

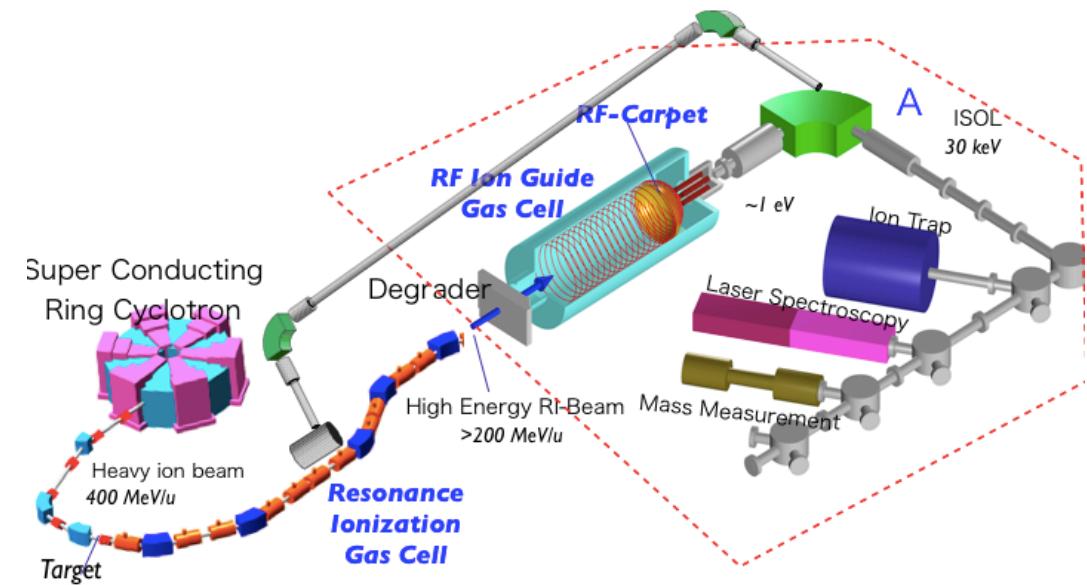
18 Mar. 2011
29 May 2012



SLOWRI 2.0

Michiharu Wada
SLOWRI Team, RNC, RIKEN

- Motivation
- Facility
- Experiment
Day 0, 1, 2
- F.A. Critics



The Mission of RIBF



独立行政法人 理化学研究所

仁科加速器研究センター

■ ホーム ■ 交通案内 ■ このサイトについて

Japanese | English

仁科センター紹介

研究施設紹介

研究

ギャラリー・パンフレット

リンク

研究会・セミナー

RIBF利用者へ

理研RIBF計画の使命

理研RIBF計画の使命は現在の世界水準を遙かに凌ぐRIビーム生成能力（RIビーム発生施設）と革新的な実験設備（RIビーム実験施設）によって

- 1) 究極の原子核モデルの構築、
- 2) 元素の起源の解明に挑戦。
さらに
- 3) 新しい産業利用を開拓する。

“Constructing an Ultimate Nuclear Model”

“Try to Clarify the Origin of Elements”

“Explore new Industrial Applications”

What is Ultimate Nuclear Model?

- A nuclear model that describes all properties of all atomic nuclei.

***We are very much behind the goal.
Not sure whether it is possible or not.***

“An atomic nucleus is an elephant”

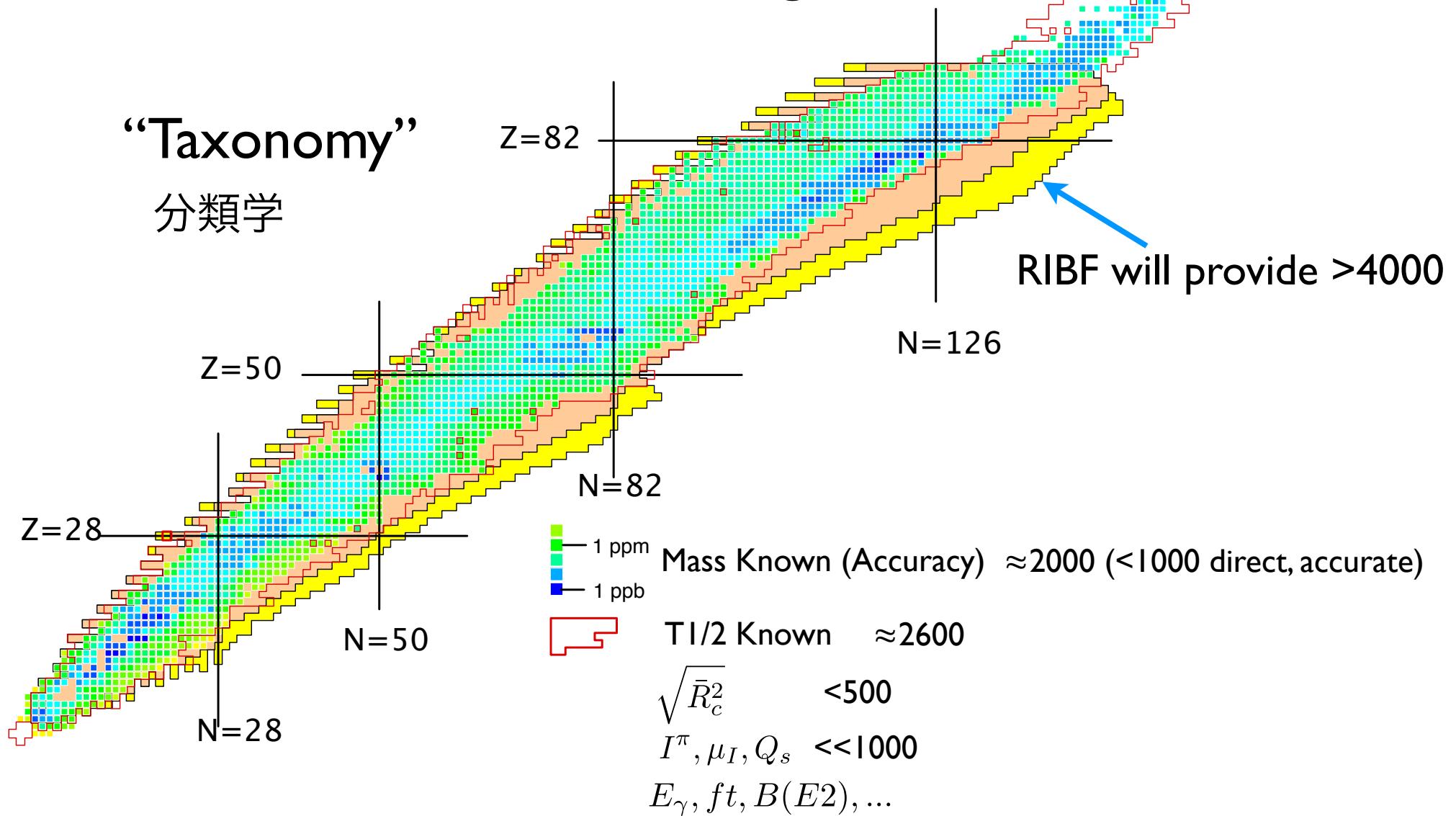
Jacek Dobaczewski



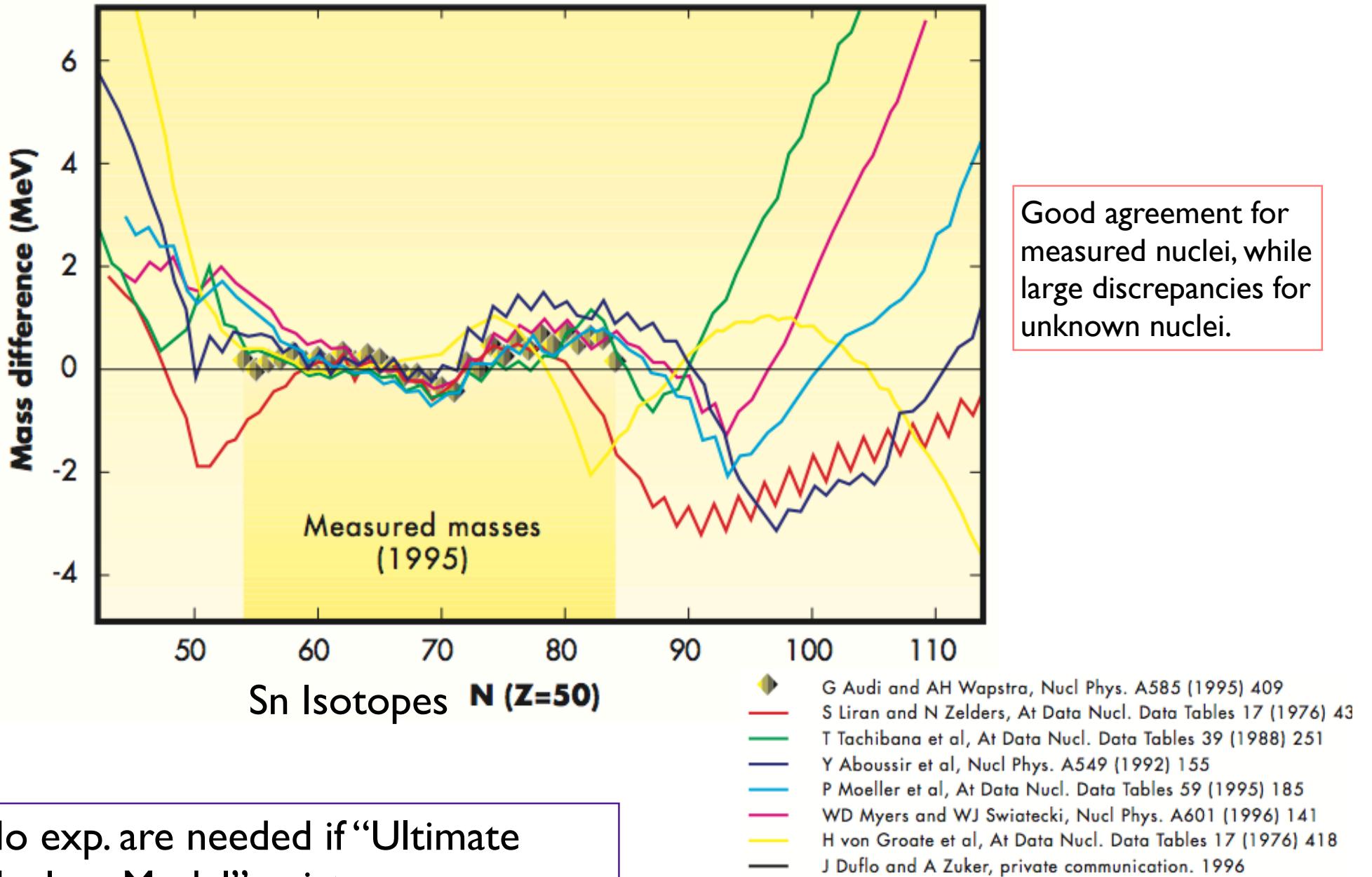
no way to describe an atomic nucleus with a few parameters

1st things to do:

Accumulate more knowledge on atomic nuclei



Mass Prediction by different nuclear models



Mass predictions for Cs isotopes

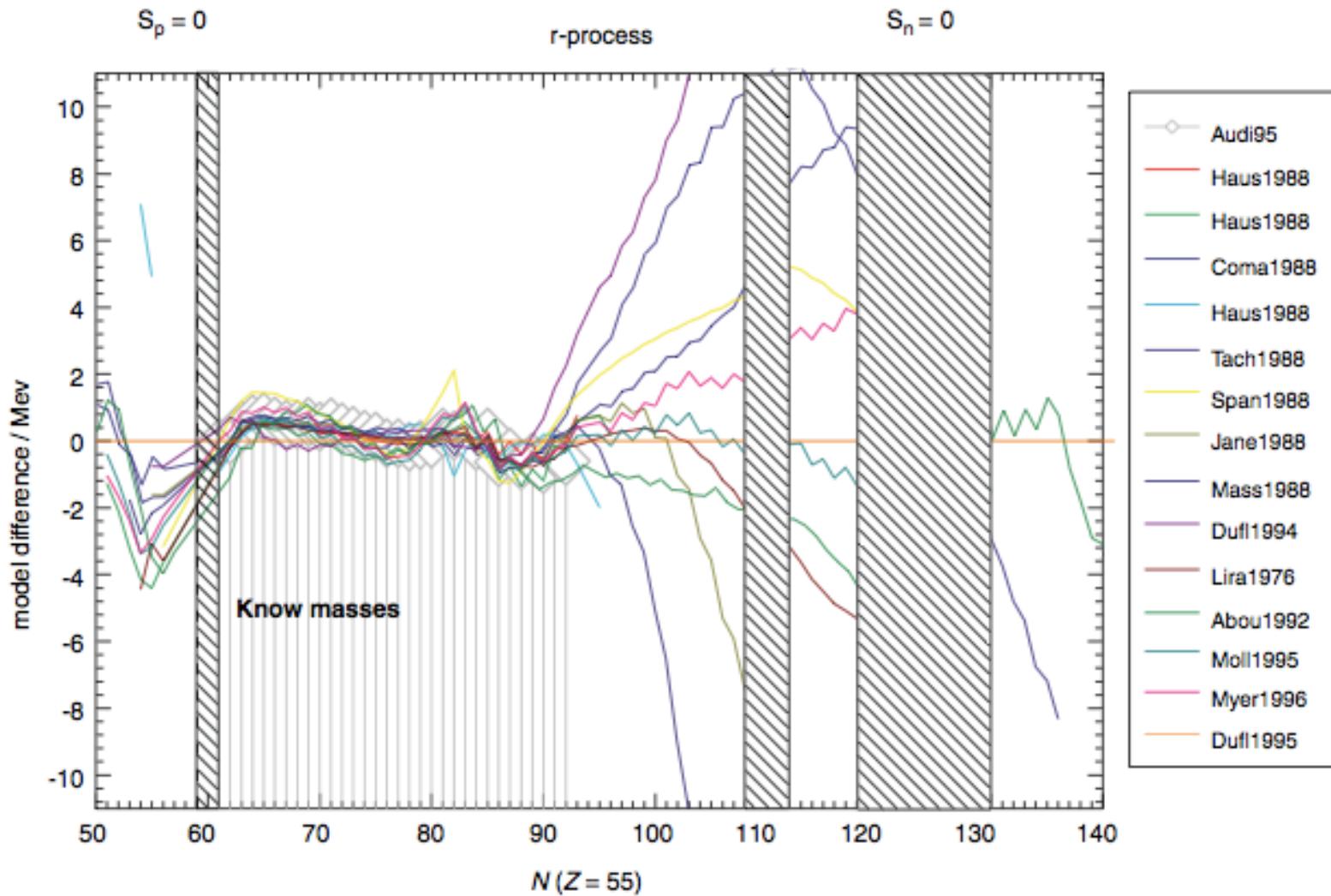


Fig. 42. (Color) Differences in mass predictions of various theoretical mass models and experimental data to predictions of the Duflo-Zucker mass model [312] as a function of N for cesium isotopes (Cs , $Z = 55$). Since the model parameters are adjusted to measured masses, the agreement is very good where masses are known. The used mass models listed in the legend are from [287,301,302,305,312–321] or private communication. The possible region where the proton S_p (around $N = 60$) and neutron S_n (around $N = 125$) separation energy gets zero is indicated. The rapid neutron capture process path could cross between $N = 108$ and 112 , depending on the astrophysical conditions.

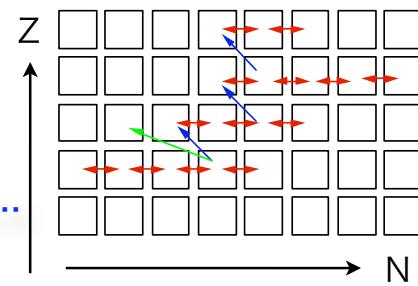
“Try to Clarify the Origin of Elements”

“Try to Clarify the Origin of Elements”

Explosive n -capture process

reaction of unstable nuclei

Mass, Life, Branching r., ...
 $S_n, T_{1/2}, P_n \quad \sigma_n$



$(n, \gamma) \leftrightarrow (\gamma, n)$ Equilibrium

$$\frac{Y(Z, A+1)}{Y(Z, A)} \propto \rho_n \exp \frac{S_n(Z, A+1)}{kT}$$

“Try to Clarify the Origin of Elements”

Nucleosynthesis in the r-process

JINA

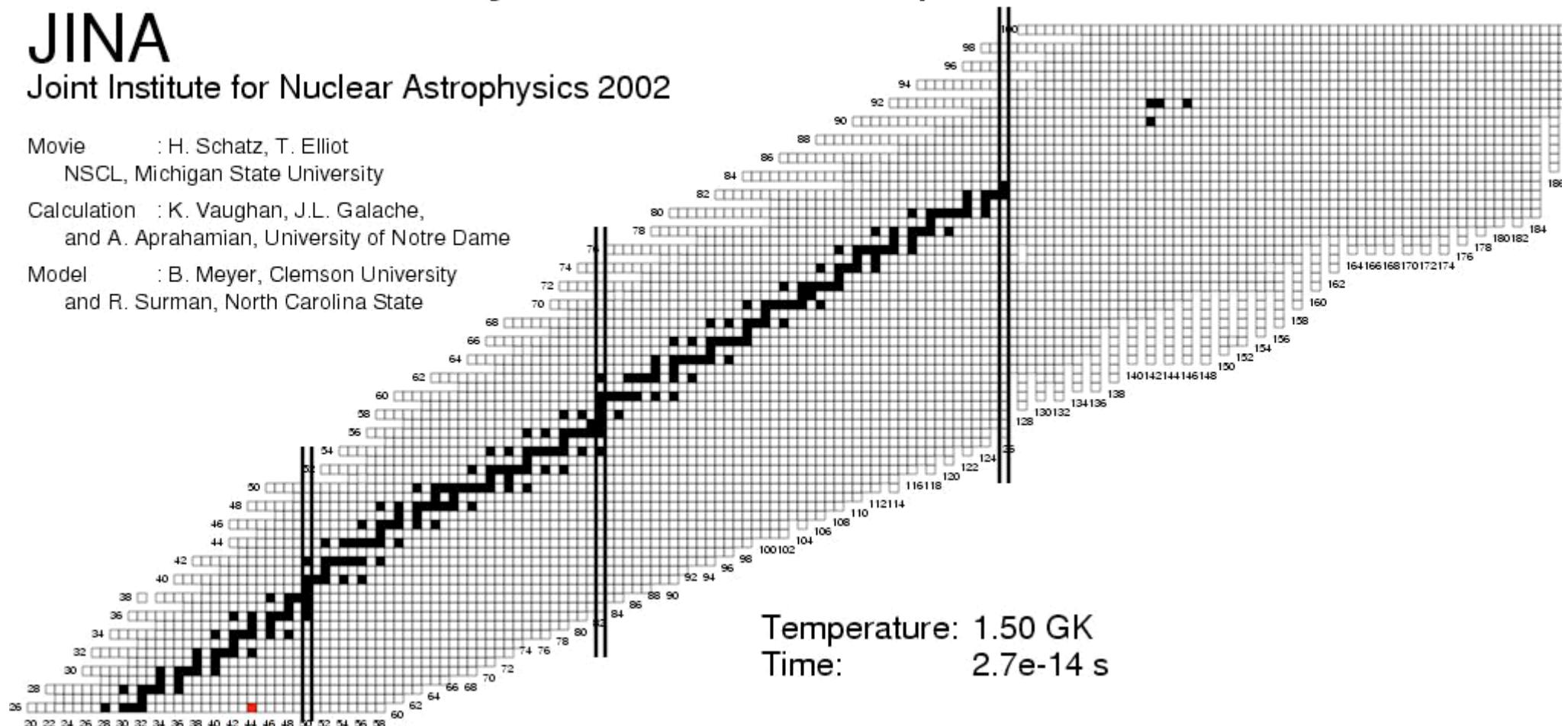
Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliot

NSCL, Michigan State University

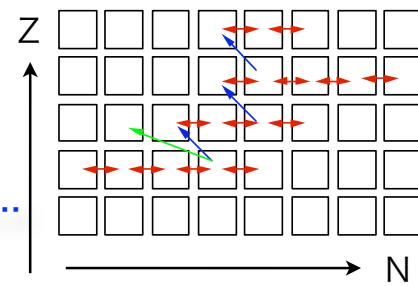
Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State



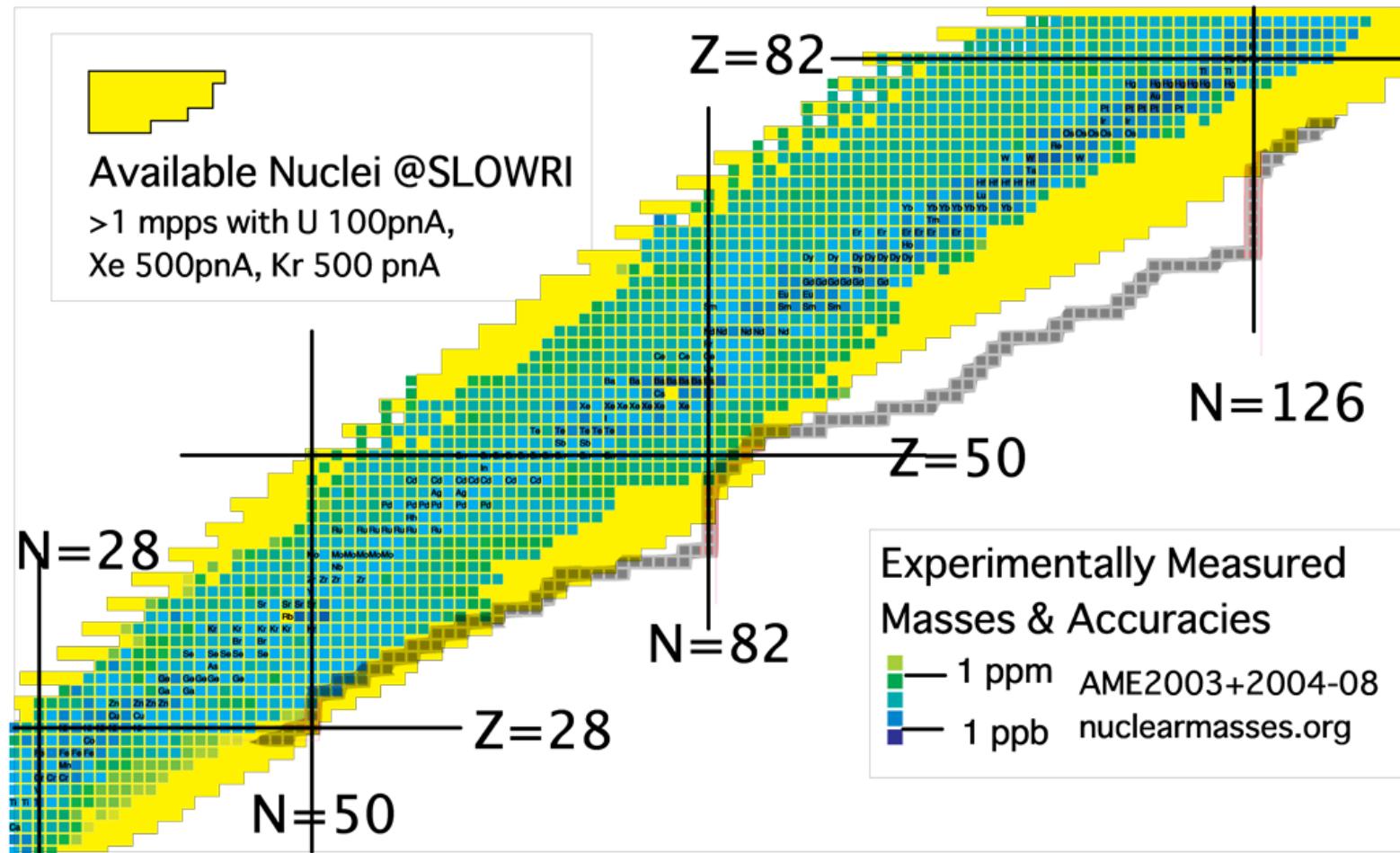
Explosive n-capture process
reaction of unstable nuclei

Mass, Life, Branching r, ...
 $S_n, T_{1/2}, P_n \sigma_n$



$(n, \gamma) \leftrightarrow (\gamma, n)$ Equilibrium

$$\frac{Y(Z, A+1)}{Y(Z, A)} \propto \rho_n \exp \frac{S_n(Z, A+1)}{kT}$$



static properties

Mass measurements

ion traps

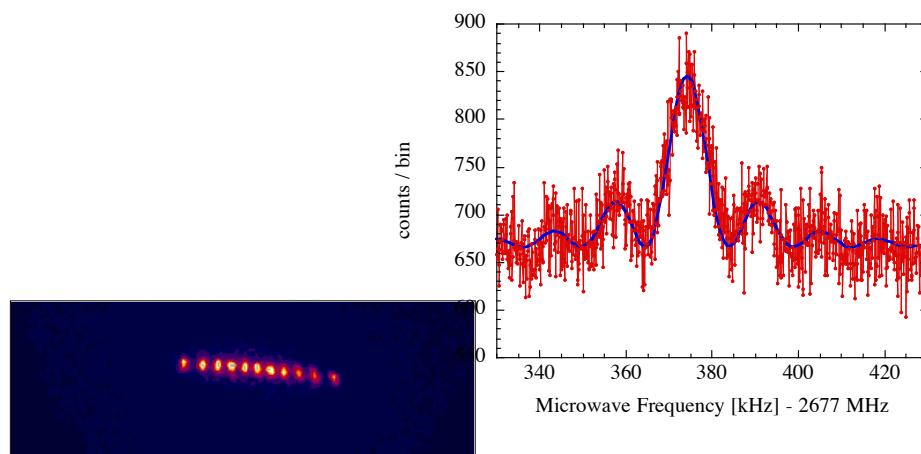
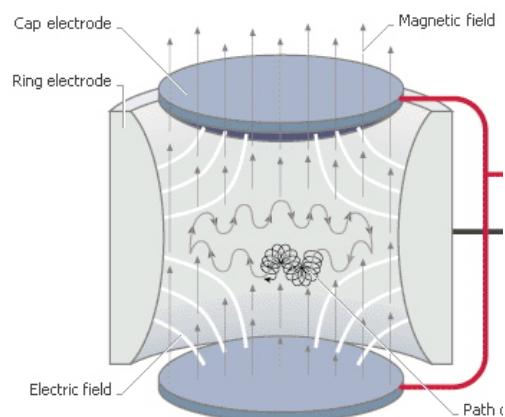
Decay studies

pure, thin source

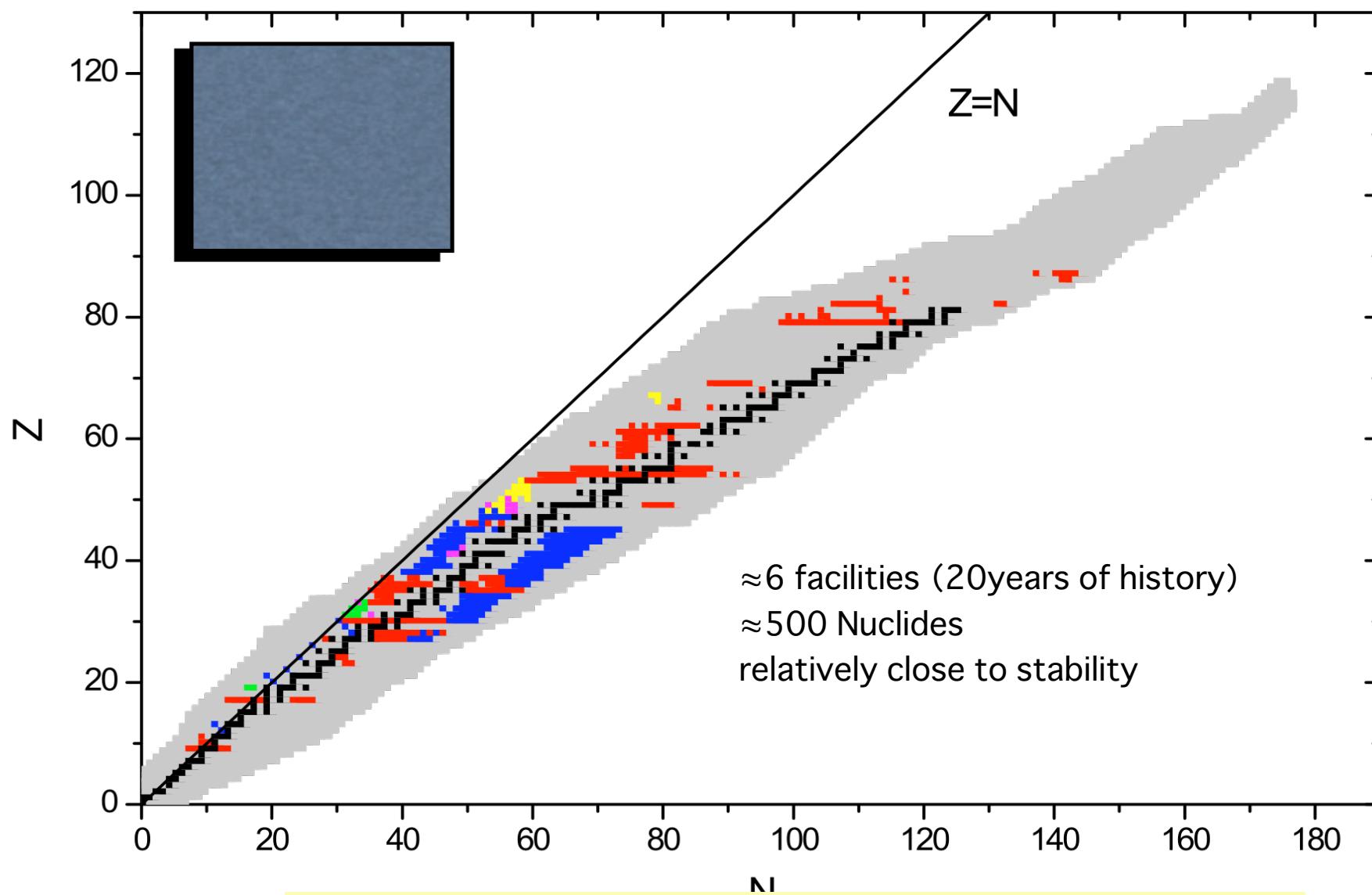
Radii, Spin, Moments, ...

