Beam Cooling
Status and Perspectives

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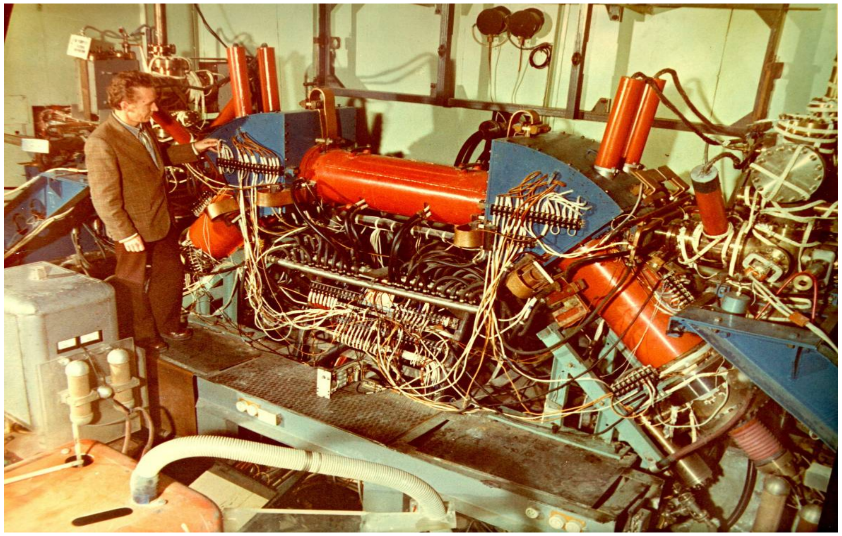
Outline

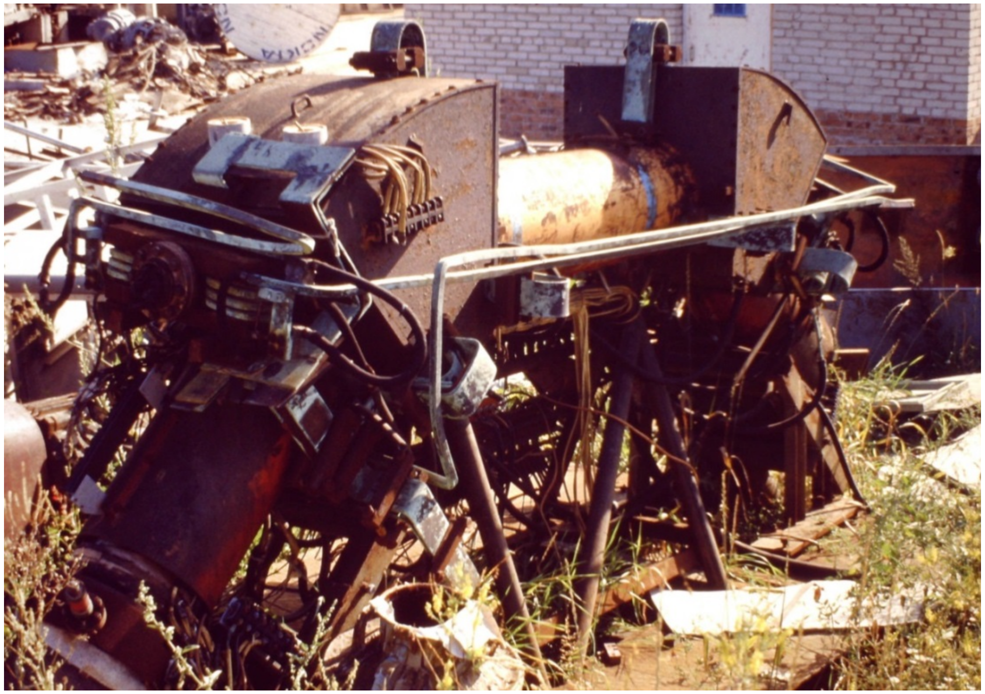
- Electron Cooling
- Stochastic Cooling
- Laser Cooling
- Beam Crystallization
- New Facilities

Electron Cooling

Proposed in 1967 by G. Budker
first experimental demonstration in 1974 at NAP-M ring
many systematic measurements and investigations,
e.g. fast magnetized cooling, beam crystallization
thorough understanding (experiments, theory) of electron cooling in the non-relativistic regime and for moderate beam intensities



First Electron Cooler
EPOChA in 1987 →
after many successful experiments in NAP-M



Electron Cooling

Around 1990: various storage ring projects started with experiments
based on the availability of cooling, e.g. internal targets, precision experiments
most of them designed their own electron coolers

new aspects: other beam particles, e.g. antiprotons, heavy ions, rare isotopes
various schemes for beam accumulation (longitudinal and transverse)
have been developed (TSR, LEAR, ESR)

some of those electron cooling systems have been decommissioned
(e.g. IUCF, CELSIUS), some have or will have a new life
(LEAR -> AD, CRYRING -> GSI/FAIR, TSR -> HIE-ISOLDE/CERN)

some new aspects have been studied:
transverse magnetic beam expansion
reduction of transverse electron temperature
use of cryogenic cathodes, reduction of longitudinal electron temperature
special transverse distribution of electron beam, hollow electron beam

23 Electron Cooling Systems

NAP-M, Novosibirsk, Russia, 1974 #
ICE-Ring, CERN, Switzerland, 1979
pbar-Source, Fermilab, Chicago, USA, 1980
MOSOL, Novosibirsk, Russia, 1986 #
LEAR, CERN, Switzerland, 1987
IUCF Cooler, Bloomington, Indiana, 1988
TSR, Heidelberg 1988 and 2004
TARN II, Tokyo, Japan, 1989
CELSIUS, Uppsala, Sweden, 1989
ESR, Darmstadt Germany, 1990
ASTRID, Aarhus, Denmark, 1992
CRYRING, Stockholm, Sweden, 1992
COSY, Jülich, 1993 and 2013 #
SIS18, Darmstadt, 1998 #
Antiproton Decelerator AD, CERN, Switzerland, 1998
HIMAC, Chiba, Japan, 2000
LEIR, CERN, Switzerland, 2005 #
Recycler, Fermilab, Chicago, USA, 2005
S-LSR, Kyoto, Japan, 2005
CSRm, IMP Lanzhou, China, 2005 #
CSRe, IMP Lanzhou, China, 2008 #

decommissioned

in operation

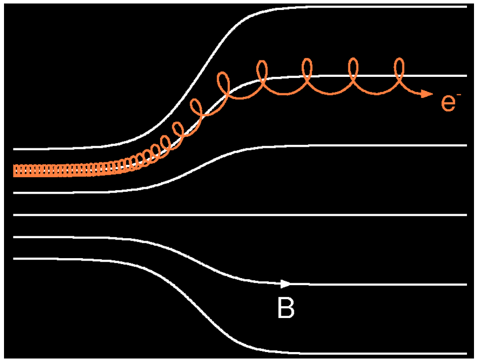
built at BINP

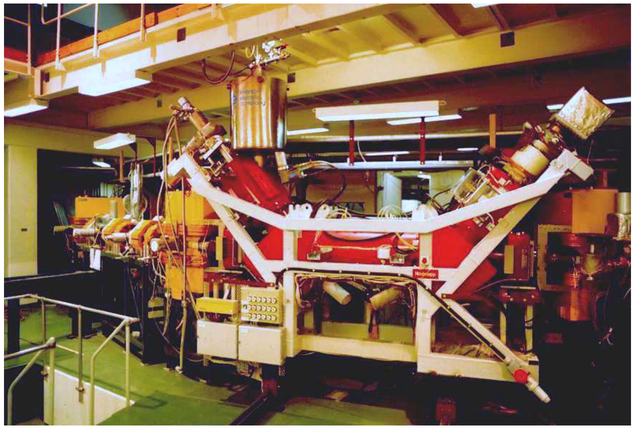
Electron Cooling

increased flexibility in transverse electron beam properties

transverse (adiabatic) magnetic expansion
increase of electron beam radius
reduction of transverse temperature

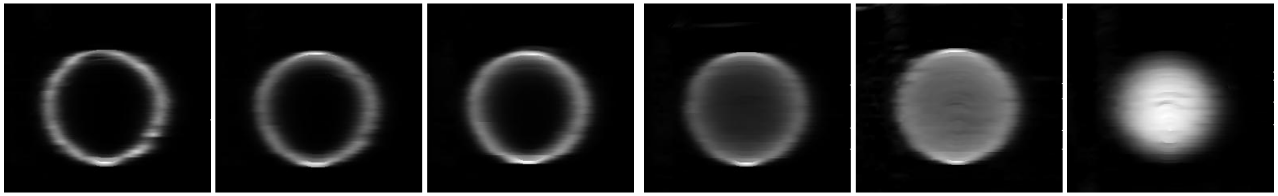
- higher cooling rate
- improved resolution
- in combination with cryogenic cathode even further reduction of electron beam temperature





first demonstration at CRYRING

variable electron beam profile installed at CSRm/e and LEIR, designed and built at BINP



