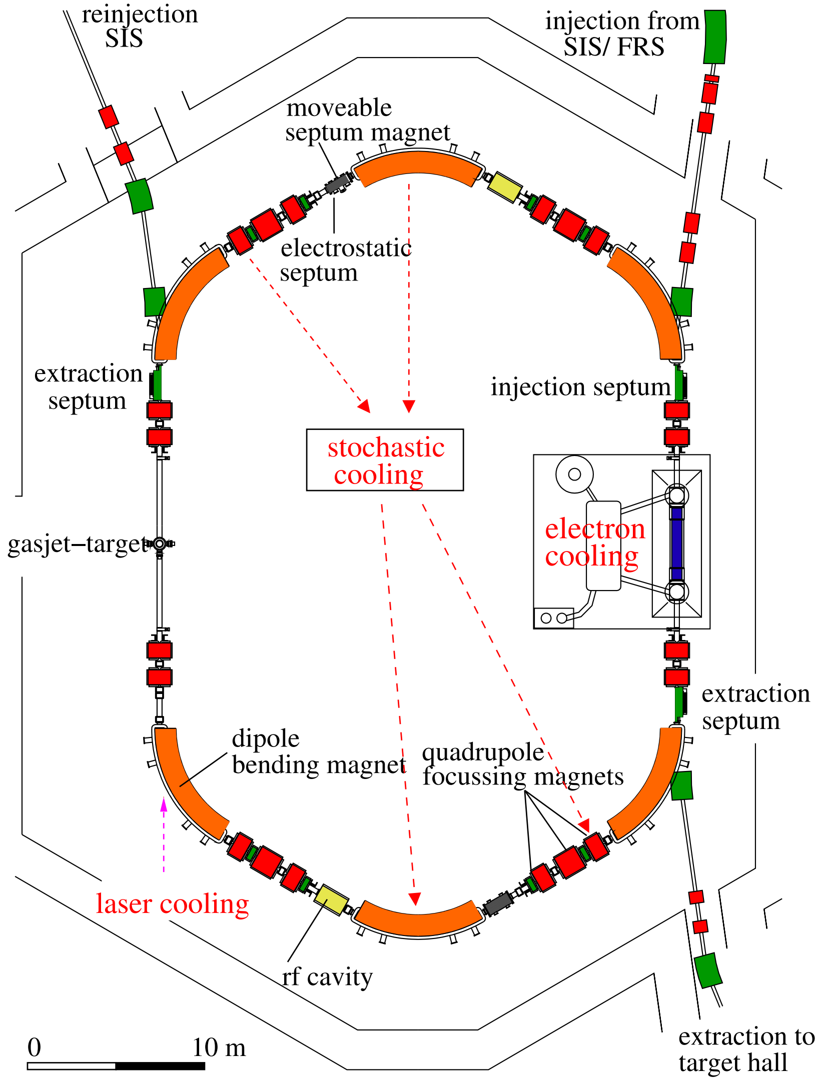
Status and Prospects of ESR and CRYRING

M. Steck

Stored Beams Division

ESR Operation



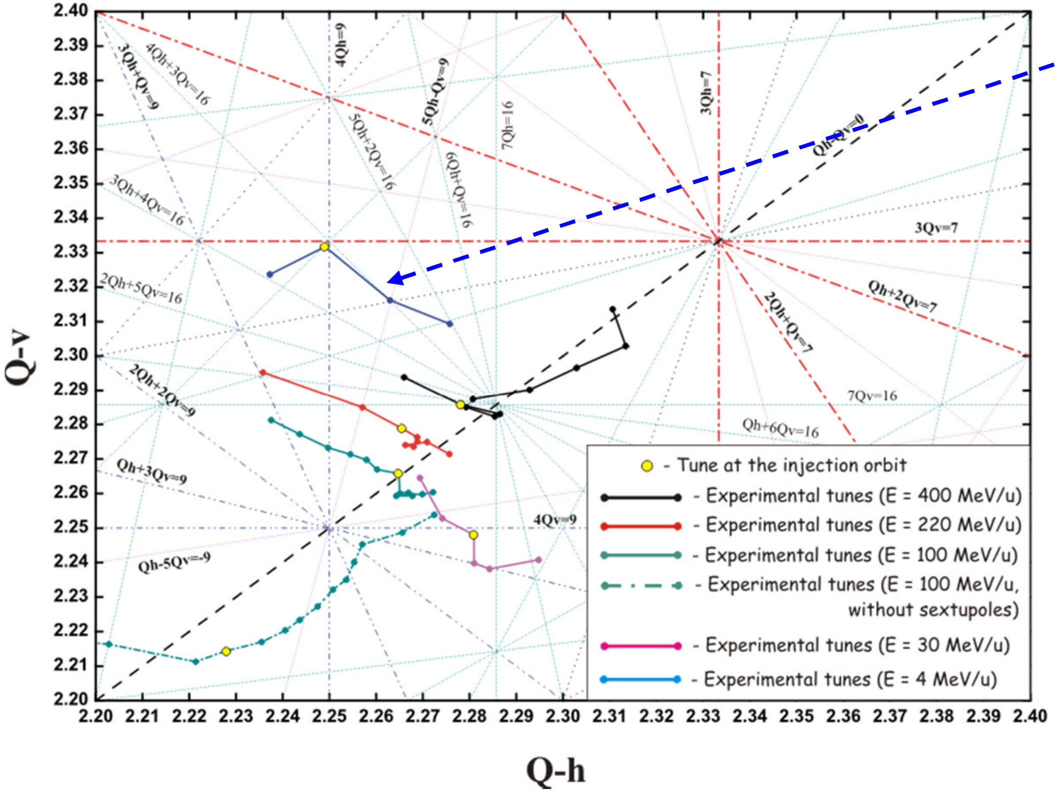
- Fast injection (stable ions / RIBs)
- Stochastic cooling (≥ 400 MeV/u)
- Electron cooling (3 - 430 MeV/u)
- Laser cooling (C^{3+} 120 MeV/u)
- Internal gas jet target
- Laser experiments
- Acceleration/deceleration (down to 3 MeV/u)
- Fast extraction (reinjection to SIS / HITRAP)
- Slow (resonant) extraction
- Ultraslow extraction (charge change)
- Beam accumulation
- Multi charge state/multi component operation
- Schottky mass spectrometry
- Isochronous mode (TOF detector)

All these modes work somehow, but all are far from perfect or routine.

Ion Optical Studies

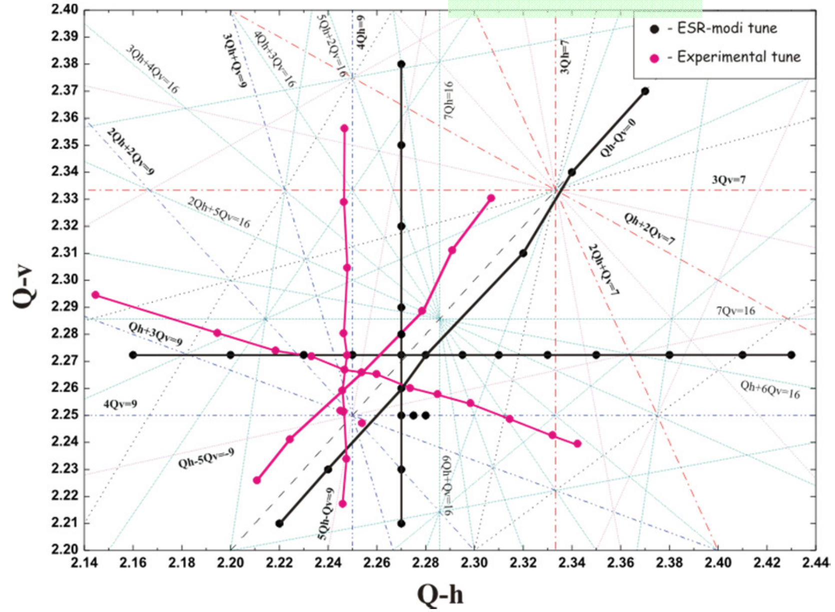
Tune Measurements

motivation: long-standing (wrong quadrupole strength, since 1990) and unexplained beam loss (meanwhile solved)



Some systematic measurements at 4 MeV/u (lifetime, intensity limit such studies)

S. Litvinov

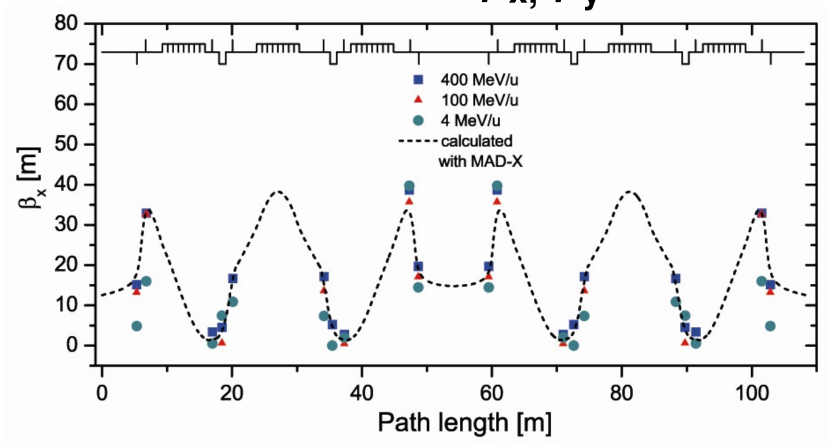


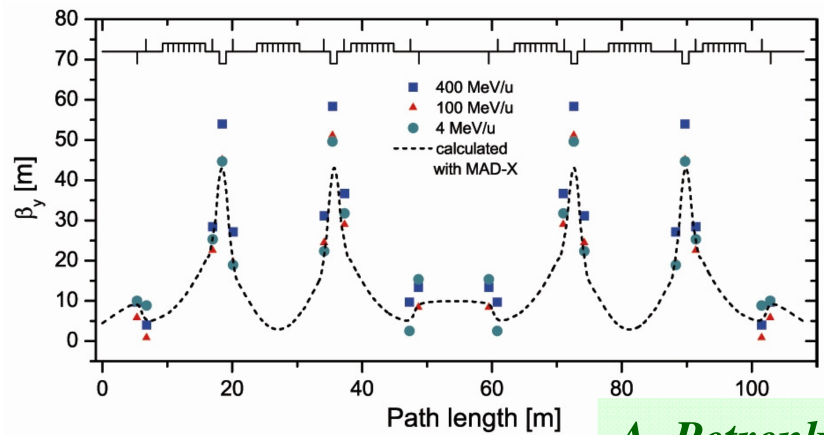
Improvement of ring model is prerequisite for a simplified and automated ring operation

Ion Optical Studies

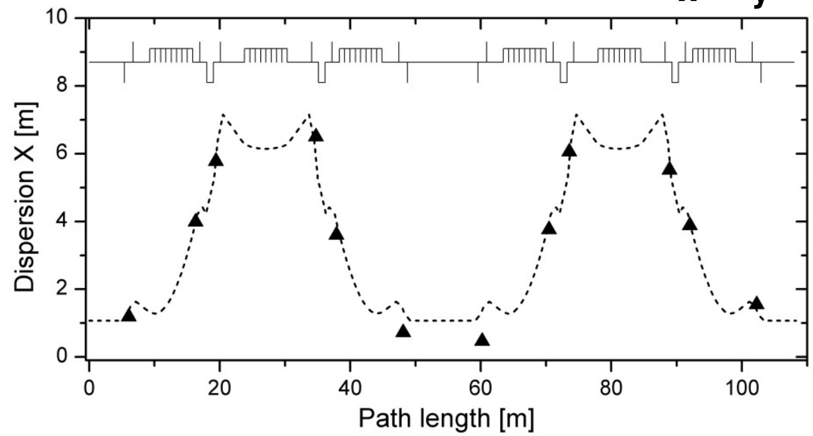
Tune Response and Dispersion

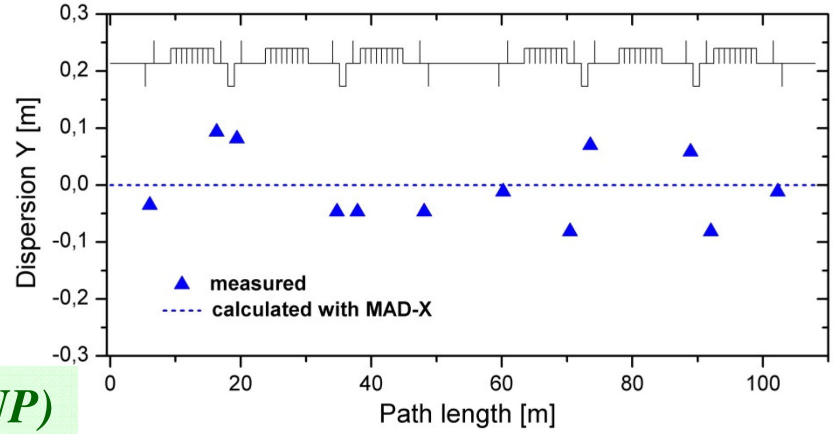
Beta functions β_x, β_y





Dispersion functions D_x,D_y





A. Petrenko (BINP)

Tune response measurements

beta function $\beta \simeq \frac{4\pi}{l}\frac{\partial \nu}{\partial K_1}, \quad K_1 = \frac{1}{B\rho}\left|\frac{\partial B_y}{\partial x}\right|$

