High Intensity Issues in Storage Rings

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In storage rings intensity issues are mainly related to high brightness, rather than high intensity

Beam cooling plays an important role

- **to prepare high quality beams for experiments**
  - **including internal targets**
- **to support efficient operation**
- **to achieve long beam lifetime (minutes to days)**

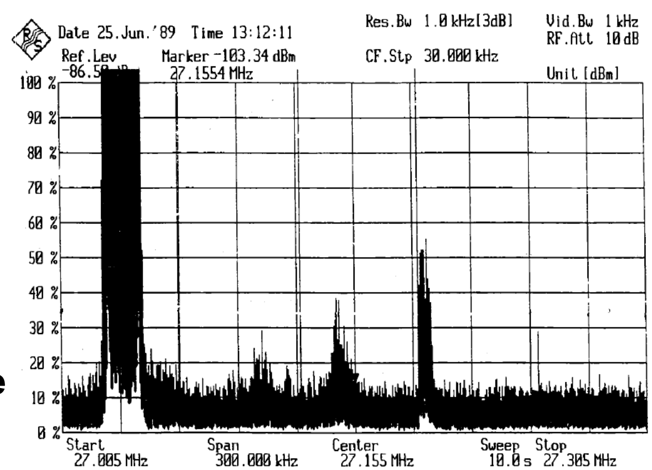
First Experience with High Intensity Stored Ions

Test Storage Ring TSR, MPI Heidelberg

from: https://www.mpi-hd.mpg.de/blaum/storage-rings/tsr/tsr_intensities.de.html

Beam	Energy [MeV]	Intensity [μA]
p	21	2400
HD^+	2	40
$^7Li^+$	13.4	23
$^9Be^+$	7.3	6
$^{12}C^{6+}$	73.3	**18000**
$^{32}S^{16+}$	195	1600
$^{35}Cl^{17+}$	293	1000
$^{56}Fe^{18+}$	240	300
$^{63}Cu^{26+}$	510	110
$^{80}Se^{25+}$	480	110
$^{197}Au^{50+}$	695	3

rf stacking
deceleration within the momentum acceptance

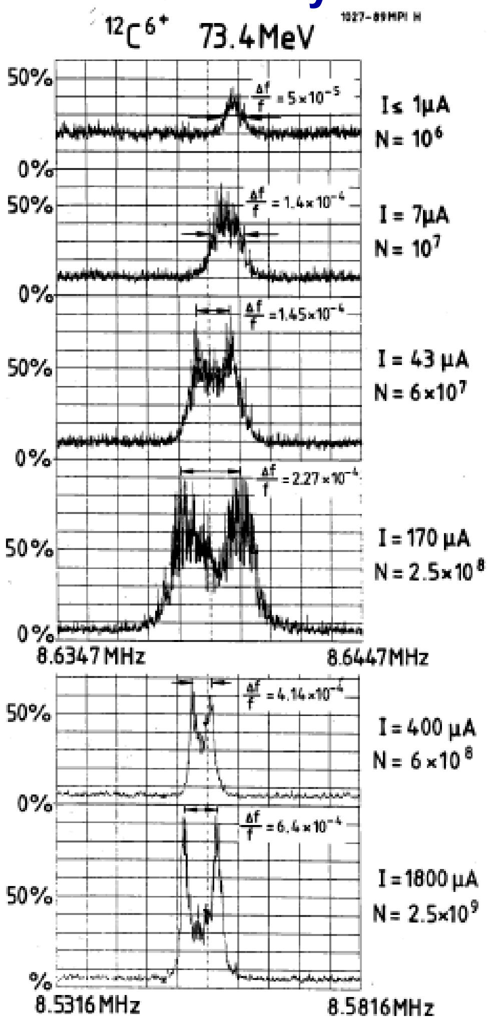


accumulated by multiturn injection and rf stacking
(injected current only 15 μA)

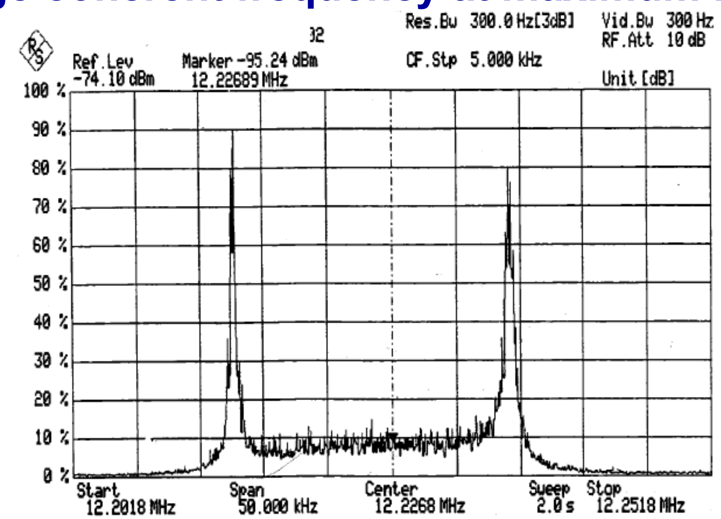
high intensity cooled beam: achieved by intentional degradation of cooling

Coherent Behavior of Schottky Noise

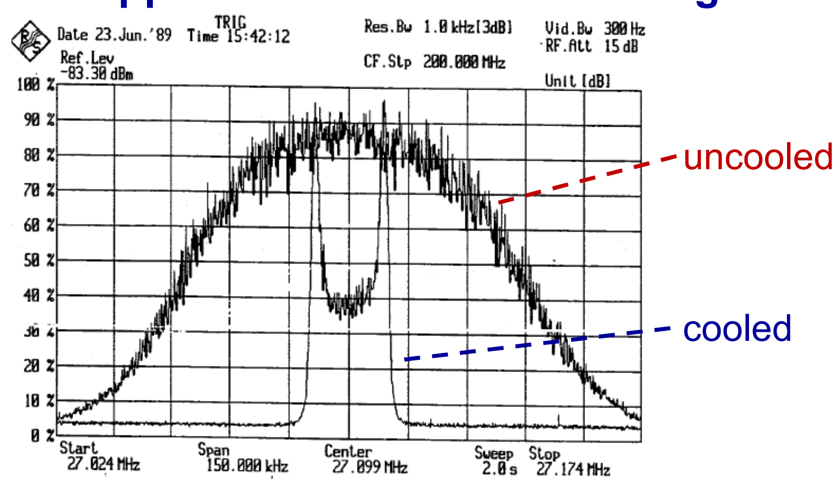
intensity dependence of coherent Schottky noise



large coherent frequency at maximum intensity

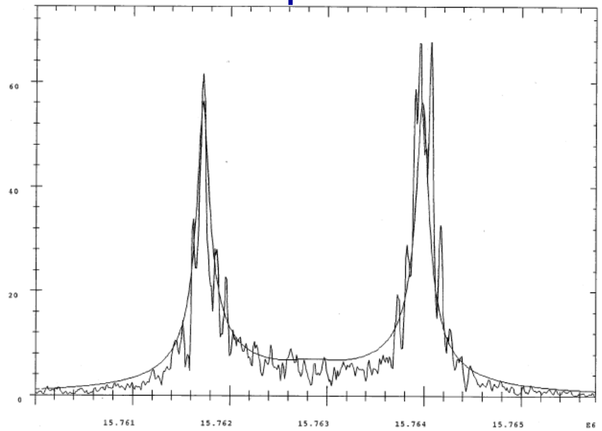


noise suppression of cooled beam signal

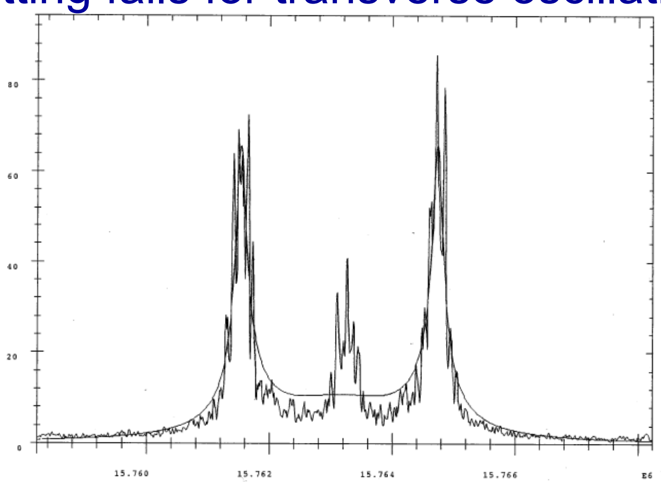


Additional Observations at High Intensity

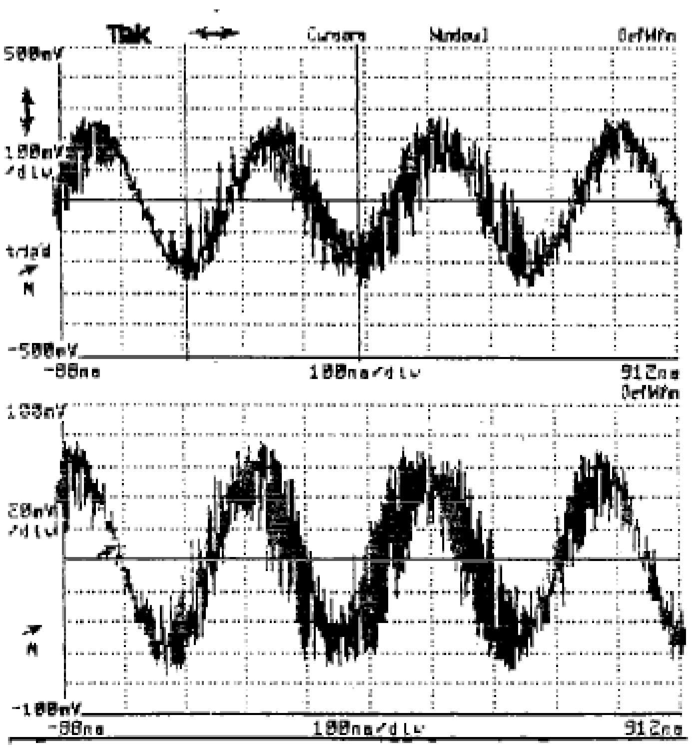
fitting curves of coherent signal
to extract beam parameters



