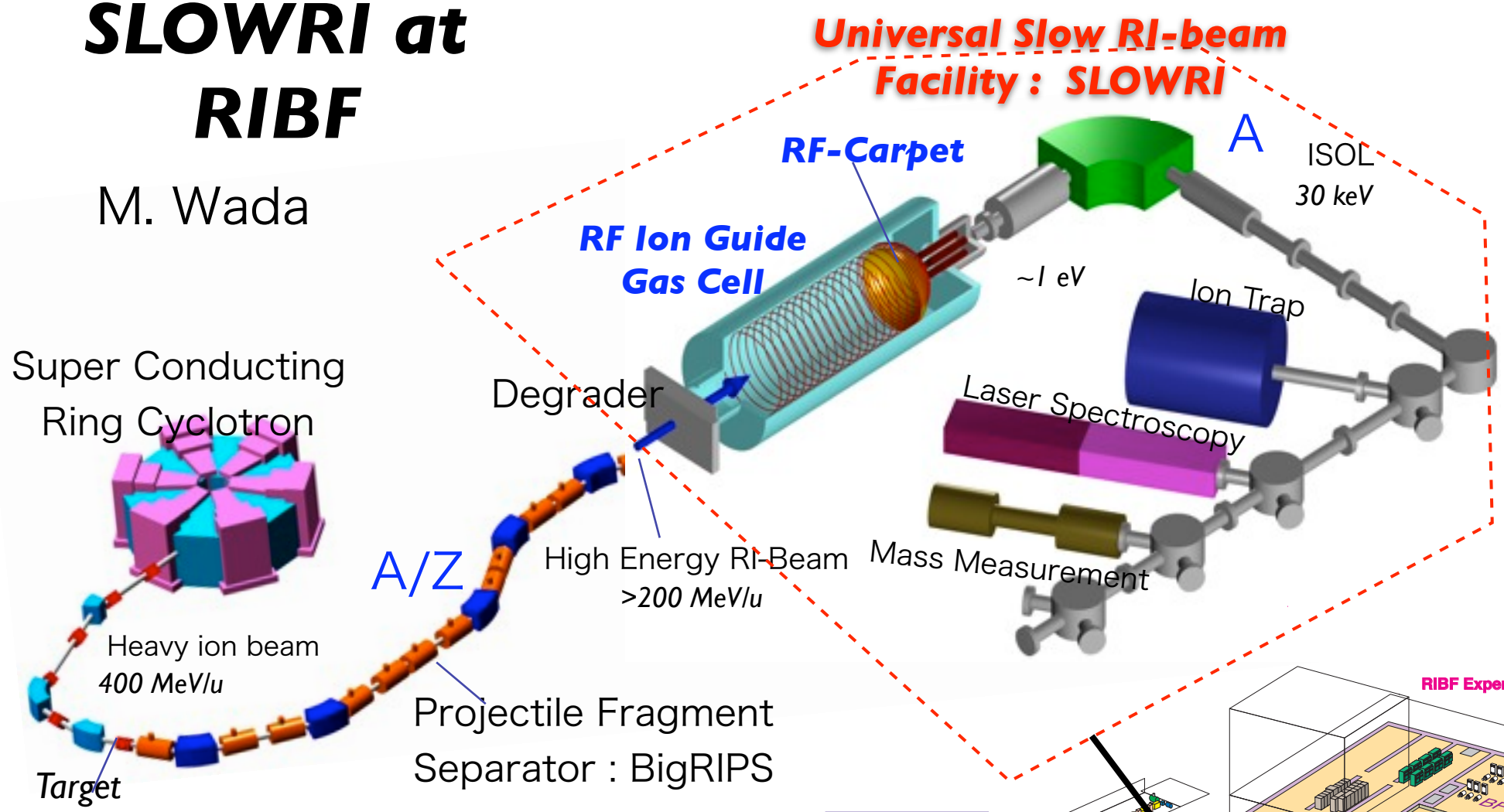
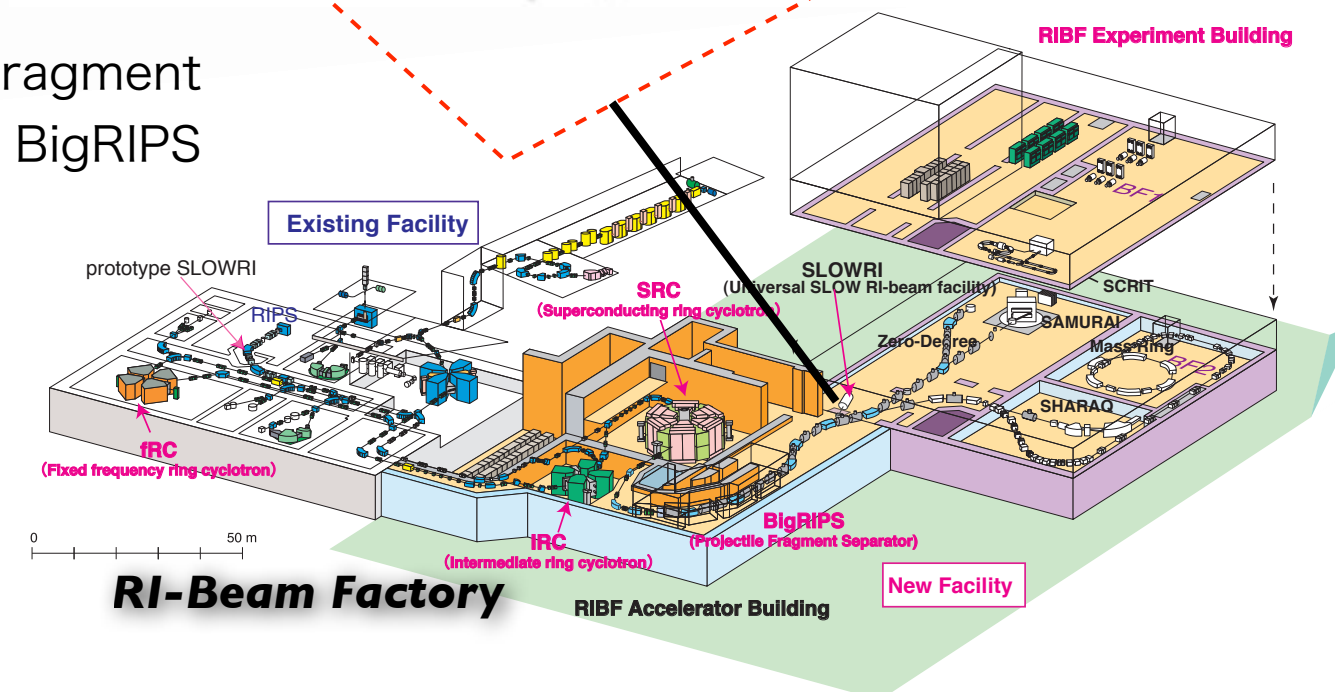
SLOWRI at RIBF

M. Wada

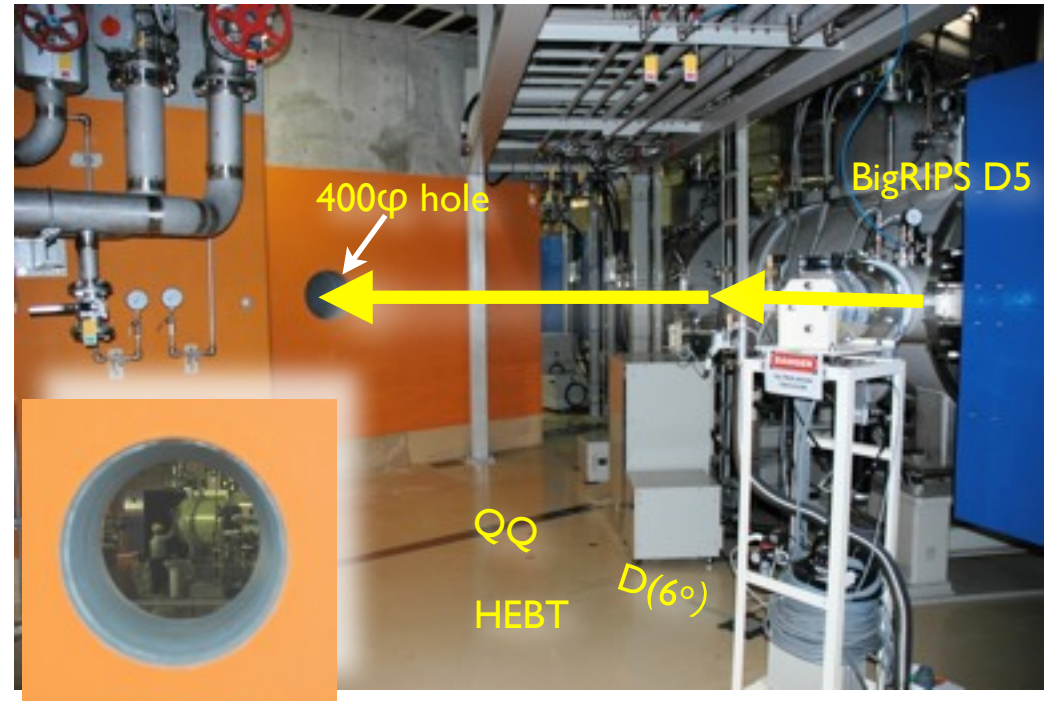


all elements
high pure
low emittance
0-30 KeV



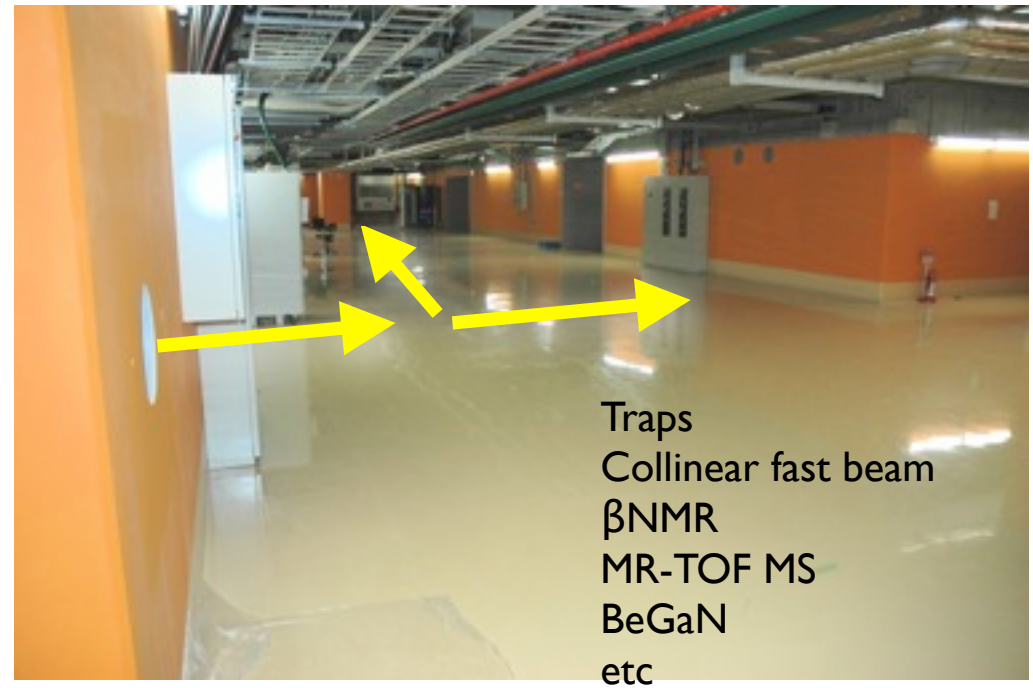
RF Ion Guide Gas Cell location

BigRIPS to SLOWRI

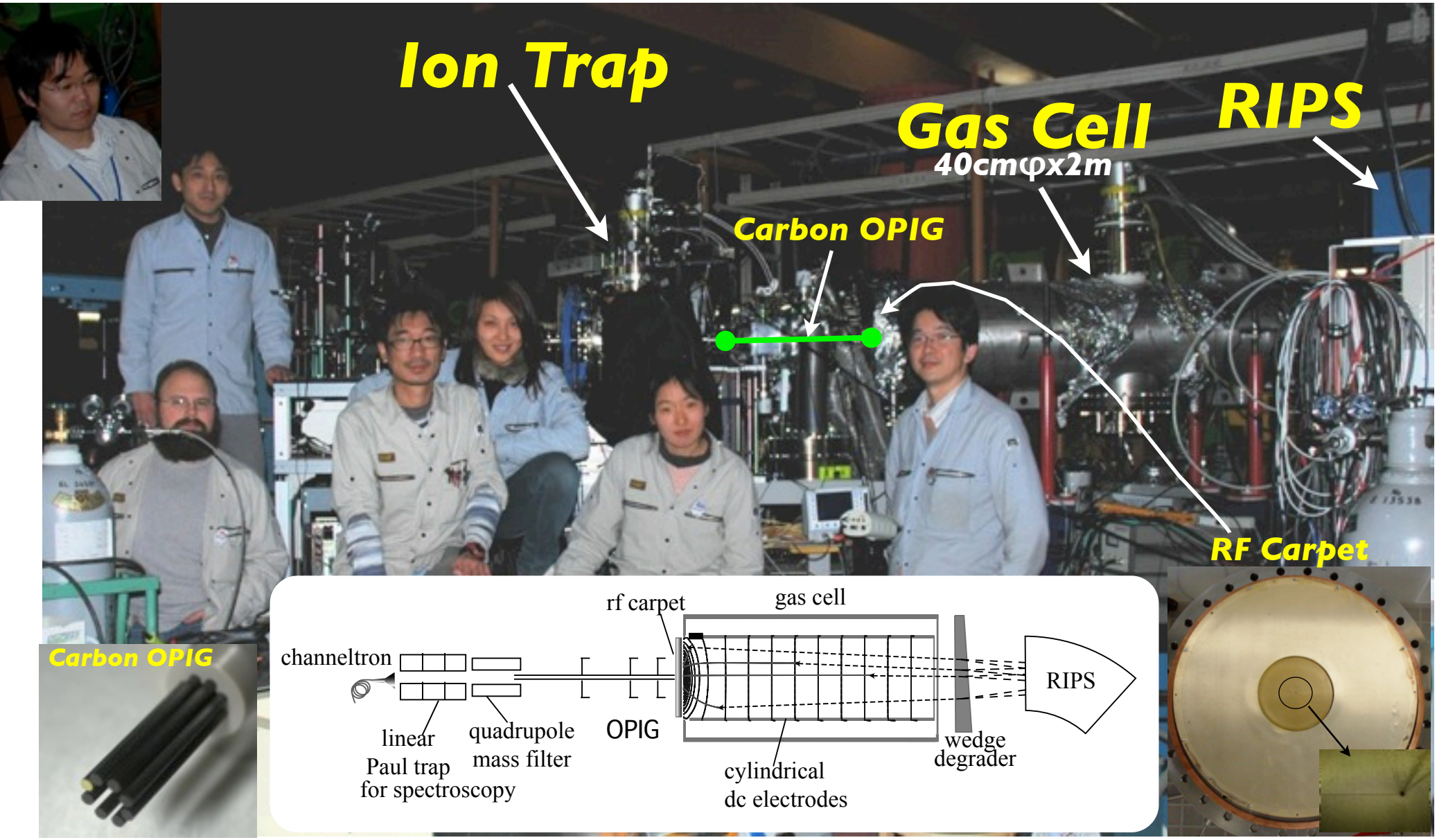


to B3F

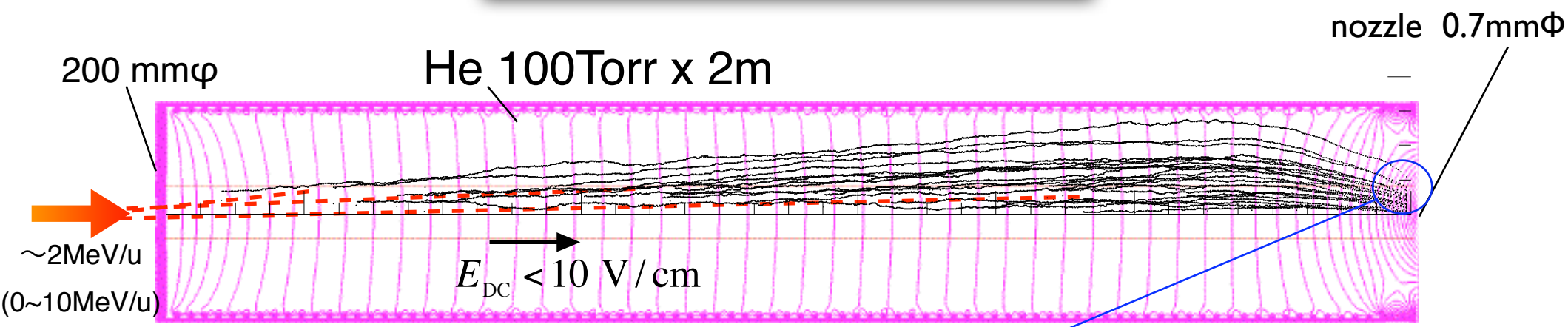
SLOWRI Experiment Room (B3F)



