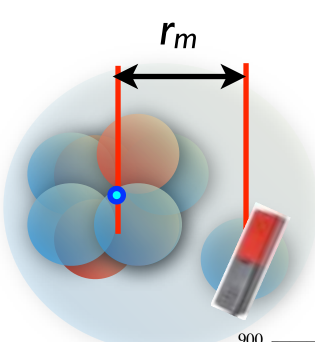
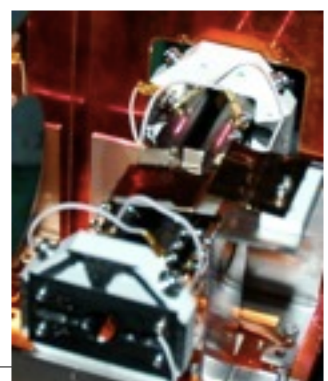
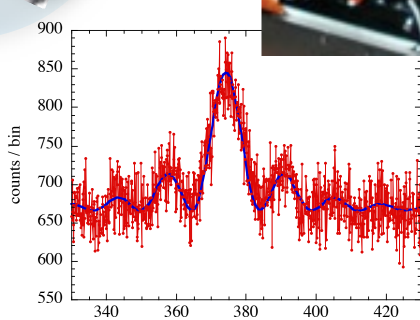
Precision optical spectroscopy of radioactive Be isotopes produced in projectile fragmentation

Michiharu Wada and SLOWRI Collaboration
RIKEN

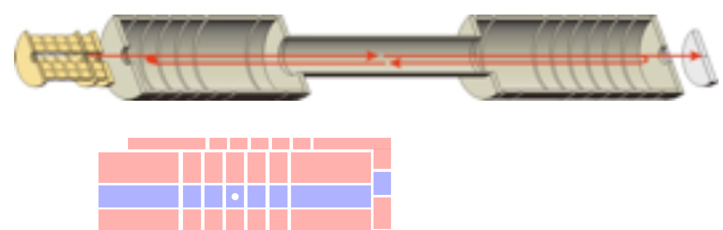
1. Optical Spectroscopy of Be







2. Mass Spectrograph for short-lived nuclei



3.New Facility at RIKEN

A goal of Nuclear Physics: THE Nuclear Model

uniquely describes all properties of all nuclides

Static Properties

- **Mass**
- **Size**

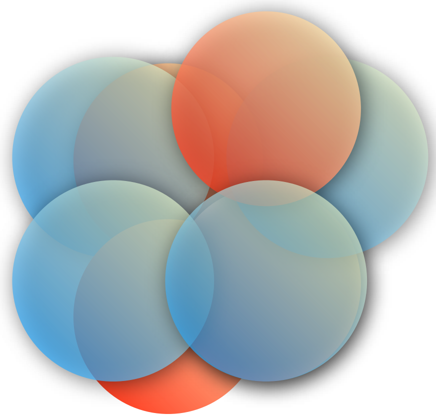
Moments

Spin

Parity

$T_{1/2}$

stable: ~250
discovered: ~3000
expected: ~10000



Dynamic Properties

.....

Cross Sections

Level Scheme

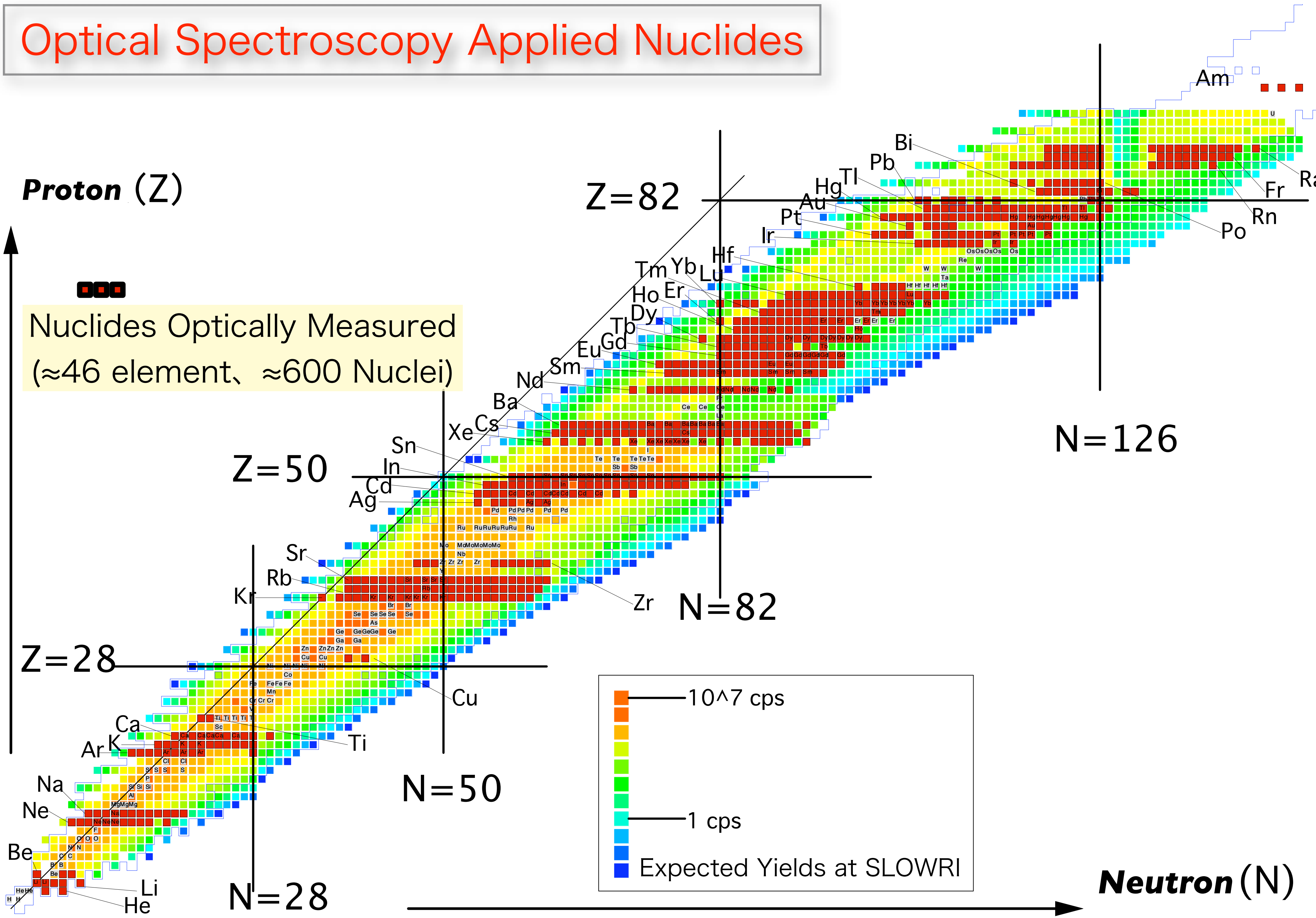
$P_{n,p,\gamma ..}$ .....

optical spectroscopy

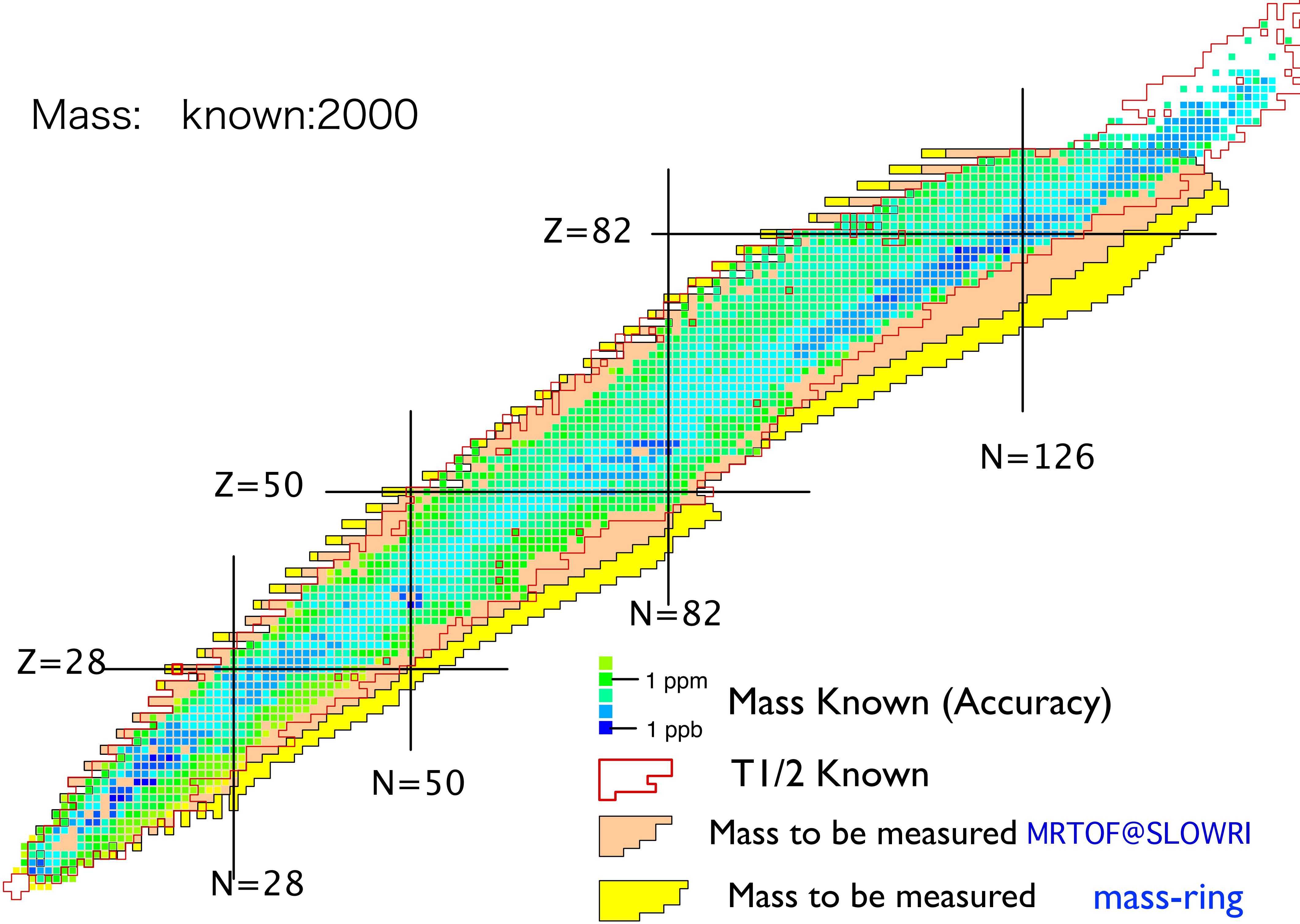
model independent manner

We know only a few of them for radioactive nuclei

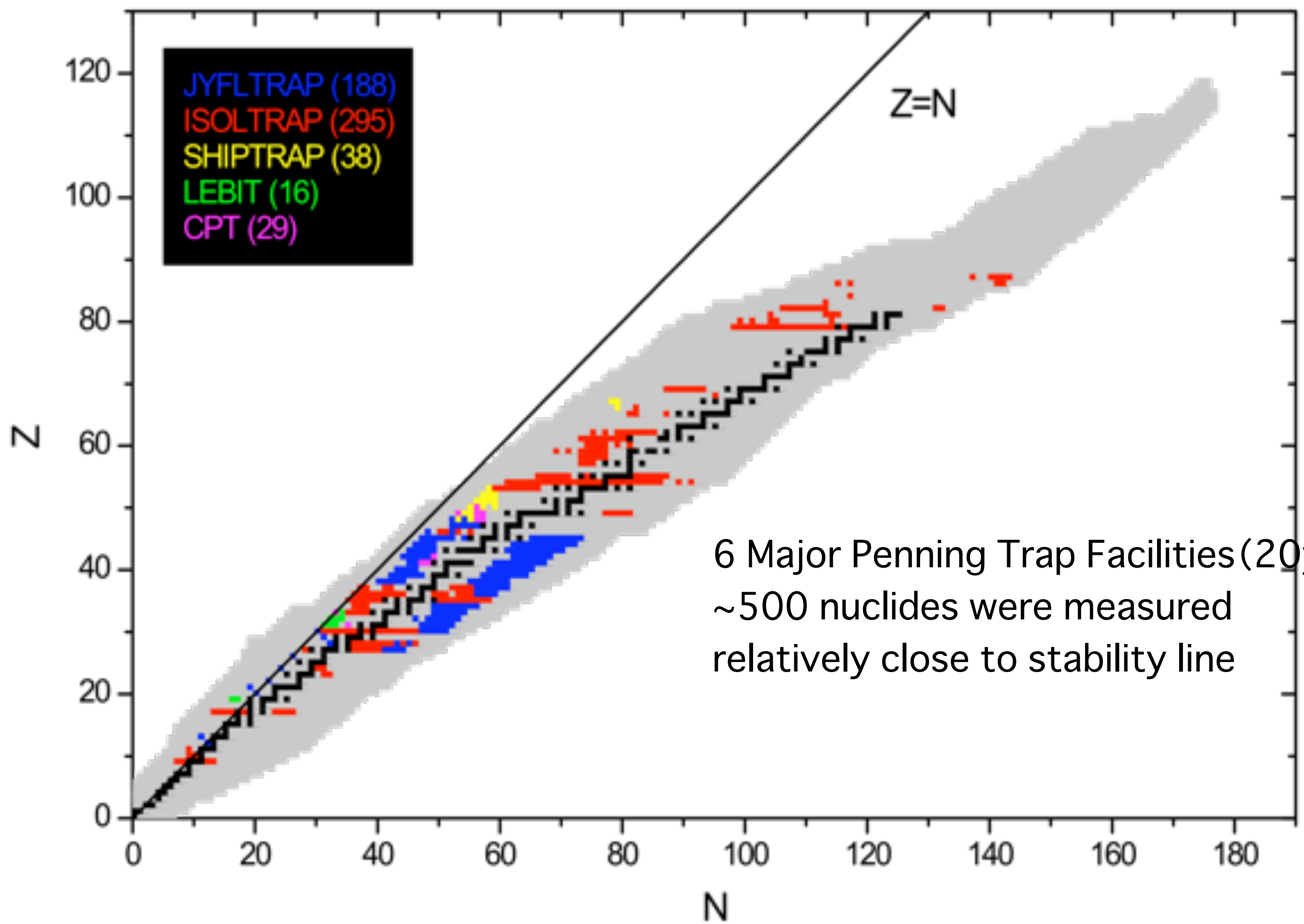
Optical Spectroscopy Applied Nuclides



Mass: known:2000



Penning Trap Performance



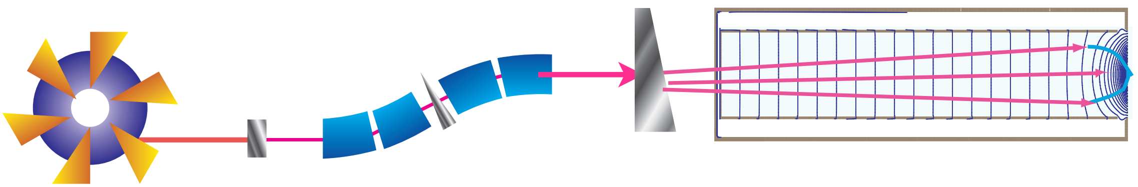
6 Major Penning Trap Facilities(20years)
~500 nuclides were measured
relatively close to stability line

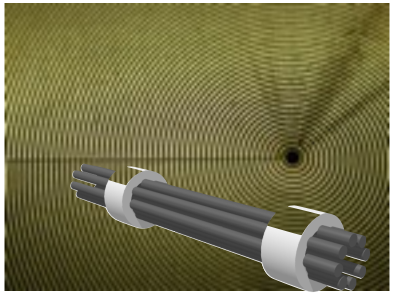
A. Jokinen

Comprehensive Measurements of All Nuclides

Universal Methods to Produce Unstable Nuclei

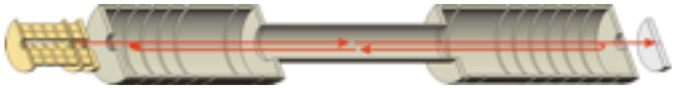
In-flight Separators, Gas catcher cooler,...





