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Beta-decay of highly-charged ions

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Seminar on „Aktuelle Probleme der Beschleuniger- und angewandten Schwerionenphysik“

Institut für Angewandte Physik,
J. W. Goethe-Universität Frankfurt am Main
12 November 2010

Beta decay

Nuclear weak decay in general form:

$$n + \nu_e \leftrightarrow p + e^-$$

i) continuum beta decay:

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad \beta^- - \text{decay}$$

$$p \rightarrow n + e^+ + \nu_e \qquad \beta^+ - \text{decay}$$

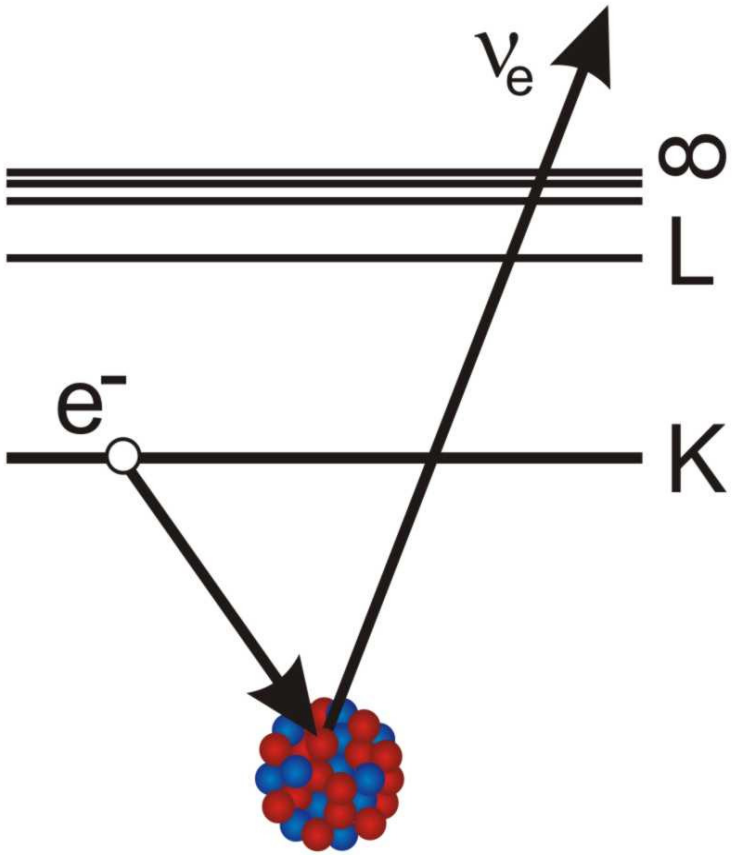
ii) two-body beta decay:

$$p + e_b^- \rightarrow n + \nu_e \qquad \text{Orbital electron capture (EC)}$$

$$n \rightarrow p + e_b^- + \bar{\nu}_e \qquad \text{Bound state beta decay } (\beta_b^-)$$

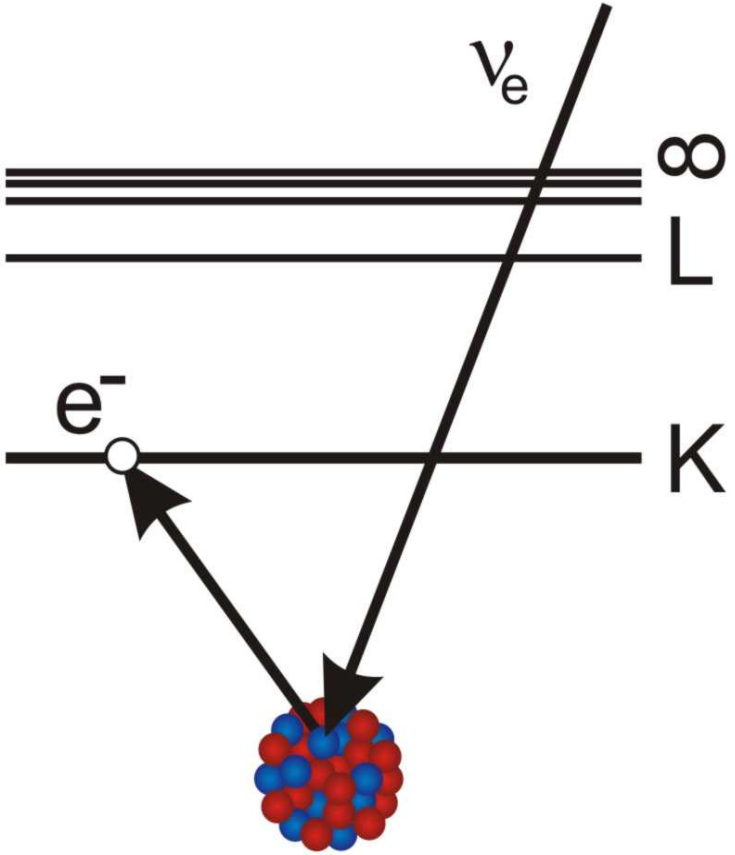
$$p + e^- \rightarrow n + \nu_e \qquad \text{Free electron capture}$$

Two-body beta decay



(Z,N) → (Z-1,N+1)

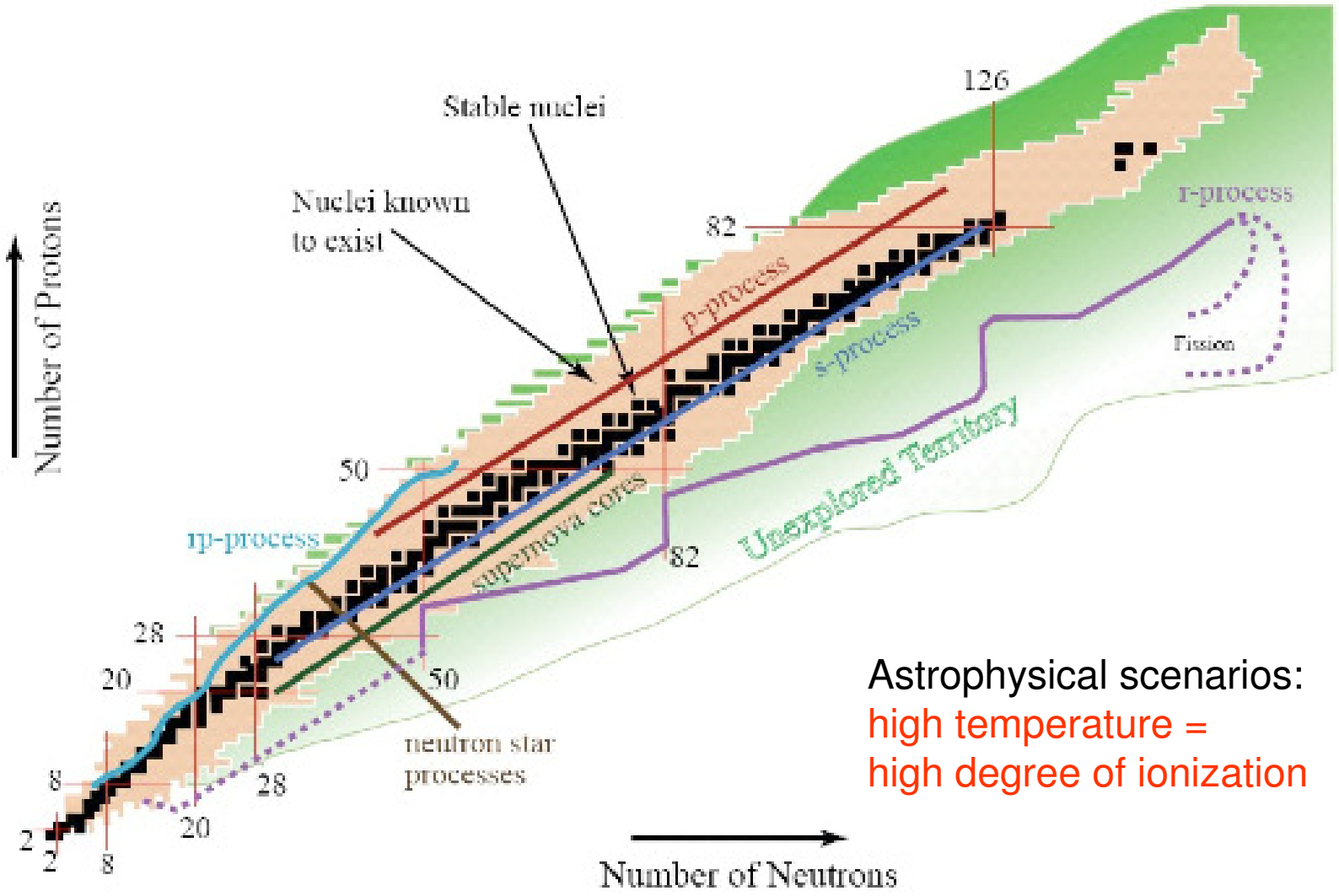
EC



(Z,N) → (Z+1,N-1)

