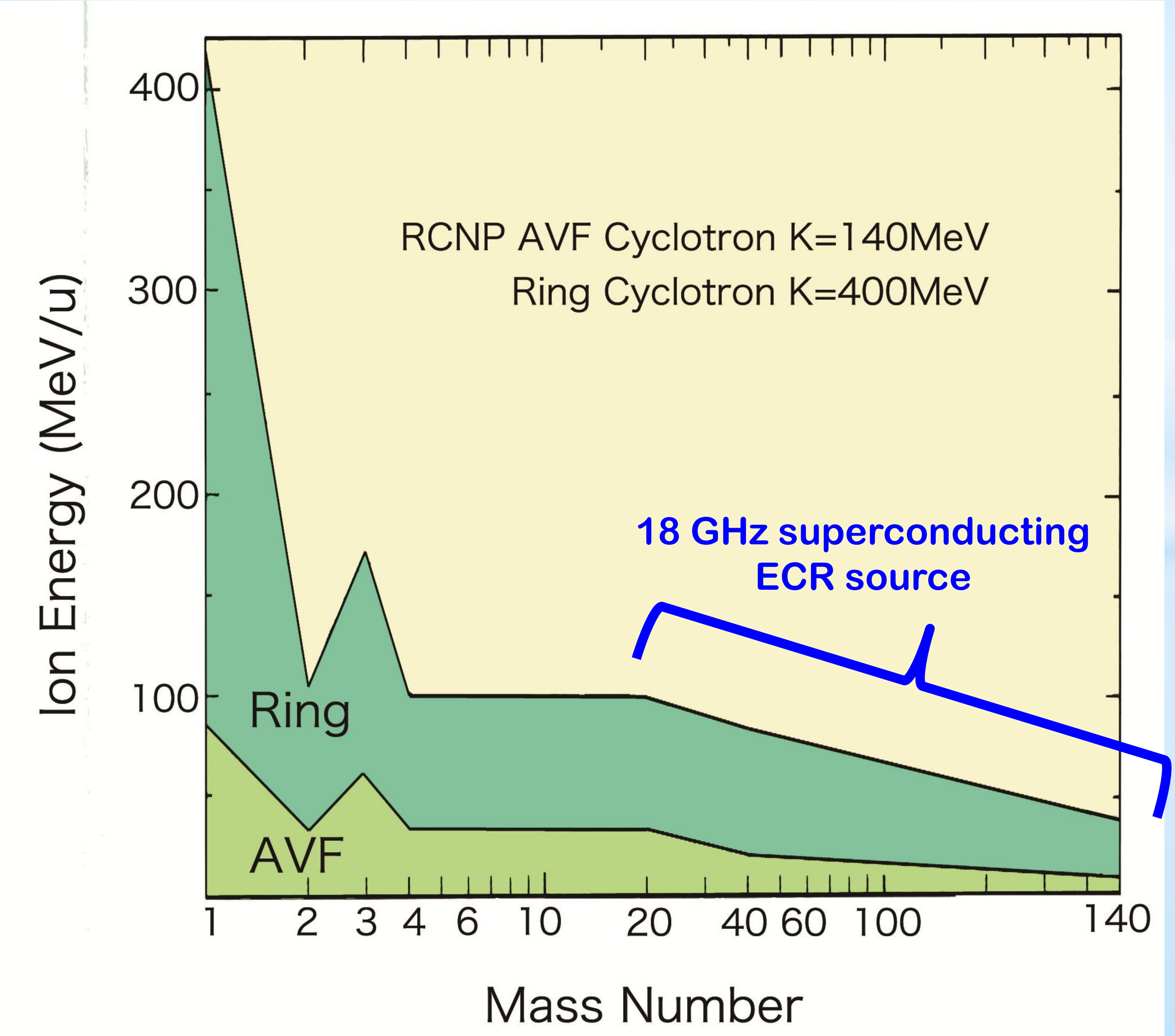
- RF 30～52 MHz
- Acc. harmonics 6, 10, 12, 18
- Average field 8 kG(max.17.5)

● Characteristics

- Beam power : 0.44kW for proton
- Energy spread : $\Delta E/E \sim 0.01\%$
- Mag. Field stability : $\Delta B/B < 0.001\%$

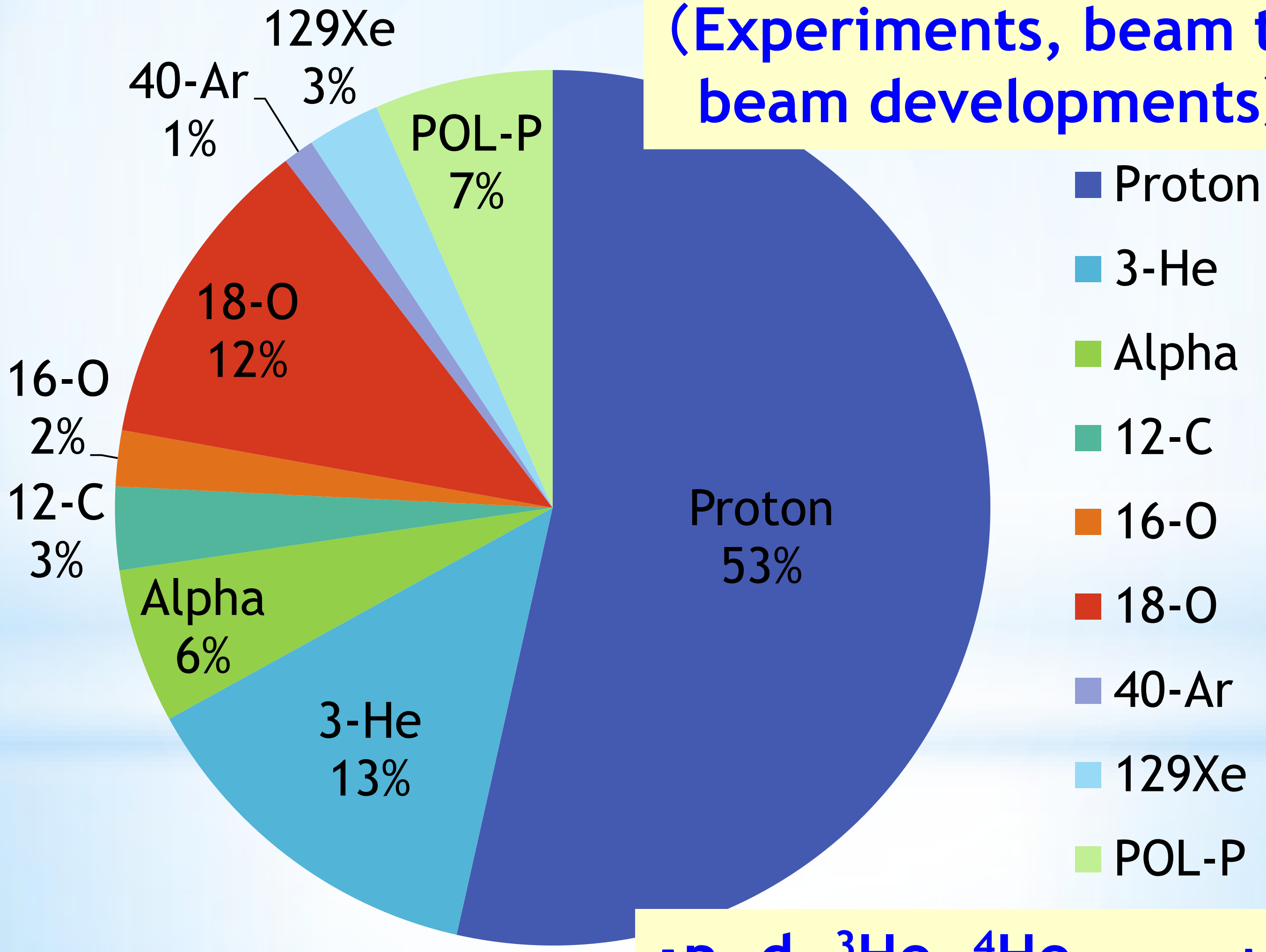


* Ion beams available at RCNP



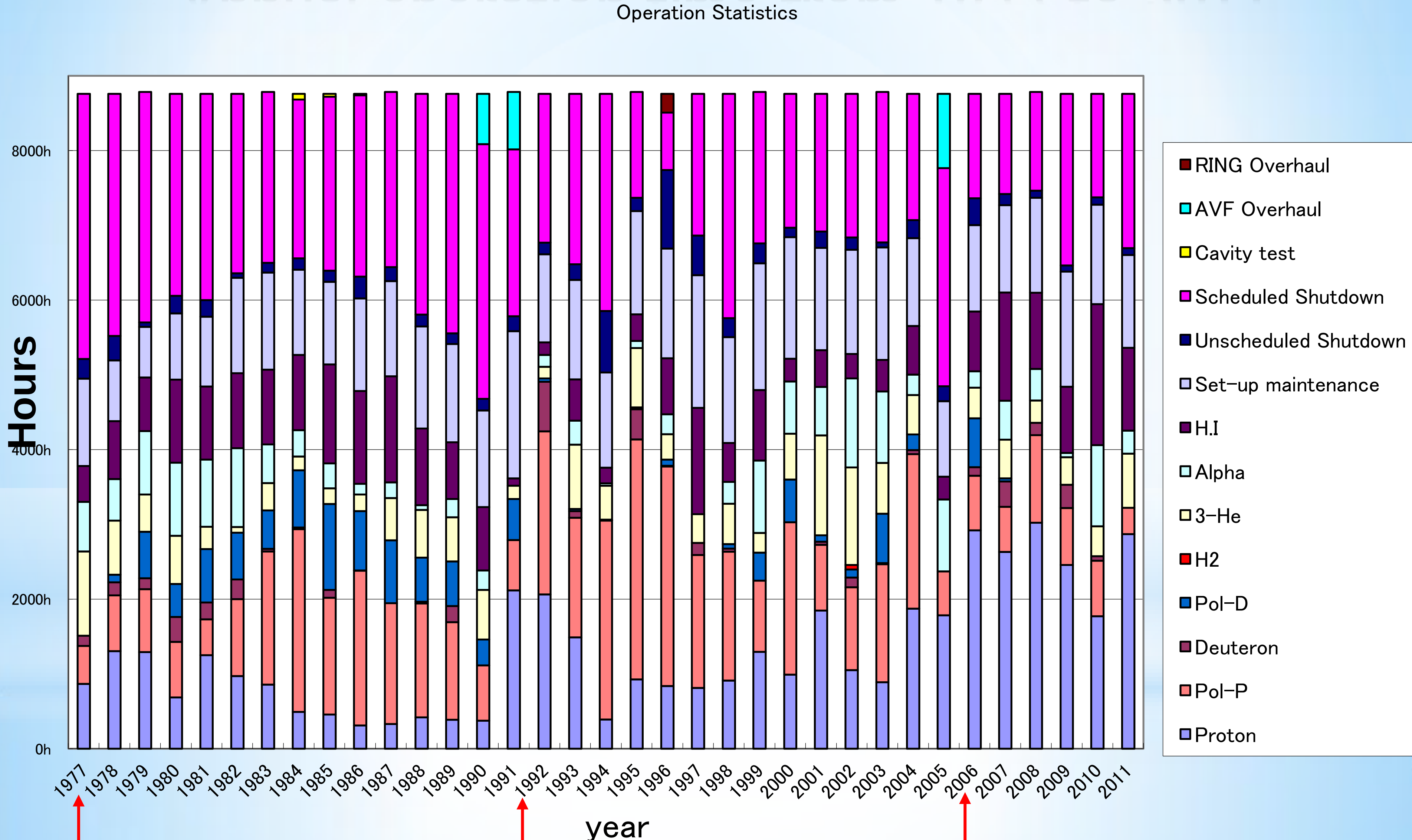
* Cyclotron operation data in 2011

Total : 5362 hours
(Experiments, beam tuning, beam developments)



- **p, d, ^{3}He, ^{4}He : 4253 h**
- **Heavy ions (≧^{12}C) : 1109 h**

* Annual operation time from 1977 to 2011



K140 AVF cyclotron was commissioned.

K400 Ring cyclotron was commissioned.

Upgrade of K140 AVF cyclotron for increase of heavy-ion beam intensity

2. High quality beam for precise nuclear physics experiments

* Requirements for Beam Conditions

Conditions	High Intensity Mode	High Resolution Mode
Intensity	5~10 μA	> 100 nA (achromatic)
Energy spread $\Delta E/E$	$< 10^{-3}$	$< 1 \times 10^{-4}$ (achromatic) $< 5 \times 10^{-5}$ (dispersive)
Emittance	1~3 π mm·mr	< 1 π mm·mr
Extraction	single-turn	single-turn
Transmission efficiency	high	very high
Beam halo	(large)	halo-free

