ESR
(Experimental Storage Ring)
an Extremely versatile Storage Ring

M. Steck

Storage Rings

GSI Accelerator Operations

What is Extreme?

ion species p ,..., Li^{1+}, $C^{3+,6+}$,..., $Xe^{52+,53+,54+}$,..., $U^{89+,90+,91+,92+}$, RIBs

energy 3 .... 400(550) MeV/u (for U^{92+})

acceptance (design) $A_h \sim 400$ µm, $A_v \sim 150$ µm, $\Delta p/p \sim \pm 3$ %

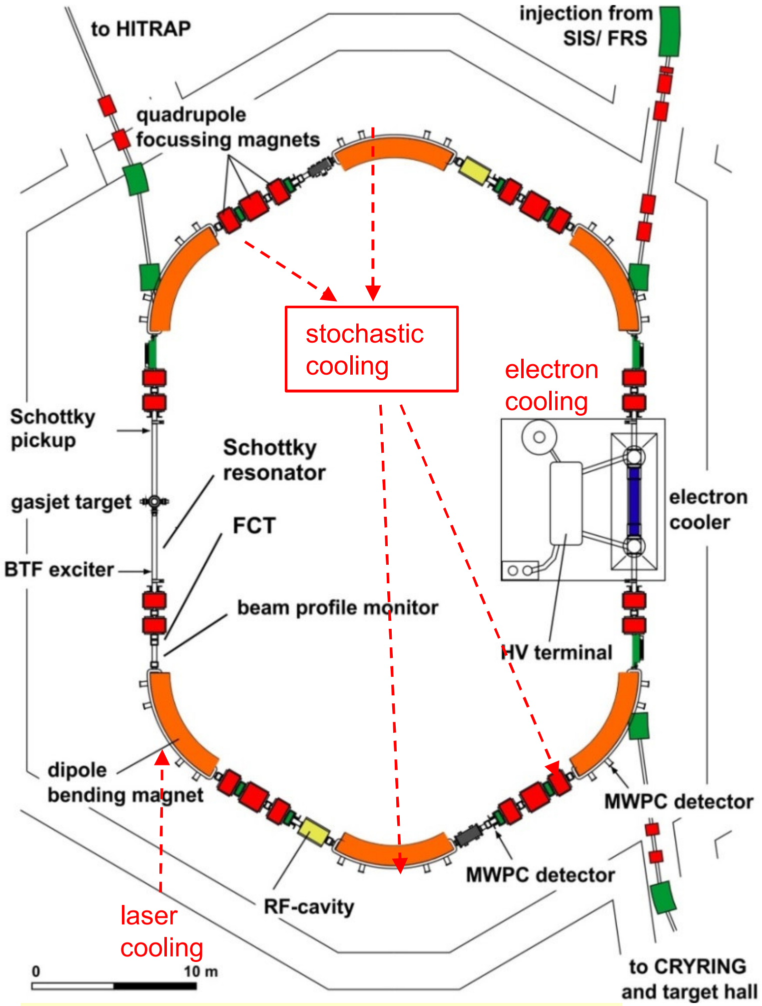
intensity single ions …. some 10^9 cooled ions

beam emittance 10^{-7} … 10 µm

beam momentum spread 10^{-7} … 10^{-3}

lifetime milliseconds to hours (depending on energy, species)

Operation Modes of the ESR



circumference 108.36 m
bending power 10 Tm

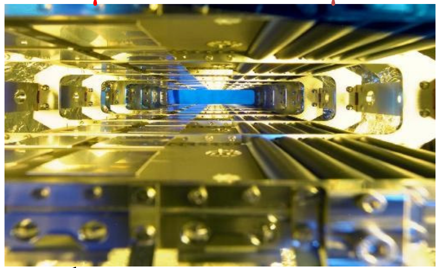
Storage of Highly Charged Ions (HCI) and Rare Isotope Beams (RIB) after fast injection e.g. U^{92+}: in the energy range 3 - 550 MeV/u

Stochastic cooling ($\geq$ 400 MeV/u)
Electron cooling (3 - 430 MeV/u)
Laser cooling (C^{3+} 120 MeV/u)
Beam accumulation
Deceleration (down to 3 MeV/u)
Fast extraction (HITRAP/CRYRING)
Slow (resonant) extraction
Ultraslow extraction (charge change)
Multi charge state/multi component operation
Schottky Mass Spectrometry (SMS) of RIBs
Isochronous mode (TOF detector)
Internal gas jet target

Beam Cooling

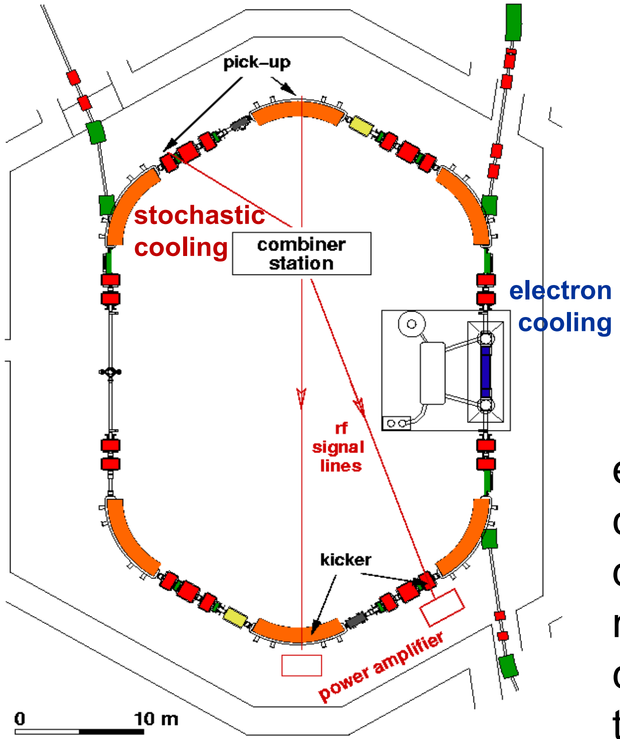
stochastic pre-cooling on the injection orbit

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


electrodes


combiner station


power amplifiers



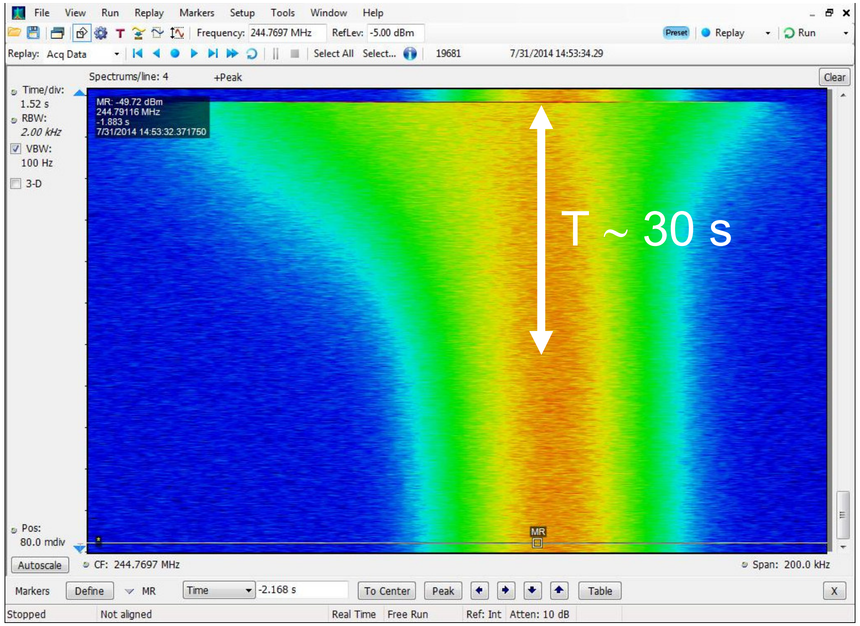
electron cooling

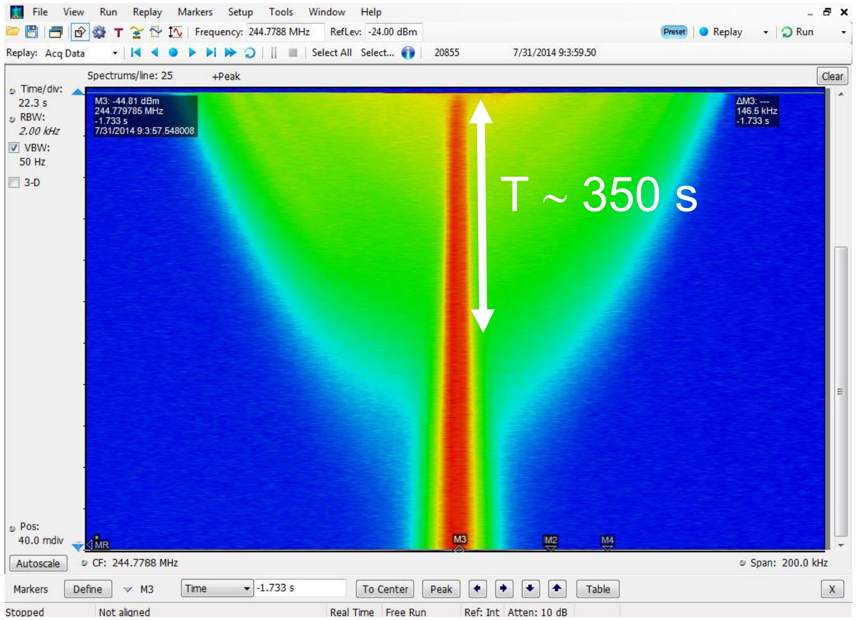
energy	1.6 – 250 keV
current	0.001 – 1 A
diameter	50.8 mm
magnetic field	0.01 - 0.2 T
collection efficiency	0.9998
transverse temperature	0.1 eV
longitudinal temperature	~0.1 meV
vacuum	1×10^{-11} mbar

Cooling of the Injected Beam

- The injection energy of the ESR is flexible (30 - 500 MeV/u)
- 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

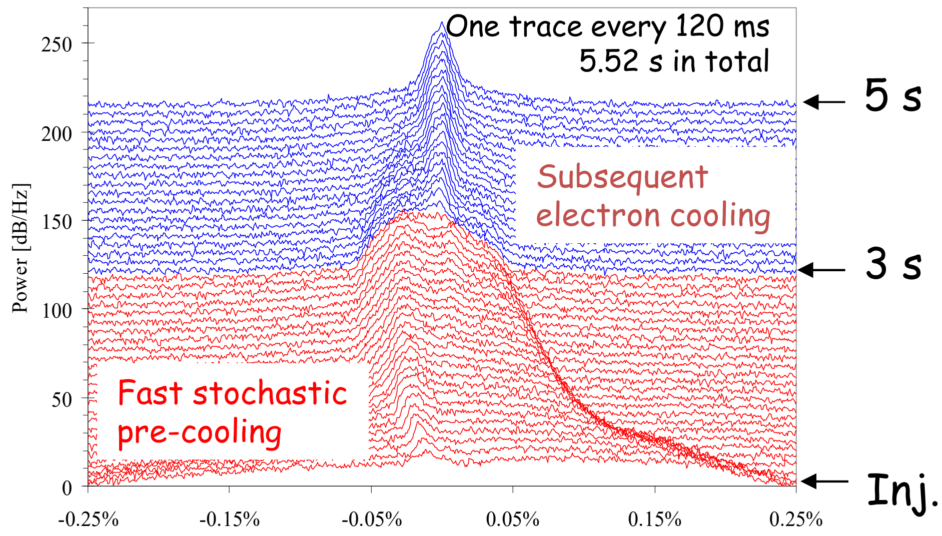
stochastic cooling | protons 400 MeV | electron cooling (I_{el}=0.25 A)





