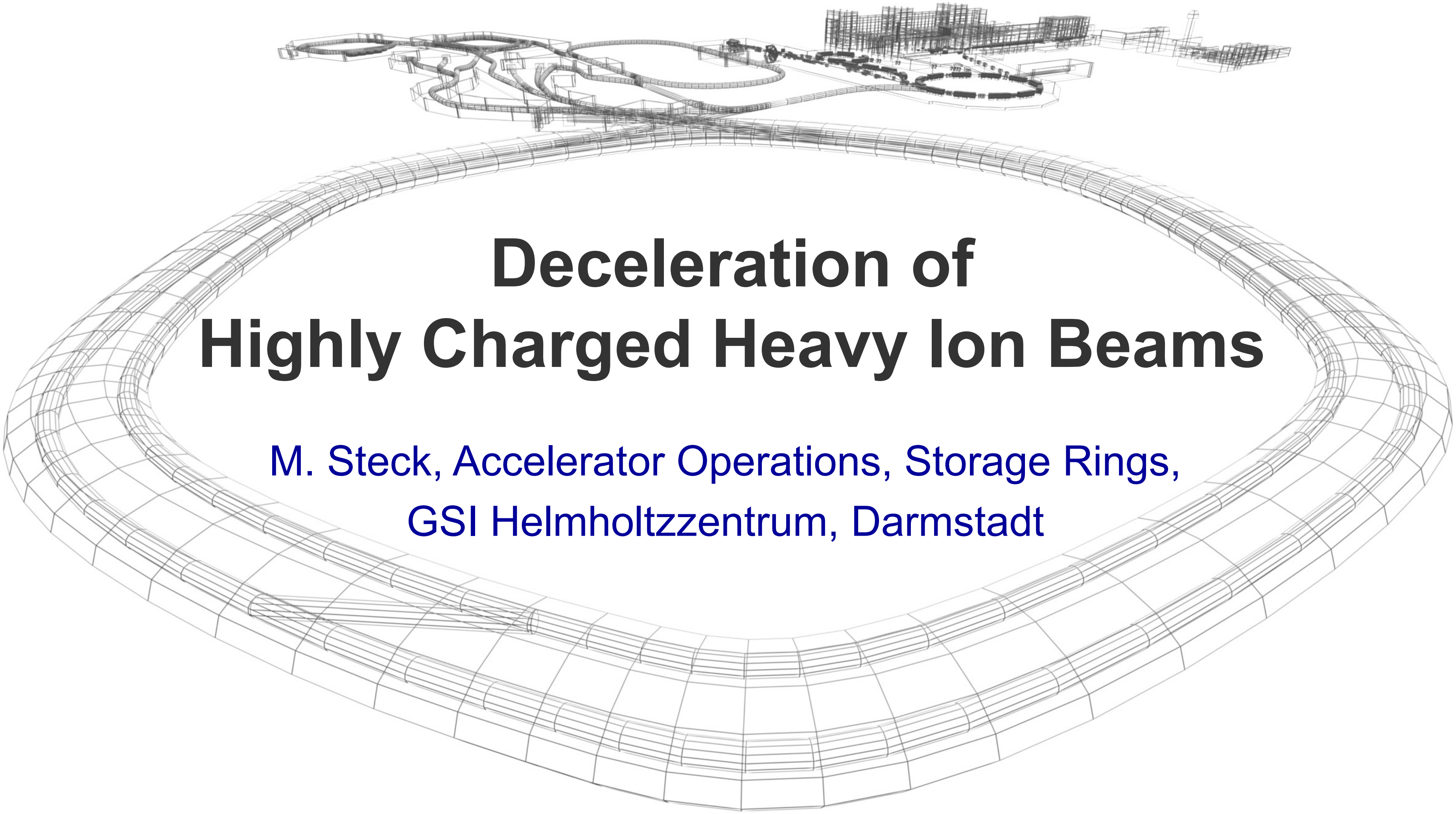


Deceleration of Highly Charged Heavy Ion Beams

M. Steck, Accelerator Operations, Storage Rings,
GSI Helmholtzzentrum, Darmstadt

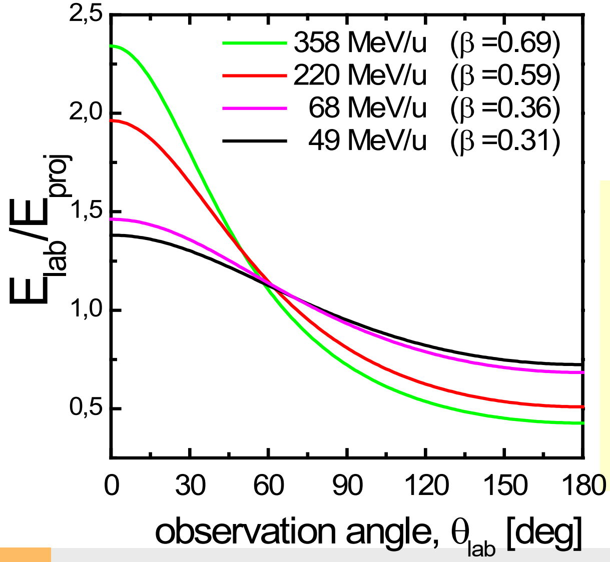
Decelerated Beams for Atomic Physics

relativistic Doppler transformation

$$E_{lab} = \frac{E_{proj}}{\gamma \cdot (1 - \beta \cdot \cos\theta_{lab})}$$

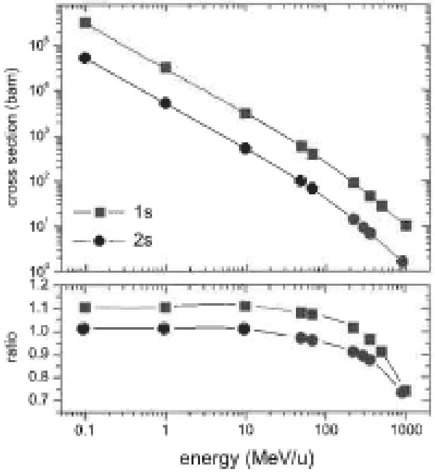
relativistic transformation of solid angle:

$$\Delta\Omega_{lab} = \frac{\Delta\Omega_{proj}}{\gamma^2 \cdot (1 - \beta \cdot \cos\theta_{lab})^2}$$



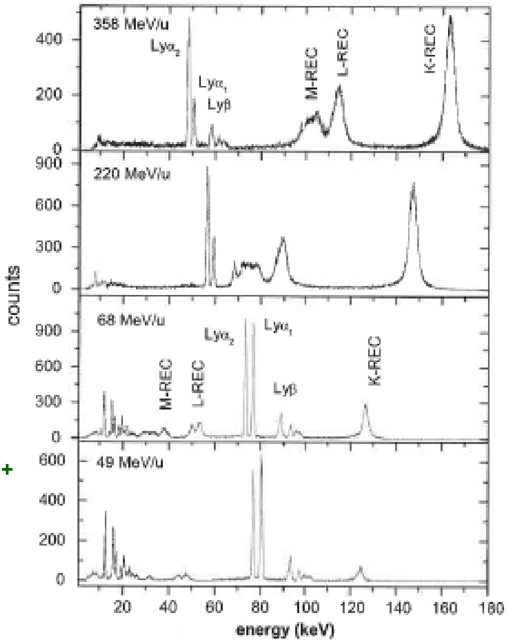
E_{lab}: photon energy im lab system

E_{proj}:photon energy in emitter system



radiative recombination U^{92+}

J. Eichler, T. Stöhlker / Physics Reports 439 (2007) 1–99

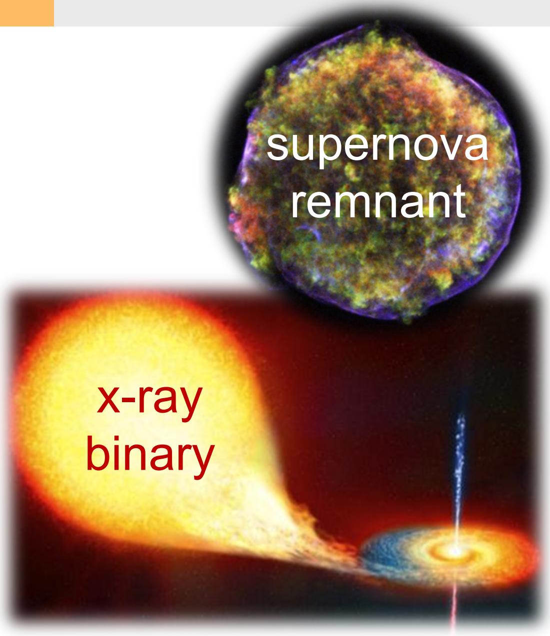


X-rays of REC U^{92+} -> N_2

deceleration reduces:
- dependence on velocity and observation angle θ_{lab}
- influence of energy and intensity

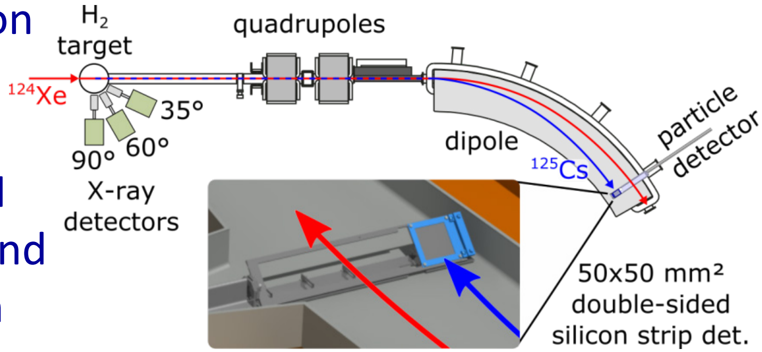
deceleration:
- provides increased reaction cross sections
- opens new reaction channels (transitions, polarization)