* Flat-topping using k-th harmonics

●En

N_{dee}: N

V_1: Fu

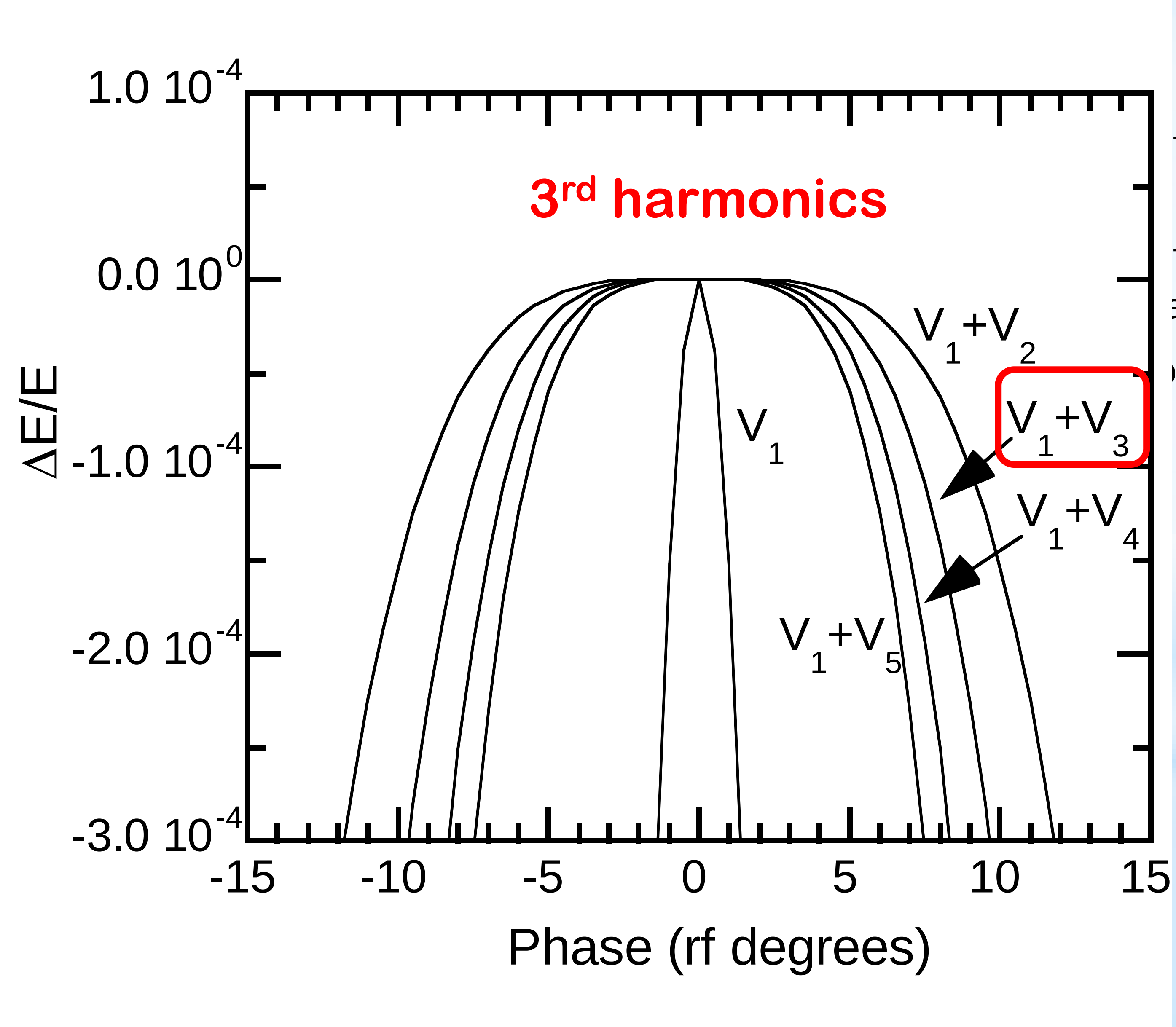
α: Pha

Fo

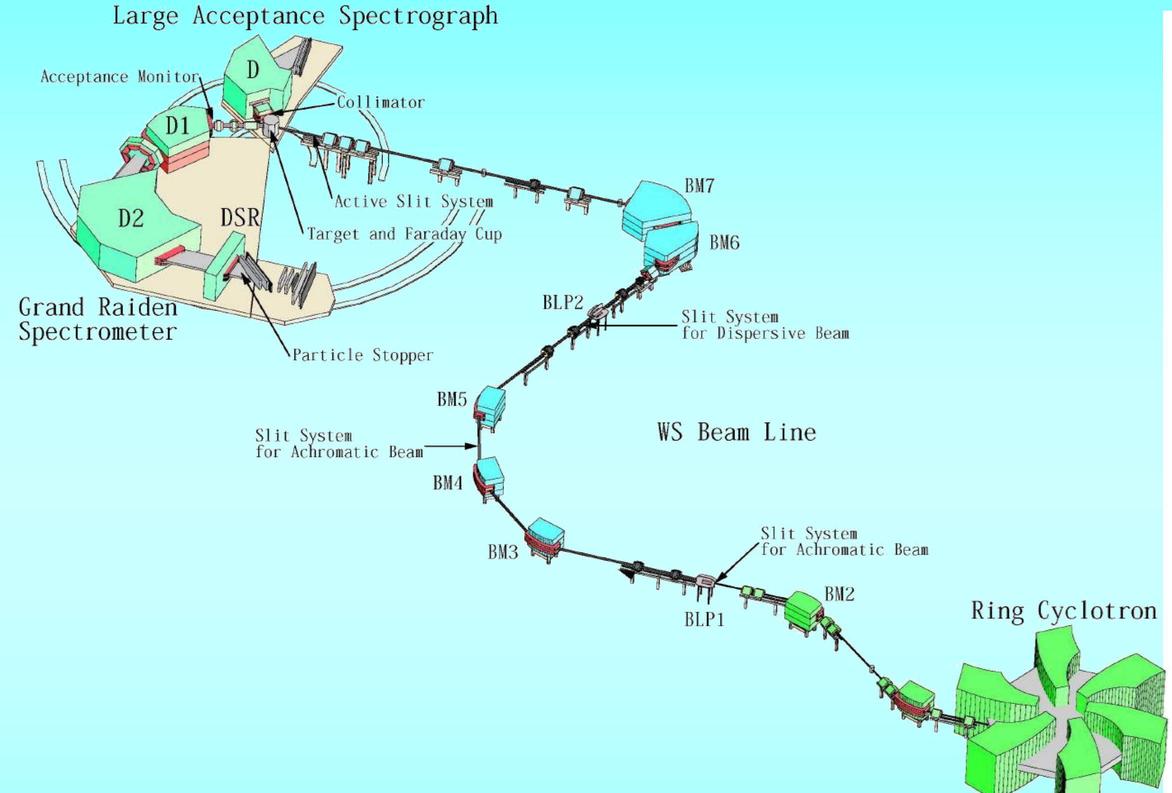
Co

ate

on harmonics



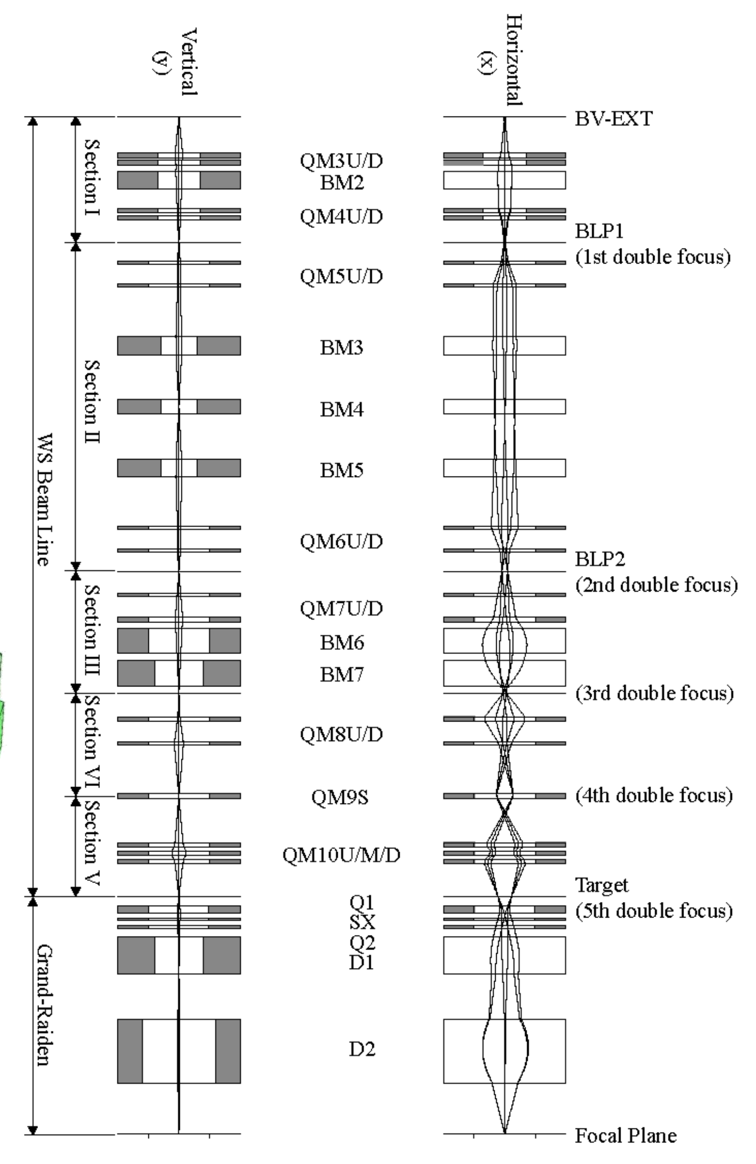
Lateral and Angular dispersion matching between WS-beam line and Grand RAIDEN



WS Beam Line and Two-Arm Spectrometers at RCNP

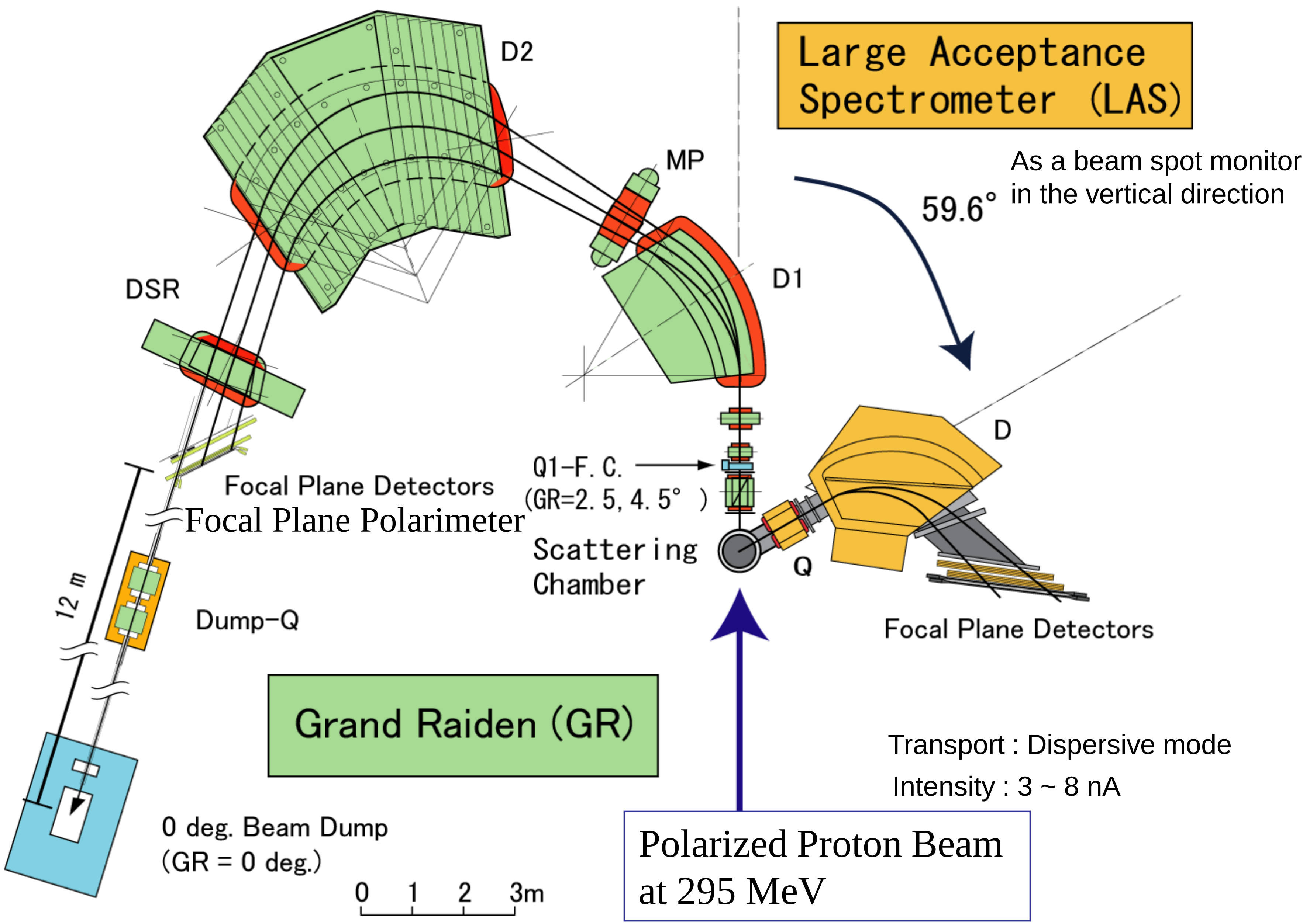
$$x = x_0(s_{11}b_{11}T' + s_{12}b_{21}) - \theta_0(s_{11}b_{12}T' + s_{12}b_{22}) + \delta_0(s_{11}b_{16}T + s_{12}b_{26} + s_{16}C) - \Theta(s_{12} + s_{16}K) \quad (1)$$

$$\theta = x_0(s_{21}b_{11}T' + s_{22}b_{21}) - \theta_0(s_{21}b_{12}T' + s_{22}b_{22}) + \delta_0(s_{21}b_{16}T + s_{22}b_{26} + s_{26}C) - \Theta(s_{22} + s_{26}K) \quad (2)$$




Grand-RAIDEN
LAS
(Large Acceptance
Spectrometer)

Spectrometers in the 0-deg. experiment setup

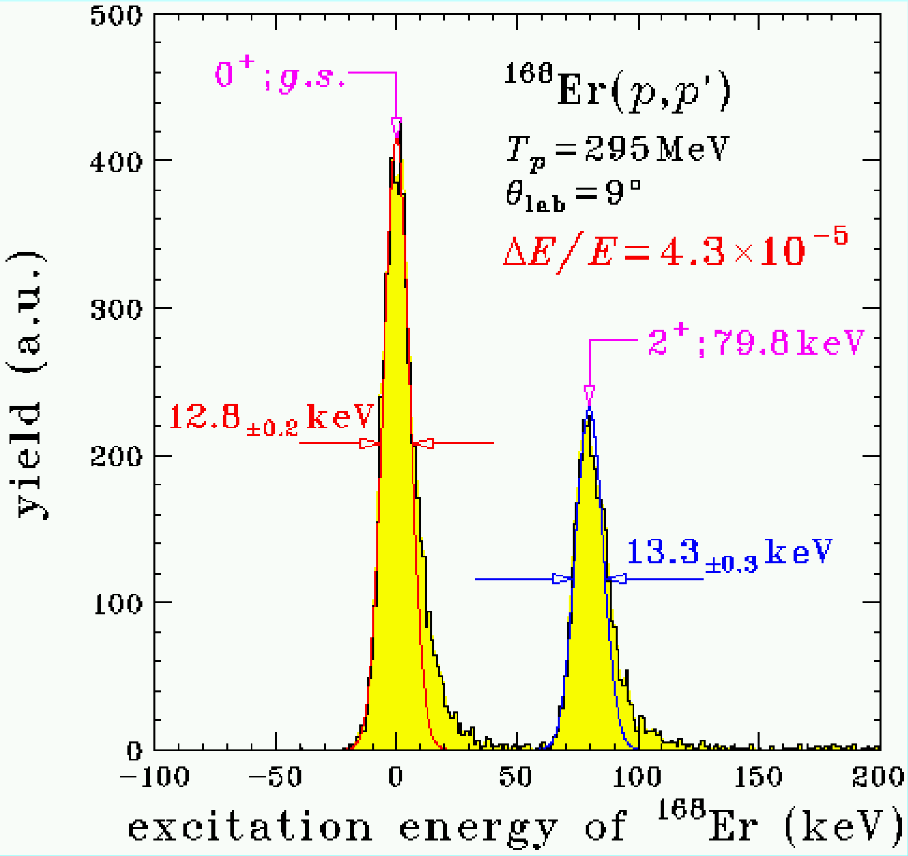


Ultrahigh Energy Resolution Experiment Using the High Quality Beam

ΔE = 12.8 keV

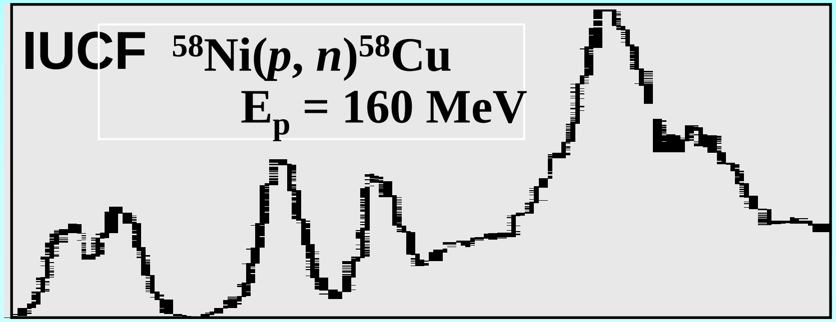
achieved by 300MeV proton

World record !!