Combination of Stochastic and Electron Cooling

stochastic pre-cooling + **final electron cooling**
immediately after injection

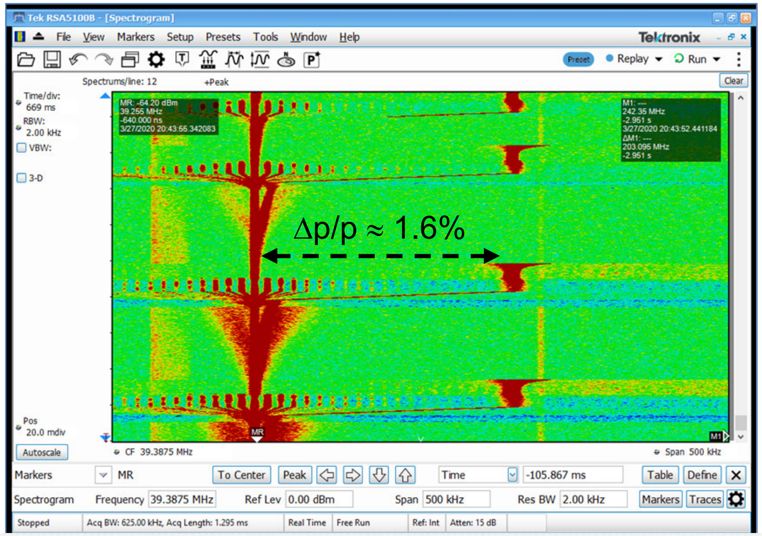


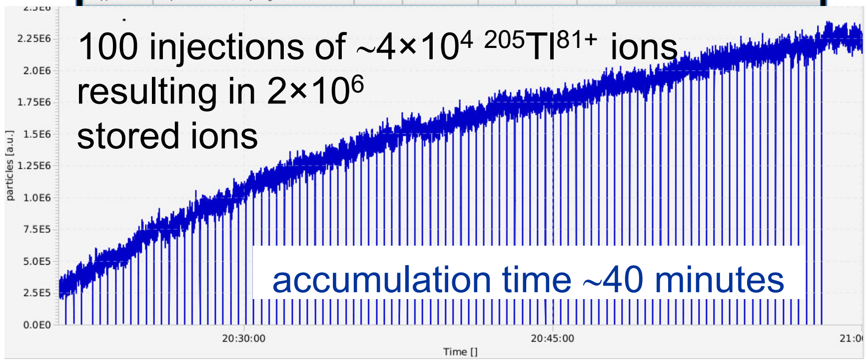
Primary Uranium beam
heated in thick target

Stochastic pre-cooling reduces the total cooling time to a few seconds, electron cooling only takes some 10 s

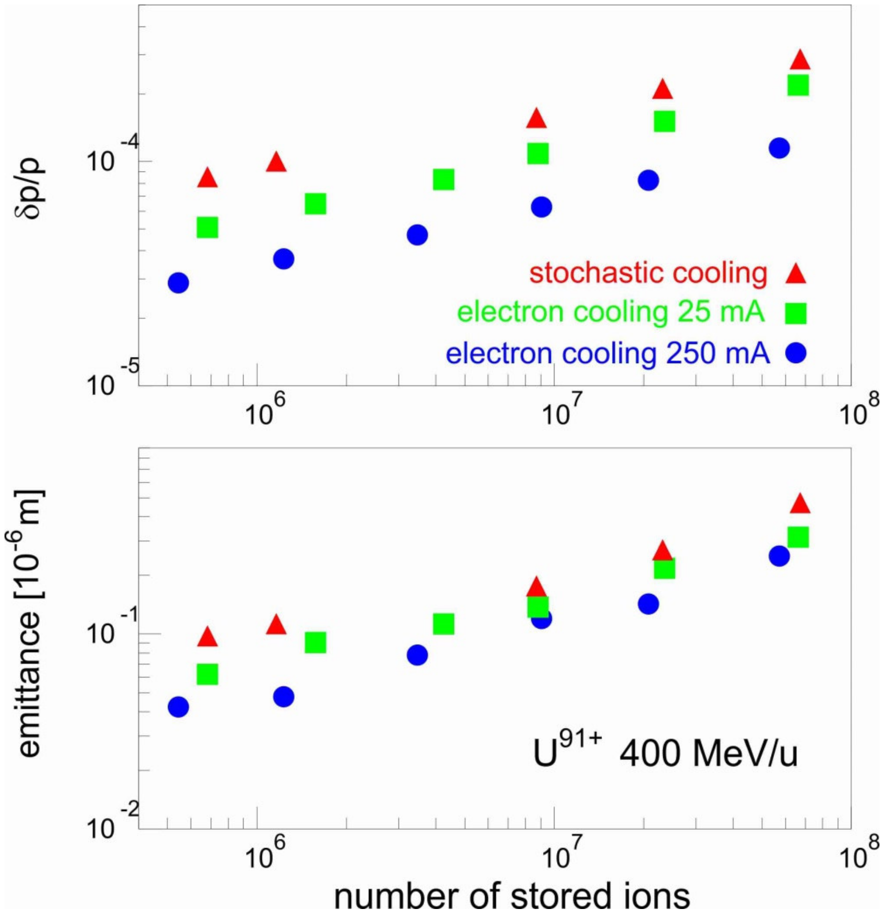
Accumulation of secondary beams

1) stochastic cooling on injection orbit
2) rf stacking
3) electron cooling of stack





Equilibrium Beam Parameters of Cooled Beams in the ESR



equilibrium values limited by intrabeam scattering (IBS)

Electron cooling results in smaller momentum spread and emittance compared to stochastic cooling.

The equilibrium is a balance between the cooling rate and the heating rate by intrabeam scattering.

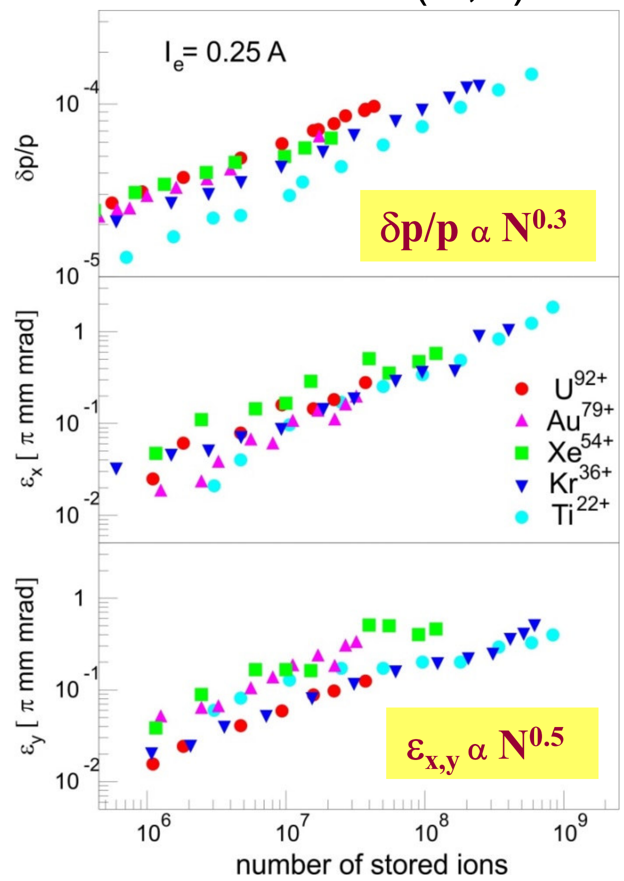
calculated IBS-heating/cooling rate [s^{-1}]

	longit.	transv.
stoch. cool. (Palmer)	0.9 - 2.2	0.5 - 1.3
elec. cool. [25 mA]	2.0 - 6.0	1.4 - 3.3
elec. cool. [250 mA]	18 - 58	7 - 10

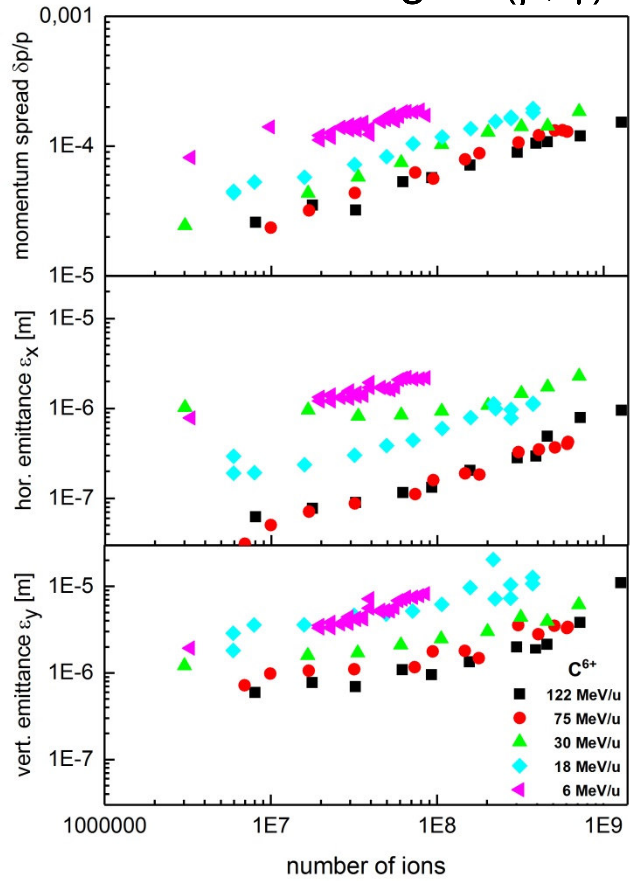
$\Rightarrow$ **Electron cooling is more powerful for cold beams.**

Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)

different ions (Q,A)



different energies (β, γ)

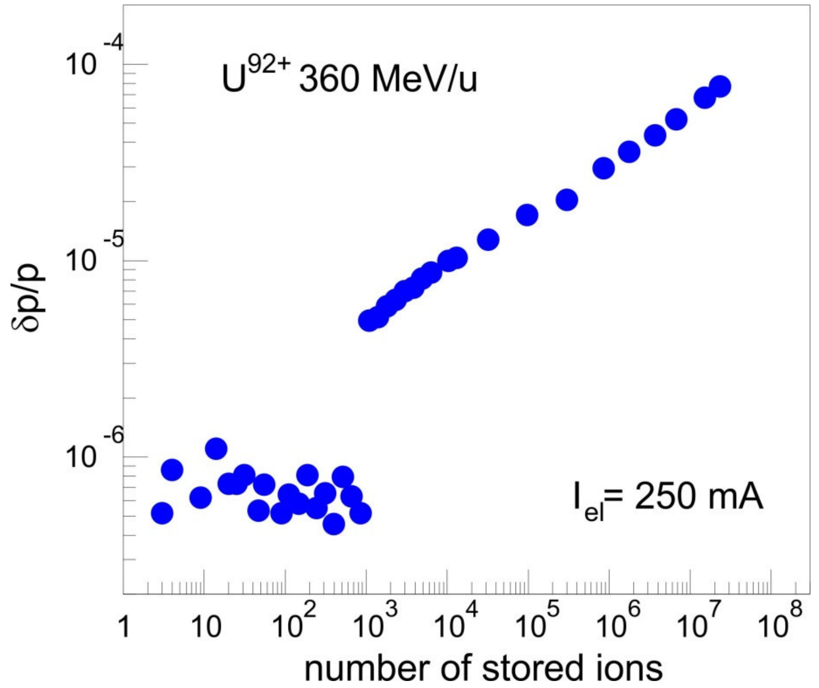


IBS: total phase space volume increases with ion beam intensity and ion charge

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

Observation of Ultra-cold Beam

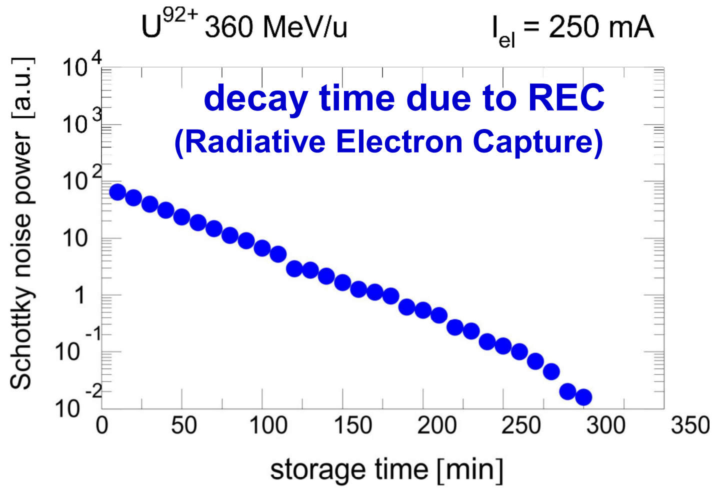
Reduction of momentum spread

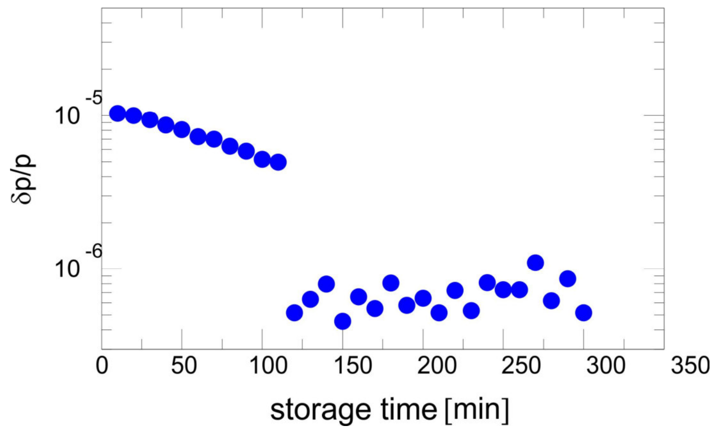


sudden reduction of the momentum spread for less than about one thousand stored ions

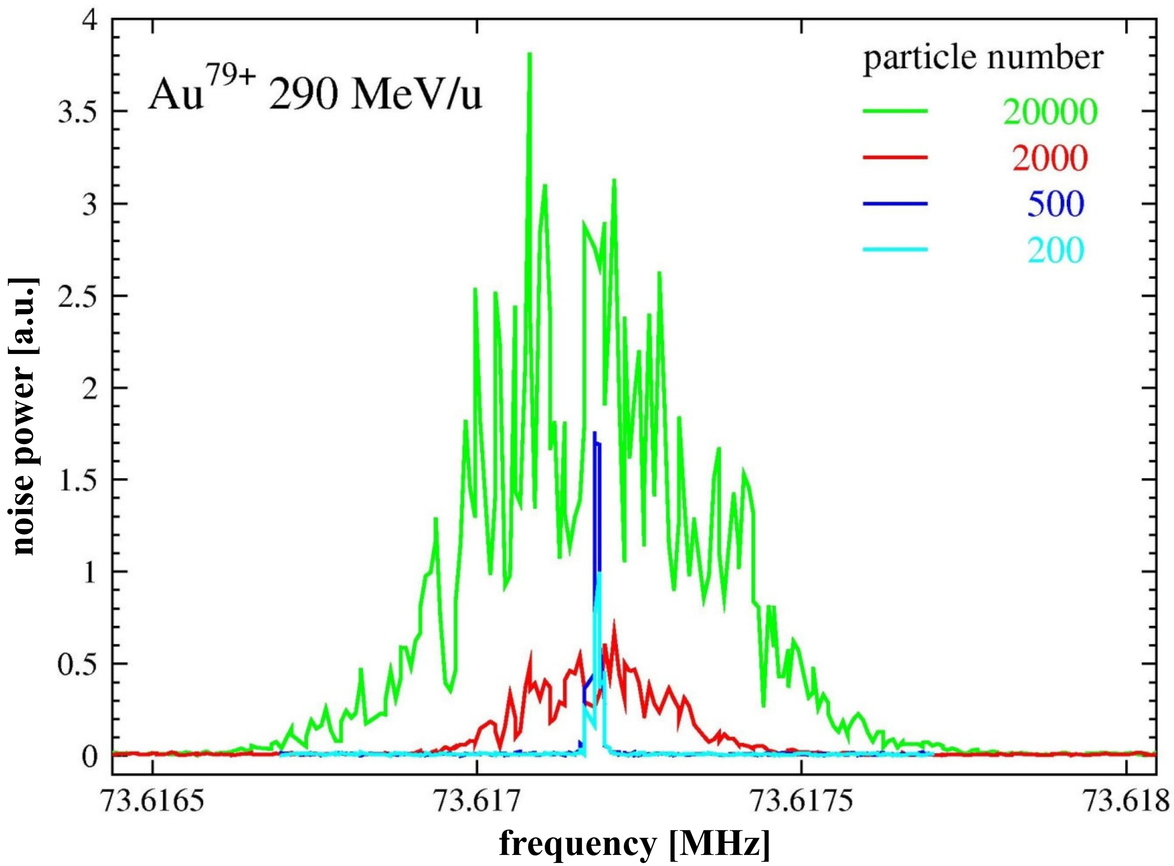
⇒ linear ordering in ion string

temporal evolution of Schottky noise allows independent determination of particle number





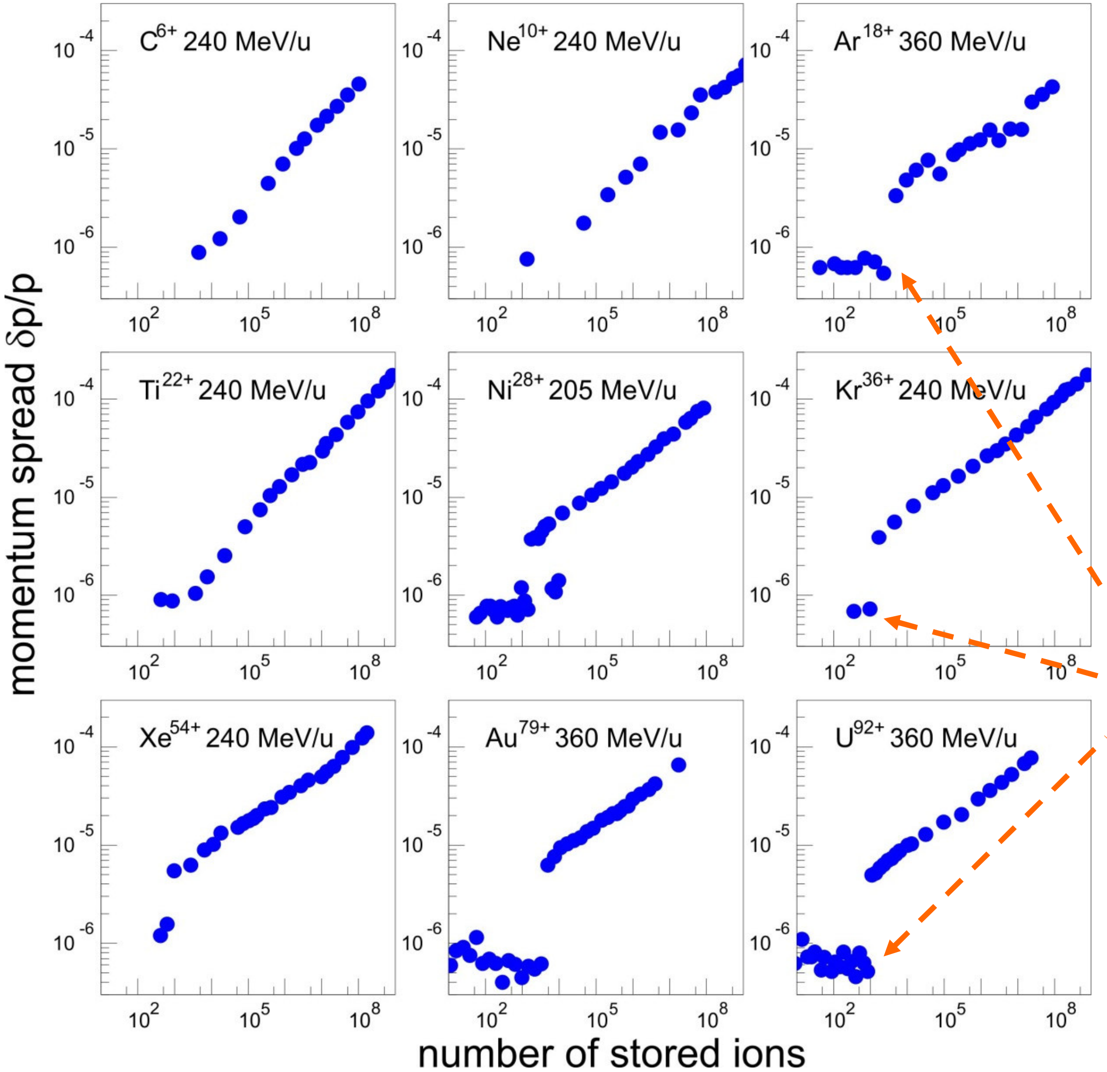
Schottky Noise Signal at Transition to Ordered Beam



The frequency (momentum) spread can be derived from the distribution.

The integrated noise power is proportional to the particle number.

Ordering Effect for Different Ions

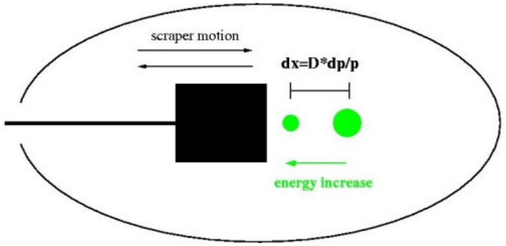


Measurement of momentum spread for a fixed electron current of 0.25 A and variation of stored ion number:
Transition to ordered state is observed around 1000 stored ions.
No dependence on ion species is evident.

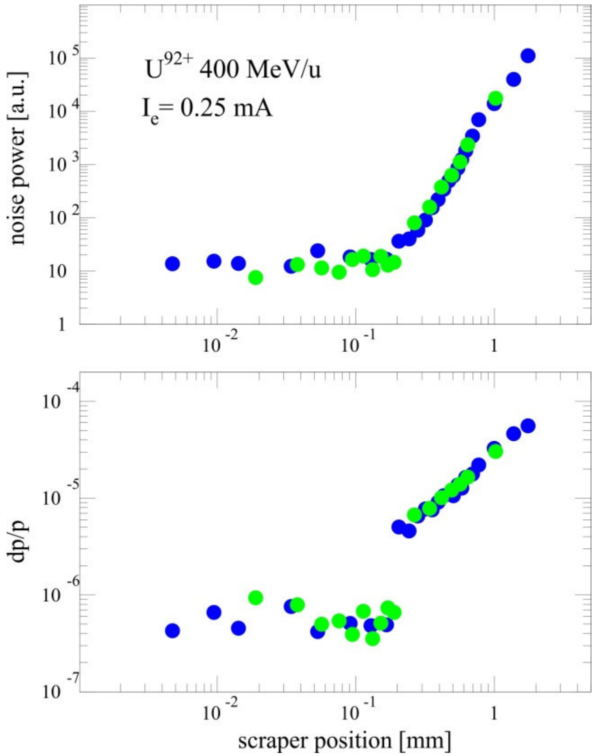
The minimum momentum (frequency) spread is the same for all ion species.
It is determined by the stability of magnet power supplies.

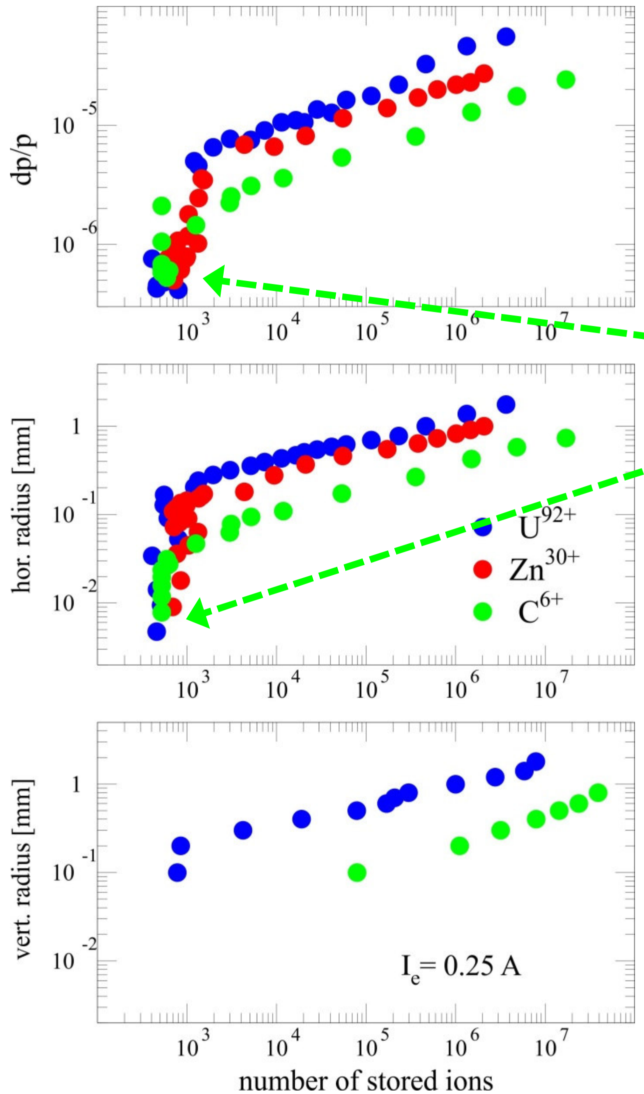
stability of power converters limits the frequency stability

Transverse Beam Size of Ultra-cold Beam



good reproducibility of the scraper measurement





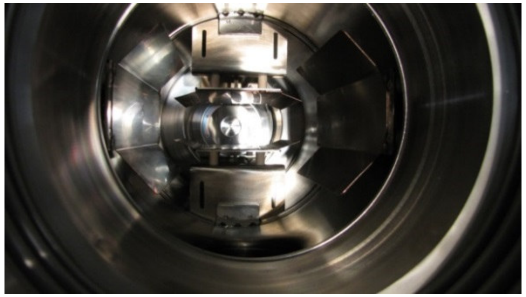
lowest temperature for C^{6+} at 4800 MeV

$kT_{\parallel}$= 0.26 meV

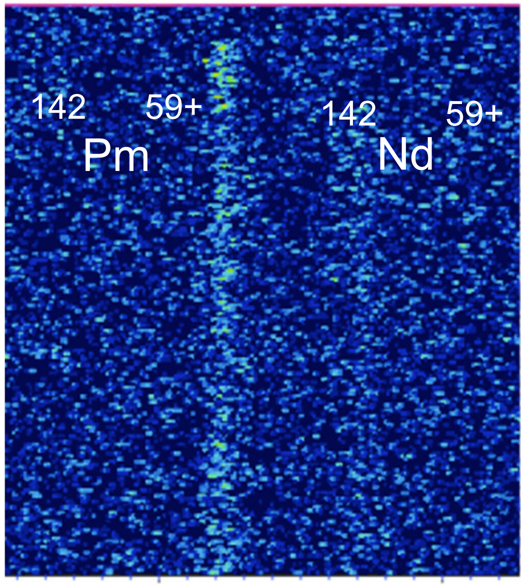
kT_x= 0.14 meV

minimum ion temperature of the order of the longitudinal electron temperature
$\Rightarrow$ magnetized cooling

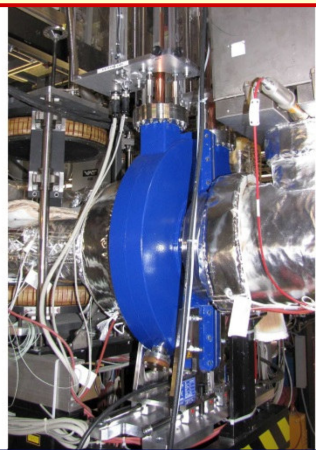
Schottky Resonator

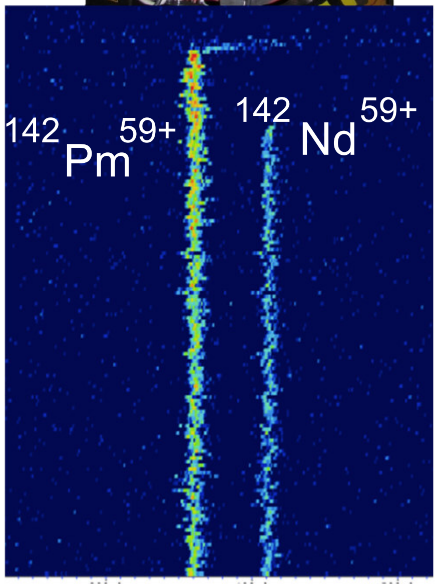


Broad-band
Schottky pickup
Resonant circuit
at 30th harmonic

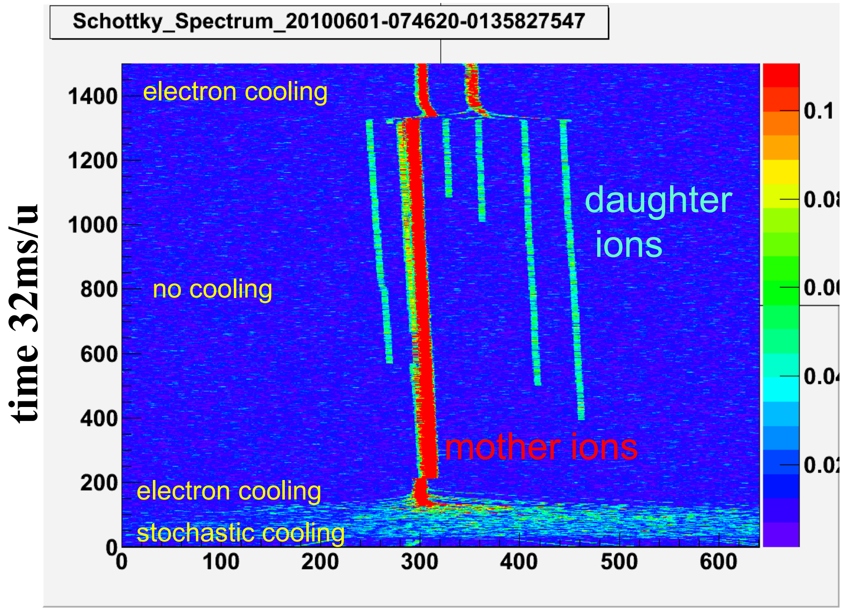


Resonator Cavity
124th harmonic





single ion detection (without cooling)

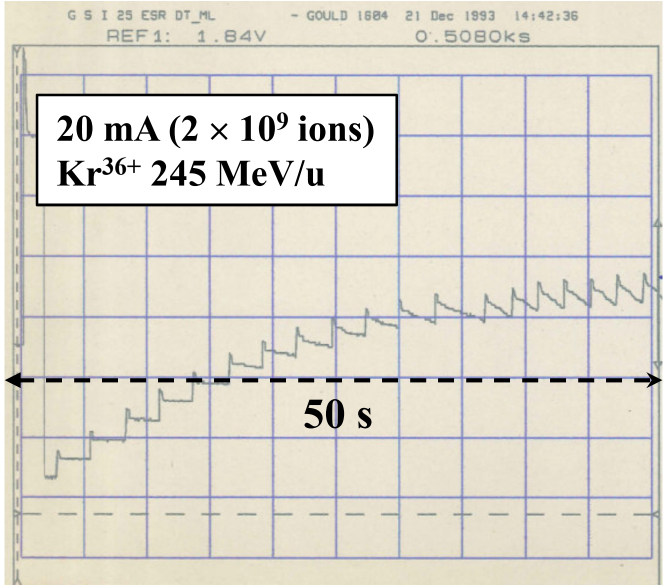


studies of nuclear decays

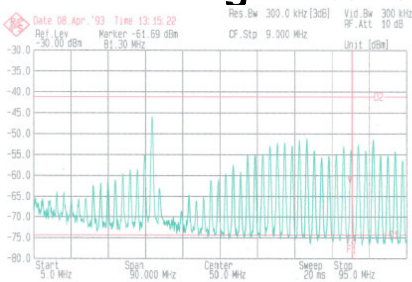
improved sensitivity and time resolution

no sensitivity at low beam energy

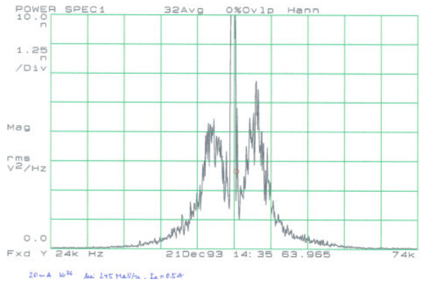
High Intensity Cooled Beams



high intensity observations

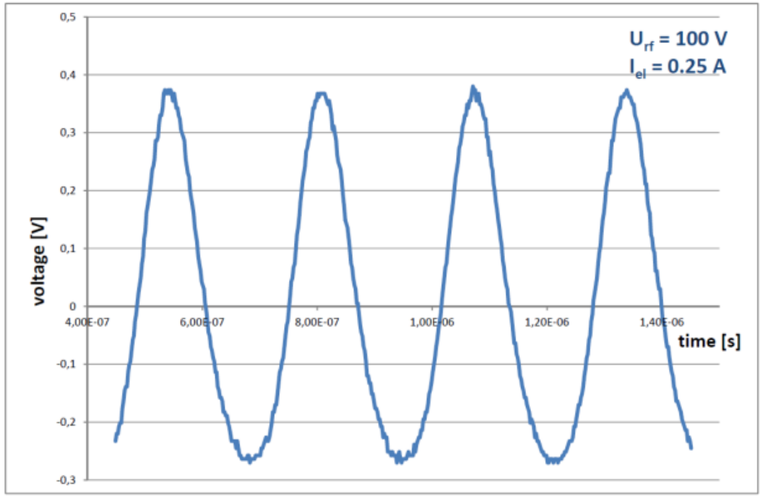


transverse coherent Schottky signal 0-90 MHz



longitudinal Schottky signal with central coherent peak

18 mA Xe^{54+} 350 MeV/u bunched (h=2, B=0.40) corresponding to over 40 mA coasting beam



what matters?
cooling⇒ emittance, momentum spread
orbit, tune, chromaticity, impedances

no feedback system for regular operation, only some basic studies in the past

Decelerated Highly Charged Ion and Rare Isotope Beams for Physics

relativistic Doppler transformation

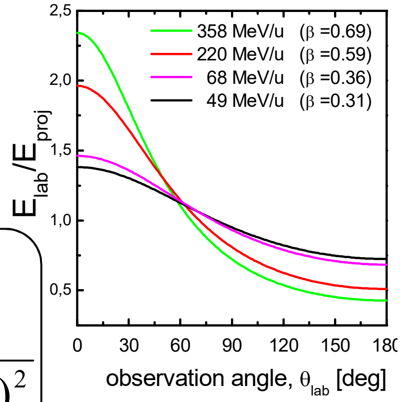
$$E_{lab} = \frac{E_{proj}}{\gamma \cdot (1 - \beta \cdot \cos\theta_{lab})}$$

relativistic transformation of solid angle:

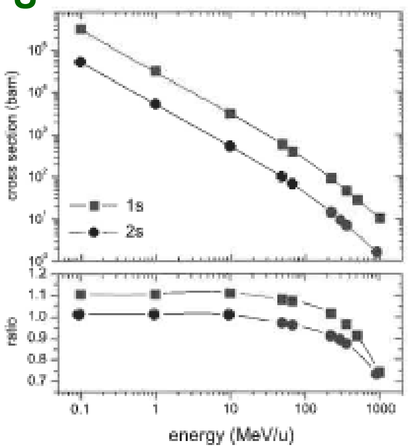
$$\Delta\Omega_{lab} = \frac{\Delta\Omega_{proj}}{\gamma^2 \cdot (1 - \beta \cdot \cos\theta_{lab})^2}$$

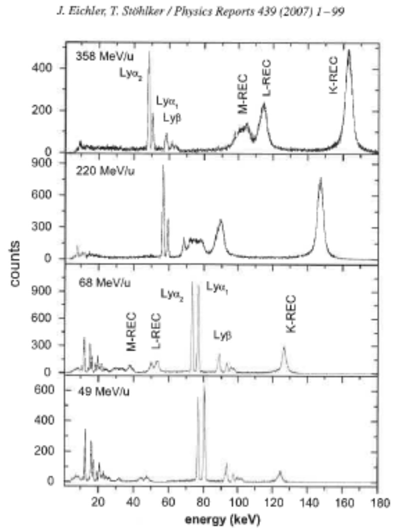
E_{lab}: photon energy in lab system

E_{proj}: photon energy in emitter system



radiative recombination U^{92+}





X-rays of REC $U^{92+} \to N_2$

Benefits for Atomic Physics

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

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

Benefits for Nuclear Physics

- access to the Gamov window (nuclear physics of stars)
- studies in inverse kinematics

Deceleration 400 to 4 MeV/u

Ni^{28+} 400 → 30 → 4 MeV/u

1100 µA → 180 µA → 25 µA

45% 37 %

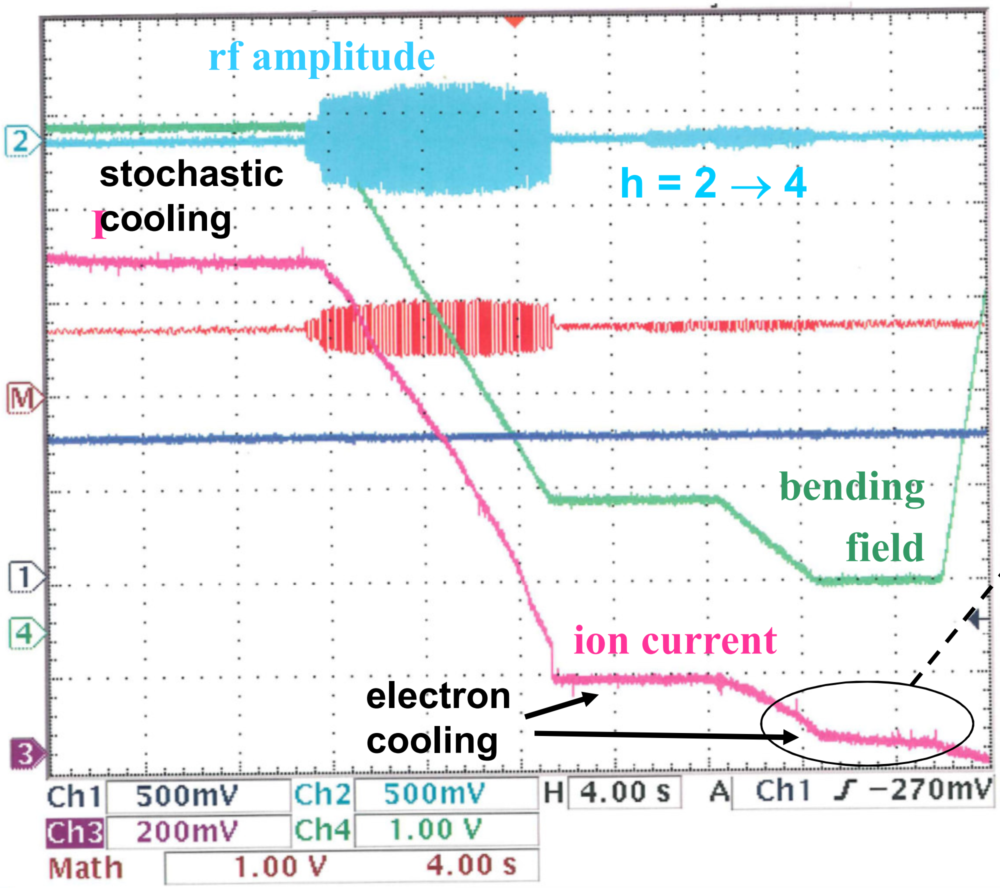
cycle time

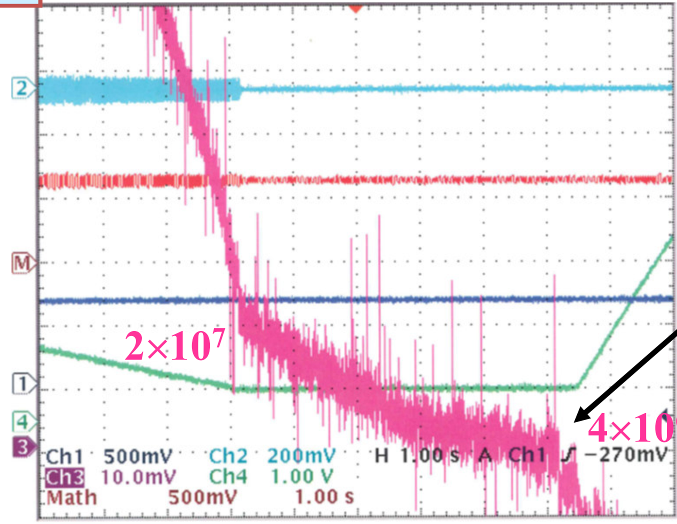
45 s

Main losses:

End of ramp

Storage and cooling at low energy





extraction

beam half life (vacuum dominated):

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

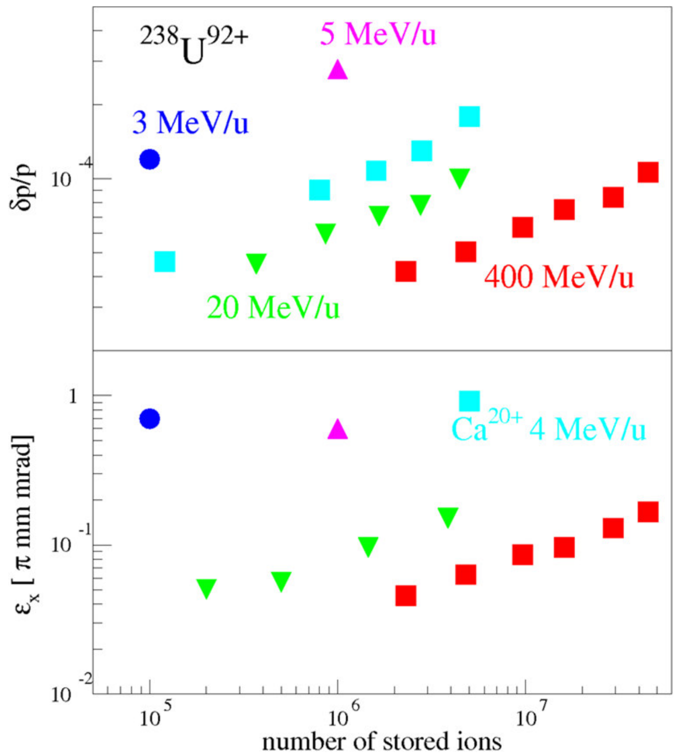
4 MeV/u: $T_{1/2} \approx 2$ s

limits to faster cycle time:

- orbit control for fast ramp rate
- cooling times

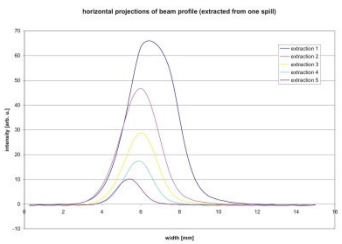
Properties of Decelerated Beams

Beam parameters due to equilibrium between IBS and electron cooling

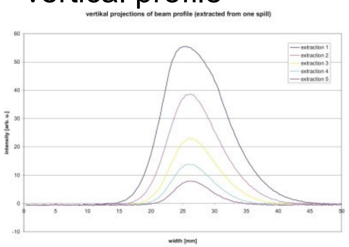


fast extracted beam
Ca^{20+} 4 MeV/u

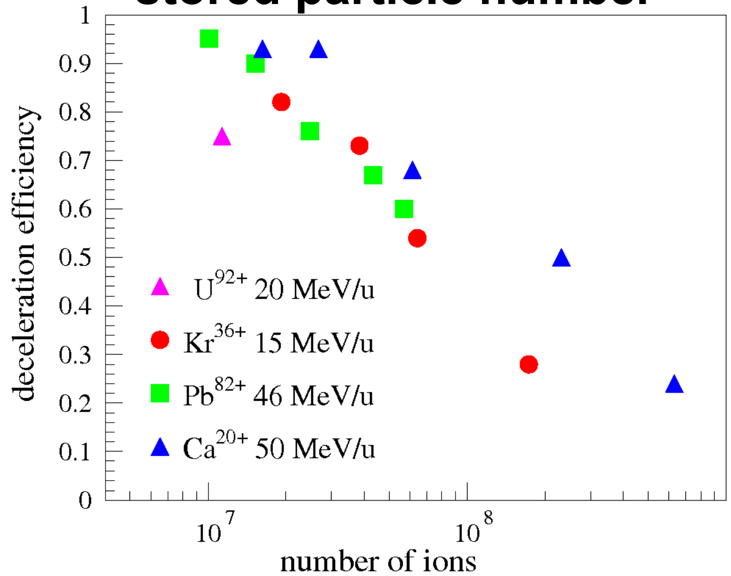
horizontal profile



vertical profile



Losses increase with stored particle number



Control of the beam parameters, emittance (cooling) and bunch length (rf voltage), is challenging

Space charge limit due to incoherent tune shift

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

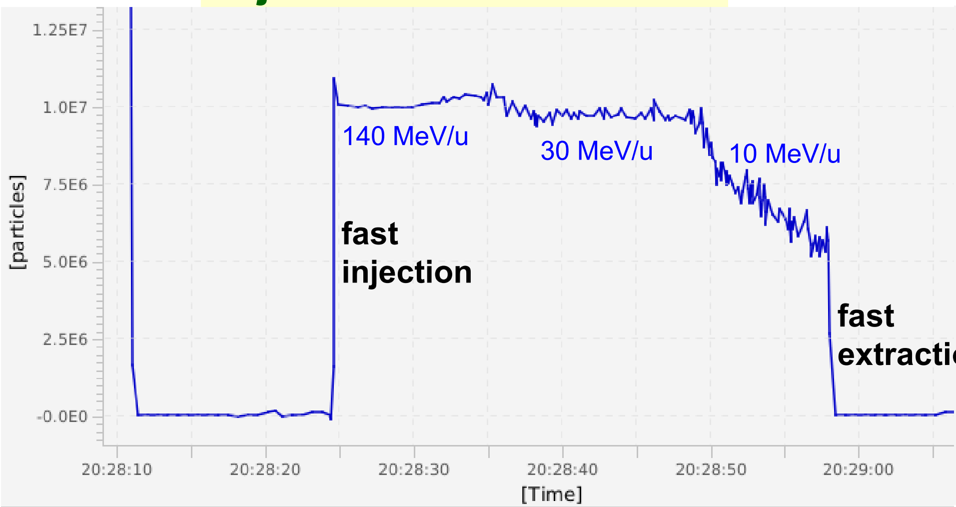
$$\Delta Q_x \simeq \frac{r_p Z^2 N}{2\pi A \beta^2 \gamma^3 B \epsilon_x}, \; g = 1, \epsilon_x = \epsilon_y, Q_x = Q_y$$

space charge limit U^{92+} at 4 MeV/u for $\Delta Q_x = 0.1$:
2 μs bunch with $\varepsilon_x = \varepsilon_y = 10^{-6}$ m $\Rightarrow$ <u>$N \leq 1 \times 10^7$</u>

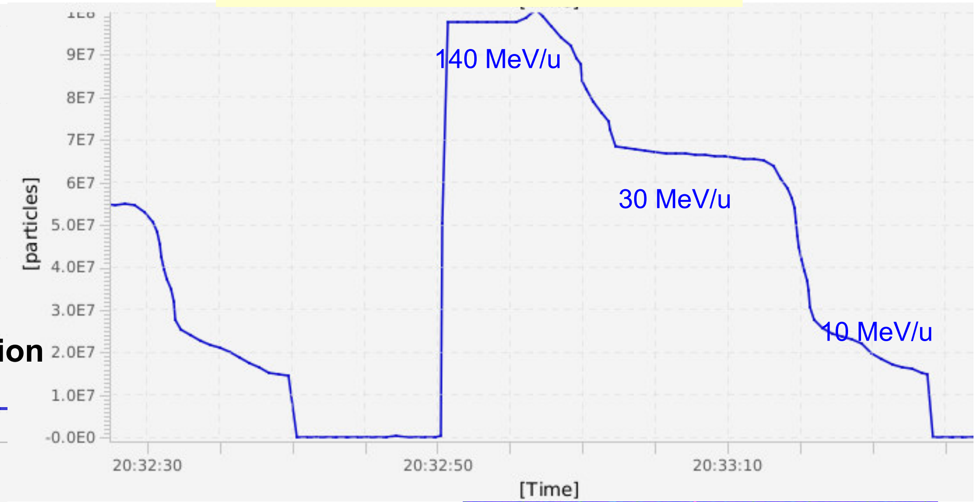
Efficiency of Deceleration 2021

deceleration Ag^{47+} from 140 to 30 and 10 MeV/u and extraction to CRYRING

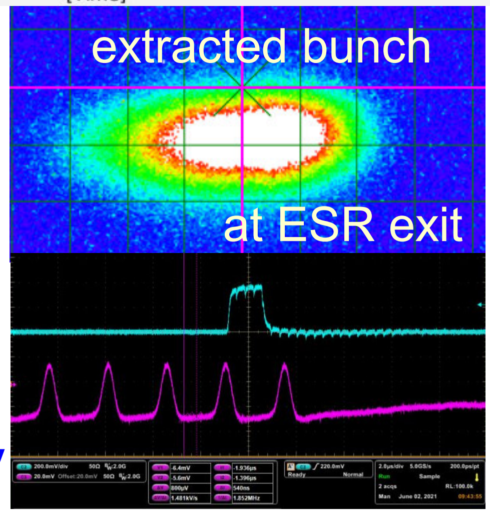
injection of 1×10^7 ions



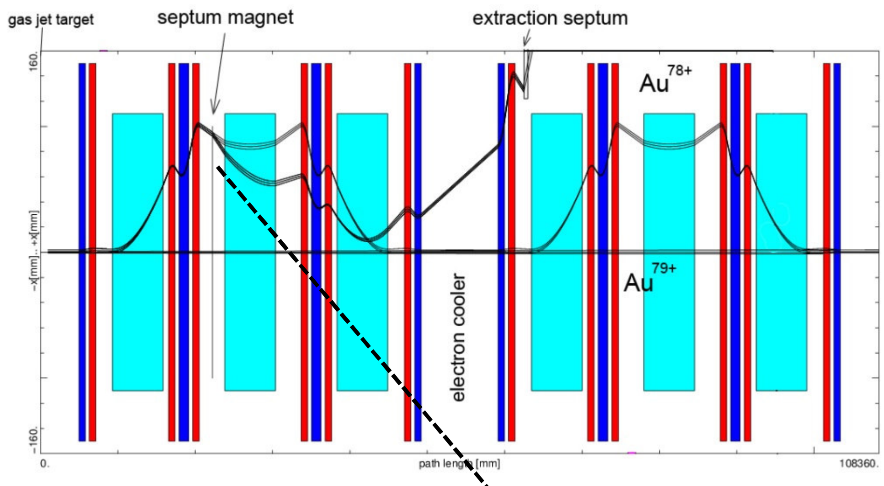
injection of 1×10^8 ions

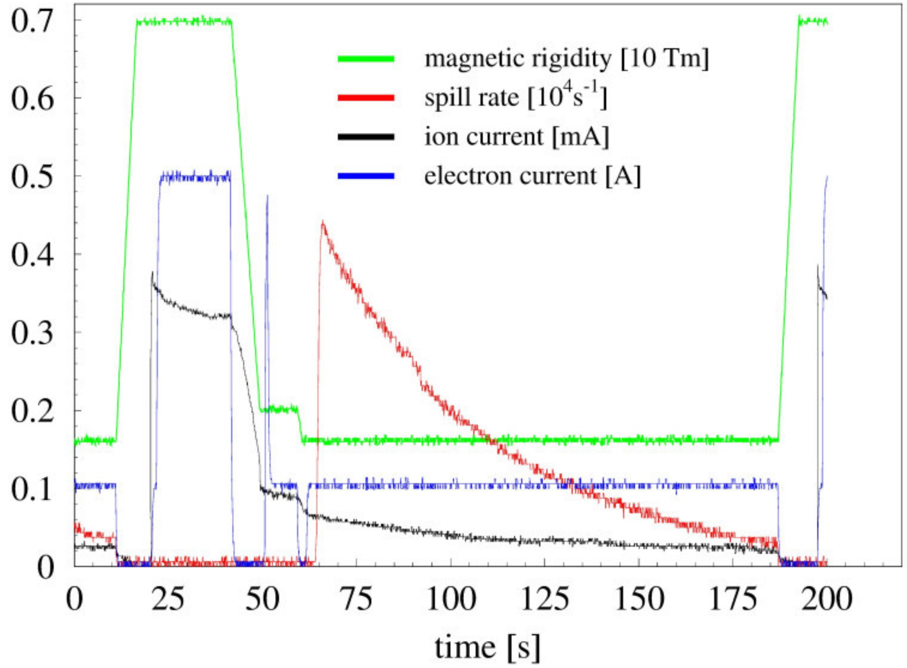


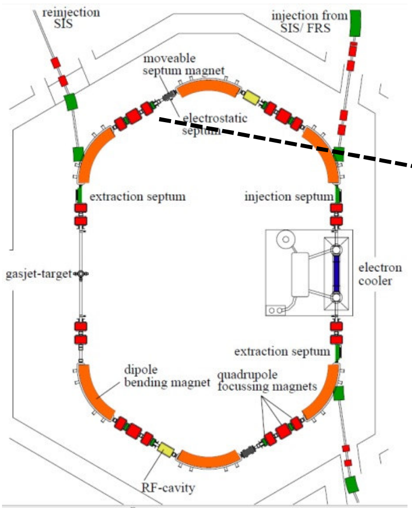
- **cycle time of 35 second**
- **electron cooling at 140, 30 and 10 MeV/u**
- **poor lifetime (vacuum) with half life 12 s at 10 MeV/u**
- **extracted particle number 1-2 × 10^7 (cooled) ions per cycle limited by slow regulation of electron cooler accel. high voltage**
- **bunching into single bunch with new MA filled Barrier Bucket cavity**

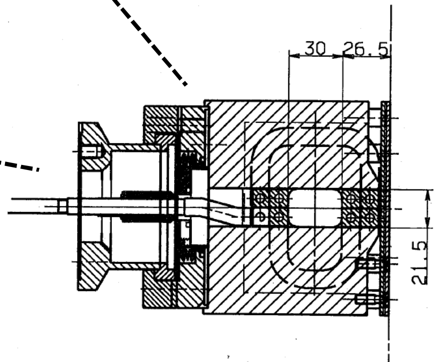


Ultra-slow Extraction by Charge Change









septum magnet installed in UHV

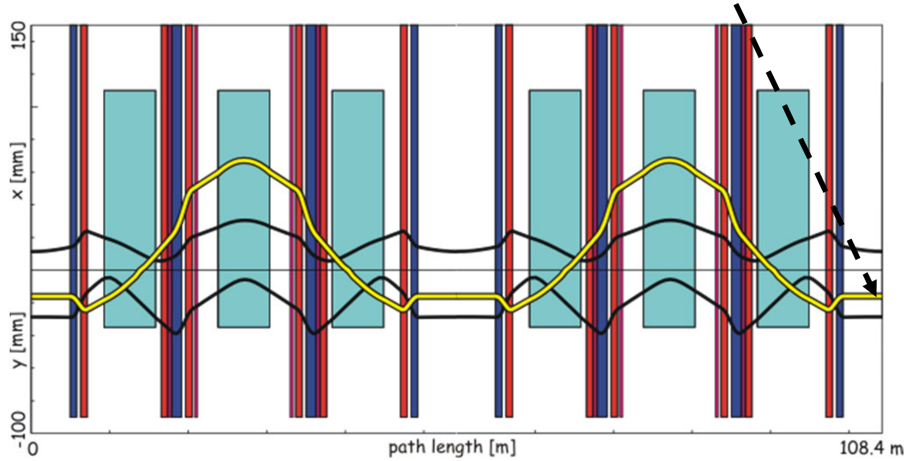
- extracted cooled beam at injection energy or after deceleration (so far: to ≥ 20 MeV/u)
- small emittance
- good control of extraction rate
- extraction time flexible: seconds to hours

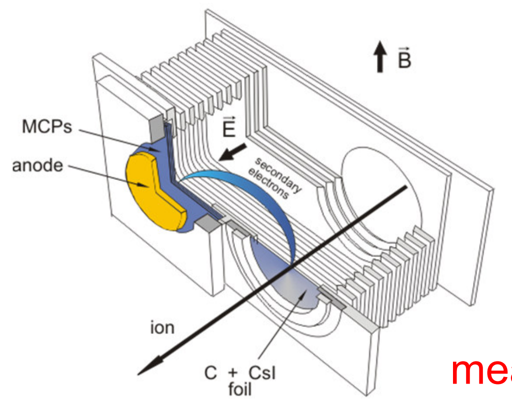
Isochronous Mode $\gamma_t = \gamma$

Isochronous Mode with large negative dispersion (- 8 m) at ToF detector

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

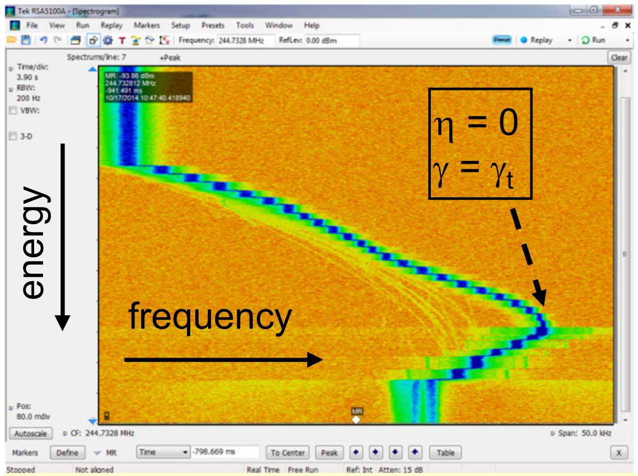
(= 0 ,if $\gamma = \gamma_t$)

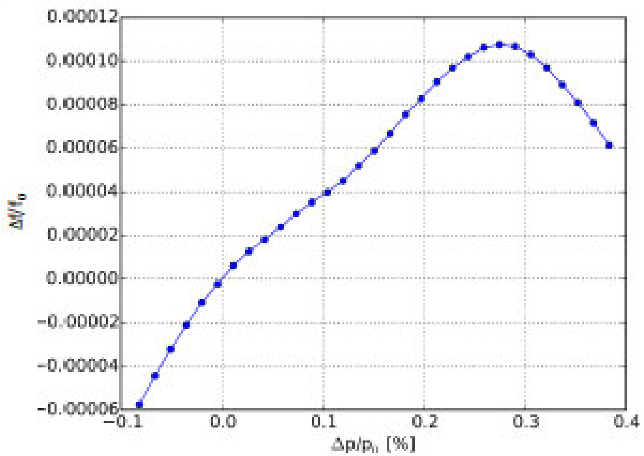


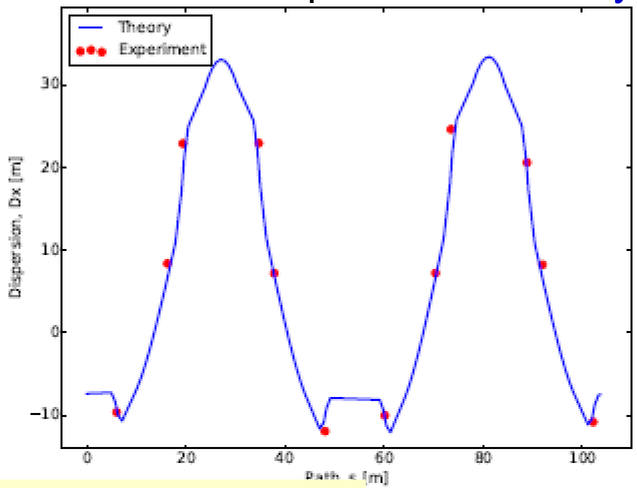


used in mass measurements with a ToF detector

measured dispersion value compared with theory

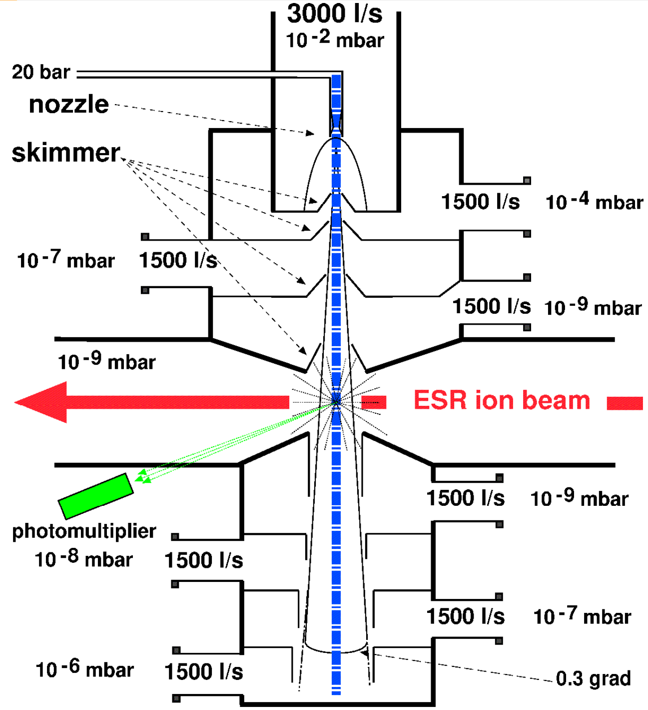


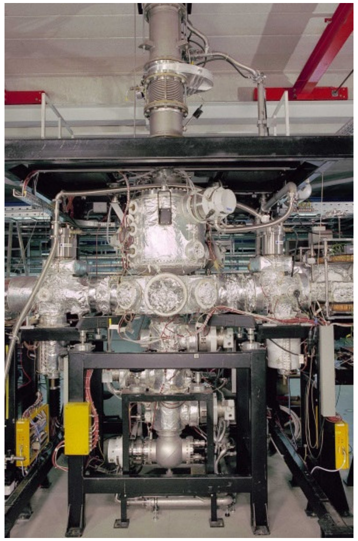


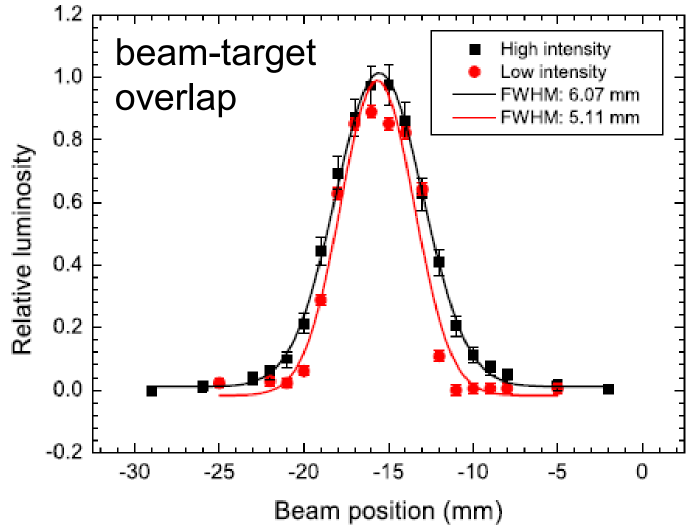


measurement of transition energy by variation of beam energy with the electron cooler

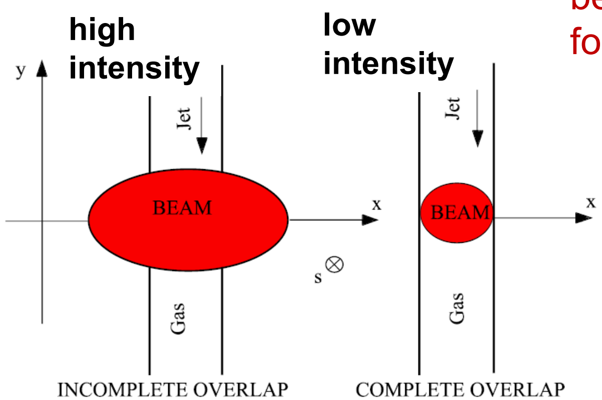
Internal Target







beam diameter 3.3 mm
for 1.2 × 10^9 Ar^{18+} ions



Target gas	Area density [cm^{-2}]	T_0 [K]
Helium	1×10^{13}	20
Hydrogen	3×10^{13}	40
Nitrogen	8×10^{12}	130
Argon	3.5×10^{12}	300
Krypton	1.5×10^{12}	300
Xenon	6×10^{12}	300