Development of RF-carpet ion guide & Spectroscopy of Be Isotopes at Prototype SLOWRI



RF-Carpet Ion Guide™



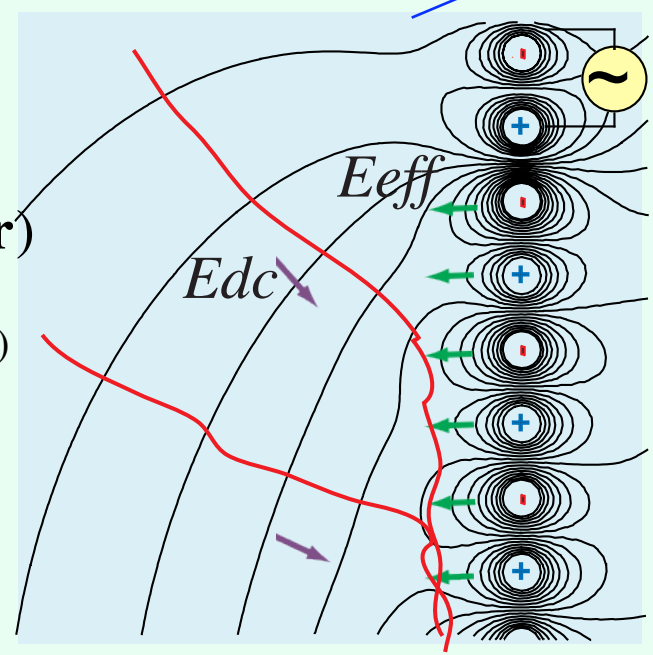
RF gradient Field: Barrier

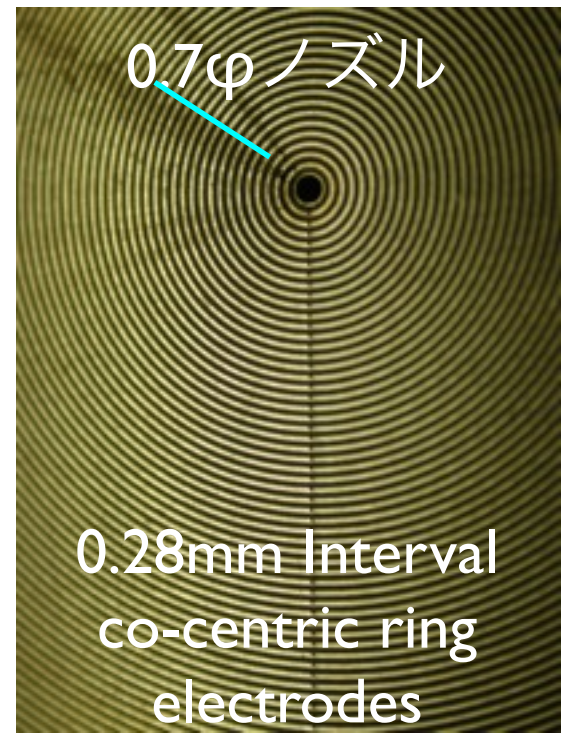
$$\overline{F} = -\frac{e^2}{4m}\frac{1}{(\Omega^2 + 1/\tau_v^2)}\nabla \mathbf{E}_{rf}^2(\mathbf{r})$$

$(\mathbf{E}(\mathbf{r},t) = \mathbf{E}_{rf}(\mathbf{r})\cos(\Omega t),\ \tau_v$: relax time)

$$E^{\max}_{\text{eff in gas}} = \frac{m\mu^2 V_{rf}^2}{e r_0^3}$$

$2r_0 \approx$ electrode distance





M.Wada et al, NIM B204 (2003) 570.

Proposed in 1997。 Proof of Principle in 2000。 100MeV/u Li8 in 2003。

used for Be spectroscopy in 2005-09。 standard technology in worldwide

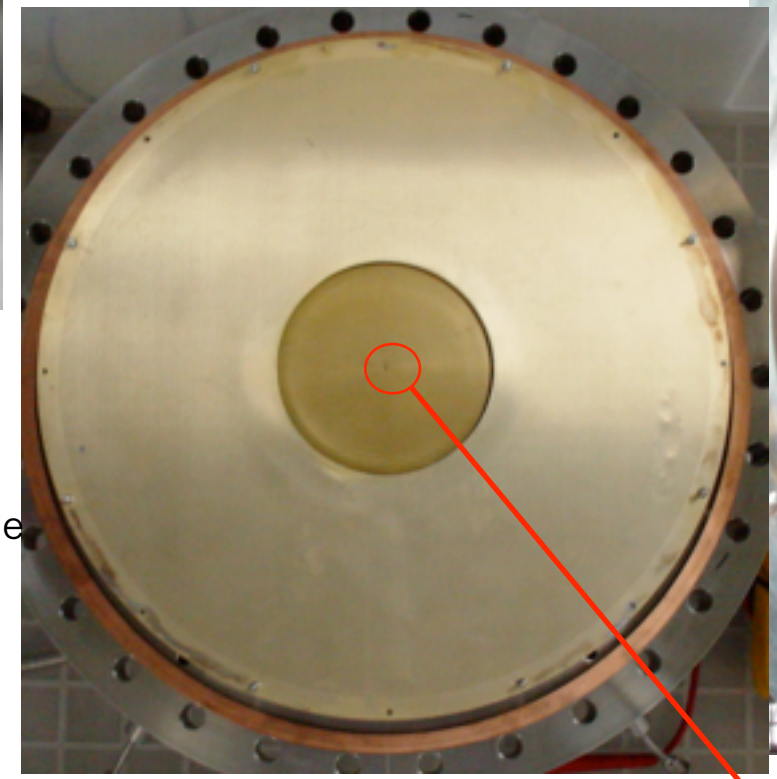
Photo Gallery

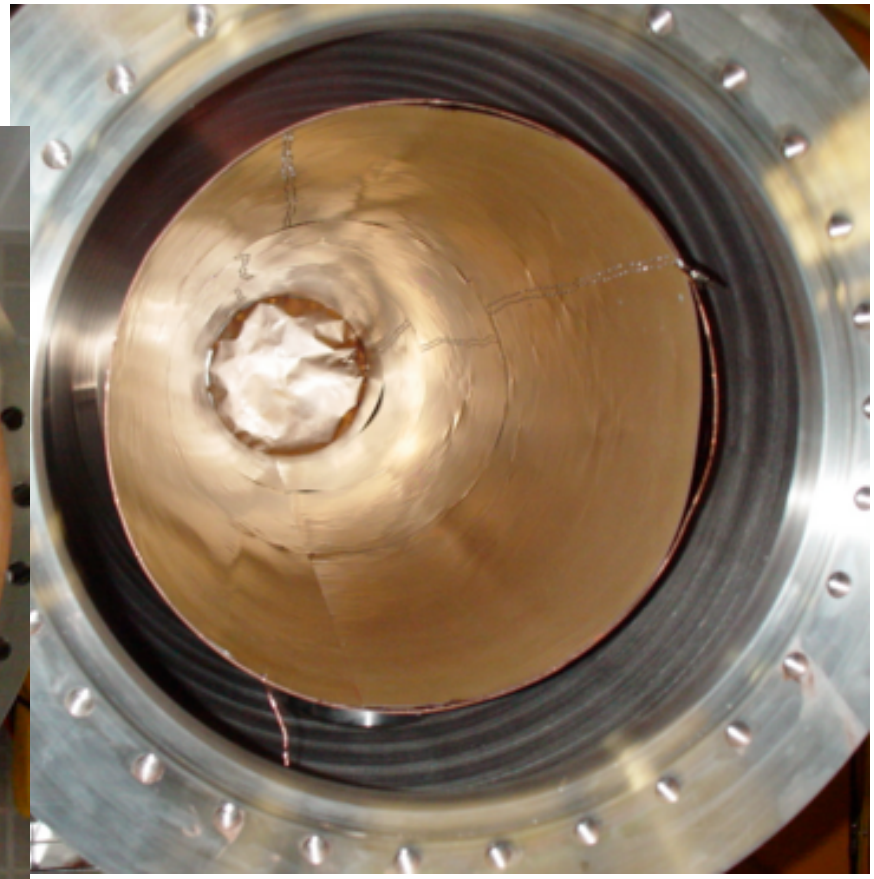
OPIG rf octopole beam guide made of CFRP

SPIG

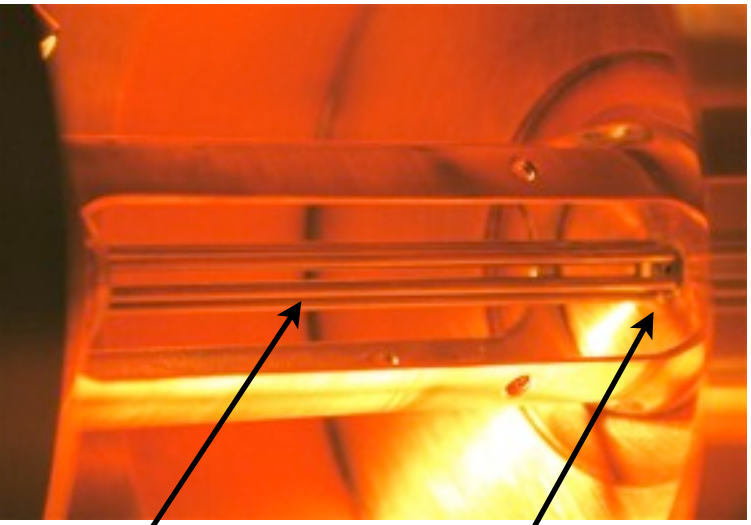
RF six-pole ion beam guide made of 6-0.8 mmϕ Mo rods transports ions to high vaccum.

22MHz 200V





Cylinder DC-Electrodes in Gas Cell

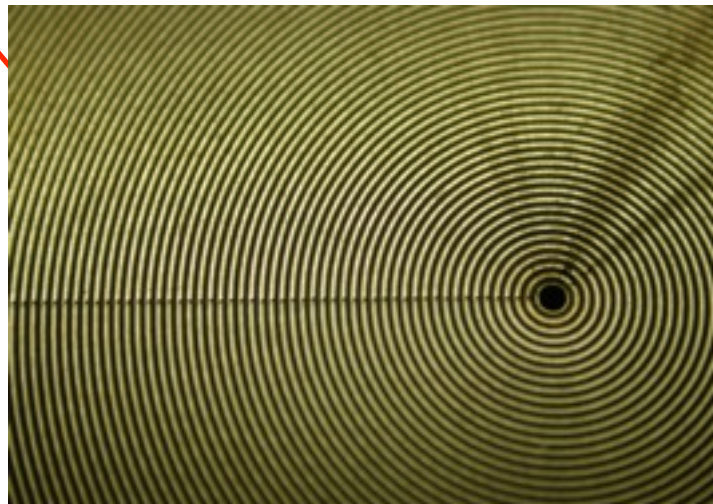


SPIG & Nozzle

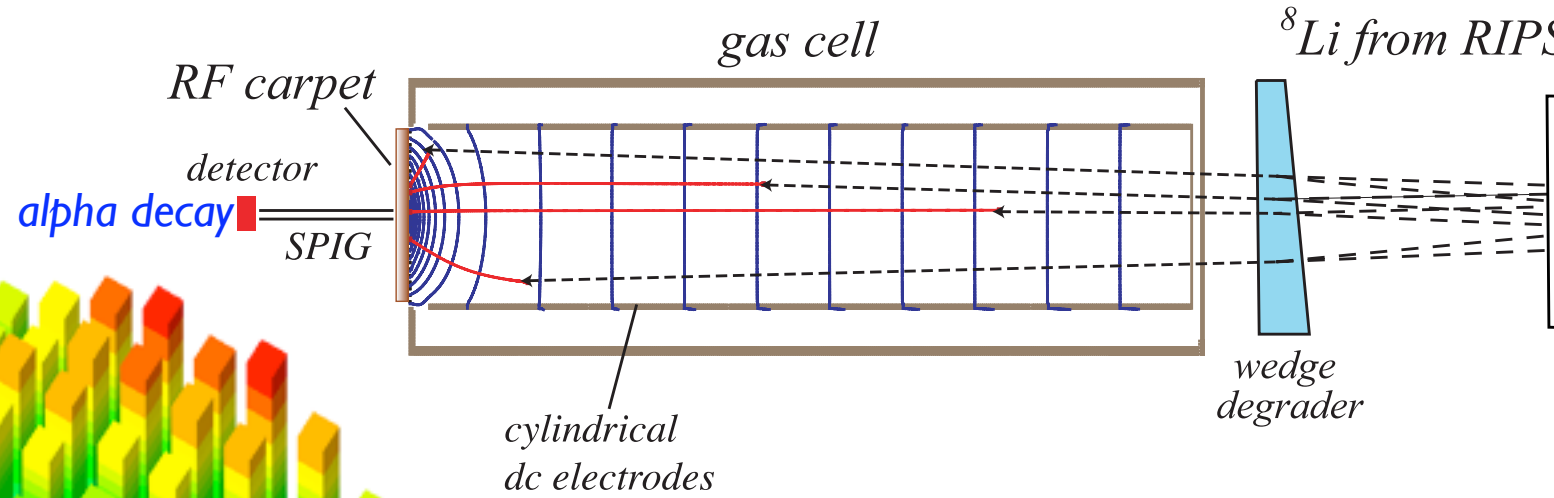
RF Carpet

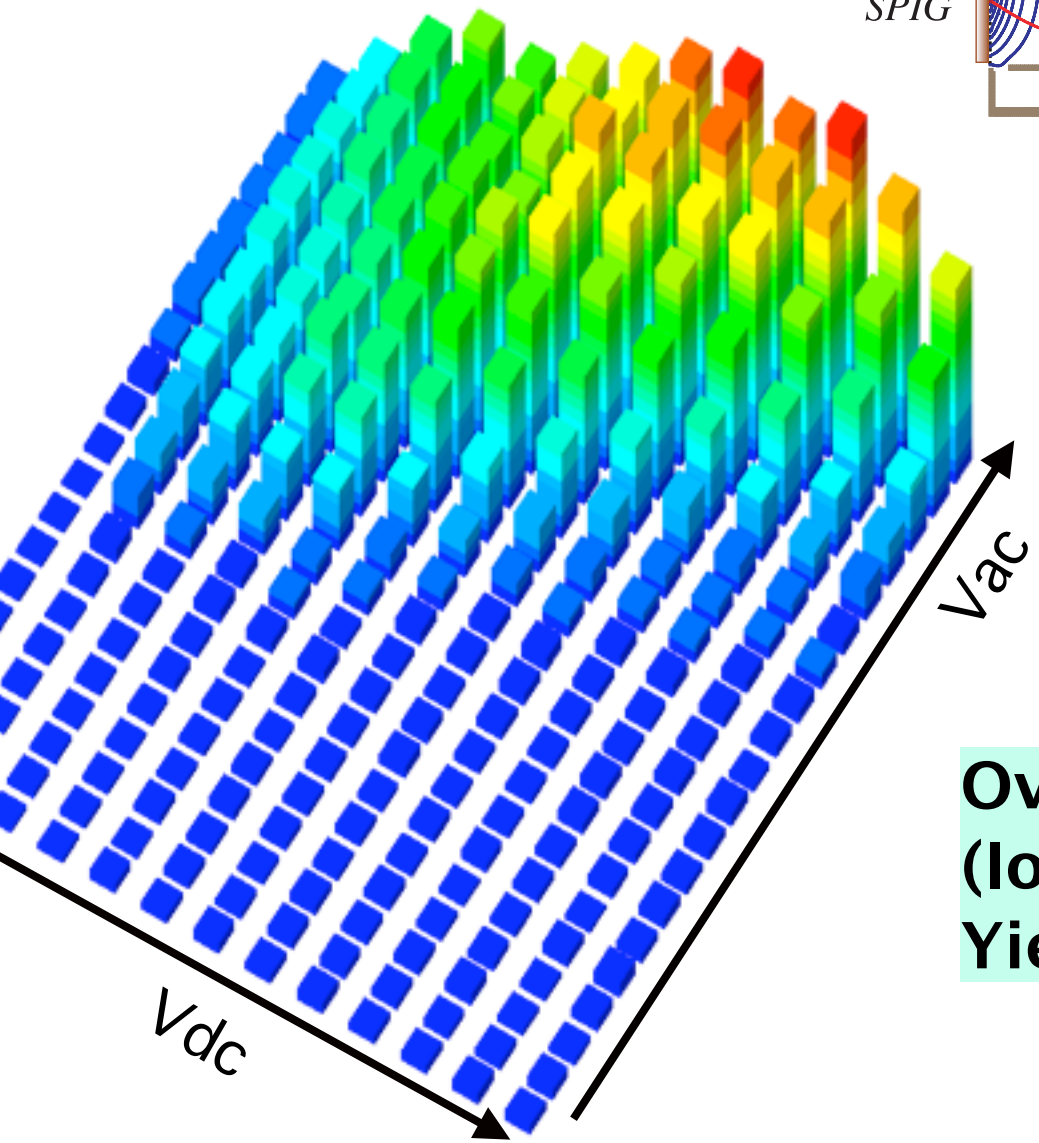
Central part is made of RF ring-electrodes with 0.28mm interval. An exit of 0.7 mmϕ is located at the center.