optical spectroscopy

} Slow or Trapped
RI



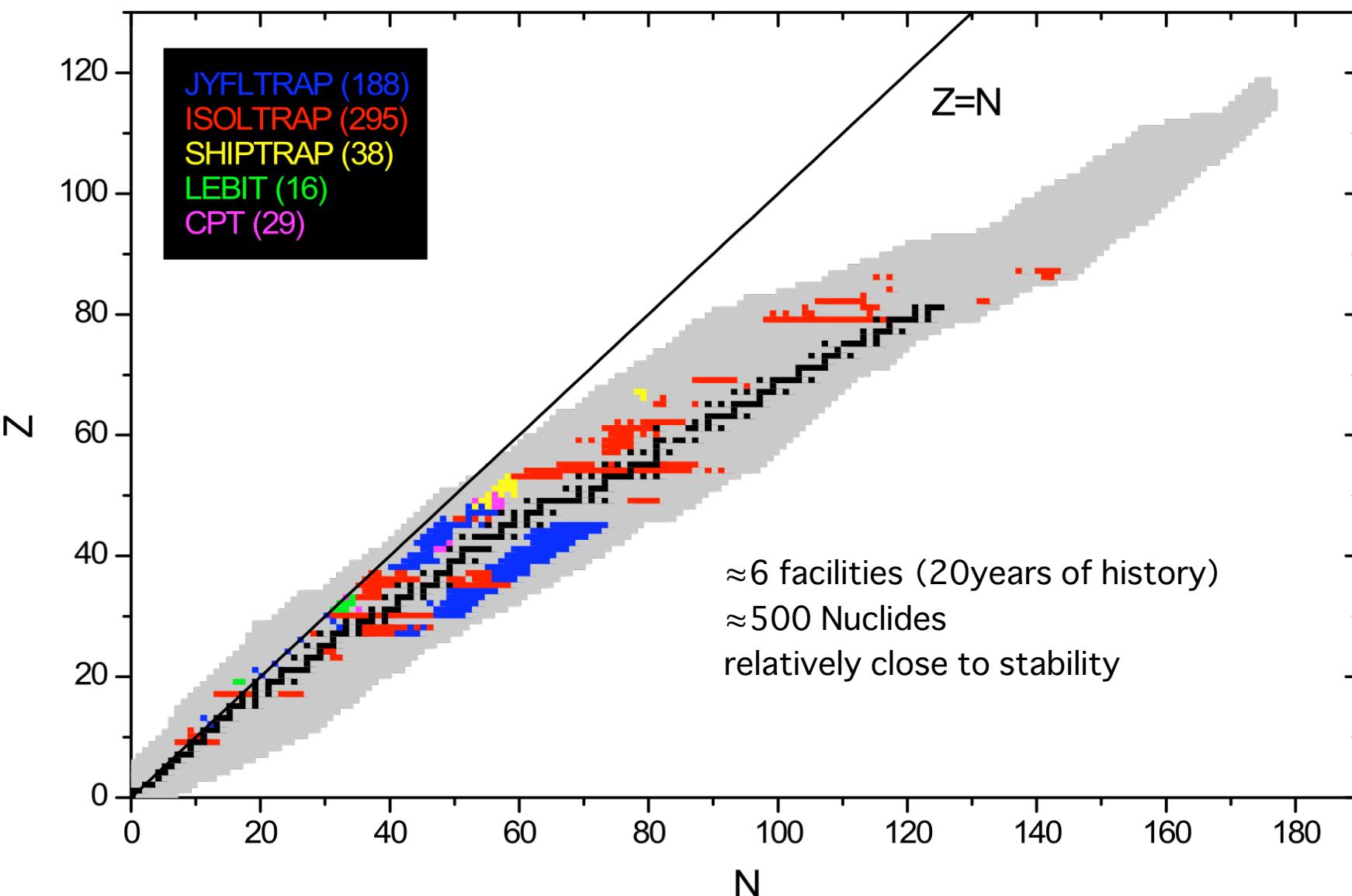
Precision Mass Measurements with Penning Trap Mass Spectrometer



ISOLDE (ISOL) runs out (elements, life-time)

JYFL (IGISOL) 3000 hours/y (relatively close to stability)

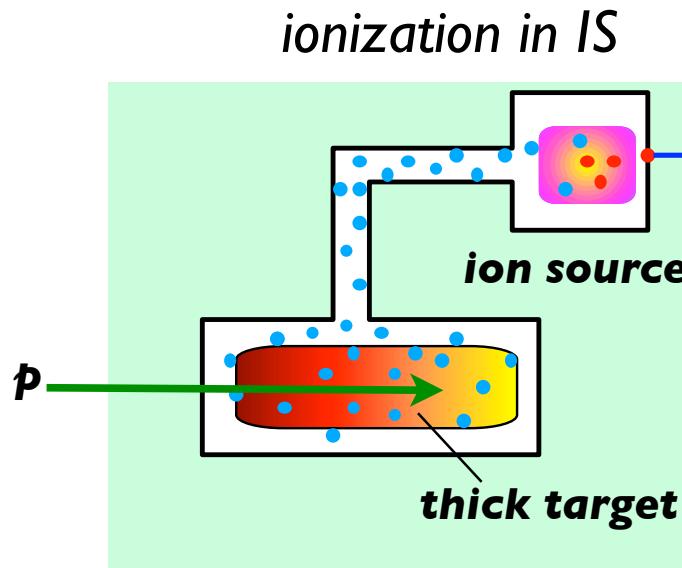
Precision Mass Measurements with Penning Trap Mass Spectrometer



**comprehensive study of RI
since '60s**

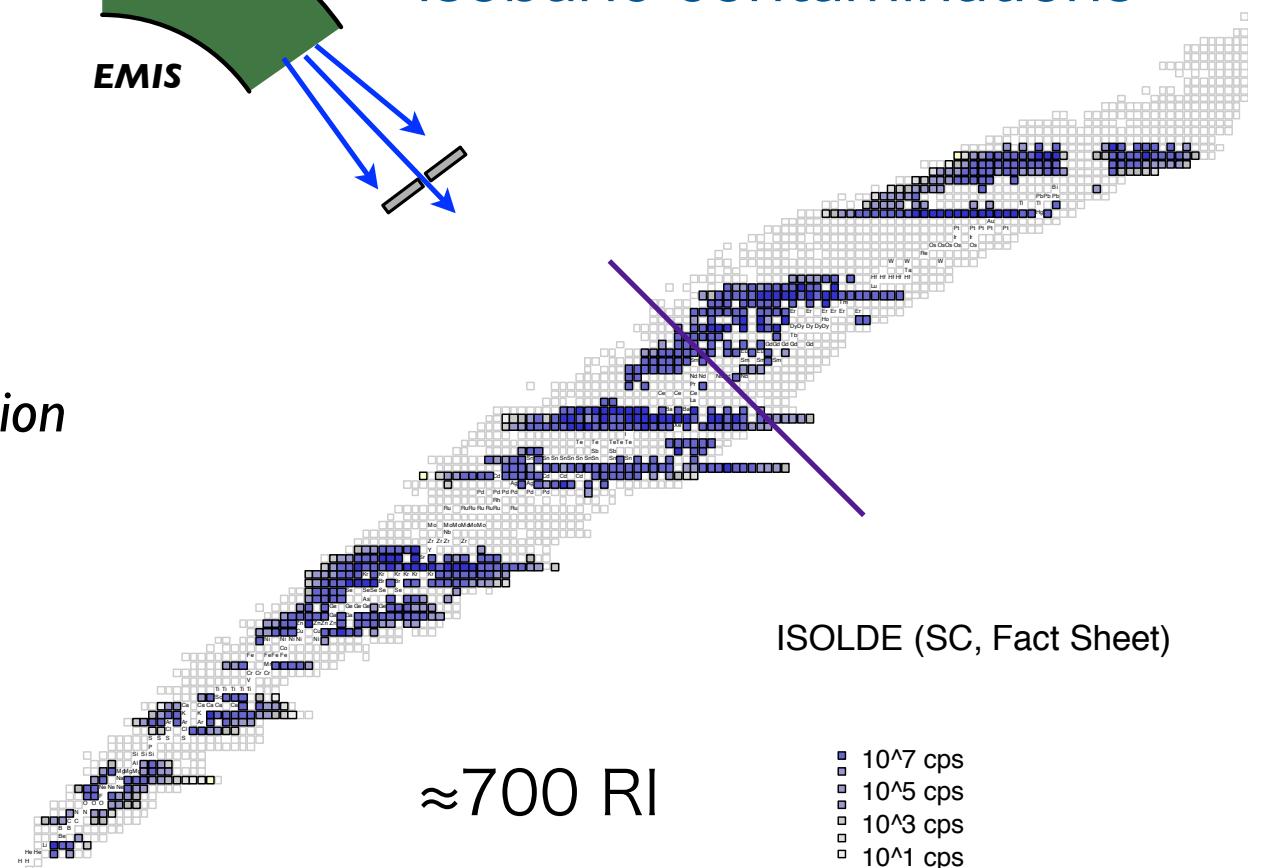
ISOL **ISOLDE, OSIRIS, TRISTAN,
TISOL**

**High Yield, but difficult for
Refractory elements,
Chemically active elements**
Isobaric contaminations



stop in target, diffusion, evaporation

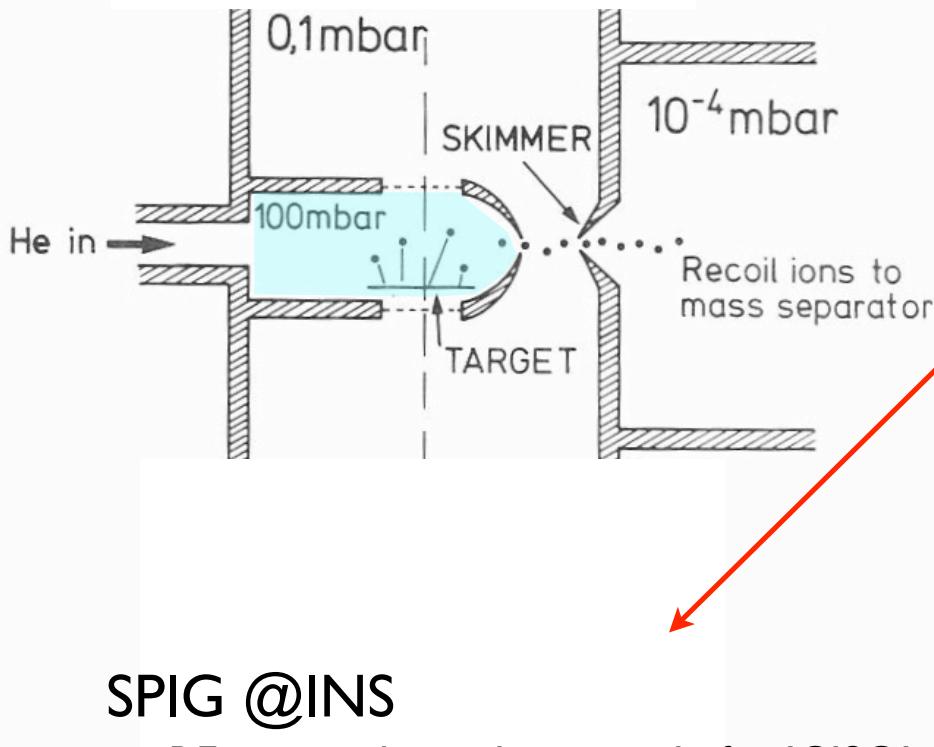
**note: laser ion source
just supports
ionization process,
not in target**



First Break Through: IGISOL @JYFL

J.Arje, K.Valli: NIM 179(1981)533.

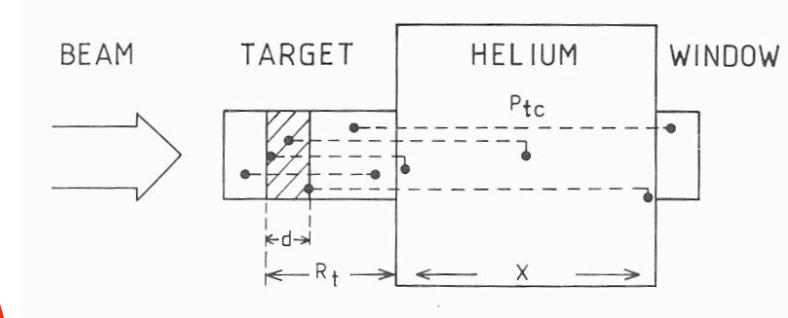
Ion Guide ISOL



ISOL for All Elements, Fast Extraction

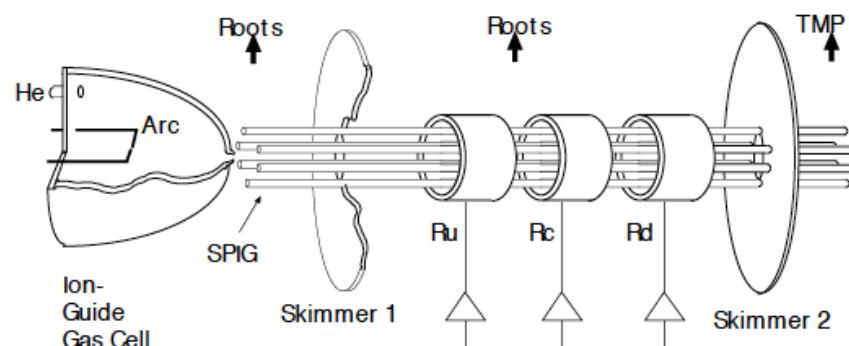
Problems:

- 1) Poor Emittance (Gas Collision)
- 2) Low Yield (Thin Effective Target)



SPIG @INS

RF sextupole ion beam guide for IGISOL



Large Cell? Slow Extraction!

Electric Field in Cell!

RF Ion Guide

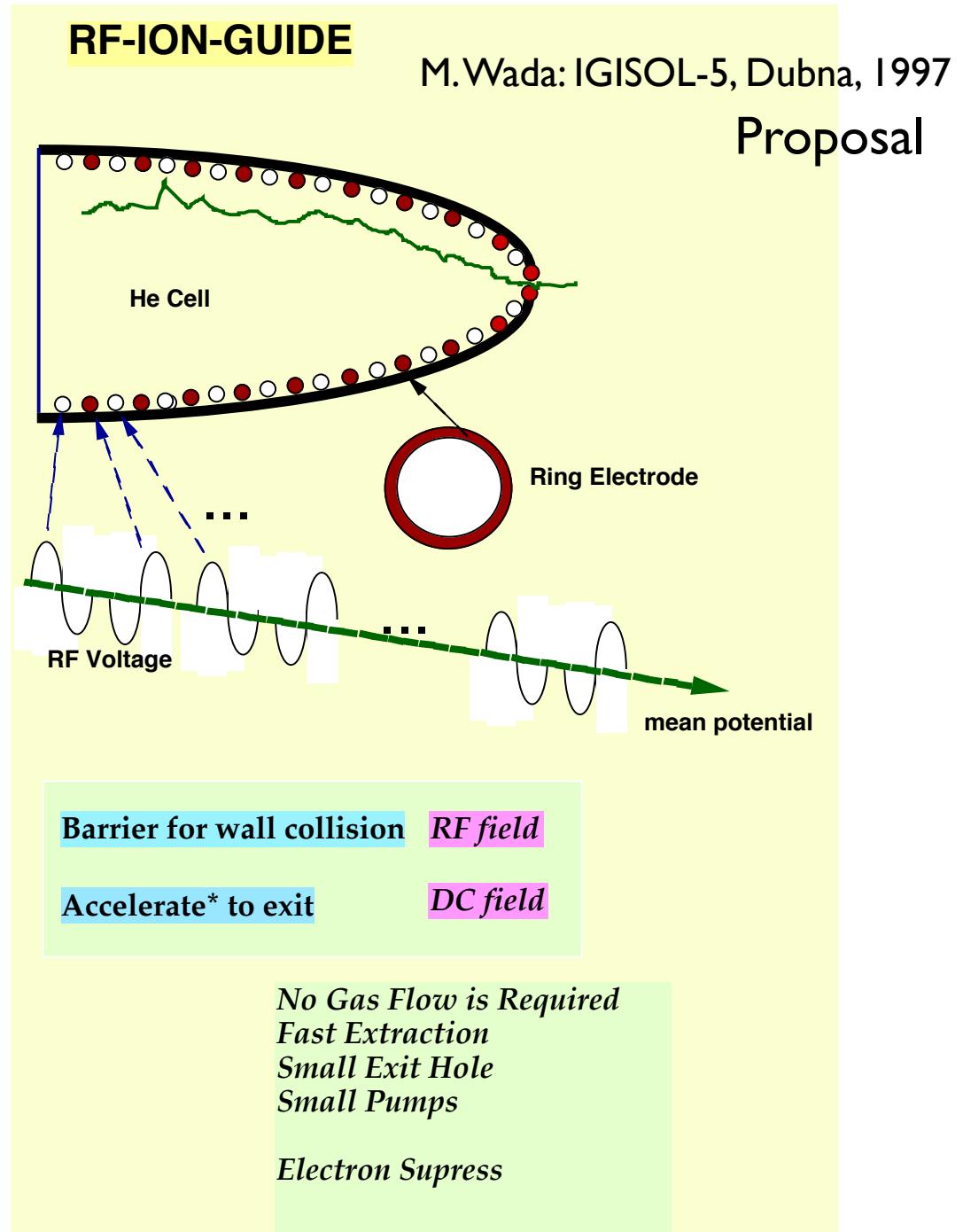
H. Xu, M. Wada, I. Katayama et al: NIM A222(1993)274.

S. Fujitaka, M. Wada, I. Katayama et al: NIMB126(1997)386.

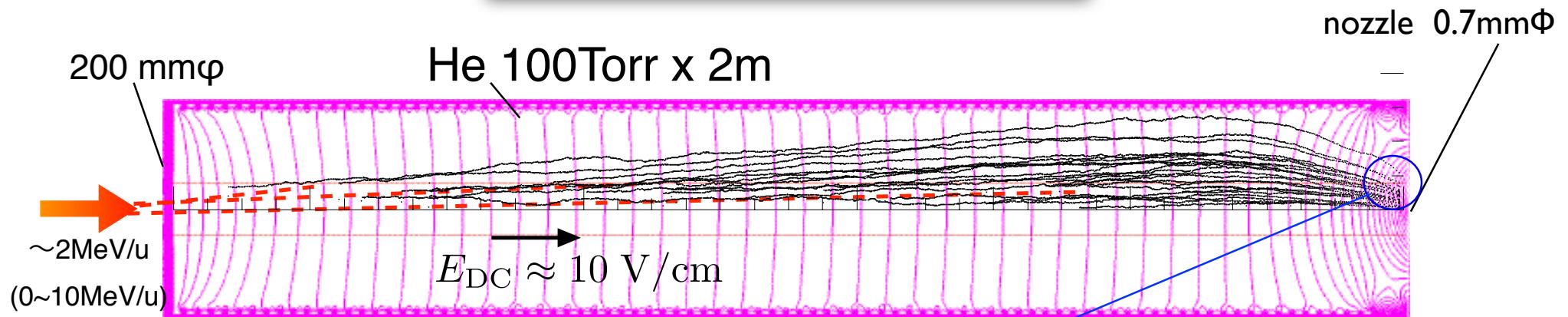
Brief History of Development

~ Rome was not build in a day ~

- RF Trap (W. Paul, 1953)
- Electric Curtain (Masuda, 1972)
- IGISOL (J.Arje, 1981)
- SPIG (1993)
- Cyclotron Ion Guide(1997)
- RF-ionguide (1997)
- Off-line experiments (1998~)
- On-line experiments (2000~)



RF-Carpet Ion Guide™



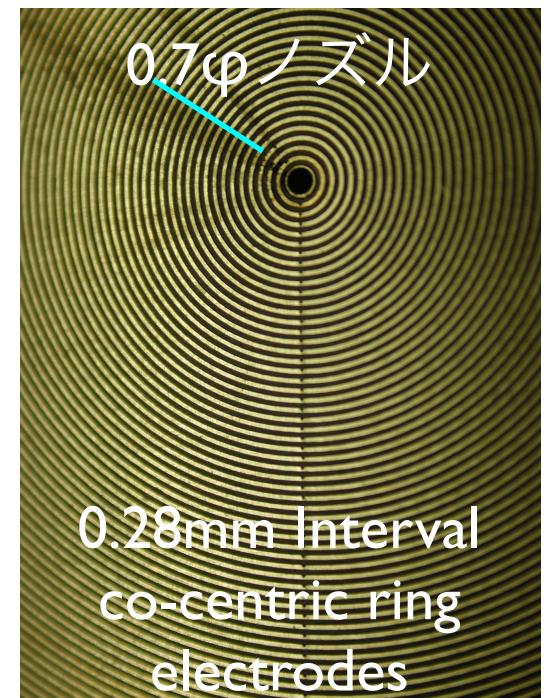
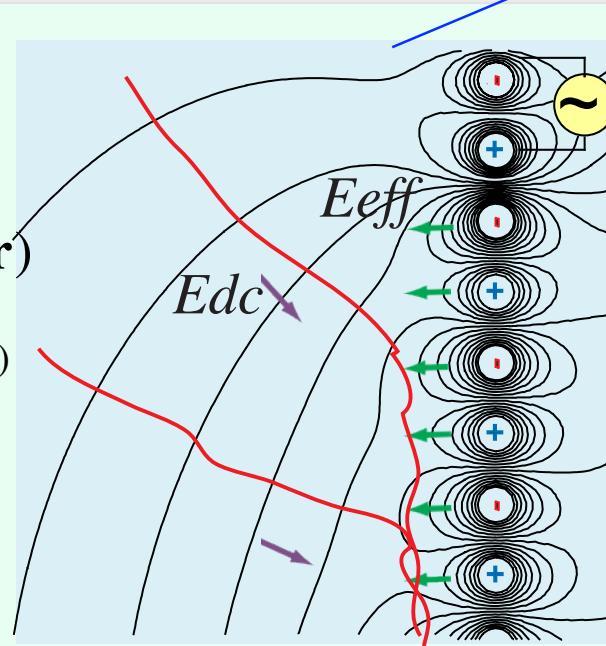
RF gradient Field: Barrier

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

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

$$E_{\text{eff in gas}}^{\max} = \frac{m\mu^2 V_{rf}^2}{er_0^3}$$

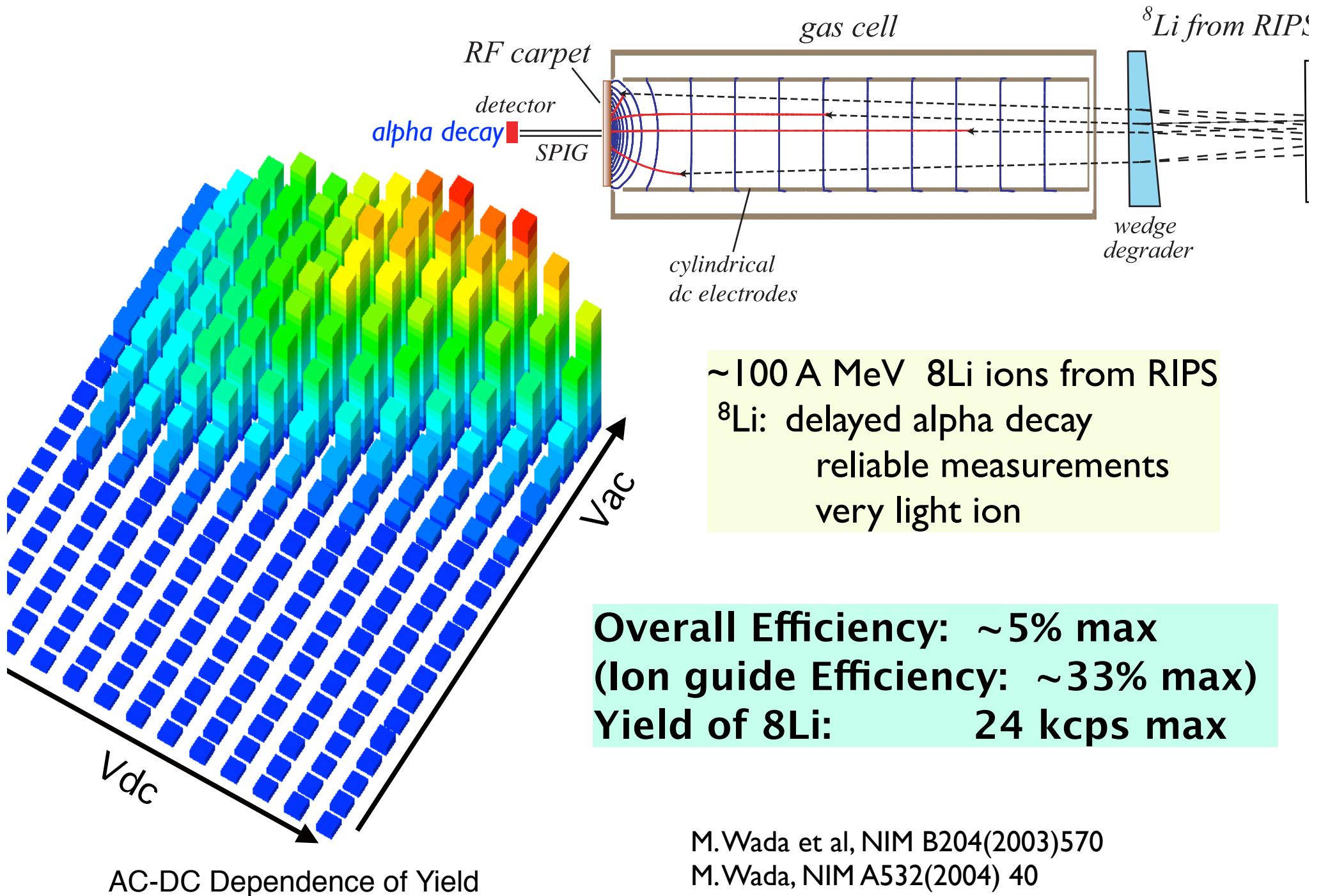
$2r_0 \approx \text{electrode distance}$