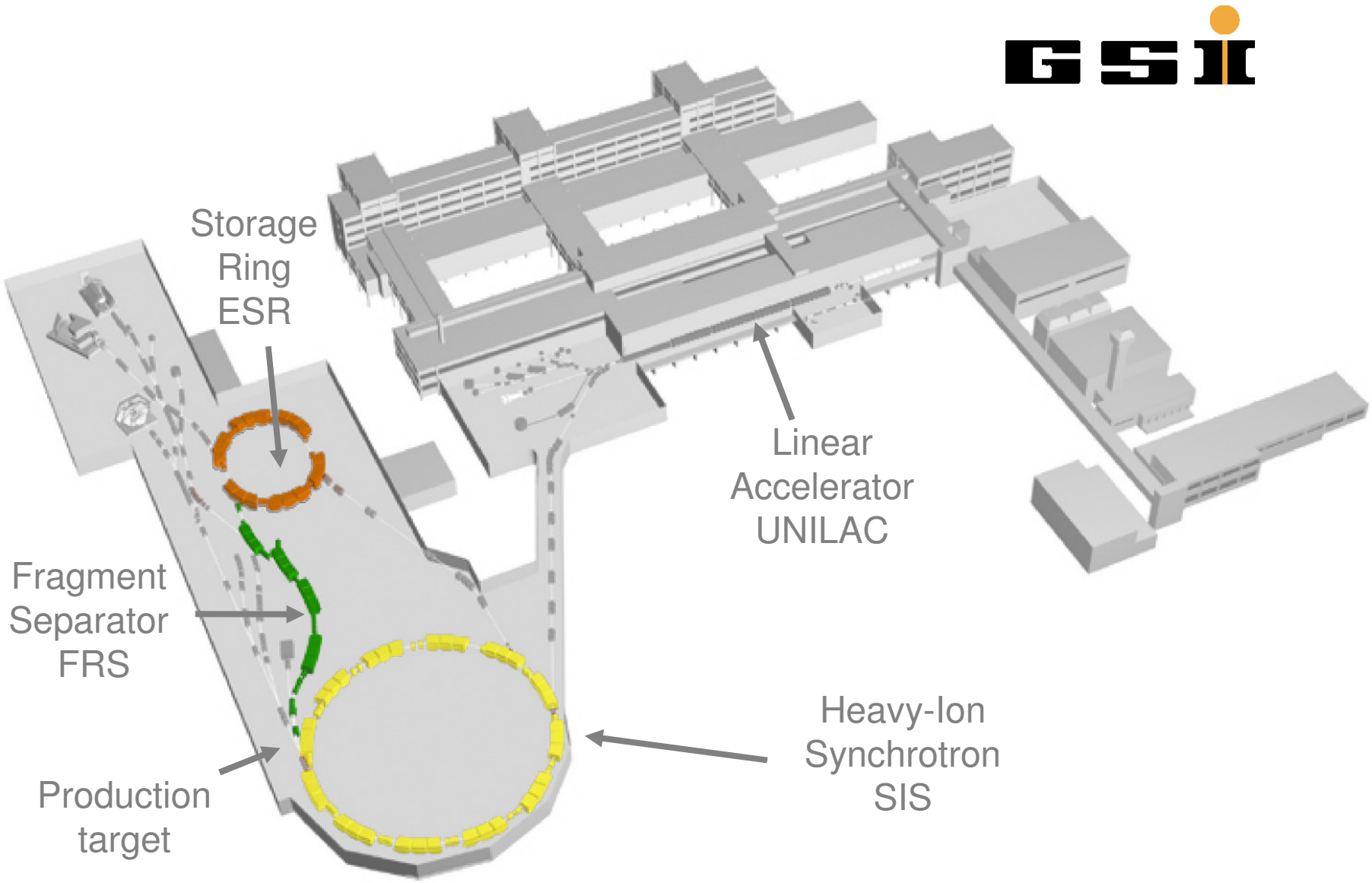
β_b^-

Nucleosynthesis on the Chart of the Nuclides

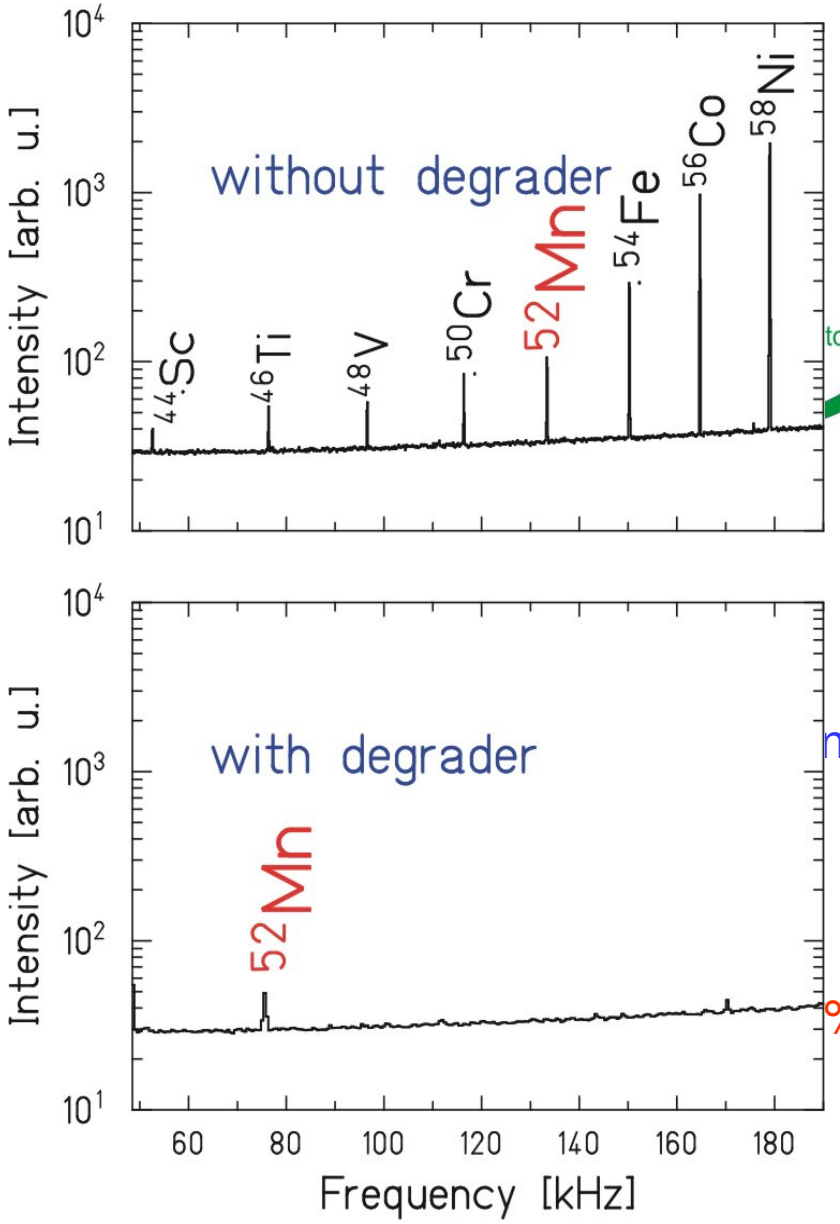


Astrophysical scenarios:
high temperature =
high degree of ionization

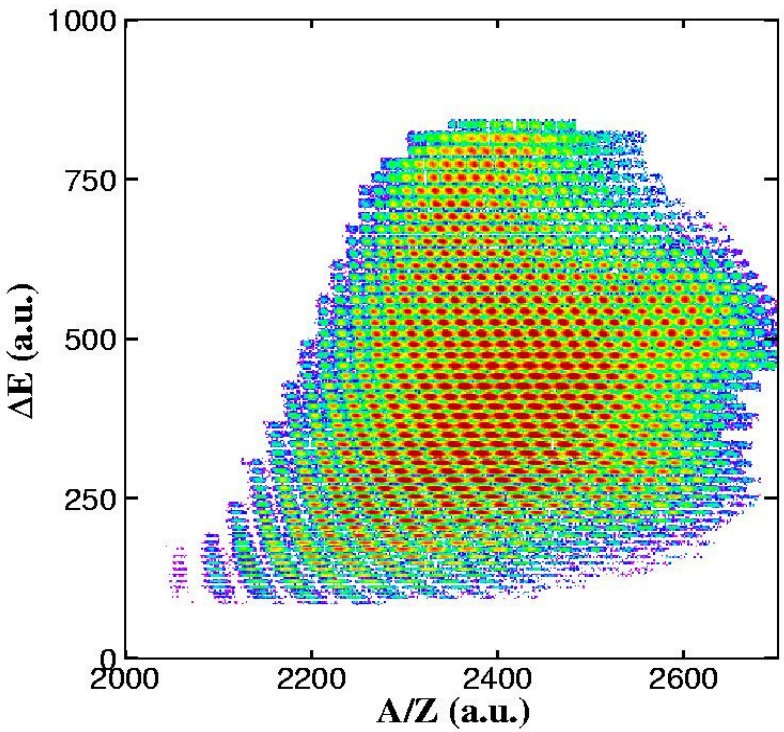
Secondary beam facility at GSI



Production & Separation of Exotic Nuclei



About 1000 nuclear residues identified



A/Z-resolution ~10^{-3}

J. Pereira et al., PRC (2007)

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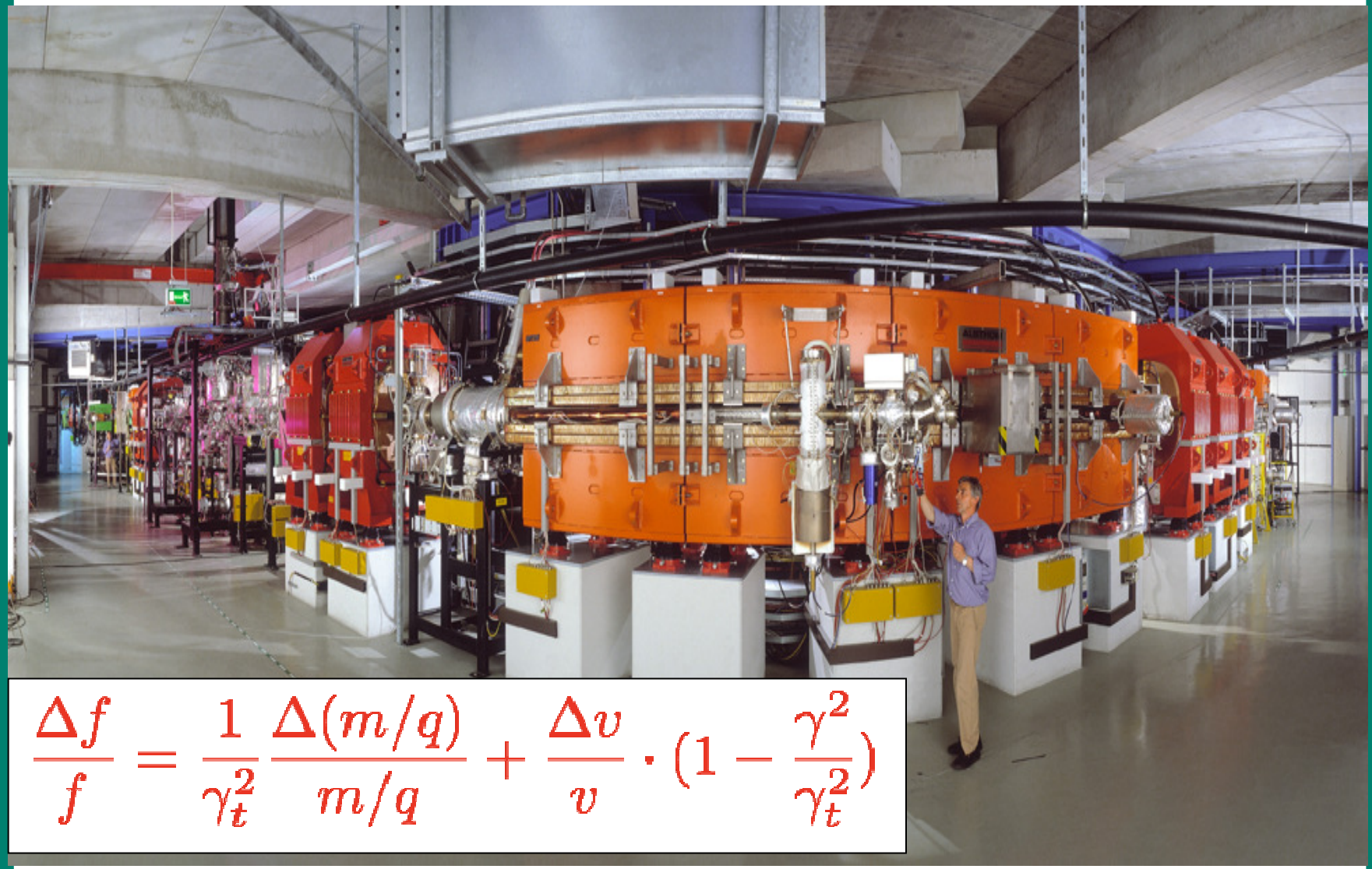
Experimental Storage Ring at GSI



$$\frac{\Delta f}{f} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\cdot\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

ESR: B. Franzke, NIM B 24/25 (1987) 18

Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

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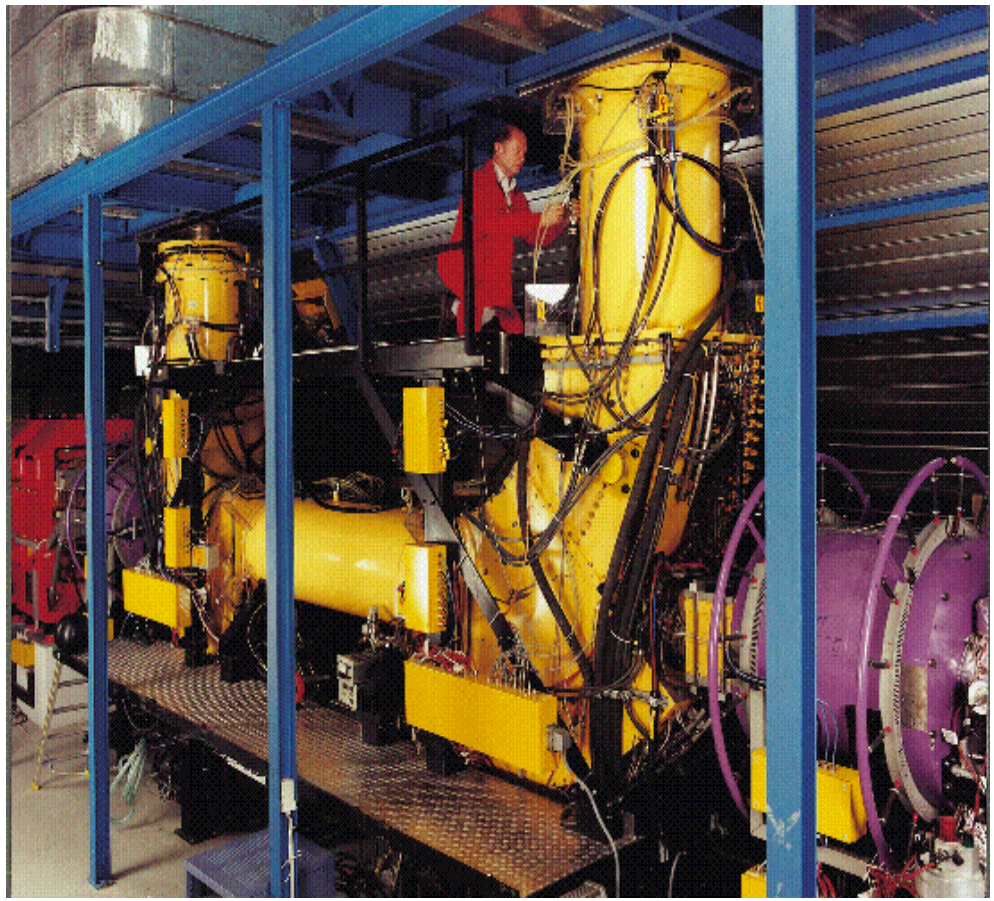
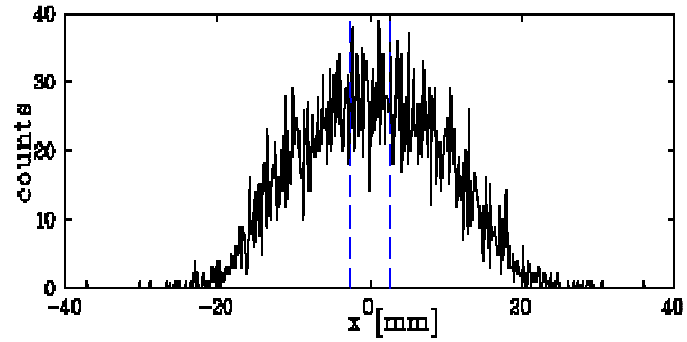
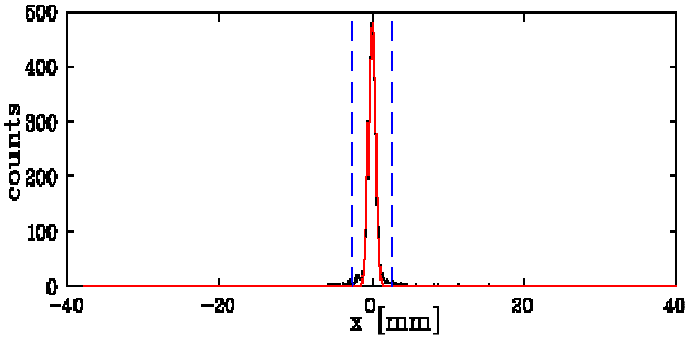
Electron Cooling



momentum exchange with 'cold', collinear e- beam. The ions get the sharp velocity of the electrons, small size and divergence





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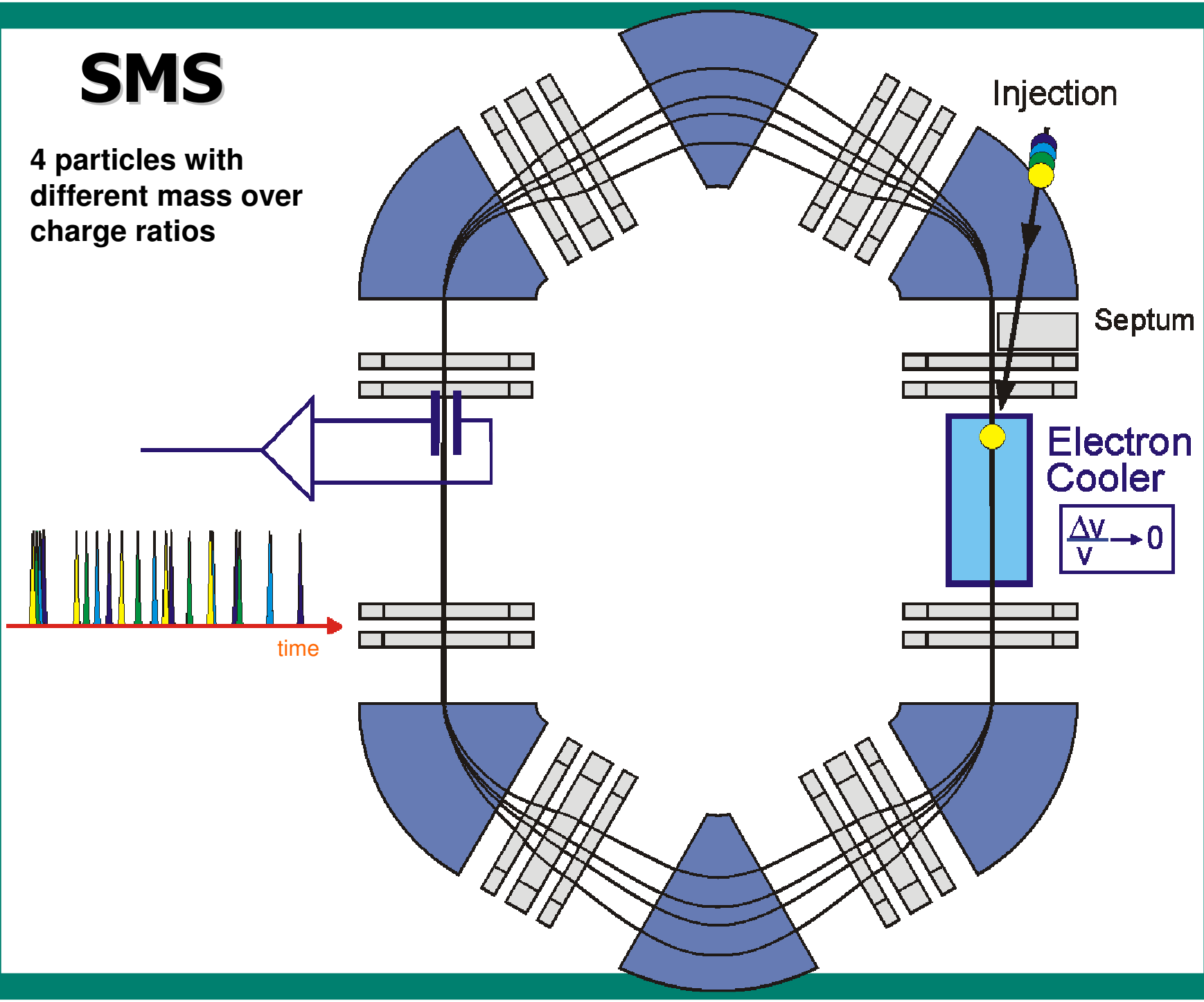
SMS

4 particles with different mass over charge ratios



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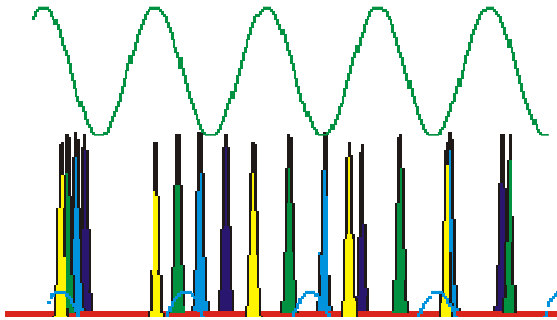
Schottky Mass Spectrometry

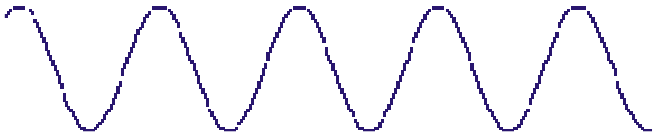
$\mathrm{Sin}(\omega_1)$



$\mathrm{Sin}(\omega_2)$

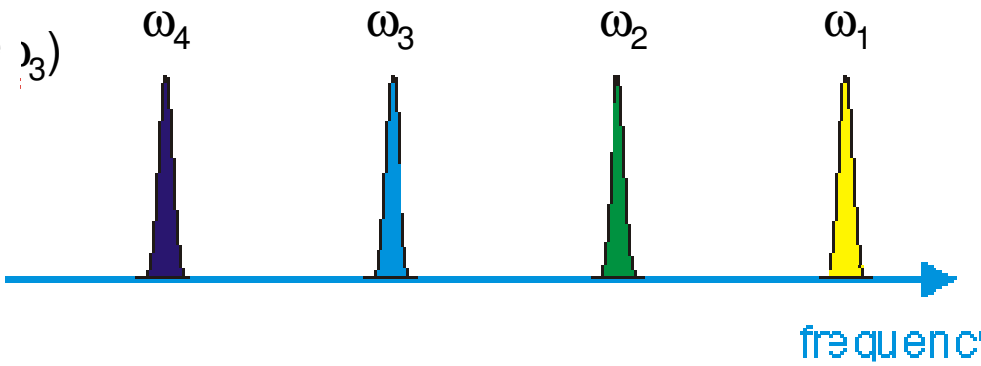
time

$\mathrm{Sin}(\omega_3)$



$\mathrm{Sin}(\omega_4)$

Fast Fourier Transform



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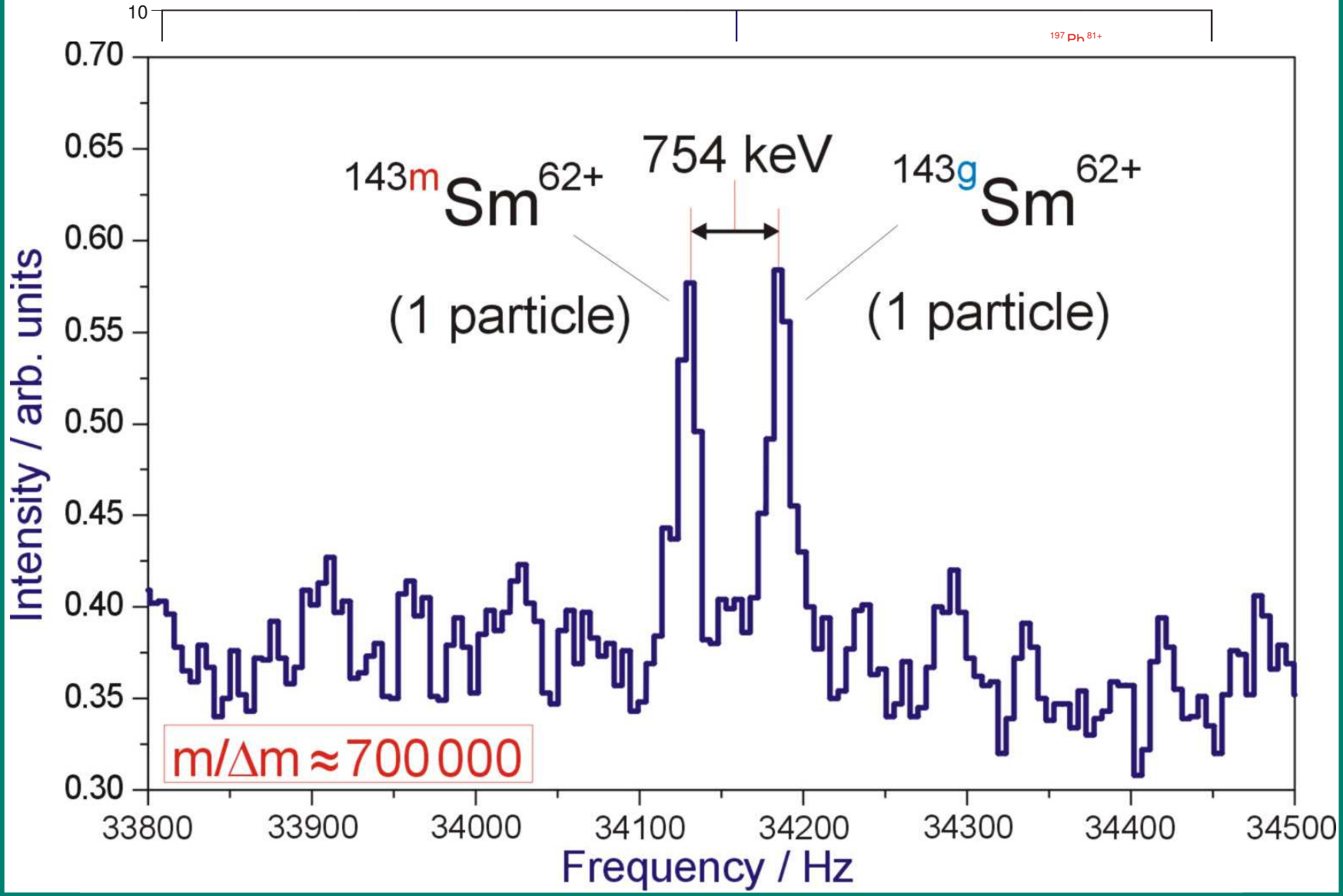
Broad-Band Schottky Frequency Spectra