dispersion measurements

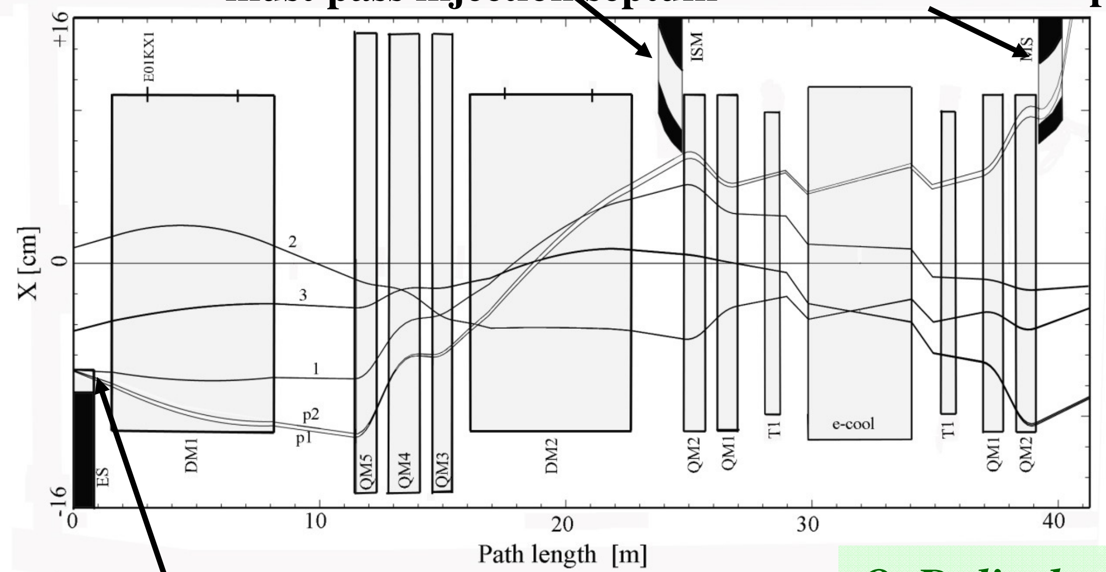
$$D_x = \frac{\Delta x}{\Delta p/p}$$

Slow (Resonant) Extraction from ESR

test with Ar^{18+} 100 MeV/u

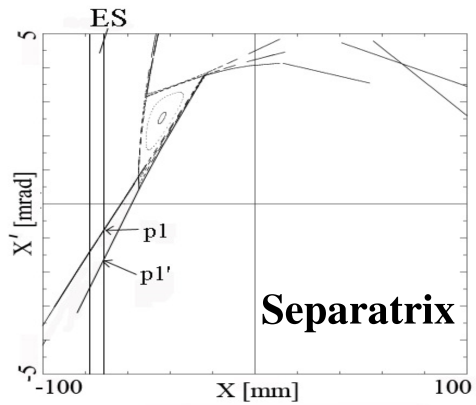
must pass injection septum

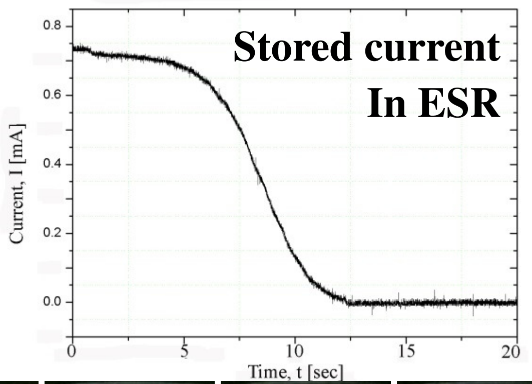
extraction septum



Kick in electrostatic septum

O. Dolinskyy



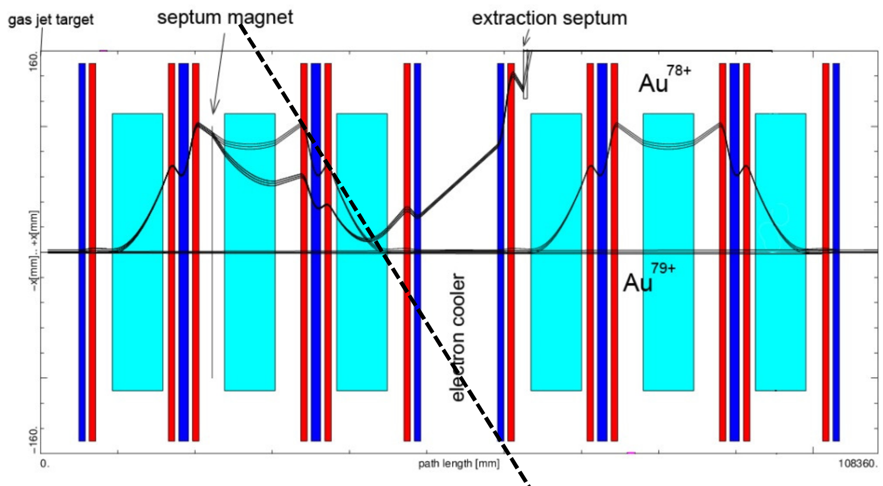


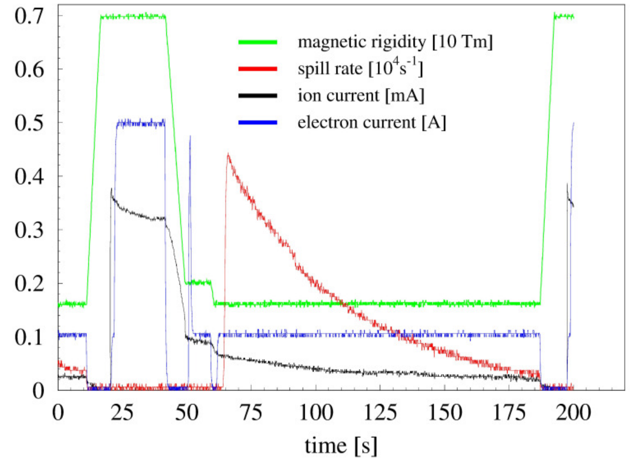
Beam profile on fluorescent screen (every second)

Beam center was moving during extraction

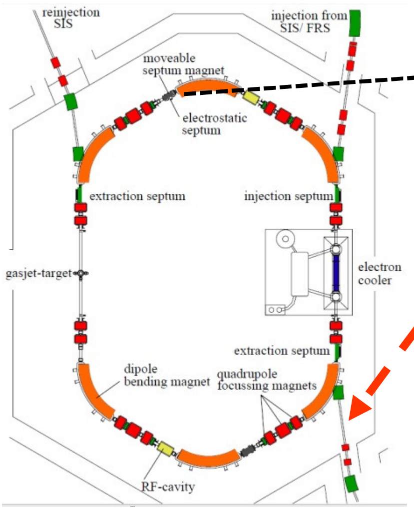
Successful proof of feasibility, but extraction of decelerated beams will require much more efforts

Slow Extraction by Charge Change

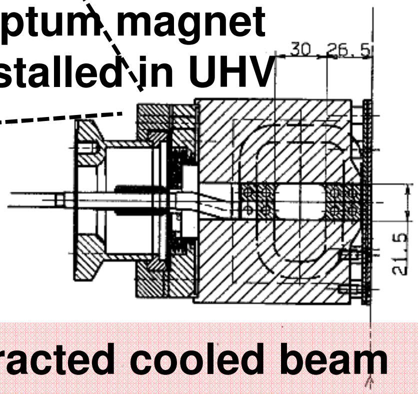


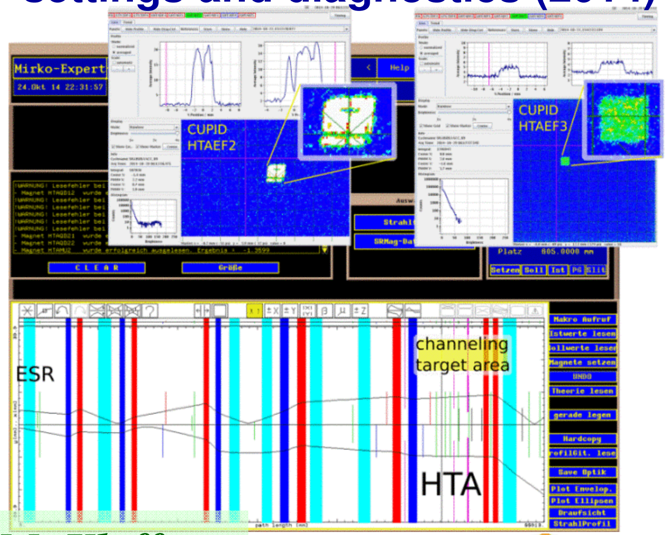


improvement of beamline settings and diagnostics (2014)



septum magnet installed in UHV





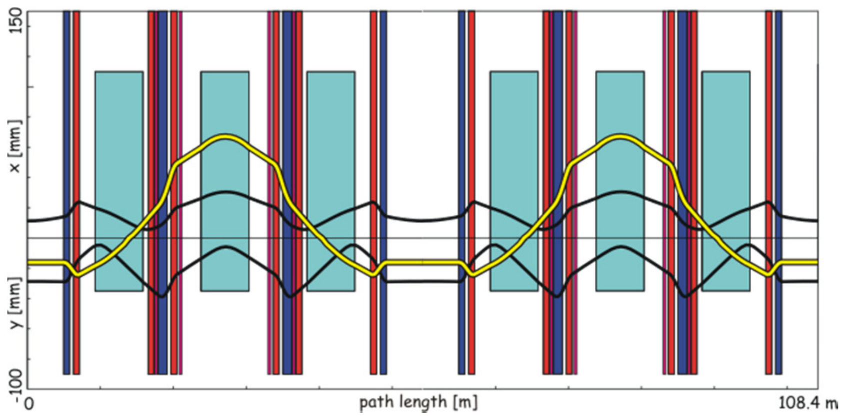
extracted cooled beam

- after deceleration (to ≥ 20 MeV/u)
- small emittance
- good control of extraction rate
- extraction time minutes to hours

C.M. Kleffner

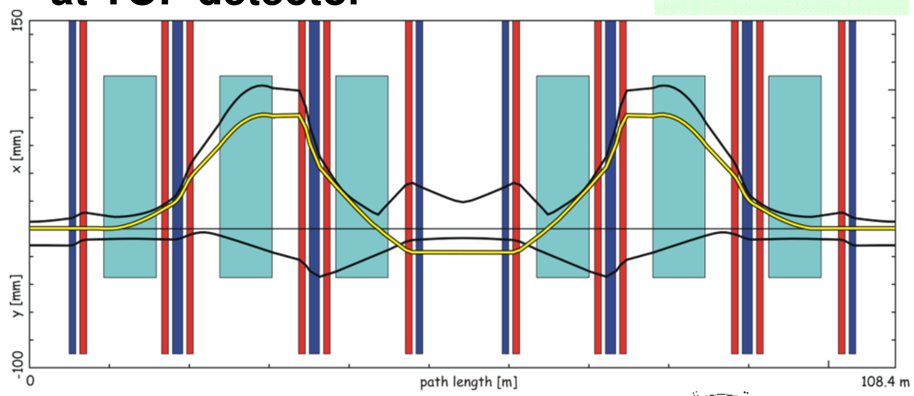
New Isochronous Mode
for Mass Measurements with the ToF Detector

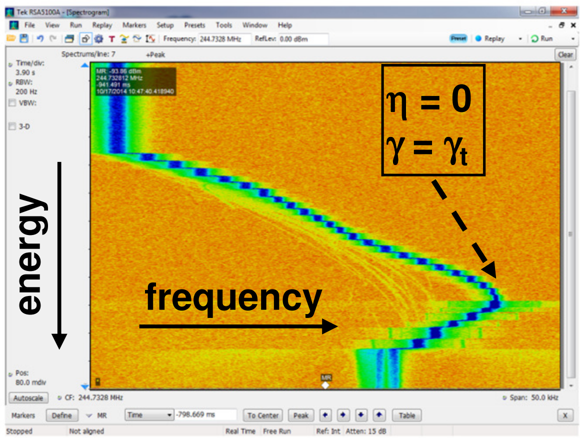
Old Mode
with large negative dispersion (-8 m)
at TOF detector



New Mode
with reduced dispersion
at TOF detector

S. Litvinov





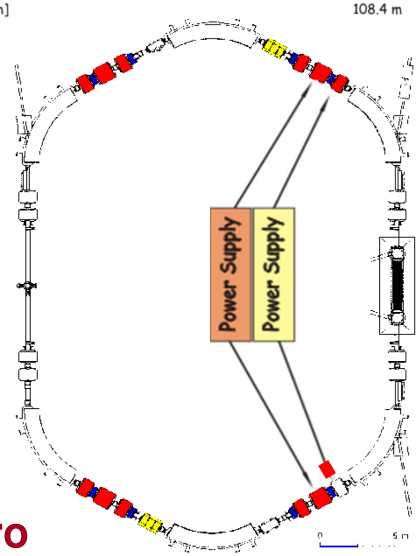
measurement of transition energy
by variation of beam energy

New mode makes use of the availability of ten individual quadrupole power converters (breaking the symmetry).

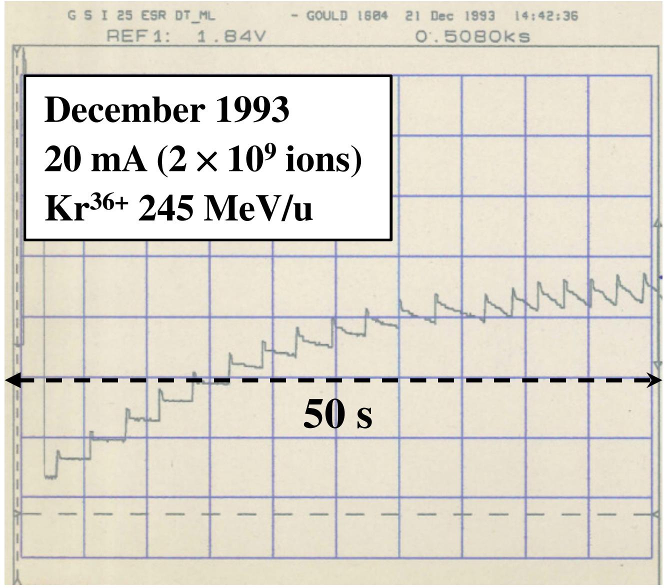
First experiment showed dispersion of +13 m at the ToF detector

new calculations available
further experiments needed

- **bring dispersion at TOF detector to zero**
- **improve transmission from FRS to ESR**

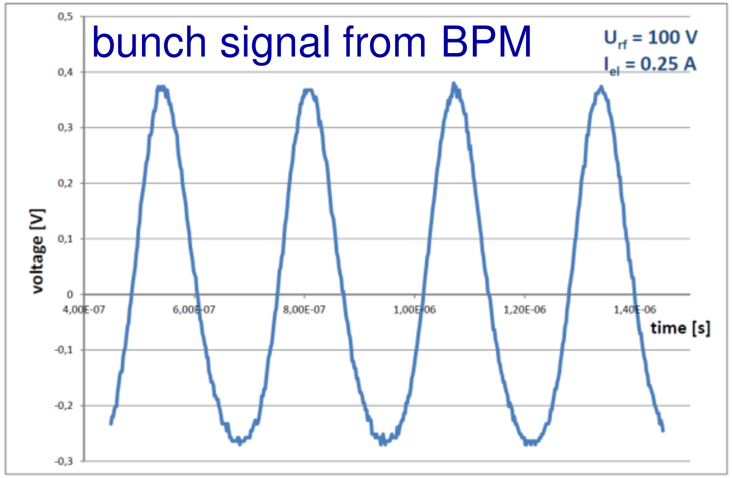


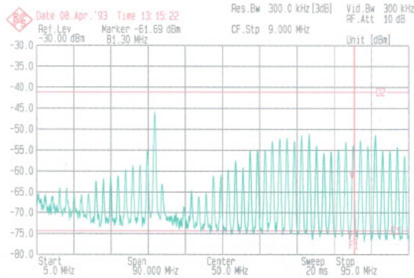
High Intensity Cooled Beams



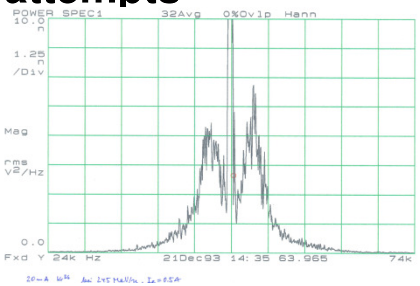
high intensity attempts

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





transverse coherent Schottky signal 0-90 MHz



longitudinal Schottky signal with central coherent peak

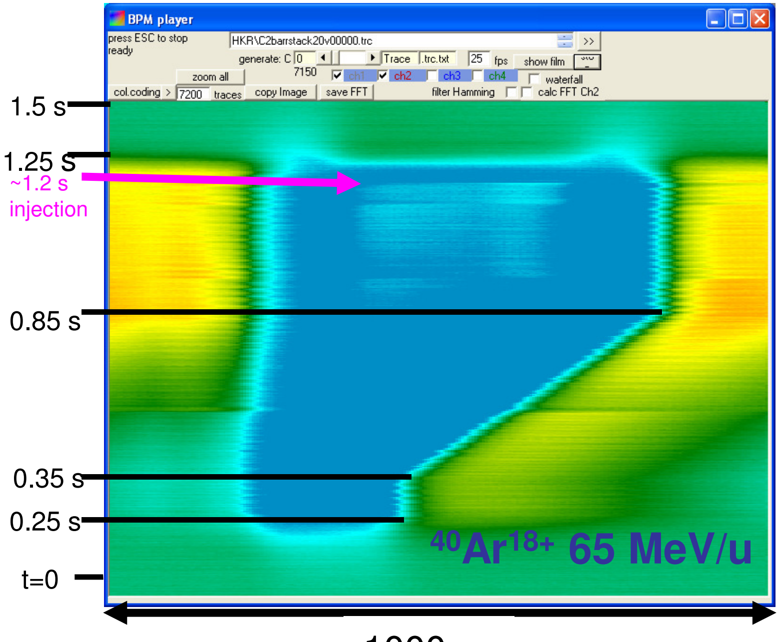
observations and attempts to apply feedback were not conclusive

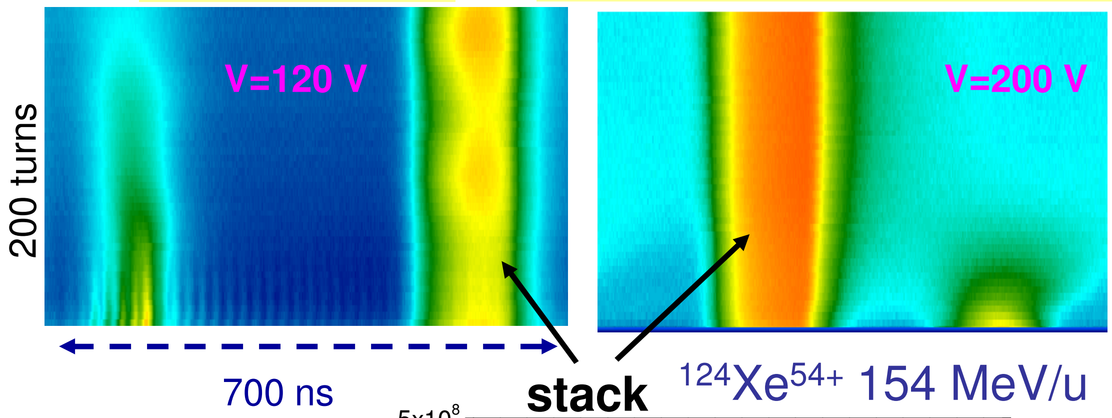
what matters?
cooling⇒ emittance, momentum spread
orbit, tune, chromaticity, impedances

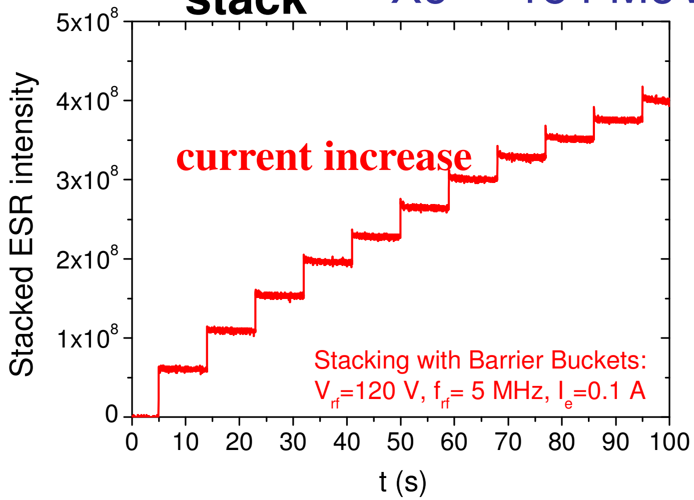
high intensity operation, particularly with cooled beams, is arts, not science; predictions for the future are doubtful

Longitudinal Accumulation with RF and Electron Cooling

moving barriers | **fixed barrier** | **h=1 unstable fixed point**







<u>three schemes were successfully tested:</u>

moving barriers, fixed barrier,
h=1 unstable fixed point

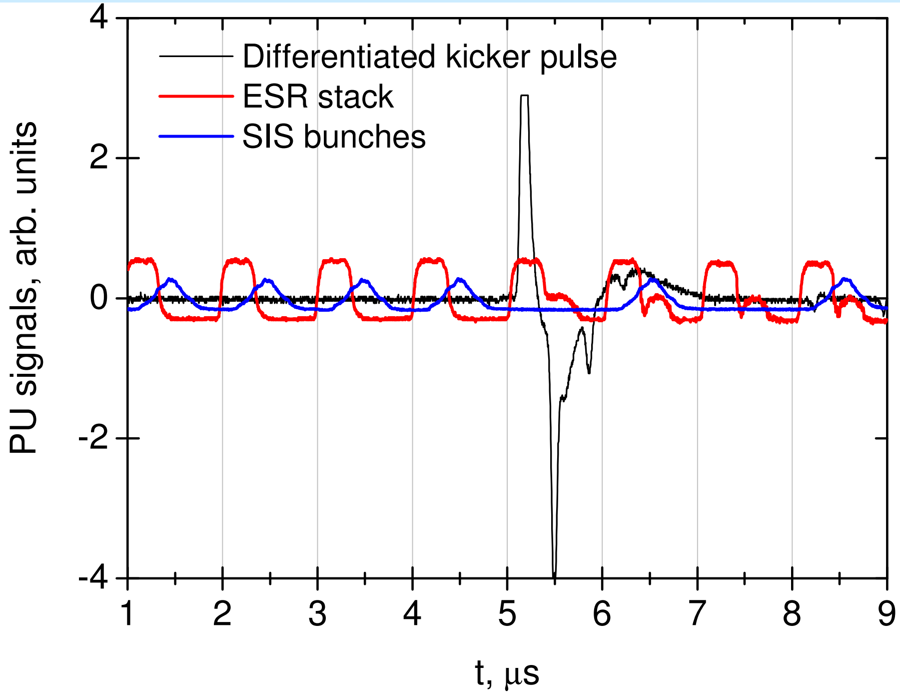
cooling times were close to expectations
efficient accumulation

high quality timing and kicker pulses required
Intensity limits: rf voltage and instabilities

only test mode, operation with control system is not implemented

Barrier Bucket Accumulation

Accumulation with Barrier Bucket rf voltage

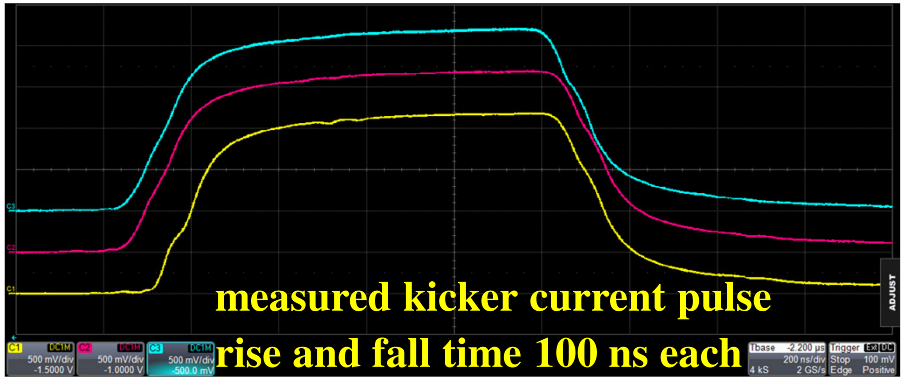


Limits of existing ESR BB system:

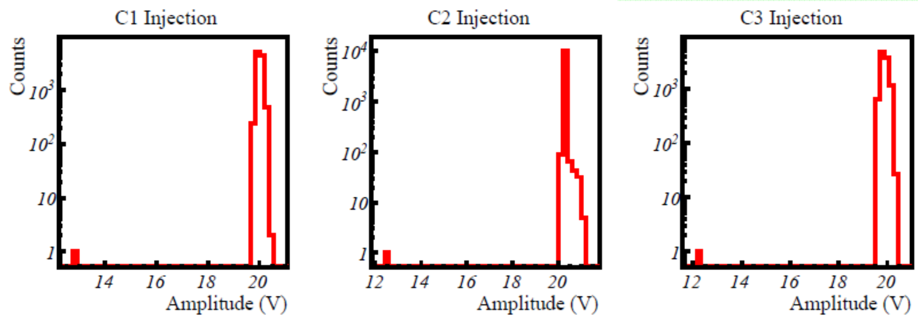
rf voltage amplitude120 V, band width 5 MHz

A dedicated BB system based on magnetic alloy is under construction, completion expected end of 2016

Precise synchronization and timing of three kicker modules



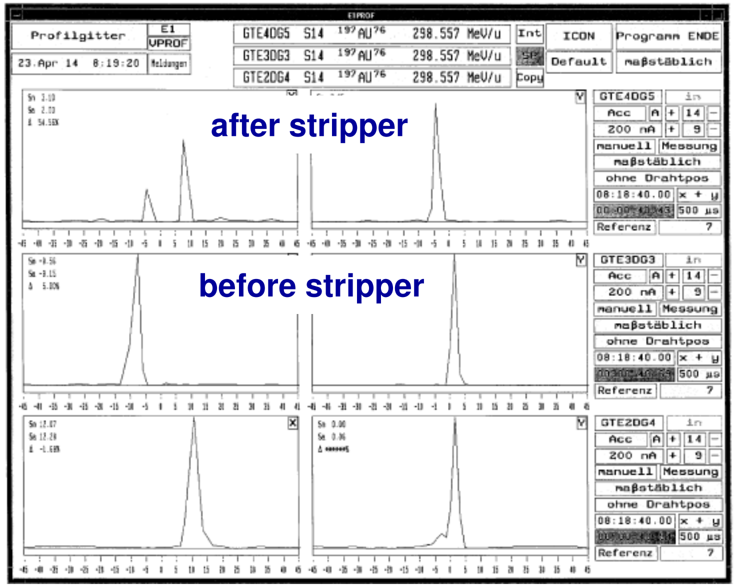
J. Piotrowski



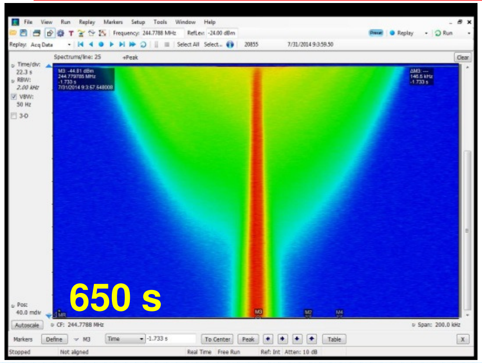
statistics from GO-experiment 10/2014
one miss in ten thousand shots

Cooled Beam Quality from SIS

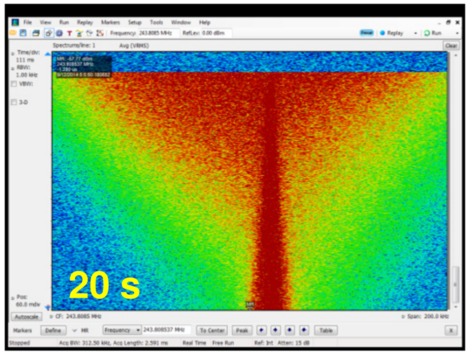
small transverse emittance



unexplained large momentum spread

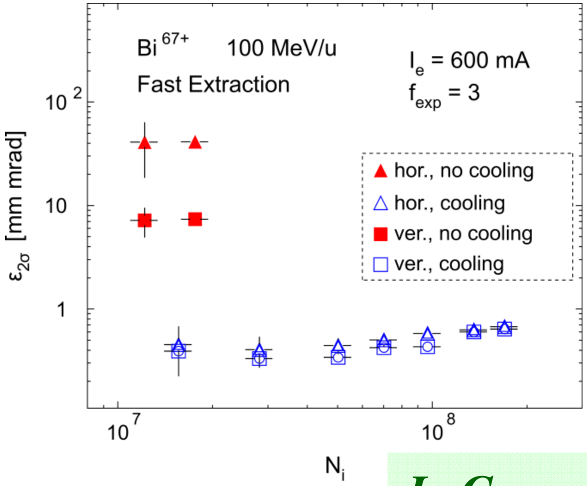


protons 400 MeV $\Delta p/p = 1.8\times10^{-3}$



Xe^{54+} 50 MeV/u $\Delta p/p = 1.2\times10^{-3}$

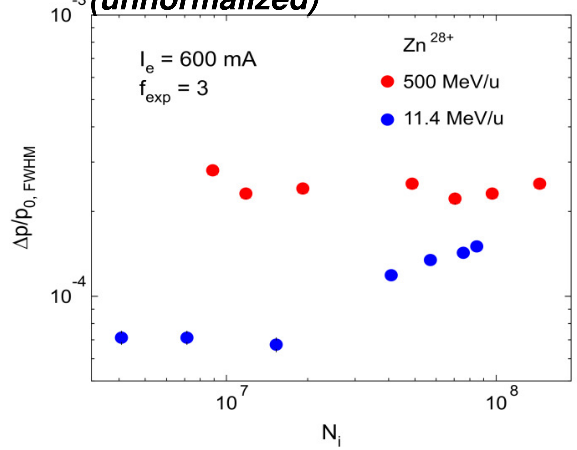
SIS beam emittance



L. Groening (1998)

SIS beam momentum spread

(unnormalized)



Beam Cooling

stochastic pre-cooling on injection orbit

energy <u>400</u> (-550) MeV/u

bandwidth 0.8 GHz (range 0.9-1.7 GHz)

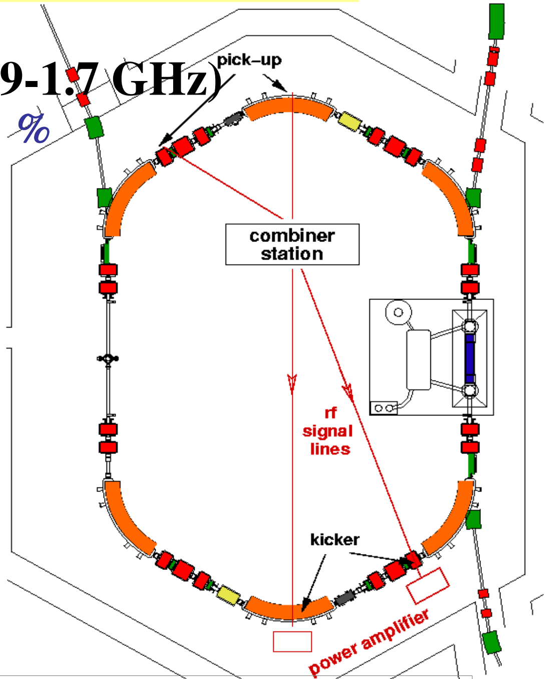
$\delta p/p = \pm 0.35\ \%$ → $\delta p/p = \pm 0.01\ \%$

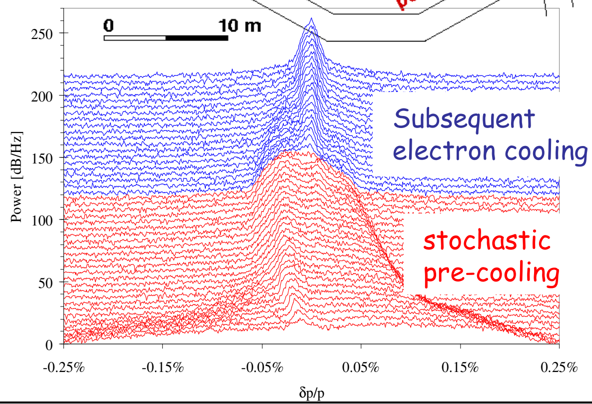
$\varepsilon = 10\ \mu m$ → $\varepsilon = 2\ \mu m$

electrodes

combiner station

power amplifiers

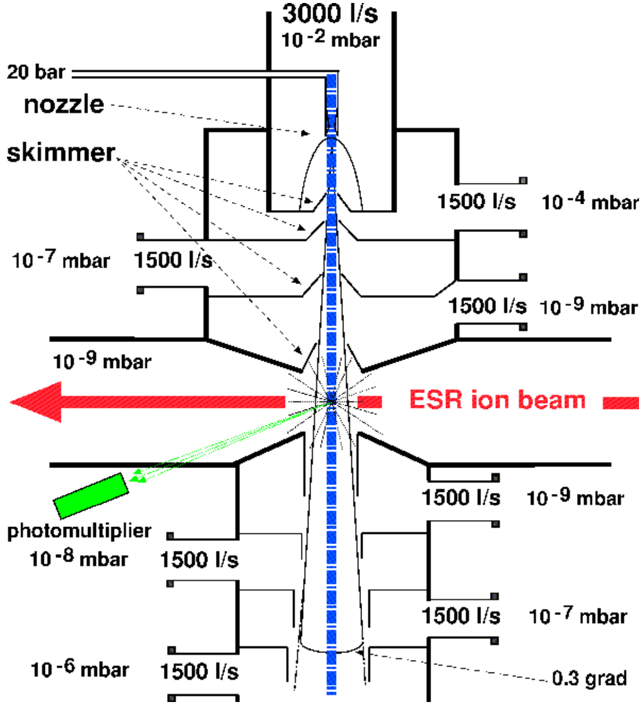


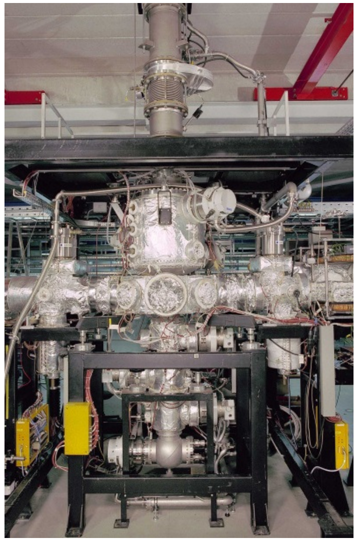


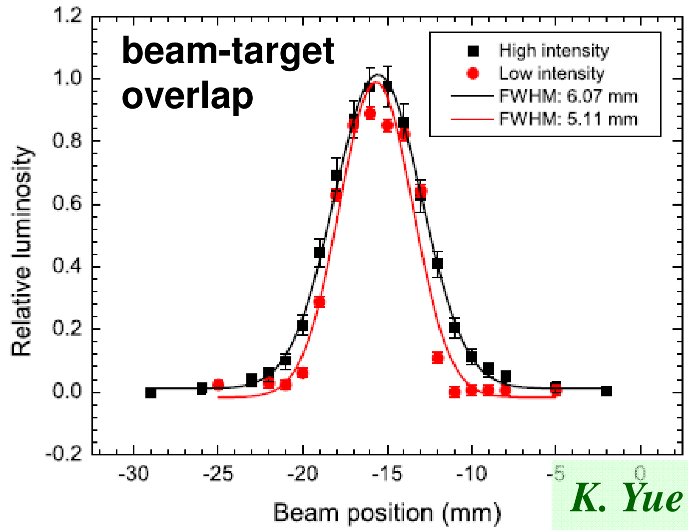
electron cooling

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
transv. temperature	0.1 eV
longitud. temperature	~0.1 meV
vacuum	1×10^{-11} mbar

Internal Target

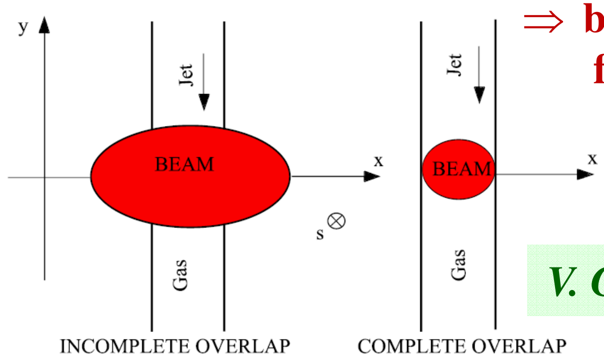






K. Yue

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



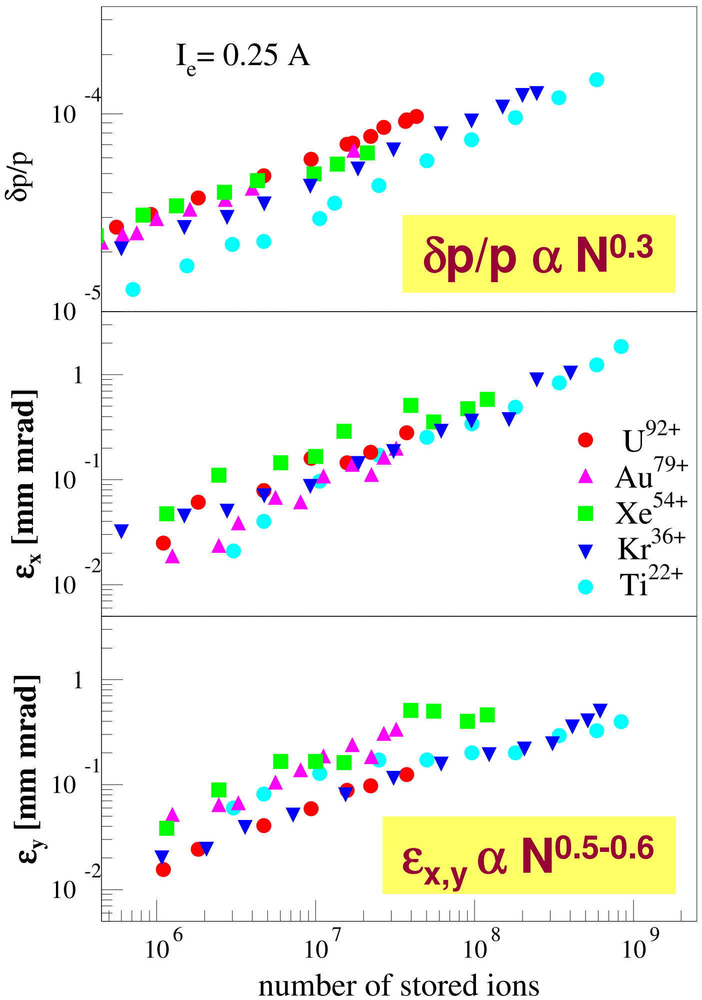
V. Gostishchev

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

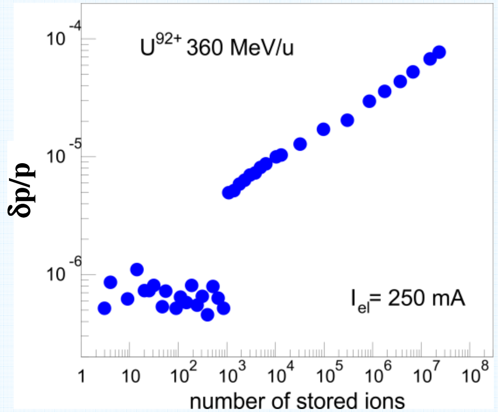
presently available target densities *N. Petridis*

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

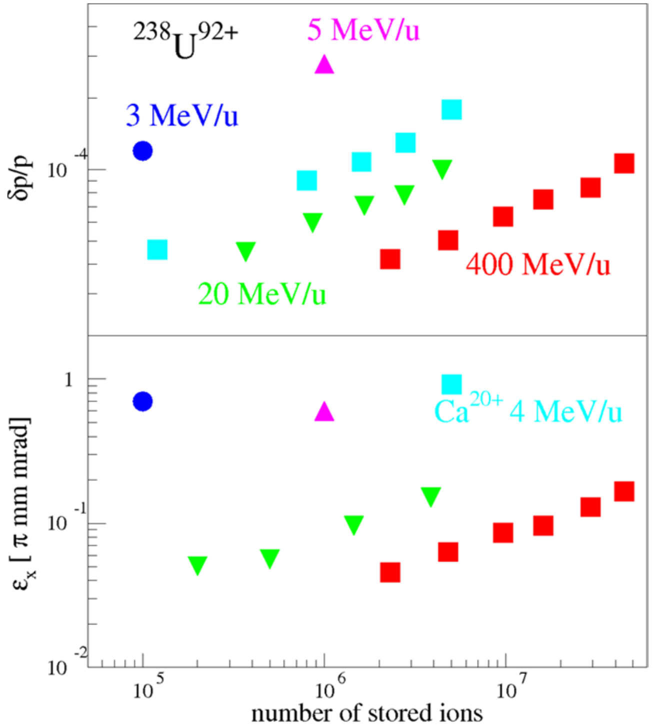
Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)



suppression of IBS for low intensity (N≤1000)



important for mass measurements by SMS

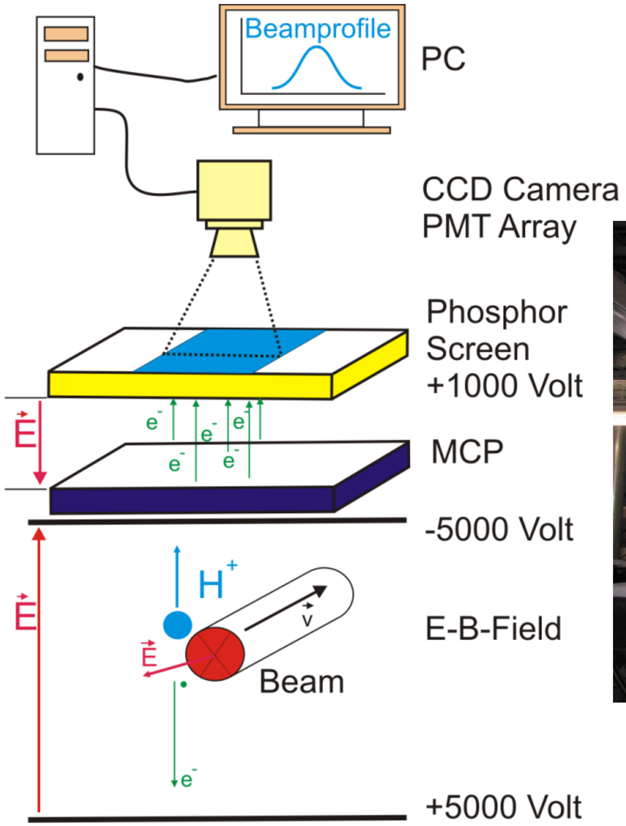


total phase space volume increases with ion beam intensity and ion charge

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

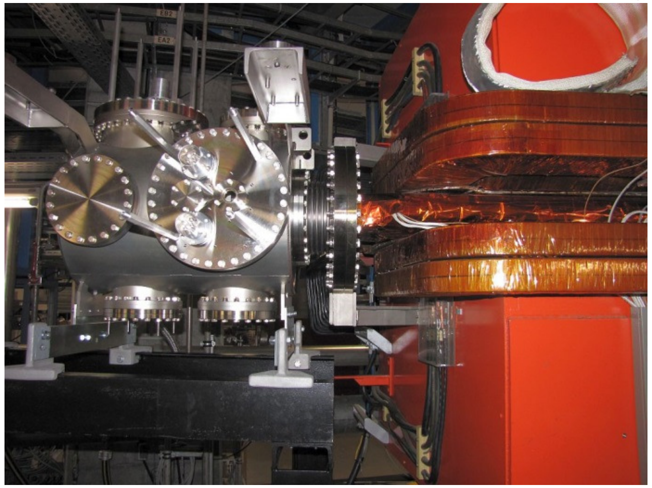
heating rate mostly dominated by IBS, not by target

Transverse Diagnostics

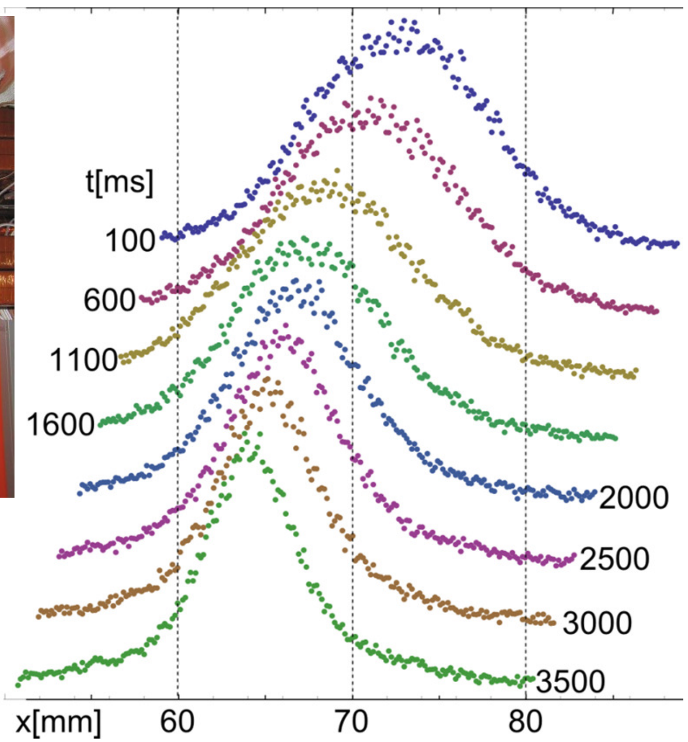


beam profile monitor

version without magnetic field

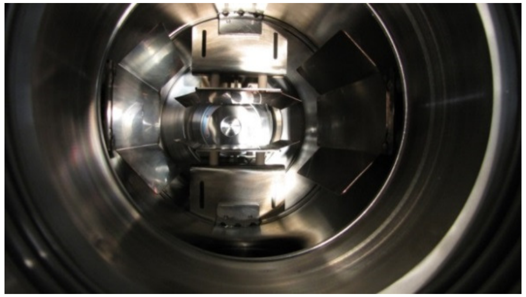


horizontal beam profile of the beam after injection into the ESR and cooling



so far only operated in an expert version,
not available for routine operation,
low energy measurements need orbit correction

New Schottky Resonator

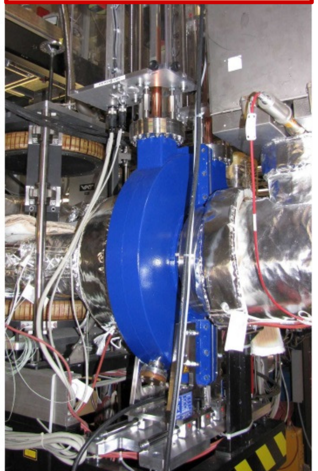


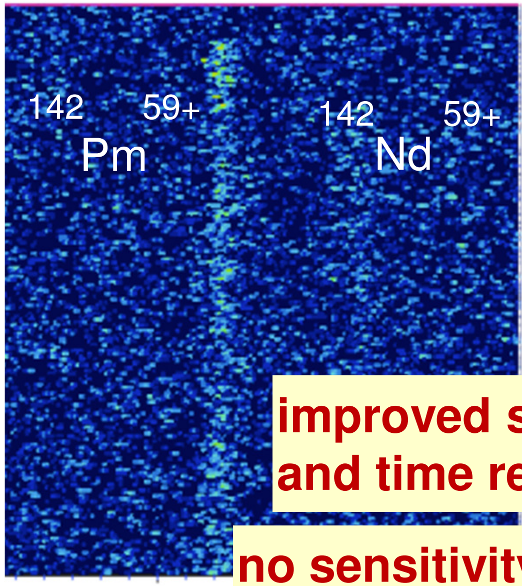
Old Schottky pickup

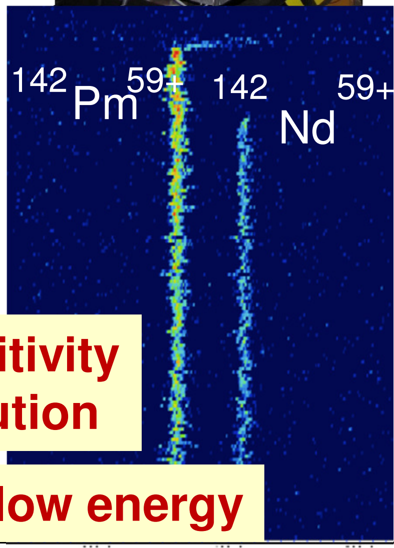
Resonant circuit at 30th harmonic

New resonator Cavity (2010)

124th harmonic



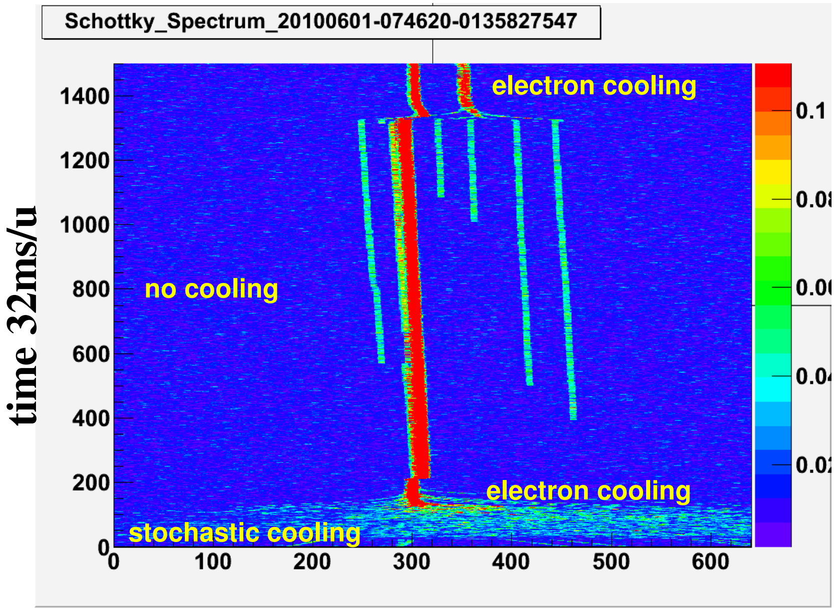




improved sensitivity and time resolution

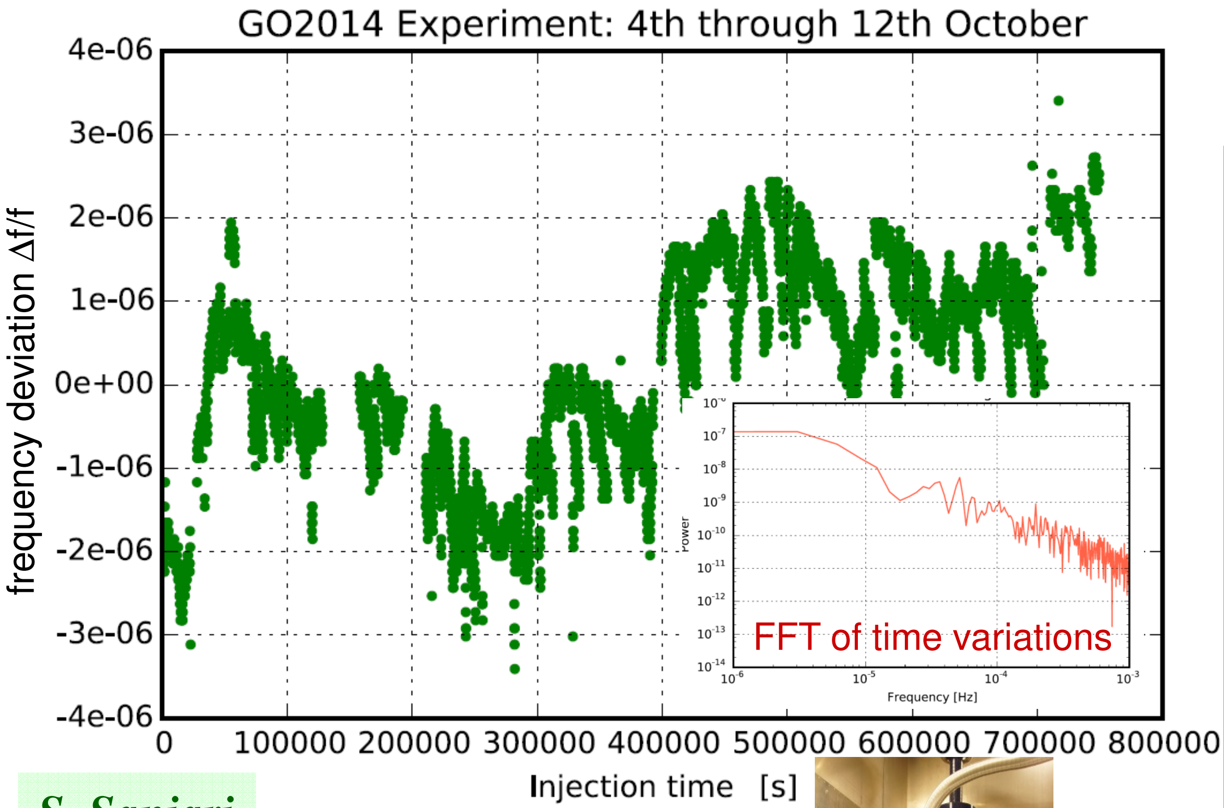
no sensitivity at low energy

single ion detection (without cooling)



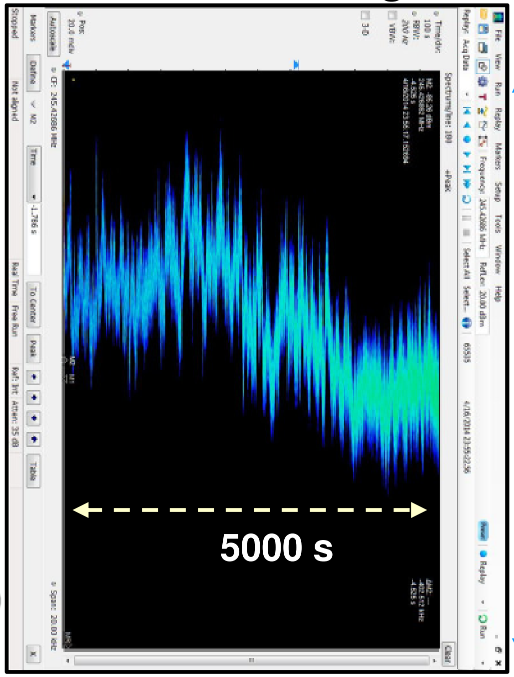
ideas for new resonant Schottky detectors, possibly with sensitivity to beam position

Stability of ESR Operation



S. Sanjari

revolution frequency variations during HFS experiment due to electron cooler high voltage



$\delta f/f = \pm 4\times10^{-5}$

commercial high voltage divider in ESR Faraday room

W. Nörtershäuser et al.

measurement of electron cooler high voltage by PTB high precision divider demonstrated during HFS experiment with Bi

Deceleration to 4 MeV/u

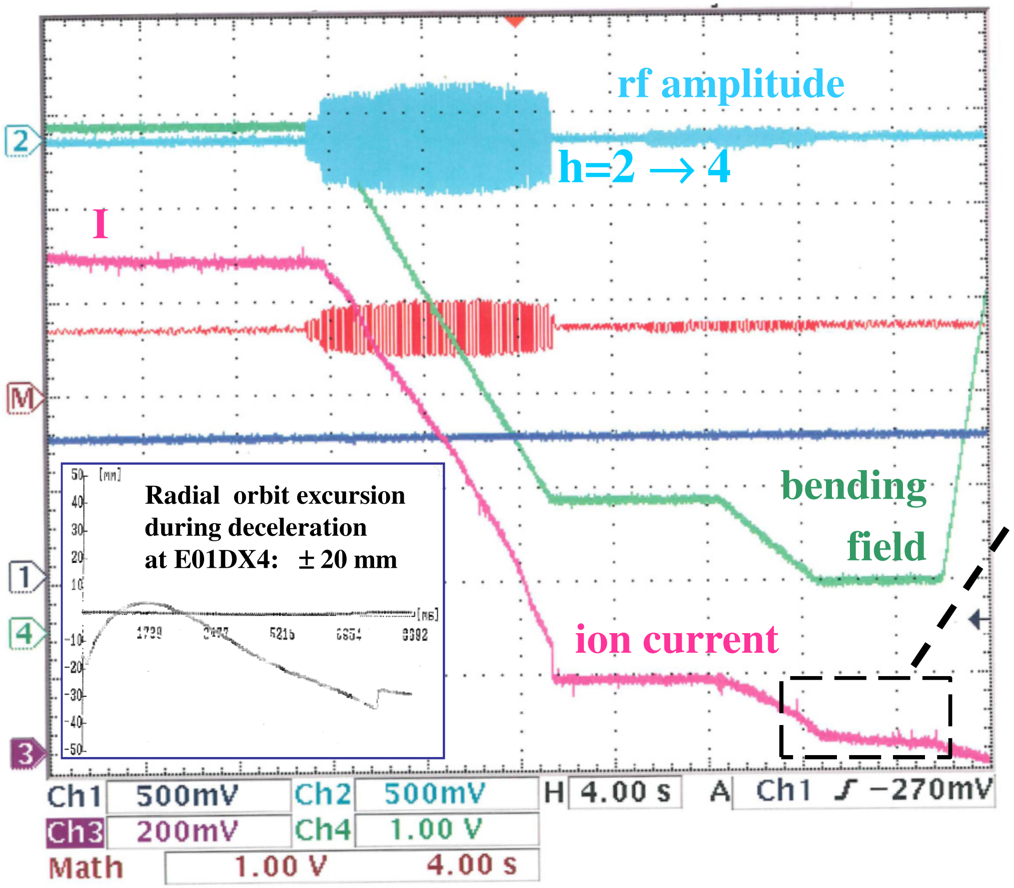
Ni^{28+} 400 → 30 → 4 MeV/u

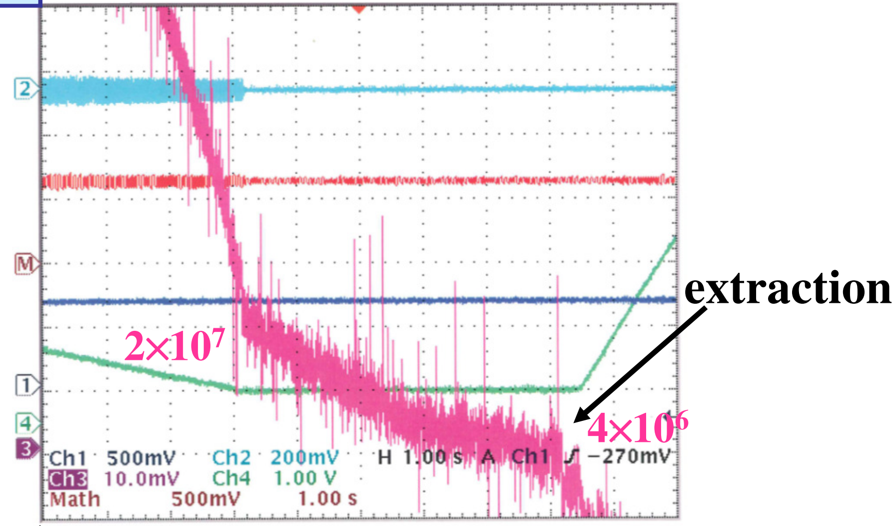
1100 μA → 180 μA → 25 μA

45 % 37 %

cycle time 45 s

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





beam half life (vacuum dominated):

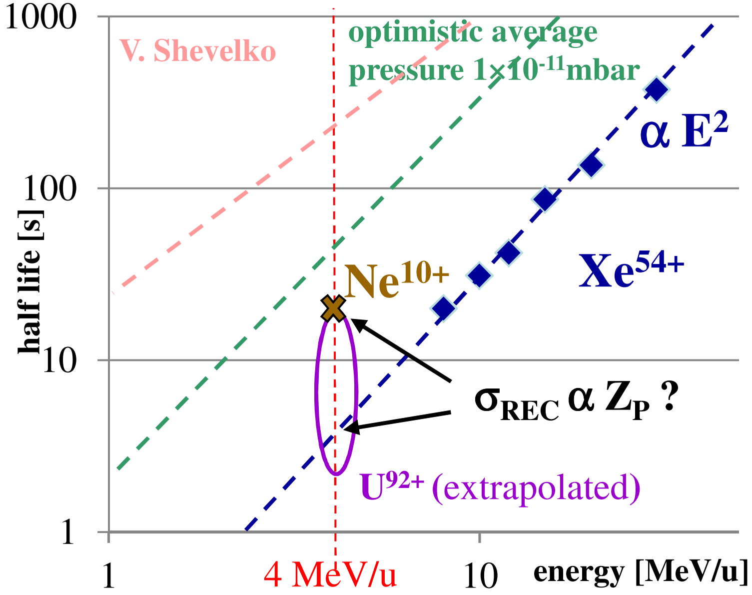
30 MeV/u: $T_{1/2} \approx 480$ s

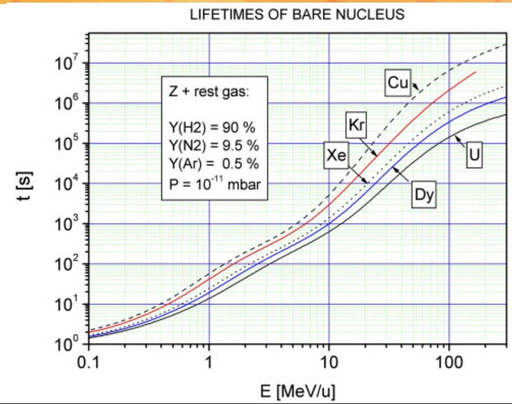
4 MeV/u: $T_{1/2} \approx 2$ s

limits to cycle time:
- orbit excursion
- cooling times

Low Energy Beams – Vacuum

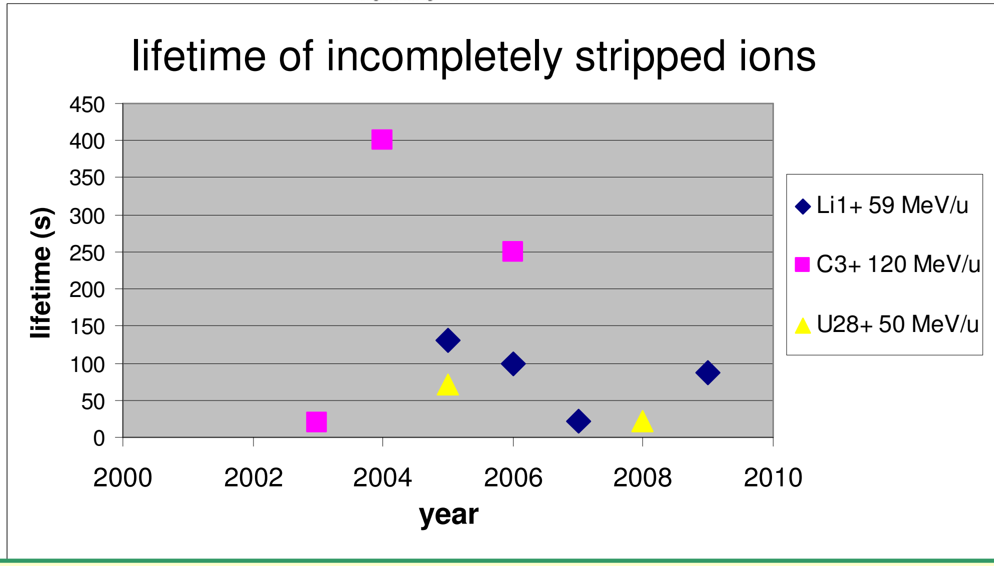
measurement in 2014 of beam half life with an average pressure of **$p \approx 1\times10^{-10}$ mbar**





V. Shevelko

simulation for CRYRING



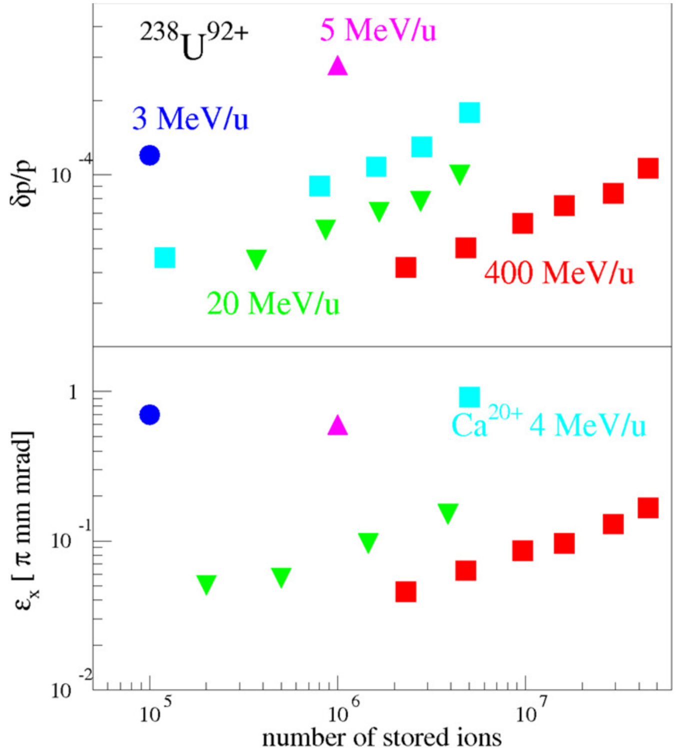
Beam lifetimes of bare ions at 4 MeV/u

- 5/07 **Ni^{28+}: ~ 5 s**
- 8/07 **Ne^{10+}: < 1 s**
- 8/08 **Au^{79+}: ~ 1.7 s**
- 2/09 **Ni^{28+}: ~ 2.5 s**
- 4/09 **Xe^{54+}: ~ 3 s**
- 5/11 **N^{7+} : 30 s**
- 4/14 **Ne^{10+}: 30 s**

Vacuum is very critical for HCI at low energy and for some incompletely stripped ions

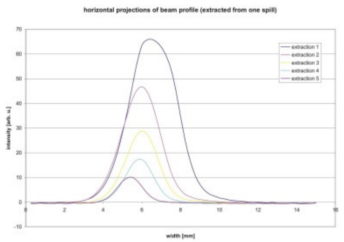
Properties of Decelerated Beams

Beam parameters due to equilibrium between IBS and electron cooling

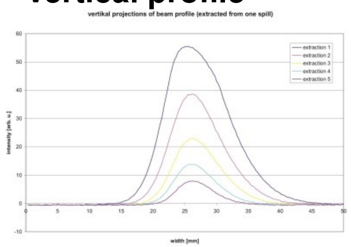


fast extracted beam Ca^{20+} 4 MeV/u

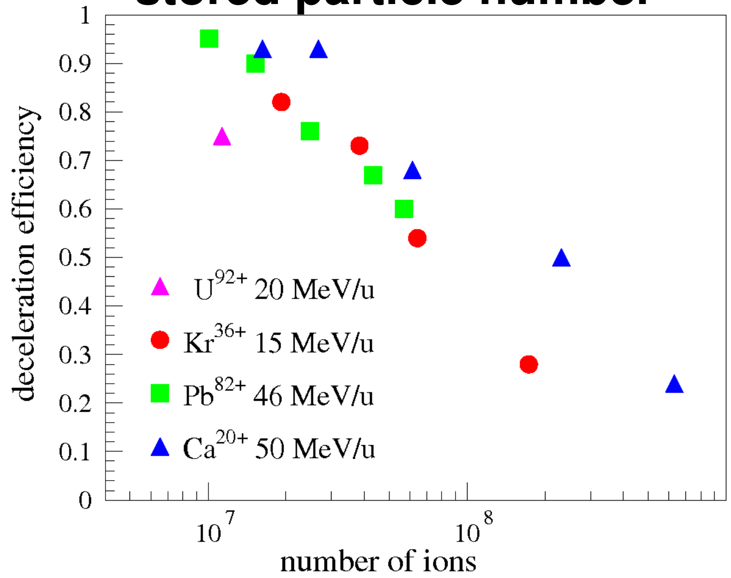
horizontal profile



vertical profile



Losses increase with stored particle number



Control of the beam parameters, emittance (cooling) and bunch length (rf voltage), is not easy

Space charge limit due to incoherent tune shift

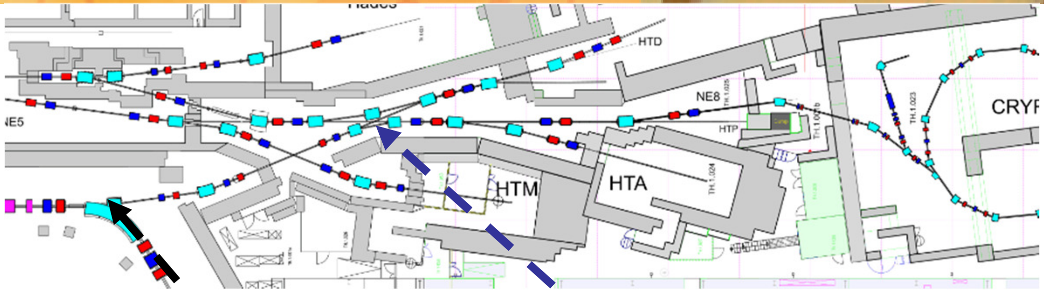
$$\Delta Q_x = \frac{r_p Z^2 N g}{\pi A \beta^2 \gamma^3 B (\epsilon_x + \sqrt{\epsilon_x \epsilon_y Q_x / Q_y})}$$

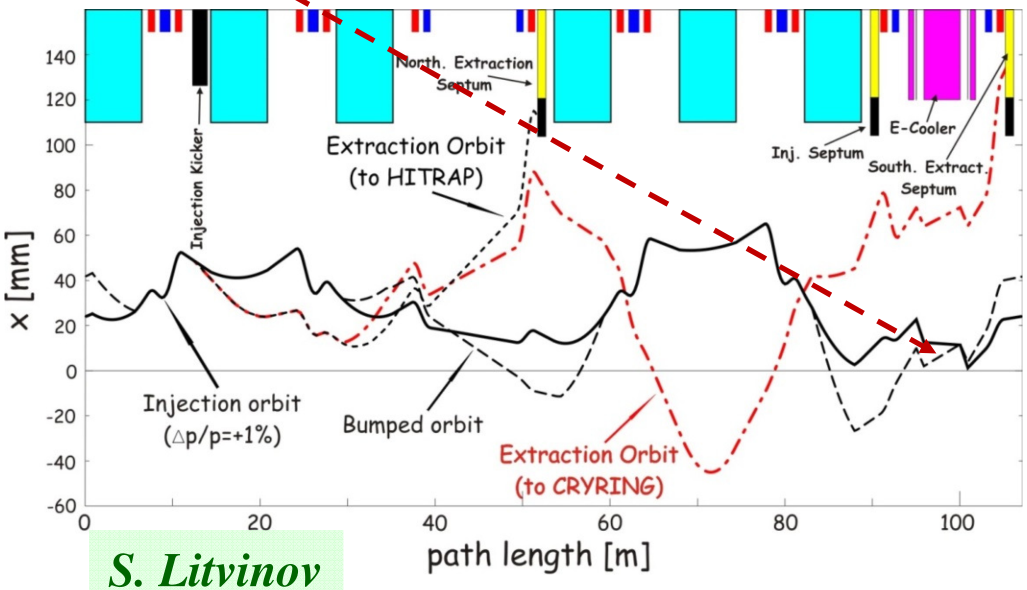
$$\Delta Q_x \simeq \frac{r_p Z^2 N}{2\pi A \beta^2 \gamma^3 B \epsilon_x}, \; g = 1, \epsilon_x = \epsilon_y, Q_x = Q_y$$

space charge limit U^{92+} at 4 MeV/u for $\Delta Q_x = 0.1$:
2 μs bunch with $\varepsilon_x = \varepsilon_y = 1\pi$ mm mrad $\Rightarrow$ $\underline{N \leq 1 \times 10^7}$

Fast Beam Extraction towards HITRAP

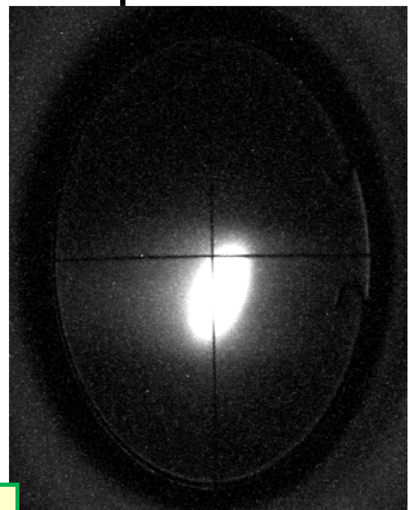
missing extraction kicker for extraction towards the south
⇒ distorted closed orbit for the extraction towards CRYRING using the existing ESR injection kicker
<u>no cooling</u> during extraction