Decelerated 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

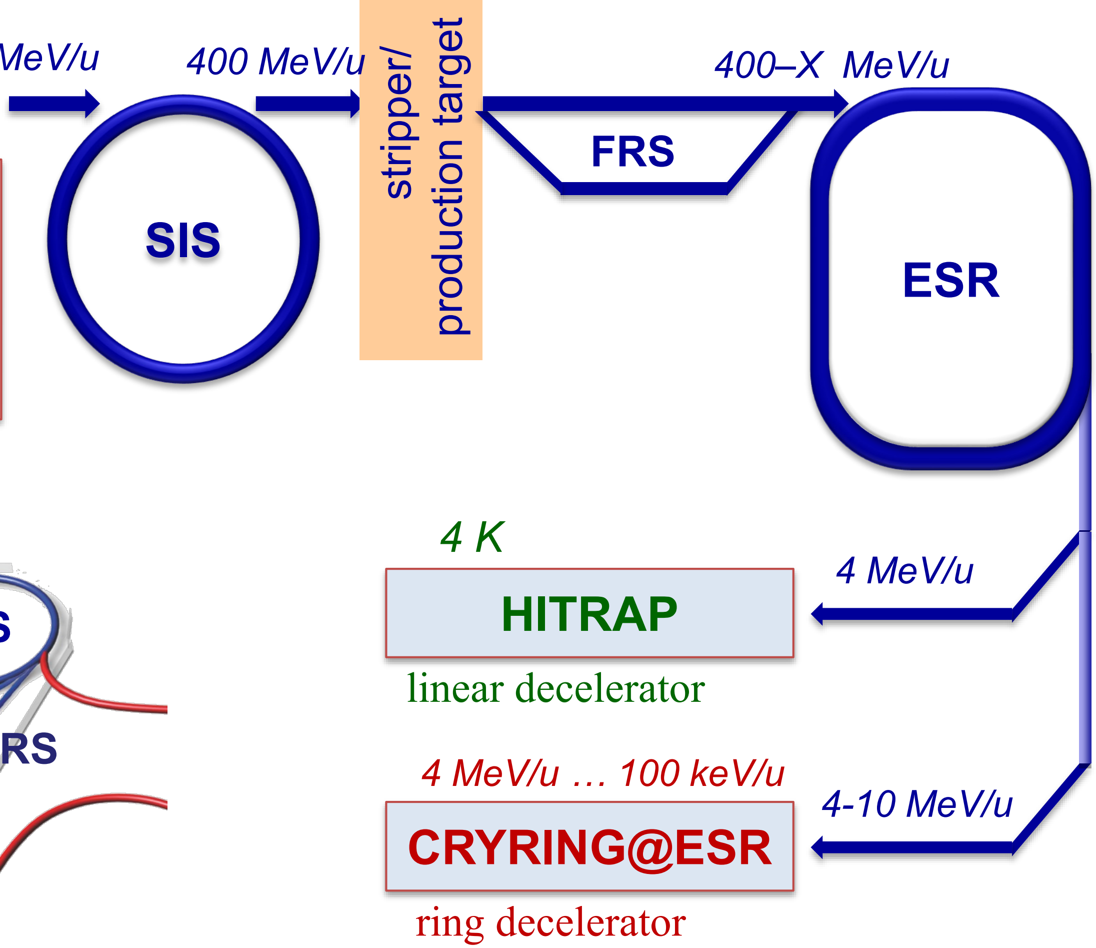
Jan Glorius

The GSI Deceleration Facility

Slow, heavy, highly charged Ions stored and well controlled

Energy range 10 MeV/u to sub eV/ion

10^5 to 10^7 highly charged ions. e.g. U^{91+}



UNILAC

11.4 MeV/u

SIS

400 MeV/u

stripper/
production target

FRS

400–X MeV/u

ESR

4 K

HITRAP

linear decelerator

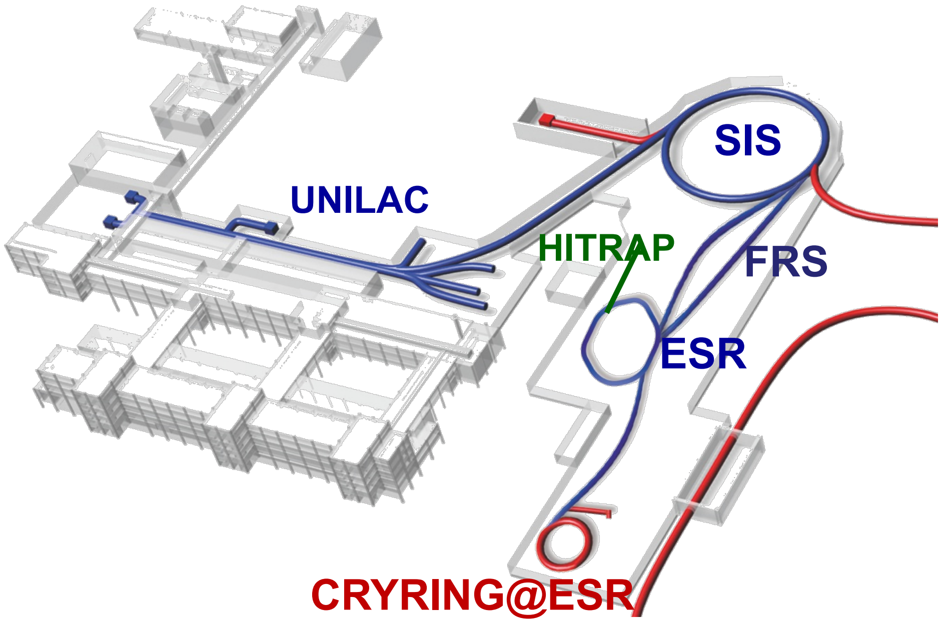
4 MeV/u

4 MeV/u … 100 keV/u

CRYRING@ESR

ring decelerator

4-10 MeV/u



Requests for the Deceleration of HCI and RI Beams in the ESR

good beam quality of stored beam ⇒ high precision experiments

high luminosity with internal target for internal experiment

long lifetime of stored beam ⇒ vacuum pressure 10^{-11} mbar or below

fast extraction at 4 MeV/u for HITRAP, defined by the linac injection energy

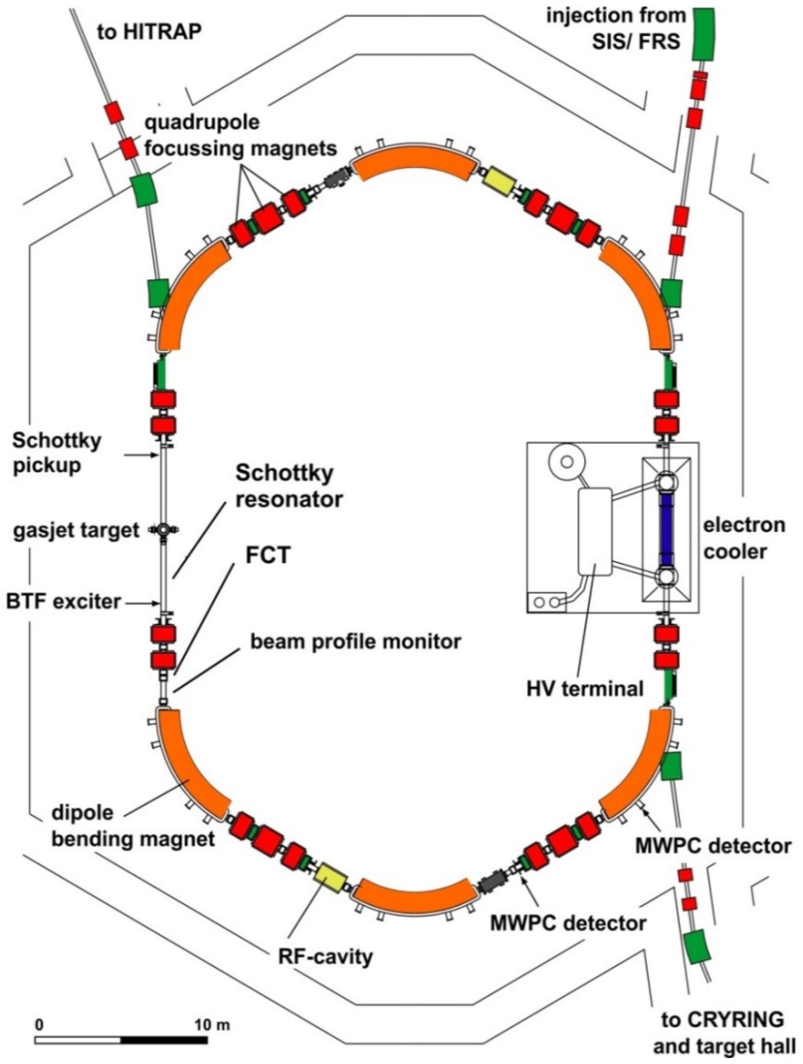
fast extraction below ~10 MeV/u for CRYRING, defined by bending power

slow extraction employing charge changing processes (cooler, target)

maximum intensity (particles per time interval) to HITRAP/CRYRING

i.e. large particle number, short cycle time

The Heavy Ion Storage Ring ESR



Fast injection (stable HCIs / RIBs)

Stochastic cooling (≥ 400 MeV/u)

Electron cooling (3 - 430 MeV/u)

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

Deceleration (down to 3 MeV/u)

Fast extraction (HITRAP/CRYRING@ESR)

Slow (resonant) extraction

Ultraslow extraction (charge change)

Beam accumulation

Internal gas jet target

Multi charge state operation

Schottky mass spectrometry of RIBs

Isochronous mode (TOF detector)

Beam Cooling at the ESR

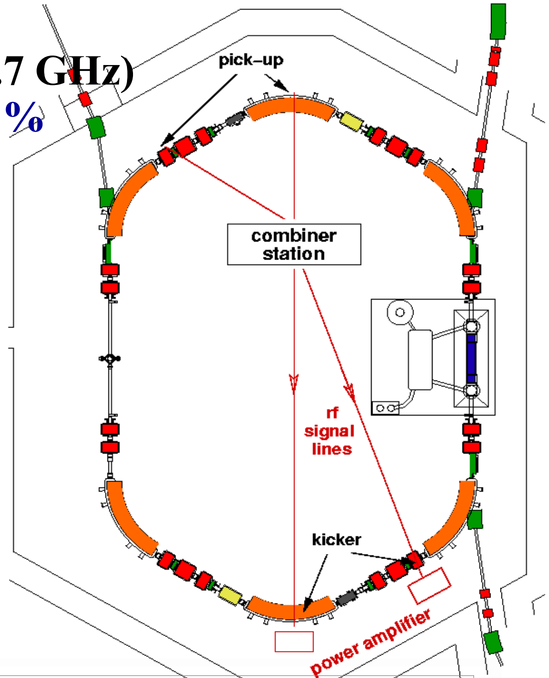
stochastic pre-cooling on the injection orbit

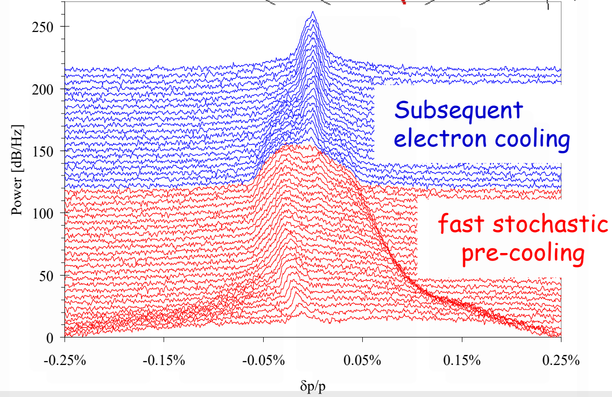
energy <u>400</u> (-550) MeV/u
bandwidth 0.8 GHz (range 0.9-1.7 GHz)
$\delta p/p = \pm 0.35$ % → $\delta p/p = \pm 0.01$ %
$\varepsilon = 10$ µm → $\varepsilon = 2$ µm


electrodes


combiner station


power amplifiers





electron cooling

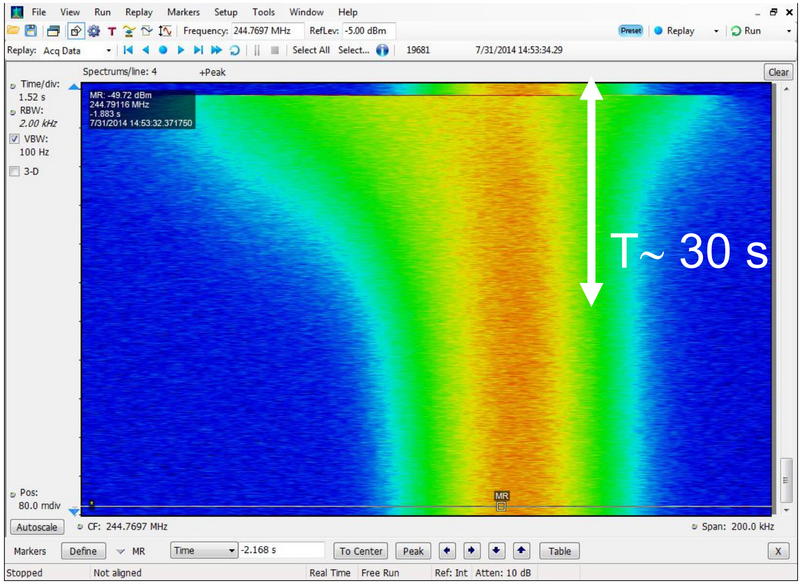
electron energy	1.6 – 250 keV
electron current	0.001 – 1 A
beam diameter	50.8 mm
magnetic field	0.01 - 0.2 T
collection efficiency	0.9998
transverse temperature	0.1 eV
longitudinal temperature	~0.1 meV
vacuum	2×10^{-11} mbar