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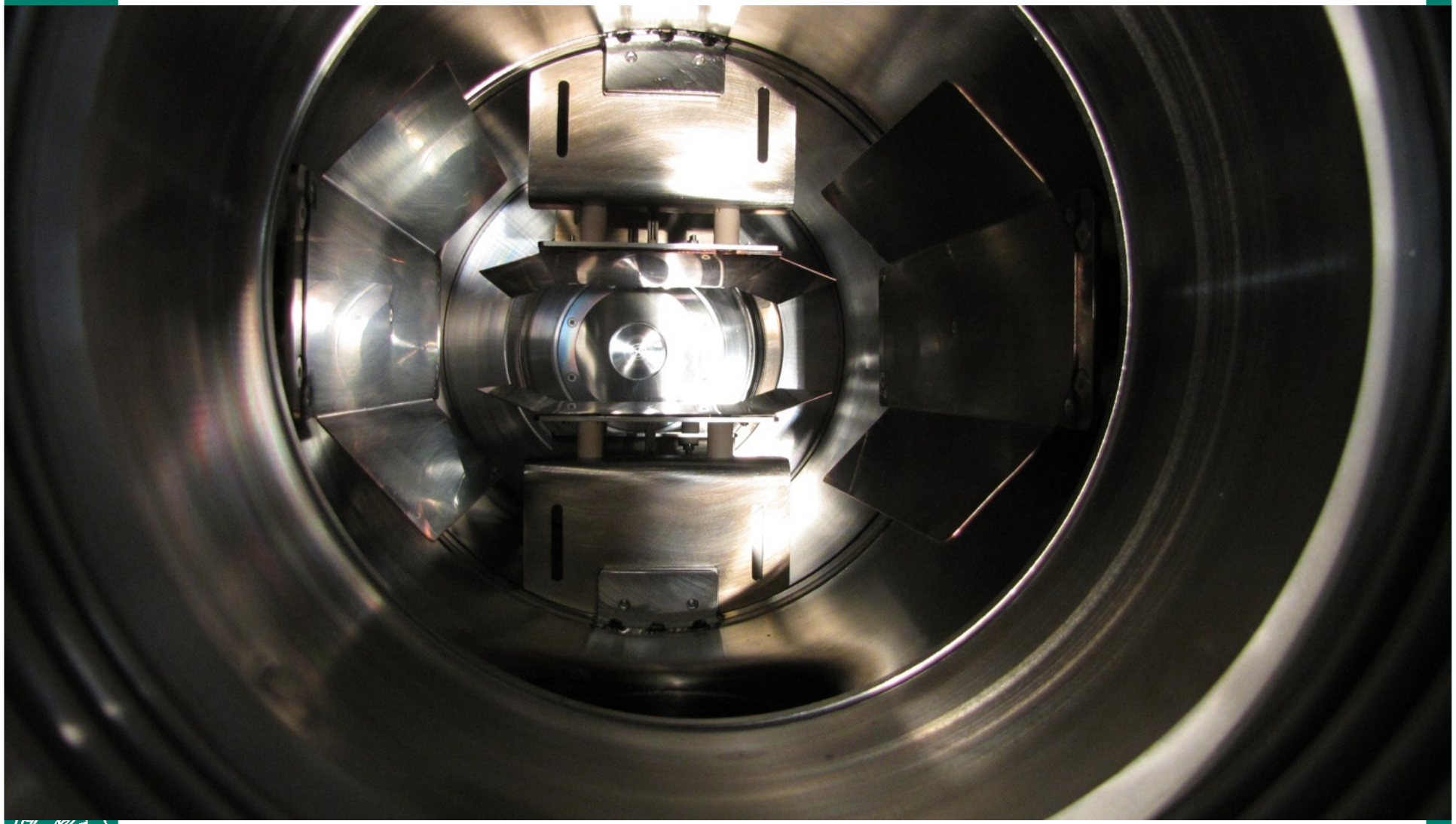
Capacitive Schottky Pick-Up in the ESR



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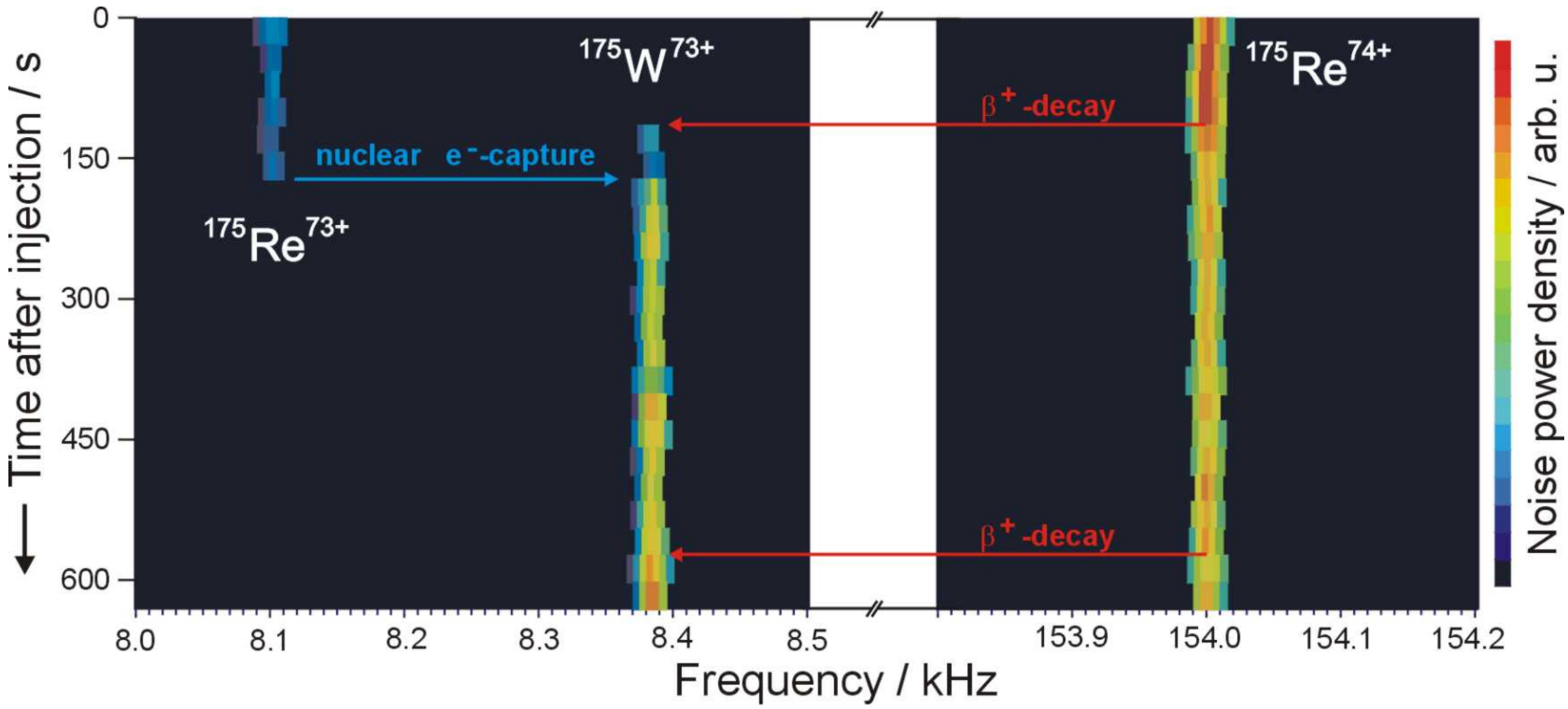
Nuclear Decays of Stored Single Ions

Time-resolved SMS is a perfect tool to study decays in the ESR



EC, β+,β-, bound-state β, and IT decays were observed

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Fully-Ionized Atoms

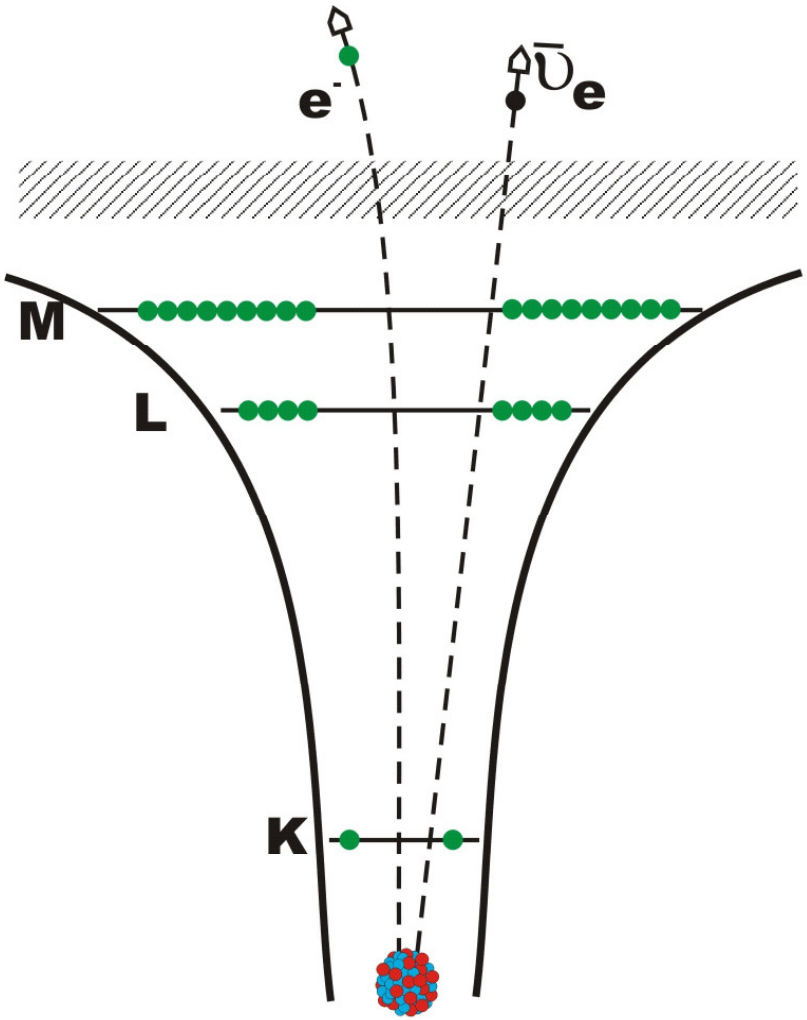
John N. Bahcall, "Theory of Bound-State Beta Decay",
Phys. Rev. 124 (1961) 495

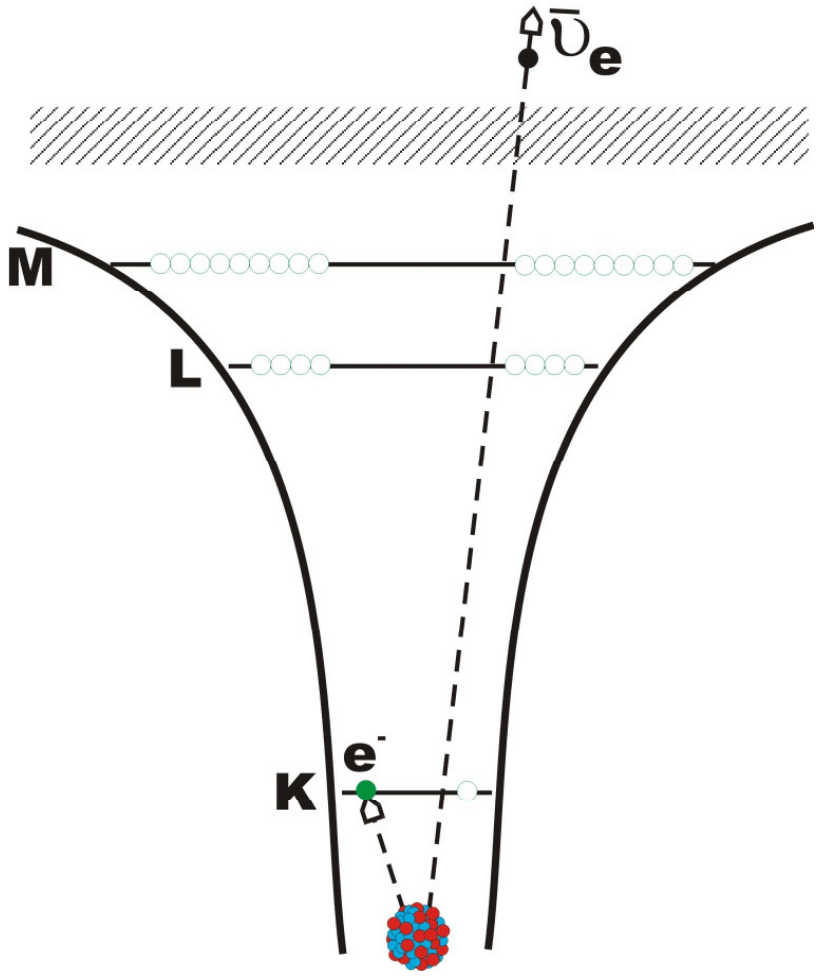
John N. Bahcall, "Beta Decay in Stellar Interiors",
Phys. Rev. 126 (1962) 1143

Koji Takahashi, Koichi Yokoi,
"Nuclear Beta-Decays of Highly-Ionized Heavy Atoms in Stellar Interiors",
Nucl. Phys. A 404 (1983) 578

Koji Takahashi, Koichi Yokoi,
"Beta-Decay Rates of Highly-Ionized Heavy Atoms in Stellar Interiors",
Atomic Data Nucl. Data Tables 36 (1987) 375

Bound-State β-decay





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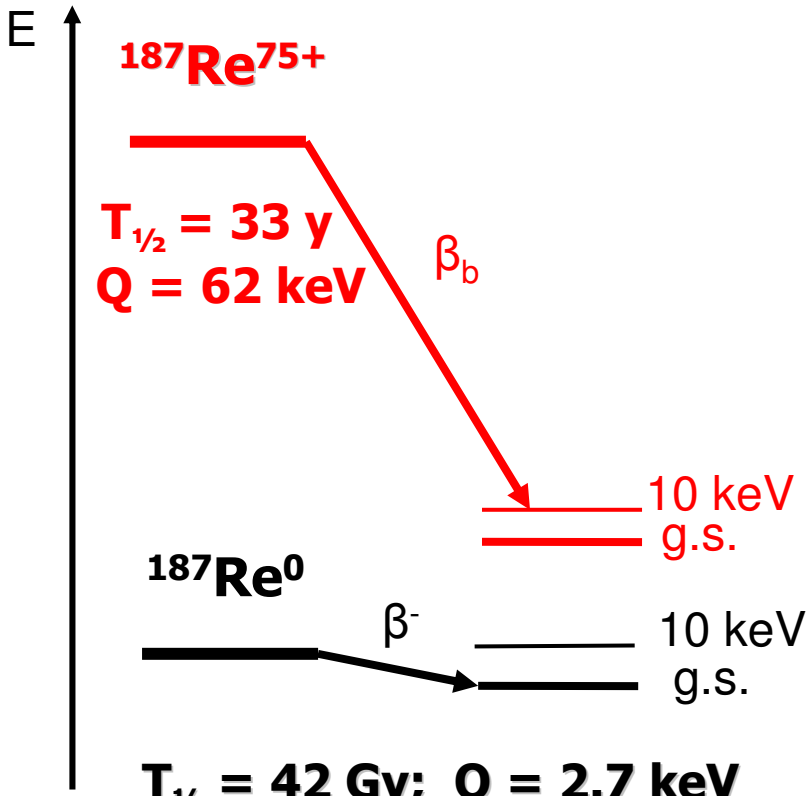
Bound-State β-decay of ^{187}Re