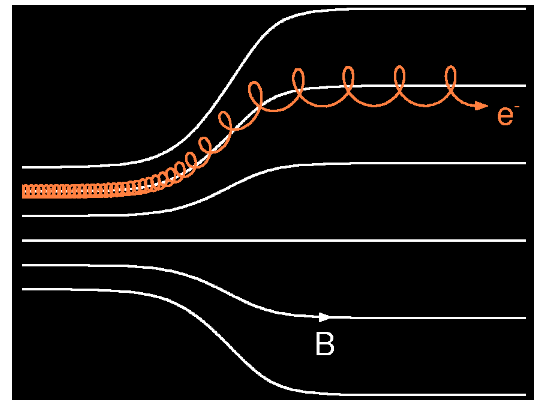
application: avoid overcooling, reduce recombination

now routinely available in low energy electron coolers

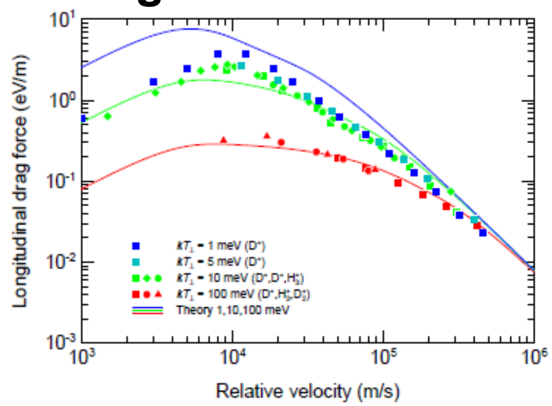
Electron Cooling

transverse (adiabatic) magnetic expansion

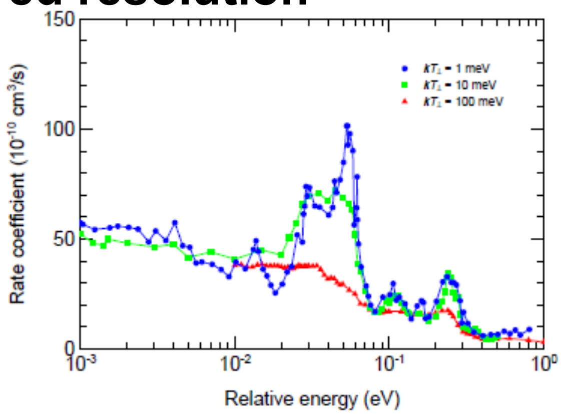
increase of electron beam radius
reduction of transverse temperature



- **higher cooling force/rate**



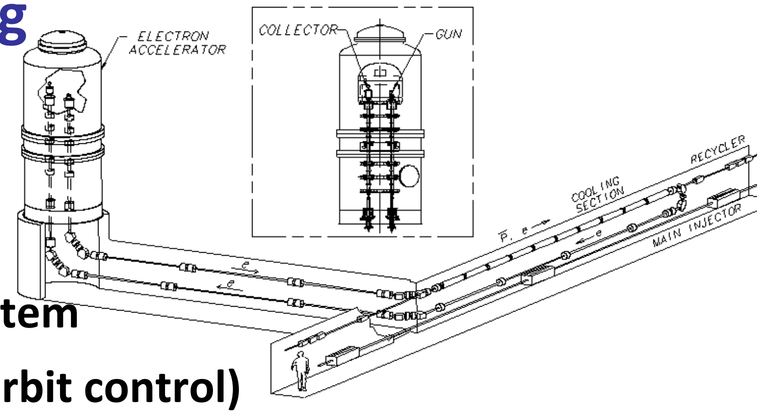
- **improved resolution**



however:
the magnetic expansion results in a reduction of the electron density which counterbalances the increased (normalized) cooling force

Electron Cooling at Higher Energies

Recycler Electron Cooling System operating at 4.3 MeV and up to 0.5 A



start of the project 1995

one decade of developments and offline tests of the system

many special features were implemented (diagnostics, orbit control)

first demonstration of cooling of antiprotons in the Recycler in 2005

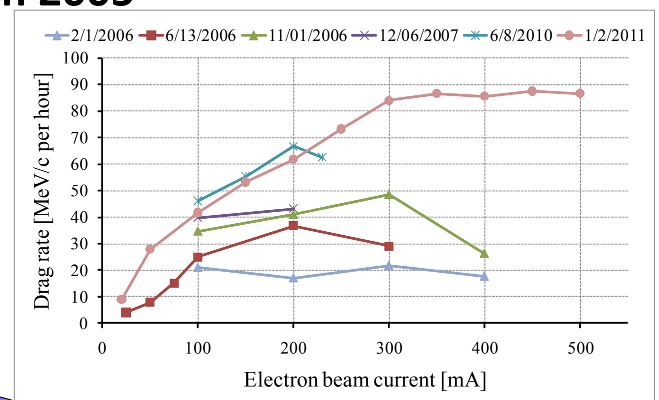
detailed studies to optimize performance

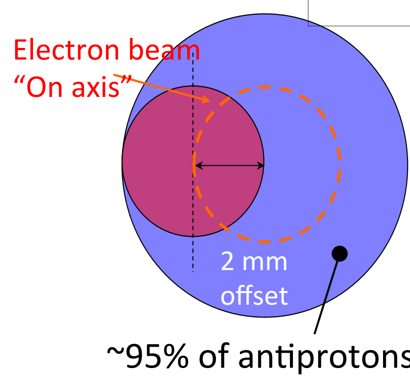
unusual tricks (contradicting textbook wisdom)

early end 2011, due to the shutdown of the Tevatron

Recycler electron cooling was not only dealing
with highest beam energies,
but also with highest (hadron) beam currents

Recycler is a non-magnetized cooling system

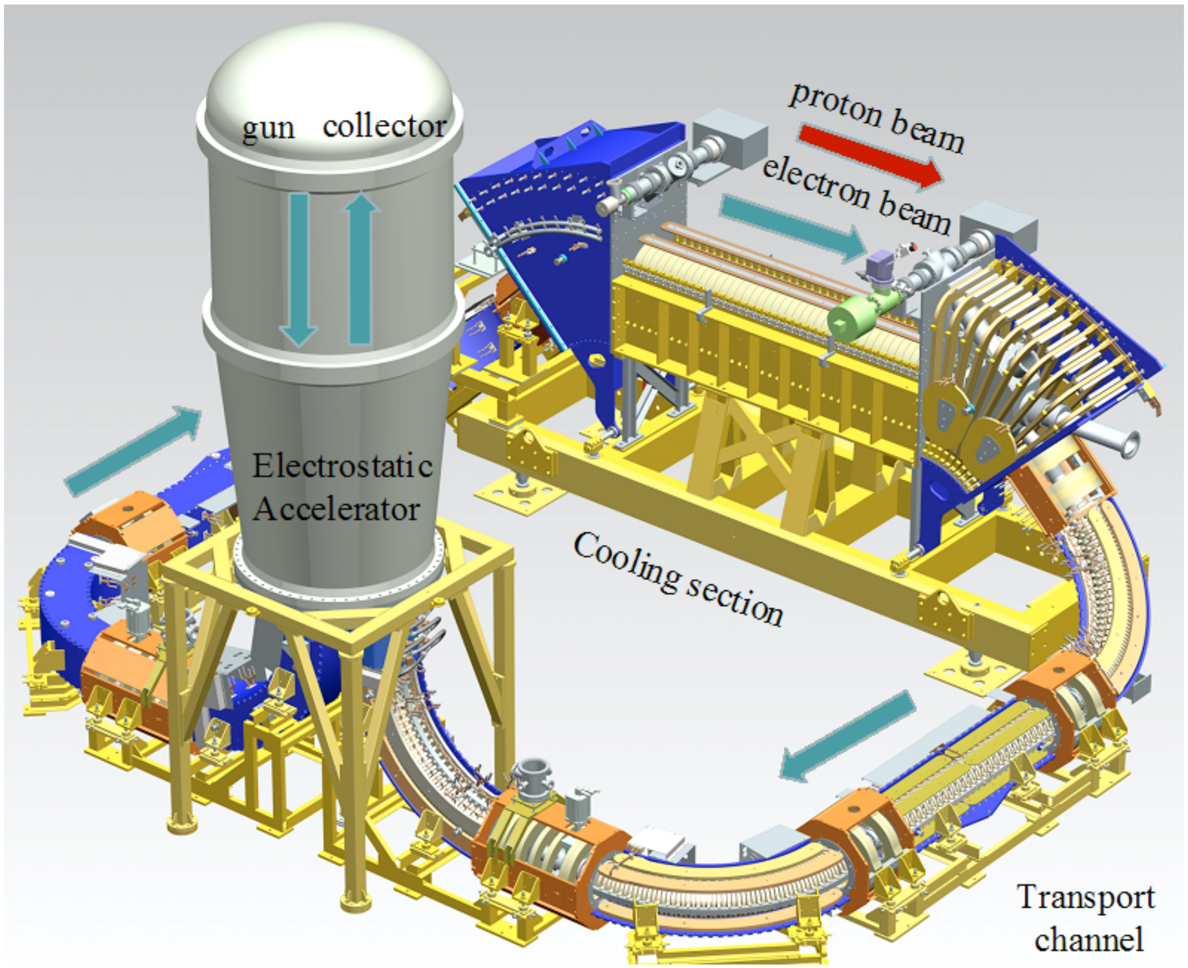




Electron Cooling at Higher Energies

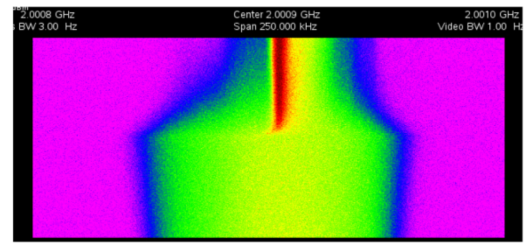
2 MeV COSY/BINP Electron Cooler

designed for magnetized cooling

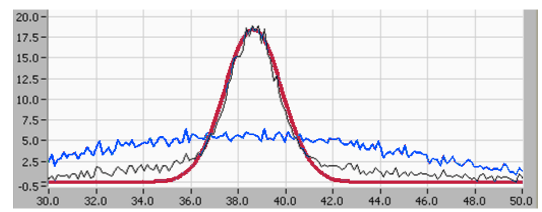


energy 0.025 – 2 .0 MeV
electron current 0.1 – 3.0 A
diameter 10 - 30 mm
magnetic field 0.05 – 0.2 T
cooling section length 2.69 m
vacuum pressure < 10^{-9} mbar

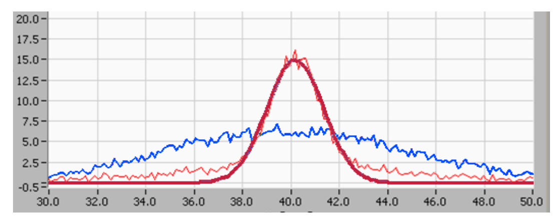
longitudinal at 900 keV



horizontal at 109 keV



vertical



Electron Cooling

All existing electron cooling system use
dc electron beam and
magnetized electron beam (confined by a strong magnetic field).