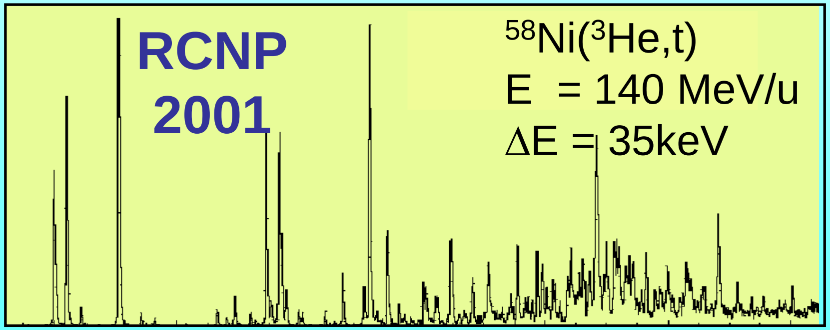
Comparison of resolutions

Ordinary resolution measured in the (p,n) experiment



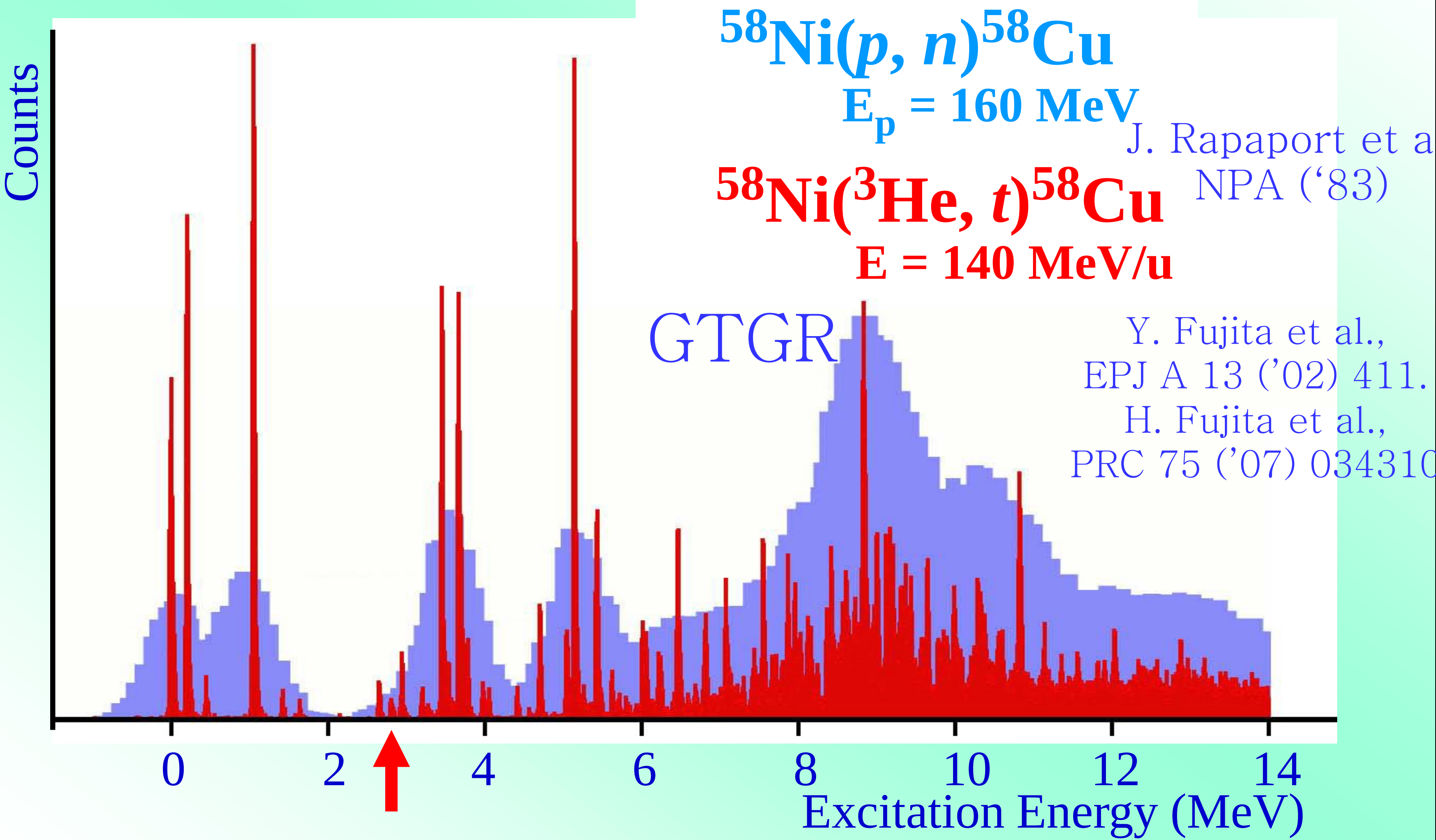
J. Rapaport NPA ('83)

Ultrahigh resolution achieved in the (^{3}He,t) experiment



Comparison of (p, n) and (^{3}He,t) 0° spectra

Study of GT excitations (caused by στ operator) !



Example of experiments at Grand-RAIDEN (not completed)

p and *n* distribution via (*p*, *p*)
Zenihiro, Matsuda, Sakaguchi

Complete E1/M1 response via (*p*, *p*') @ 0-degree
A. Tamii, P. von Neumann-Cosel

α cluster via (α, α')
Kawabata, M. Itoh

Spin/Isospin response via (^{3}He, *t*)
Y. Fujita, H. Fujita

Medium effect via (*p*,2*p*) / (*p*,*pn*)
Noro, Wakasa

Tensor component via high energy (*p*,*d*)
O. H. Jin, I. Tanihata

pn-paring via (^{3}He, *p*) / (*p*, ^{3}He) @ low energy
J. Lee

Double charge exchange (^{18}O, ^{18}Ne)
T. Uesaka, Takahisa

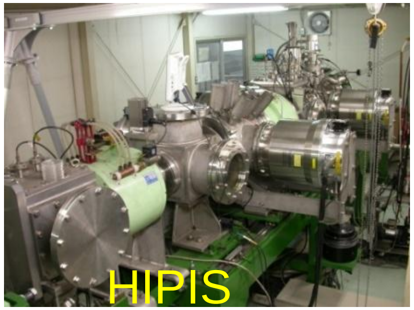
3. Intense proton beam for applications using secondarily-produced particles

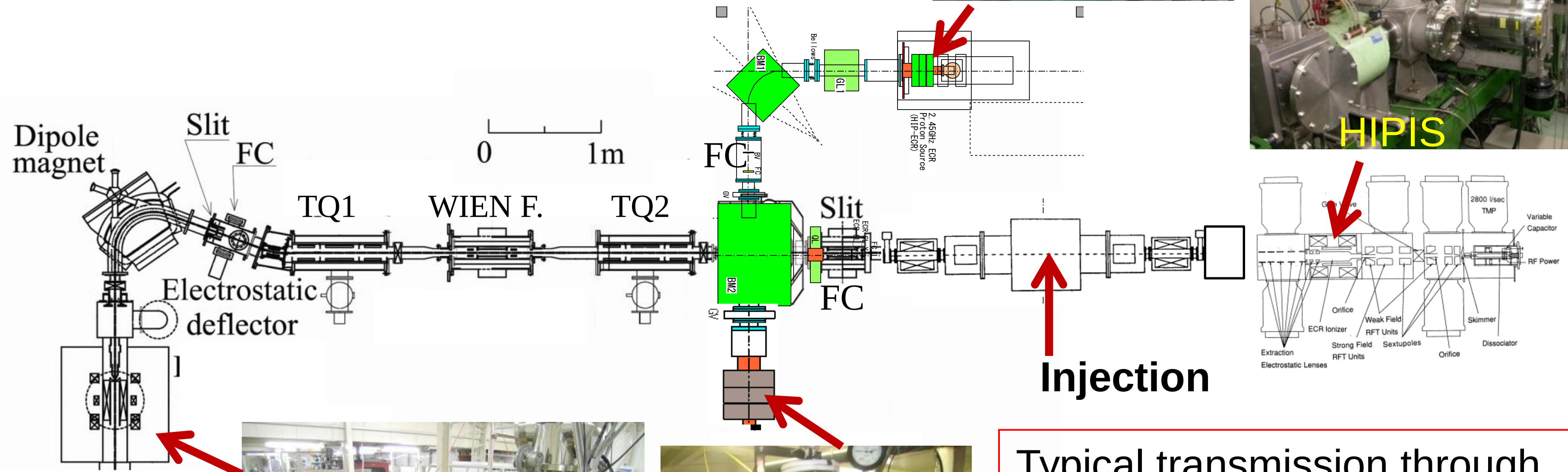
* Requirements for Beam Conditions

Conditions	High Intensity Mode	High Resolution Mode
Intensity	Present Max. 1.1 μA 5~10 μA	> 100 nA (achromatic)
Energy spread $\Delta E/E$	$< 10^{-3}$	$< 1 \times 10^{-4}$ (achromatic) $< 5 \times 10^{-5}$ (dispersive)
Emittance	1~3 π mm·mr	< 1 π mm·mr
Extraction	single-turn	single-turn
Transmission efficiency	high	very high
Beam halo	(large)	halo-free

RCNP Ion Source Complex

18GHz SC-ECR for heavy ions
NEOMAFIOS for p, d, He, Li ~ Mg, Ar
2.45GHz HIPECR for intense p
HIPIS for polarized p, d



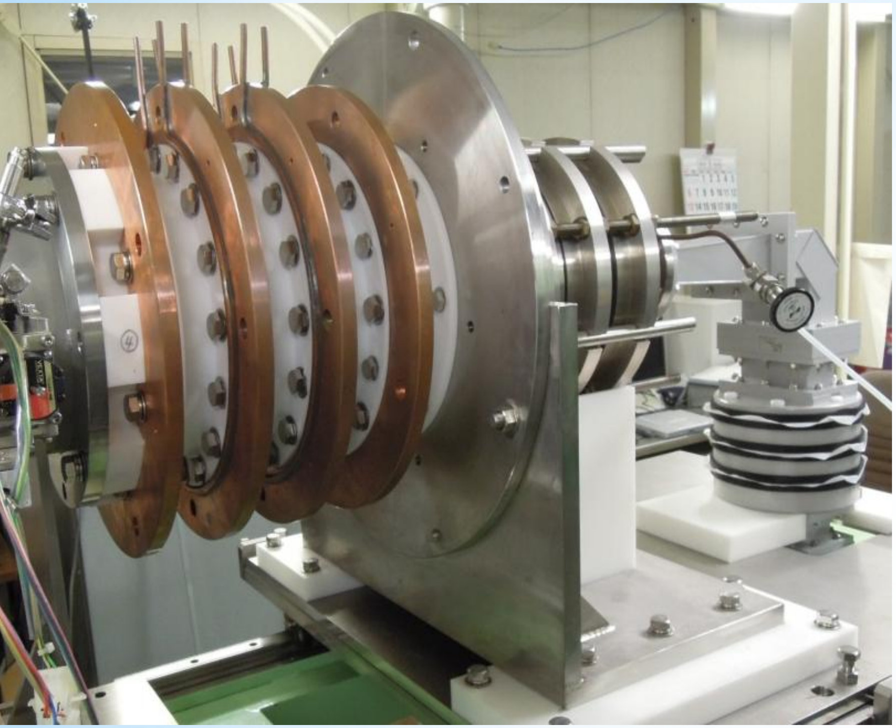


Typical transmission through AVF cyclotron is 5 - 7 %.