F. Bosch et al., Phys. Rev. Lett. 77 (1996) 5190

radioactive clock

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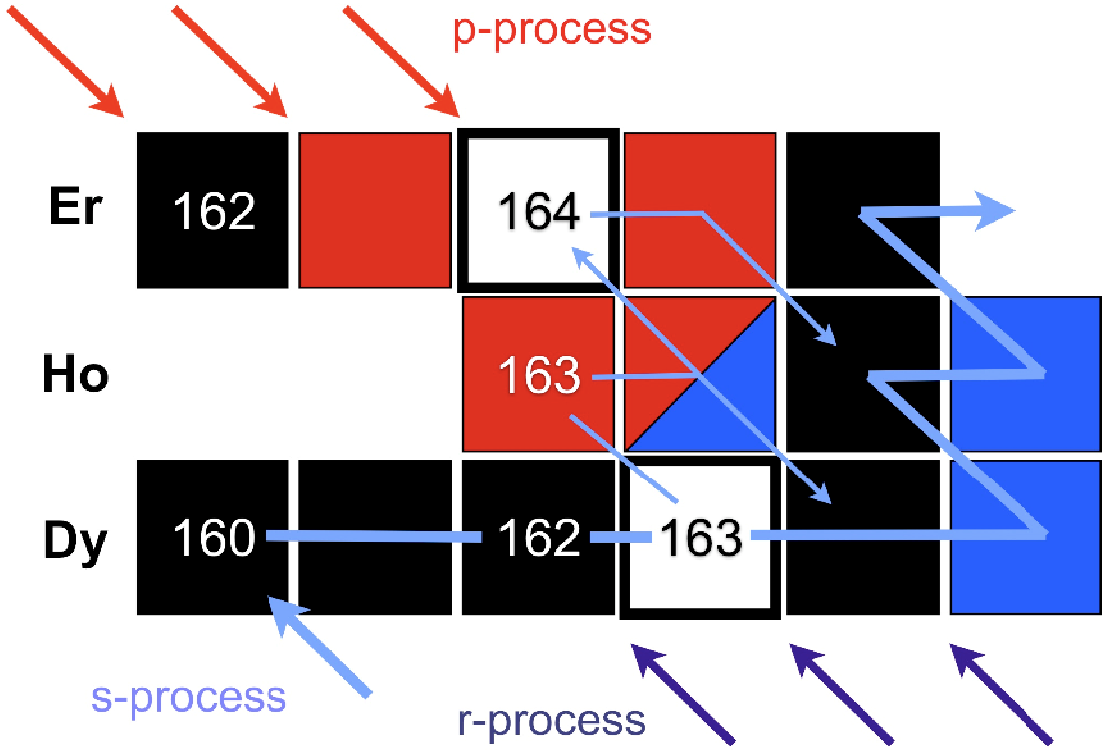
Bound-State β-decay of ^{163}Dy

s process: slow neutron capture and β- decay near valley of β stability at kT = 30 keV; → high atomic charge state → bound-state β decay

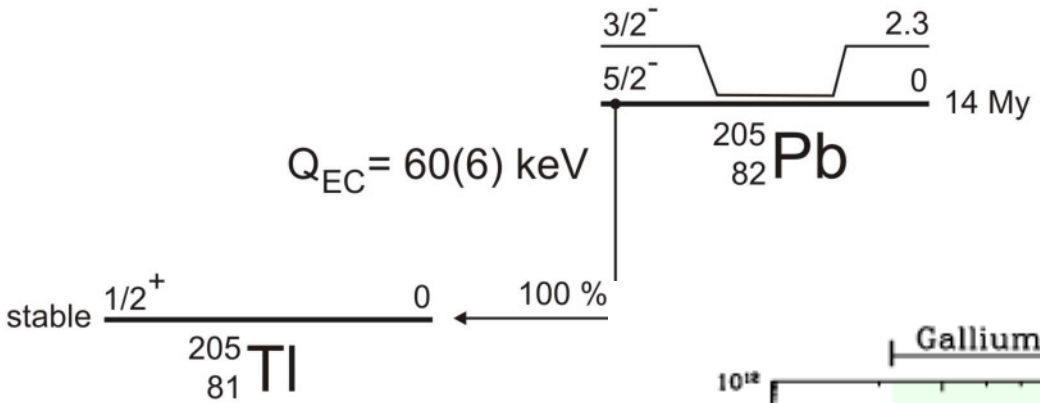


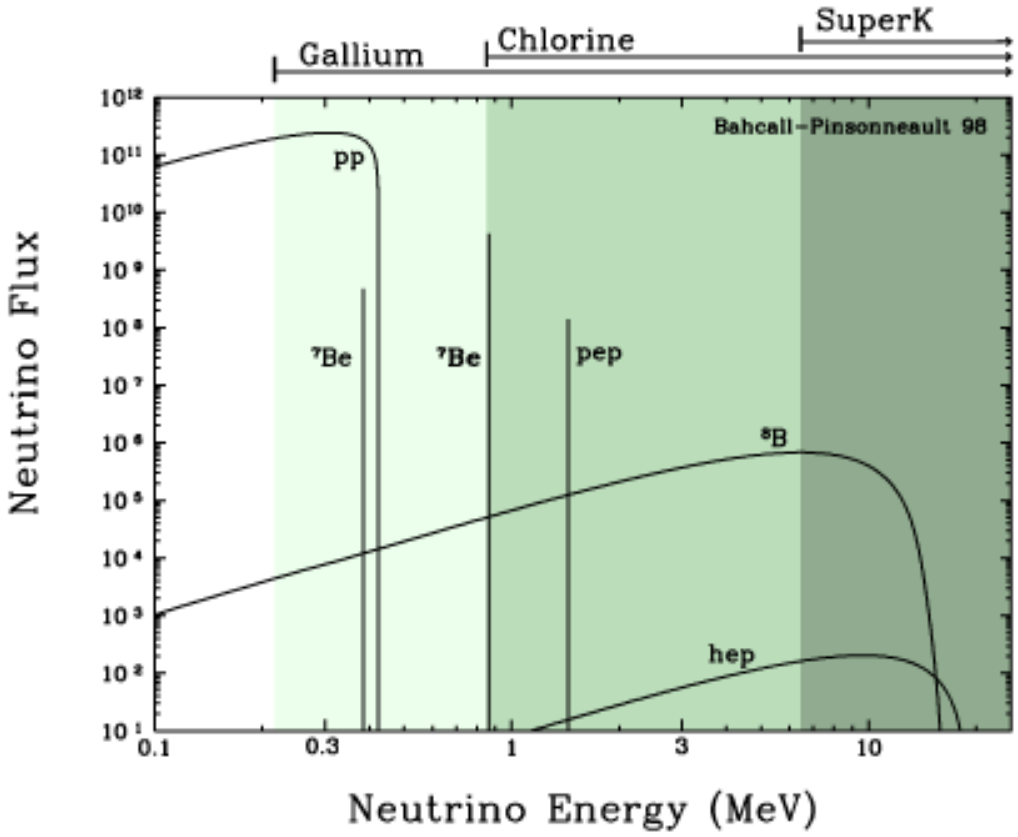
$T_{1/2}$ = 48 days

branchings caused by bound-state β decay

M. Jung et al., Phys. Rev. Lett. 69 (1992) 2164

Bound-State β-decay of ^{205}Tl





F. Bosch et al., GSI Proposal, 1992 & 2010

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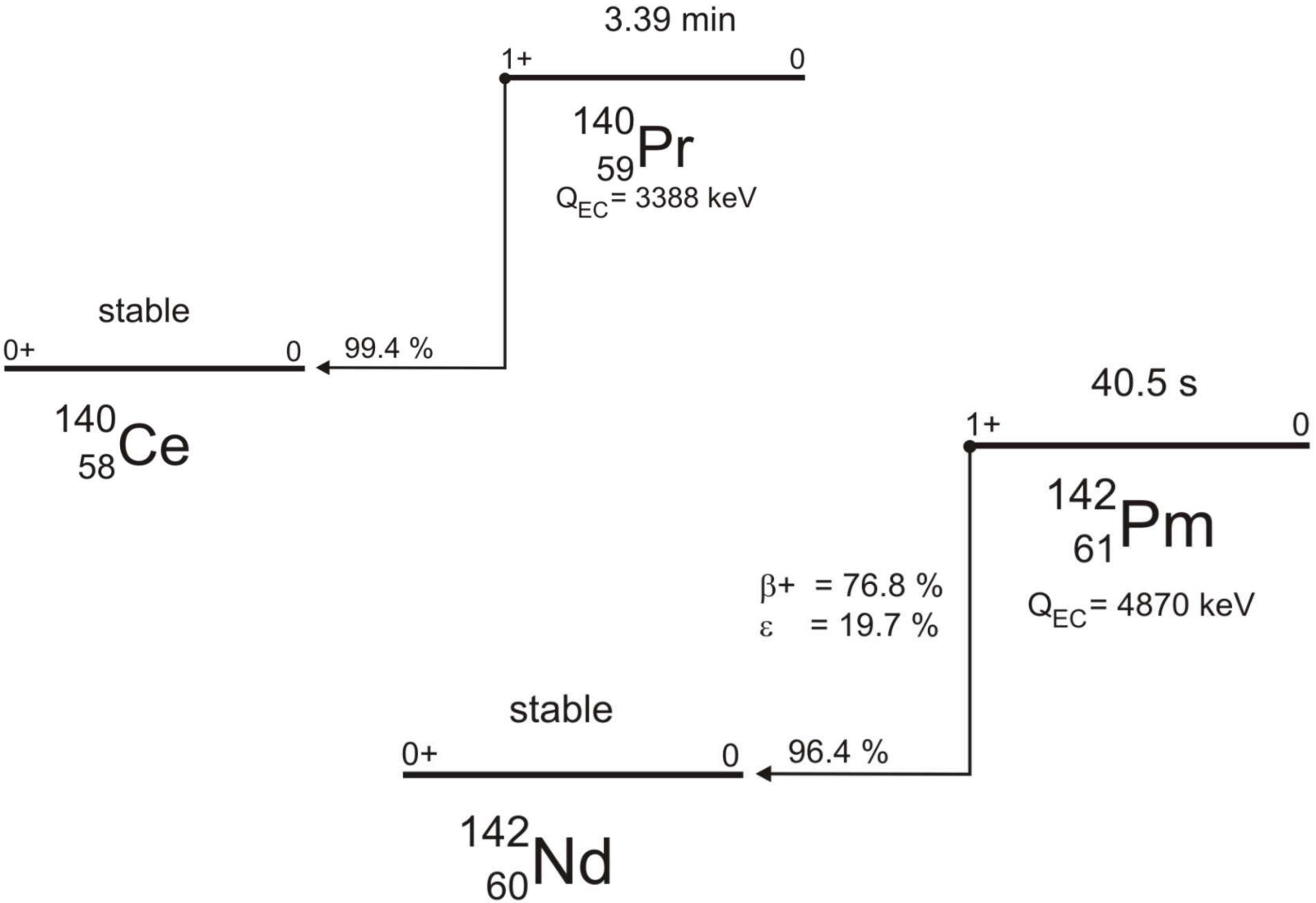
Hydrogen-Like Atoms

I. Iben et al., "The Effect of Be7 K-Capture on the Solar Neutrino Flux",
Ap. J. 150 (1967) 1001

L.M. Folan, V.I. Tsifrinovich,
"Effects of the Hyperfine Interaction on Orbital Electron Capture",
Phys. Rev. Lett. 74 (1995) 499

Orbital Electron Capture in H-Like Ions

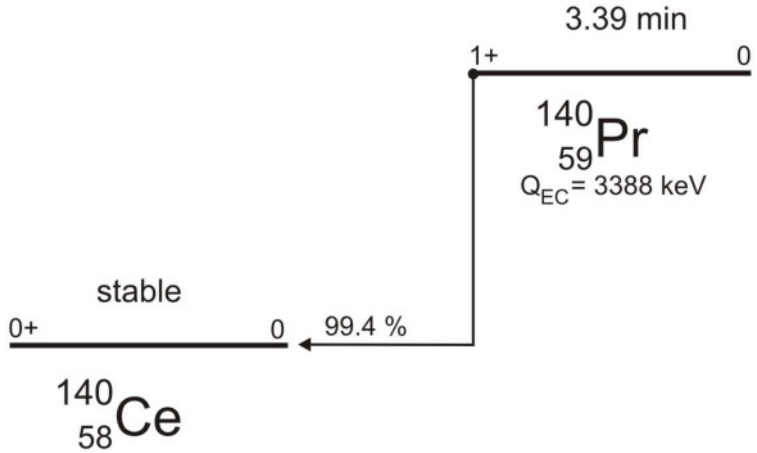


Orbital Electron Capture

Conventional EC-theory:

W.Bambynek et al., Rev. Mod. Phys 49, 1977

Gamow-Teller allowed transition $1^+ \rightarrow 0^+$



S-electron density at the nucleus:

$|f_S(0)|^2 \propto 1/ n^3$

P_{EC} (neutral atom) $\propto 2 \sum 1/ n^3 = 2.4$

P_K (H-like) $\propto 1 * 1/ 1^3 = 1$

Conclusion:
H-Like ion should have 41% longer half-life

λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

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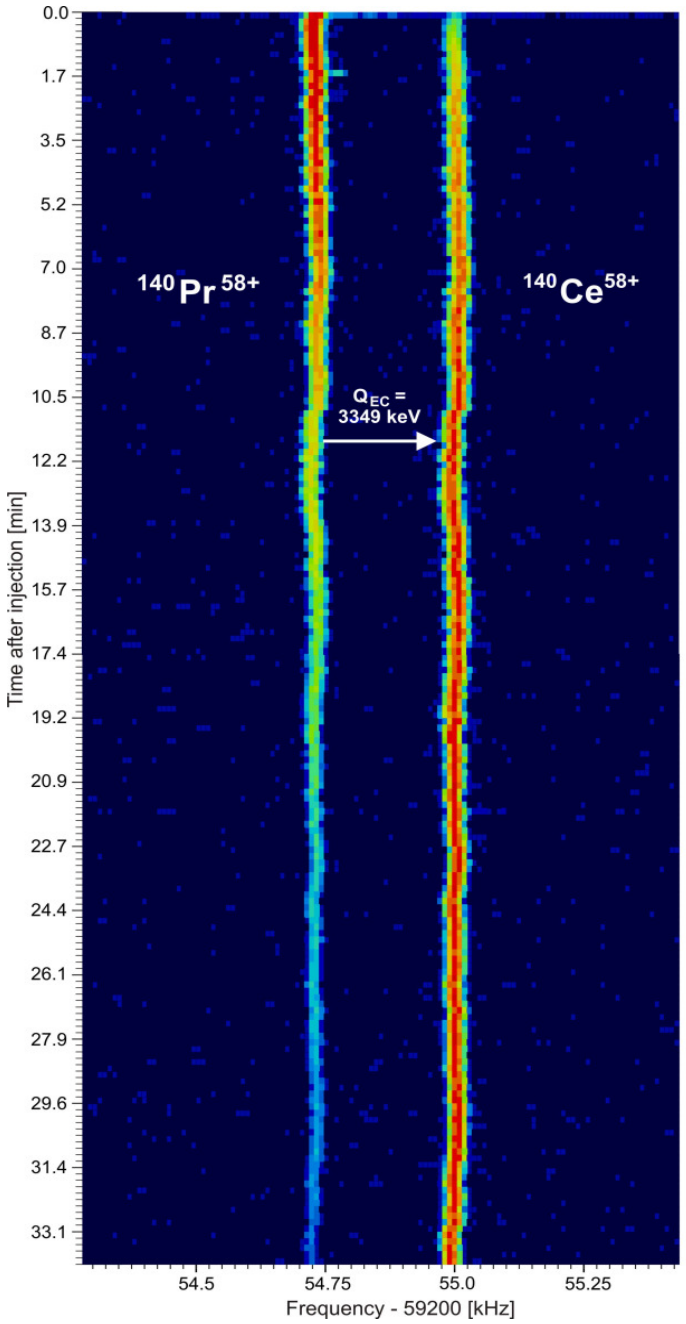