Proposed in 1997. Proof of Principle in 2000. 100MeV/u Li8 in 2003.
used for Be spectroscopy in 2005-09. standard technology in worldwide

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

Yield and efficiency of slow Li-8 ions

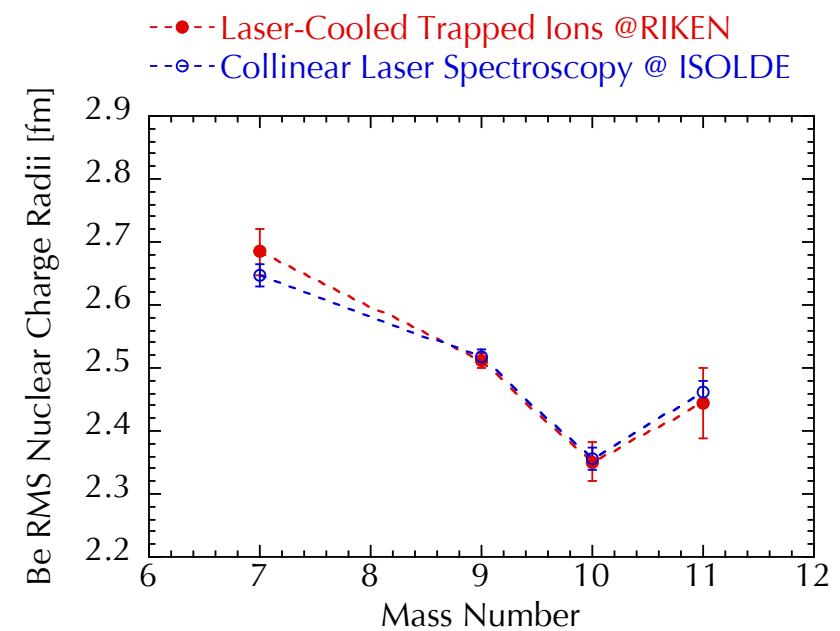
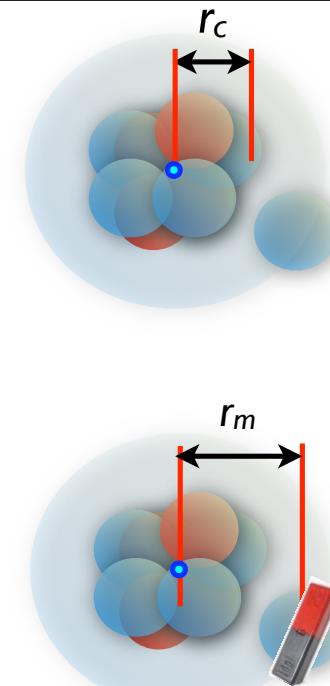
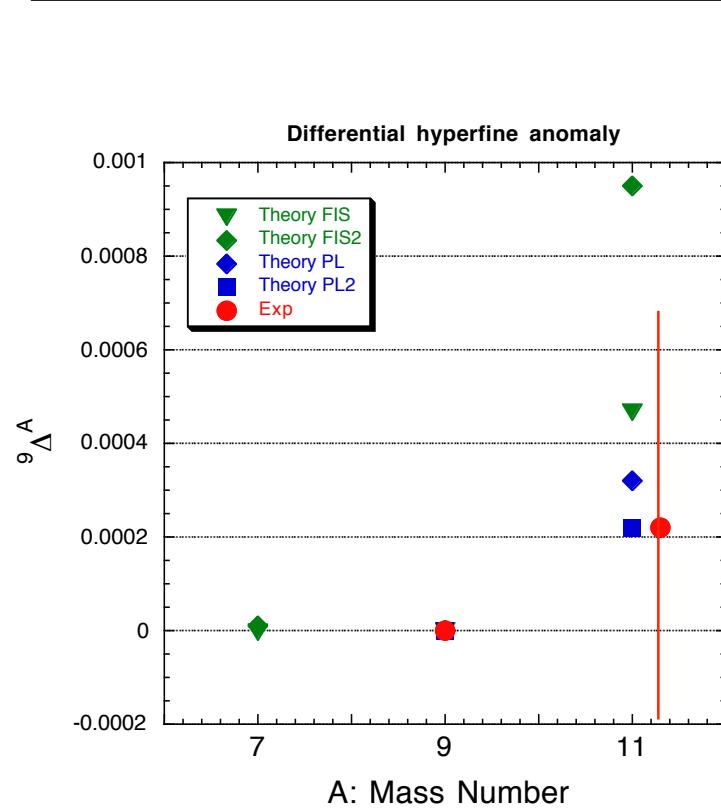


Charge & Magnetization Radii of Be Isotopes

Our Works

	Be7	Be9	Be10	Be11
HFS constant A (MHz)	-742.77228(43)	-625.0088370529(11)	-	-2677.302988(72)
Nuclear Mag. Moment (n.m) by beta-NMR	[-1.39928(2)]	-1.177432(3)	-	[-1.6812(5)] (-1.6816(8))
S1/2-P3/2 Opt.Transition (MHz)	957347372.4(1.6)	957396618.7(0.6)	957413945.1(0.9)	957 428 188.9(2.9)

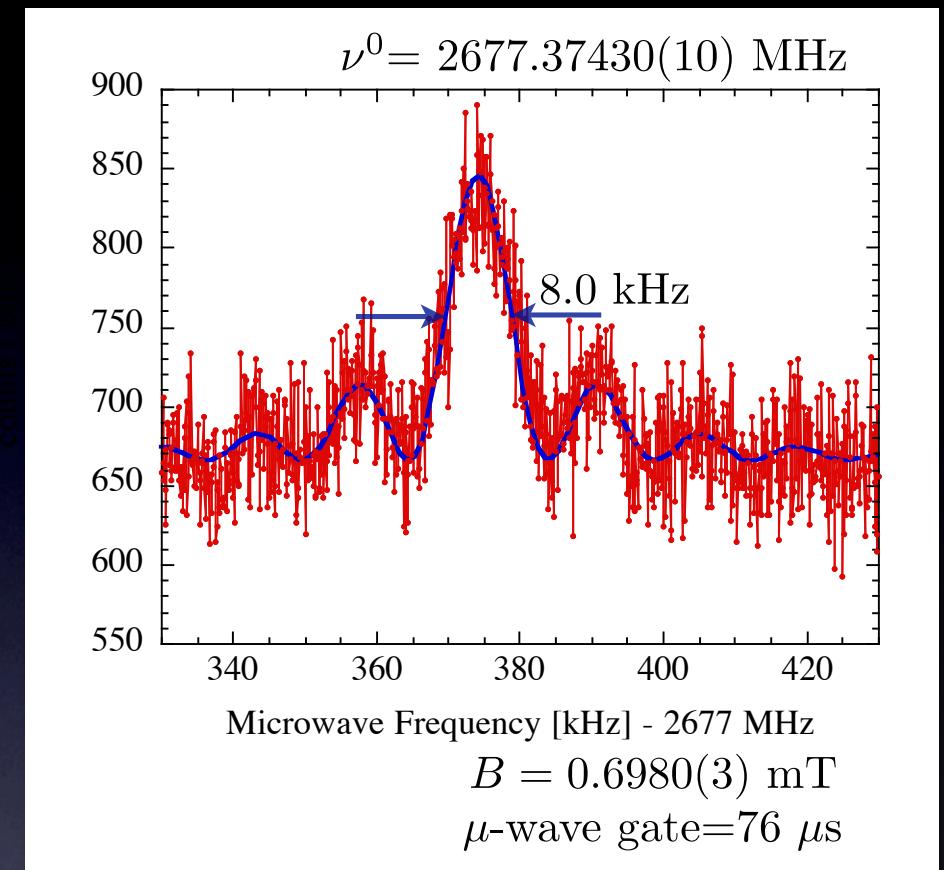
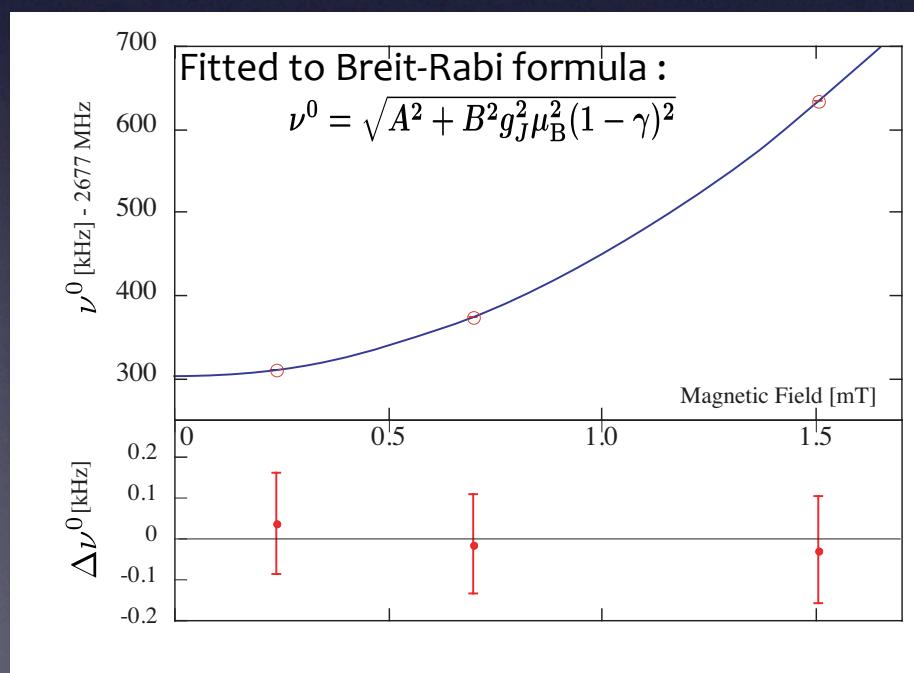
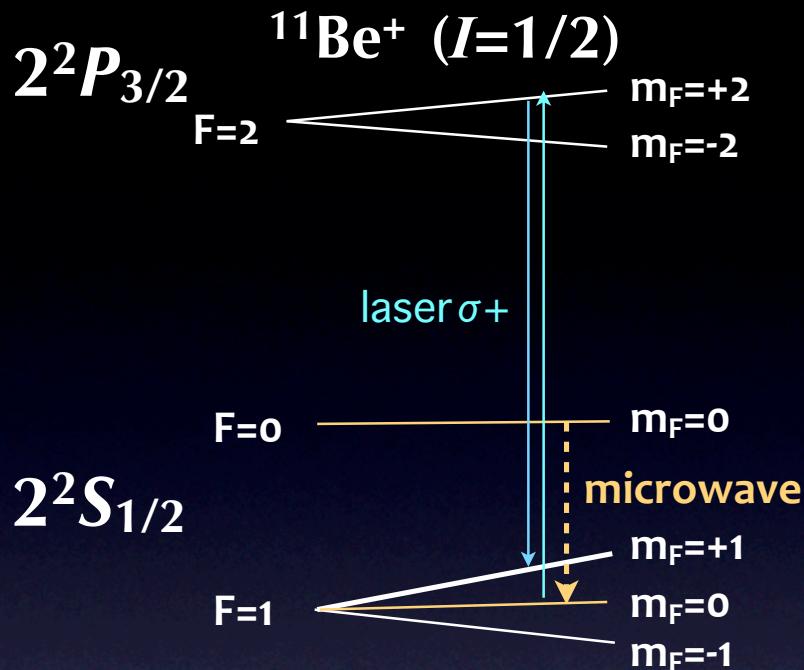
* W. Geithner
PRL 83(1995)



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

**neutron halo
of ${}^{11}\text{Be}$**

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



→ $A_{11} = -2677.30 \text{ MHz } (3 \cdot 10^{-8})$

$A \Rightarrow \mu_I = -1.68 \text{ } () \quad |^9\Delta^{11}| < 10^{-4}$

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

Physics
spotlighting exceptional research

American Physical Society

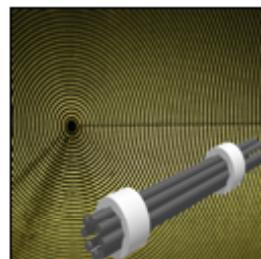
APS physics

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APS » Journals » Physics » Synopses » How do you trap a very high-energy ion?

How do you trap a very high-energy ion?



Precision Measurement of the Hyperfine Structure of Laser-Cooled Radioactive ${}^7\text{Be}^+$ Ions Produced by Projectile Fragmentation

K. Okada, M. Wada, T. Nakamura, A. Takamine, V. Lioubimov, P. Schury, Y. Ishida, T. Sonoda, M. Ogawa, Y. Yamazaki, Y. Kanai, T. M. Kojima, A. Yoshida, T. Kubo, I. Katayama, S. Ohtani, H. Wollnik, and H. A. Schuessler

Phys. Rev. Lett. 101, 212502 (Published November 18, 2008)

 ShareThis • Nuclear Physics

Measurements of nuclear moments give details about nuclear structure that cannot be obtained in any other way. However, traditional methods like nuclear magnetic resonance (NMR) and nuclear quadrupole resonance (NQR) require large numbers of stable nuclei to make a measurement and cannot be applied to unstable radioactive nuclei, which are usually produced in very small numbers. Instead, these unstable nuclei are best measured in traps, where atoms can be held for a long enough time to make sensitive measurements. The challenge is to take nuclei that were created in a high-energy collision and slow, trap, and cool them to make a precision measurement.

Writing in *Physical Review Letters*, a group at the newly commissioned Slow Radioactive Ion (SLOWRI) facility at RIKEN in Japan reports they have trapped and measured the magnetic moment of unstable ${}^7\text{Be}$ ions. The group starts with ${}^7\text{Be}$ ions from a high-energy fragmentation reaction and cools away 15 orders of magnitude in their kinetic energy, leaving trapped ions with temperatures less than 10 mK. The RIKEN team then used a laser method to measure the atomic hyperfine structure of the ions to deduce the nuclear magnetic moment of ${}^7\text{Be}$.



PRL Celebrates 50 Years

- Editorials and Essays
- Milestone Letters
- PRL Timeline
- Special Events

Coming Soon in Physics

- Iron strength for magnetic semiconductors

Now in Focus

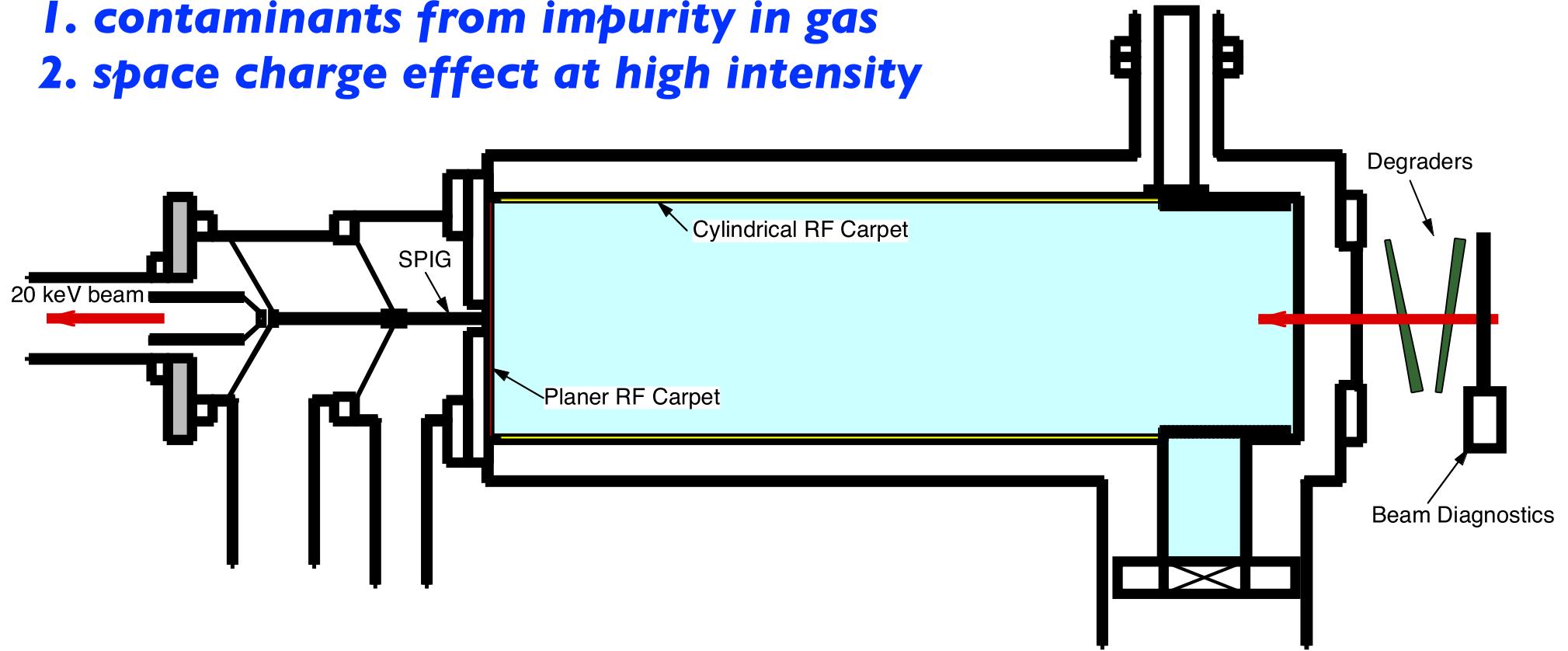
Light Bends Glass

December 10, 2008

An experiment showing that an optical fiber recoils as light exits it addresses a century-old controversy over the momentum of light in transparent materials.

Next Gen. Ion Guide Gas Cell

- 1. contaminants from impurity in gas**
- 2. space charge effect at high intensity**

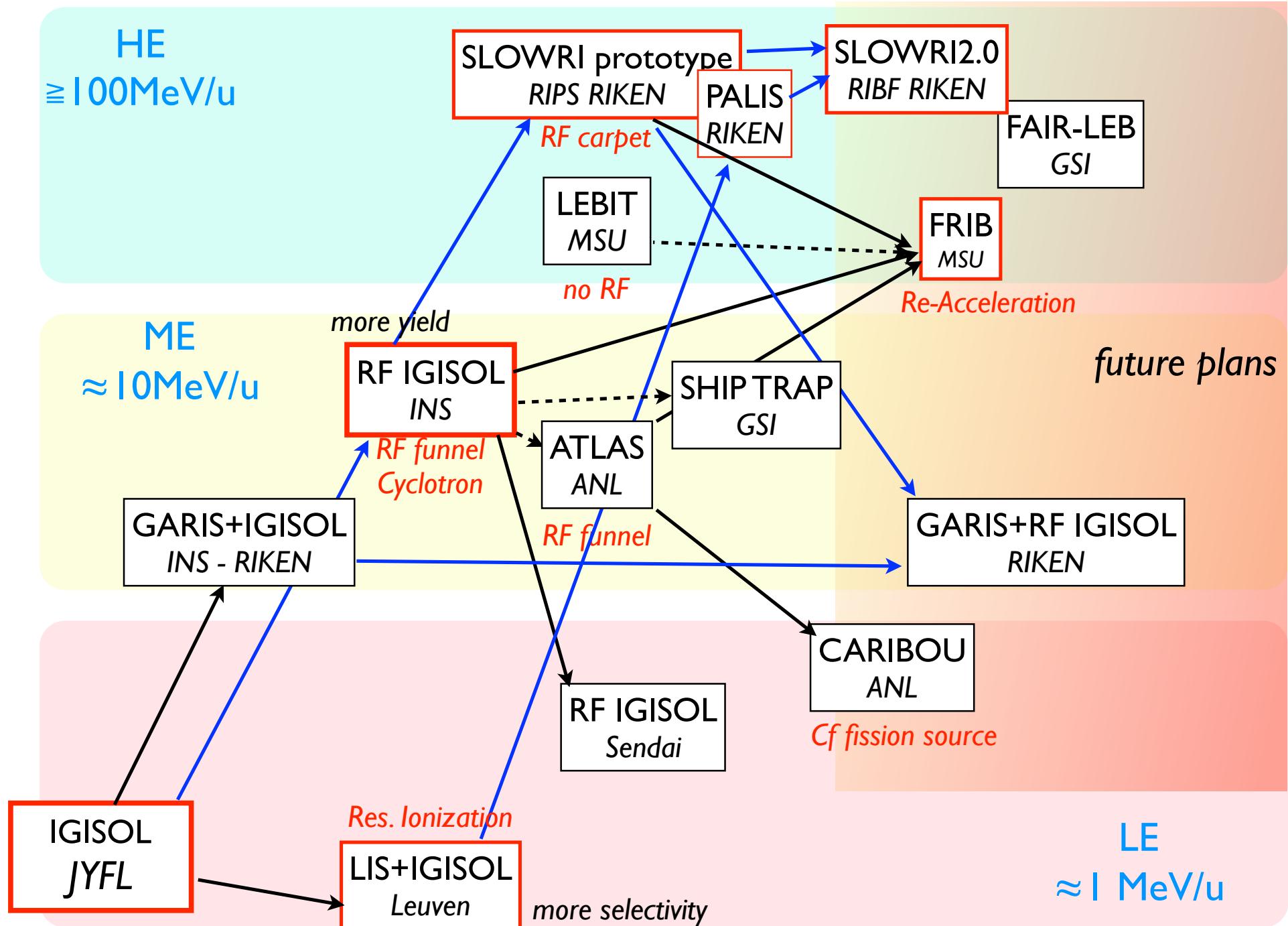


- Fully covered RF carpets (planer & cylindrical)
- Cryogenic cooling by thermal isolation

MSU: Ion surfing (traveling wave)

KVI: big cryogenic gas cell for FAIR LEB

Gas Cell Genealogy



“super-ISOLDE” \approx **SLOWRI@RIBF**

Universal Slow RI-beam Facility

SLOWRI

RI-Beam Factory

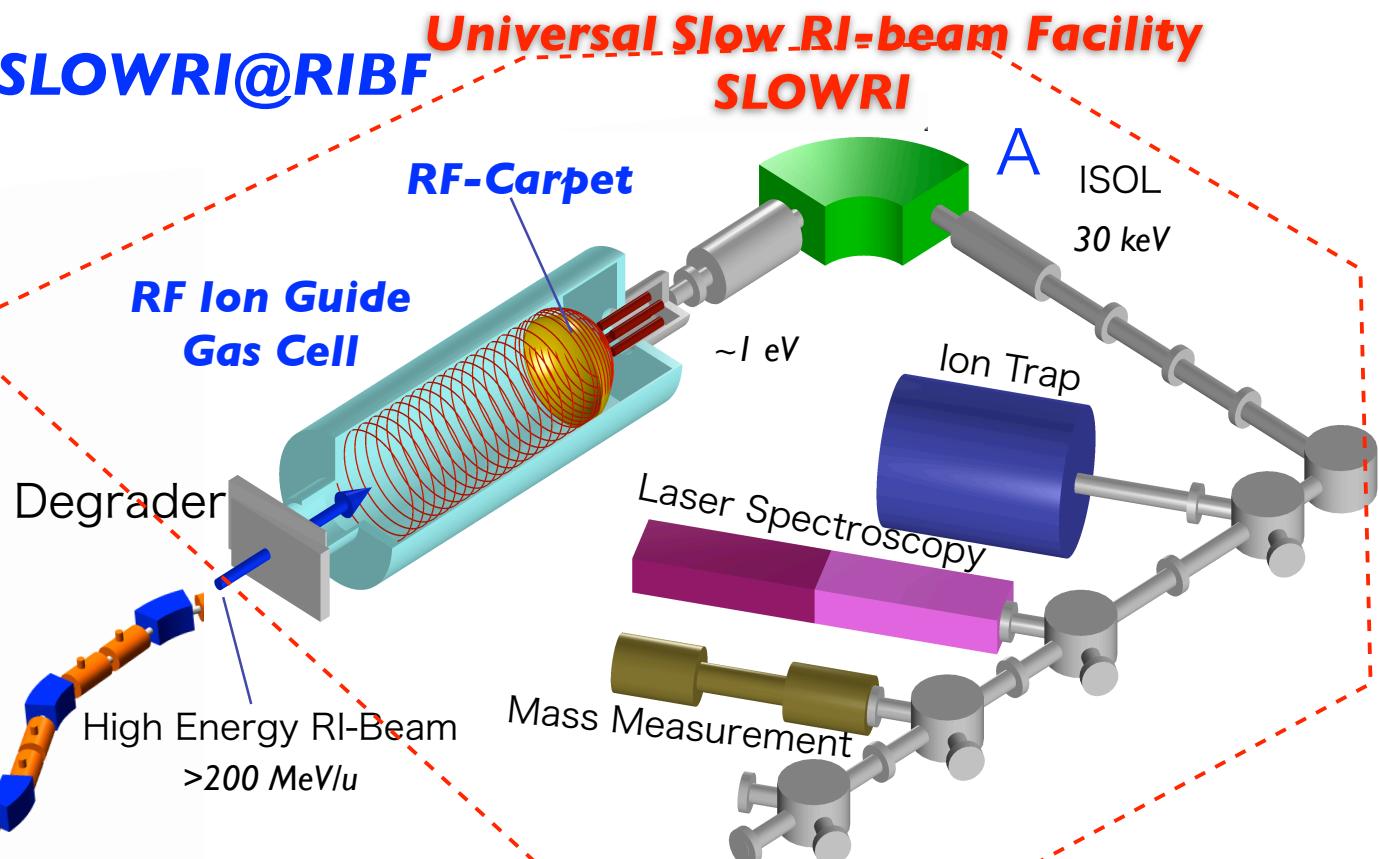
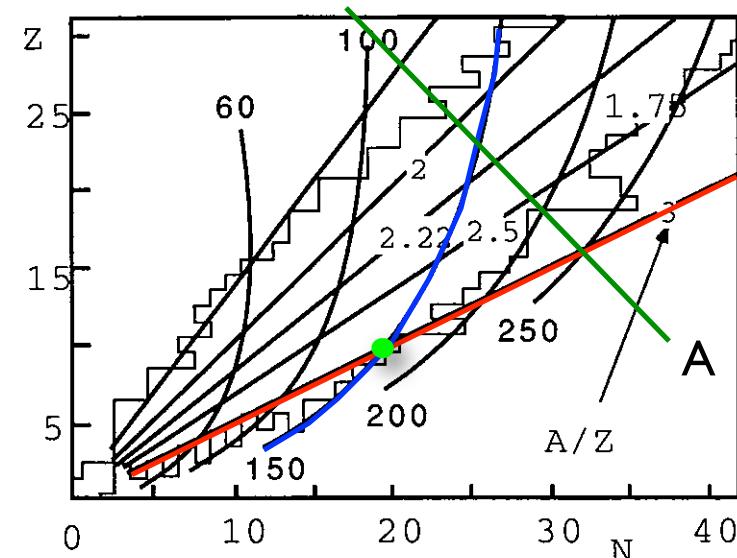
Super Conducting
Ring Cyclotron