The standard electron cooling systems cover the energy range from a few hundred eV up to 300 keV, customized available from BINP.

The new COSY electron cooling system will extend the energy to 2 MeV.

The Recycler electron cooling system was exceptional:
fixed electron energy of 4.3 MeV and lumped magnetic elements for the electron beam transport.

Any extension of the electron beam energy beyond 4 MeV with electrostatic acceleration will be difficult with existing electrostatic technology.

Some of the aspects will be discussed on COOL 15:
high voltage generation
power transmission to high potential
generation of magnetic guiding field.

Electron Cooling at Highest Energies

acceleration by electrostatic accelerator is limited to 10 – 15 MeV
higher energies need a different approach
acceleration by rf systems will provide unlimited electron energies
various projects will benefit from such a development: RHIC, EIC, LHC
also Coherent Electron Cooling requires intense cold electron beams

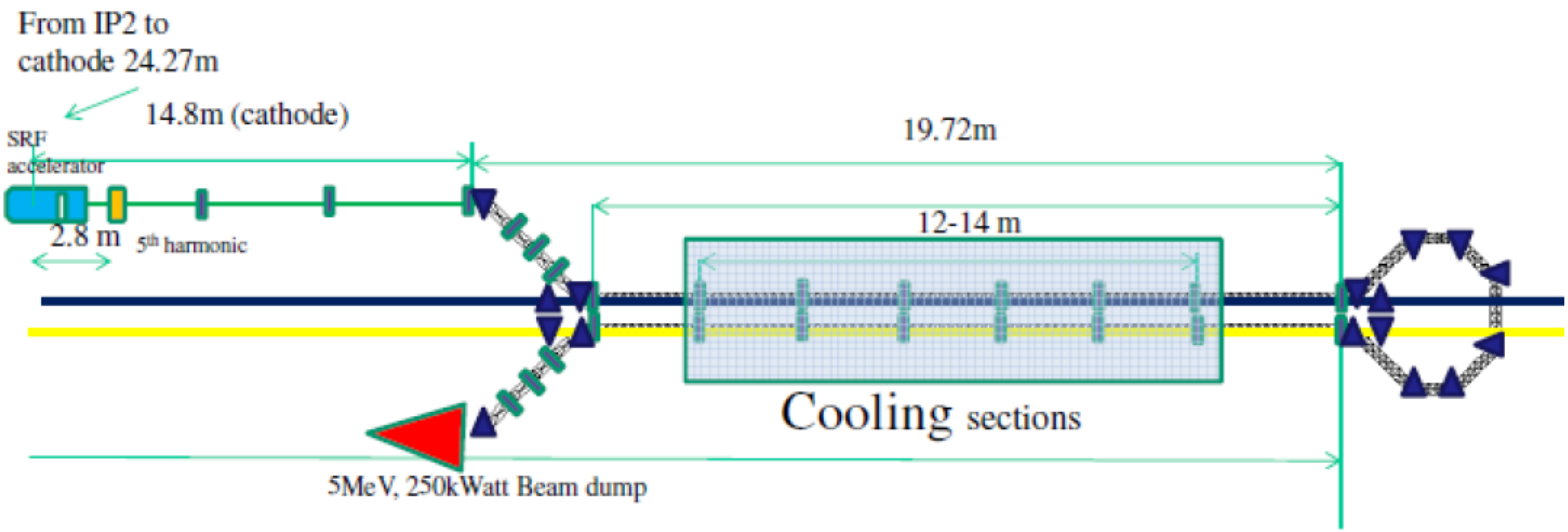
A concerted efforts to develop bunched electron beams for electron cooling is highly desirable.

main issues of cooling with bunched electron beams:
high current electron sources
linear accelerator
recirculator/storage ring
extremely fast kickers

bunched electron beam cooling
optimized beam dynamics (longitudinal and transverse) and optics
efficient recuperation
synchronization of ion and electron beam

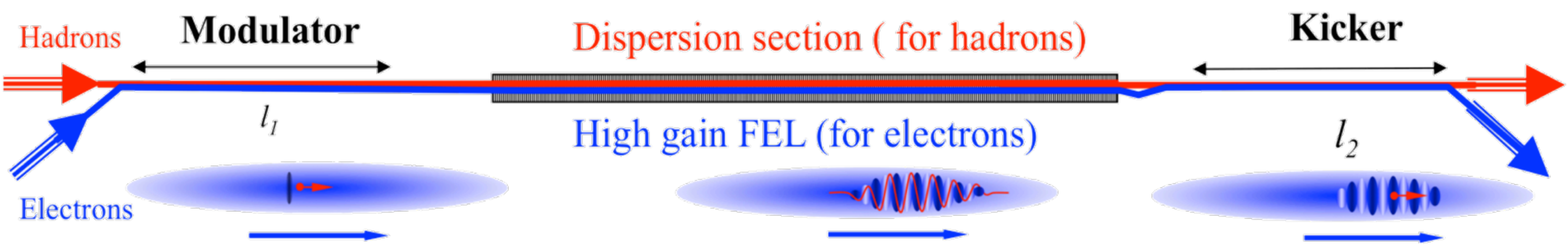
Electron Cooling with a Bunched Electron Beam

cooling of the two counterpropagating ion beams in RHIC by
an electron beam from a superconducting rf gun
energy up to 5 MeV, current up to 1 A (peak)

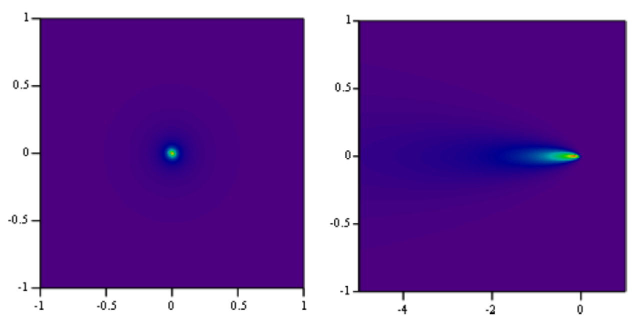


The LEReC electron cooling system can be scaled to higher energies and to the electron beam system for Coherent Electron Cooling.

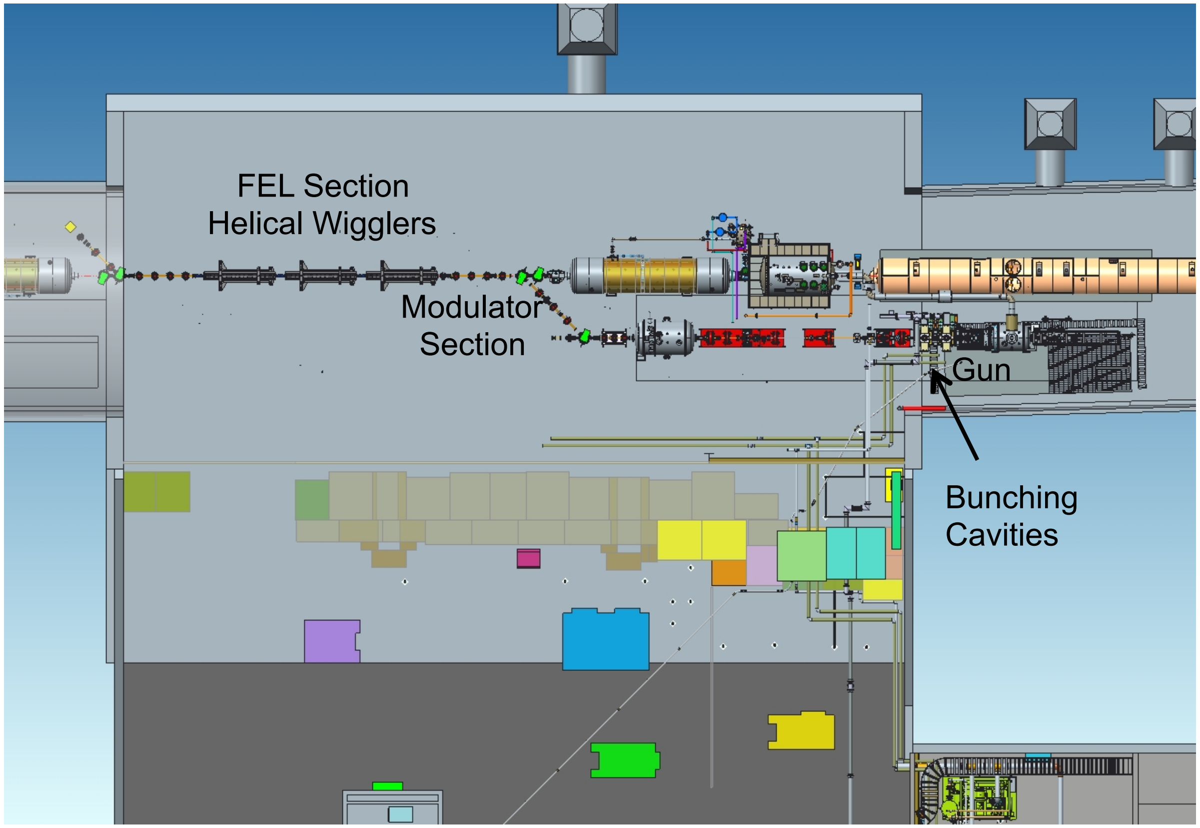
Coherent Electron Cooling



preparation of a test experiment at RHIC



simulations of an ion in the electron plasma



Electron Cooling at Lowest Energies

lowest reported electron energy for cooling was 11 eV (CRYRING)
with an electron current of 0.05 mA
low currents still give reasonable electron density

low cooling energies will be required in the ELENA project,
in CRYRING@ESR and potentially in the CSR

no technological challenges, but specific issues have to be expected

- stability of power supplies
- influence of magnetic fields (unwanted and stray fields)
- vacuum, mainly because of the heavy beam (ions, molecules)
- space charge