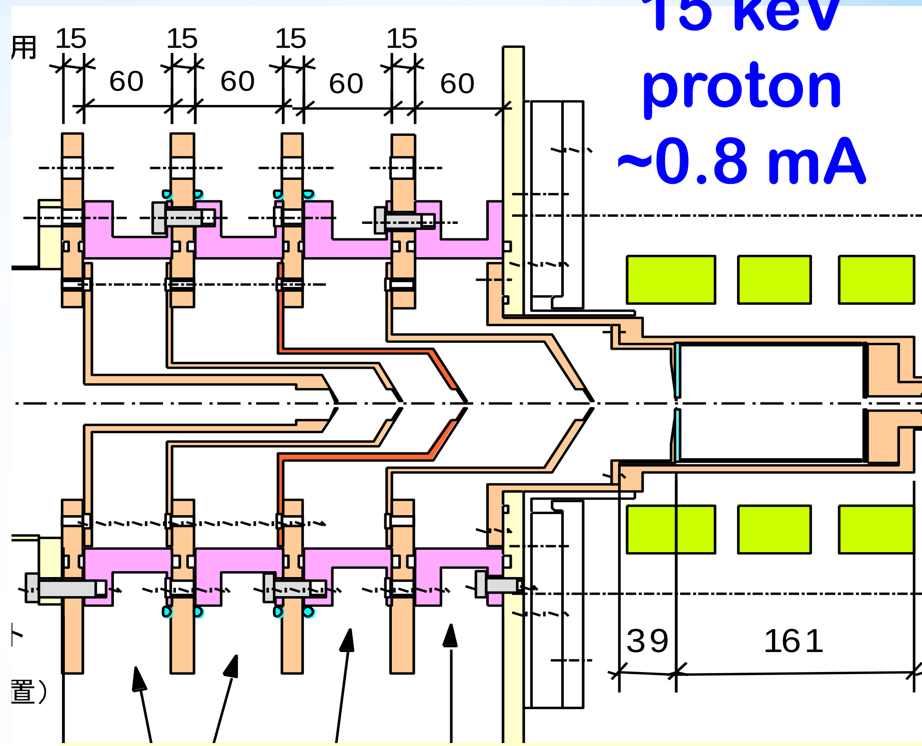
90 % emittance:

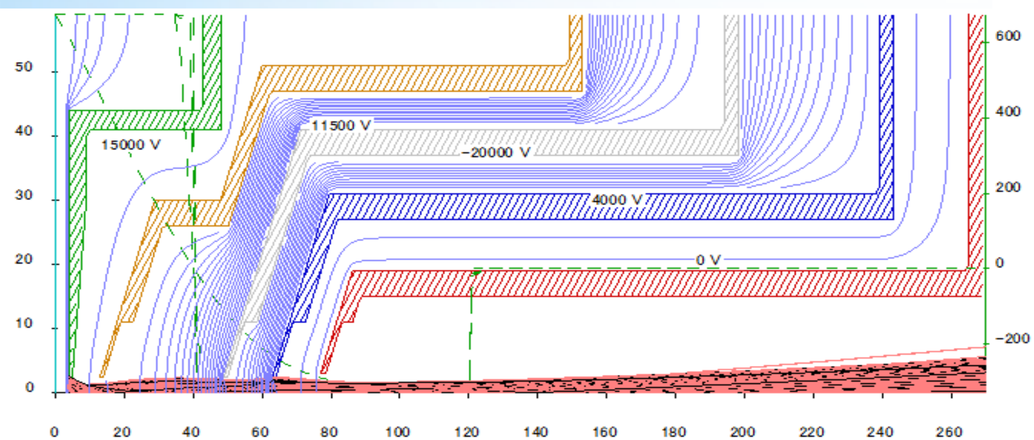
$\varepsilon_x = 6\pi$ mm･mrad、
$\varepsilon_y = 10\pi$ mm･mrad

*2.45 GHz intense proton source



15 keV proton ~0.8 mA





Simulation in the extraction region by IGUN

– Transmission : 85%

– Emittance : 12 π mm･mr

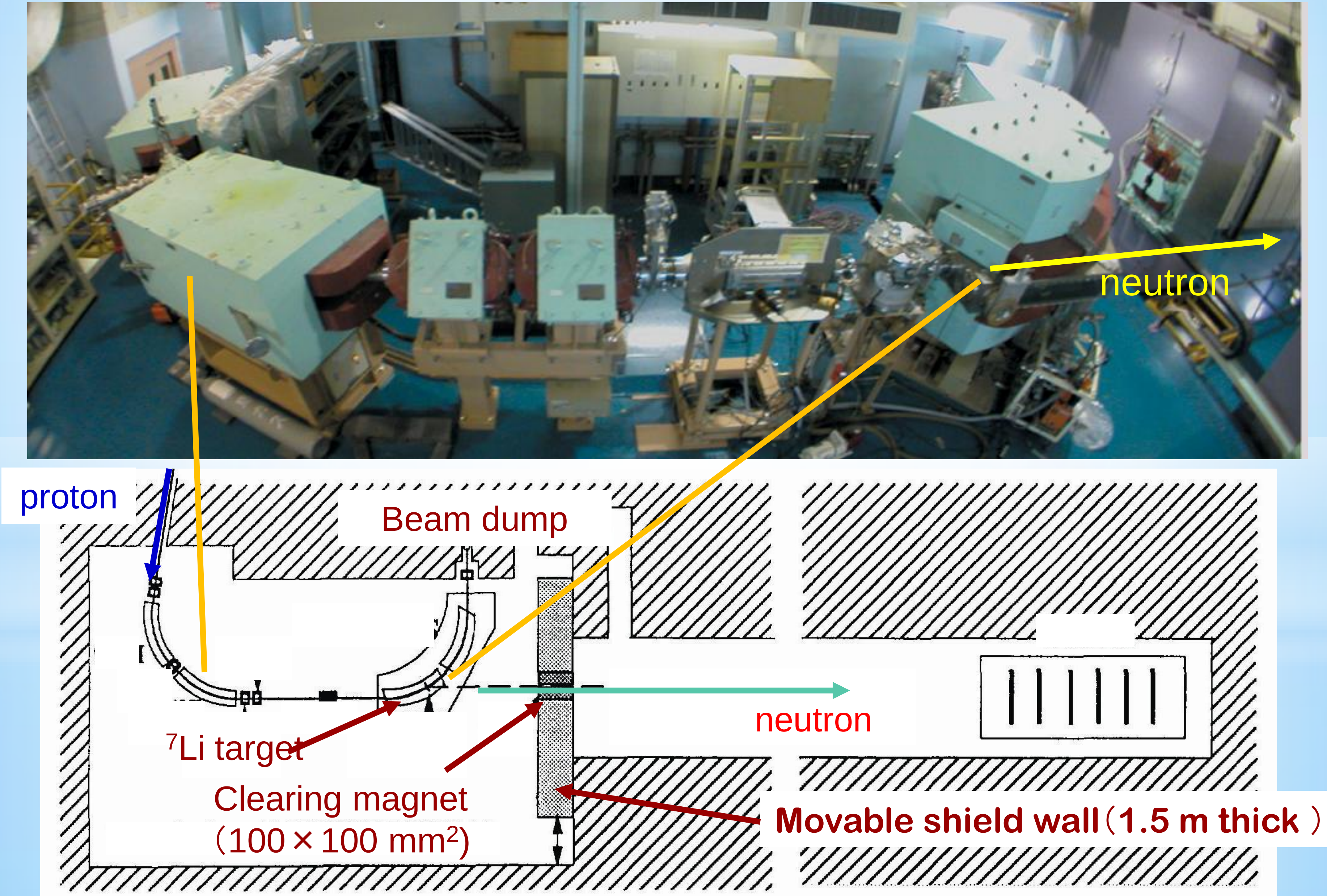
– Brightness : 2.4×10^{-6} A/(mm･mr)^2

*Neutron experiments

- Applications
  - Nuclear reaction Data Base
  - Radiation effects on RAM, power devices, etc.
  - Radioisotopes for nuclear medicines
- Fundamental physics
  - Neutron EDM measurements

* Neutron and muon experiments

* Quasi mono-energy neutron source



Intensity and peak:tails of neutrons above 100 MeV

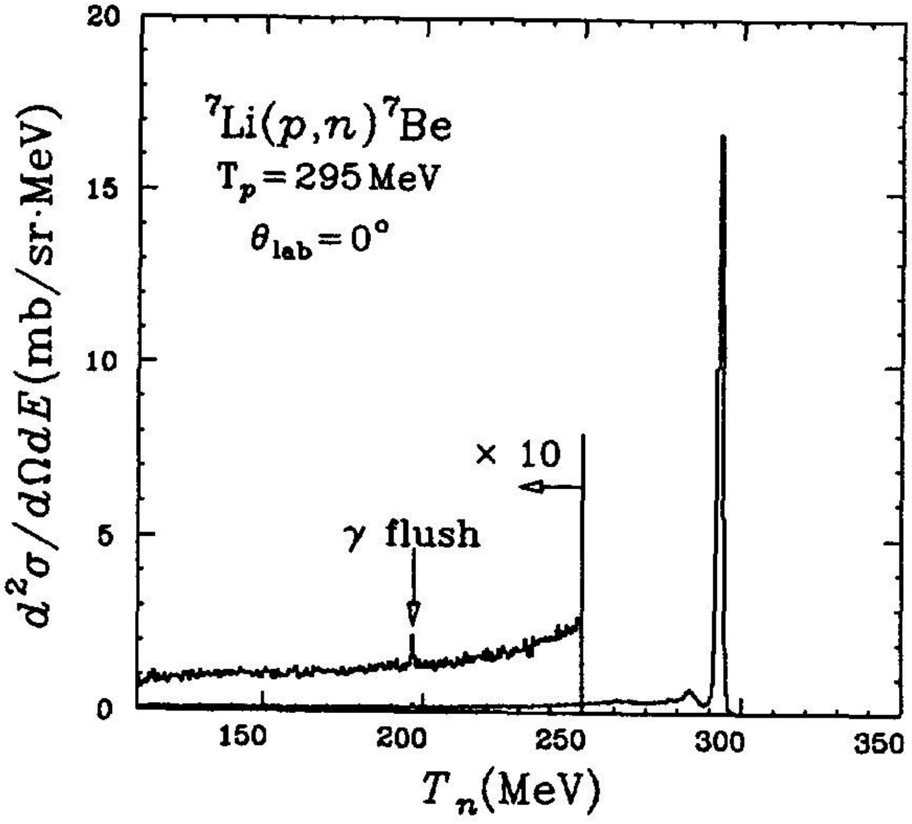


Fig. 11. Neutron energy spectrum for the ^{7}Li(p, n)^{7}Be reaction at 295 MeV and 0°. See text for detail.