13MHz 150V



Yield and efficiency of slow Li-8 ions





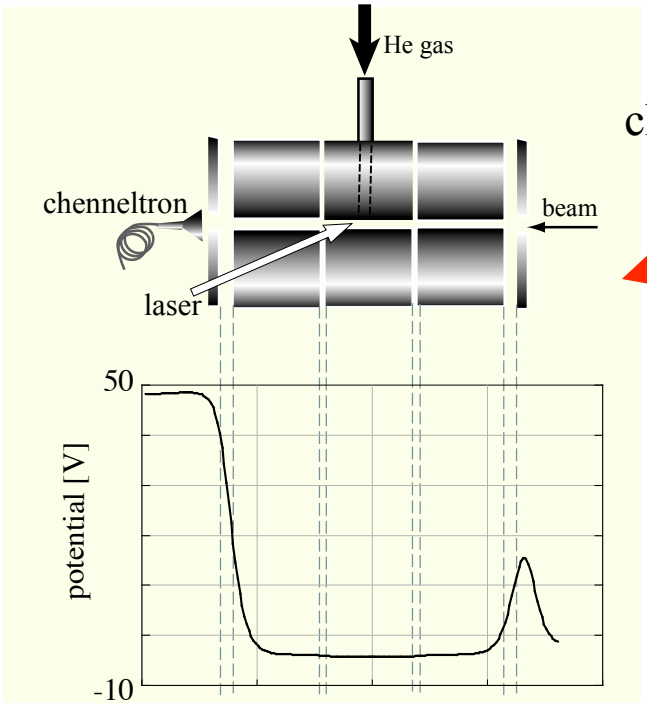
AC-DC Dependence of Yield

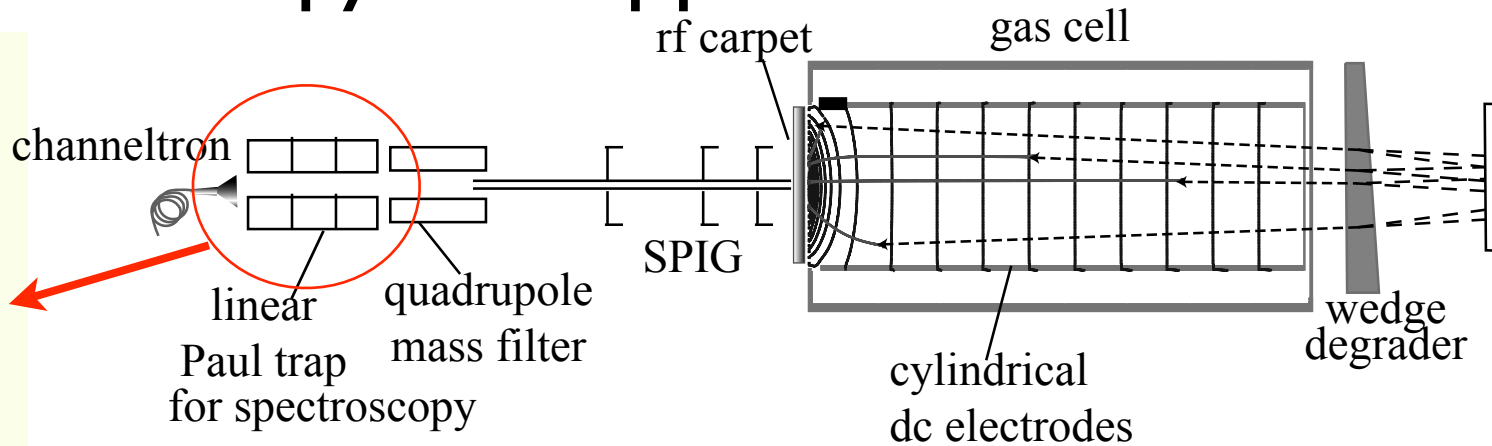
~100 A MeV 8Li ions from RIPS
^{8}Li: delayed alpha decay
reliable measurements
very light ion

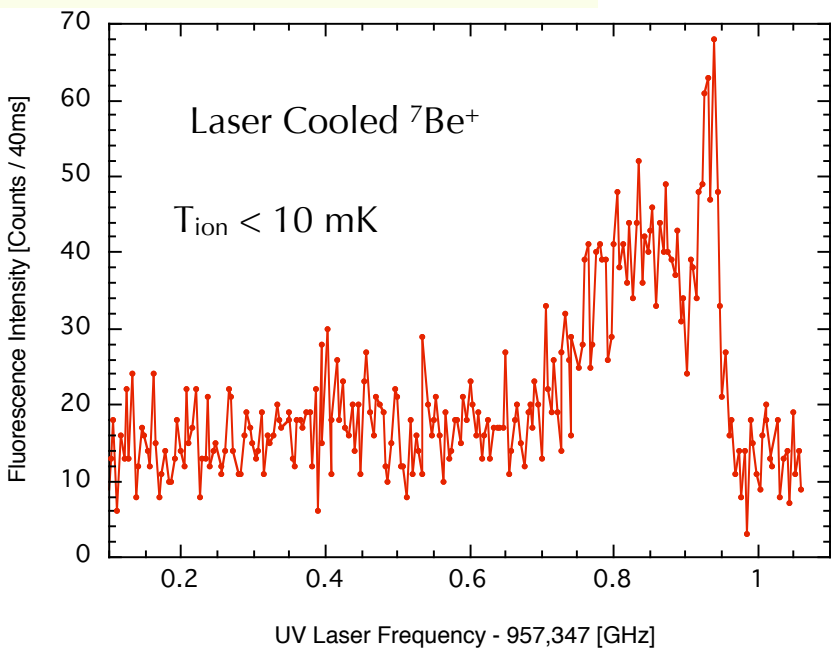
Overall Efficiency: ~5% max
(Ion guide Efficiency: ~33% max)
Yield of 8Li: 24 kcps max

M. Wada et al, NIM B204(2003)570
M. Wada, NIM A532(2004) 40
A. Takamine et al, RSI 76(2005) 103503

Laser Spectroscopy of Trapped Be ions

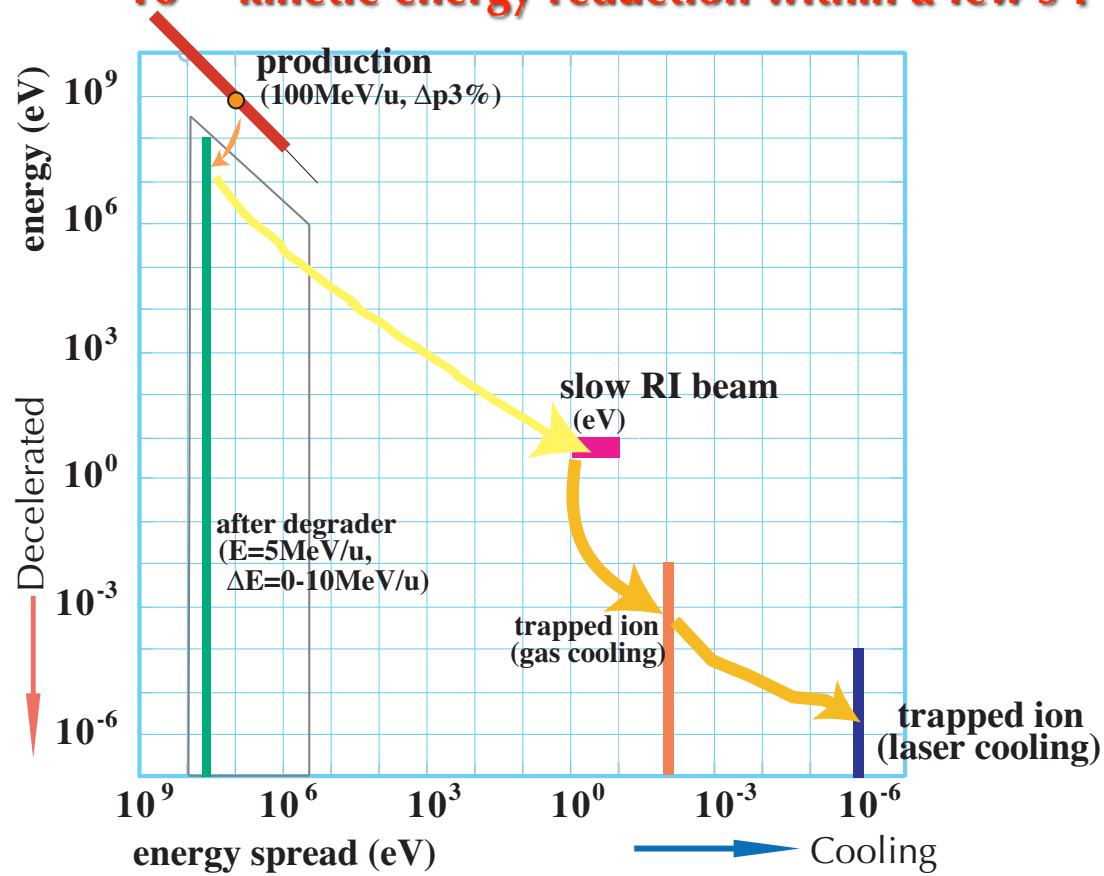






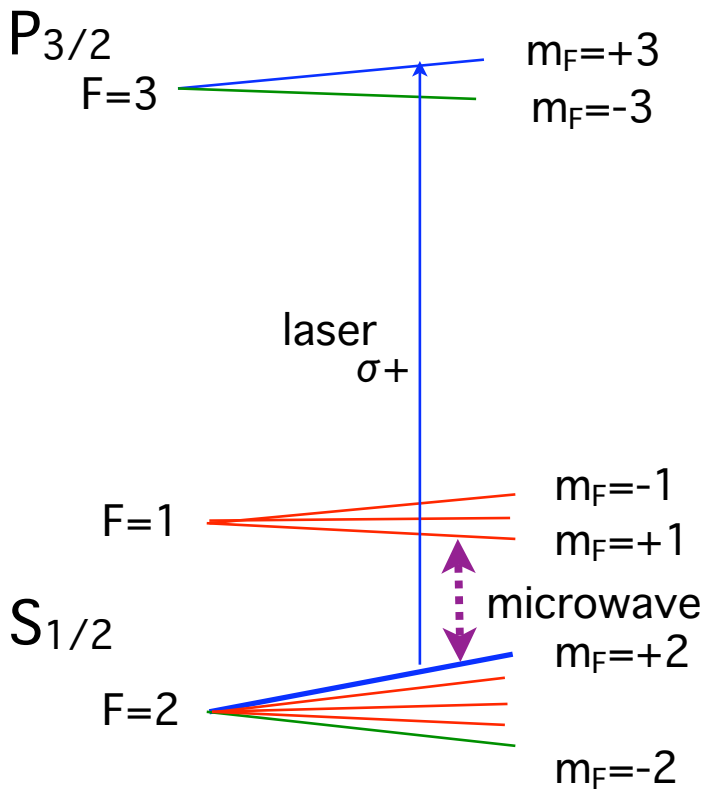
T. Nakamura *et al.*, PRA 74, 052503 (2004)
K. Okada *et al.*, PRL 101, 212502 (2008)

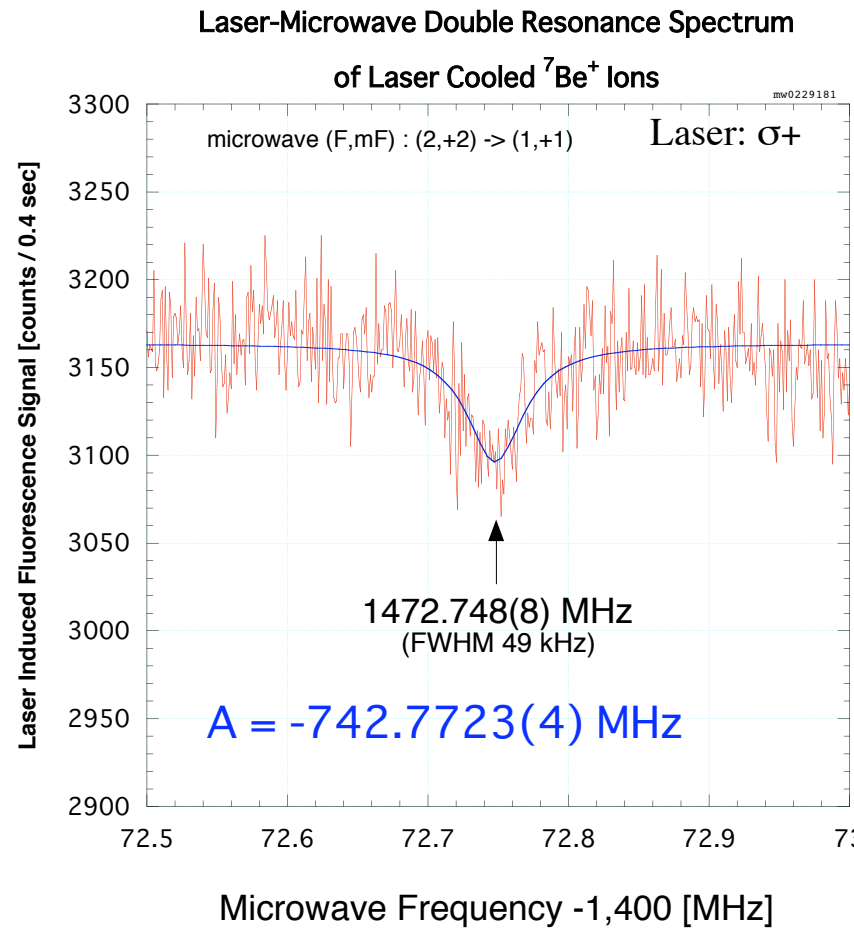
10^{-15} kinetic energy reduction within a few s !