Stochastic Cooling

developed to produce useful intensities of antiprotons
crucial for successful experiments with high luminosity p-pbar collision

Þ $W^{\pm}$ and Z boson observation honored with Nobel prize

most beneficial for hot beams,
e.g. secondary beam production in a thick target

The method was developed and refined at CERN and Fermilab
over more than a decade
(both had a similar scenario, but significant differences in detail)

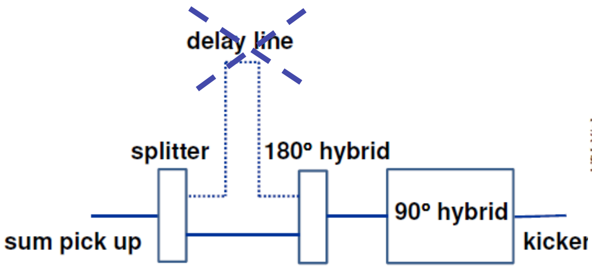
end of p-pbar collisions at CERN in 1996, at Fermilab in 2011

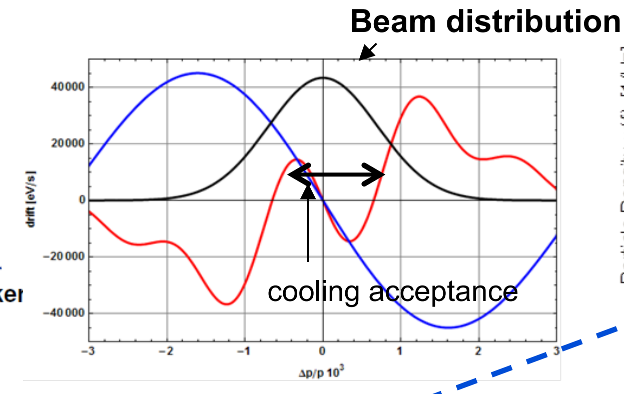
remainders of the early stochastic cooling systems are installed
in AD at CERN and routinely operated for antiproton deceleration

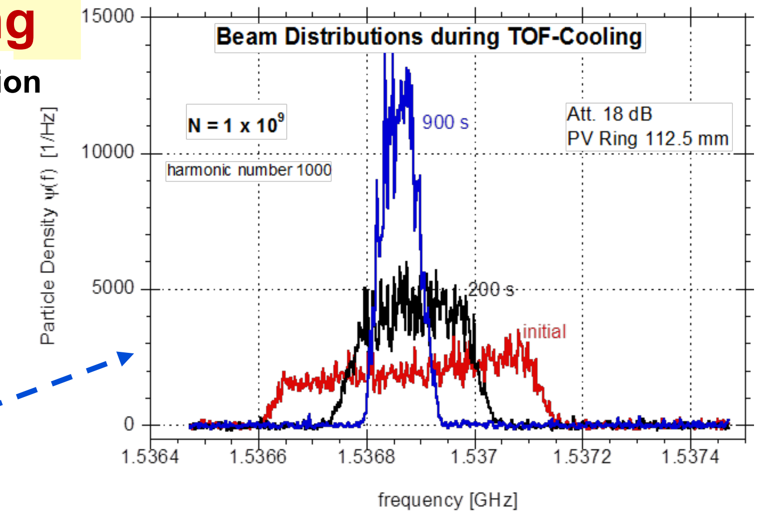
The concept for the production of antiprotons at FAIR
follows in various aspects the previous approaches.

Stochastic Cooling

experiments with Time-of-Flight (ToF) cooling



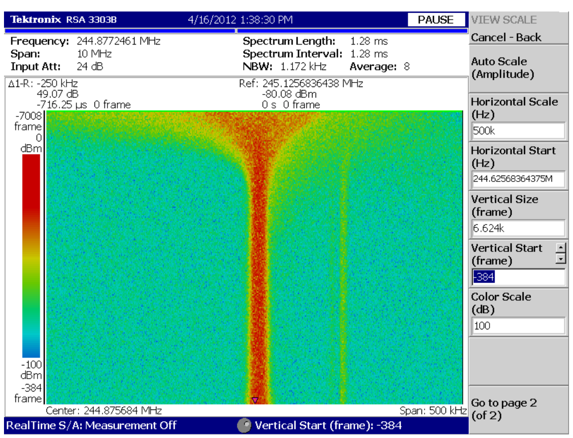




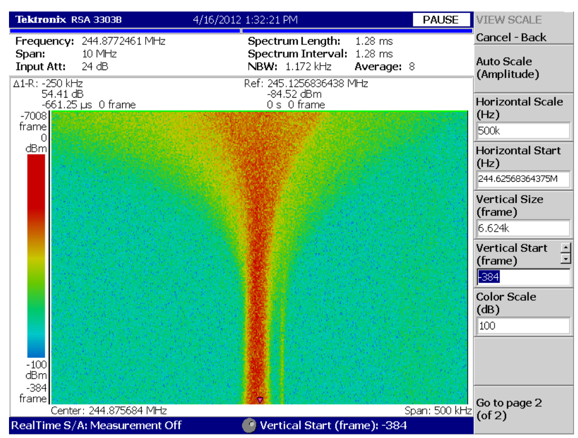
first demonstration in COSY (FZJ) with a
2.6 GeV/c proton beam of 10^9 particles, bandwidth 1-3 GHz

stochastic cooling of 400 MeV/u Ar^{18+} ions in the ESR (GSI), bandwidth 0.9–1.7 GHz

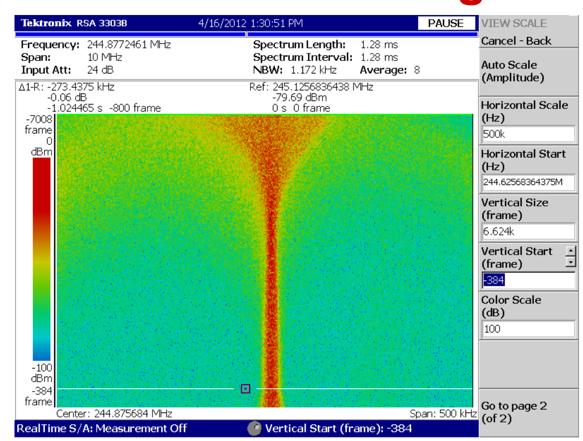
Palmer cooling



ToF cooling



Notch filter cooling



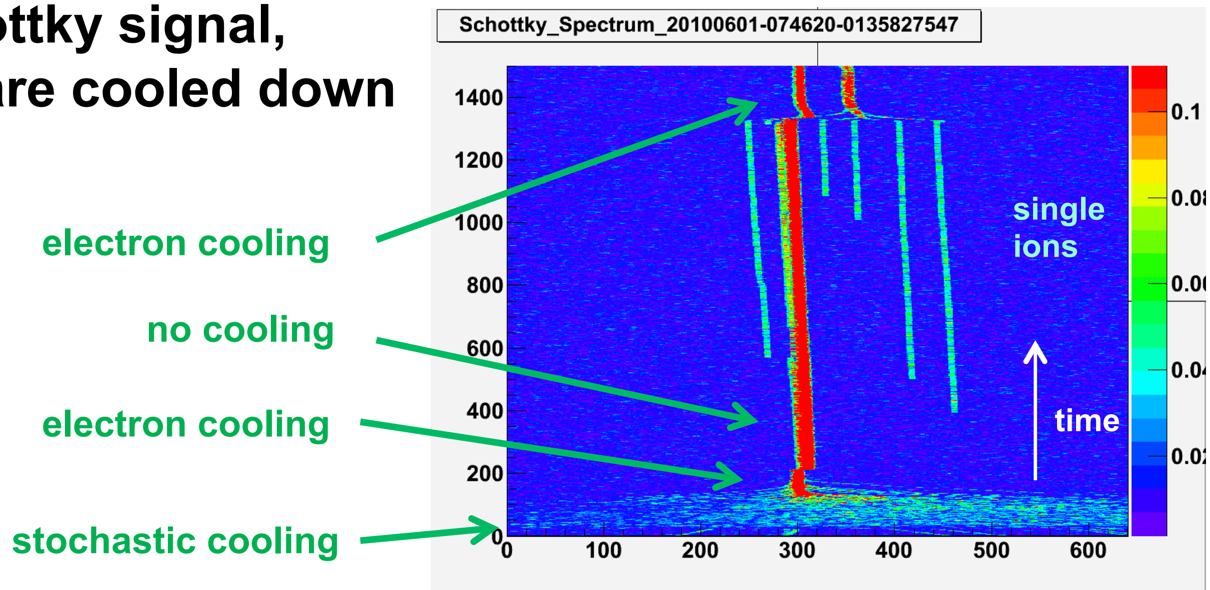
Stochastic Cooling

activities on stochastic cooling continue at smaller machines

COSY (FZ Jülich) performs cooling of protons

ESR (GSI) uses stochastic cooling,
preferably as a pre-cooling system for
rare isotopes (in combination with electron cooling)