H. Sakai et al.,

Nucl. Instr. Meth. A 369 (1996) 120-134

^{7}Li target: 1 cm（0.535 g/cm^2）

Proton current: 1 μA

Distance from the target: 8 m

↓

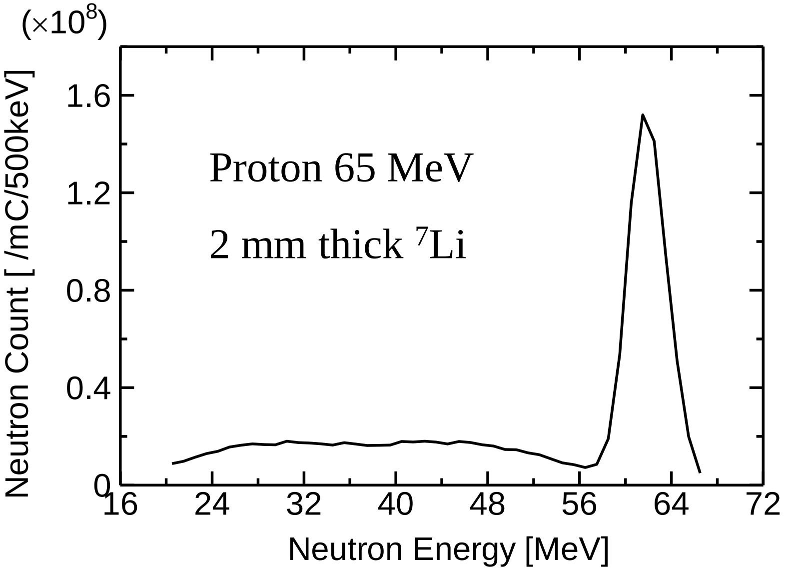
1.1×10^4 n/cm^2/s

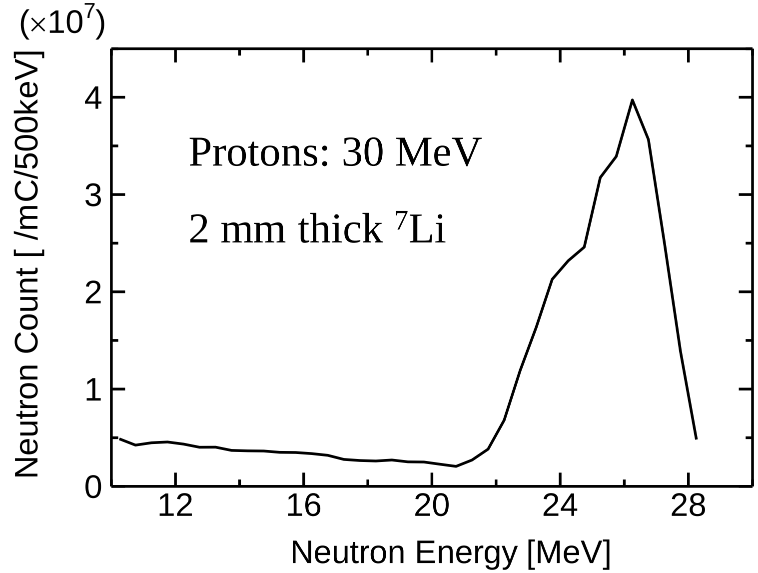
peak：tails≒1:1

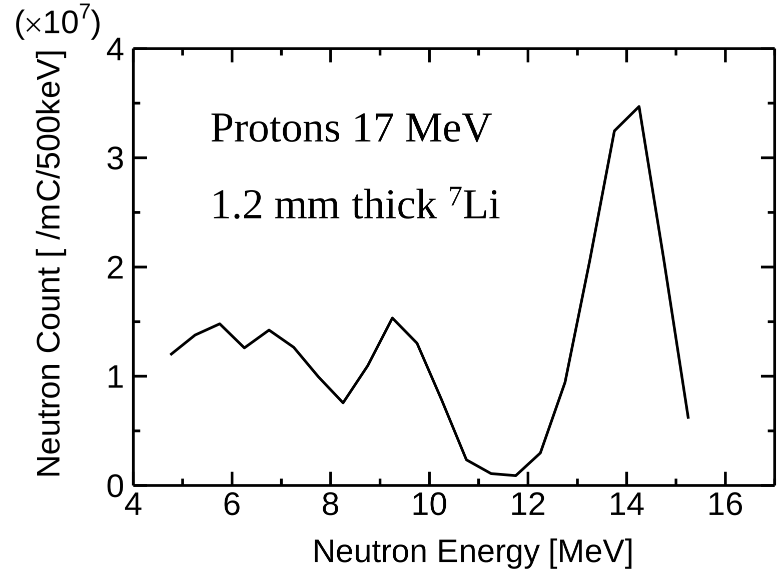
$\Delta E \approx 2-5$ MeV

Intensity and peak:tails of neutrons at low energies

$^{7}Li\ (p, n)\ ^{7}Be$







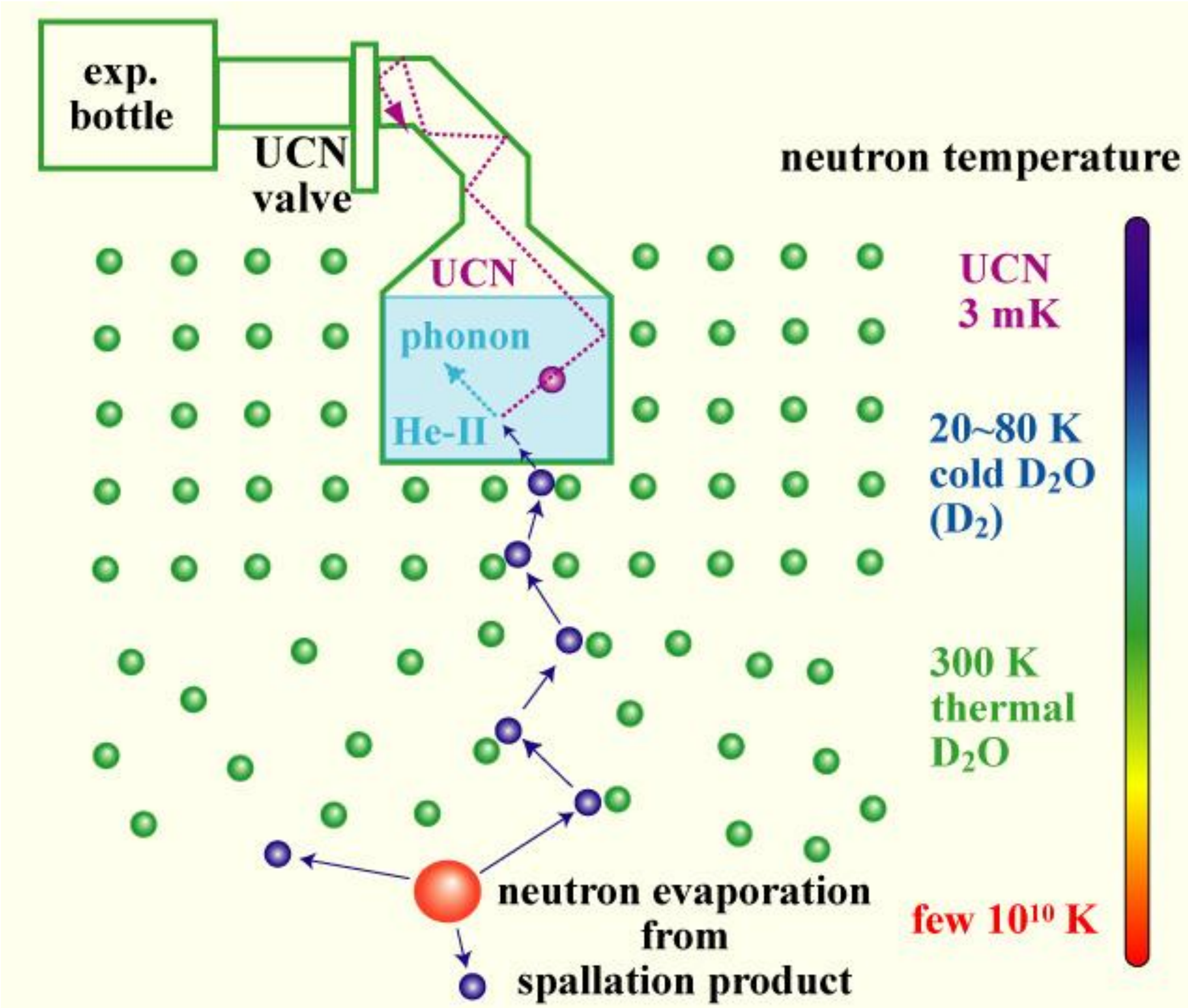
Intensity of neutrons normalized by the beam current, the target thickness and the solid angle;

(65 MeV) : (30 MeV) : (17 MeV)

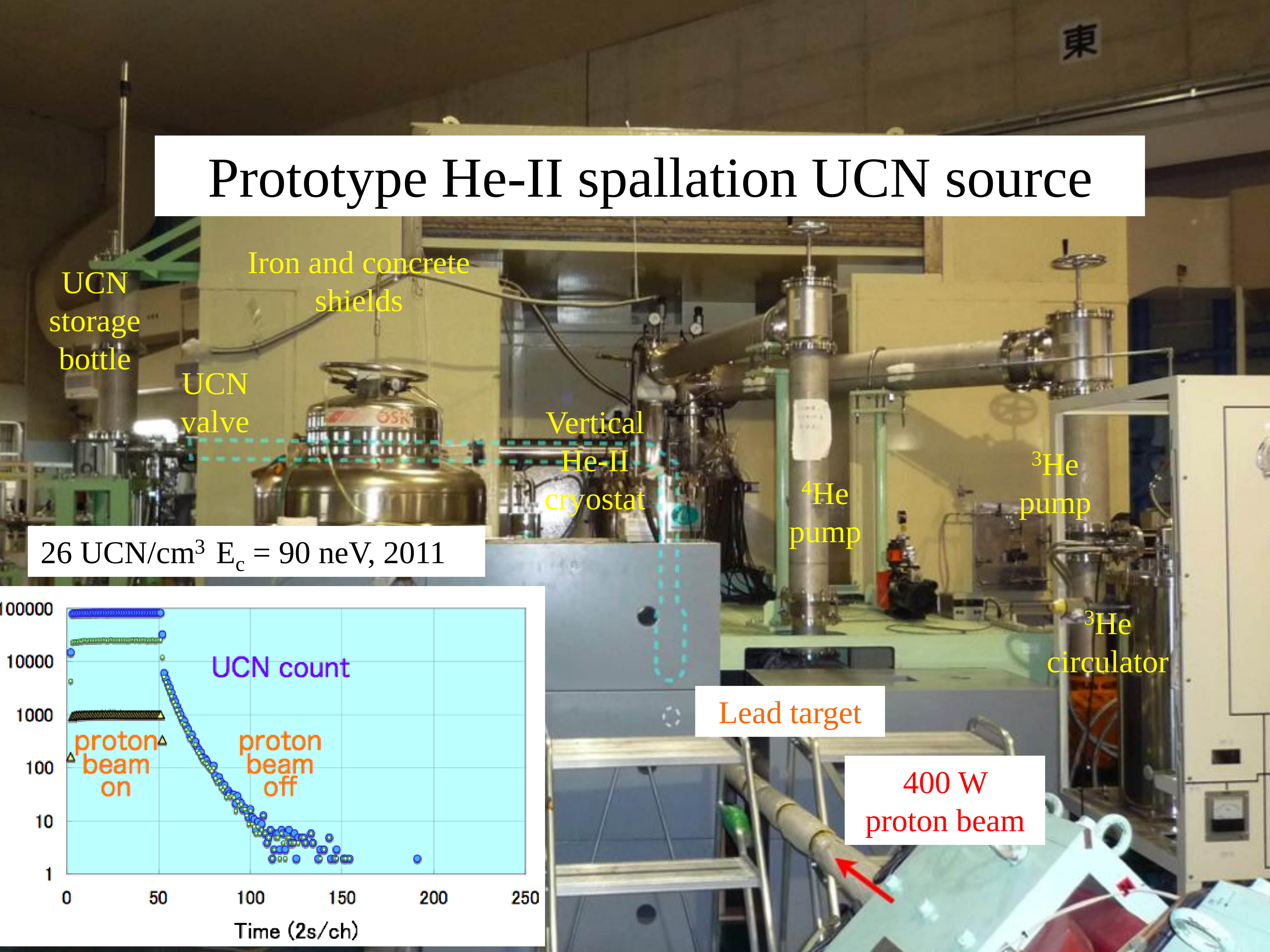
＝1 : 0.21 : 0.11

Ultra-cold neutrons

High density UCN production

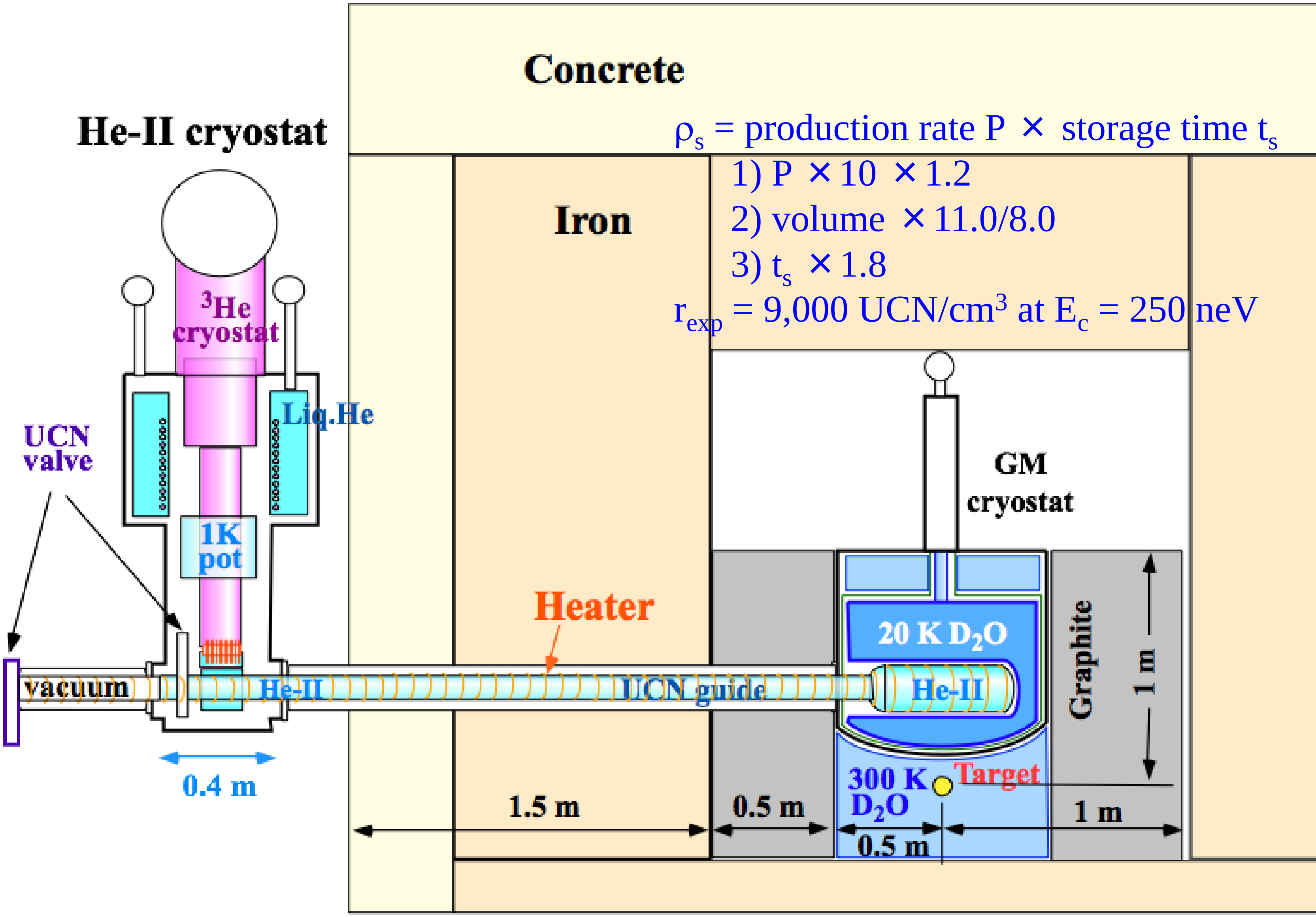


Prototype He-II spallation UCN source



26 UCN/cm^3 E_c = 90 neV, 2011

New UCN source under construction



ρ_s = production rate P $\times$ storage time t_s

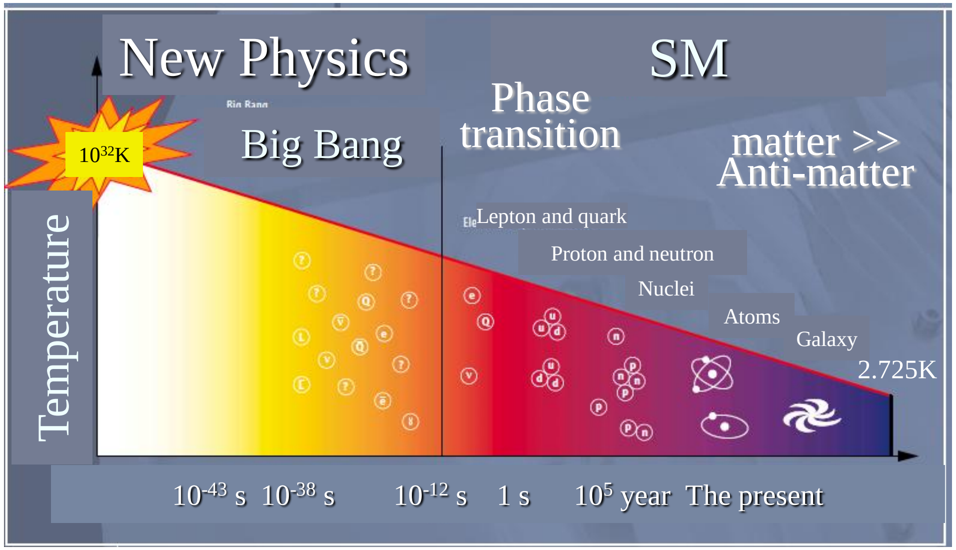
1) P $\times$10 $\times$1.2

2) volume $\times$11.0/8.0

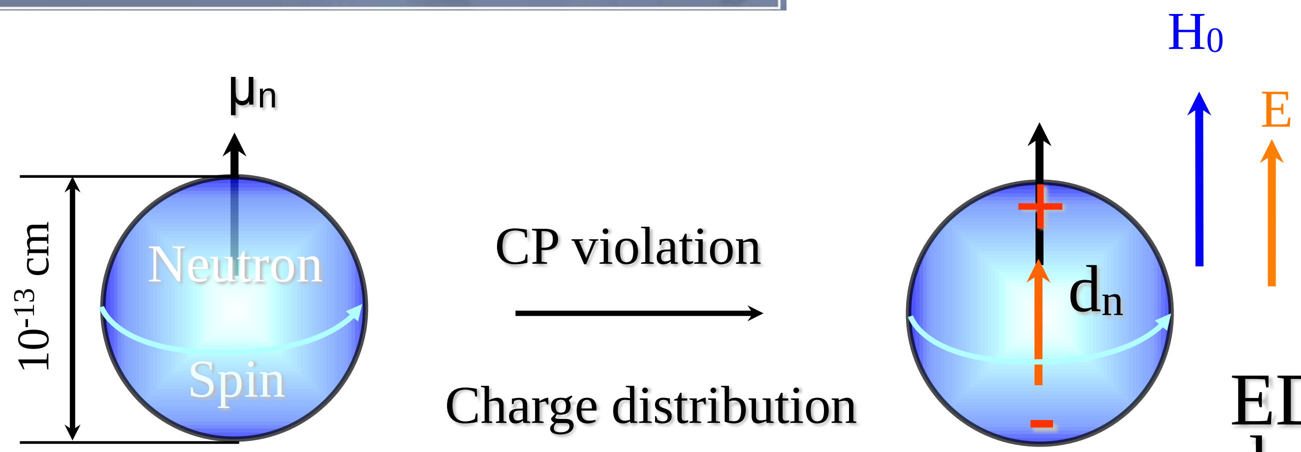
3) t_s $\times$1.8

r_{exp} = 9,000 UCN/cm^3 at E_c = 250 neV

Electric Dipole Moment



Existence of the Electric Dipole Moment of a particle violates P invariance as well as T, and so leads CP violation.



