Heavy Ion Storage Rings

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Joint EMMI / JINA-CEE Workshop on
"Nuclear Astrophysics at Storage Rings and Recoil Separators"
13-15 March 2018, GSI, Darmstadt, Germany

Physics at Storage Rings

Single-particle sensitivity | High atomic charge states | Long storage times
Broad-band measurements | High resolving power | Very short lifetimes

Direct mass measurements of exotic nuclei

Radioactive decay of highly-charged ions

Charge radii measurements [DR, scattering]

Experiments with polarized beams

Experiments with isomeric beams [DR, reactions]

Nuclear magnetic moments [DR]

Astrophysical reactions [(p,g), (a,g) ...]

In-ring nuclear reactions

Experimental Storage Ring ESR

Experimental Cooler-Storage Ring CSRe

Low-Energy Storage Ring TSR at ISOLDE

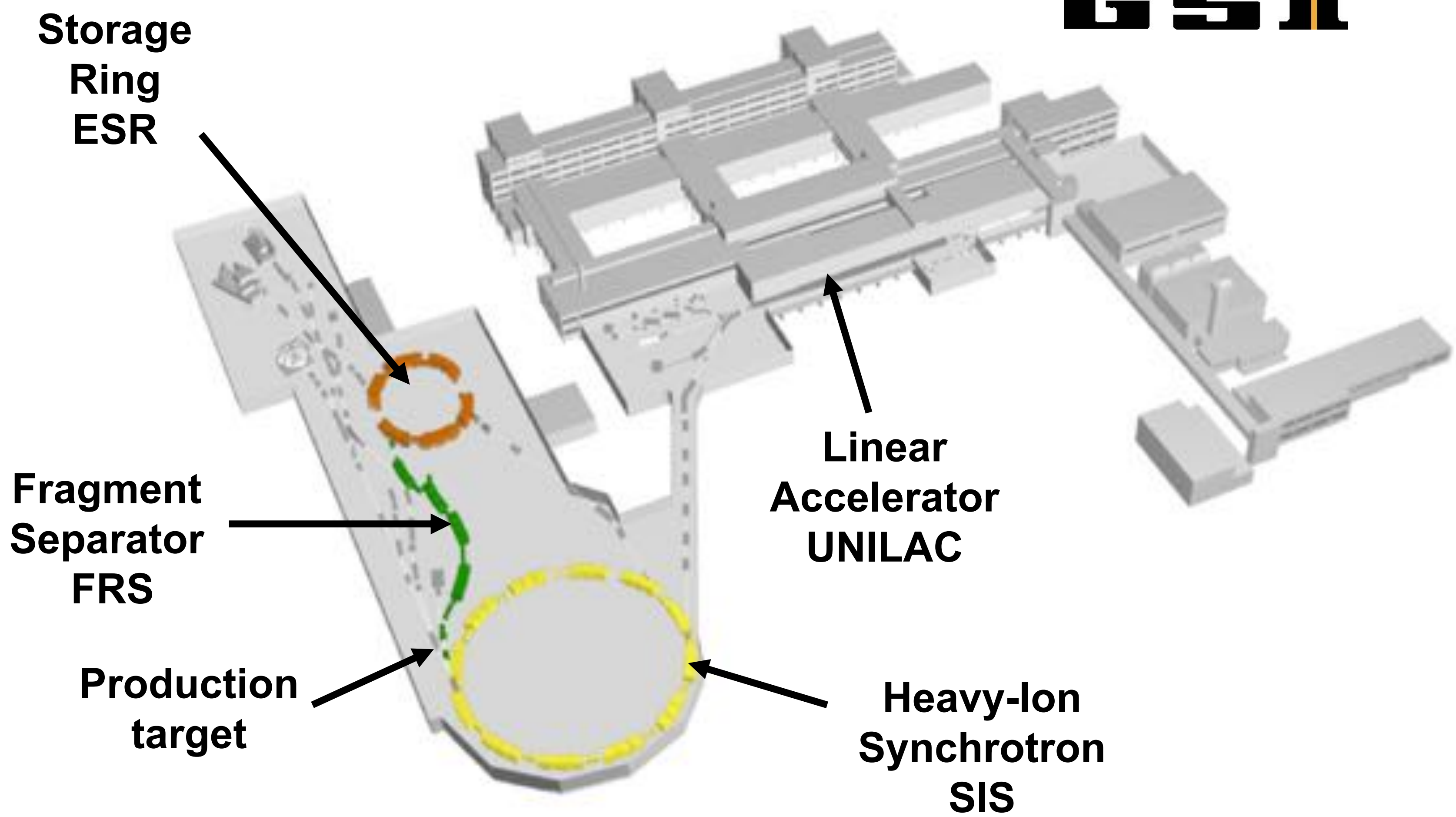
New Storage Ring Complex at FAIR

New Storage Ring Complex at HIAF

Low energy ring CryRING@ESR

R3-RING at RIKEN

Secondary Beams of Short-Lived Nuclei

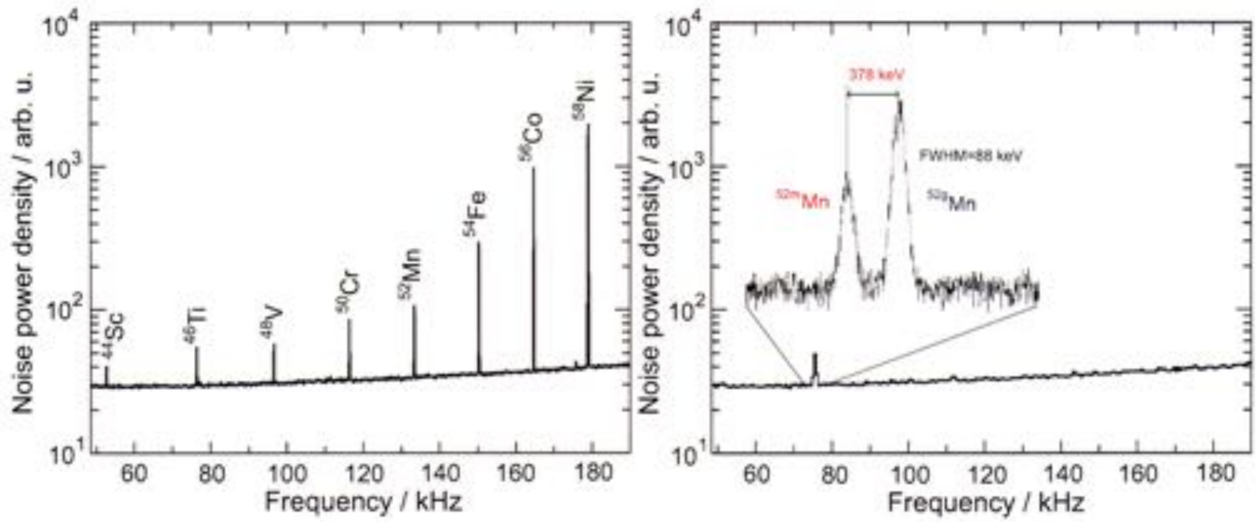


Production & Separation of Exotic Nuclei

Primary beams @ 400-1000 MeV/u

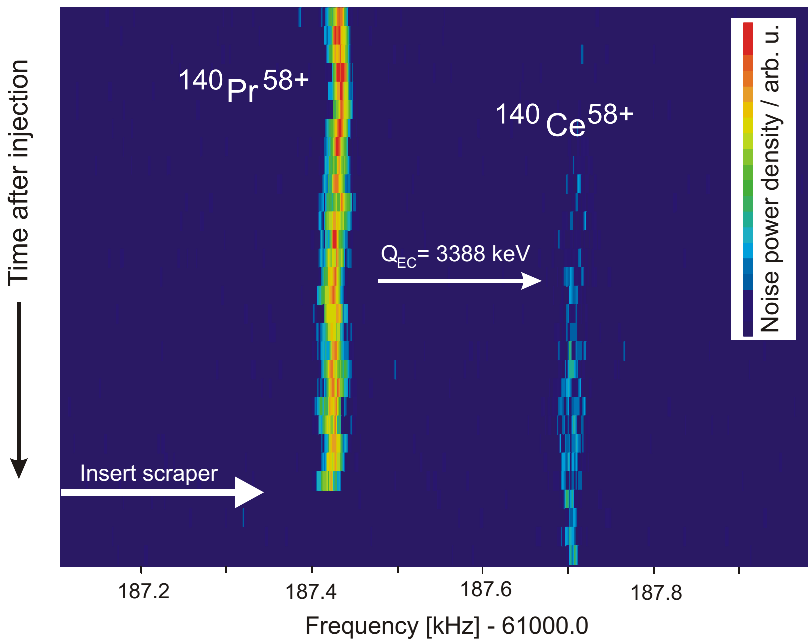
Highly-Charged Ions (0, 1, 2 … bound electrons)