Efficient & Quick Methods to Measure the Properties

Ion Traps, Lasers, MRTOF Mass Spectrograph



More Beam Time

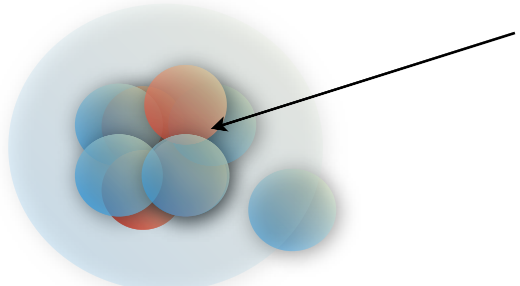
Parasitic Beam

Optical Spectroscopy of Be Isotopes

proposed: M. Wada et al, NPA(1997)356c

^{11}Be

Z=4
N=7
(T1/2=13s)



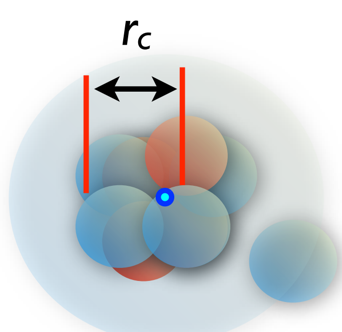
^{10}Be

Z= 4
N= 6

Core + One loosely bound Neutron

Charge Radius

IS (E0)

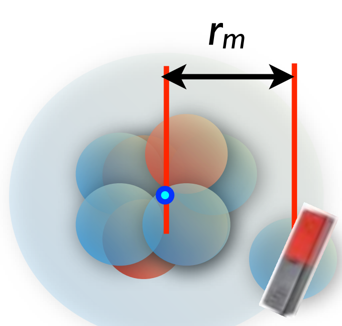


Volume without Charge-less Neutron

Magnetization Radius

IS (M1)

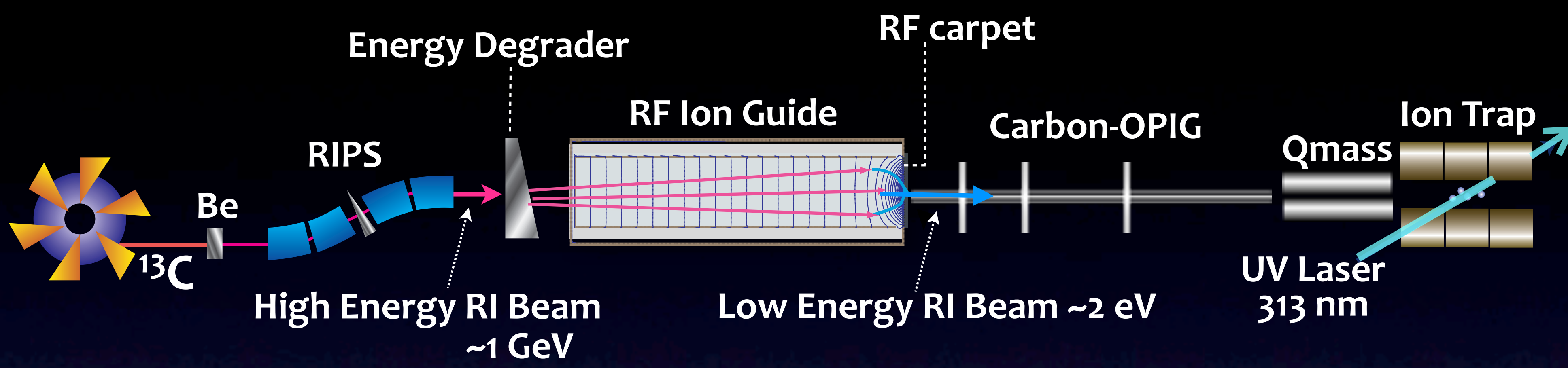
Distribution of Valence Neutron

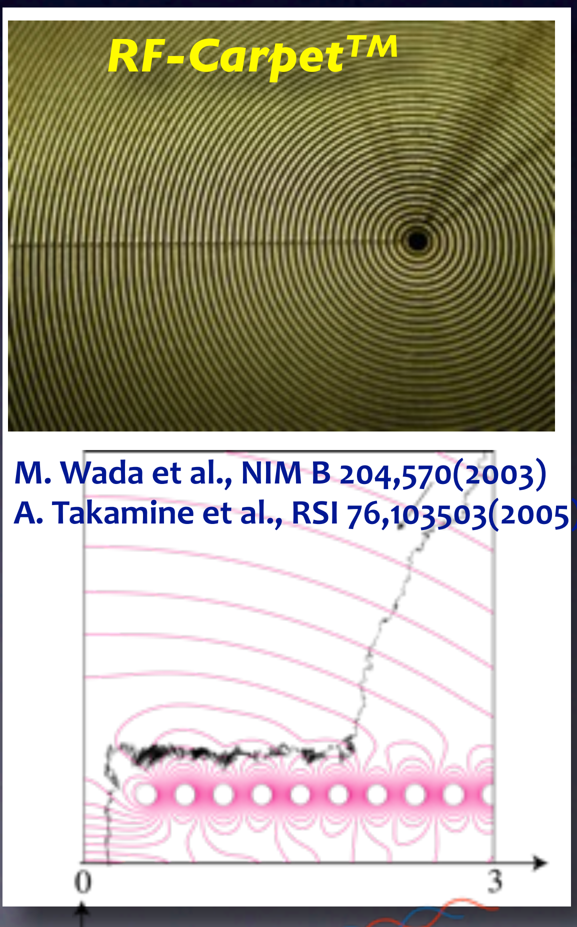


Single Valence Neutron carries most of Magnetization of Nucleus

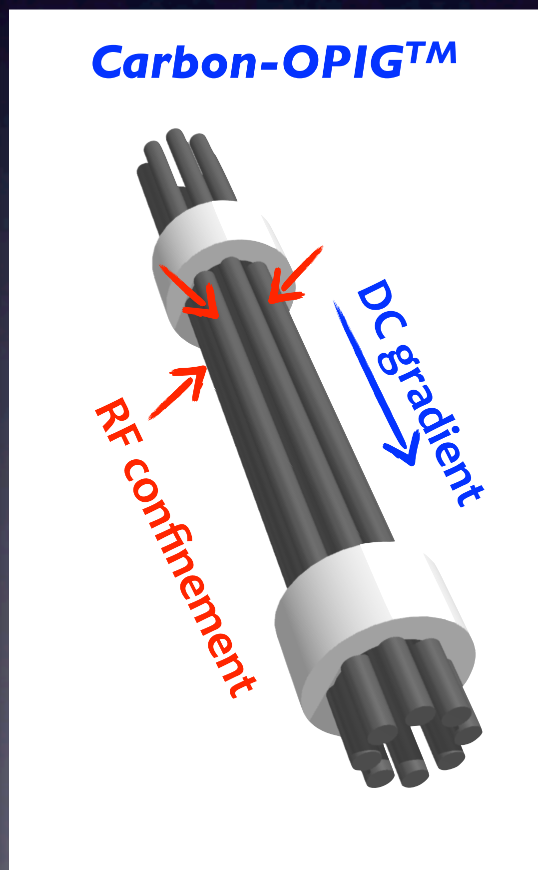
Cancelled in the Core
(core polarization still exist)

Experimental Setup : SLOWRI prototype @ RIBF, RIKEN

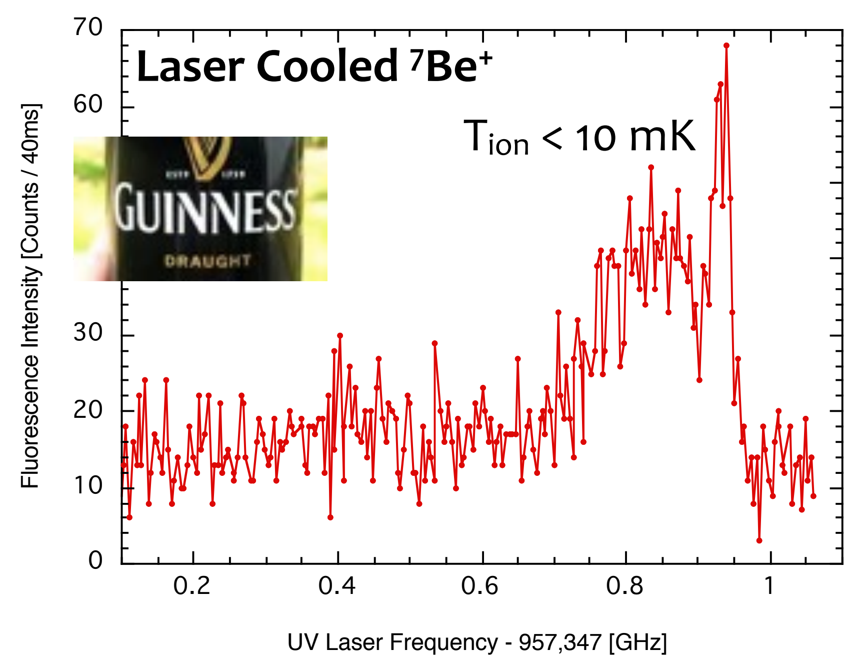




M. Wada et al., NIM B 204,570(2003)
A. Takamine et al., RSI 76,103503(2005)



10^{-15} -fold reduction of kinetic energy!



T. Nakamura *et al.*, PRA 74, 052503 (2004)
K. Okada *et al.*, PRL 101, 212502 (2008)

Field Shift → Charge Radii

Finite Mass and Volume of a Nucleus cause a Shift in Optical Transition Energy

Atomic Energy Level — Mass Dependent — Volume Dependent

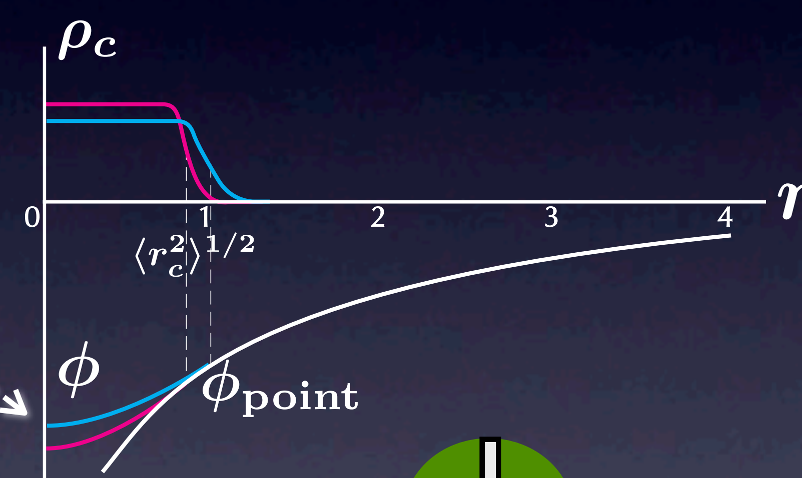
$$\epsilon_A = \epsilon_\infty - \frac{\mu_A}{M_A}\epsilon^\infty + \frac{\mu_A}{M_A}\frac{1}{m_e}\sum_{i<j}^{N} \mathrm{p}_i \cdot \mathrm{p}_j + \frac{2\pi}{3} Z|\psi(0)|^2 \langle r_c^2 \rangle$$

for Infinite Mass & Point Charge

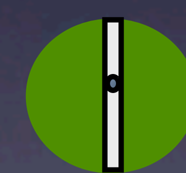
Normal Mass Shift
(ease to calculate)

Specific Mass Shift
(difficult to calculate)

Field Shift



Shallower Coulomb potential for electrons in a nucleus



for Be^+ $2^2S \rightarrow 2^2P$

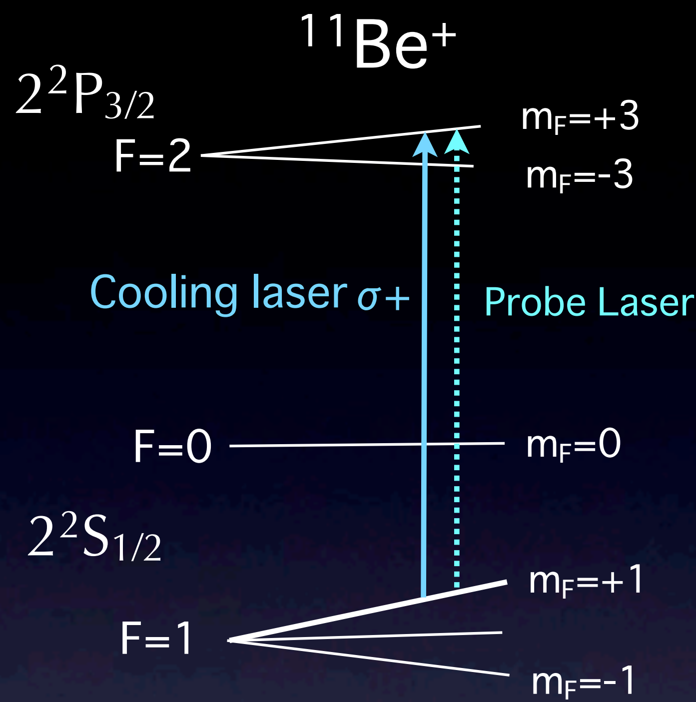
Absolute transition frequency	~1 000 000 000 MHz
Isotope Shift	~ 10 000 MHz
Mass Shift	~ 10 000 MHz
Field Shift	~ 10 MHz

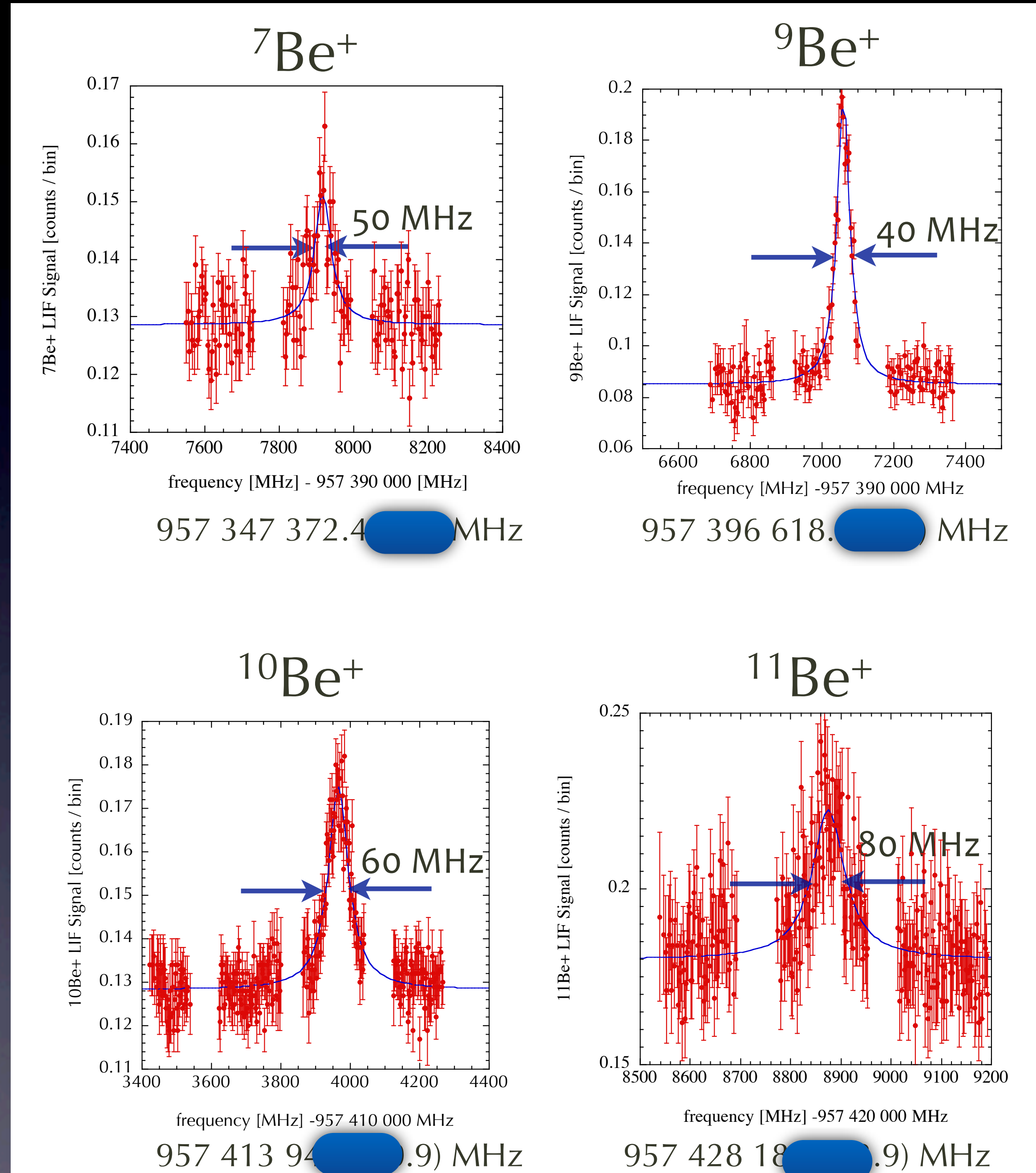
$$F = \frac{2\pi}{3} Z\Delta|\psi(0)|^2 = -16.912\ \mathrm{MHz/fm^2}$$ Yan et al, PRL **100**, 243002 (2008)