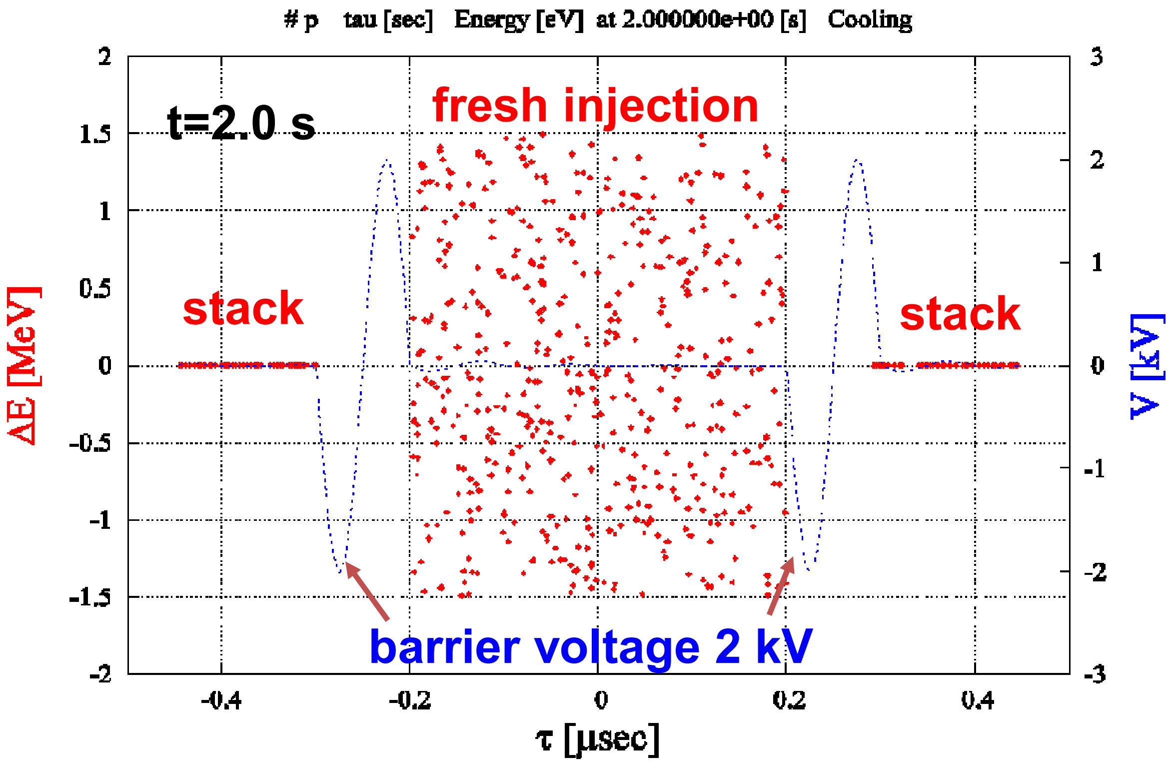
presently available target densities

The luminosity in target experiments with cooled beams does not linearly increase with the beam intensity.

Barrier Bucket Accumulation Scenario proposed for FAIR: RIBs in NESR

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

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

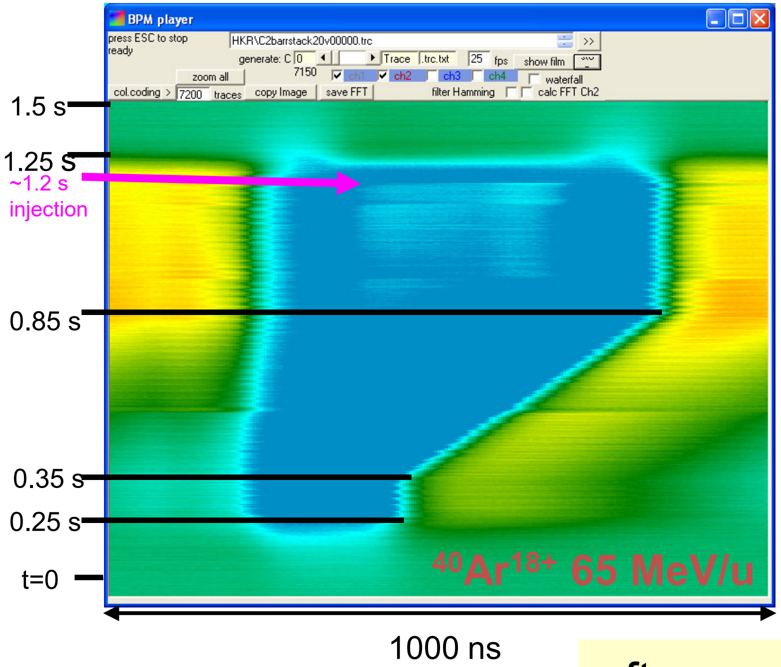
E_k = 740 MeV/u

Longitudinal stacking with Barrier Buckets

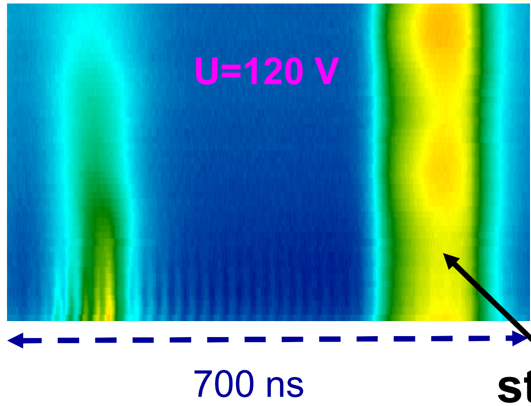
(simulation by T. Katayama)

Experimental Test of Accumulation with Barriers and Electron Cooling

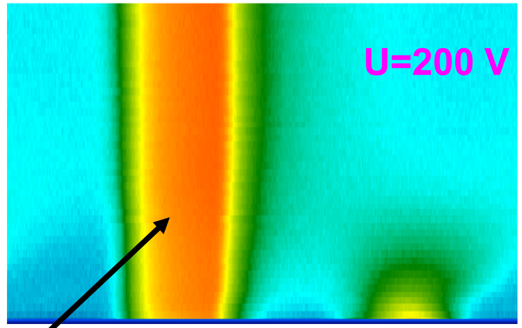
moving barriers



fixed barrier



h=1 unstable fixed point

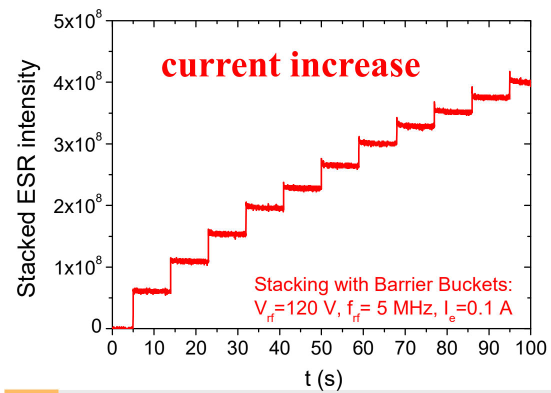


stack

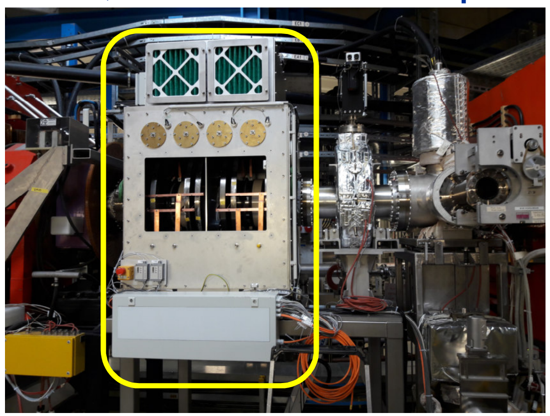
$^{124}Xe^{54+}$ 154 MeV/u

three schemes were successfully tested:

moving barriers, fixed barrier, h=1 unstable f. p.
efficient accumulation



after successful proof of principle with modified ferrite cavity a dedicated magnetic alloy filled barrier bucket cavity was installed which allows flexible rf voltages



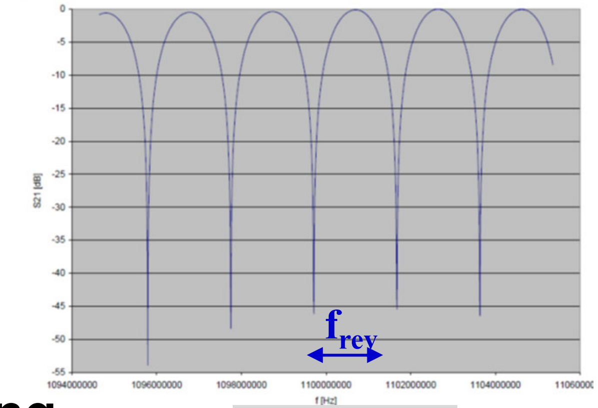
same accumulation scheme with stochastic cooling tested

Notch Filter Cooling Test at the ESR

Optical delay line installed in the ESR for tests of TOF and notch filter cooling

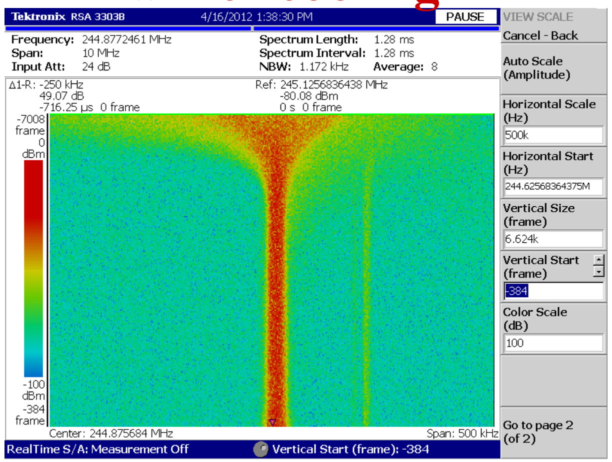
using existing electrodes designed for Palmer cooling

Test of FAIR set-up

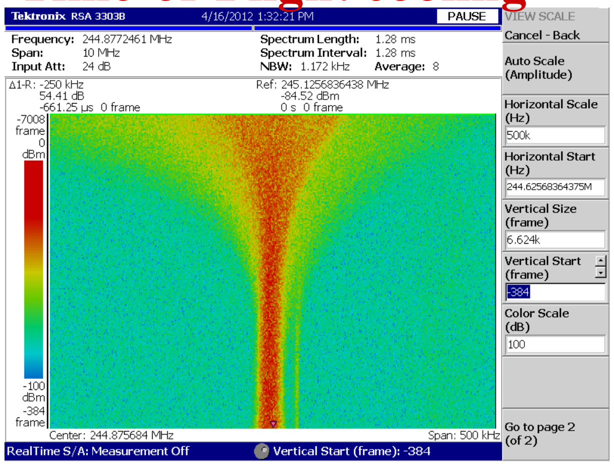


notches

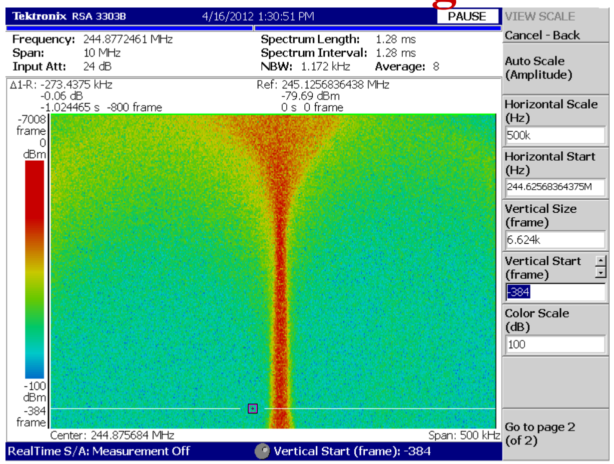
Palmer cooling



Time-of-Flight cooling



Notch filter cooling



Ar^{18+} 400 MeV/u

Summary

Various operation modes of the ESR have been developed over the years

Beam cooling is an indispensable prerequisite for ESR operation

ESR still serves a broad physics program in atomic and nuclear physics with highly charged ions which will continue into the operation of FAIR

ESR serves as a test bed for concepts required for FAIR

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  B. Franzke