In-Flight separation within ~ 150 ns

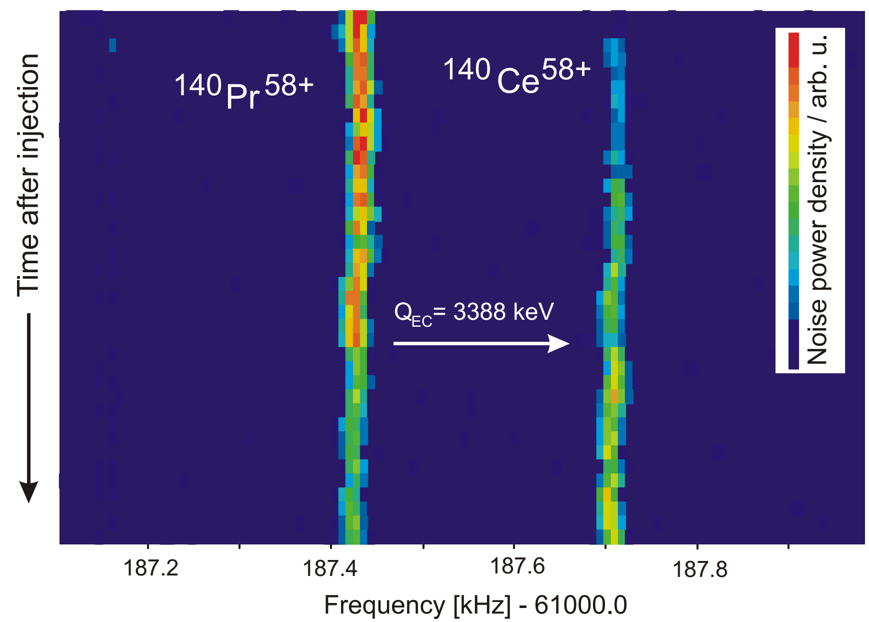


HELMHOLTZ
GEMEINSCHAFT

Pure isomeric beams

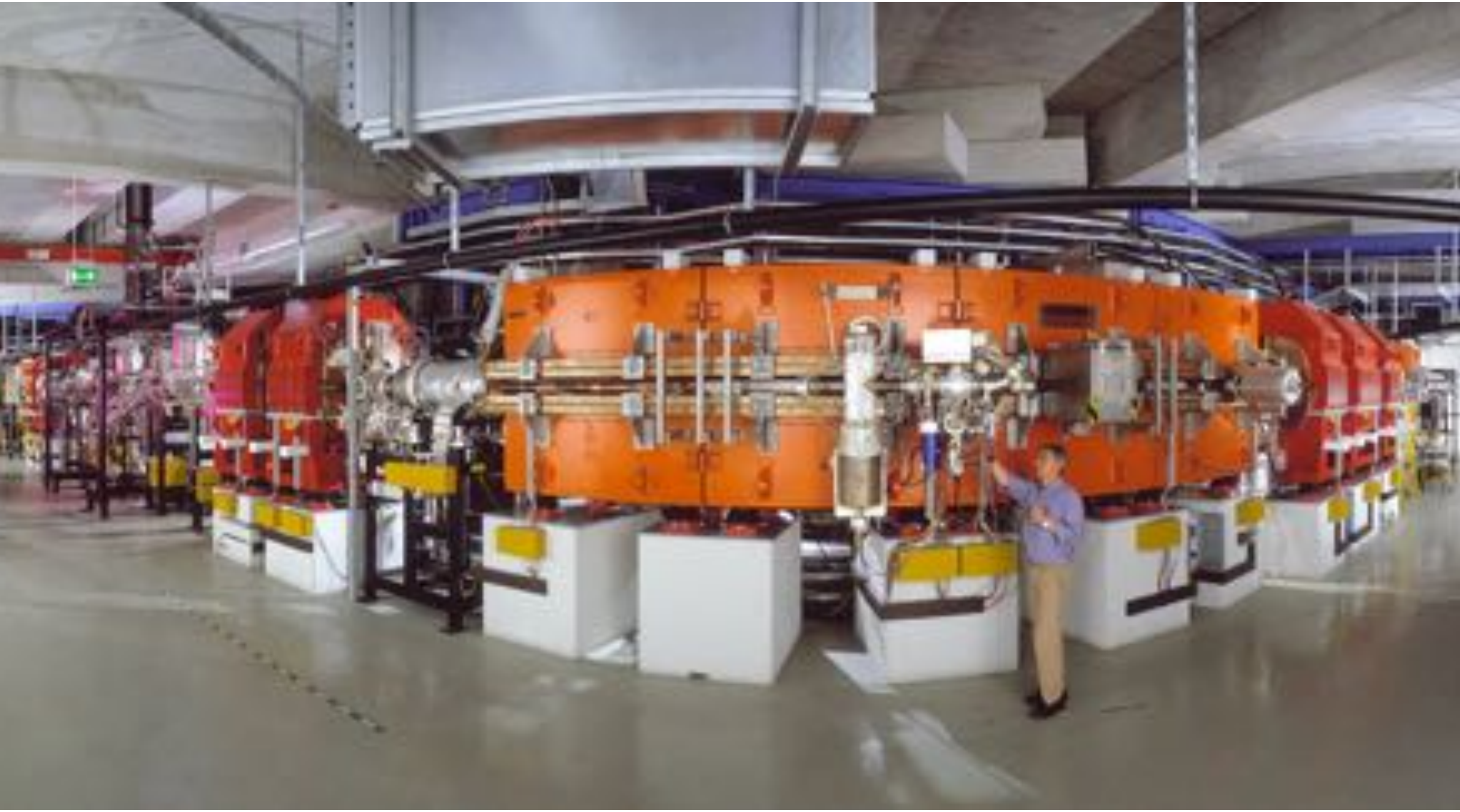


Injection length 170 s



Injection length 520 s

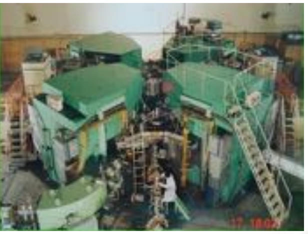
Experimental Storage Ring ESR

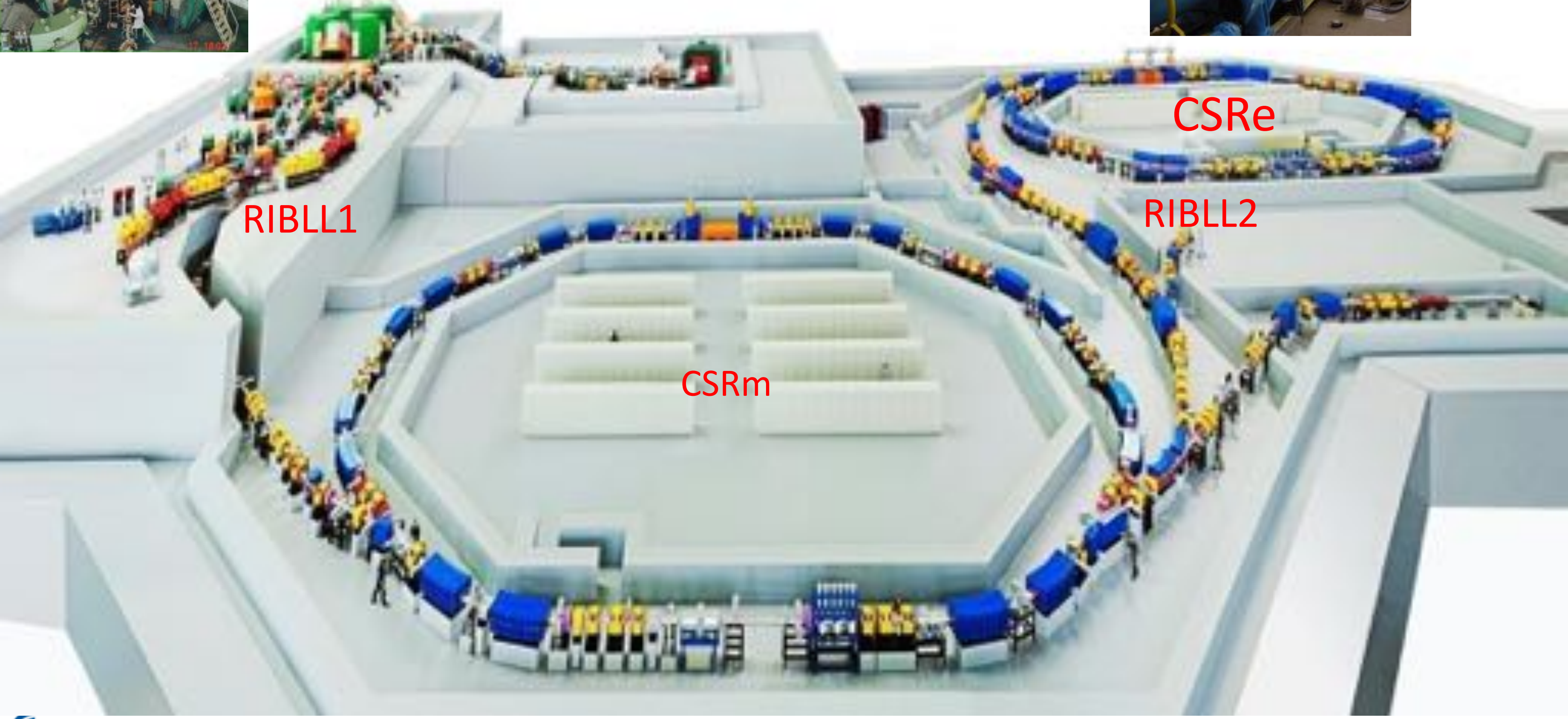


ESR: B. Franzke, NIM B 24/25 (1987) 18

Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

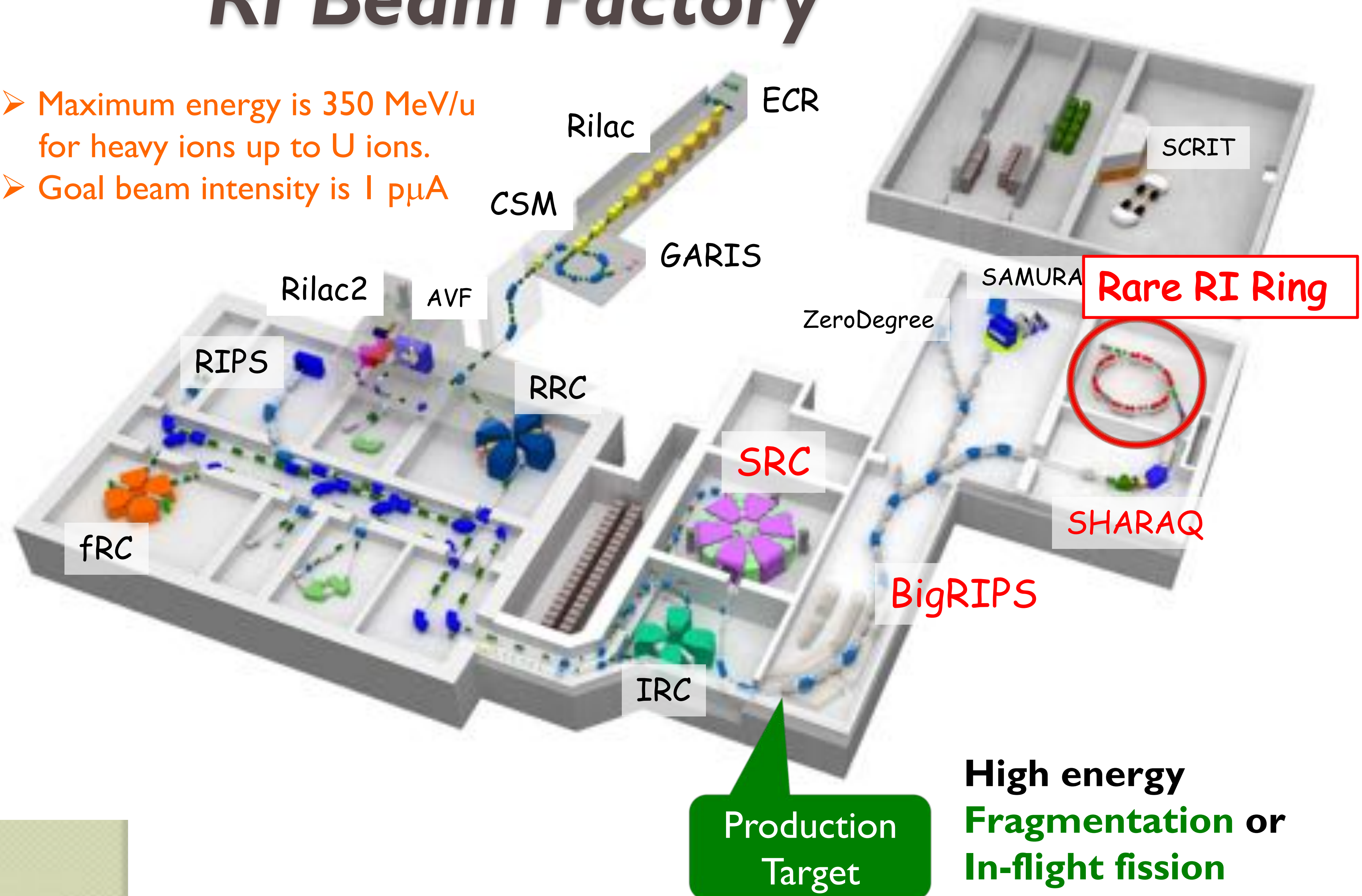
Heavy Ion Research Facility in Lanzhou (HIRFL)





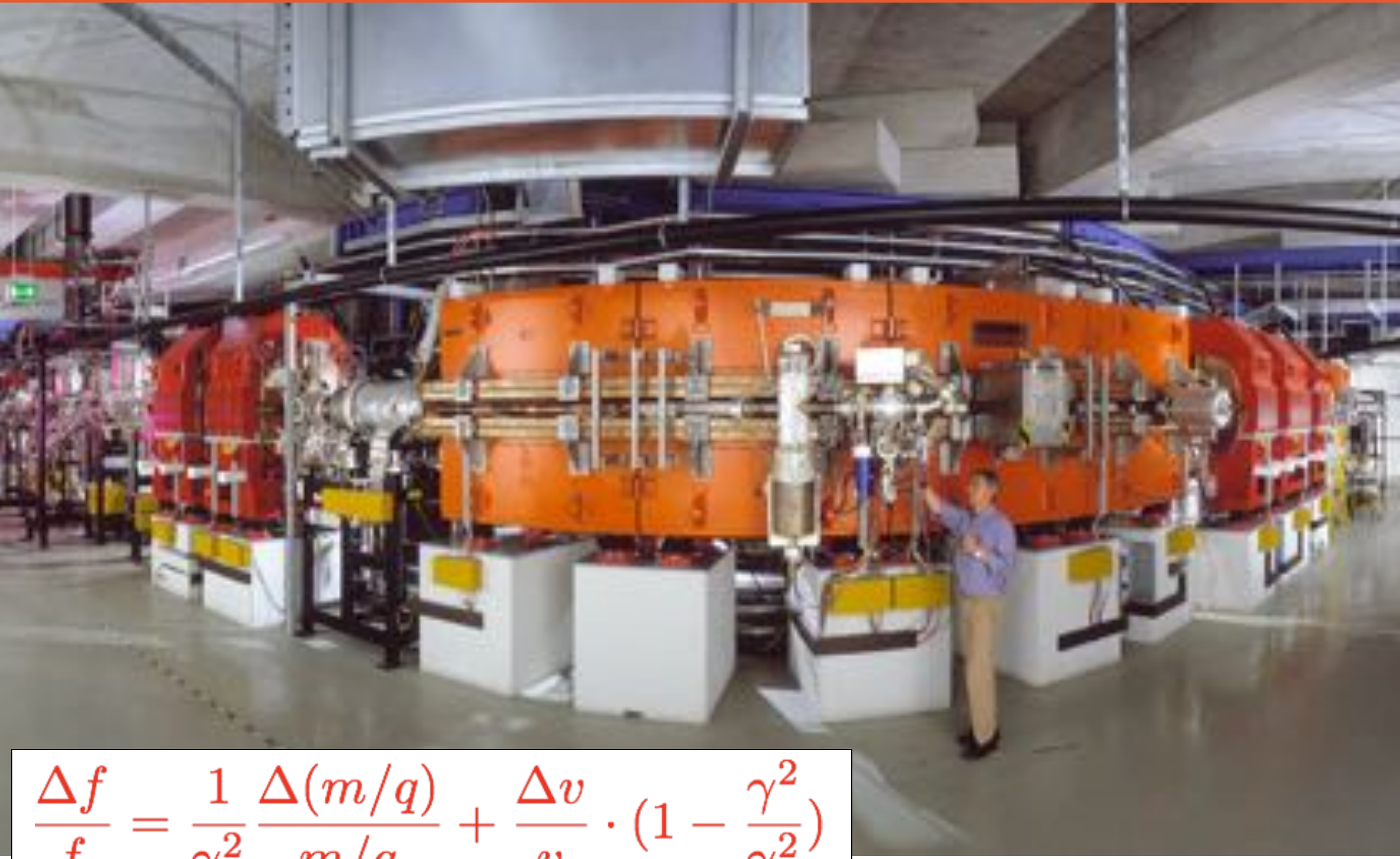
RI Beam Factory

- Maximum energy is 350 MeV/u for heavy ions up to U ions.
- Goal beam intensity is 1 pμA



High energy
Fragmentation or
In-flight fission

ESR : E_{max} = 420 MeV/u, 10 Tm; e^-, stochastic cooling



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

BEAM COOLING

Cooling techniques applied at ion rings

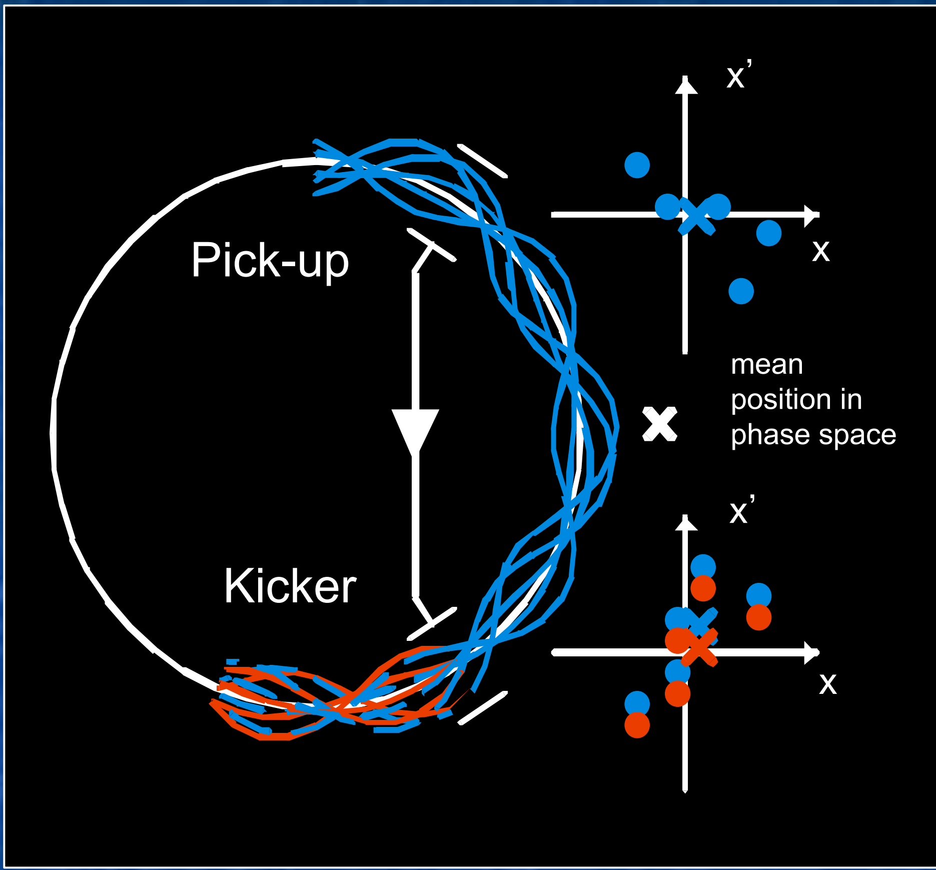
One may overcome Liouville theorem by applying external forces, with the aid of, e.g. :

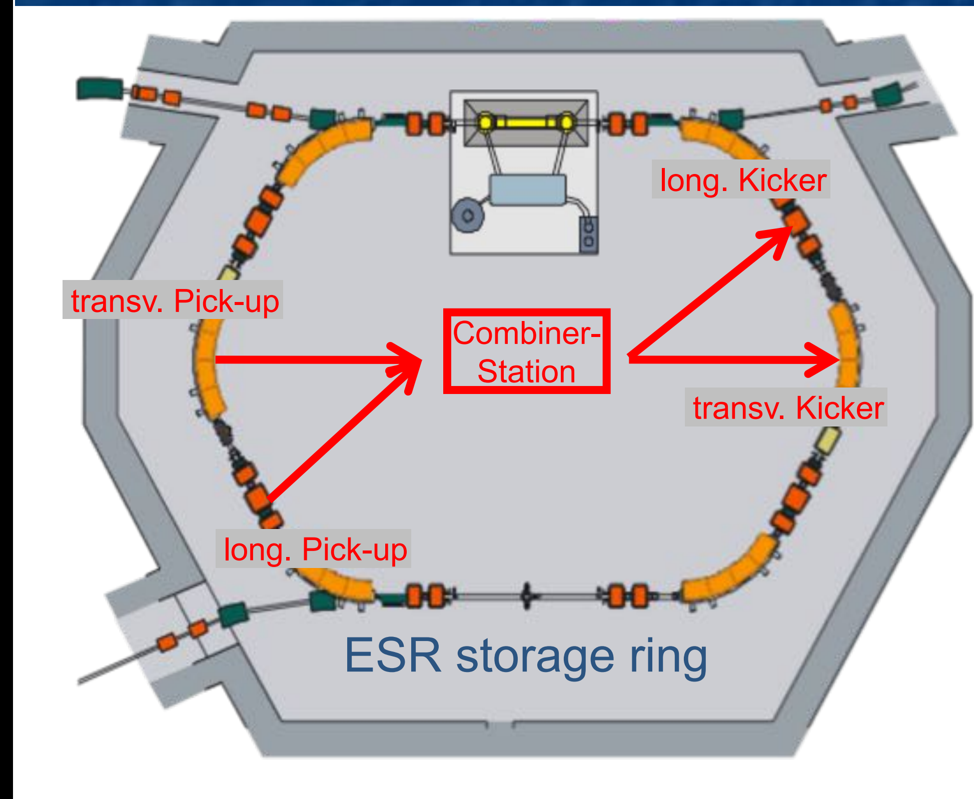
- Lasers = transfer of momentum

- Electrons = mixing of temperatures

- Stochastic = self-correction

Stochastic cooling (self-correction of trajectory)

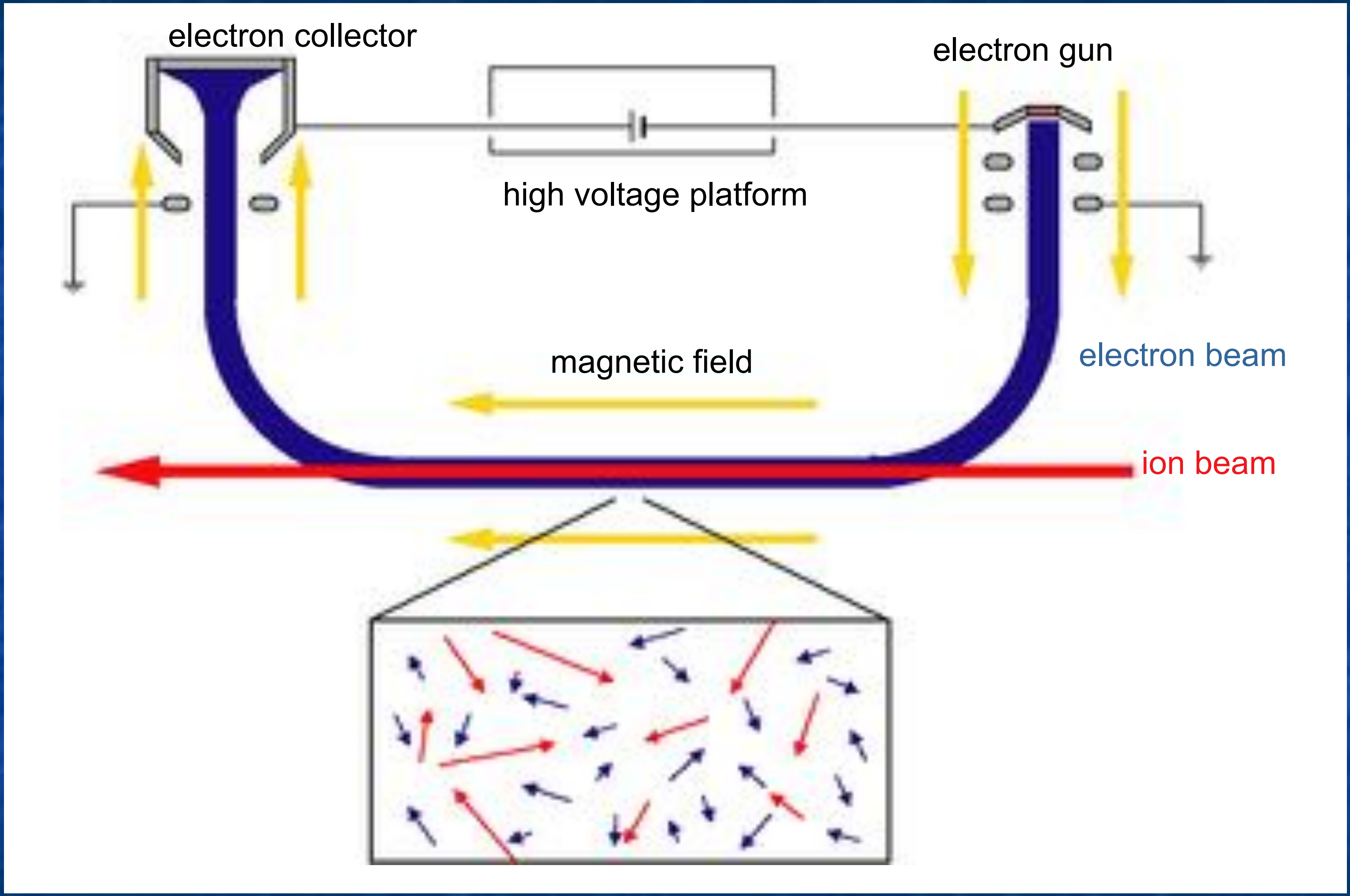




Stochastic cooling is in particular efficient for hot ion beams

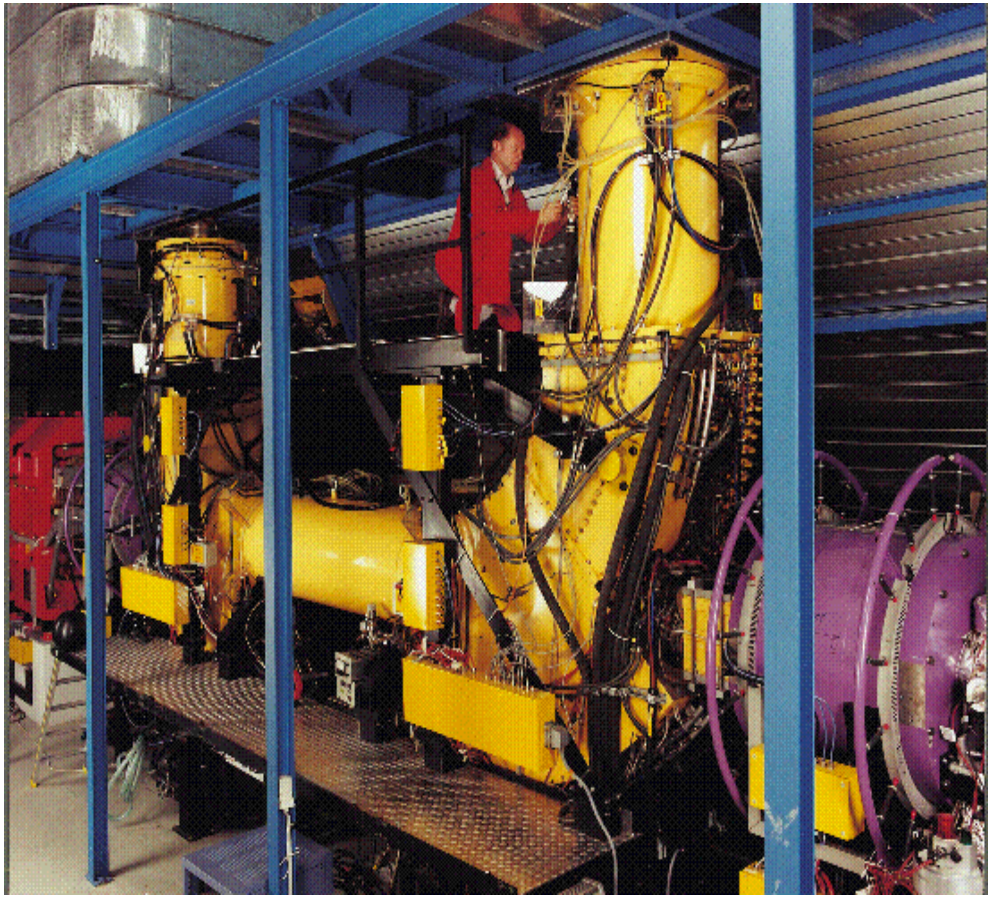
Cooling time τ scales as N_{ion} / bandwith

Electron cooling (cold bath for ions)

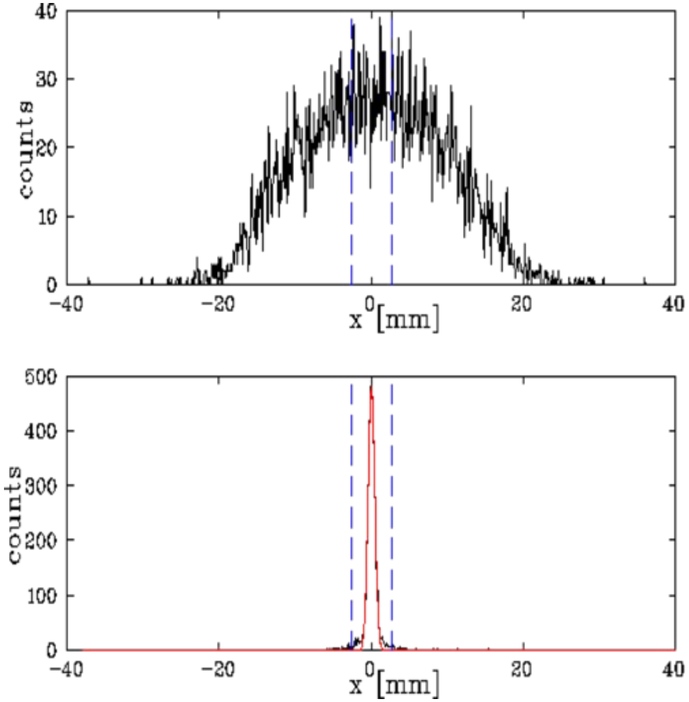


Same mean velocity of e^- and ions;
strong magnetic guiding field; substitution of e^- after a cycle

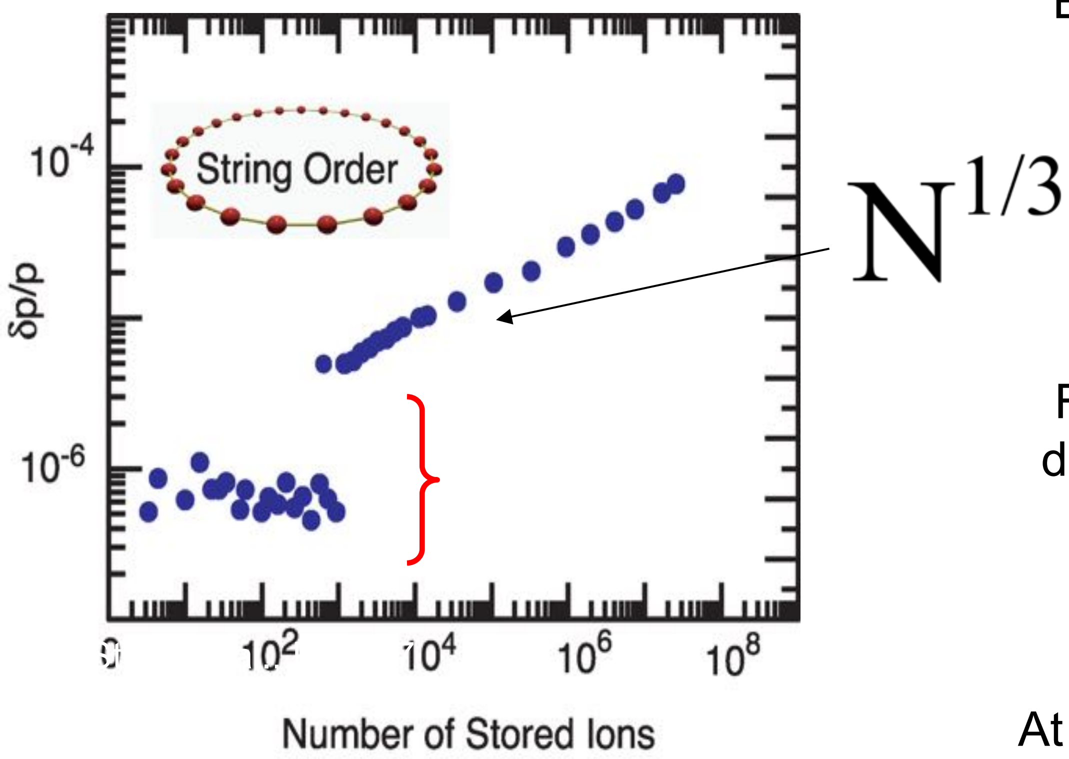
Electron Cooling



momentum exchange with 'cold', collinear e- beam. The ions get the sharp velocity of the electrons, small size and divergence



Electron cooling (phase transition)

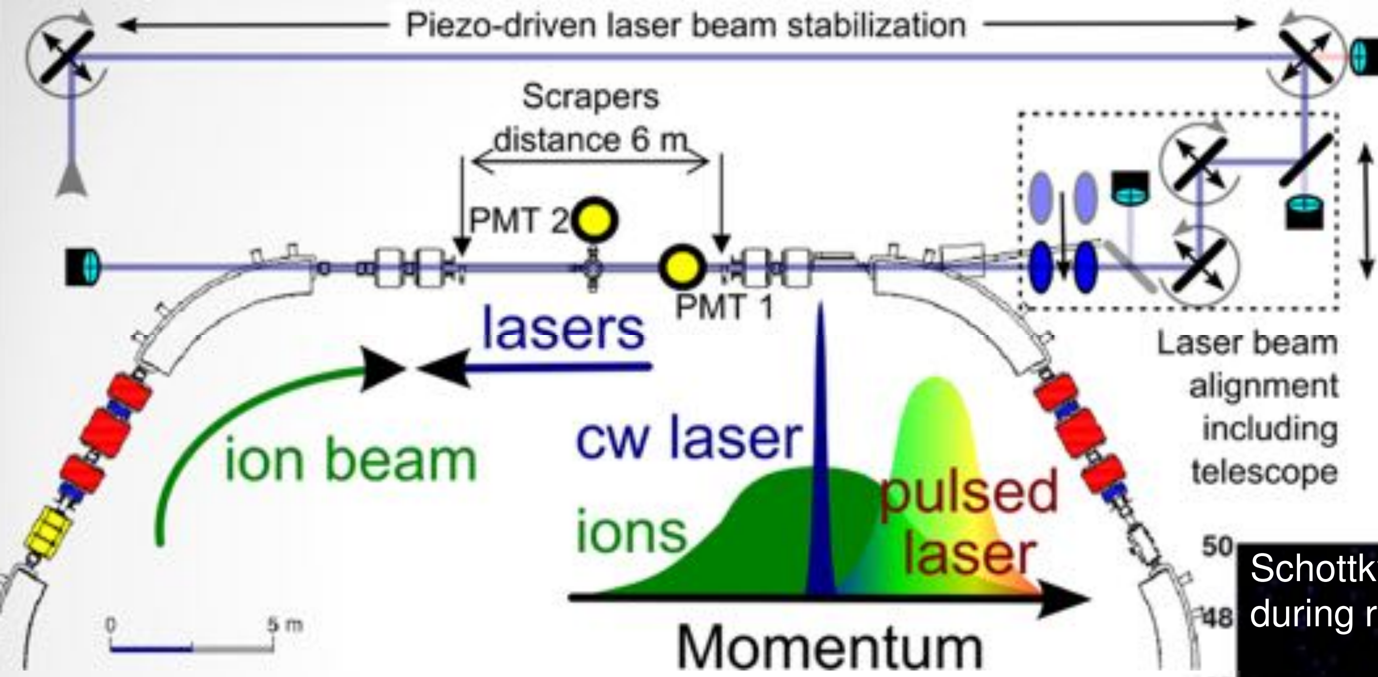


ESR: circumference ≈ 10^4 cm

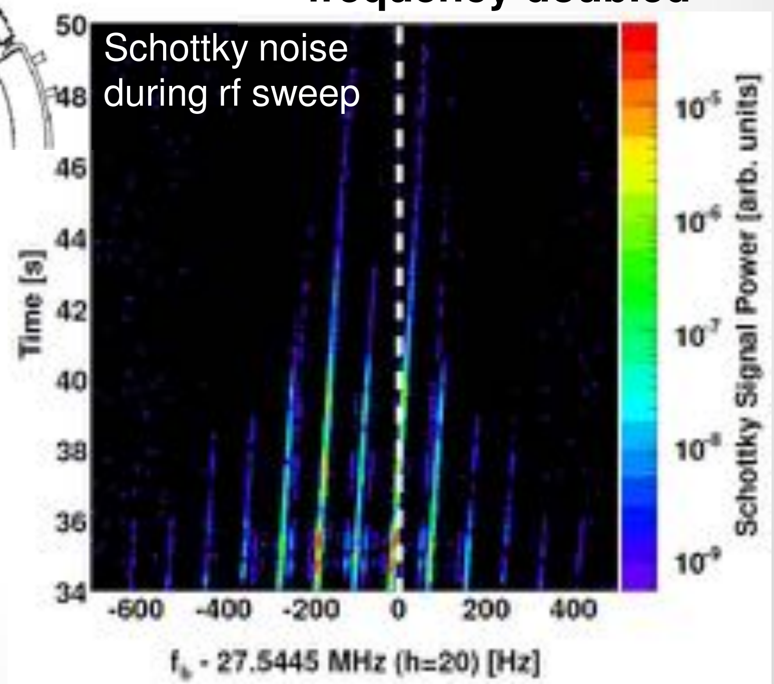
For 1000 stored ions, the mean distance amounts to about 10 cm

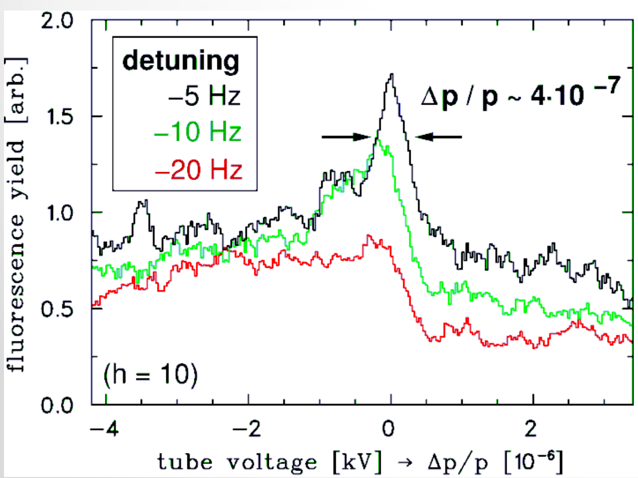
At mean distances of about 10 cm and larger intra-beam-scattering disappeared

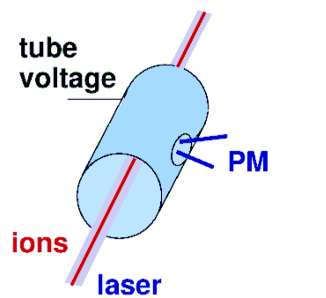
Laser Cooling of C^{3+} at the ESR



Argon ion laser
(257.3 nm)
frequency doubled







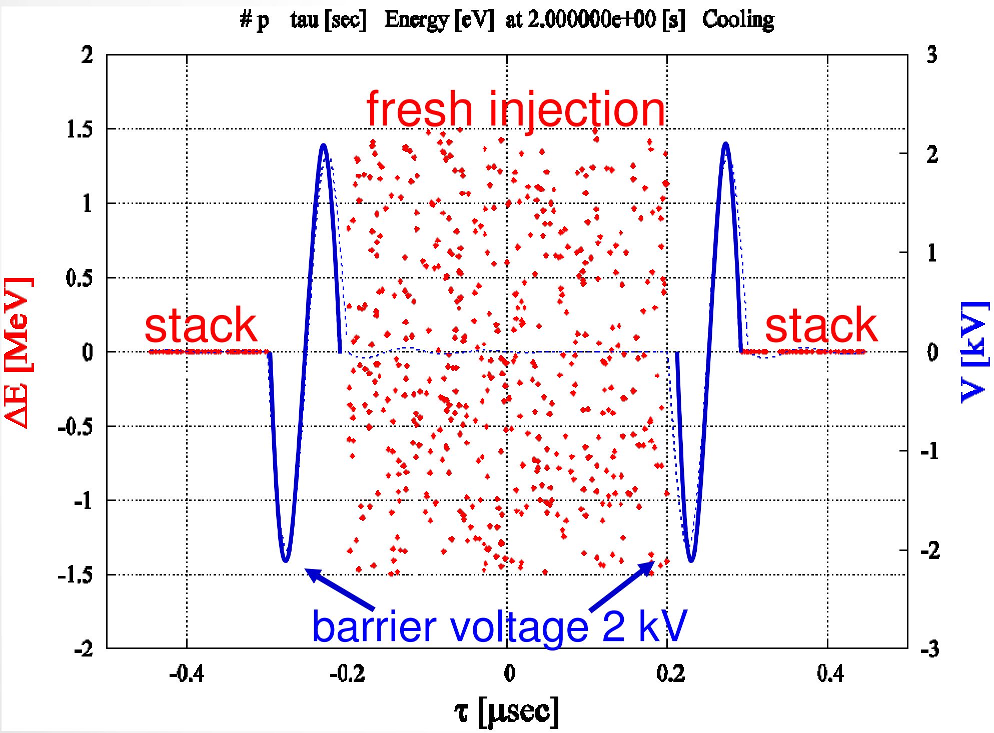
fluorescence
light detection

M. Steck GSI Helmholtzzentrum Darmstadt

ACCUMULATION

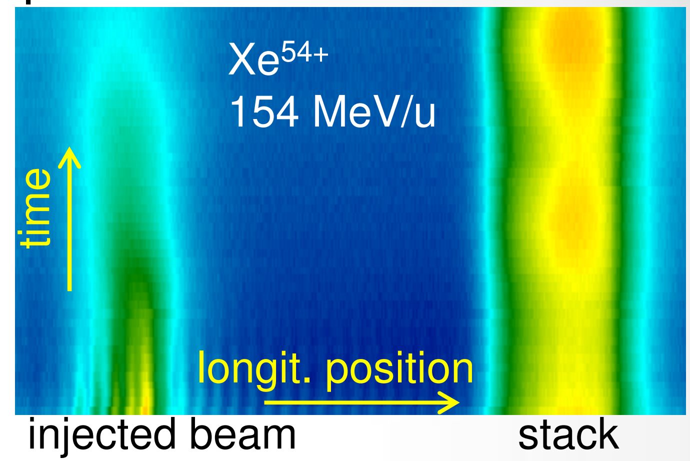
Accumulation of Secondary Particles

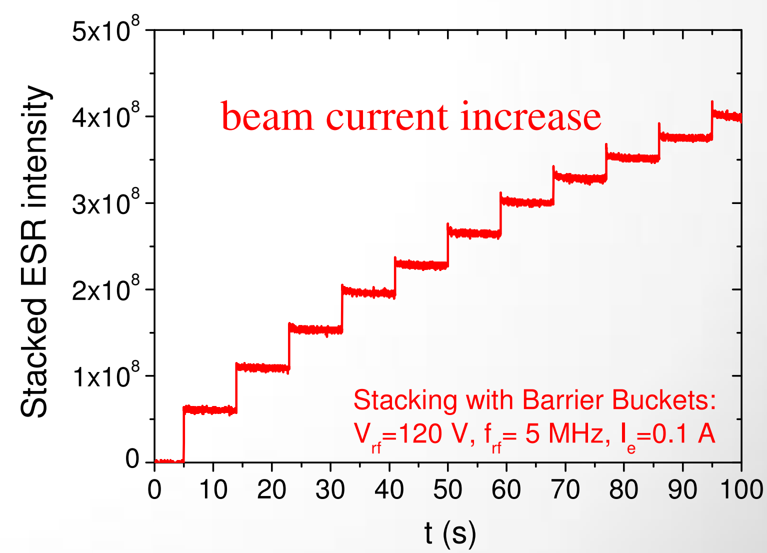
basic idea: confine stored beam to a fraction of the circumference, inject into gap and apply cooling to merge the two beam components
⇒ fast increase of intensity (for secondary beams)



simulation of longitudinal stacking
with barrier buckets and electron cooling

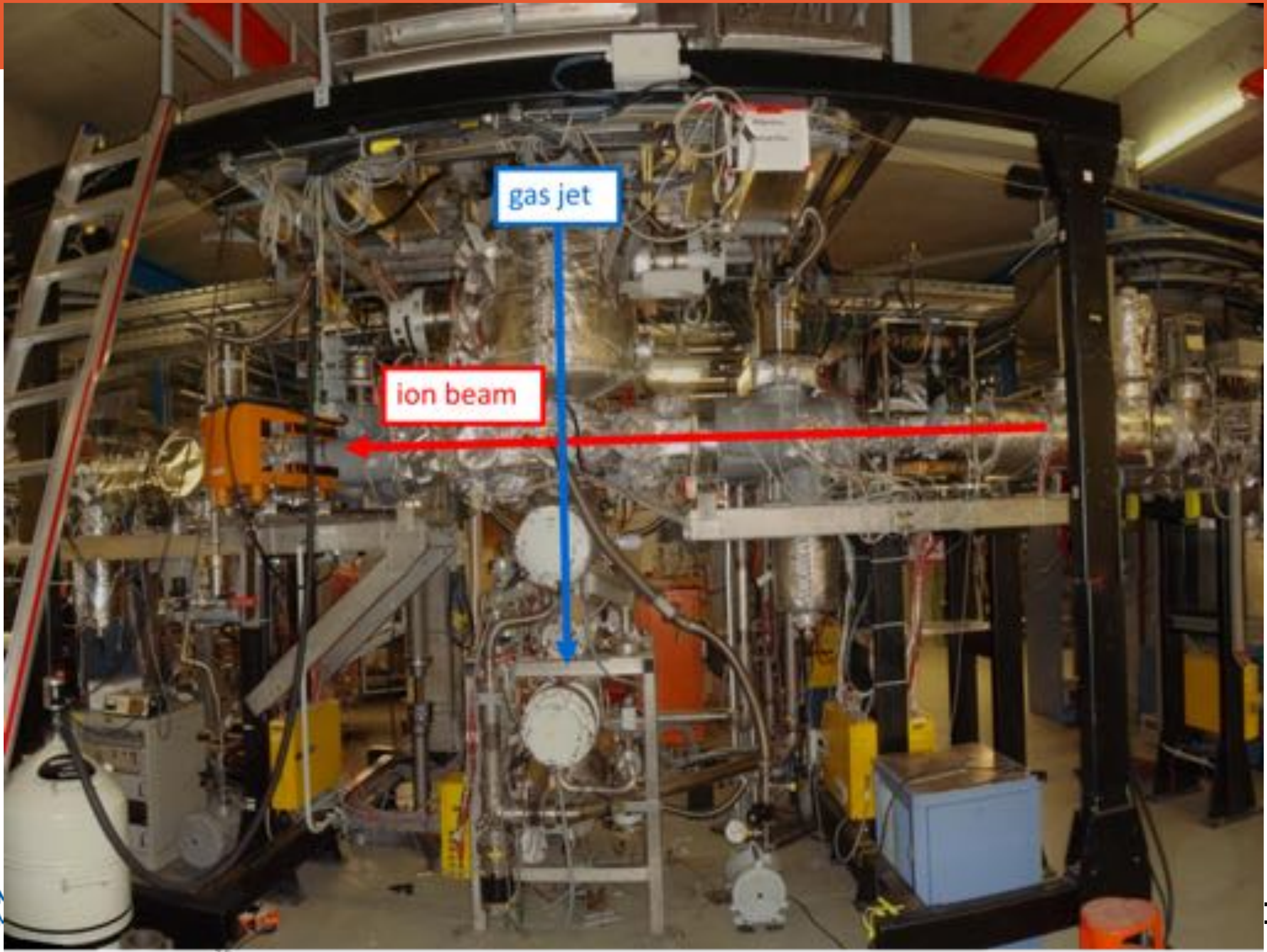
experimental verification at ESR





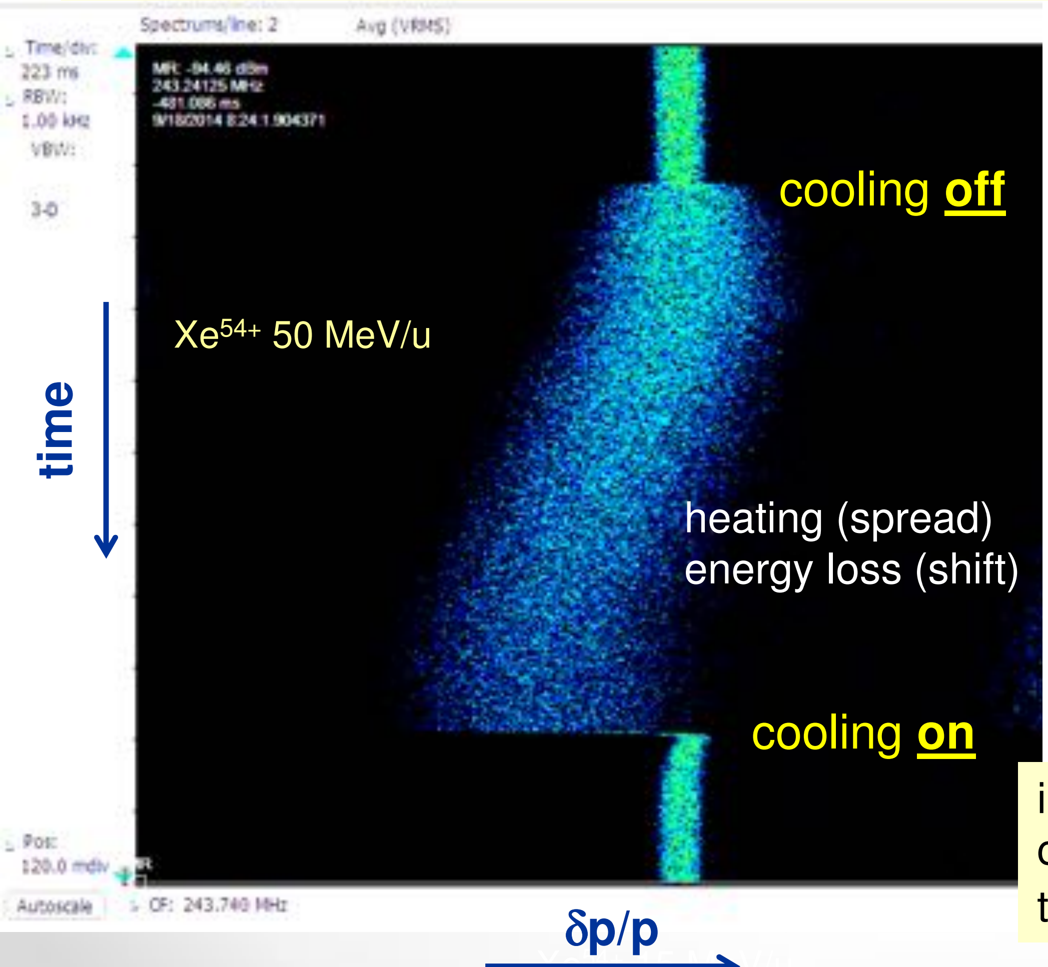
INTERNAL TARGETS

Gas Jet Target at the ESR

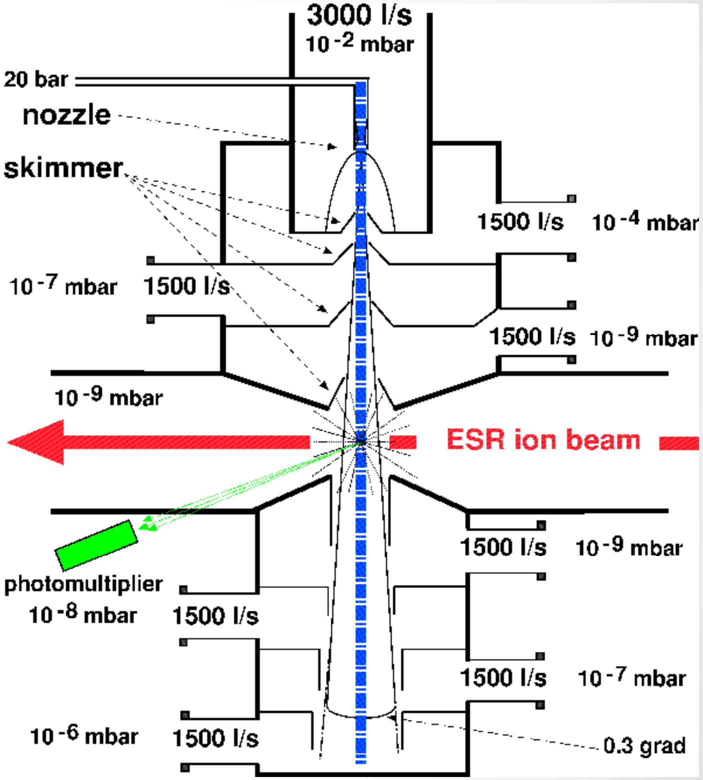


Compensation of Heating by an Internal Target

beam momentum (energy)
observation of average value and spread



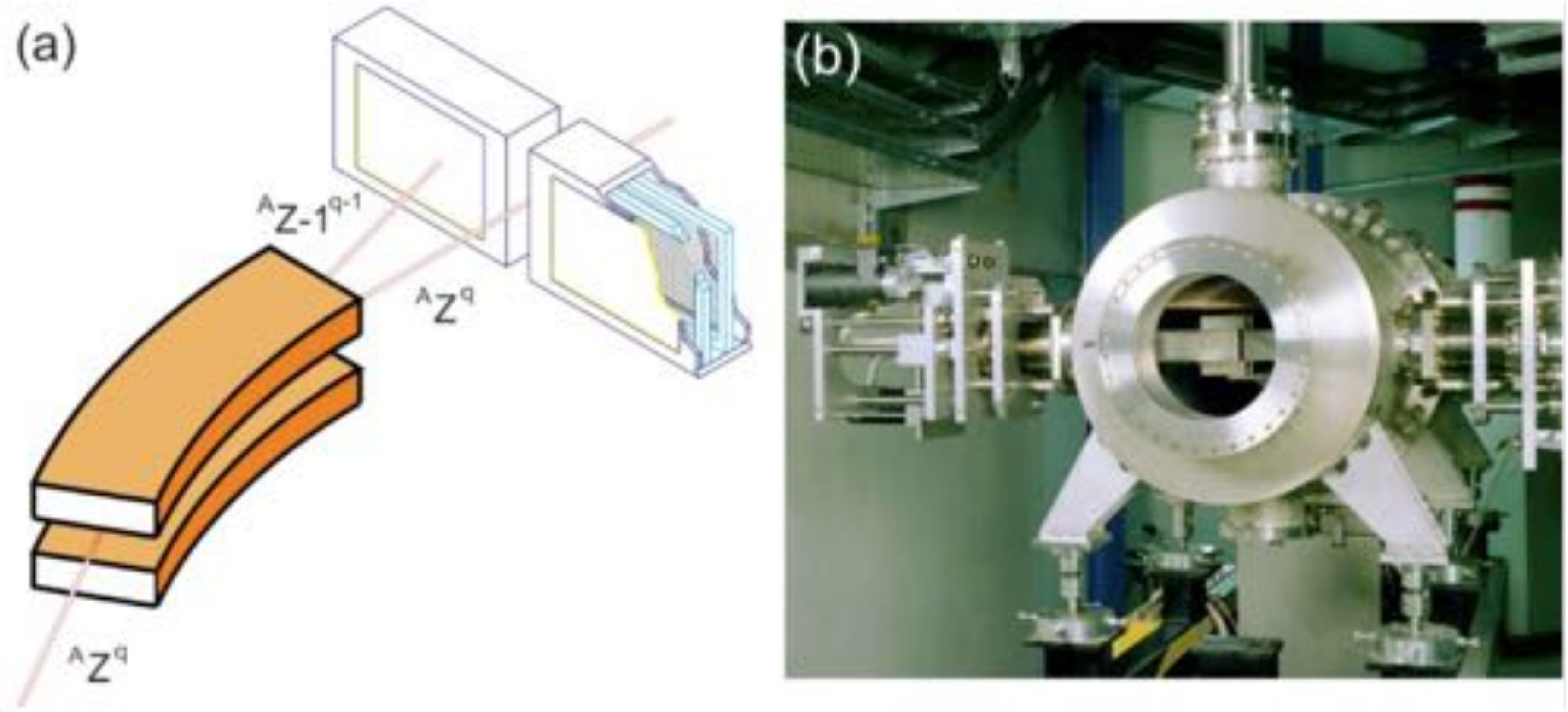
internal gas jet target



in addition:
compensation of emittance increase due to target: $\delta\varepsilon = 1/2\ \beta_{x,y}\ \theta_{rms}^2$ per target passage

PARTICLE DETECTORS

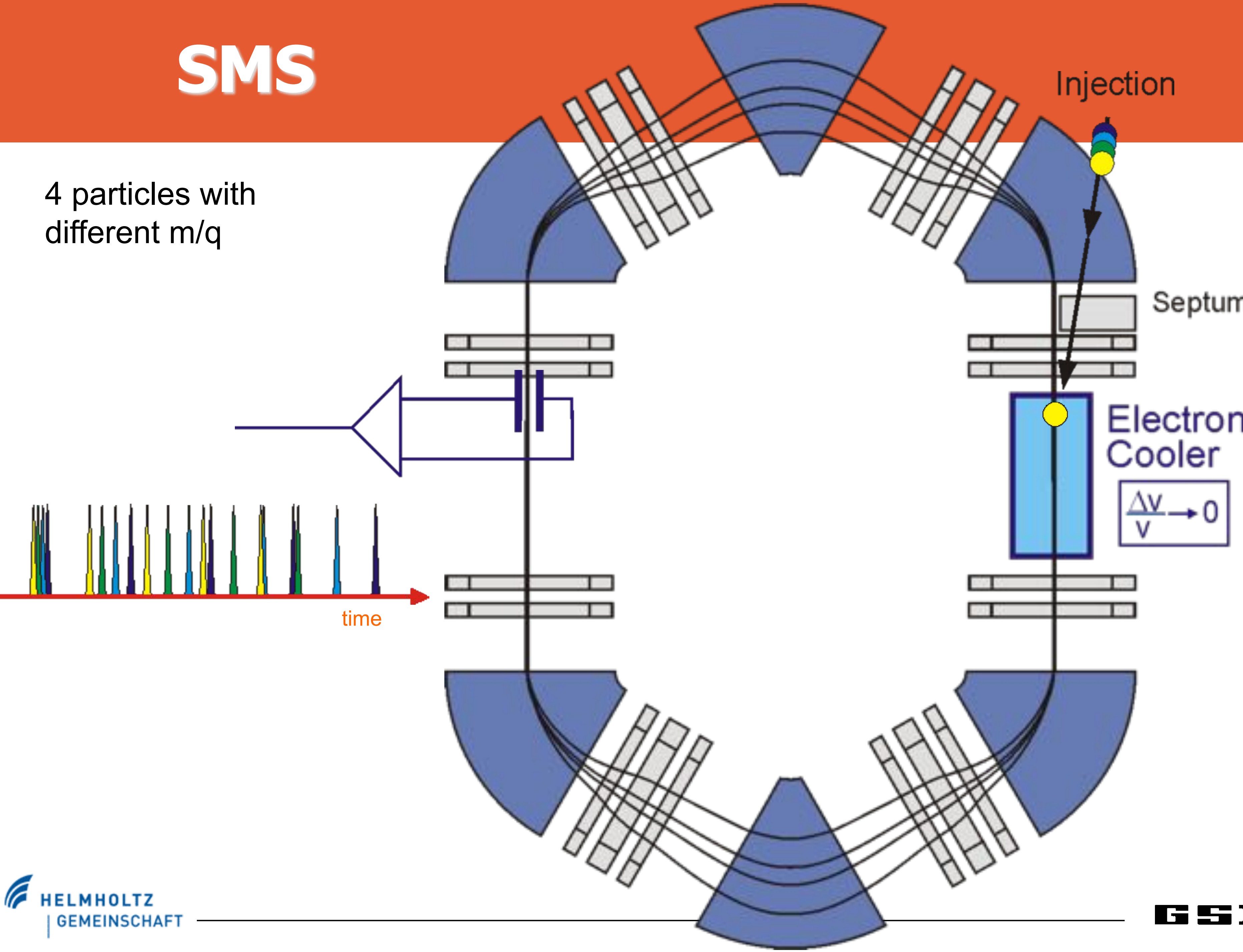
Particle detectors



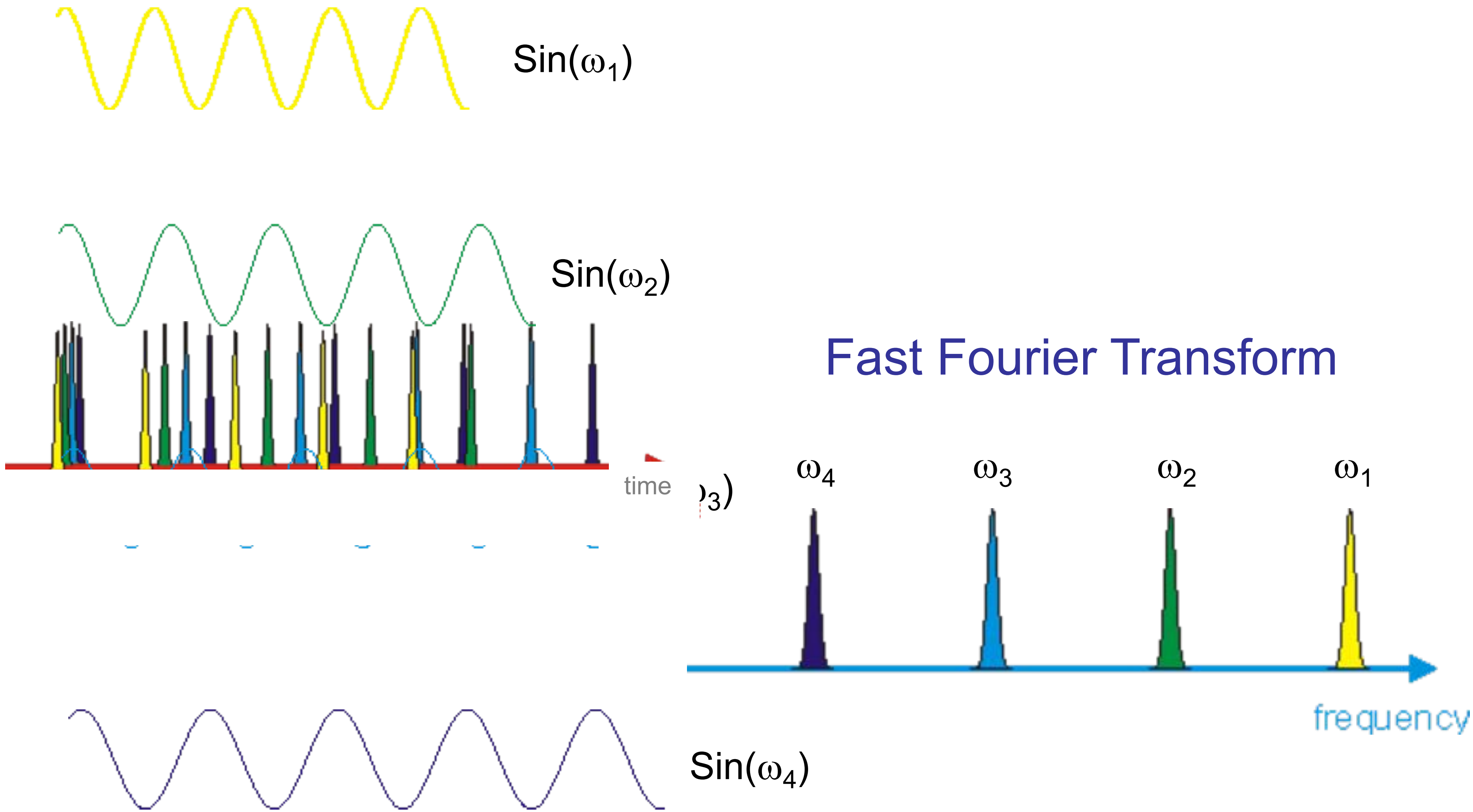
SCHOTTKY SPECTROSCOPY

SMS

4 particles with different m/q

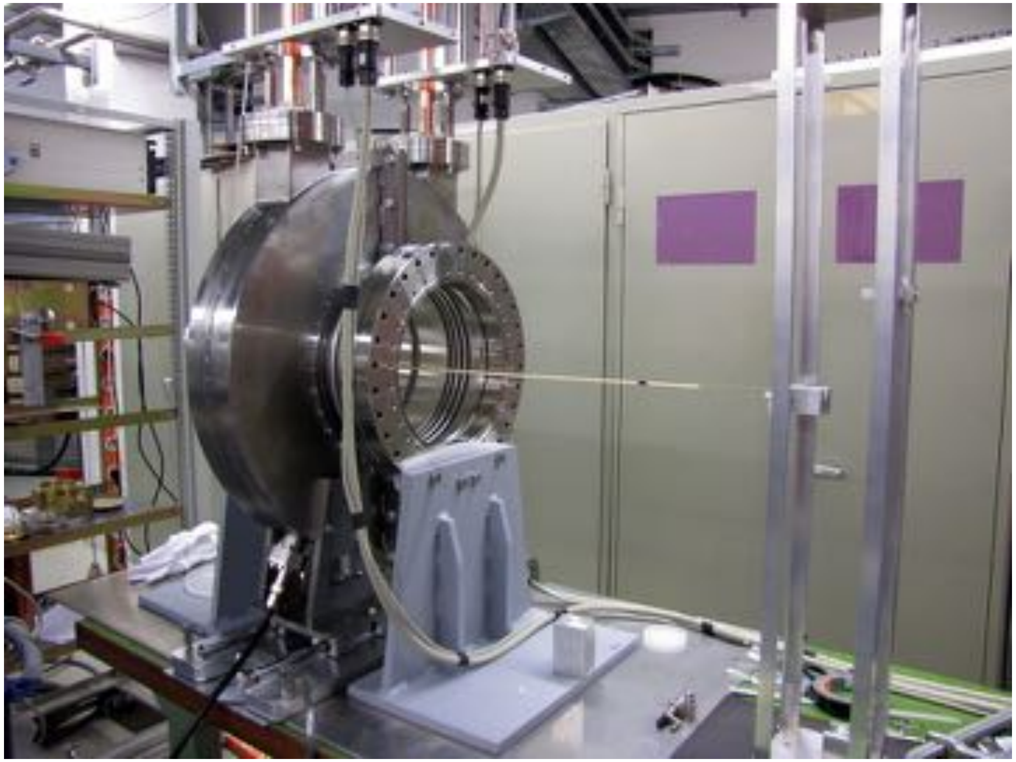


SMS



Sin(ω1)
Sin(ω2)
time
Fast Fourier Transform
ω4
ω3
ω2
ω1
frequency
Sin(ω4)

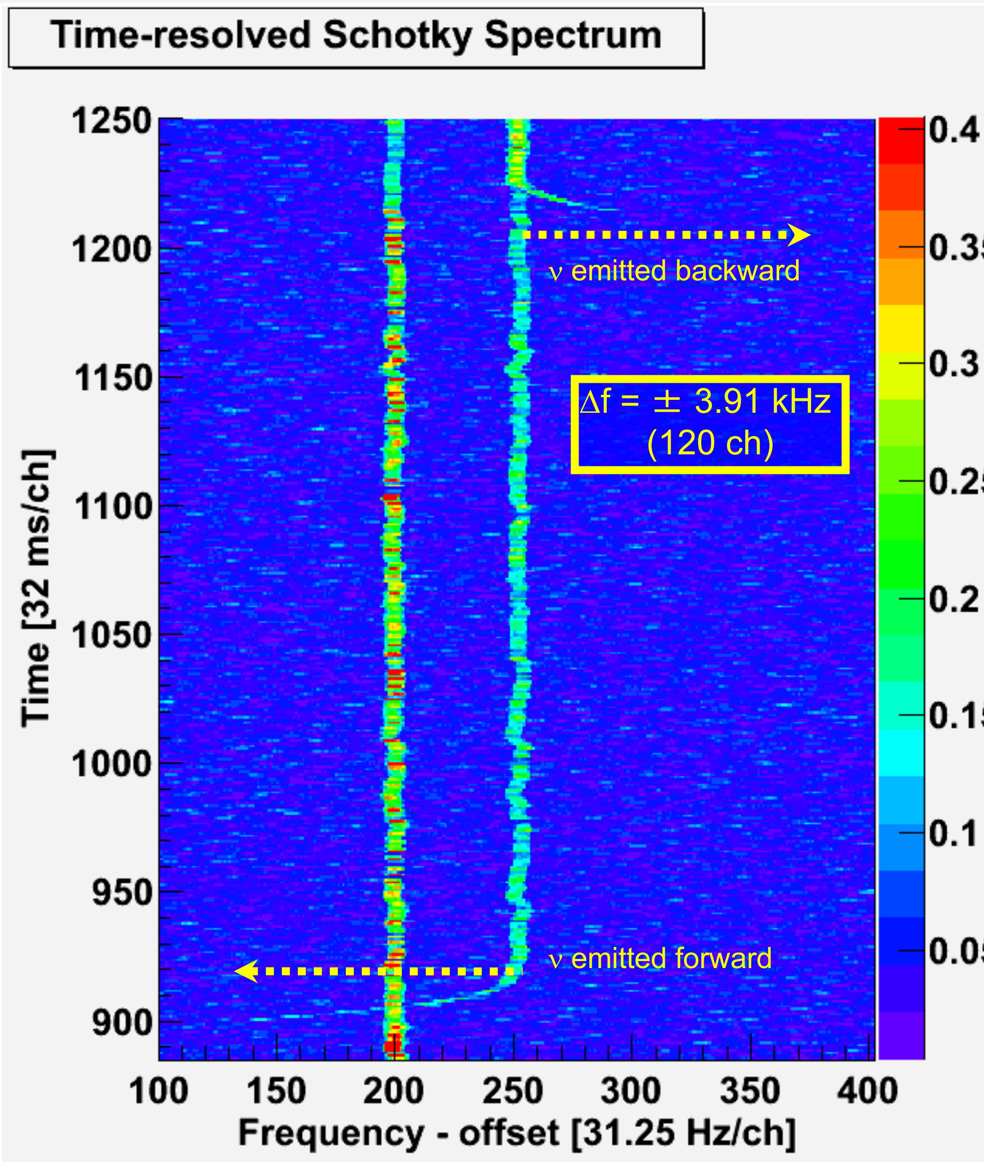
New Resonant Schottky Cavity

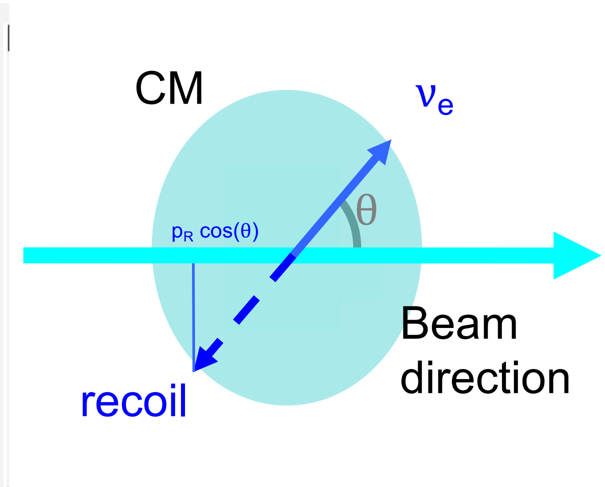


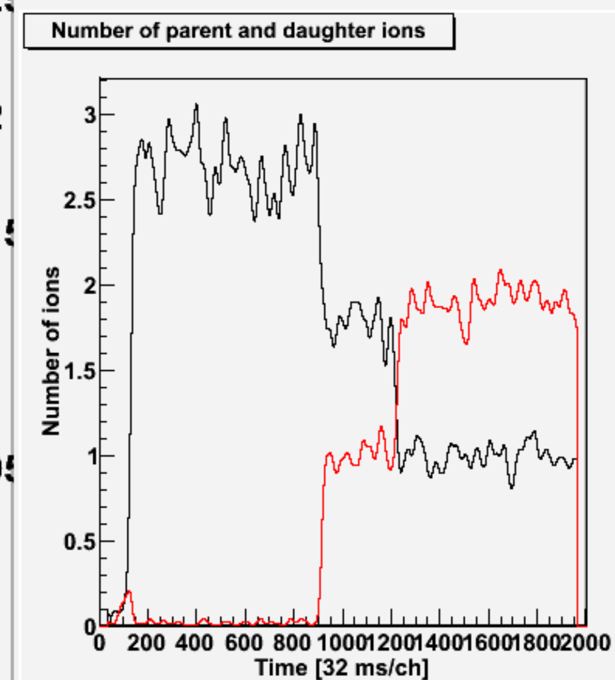
The signal-to-noise ratio is improved by a factor of about 100

F. Nolden et al., Nucl. Instr. Meth. A (2011)

Three Parent He-Like ^{142}Pm Ions







Astrophysical reactions – Zuzana, Jan, Carlo, Oliver, Beatriz, Rene

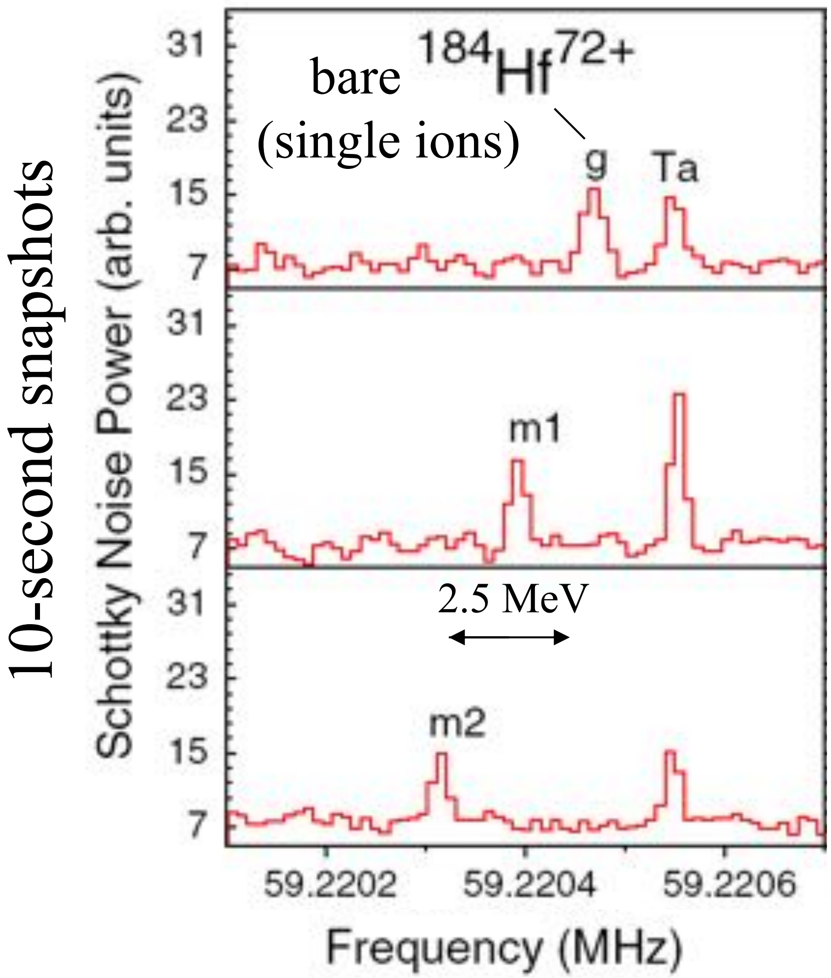
Lifetimes – Ragandeep

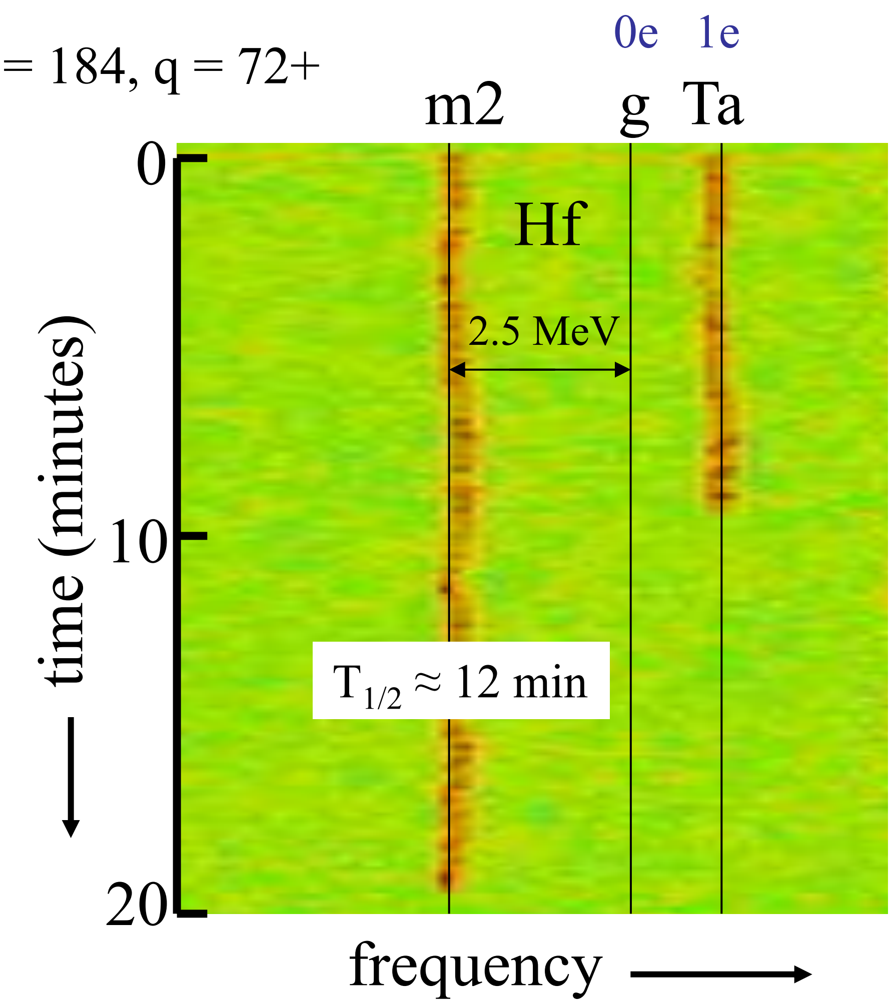
Masses - Ruijiu

EXAMPLE 1
LONG-LIVED ISOMERIC STATES

E122

High-K isomers in n-rich ^{184}Hf



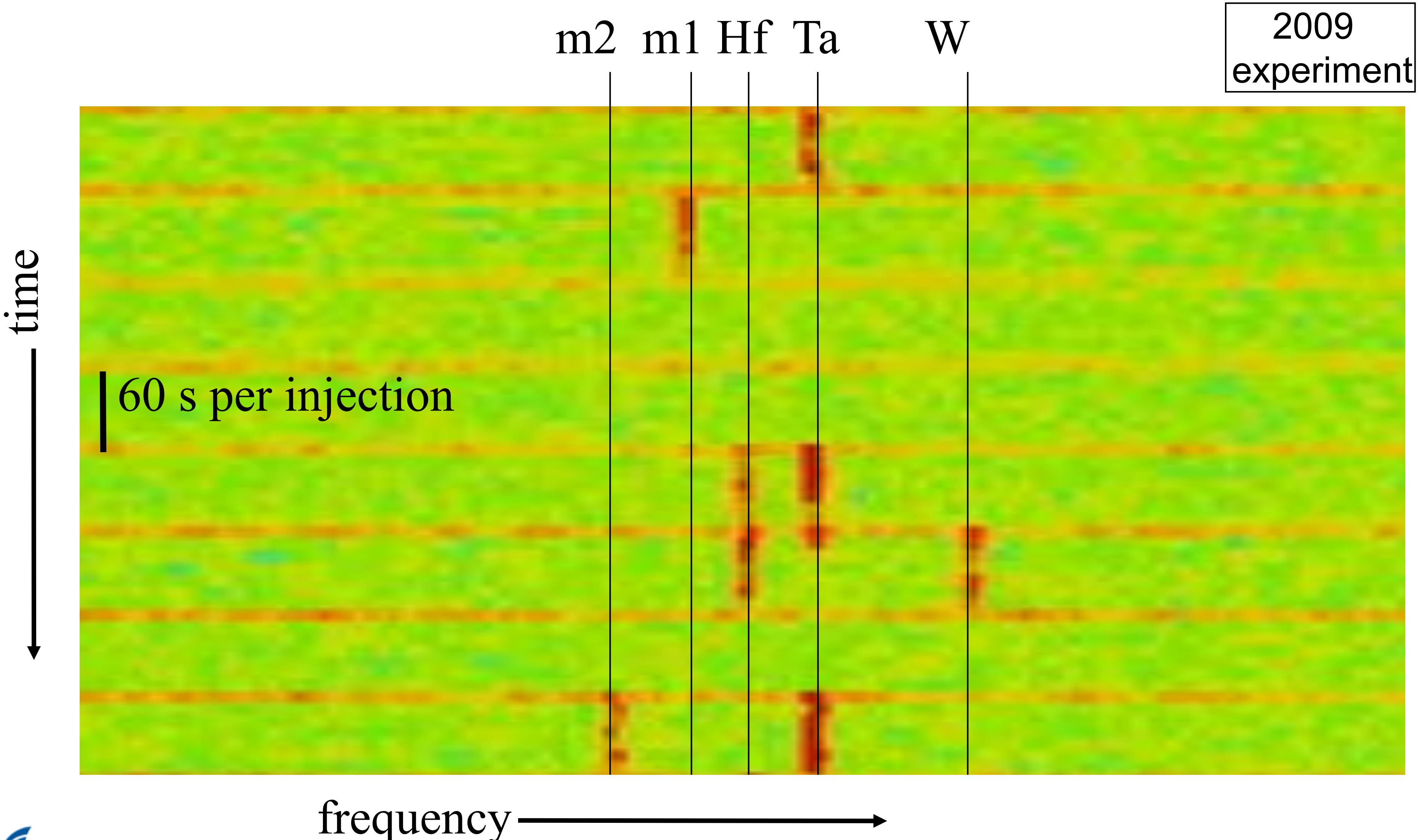


- first observation of *m2* isomer
- long-lived β-decaying isomer

Reed et al., Phys. Rev. Lett. 105 (2010) 172501

E122

A=184 (72$^+$) isobars and isomers



Reed et al., Phys. Rev. Lett. 105 (2010) 172501

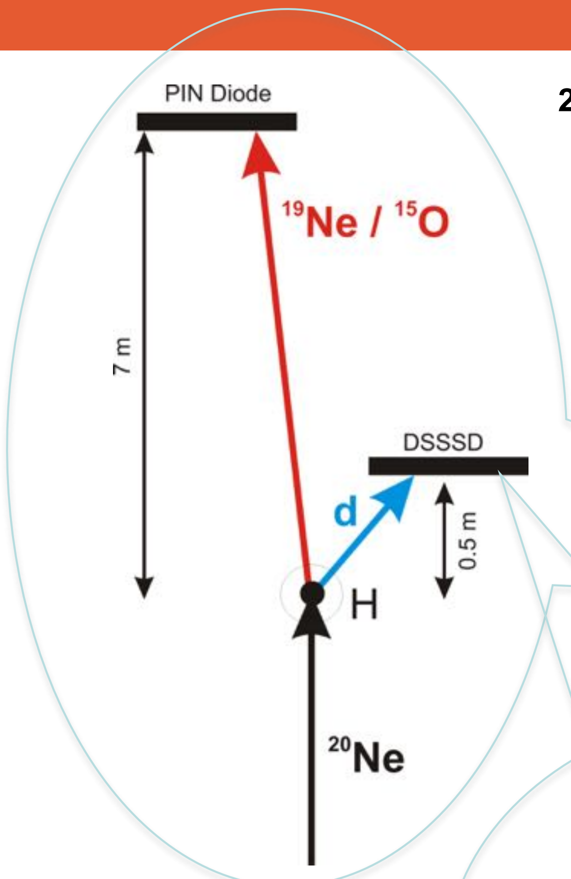
EXAMPLE 2

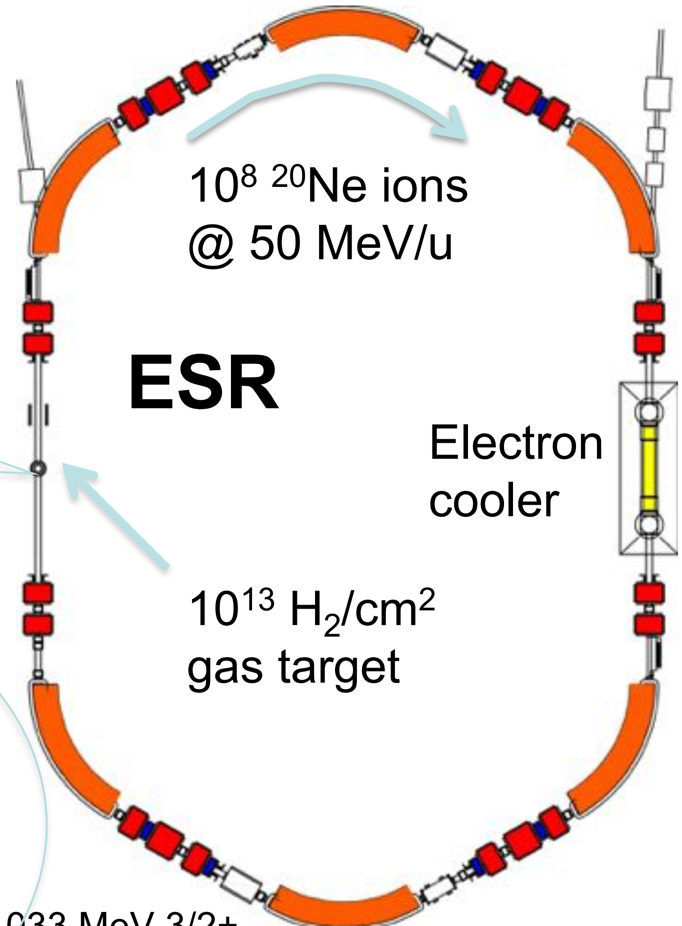
$^{15}O(a,g)^{19}Ne$

First transfer reaction measurement at the ESR

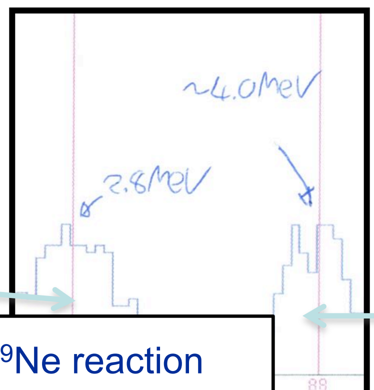
Experiment: 08-14 October 2012

$^{20}Ne(p,d)^{19}Ne$ reaction





Online data



2.795 MeV 1/2- state in ^{19}Ne

4.033 MeV 3/2+ state in ^{19}Ne

New ESR proposal to study $^{20}Ne(p,t)^{19}Ne$ reaction

P.J. Woods, Yu.A. Litvinov, et al., GSI Proposal E087

D. Doherty et al., Phys. Scripta T (2015)

TSR @ Hie-Isolde

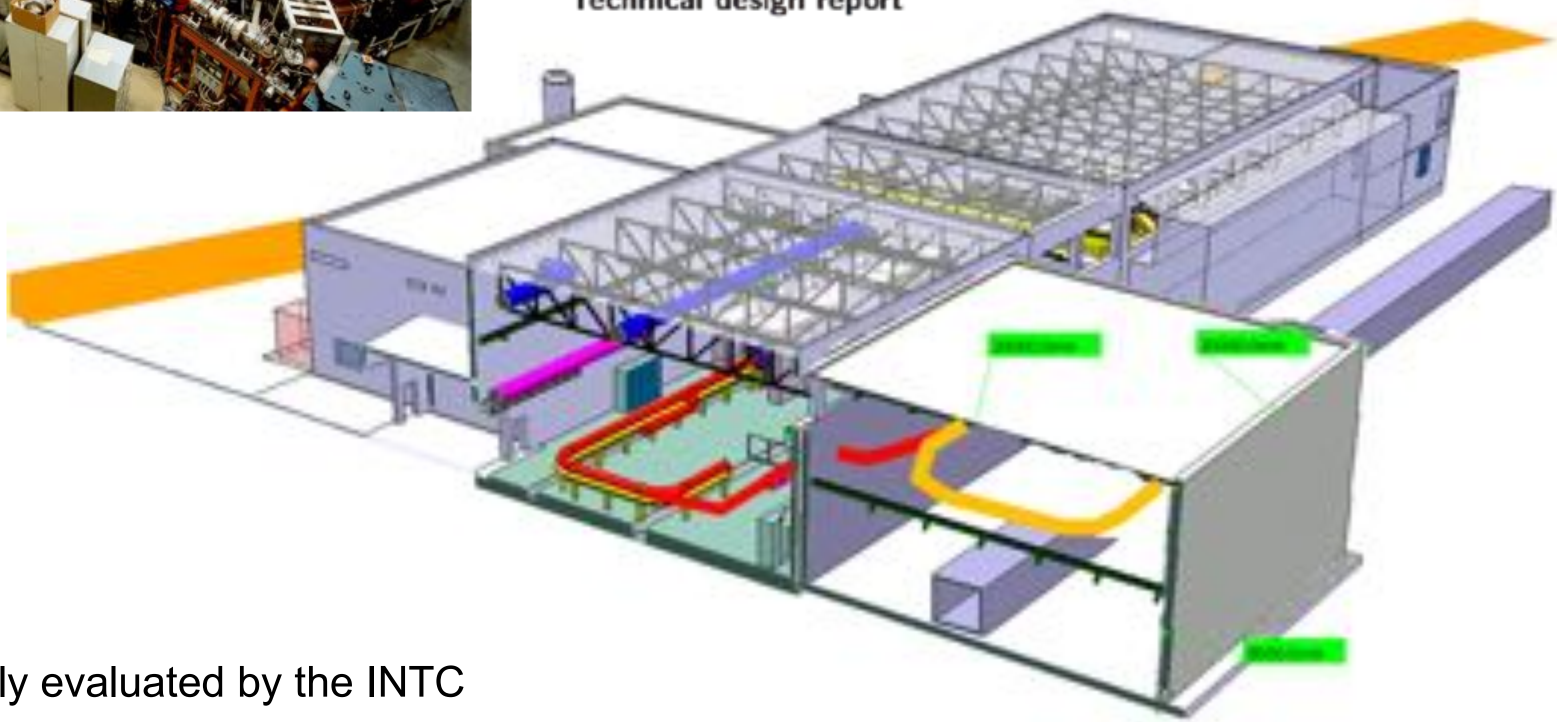
Eur. Phys. J. Special Topics 207, 1–117 (2012)
© EDP Sciences, Springer-Verlag 2012
DOI: 10.1140/epjst/e2012-01599-9

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

Storage ring at HIE-ISOLDE

Technical design report

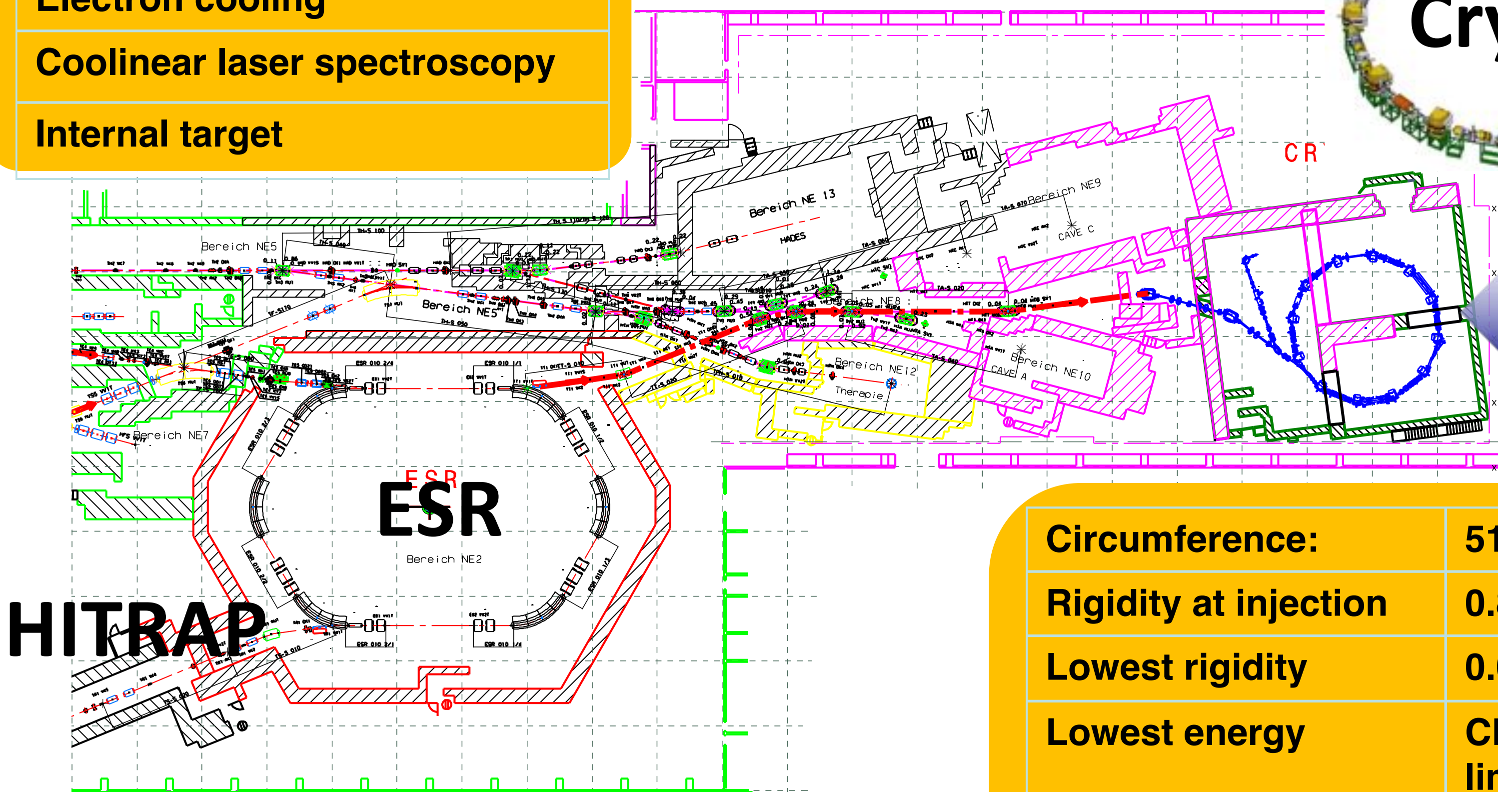


TDR positively evaluated by the INTC

CRYRING@ESR

Project coordination:
F. Herfurth & M. Lestinsky

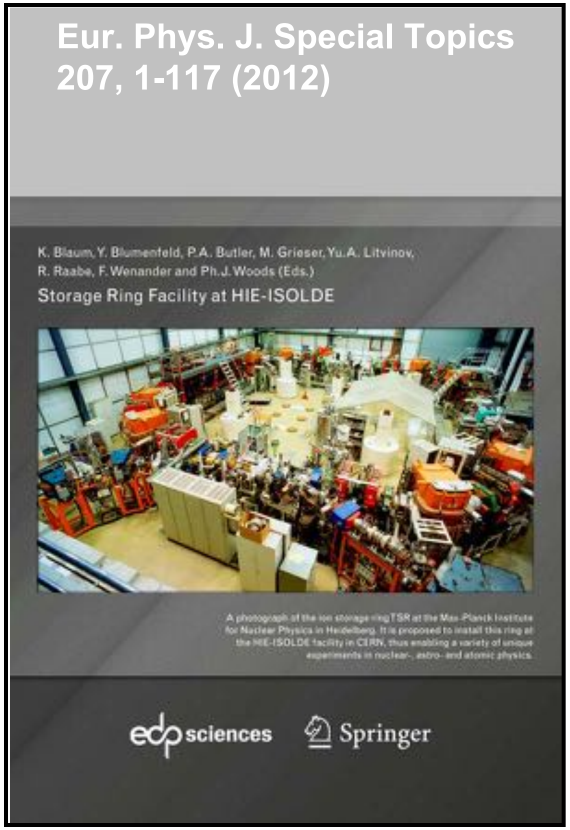
Electron cooling
Coolinear laser spectroscopy
Internal target