Precision hfs measurement of Be-7

Okada et al, PRL 101, 212502 (2008)





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

$$\nu^+, \nu^- \rightarrow A = -742.7723(4)\ \mathrm{MHz}$$

$$\frac{\mathrm{d}\nu}{\mathrm{d}B} = \mu_\mathrm{B}\frac{4I}{2I+1} = 21\ \mathrm{MHz/mT} \qquad I = 3/2$$

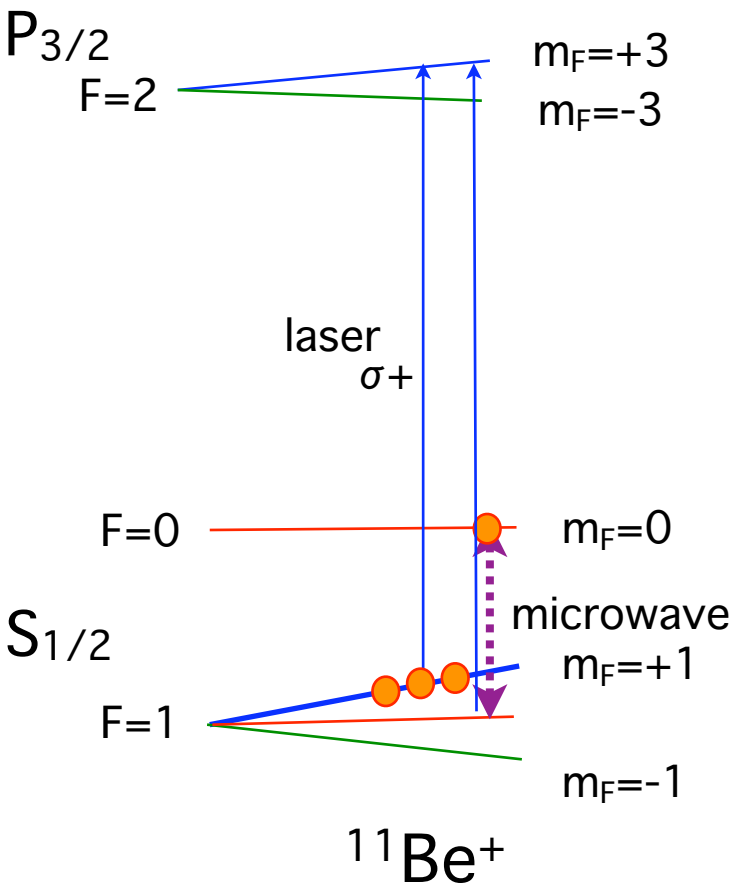
$$A \longrightarrow \quad \mu_I = -1.39928(2)$$

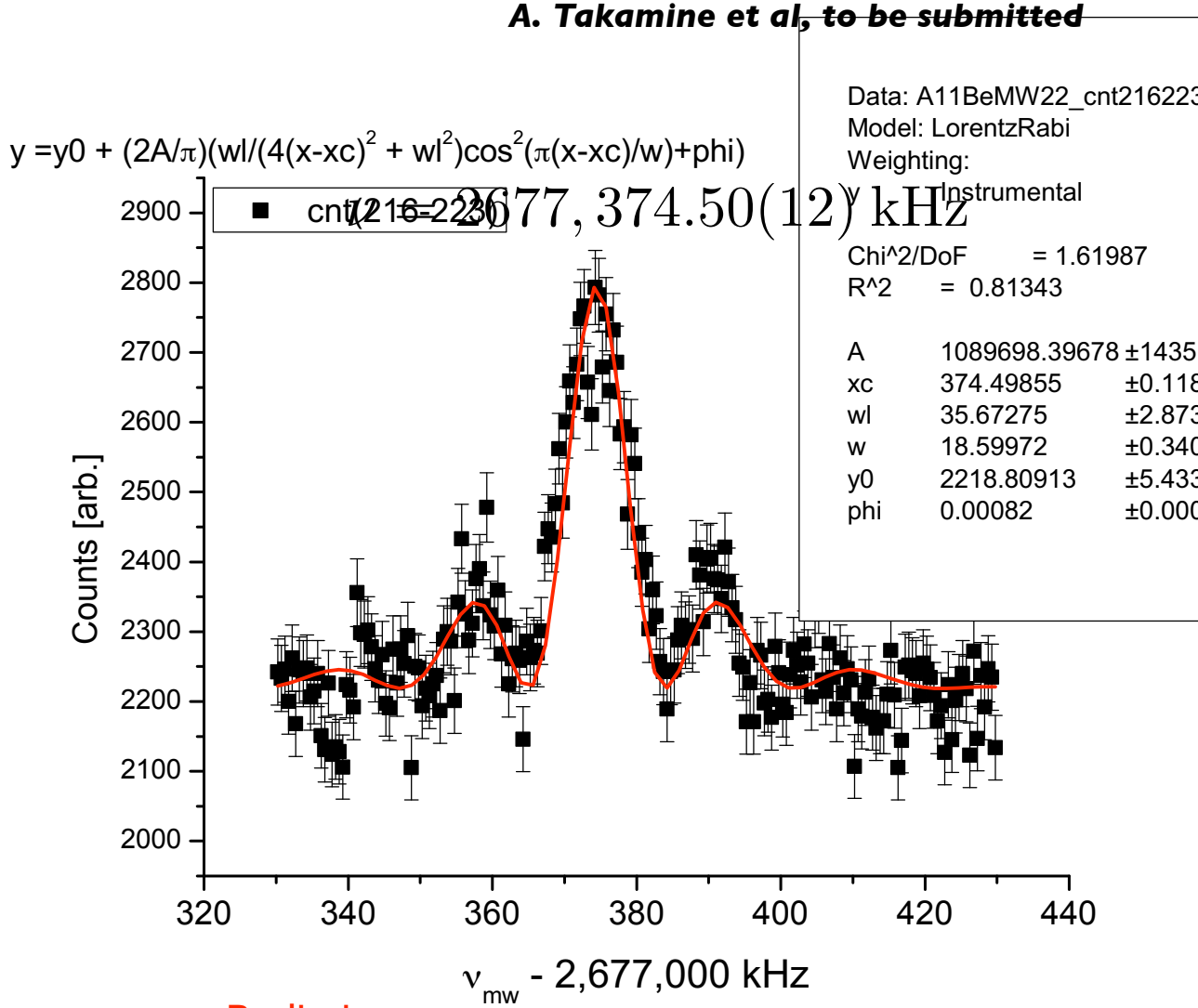
$$|\Delta_{7,9}| < 10^{-5}$$

cf. S.Kapperts eta
ENAM98

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

A. Takamine et al, to be submitted





Preliminary

Residual population in F=0 state is induced to F=1, mF=0 state, then cooling laser can excite

mF-mF' = 0 - 0 (Field indenpendent, 1st order)

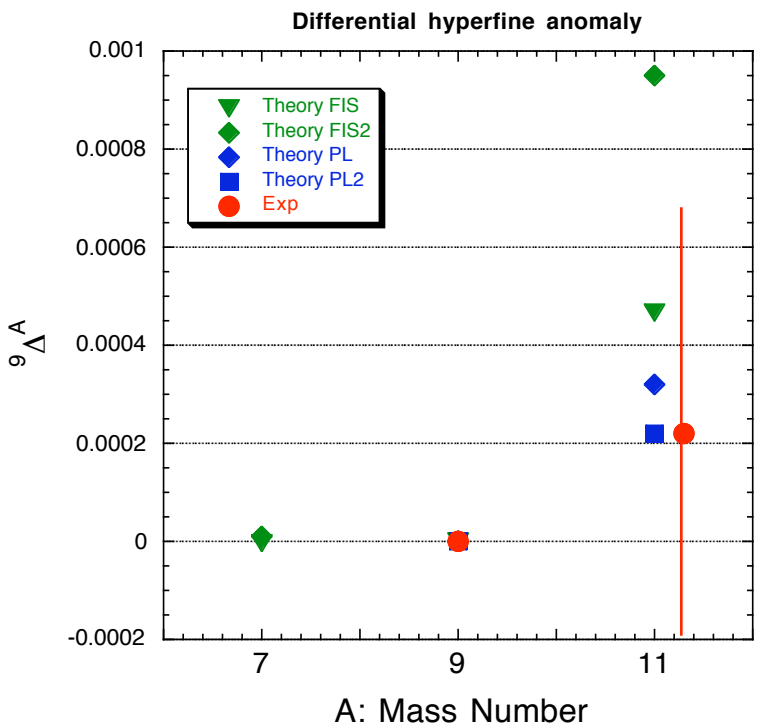
$$A = -2677.302945(72)\ \mathrm{MHz}\ (3 \cdot 10^{-8})$$

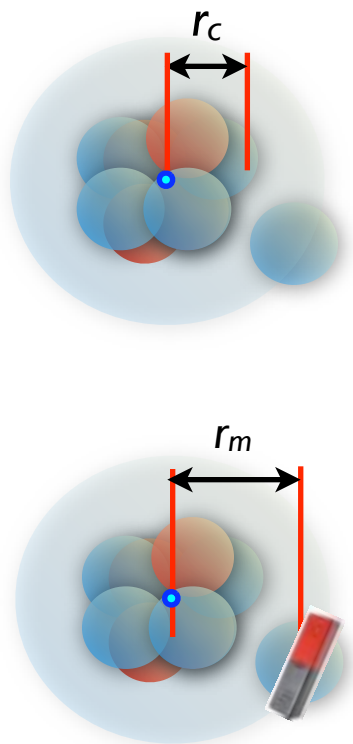
$$\frac{\mathrm{d}\nu}{\mathrm{d}B} = \mu_{\mathrm{B}} \frac{4I}{2I+1} = 14\ \mathrm{MHz/mT} \longrightarrow I = 1/2$$

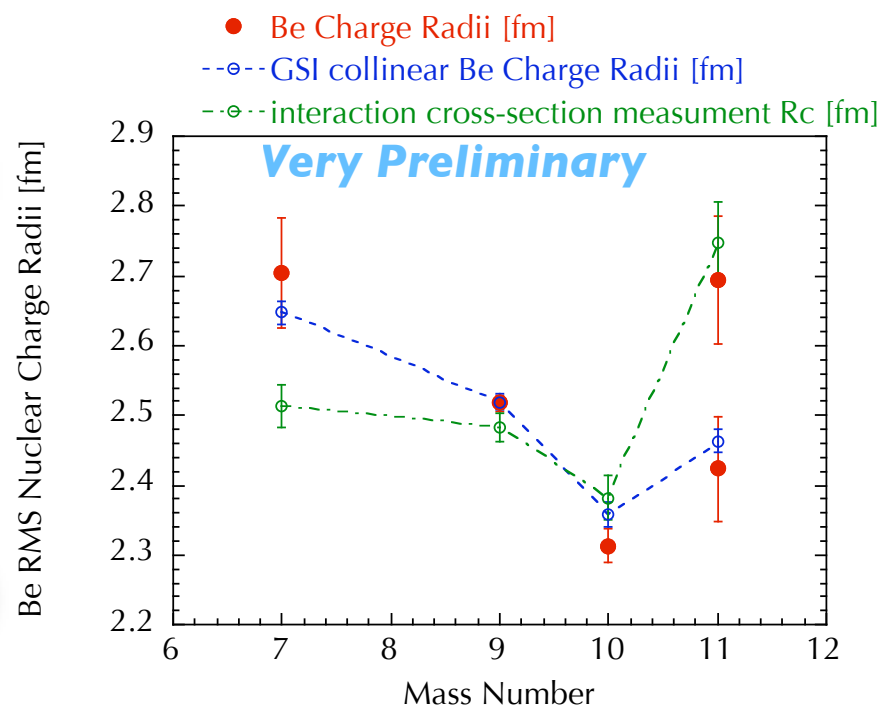
$$\mu_I(^{11}\mathrm{Be}) = -1.6812(5)\ \mathrm{n.m.}$$

Charge & Magnetization Radii of Be Isotopes

	Be7	Be9	Be10	Be11
HFS constant A (MHz)	-742.7722(4)	-625.0088370529(11)	-	-2677.308(2)
Nuclear Mag. Moment (n.m)	[-1.39928(2)]	-1.177432(3)	-	(-)1.6816(8)
S-P Opt. Transition [THz]	957347372.4(1.6)	957396620.6(2.7)	957413949.8(0.5)	957428168.9(2.5) 957 428 191.9(4.4)





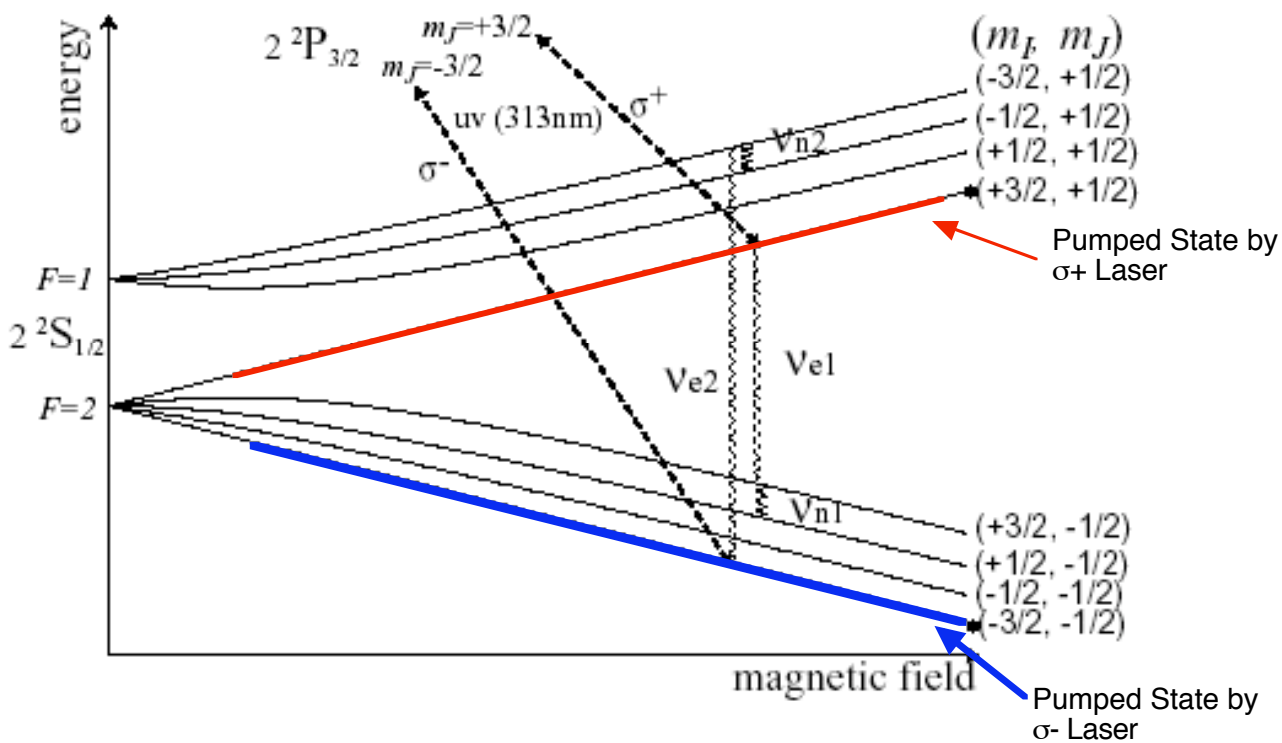


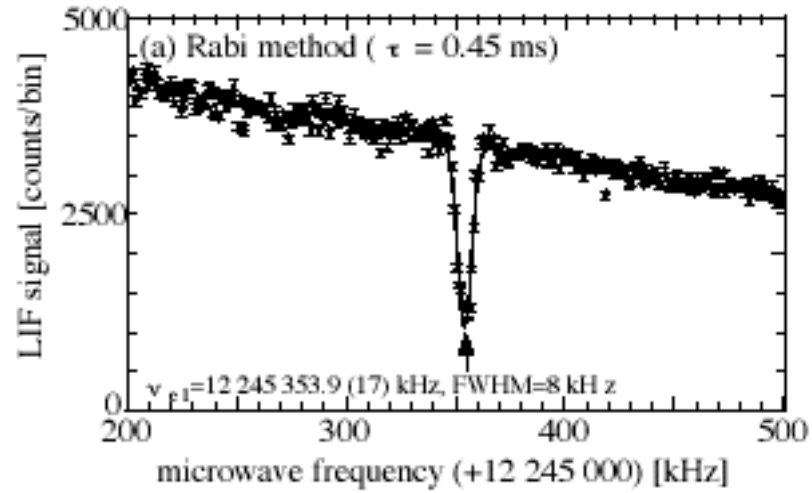
neutron halo of ^{11}Be

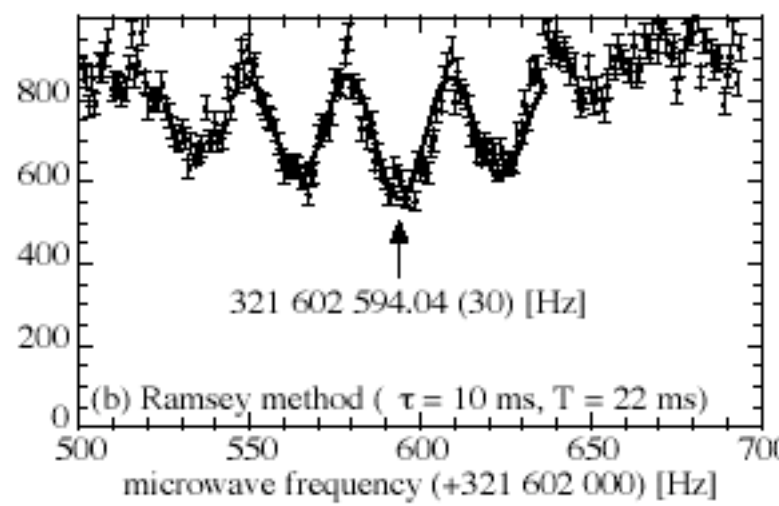
$$^{9}\Delta^{11} = \frac{A_9/\mu_9}{A_{11}/\mu_{11}} - 1 = 2.2(48) \times 10^{-4}$$

Accurate and independent measurement of μ_I and A

Zeeman Splittings of the Ground-State Hyperfine Structure of ^{9}Be







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 (2002) 329.