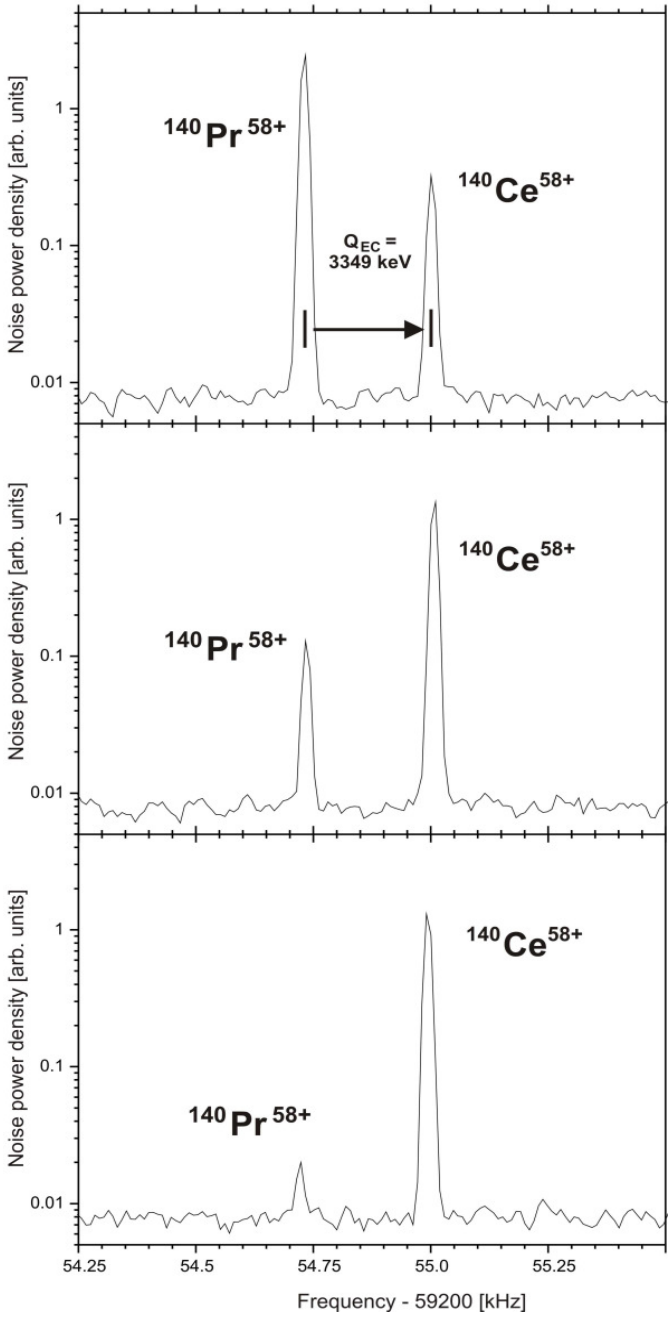

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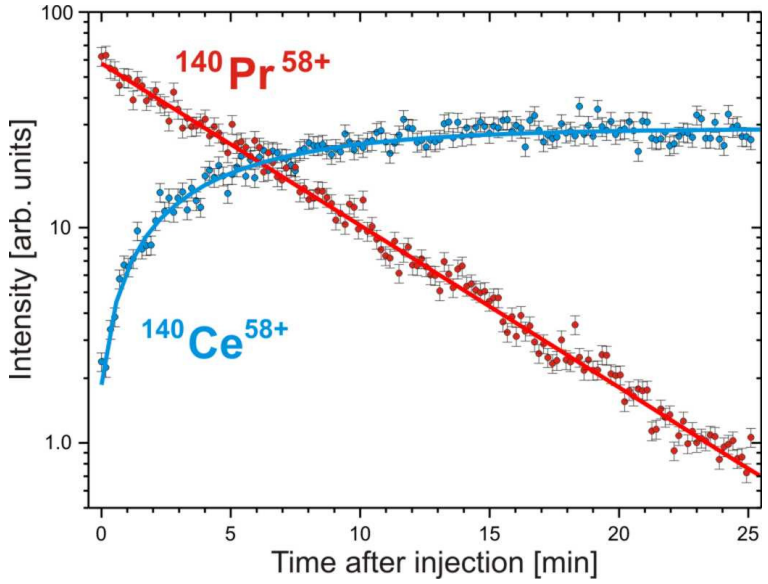
EC in Hydrogen-like Ions

Expectation: λ_{EC}(H-like)/λ_{EC}(He-like) ≈ 0.5

^{140}Pr

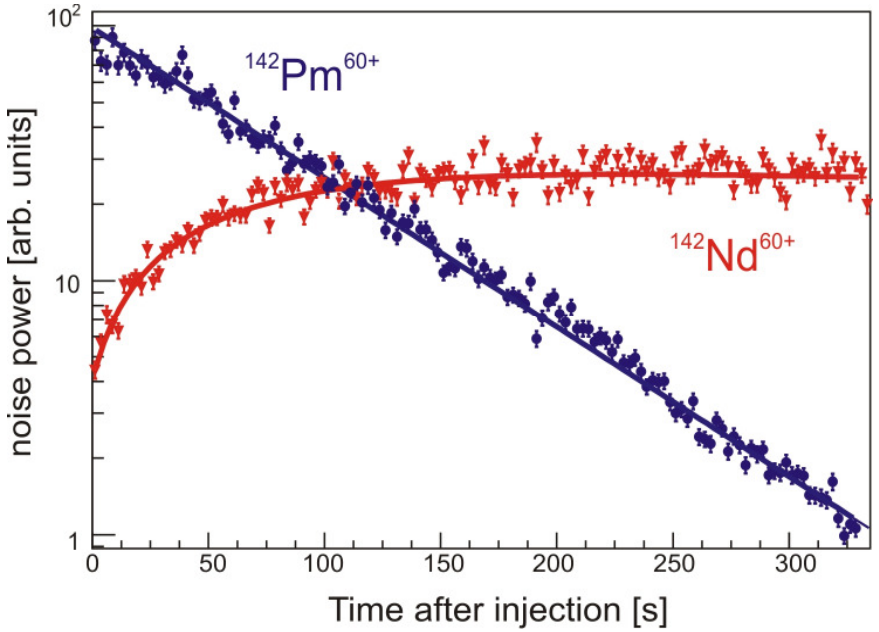
λ_{EC}(H-like)/λ_{EC}(He-like) = 1.49(8)



Yu.Litvinov et al., Phys. Rev. Lett. 99 (2007) 262501

^{142}Pm

λ_{EC}(H-like)/λ_{EC}(He-like) = 1.44(6)



N. Winckler et al., Phys. Lett. B579 (2009) 36

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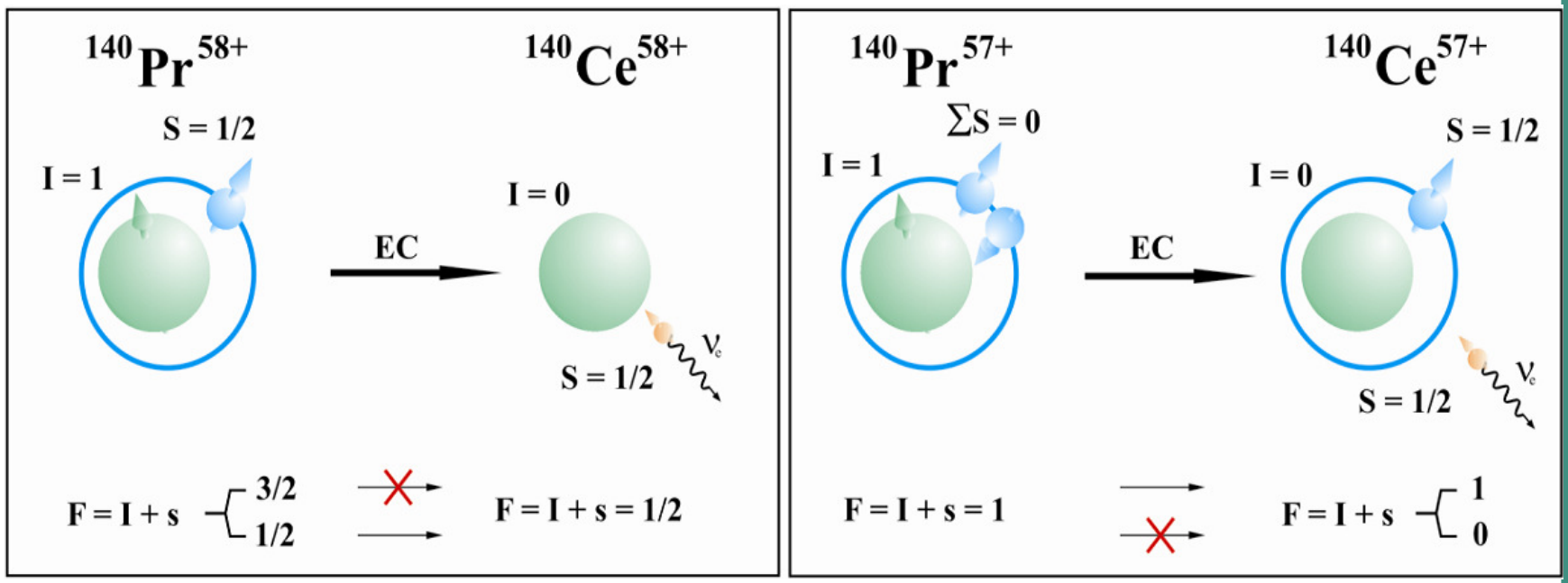
Electron Capture in Hydrogen-like Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$



$\mu = +2.7812\mu_N$

I. N. Borzov et al., Phys. At. Nucl. (2009)

Theory: $\lambda(H)/\lambda(He) = (2I+1)/(2F+1)$

Z. Patyk et al., Phys. Rev. C 77 (2008) 014306

		Theory	Measurement
Ratio H/He:	^{140}Pr	3/2	1.49 (9)
	^{142}Pm	3/2	1.44 (6)

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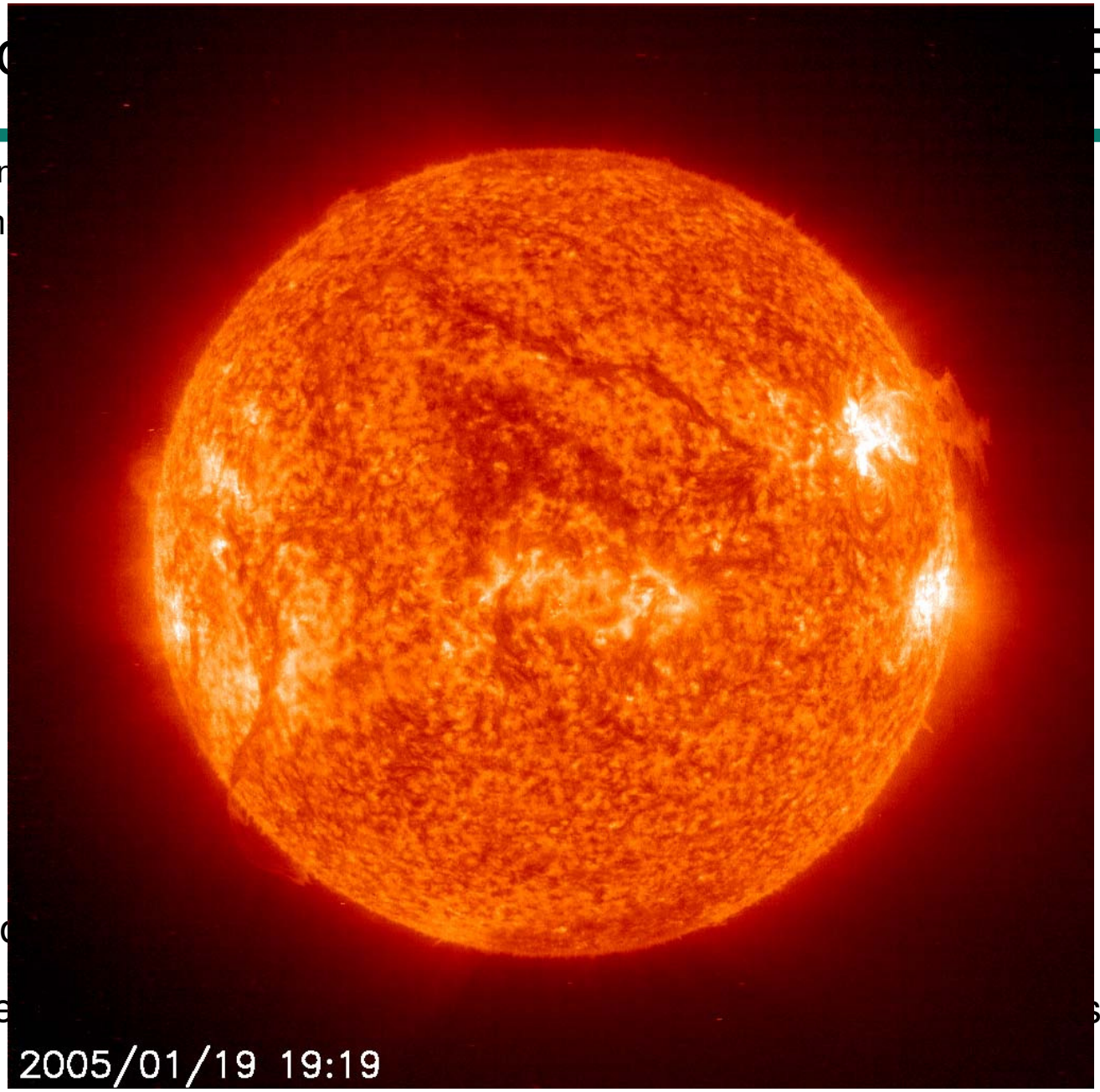

Sc Be

A.V. Gruzin

Ionization

Transitio

Howeve state

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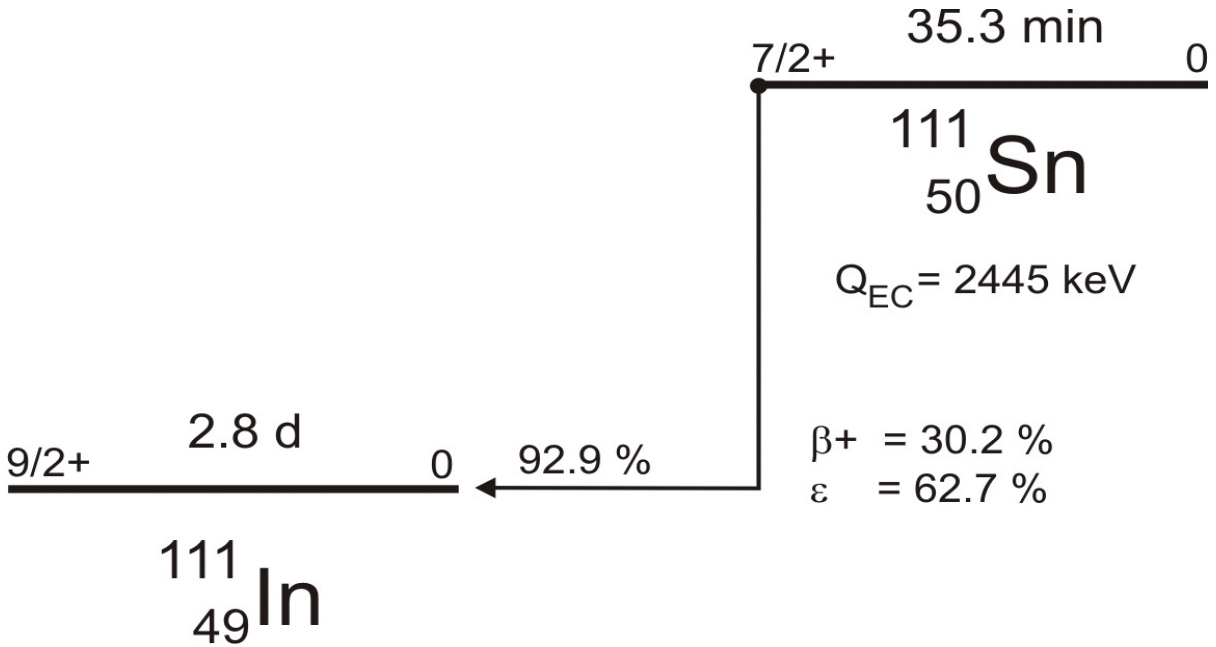
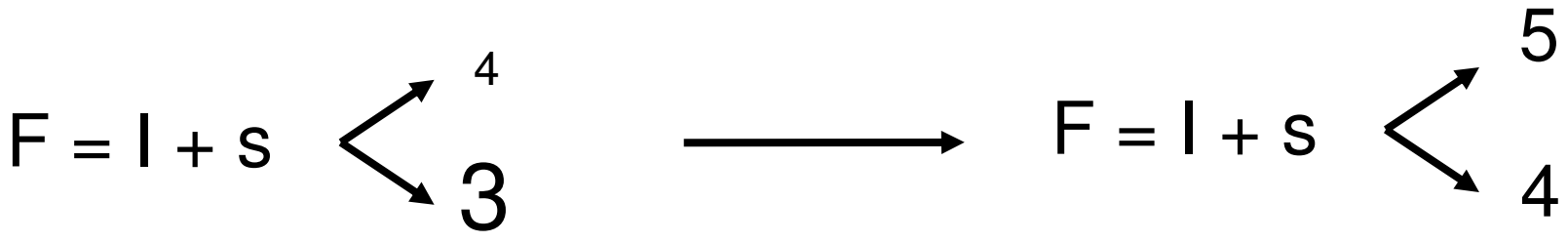
Electron Capture in Hydrogen-like Ions





Possibility to address the electron screening in beta decay under very clean conditions !