EDM
d_n (e ･ cm)

Measurement of $\mu_n H_0 \pm d_n E$

White neutrons

* Radiation effects of terrestrial neutrons on LSIs

Average SER (Soft Error Rate) in SRAM ~ 1,000 FIT*/Mb

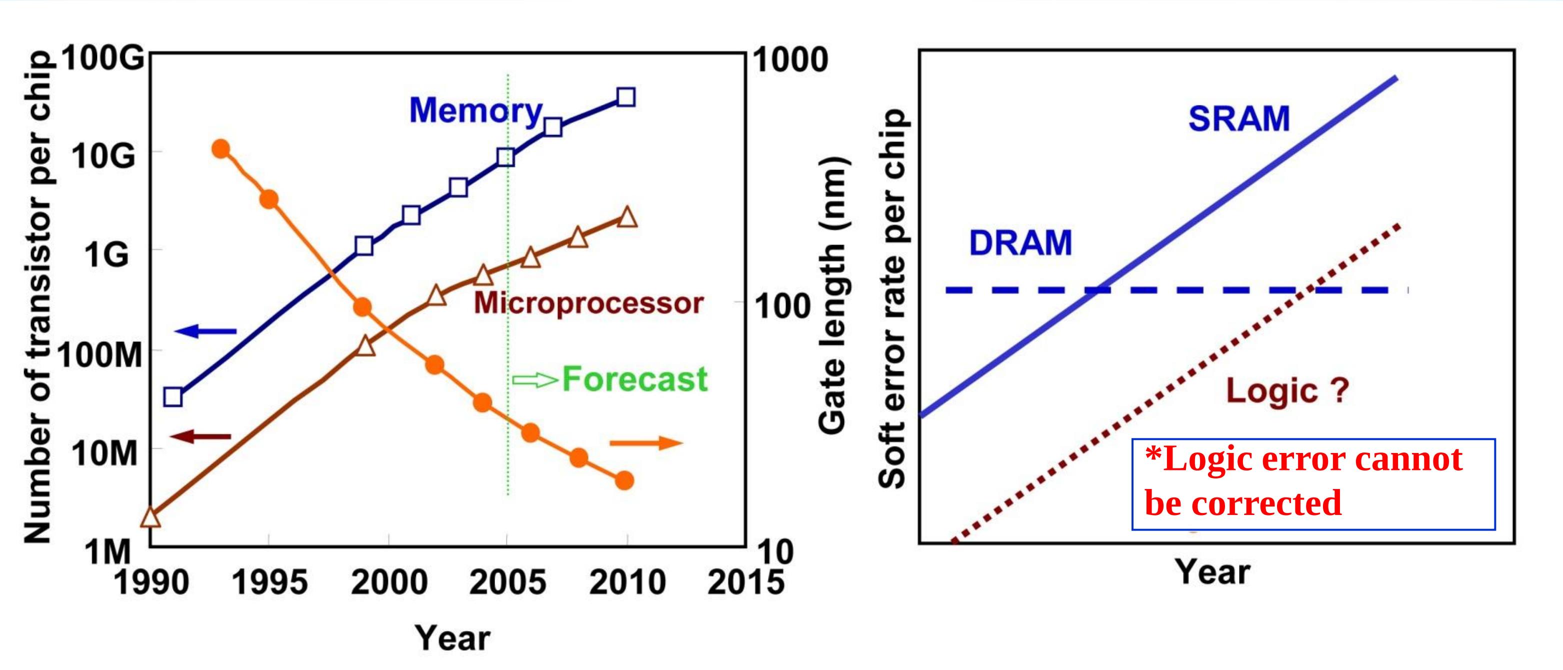
SRAMs in a system (server, etc)   ~ 1Gb/system

10^6 FIT/system

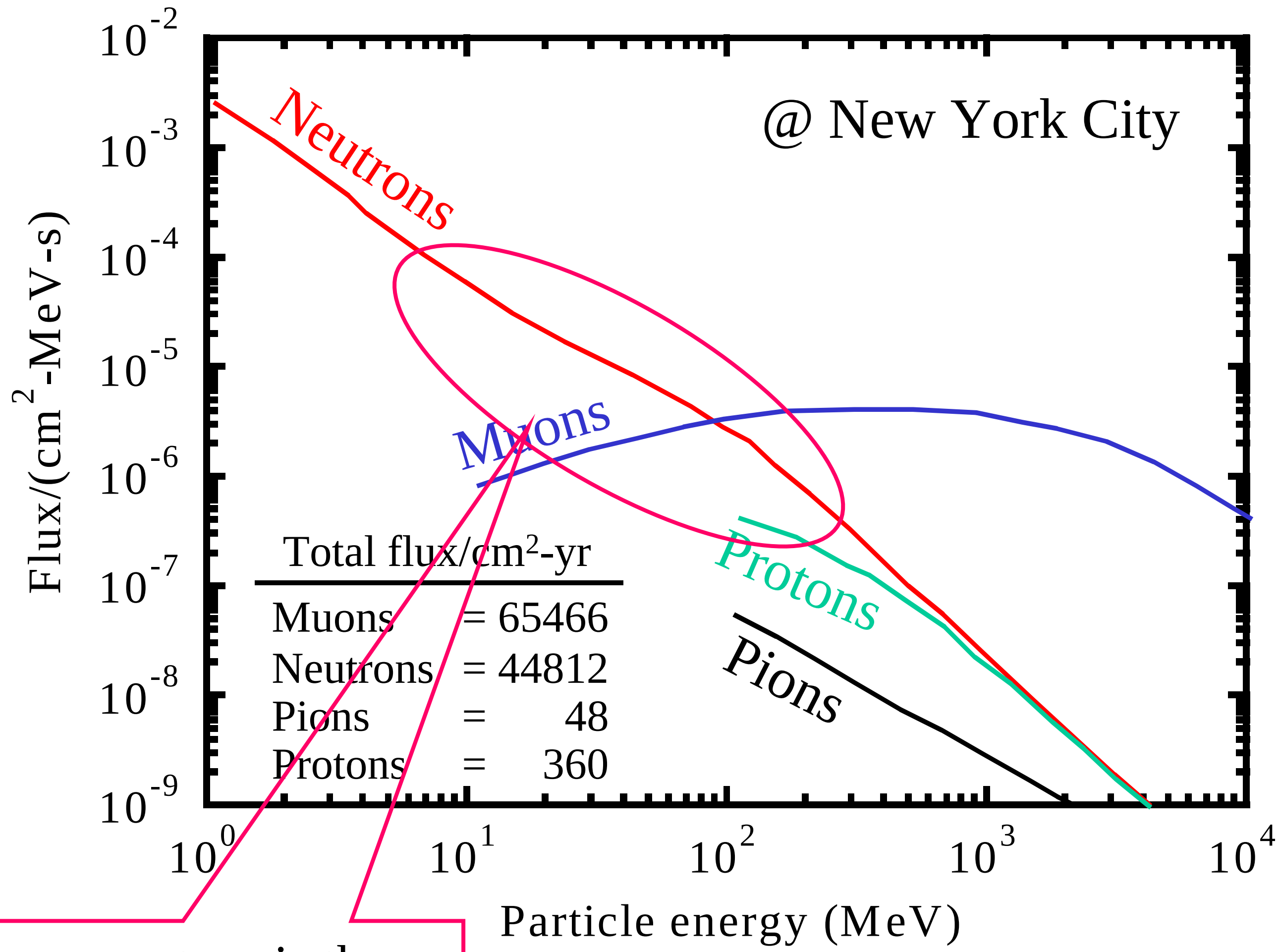
~ 10^{-3} error/hour/system

~ 10 errors/year/system

***1 FIT = 1 error/10^9 hours**



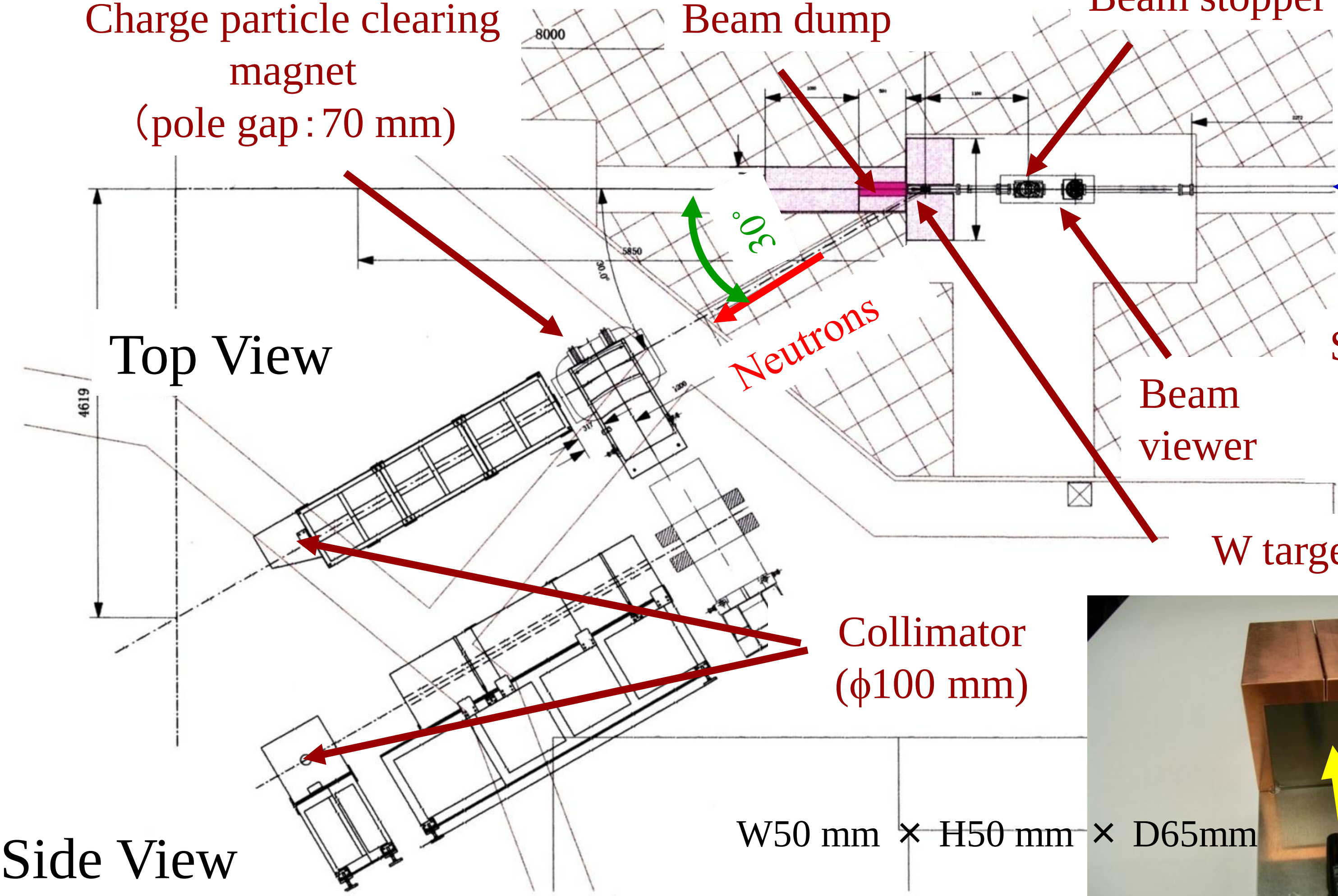
Cosmic rays in the terrestrial environment



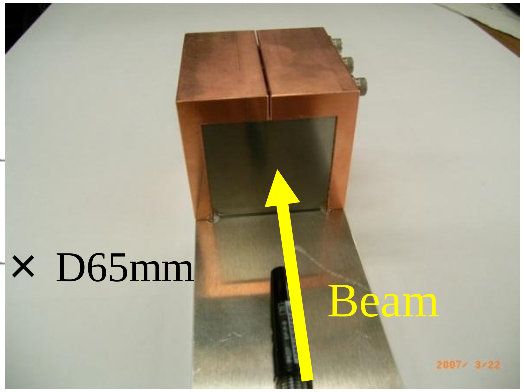
High energy neutron is the main source of the soft errors on LSIs on the earth.