1% of r_c ↔ 2 MHz

requires an accuracy of 10^{-9}

$2^2S_{1/2}$ - $2^2P_{3/2}$ Transition Measurement





^{11}Be		957,428,1[redacted]MHz
^{9}Be	−)	957,396,6[redacted]MHz
Isotope Shift		31,570.2 MHz
−) Mass Shift		31,563.9 MHz
Field Shift		[redacted]3.0) MHz

Shift of Charge Radii

$$\delta\langle r_c^2\rangle^{A.A'} = \frac{\text{Field Shift}}{-16.912\ \text{MHz}}$$

A. Takamine *et al., to be submitted*

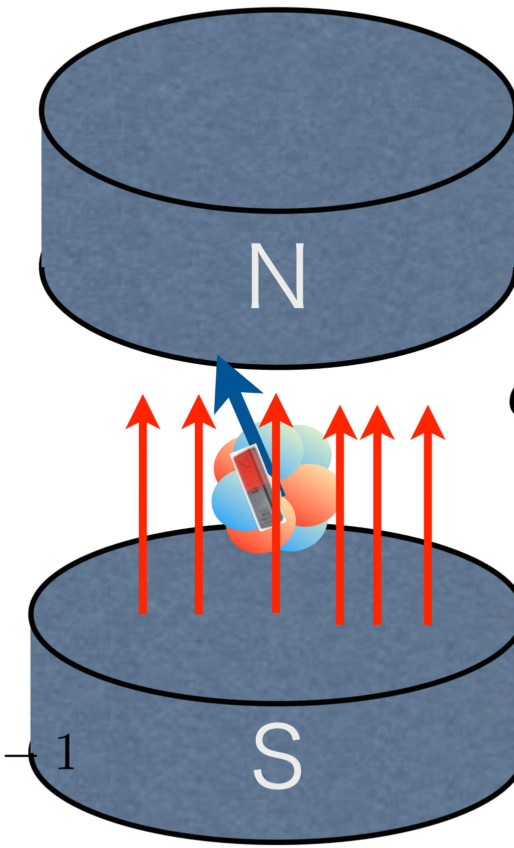
Hyperfine Constant

(S-state)

Nuclear g-factor

Different Quantities,

Comparison provide magnetic radius



Observation from ∞

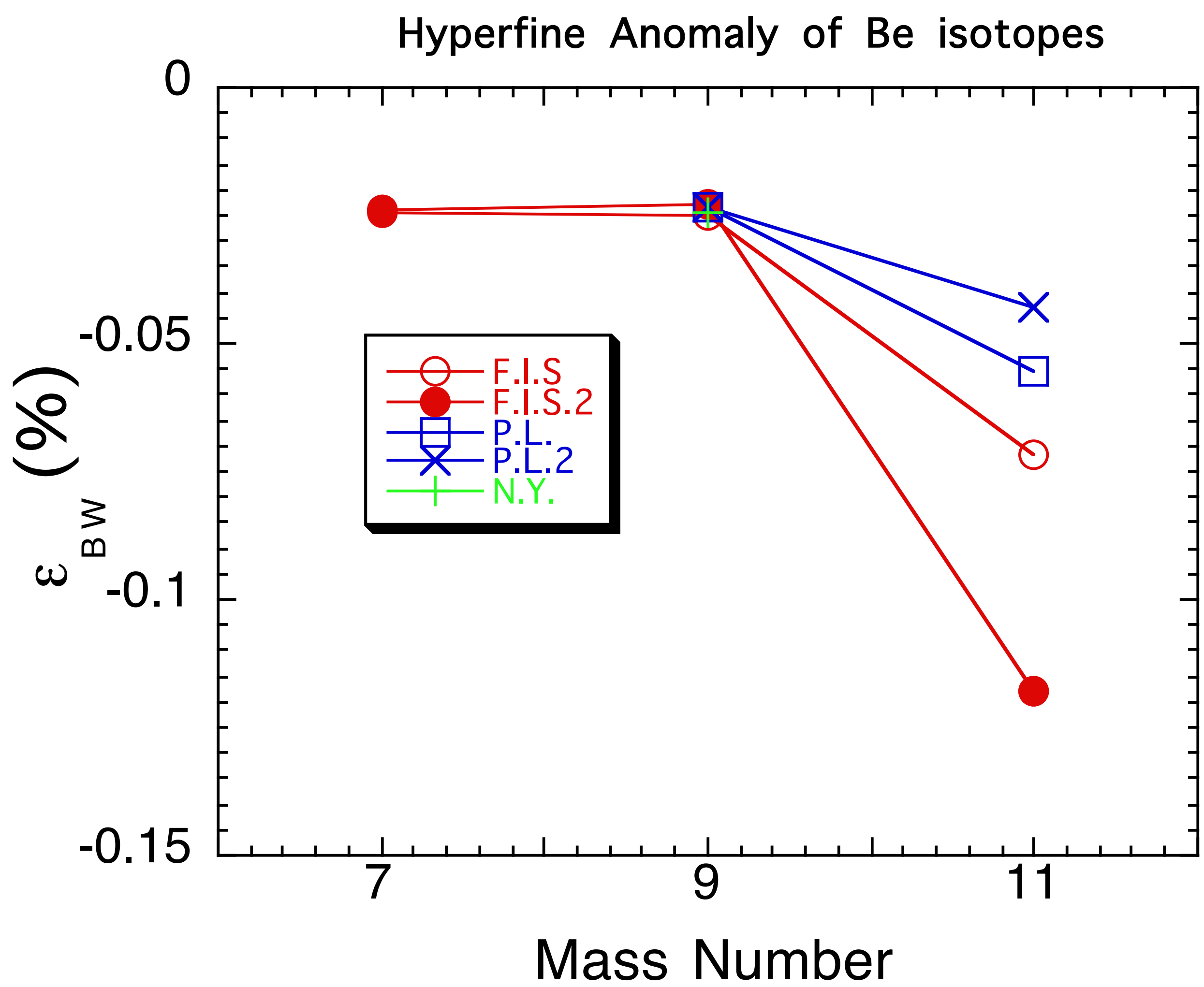
$$A = A_{\text{point}}(1+\epsilon)$$

$${}^{11}\Delta^{9} = \epsilon_{11} - \epsilon_{9} \approx \frac{A_{11}/(\mu_{11}/I_{11})}{A_{9}/(\mu_{9}/I_{9})} - 1$$

Nuclear Magnetization probed by ***strong inhomogeneous*** magnetic field due to s-electron

Nuclear Magnetization probed by ***very homogeneous*** external magnetic field

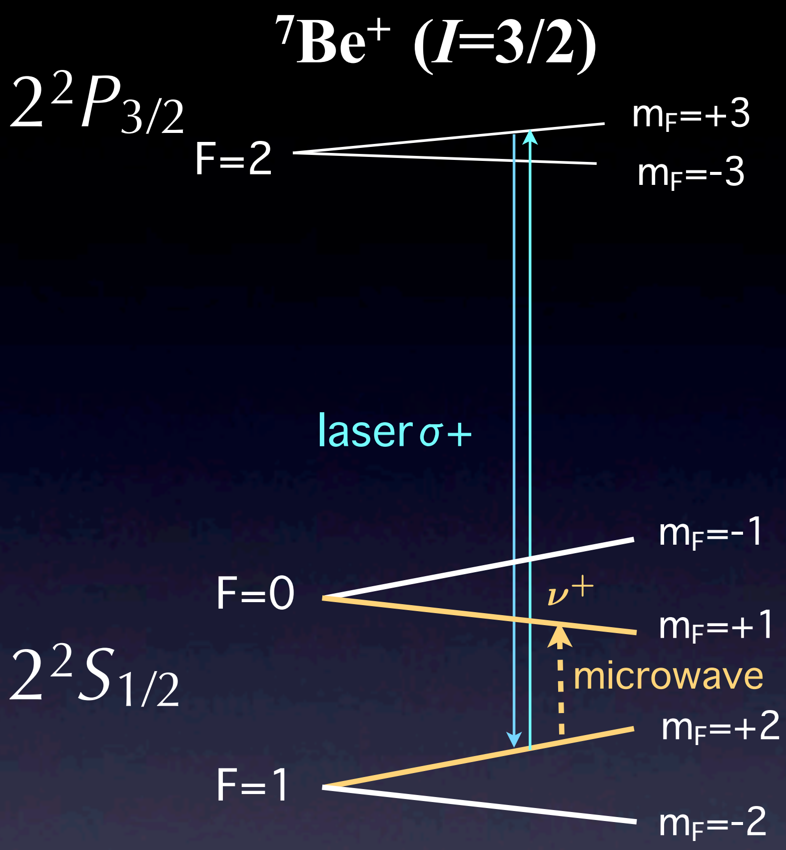
theoretical prediction of HFA for Be isotopes

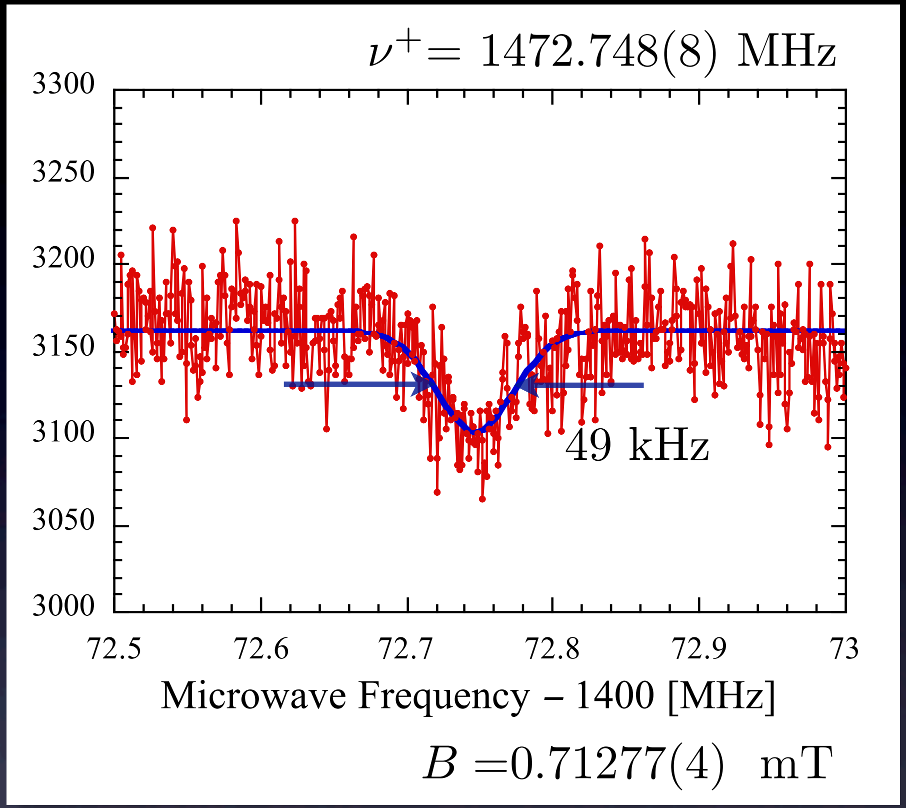


Large ε_BW is expected for 11Be, due to extended halo neutron

FIS: Fujita Ito Suzuki, PRC59(1999)210
P.L.: Parfenova, Leclercq-Willain, PRC72(2005)024312
N.Y.:Yamanaka, HFI, 127(2000)129.

HFS Spectroscopy of $^7Be^+$





Laser-Microwave Double Resonance

1. Optical Pumping to Recyclable State by σ+ or σ- Laser
2. Laser Cooling
3. Microwave induces hf transition
4. Fluorescence detects population

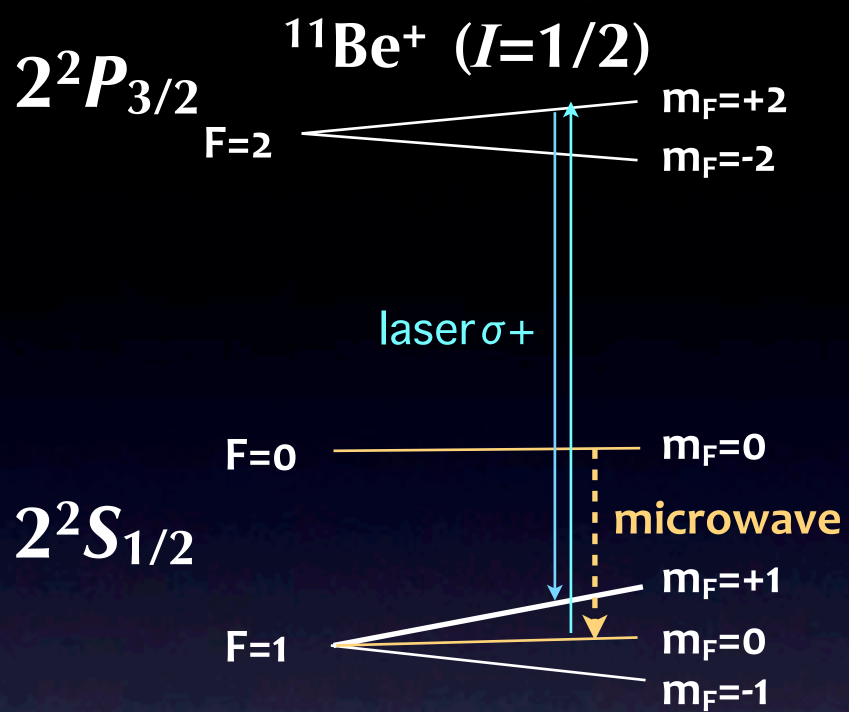
$$\nu^+, \nu^- \Rightarrow A = -742.77228(43)\ \text{MHz}\ (5\cdot 10^{-7})$$

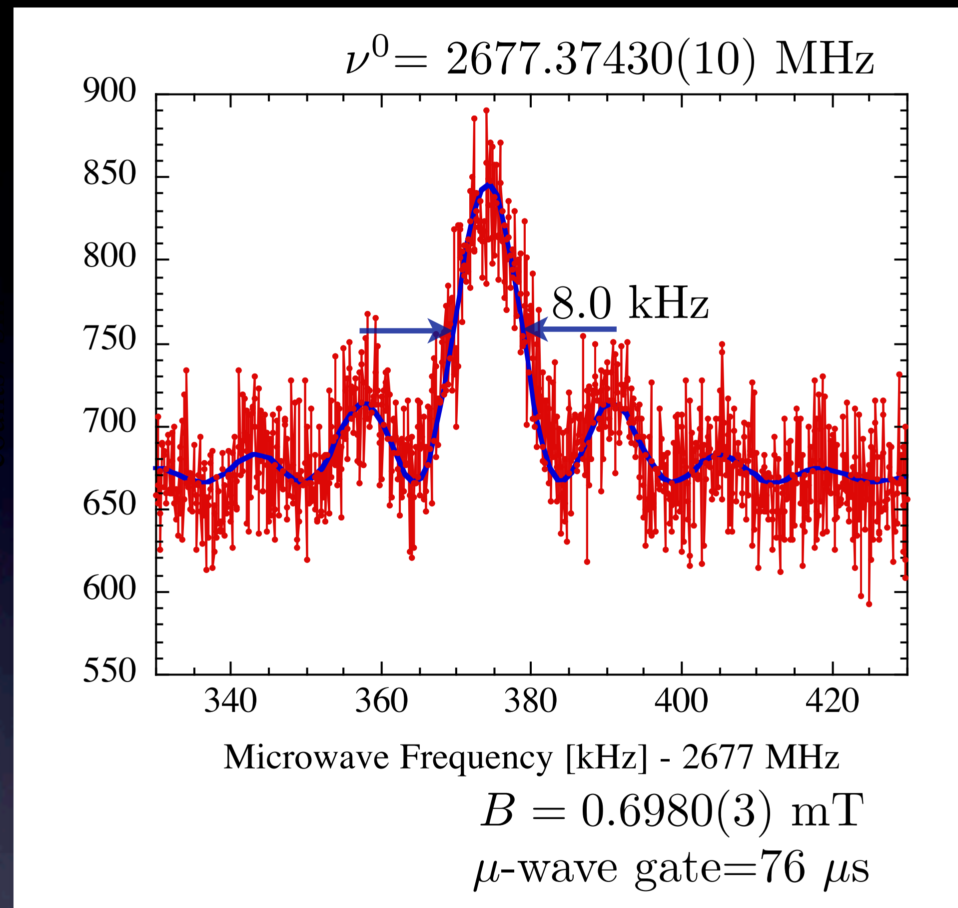
$$\frac{d\nu}{dB} = \mu_B \frac{4I}{2I+1} = 21\ \text{MHz/mT} \Rightarrow I = 3/2$$

