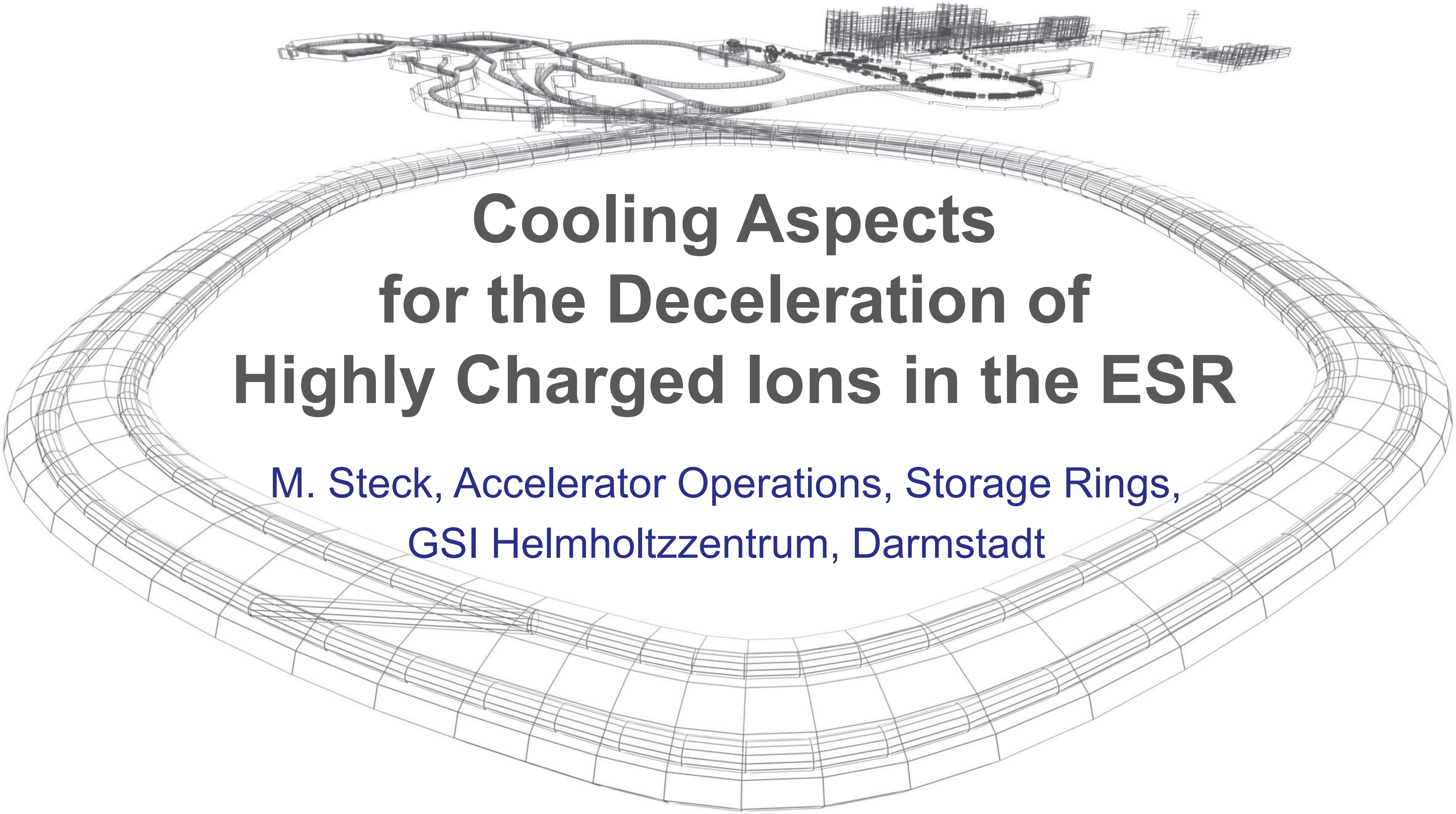
GSI Helmholtzzentrum für Schwerionenforschung GmbH



Cooling Aspects for the Deceleration of Highly Charged Ions in the ESR

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

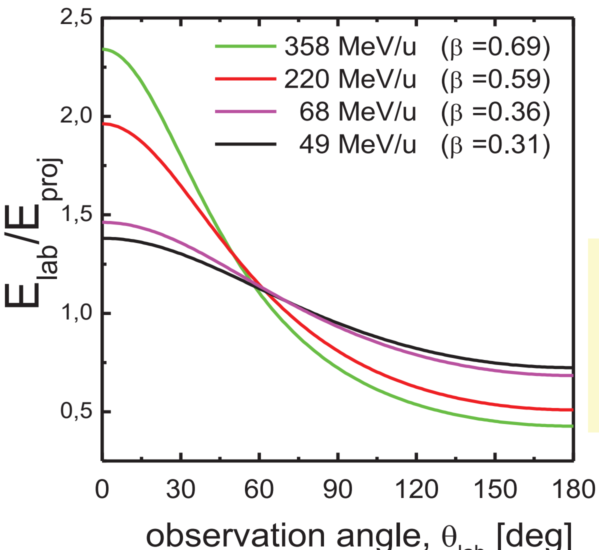
Decelerated Beams for Atomic Physics

relativistic Doppler transformation

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

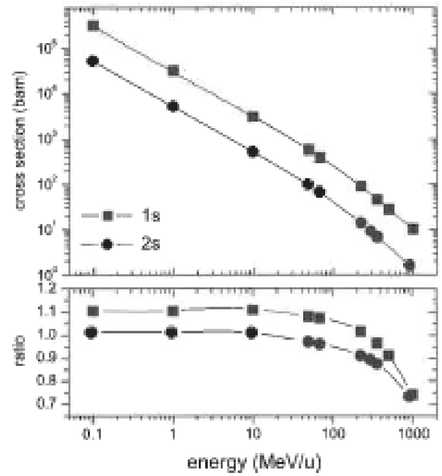
relativistic transformation of solid angle:

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



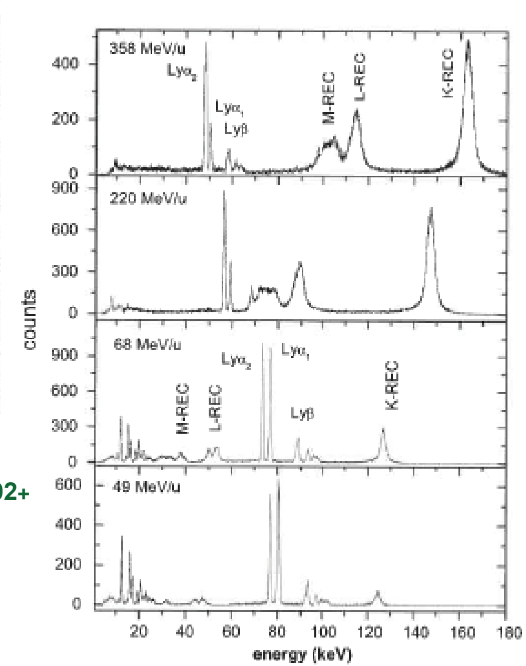
E_{lab}: photon energy im lab system

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

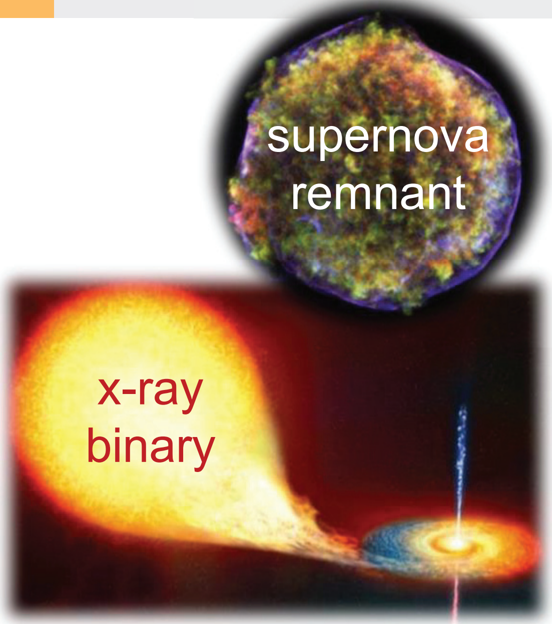
deceleration reduces:

- dependence on velocity and observation angle θ_{lab}

deceleration:

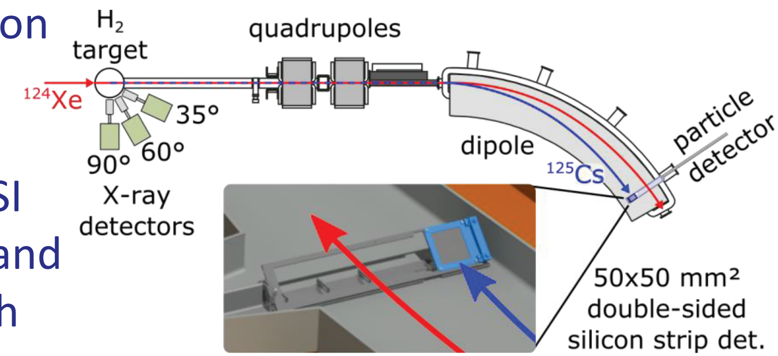
- provides increased reaction cross sections
- opens new reaction channels (transitions, polarization)