Heavy ion beam
400 MeV/u

Target

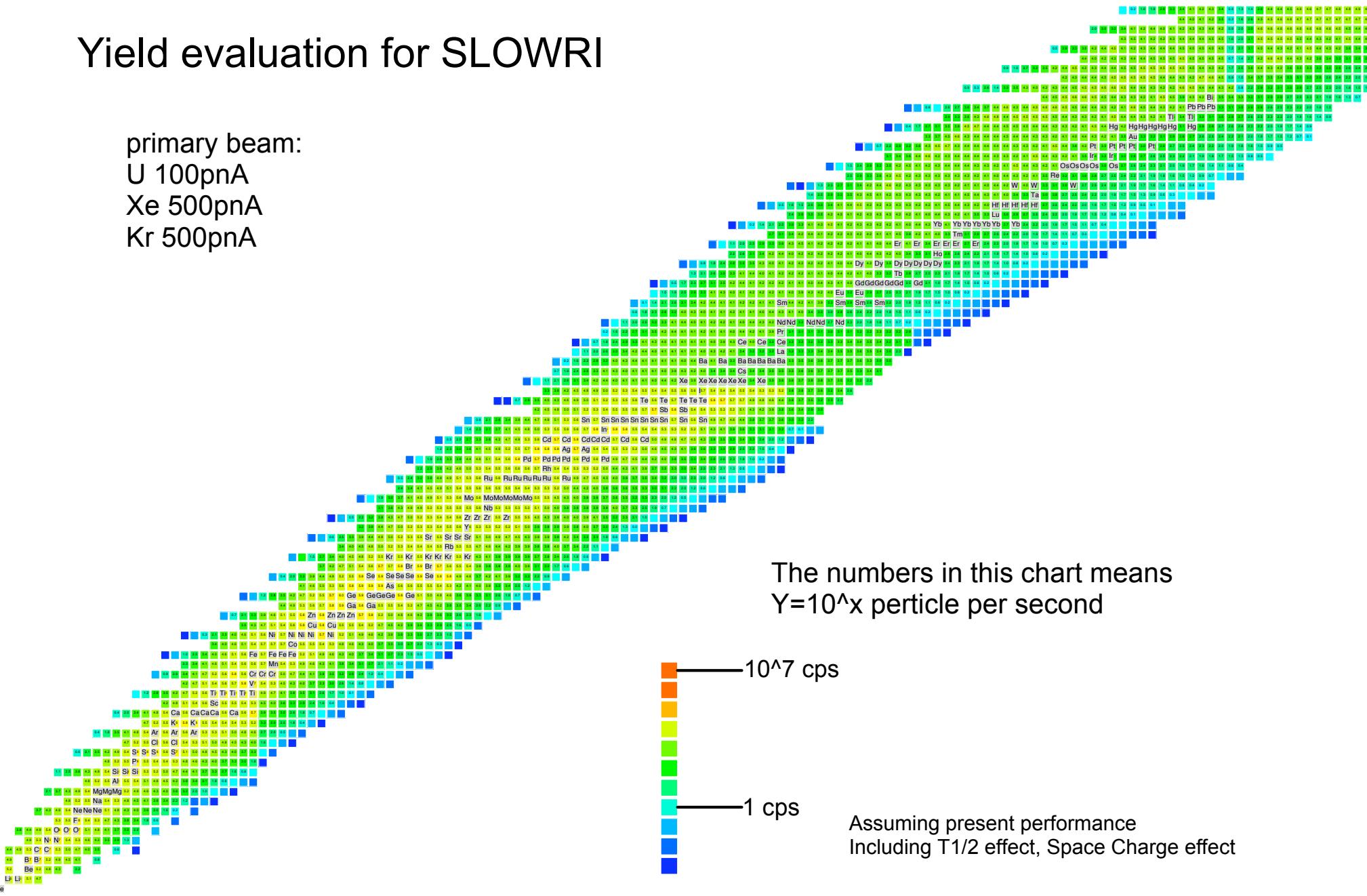
A/Z



**all elements
high pure
low emittance
0-30 KeV**

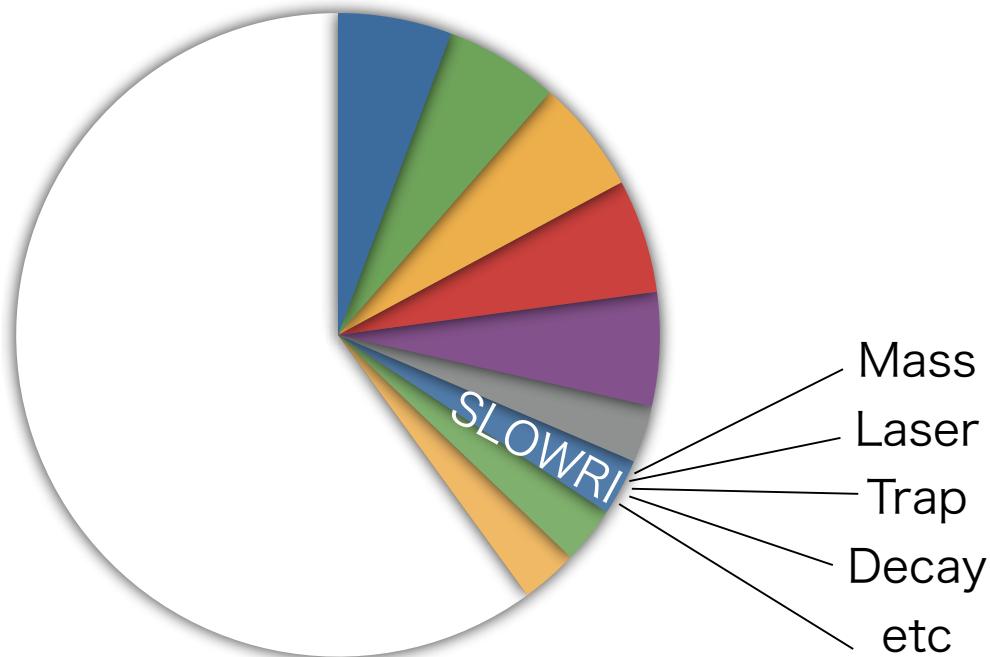
Yield evaluation for SLOWRI

primary beam:
 U 100pnA
 Xe 500pnA
 Kr 500pnA



Available Beam Time

RIBF

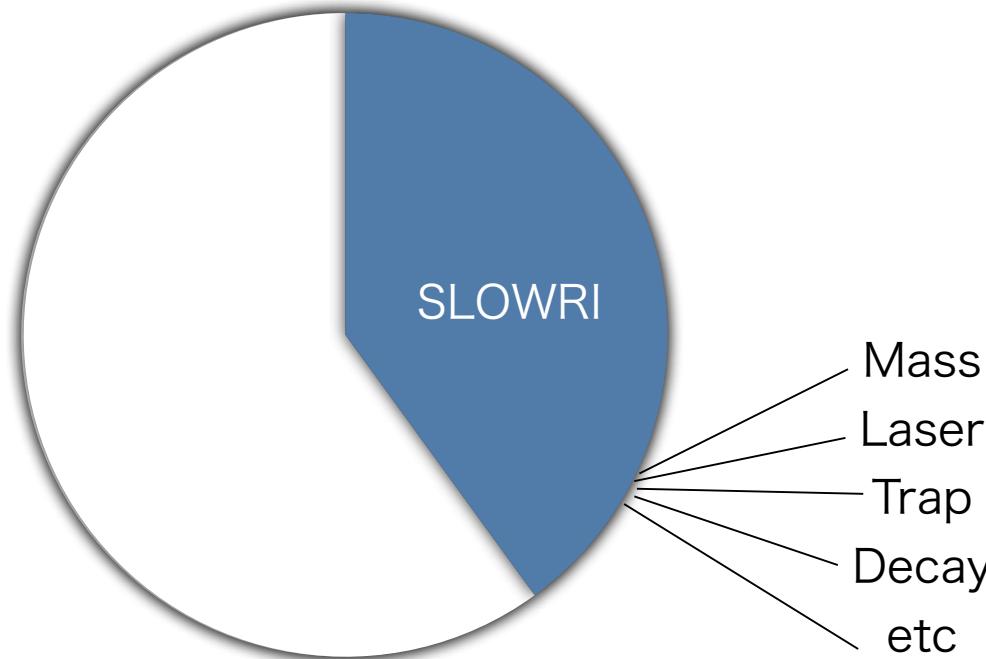


5 months/y

2 weeks/y for SLOWRI ??

Available Beam Time

RIBF

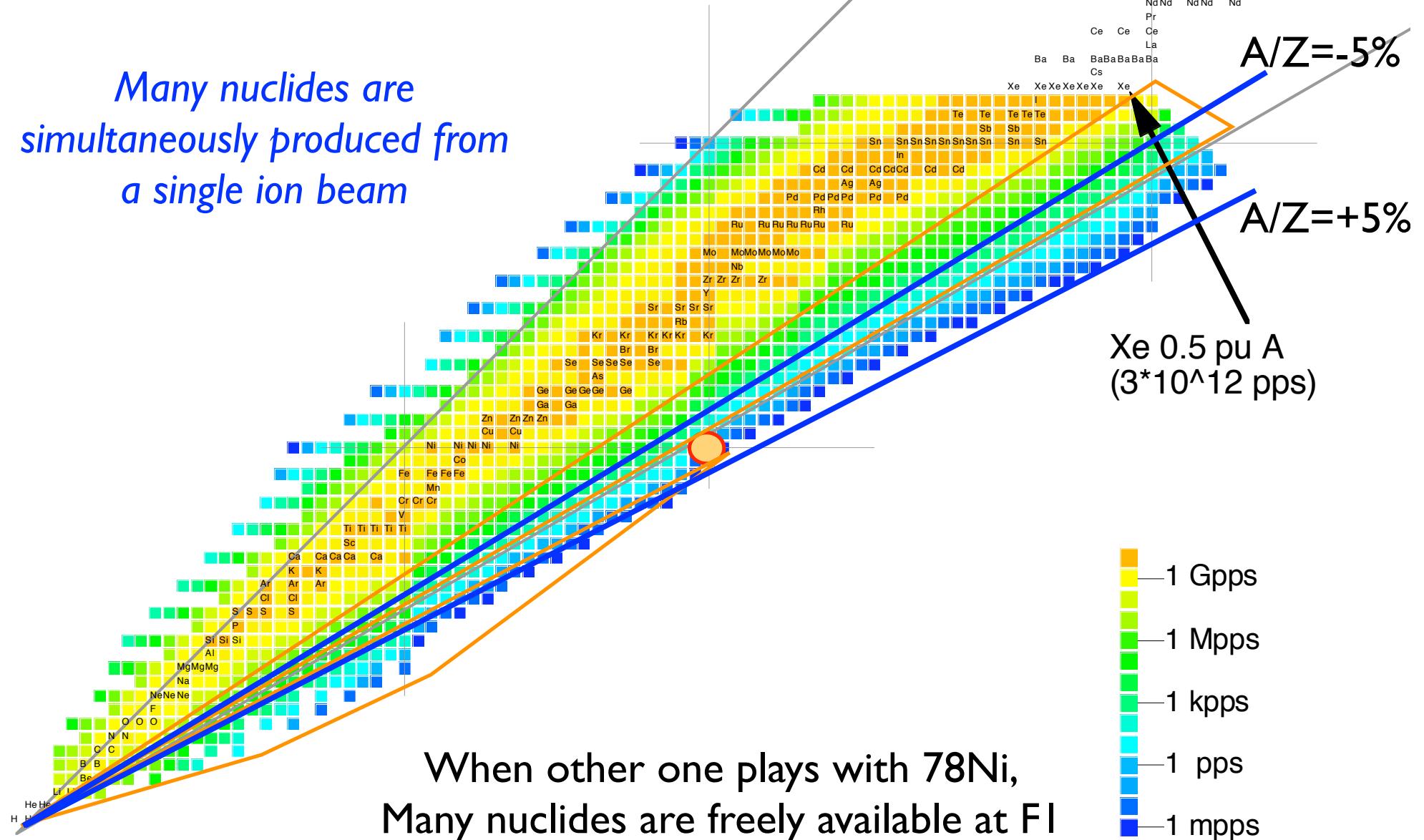


5 months/y
2 weeks/y for SLOWRI ??

5 mon./y for SLOWRI !!

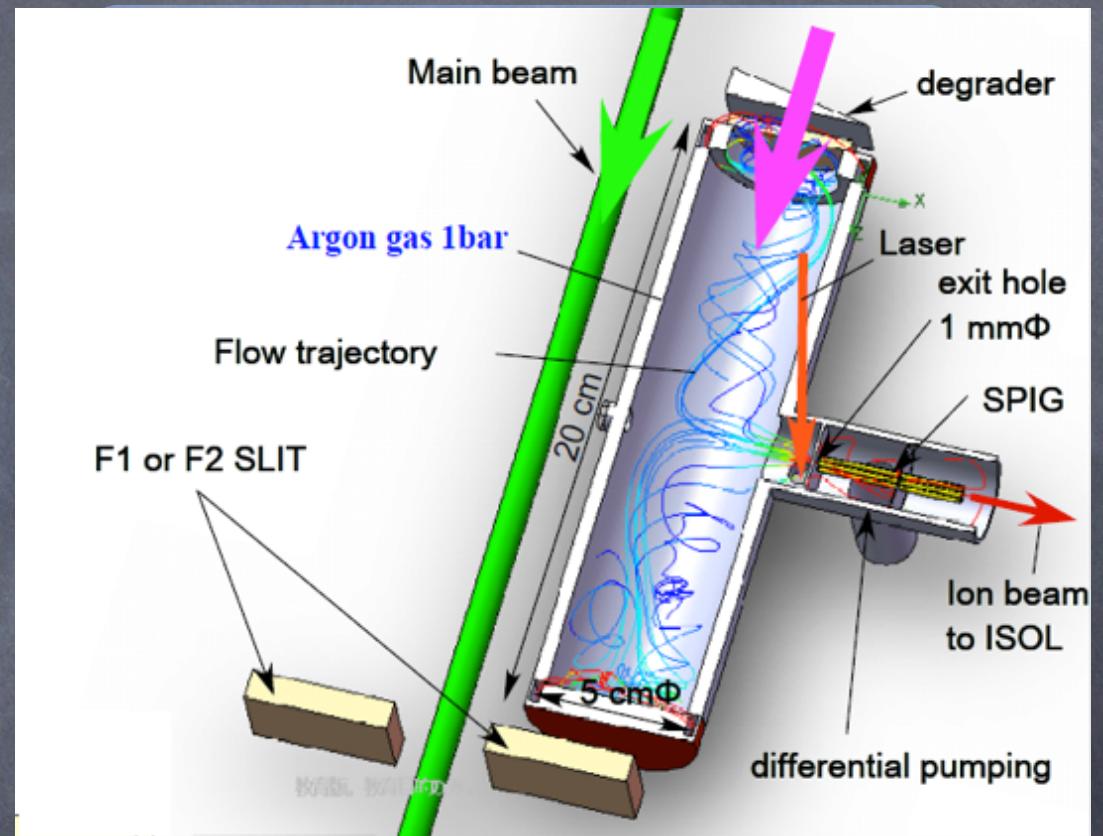
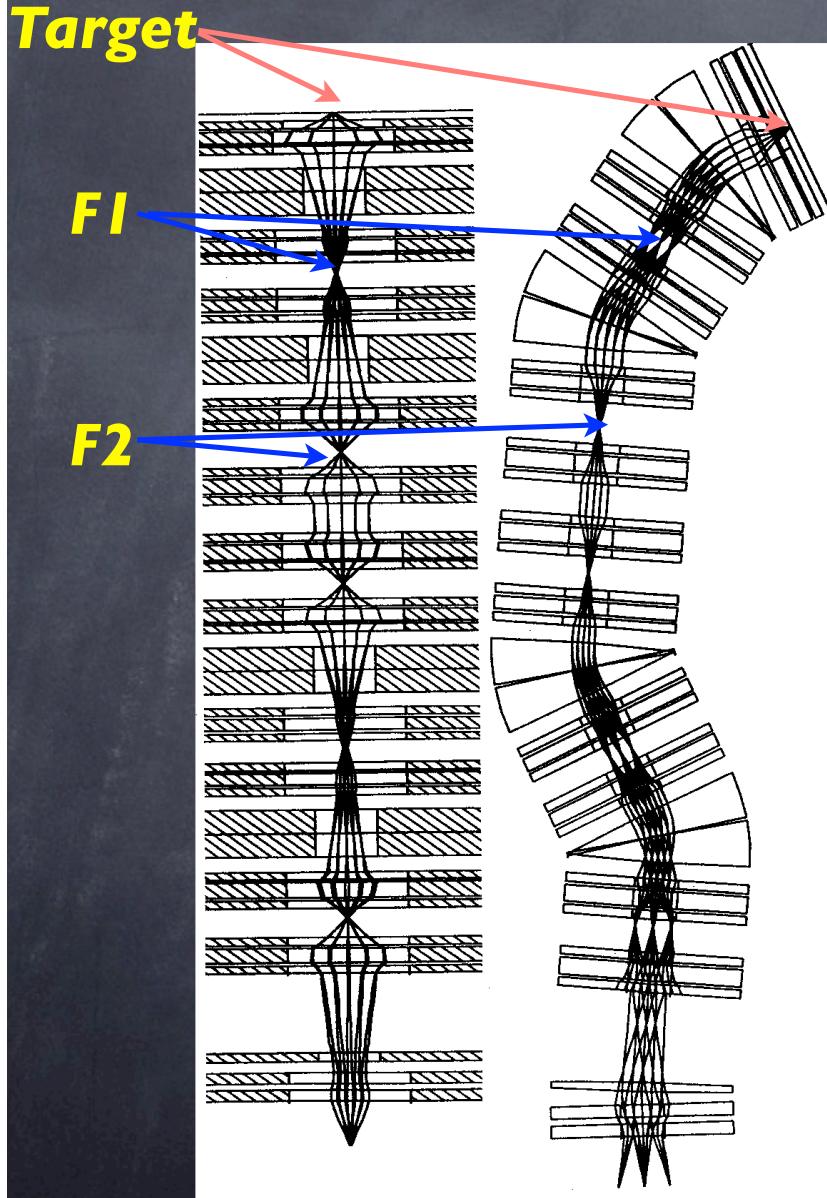
Projectile Fragmentation from, e.g., 350A MeV Xe|36 0.5puA

Many nuclides are simultaneously produced from a single ion beam



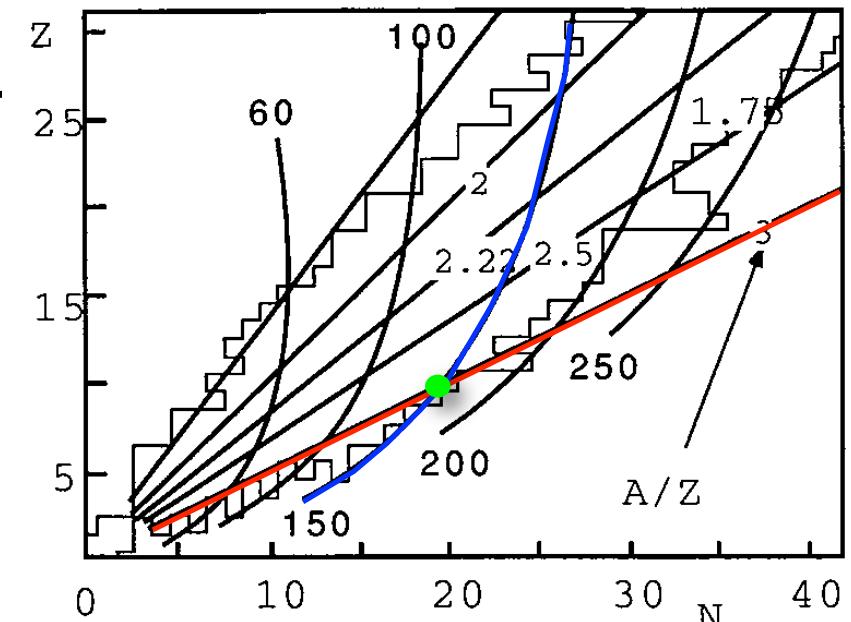
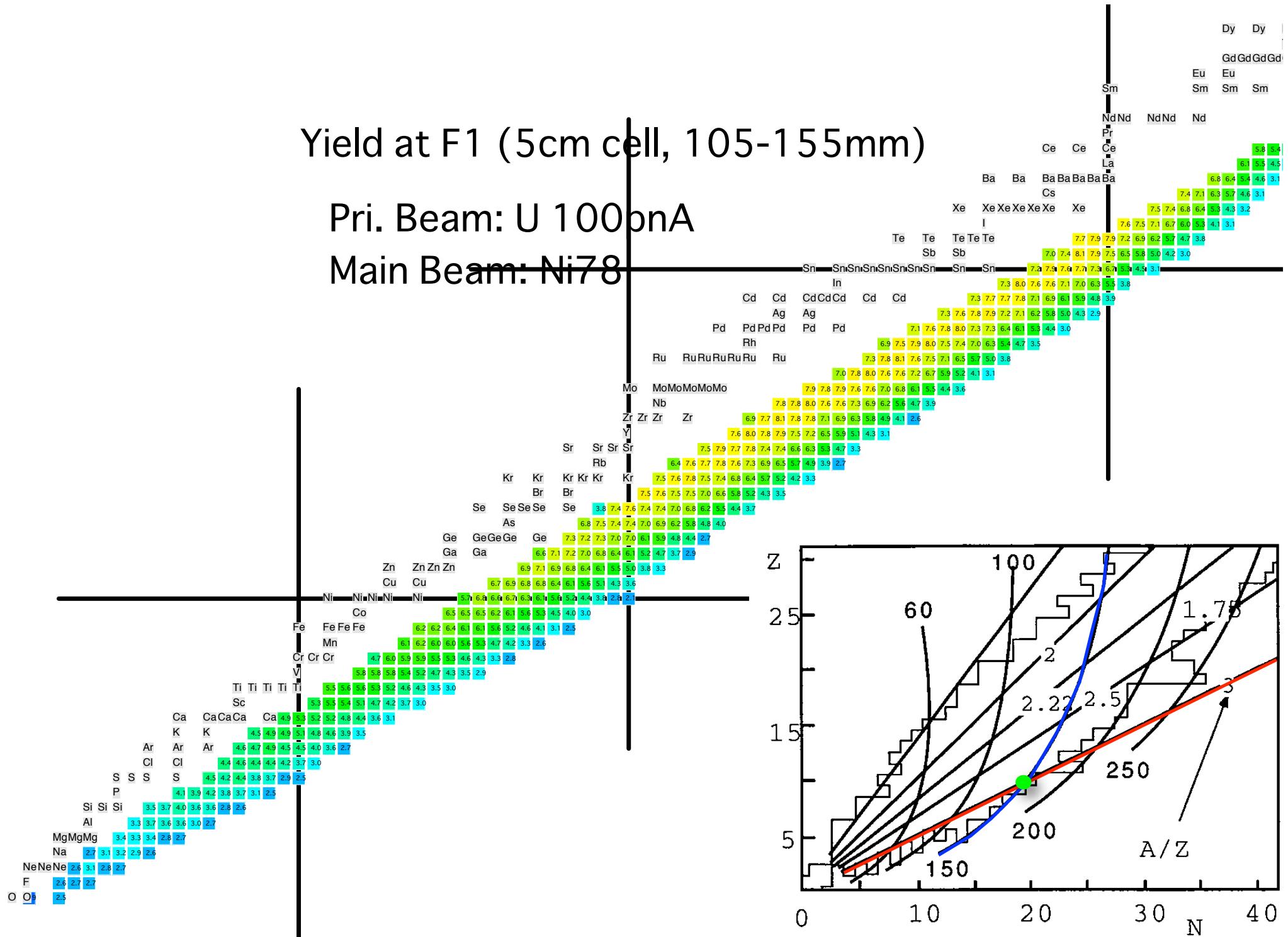
PALIS

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*

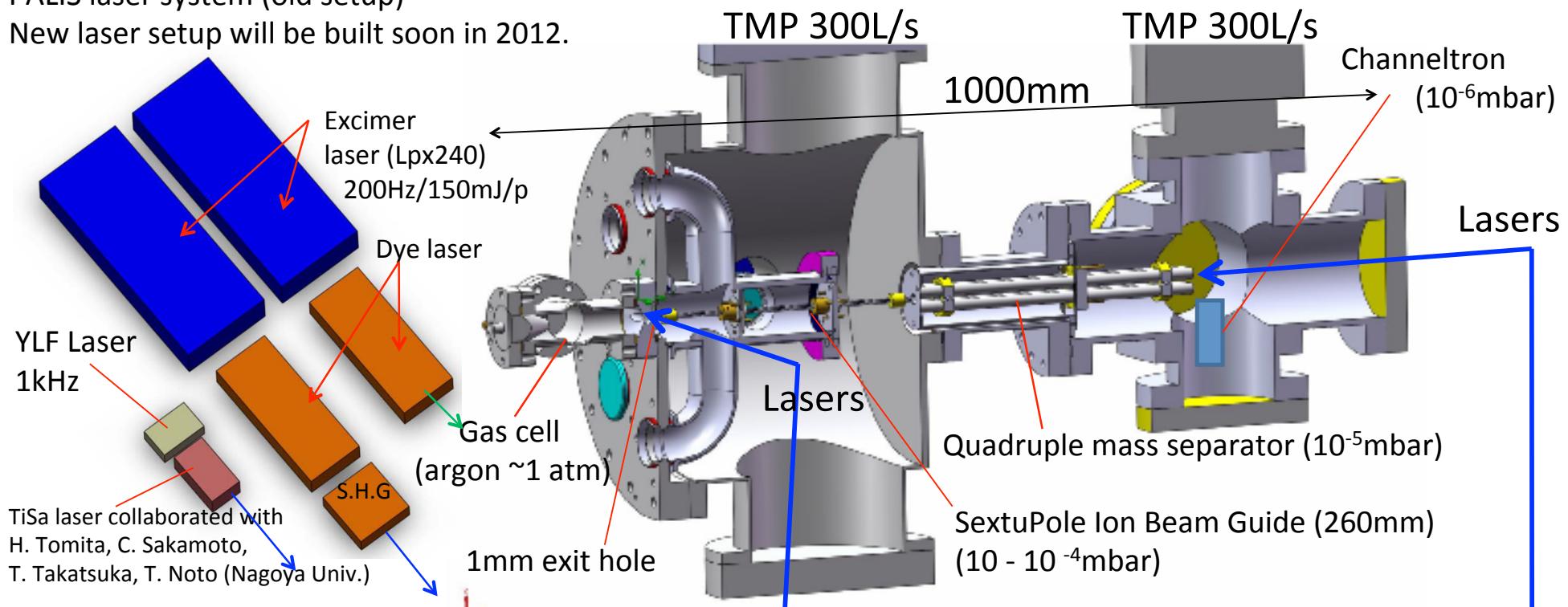


Development of the prototype PALIS system (2010-2012)

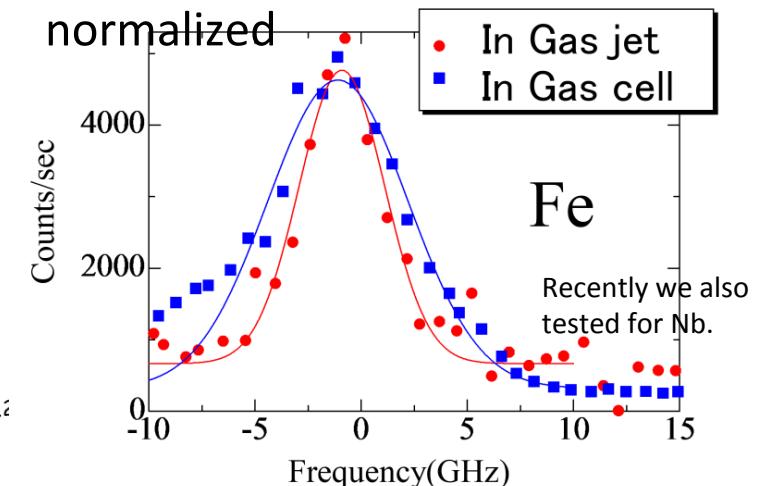
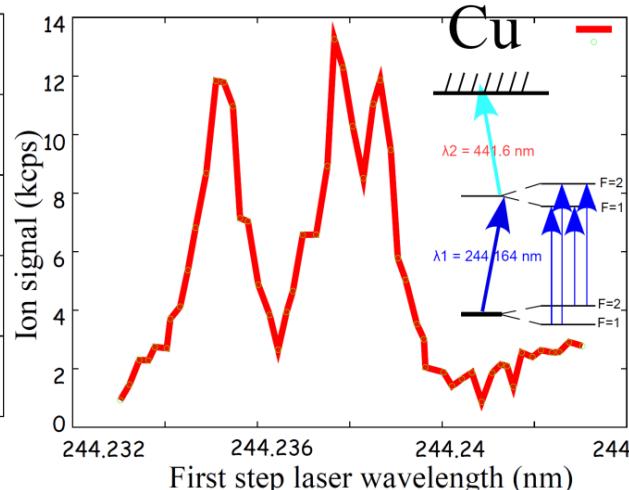
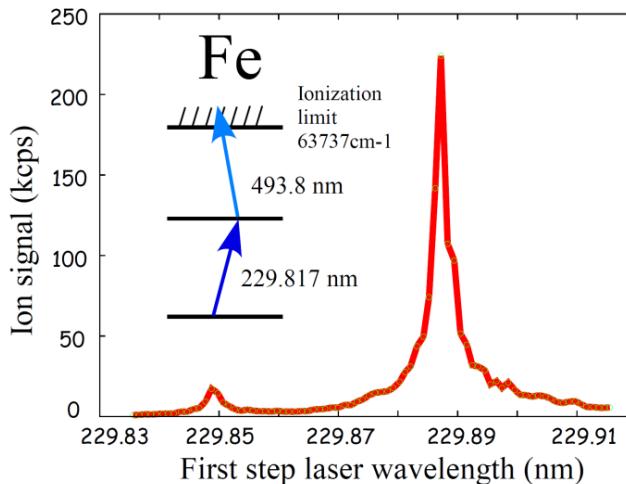
T.Sonoda

PALIS laser system (old setup)

New laser setup will be built soon in 2012.