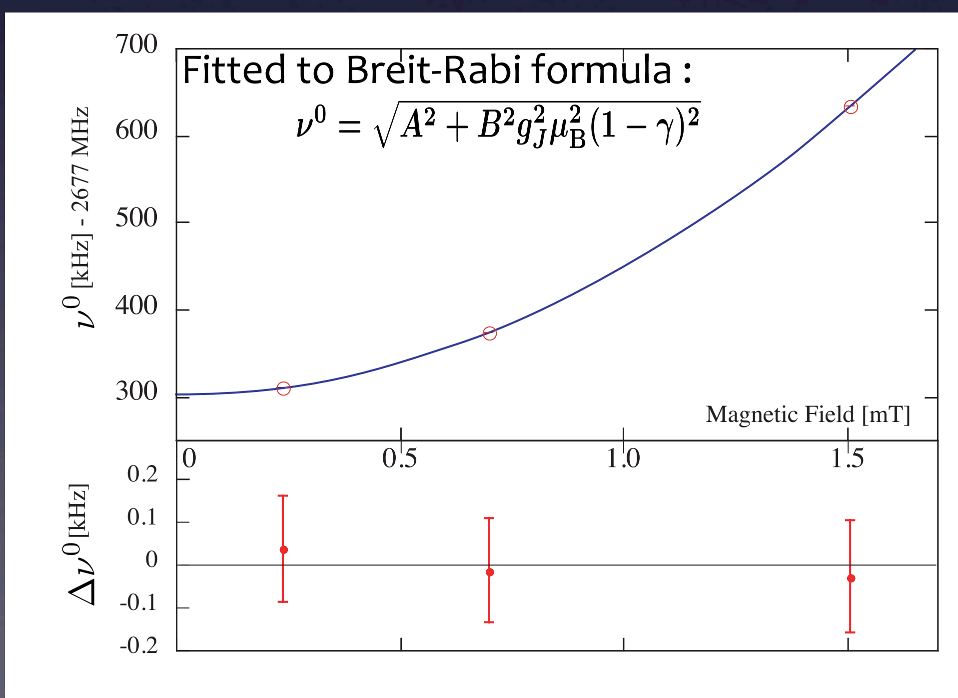
$$A \Rightarrow \mu_I = -1.39928(1) \quad |{}^7\Delta^9| < 10^{-5}$$

K. Okada *et al.*, PRL 101, 212502 (2008)

HFS Spectroscopy of $^{11}Be^+$ ($T_{1/2}$=13.8s)







$A_{11} = -2677.30$[redacted]$Hz\ (3 \cdot 10^{-8})$

$A \Rightarrow \mu_I = -1.6812(2) \quad |^9\Delta^{11}| < 10^{-4}$

$\frac{d\nu}{dB} = \mu_B \frac{4I}{2I+1} = 14\ \mathrm{MHz/mT} \Rightarrow I = 1/2$

A. Takamine *et al., to be submitted*

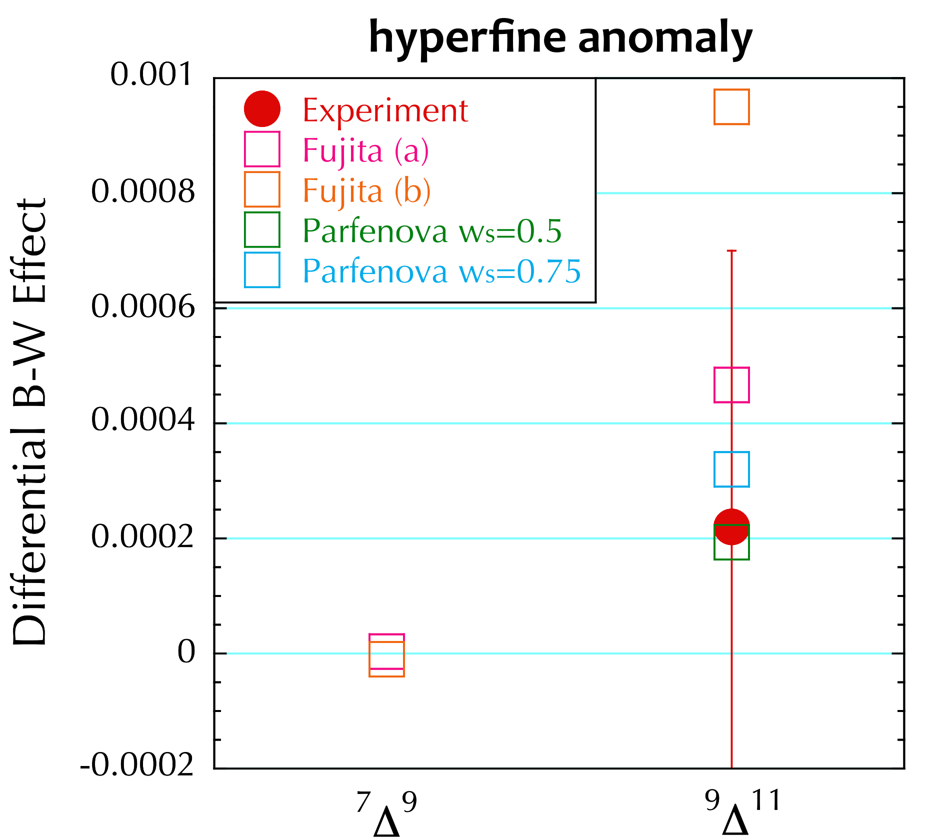
Results of Be HFS Spectroscopy

Our Works

	Be-7	Be-9	Be-11
HFS constant *A* [MHz]	-742.77228(43)	-625.0088370529(11)**	-2677.3[redacted]
Nuclear Mag. Moment [n.m]		-1.177432(3)	(-)1.6816(8)*
{deduced from *A*}	{ -1.39928(2) }		{ -1.6812(2) }

* W. Geithner *et al.*, PRL 83(1999)3792

** J. Bollinger *et al.*,



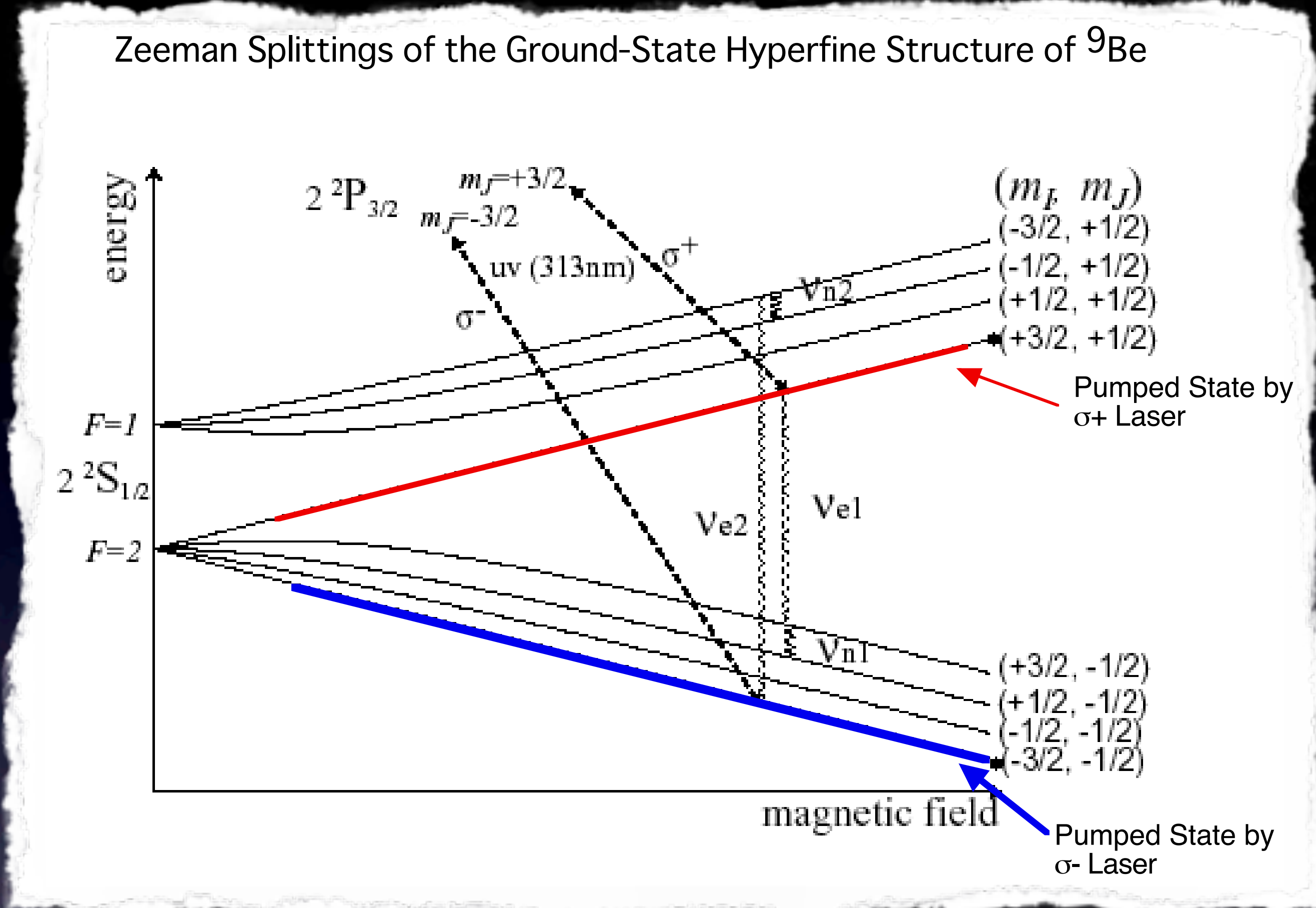
A. Takamine *et al.*, *to be submitted*

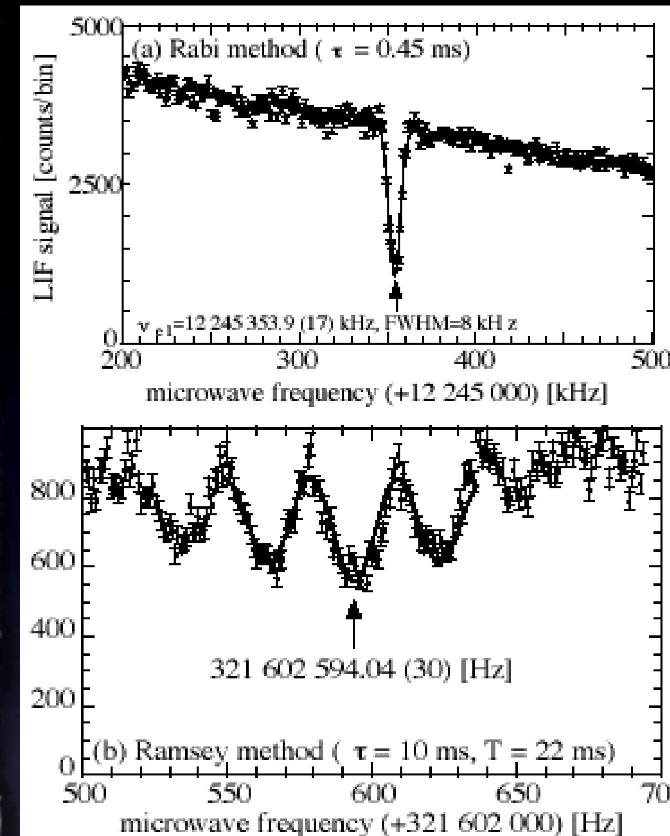
$$^{9}\Delta^{11} = \frac{A_9/\mu_9}{A_{11}/\mu_{11}} - 1 = 2.2(48) \times 10^{-4}$$

- More than one order of magnitude better accuracy for μ_I is required.
  → **Planning to remeasure @RIKEN**

- More seriously, β-NMR method cannot be applied for Be-7.
  → **How to measure it ?**

Accurate and Independent Measurement of μ_I and A





Breit-Rabi's Formula:

$$W_F(m_J, m_I, b) = -\frac{A}{4} - (m_J + m_I)\gamma b + m_J\sqrt{A^2(\tfrac{1}{2}+I)^2 + 2A(m_J+m_I)(\gamma-1)b + (\gamma-1)^2 b^2}$$

$$b = g_J \mu_B B_0 / h, \quad \gamma = g_I' / g_J$$

$$A = -625\,008\,835.23\,(75)\ \text{Hz}$$

$$g_I' / g_J = 2.134\,780\,33\,(28) \times 10^{-4}$$

T. Nakamura *et al.*, Opt. Comm 205,329 (2002)

→ $^7Be^+$, $^{11}Be^+$

→ B-W effect

TO DO

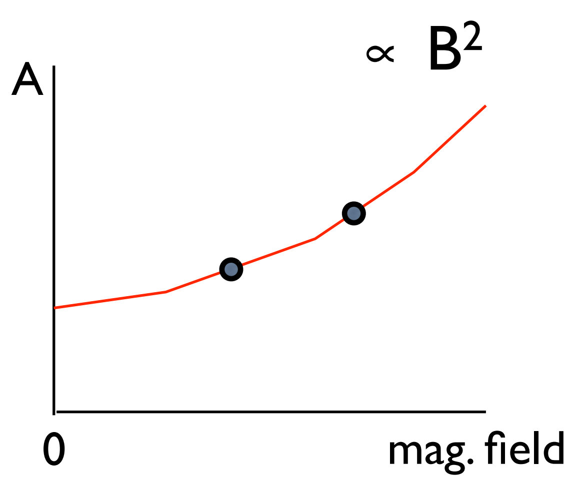
a spin off

Is a HFS constant a constant ?