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

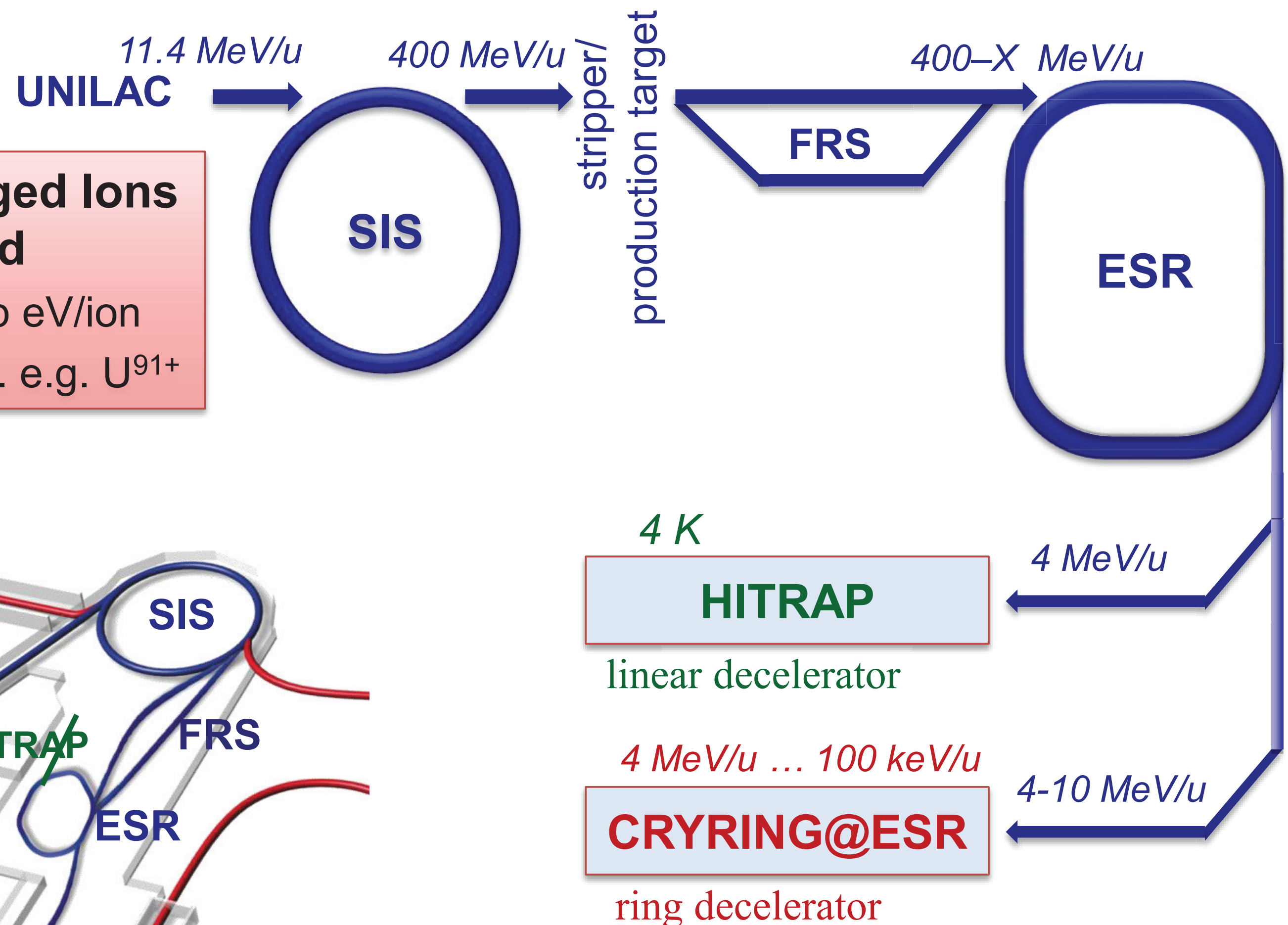
Jan Glorius

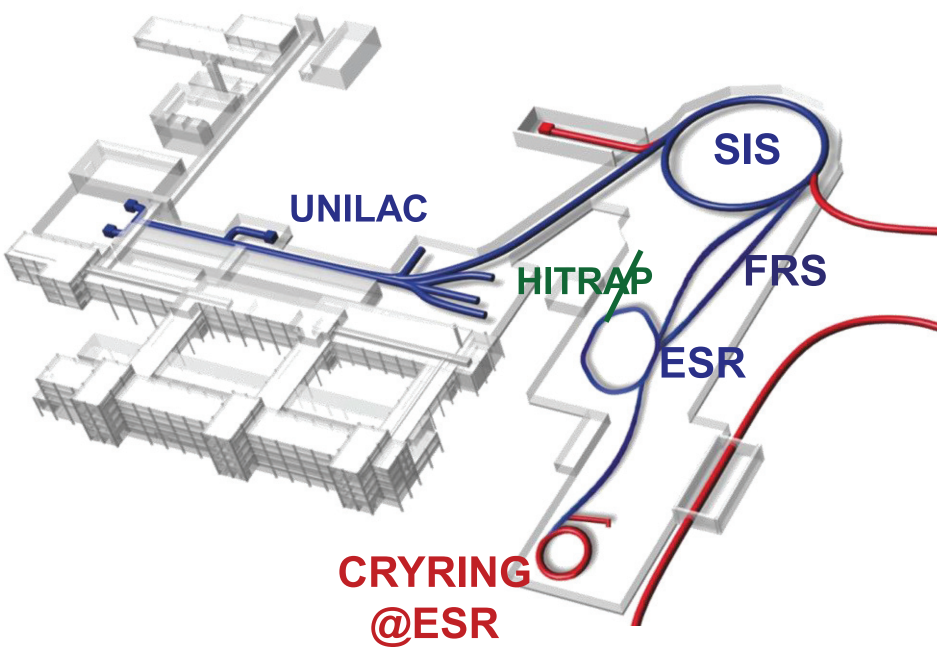
HITRAP and CRYRING@ESR

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+}



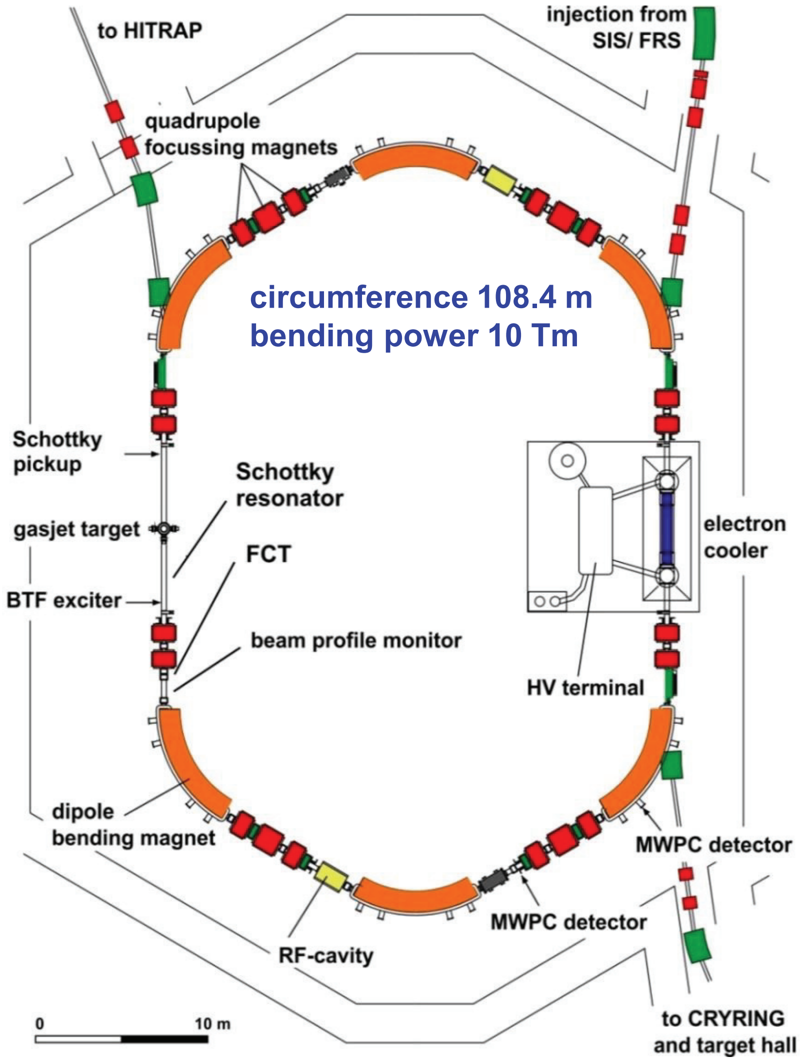


Goals for Deceleration in the ESR

- 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 HITRAP linac
- 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