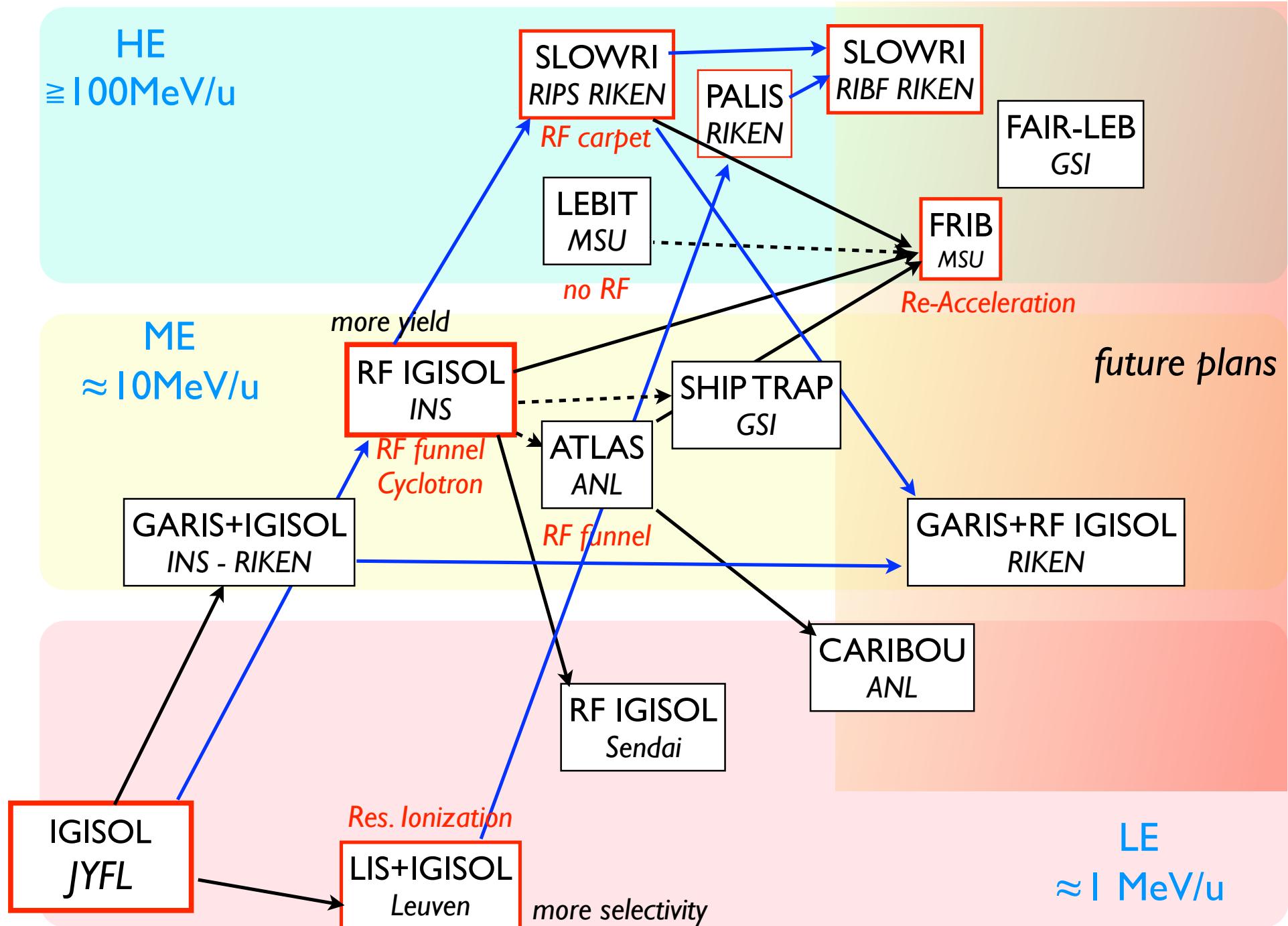


Ionization inside gas cell and its extraction to the high vacuum

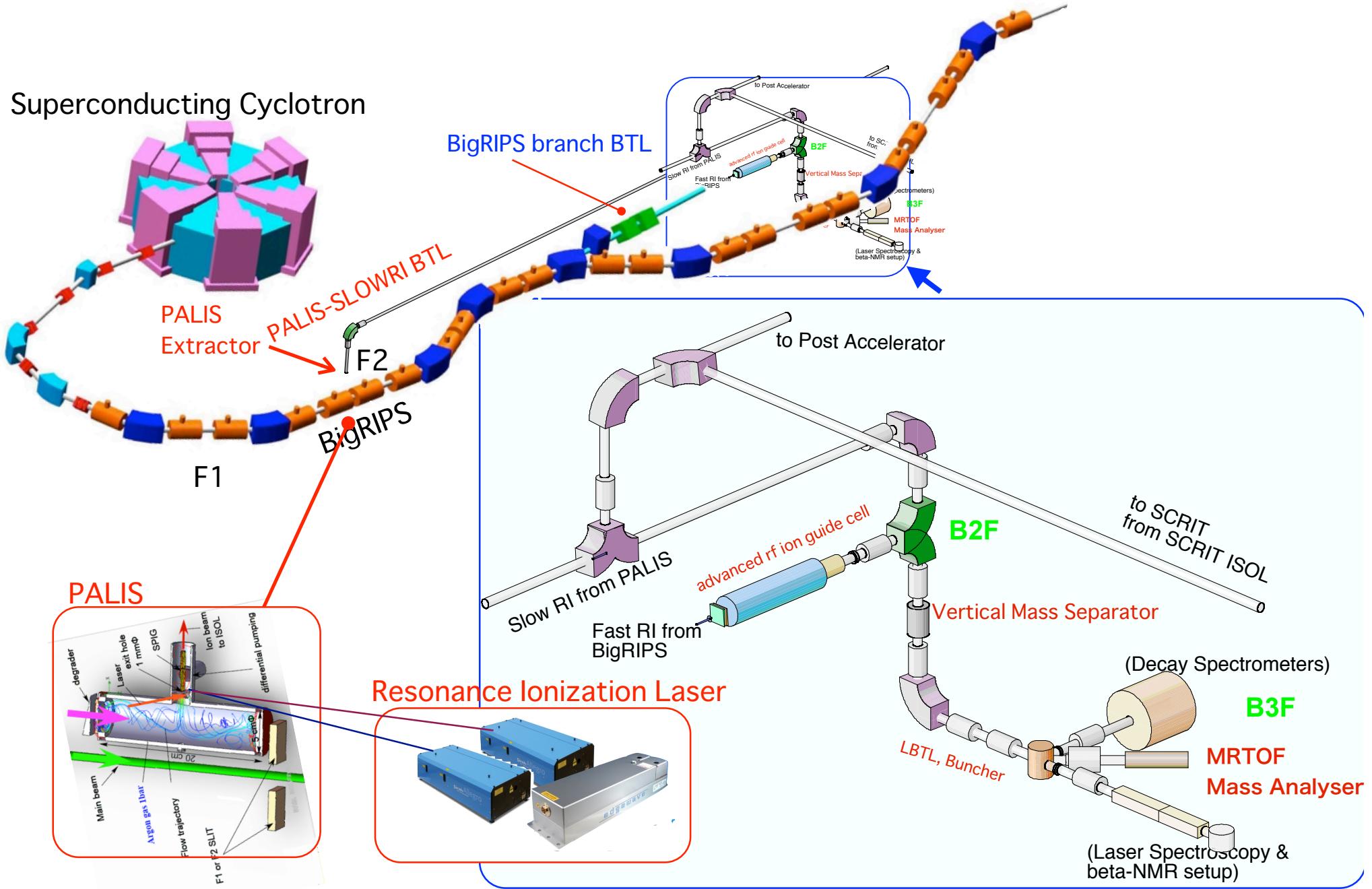


We also ionized for Co, Ni, Ti, Sn, Pd, Nb.

Gas Cell Genealogy

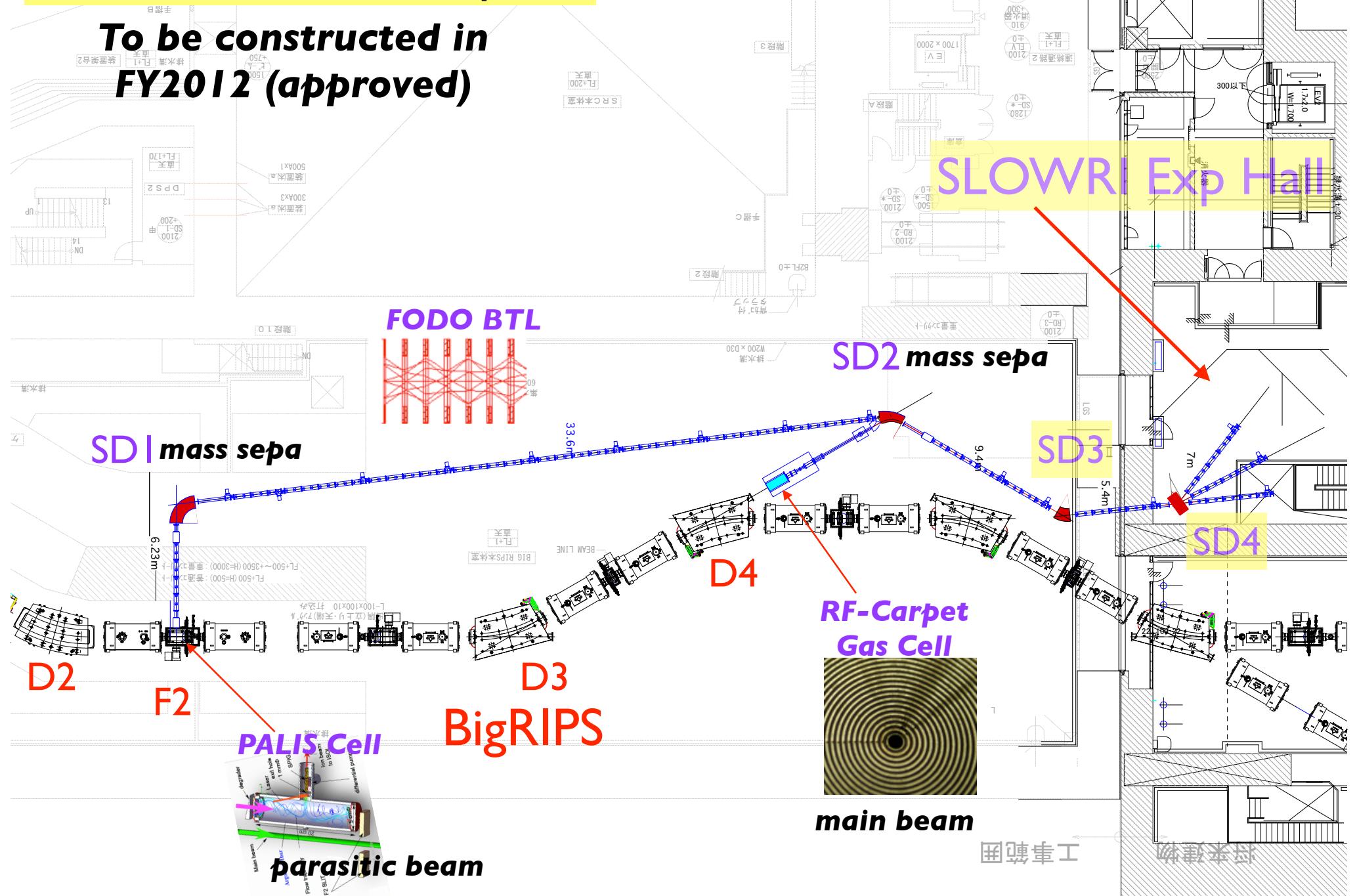


SLOWRI 2011 original plan

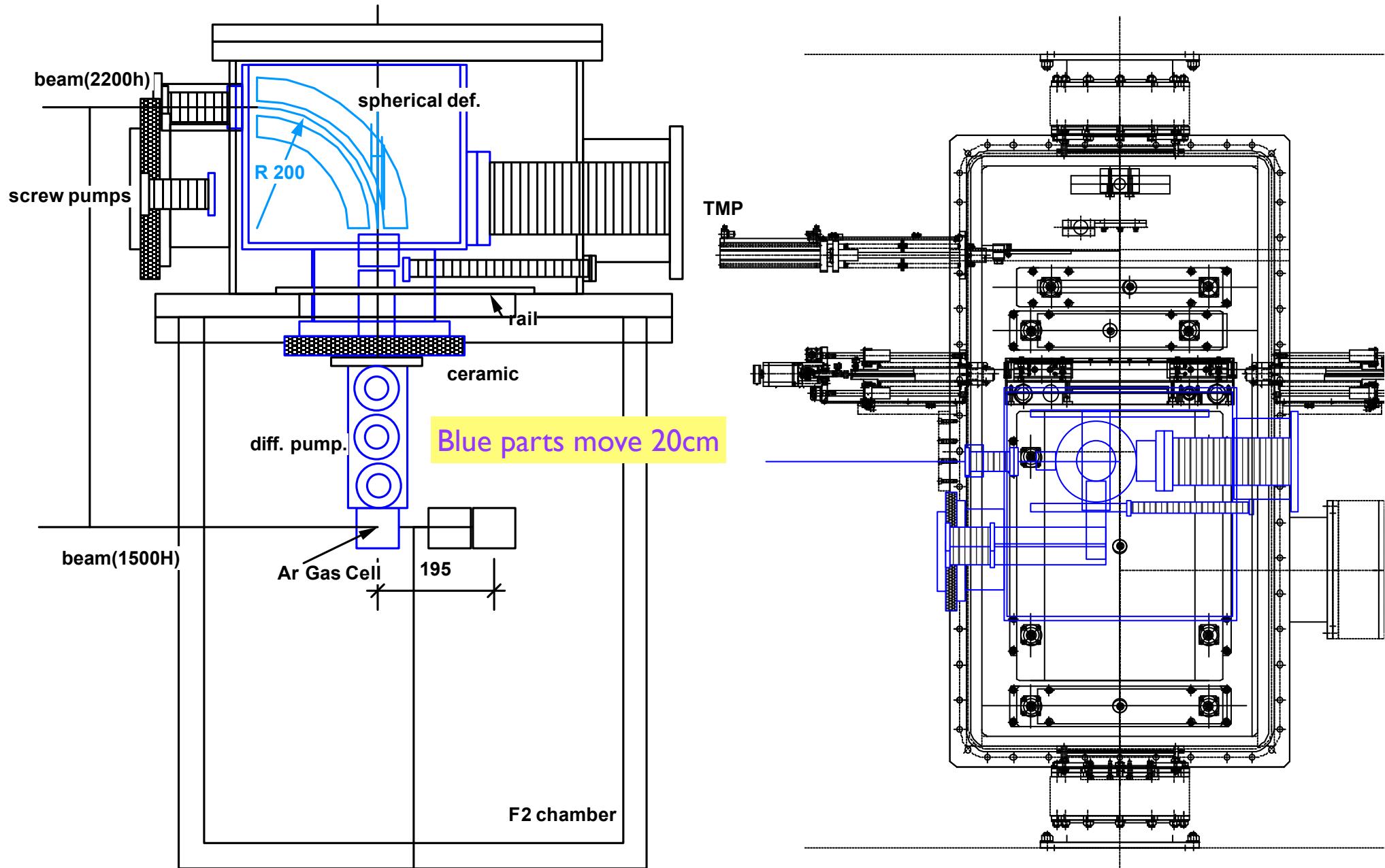


SLOWRI 2.0 floor plan

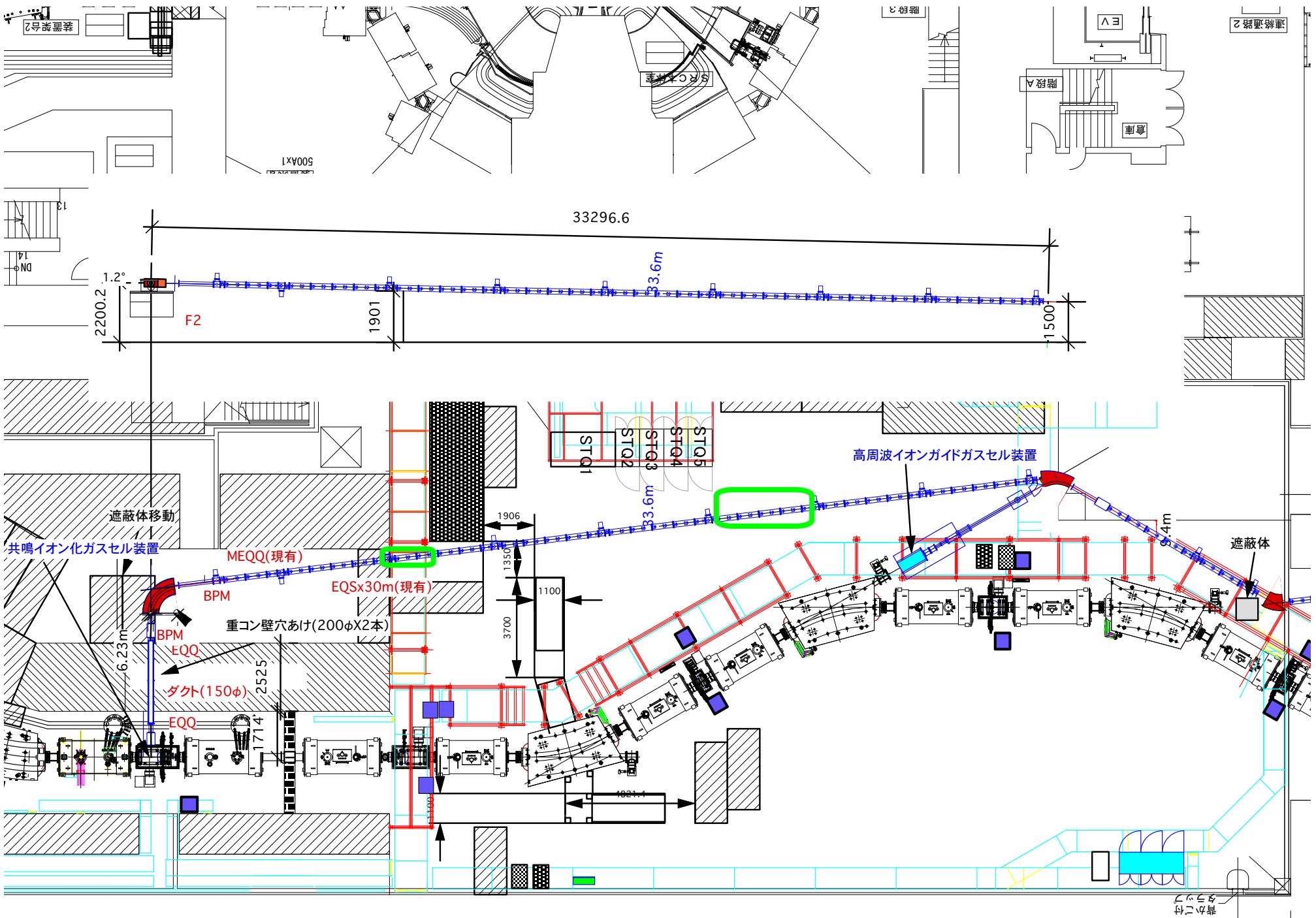
To be constructed in
FY2012 (approved)

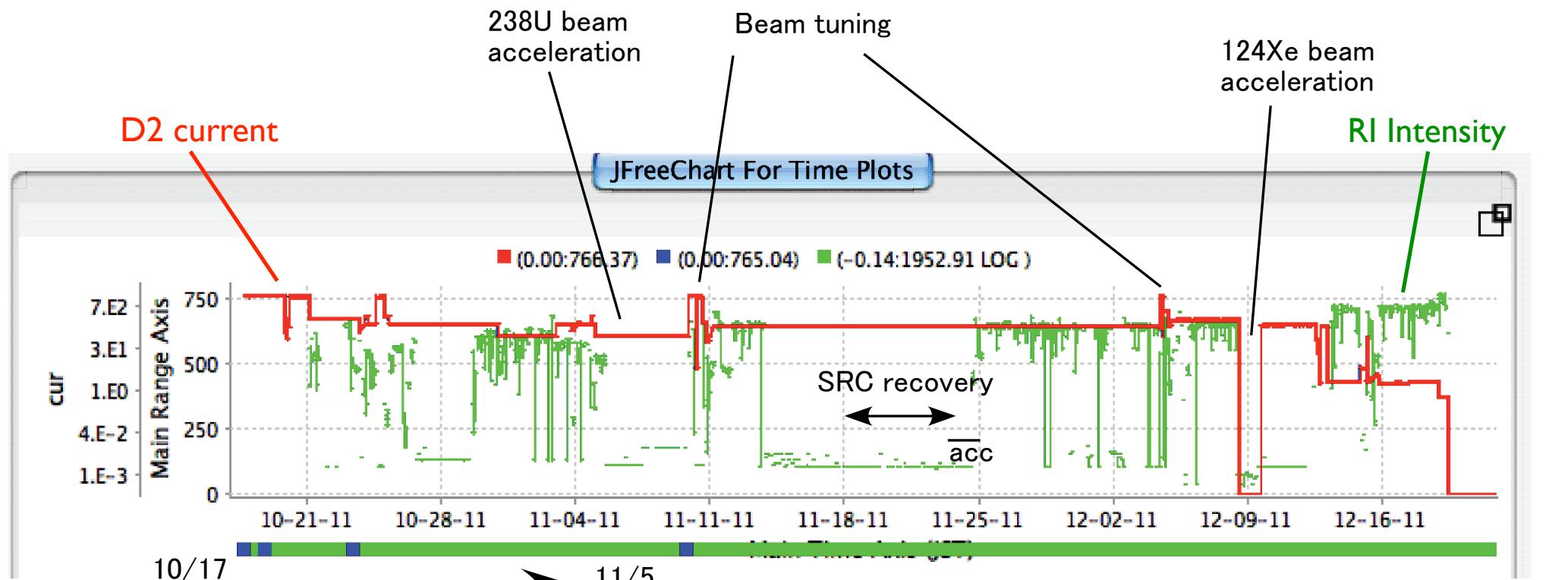


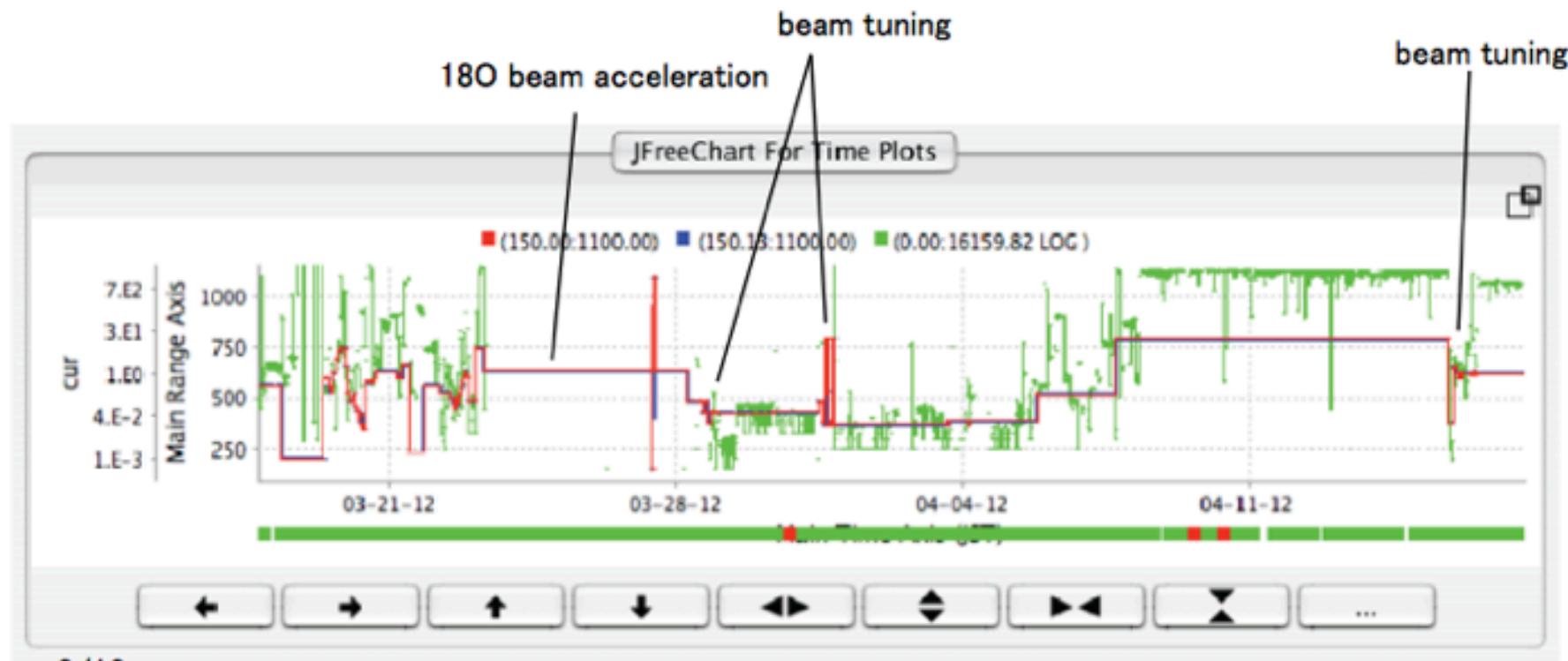
PALIS at F2 chamber (plan B)



The 30m BTL can be inclined by 1.2 degree







3/16 13:00 → 3/23 9:00

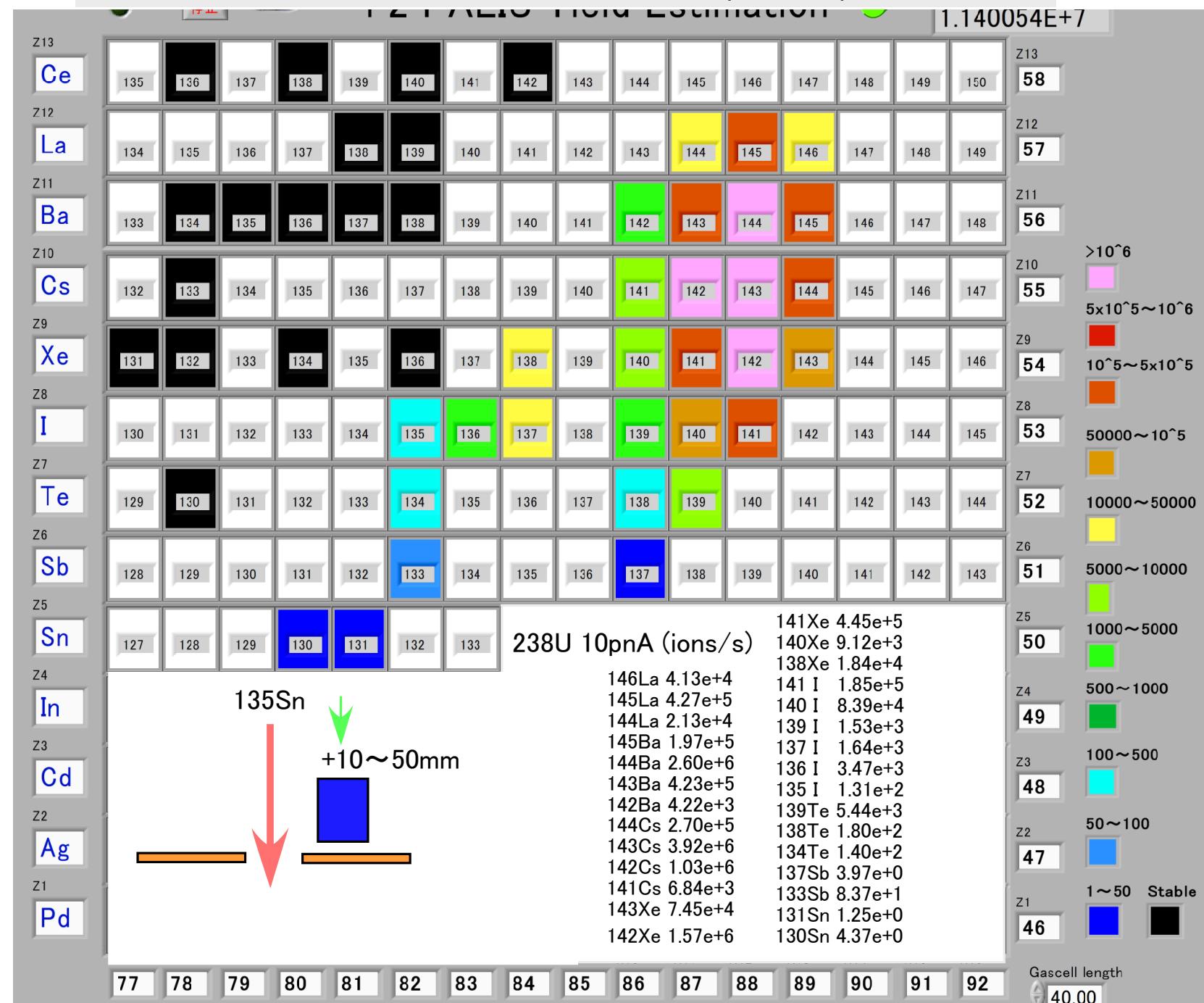
実験責任者 ピームコース 一次ピーム エネルギー
米田 SAMURAI 180 345MeV/u (Max 100pnA)