$^9Be^+$

A	g_I/g_J x10^{-4}	magnetic field	
-625 008 837.053(11) Hz	2.134 779 852(3)	6.8 / 8.2 kG clock condition	J.J. Bollinger *et al.*, PRL 54, 1000 (1985)
-625 008 835.23(75) Hz	2.134 780 33(28)	4.7 kG	T. Nakamura *et al.*, Opt. Com 205,329 (2002)

2σ discrepancy



* measurement at B=0 (0-0 transition in $^{11}Be+$)

* measurement for isotopes (gl, ml)

High field correction (by W.M. Itano)

$$\boldsymbol{p}_i \longrightarrow \boldsymbol{p}_i + \frac{e}{c}\boldsymbol{A}(\boldsymbol{r}_i)$$

$$T = \sum_i^N \frac{\boldsymbol{p}_i^2}{2m} \longrightarrow \sum_i^N \frac{(\boldsymbol{p}_i + \frac{e}{c}\boldsymbol{A}(\boldsymbol{r}_i))^2}{2m}$$

Quadratic corrections for each electrons

$$\frac{e^2}{8mc^2}(x_i^2 + y_i^2)B^2$$

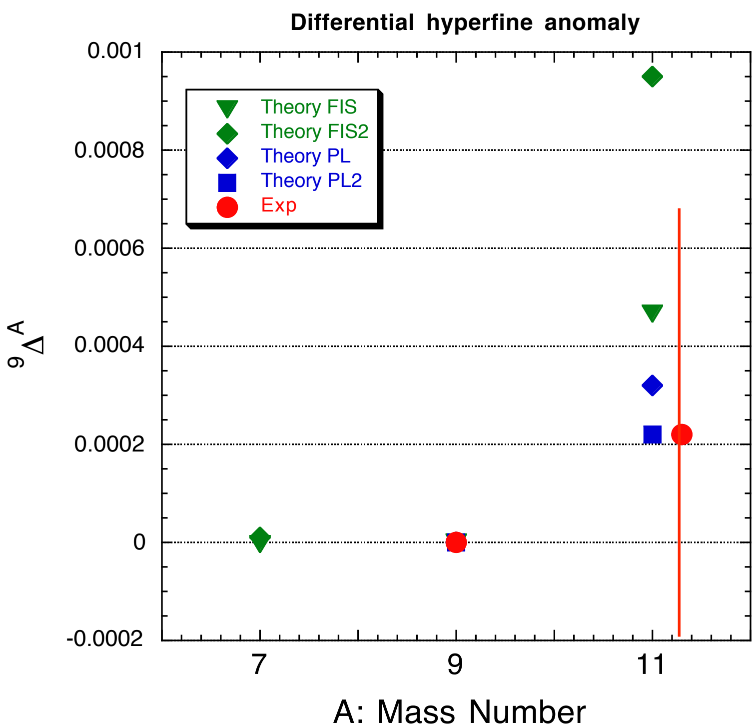
$$\propto g_I m_I m_J B^2$$

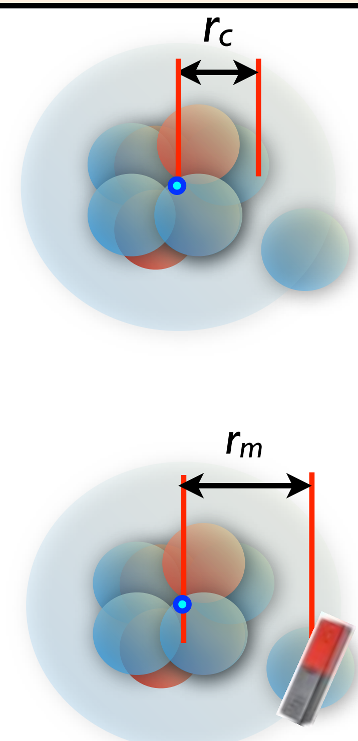
Charge & Magnetization Radii of Be Isotopes

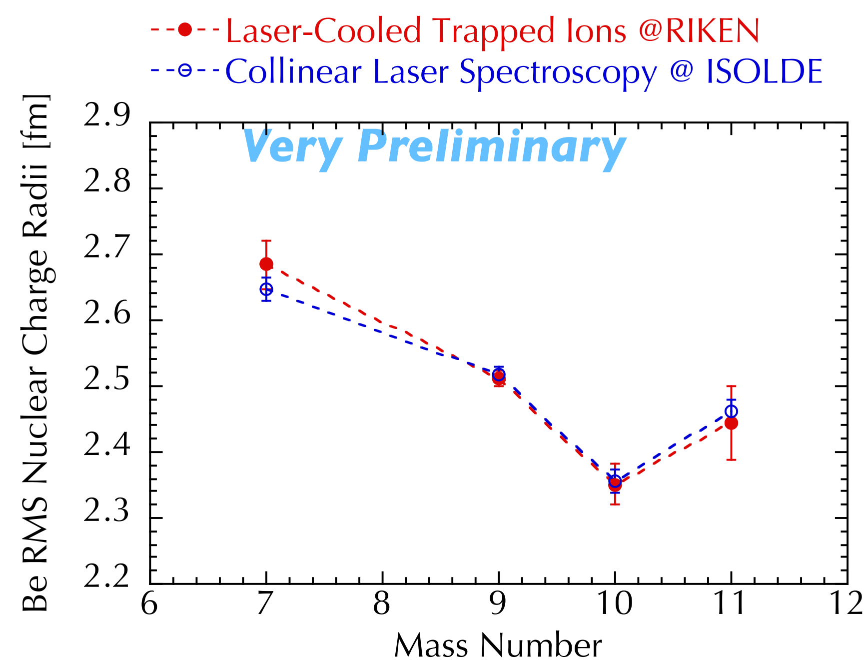
Our Works

	Be7	Be9	Be10	Be11
HFS constant A (MHz)	-742.77228(43)	-625.0088370529(11)	-	-2677.3[redacted]
Nuclear Mag. Moment (n.m)	[-1.39928(2)]	-1.177432(3)	-	[-1.6812(5)]
by beta-NMR				(-)1.6816(8)
S1/2-P3/2 Opt. Transition (MHz)	95734737[redacted]	95739661[redacted]	95741394[redacted]	957 428 18[redacted]

* W. Geithner PRL 83(1999



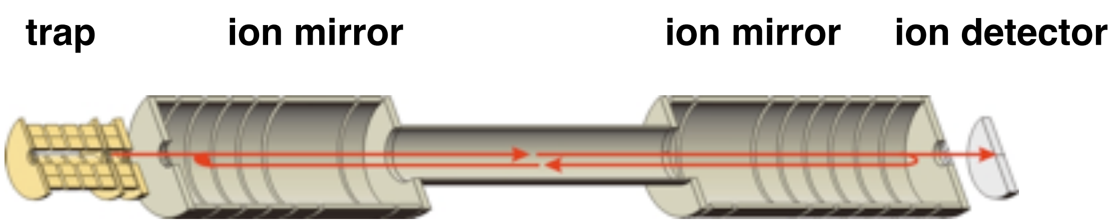


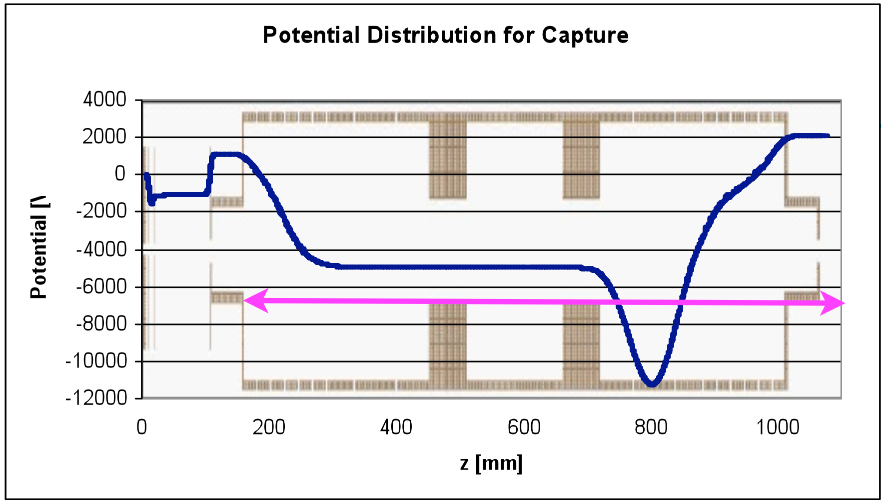


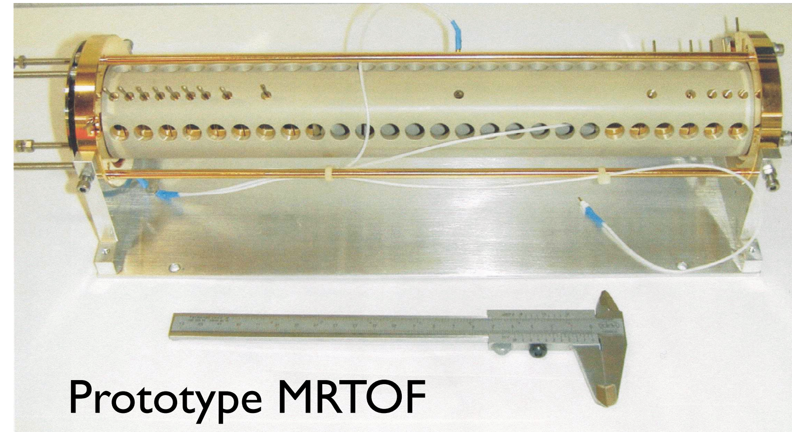
neutron halo of ^{11}Be

$$^9\Delta^{11} = \frac{A_9/\mu_9}{A_{11}/\mu_{11}} - 1 = 2.2(48) \times 10^{-4}$$

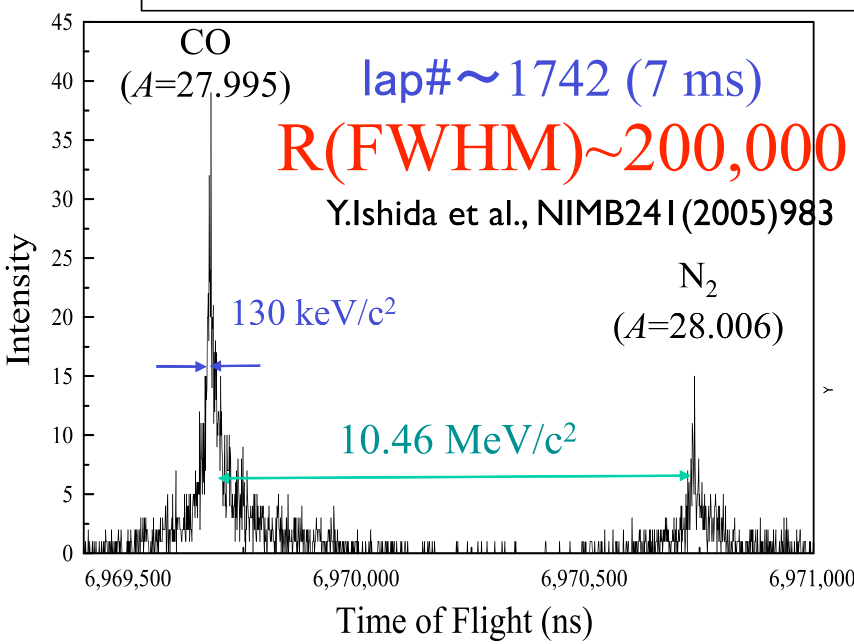
Multi-Reflection TOF Mass Spectrograph





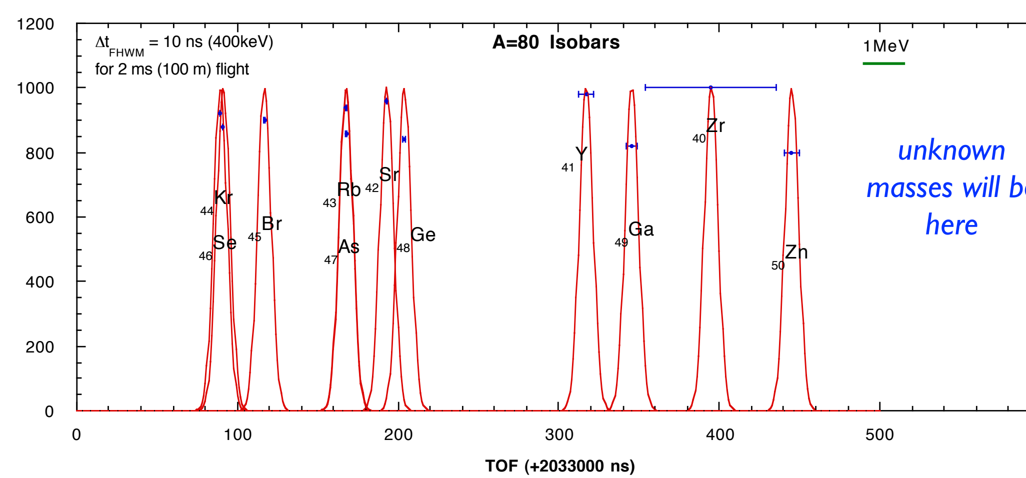


- Easy Calibration.
- No Scan, Higher Statistical Efficiency
- δM ~ 10 keV/c^2 is achievable in short period(2 ms)

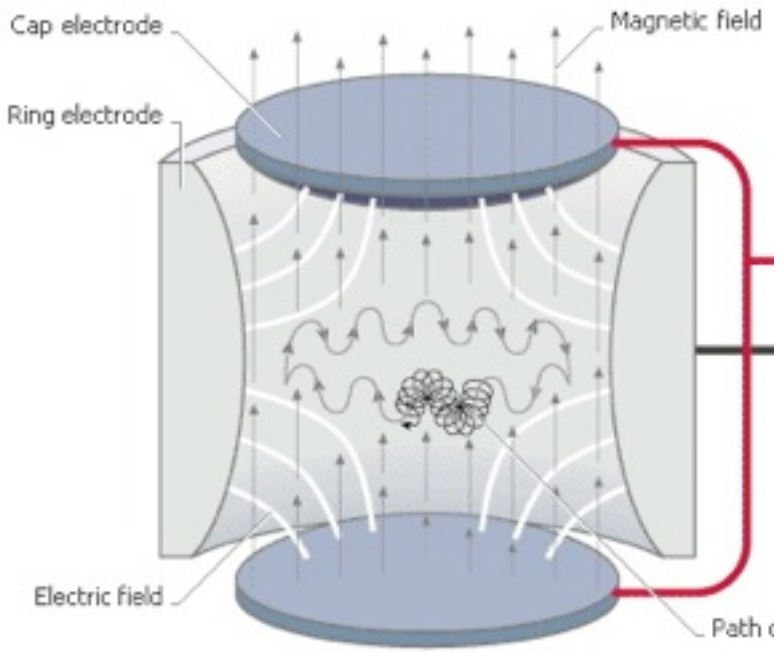


Test result with a small prototype

All Isobars in Single Spectrum



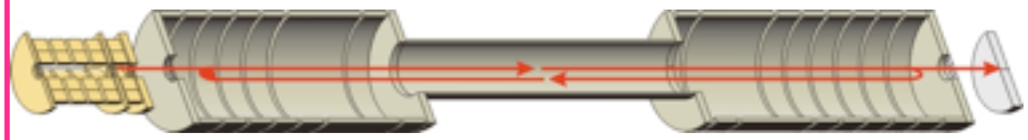
Penning Trap vs. MRTOF



$$f_{\rm cyc} = \frac{qB}{2\pi m}$$

MRP

$$R_{\rm m} \equiv \frac{m}{\Delta m} \approx \frac{qB}{m} t_{\rm obs}, \quad t_{\rm obs} \leq\sim 2T_{1/2}$$



$$t_{\rm tof} = L\sqrt{\frac{m}{2K}}, \quad \frac{\partial t_{\rm tof}}{\partial K} \approx 0$$

Energy Isochronous

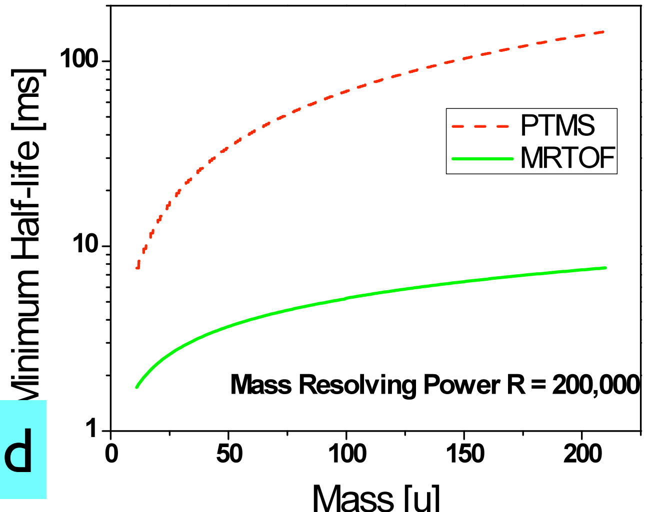
$$R_{\rm m} \equiv \frac{m}{\Delta m} = \frac{1}{2}\frac{t_{\rm tof}}{\Delta t} \propto \frac{1}{\sqrt{m}}$$