Cooling after Injection

- **The injection energy of the ESR is flexible (30 - 400 MeV/u)**
- **the production rate of highly charged heavy ions increases with energy, but at higher energy cooling time increases ⇒ trade-off for maximum luminosity**
- **electron cooling can be applied for any energy ≤ 430 MeV/u**
- **stochastic cooling is presently available at 400 MeV/u but could be extended to higher energies (up to 550 MeV/u)**
- **at 400 MeV/u stochastic cooling is faster than electron cooling**

protons 400 MeV

stochastic cooling



Frequency: 244.7697 MHz RefLev: -5.00 dBm

Replay: Acq Data 19681 7/31/2014 14:53:34.29

Spectrums/line: 4 +Peak

Time/div: 1.52 s

RBW: 2.00 kHz

VBW: 100 Hz

MR: -49.72 dBm
244.79116 MHz
-1.883 s
7/31/2014 14:53:32.371750

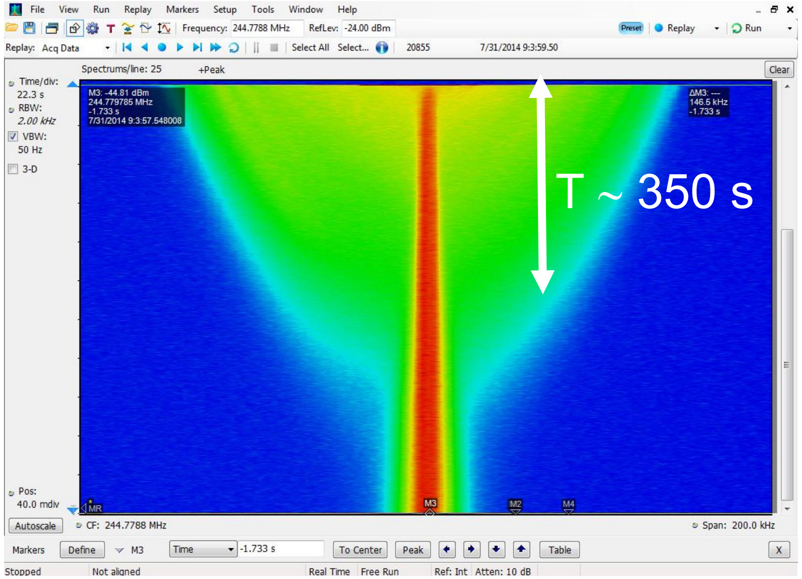
Pos: 80.0 mdiv

CF: 244.7697 MHz Span: 200.0 kHz

Markers MR Time -2.168 s

Stopped Not aligned Real Time Free Run Ref: Int Atten: 10 dB

electron cooling (I_{el}=0.25 A)



Frequency: 244.7788 MHz RefLev: -24.00 dBm

Replay: Acq Data 20855 7/31/2014 9:3:59.50

Spectrums/line: 25 +Peak

Time/div: 22.3 s

RBW: 2.00 kHz

VBW: 50 Hz

M3: -44.81 dBm
244.779785 MHz
-1.733 s
7/31/2014 9:3:57.548008

ΔM3: ---
146.5 kHz
-1.733 s

Pos: 40.0 mdiv

CF: 244.7788 MHz Span: 200.0 kHz

Markers M3 Time -1.733 s

Stopped Not aligned Real Time Free Run Ref: Int Atten: 10 dB

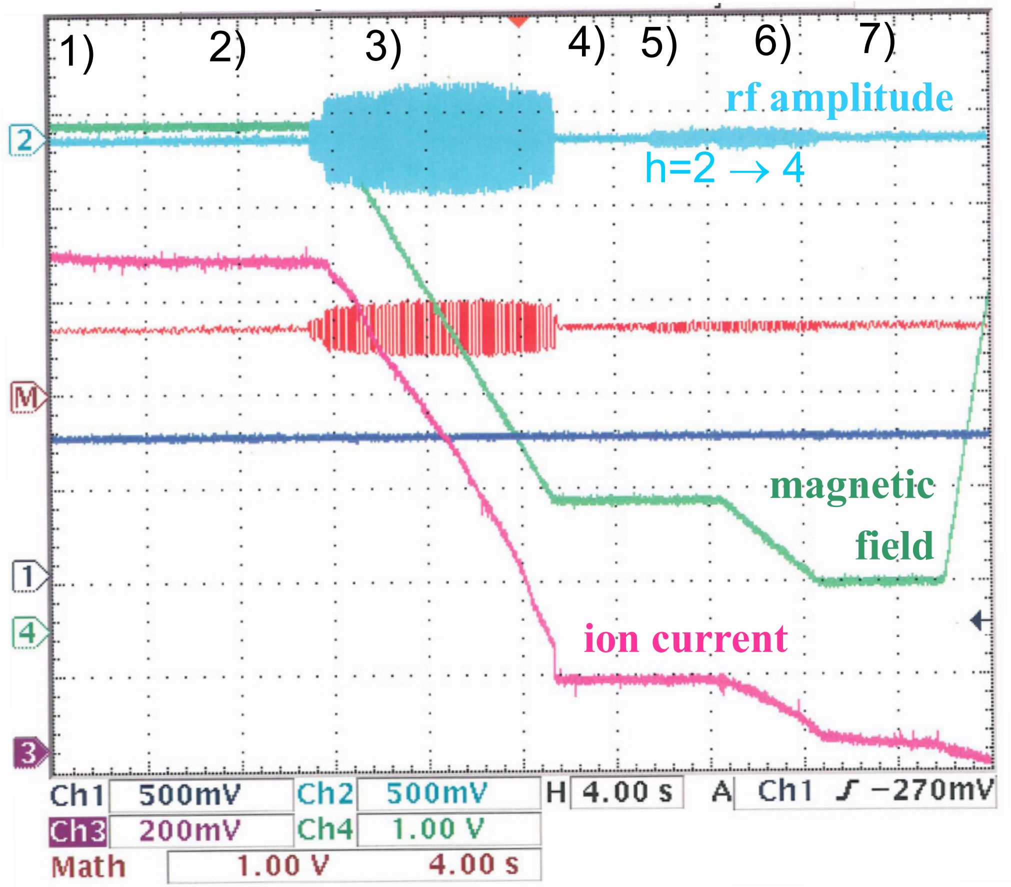
Typical ESR Deceleration Cycle

Ni^{28+} 400 → 30 → 4 MeV/u

1100 μA → 180 μA → 25 μA

45% 37 %

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

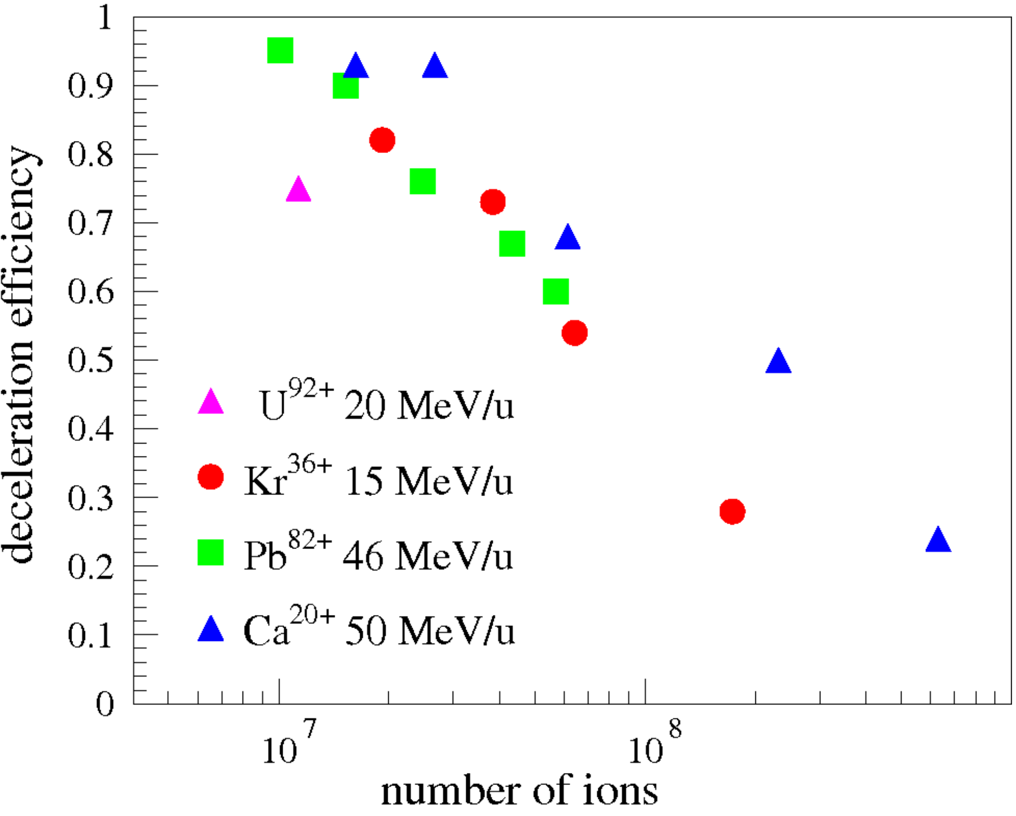
6) deceleration to final energy

7) electron cooling, bunching, extraction

maximum change of p (Bρ): 13

Efficiency of Deceleration (2000-2015)

Losses increase with increase of initial stored particle number most likely due to IBS



in a bunched beam during deceleration transverse emittance is growing due to

- intrabeam scattering (no cooling during deceleration),
- larger emittance of bunched beam
- adiabatic emittance growth ($\propto 1/\beta\gamma$)

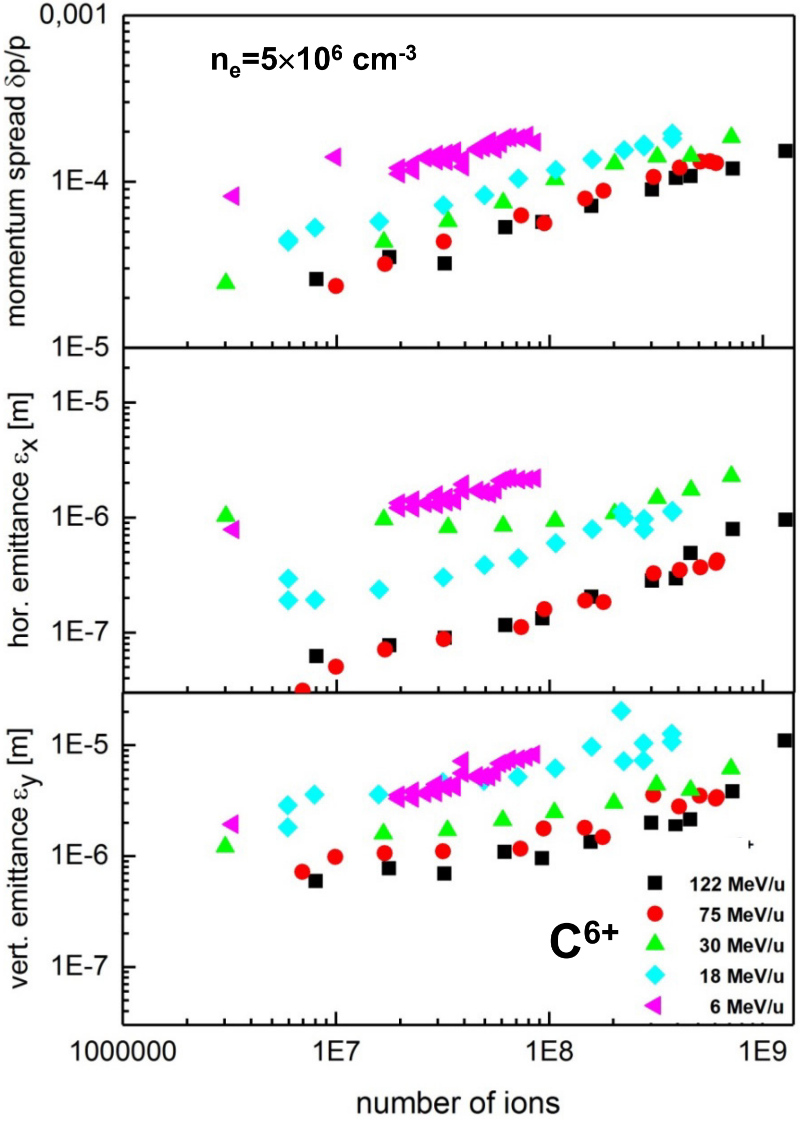
during deceleration the beam is also approaching the space charge dominated regime

$$\Delta Q_x = \frac{r_p Z^2 N g}{\pi A \beta^2 \gamma^3 B(\epsilon_x + \sqrt{\epsilon_x \epsilon_y Q_x / Q_y})}$$

$$\Delta Q_x \simeq \frac{r_p Z^2 N}{2\pi A \beta^2 \gamma^3 B \epsilon_x},$$

$$g = 1, \epsilon_x = \epsilon_y, Q_x = Q_y$$

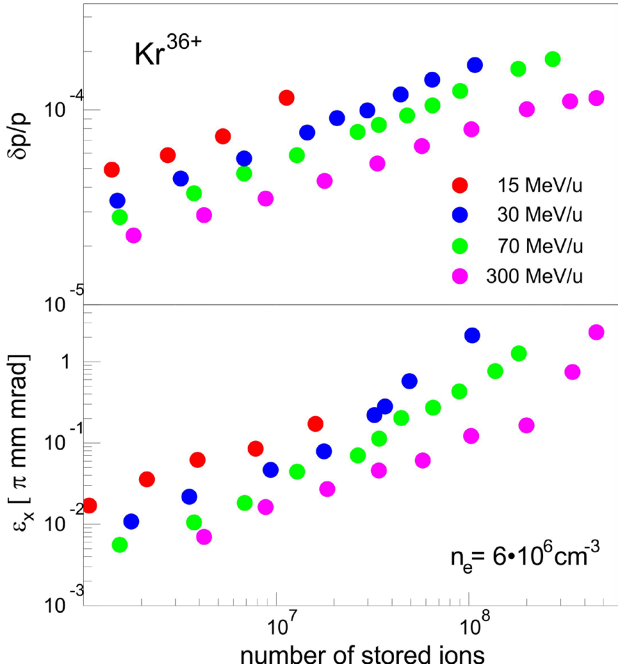
Beam Parameters of Decelerated Ions



Intrabeam Scattering rate

$$\tau_{IBS}^{-1} = \frac{Q^4 e^4}{(Am_i)^2} \cdot \frac{N}{C\varepsilon_h \varepsilon_v \delta p / p} \cdot \frac{1}{(\gamma^4 \beta^3 c^3)} \cdot 4\pi L_C^{IBS}$$