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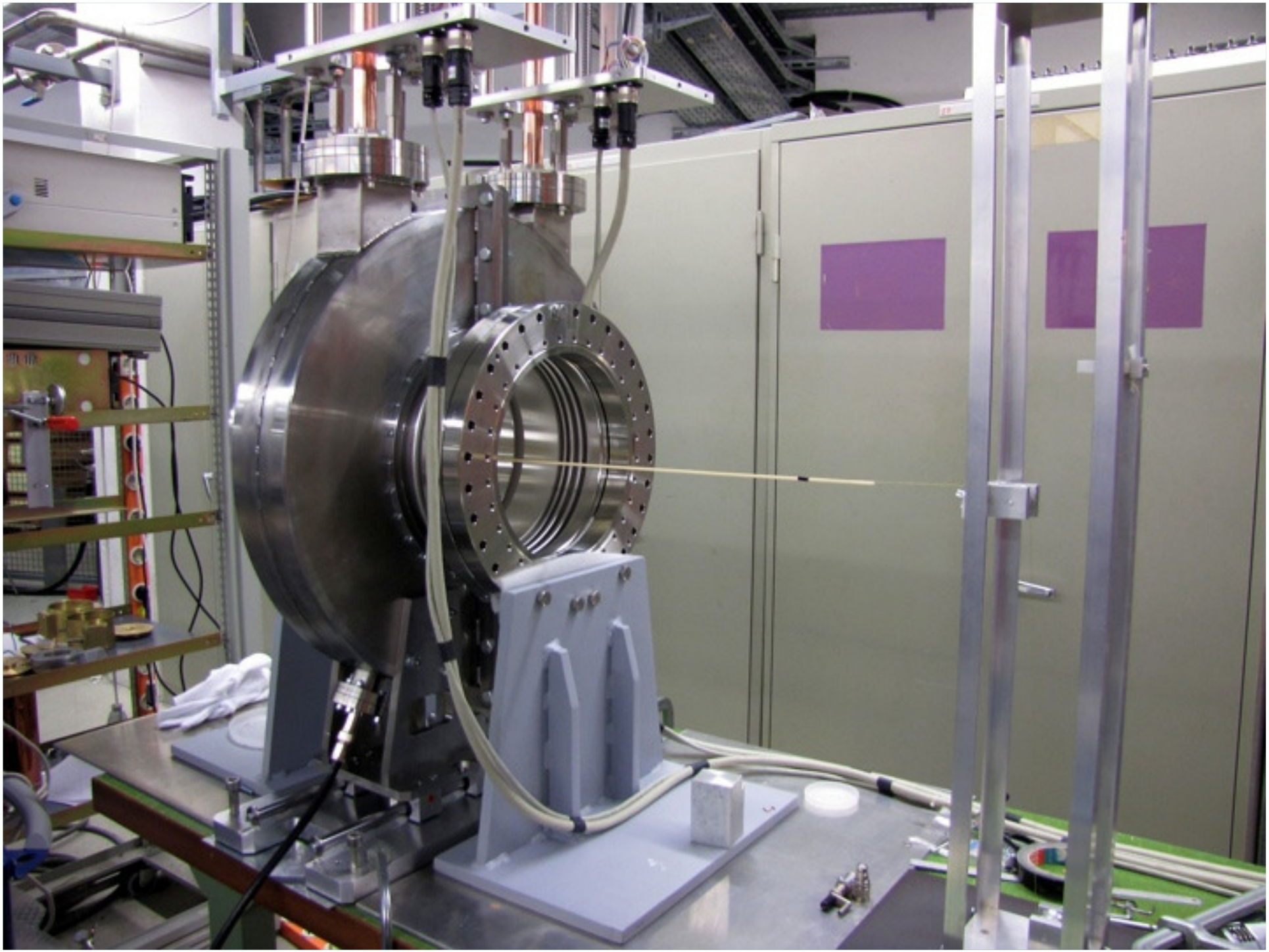
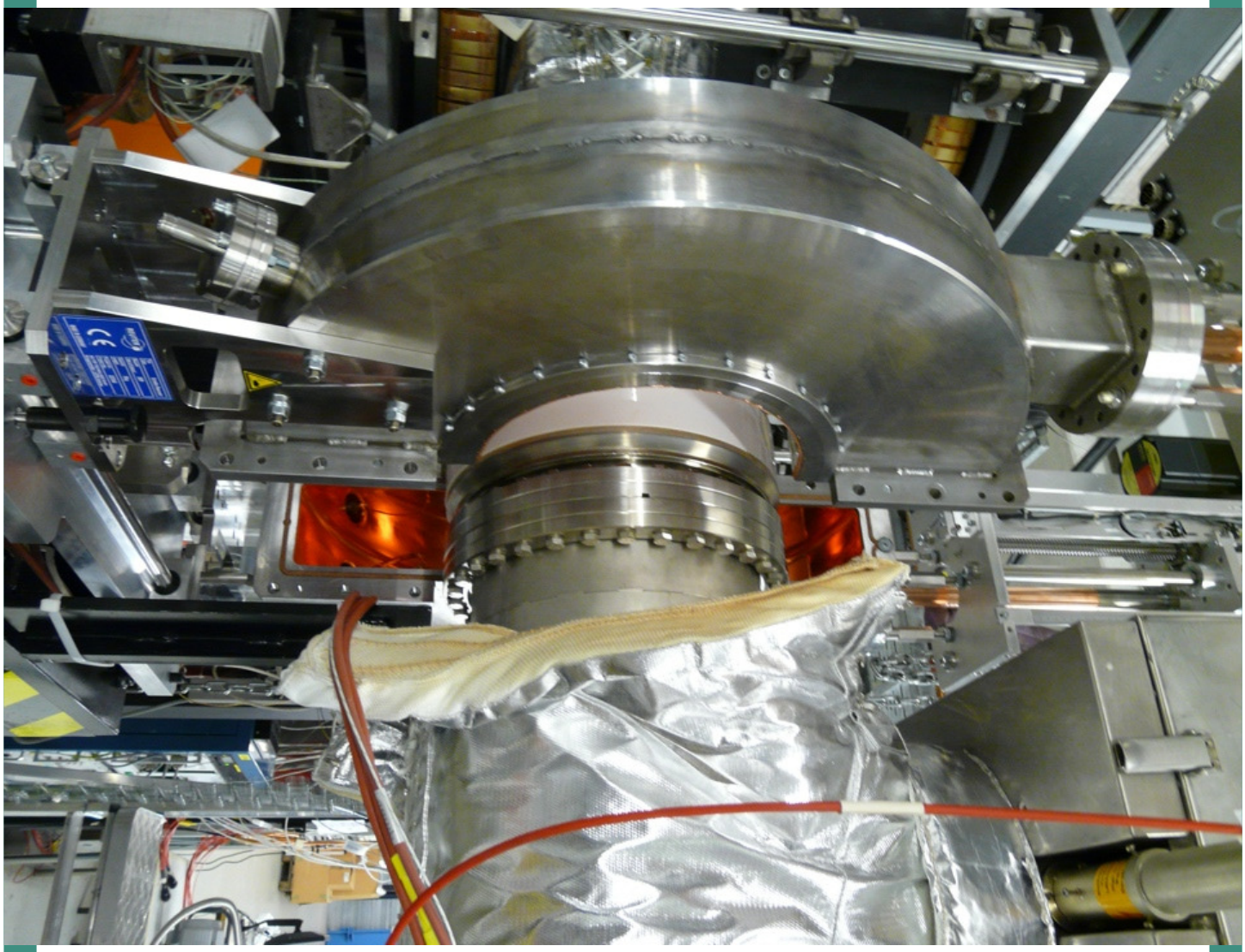
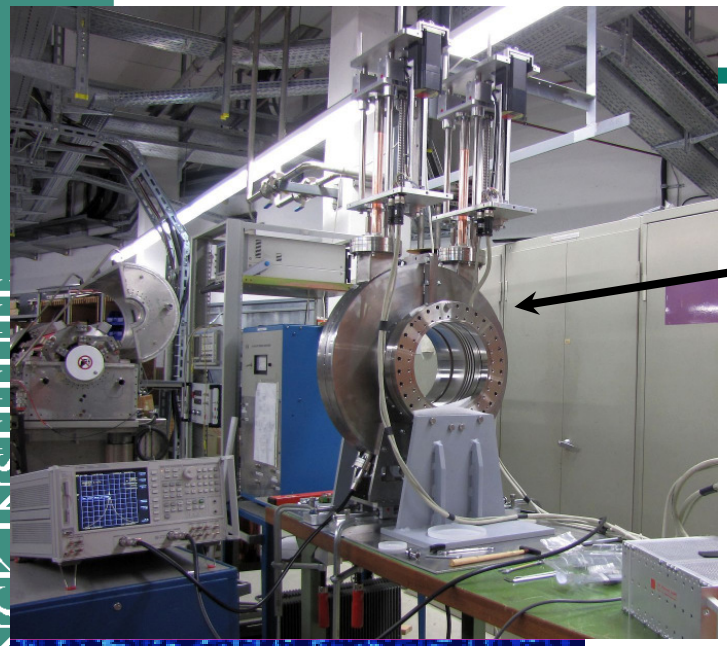
Resonant Schottky Pick-up



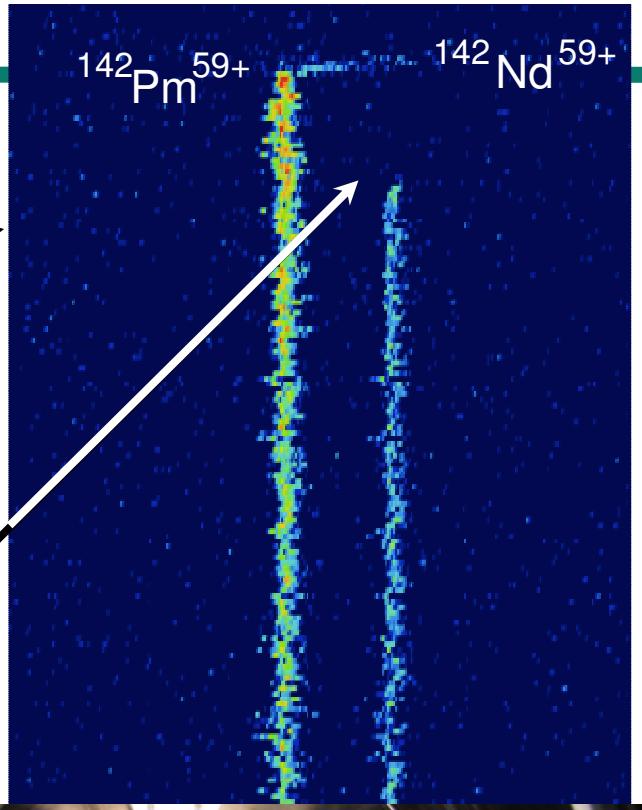
Max Planck Institute for Nuclear Physics



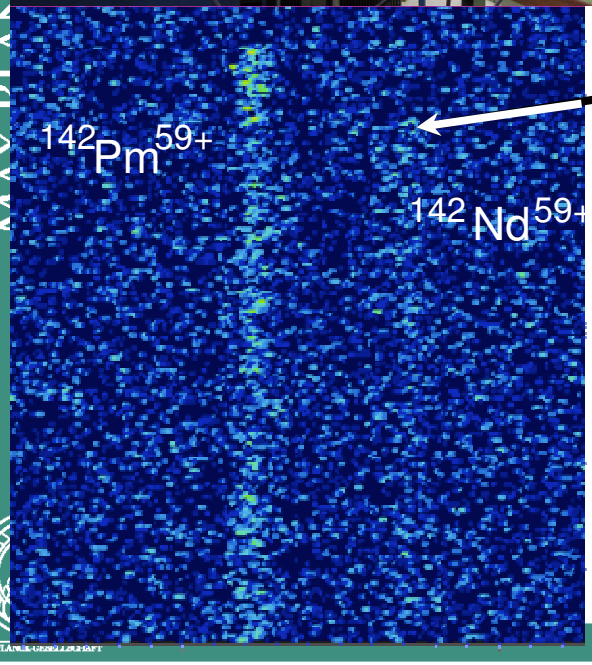
First EC-decay of He-like ^{142}Pm ions measured in E082



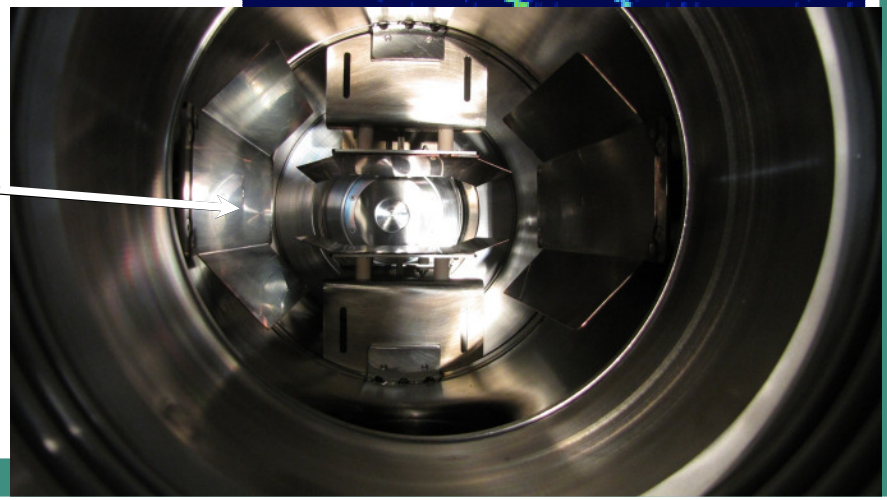
New resonator cavity (2010)
124th harmonic



the same decay:
improvement by
a factor of about 100



Old Schottky pickup (1992)
30th harmonic



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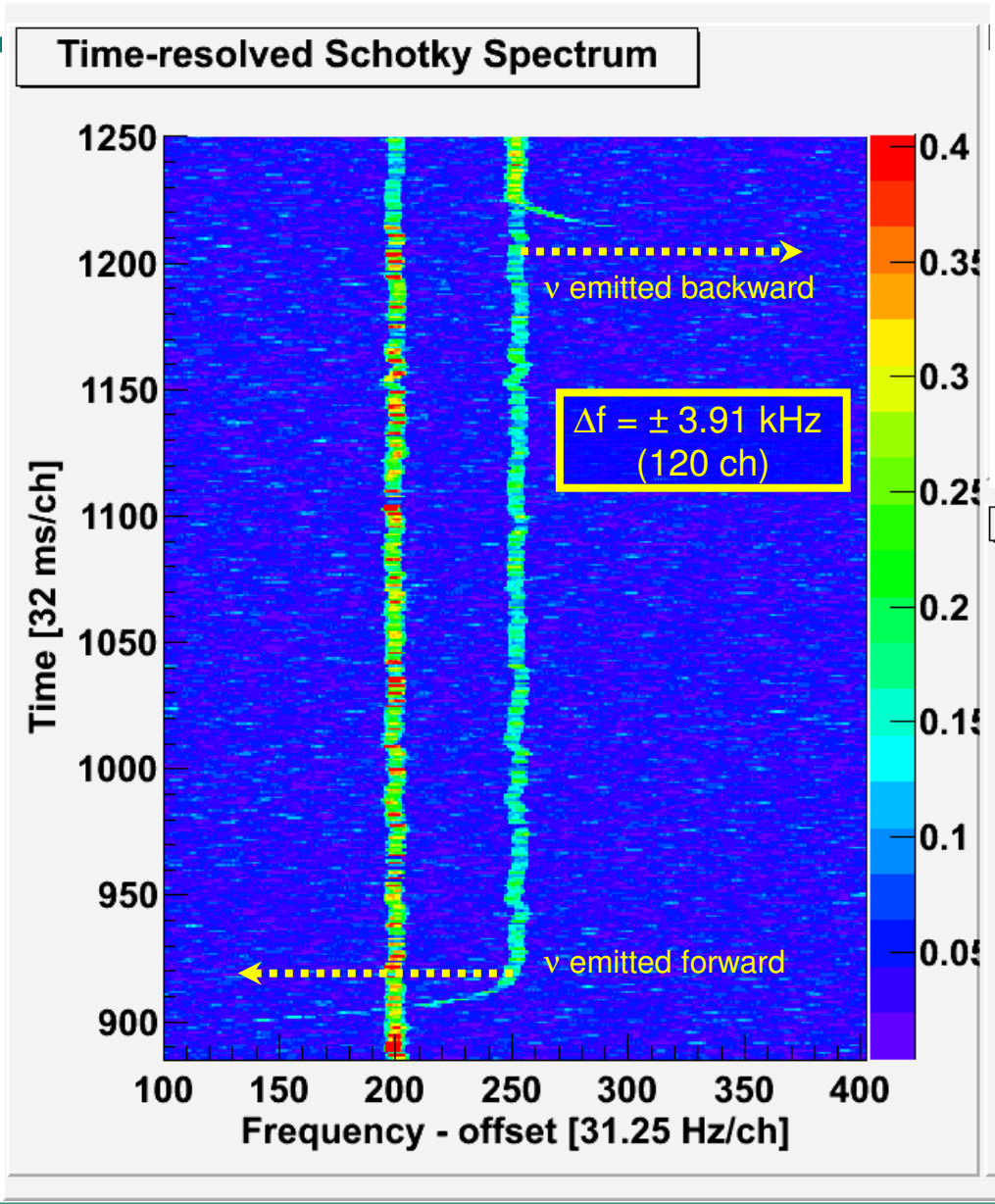
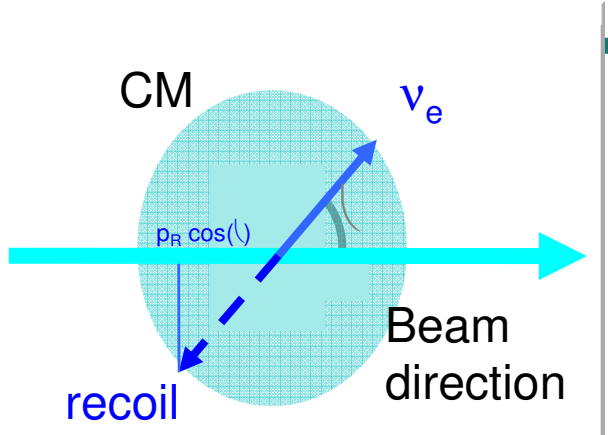
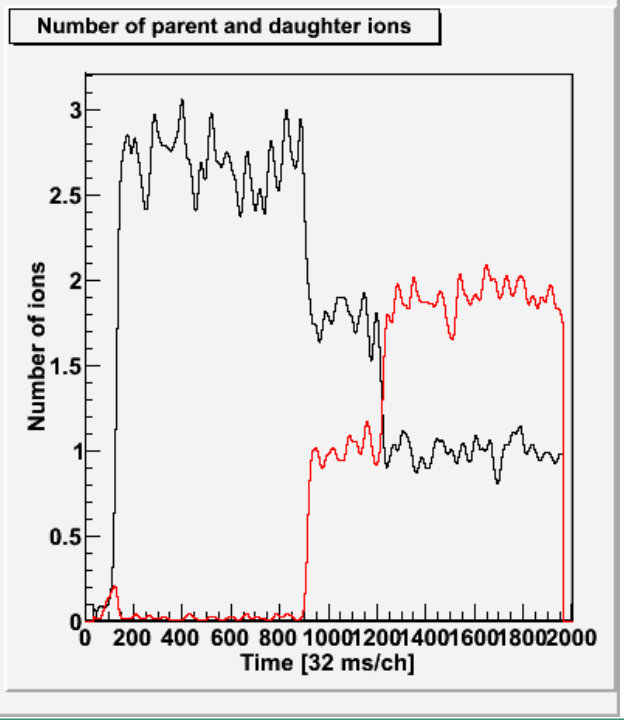
3 parent ions: 2 EC-decays