MRP: Better MRP for Heavy, Short-lived Nuclei

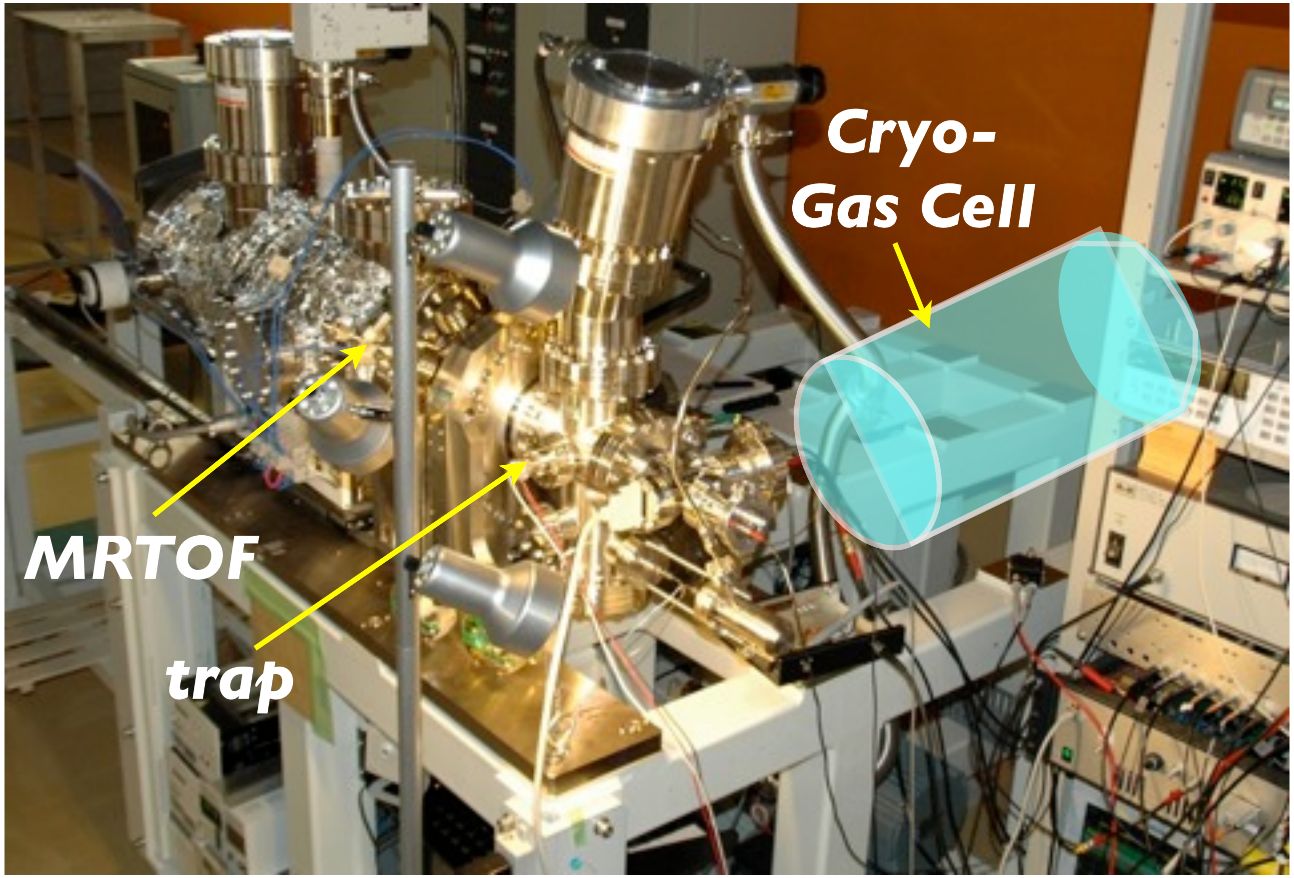
Heavy Molecule too !

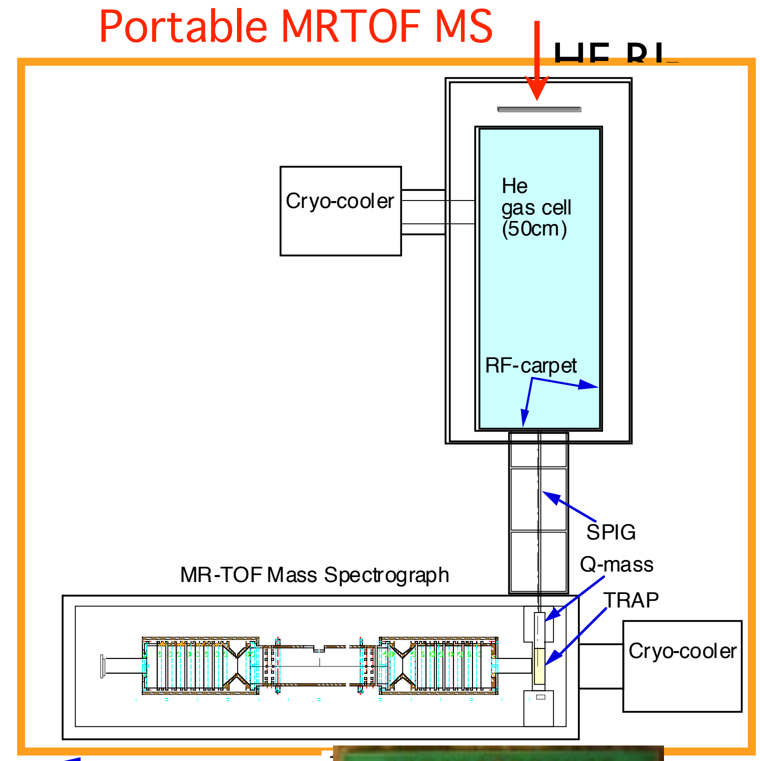
$$\frac{\delta m}{m} \approx \frac{1}{R_{\rm m}\sqrt{N}}$$

