Single Particle Detection with a Schottky Resonator

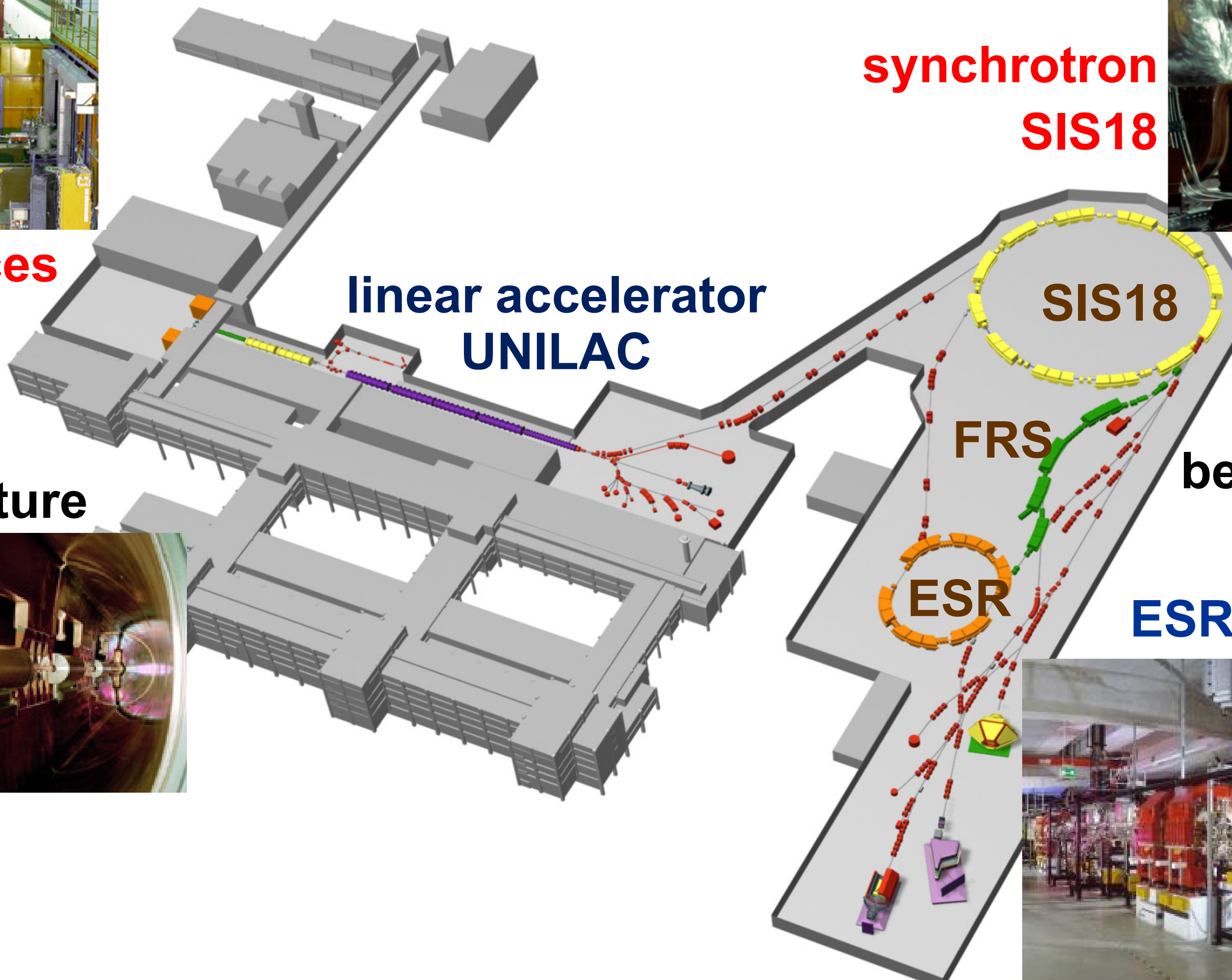
Markus Steck,
Storage Rings, GSI Darmstadt

and
P. Hülsmann, Y. Litvinov, F. Nolden, C. Peschke, P. Petri, S. Sanjari, I. Schurig, GSI Darmstadt

X. Chen, J. Wu, IMP Lanzhou, China

The GSI Accelerators: UNILAC, SIS18 and ESR

Ion sources

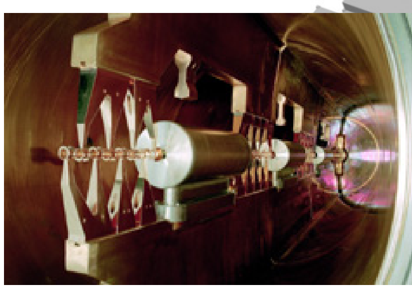


linear accelerator
UNILAC

synchrotron
SIS18

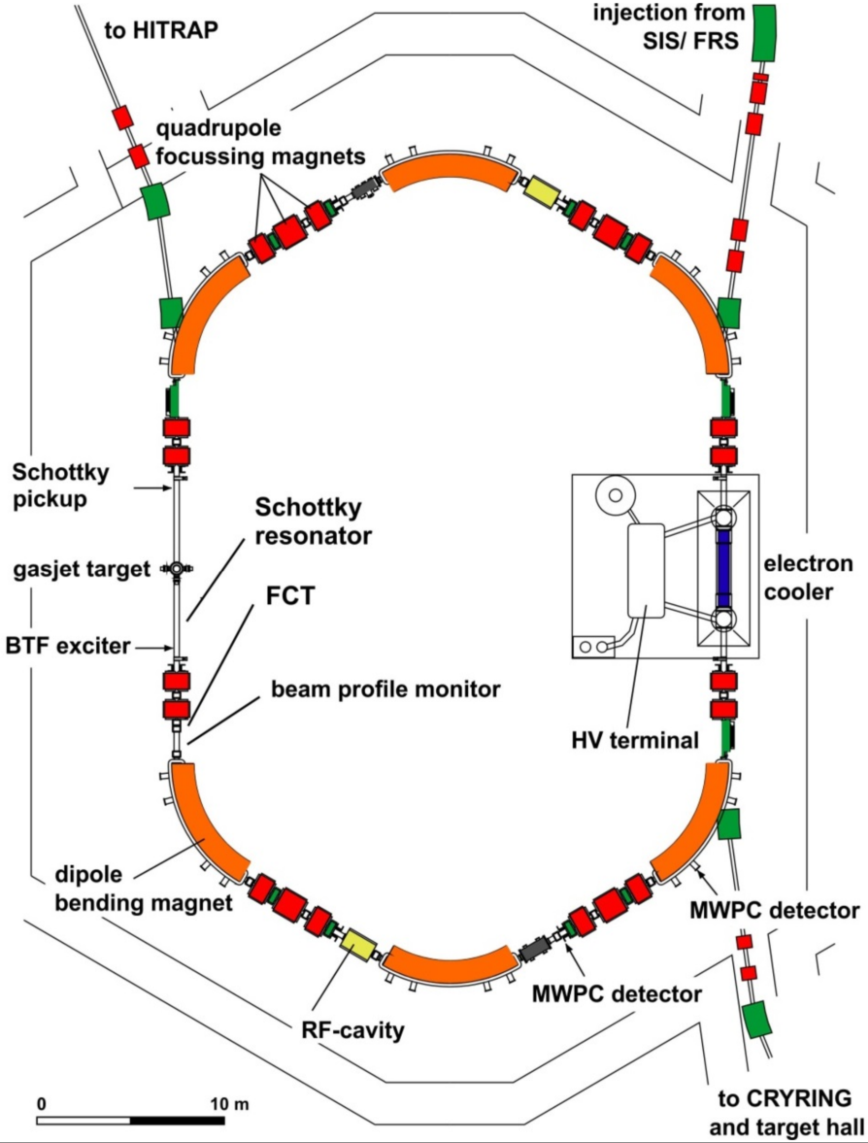
in future → beams to SIS100

IH structure



ESR Storage Ring

Experimental Storage Ring



Fast injection (stable ions / RIBs)

Stochastic cooling (≥ 400 MeV/u)

Electron cooling (3 - 430 MeV/u)

Laser cooling (C^{3+} 120 MeV/u)

Internal gas jet target

Laser experiments

Deceleration (down to 3 MeV/u)

Fast extraction (HITRAP/CRYRING)

Slow (resonant) extraction

Ultraslow extraction (charge change)

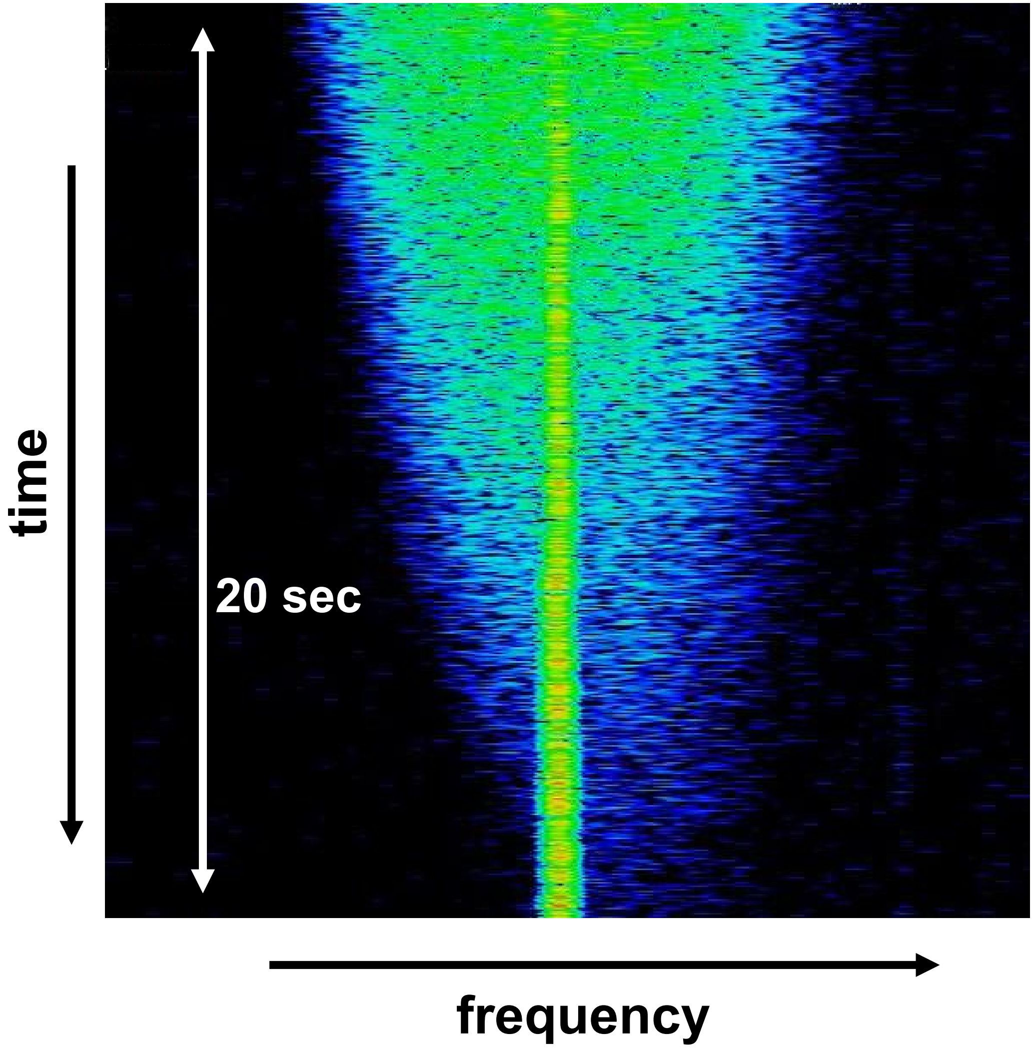
Beam accumulation

Multi charge state/
multi component operation

Schottky mass spectrometry

Isochronous mode

Schottky Noise Measurement



some 10^7 $^{197}Au^{76+}$ ions
at an energy of 300 MeV/u
cooling process
with electron cooling

reduction of momentum spread

initial value: about 10^{-3}

final value: some 10^{-5}

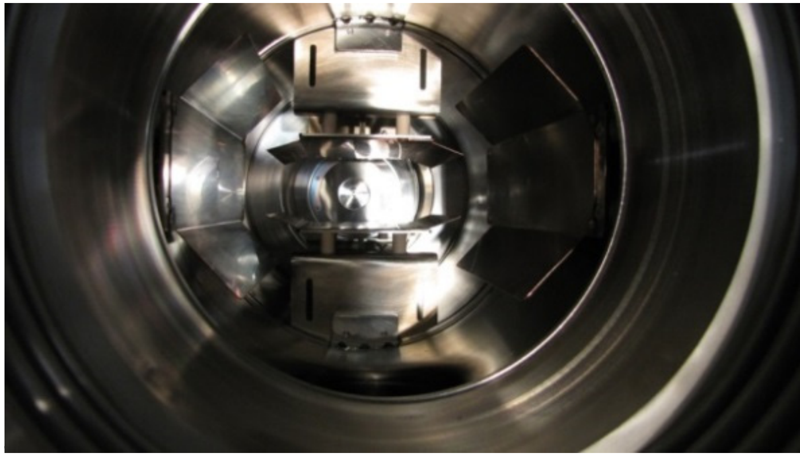
Schottky noise analysis

⇒ momentum spread

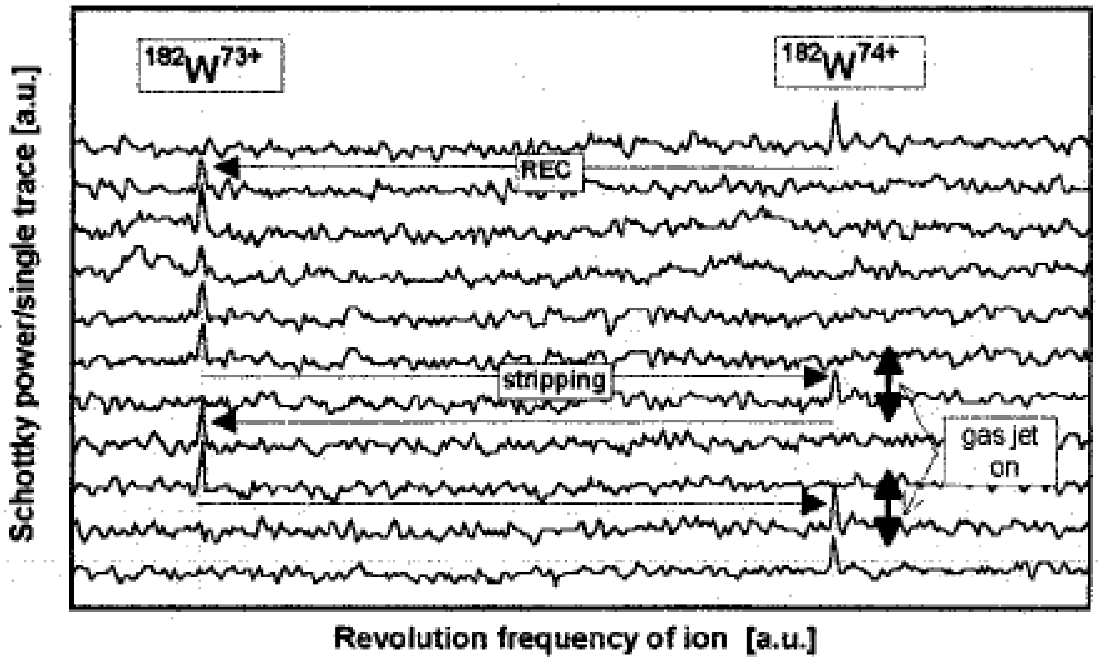
momentum ⇒ velocity
mass
charge

Single Particle Detection in ESR

standard capacitive Schottky noise pick-up
broad band (~ 1-150 MHz)
resonant circuit (30-80 MHz)



from GSI Scientific Report 1995



single tungsten (^{182}W) ion cooled by electron cooling
$\Rightarrow$ recombination 74+ $\rightarrow$ 73+

interacting with internal target
$\Rightarrow$ ionization 73+ $\rightarrow$ 74+

Schottky signal power $P = N \underline{(Qe)}^2 f_o^2$

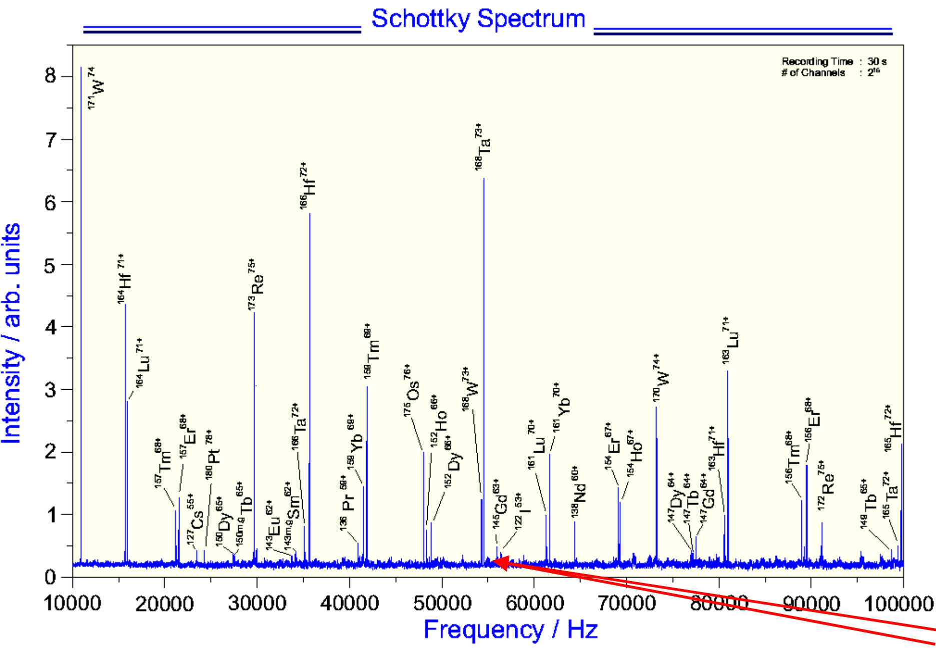
Schottky Mass Spectrometry

Injection of cocktail rare isotope beam from fragment separator FRS

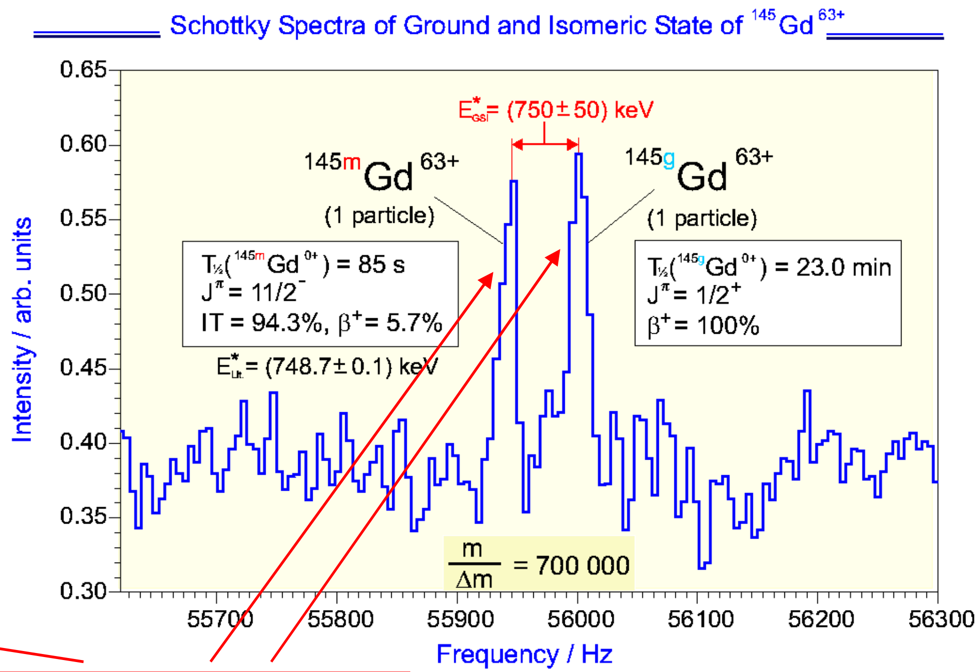
Cooling (stochastic pre-cooling + final electron cooling)

Achieved momentum spread ($\delta p/p = 5\times10^{-7}$, $\delta f/f = 2\times10^{-7}$)

broad band spectrum



zoom of broad band spectrum

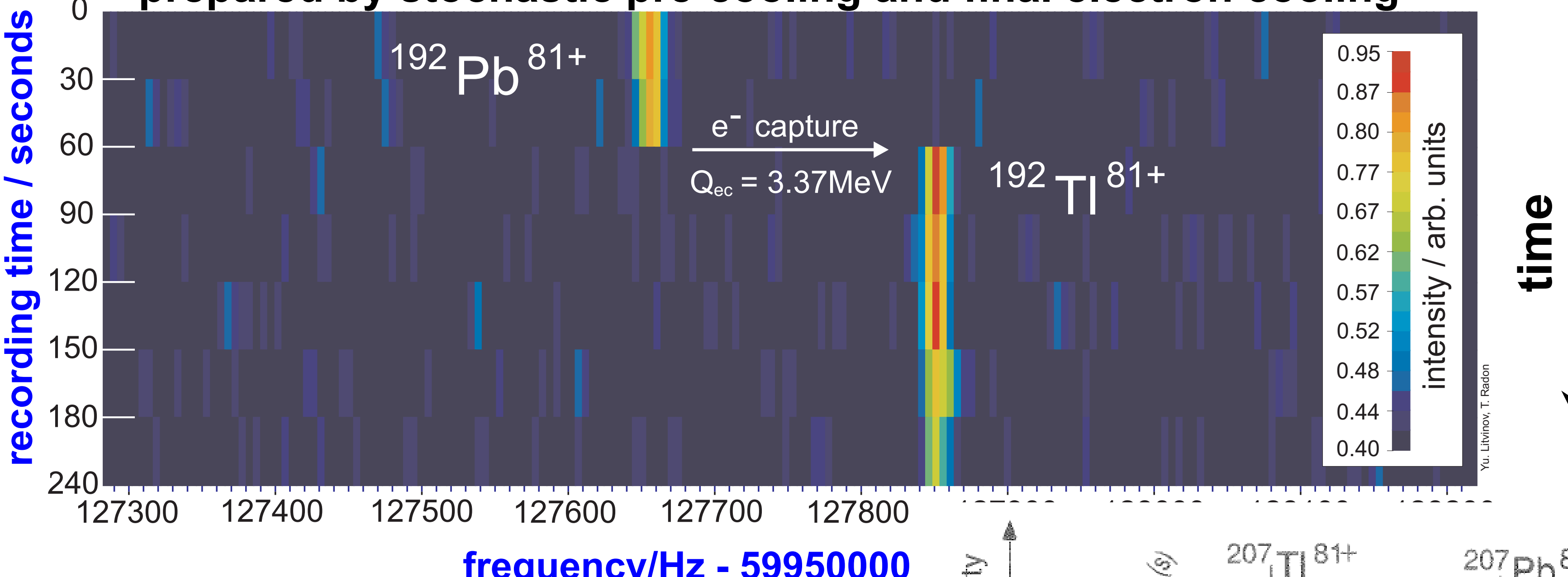


Two single ions !

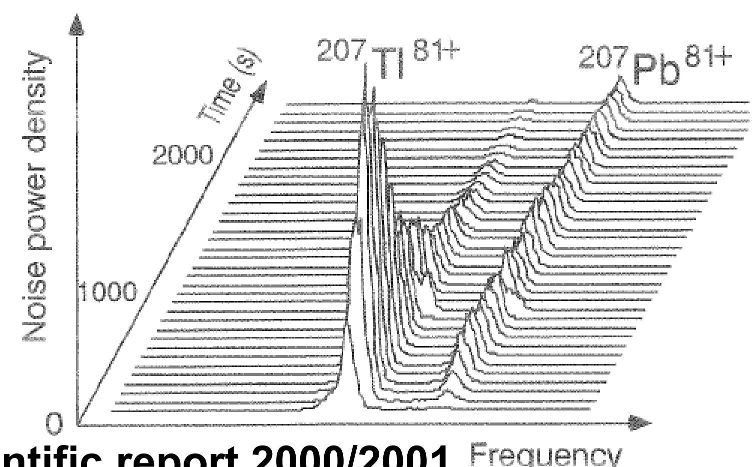
Frequency: $\Delta f = f - f_{lo}$

Radioactive Decay of a Single Particle

Schottky noise signal of the decay of a single rare isotope prepared by stochastic pre-cooling and final electron cooling



low signal to noise ratio
time resolution is limited
averaging over many seconds



from GSI scientific report 2000/2001

Design Considerations for a Schottky Resonator in the ESR

increased sensitivity to single ions

faster detection of single ions
⇒ measurement of decay time with millisecond resolution

UHV compatibility

decoupling of the resonator from the beam at high intensity

tuning range of resonant frequency

frequency band width up to one percent ⇒ moderate Q

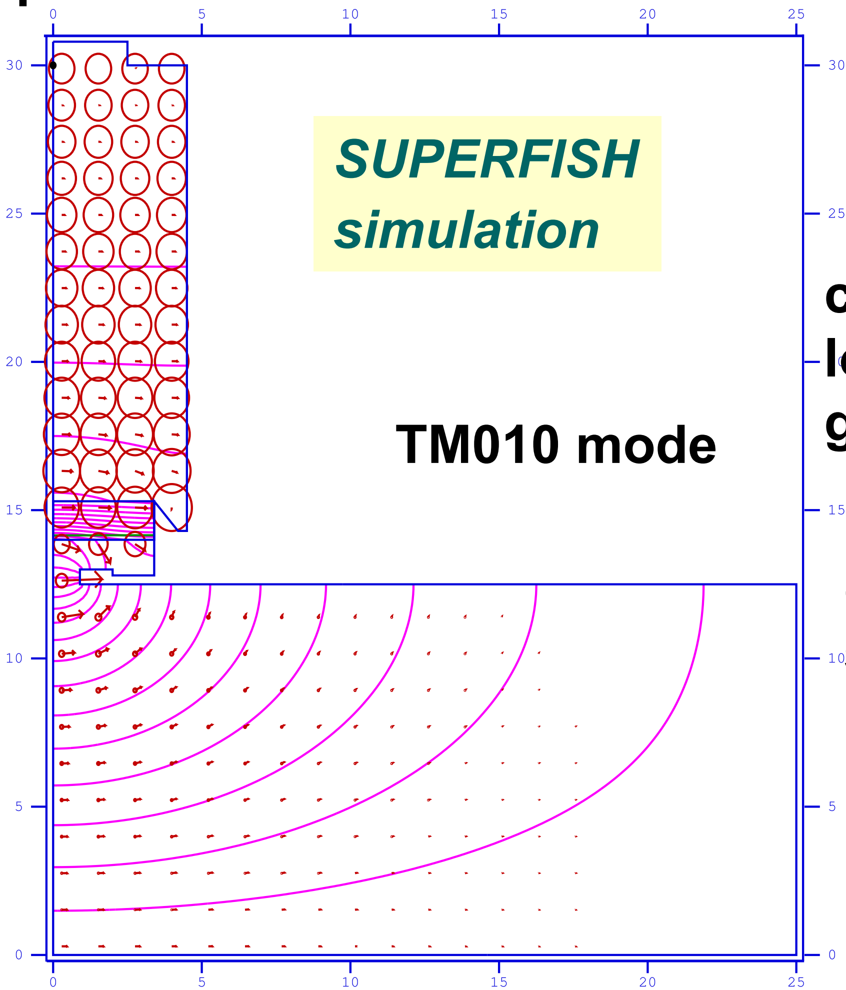
choice of resonant frequency

larger sensitivity	<=>	better time resolution
(lower frequency)		(higher frequency)

mechanical dimensions of cavity (space restrictions)

Pillbox Type Cavity

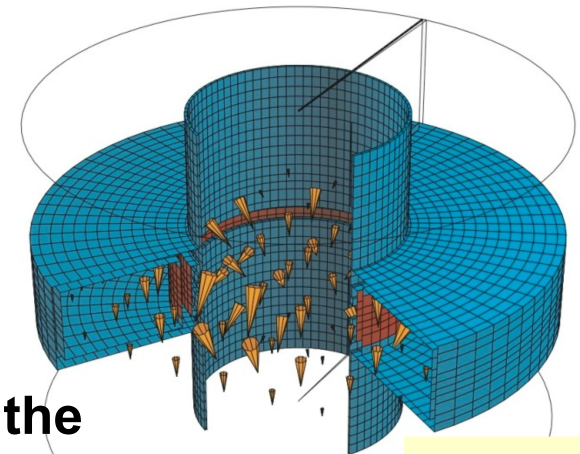
resonant frequency ~ 244 MHz,
pillbox radius 30 cm



SUPERFISH simulation

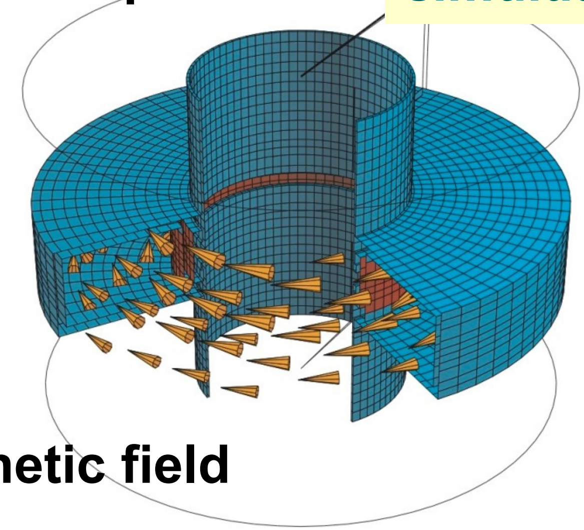
TM010 mode

coupling to the longitudinal electric field generated by the particle



CST-MAFIA simulation

cylindrical symmetry



magnetic field

Signal to Noise Ratio of a Single Particle

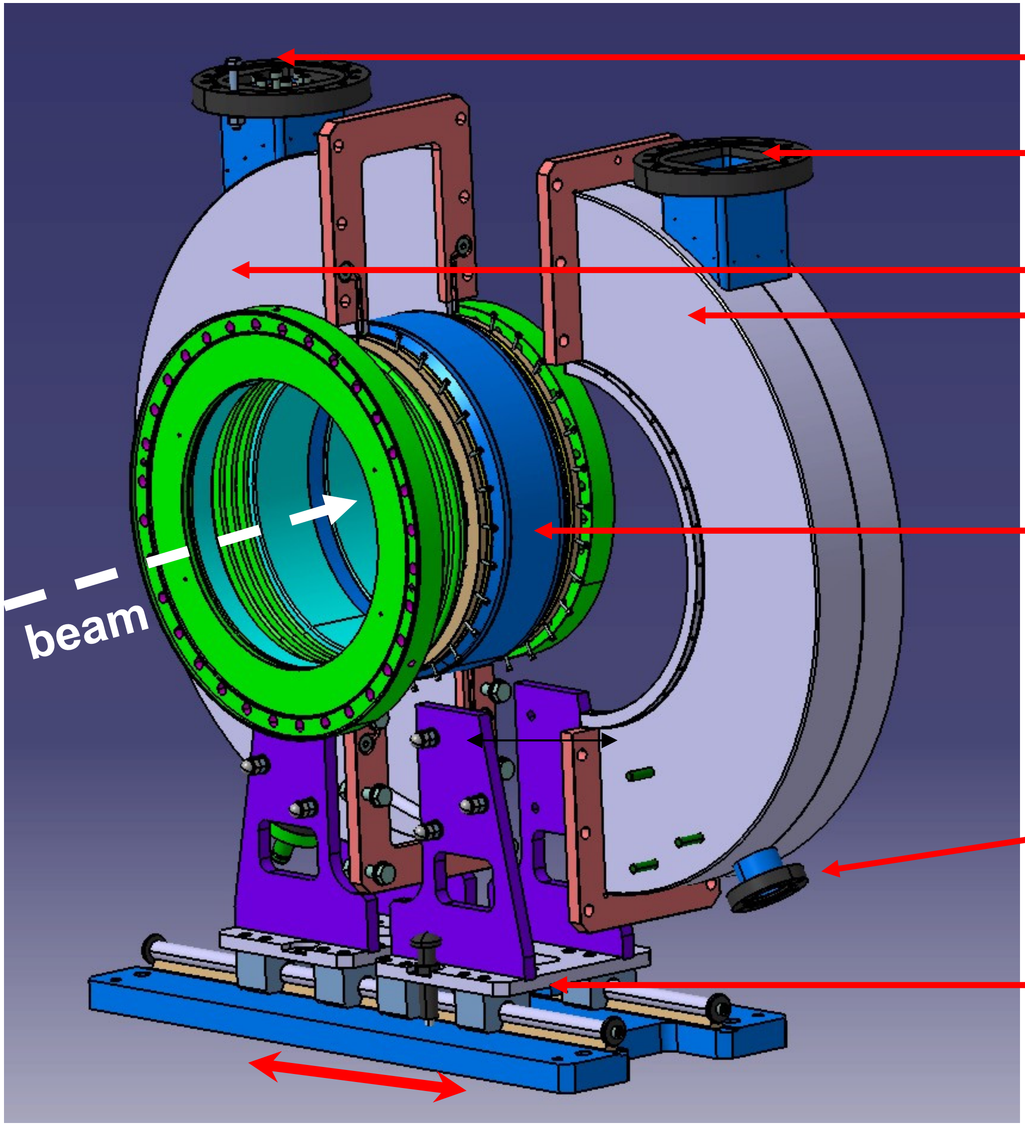
single particle power on resonance:

$$P = \frac{1}{4} I^2 R_S = \frac{1}{4} (qef_0)^2 R_S$$

quality factor	$Q_{unloaded} = 1130$
shunt impedance	$R_s(\beta=0.7) = 40\ k\Omega$
signal power	$P = q^2 \times 1\times10^{-21}$ W
frequency resolution	$\delta f/f = 10^{-6}$ (very cool beams, single particle)
electronic noise floor	$dP_{noise}/df = -173$ dBm $= 5 \times 10^{-21}$ W/Hz

$$P_{noise} < P(q) \Rightarrow q \gtrsim 30$$

Basic Resonator Design



flanges for installation of frequency tuners

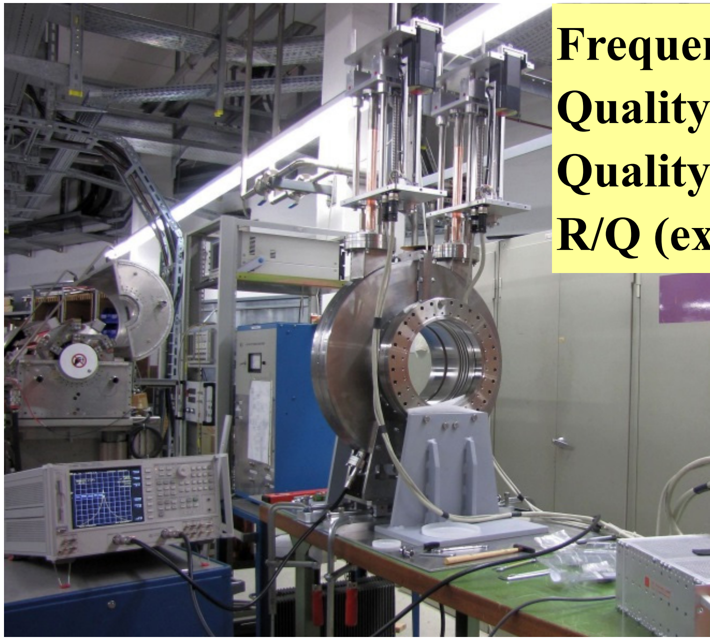
two resonator halves, air filled

ceramic gap

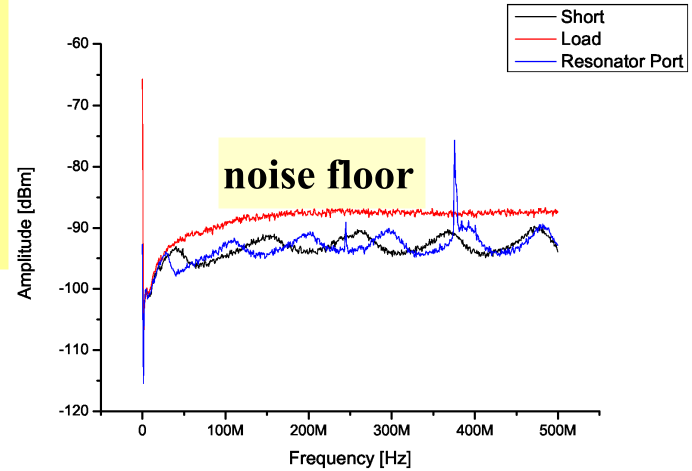
flange for coupling loop

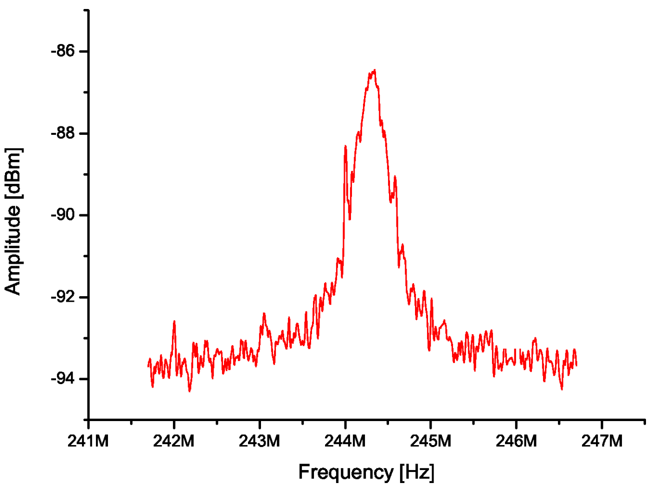
dismountable assembly

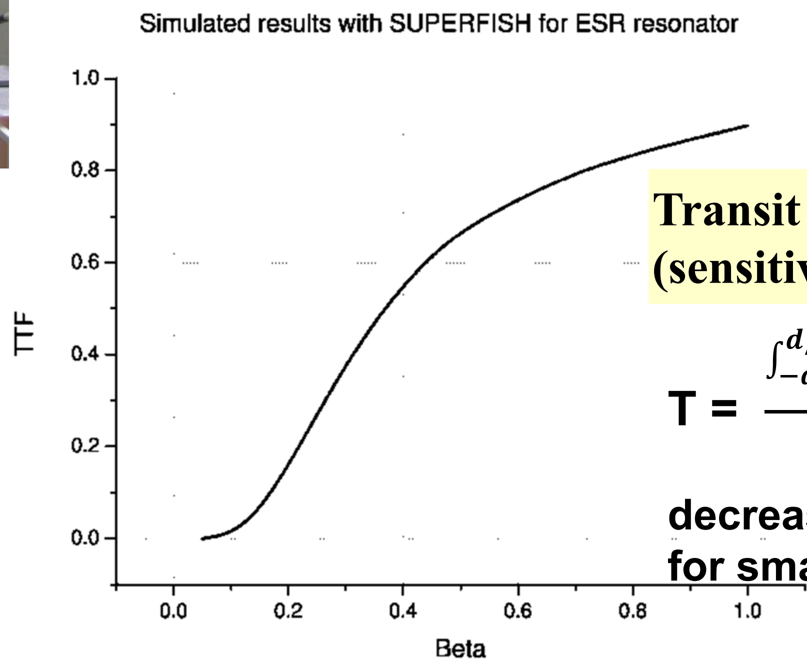
Schottky Resonator Properties



Frequency	244 ± 2.5 MHz
Quality factor (unloaded)	1130
Quality factor calc.	1940/3837
R/Q (experimental)	50.7 Ω





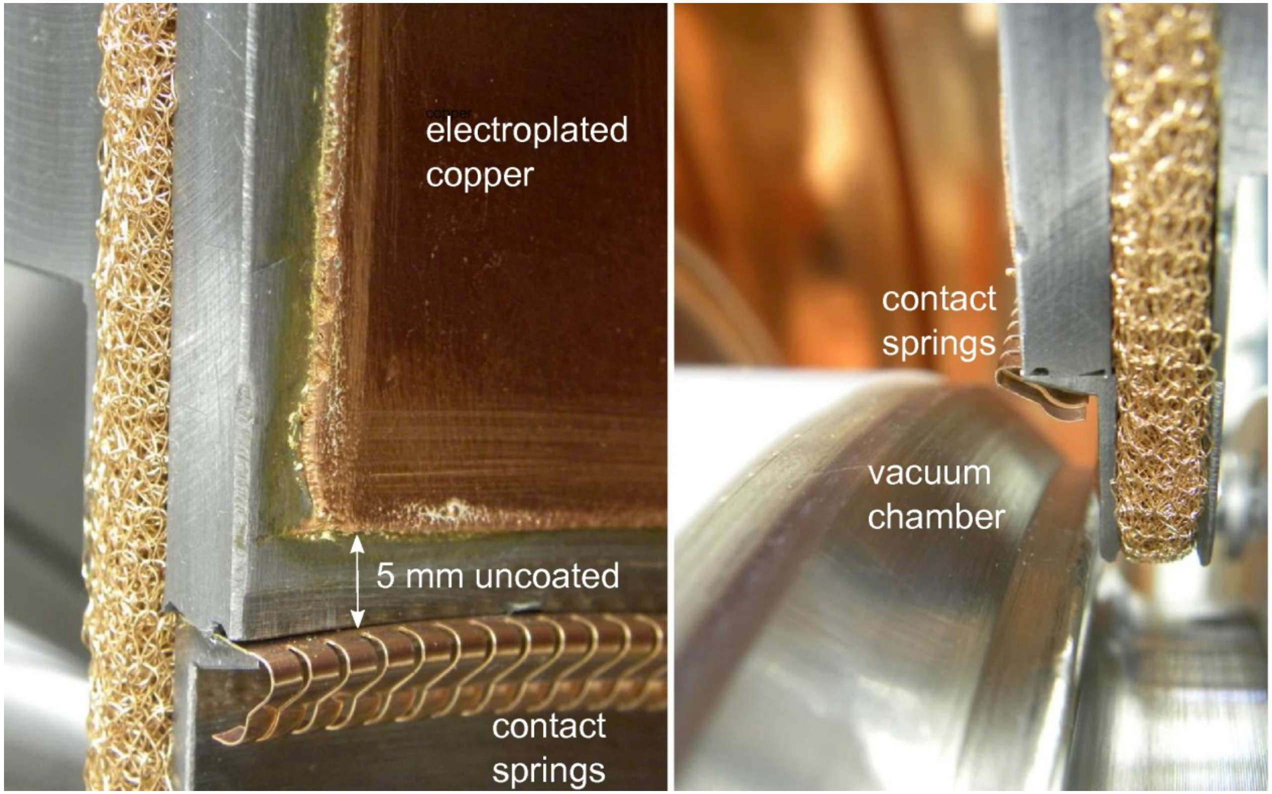


Transit time factor (sensitivity vs velocity)

$$T = \frac{\int_{-d/2}^{d/2} E_z cos\left(\frac{2\pi}{\beta\lambda}z\right)dz}{\int_{-d/2}^{d/2} Ez\, dz}$$

decreasing sensitivity for small beam velocity

Reduction of Quality Factor



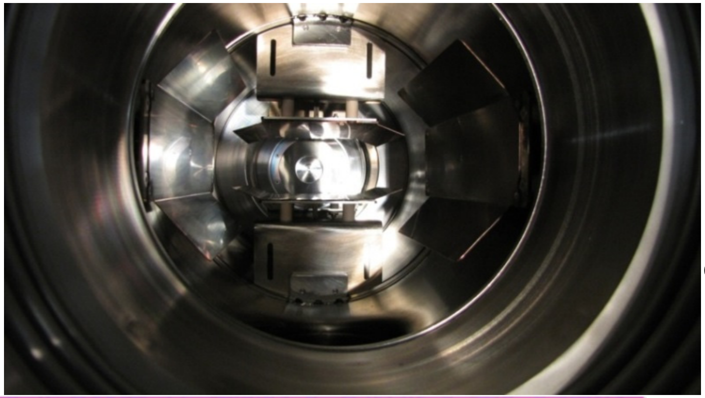
Dielectric losses in ceramics

Losses in stainless steel inside vacuum chamber

Partially exposed construction steel surface

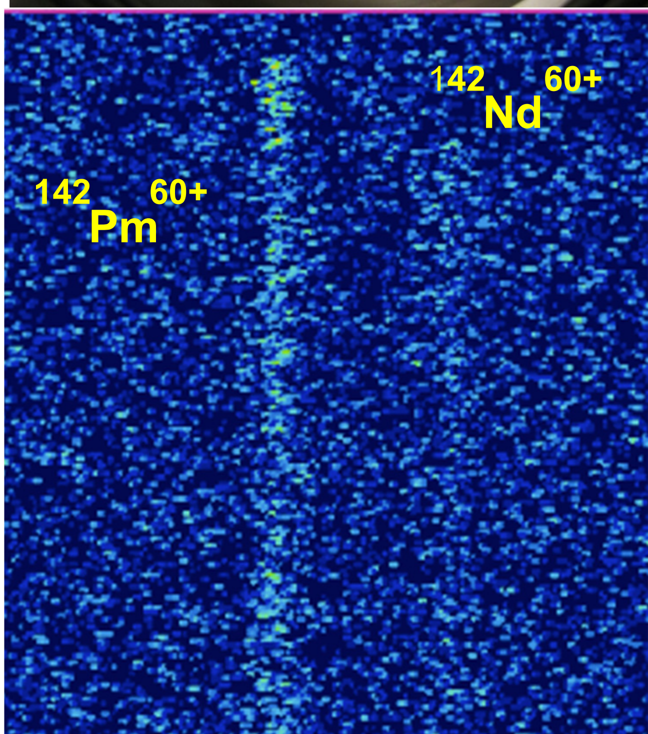
no problem, as larger band width is requested anyhow

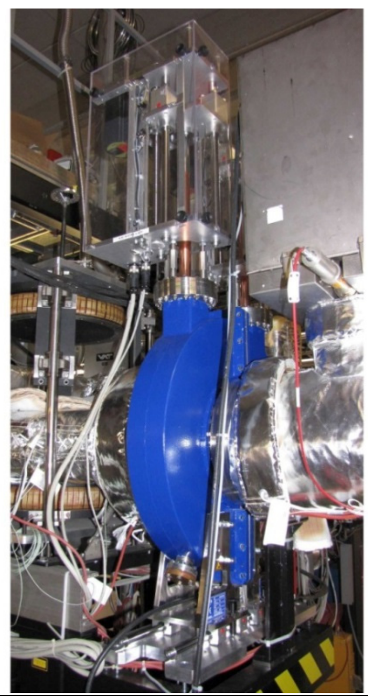
New Schottky Resonator

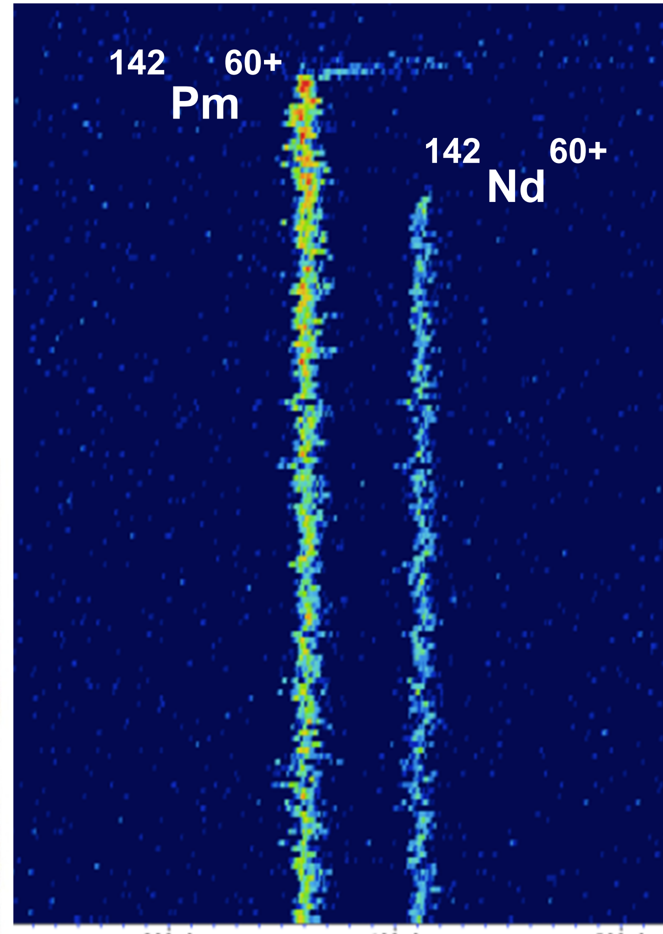


Old Schottky
Pick-up

Stripline electrode
with resonant circuit
matched to 30th harmonic
of the revolution frequency





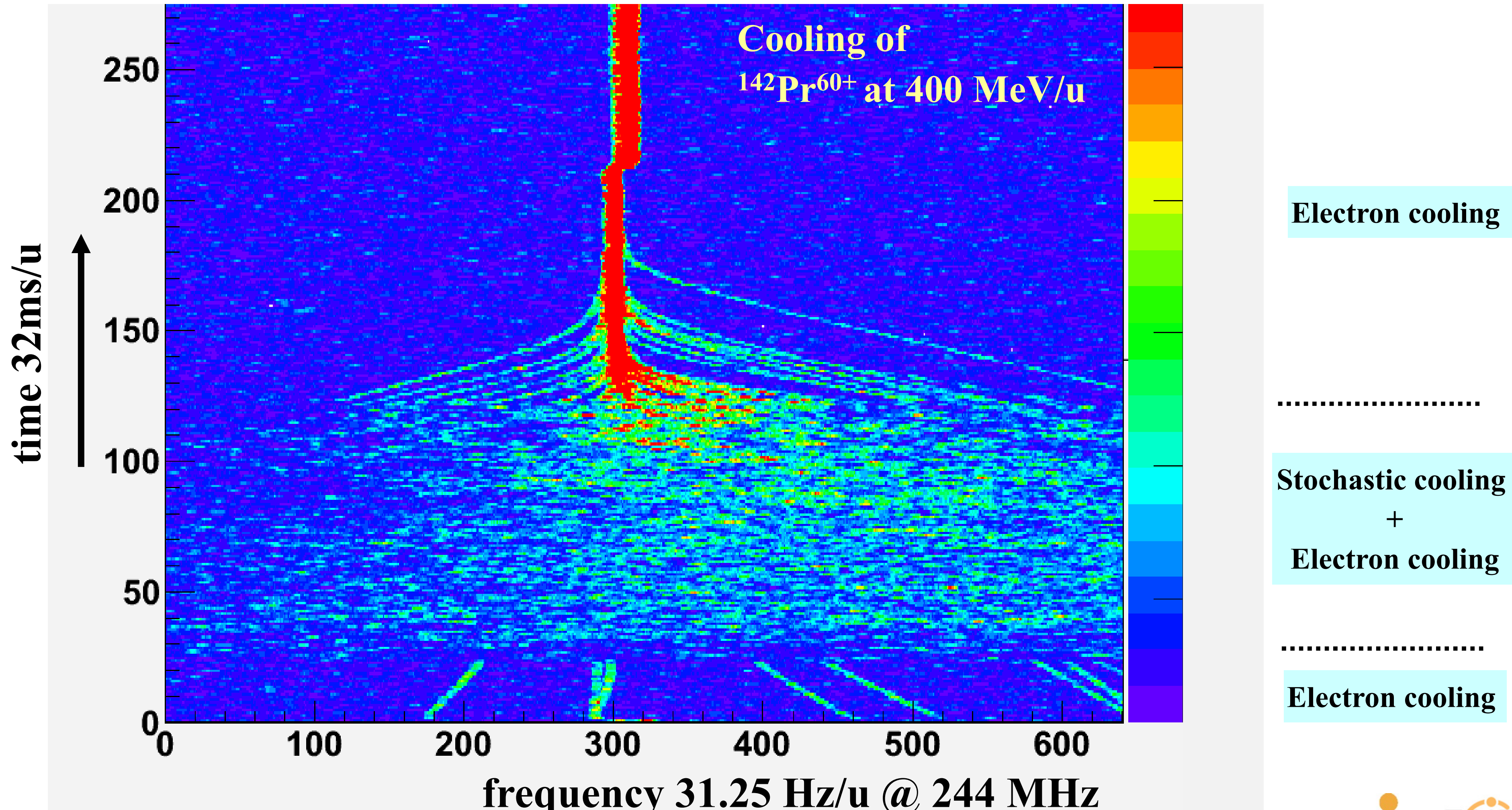


New Resonator Cavity
(pill box type)

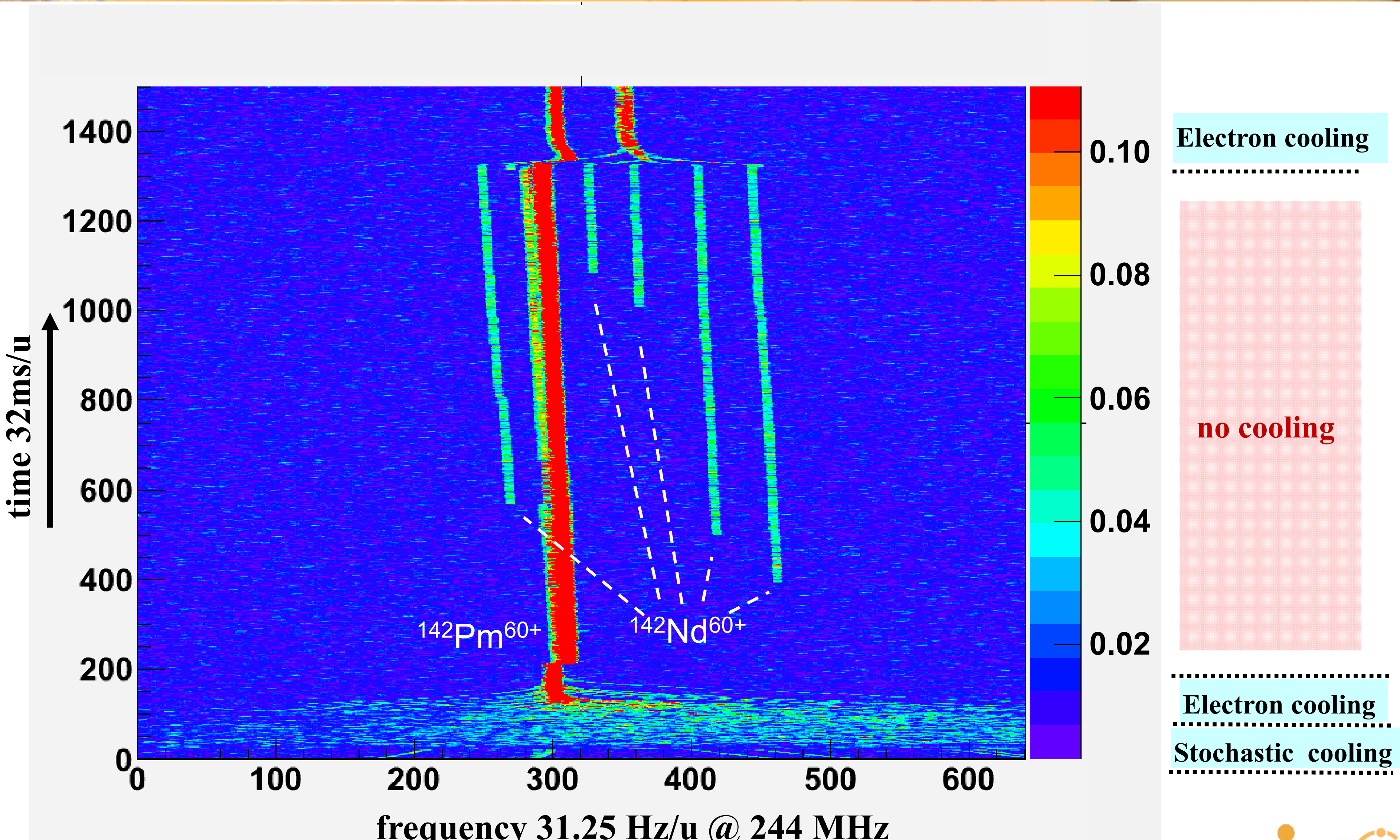
124th harmonic of the revolution frequency

Measurement of Cooling Process

combined effect of stochastic and electron cooling



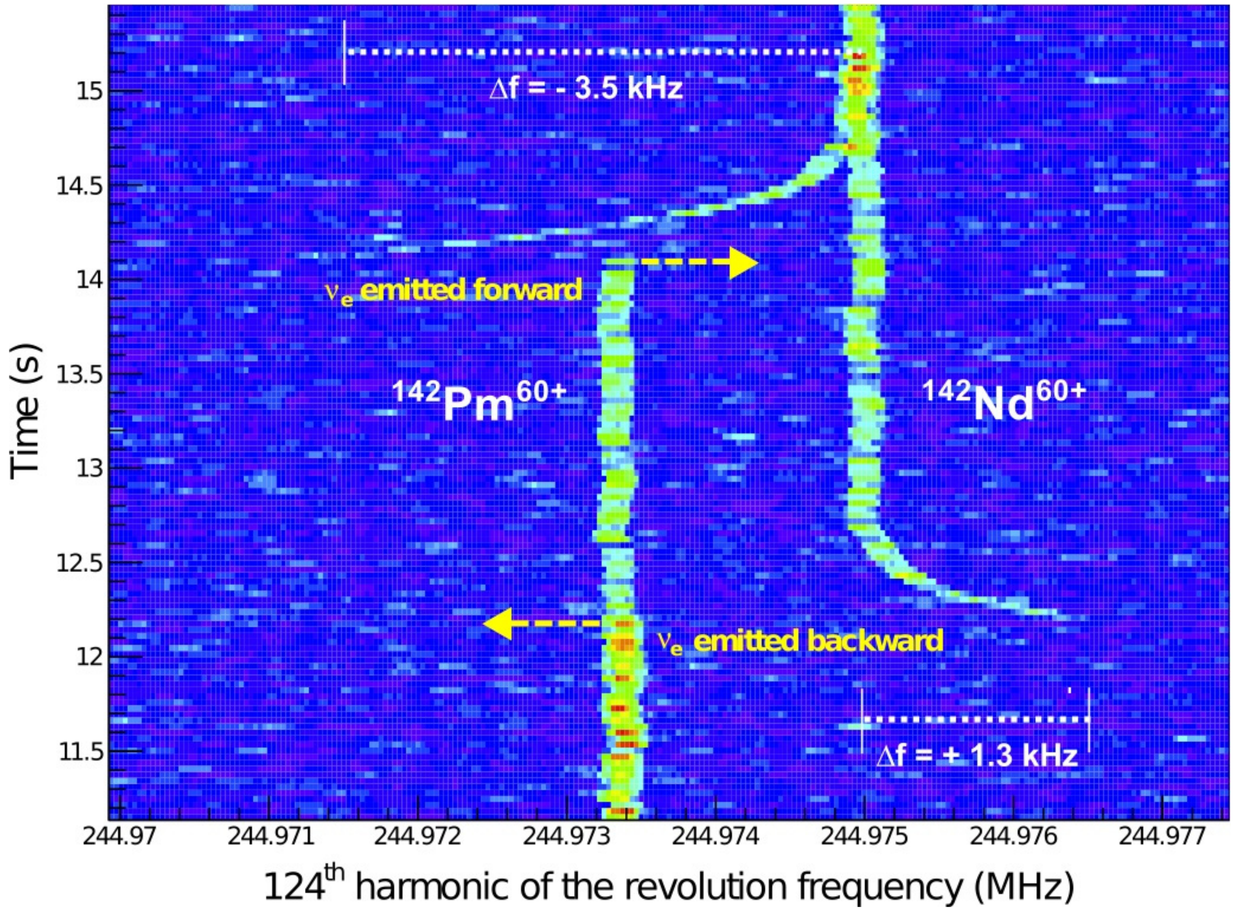
Measurement of Radioactive Decay



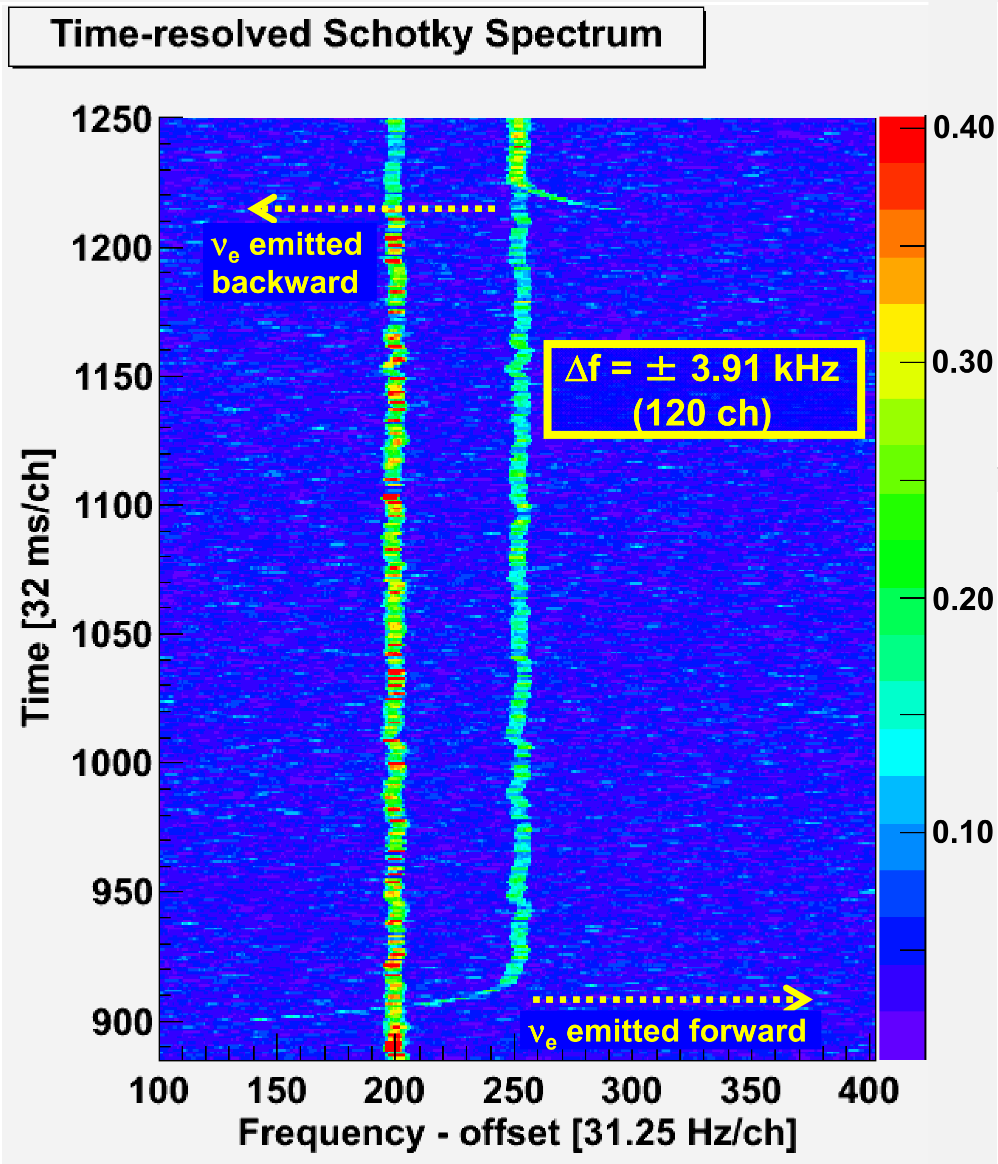
Measurement of Electron Capture Decay

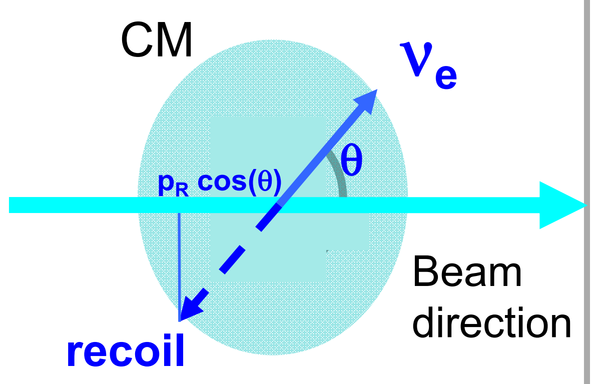
$$^{142}Pm^{60+} + e^{-} \rightarrow {}^{142}Nd^{60+} + \nu_e$$

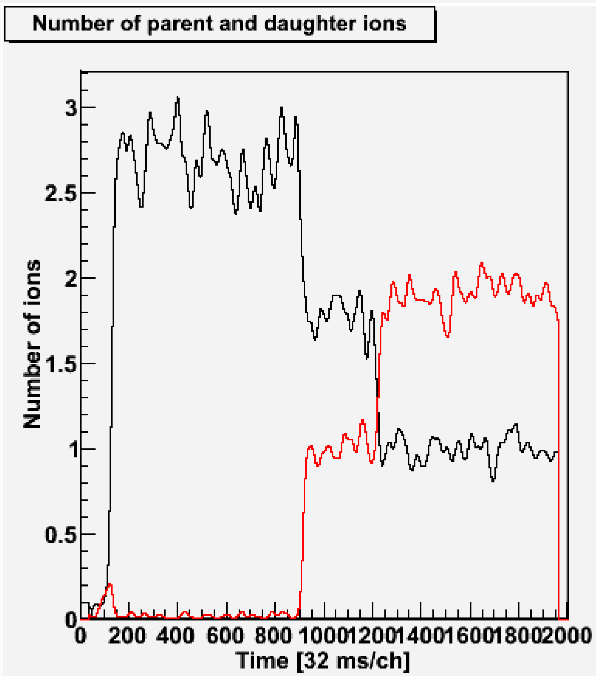
isotropic emission of neutrino ⇒ transfer of energy 90 eV to daughter ion



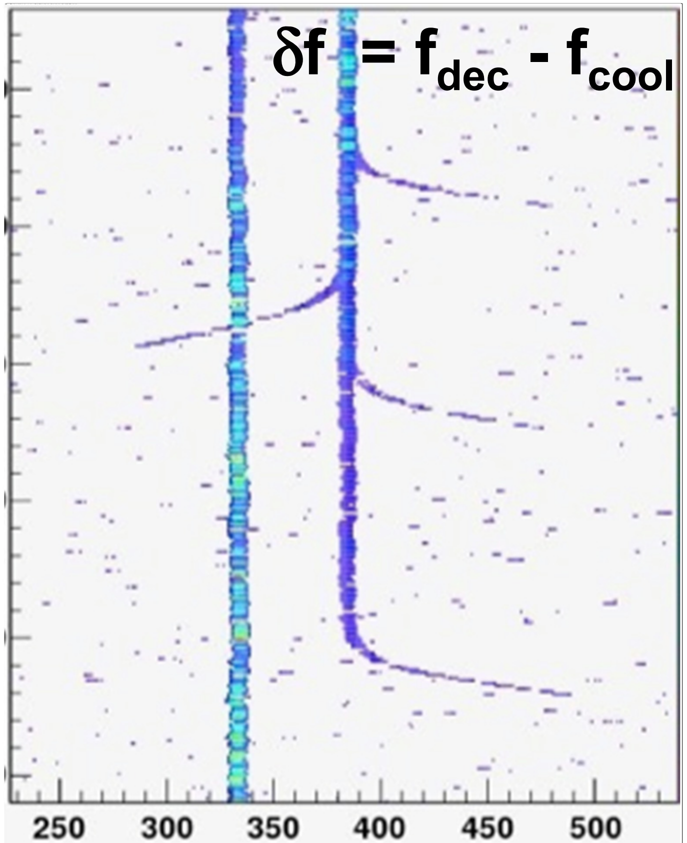
Three Parent H-Like ^{142}Pm Ions





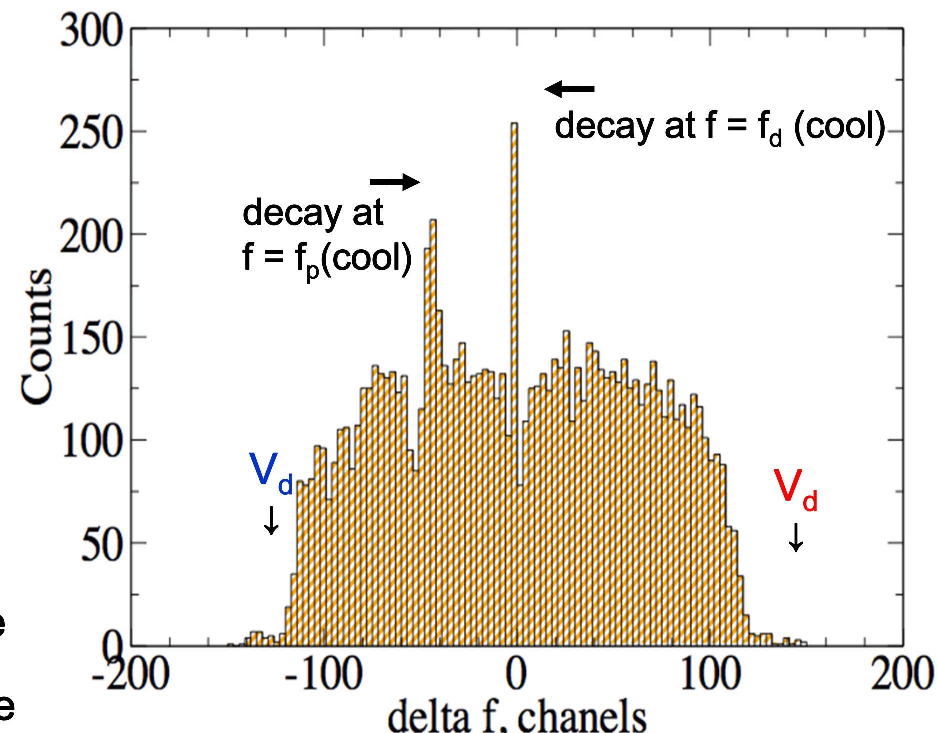


Revolution Frequency Difference δf of the Recoils just after Decay



momentum conservation:
from v_d and m_d one gets the momentum of the (monochromatic) neutrino: $(pc)_d = m_d cv_d = (pc)_\nu$

energy conservation:
from m_p and m_d one gets its energy:
$E_\nu = (m_p - m_d)\, c^2$ and then $\beta_\nu = E_\nu / (pc)_\nu$

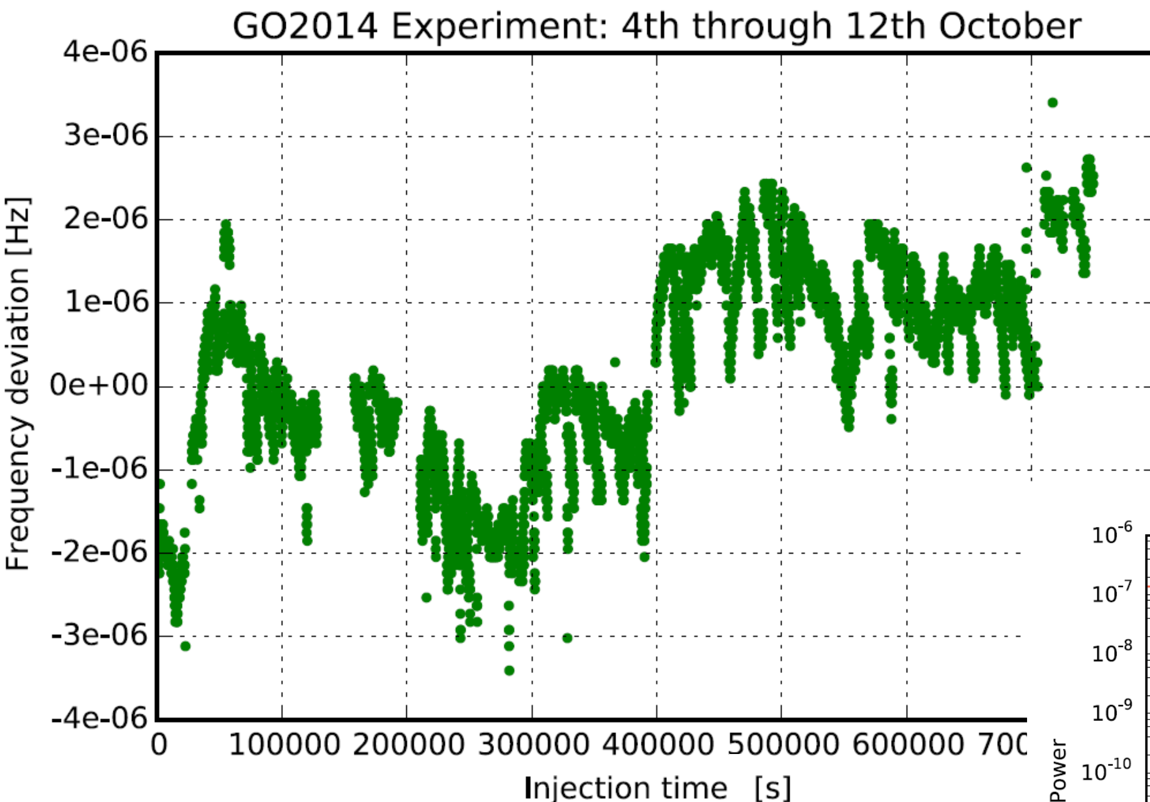


For a (longitudinally) unpolarized beam the distribution should have a rectangular shape

For a (steadily controlled) polarized beam the distribution would provide the helicity of the neutrino

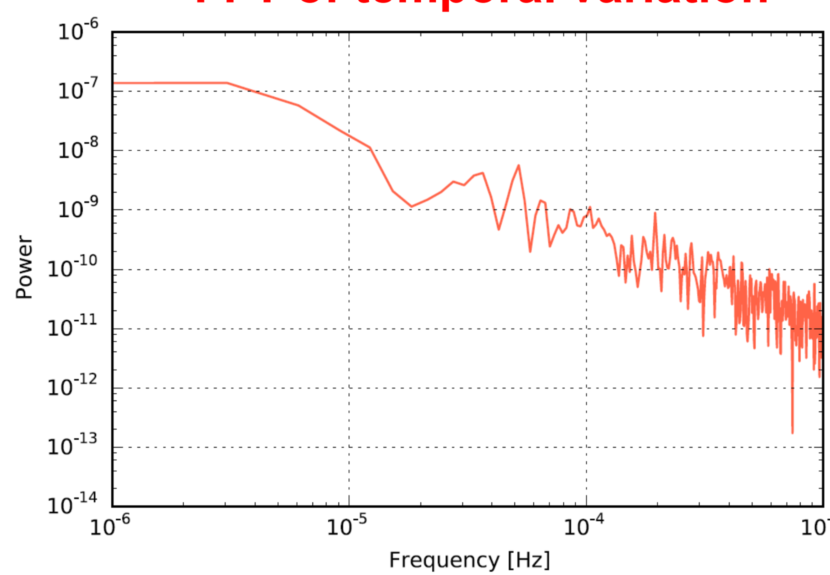
⇒ no polarization

Stability of Revolution Frequency



frequency variation over one week determined from the peak position

FFT of temporal variation

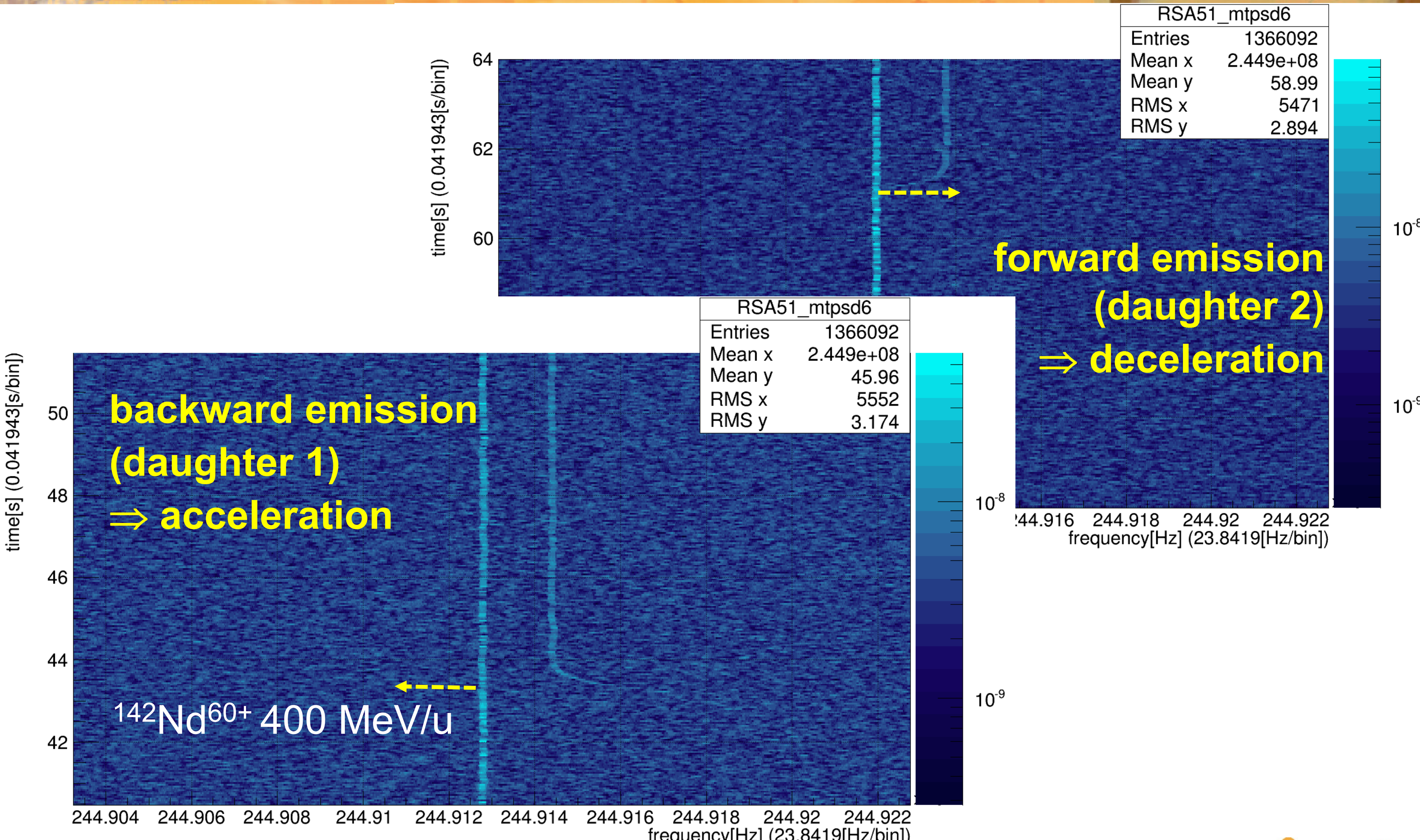


variations of revolution frequency over one week: $\leq \pm 3\times10^{-6}$

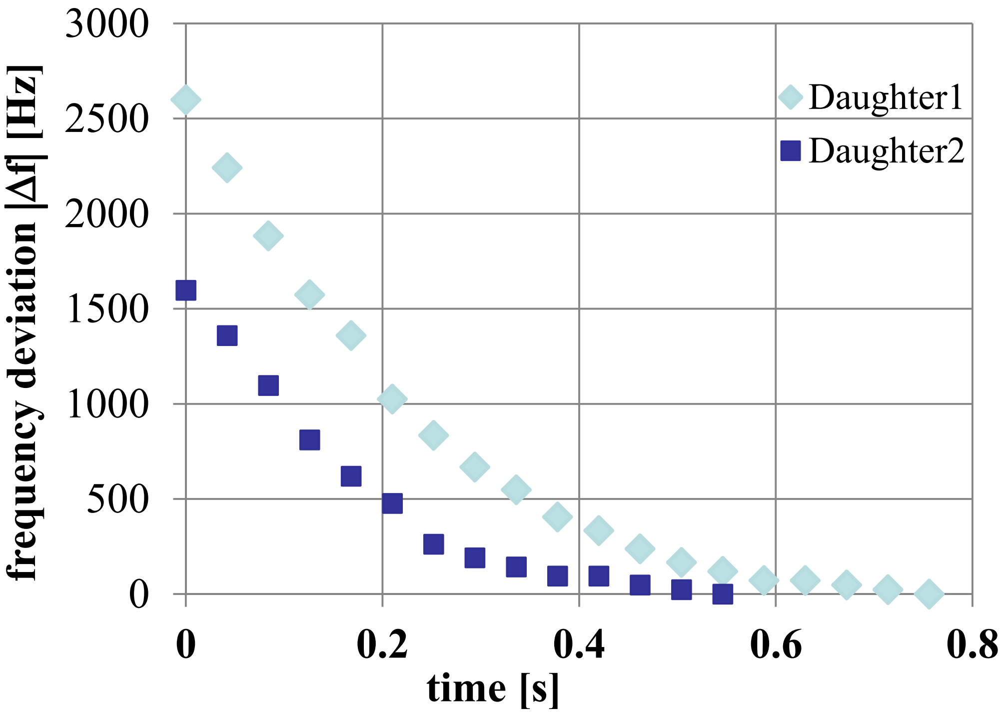
stability of magnet power converters

stability of electron beam (energy)

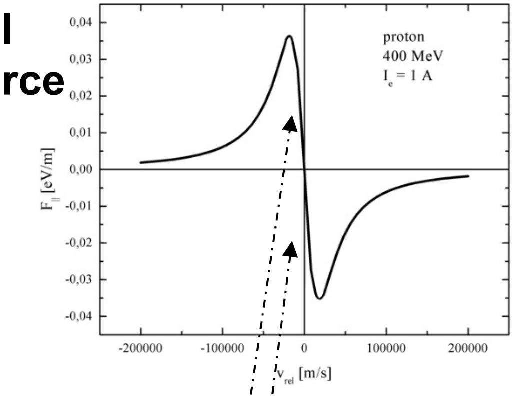
Analysis of Cooling Process



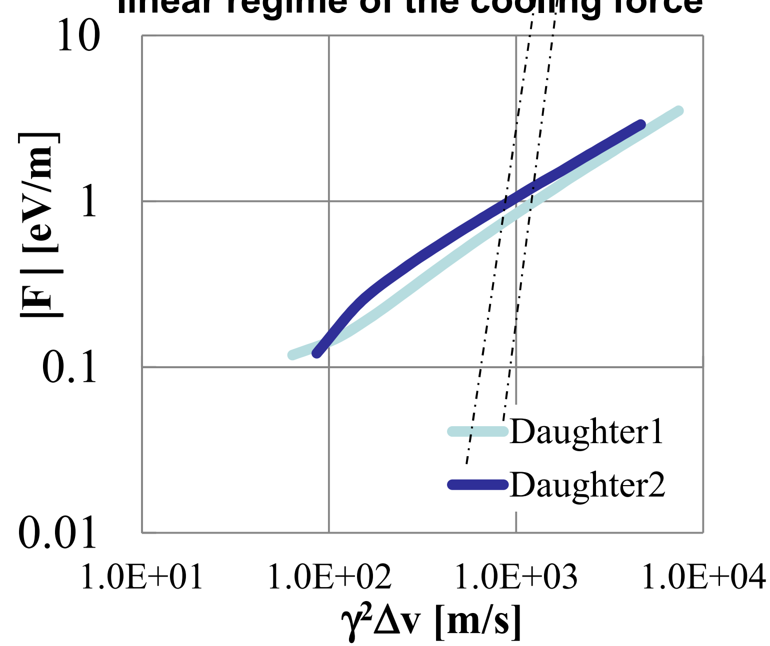
Analysis of Cooling Process



theoretical cooling force



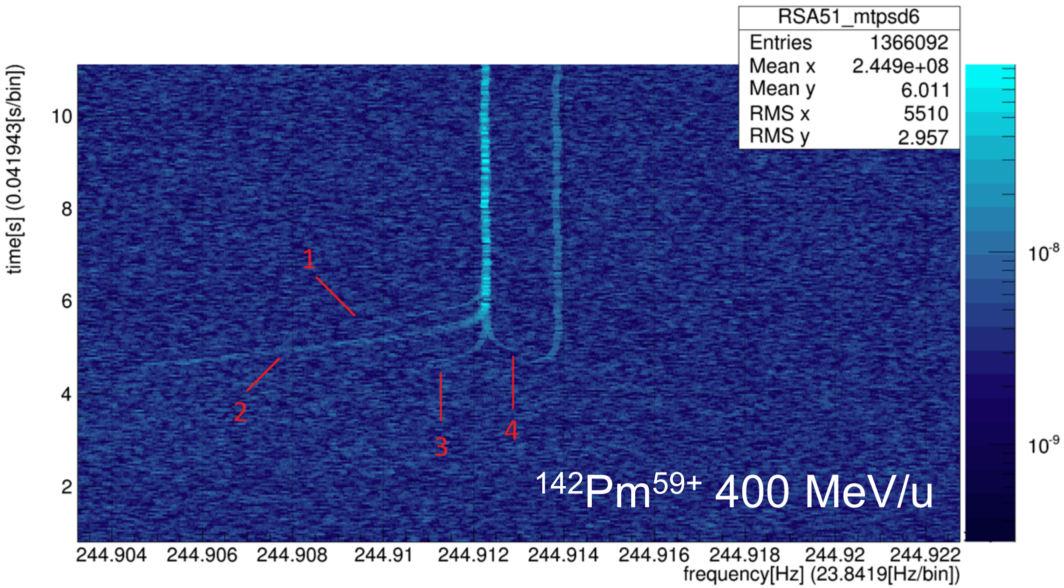
linear regime of the cooling force

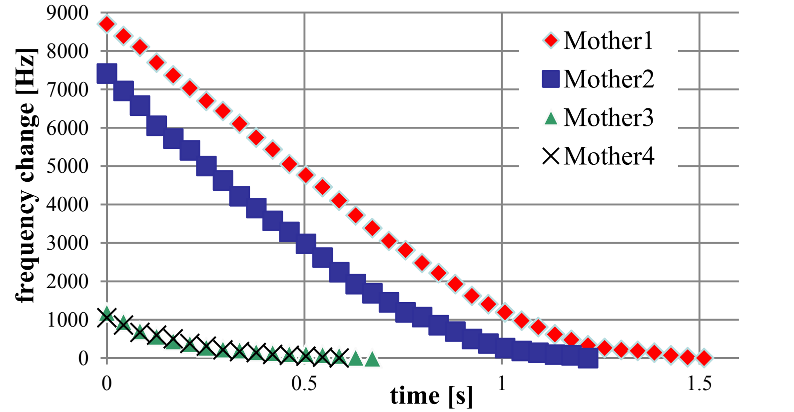


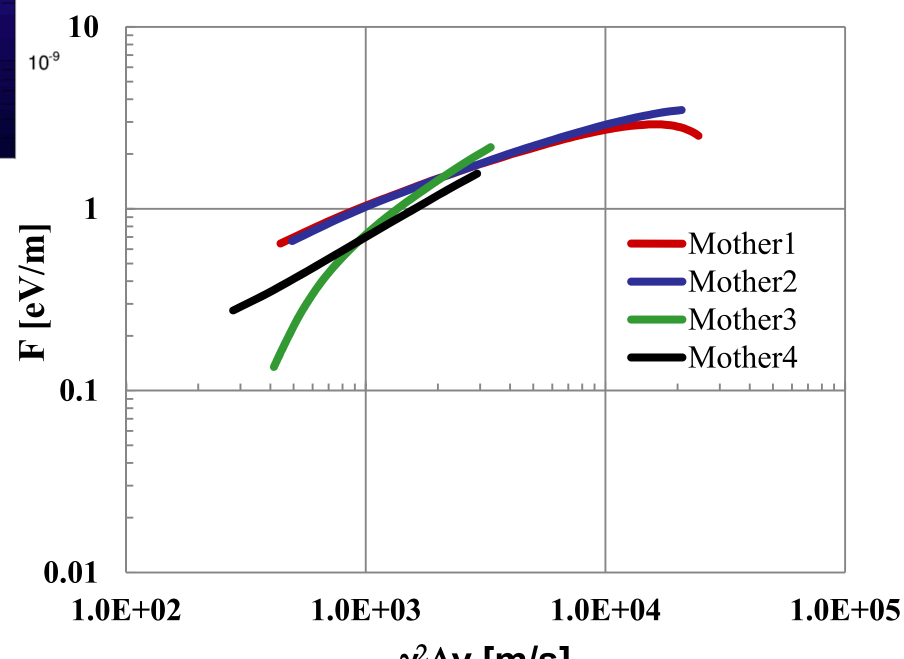
force $F = \frac{\partial p}{\partial t} = \frac{1}{\eta} \frac{1}{f} p \frac{\partial f}{\partial t}$

relative velocity $\gamma^2 \Delta v = \frac{1}{\eta} v_0 \frac{\Delta f}{f}$

Analysis of Cooling Process







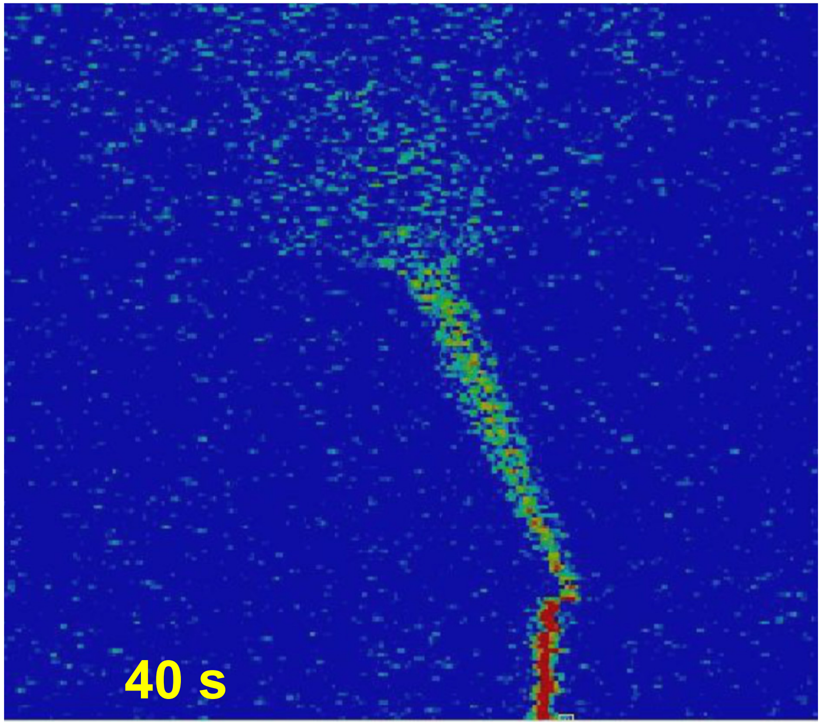
cooling force depends on initial parameters of the ion (single particle emittance)

ions start with different relative velocities (longitudinal and transverse)

for single ions:
no uncertainty due to finite ion distribution

High Sensitivity Measurement of Interaction with Matter

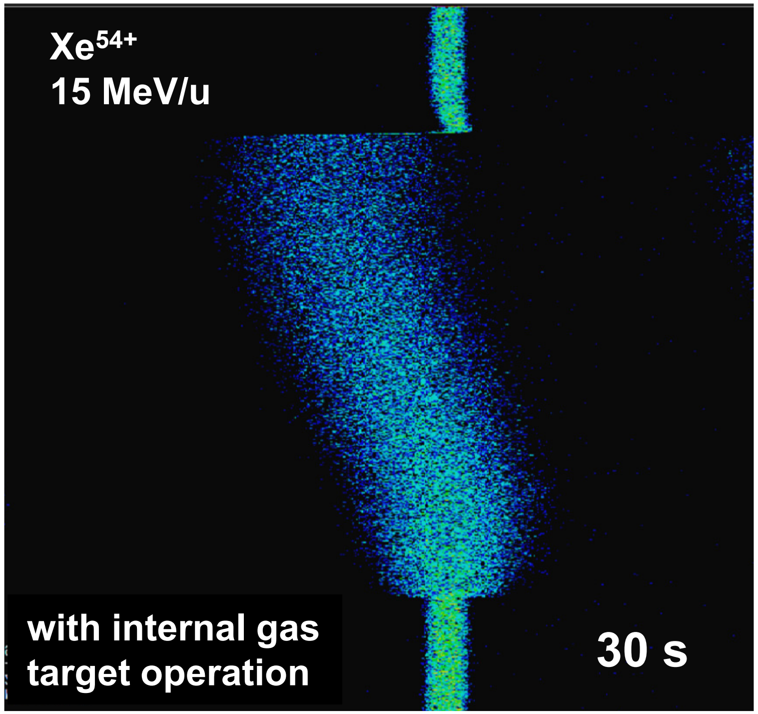
deceleration in residual gas



dp/p=1×10^{-5}

time

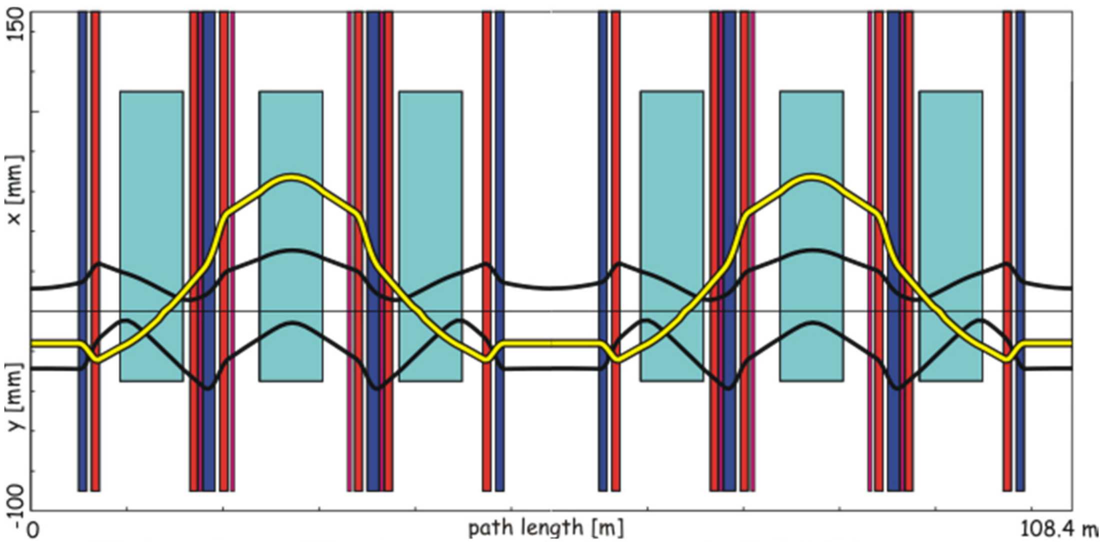
deceleration in internal target



dp/p=1×10^{-3}

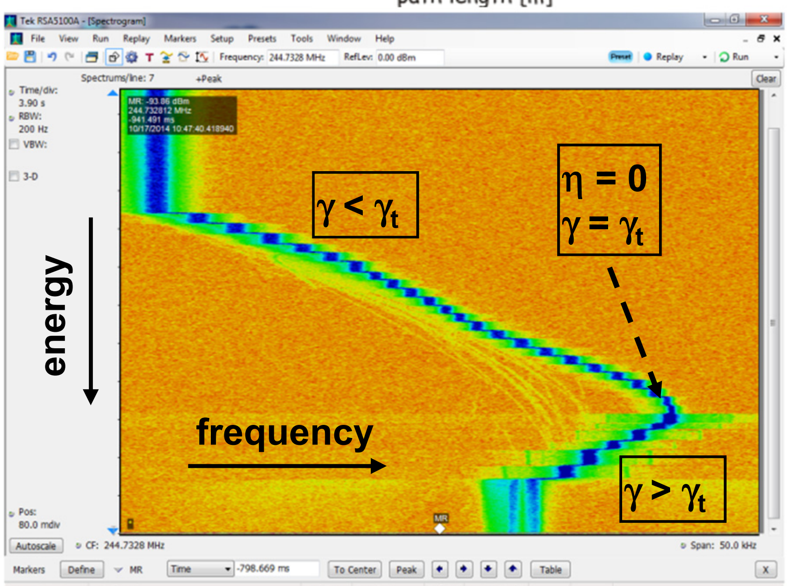
Measurement of single ions allows the measurement of target effects without the uncertainty introduced by the beam spread

Isochronous Mode of the ESR for Mass Measurements of Short-lived Isotopes

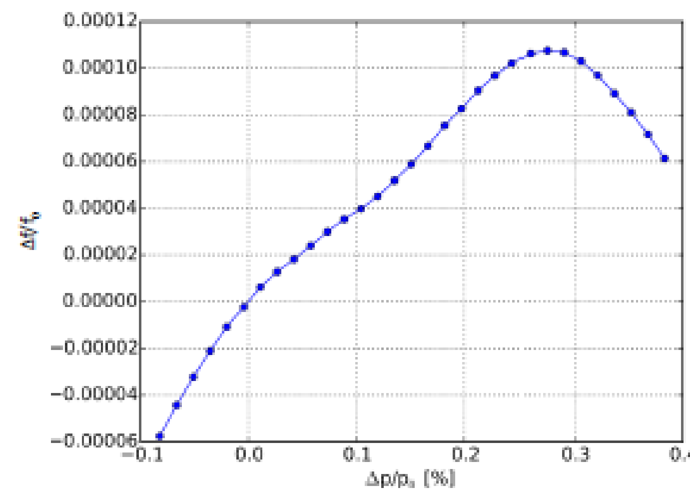


operation at transition energy:
negative dispersion in straight section makes revolution frequency independent of the beam momentum

$\underline{\eta = 0} \Leftrightarrow \gamma = \gamma_t$, (transition energy γ_t)



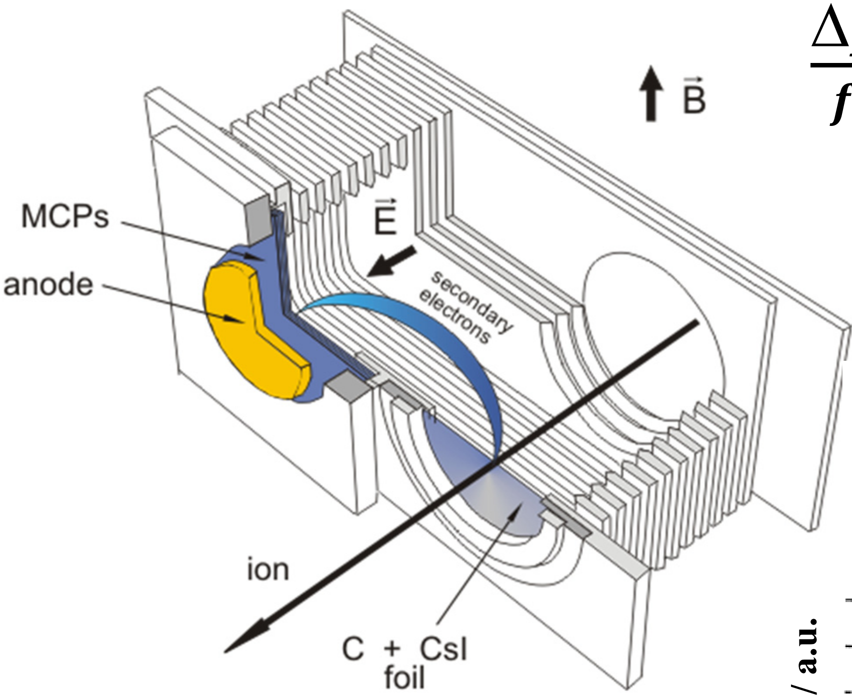
measurement o
transition energ
by variation of
beam energy

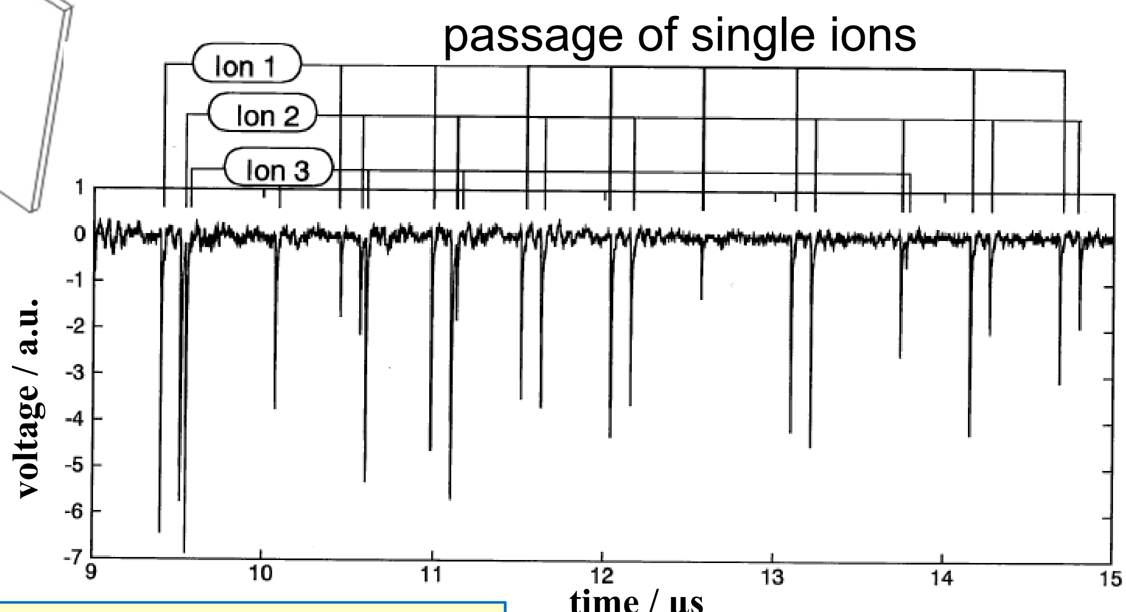


ToF Detector

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

(if $\gamma = \gamma_t$)



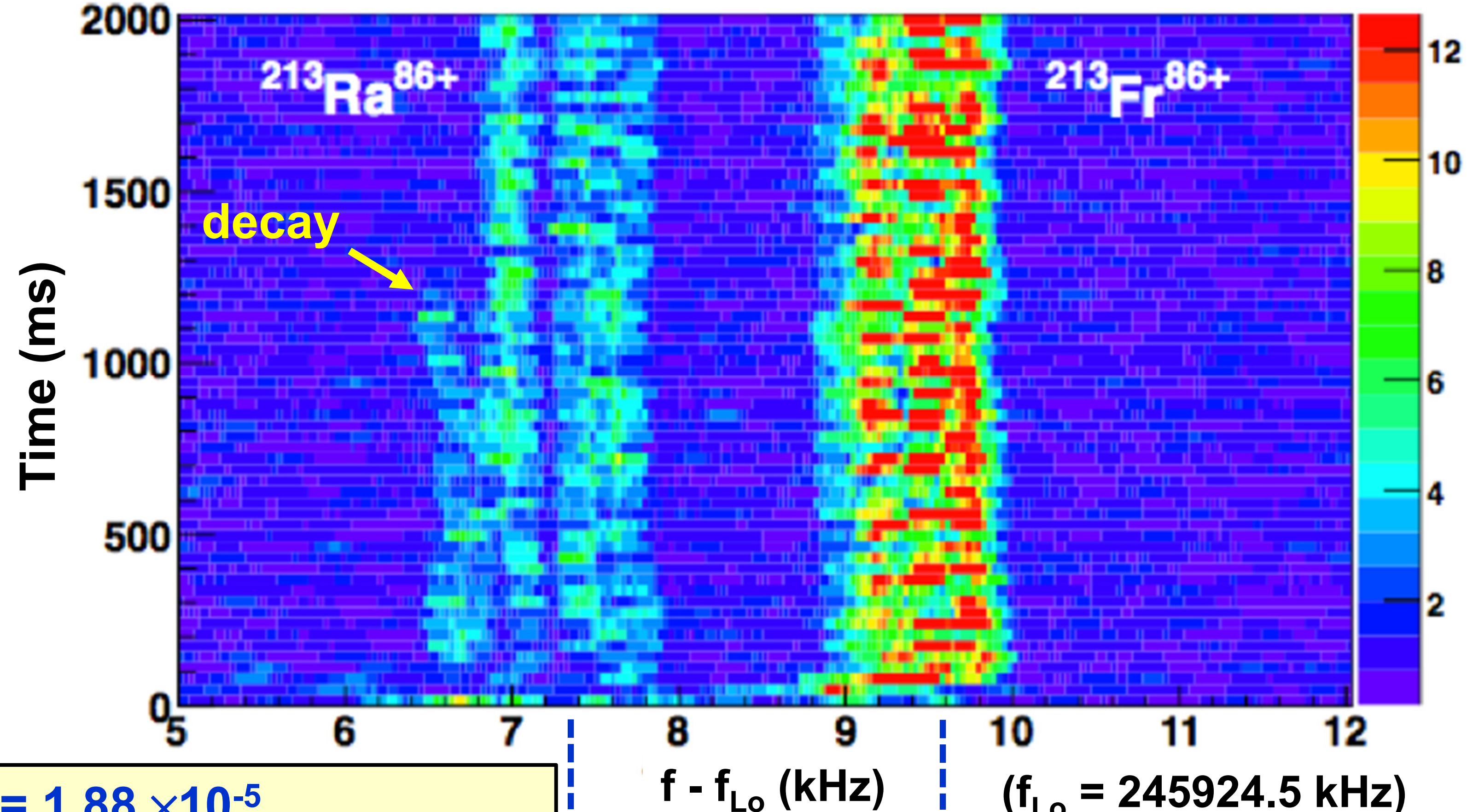


ion is lost after a few thousand turns due to energy loss in foil,
⇒ a few milliseconds of storage

a Schottky detector with millisecond measuring time should be competitive or even superior

Resonator Measurement in Isochronous Mode

detection of the decay of a radioactive ion in the isochronous mode injected with a momentum spread of ± 0.2 % (no cooling)



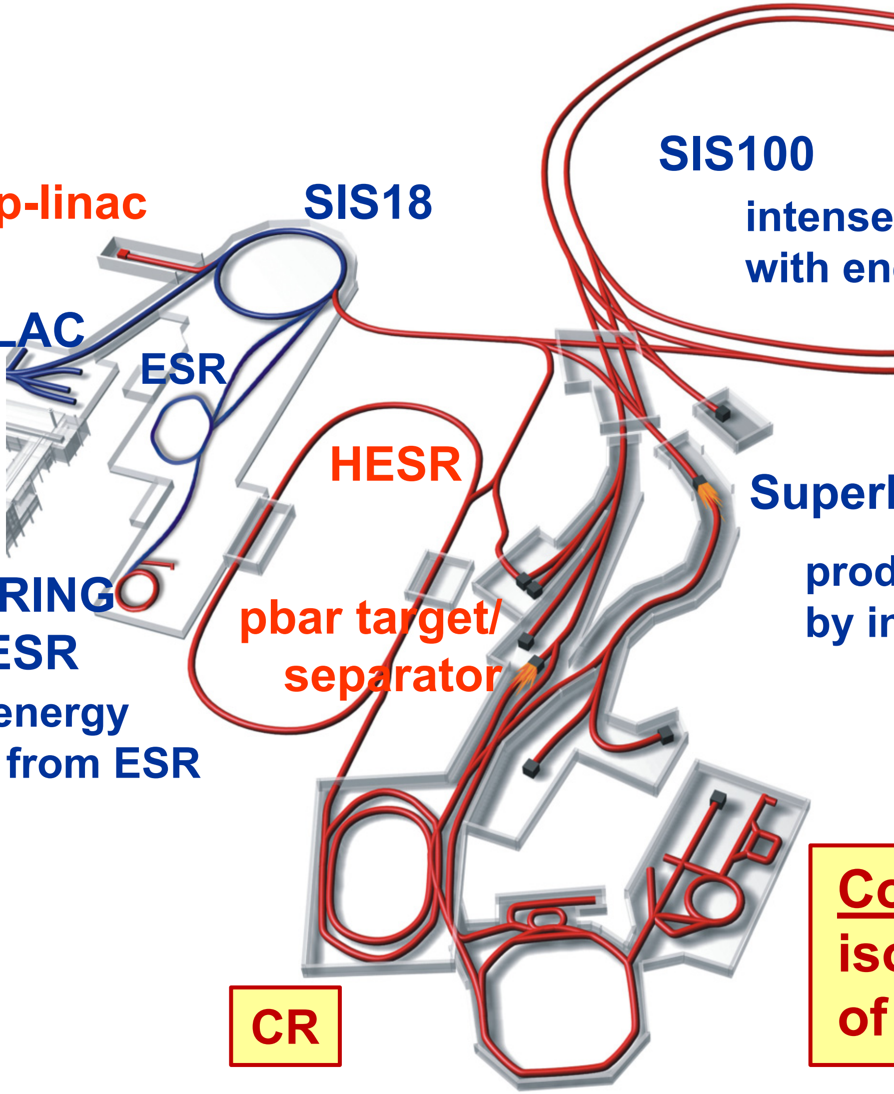
(f_{Lo} = 245924.5 kHz)

$\Delta m/m = 1.88 \times 10^{-5}$

$\Rightarrow \Delta f/f = 1/\gamma_t^2 \times \Delta m/m = 9.2 \times 10^{-6}$

$\Rightarrow \Delta f = 2.3$ kHz

FAIR - Modularized Start Version (MSV)



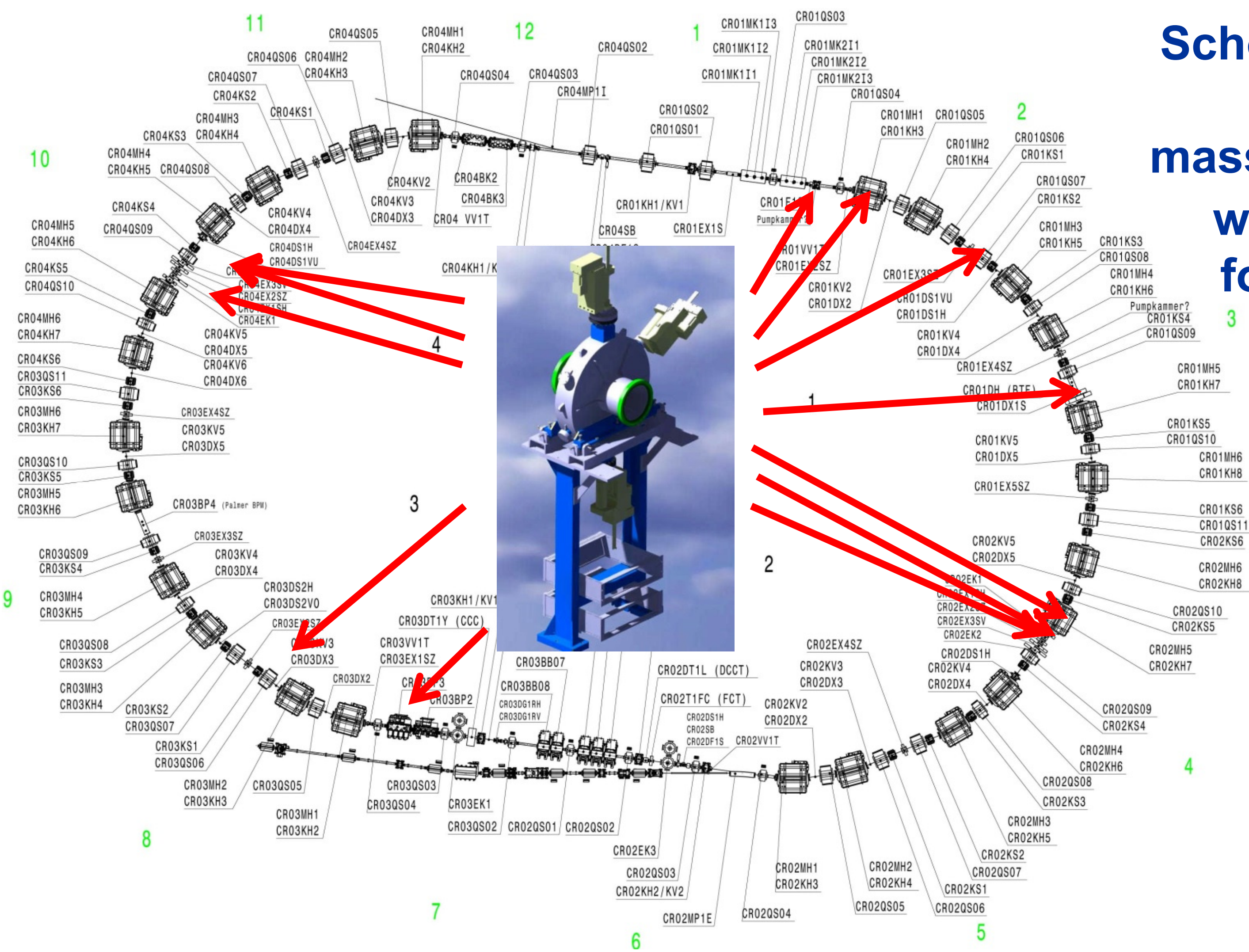
SIS100
intense, primary heavy ion beams with energies up to 1.5 GeV/u

SuperFRS
production of rare isotope beams (RIBs) by in-flight separation

CRYRING @ESR
low energy ions from ESR

<u>Collector Ring CR</u>:
isochronous mass measurements of RIBs with energies 400-740 MeV/u

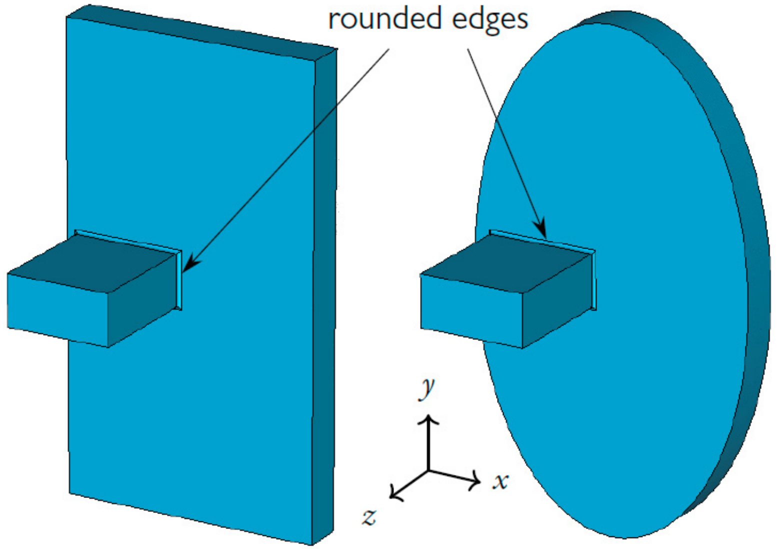
Schottky Resonators in the Collector Ring of FAIR



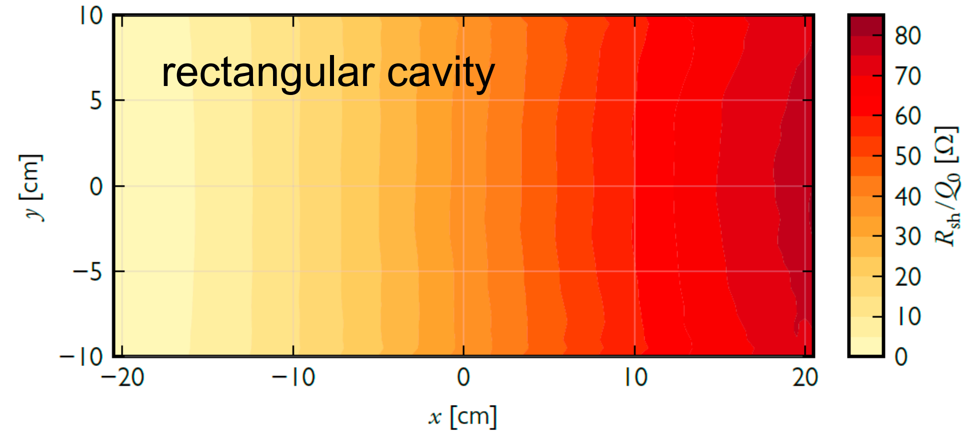
Schottky resonators for isochronous mass measurements will also be useful for diagnostics of antiprotons with high sensitivity

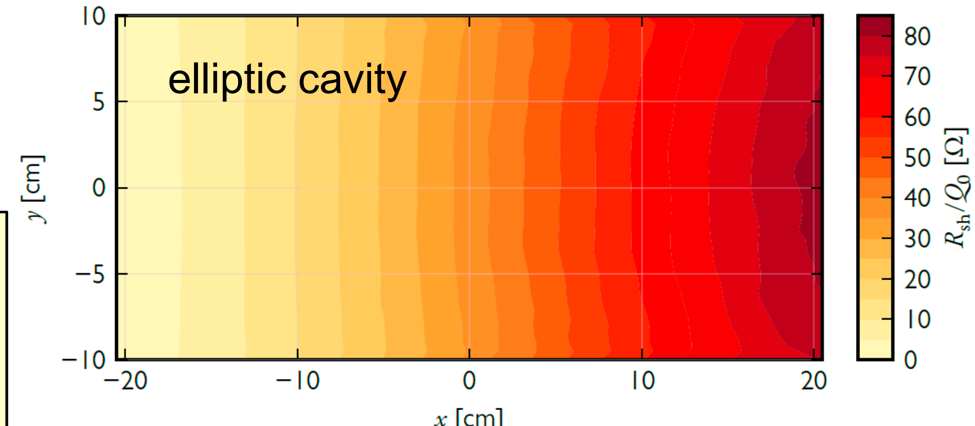
Position Sensitive Schottky Resonator

beam pipe offset from cavity center



position dependent shunt impedance
⇒ Schottky noise signal power P(x)





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

horizontal position in dispersive section is related to particle velocity (momentum)

⇒ **correction for deviations $\gamma = \gamma_t + \delta\gamma$ by measurement of δp or δv**

(normalization to normal cavity signal)

X. Chen, PhD thesis, supported by EU-contract No. PITN-GA-2011-289486

thank you
for your attention