Planned & Possible Exp. @ SLOWRI

1. Mass Measurements (MR-TOF-MS)
2. Charge Radii (Collinear Laser Spectroscopy)
3. Hyperfine Structure (Trap, Laser-MW Spectroscopy)
4. T1/2, Qβ, B.R.(βγ-delayed particle spectroscopy)
5. Nuclear Moments (hfs, β-NMR, PAC)
6. Fundamental Symmetry (β-decay in free space)
7. Highly charged RI (EBIT)
8. Antiprotonic Radioactive Atoms
9. Inbeam-γ, Astrophysics (post acceleration)

Mass known:≈2000 → ≈3000 1.5 X Expands

Opt. Spectroscopy ≈600 → >1200 2 X Knowledge

RF Ion guide

Slow-RI

All Elements

Pure, Efficient

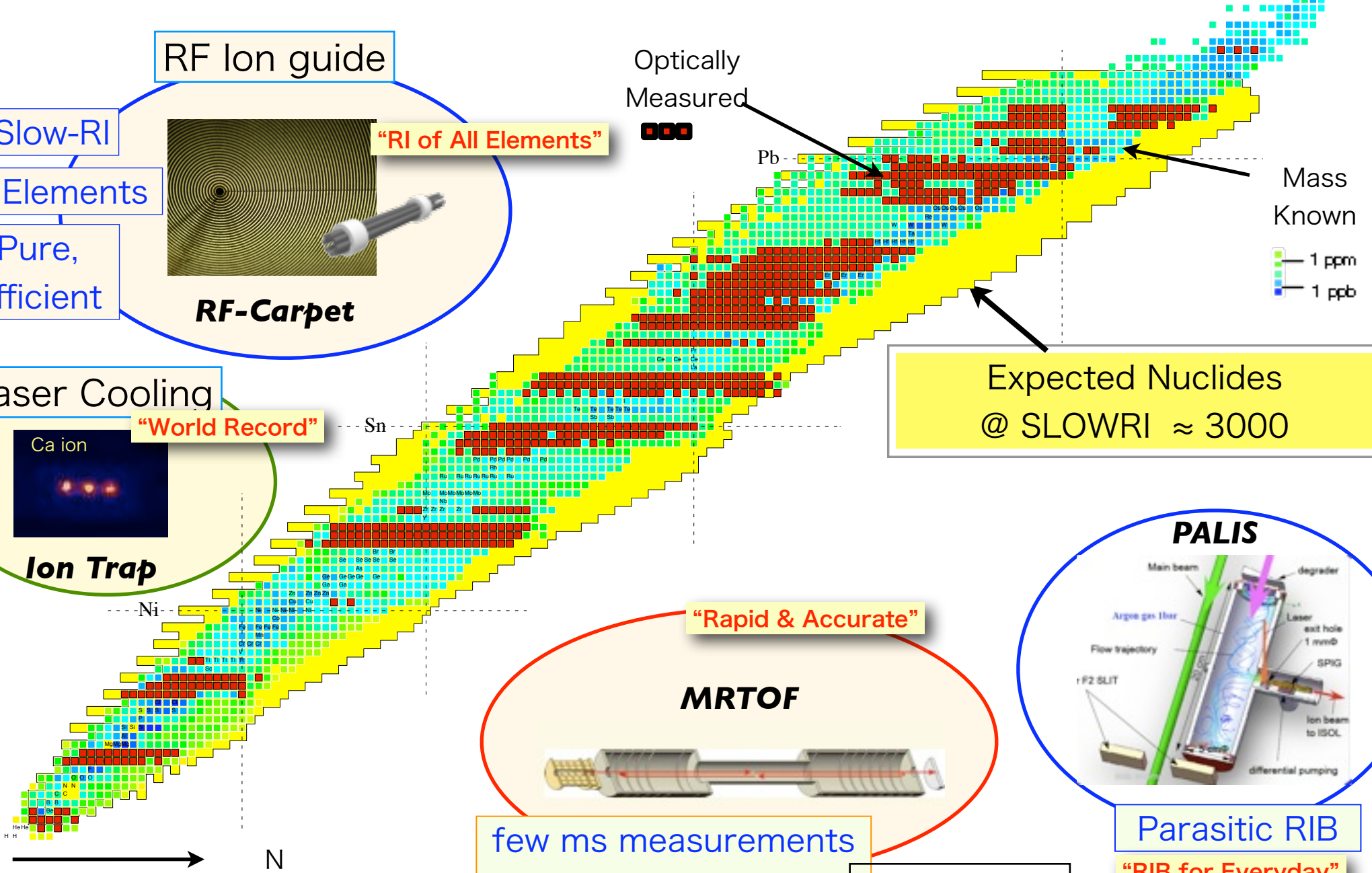
"RI of All Elements"

RF-Carpet

Laser Cooling

"World Record"

Ion Trap



Expected Nuclides @ SLOWRI ≈ 3000

"Rapid & Accurate"

MRTOF

few ms measurements

R_m≈1,000,000

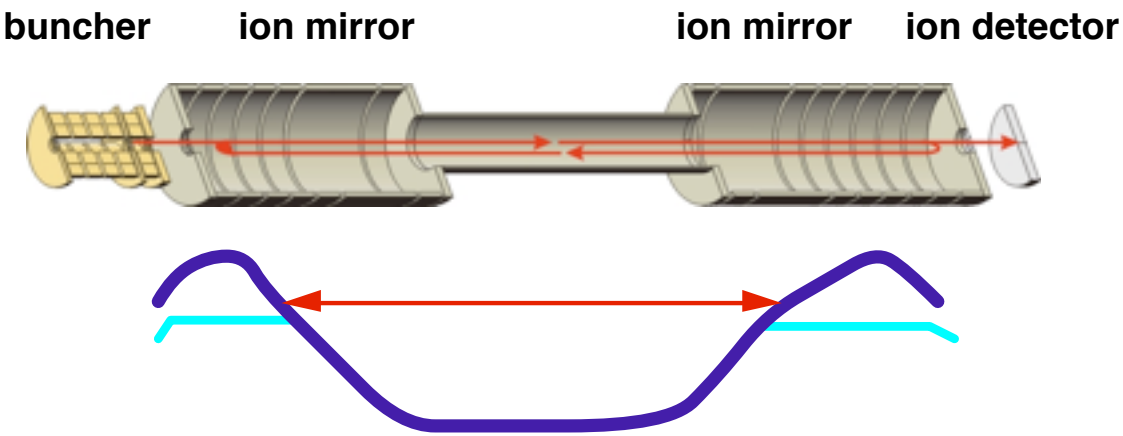
δ m/m≈10^{-7}

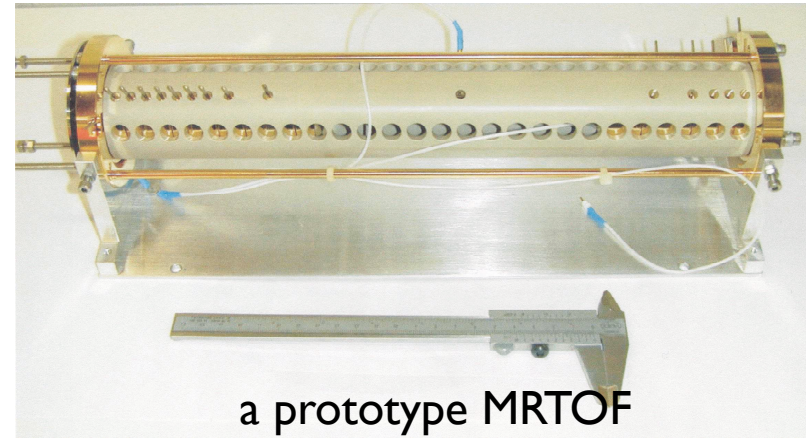
PALIS

Parasitic RIB

"RIB for Everyday"

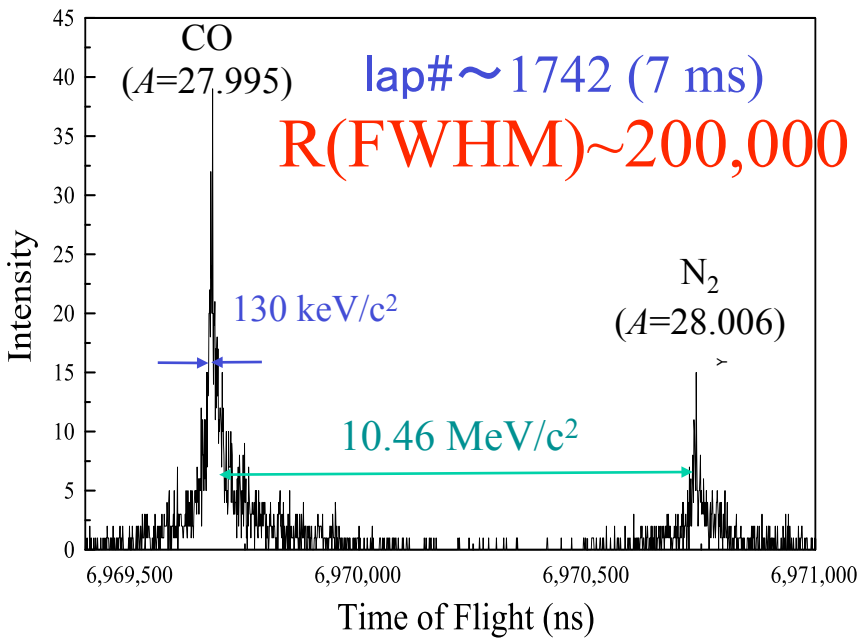
MRTOF Mass Spectrograph

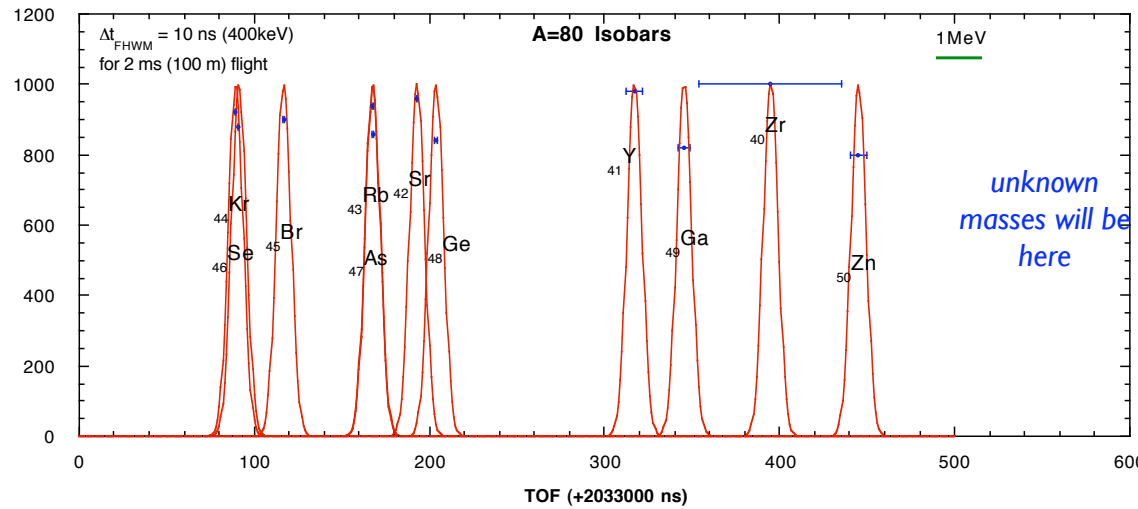




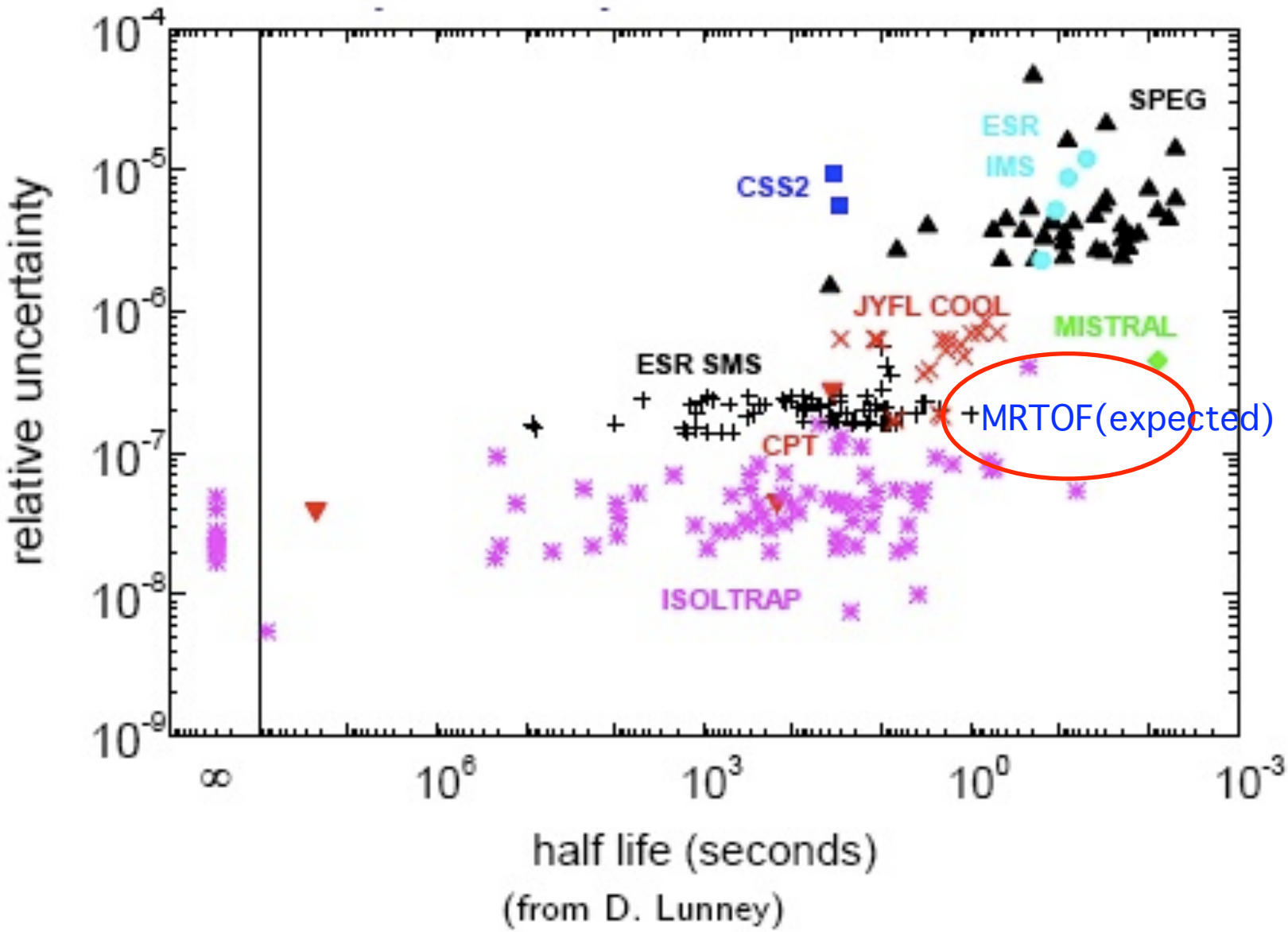
- All isobars are measured (simultaneously) in one spectrum.
- No scan is needed, all particles contribute to statistics.
- $\Delta M \sim 10$ keV/c^2 is feasible in 2 ms cycle.