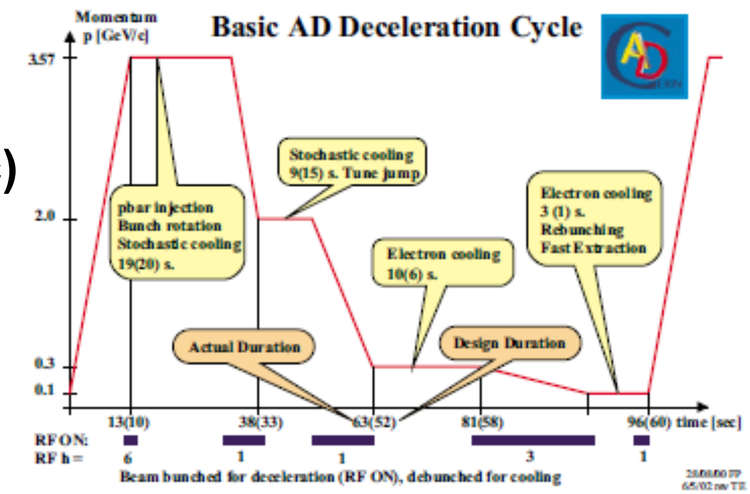
profits from stronger Schottky signal,
few and even single ions are cooled down
and can be detected



Combination of Stochastic Cooling and Electron Cooling

stochastic cooling: hot beams, low or moderate intensity, high energy
electron cooling: tepid to cold beams, low energy ([illegible]^2)
consequence: complimentary use of the two methods

AD(CERN): antiprotons
stochastic cooling at 3.57 GeV/c and 2 GeV/c
electron cooling after deceleration (300, 100 MeV/c)



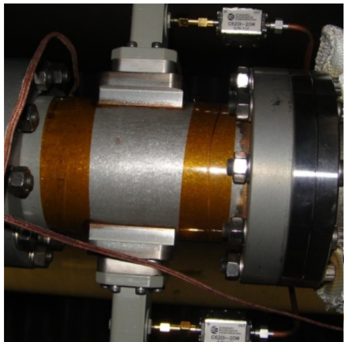
ESR(GSI): heavy ion and rare isotopes
stochastic cooling at injection energy (400 MeV/u)
electron cooling after deceleration (30, 4 MeV/u)
stochastic pre-cooling, final electron cooling

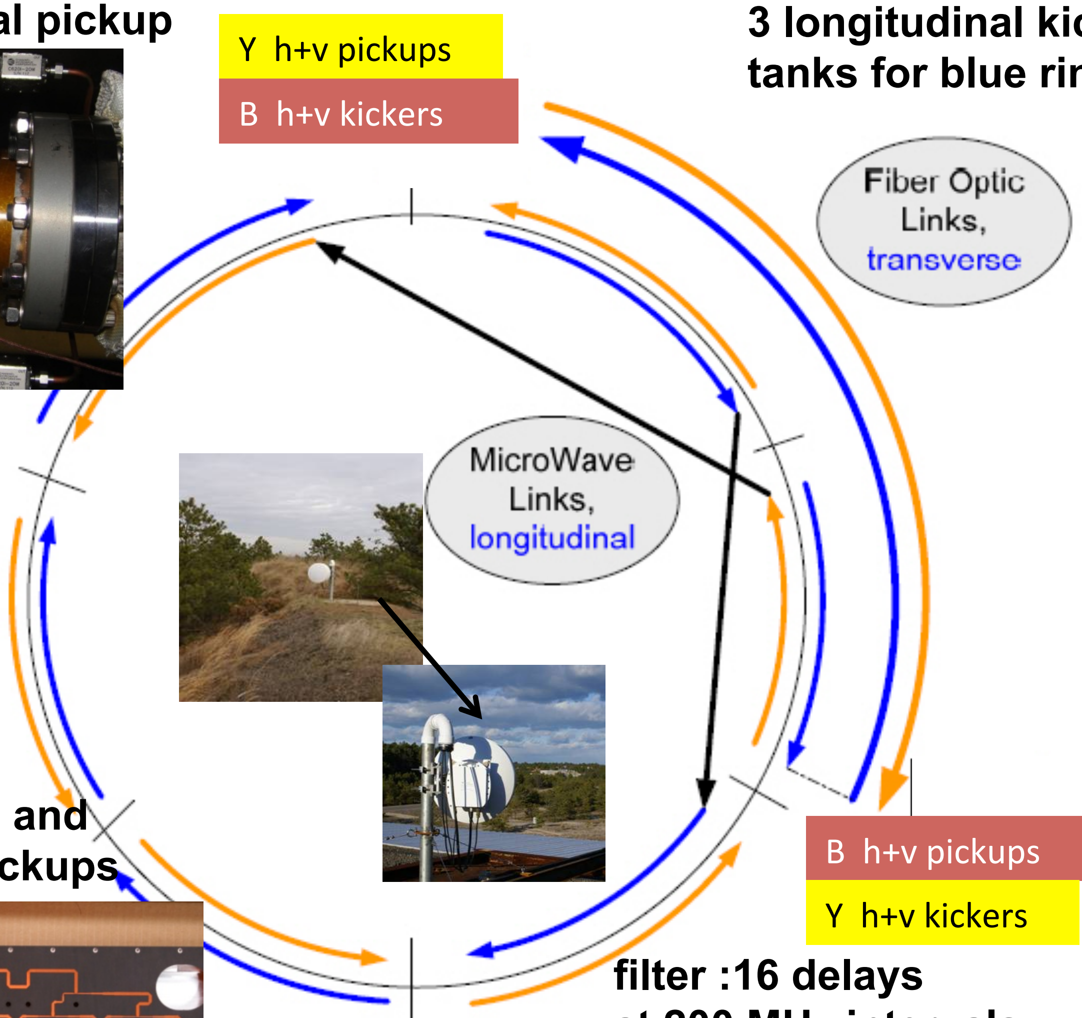
Recycler(Fermilab): antiprotons
electron cooling supported accumulation of highest intensities of antiprotons when stochastic cooling was too weak

both methods and their combination will be important in the projects FAIR, HIAF, NICA

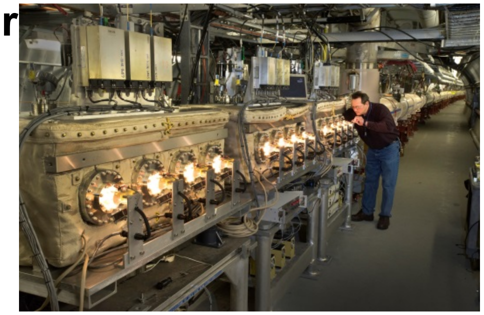
RHIC – 3D stochastic cooling for heavy ions

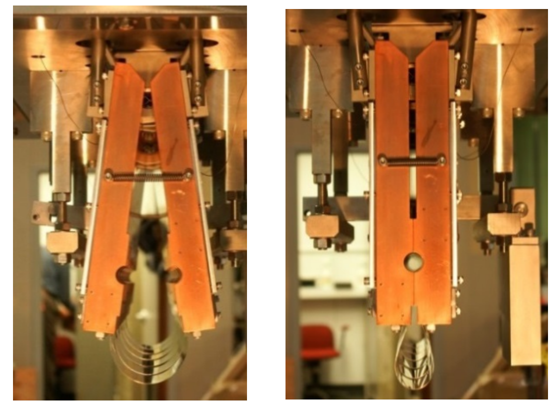
longitudinal pickup





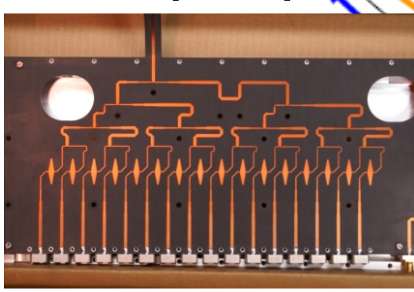
3 longitudinal kicker tanks for blue ring



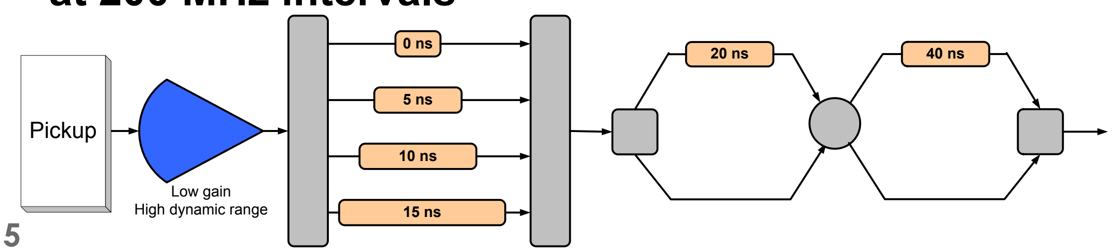


longitudinal kicker open for injection and ramping (left), closed during cooling (right)