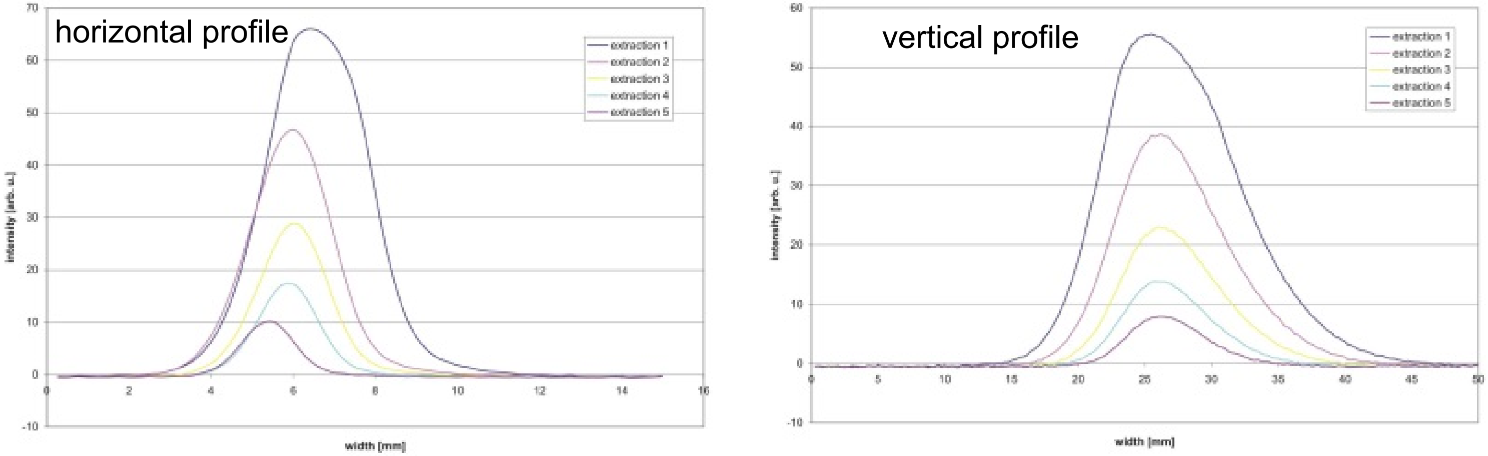
in case of equipartitioning:
emittance increases ≈ proportional βγ



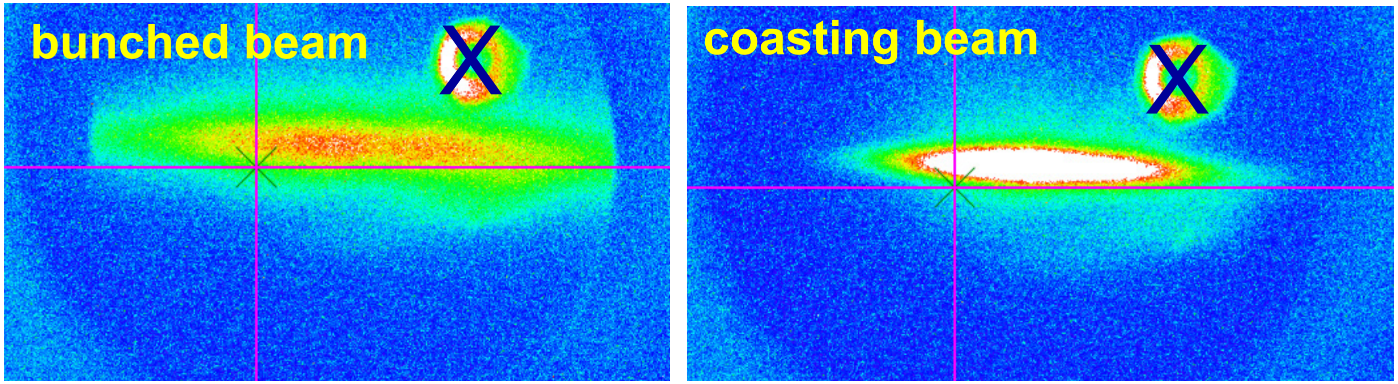
Emittance of Extracted Decelerated Beam

fast extracted beam
Ca^{20+} 4 MeV/u

successive extractions with decreasing intensity



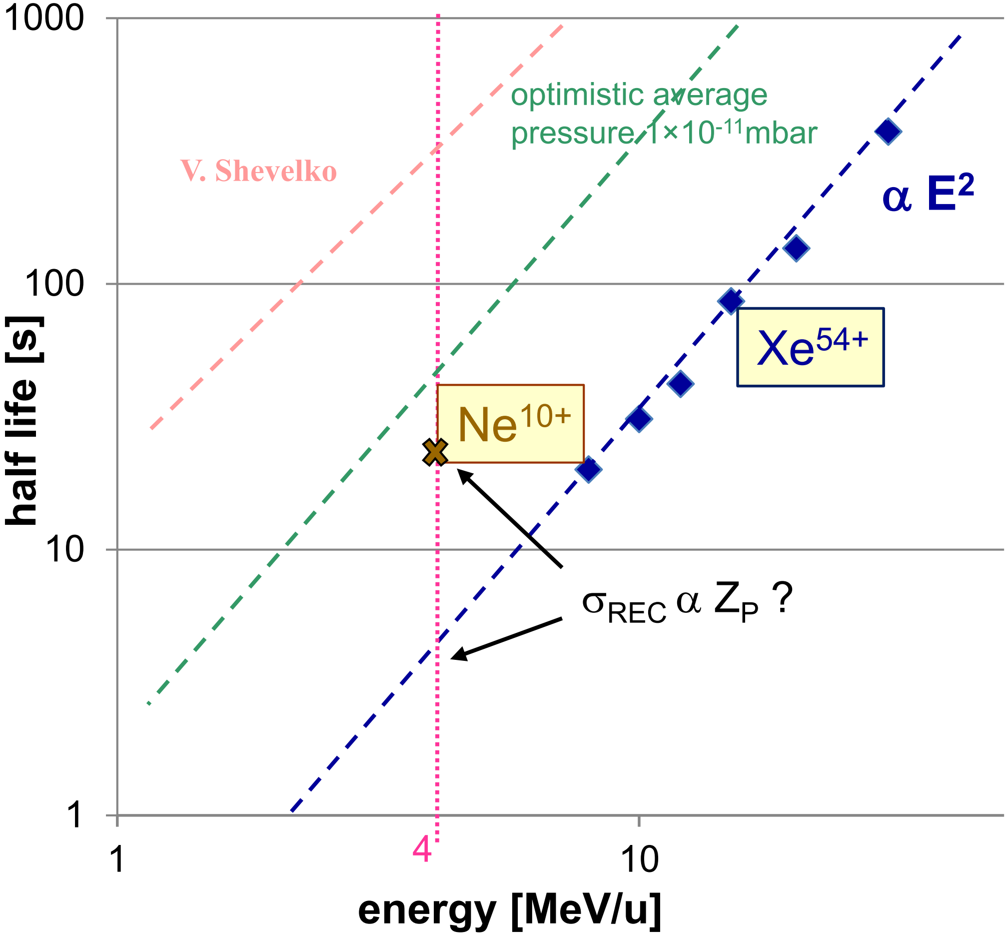
fast extracted beam
Ni^{28+} 4 MeV/u
about 1 × 10^7 ions



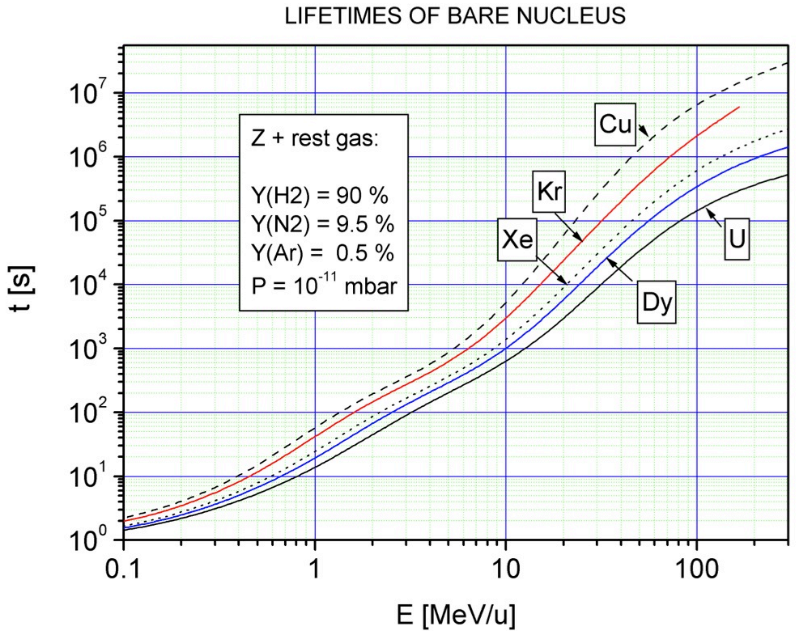
the increase of the beam emittance with intensity due to IBS reflects in the beam size of the extracted cooled beam

Low Energy Beams – Vacuum

measurement of beam half life with
an average pressure of p ≈ **1×10^{-10} mbar**



simulation for CRYRING *V. Shevelko*



lifetime in the residual gas and cooling time can be of similar value
⇒ excellent vacuum and fast cooling are crucial for low energy highly charged ions