3/29 → 3/31
9:00 9:00

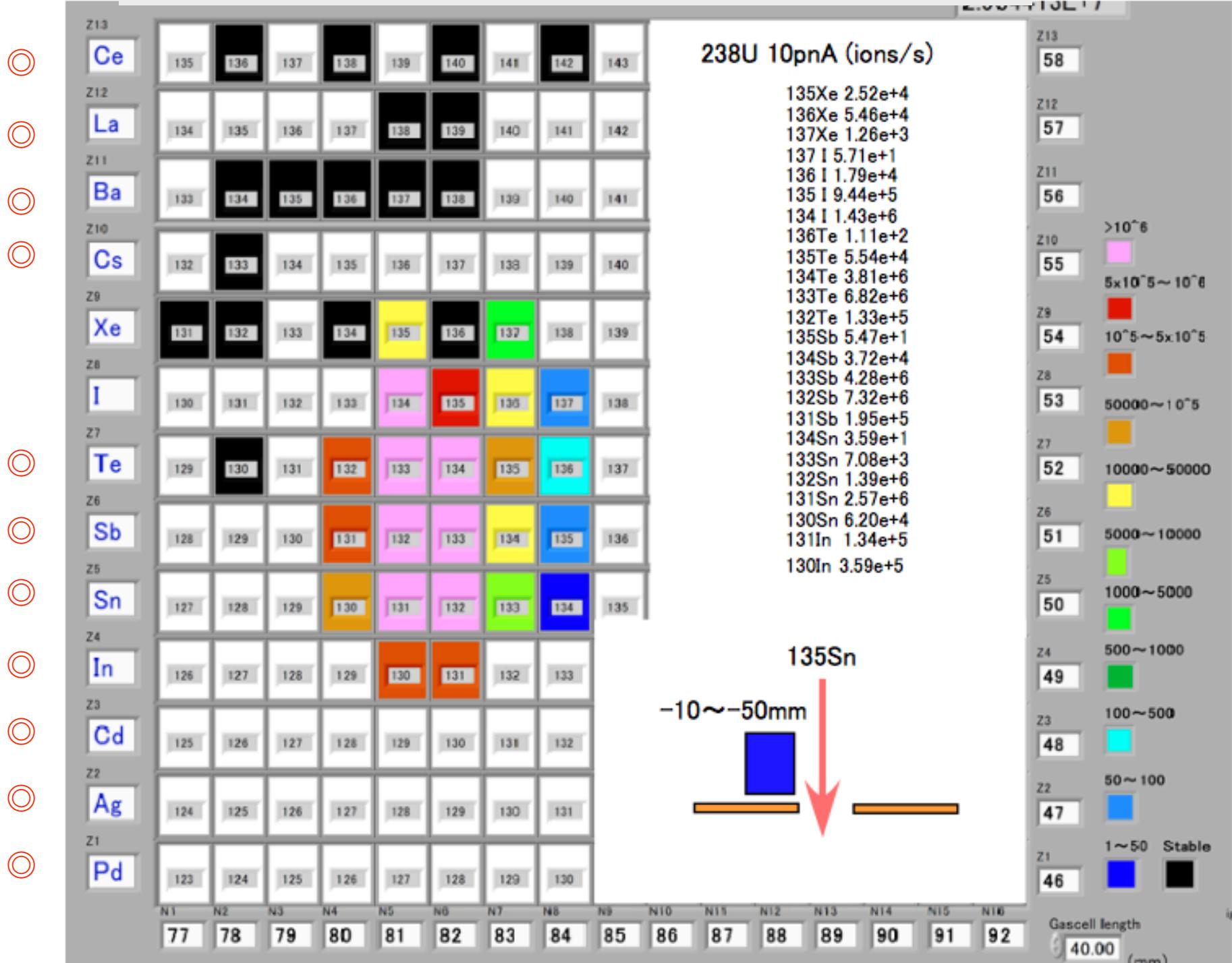
3/31 9:00 → 4/1 9:00

4/1
21:00 → 4/15
21:00
実験責任者 ビームコース 一次ビーム エネルギー
下浦 SHARAQ 180 345MeV/u (Max 100pnA)

4-8, Dec. 2011, Aoi et al, (Sn I 35)



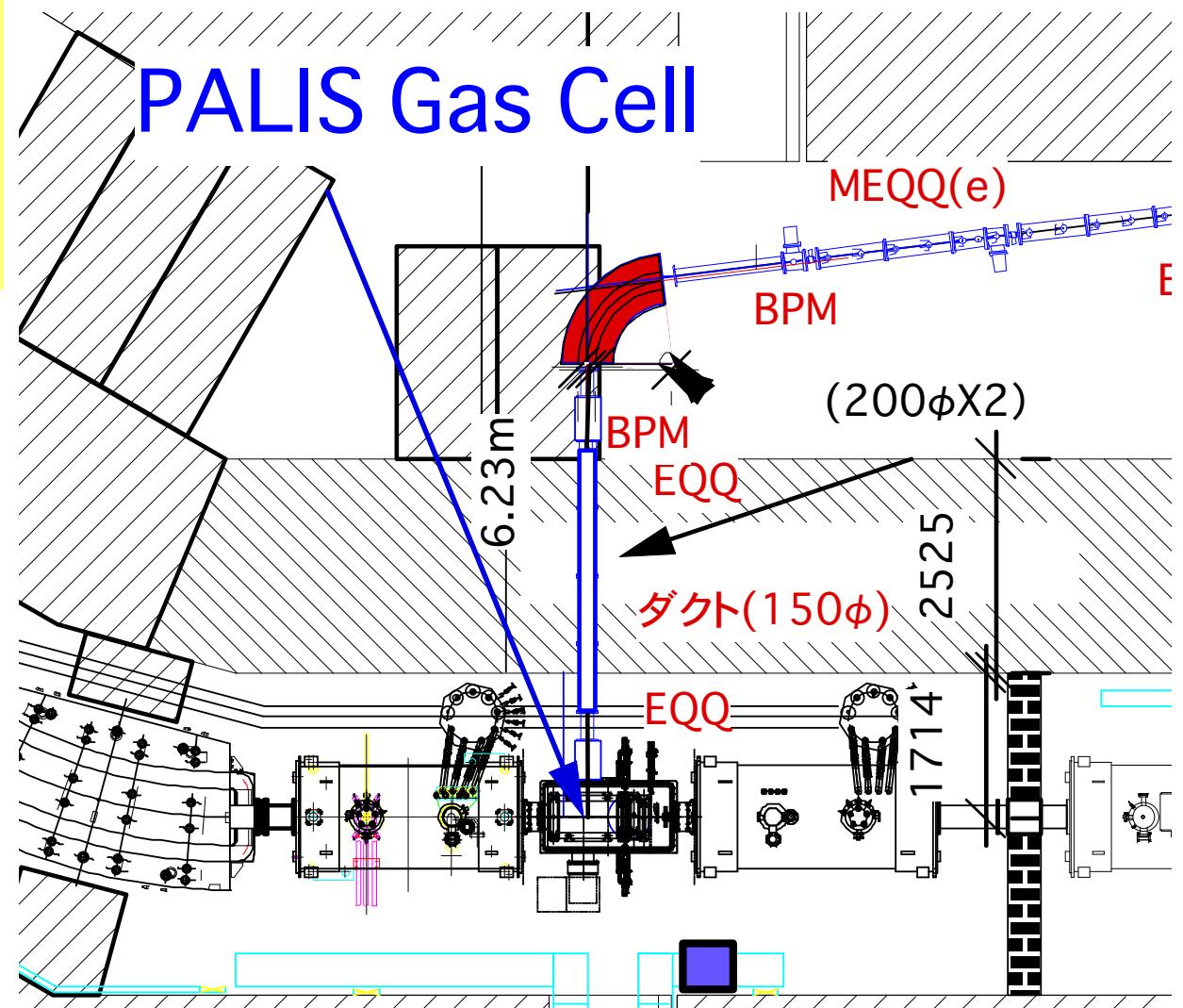
4-8, Dec. 2011, Aoi et al, (Sn135)



Day Zero exp.

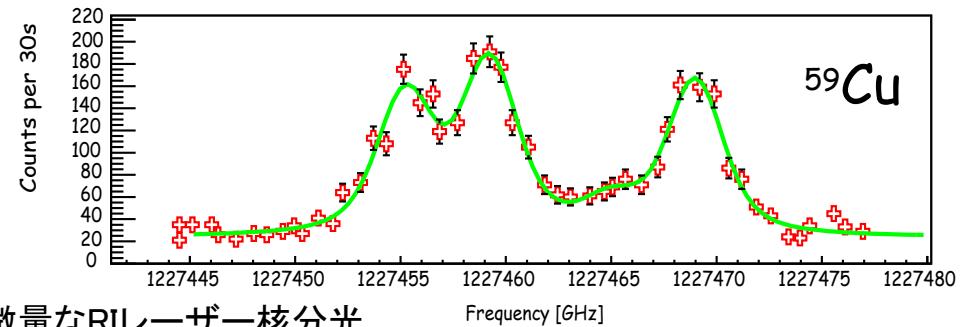
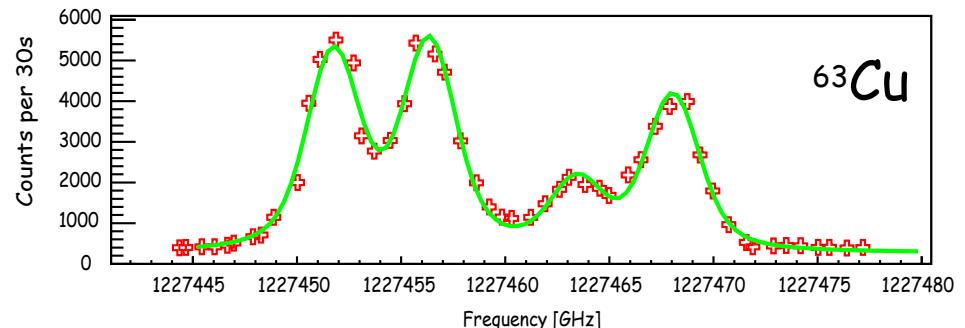
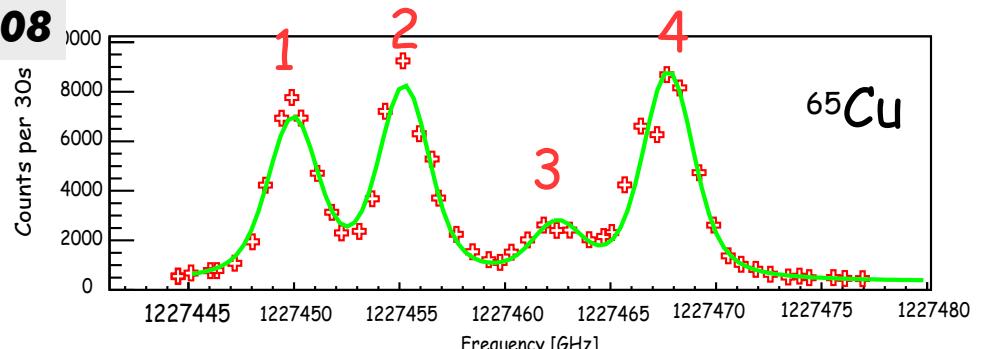
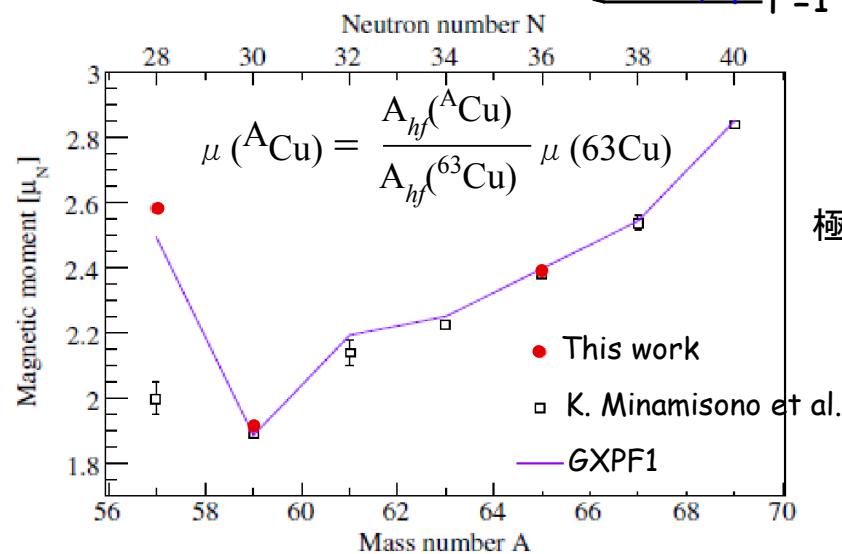
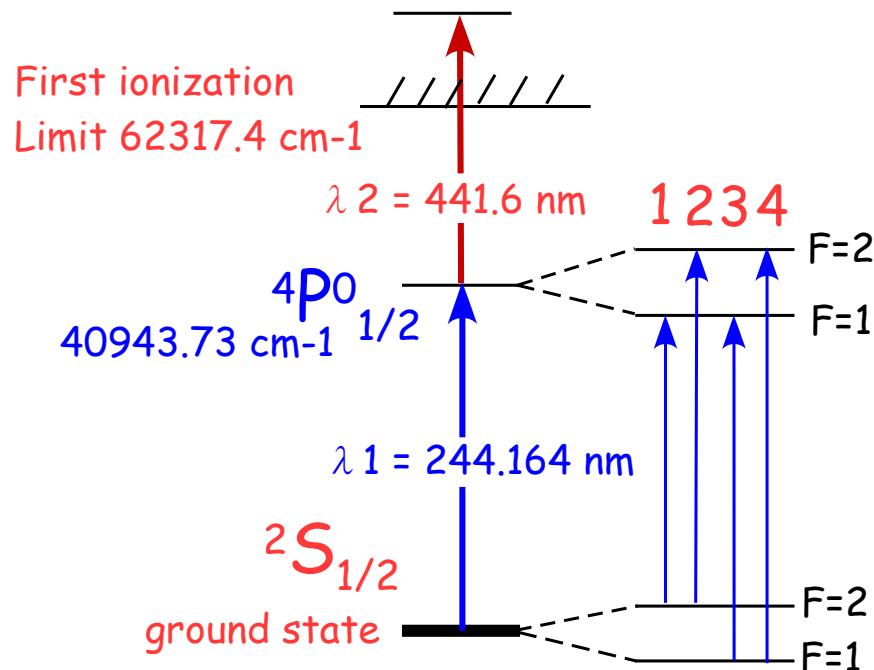
exp. during commissioning

Resonance Ionization
Spectroscopy
at PALIS and up to
SDI, BPM

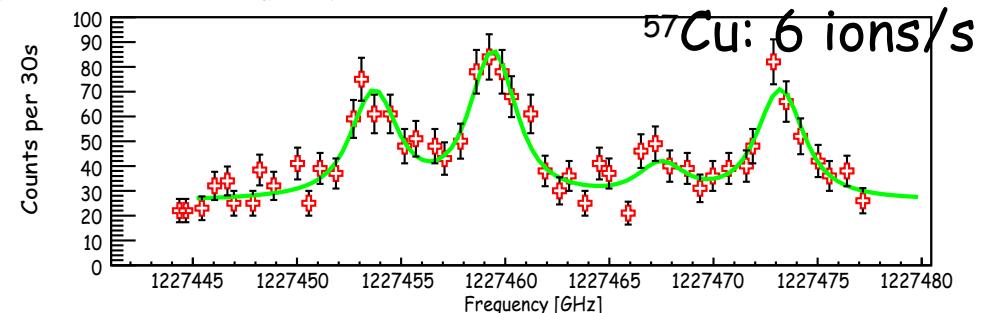


Ex. RIS Spectroscopy in Gas Cell @Leuven 2008

$\text{Cu}^+ + e^-$ Autoionizing state



極微量なRILレーザー核分光



T.E. Cocolios, A.N. Andreyev, B. Bastin, N. Bree, J. Buscher, J. Elseviers, J. Gentens, M. Huyse, Yu. Kudryavtsev, D. Pauwels, T. Sonoda, P. Van den Bergh and P. Van Duppen Phys. Rev. Lett. 103, 102501-3 (2009).

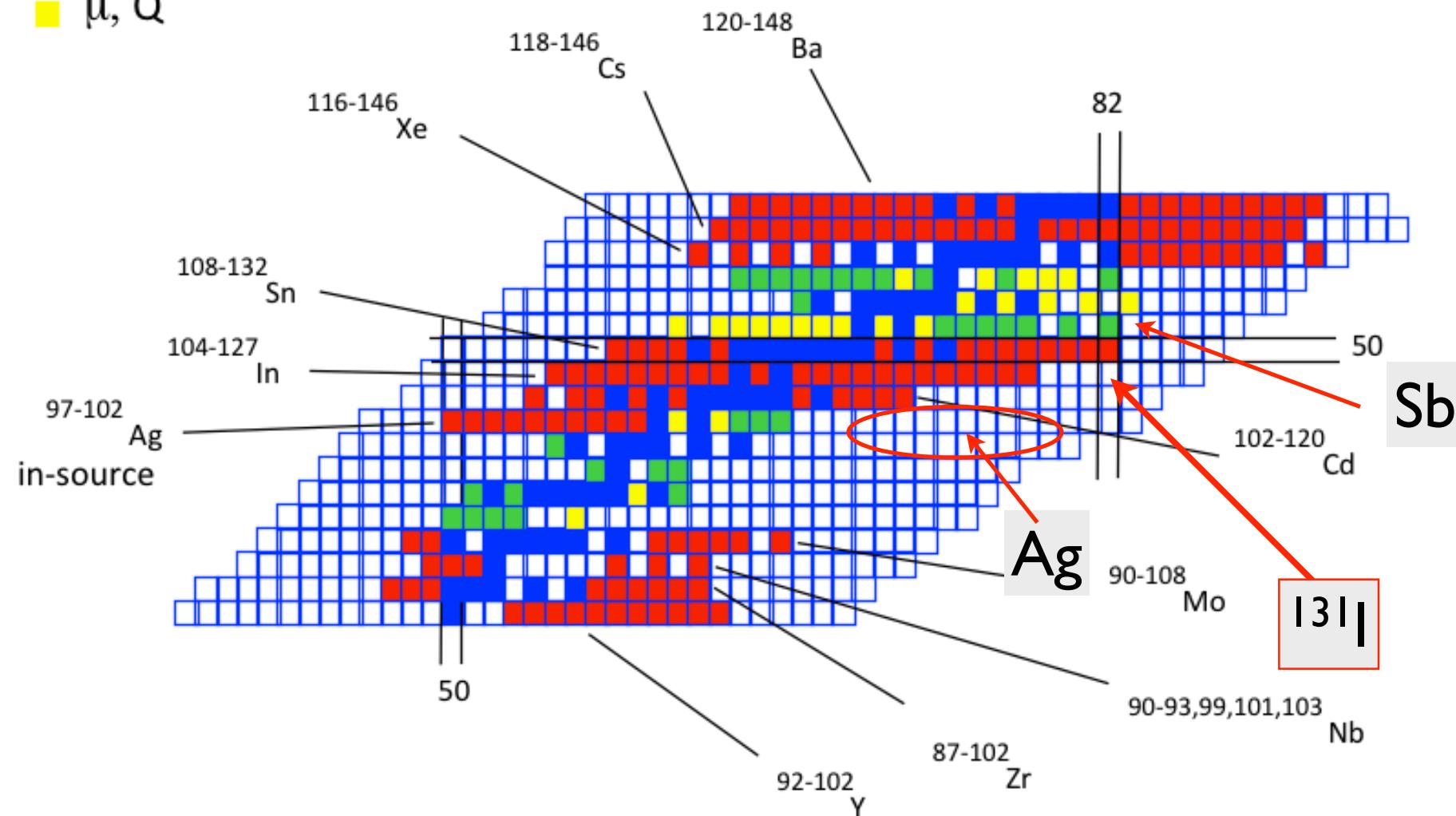
■ already studied by
laser spectroscopy

■ stable

■ μ

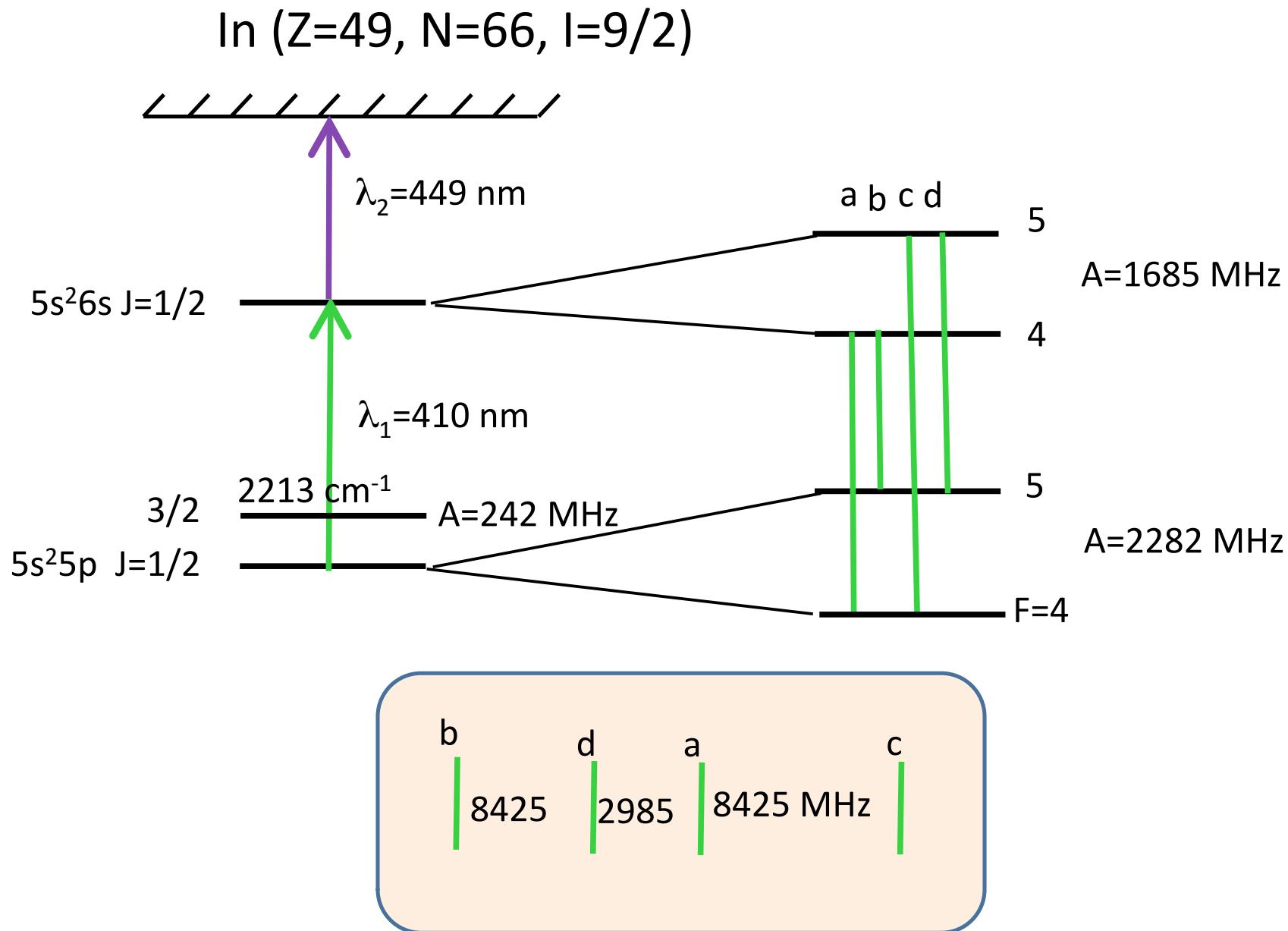
■ μ, Q

H. Iimura
JAEA

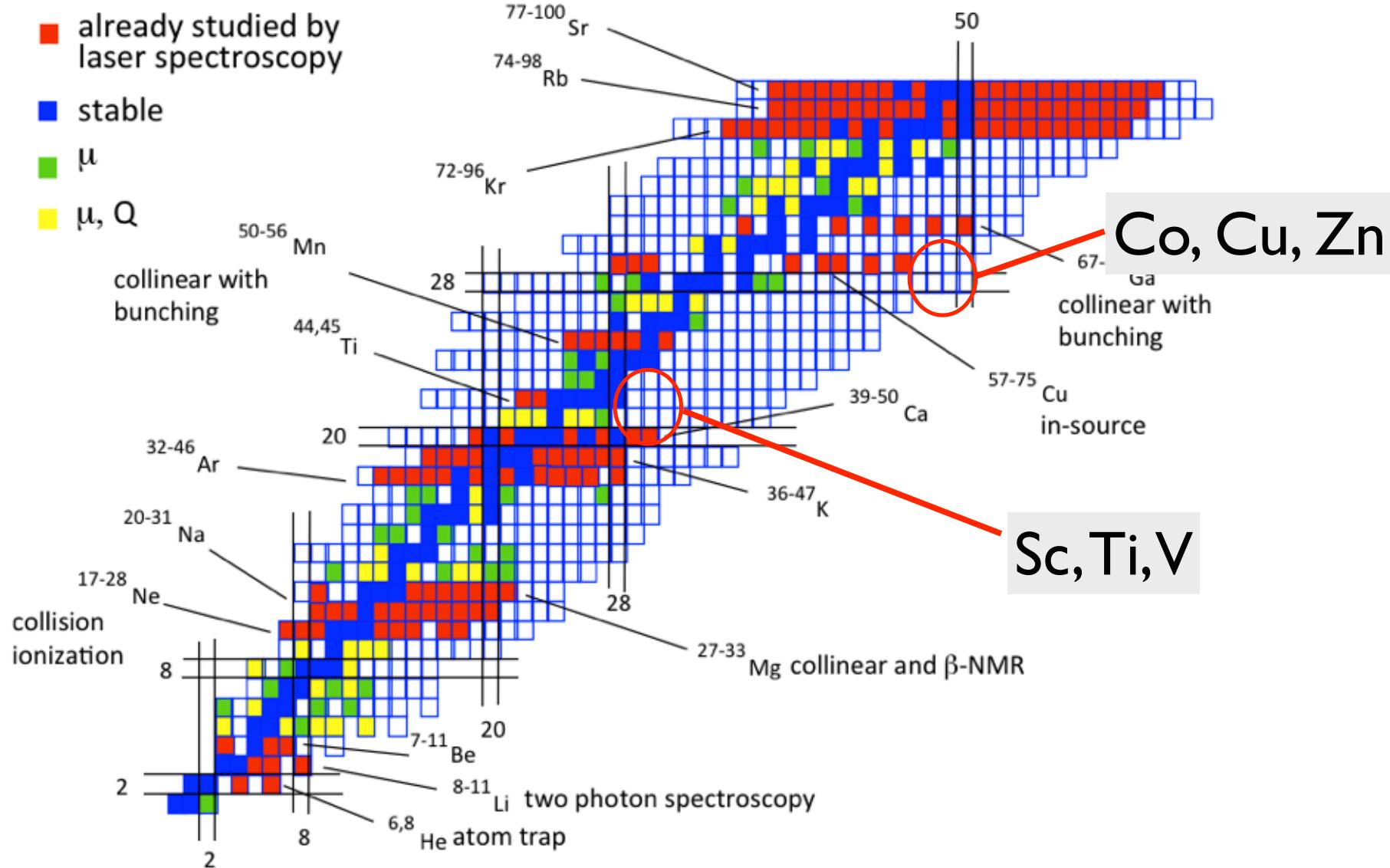


In: very large hfs.