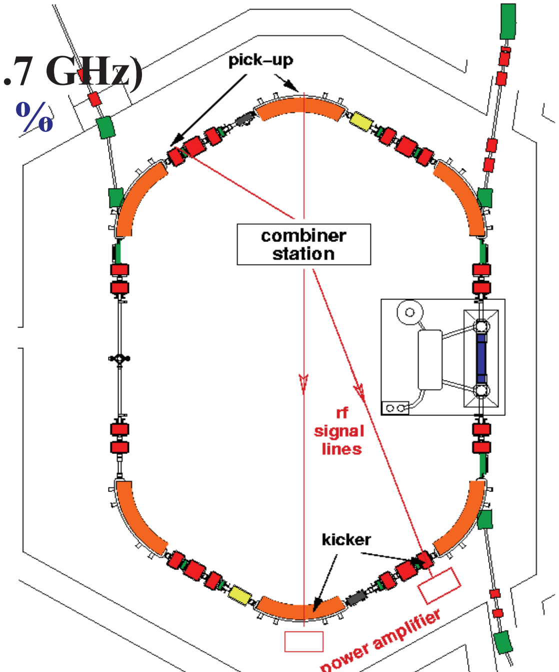


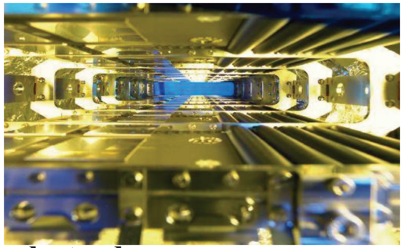
- Fast injection (stable ions / RIBs)
- Stochastic cooling (≥ 400 MeV/u)
- Electron cooling (3 - 430 MeV/u)
- Laser cooling (C^{3+} 120 MeV/u)
- Internal gas jet target
- Deceleration (down to 3 MeV/u)
- Fast extraction (HITRAP/CRYRING@ESR)
- Slow (resonant) extraction
- Ultraslow extraction (charge change)
- Beam accumulation
- 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

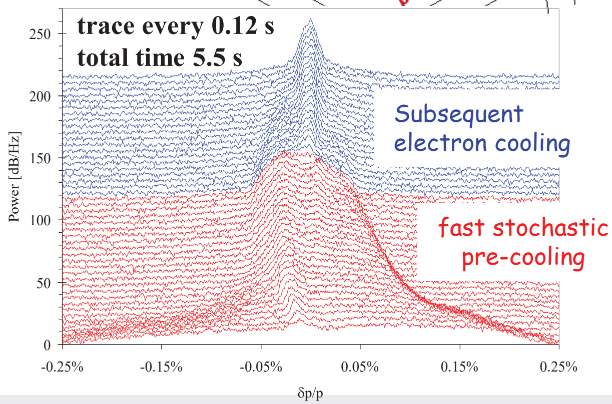
energy <u>400</u> (-550) MeV/u
bandwidth 0.8 GHz (range 0.9-1.7 GHz)
$\delta p/p = \pm 0.35\ \%$ → $\delta p/p = \pm 0.01\ \%$
$\varepsilon = 10\ \mu m$ → $\varepsilon = 2\ \mu m$




electrodes


combiner station


power amplifiers



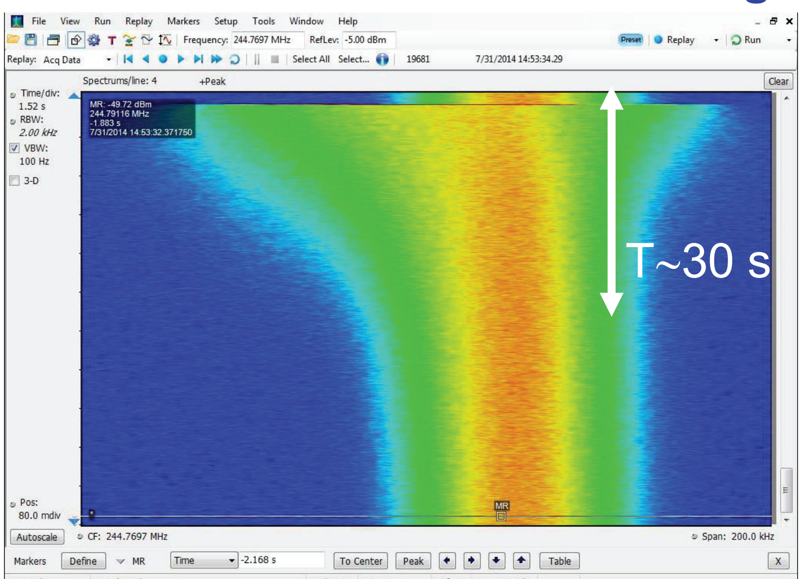
electron cooling

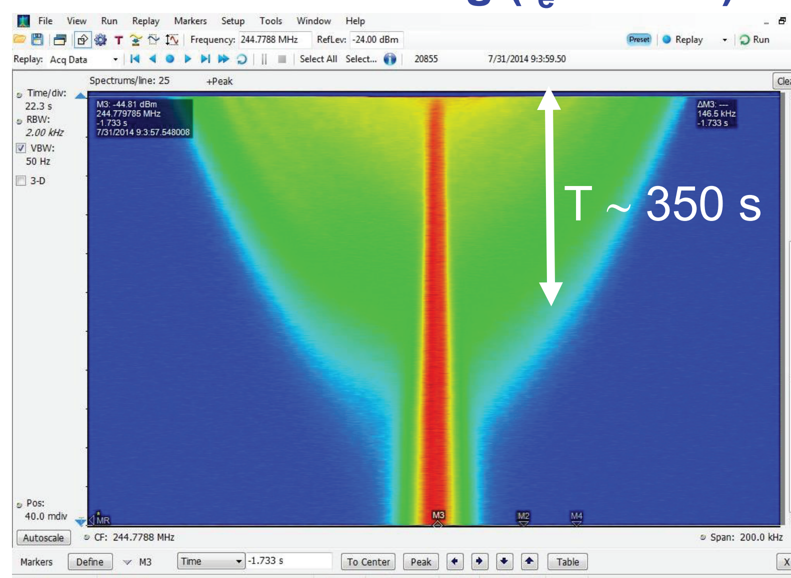
electron energy	1.6 – 250 keV
electron current	0.001 – 1 A
beam diameter	50.8 mm
magnetic field	0.01 - 0.2 T
collection efficiency	0.9998
transverse temperature	0.1 eV
longitudinal temperature	~0.1 meV
vacuum	1×10^{-11} mbar

Cooling after Injection

- The injection energy of the ESR is flexible (30- 500 MeV/u)
- the production rate of highly charged heavy ions increases with energy, but the larger energy reduction conflicts ⇒ the production rate needs to be traded off
- 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 initially faster than electron cooling