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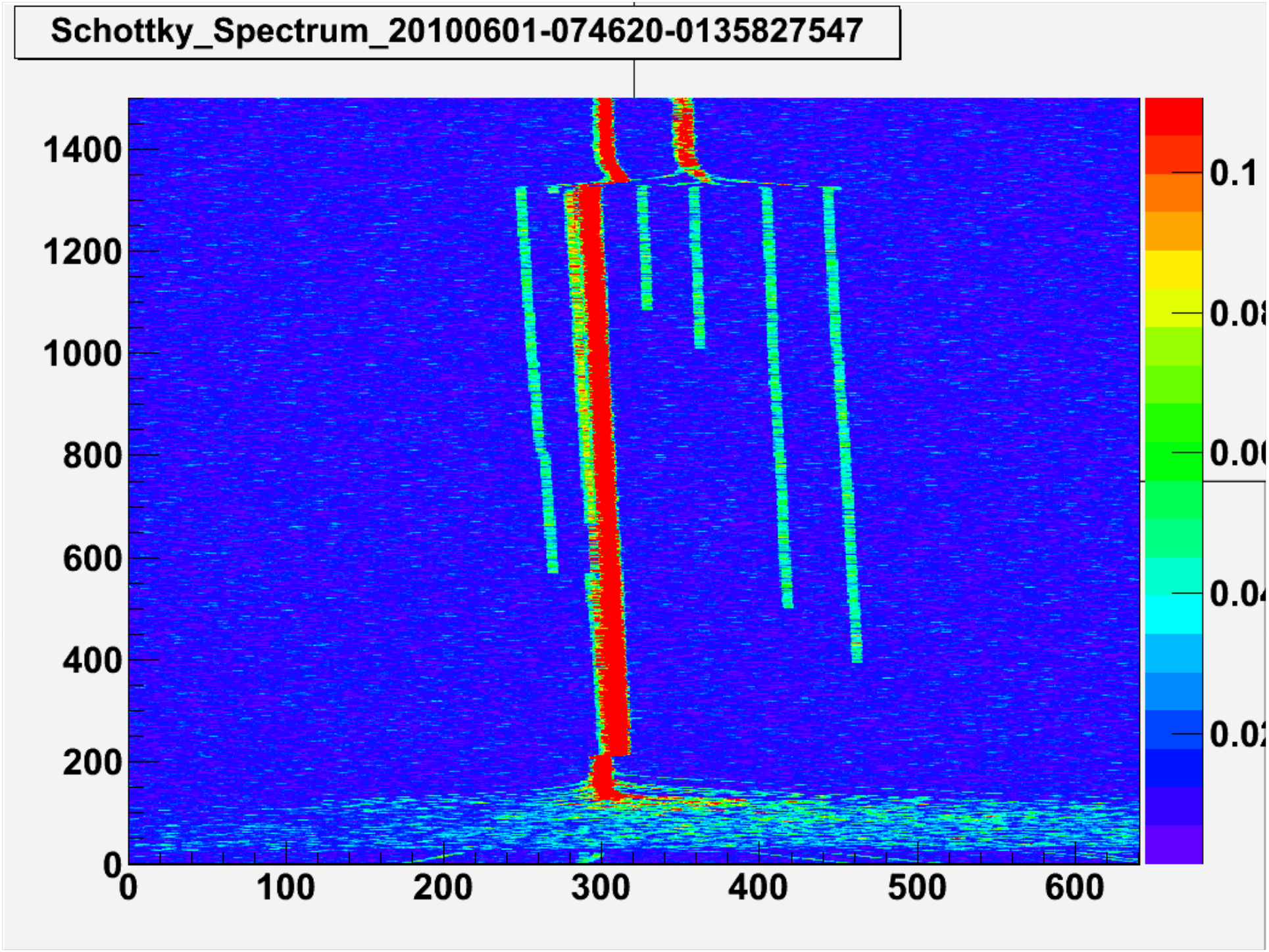
Schottky_Spectrum_20100601-074620-0135827547
1400
1200
1000
800
600
400
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0
0
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200
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600
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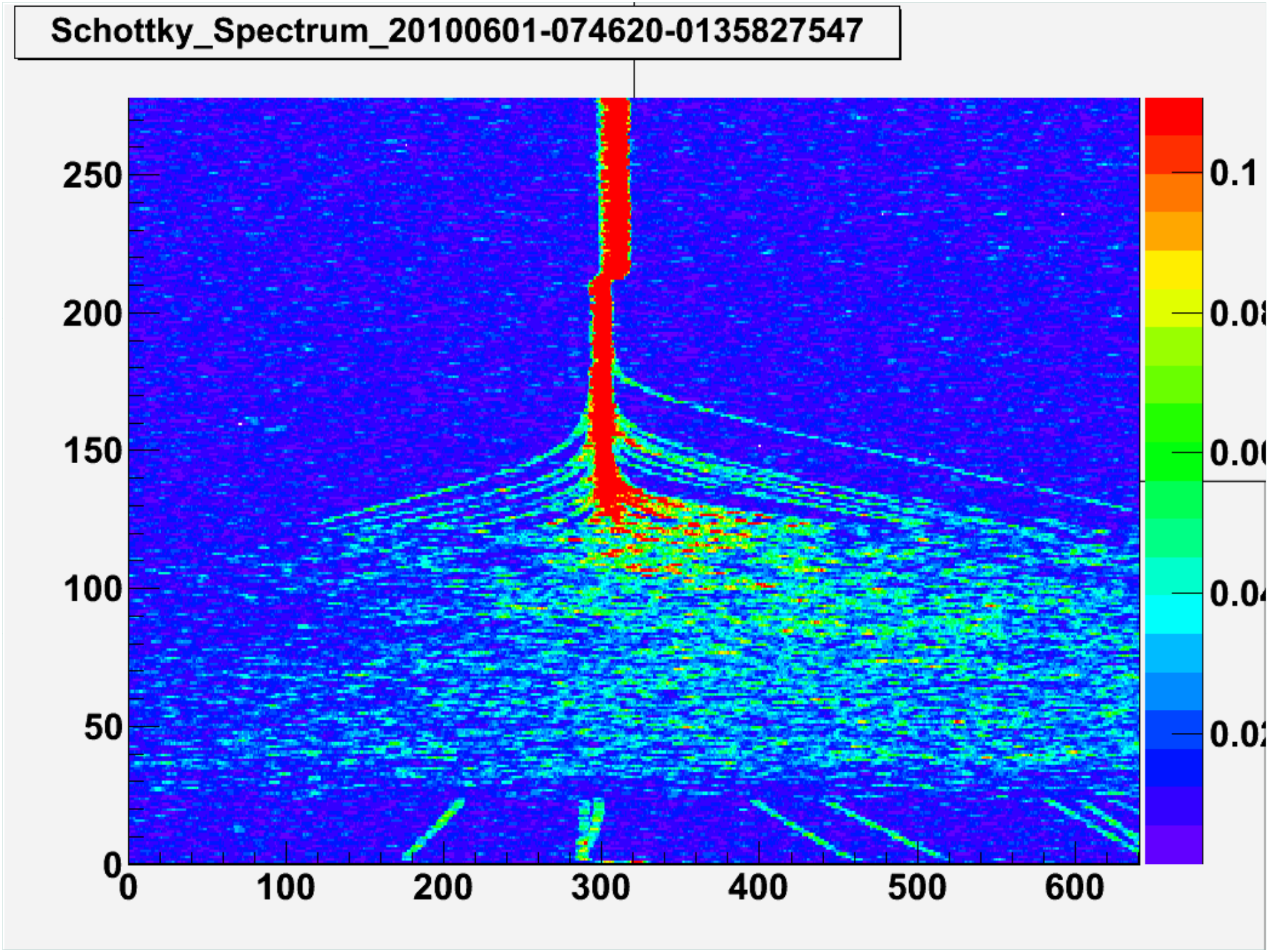
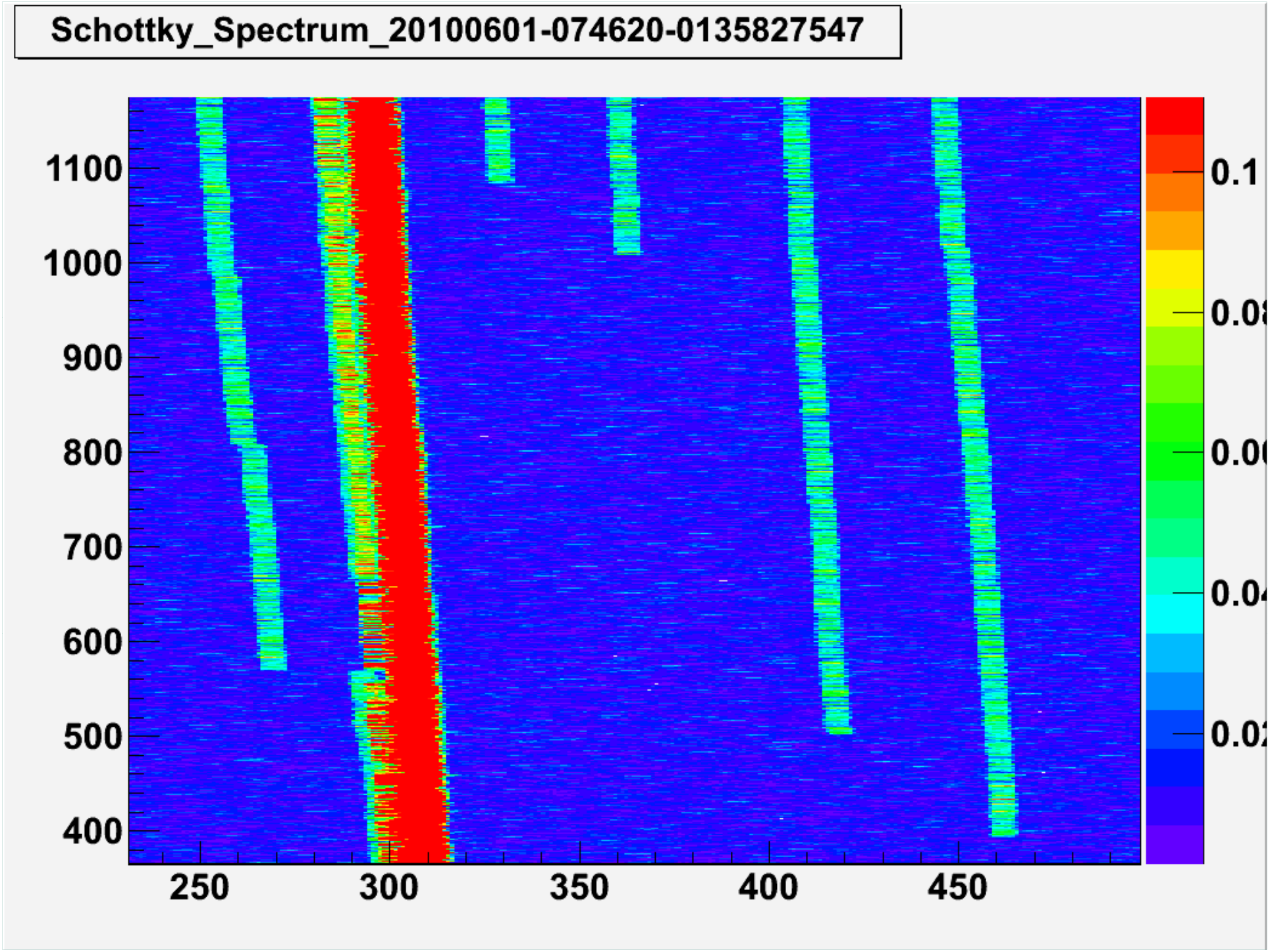
0.08
0.06
0.04
0.02