Deceleration to 4 MeV/u

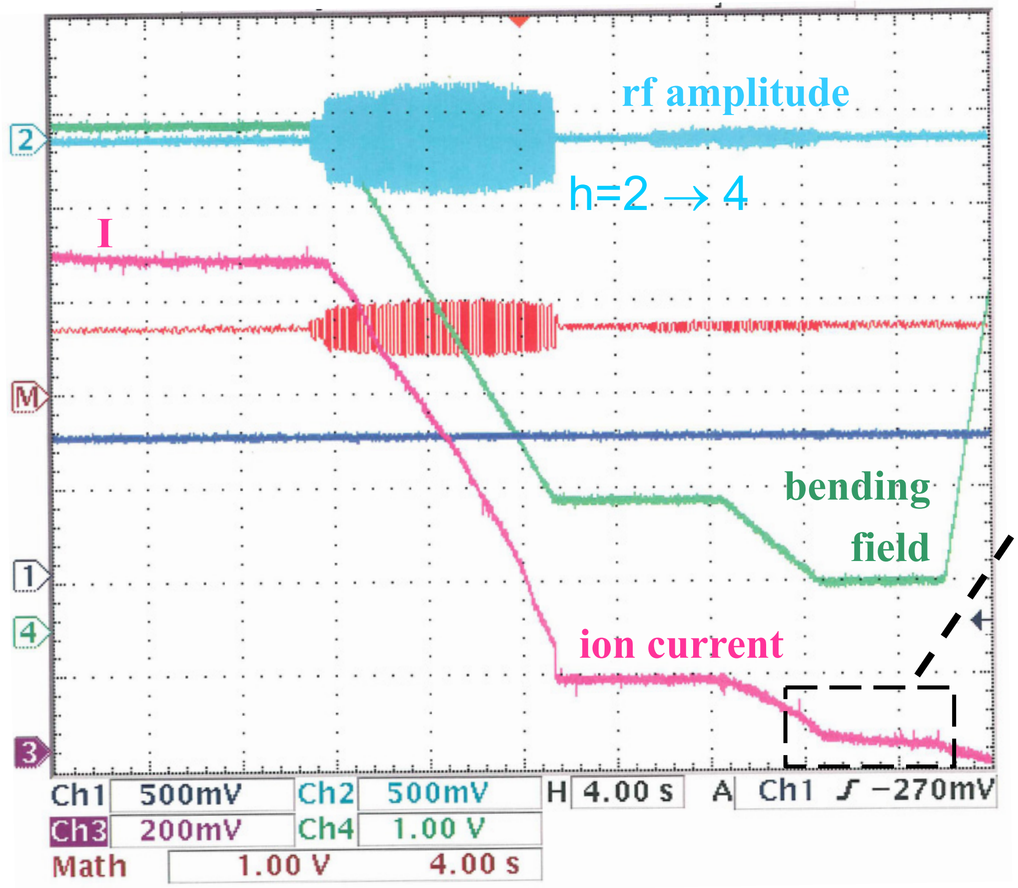
Ni^{28+} 400 → 30 → 4 MeV/u

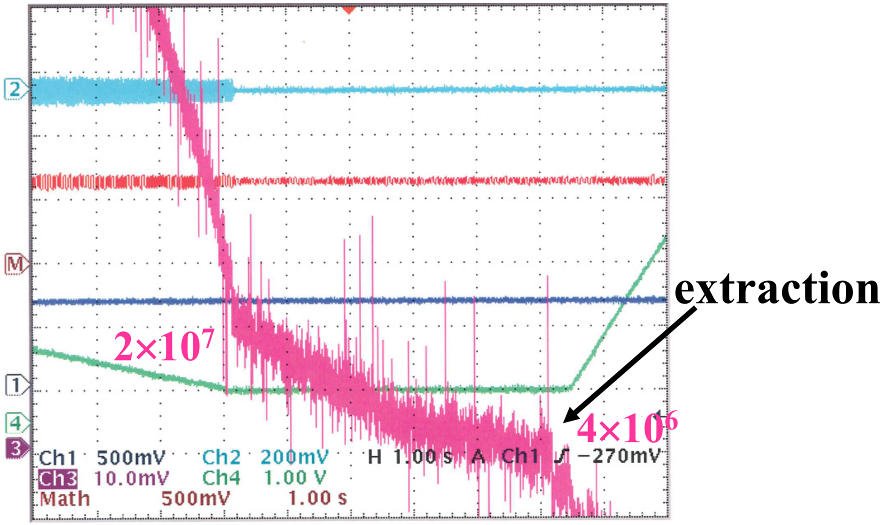
1100 μA → 180 μA → 25 μA

45% 37 %

cycle time
45 s

Main losses:
End of ramp
Storage and cooling at low energy





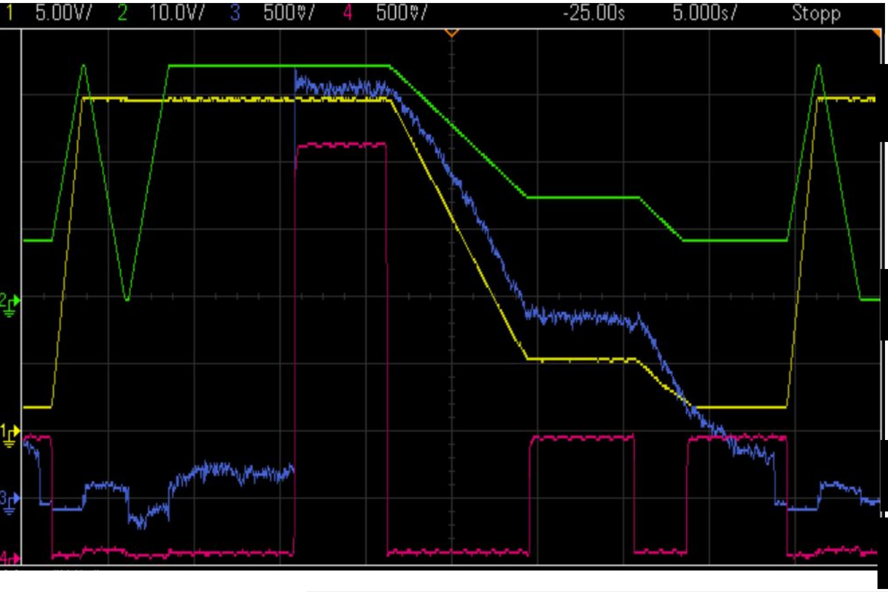
beam half life (vacuum dominated):

30 MeV/u: $T_{1/2} \approx 480$ s
4 MeV/u: $T_{1/2} \approx 2$ s

ESR Deceleration Cycle 2022

Au^{78+}: 145 → 30 → 10 MeV/u

with fast extraction for CRYRING@ESR



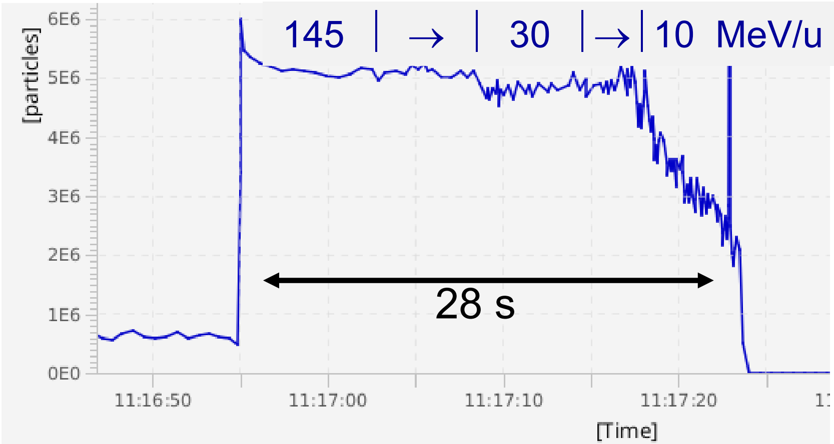
high voltage of electron cooler (electron energy)

electron cooling is applied at all three plateaus

dipole field strength

ion current

electron current (300/100 mA)



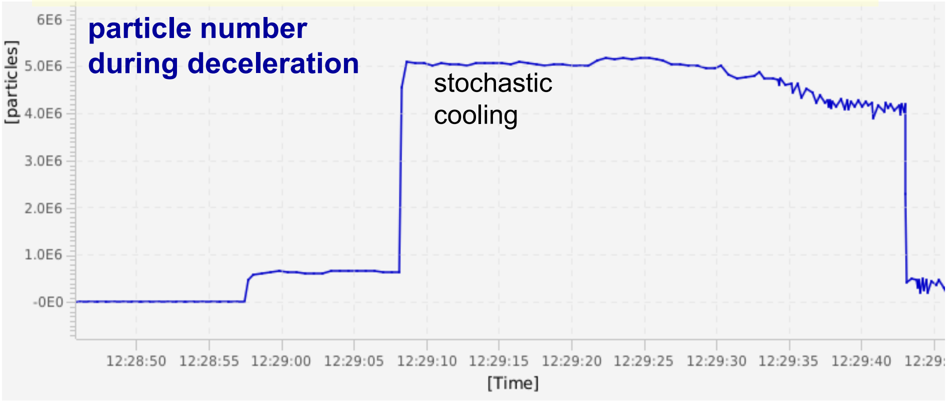
For intensity below 10^7 particle loss less than 20 % from 145 to 10 MeV/u

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

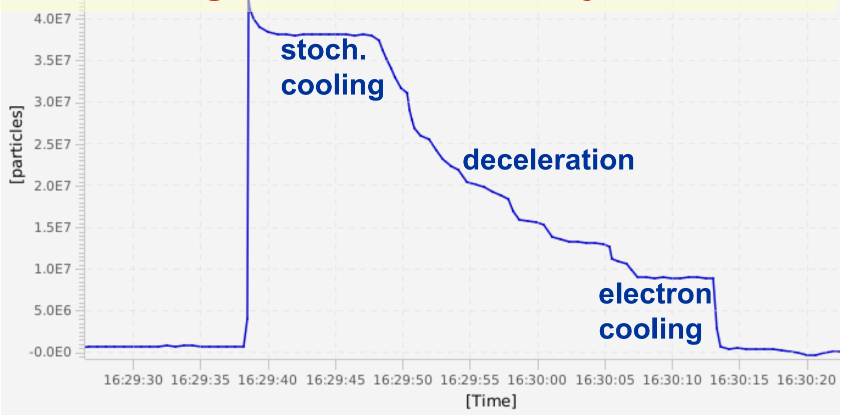
Efficiency of Deceleration 2020

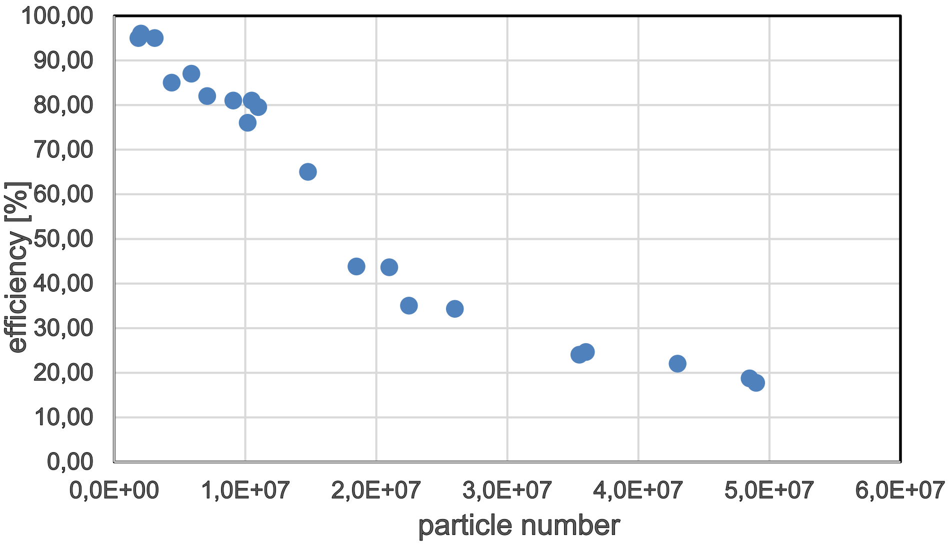
deceleration cycle Bi^{83+} from 400 to 30 MeV/u

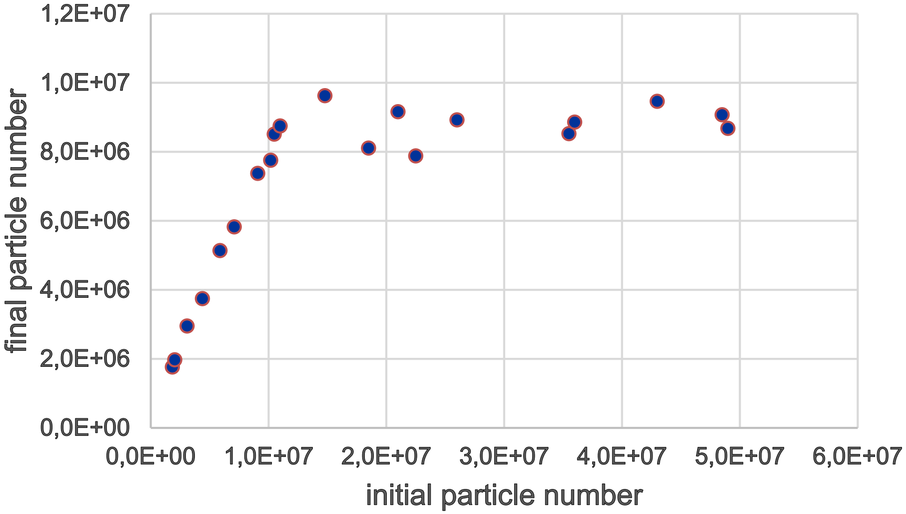
loss-free deceleration of some 10^{6} ions



increasing loss above 10^{7} injected ions







Space Charge Limit

Space charge limit due to incoherent tune shift

$$\Delta Q_x = \frac{r_p Z^2 N g}{\pi A \beta^2 \gamma^3 B(\epsilon_x + \sqrt{\epsilon_x \epsilon_y Q_x / Q_y})}$$

$$\Delta Q_x \simeq \frac{r_p Z^2 N}{2\pi A \beta^2 \gamma^3 B \epsilon_x}, \qquad g = 1, \epsilon_x = \epsilon_y, Q_x = Q_y$$

at 4 MeV/u, for $\Delta Q_x = 0.1$ and $\varepsilon_x = 1$ mm mrad:

$$N \leq 8.7 \times 10^8 \frac{A}{Z^2} \cdot B$$

Coasting (B=1):

Ne^{10+}: 1.8×10^8

Kr^{36+}: 5.8×10^7

U^{92+}: 2.5×10^7

Bunched (≤ 1μs, B=1/5):

Ne^{10+}: 4×10^7

Kr^{36+}: 1×10^7

U^{92+}: 5×10^6

For bunched beam the intensity limit is decreased by the bunching factor.