protons 400 MeV stochastic cooling **electron cooling (I_e=0.25 A)**





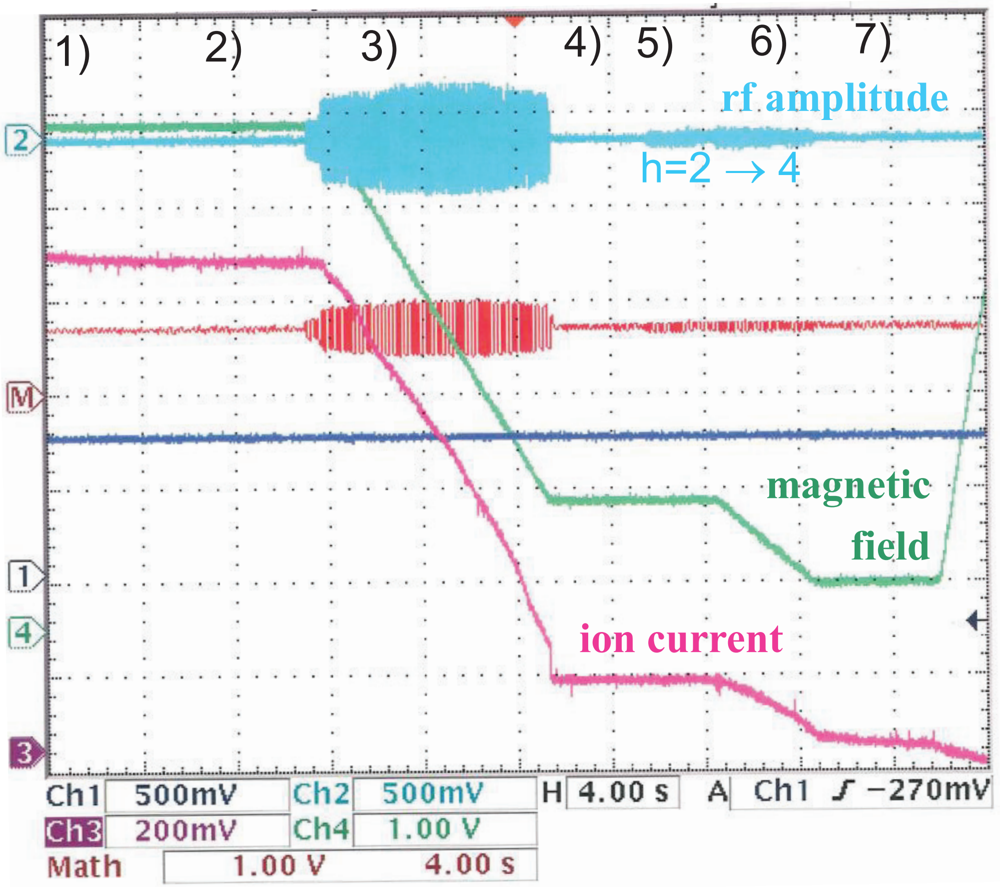
Typical ESR Deceleration Cycle

Ni^{28+} 400 → 30 → 4 MeV/u

1100 µA → 180 µA → 25 µA

45% 37 %

cycle time 45 s

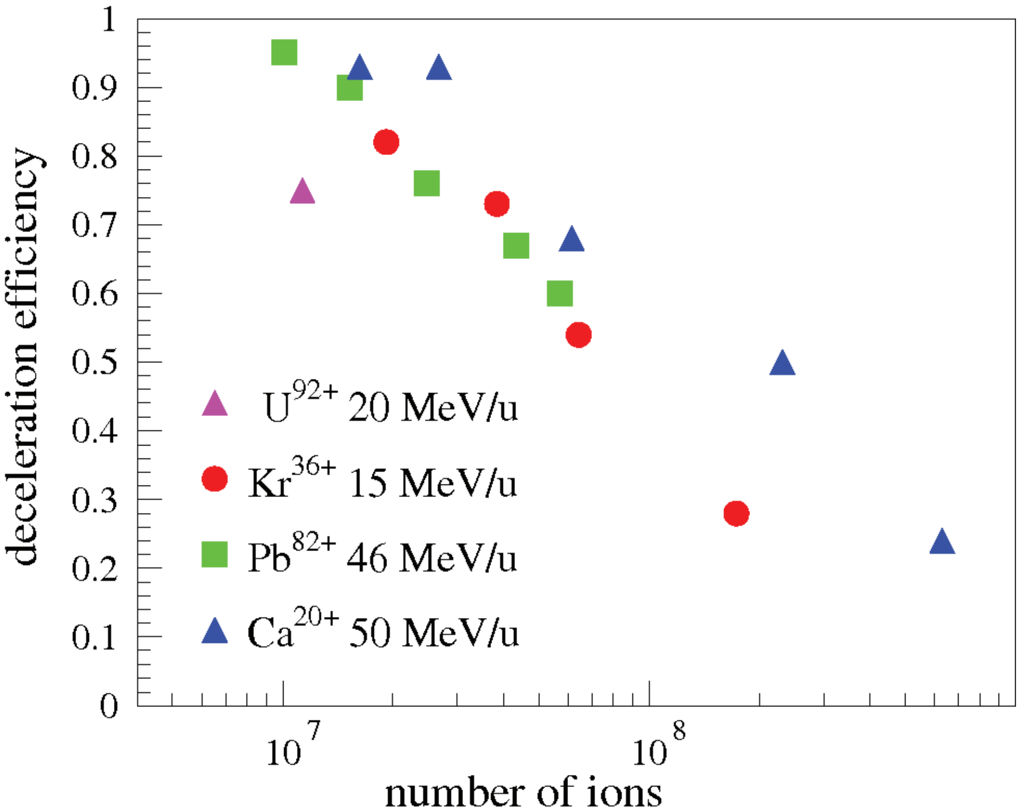


1) injection (at 400 MeV/u)
2) stochastic/electron cooling
 (controlled ramp of cooler HV is difficult)
3) deceleration to 30 MeV/u
4) electron cooling
5) changing rf harmonic 2 → 4
6) deceleration to final energy
7) electron cooling, bunching, extraction

maximum change of p (Bρ): 13

Efficiency of Deceleration

Relative losses increase with increase of the initial stored particle number most likely due to Intrabeam Scattering



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

- no cooling,
- larger emittance of bunched beam

and due to adiabatic emittance growth (α 1/βγ)

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

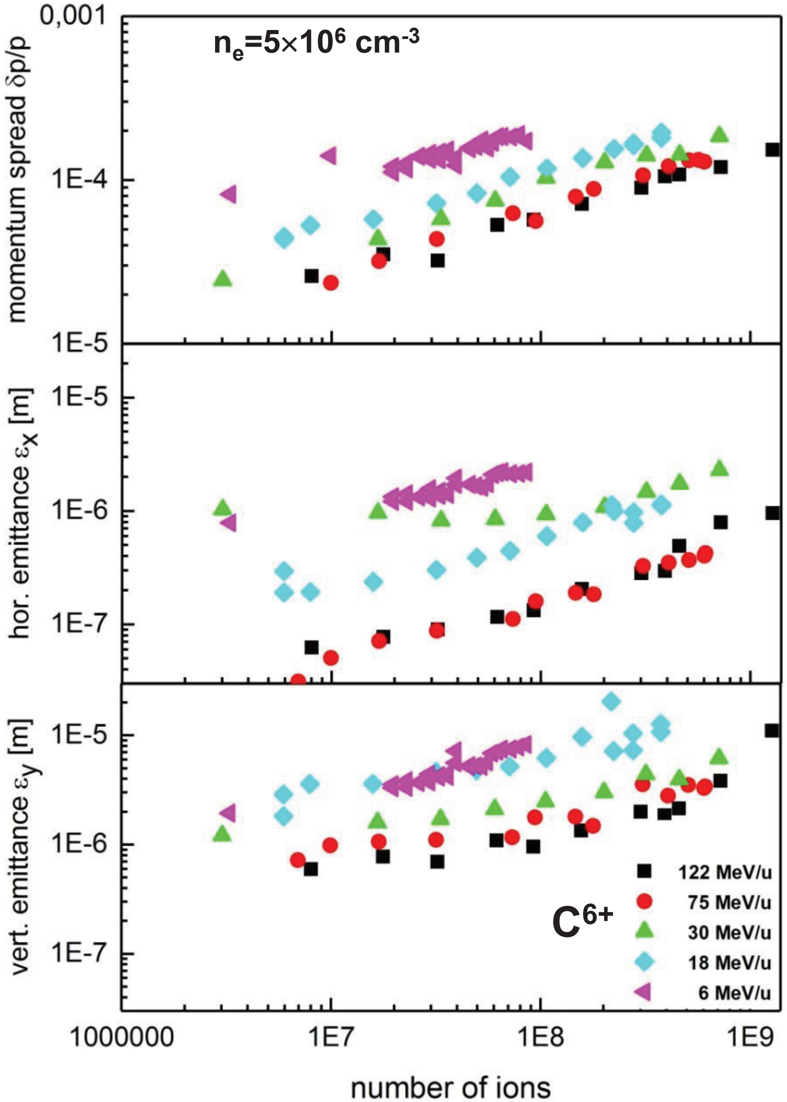
$$\Delta Q_x = \frac{r_p Z^2 N g}{\pi A \beta^2 \gamma^3 B(\epsilon_x + \sqrt{\epsilon_x \epsilon_y Q_x / Q_y})}$$

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

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

lower energies than 15 MeV/u require a change to a higher rf harmonic

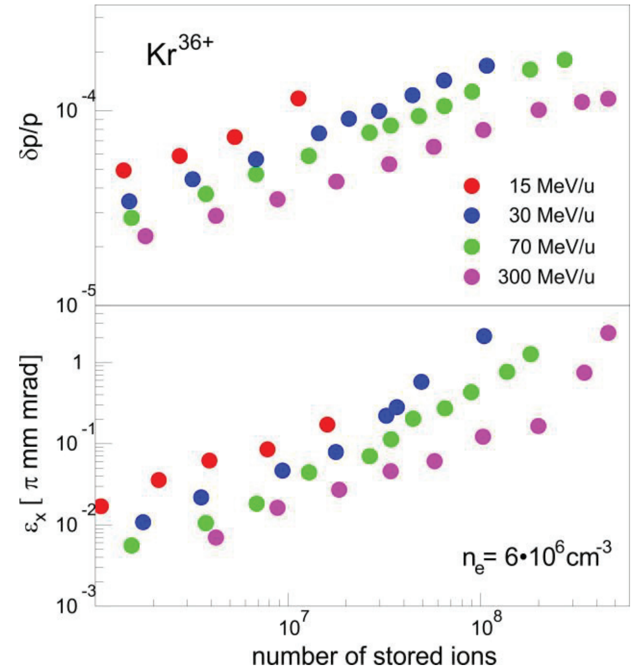
Beam Parameters of Decelerated Ions



Intrabeam Scattering rate

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

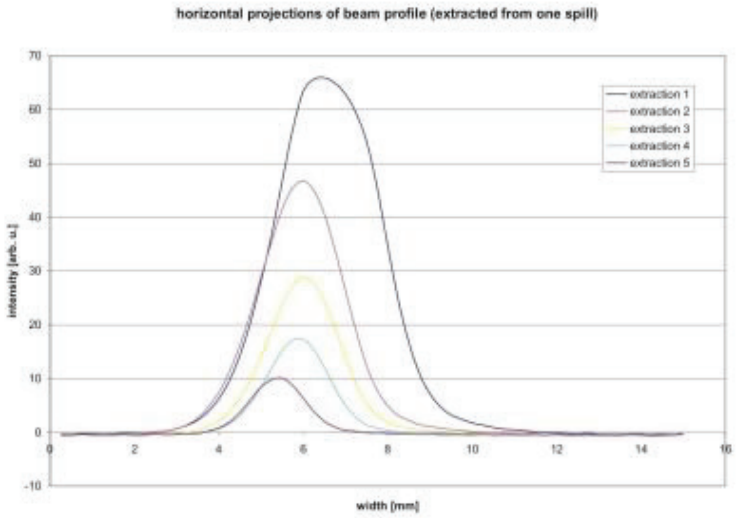
in case of equipartitioning:
emittance increases ≈ proportional βγ