^{131}In : double magic - p easy to interpret

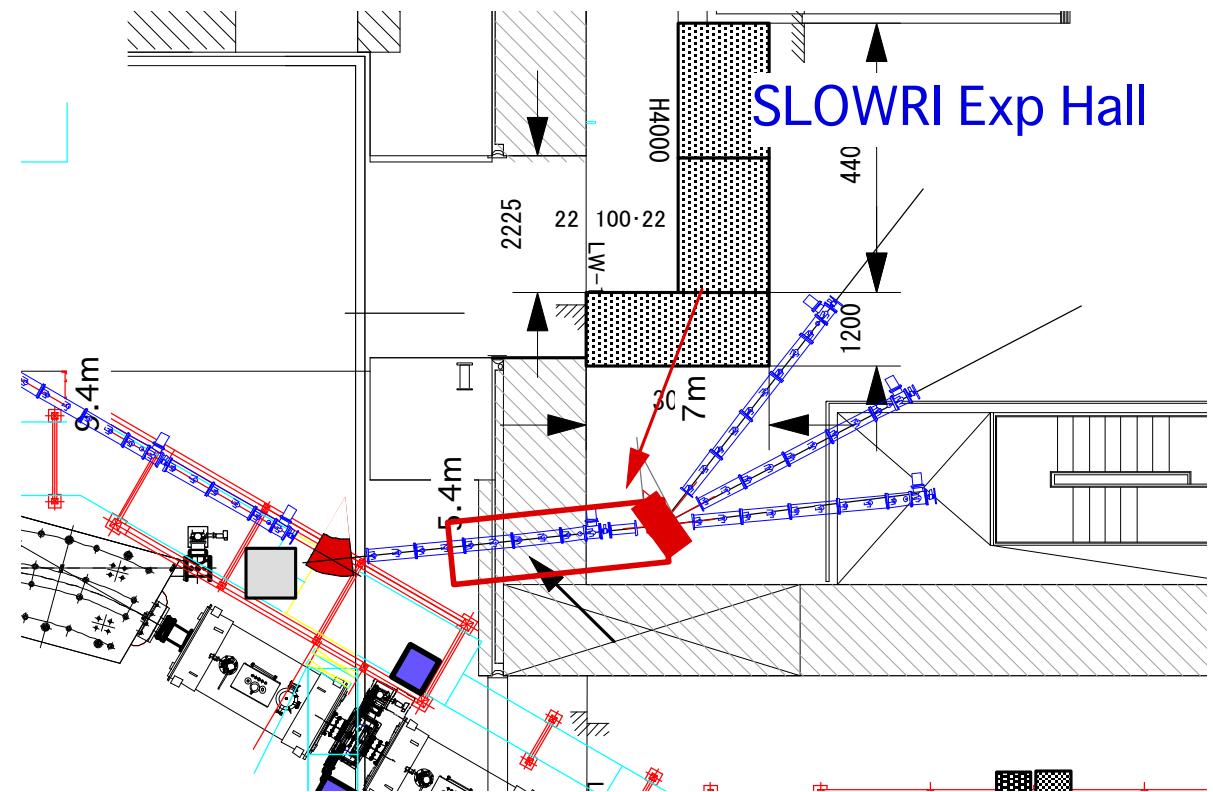


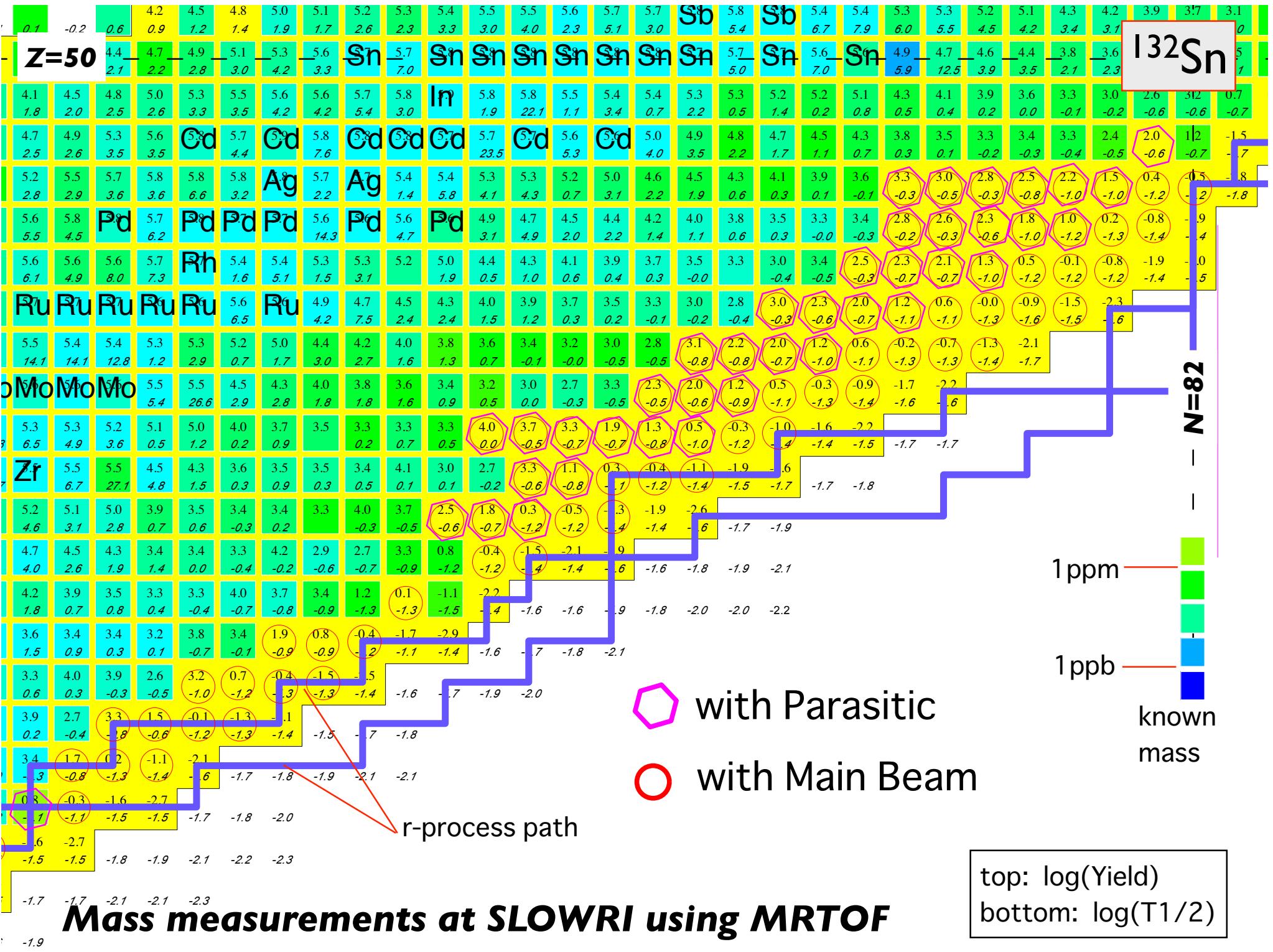
other RIS candidates



Day One, Two exp.

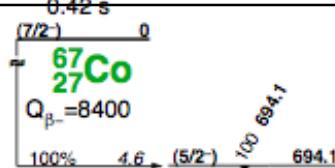
- Direct Mass Measurements with MRTOF-MS
- Collinear Spectroscopy
- Decay Spectroscopy





Mass Measurements of Short-lived Nuclei

Q-value (decay or reaction)



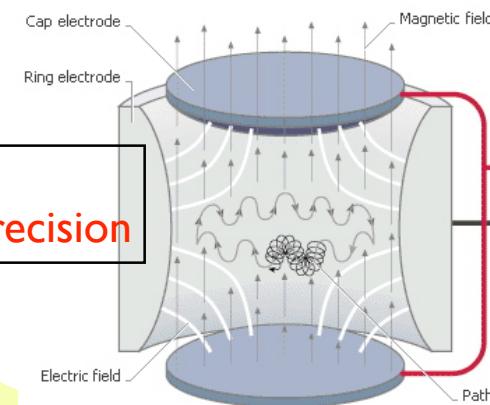
Universal Ambiguity from levels



indirect

direct

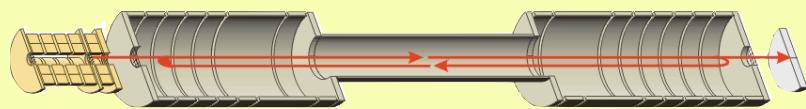
Penning Trap



Slow Ultra precision

New method

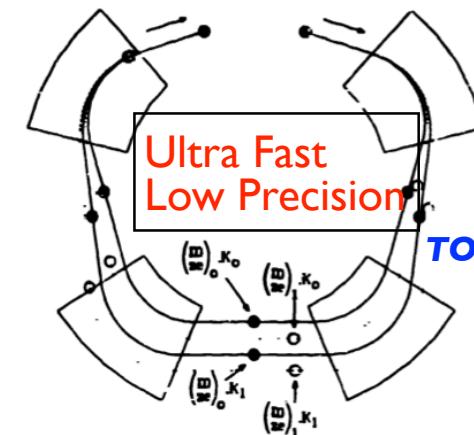
MRTOF (多重反射型TOF)



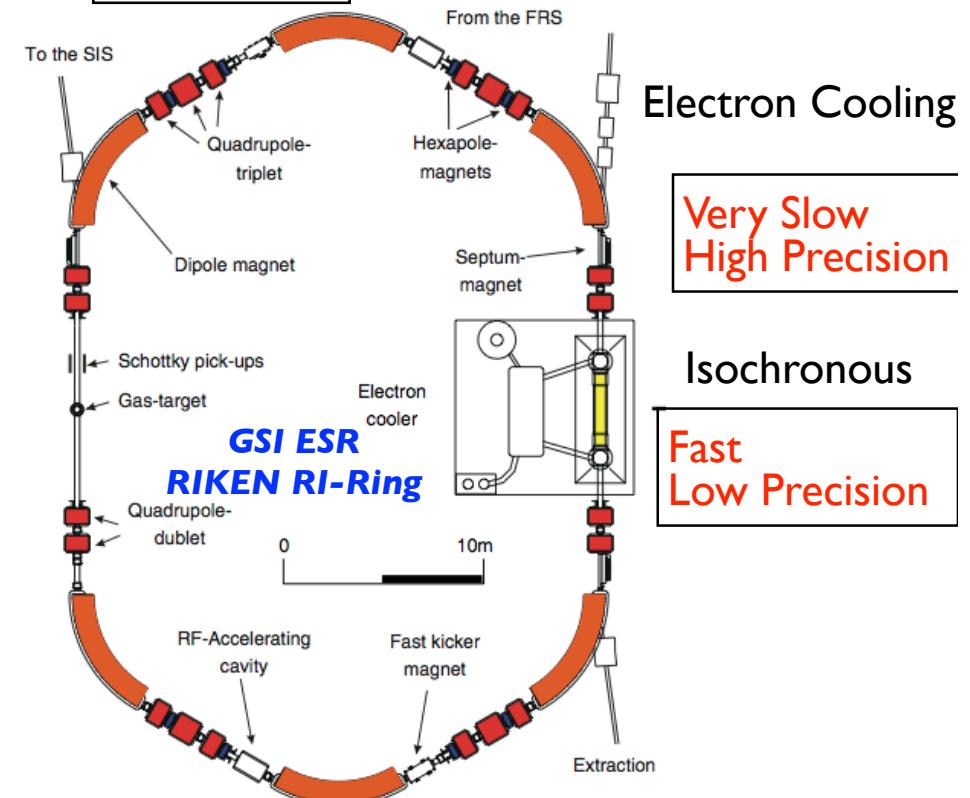
RIKEN, Giessen ..

Fast High Precision

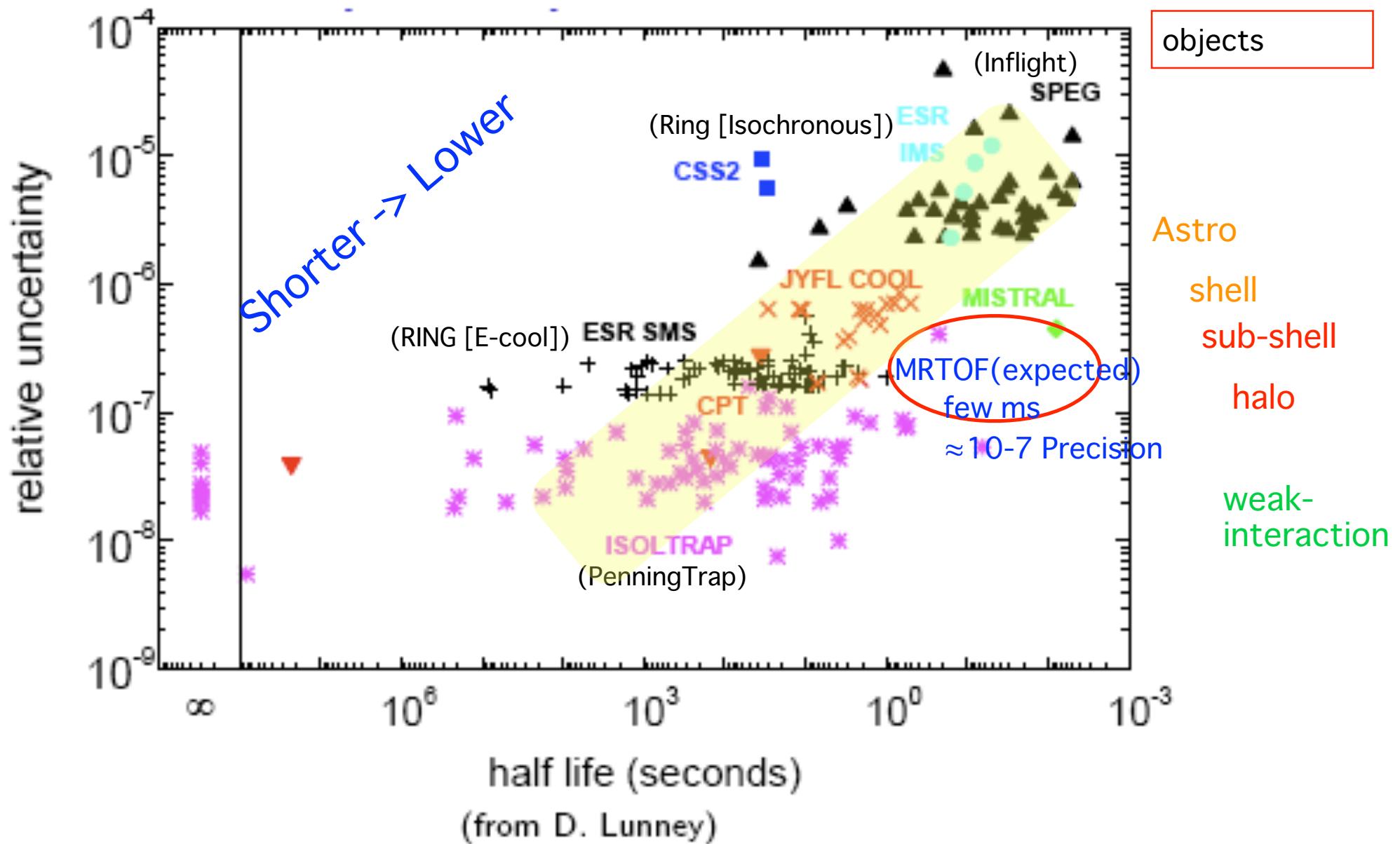
In-flight spectrometer



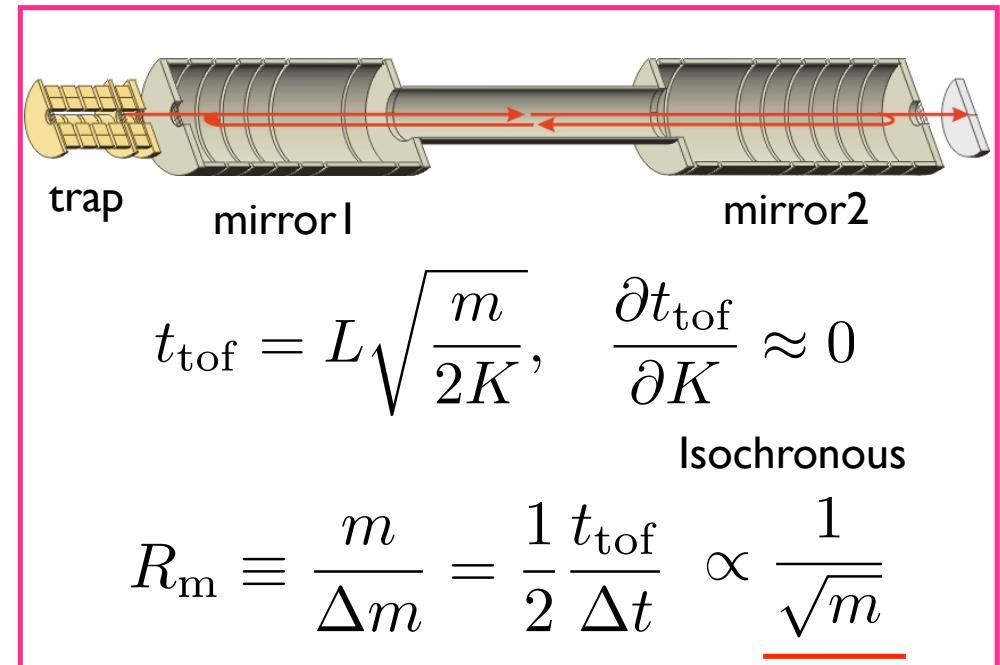
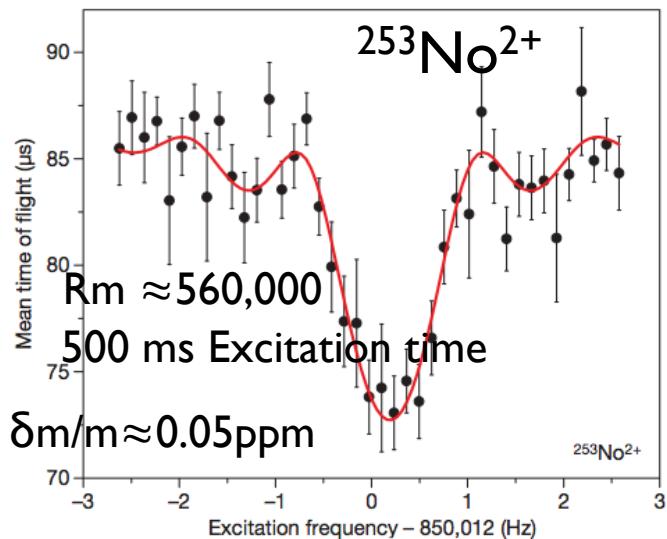
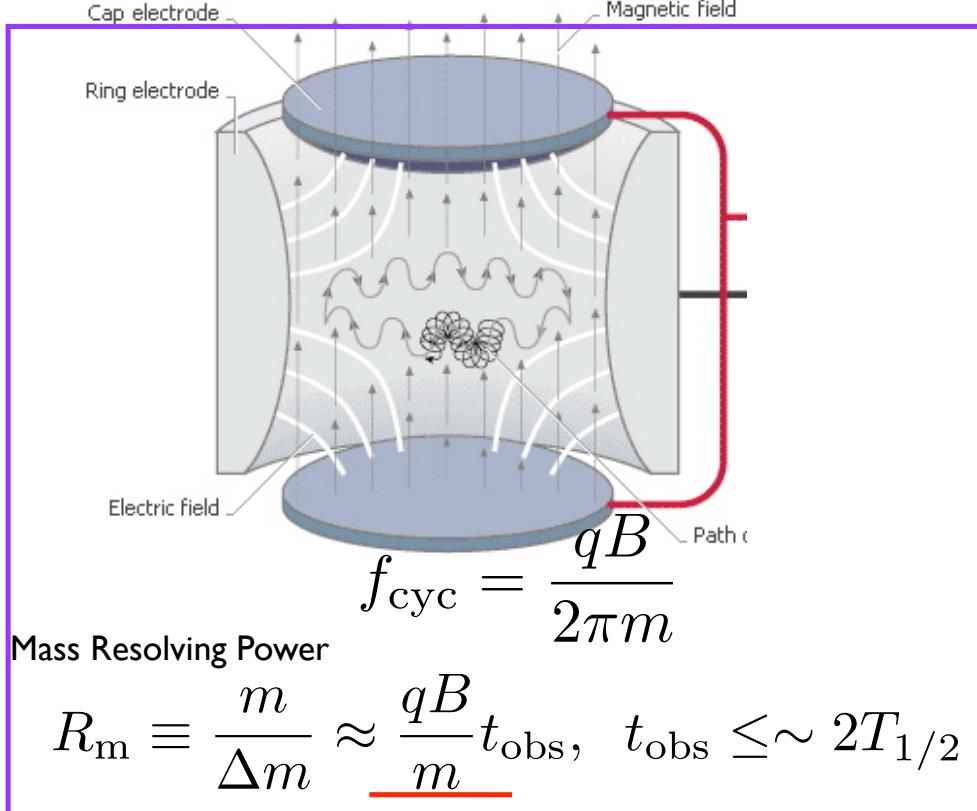
Storage Ring



Relative Mass Uncertainty and Half-life



Penning Trap Mass Spectrometer vs. MTOF Mass Spectrograph



For short-lived heavy nuclei,
MTOF overtakes PTMS

Chemical
molecules, too

$$\frac{\delta m}{m} \approx \frac{1}{R_m \sqrt{N}}$$

mass precision is
given by MRP and
statistics

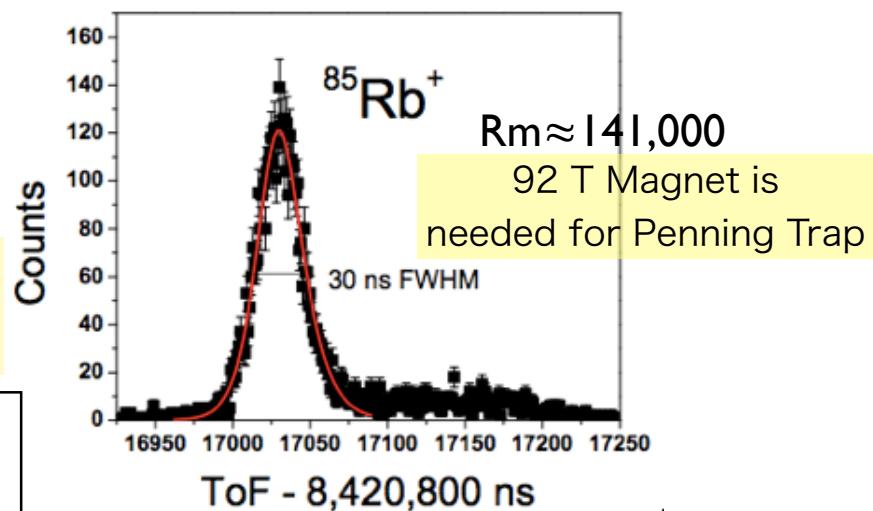
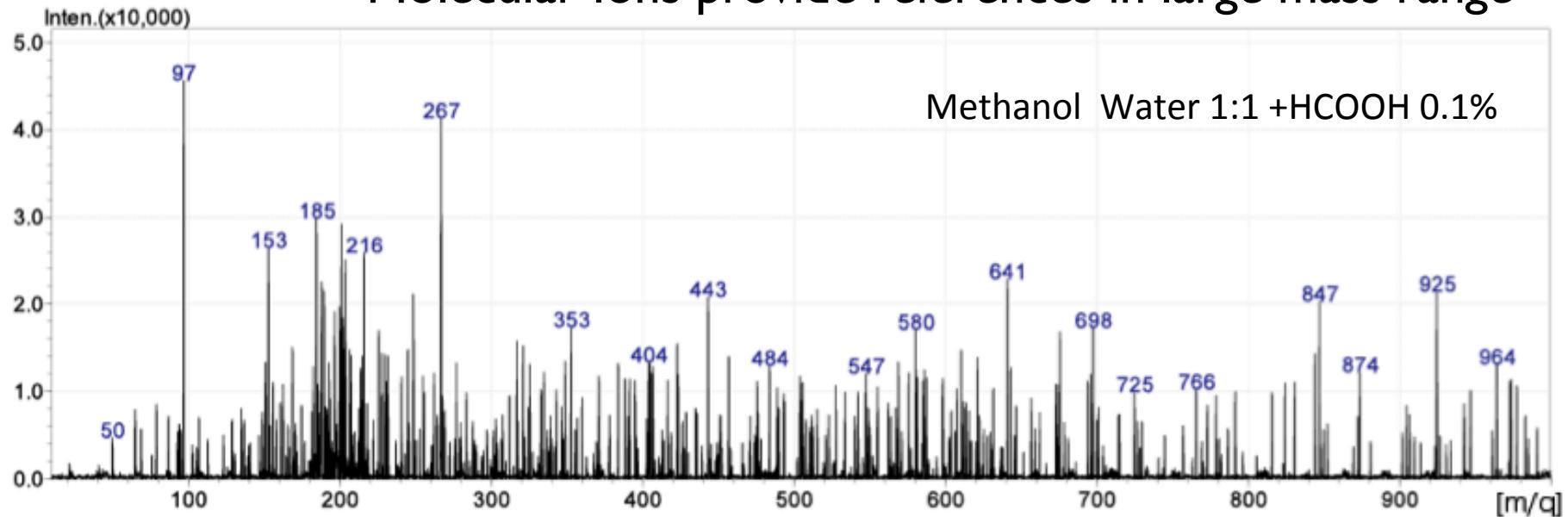


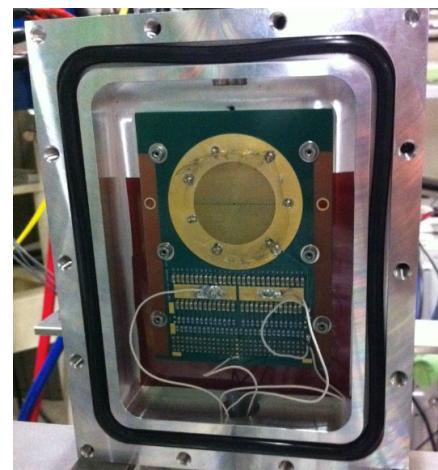
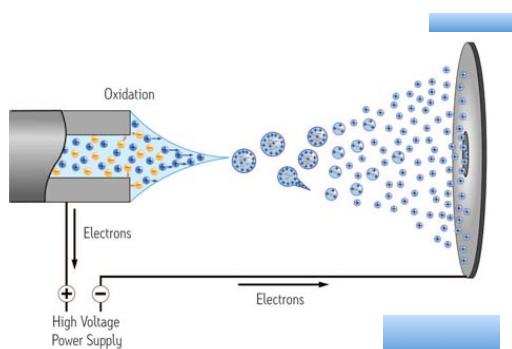
Figure 1 | Cyclotron resonance curve of $^{253}\text{No}^{2+}$. The solid line is a fit of the theoretical line shape to the experimental data (filled black circles). Error