horizontal and vertical pickups

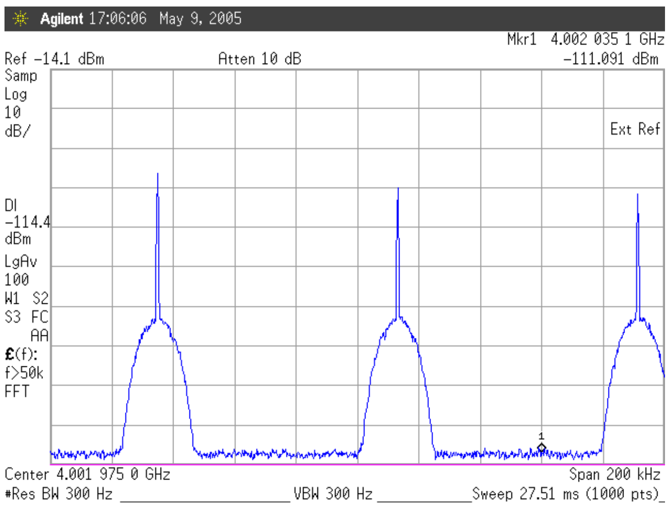


filter :16 delays at 200 MHz intervals

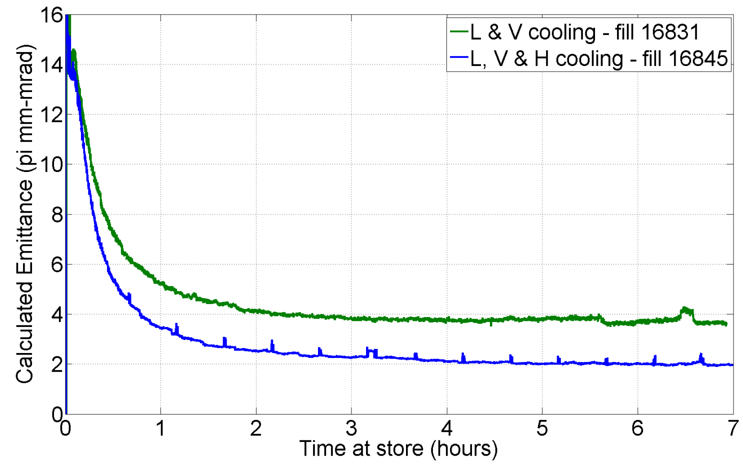


RHIC Stochastic Cooling Performance

first stochastic cooling (5-9 GHz) of a bunched beam in a collider

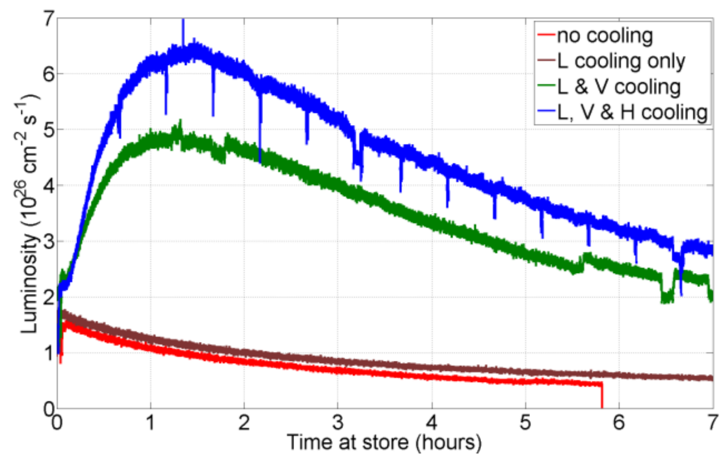


Schottky spectrum
with coherent lines



transverse emittance reduction
cooling time: 1/2 hour

stochastic cooling in collisions
gold – gold
uranium – uranium
gold - copper



luminosity increase by a factor of five
for uranium-uranium collisions

RHIC success triggered interest to apply
stochastic cooling in the NICA collider

Laser Cooling

originally developed for cooling of ions at rest in traps

first laser cooling of fast ions in storage rings in TSR and ASTRID in 1990

experiments with $^{7}Li^{+}$, $^{9}Be^{+}$ and $^{24}Mg^{+}$ ions continued for about a decade

very low longitudinal temperatures were observed: 2-15 K

coupling to the transverse degree of freedom by IBS was demonstrated

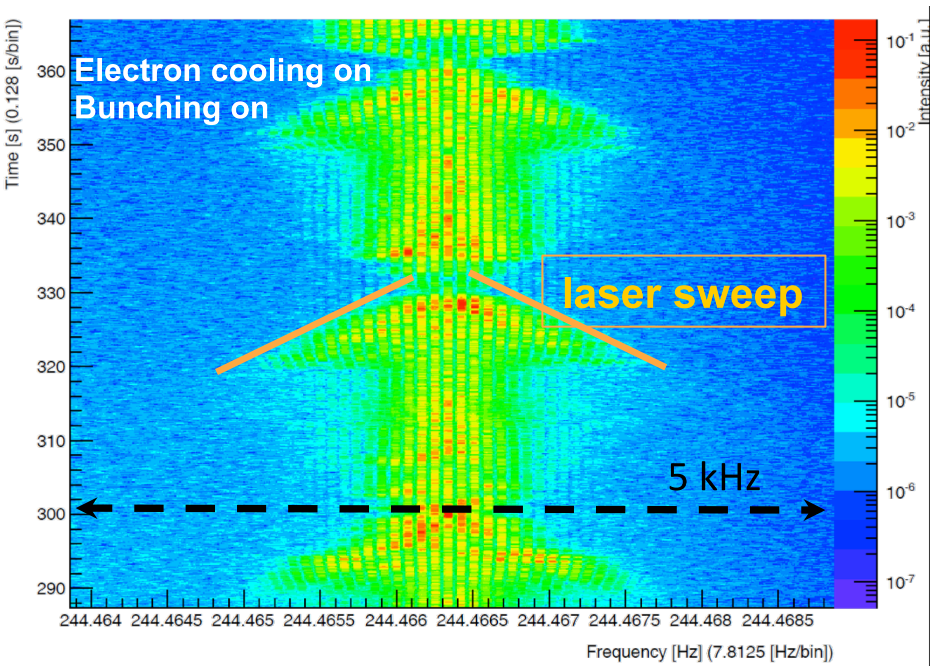
nevertheless the ion beams were transversely rather diffuse

from 1999 to 2003 activities at the PALLAS storage ring with slow Mg ions

in PALLAS clear demonstration of beam crystallization was achieved,
in contrast to the magnetic storage rings

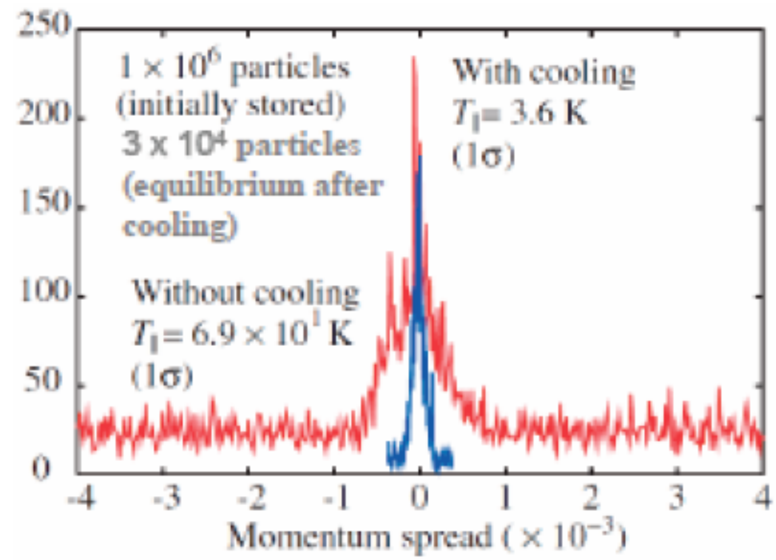
Laser Cooling

laser cooling of $^{12}C^{3+}$ 122 MeV/u at the ESR

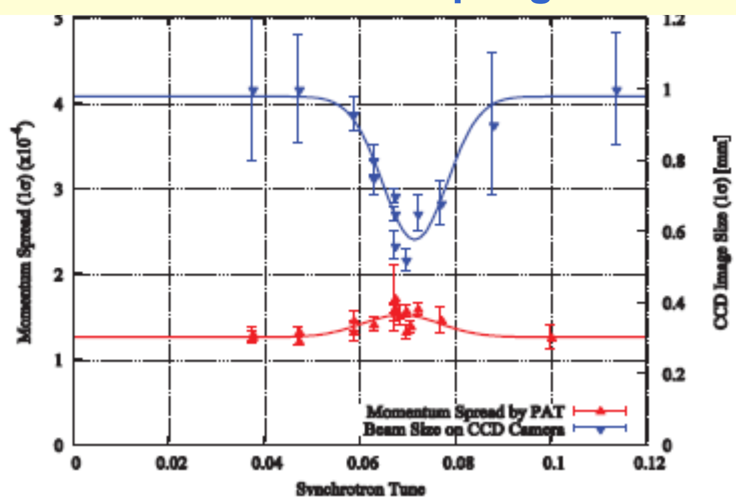


frequency (189th harmonic)
244.466 MHz

laser cooling of $^{24}Mg^{+}$ 40 keV at the S-LSR



transverse cooling by synchro-betatron resonance coupling



Laser Cooling

recent activities were aiming at:

a coupling mechanism from the longitudinal to the transverse degree of freedom

optimization of ion beam bunching

improved detection methods for fluorescent light and ion beam properties

increase of capture range of laser system: scanning of laser frequency, pulsed laser

activities at S-LSR seem to have stopped

there are ongoing activities on cooling of C^{3+} at ESR and CSRe

future plans:

cooling of highly charged ions at relativistic energies: FAIR/SIS100, HIAF/CRing

advantages at relativistic energies:

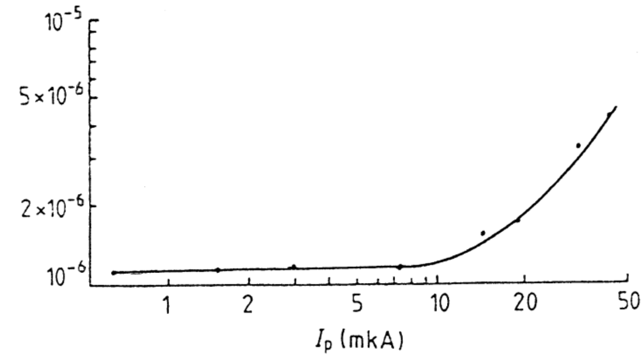
higher transition energies in particle rest frame available

increase of cooling force with $\gamma^{3\ (?)}$

forward peak of fluorescent light as diagnostics

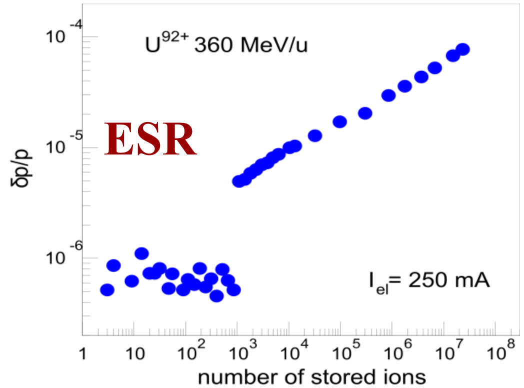
Crystallization

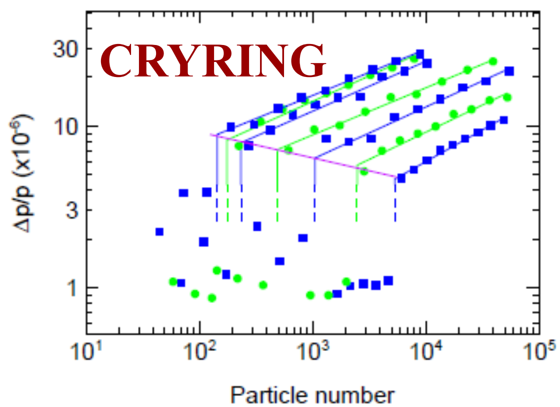
enthusiasm after observation of anomaly in the Schottky noise of low intensity electron cooled protons at NAP-M (1984)

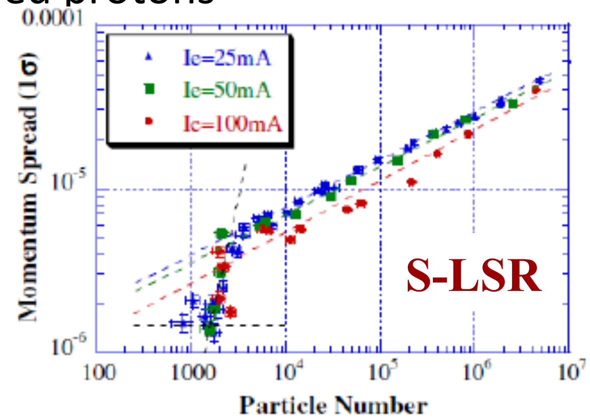


an even stronger anomaly was observed with electron cooled heavy ions at the ESR, and later at CRYRING and SIS18

The same signature was confirmed in the S-LSR for electron cooled protons



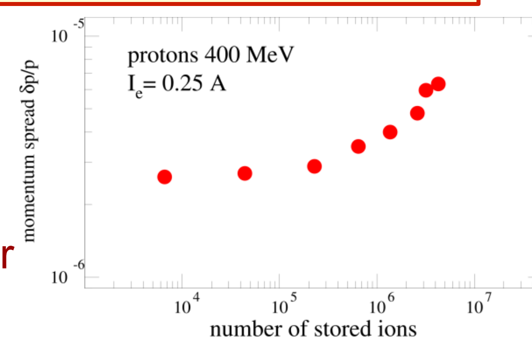




common interpretation: formation of a one-dimensional ordered structure (string)

at the ESR for protons the momentum spread measurement is limited by the ripple of the magnet power converters (2007) (lower magnetic rigidity of protons)

reconfirmed in 2014 with more sensitive Schottky noise detector



Crystallization

Although laser cooling was considered to promise even lower temperatures
the experiments did not evidence clear signatures of a phase transition
main reason might be the lack of transverse cooling
longitudinal temperature with laser cooling down to 0.4 K have been reported,
but transverse temperature is much higher

with electron cooling:
for light ions both longitudinal and transverse temperatures below 3 K were observed,
for heavier ions (higher charge) both temperatures are some ten K.

plasma parameter benefits from high charge: $$\Gamma = \frac{U_{Coul}}{k_B T} = \frac{q^2 e^2}{4\pi\varepsilon_0 a k_B T}$$

theoretical studies showed that for higher dimensional structures special requirements to the storage ring parameters are desired ➔ **dedicated ring**

conditions to reach crystalline state:

- operation below transition energy
- phase advance per lattice period smaller than 90 degrees (very weak focusing)
- tapered cooling to compensate shear forces

Further experiments will certainly require advanced diagnostics.

Operational Machines with Beam Cooling

AD (CERN): stochastic and electron cooling

COSY (FZ Jülich): stochastic and electron cooling

CSRm (IMP Lanzhou): electron cooling, accumulation

CSRe (IMP Lanzhou): electron cooling, stochastic and laser cooling in prep.

ESR (GSI): stochastic, electron and laser cooling, accumulation

HIMAC (NIRS Chiba): electron cooling

LEIR (CERN): electron cooling, accumulation

RHIC (BNL): bunched beam stochastic cooling for collisions

SIS18(GSI): electron cooling, accumulation

S-LSR (Kyoto University): electron cooling, laser cooling

combination of cooling methods is common to various machines
either for pre-cooling or complimentary in different energy regimes
integrated in rather complex machine operation
main tasks: highest beam quality, compensation of target heating
accumulation of secondary beam, high intensity beams (!)

New Facilities

FAIR, Darmstadt
various stochastic cooling systems for ions and antiprotons, accumulation

NICA, JINR Dubna
electron cooling for accumulation, stochastic cooling in collider

HIAF, IMP Lanzhou
electron cooling of high intensity heavy ions, stochastic cooling

MEIC, JLab and **eRHIC, BNL**
electron-ion colliders, high energy electron cooling

ELENA, CERN
electron cooling of antiprotons at low energy

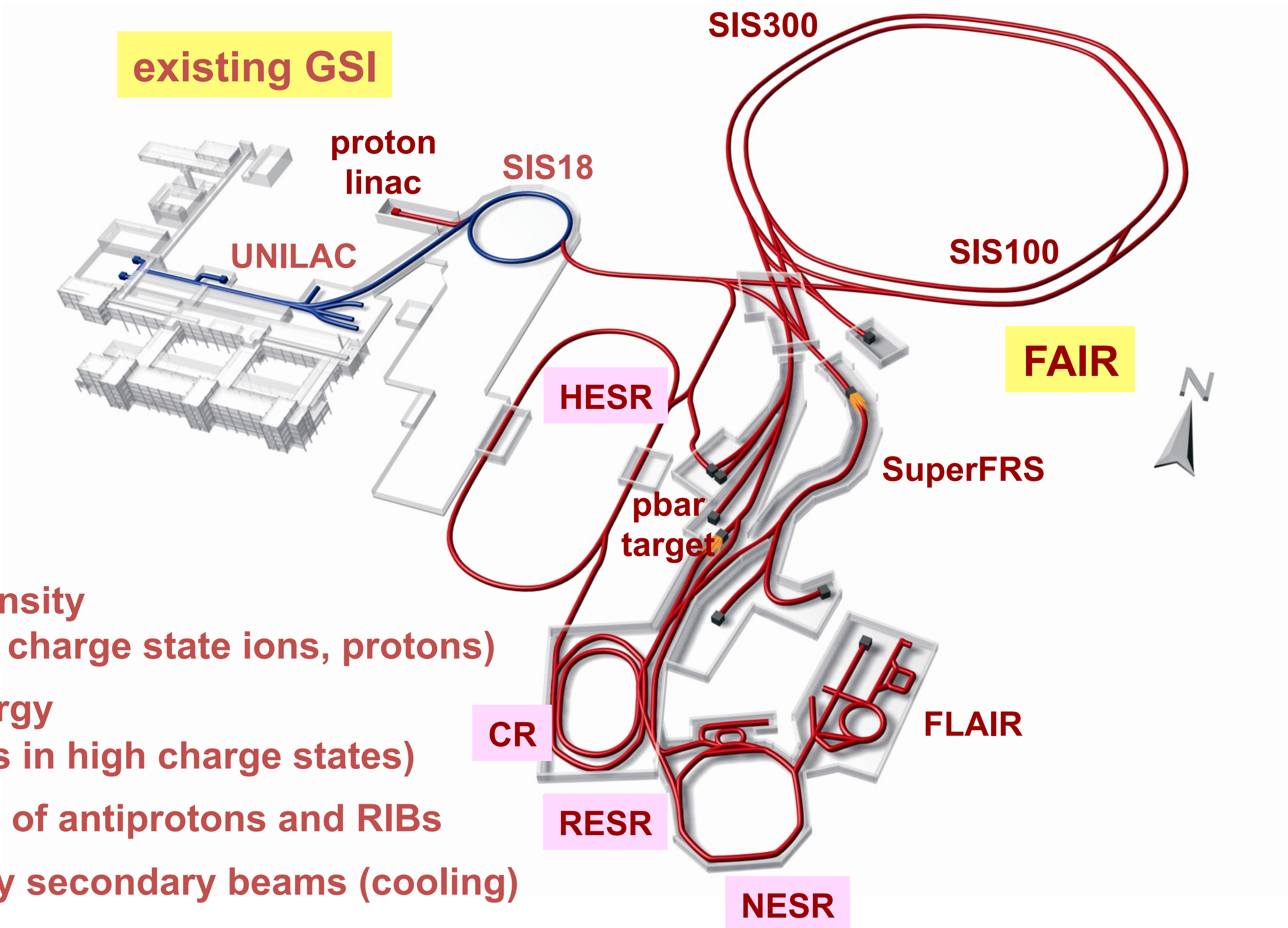
IOTA, FNAL
accelerator physics test facility, optical stochastic cooling