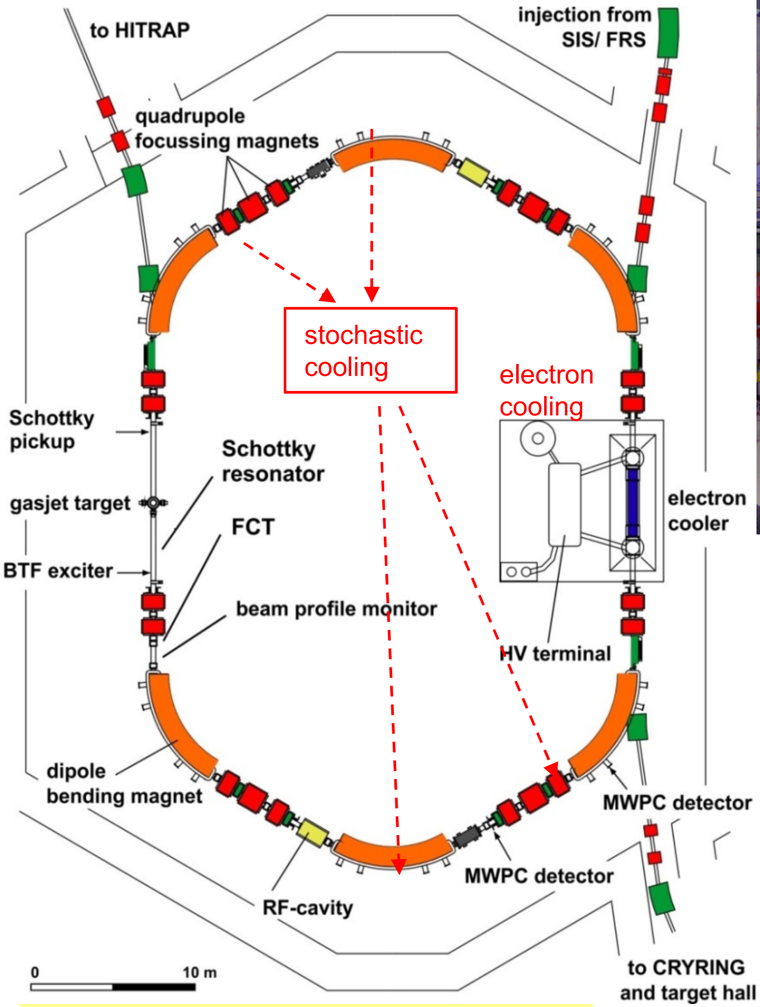
fitting fails for transverse oscillations



pick-up time domain signal revealing
transverse coherent oscillations



The Heavy Ion Storage Ring ESR



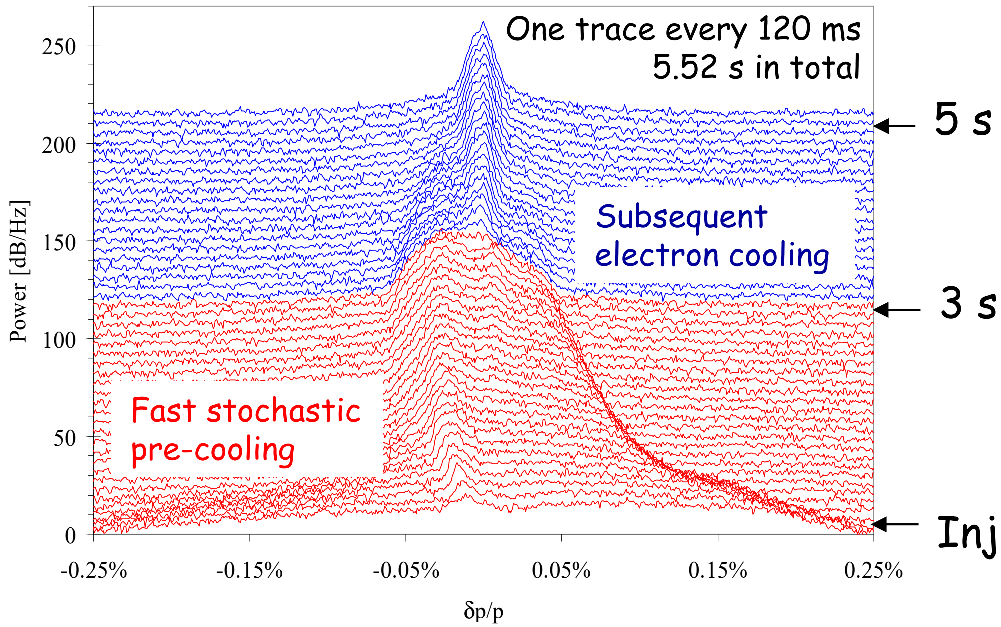
circumference 108.36 m
bending power 10 Tm

electron cooling
energy 3-430 MeV/u
electron current 0.001-1 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

Combination of Stochastic and Electron Cooling

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

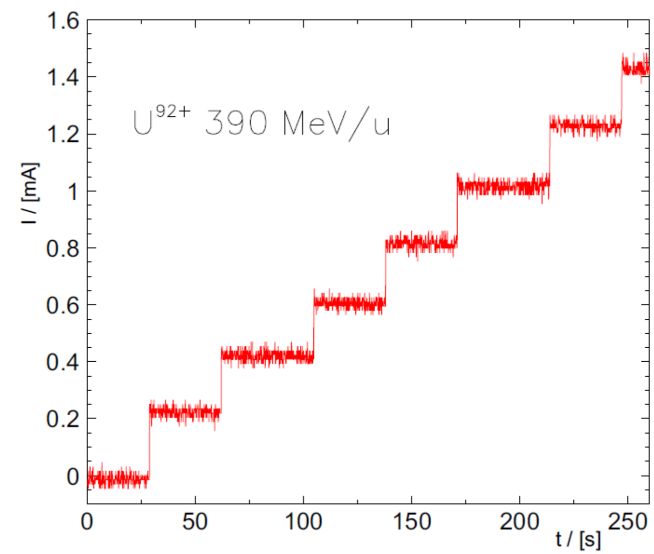


Primary Uranium beam heated in thick target

Stochastic pre-cooling reduces the total cooling time to a few seconds, electron cooling only takes 10 - 60 s

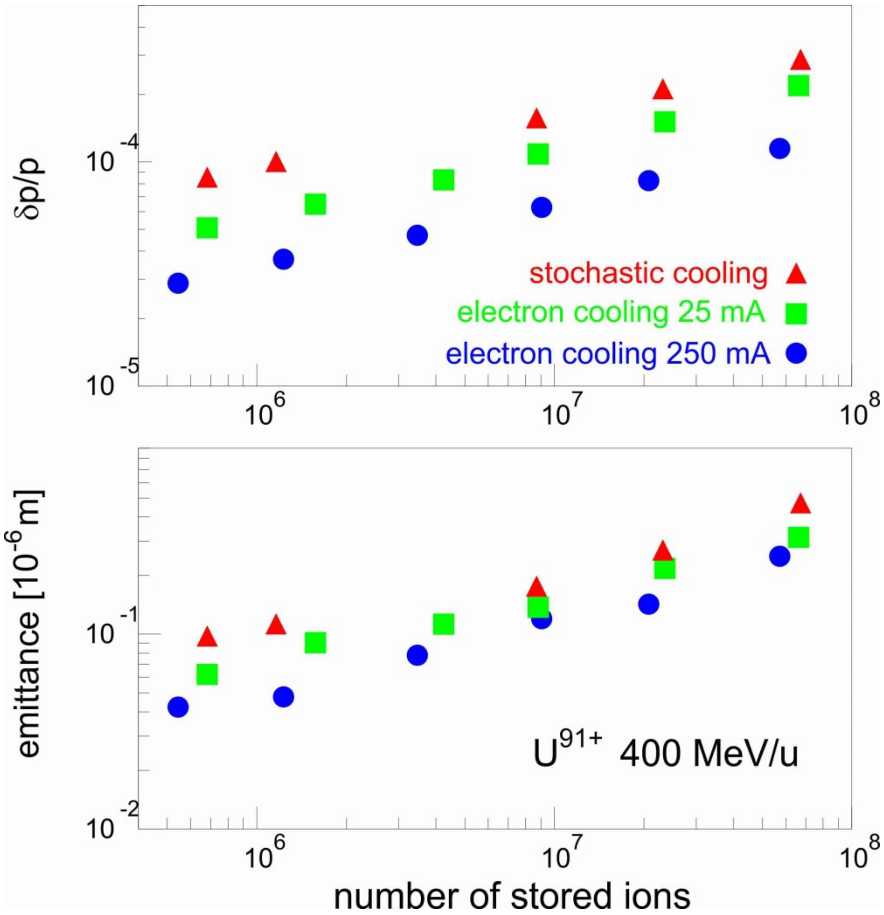
Accumulation of secondary beams

1) s.c. on injection orbit
2) rf stacking
3) electron cooling of stack



Intensity increase for secondary beams

Equilibrium Beam Parameters of Cooled Heavy Ion Beams in the ESR



beam quality is limited by intrabeam scattering

Electron cooling results in smaller momentum spread and smaller 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}]

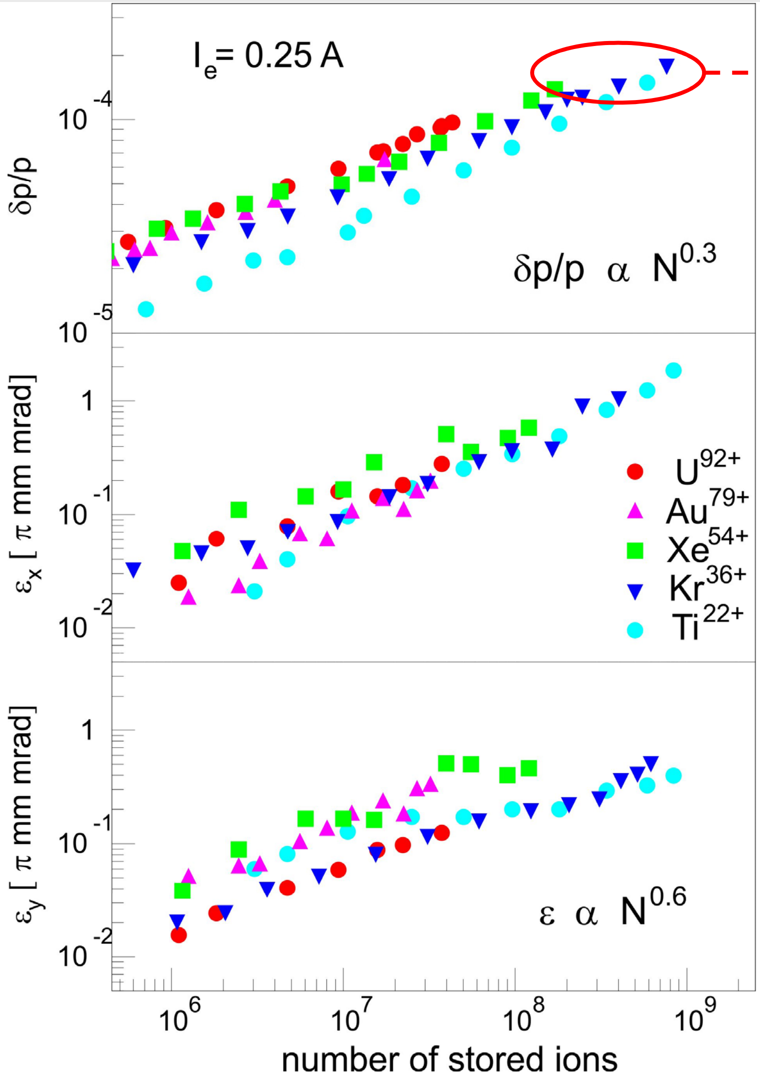
CERN code INTRABT

	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

⇒ **Electron cooling is most powerful for cold beams.**

stochastic cooling time increases α N_i

Beam Quality with Electron Cooling in ESR



stable current of up to 10 mA could be achieved for lighter ions

for heavier ions somewhat lower intensities were available

beam parameters governed by intrabeam scattering (IBS)

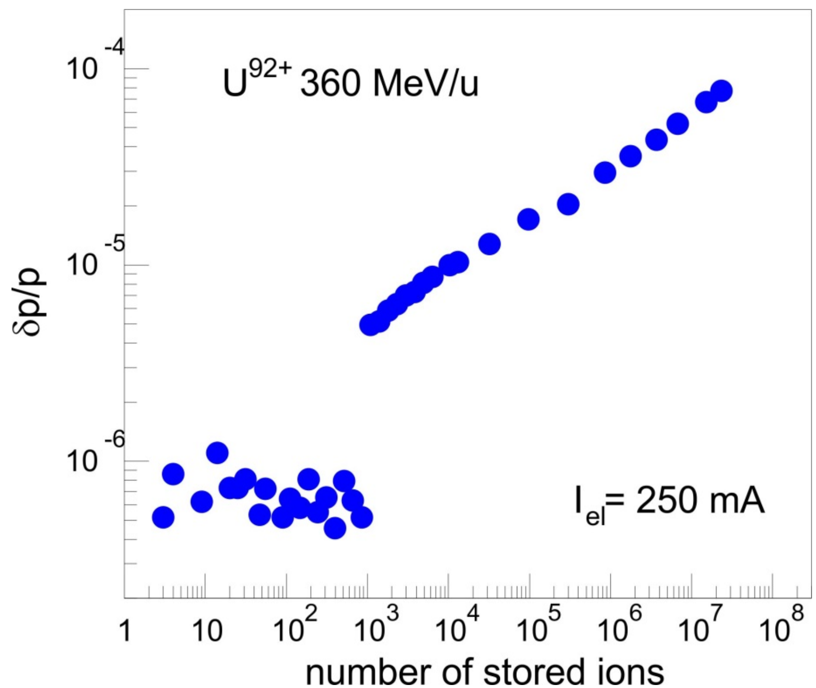
$$\tau_{IBS}^{-1} = \frac{q^4 e^4}{(Am_i)^2} \cdot \frac{N}{C\varepsilon_h \varepsilon_v \delta p/p} \cdot \frac{1}{(\gamma^4 \beta^3 c^3)} \cdot 4\pi L_C^{IBS}$$

in equilibrium with electron cooling

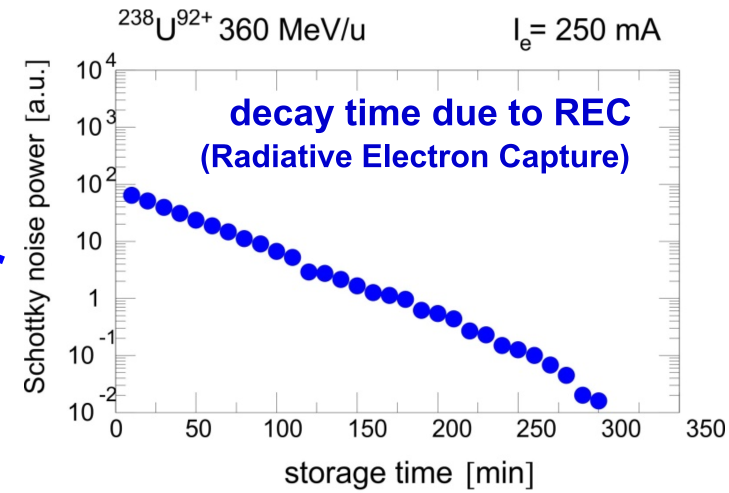
$$\tau_{ec}^{-1} \propto \frac{q^2}{A} \frac{n_e \eta}{\gamma^2}$$

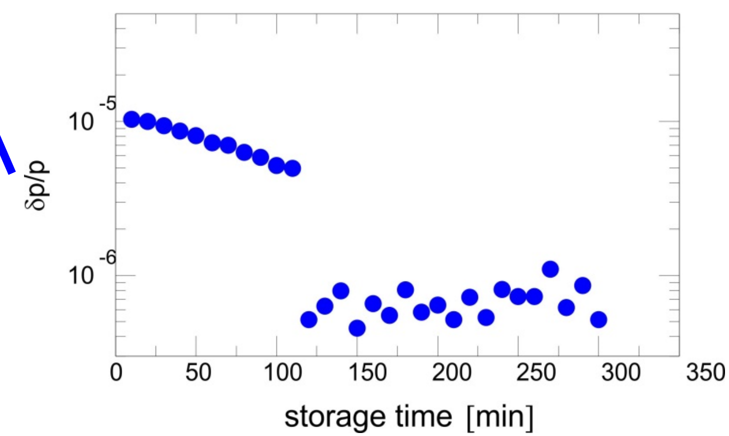
Observation of Ultra-cold Beam

reduction of momentum spread



temporal evolution of Schottky noise allows independent determination of particle number

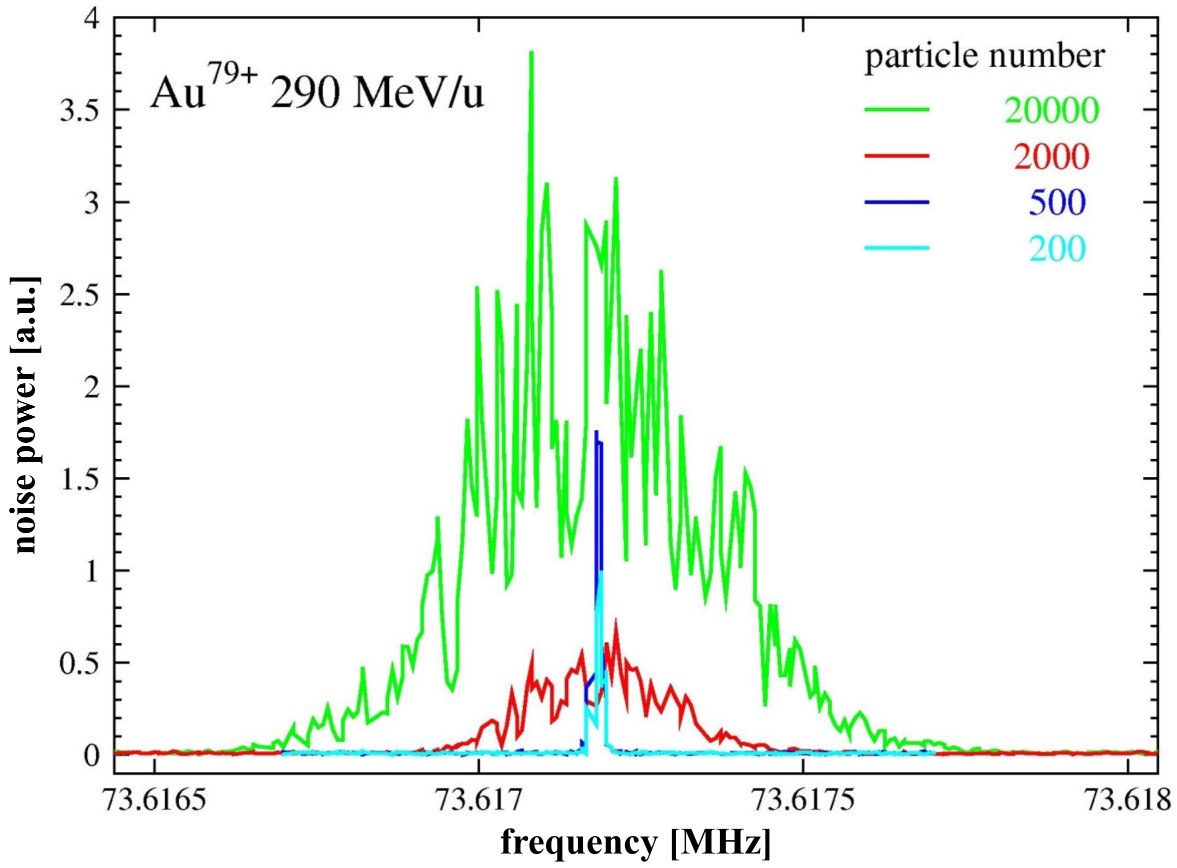




sudden reduction of the momentum spread for less than about one thousand stored ions

⇒ linear ordering in ion string

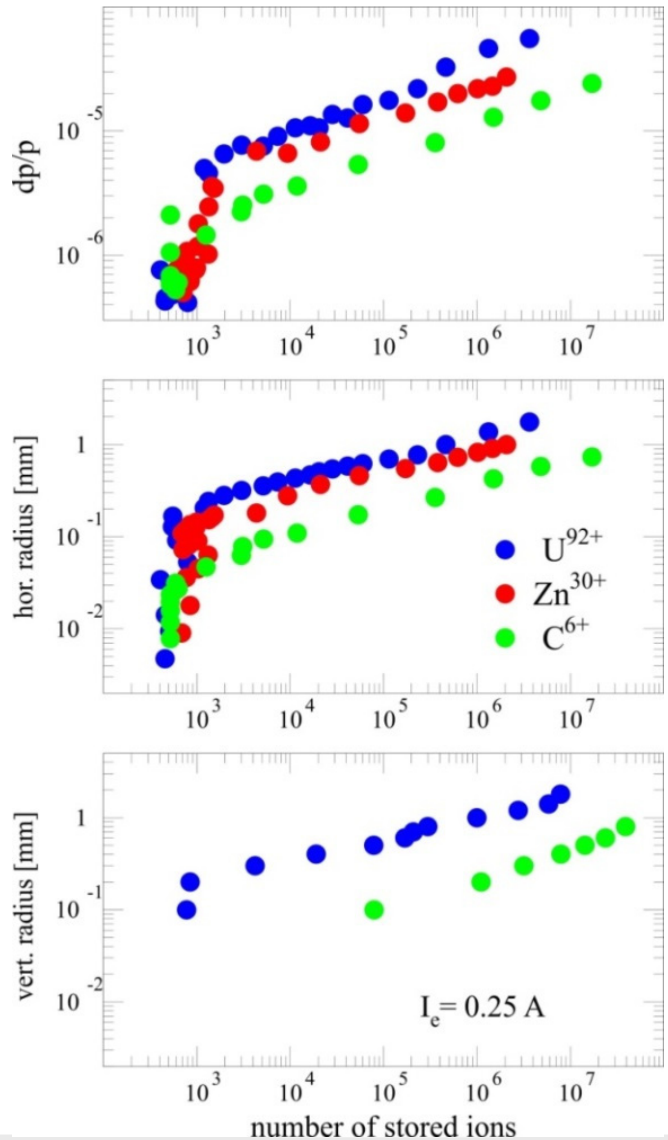
Schottky Noise Signal at Transition to Ordered Beam



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

The integrated noise power is proportional to the particle number.

Plasma Parameter



Plasma parameter $\Gamma = \frac{U_{Coul}}{k_B T} = \frac{q^2 e^2}{4\pi\varepsilon_0 a k_B T}$

$a_\perp = x_{rms}$ $\qquad a_\parallel = \gamma C/N$

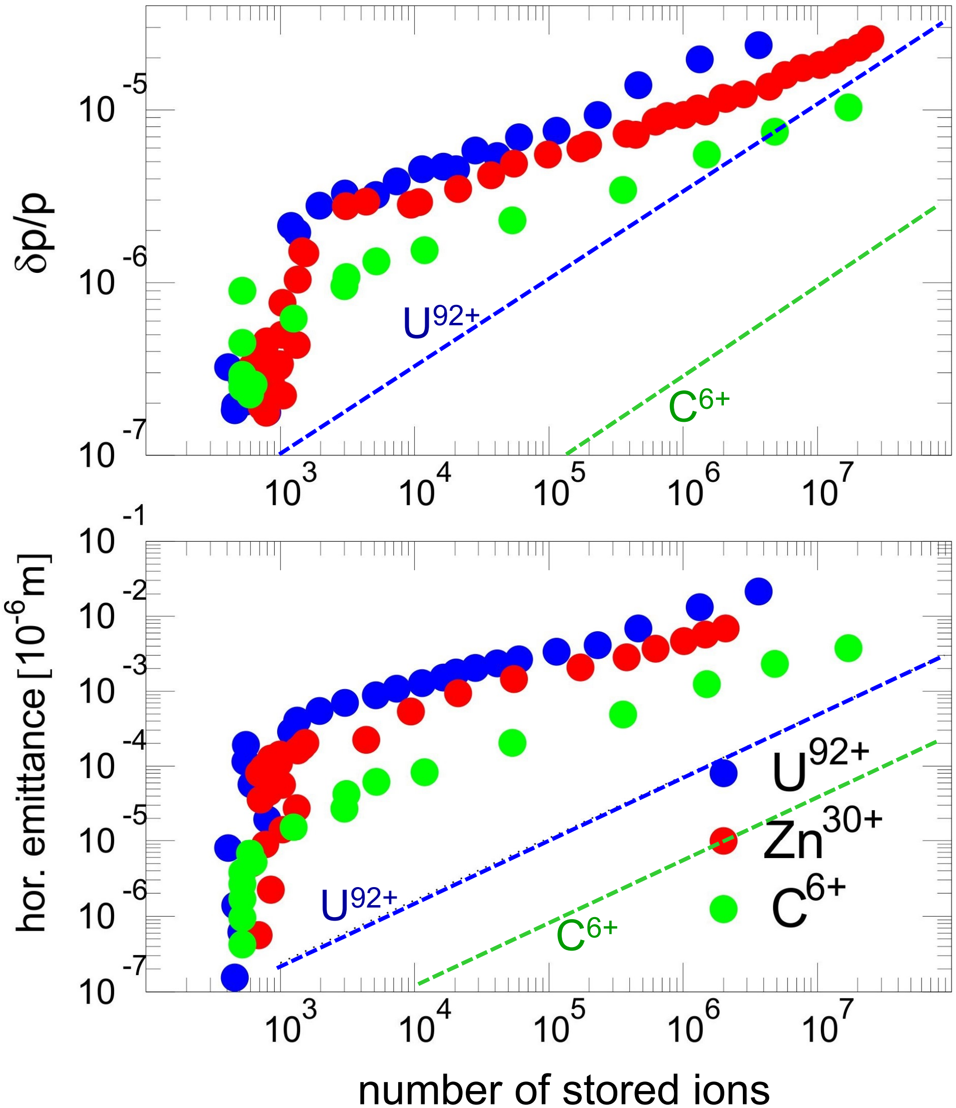
typical values (meV) of beam parameters below transition:

	C^{6+}	Zn^{30+}	U^{92+}
$k_B T_x$	0.14	1.0	0.93
$k_B T_\parallel$	0.26	1.5	5.0
$U_\perp$	194	3960	84260
$U_\parallel$	0.002	0.1	0.63

$$\frac{1}{2} k_B T_\perp = \frac{1}{2} m v_\perp^2 = \frac{1}{2} m c^2 \beta^2 \gamma^2 \theta_\perp^2$$

$$\frac{1}{2} k_B T_\parallel = \frac{1}{2} m v_\parallel^2 = \frac{1}{2} m c^2 \beta^2 (\frac{\delta p_\parallel}{p})^2$$

Intensity limits



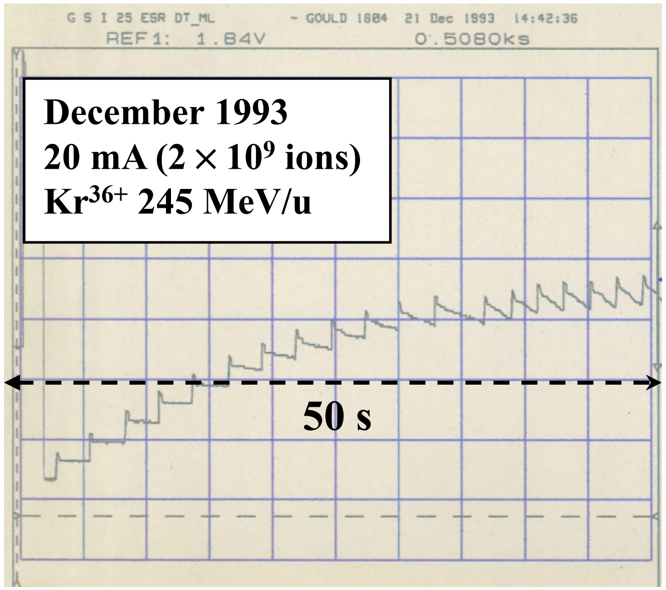
Keil-Schnell criterion

$$\left(\frac{\delta p}{p}\right)^2 \geq \frac{N\, q^2\, e^2}{|\eta|\beta\gamma A m_0 c C}\, \frac{\pi}{ln2}\, \left|\frac{Z_{\parallel}}{m}\right|$$

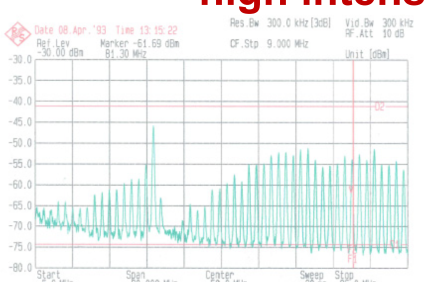
space charge limit (ΔQ = 0.01)

$$\Delta Q = - \frac{r_p\, N i\, q^2}{2\pi\, A\beta^2\gamma^3\varepsilon_x}$$

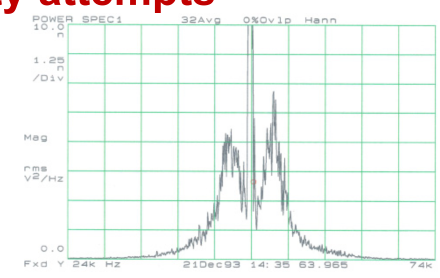
High Intensity Cooled ESR Beams



high intensity attempts



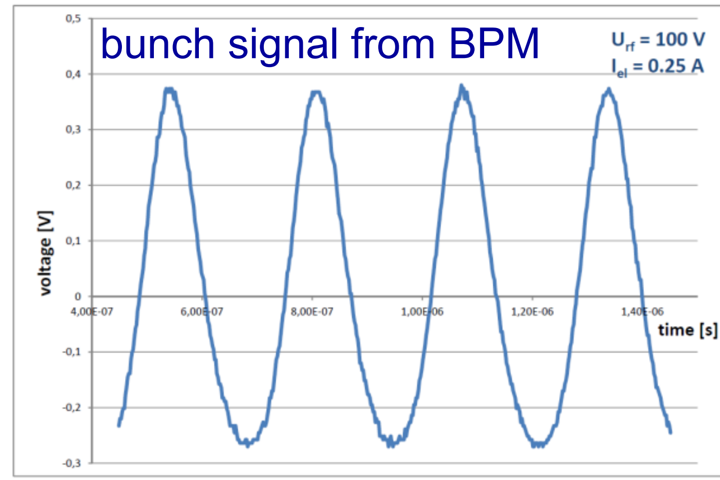
transverse coherent Schottky signal 0-90 MHz



longitudinal Schottky signal with central coherent peak

observations and attempts to apply feedback were not conclusive

December 2005
18 mA Xe^{54+} 350 MeV/u bunched (h=2, B=0.40) corresponding to over 40 mA coasting beam

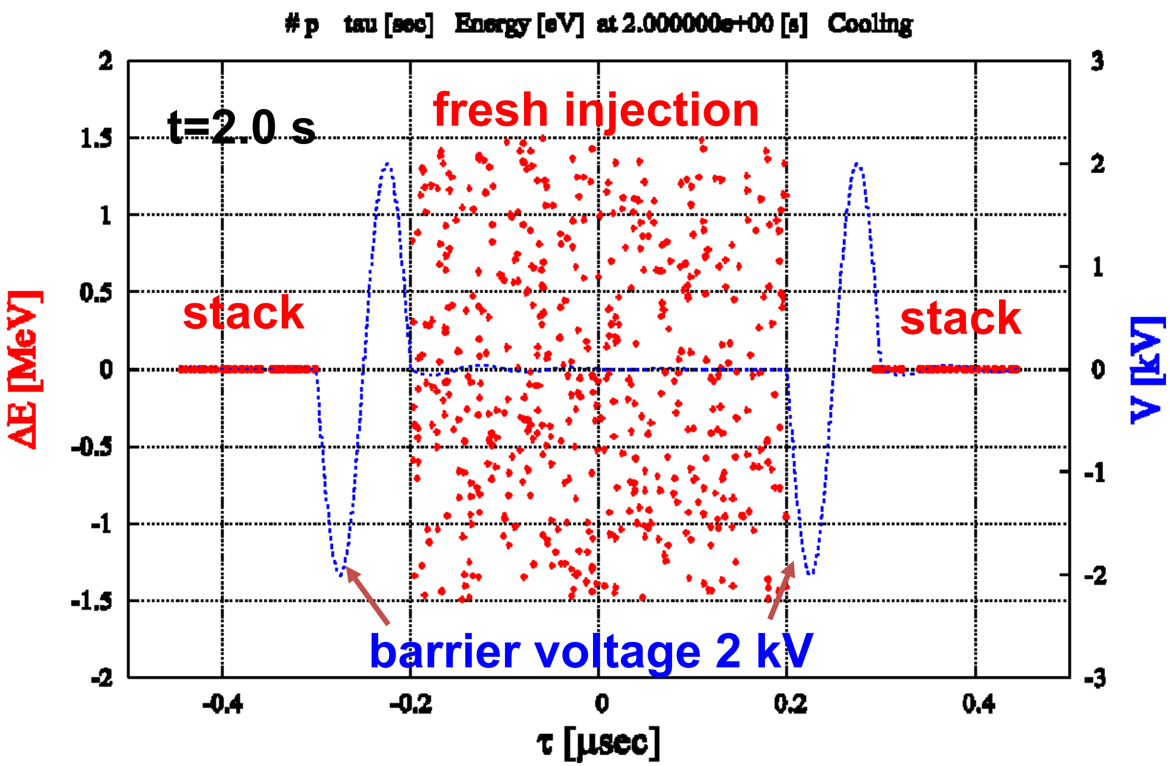


what matters?
cooling ⇒ emittance, momentum spread
orbit, tune, chromaticity, impedances

Accumulation of RIBs by Barrier Buckets

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)



proposed for the NESR Storage Ring of FAIR

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

E_k = 740 MeV/u

Longitudinal stacking with Barrier Buckets

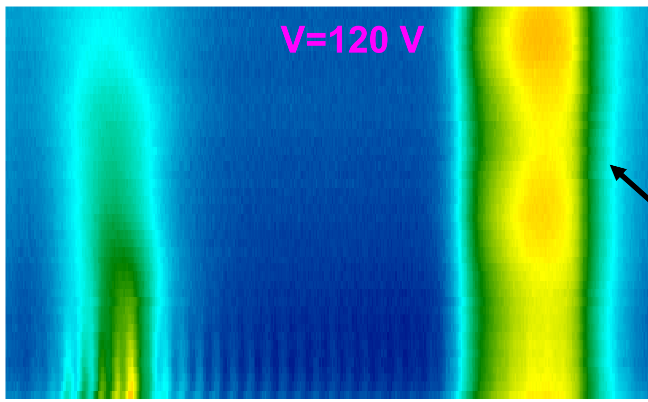
(simulation by T. Katayama)

revolution time 0.9 μs ⇒ rather short bunches of stored cooled beam

Longitudinal Accumulation in the ESR

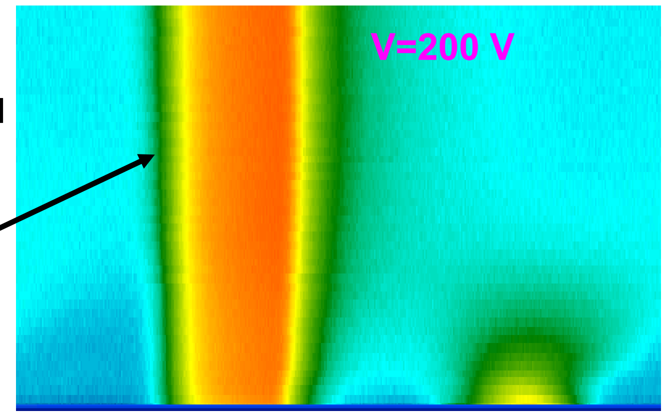
fixed barrier

200 turns/frame



700 ns

h=1 unstable fixed point

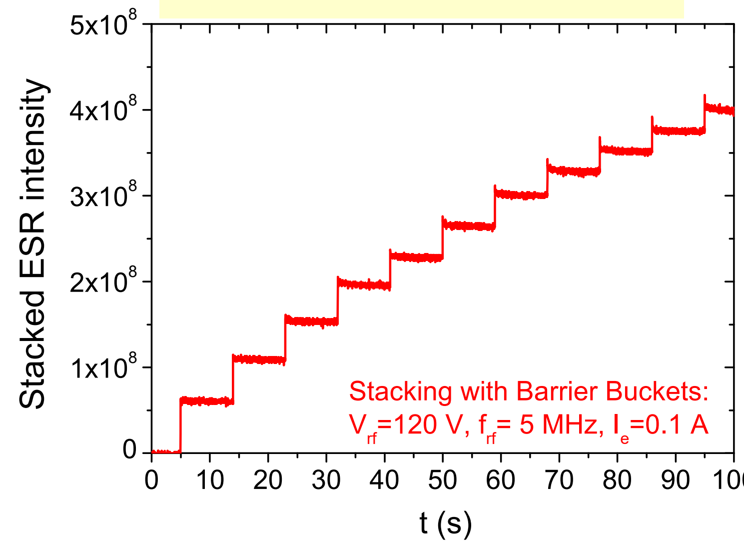


$^{124}Xe^{54+}$

154 MeV/u

stack

fast beam accumulation



accumulation schemes work well:

cooling times close to expectations

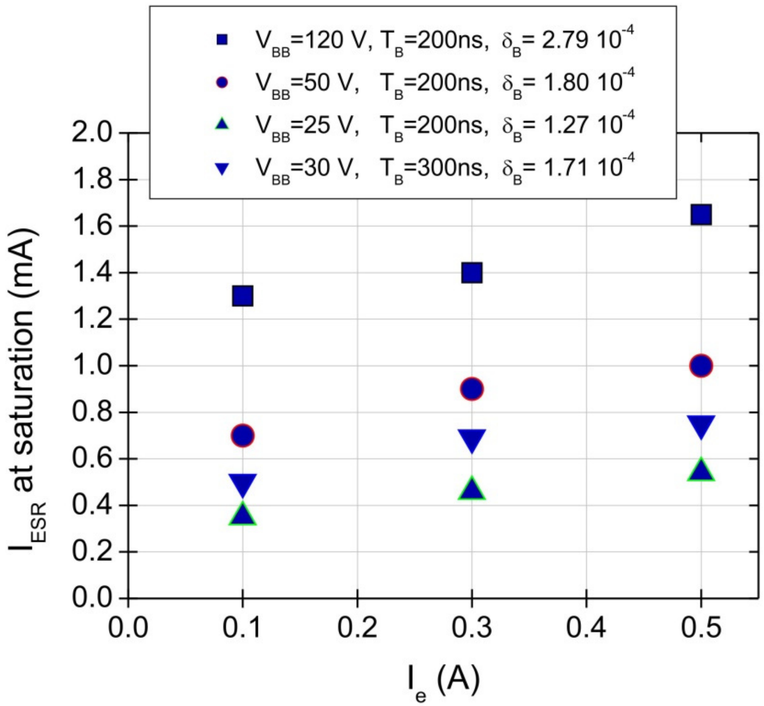
efficient accumulation

high quality timing and kicker pulses required

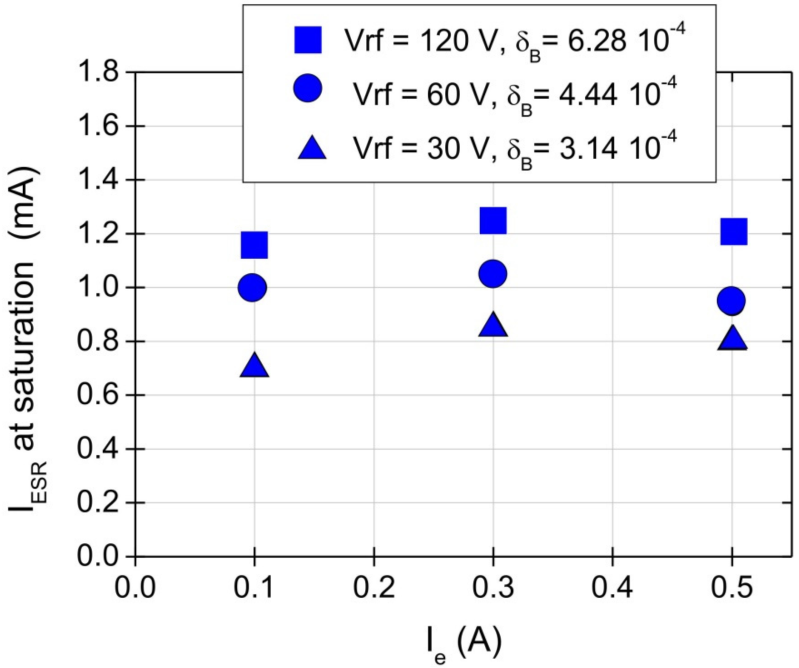
Intensity limits: rf voltage and instabilities

Intensity Limits of Stacking

Stacking with Barrier Buckets

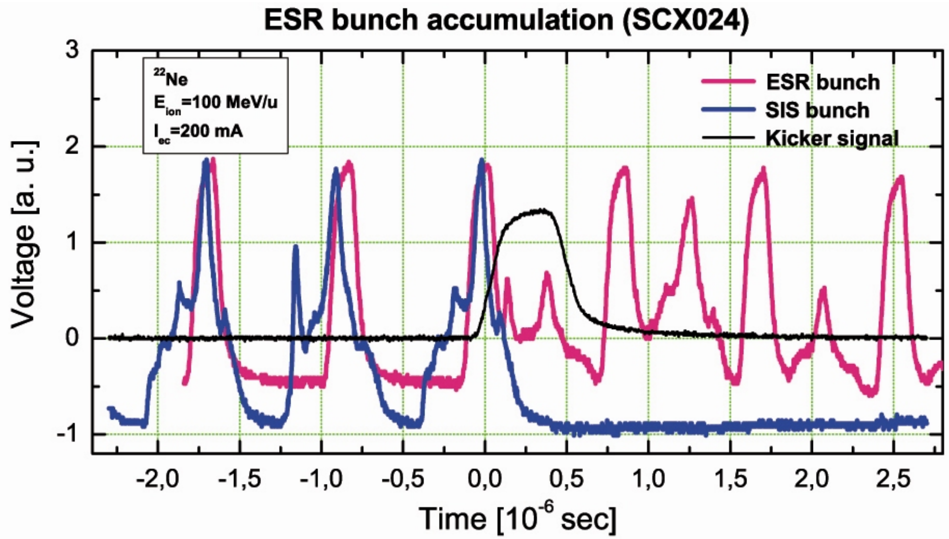


Stacking at Unstable Fixed Point h=1



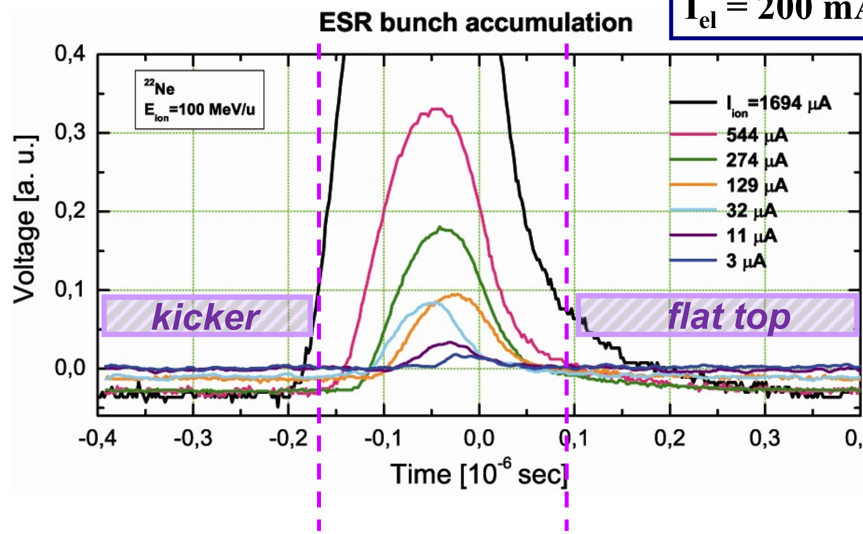
barrier height and cooling rate determine the intensity limit

Accumulation of $^{22}Ne^{10+}$ at 100 MeV/u

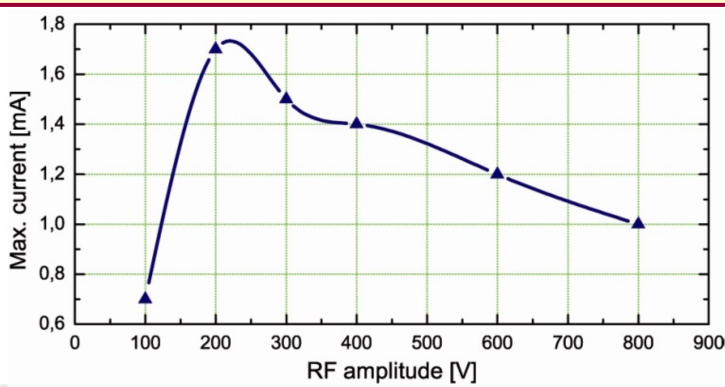


Cooled ESR bunch (h=1)

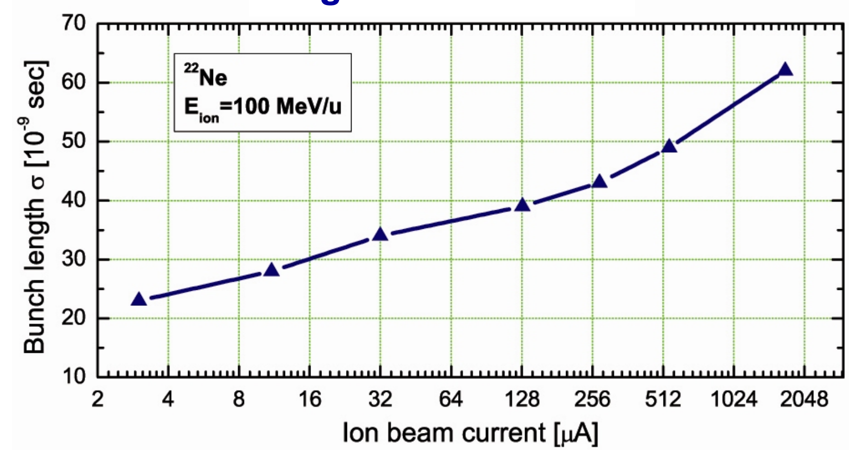
U_{rf} = 200 V
I_{el} = 200 mA



Intensity limit is a trade off between bunch length (≤ 200 ns) and local ion current (≤ 6-8 mA)

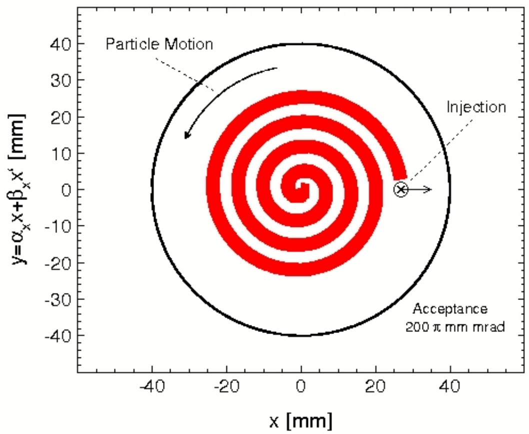


Length of ion bunch

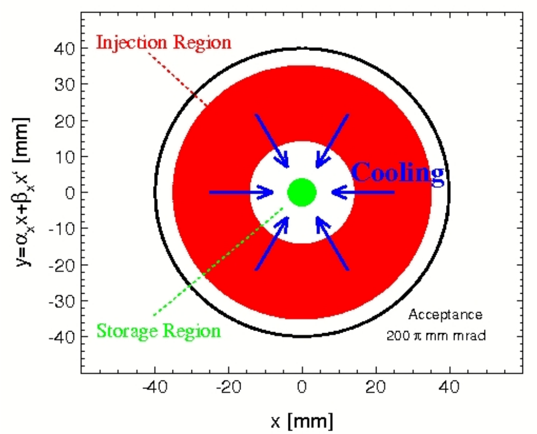


Transverse Cooling for Accumulation in SIS

standard multiturn injection

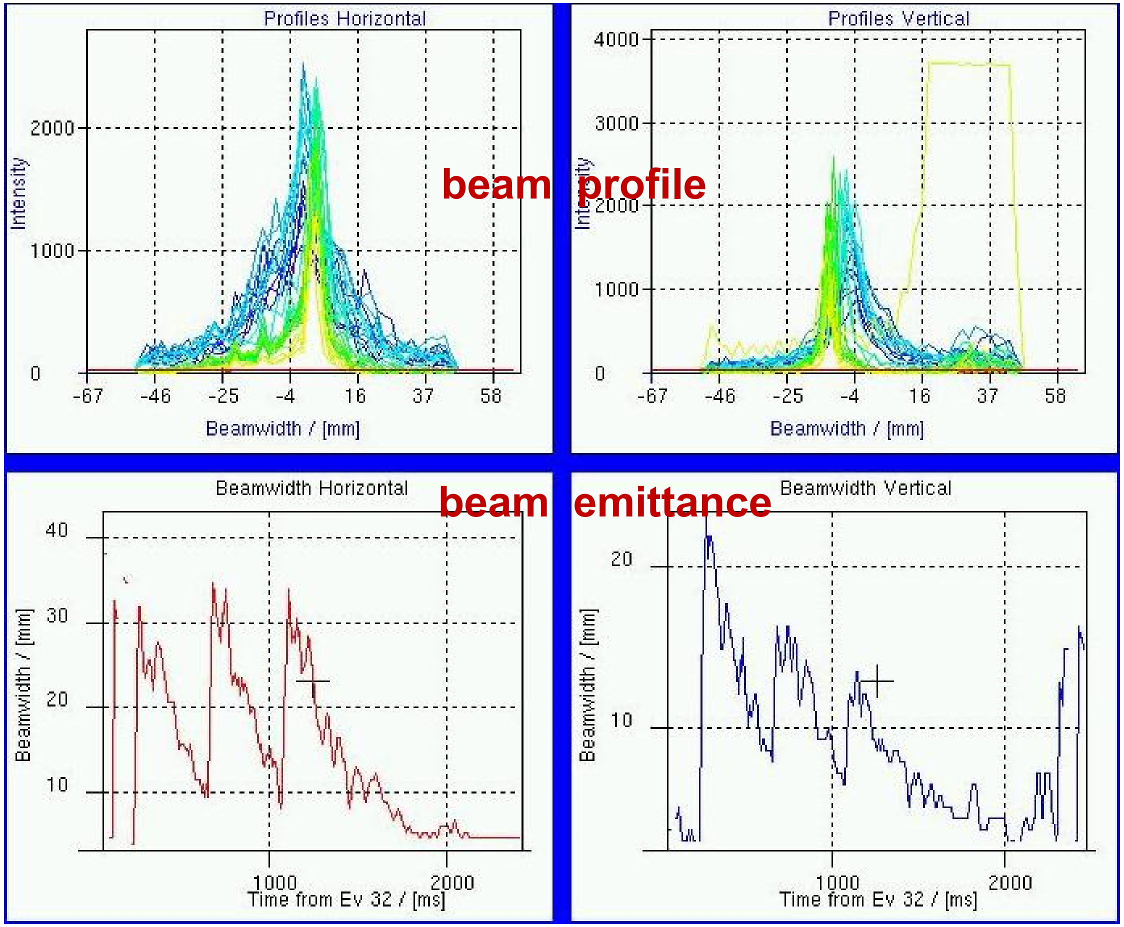


fast accumulation by multiple multiturn injection with electron cooling



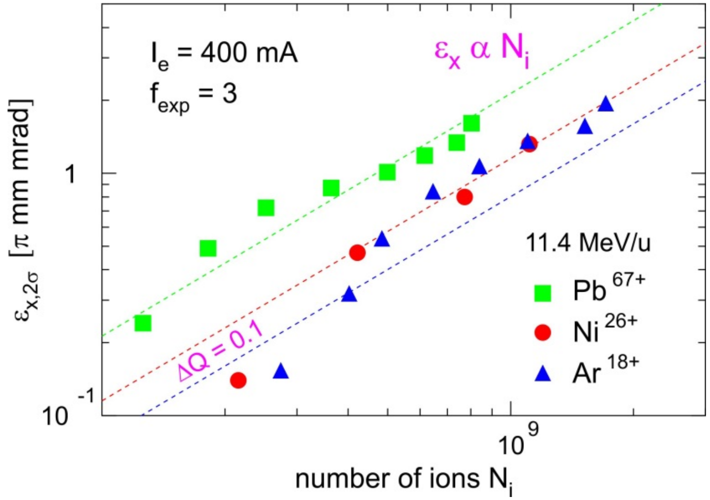
fast transverse cooling

horizontal **vertical**

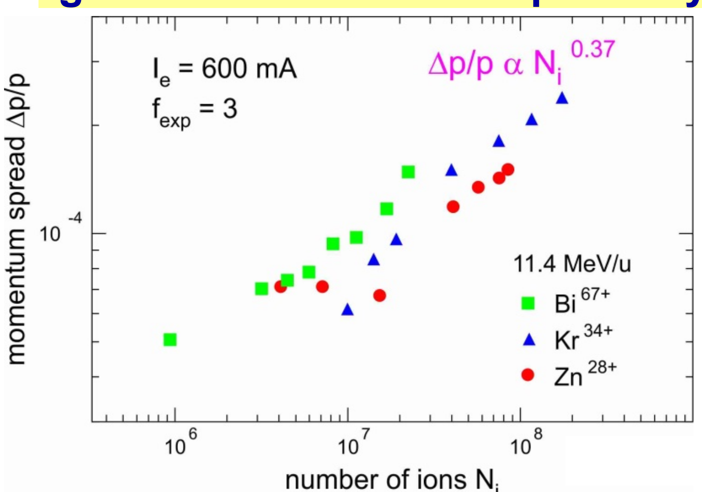


Limits of Beam Accumulation by MMTI

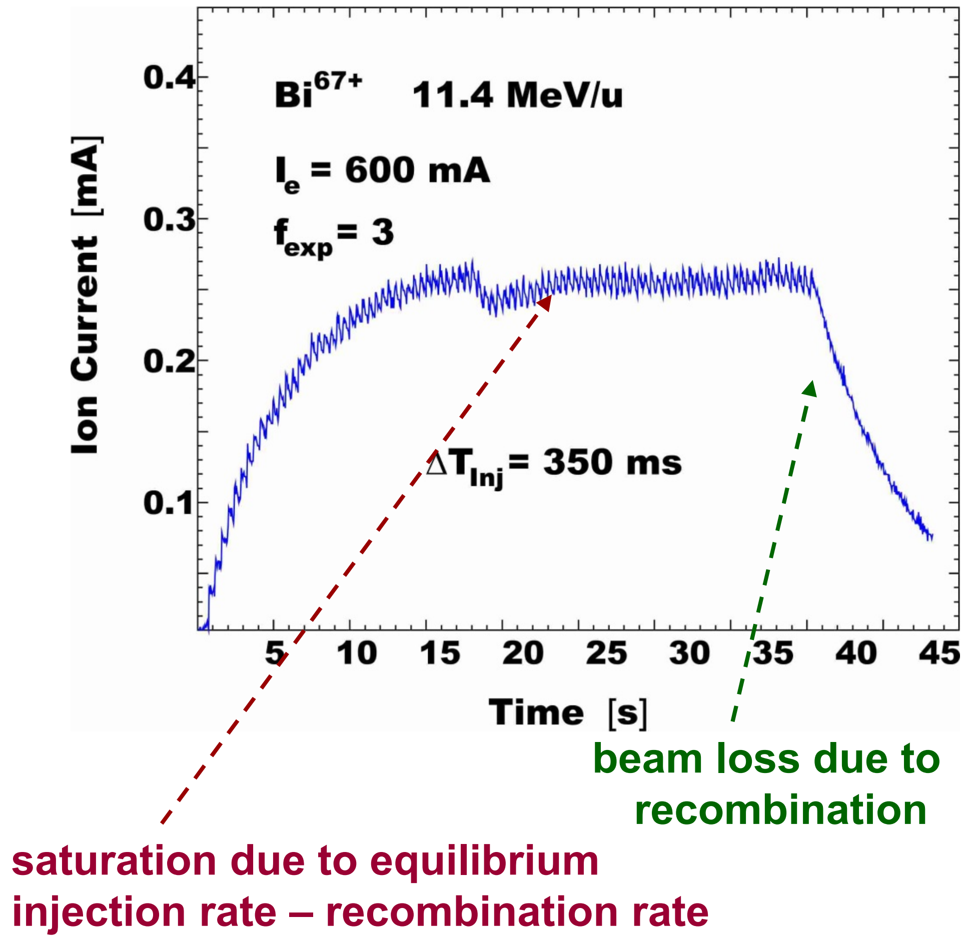
emittance growth by space charge



growth of momentum spread by IBS

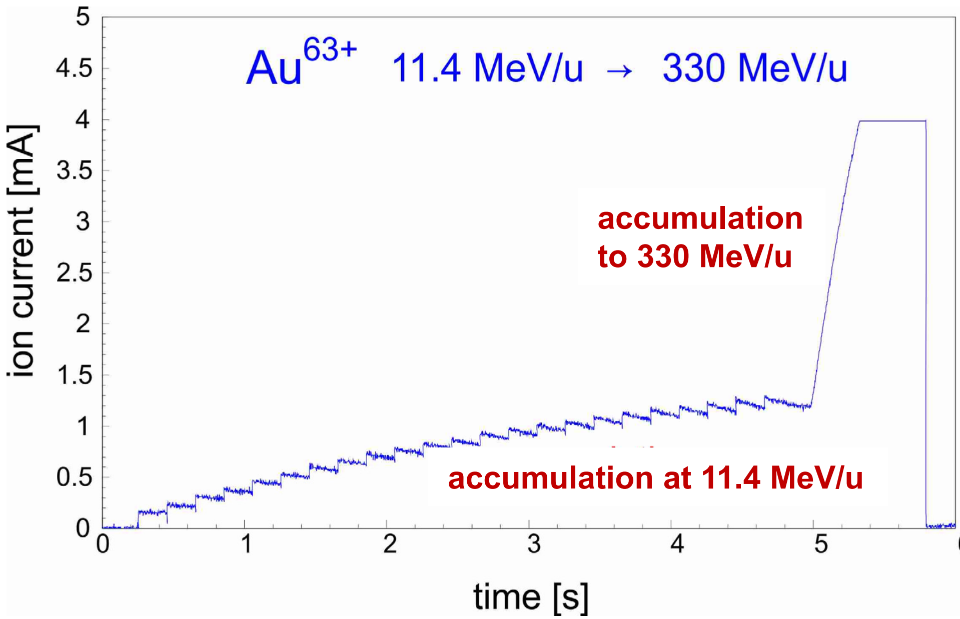


beam lifetime (recombination, vacuum) must be long compared to cooling time

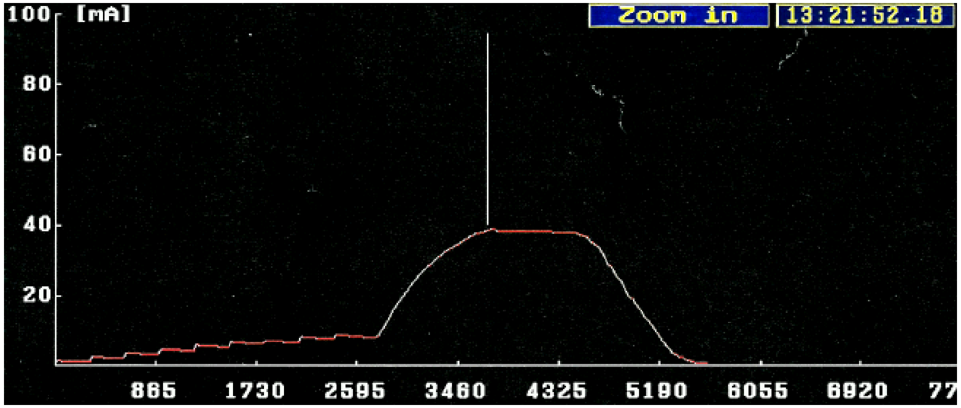


High Intensity Cooled Beam at SIS18

high intensity beams of a few milliAmperes have been accumulated routinely in SIS18



during operation with high intensity uranium beams a limit of around 10 mA (3×10^9 ions of $^{238}U^{73+}$ at 11.4 MeV/u) was encountered, accompanied by collective transverse beam oscillations



Unexplained Loss of High Intensity Beams

CELSIUS Uppsala (Beam Cooling Montreux 1993)

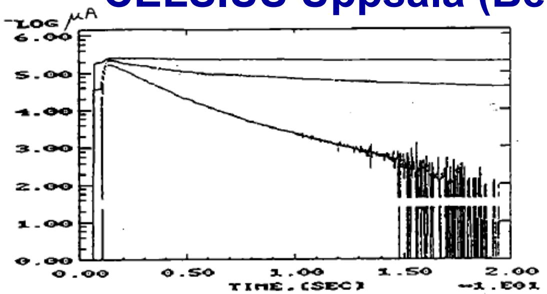


Fig. 3. Measurement of intensity (shown as ^{10}log of μA) vs. time (from zero to 20 s) for a bunched beam of 48 MeV protons (rf. voltage about 200 V), without electrons (best lifetime), with 400 mA electron beam with 4 cm diameter, and with 100 mA of electron beam with 2 cm diameter (worst lifetime).

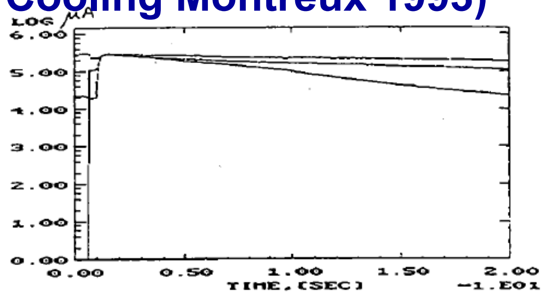


Fig. 4. As fig. 3 but for coasting beam of 48 MeV protons. The best lifetime is without electrons. The next curve is with 400 mA electron beam with 4 cm diameter. The worst lifetime is with 100 mA electron beam with 2 cm diameter.

COSY Jülich (annual report 2003)

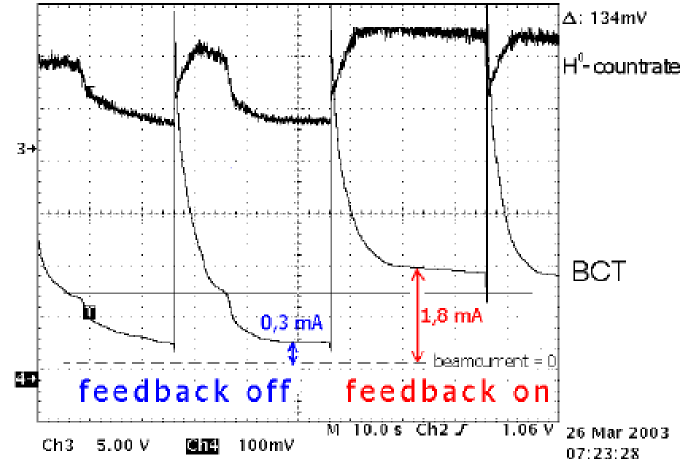
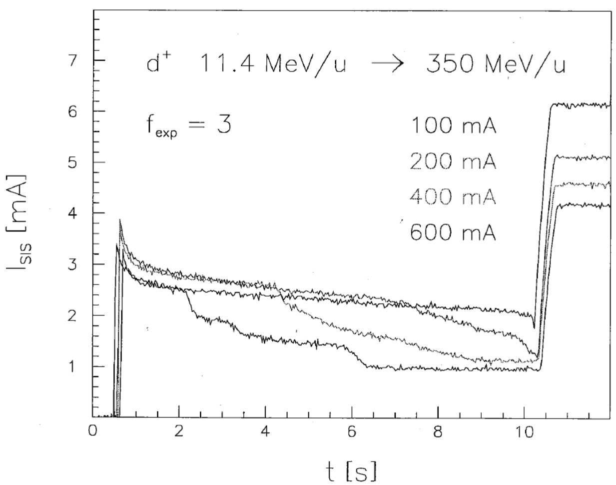


Fig. 3: BCT and H^0-countrate signals without FB and with FB switched on. Time scale 10 s/div.

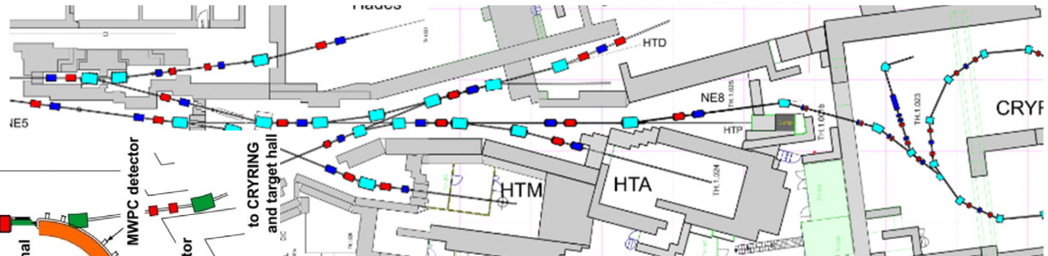
electron cooling of deuterons in SIS18

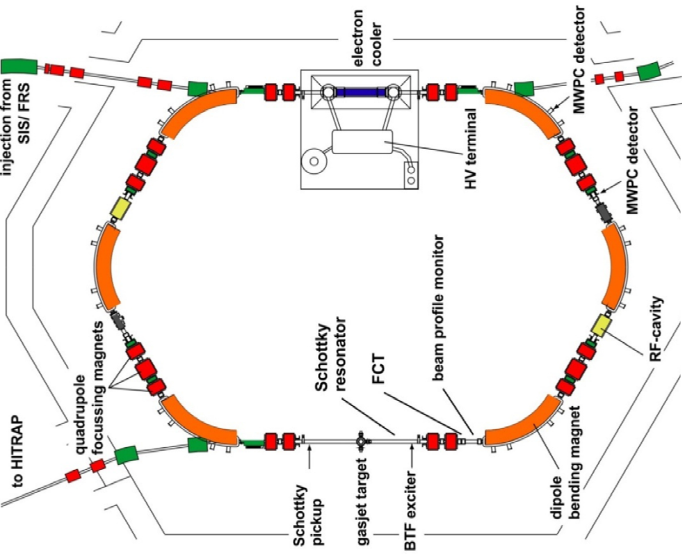


Losses during cooling of the initially hot injected ion beam

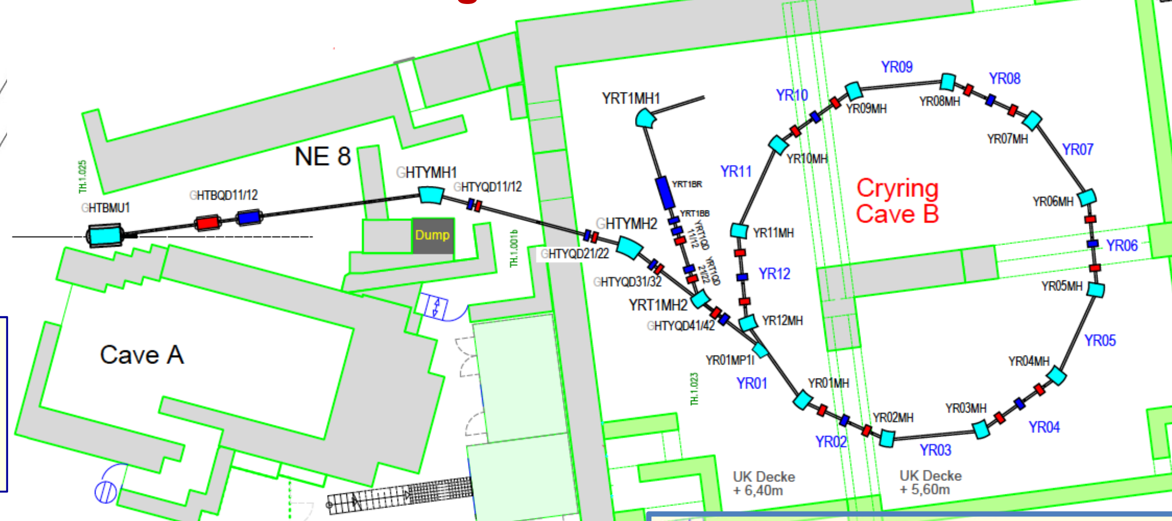
possible reasons:
transverse instabilities
non-linear resonances
impedance of electron beam
heating due to non-linear fields of the electron beam

Connecting ESR to CRYRING@ESR

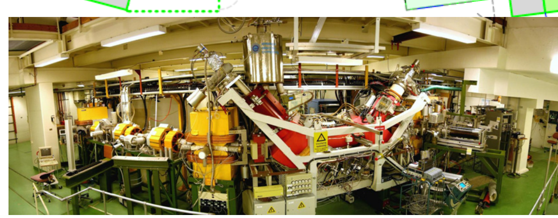




goal: stored, cooled highly charged ions at lowest energies

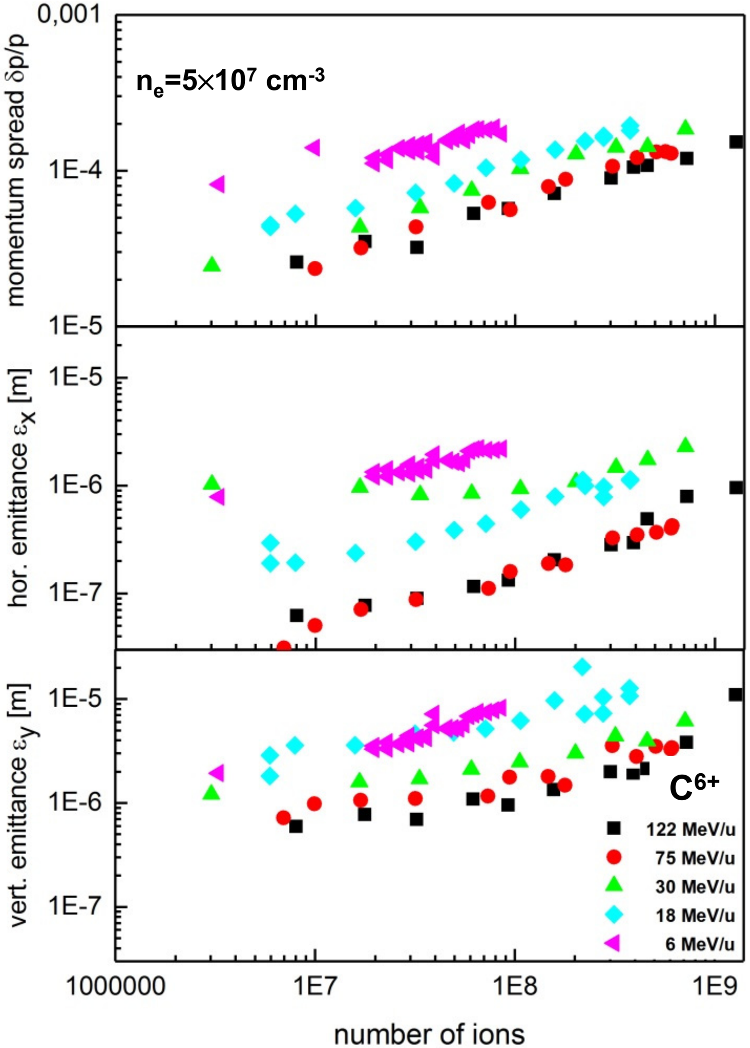


ESR decelerates highly charged ions or rare isotope beams from 400 MeV/u to 4-15 MeV/u