Simple device but advantage to Penning Trap for short-lived nuclei





mass uncertainty and half-life

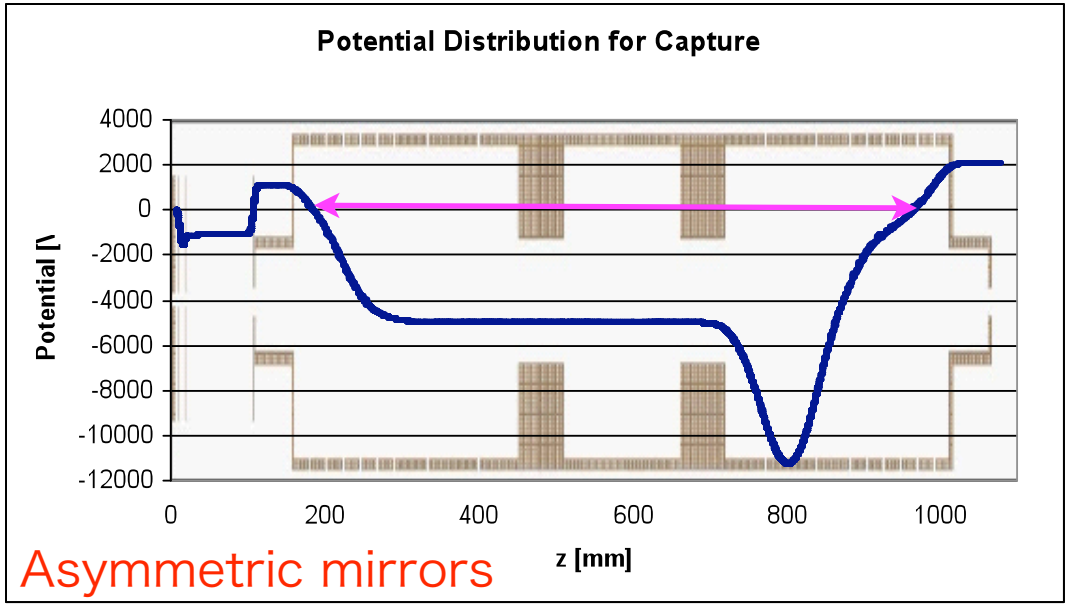


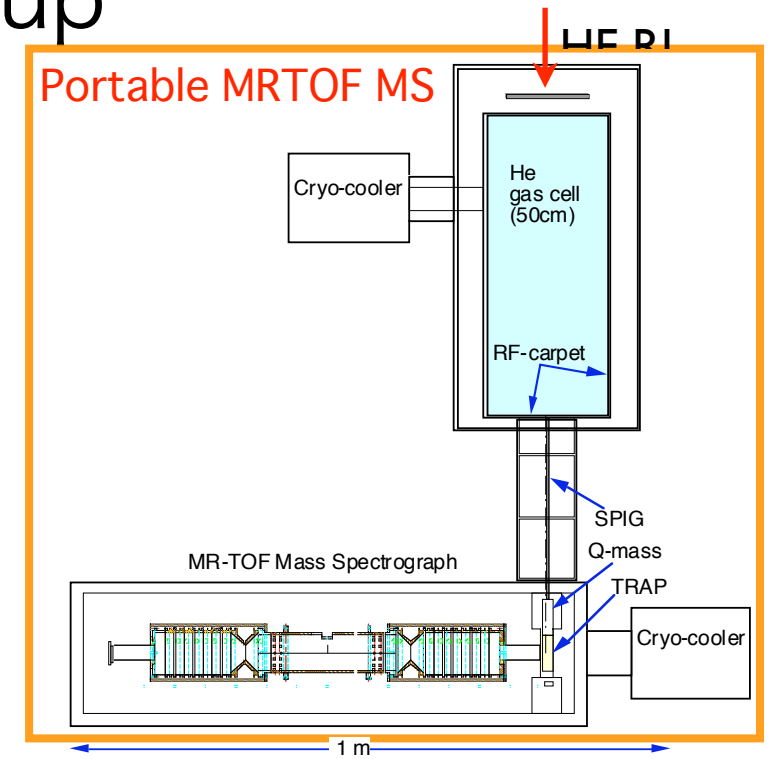
(from D. Lunney)

new MRTOF setup

MRP ≈ 2,500,000 (opt. lim.)

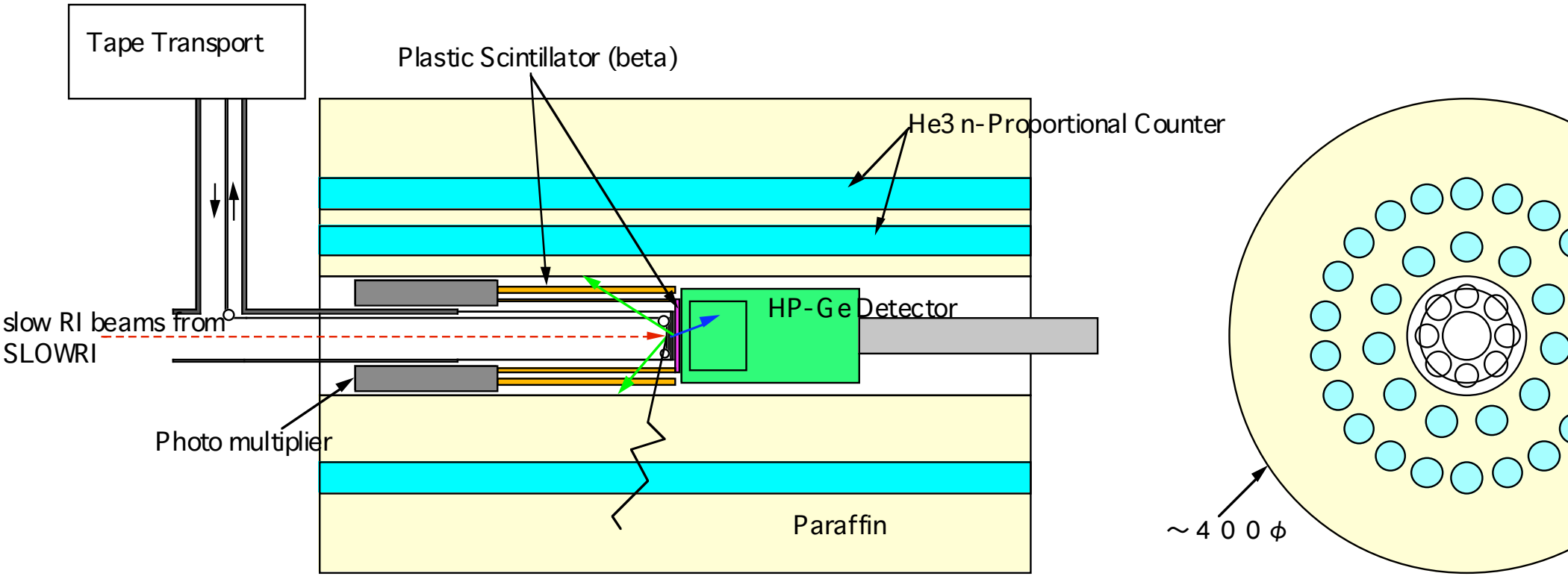
≈ 1,000,000 (practical)





BeGan (βγn counter)

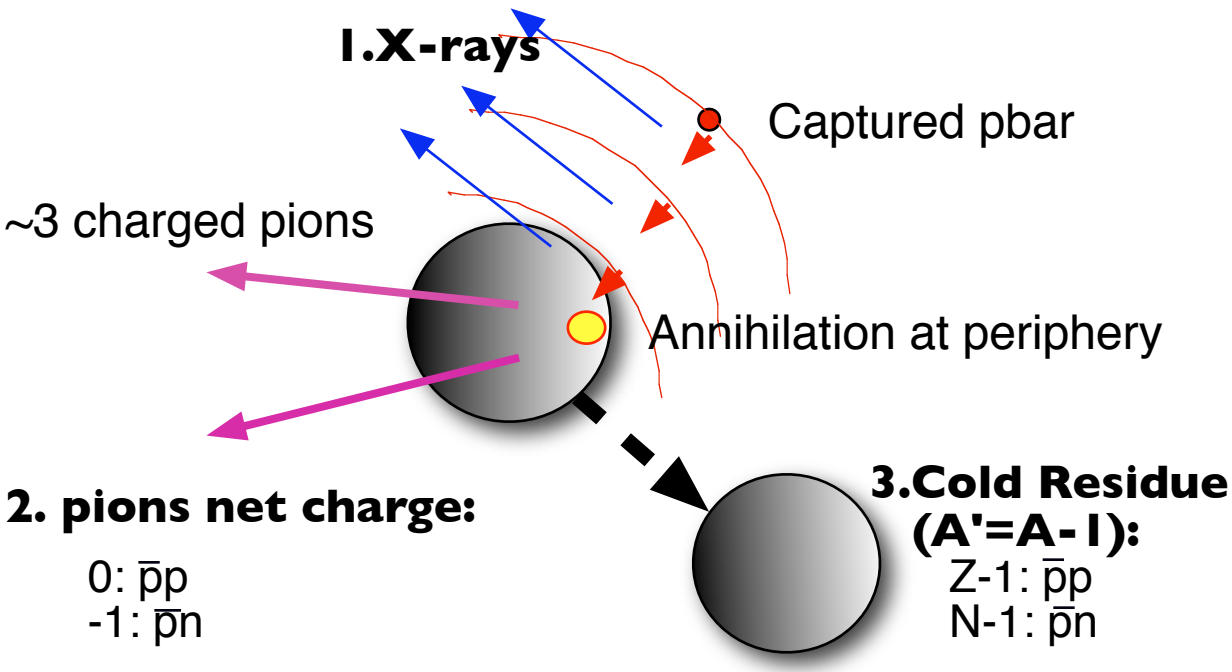
$T_{1/2}$, Q_β, Branching Ratio measurements for pure RI at low background



plan

absolute efficiency: β 90%, γ 5%@1MeV, n 40%

Antiprotonic radioactive atoms (Exo+pbar)



A new probe for nuclear structure study of unstable nuclei

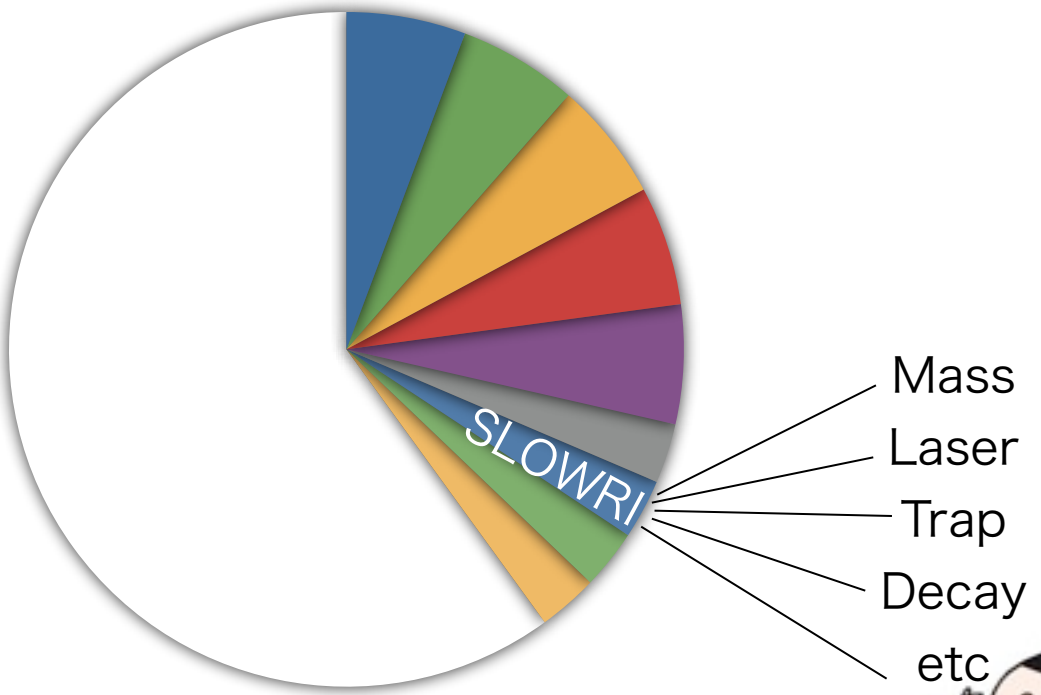
*** annihilation at $\rho = 0.001 \sim 0.05\rho_0$**
*** pbar distinguishes p and n**

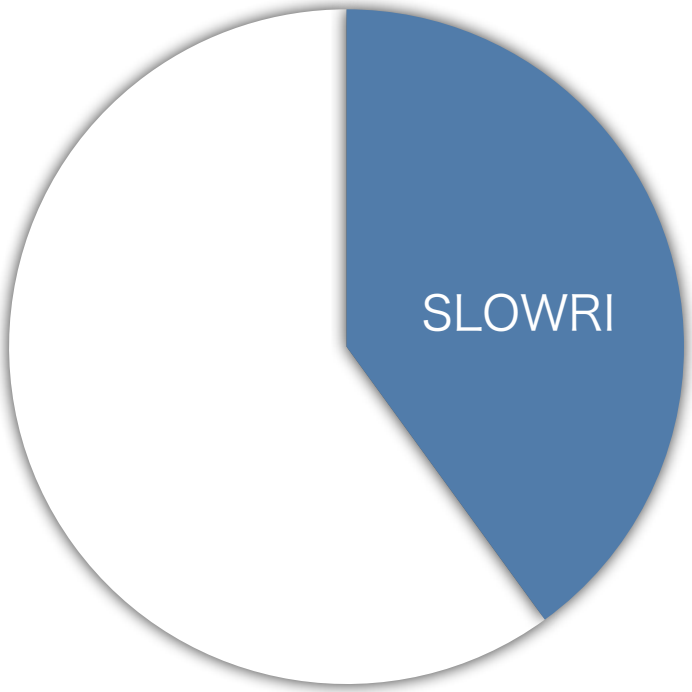
physical quantity	***observable***	***method***	***for RIB****	***previous works for stable nuclei***
nuclear size	X-ray (min. n,l)		?	Trzcinska et al, PRL87(2001) 82501
p,n abundance at nuclear surface	pion net charge	calorimetric		Bugg et al, bubble chamber exp. for C,Ti,Ta,Pb. PRL31(1973)475
		statistical	O	
	cold residue	gamma-ray		Jastrebski et al, Nucl. Phys A558(1993)405c
		recoil momentum Pl	O	
surface nucleon's momentum	cold residue	recoil momentum	?	