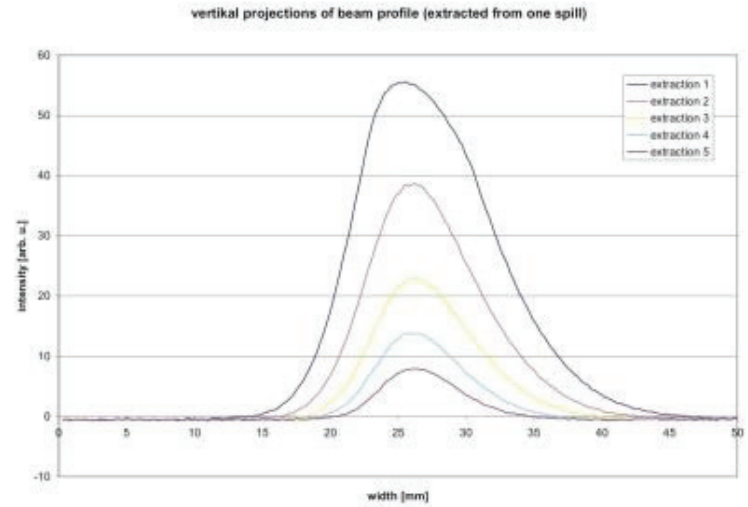
Emittance of Extracted Decelerated Beam

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

horizontal profile



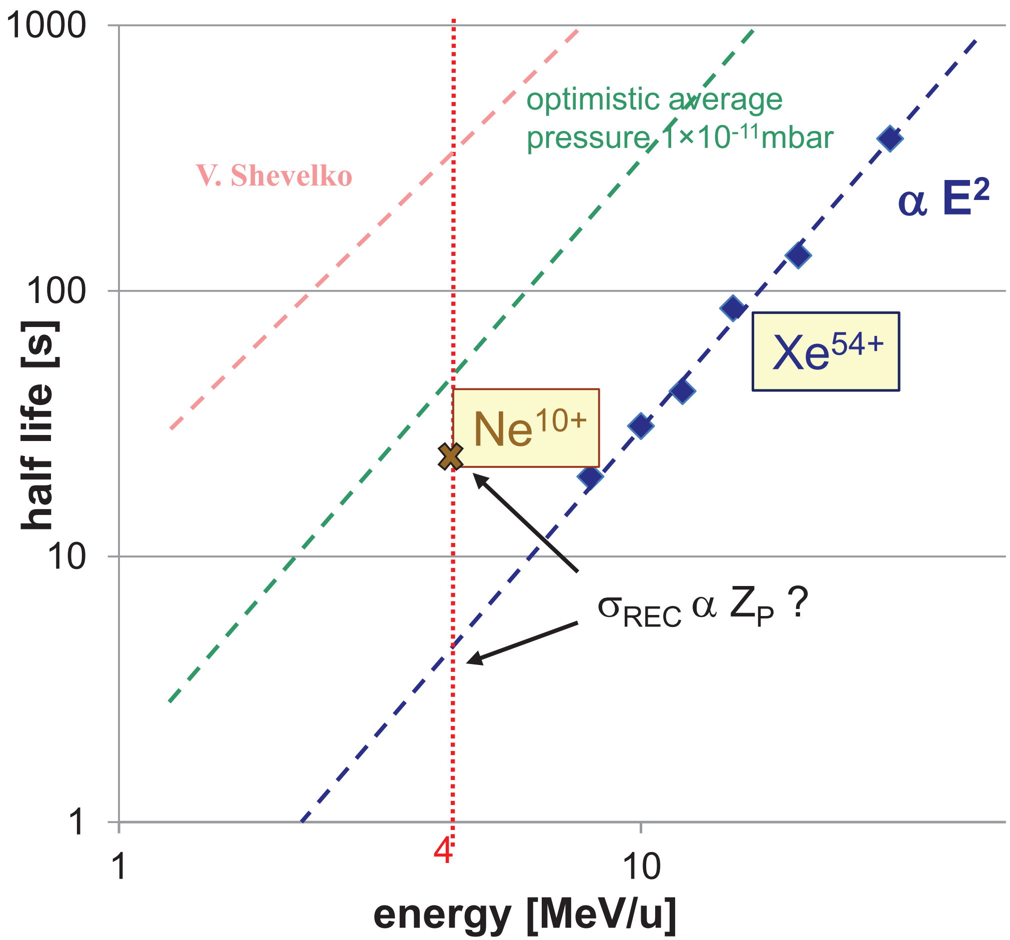
vertical profile



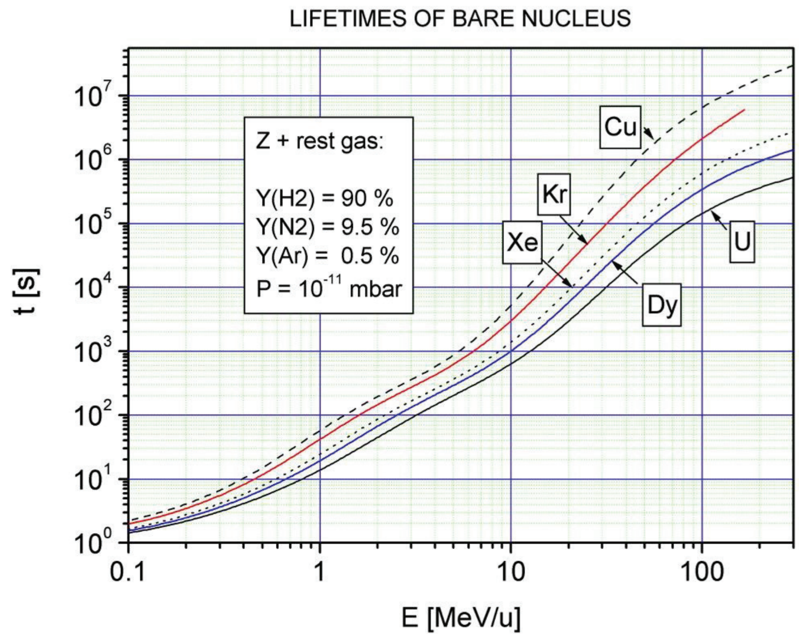
the increase of the beam emittance with intensity due to IBS reflects in the beam size of the extracted cooled beam