Max. rigidity 1.44 Tm
15 MeV/u U^{92+}
Min. rigidity ~ 0.054 Tm
21 keV/u U^{92+}

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

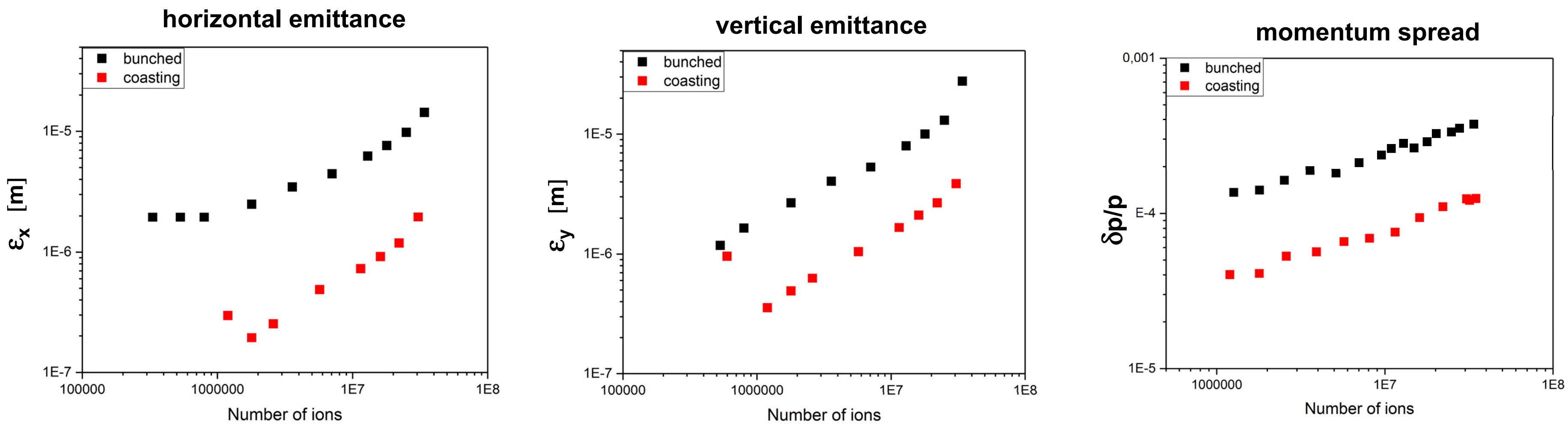
tune shift

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

increases proportional $1/(\beta^2\gamma^3)$

space charge effects are increased for low energy cooled beams

Beam Parameters of Bunched Ions



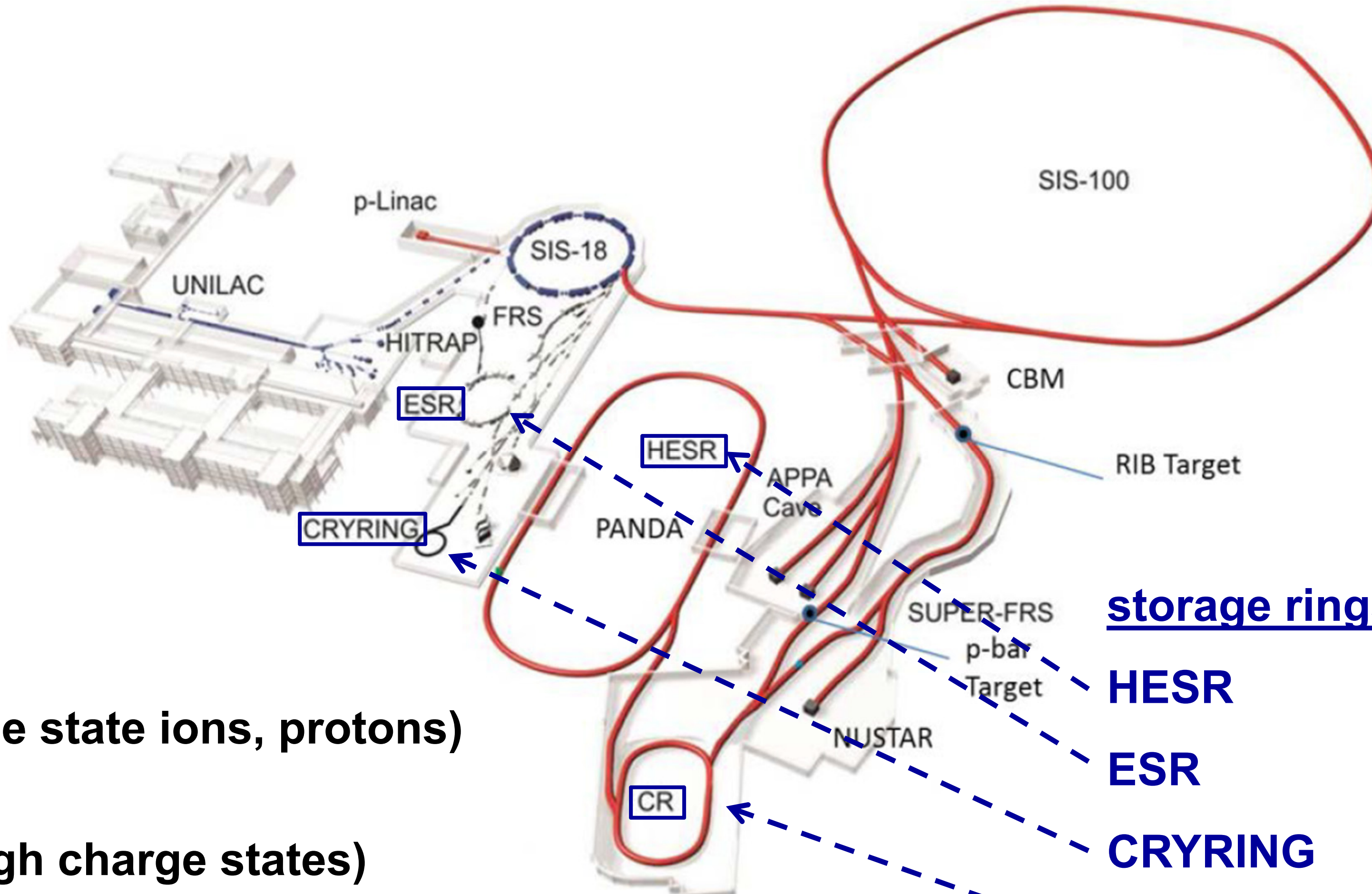
$^{238}U^{89+}$ 75 MeV/u cooled by I_{el}=0.2 A

increase of emittance (factor of 5-8) is not proportional to the bunching factor (15-50)

space charge effects are increased for bunched beams

and finally: bunching the beam for deceleration or transfer is the most critical situation with respect to space charge issues

The FAIR Facility



goals:

higher intensity
(heavy low charge state ions, protons)

higher energy
(heavy ions in high charge states)

production of antiprotons and RIBs

high quality secondary beams (cooling)

storage rings:

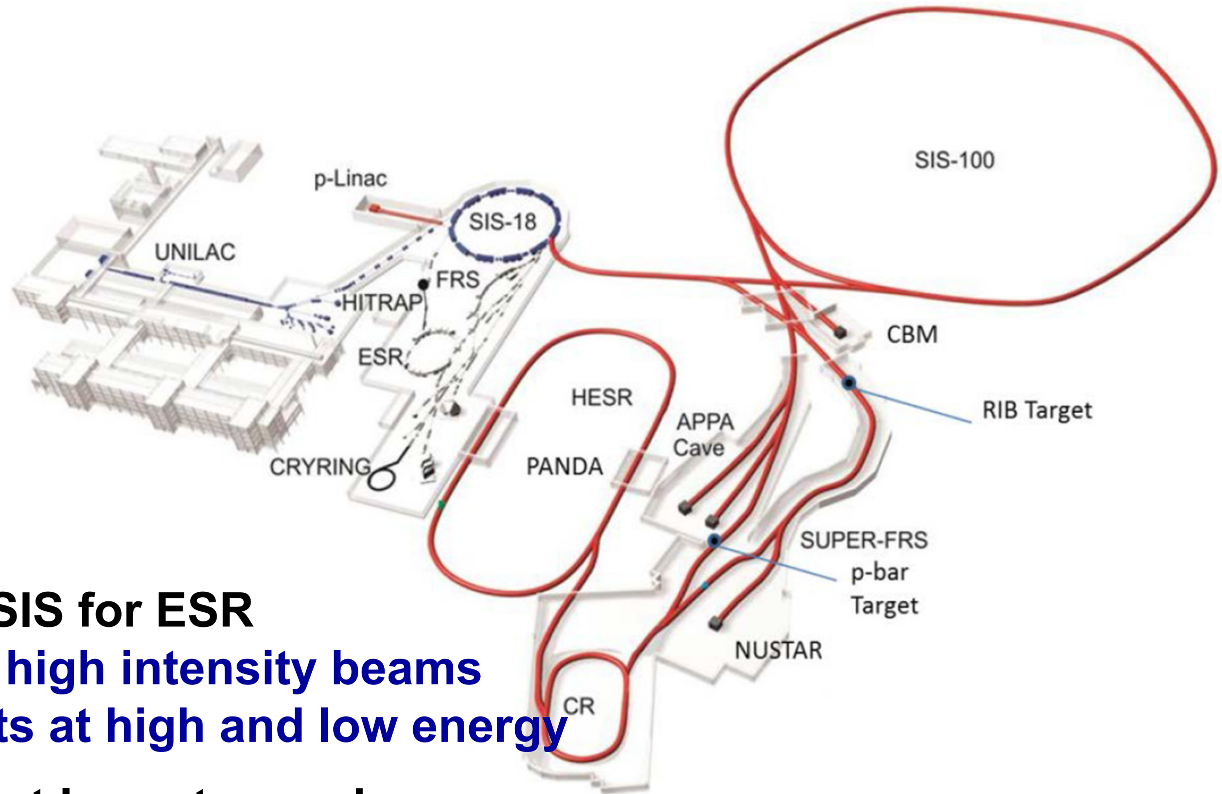
HESR

ESR

CRYRING

Collector Ring

High Brightness in FAIR Storage Rings



- **high intensity beams from SIS for ESR**
  ⇒ studies of the cooling of high intensity beams
  nuclear physics experiments at high and low energy
- **highly charged ions stored at lowest energies**
  ⇒ space charge issues in ESR and CRYRING
- **availability of dedicated barrier bucket system for accumulation of high intensity beams in ESR and HESR**
- **continue experiments with extremely cold ion beams in ESR and CRYRING**