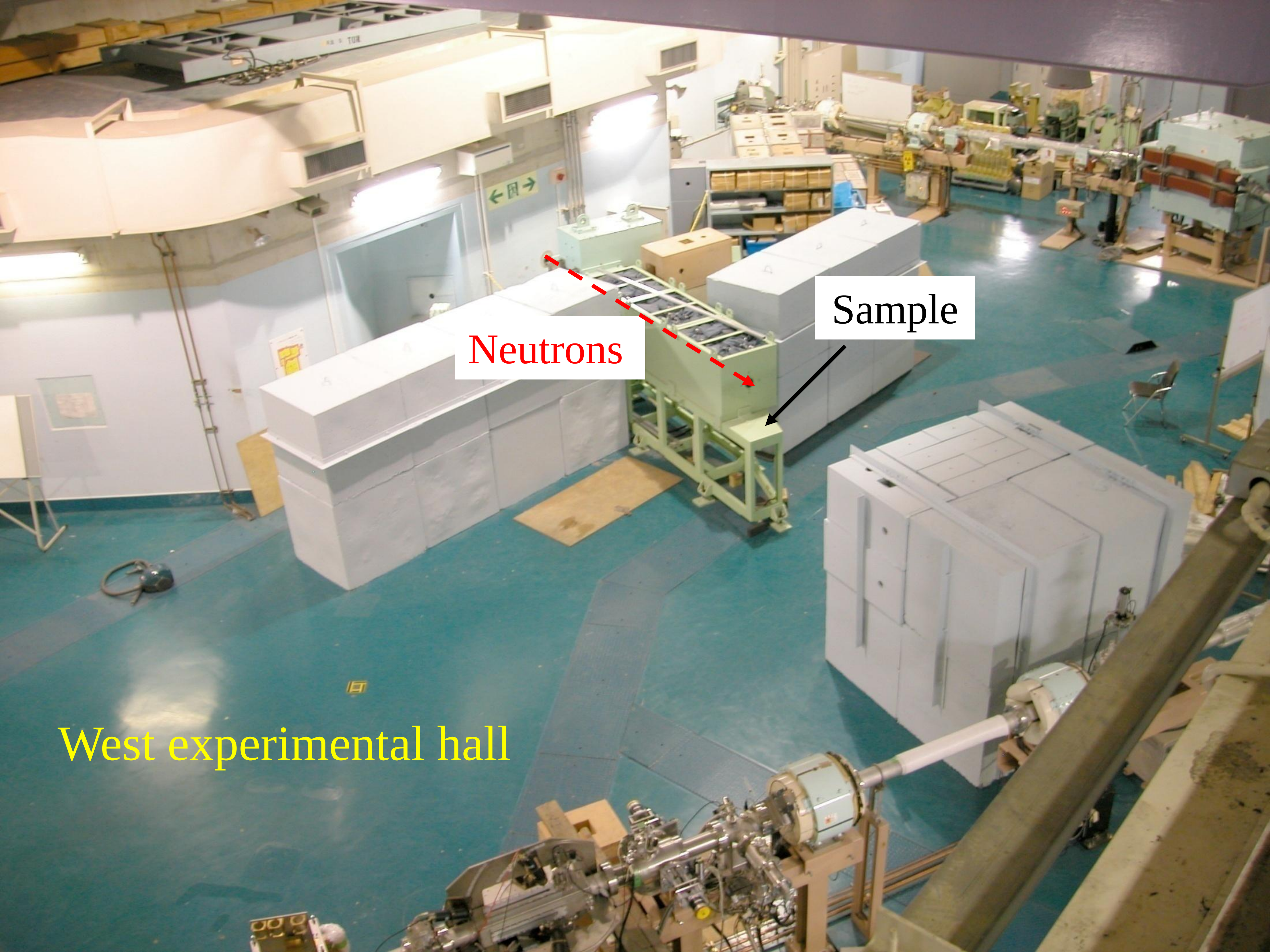
J. F. Ziegler et al., IBM J. Res. Dev. 40 (1996) 19

White neutron source@ RCNP

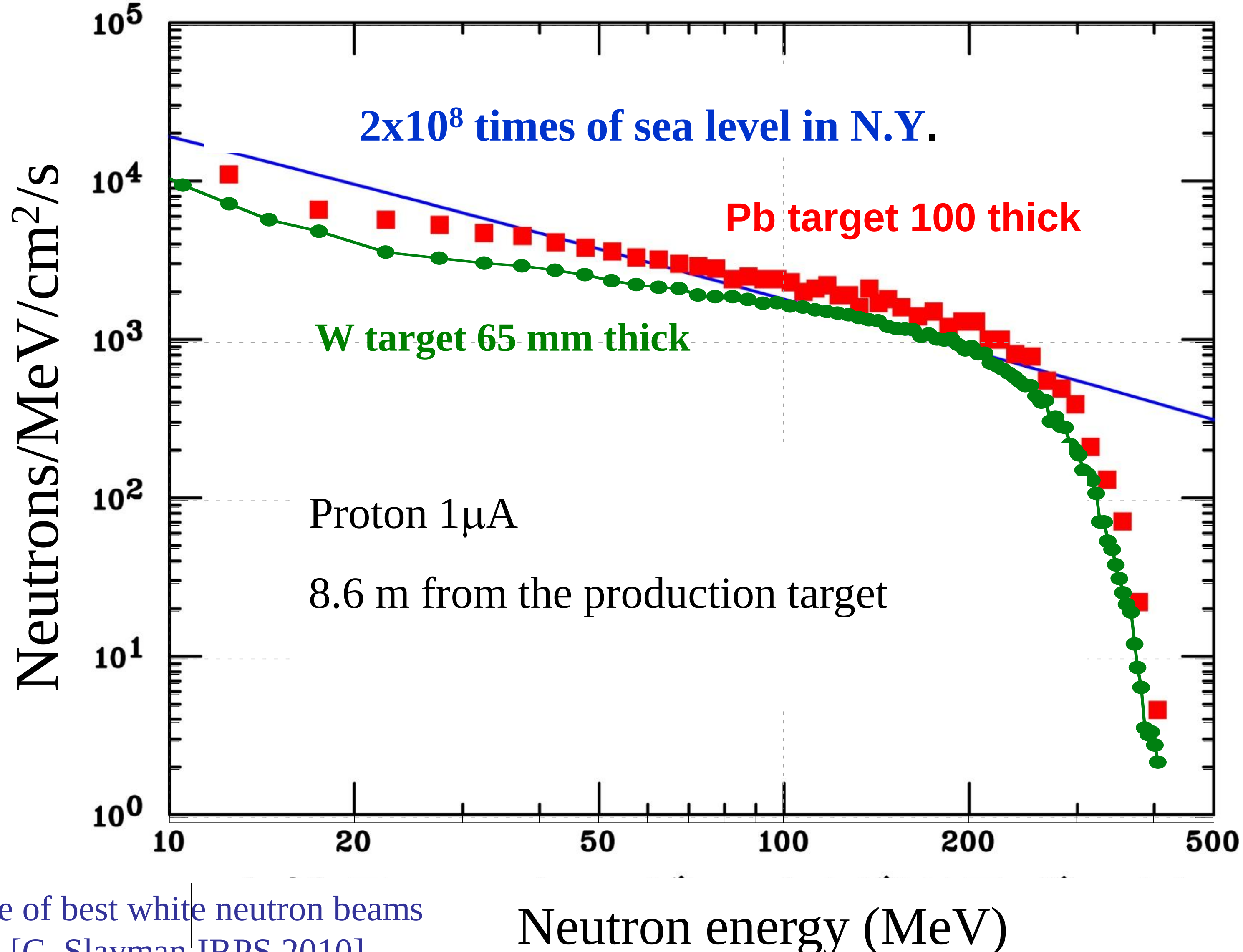


W50 mm × H50 mm × D65mm




Sample
Neutrons
West experimental hall

Neutron flux at RCNP

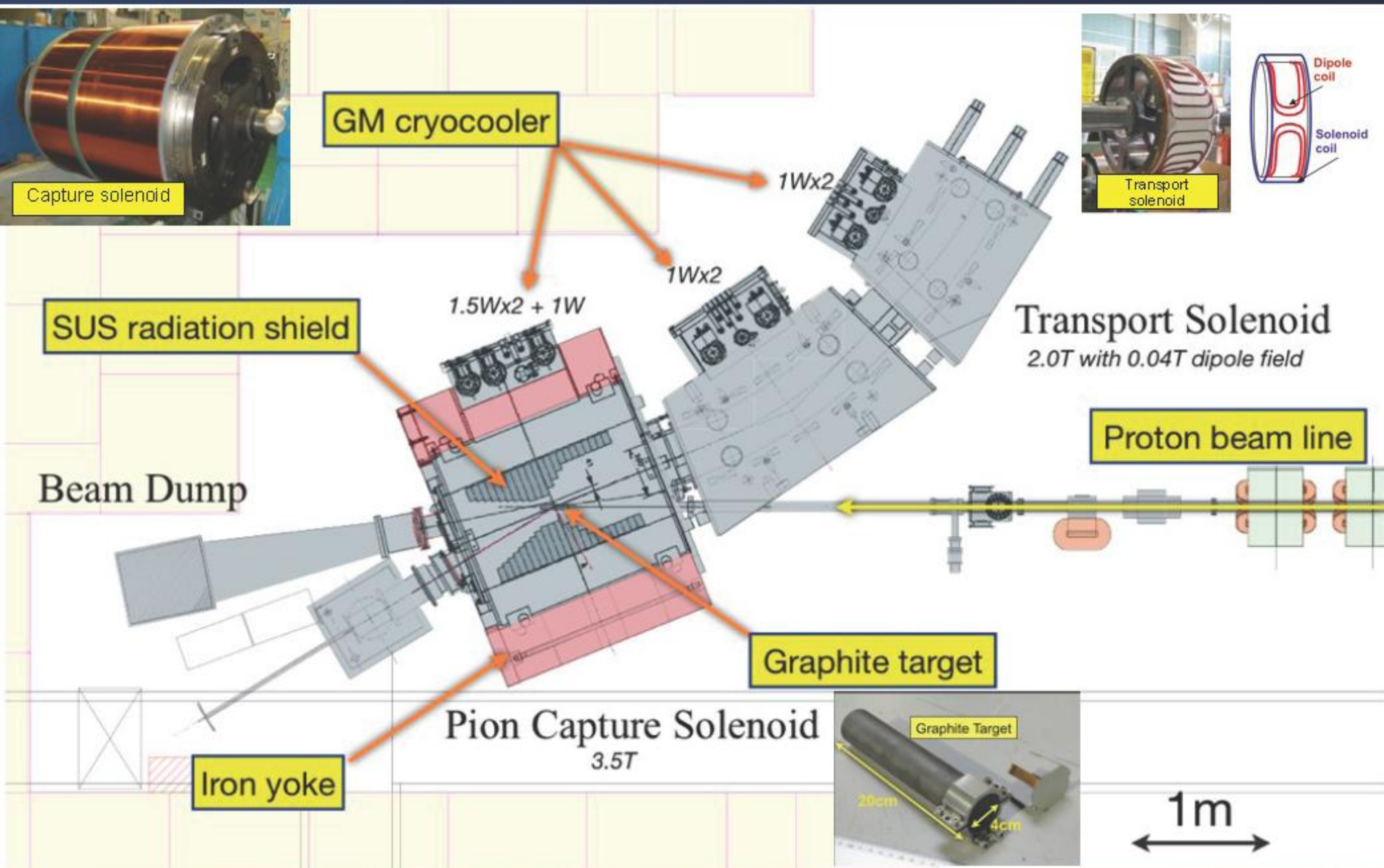


RCNP is one of best white neutron beams in the world [C. Slayman IRPS 2010]

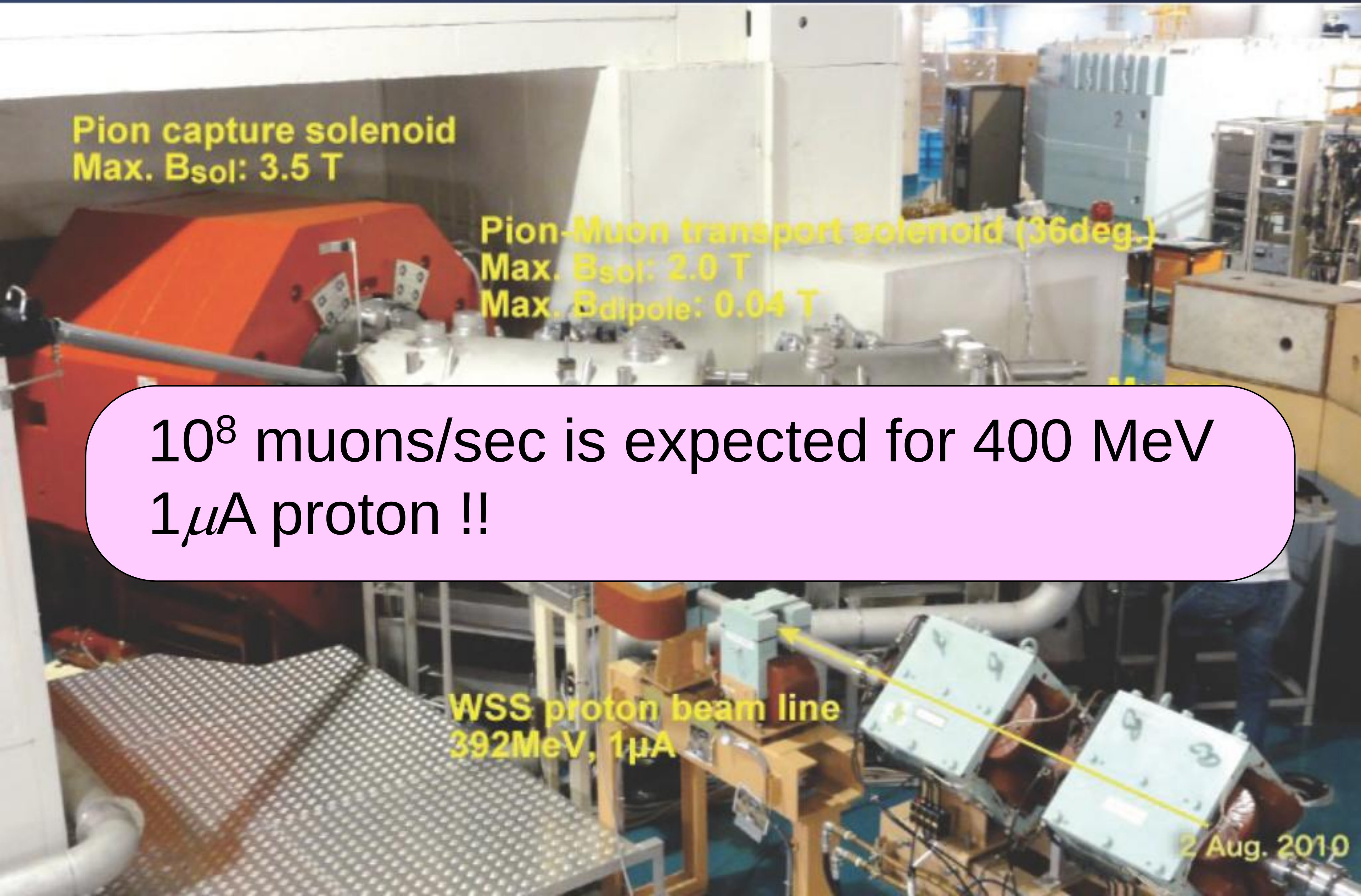
MuSIC

100m tunnel for Neutron Energy Measurement
Quasi-mono energetic neutron
RI production
UCN source
MuSIC
White neutron source

MuSIC: Present Layout



MuSIC@RCNP-West Hall (~2012 Feb)



10^8 muons/sec is expected for 400 MeV 1μA proton !!