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

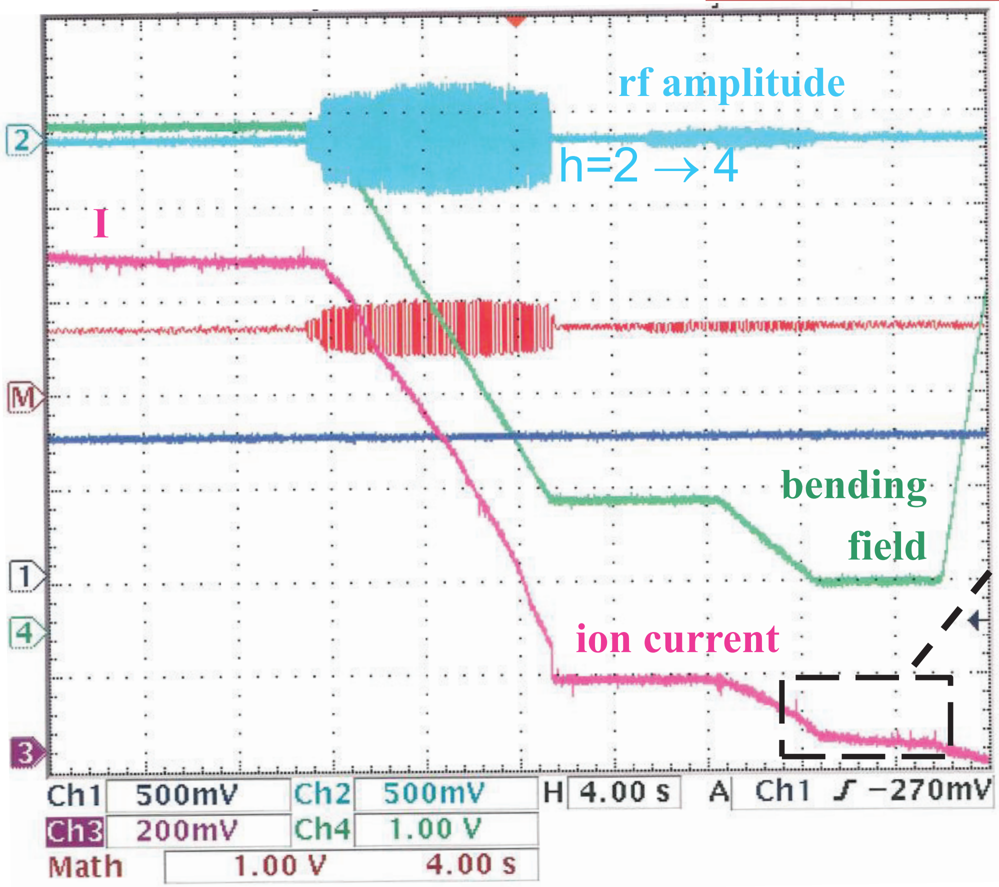
Deceleration to 4 MeV/u

Ni^{28+} 400 → 30 → 4 MeV/u

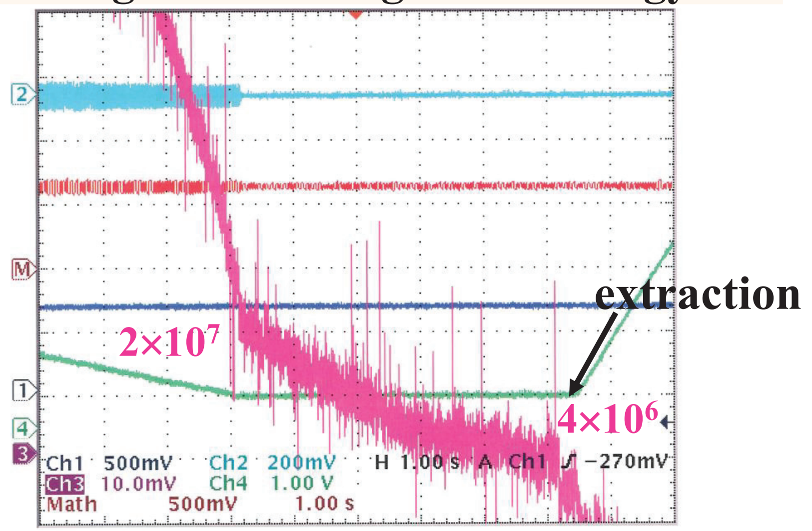
1100 μA → 180 μA → 25 μA

45% 37 %

cycle time 45 s



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

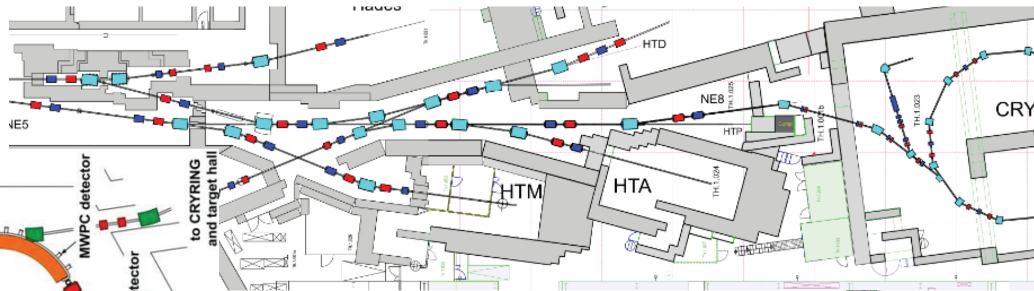


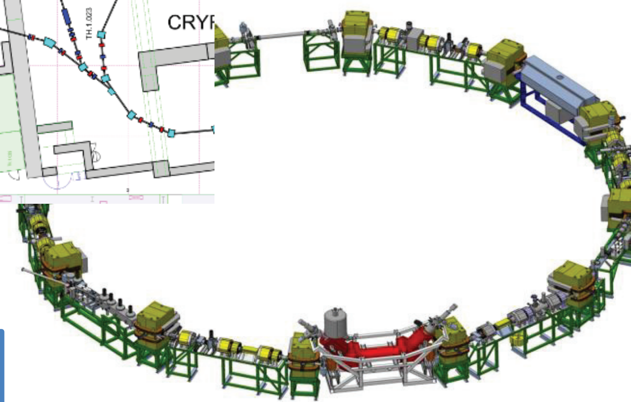
beam half life (vacuum dominated):

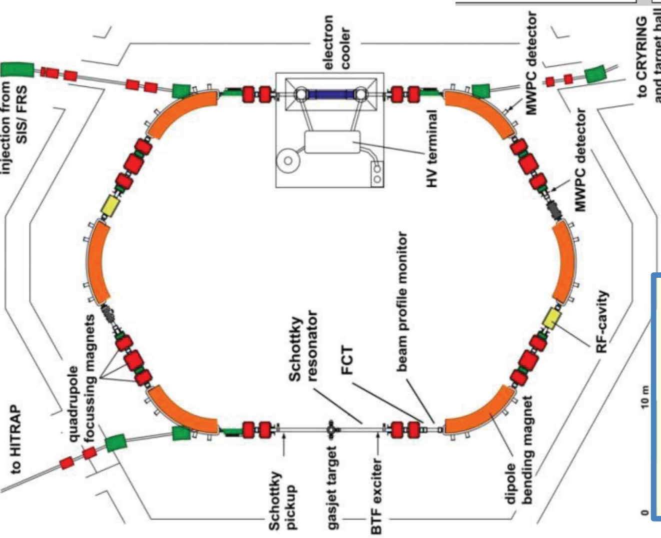
30 MeV/u: $T_{1/2} \approx 480$ s

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

Connecting ESR to CRYRING@ESR



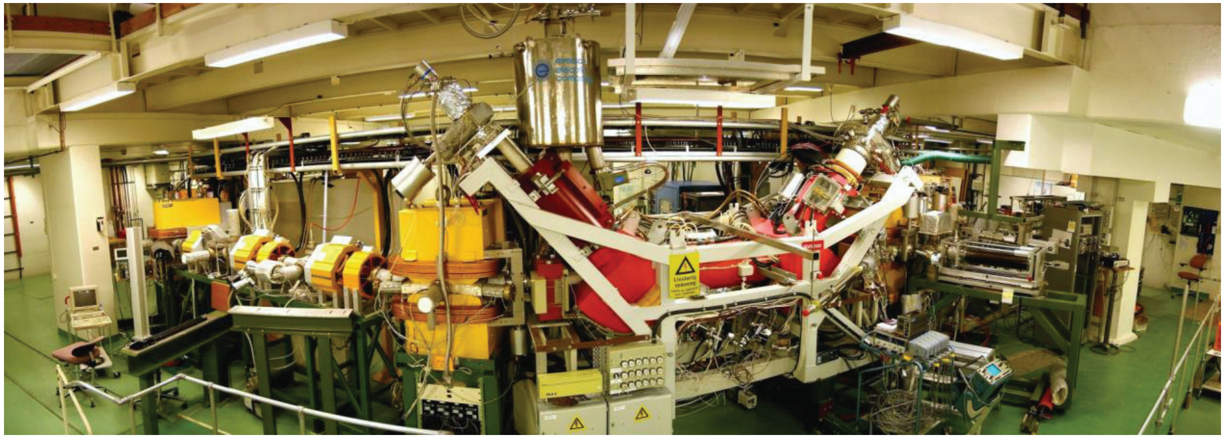




CRYRING
max. rigidity 1.44 Tm 15 MeV/u U^{92+}
min. rigidity ~ 0.054 Tm 21 keV/u U^{92+}
electron cooling with magnetic expansion factor 100