* *radioactive nuclei require efficient detection methods*

Available Beam Time

RIBF





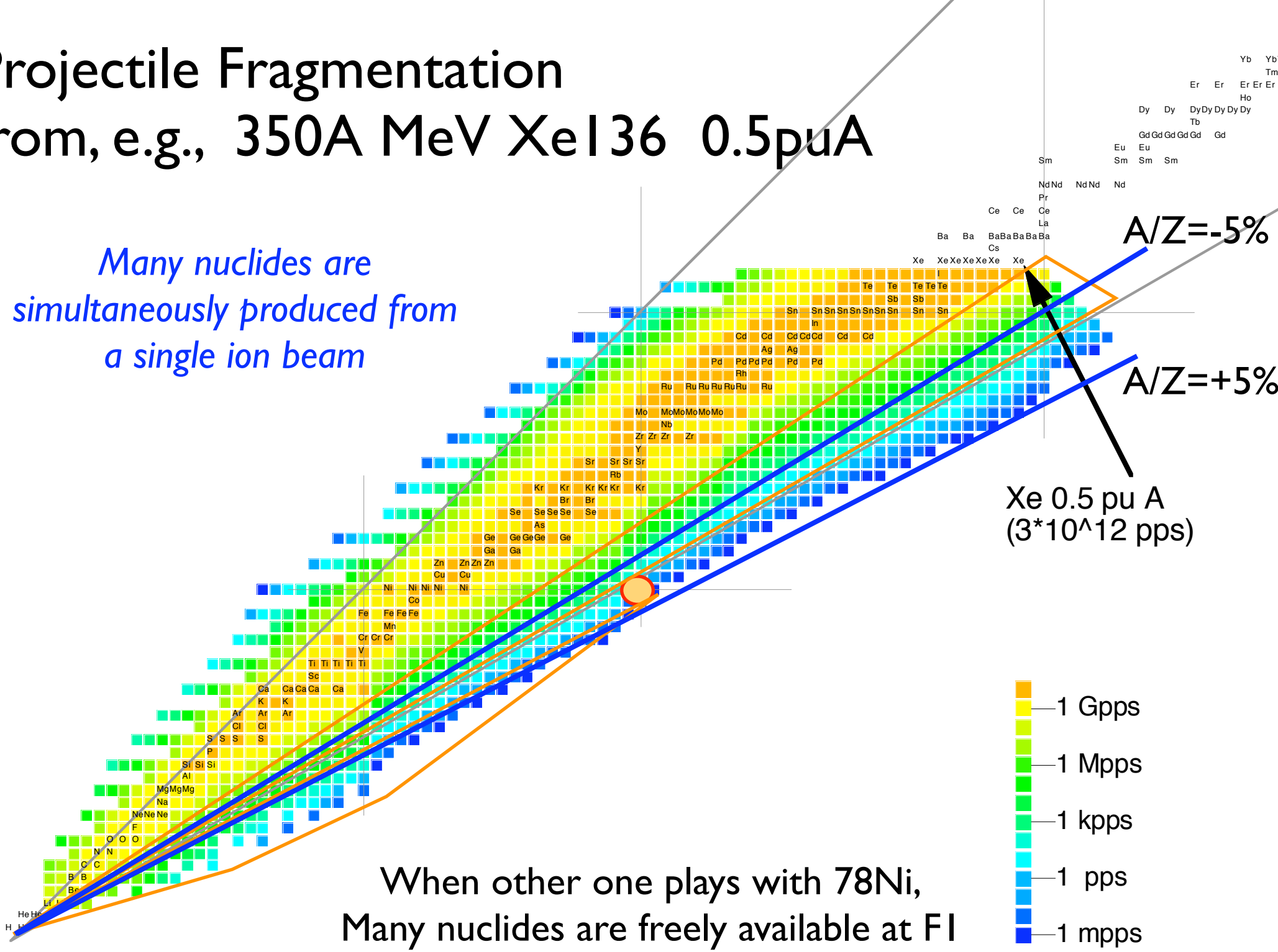
5 months/y

2 weeks/y for SLOWRI ?

5 mon./y for SLOW

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

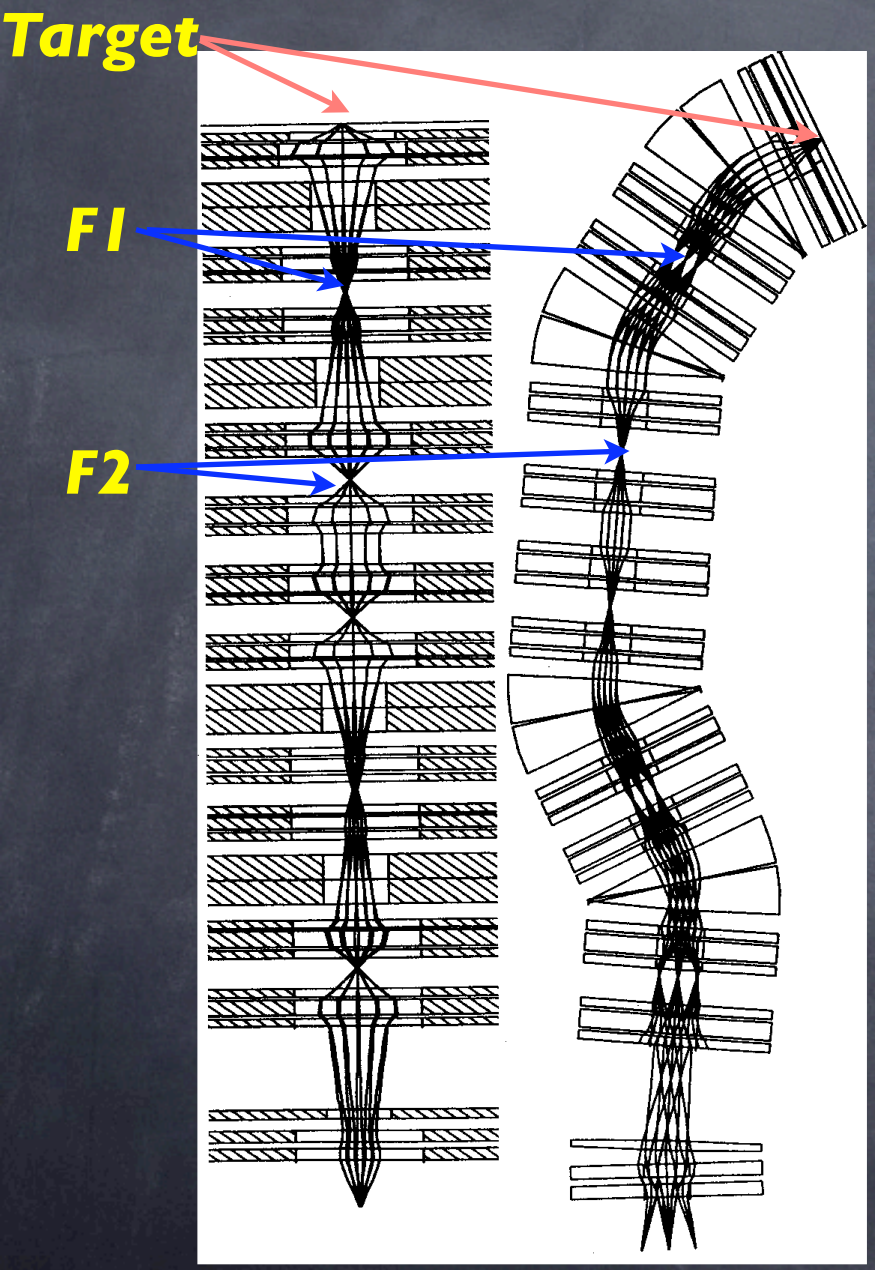
Many nuclides are simultaneously produced from a single ion beam

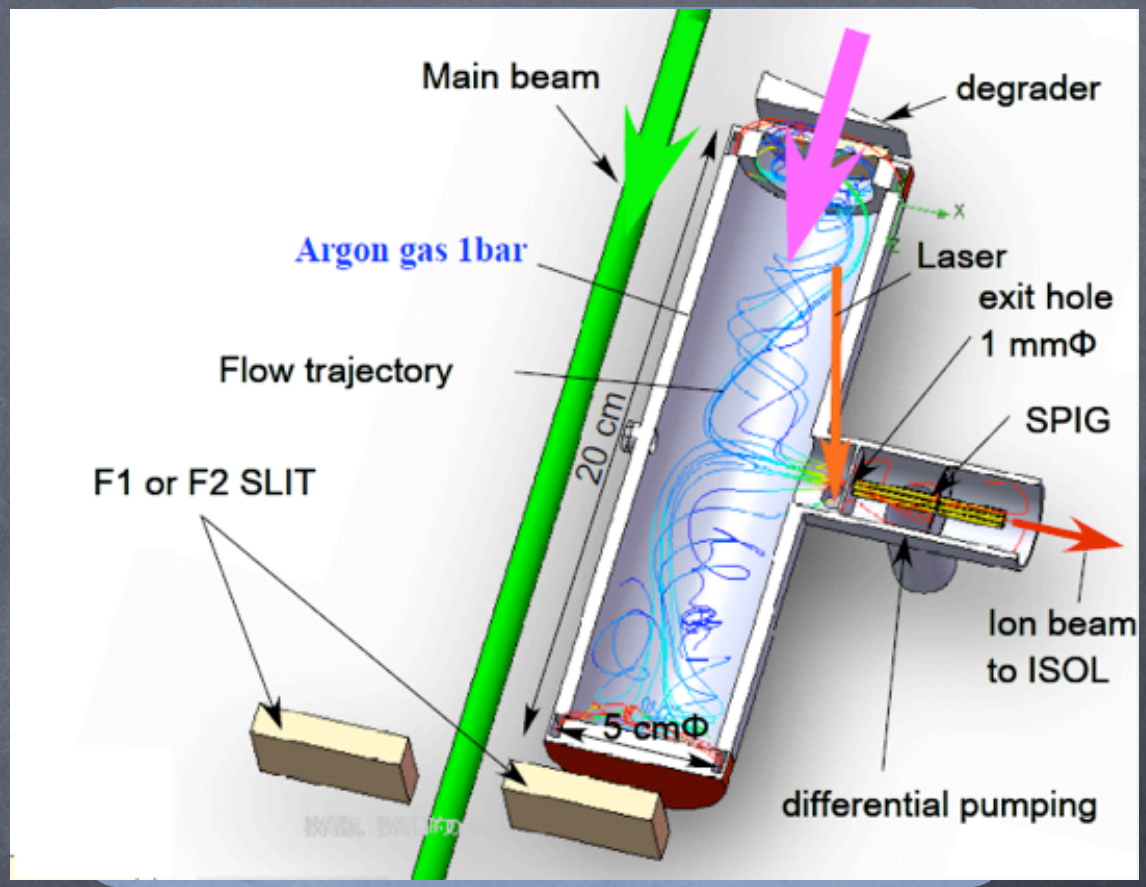


When other one plays with 78Ni,
Many nuclides are freely available at F1

PALIS

PArasitic slow RI-beam with gas catcher Laser Ion Source





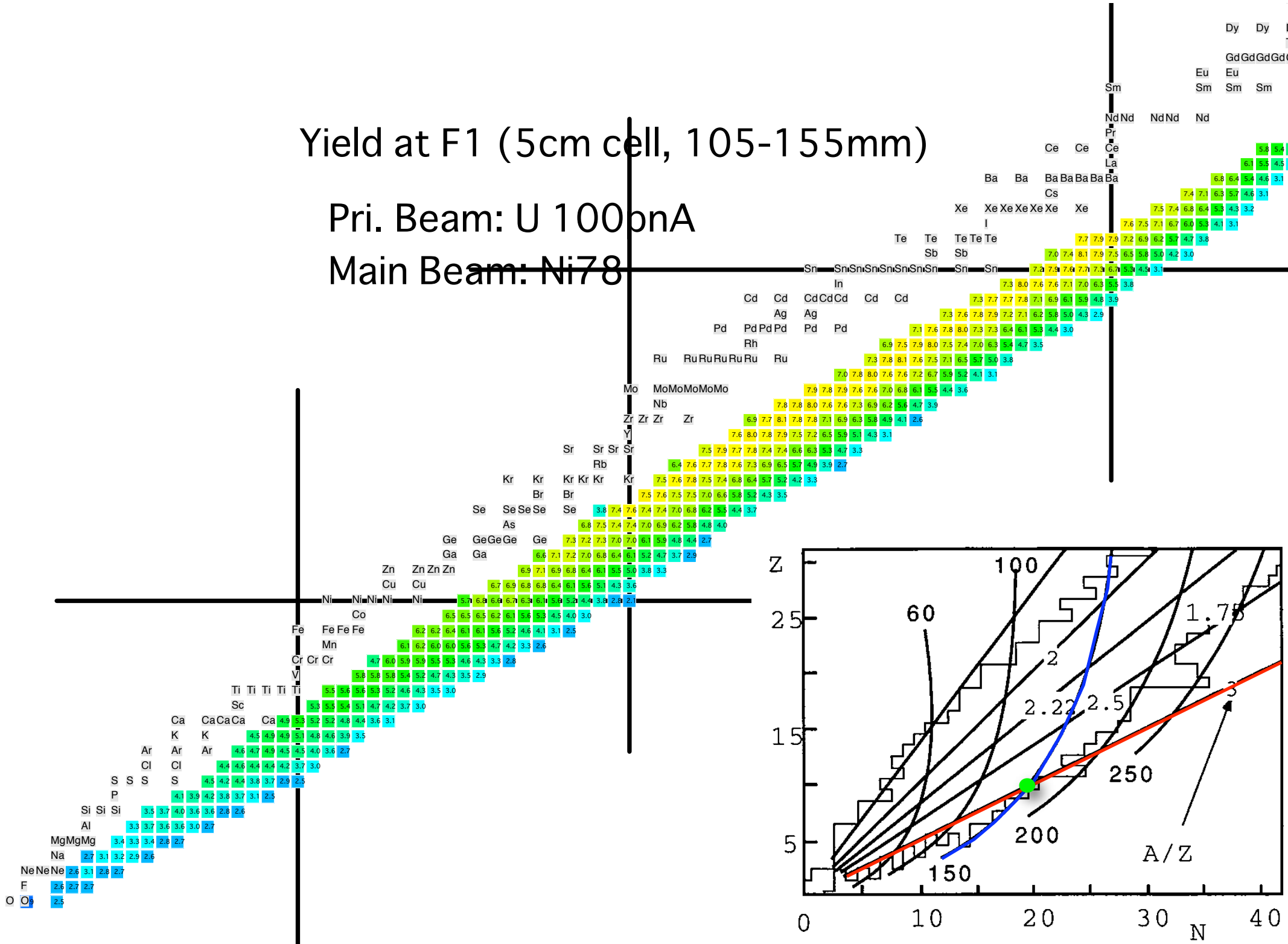
1) Stop & Neutralize in Ar (1 bar)
2) Extract by Gas Flow
3) Re-Ionize at Exit and SPIG