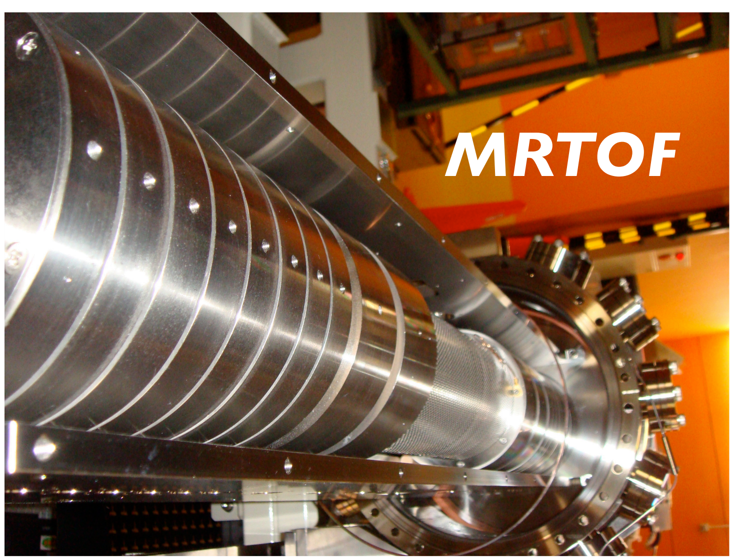
Rm=200,000
N=3000
δM~0.1ppm

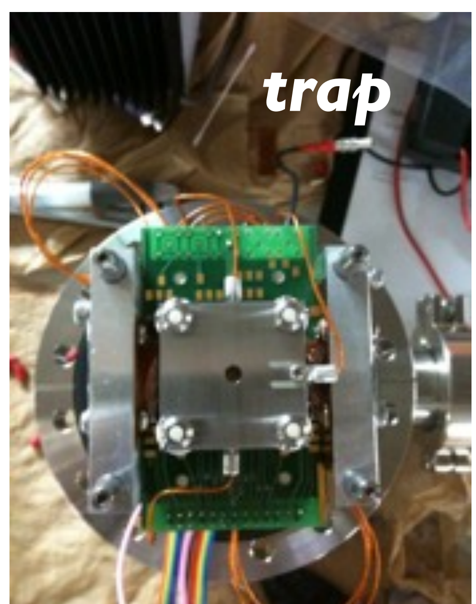


New MRTOF: MRP≈500,000 expected

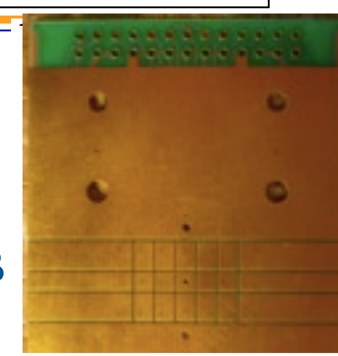


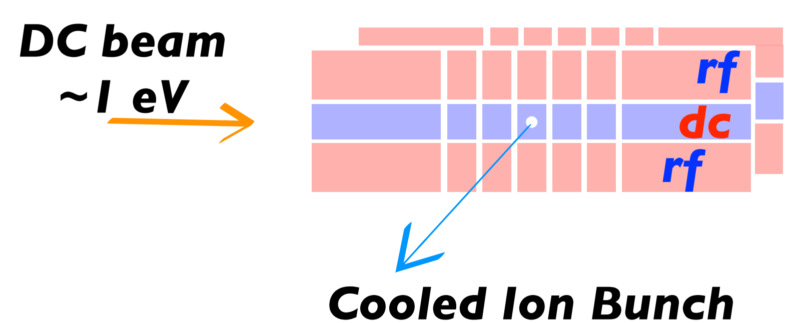






trap made of PCB

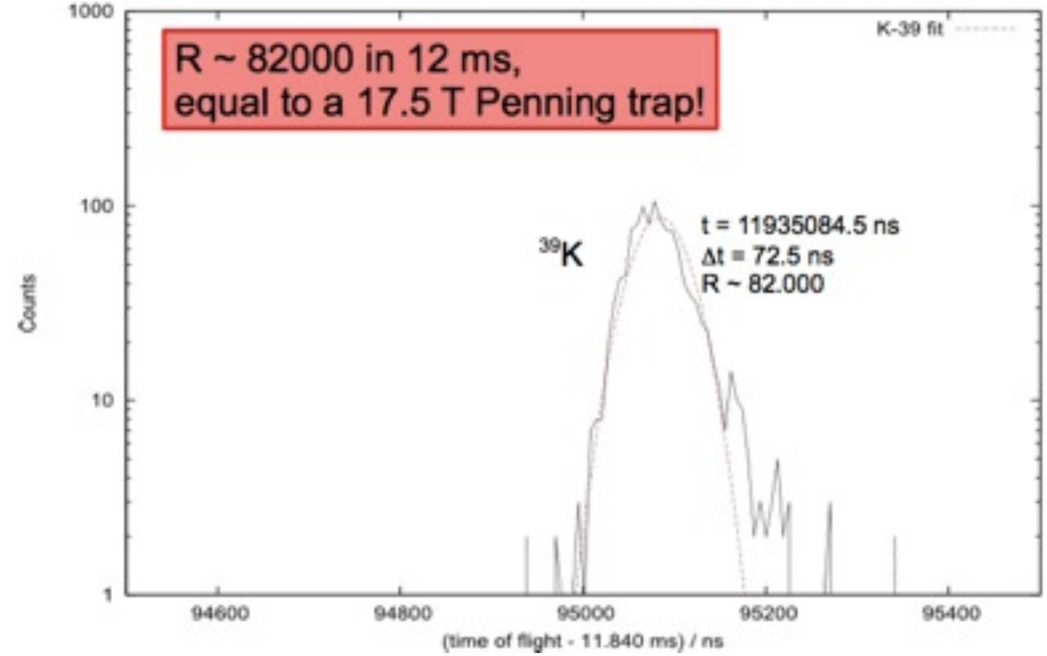




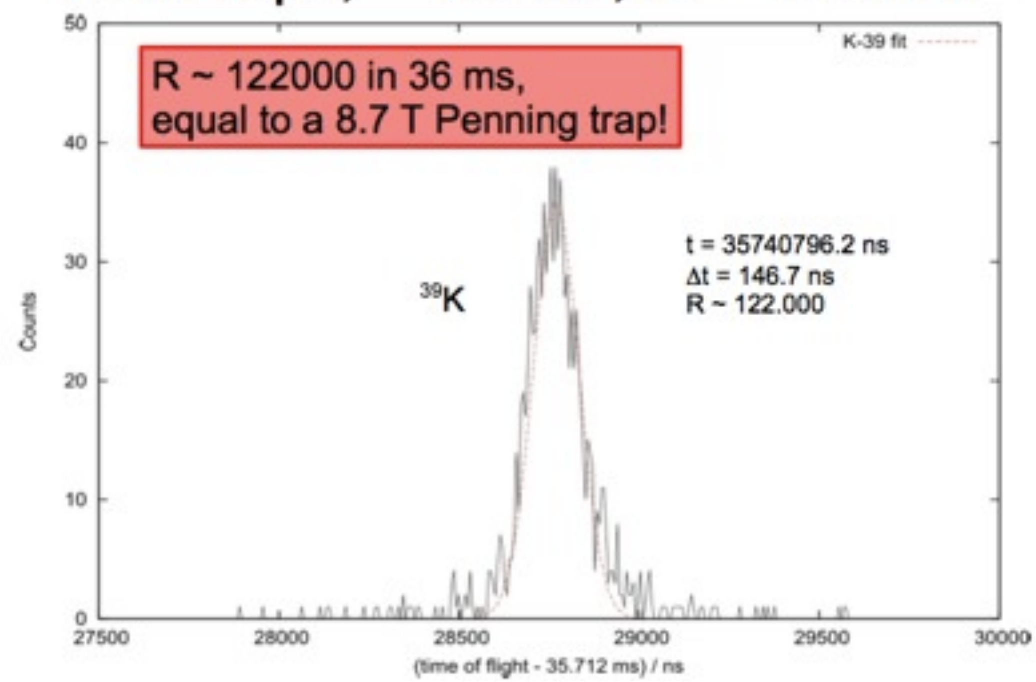
Efficiency ~10%

First Test Results of new MRTOF

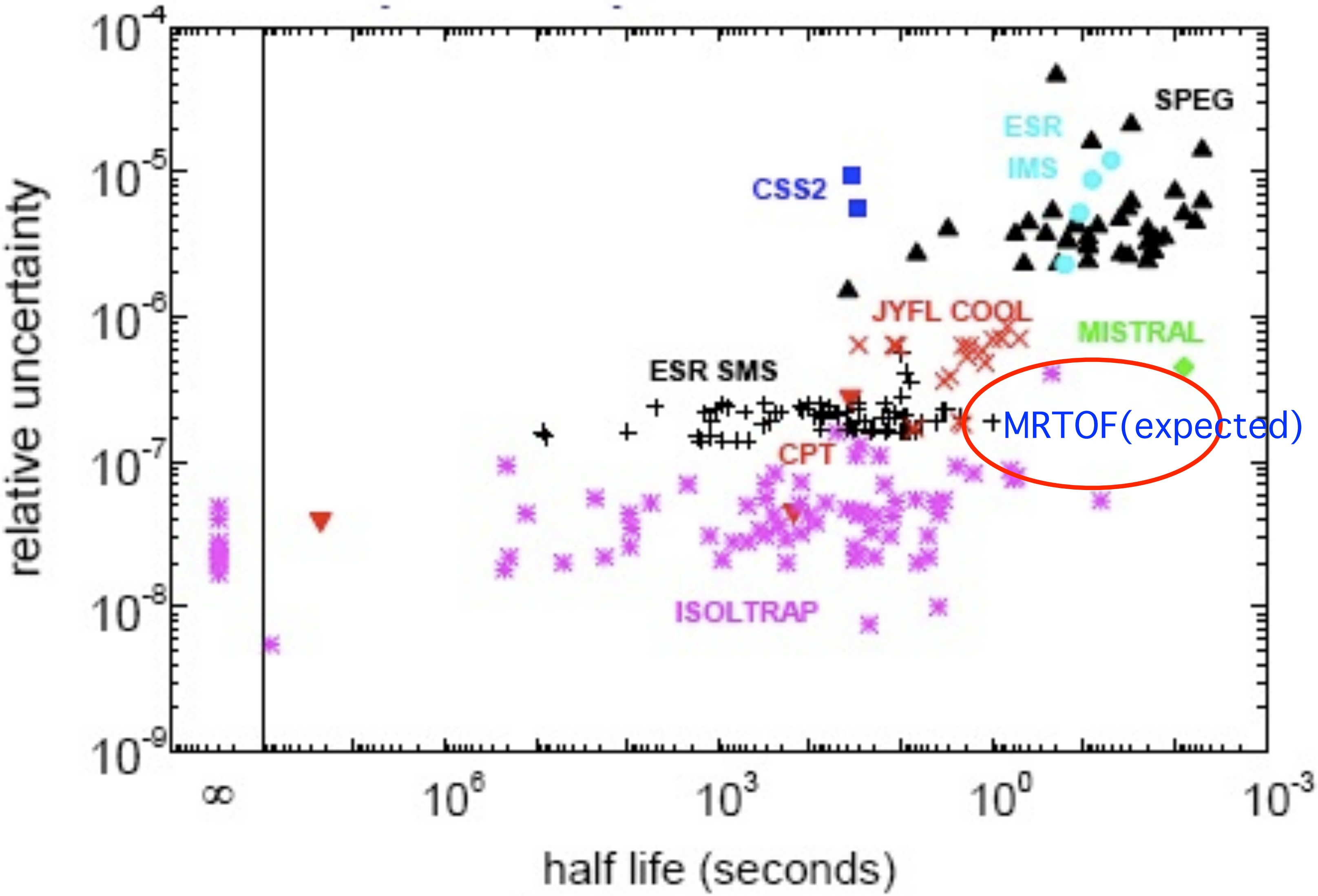
518 Laps, ~ 0.5 km, R ~ 82.000



1554 Laps, ~ 1.5 km, R ~ 122.000



mass uncertainty and half-life

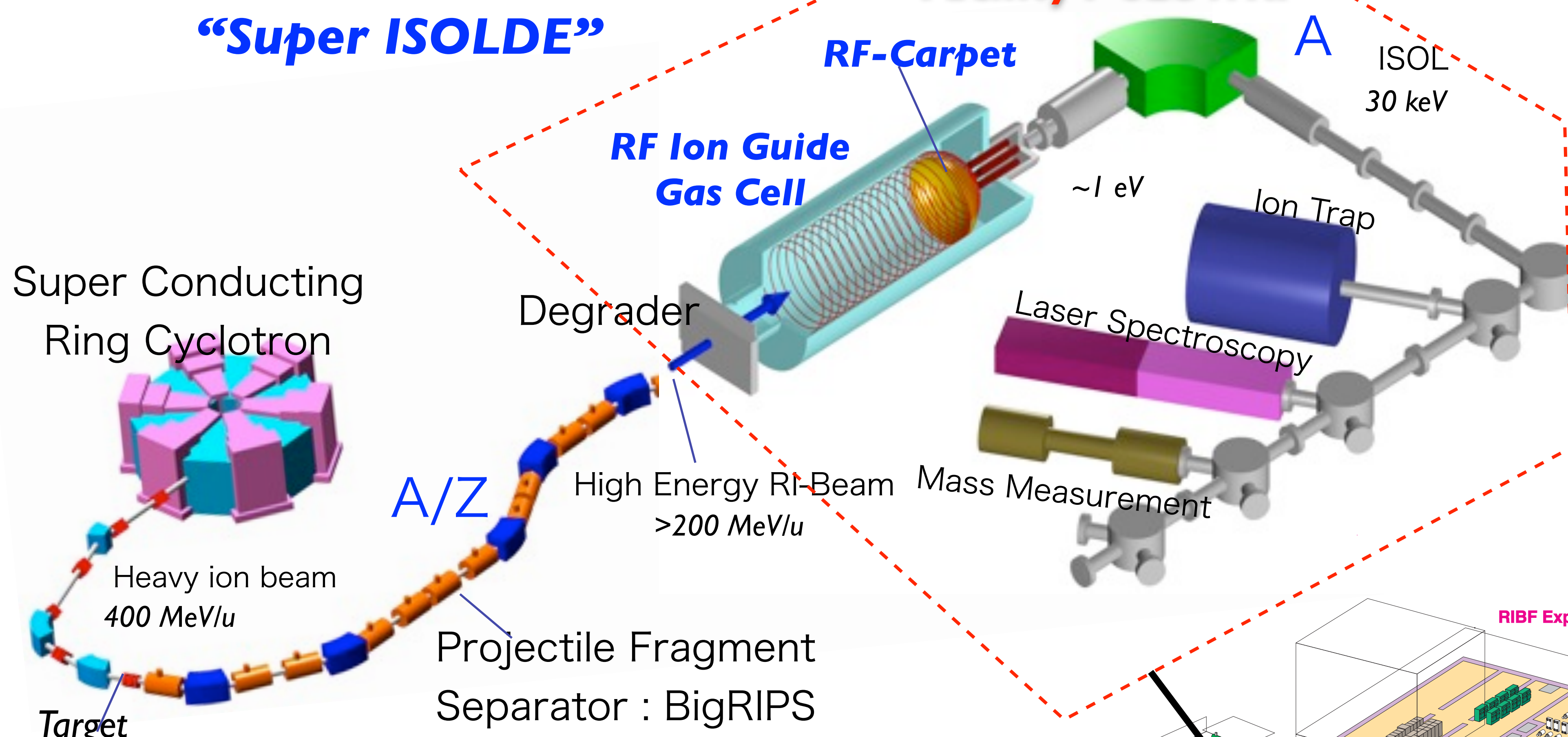


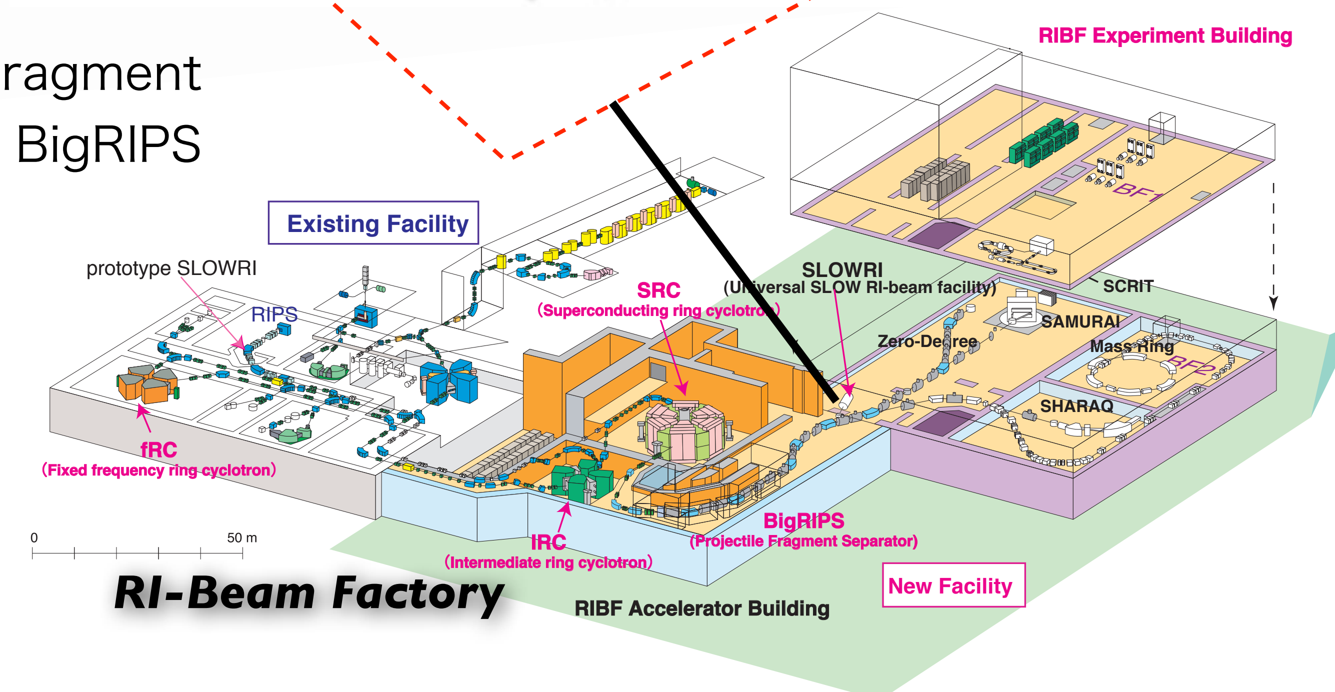
(from D. Lunney)

SLOWRI facility

Universal Slow RI-beam Facility : SLOWRI

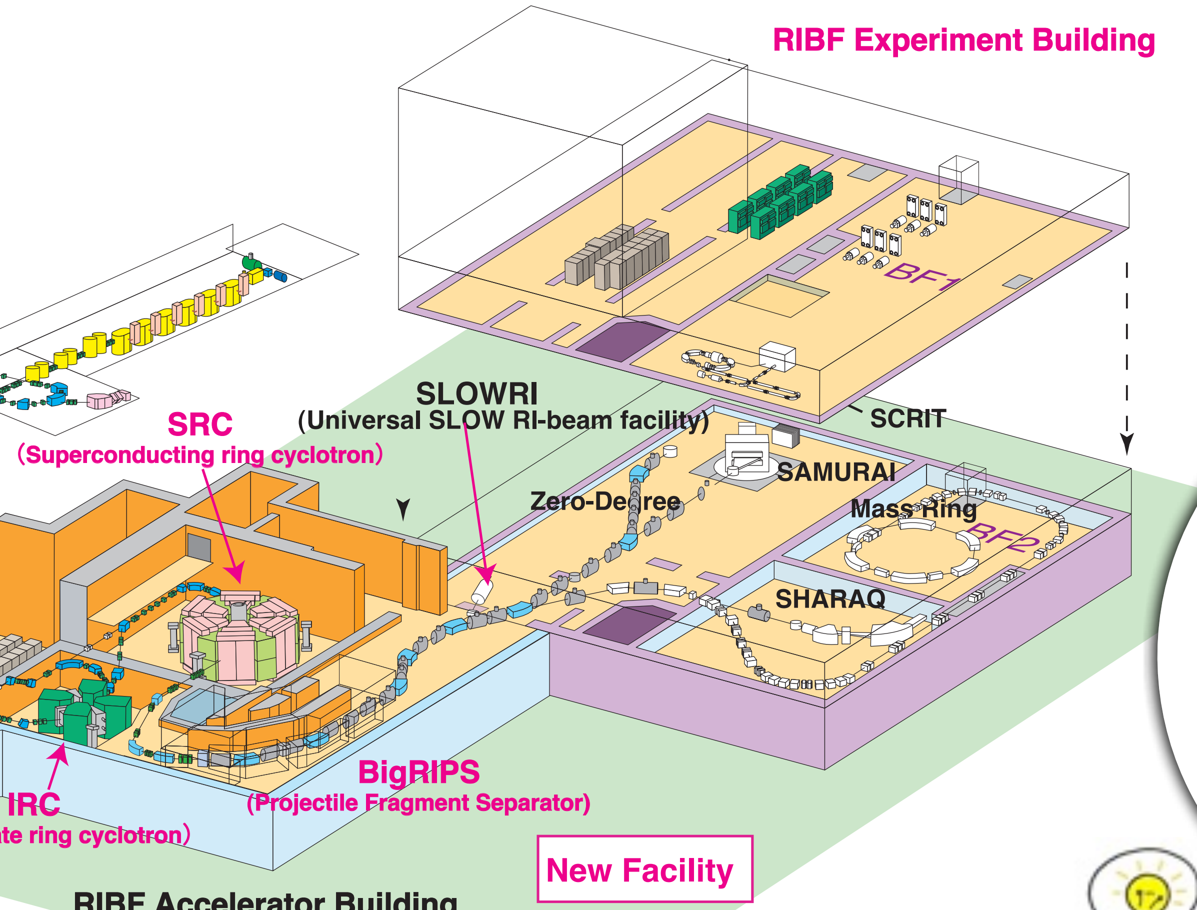
"Super ISOLDE"



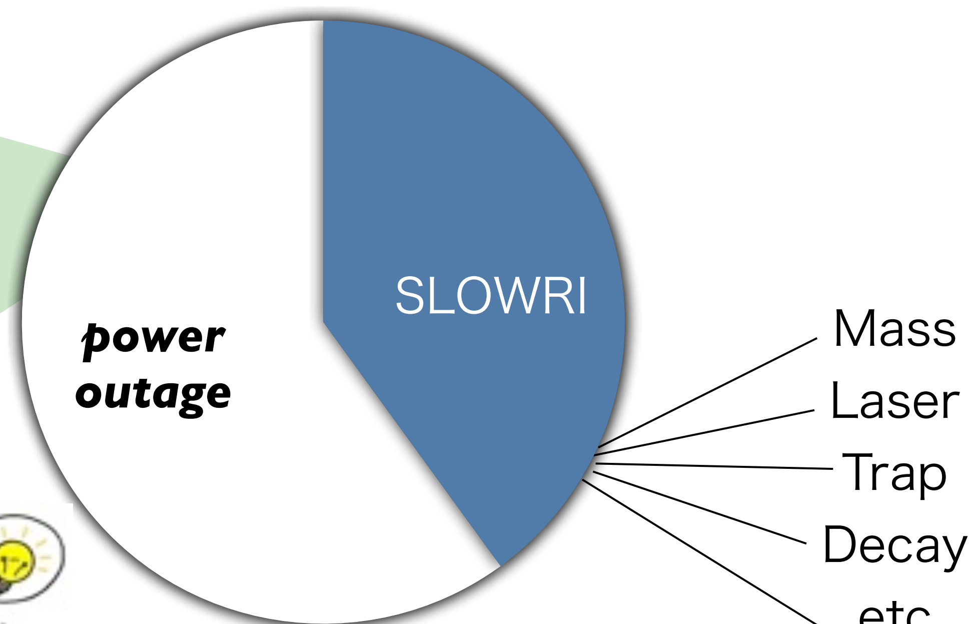


all elements
high pure
low emittance
0-30 KeV

beam time issue

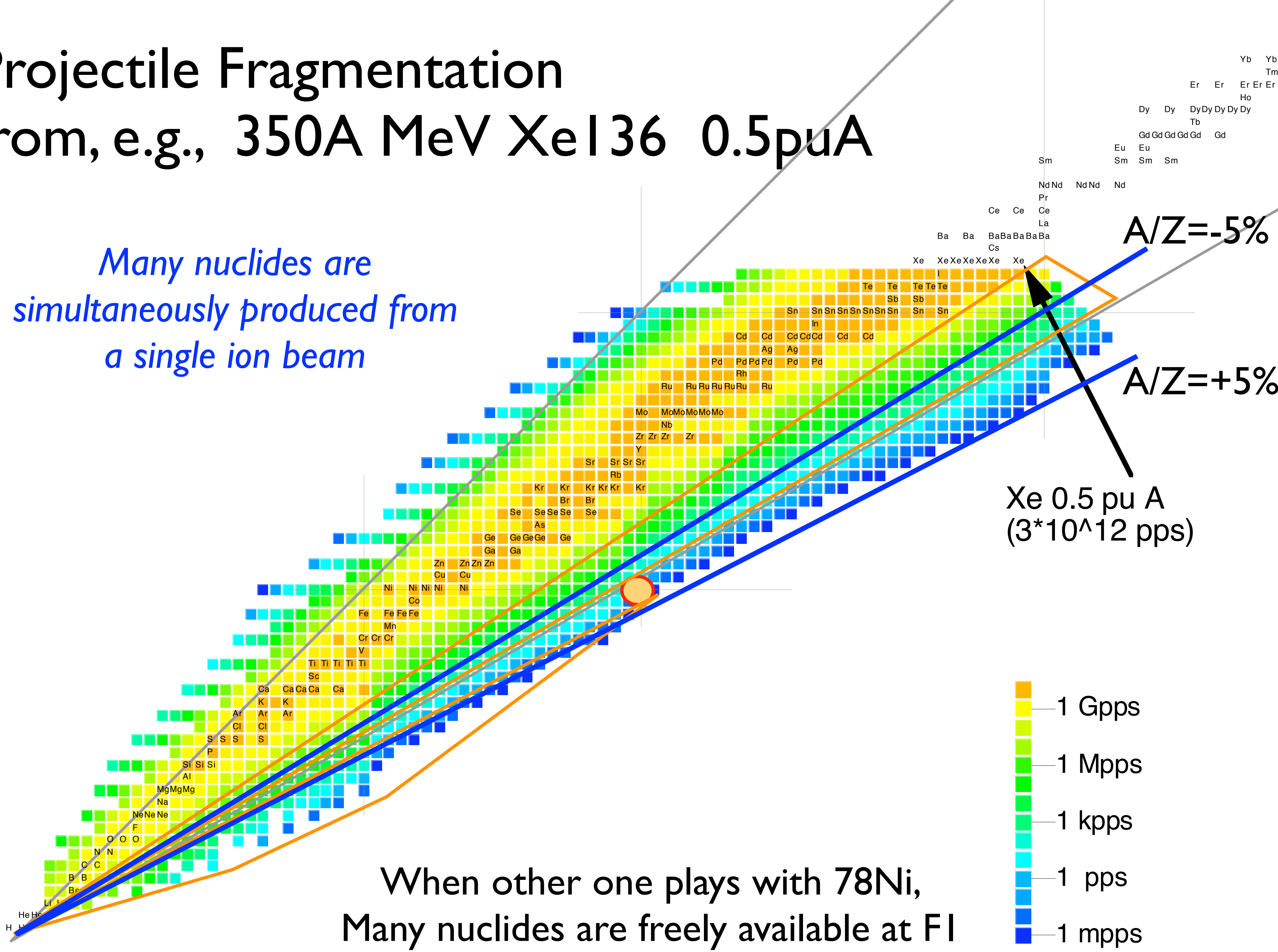


5 months/y
2 weeks/y for SLOWRI ??
5 mon./y for SLOWRI !!