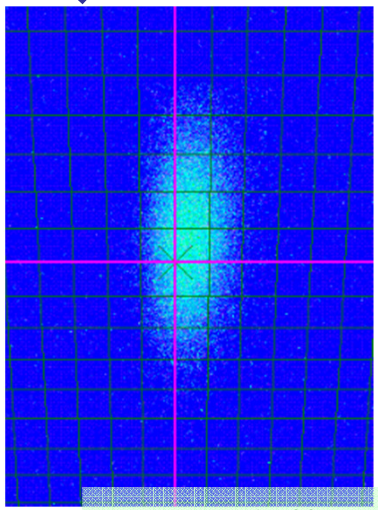


S. Litvinov

5 August 2014
exit ESR
p 200 MeV



26 August 2014
intersection
N^{7+} 4 MeV/u

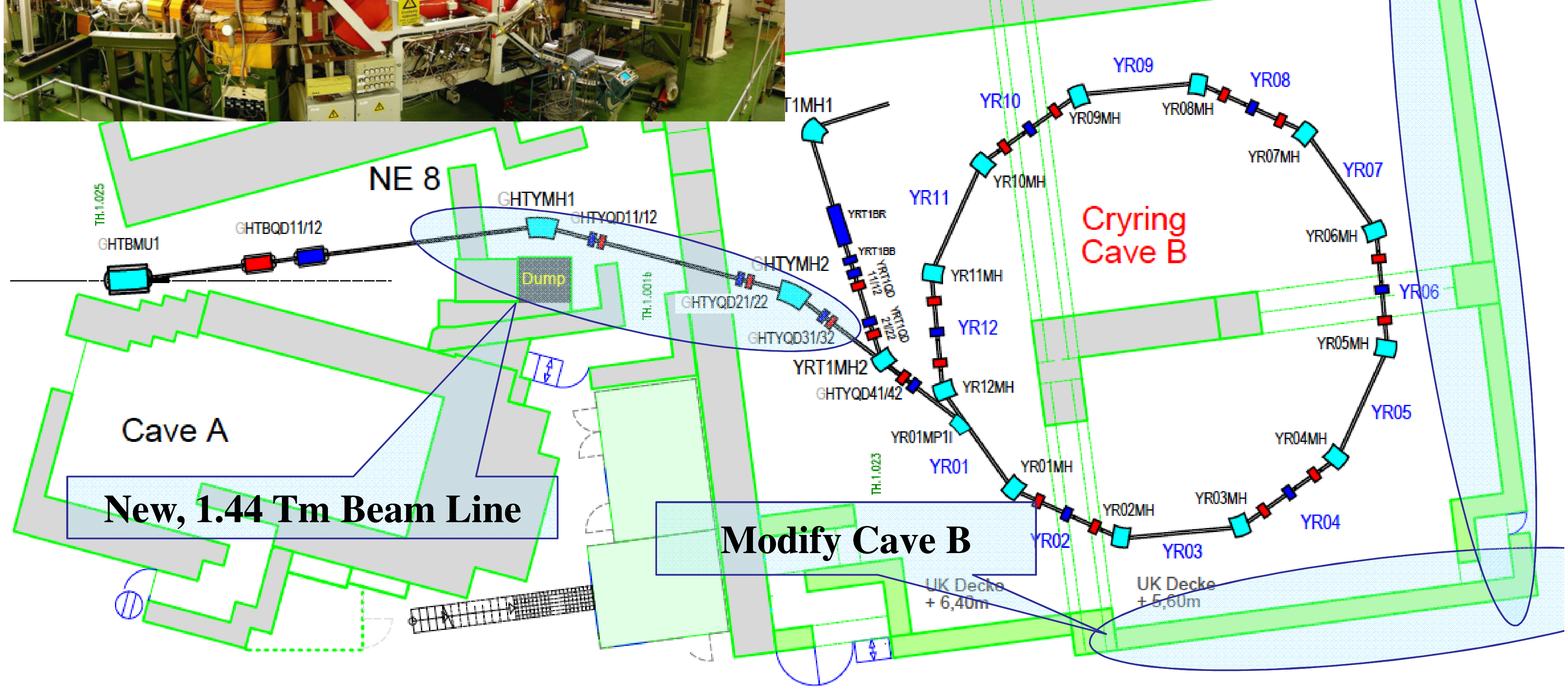


C.M. Kleffner

scheme worked (surprisingly) well
next steps: transport to the injection of CRYRING
compression into a single bunch

but: dedicated extraction kicker ?

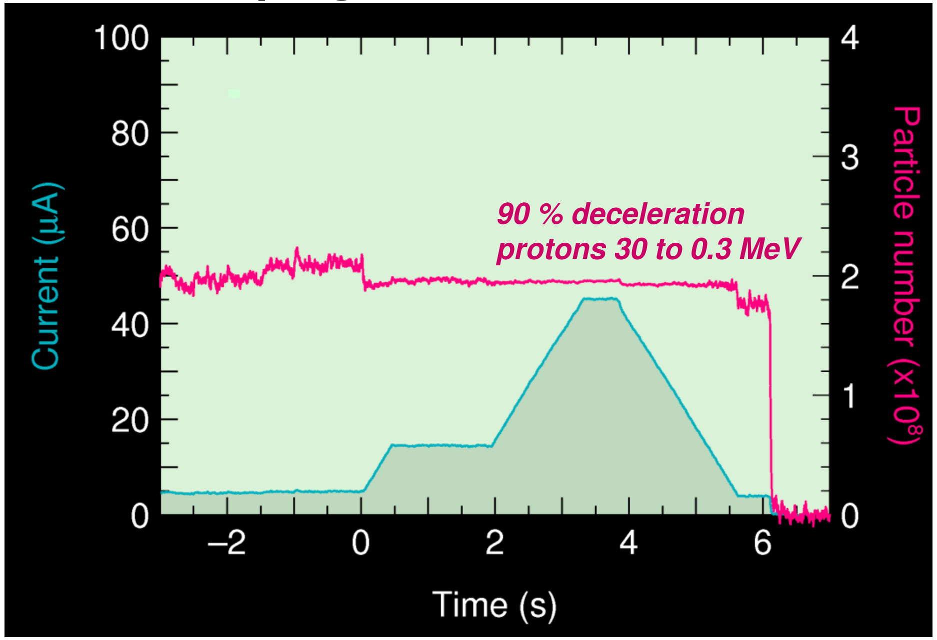
CRYRING @ ESR in former Cave B



courtesy F. Herfurth and Decelerators department

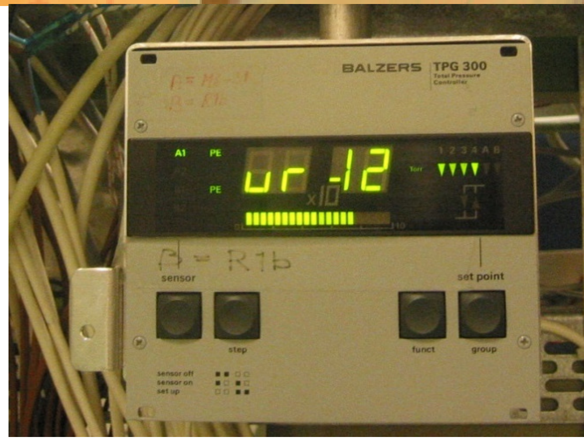
CRYRING @ MSL Stockholm

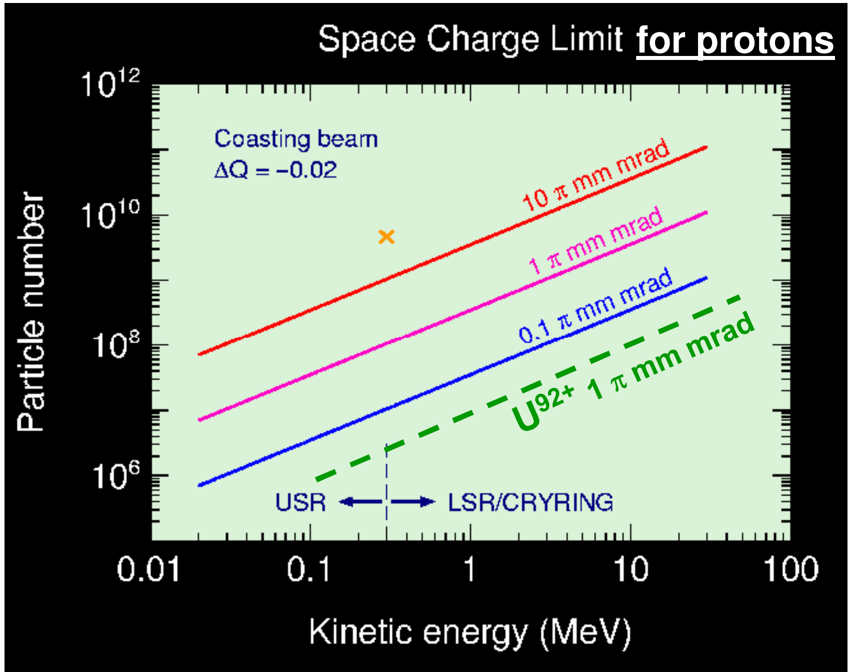
fast ramping (7 T/s)



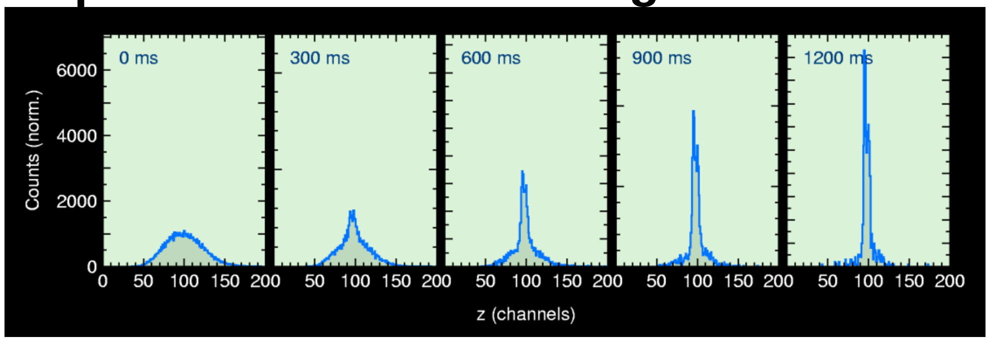
excellent vacuum
1×10^{-11} mbar

H. Danared (MSL) 2006





powerful electron cooling



CRYRING @ ESR

Max. rigidity 1.44 Tm
- 15 MeV/u U^{92+}
- 96 MeV (anti-)protons

Min. rigidity ~ 0.054 Tm
- 21 keV/u U^{92+}
- 150 keV (anti-)protons

- **FAIR Research & Development**
- Detectors and diagnostic systems
- FAIR type control system
- Training of operators on FAIR type system
- FAIR type safety and radiation monitoring/access system with real beam (standalone operation during commissioning)

- **Scientific Opportunities**
- Heavy, highly-charged cooled ions as available at GSI (up to U^{92+}, fragmentation products) at low energy 100 keV/u .. 10 MeV/u
  – bridge the energy gap between the ESR (> 4 MeV/u) and HITRAP (< 10 keV/u)

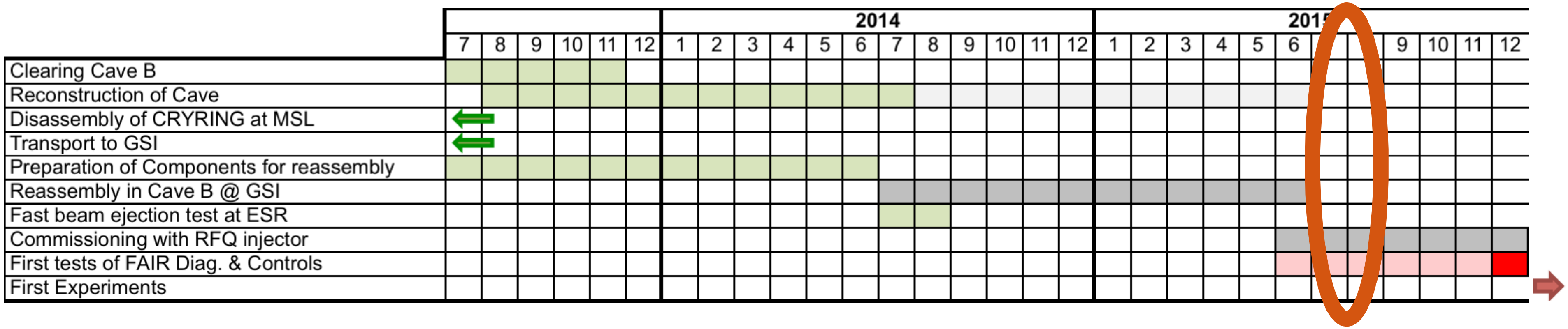
CRYRING@ESR

arrival at GSI

clearing of Cave B

Timeline CRYRING

- ring installation started, ion source and linac rf operation started



- **Continue Installation**
  - Finish cave infrastructure, connect power converters
  - Control system and diagnostics on track
  - Beam line ESR – CRYRING prepared (missing dipole chamber)