goal:
stored, cooled highly charged ions at lowest energies

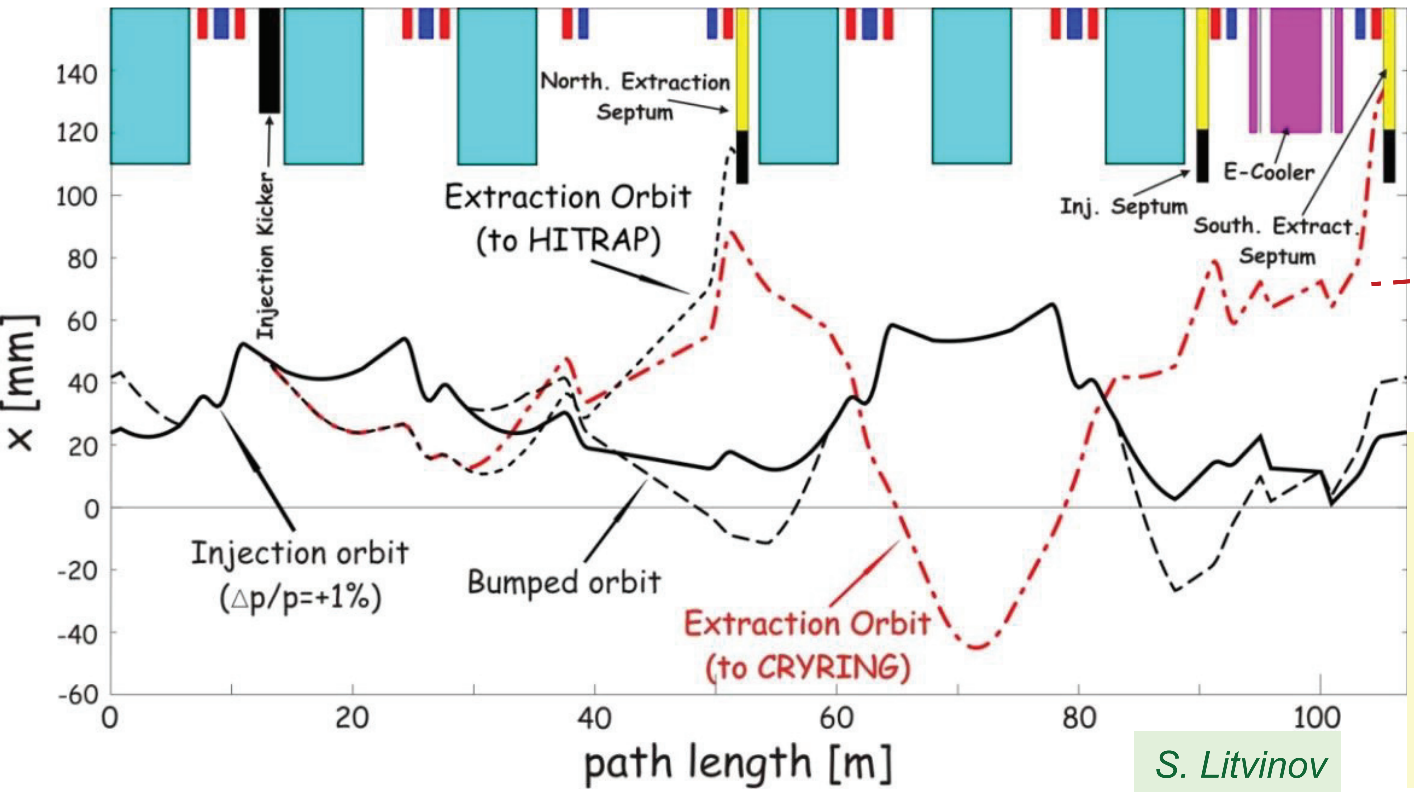
ESR decelerates cooled highly charged ions or rare isotope beams from 400 MeV/u to 4-15 MeV/u



Fast Beam Extraction from ESR to CRYRING

GSI ACC OPERATIONS

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: **no cooling** during extraction, risk of unacceptable heating and emittance growth, particularly for highly charged ions



angle in the cooler does presently not allow cooling

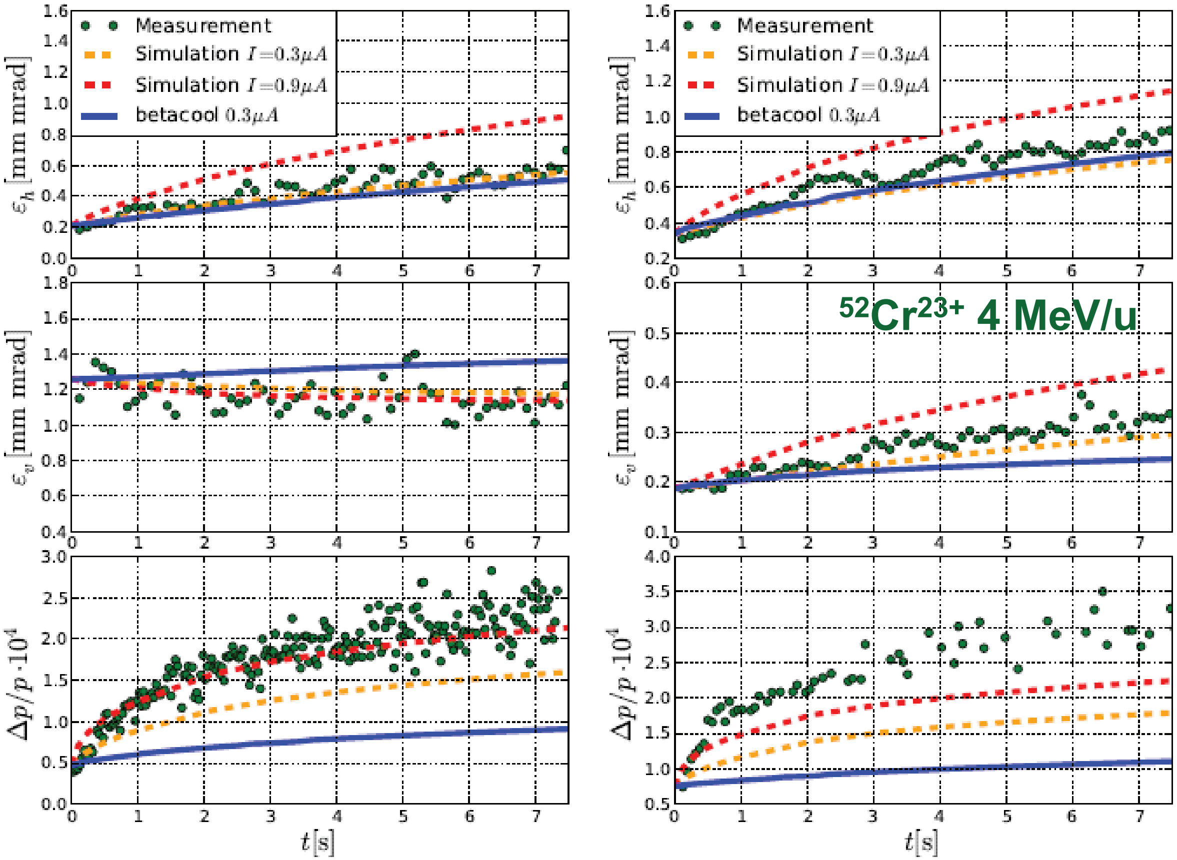
ramped electron orbit operation might solve this problem in the future

expensive remedy: additional kicker in the Northern arc

S. Litvinov

Heating by Intrabeam Scattering

Growth of Beam Emittance due to Intrabeam Scattering



(a) Start from 30mA cooler current

(b) Start from 15mA cooler current

P. Görgen, Master Thesis, 2011

stronger (faster) cooling results in faster IBS heating

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

It is an open issue whether an efficient beam transport from ESR to CRYRING can be achieved with the present extraction mode.

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

Space Charge Limit

Space charge limit due to incoherent tune shift

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

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

at 4 MeV/u, for ΔQ_x=0.1 and ε_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

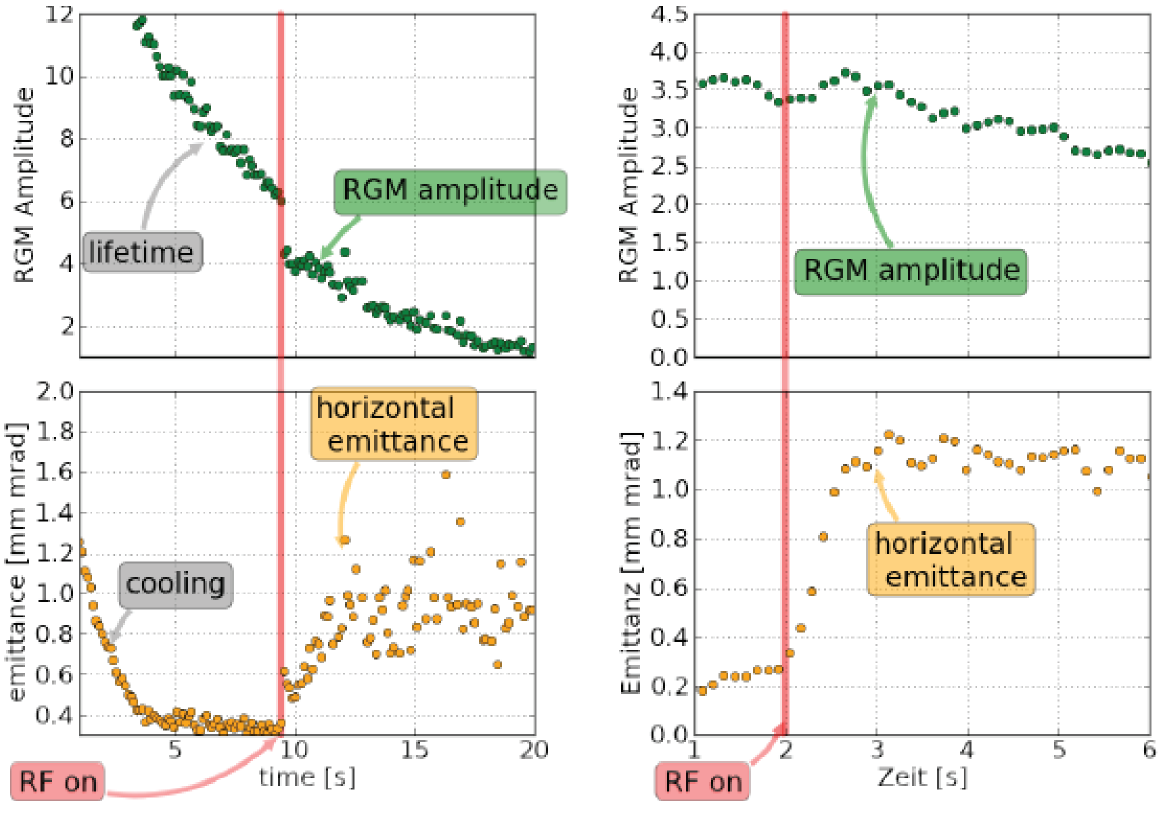
Bunched (≤ 1μs, B=1/5): Ne^{10+}: 4×10^7
Kr^{36+}: 1×10^7
U^{92+}: 5×10^6