Schottky_Spectrum_20100601-074620-0135827547
250
200
150
100
50
0
0
100
200
300
400
500
600
0.1
0.08
0.06
0.04
0.02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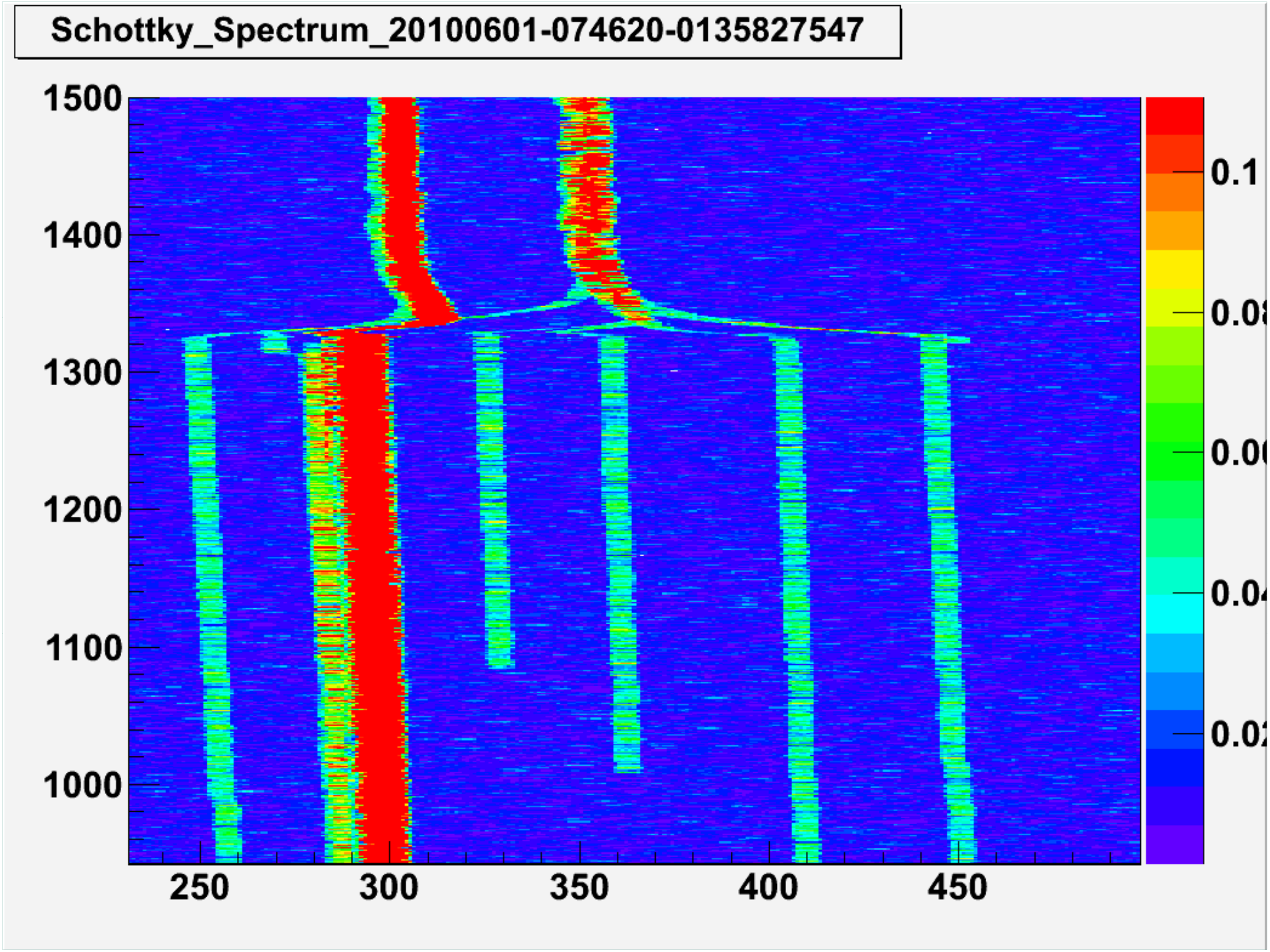
700
600
500
400
250
300
350
400
450
0.1
0.08
0.06
0.04
0.02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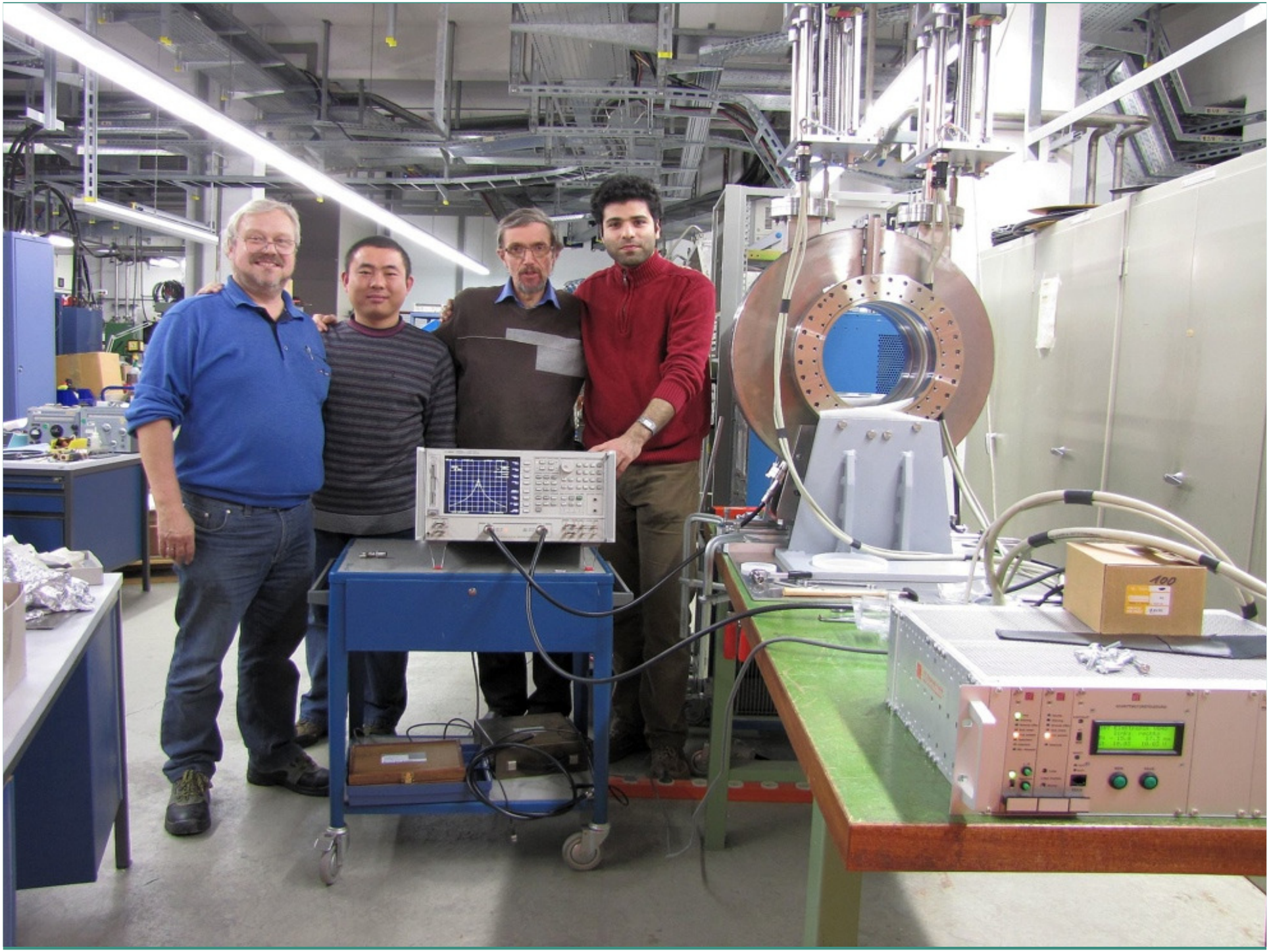
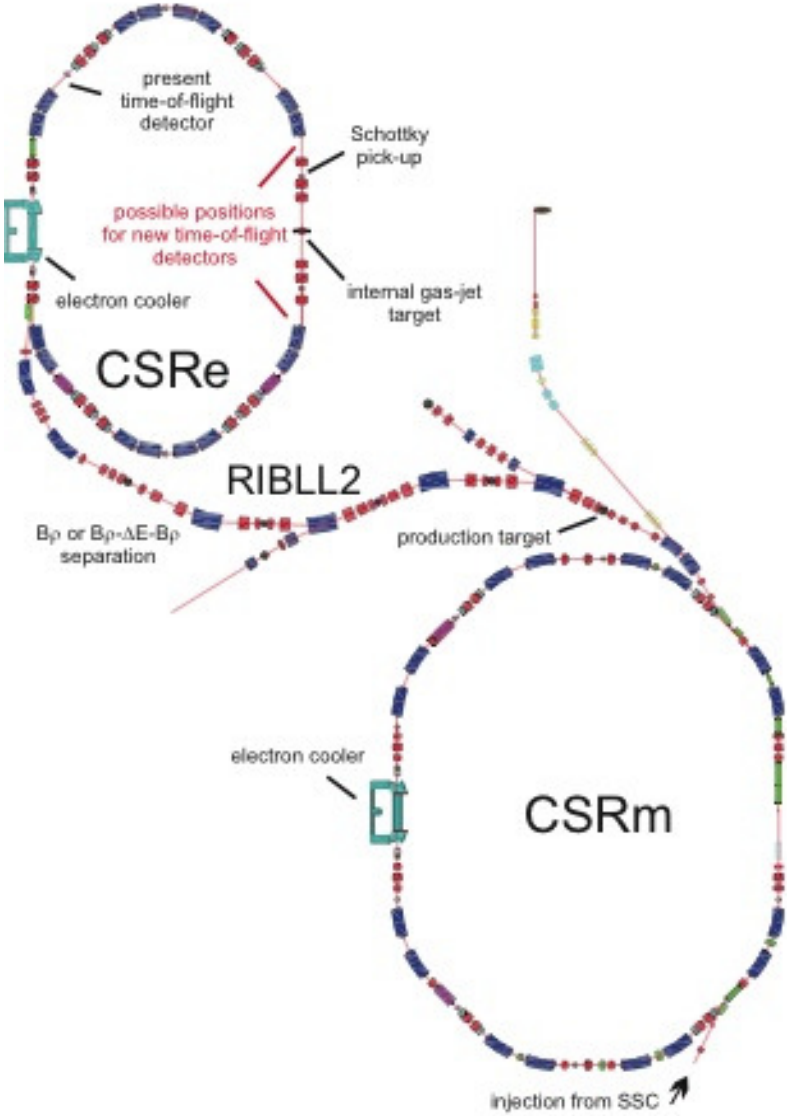
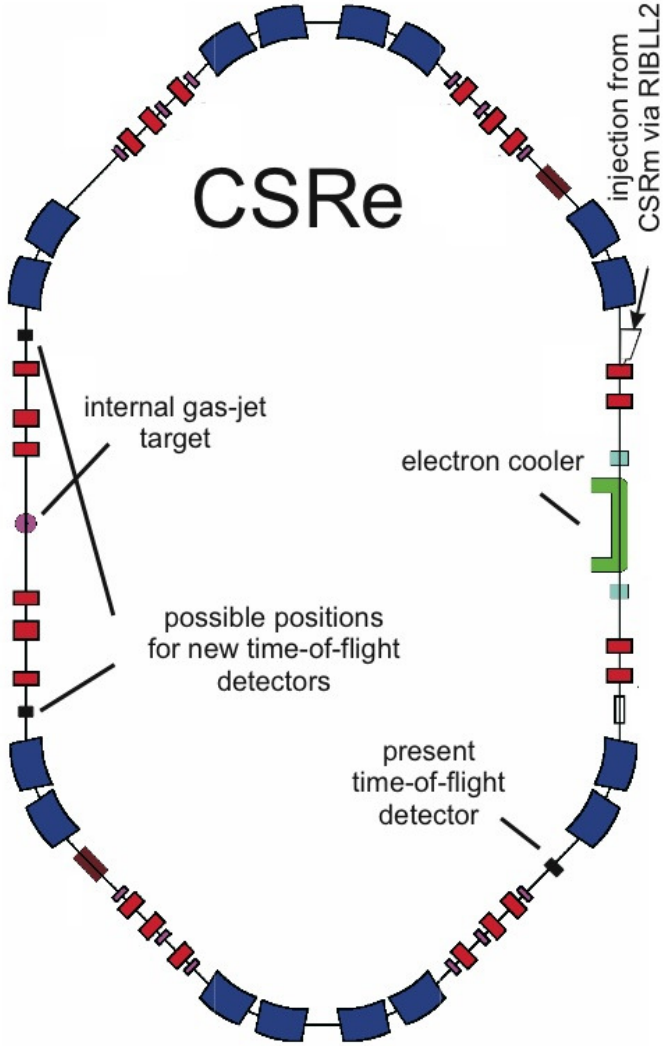


CSRm-CSRe Complex at IMP in Lanzhou





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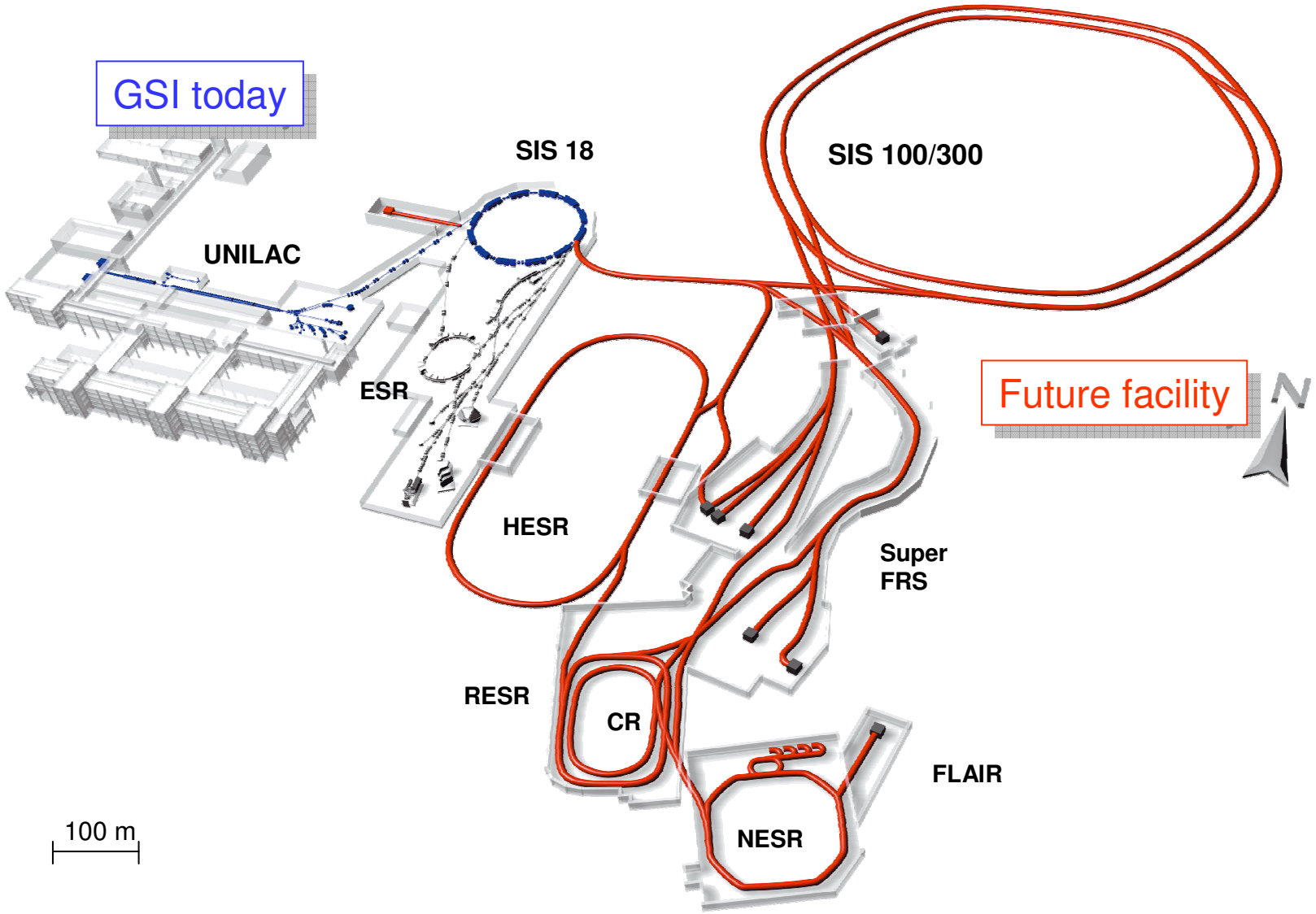
FAIR - Facility for Antiproton and Ion Research



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ILIMA: Set-Up

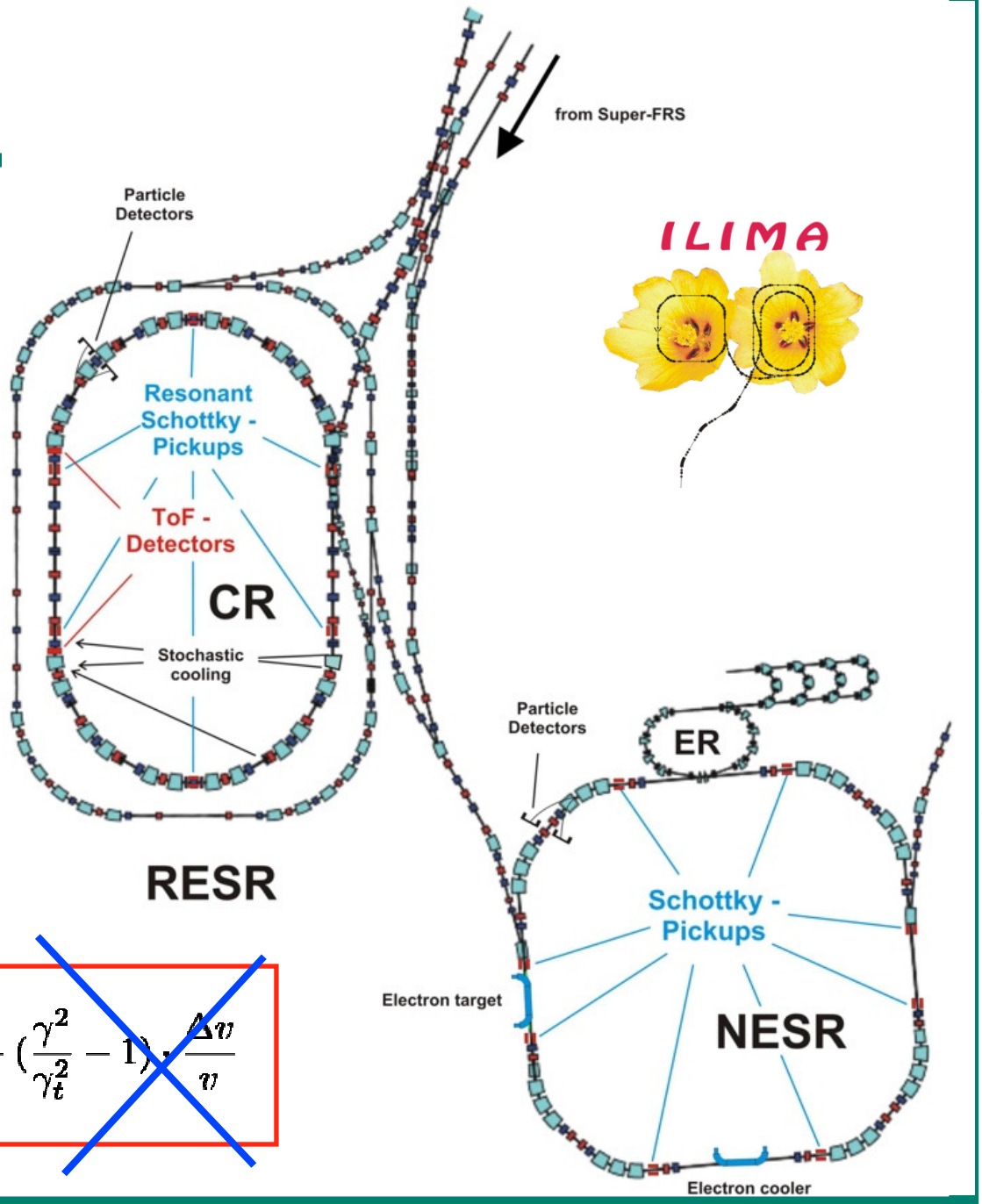
Isochronous Mass Spectrometry in the CR

$$\gamma \rightarrow \gamma_t$$

Schottky Mass Spectrometry in the CR & NESR

$$\frac{\Delta v}{v} \rightarrow 0$$

$$\frac{\Delta t}{t} = -\frac{\Delta f}{f} = \frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{m/q} + \left(\frac{\gamma^2}{\gamma_t^2} - 1\right) \cdot \frac{\Delta v}{v}$$



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Experimental Collaboration

D. Atanasov, D. Balabanski, K. Blaum, F. Bosch, D. Boutin, C. Brandau, L. Chen, Ch. Dimopoulou, H. Essel, Th. Faestermann, H. Geissel, E. Haettner, M. Hausmann, S. Hess, V. Ivanova, P. Kienle, Ch. Kozhuharov, R. Knöbel, R. Krücken, J. Kurcewicz, S.A. Litvinov, Yu.A. Litvinov, X. Ma, L. Maier, M. Mazzocco, W. Meng, F. Montes, A. Musumarra, G. Münzenberg, C. Nociforo, F. Nolden, T. Ohtsubo, A. Ozawa, W.R. Plass, A. Prochazka, R. Reuschl, S. Sanjari, Ch. Scheidenberger, D. Shubina, U. Spillmann, M. Steck, Th. Stöhlker, B. Sun, T. Suzuki, S. Torilov, X. Tu, H. Weick, M. Winkler, N. Winckler, D. Winters, N. Winters, T. Yamaguchi, G. Zhang

IMP 中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

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GSI

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