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

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

Pri. Beam: U 100pnA

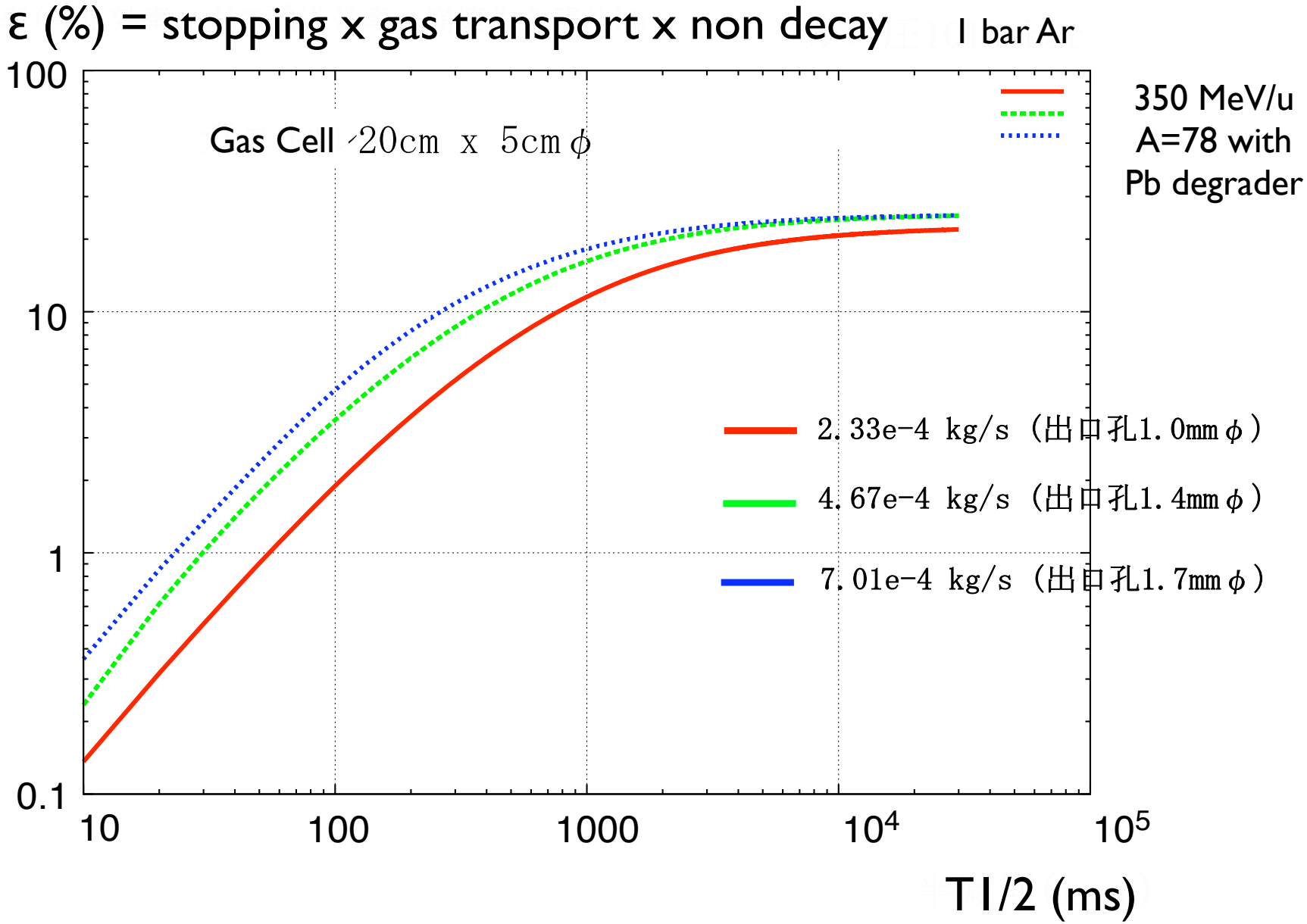
Main Beam: Ni78



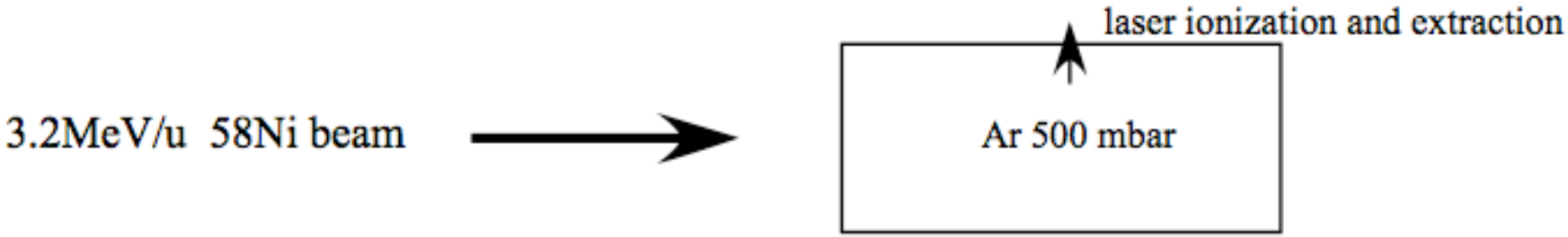
Expected efficiency

(beside laser ionization)

ε (%) = stopping x gas transport x non decay

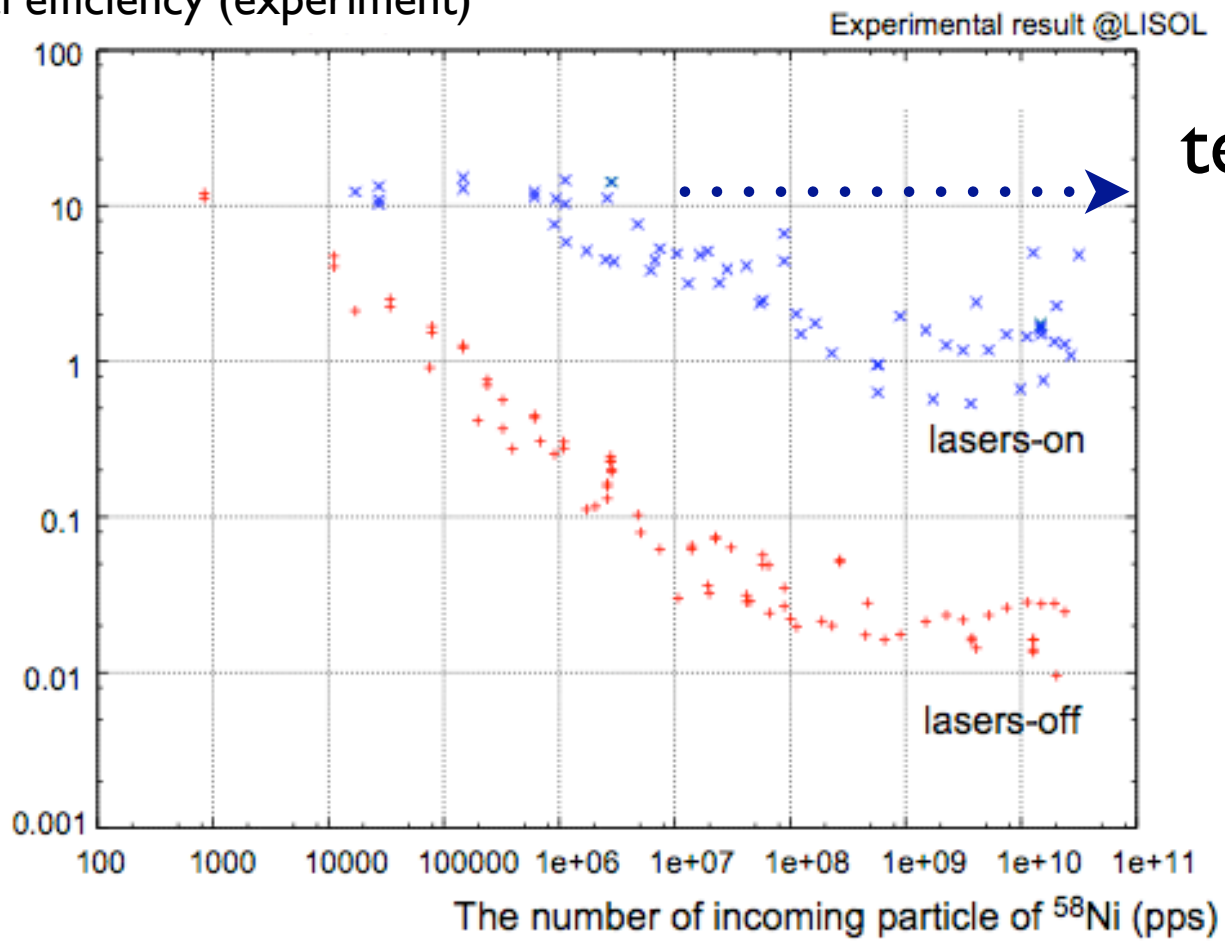


Experimental result @ K.U.Leuven LISOL



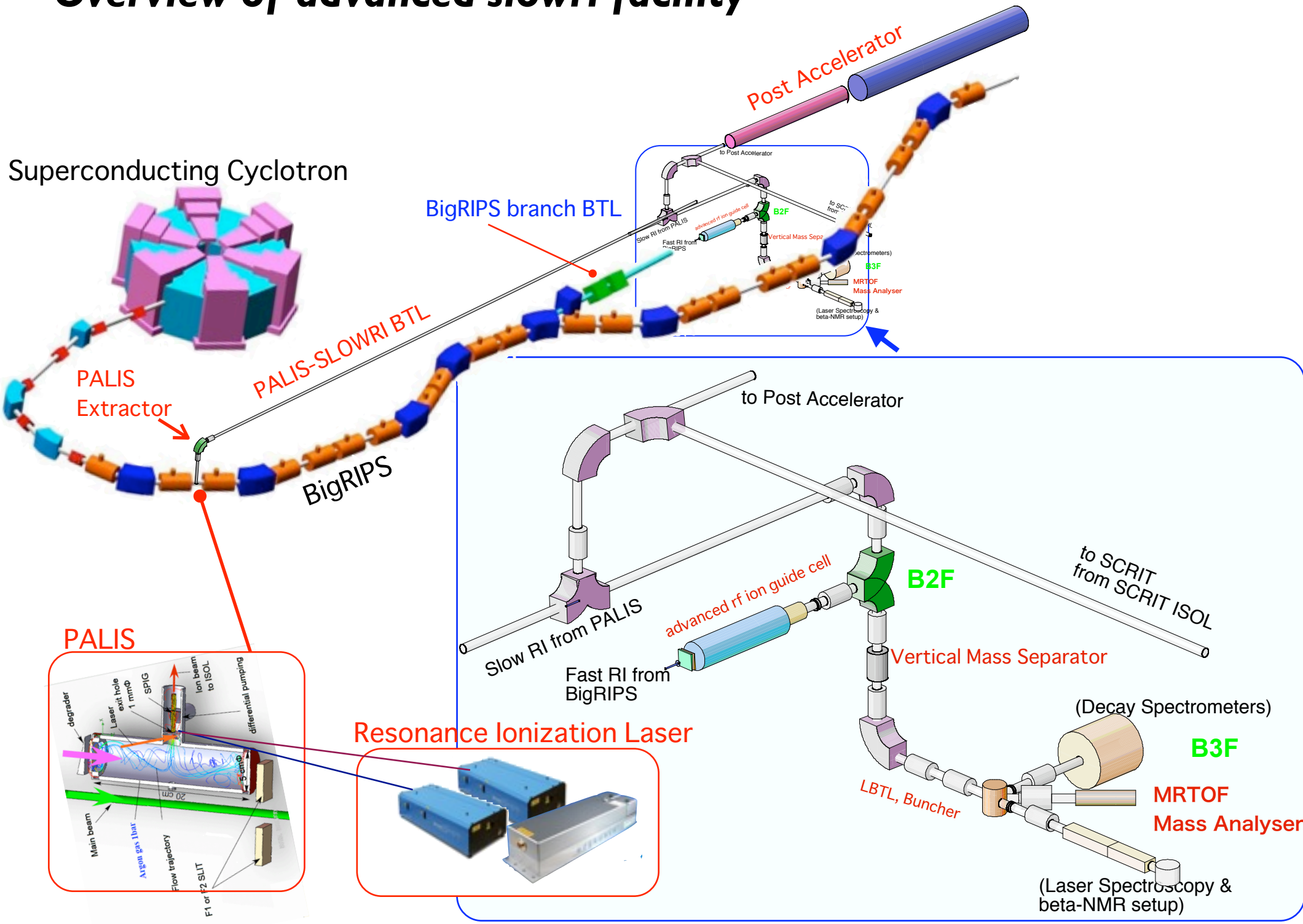
全効率　＝[質量分離後の58Niの収量]/[ガスセルに入射した58Niの収量]

total efficiency (experiment)



test at Leuven
May 17th

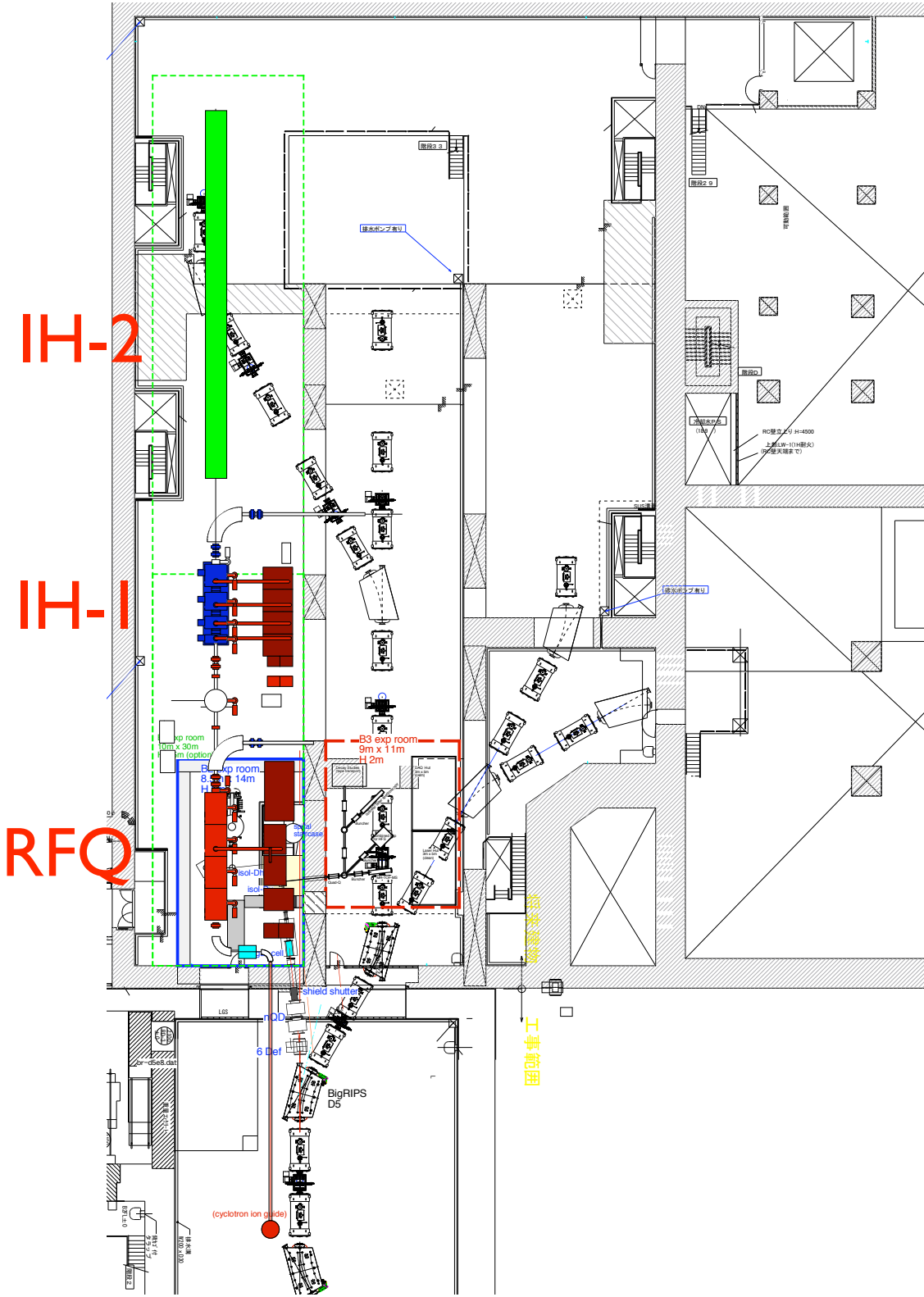
Overview of advanced slowri facility



Post Acceleration

B1 exp. room (10mx60m)

If PARIS provides high intensity slow RI-beam, for everyday post acceleration is feasible.



Pros & Cons of RF-IGISOL & PARIS

	RF-IGISOL	PARIS
universality	◎	△
high intensity	△	◎
short-lived	◎	△
total efficiency	○	△
purity	○	◎
availability	×	◎

◎ > ○ > △ > ×

collaborators

- General
  M. Wada, Y.Kanai, T.Kojima, Y.Yamazaki, T.Kubo, A.Yoshida (RIKEN),
  I. Katayama (KEK), S.Ohtani (UEC), K.Noda (NIRS)
- Gas Cell Development
  A.Takamine, P. Schury, M.Wada (RIKEN), V.Varentsov(Radium)
- HFS spectroscopy of trapped ions
  K.Okada (Sophia), A.Takamine, M.Wada, P.Schury (RIKEN)
  H.A.Schuessler (TAMU)
- Laser spectroscopy of trapped ions
  A.Takamine, M.Wada, Y.Matsuo, T.Furukawa (RIKEN)
  K.Okada (Sophia), H.A.Schuessler (TAMU)
- MRTOF mass spectrograph
  P.Schury, M.Wada, A.Takamine (RIKEN)
  H.Wollnik (Giessen), S.Schepnov (SRL)
- Collinear laser spectroscopy
  V.Lioubimov, H.A.Schuessler (TAMU), H.Iimura (JAEA),
  A.Takamine, M.Wada (RIKEN)
- beta-NMR, $\beta\gamma$n- spectroscopy
  A.Yoshimi, S.Nishimura, H. Ueno, M.Wada (RIKEN)
- Garbage Collection setup (PALIS)
  T.Sonoda, A. Takamine, M.Wada, Y. Matsuo, T. Furukawa (RIKEN), H. Tomita (Nagoya
  T. Shinozuka, T. Wakui (Sendai), Y. Kudryavtsev, P. Van Duppen, M. Huyse (Leuvan)
  S. Jeong, H. Ishiyama, Y. Watanabe, N. Imai, Y. Hirayama, H. Miyatake (KEK)