Experimental observation: with rf amplitude 100 V (h=1) the bunching factor is B≈ 1/20.

Deceleration Investigations

require precise and simultaneous measurement of:

intensity

bunching factor

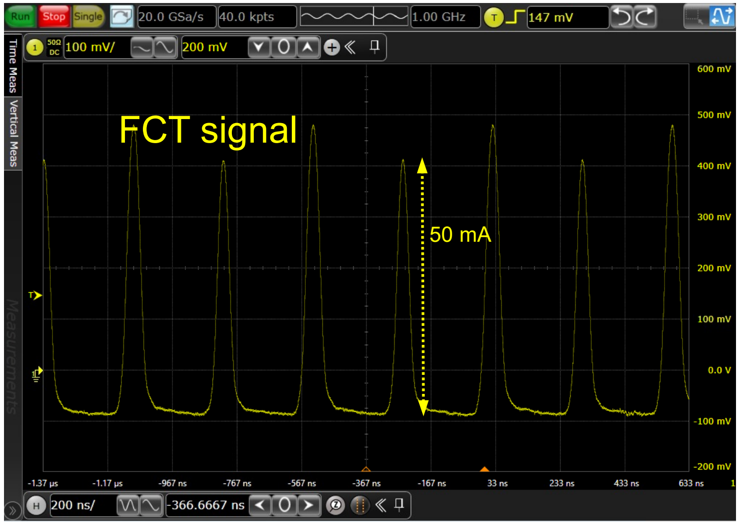
orbit

tune

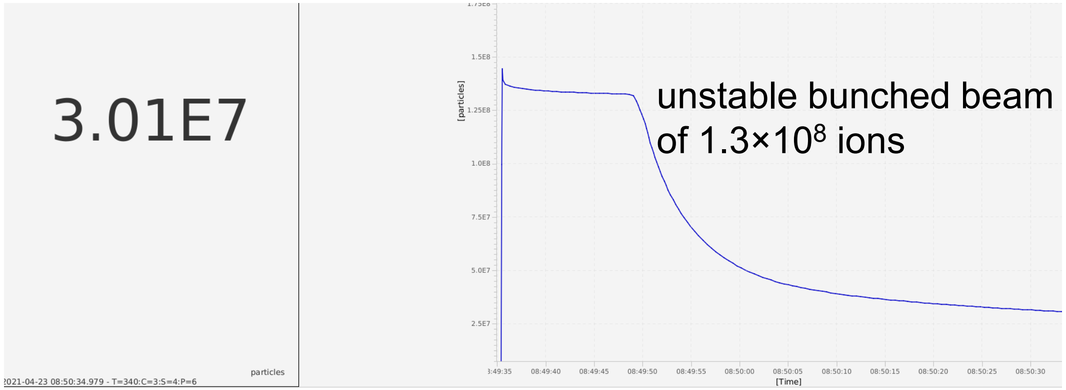
transverse emittances

….and a lot of machine development time

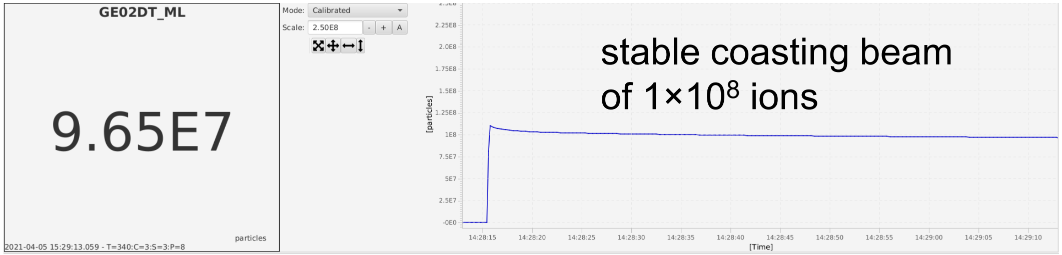
Intensity Issues during Deceleration



two cooled bunches U^{89+}at 300 MeV/u with peak current 50 to 60 mA



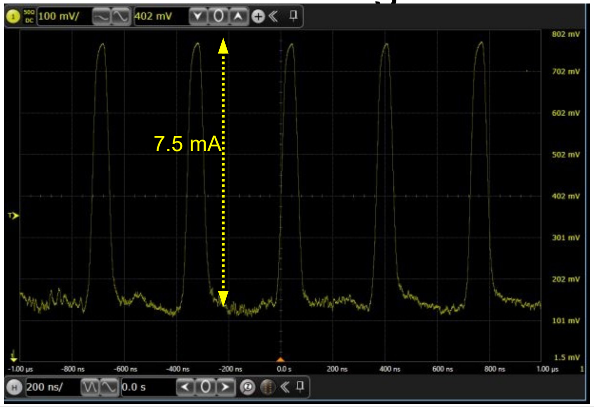
unstable bunched beam of 1.3×10^8 ions



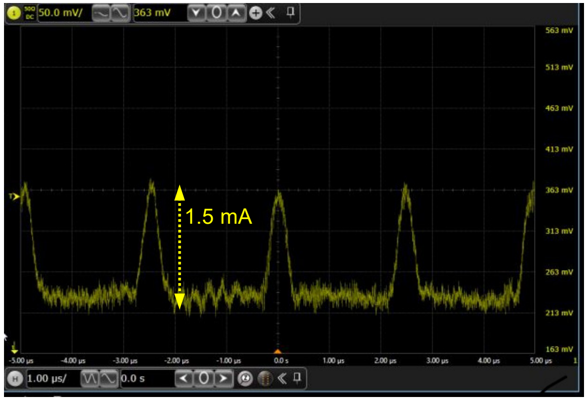
stable coasting beam of 1×10^8 ions

bunches during deceleration of Ag^{47+}

4 cooled bunches
at 30 MeV/u
dc current 0.55 mA

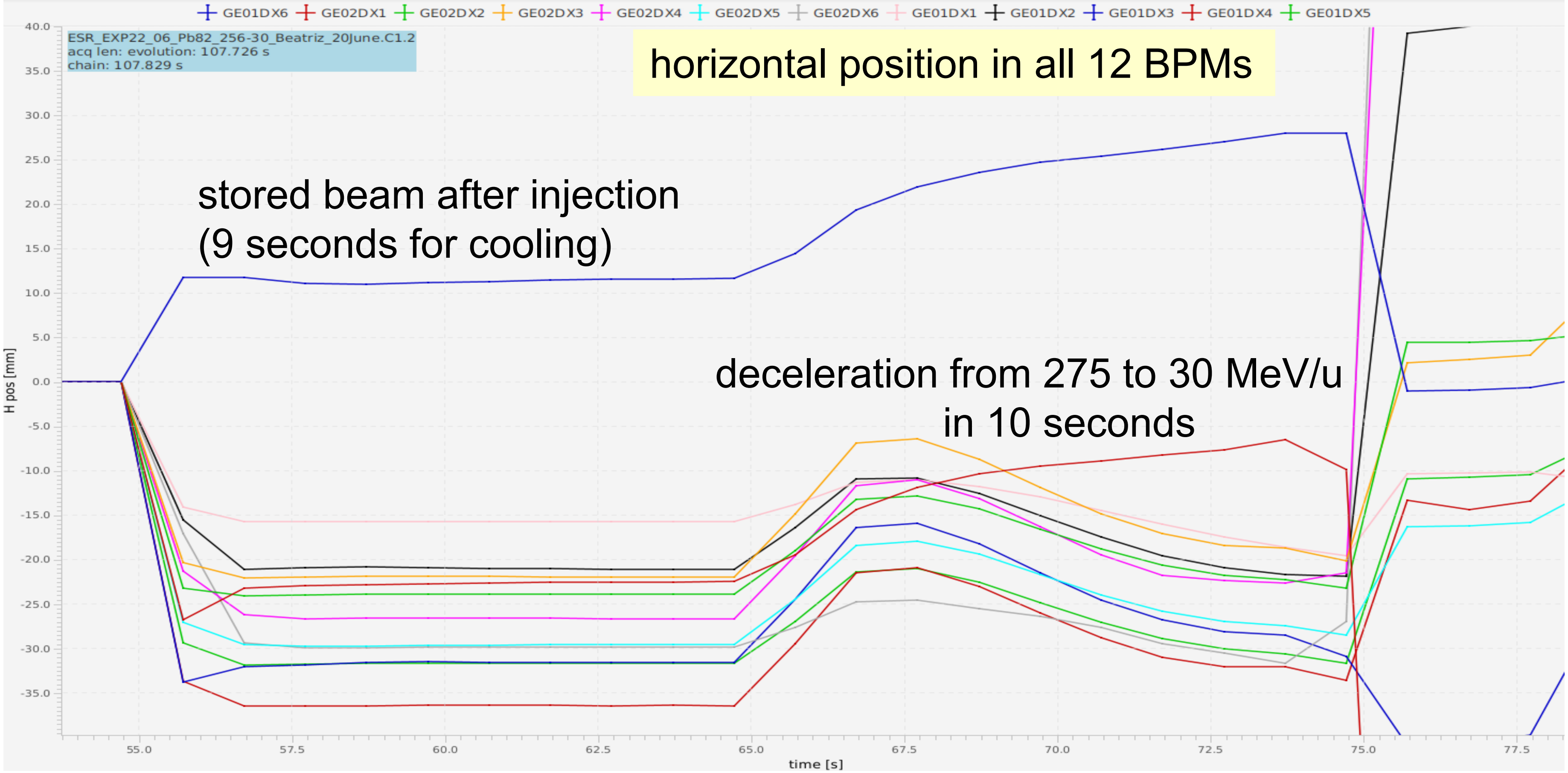


single cooled bunch
at 10 MeV/u
dc current ~0.05 mA



Orbit during Deceleration

change of position during deceleration cycle Pb^{82+} from 275 to 30 MeV/u



horizontal position in all 12 BPMs

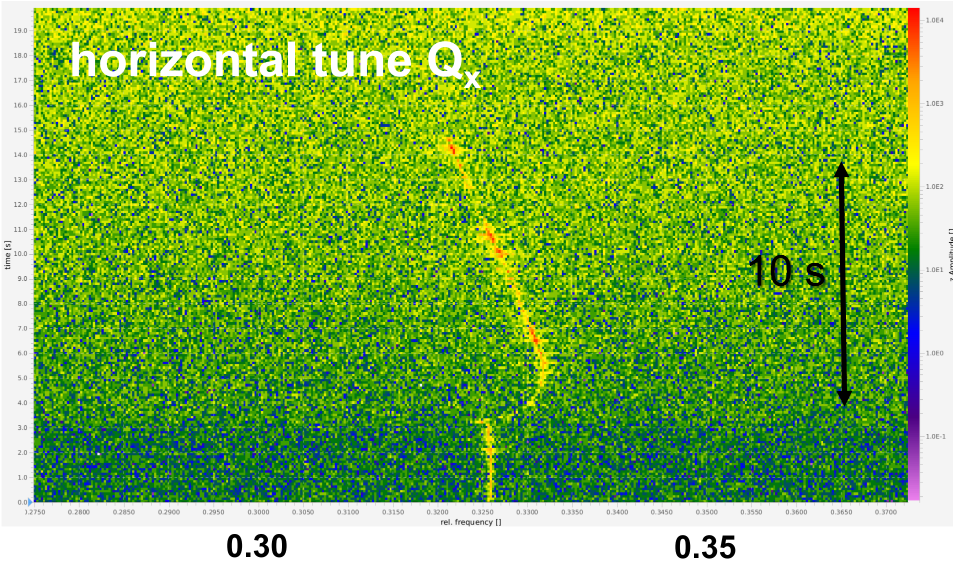
stored beam after injection
(9 seconds for cooling)