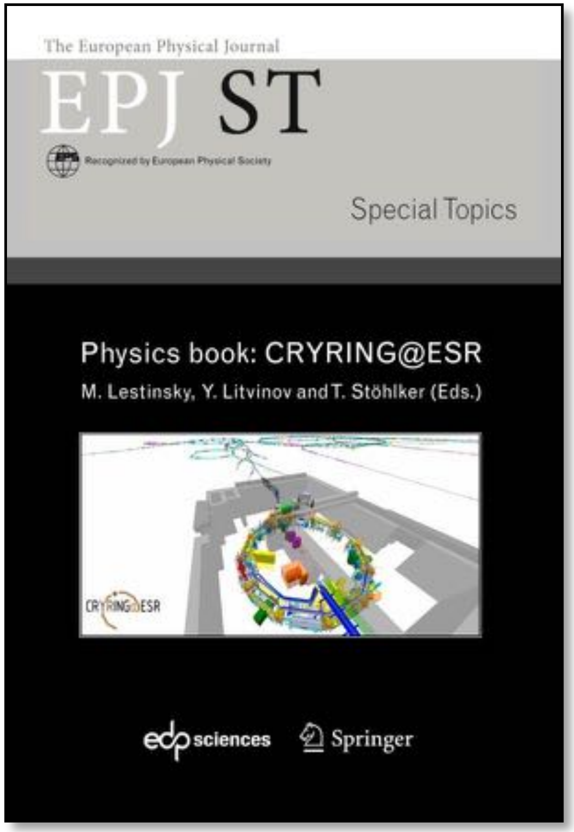
Circumference:	**51.63 m**
Rigidity at injection	**0.88 Tm (1.44 Tm)**
Lowest rigidity	**0.054 Tm**
Lowest energy	**Charge exchange limited**
Magnet ramping	**7 T/s; 1 T/s**
Vacuum system	**10^{-11} - 10^{-12} bar**
Slow extraction	

Working group report: http://www.gsi.de/en/start/fair/fair_experimente_und_kollaborationen/sparc/news.htm

Two basis publications

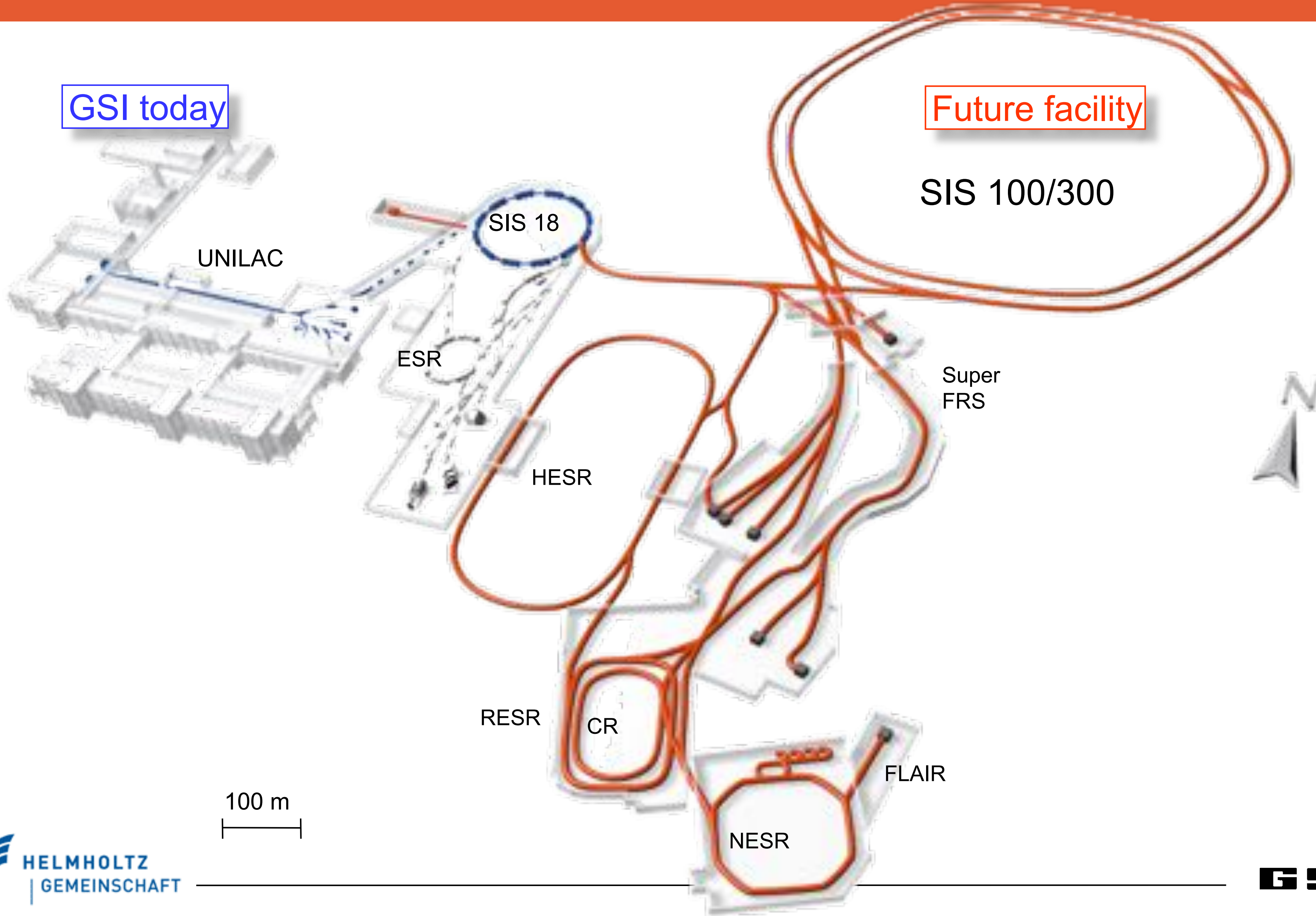


Techinical Design Report:
TSR@ISOLDE
(2012)



Physics book:
CRYRING@ESR
(2016)

FAIR - Facility for Antiproton and Ion Research



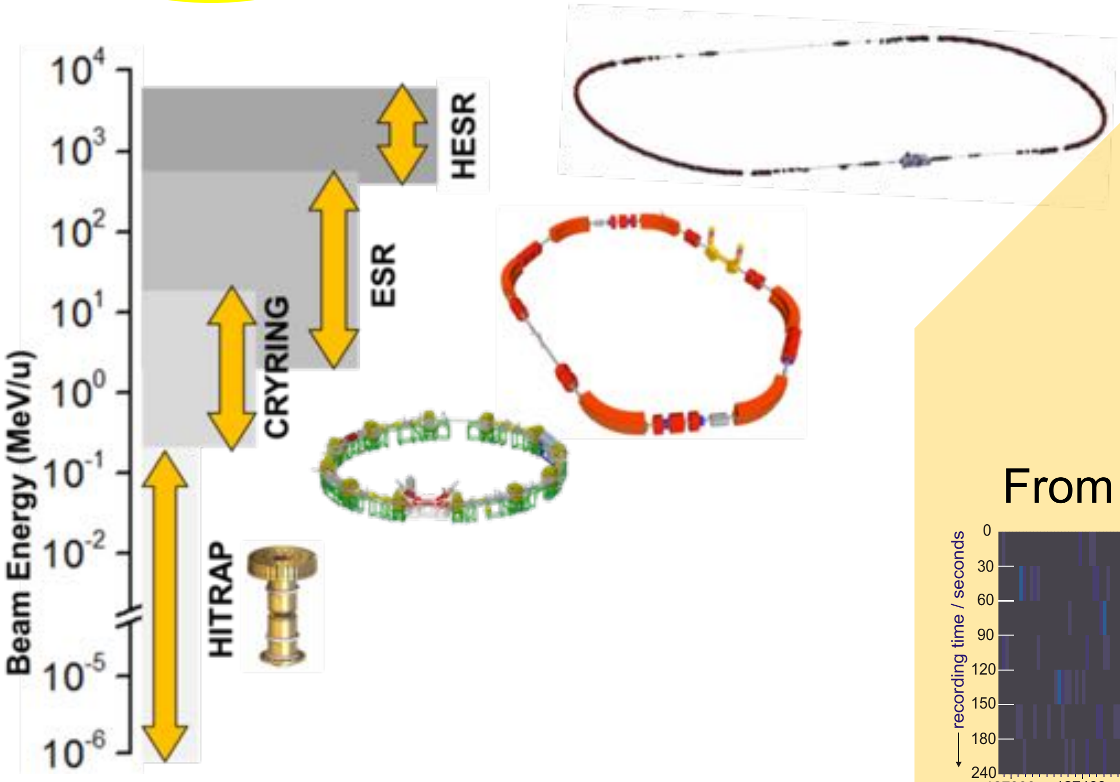
Ion Beam Facilities / Trapping & Storage

Worldwide Unique !

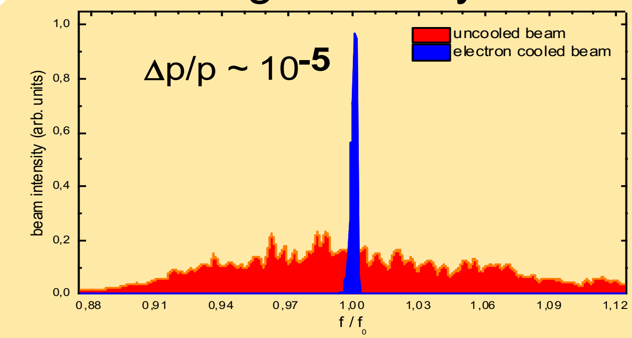
Stored and Cooled

Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei

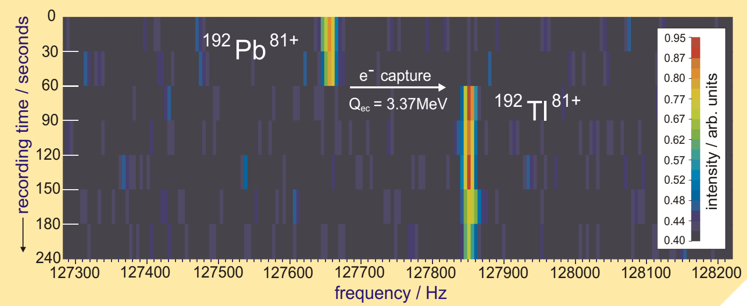
From Rest to Relativistic Energies (up to 4.9 GeV/u)



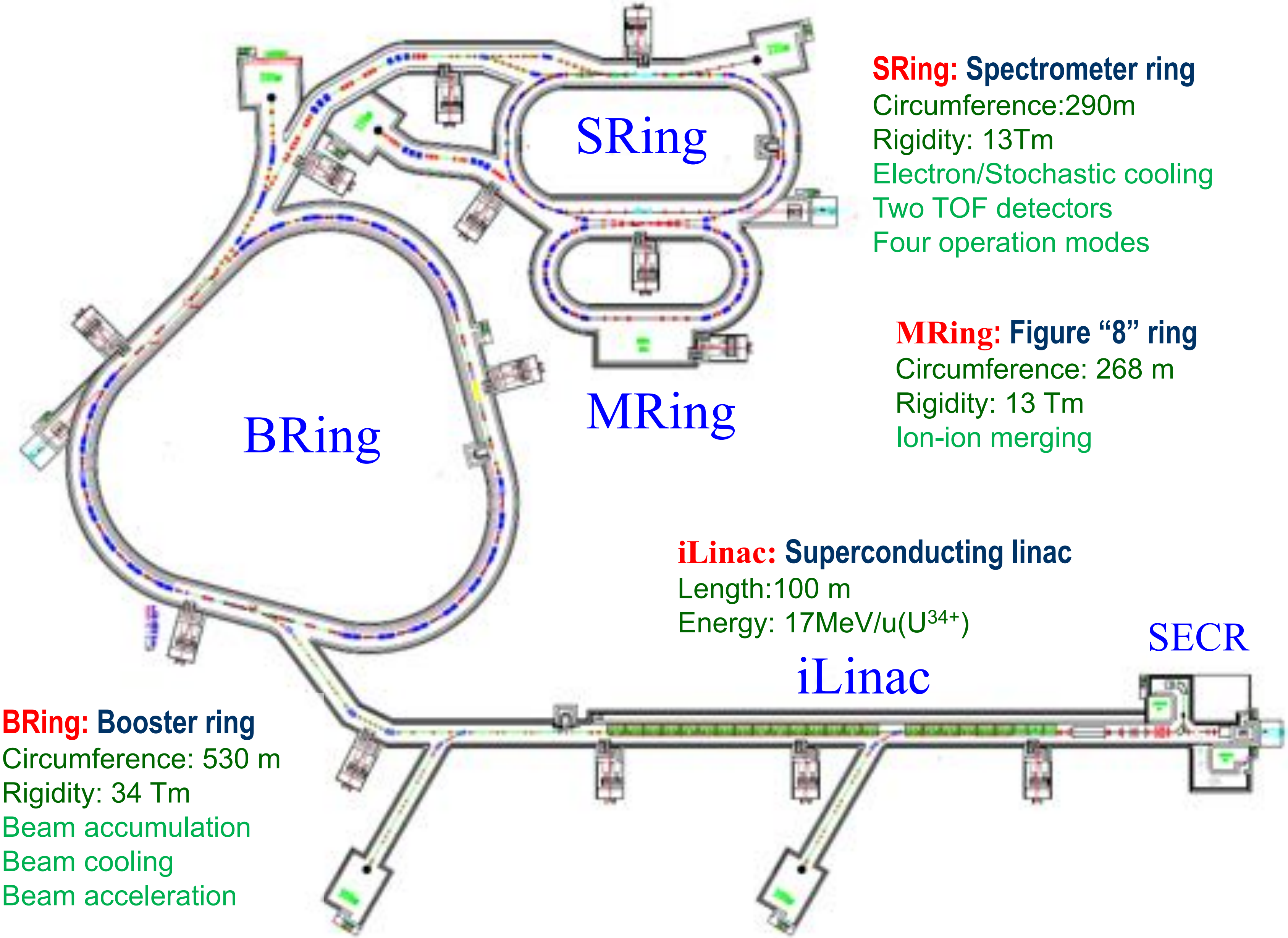
Cooling: The Key for Precision



From Single Ions to Highest Intensities



HIAF: General description – **Main components**



SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

MRing: Figure "8" ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

Why storage rings?

- Storage - efficient use of rare species
- Cooling - high quality beams
- Recirculation - high luminocities though thin targets
- Removing of contaminants
- Ultra-high vacuum – preserving atomic charge state
- Laser-ion interaction
- Various gaseous internal targets, electrons, (neutrons)
- High detection efficiencies for recoils

Many-many thanks to all colleagues from all over the world !!!

Argonne NATIONAL LABORATORY

TUM

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

HIC for FAIR Helmholtz International Center

MICHIGAN STATE UNIVERSITY

T.C. İSTANBUL ÜNİVERSİTESİ 1453

NIIGATA UNIVERSITY

BEIHANG UNIVERSITY 1952

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA SEIT 1558

THE UNIVERSITY OF EDINBURGH

INSP INSTITUT DES NANOSCIENCES DE PARIS

GSI

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

UNIVERSITY OF SURREY

RIKEN

IPN Orsay

UNIVERSITY OF LIVERPOOL

THE AUSTRALIAN NATIONAL UNIVERSITY

UNIVERSITÄT SALZBURG

Saitama University 埼玉大学

CENBG

universität mainz

CERN

IMP

筑波大学

TRIUMF

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