Examples of Muon Science at MuSIC

- Particle Physics :
  - search for $\mu \to eee$ (muon LFV) — $10^{8\text{-}9}\,\mu^+/\mathrm{sec}$
    - DC continuous beam is critical
- Nuclear Physics :
  - nuclear muon capture (NMC) — $10^{5\text{-}6}\,\mu^-/\mathrm{sec}$
  - pion capture and scattering
- Chemistry :
  - chemistry on pion/muon atoms — $10^{5\text{-}6}\,\mu^-/\mathrm{sec}$
- Materials Science :
  - μSR (a μSR apparatus is needed) — $10^{5\text{-}6}\,\mu^+/\mathrm{sec}$, polarized
- Accelerator / Instruments R&D
  - (for PRISM/neutrino factory/muon collider) :
    - Superconducting solenoid magnets
    - FFAG, RF
    - cooling methods
    - muon acceleration, deceleration, and phase rotation

* Mo-100 & Tc-99m production

Radioisotopes for medical diagnostic procedures

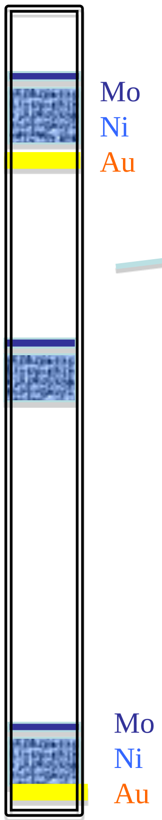
Single Photon Emission (Neutron rich)		Positron Emission (Proton rich)	
^{99m}Tc	87% (0.9M/year)	^{15}O	2%
^{67}Ga	3%	^{11}C	Research
^{201}Tl	4%	^{13}N	Research
^{111}In	1%	^{18}F	98% (^{18}FDG 0.3M/year)
^{123}I	4%	^{82}Rb	Research
^{131}I	1%	^{124}I	Research
^{133}Xe	1%	^{62}Zn	Research
		^{64}Cu	Research

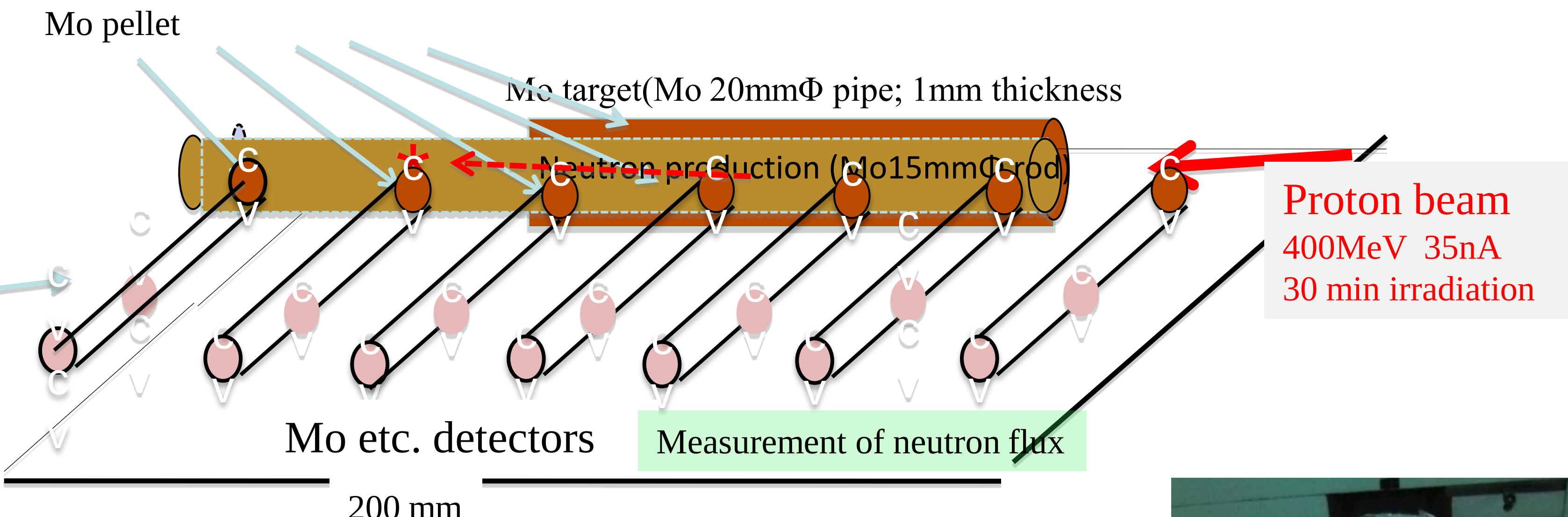
87% of ^{99}Mo ($T_{1/2}$=66h) decays to
^{99m}Tc: 143 keV isomeric state of ^{99}Tc

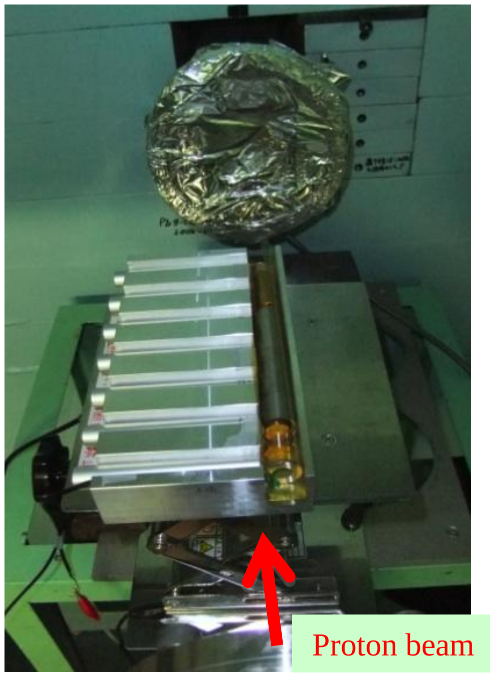
(in Japan)

(^{99m}Tc labeled tissue-specific radiopharmaceuticals)

Feasibility test to produce ^{99}Mo by spallation neutrons





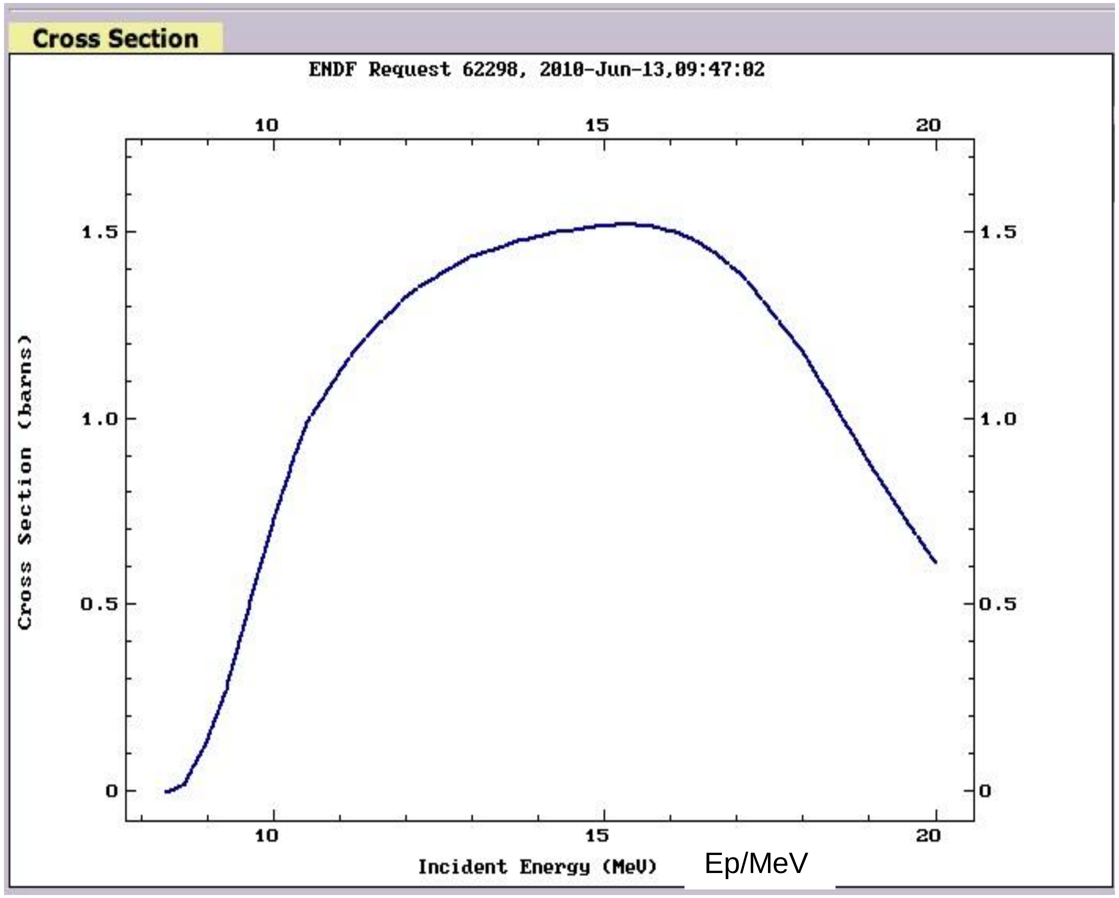


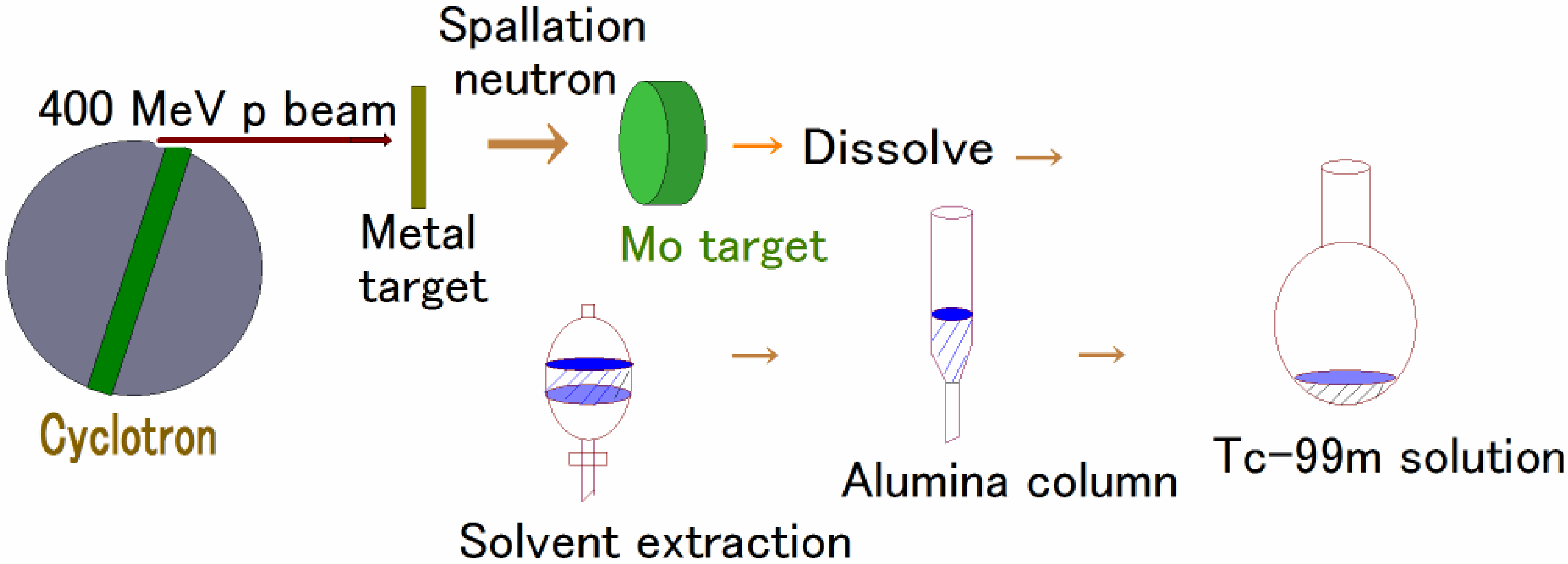
$^{100}Mo(n,2n)^{99}Mo$ Reaction

$10\ \text{MeV} < E_p < 17\ \text{MeV}$

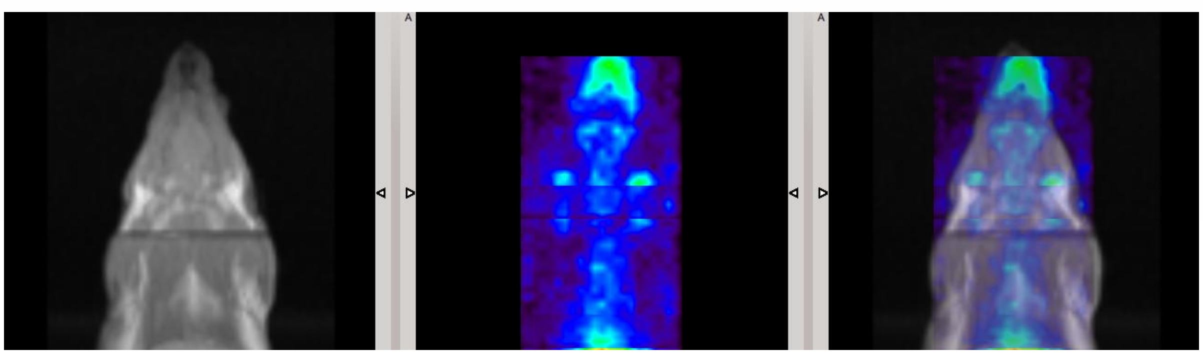
$\sigma > 1.0$ b

$\sigma_{max} = 1.5$ b





Schematic diagram for the production of ^{99m}Tc and the chemical separation



CT

SPECT

CT+SPECT

Bone scintigraphy with ^{99m}Tc-MDP using rat

Production rate

^{nat}Mo 1g

⇩

^{99}Mo: 3MBq/μA·h

4. Summary

- High quality light ion beams : $\Delta E/E = 0.01$ %
  - precise nuclear physics experiments using the Grand-RAIDEN with ultra-high energy resolution
  - A new upgrade program for improving the energy resolution has been approved and just started.
- Intense proton beam : 400 MeV x 1.1 μA = 0.44 kW
  - Neutrons and DC-muons are provided for a variety of application fields as well as the fundamental physics
  - A new project of the new accelerator complex providing a variety of high quality intense ion beams will be proposed soon.


Thank you for
your attention

* Improvement of building for earthquake-proof

- Control room is included in the reconstruction area
- Shutdown period : August, 2012 to March, 2013

Renewal of the control room