TOF→Mass: References are indispensable

Molecular Ions provide references in large mass range



Electro Spray Ion Source + Small RF carpet



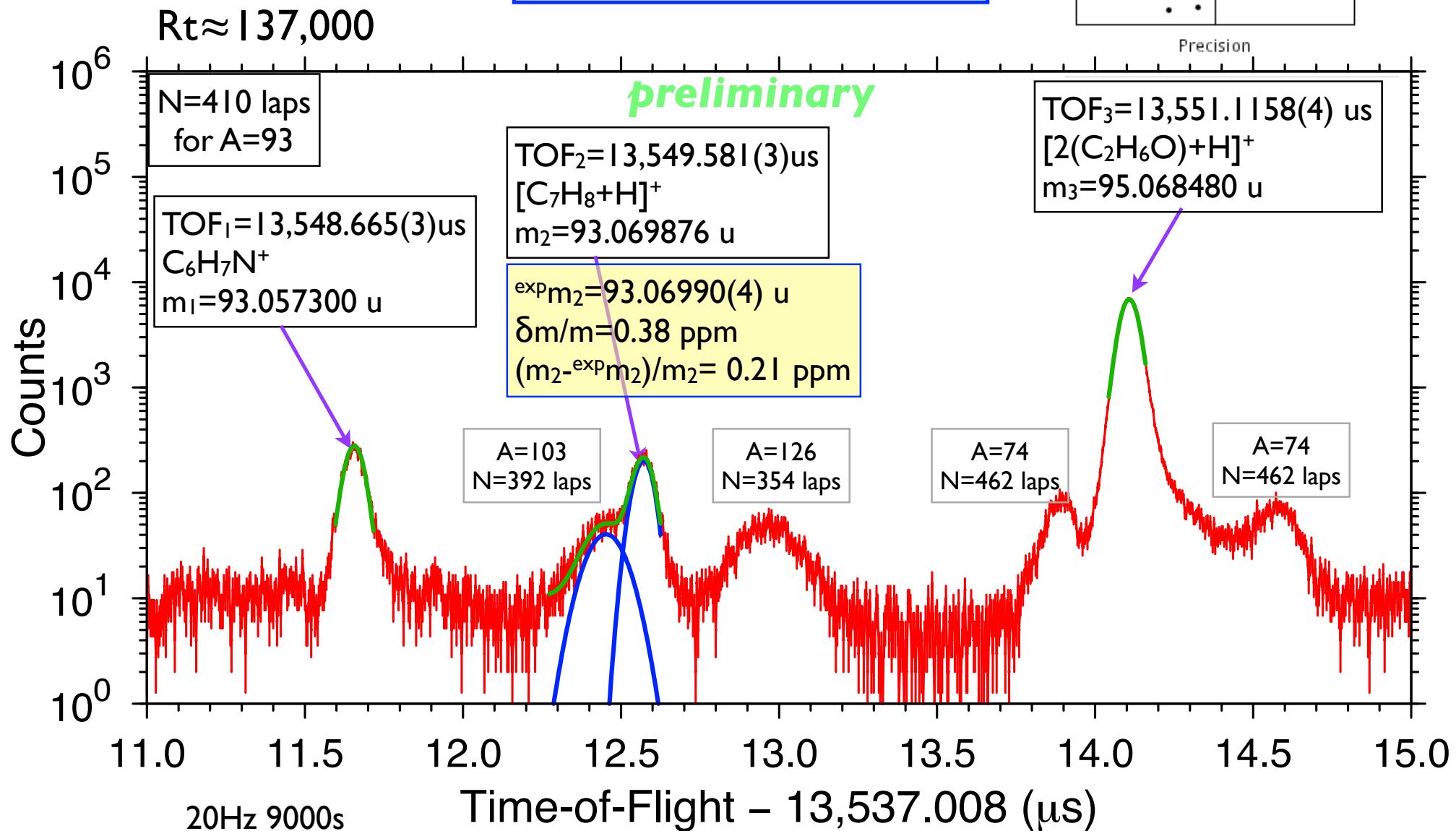
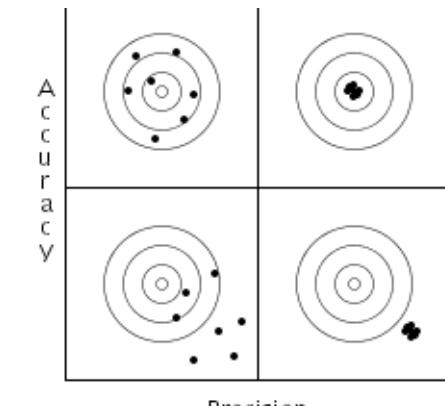
ESI attached to MRTOF for measurements



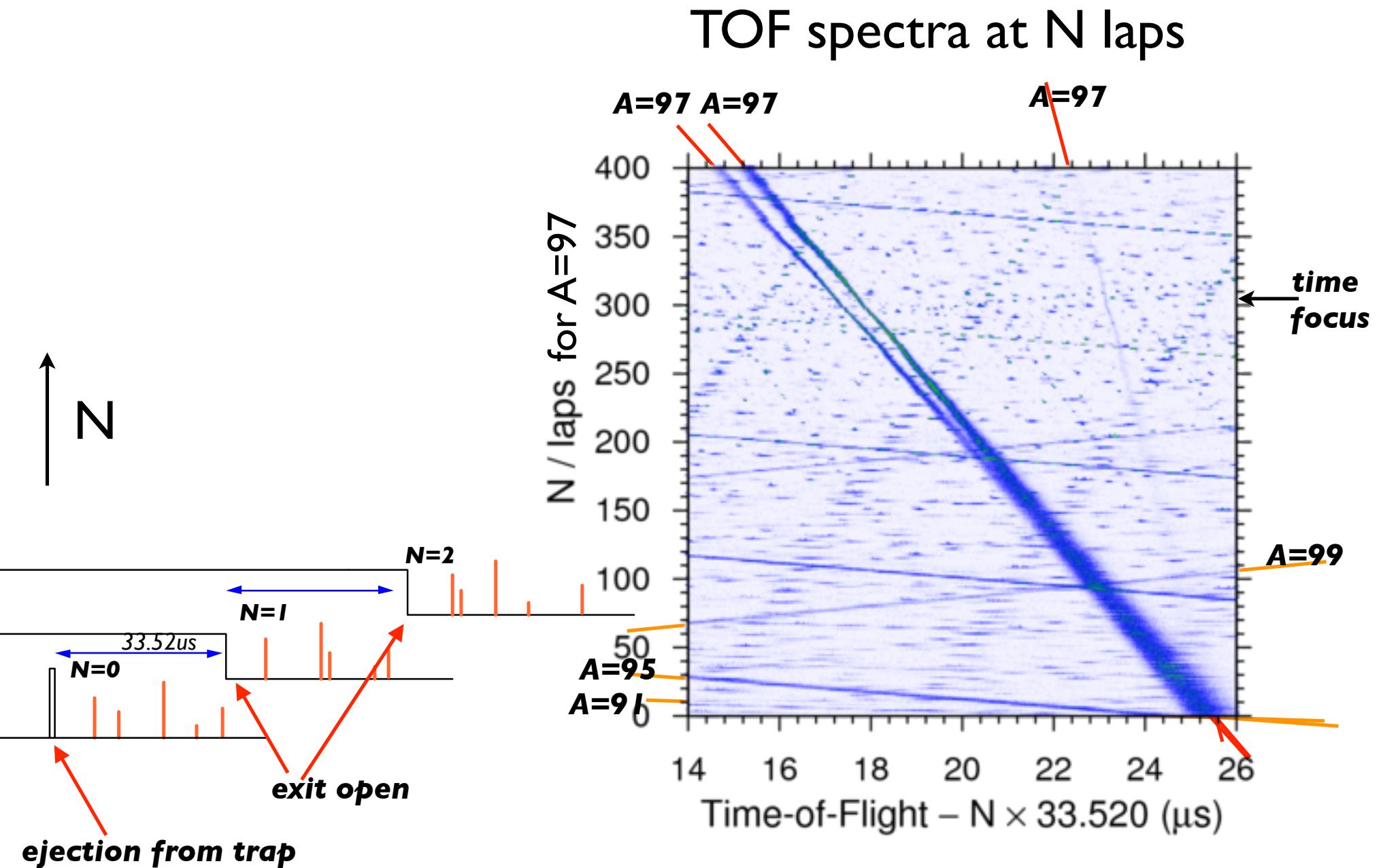
Mass Determination Test with Molecules

3 isobaric molecules ($A=93$).
Using two for references and deduce one.

精度(precision) 0.38 ppm
確度(accuracy) 0.21 ppm



Time Focus & TOF spectra at different laps



Decay Spectroscopy

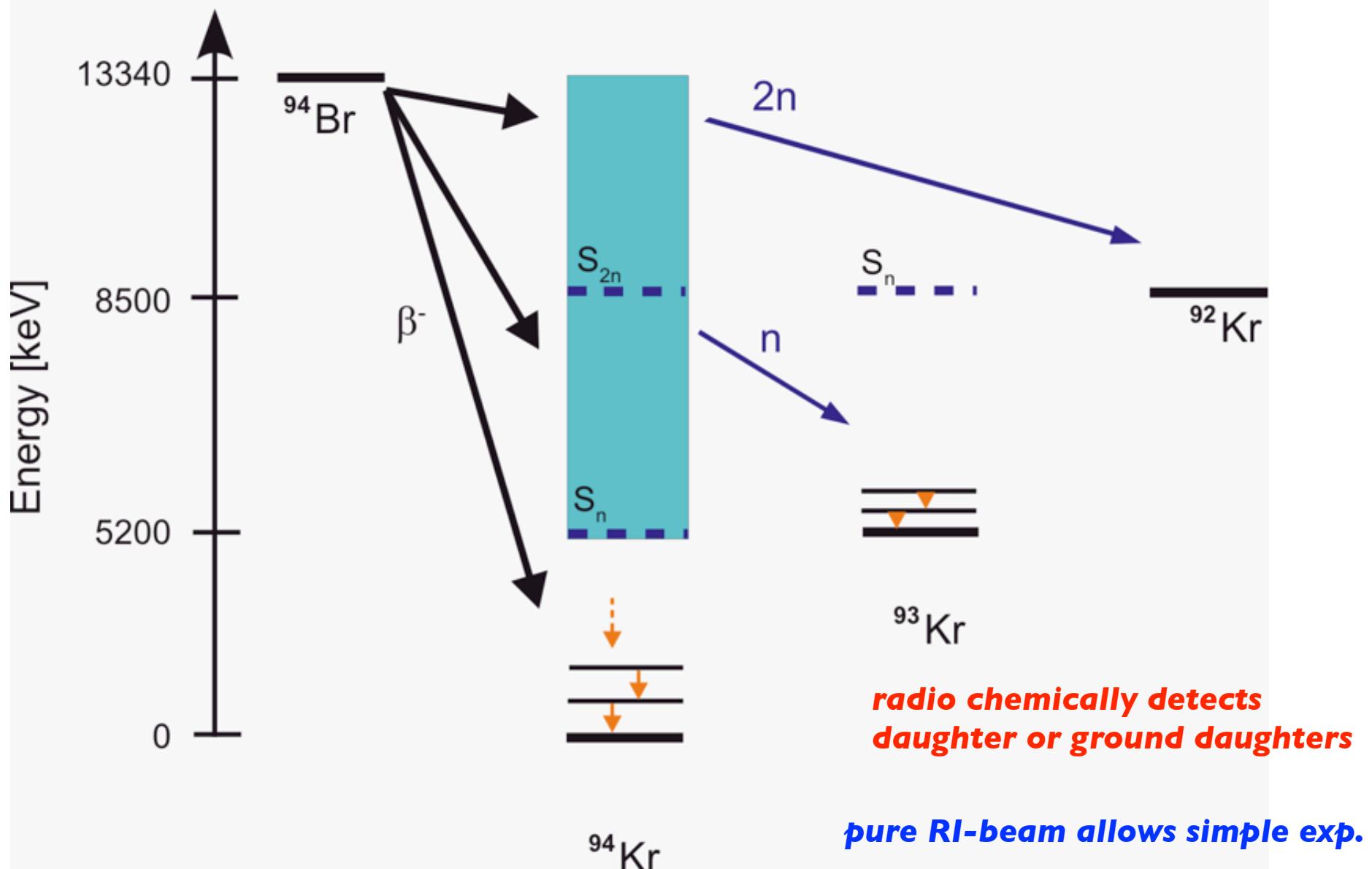
EURICA+Tape Transport ← **Pure Low-Energy RI-beams**

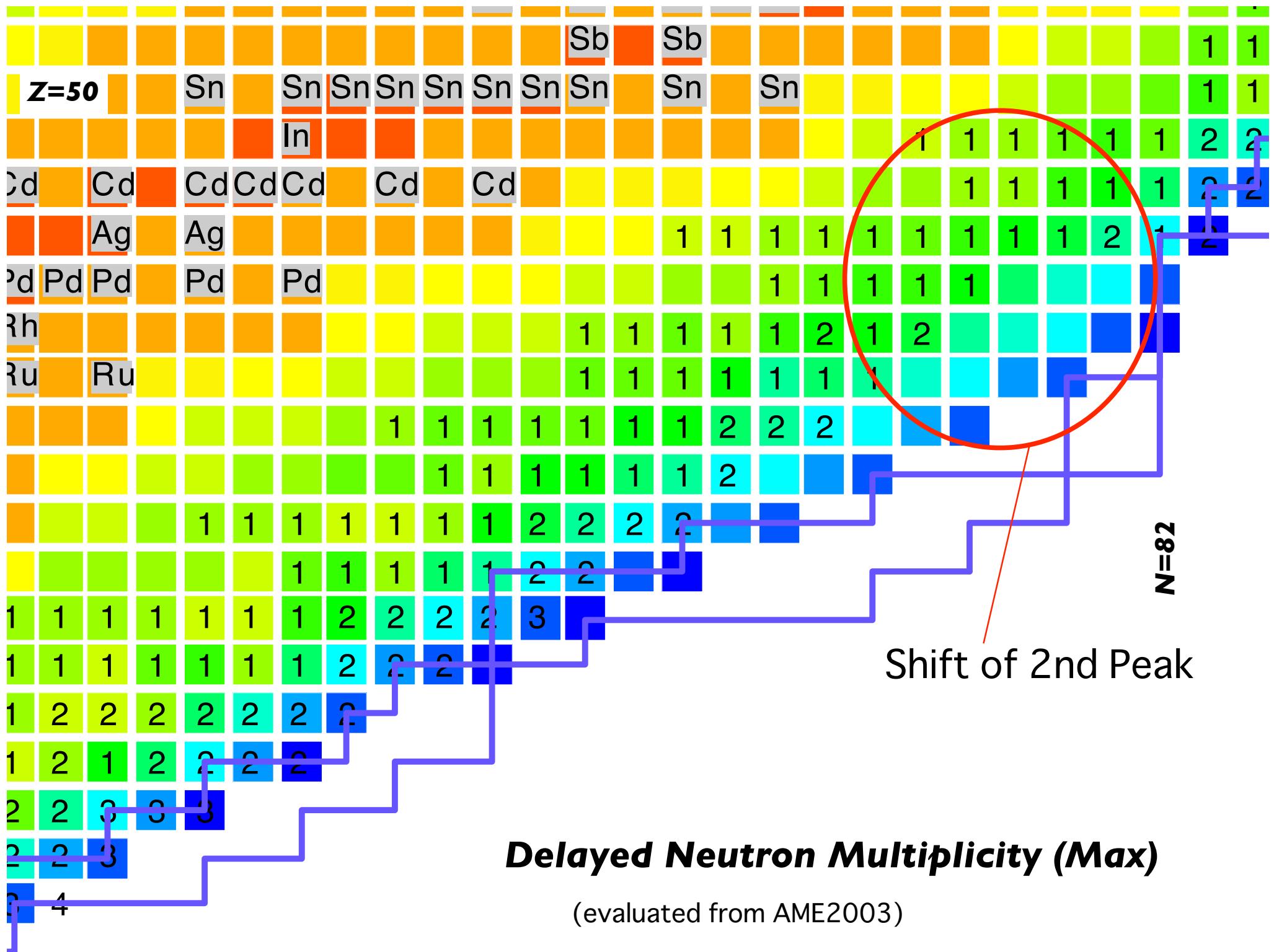


ε : 10~28%,
high granularity

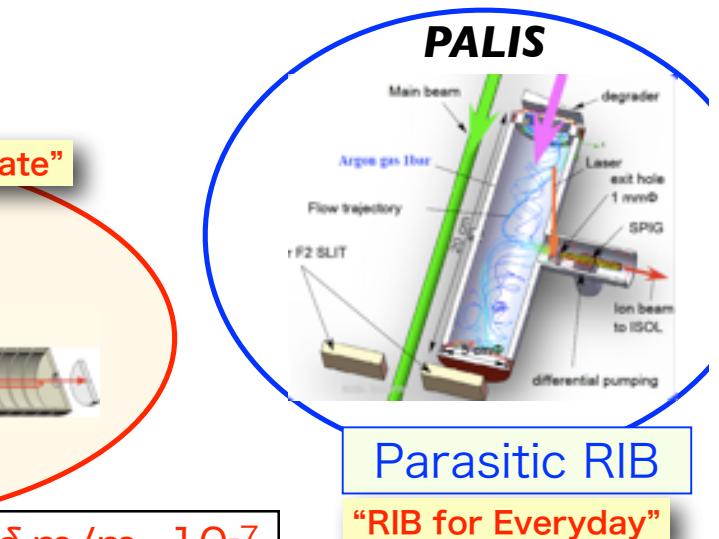
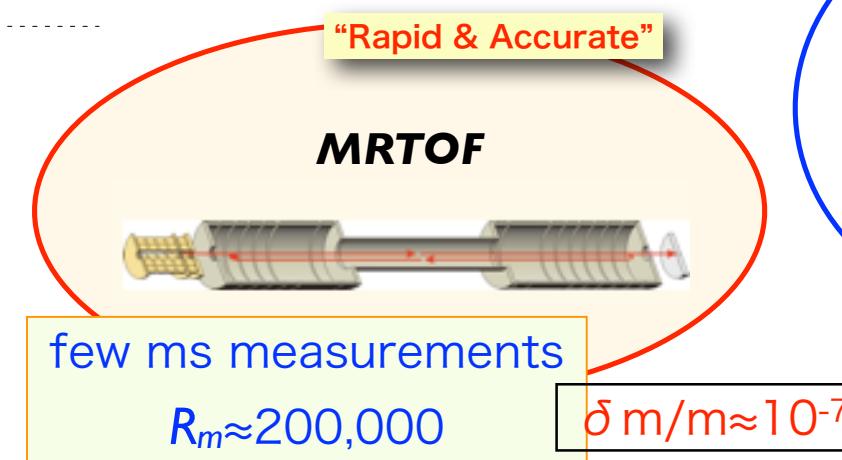
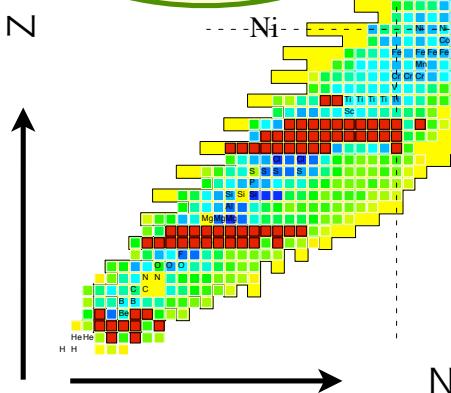
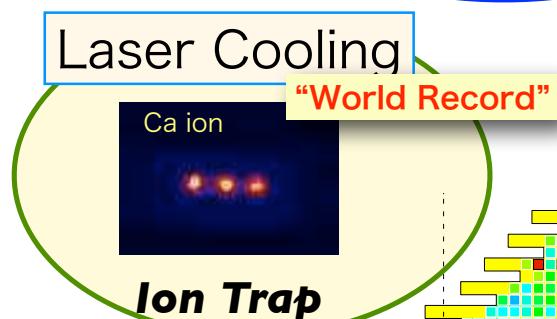
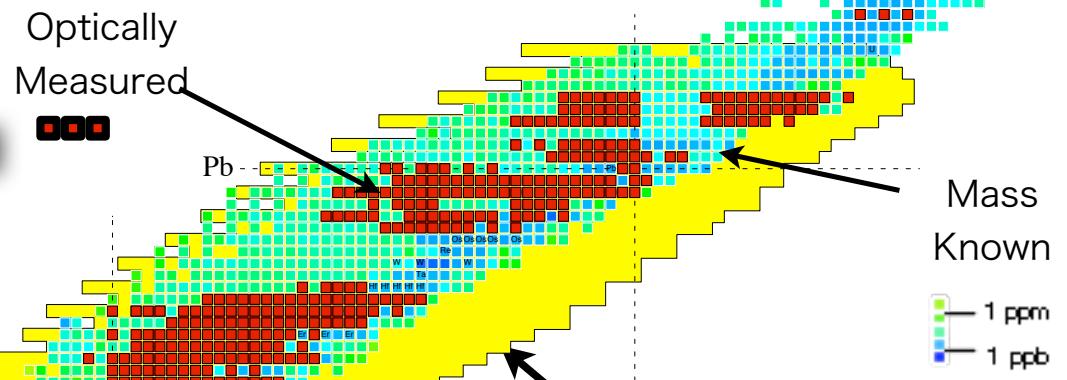
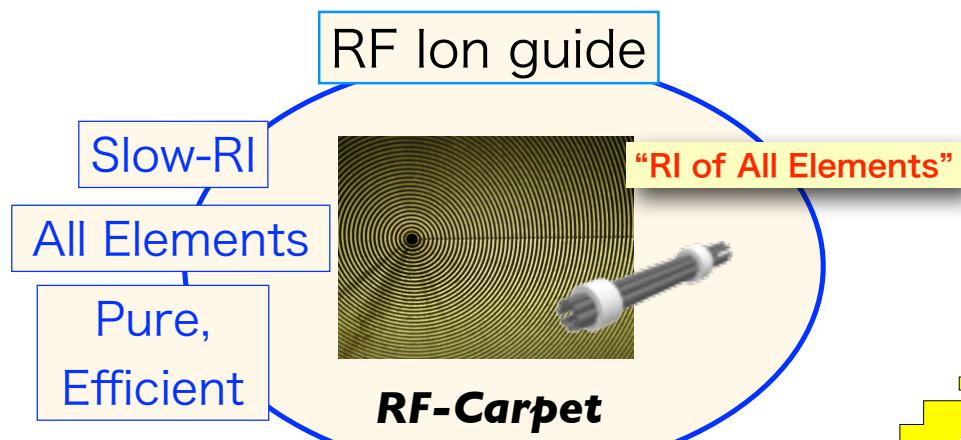
- Level Schemes
coincidence
- PAC
Magnet+ Isomeric states
- Delayed Neutron
radiochemical method

β -delayed 1n and 2n emission from ^{94}Br





Mass known: ≈ 2000 \rightarrow ≈ 3000 $1.5 \times$
 Opt. Spectroscopy ≈ 600 \rightarrow > 1200 $2 \times$ Expands
 Knowledge



Criticisms

1. Main user frequently changes Bρ
slide#35,36, fixed several days in many cases!
2. Parasitic beam has never used at RRC
sharing primary beam always causes loss, while secondary beams are always available without losses
3. RIS limits Nuclides as ISOLDE
slide#12, diffusion in target is the issue !
4. RF Gas Cell should be located freely accessible room, then 1.5 days between Main exp can be provided for SLOWRI
It is good if €1M more investment is allowed

Two type gas cell for SLOWRI

pros & cons

	RF-carpet Gas Cell	PALIS Gas Cell	ISOL
elements	≈all	≈70% elements	<50%
nominal extraction time	≈10 ms	≈0.1~1 s	≈1 s
total efficiency	≈10 %	≈1 %	
availability	< 2 weeks/year	≈everyday	

very complementary

daily exp. using PALIS,

particular nuclei using RF gas cell with main beam

Innovation of electric curtain with standing & traveling wave, in 1972

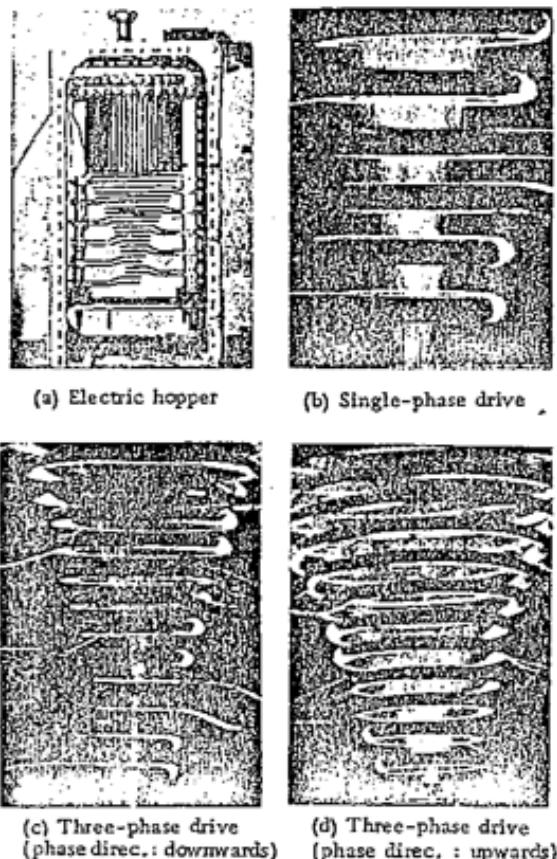


Fig. 7. Electric hopper and its modes of operation (polarity of particle charge: positive).

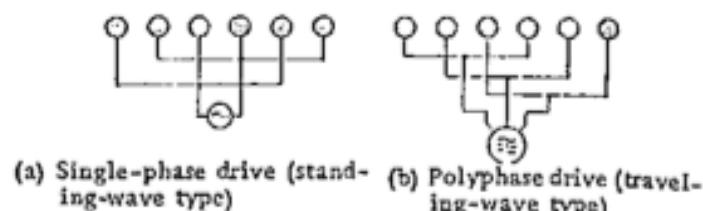


Fig. 2. Electric energization.

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IEEE, translation from Trans. IEE Japan, Vol. 92B, pp. 9-18 (1972).

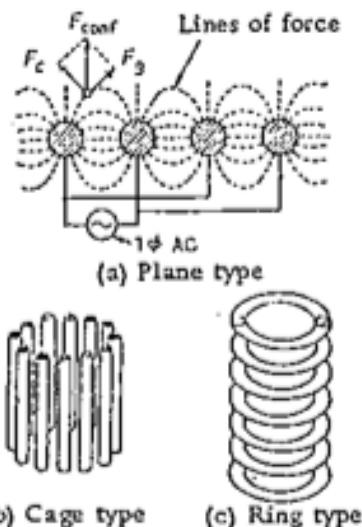


Fig. 1. Principle and basic constructions
of the electrostatic curtain.



of electrostatics and its applications, incl
pulse energization, electrodynamics of char

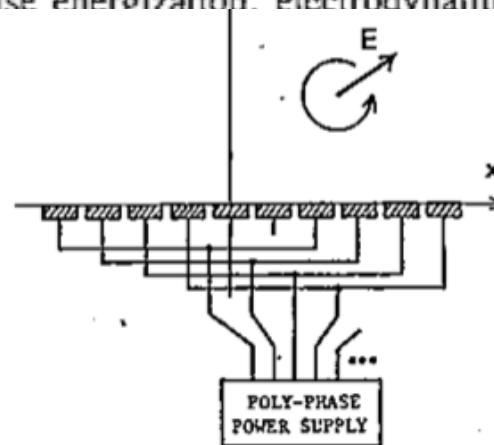


Fig. 1. Traveling-field-type electric curtain device.

- Innovation of rf hopper, curtain
 - transport aerosol, organic cell ions in air

2 or 3 Step Resonance Ionization

elements available at ISOLDE RILIS																	
1 H	ionization scheme tested																2 He
3 Li	4 Be																
11 Na	12 Mg																
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110	111	112						

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr