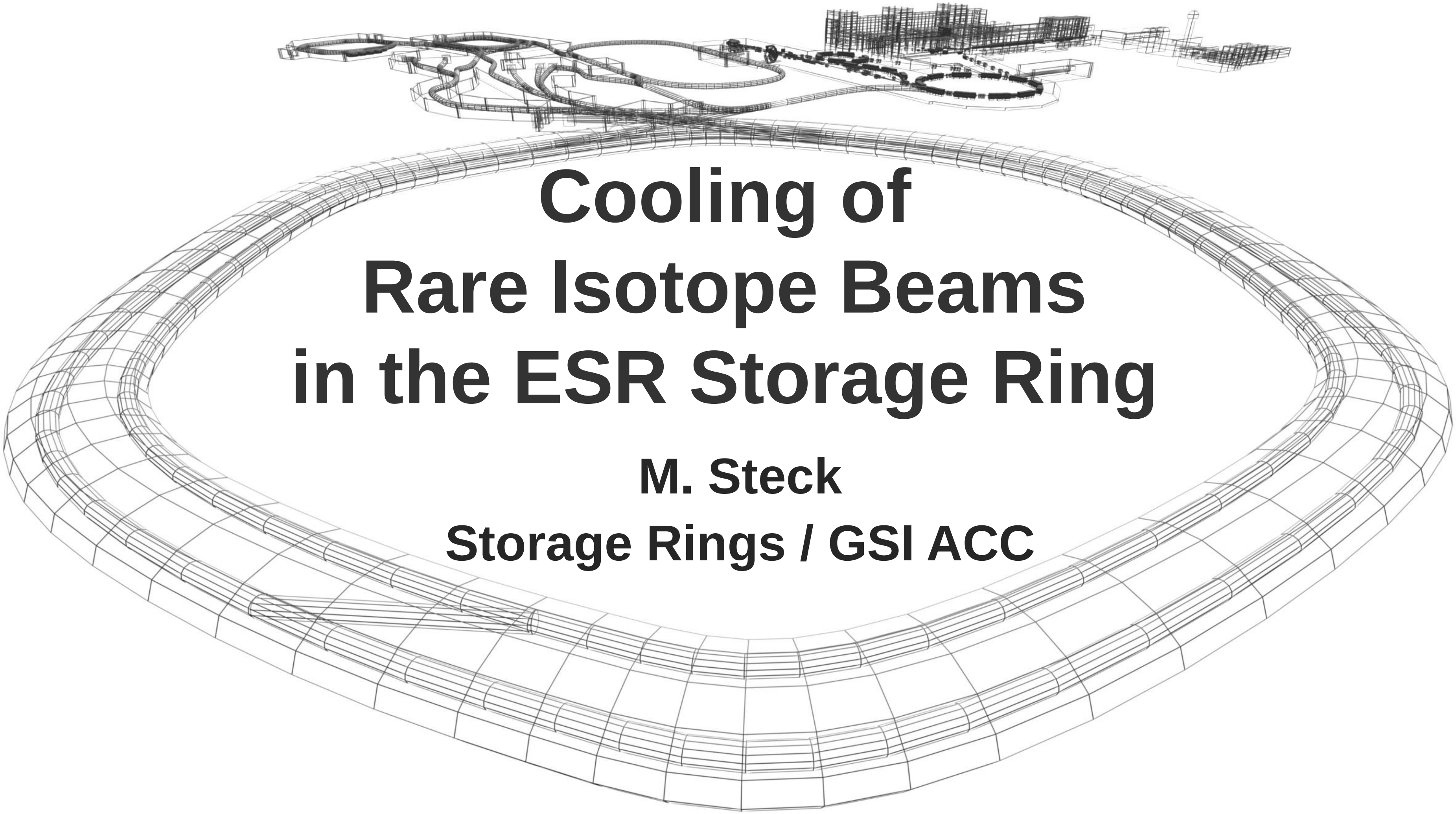


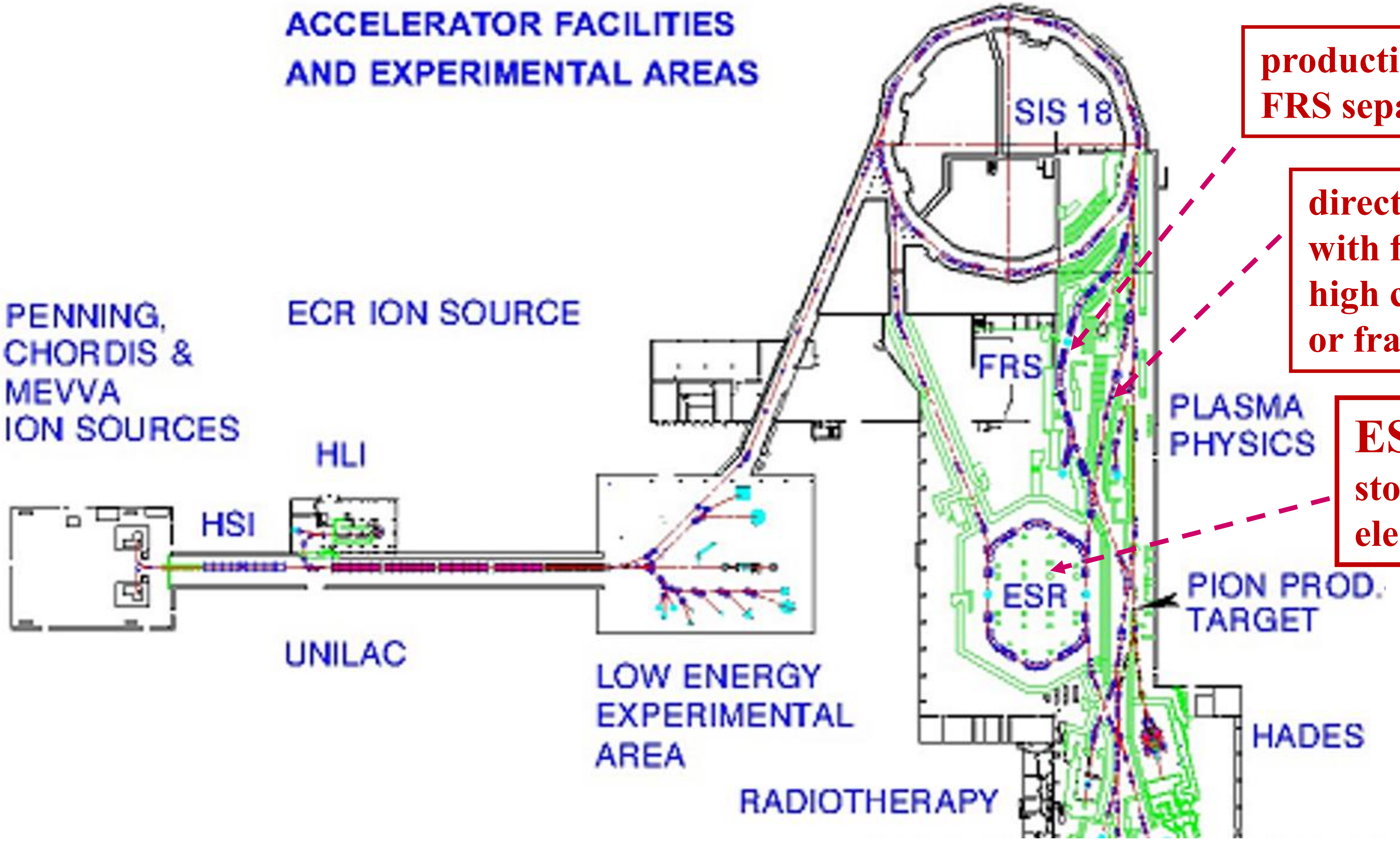
Cooling of Rare Isotope Beams in the ESR Storage Ring

M. Steck

Storage Rings / GSI ACC

Injector Chain of the ESR

SIS18 heavy ion synchrotron 20 -1000 MeV/u

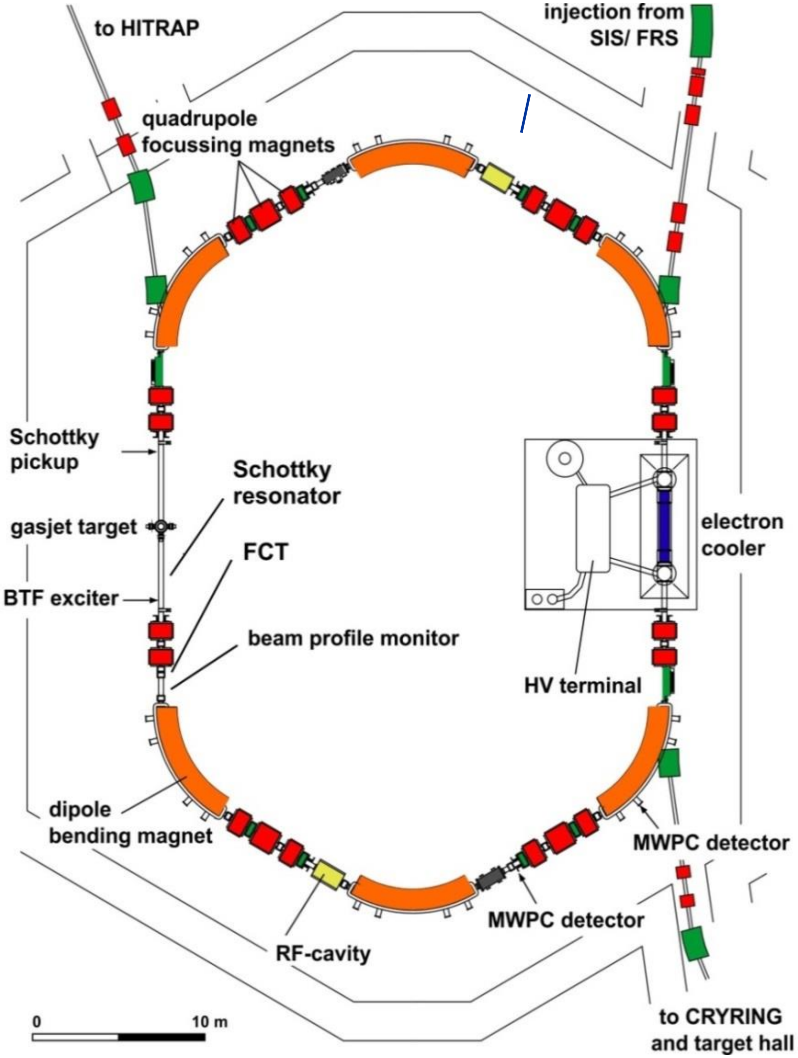


production target and FRS separator for RIBs

direct beam line with foil stripper for high charge states or fragments

ESR
stochastic cooling
electron cooling

ESR Operational Modes



Fast injection (ions and TE/FRS RIBs)

Stochastic cooling (400 MeV/u)

Electron cooling (4 - 400 MeV/u)

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

Internal gas jet target

Deceleration (down to 4 MeV/u)

Fast extraction (HITRAP/CRYRING)

Ultraslow extraction (charge change)

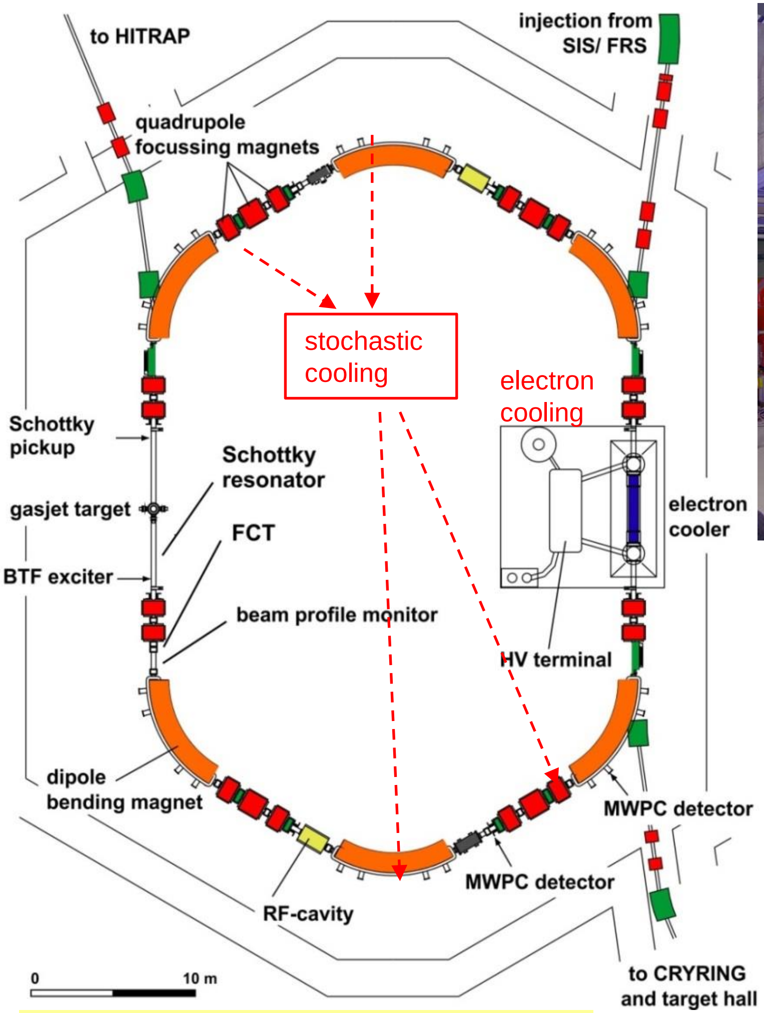
Beam accumulation

Isochronous mode (Schottky detector)

Schottky mass spectrometry of RIBs

Slow (resonant) extraction

Cooling Systems of the ESR



circumference 108.36 m
bending power 10 Tm

electron cooling
energy 3 - 430 MeV/u
electron current 1 mA - 1 A
magnetic field up to 0.2 T

stochastic cooling
energy $\geq$ 400 MeV/u
cooling acceptance:
$\delta p/p \leq$ +/- 0.35 %
$\varepsilon \leq 10\,\pi$ mm mrad

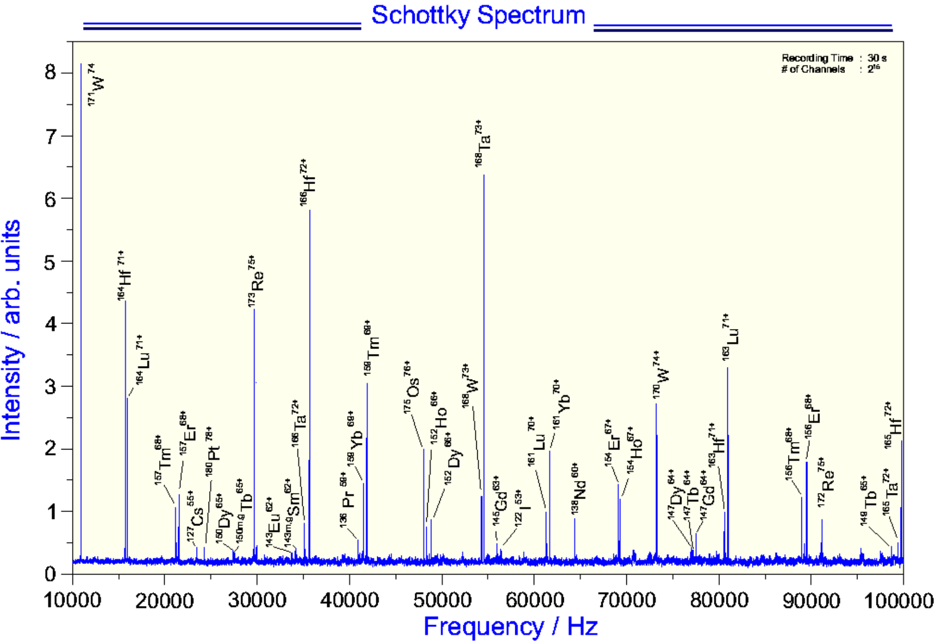
Schottky Mass Spectrometry

Injection of cocktail rare isotope beam from fragment separator FRS

Cooling (stochastic pre-cooling + final electron cooling)

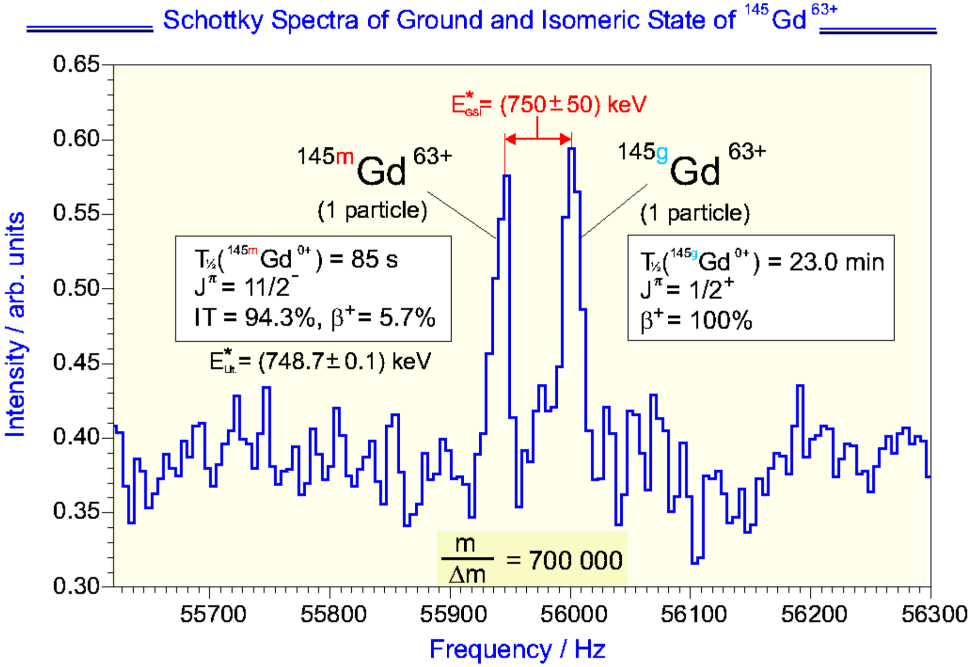
Achieved momentum spread ($\delta p/p = 5\times10^{-7}$, $\delta f/f = 2\times10^{-7}$)

broad band spectrum



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

narrow band spectrum **(zoom)**

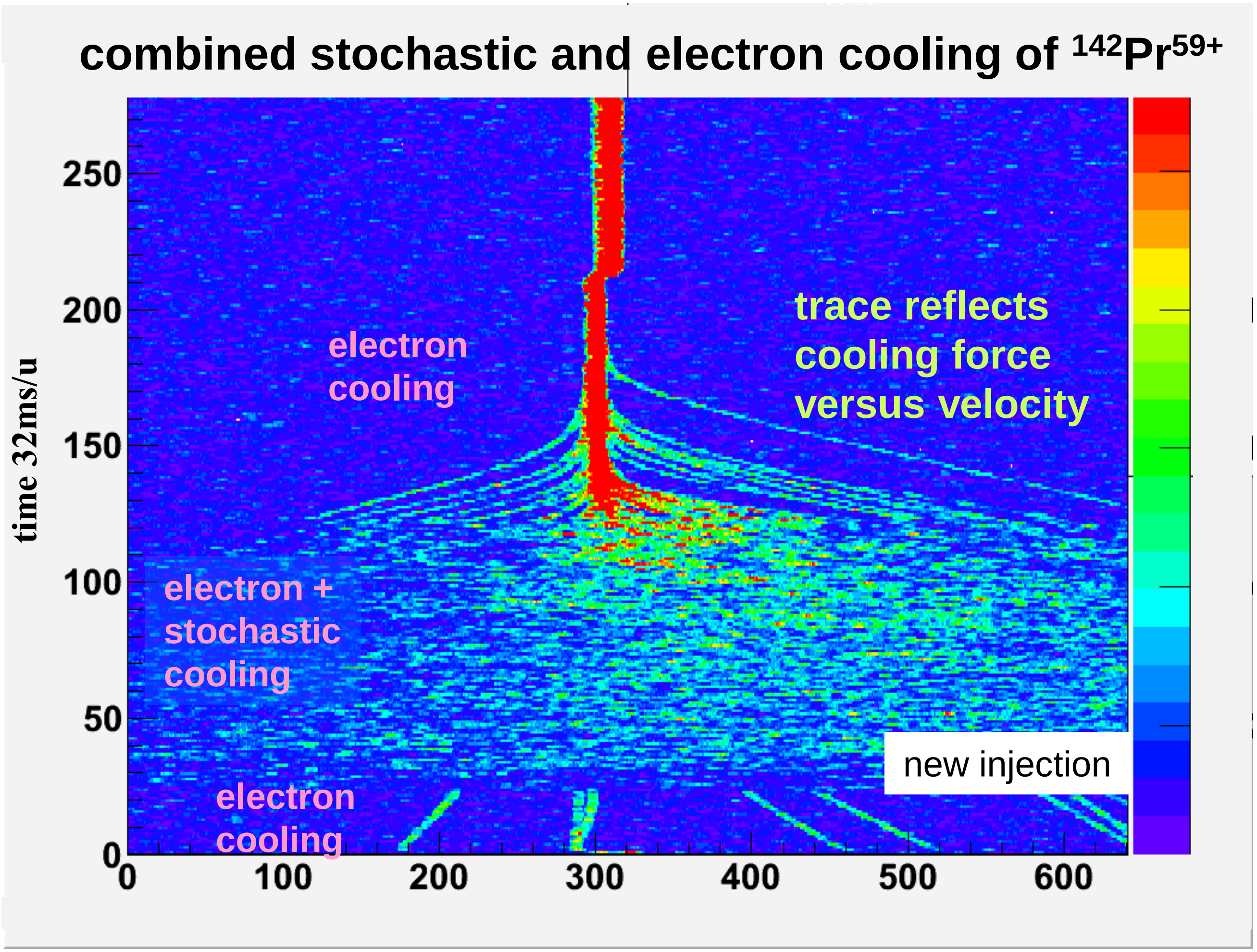


Detection of single ions !

Tracing of Single Ions

detection of single ions with resonant cavity

124th harmonic

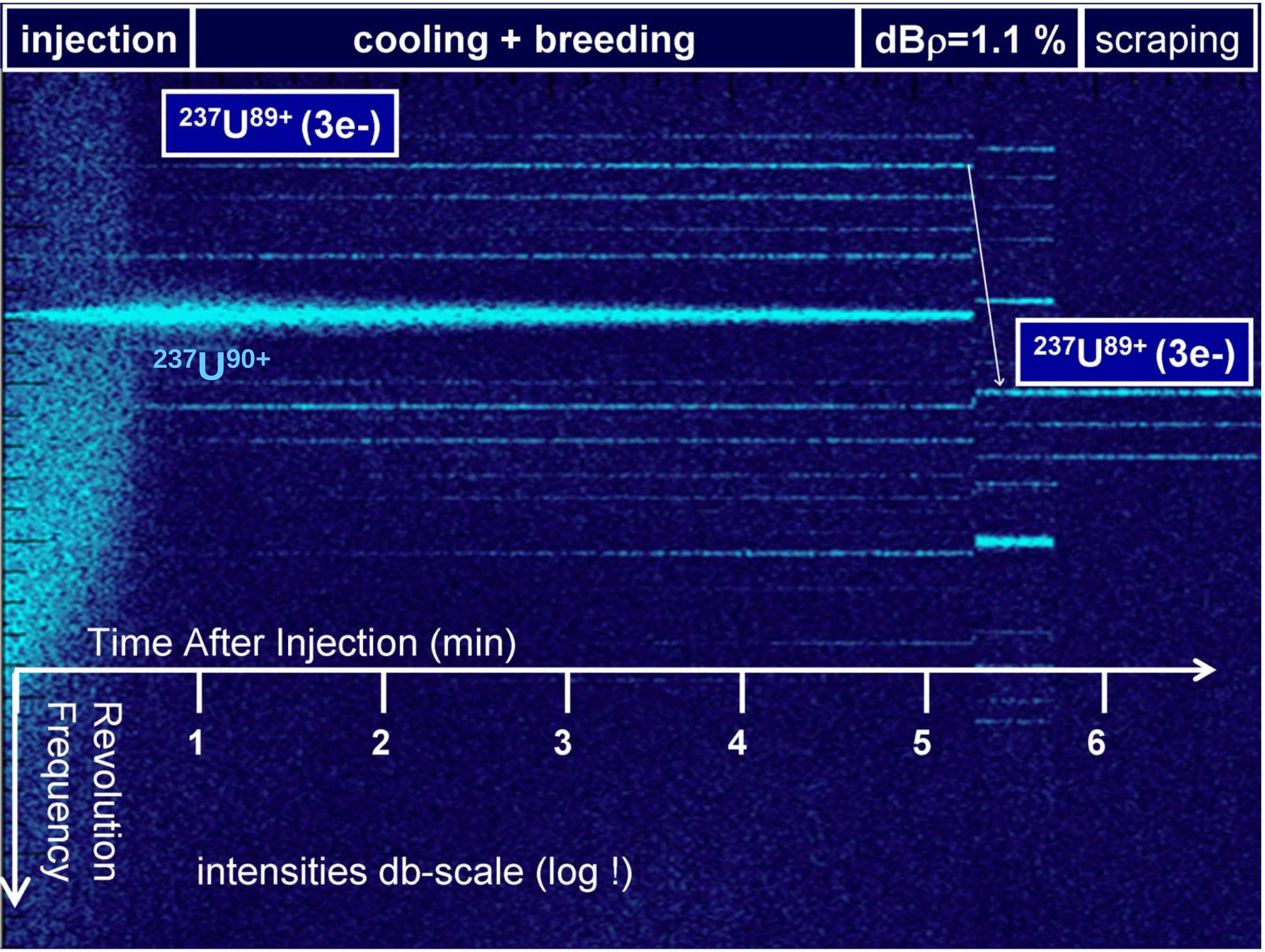


combined stochastic and electron cooling of $^{142}Pr^{59+}$

typical cooling time: 3-5 seconds

Preparation of RI Beam

isotopes are produced in a target in front of the ESR, selection is performed in the ESR



Broad isotope cocktail beam is cooled.

Isotopes are separated and can be removed selectively

⇒ purification resulting in a single- or few-component beam

(low intensity beams after electron cooling have sub-millimeter size)

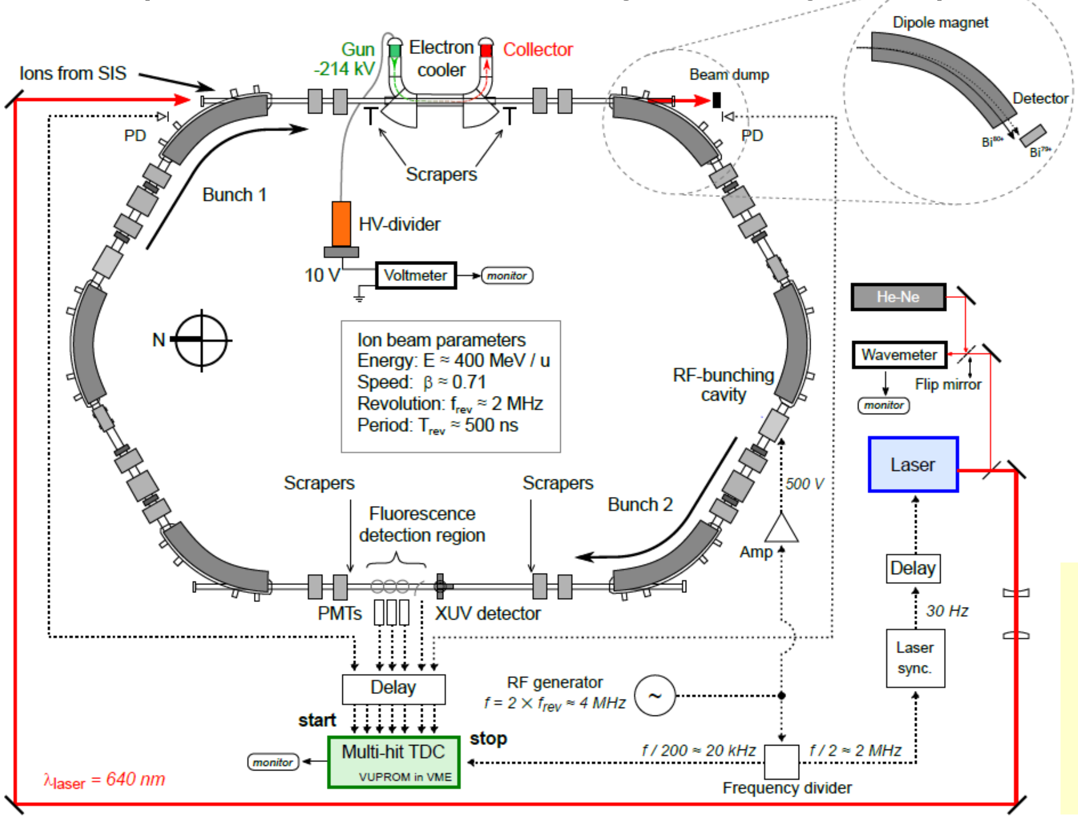
Experiment with Stored RI Beam

in 2022 first demonstration of first laser spectroscopy of a stored radioactive ^{208}Bi^{82+} beam produced from a primary ^{209}Bi beam

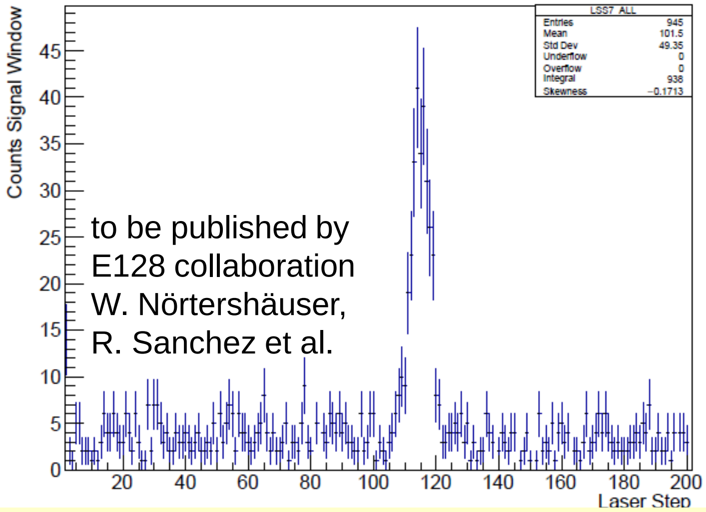
typical beam intensity 1-2×10^5 ^{208}Bi^{82+} stored ions (single injection)

precise determination of electron energy by high voltage divider (⇒ ion beam velocity)

overlap laser–ion beam is adjusted by scrapers



preliminary signal of hyperfine transition



to be published by
E128 collaboration
W. Nörtershäuser,
R. Sanchez et al.

proposed and accepted experiment aims at the measurement of the nuclear M1 magnetic transition in ^{209m}Th (nuclear clock)

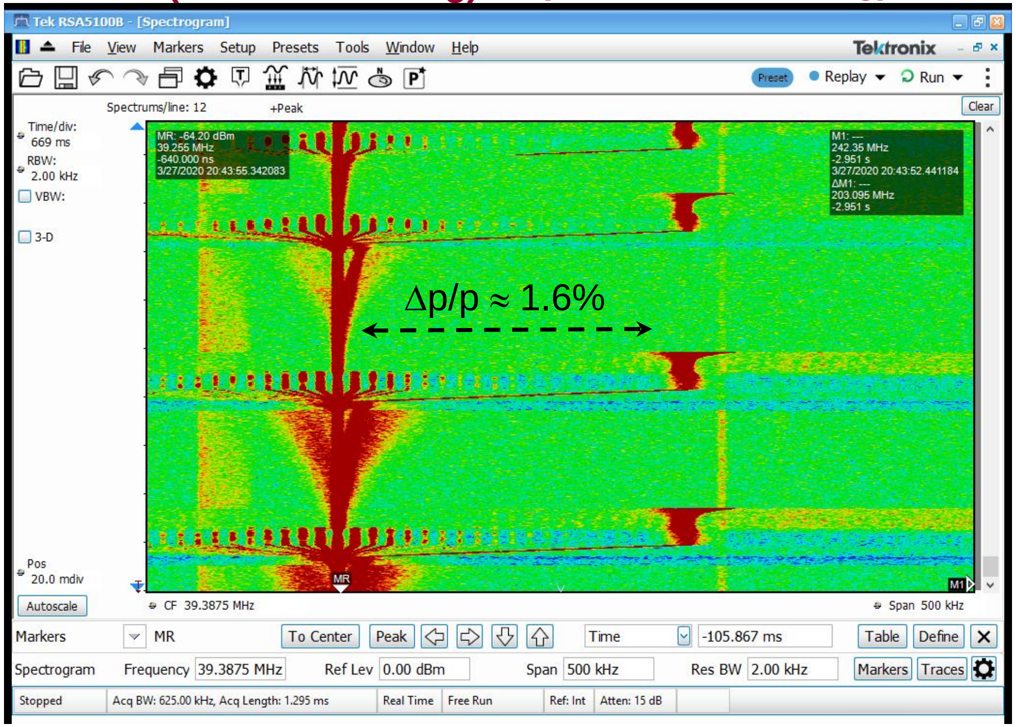
Beam Accumulation at 400 MeV/u

for many experiments the intensity of a single injection of rare isotopes is inadequate
⇒ need for beam accumulation

traditional beam accumulation at 400 MeV/u requires both stochastic and electron cooling

stack orbit (electron cooling)

injection orbit (stochastic cooling)



Spectrums/line: 12
Time/div: 669 ms
RBW: 2.00 kHz
Pos 20.0 mdiv

MR: -64.20 dBm
39.255 MHz
-640.000 ns
3/27/2020 20:43:55.342083

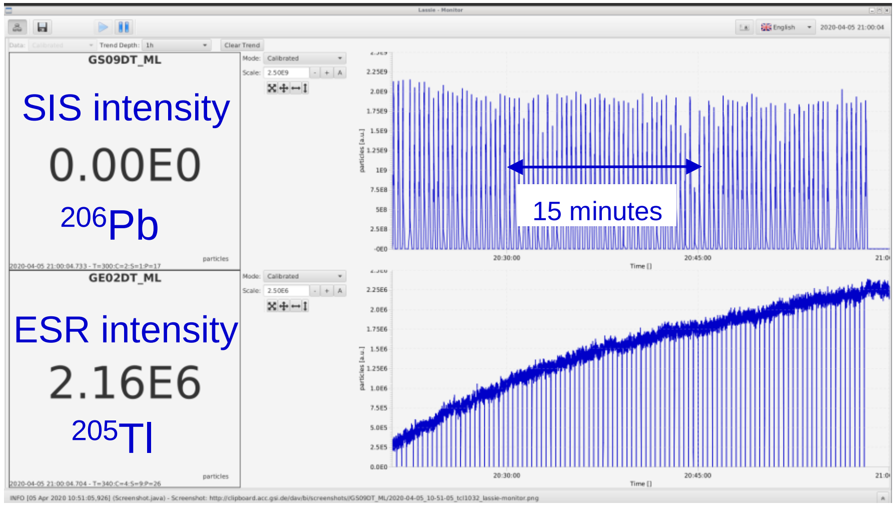
M1: ---
242.35 MHz
-2.951 s
3/27/2020 20:43:52.441184
ΔM1: ---
203.095 MHz
-2.951 s

CF 39.3875 MHz
Span 500 kHz

Markers: MR; Time: -105.867 ms

Spectrogram: Frequency 39.3875 MHz; Ref Lev 0.00 dBm; Span 500 kHz; Res BW 2.00 kHz

Stopped | Acq BW: 625.00 kHz, Acq Length: 1.295 ms | Real Time | Free Run | Ref: Int | Atten: 15 dB



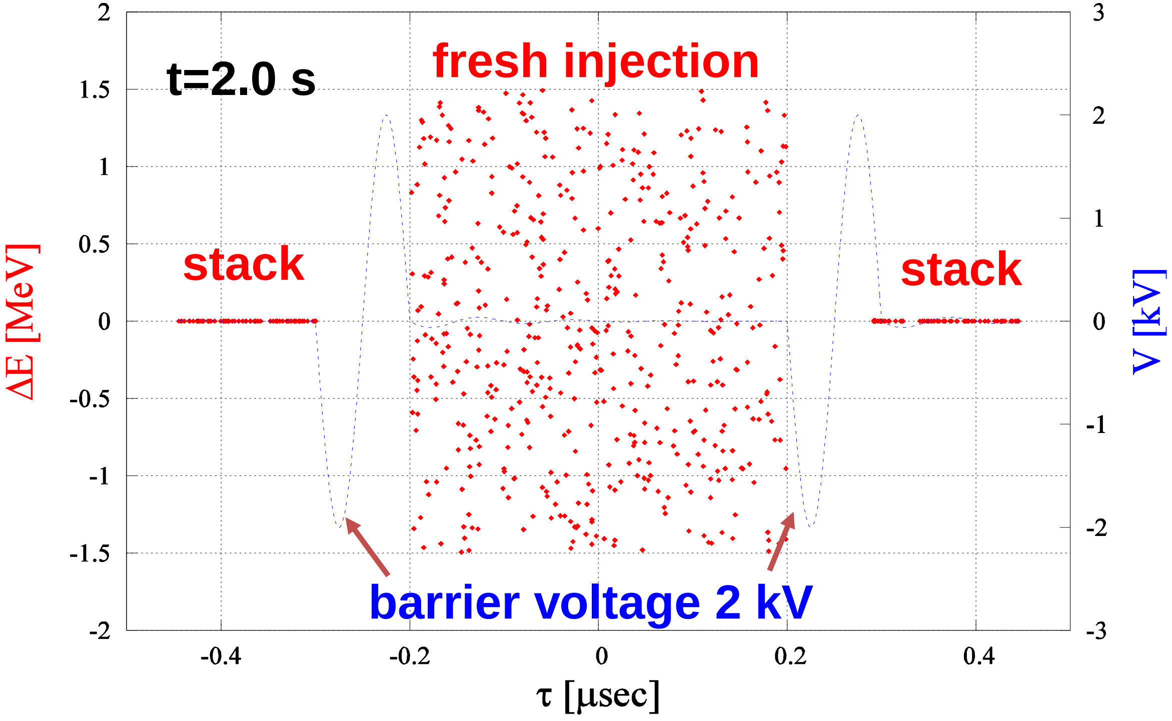
62 injections resulting in
2×10^6 $^{205}Tl^{81+}$ ions

practical time for beam accumulation depends on the lifetime of the ion

Accumulation of Rare Isotope Beams by Barrier Buckets

originally proposed for the NESR storage ring of the FAIR project
basic idea: confine stored beam to a fraction of the circumference, inject into gap
apply strong electron cooling to merge the two beam components

⇒ fast increase of intensity (for low intensity RIBs)



revolution time 0.9 µs

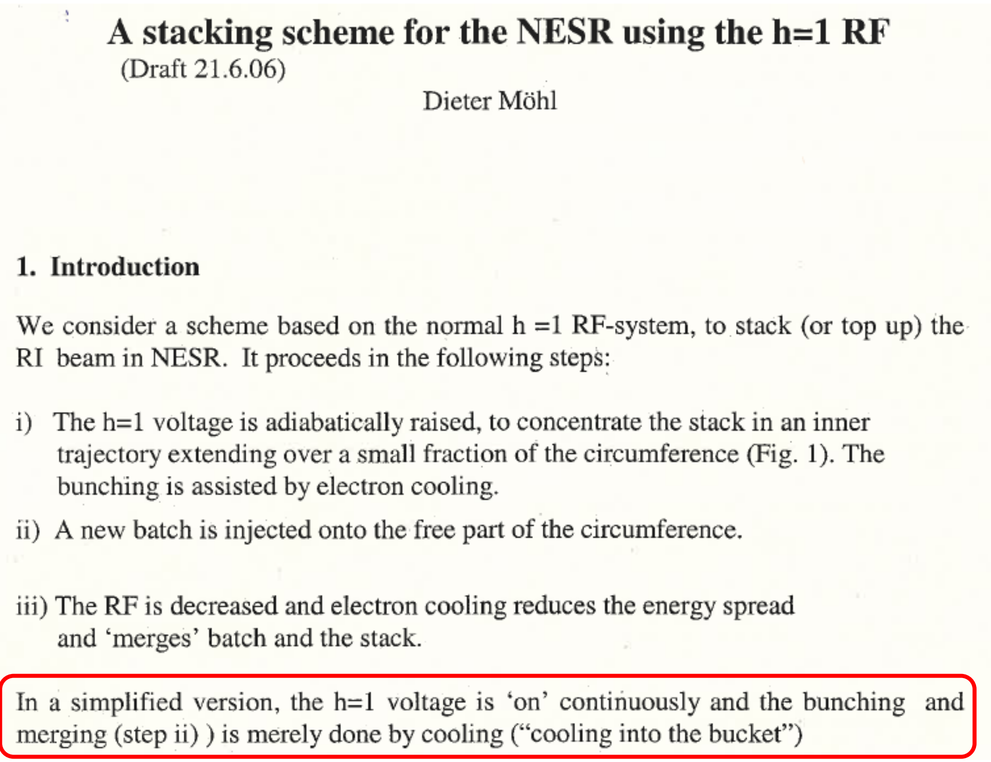
$^{132}Sn^{50+}$

E_k = 740 MeV/u

Longitudinal stacking with Barrier Buckets

(simulation by T. Katayama)

Proposal of Beam Accumulation (D. Möhl 2006)



A stacking scheme for the NESR using the h=1 RF

(Draft 21.6.06)

Dieter Möhl

1. Introduction

We consider a scheme based on the normal h =1 RF-system, to stack (or top up) the RI beam in NESR. It proceeds in the following steps:

i) The h=1 voltage is adiabatically raised, to concentrate the stack in an inner trajectory extending over a small fraction of the circumference (Fig. 1). The bunching is assisted by electron cooling.

ii) A new batch is injected onto the free part of the circumference.

iii) The RF is decreased and electron cooling reduces the energy spread and 'merges' batch and the stack.

In a simplified version, the h=1 voltage is 'on' continuously and the bunching and merging (step ii)) is merely done by cooling ("cooling into the bucket")

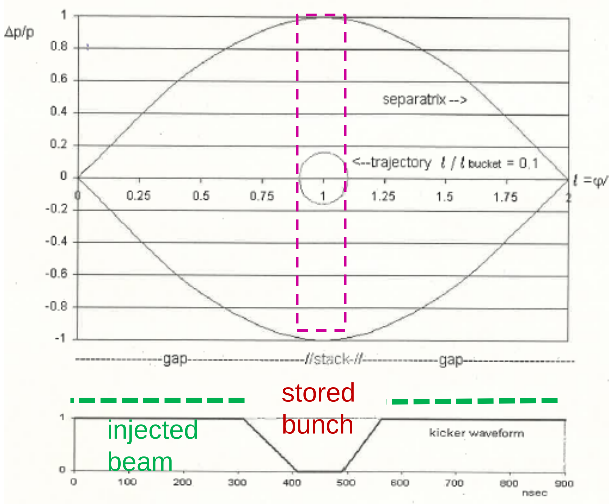
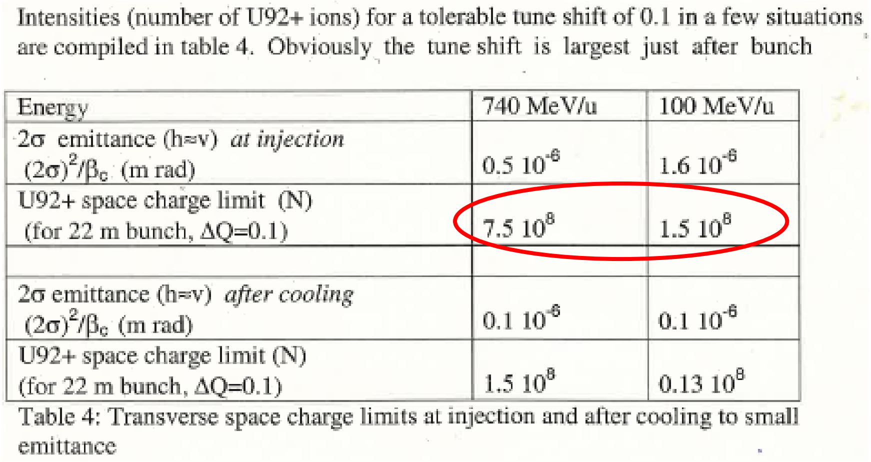


Fig. 1: Sketch of the stationary h=1 bucket, its inner trajectory covering 10% of the circumference containing the stack, and kicker waveform to inject the new batch at 740 MeV/u .



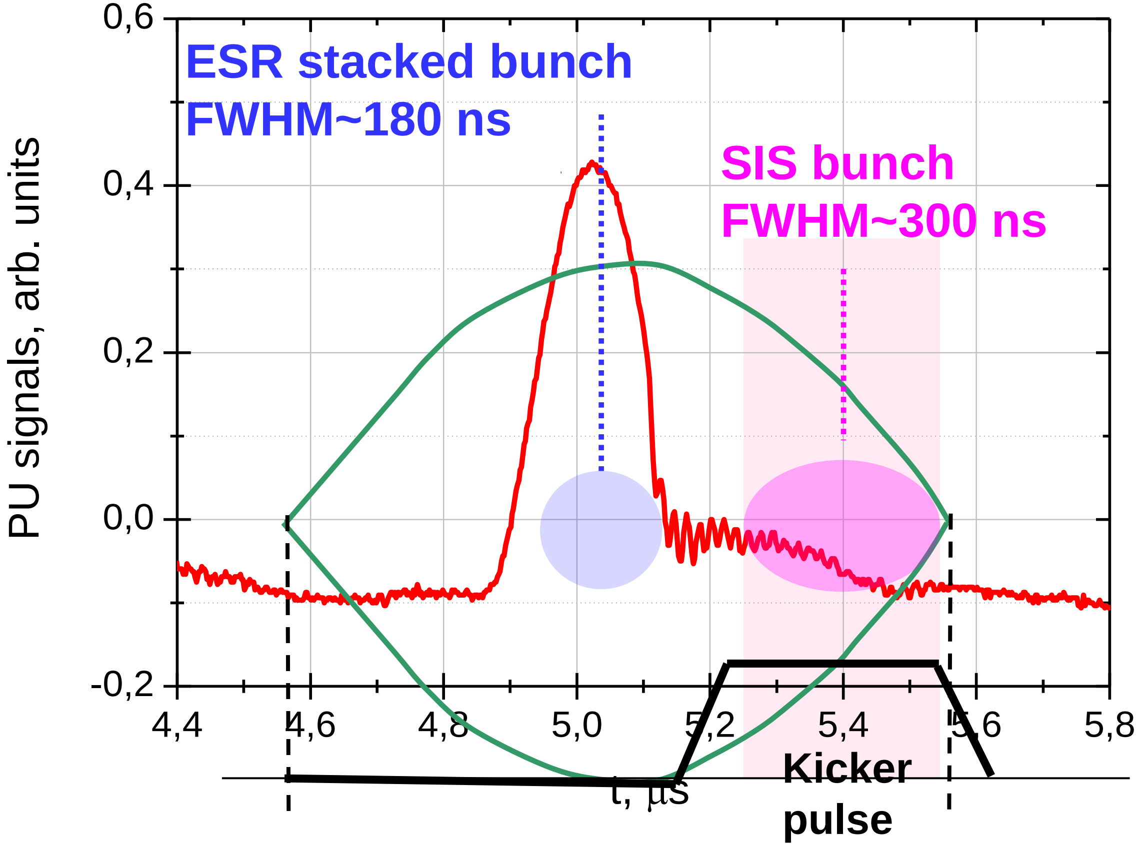
Intensities (number of U92+ ions) for a tolerable tune shift of 0.1 in a few situations are compiled in table 4. Obviously the tune shift is largest just after bunch

Energy	740 MeV/u	100 MeV/u
2σ emittance (h$\approx$v) *at injection* $(2\sigma)^2/\beta_c$ (m rad)	0.5 10^{-6}	1.6 10^{-6}
U92+ space charge limit (N) (for 22 m bunch, ΔQ=0.1)	7.5 10^8	1.5 10^8
2σ emittance (h$\approx$v) *after cooling* $(2\sigma)^2/\beta_c$ (m rad)	0.1 10^{-6}	0.1 10^{-6}
U92+ space charge limit (N) (for 22 m bunch, ΔQ=0.1)	1.5 10^8	0.13 10^8

Table 4: Transverse space charge limits at injection and after cooling to small emittance

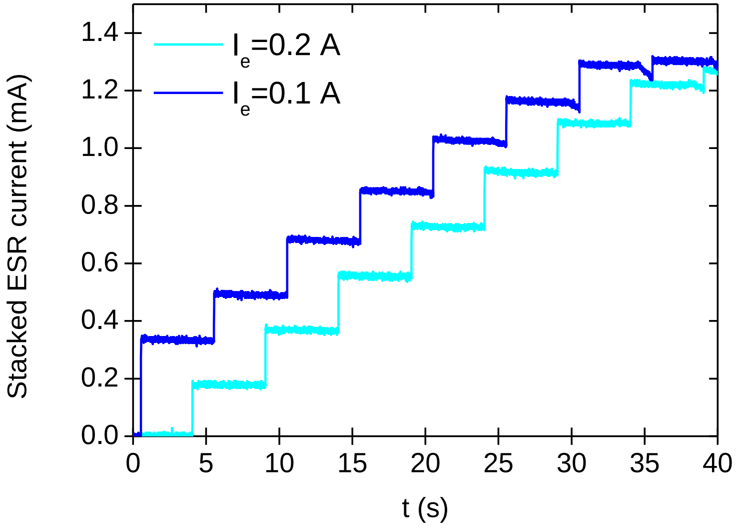
Test of Stacking with h=1 at Unstable Fixed Point (2012)

$^{40}Ar^{18+}$ 65 MeV/u



U_{rf}=60 V, f_{rf}=1 MHz (h=1), I_e=0.5 A

stacking cycle=5 s



Deficiencies (2012):

synchronization rf to kicker

precise kicker timing

length of SIS bunches

short kicker pulses

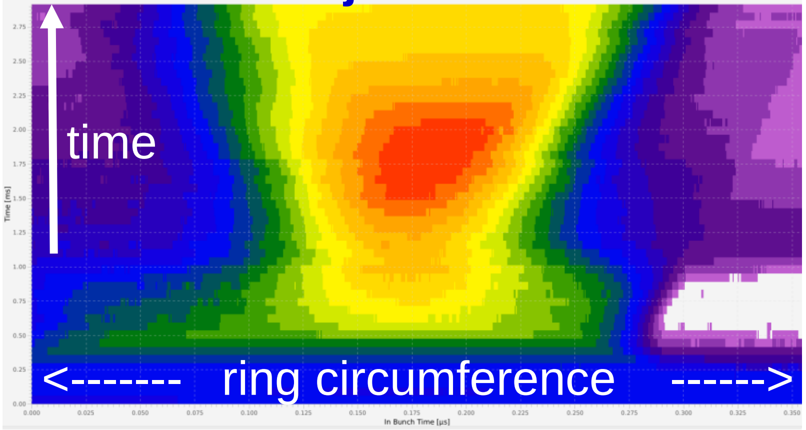
ringing (reflections) of kicker

FAIR Bunch to Bucket (B2B) Synchronization System

tested at the ESR in 2021,
now routinely operational in user beam time

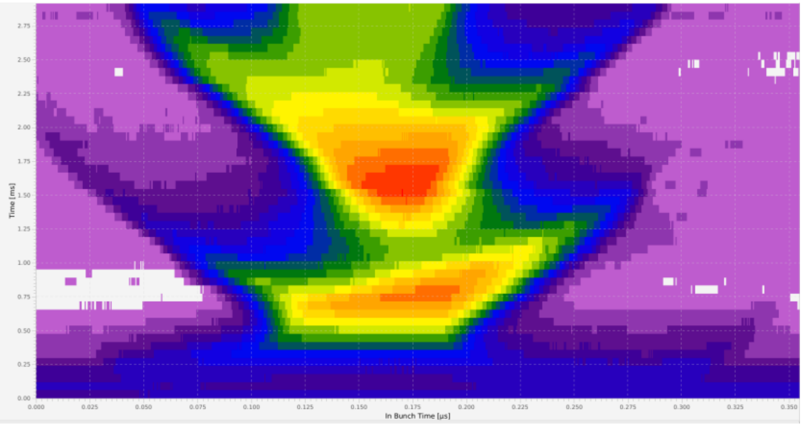
D. Beck,
D. Lens,
O. Chorniy

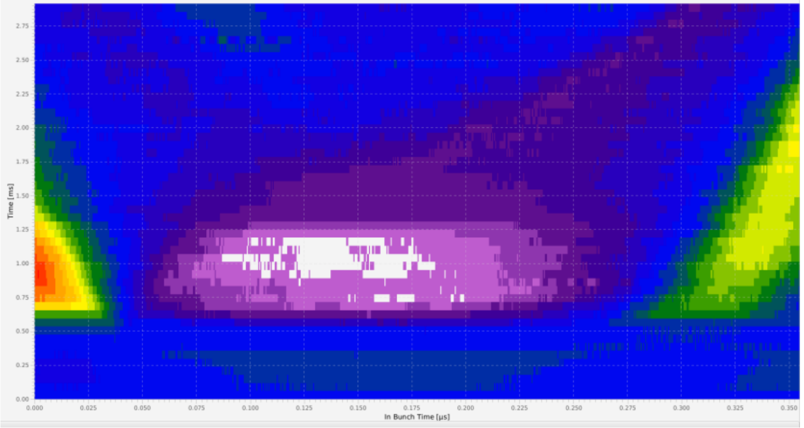
bunch after injection into the ESR



← perfect match of rf phases (SIS-ESR), injected bunch is captured in ESR rf bucket

dipole oscillations of the bunch →



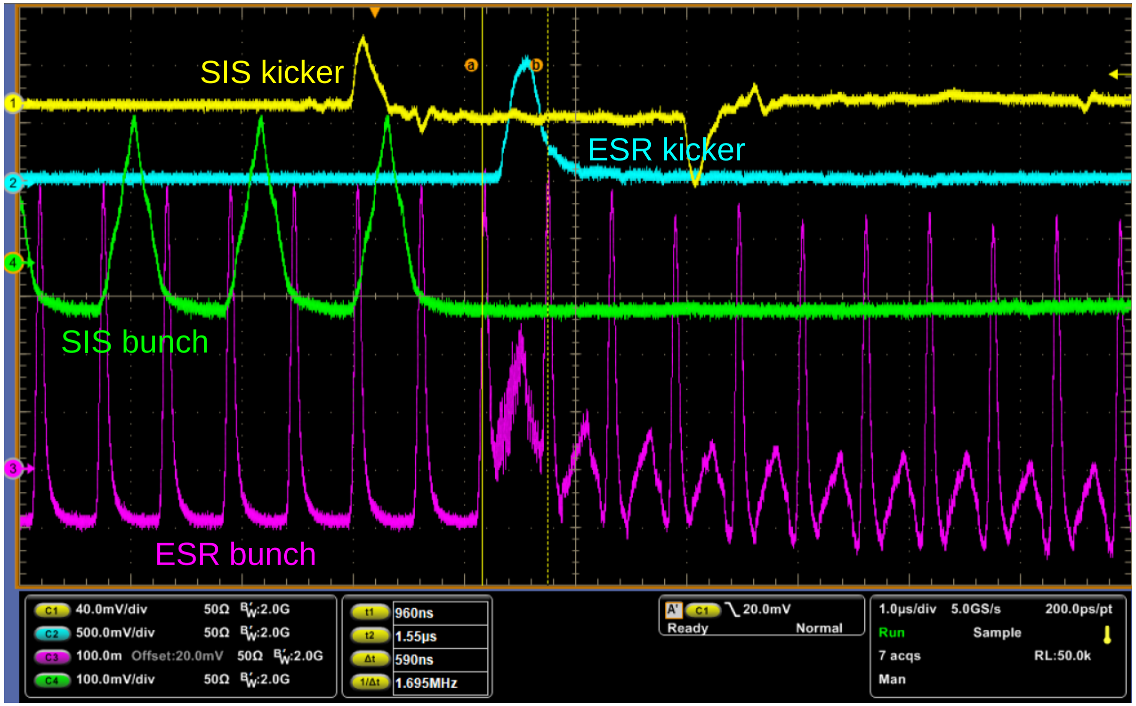


← full mismatch of rf phases

Realization of h=1 Beam Accumulation with New Bunch to Bucket System

^{208}Pb^{82+} 270 MeV/u
$N_{max} \sim 1.5 \times 10^8$

continuous electron cooling applied
with electron current 0.3 A

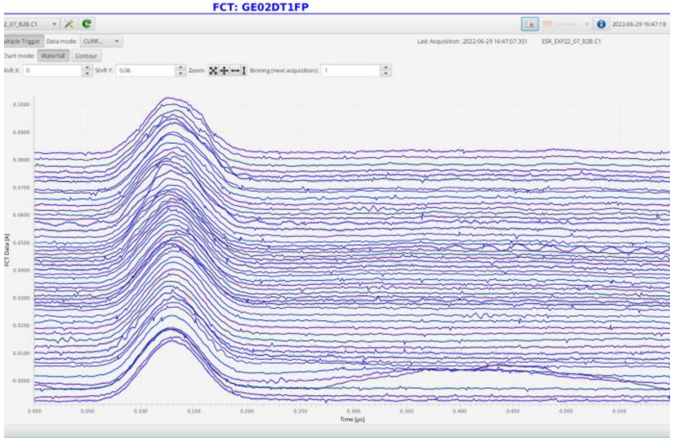


C1 40.0mV/div 50Ω BW:2.0G
C2 500.0mV/div 50Ω BW:2.0G
C3 100.0m Offset:20.0mV 50Ω BW:2.0G
C4 100.0mV/div 50Ω BW:2.0G

t1 960ns
t2 1.55µs
Δt 590ns
1/Δt 1.695MHz

A' C1 ╲ 20.0mV
Ready Normal

1.0µs/div 5.0GS/s 200.0ps/pt
Run Sample
7 acqs RL:50.0k
Man



ESR bunch measured with FCT

ESR kicker pulse length reduced from 560 to 200 ns
in order not to excite the circulating ESR bunch

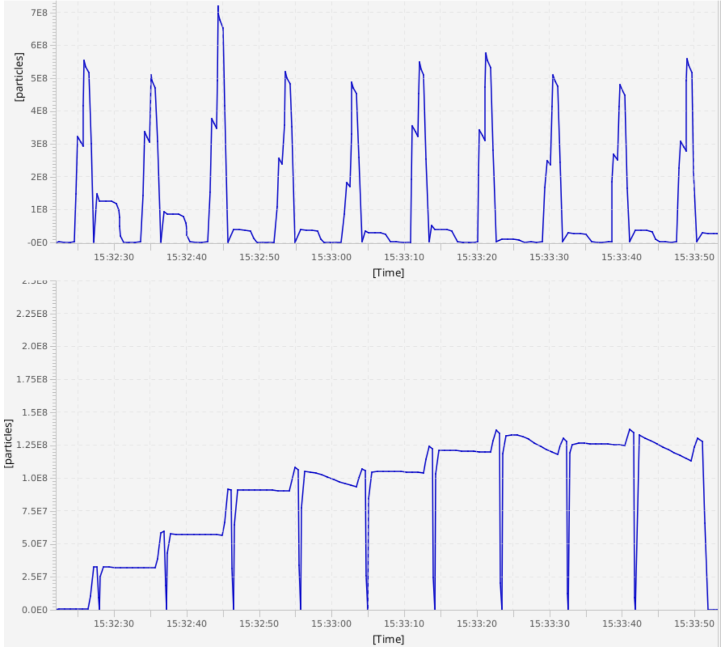
Beam Accumulation at h=1 with New Bunch to Bucket System

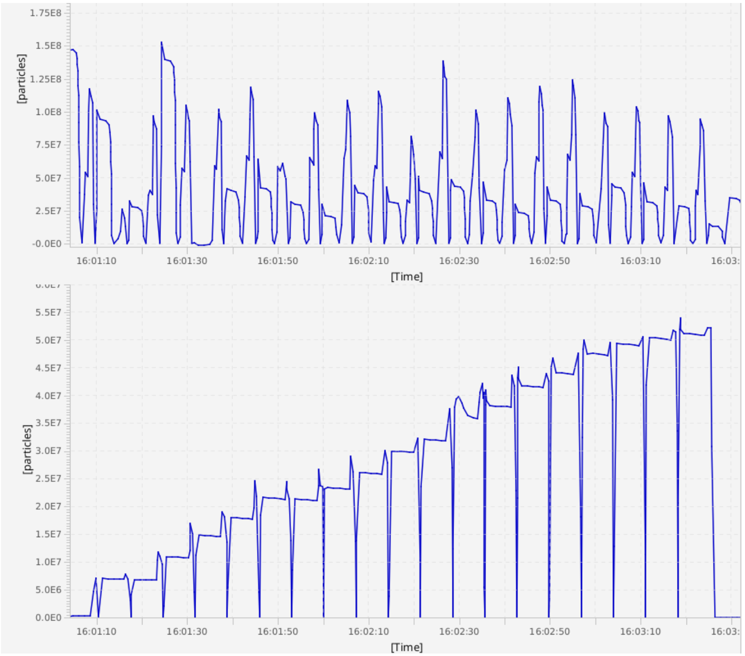
$^{208}Pb^{82+}$ 270 MeV/u

injection of single bunch from SIS onto unstable fixed point of ESR rf (h=1)

SIS cycles
2 MTI per cycle

ESR stored beam





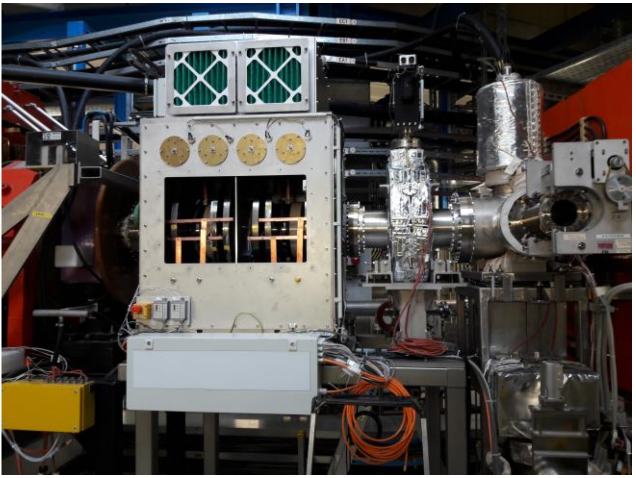
high intensity from SIS
ESR saturates around 1.3 ×10^8 ions
ESR peak bunch current 50 mA

reduced intensity from SIS ⇒
efficient accumulation in ESR

particularly suited for the accumulation of secondary beams

large flexibility:
only 1 cooling system is required
accumulation at any energy

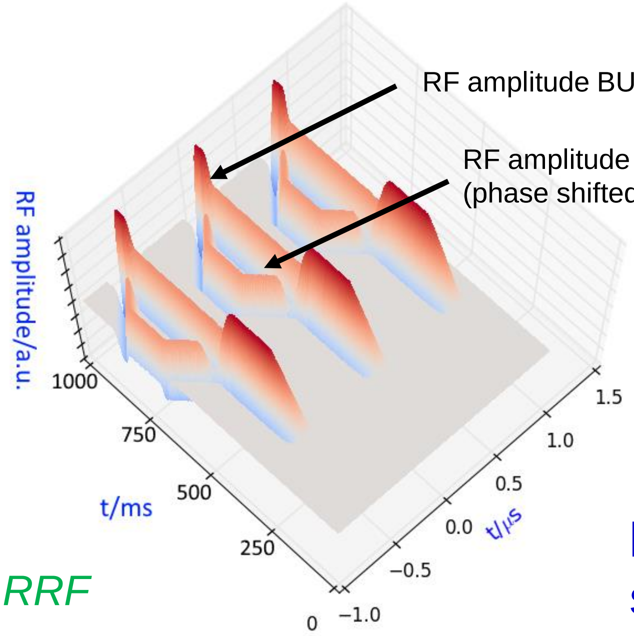
ESR Barrier Bucket RF System



Installed in 2020, presently integrated into deceleration and fast extraction of single bunch

Pulse amplitude increased to 1.2 kV (2 new amplifiers)

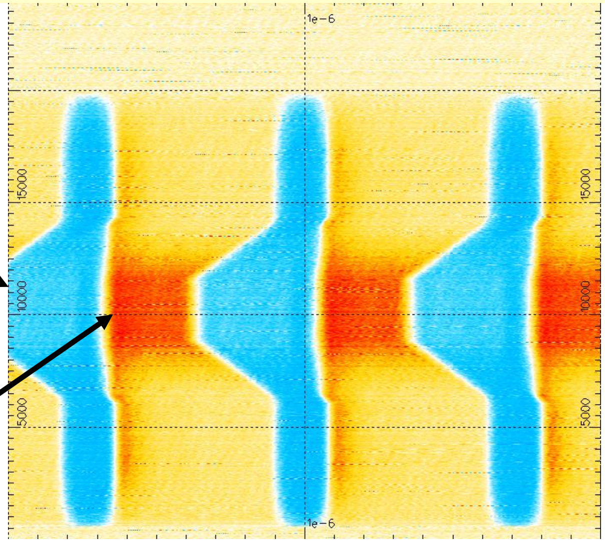
Phase shifting works as intended



RF amplitude BU1

RF amplitude BU2 (phase shifted)

BPM signal for cooled Au^{78+} beam at 144 MeV/u



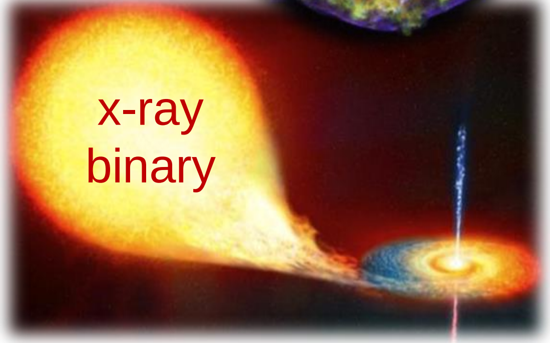
blue: particle-free zone

red: compressed bunch

low level rf system will be available for synchronization with SIS rf system in 2024

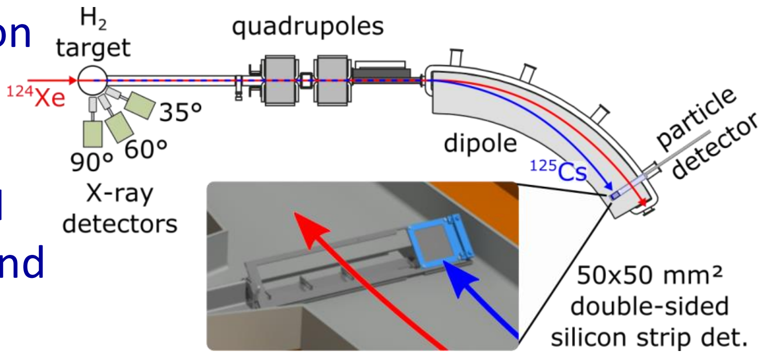
M. Frey and RRF

Decelerated Rare Isotope Beams for Nuclear Astrophysics



To investigate the origin of elements in stars, nuclear astrophysics aims for challenging reaction studies on rare ion beams.

Heavy ion storage rings at GSI provide unique possibilities and unrivalled conditions for such experiments.



Experimental setup of the reaction study ^{124}Xe(p,γ) in the ESR at beam energies as low as 5.5 MeV/u.

- high energy production & separation of radioactive beams in FRS
    - ➢ most efficient and versatile technique available
- deceleration to energies below 10 MeV/u
    - ➢ access to the famous Gamow window relevant for nuclear physics of stars
- cooled beam in combination with a thin gas jet target
    - ➢ inverse kinematics studies at unmatched energy resolution
- storage and recycling of the rare ion beam
    - ➢ extremely efficient technique for studies on beams of limited intensity

Jan Glorius

Typical ESR Deceleration Cycle

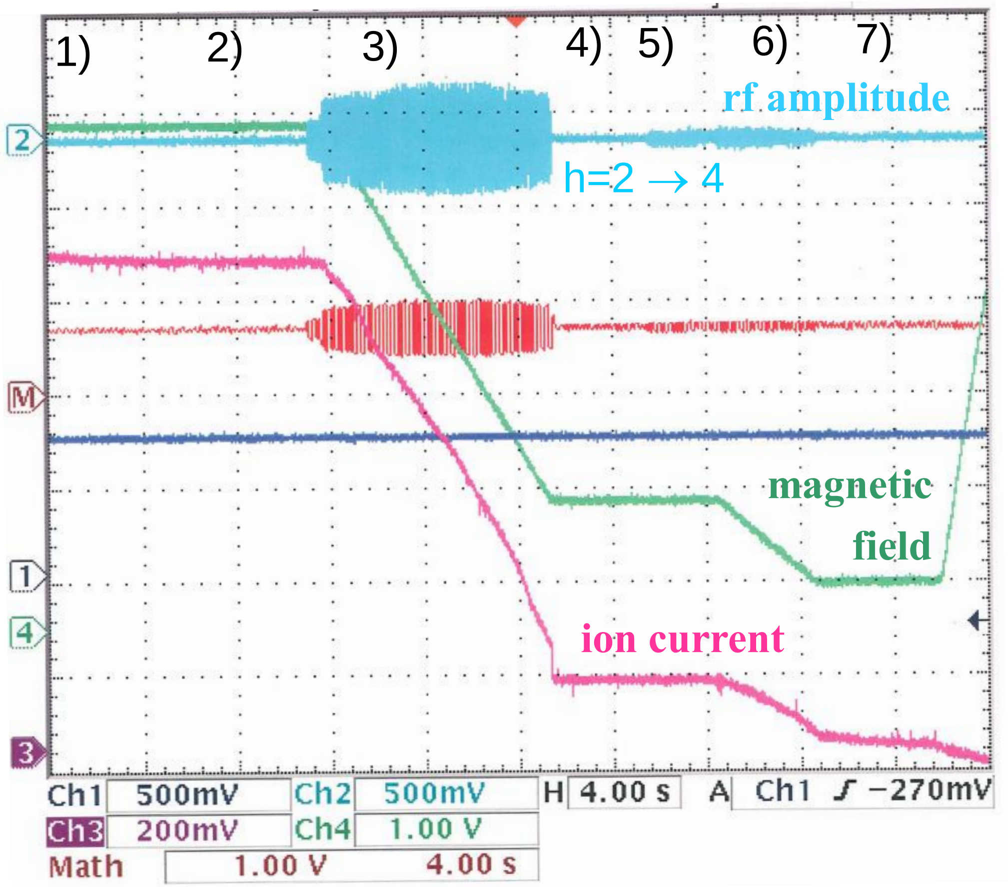
Ni^{28+} 400 → 30 → 4 MeV/u

1100 μA → 180 μA → 25 μA

45% 37 %

4 MeV/u required for HITRAP linac

cycle time 45 s



1) injection (at 400 MeV/u)

2) stochastic/electron cooling

(controlled ramp of cooler HV is difficult)

3) deceleration to 30 MeV/u

4) electron cooling

5) changing rf harmonic 2 → 4

6) deceleration to final energy

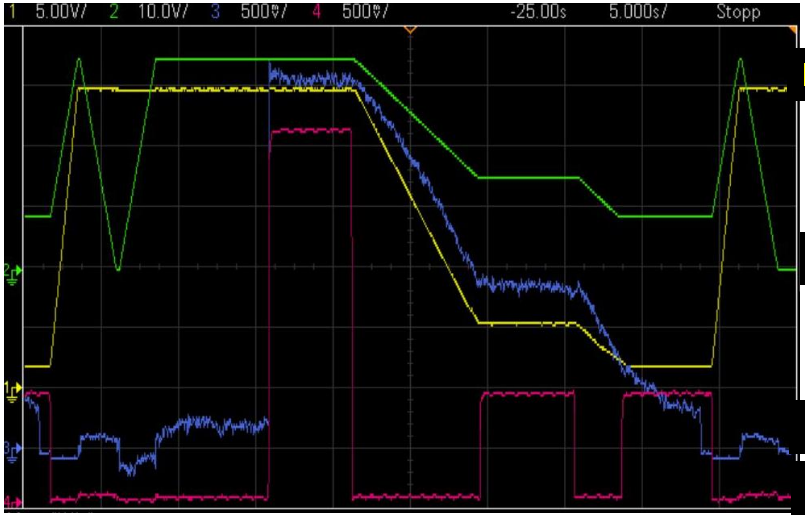
7) electron cooling, bunching, extraction

maximum change of p (Bρ): 13

Deceleration Cycle 2022

Au^{78+}: 145 → 30 → 10 MeV/u

with fast extraction for CRYRING@ESR



high voltage of electron cooler (electron energy)

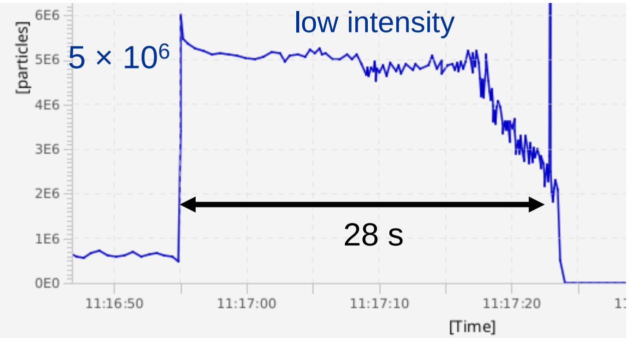
dipole field strength

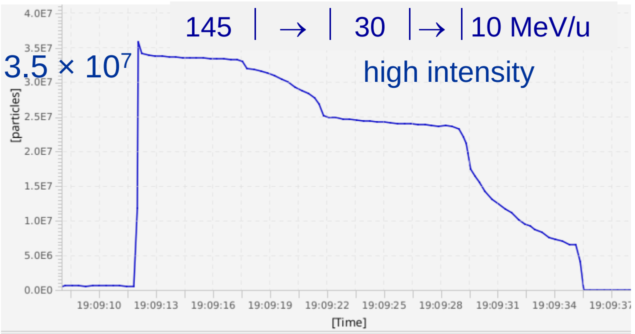
ion current

electron current (0.3/0.1 A)

electron cooling is applied at all three plateaus

particle number during deceleration





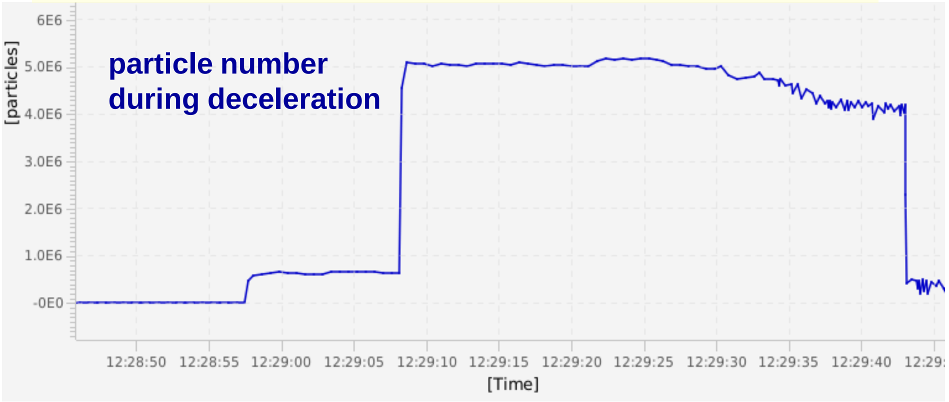
For intensity below 10^7 particle loss is less than 20 % from 145 to 10 MeV/u, but for higher initial intensity increasing relative losses were observed

fast losses at 10 MeV/u
beam lifetime due to vacuum

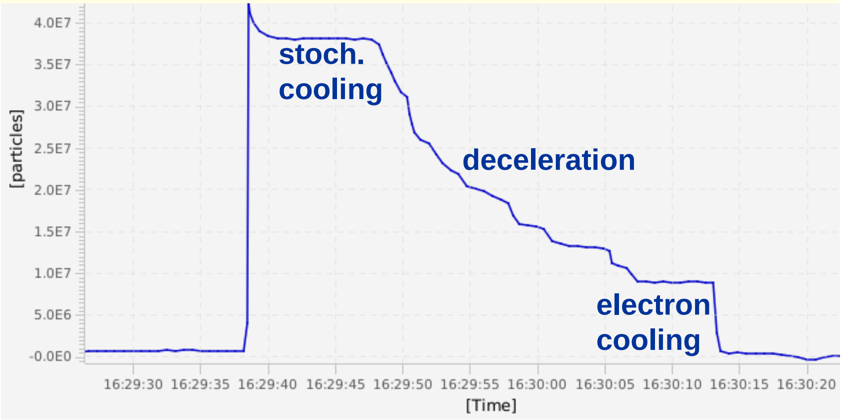
Efficiency of Deceleration 2020

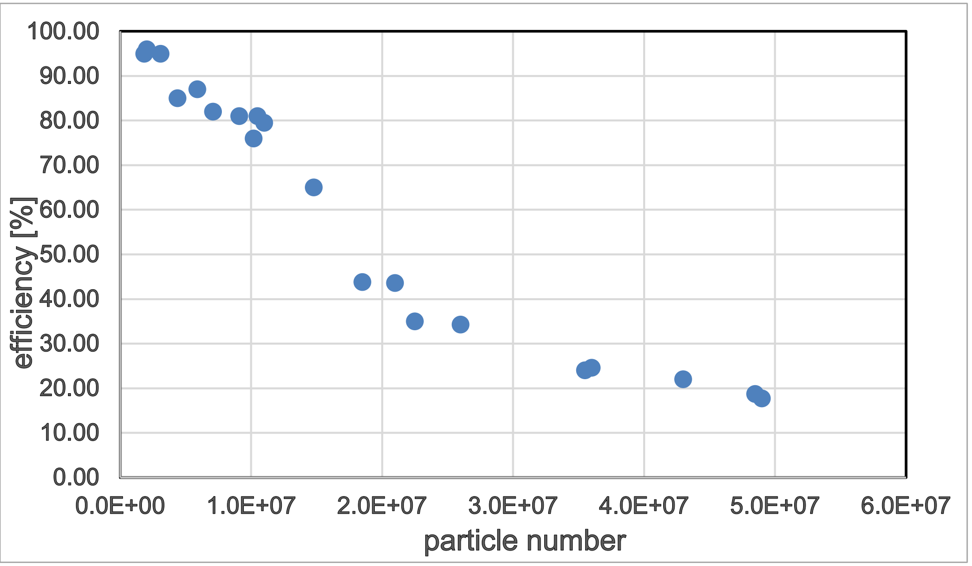
deceleration cycle Bi^{83+} from 400 to 30 MeV/u

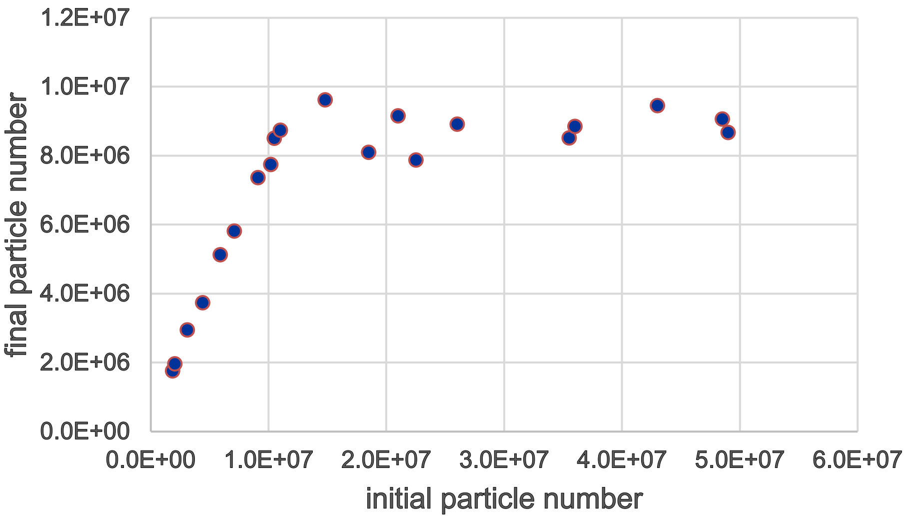
loss-free deceleration of some 10^6 ions



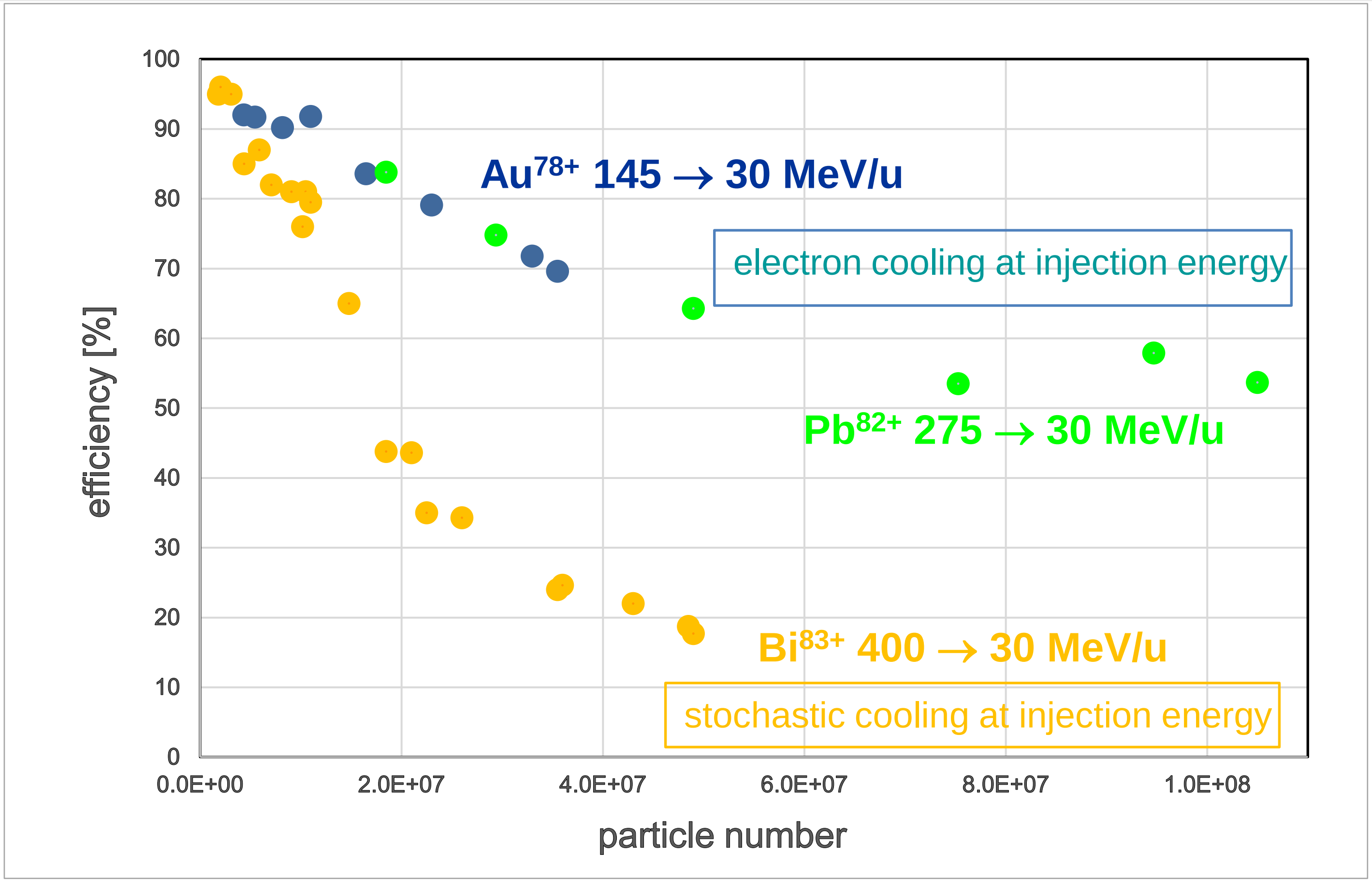
increasing loss above 10^7 injected ions







Deceleration Efficiency 2021/22



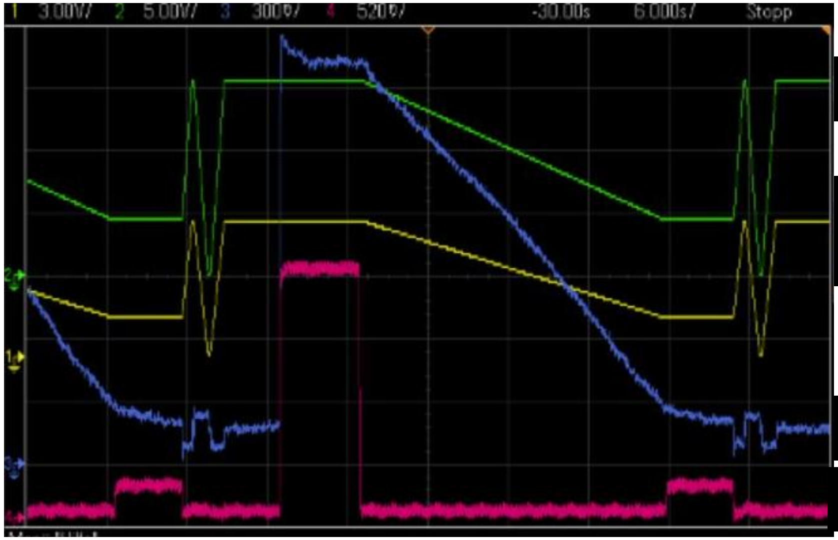
the beam loss during deceleration depends on:

- **the initial emittance**
- **the change of momentum during deceleration**

Deceleration for HITRAP 2022

Ni^{28+} 45 → 4 MeV/u

cycle with injection at lower energy to simplify deceleration cycle



dipole field strength

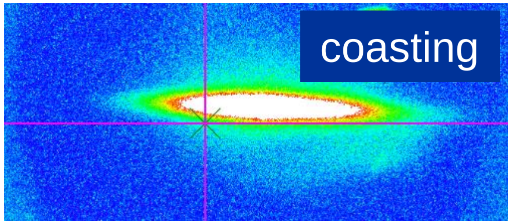
high voltage of electron cooler (electron energy)

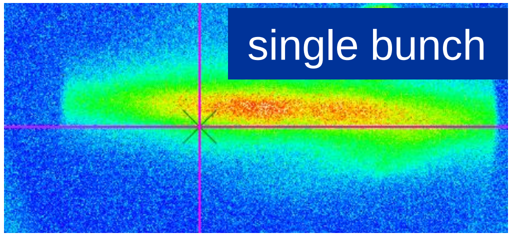
ion current

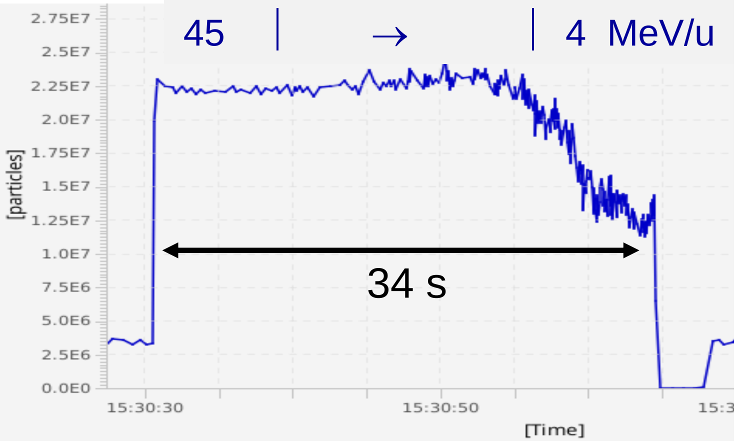
electron current (200/40 mA)

electron cooling is applied after injection and before extraction

fast extraction of beam at 4 MeV/u



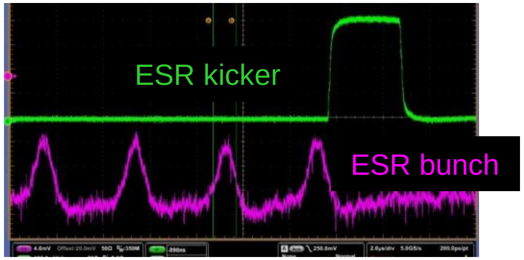




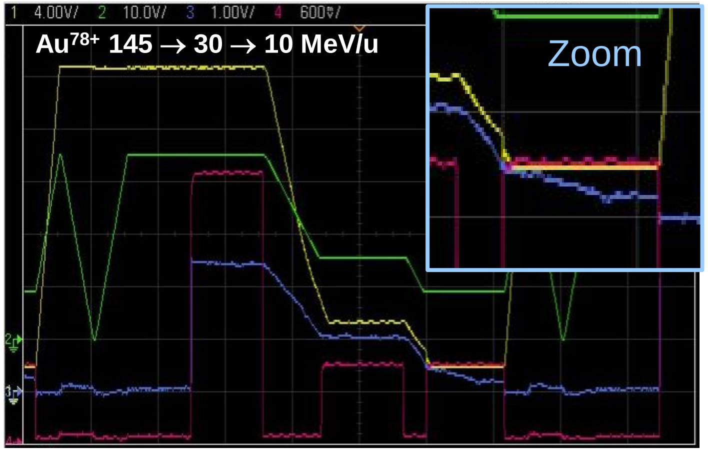
particle loss less than 20 % from 45 to 4 MeV/u

fast loss at 4 MeV/u (due to vacuum)

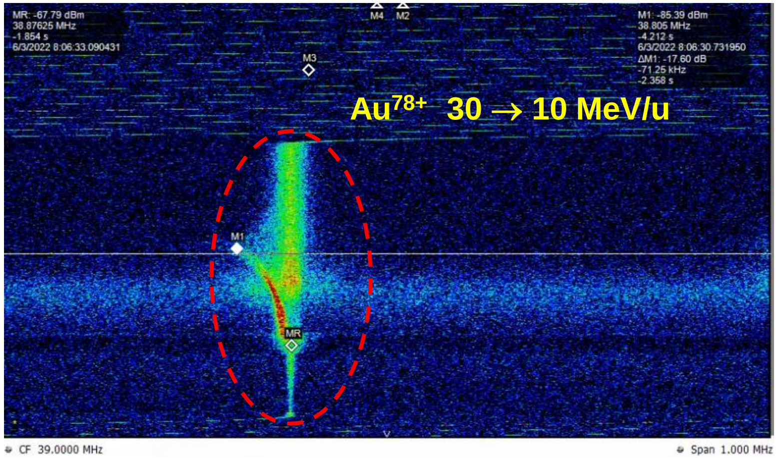
single bunch h=1

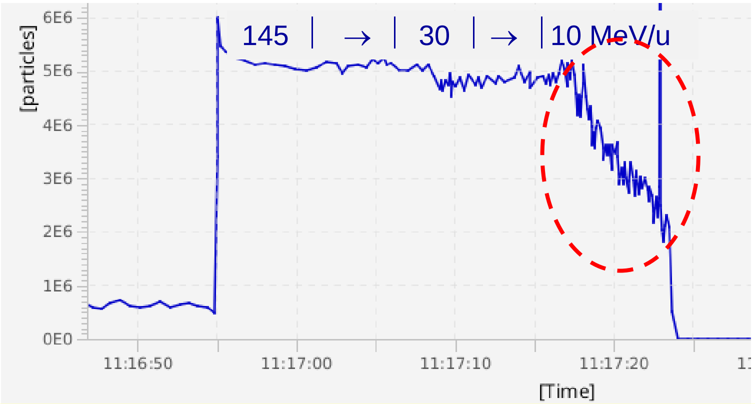


Slow Response of the Cooler High Voltage System after Ramping to Low Energy



- the high voltage load results in **a time constant of ~ 10 s**, which determines the response to ramping of the high voltage
- the high voltage power supply has **an internal regulation time of about 5 s**
- both time constants affect the time required for cooling after deceleration
- beam lifetime at low energy is determined by the poor vacuum conditions of the ESR



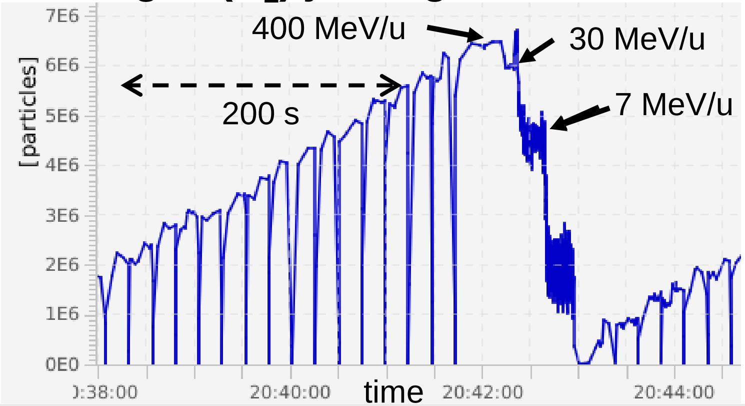


tests to reduce the delay by fast ramping of the HV or application of a special HV pattern to the drift tube are foreseen in 2024

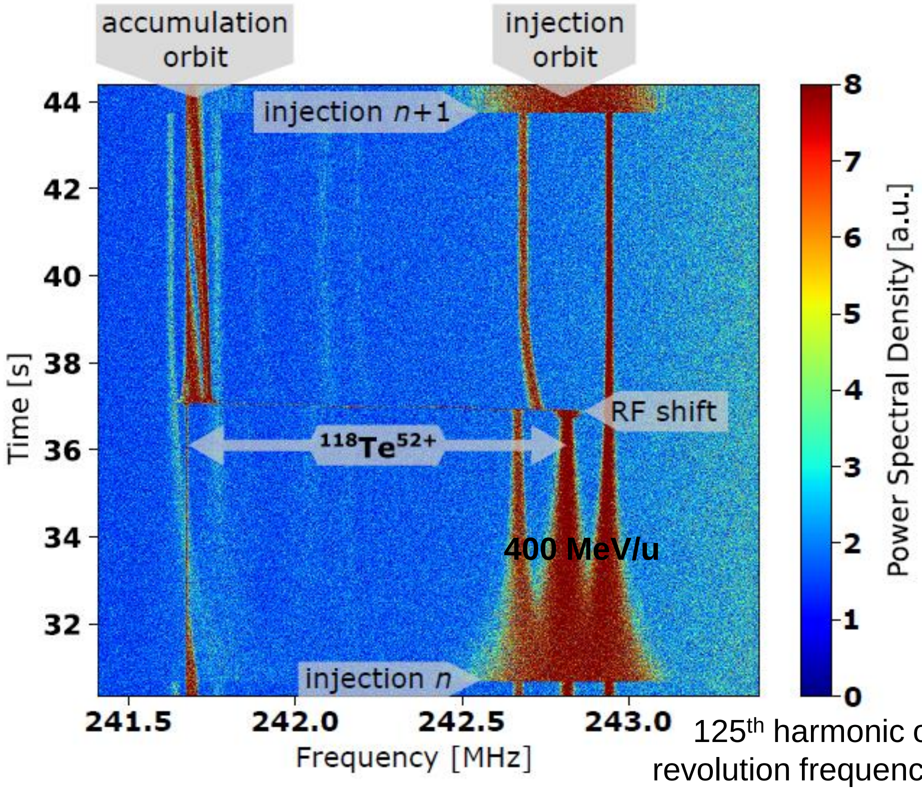
Experiment with Decelerated ^{118}Te^{52+}

Experimental procedure:

1) injection of beam at 400 MeV/u on outer ESR orbit (Δp/p= +0,8%)
2) stochastic cooling on injection orbit (~6 s)
3) rf deceleration to inner orbit (Δp/p= -0.8%)
4) electron cooling on inner orbit (~6 s)
repetition of 1) - 4) ⇒ accumulation
5) ramping of magnetic field to center beam (Δp/p= 0)
6) deceleration to 30 MeV/u
7) electron cooling and de-/rebunching h=2→4
8) deceleration to final energy (7 and 6 MeV/u)
9) electron cooling and operation of internal gas (H_2) jet target



longitudinal Schottky signal after injection of pre-separated beam from FRS



125th harmonic of revolution frequency

deceleration efficiency 400 to 7 MeV/u about 50 %

beam lifetime at 7 MeV/u: 1.5 s
with electron cooling and H_2 target

Proof of Selectivity

measurement of the X-ray spectrum of the decelerated ion beam interacting with the internal gas (H_2) jet target

⇒ no indication of contamination,
all X-ray line can be attributed to transitions of Te^{52+}

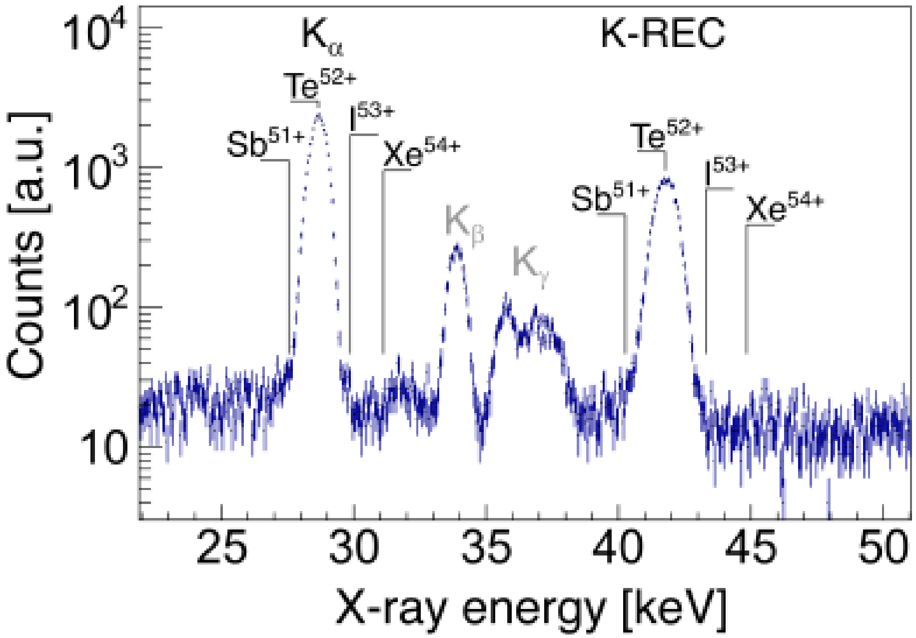


Figure 2: Energy spectrum of a germanium detector at the H_2 target under 90°, see text. All lines visible in this section can be clearly assigned to the characteristic X-ray or K-REC emission subsequent to electron capture on Te^{52+} at the target.

http://arxiv.org/abs/2305.17142

Future Scenario with Rare Isotope Beams prepared in the ESR

experiments with stored highly charges RIBs at higher energy will be continued

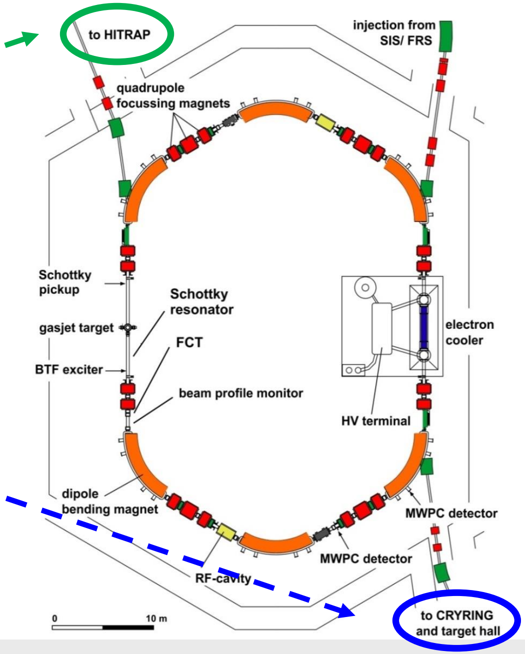
- **mass spectrometry of rare isotopes**
- **precision spectroscopy of rare isotopes**

further optimization of deceleration of rare isotopes will allow

- **experiments with increased intensities of stored rare isotopes**
- **delivery of 4 MeV/u RI beam for further deceleration in the HITRAP linac and final capture in a trap**
- **delivery of low energy rare RI beam to CRYRING@ESR for further deceleration**

Beam cooling is indispensable

in all experiments with rare isotope beams



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