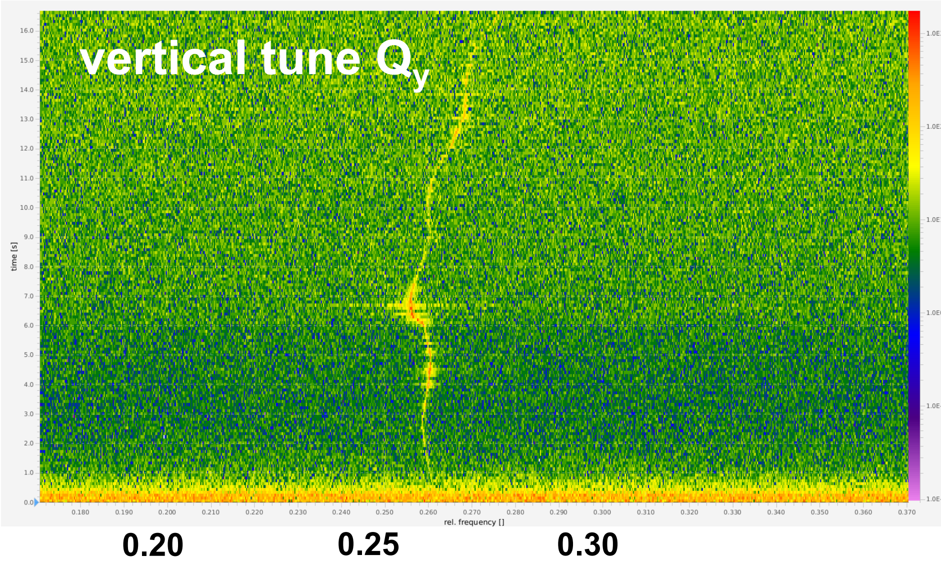
deceleration from 275 to 30 MeV/u
in 10 seconds

Tune during Deceleration

deceleration of Ni^{28+} from 45 to 4 MeV/u (for HITRAP)

excitation of bunched beam with transverse exciter (synchronized with rf frequency)
intensity: a few 10^7 particles

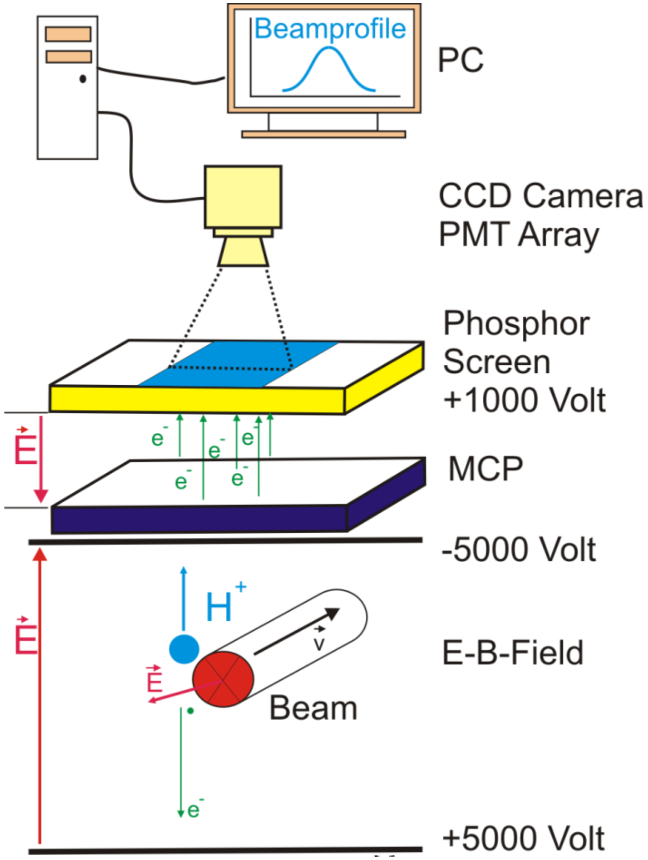




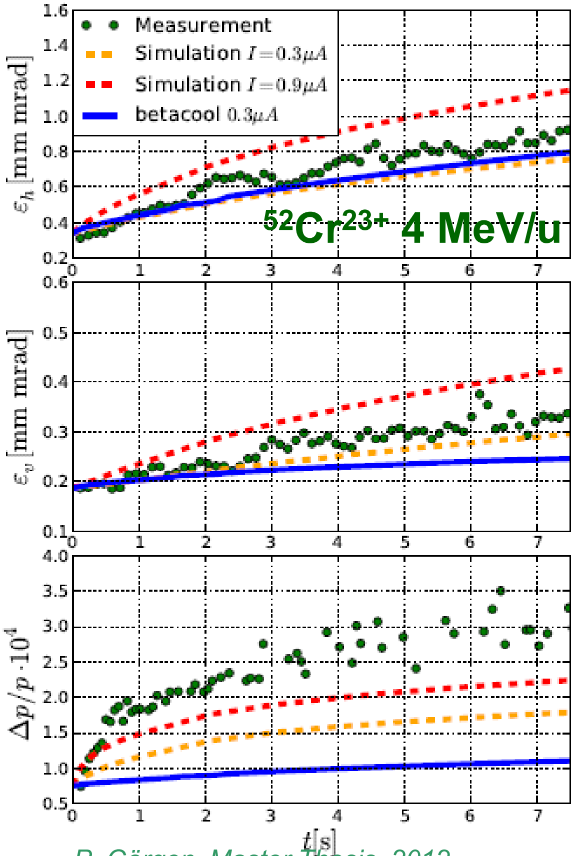
non-integer part of tune

Transverse Beam Emittance

Residual Gas Ionization Beam Profile Monitor



Growth of Beam Emittance due to Intrabeam Scattering



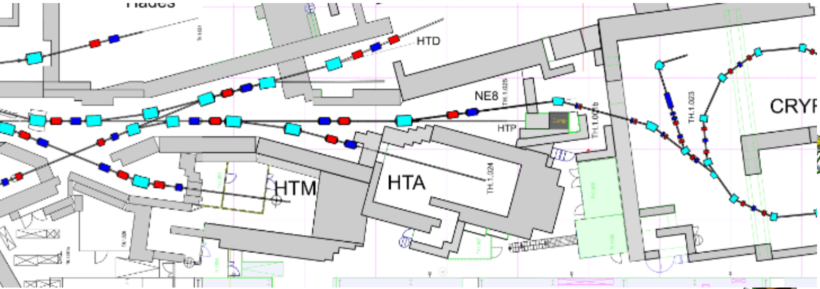
P. Görgen, Master Thesis, 2012

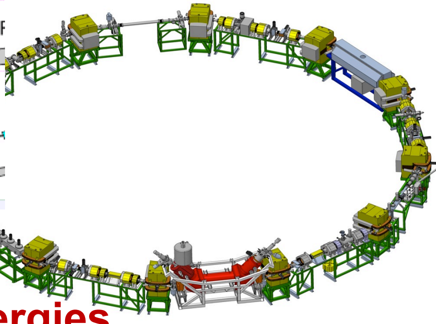
stronger (faster) cooling results in faster IBS heating

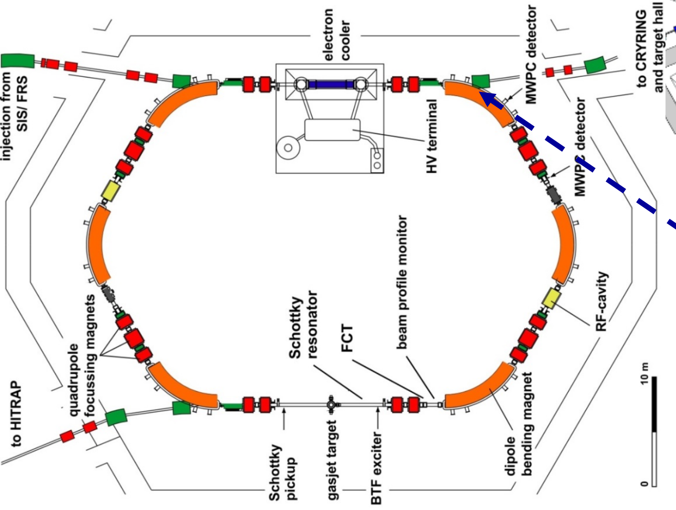
for highly charged ions IBS is expected to scale with Q^4/A^2
⇒ highly charged uranium heats up 10 times faster than Cr^{23+}

Similar observations are reported from LEIR at CDRN with Pb^{53+}at 4.2 MeV/u: heating time of order of 10 ms

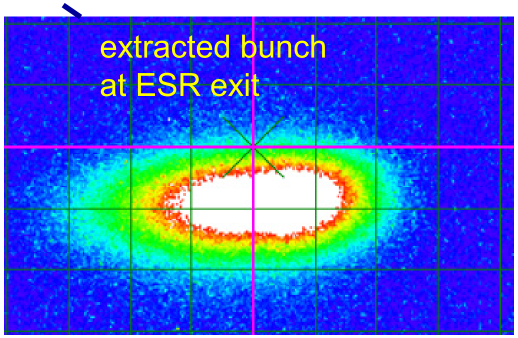
Fast Extraction
from ESR to CRYRING@ESR



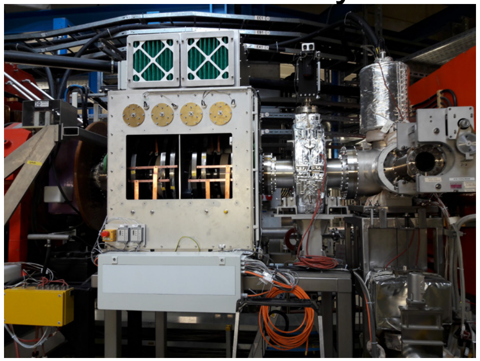




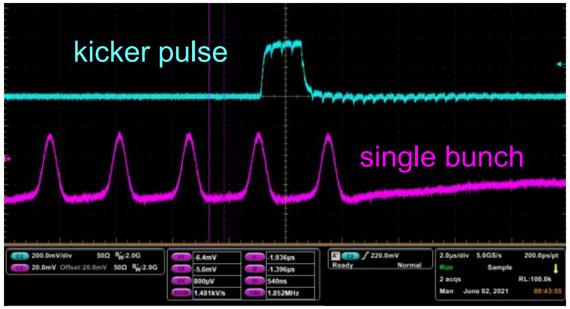
**goal: stored, cooled
highly charged ions at lowest energies**