Projectile Fragmentation
from, e.g., 350A MeV Xe136 0.5puA

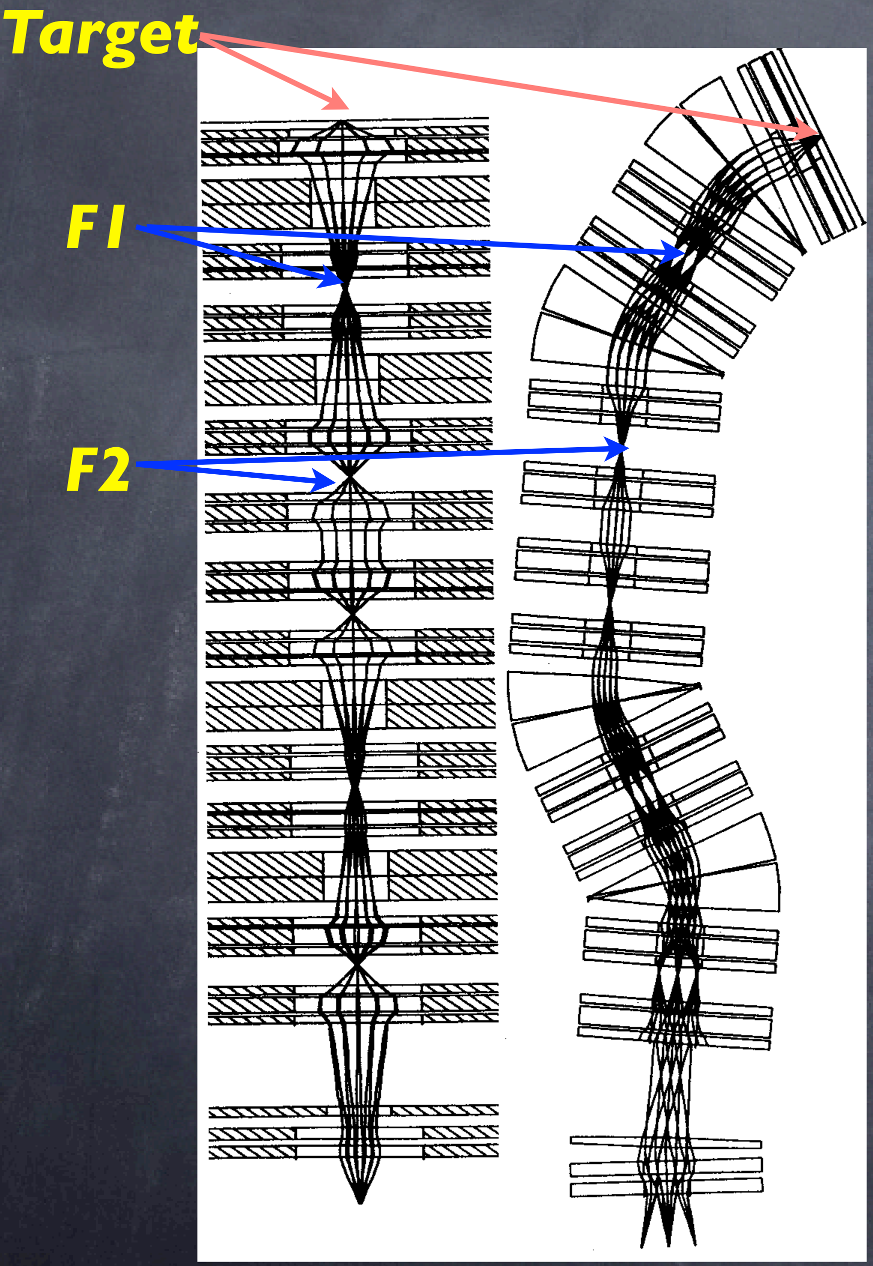
Many nuclides are simultaneously produced from a single ion beam

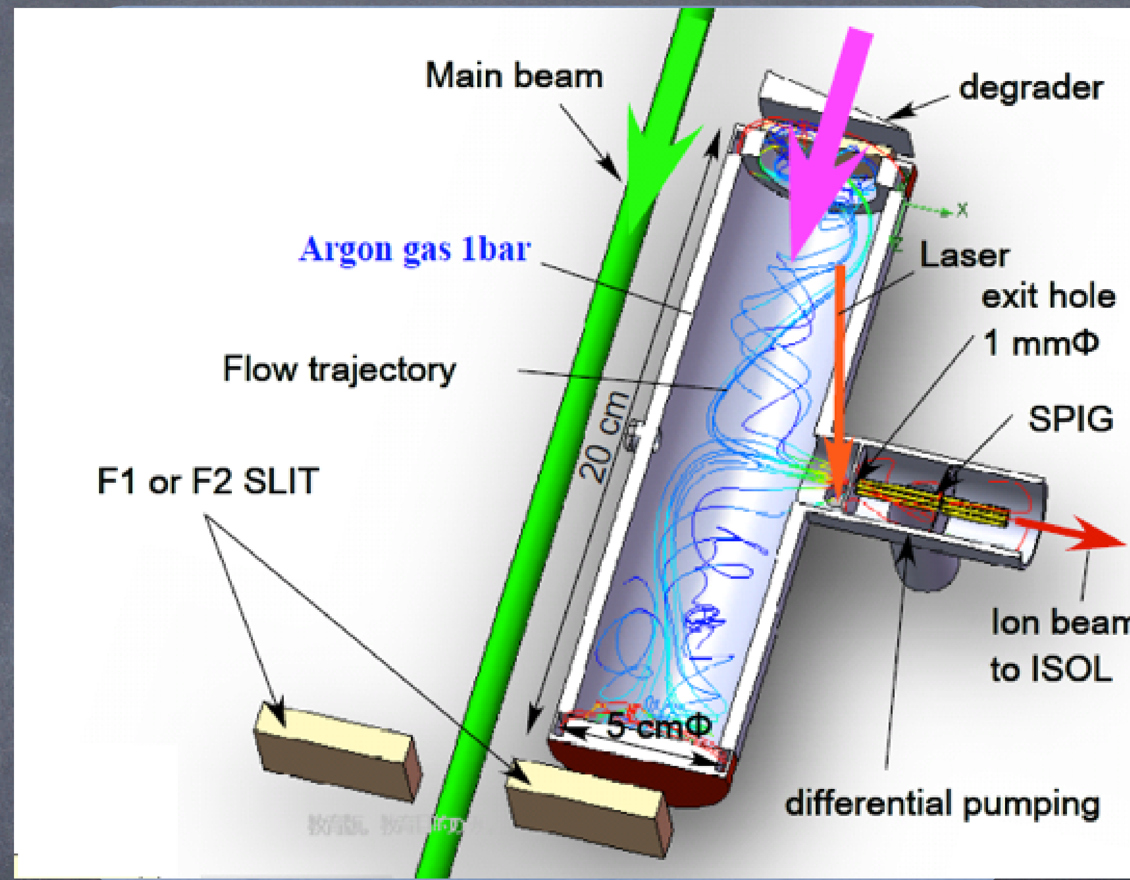


When other one plays with 78Ni,
Many nuclides are freely available at F1

PALIS

PArasitic slow RI-beam with gas catcher Laser Ion Source





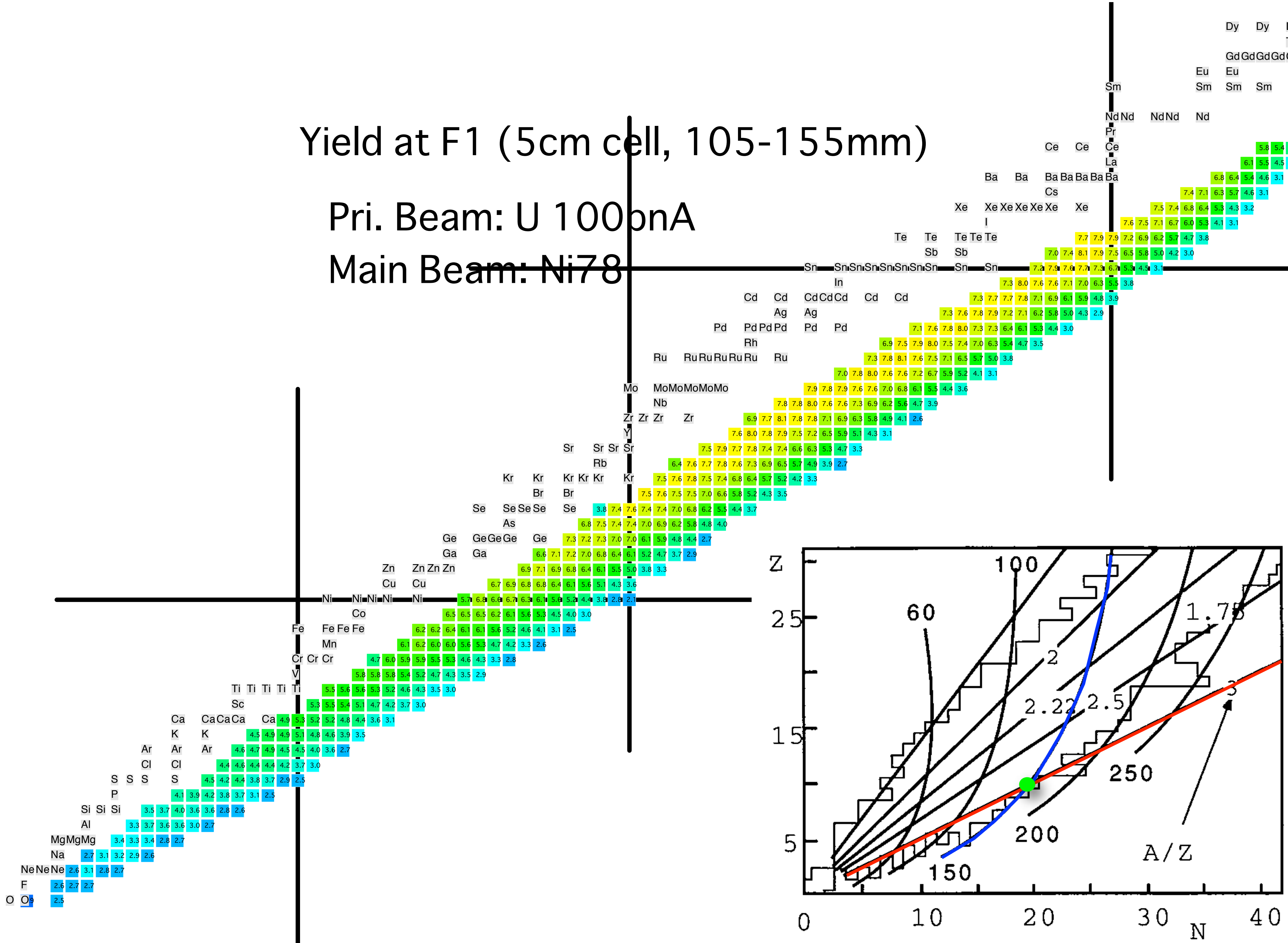
1) Stop & Neutralize in Ar (1 bar)
2) Extract by Gas Flow
3) Re-Ionize at Exit and SPIG

not universal, not very fast but A/Z, Z, A separation

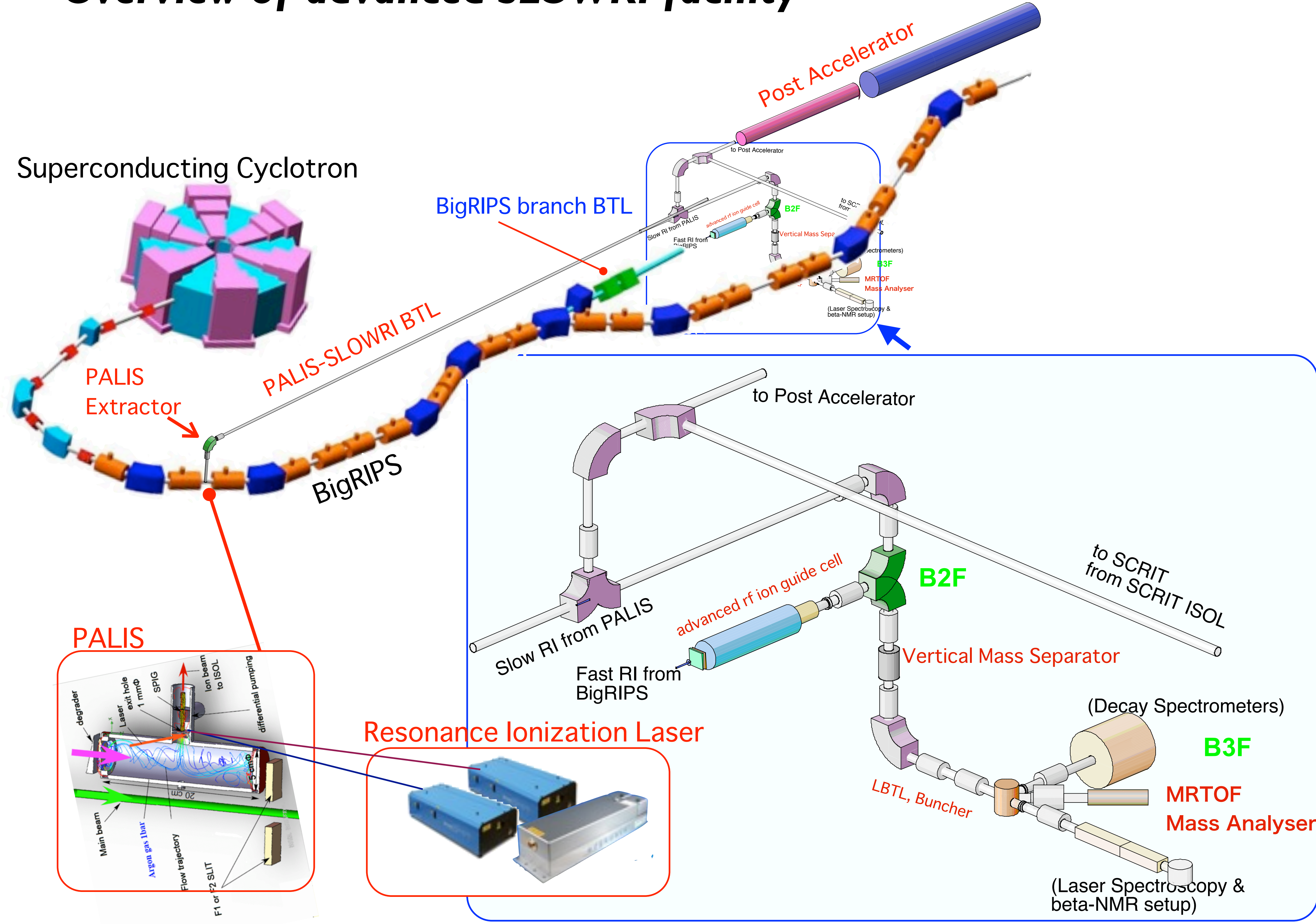
Yield at F1 (5cm cell, 105-155mm)

Pri. Beam: U 100pnA

Main Beam: Ni78



Overview of advanced SLOWRI facility



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