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

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

Loss during Bunching a Low Energy Beam

Growth after Bunching the Cooled Coasting Beam

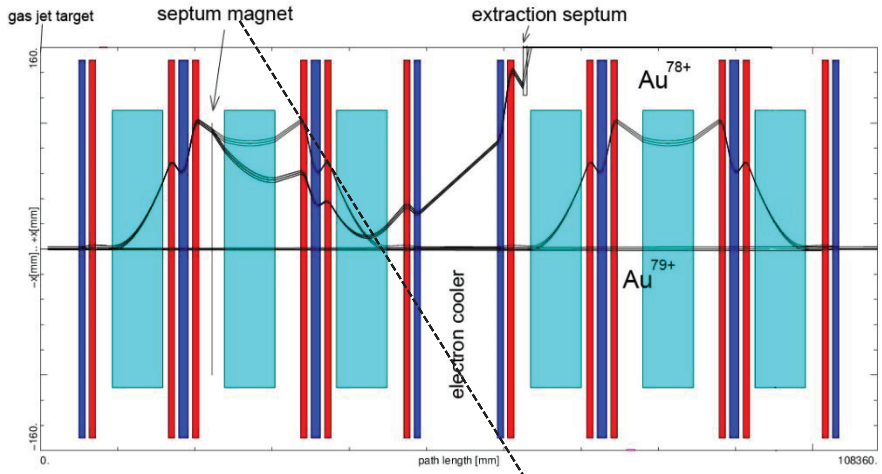


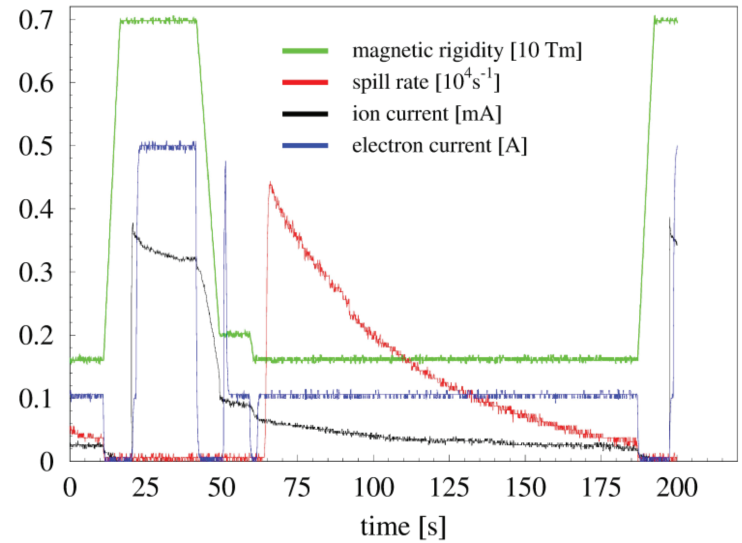
(a) Beam loss: bunching of ${}^{40}_{18}Ar^{18+}$ (b) No beam loss: bunching of ${}^{52}_{24}Cr^{23+}$

P. Görgen
Master Thesis, 2011

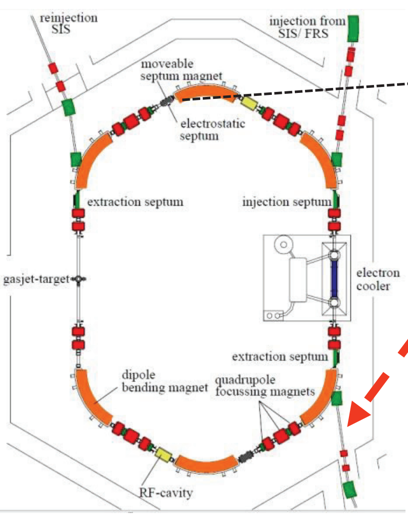
⇒ Precise control of cooling, tune and rf amplitude down to small values

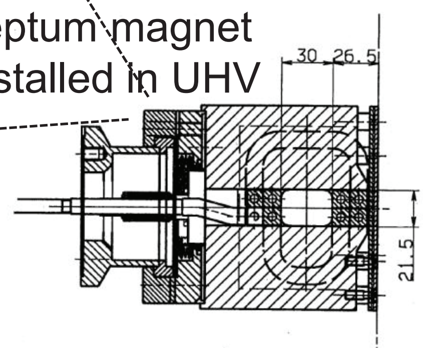
Slow Extraction by Charge Change



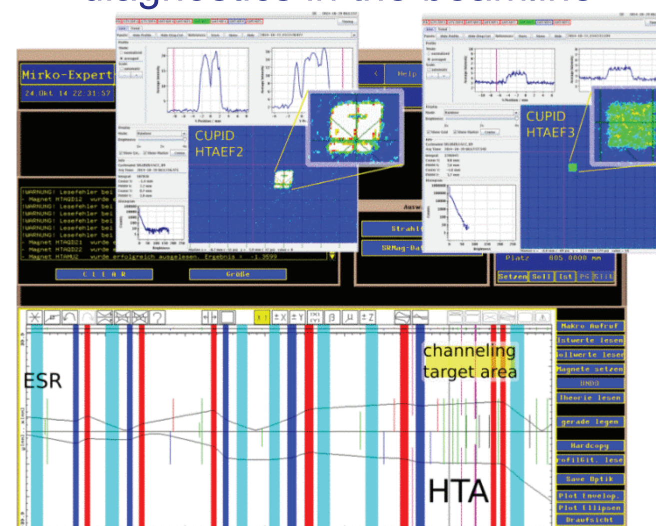


septum magnet
installed in UHV





diagnostics in the beamline



extracted cooled beam
after deceleration (to ≥ 10 MeV/u)
small emittance
good control of extraction rate
extraction time minutes to hours

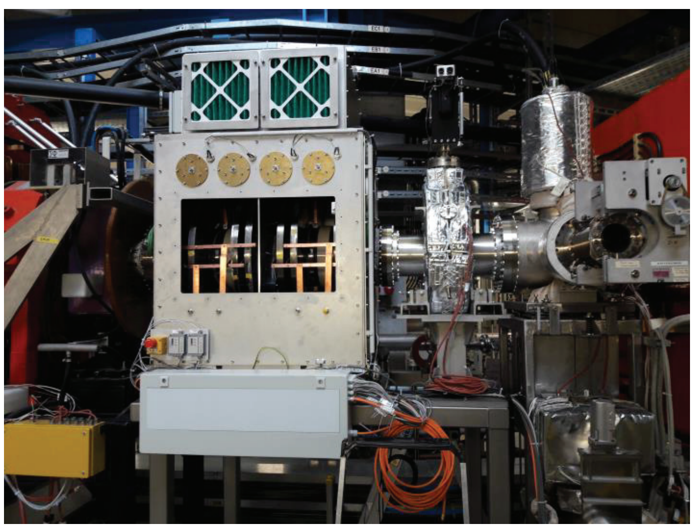
Additional Options

cooling in the storage ring allows accumulation of higher beam intensity

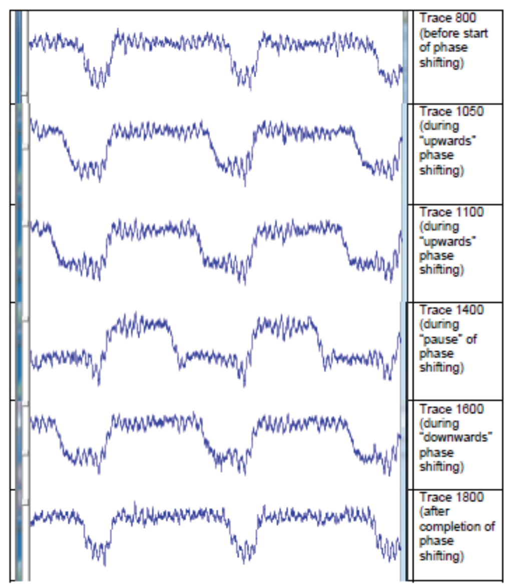
important for low intensity primary beams and secondary (rare isotope) beams

various methods are available, all based on cooling

- rf stacking (stochastic/electron cooling on injection orbit, electron cooling on stack orbit)
- barrier bucket stacking (fixed barriers, moving barriers, h=1 unstable fixed point)



new ESR barrier bucket cavity



bunch compression and decompression of an uncooled beam

also suitable for flexible creation of bunches at very low energy

Outlook

Optimization of the deceleration cycle of the ESR mainly means optimization

of the parameters of the cooling systems (reduction of cooling time)

in addition: faster ramping is supported by the hardware

new controls should be seminal to employ this feature

Main goal of the coming re-commissioning of the ESR is short cycle times

optimization of cooling

flexible ring operation.

The main tool is the new FAIR-type control system LSA (LHC software architecture).

It should provide increased flexibility in tuning the subsystems.

Thanks to you

and to my collaborators

C. Dimopoulou, R. Heß, R. Joseph, C. Kleffner,

S. Litvinov, F. Nolden, D. Winters