new barrier bucket rf system



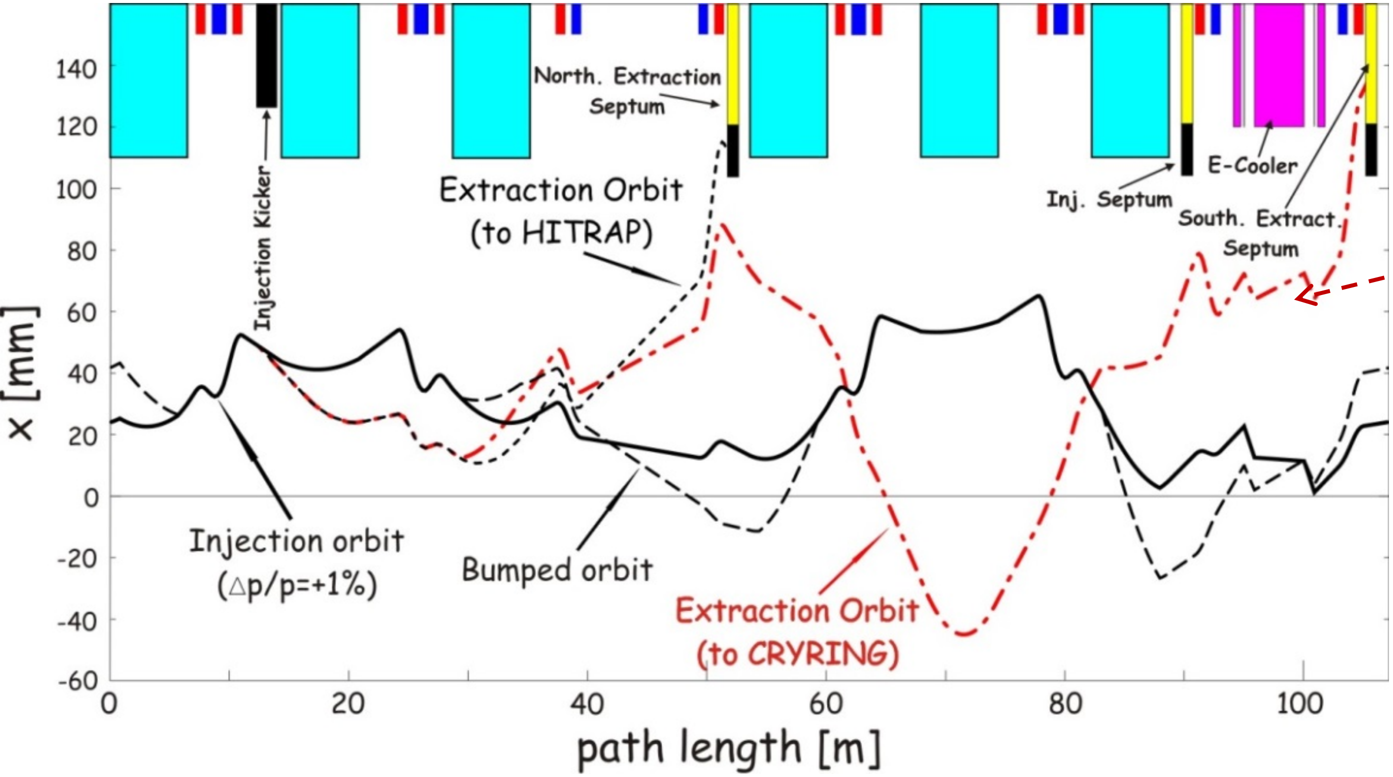
ESR decelerates cooled highly charged ions or rare isotope beams from 400 MeV/u to 4-14 MeV/u



single cooled bunch
before extraction from ESR
compressed by
new barrier bucket rf system

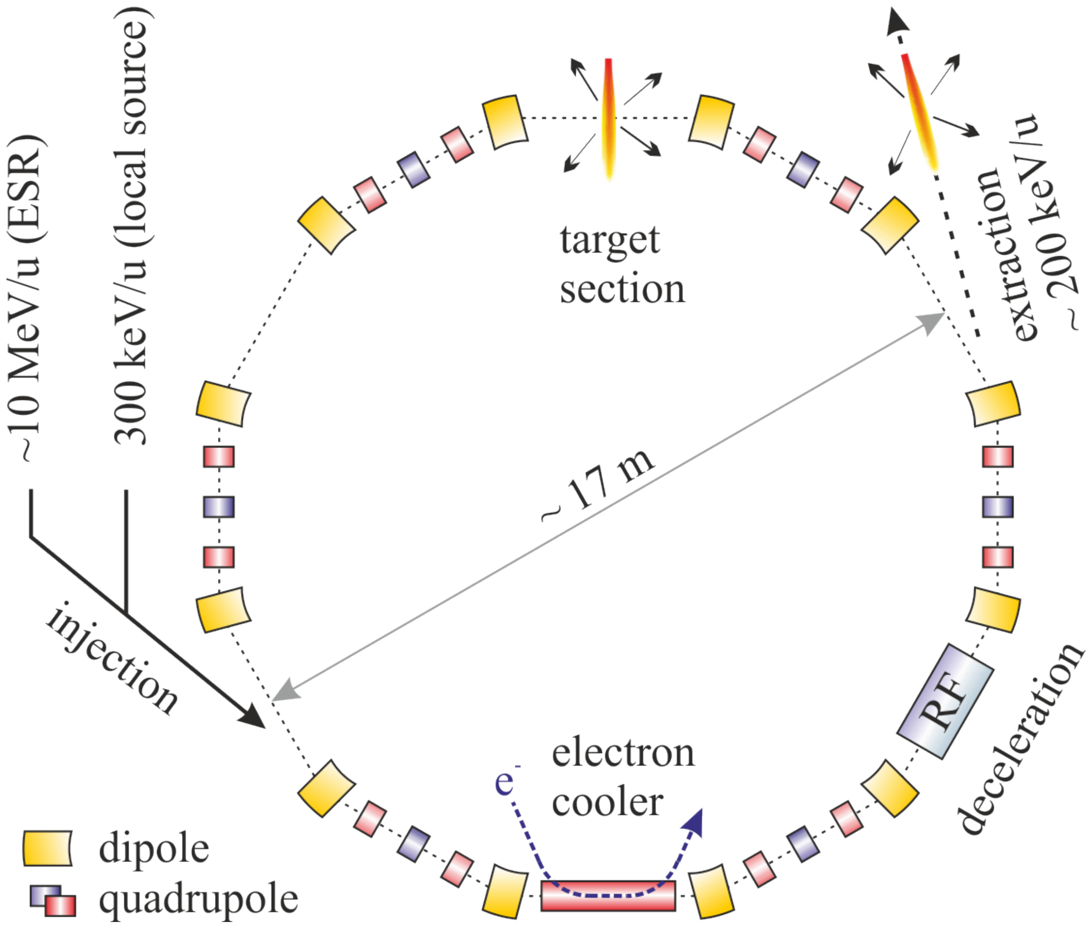
Fast Beam Extraction from ESR to CRYRING

fast beam extraction from ESR to CRYRING is employing a sophisticated scheme with a distorted closed orbit for the circulating beam before extraction to CRYRING
consequence: cooling is difficult during extraction, risk of unacceptable heating and emittance growth, particularly for highly charged ions
(expensive remedy: additional kicker in the northern arc)

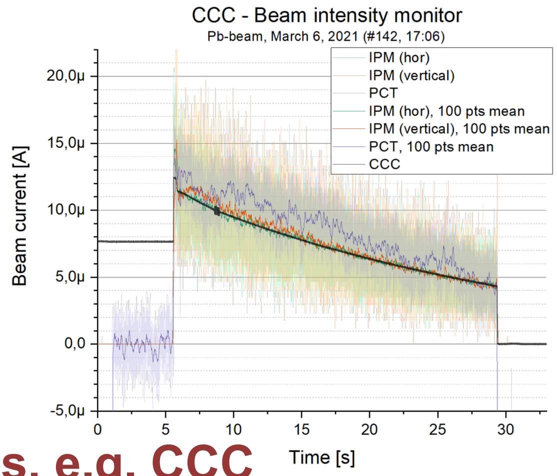


angle in the electron cooling section hampers good cooling

CRYRING@ESR Parameters



Circumference	54.17 m (ESR/2)
Vacuum pressure	10^{-11}-10^{-12} mbar
Ion energy	< 300 keV/u - 14 MeV/u
Rigidity for ions	0.054 - 1.44 Tm
Magnet ramping	1 T/s (4 T/s, 7 T/s)
Stand-alone operation	local ion beam (300 keV/u, q/A > 0.25)
Beam injection	multiturn and fast
Beam extraction	slow and fast

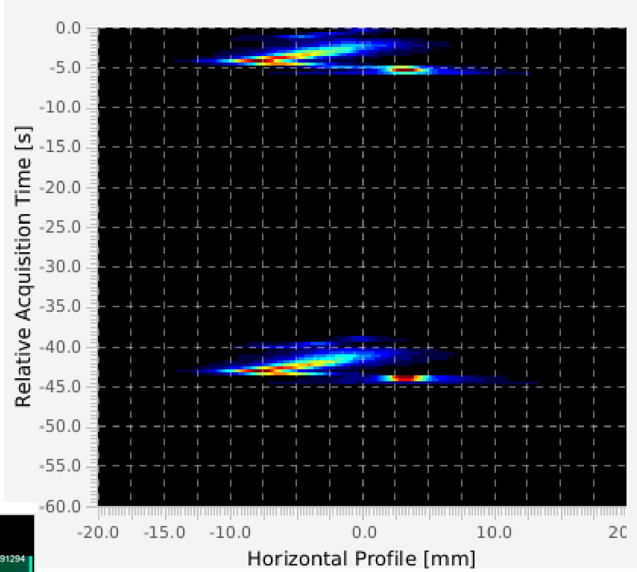


test bed for new controls and advanced components, e.g. CCC

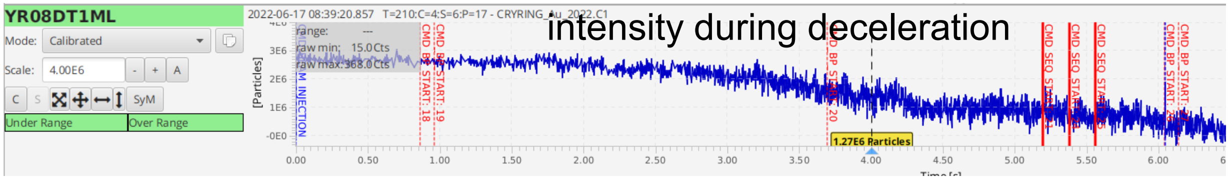
Deceleration of HCI in CRYRING@ESR

Pb^{82+} injected with 10 MeV/u from ESR

beam profile
during deceleration



decelerated in CRYRING@ESR to 2 MeV/u

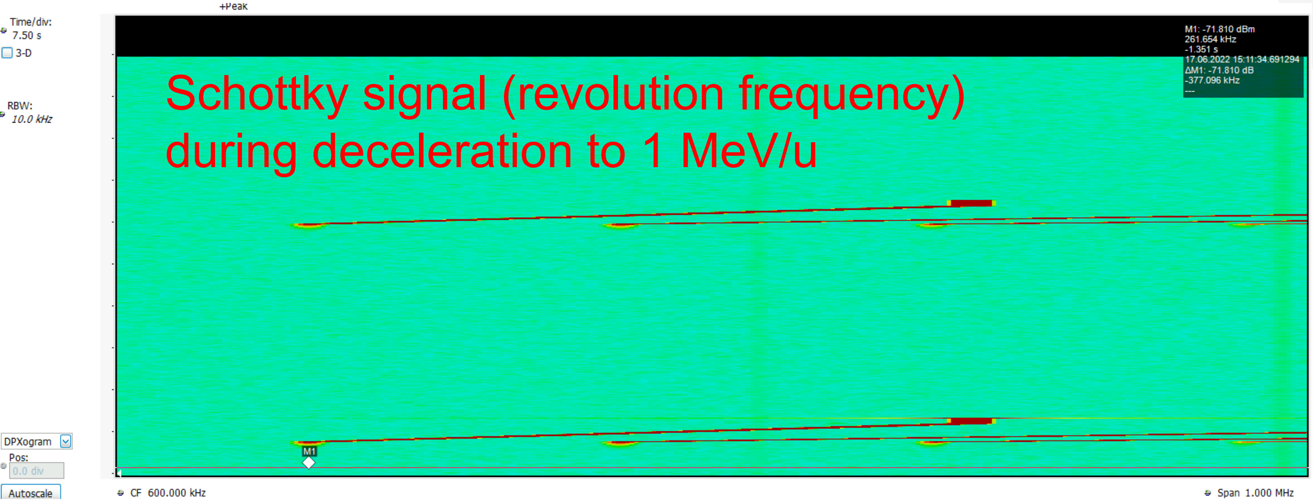


intensity during deceleration

10 MeV/u
3×10^{6} particles

2 MeV/u
5×10^{5} particles

1 s electron cooling -> at injection energy **2 s deceleration ->** **1 s electron cooling at lower energy**



Schottky signal (revolution frequency)
during deceleration to 1 MeV/u

Deceleration is a Complex Interplay

initial or intermediate cooling (stochastic ↔ electron cooling)

- determines cooling time and beam emittances

ramp rate and consequently cycle time

- is linked to orbit and tune variation which determine losses
- is linked to rf amplitude which determines bunching factor (local beam current)
- determines losses due to vacuum
- can be limited by power supplies (in particular, if electron cooling is employed)

intermediate and final cooling

- damps unwanted growth of emittance as a result of deceleration
- can result in space charge effects (at low energy)
- cooling time should be shorter than beam lifetime

The optimization of a deceleration cycle is aiming at balancing the beneficial and adverse effects of the various deceleration parameters

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