TSR@ISOLDE, MPI Heidelberg/CERN
electron cooling of rare isotopes

CRYRING@ESR, GSI/FAIR Darmstadt
electron cooling of low energy heavy ions

CSR, MPI Heidelberg
low energy electron cooling in electrostatic ring

The FAIR Accelerator Facility (2007)



goals:

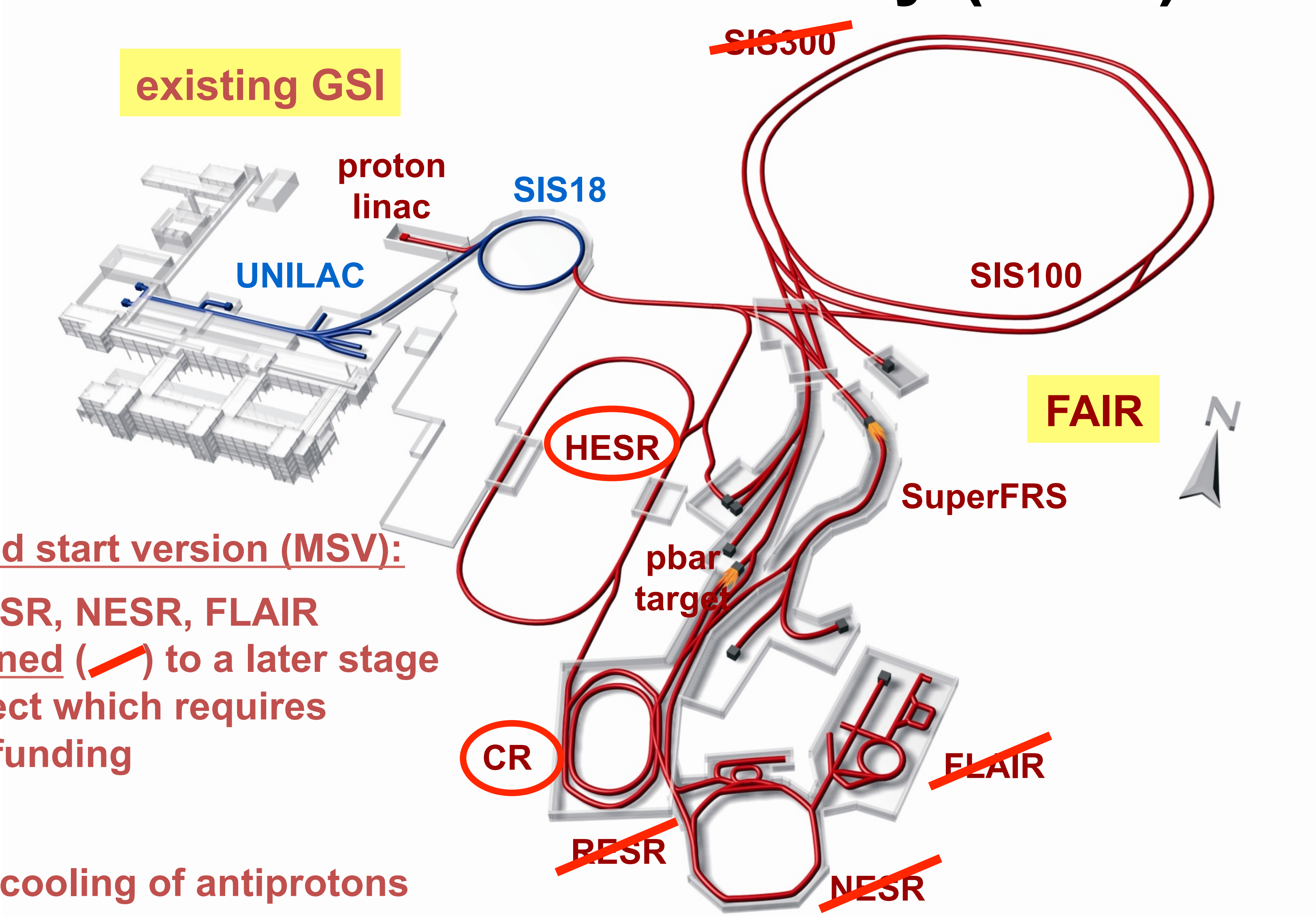
higher intensity
(heavy low charge state ions, protons)

higher energy
(heavy ions in high charge states)

production of antiprotons and RIBs

high quality secondary beams (cooling)

The FAIR Accelerator Facility (2009)



modularized start version (MSV):

SIS300, RESR, NESR, FLAIR are postponed ( ) to a later stage of the project which requires additional funding

cooling:

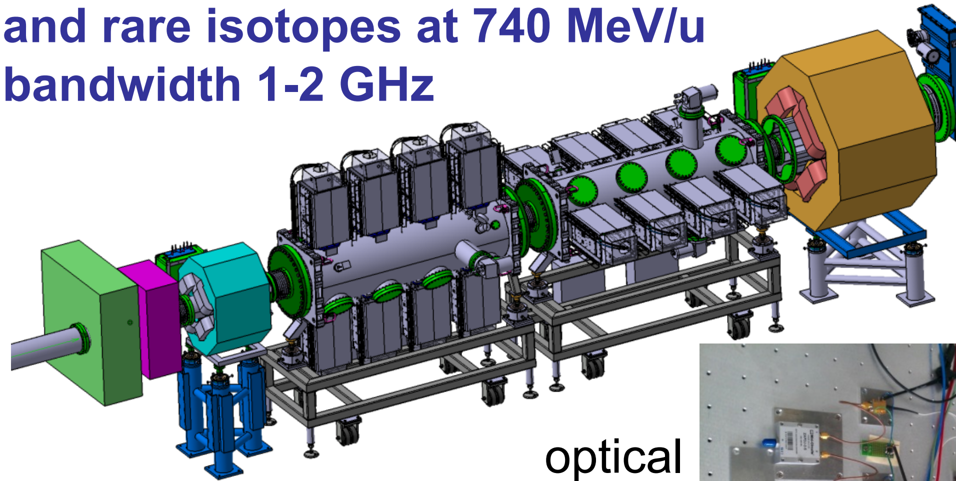
stochastic cooling of antiprotons and rare isotopes in CR and ions and antiprotons in the HESR

present slogan: 11@22

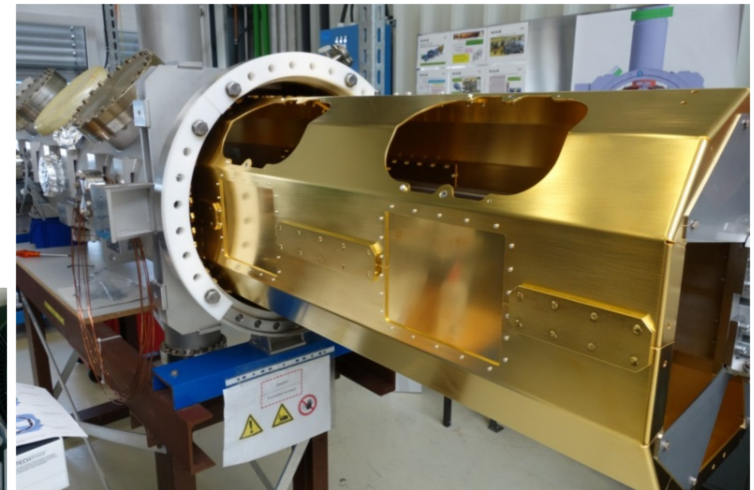
(11 experiments should be possible in 2022)

CR Stochastic Cooling

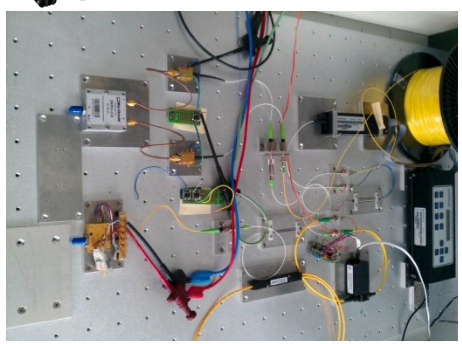
stochastic cooling of antiprotons at 3 GeV
and rare isotopes at 740 MeV/u
bandwidth 1-2 GHz



gold-plated thermal shield
(electrodes cooled to 20 K)

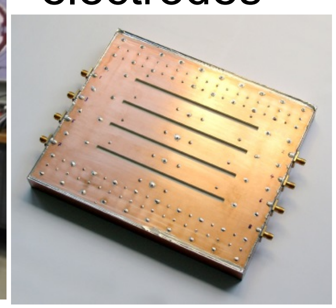


optical
notch
filter

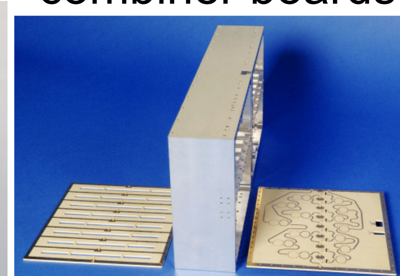


test stand

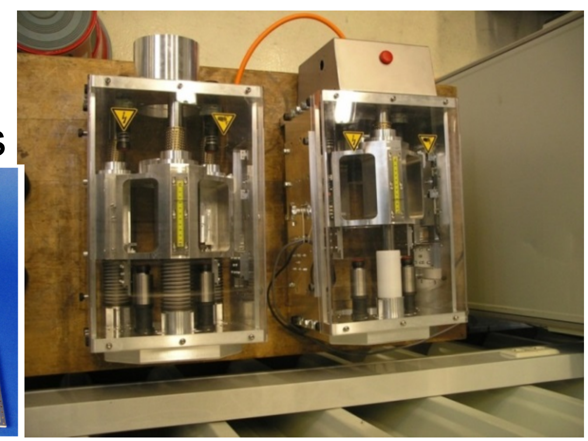
slotline type
electrodes



milled module
body with
combiner boards

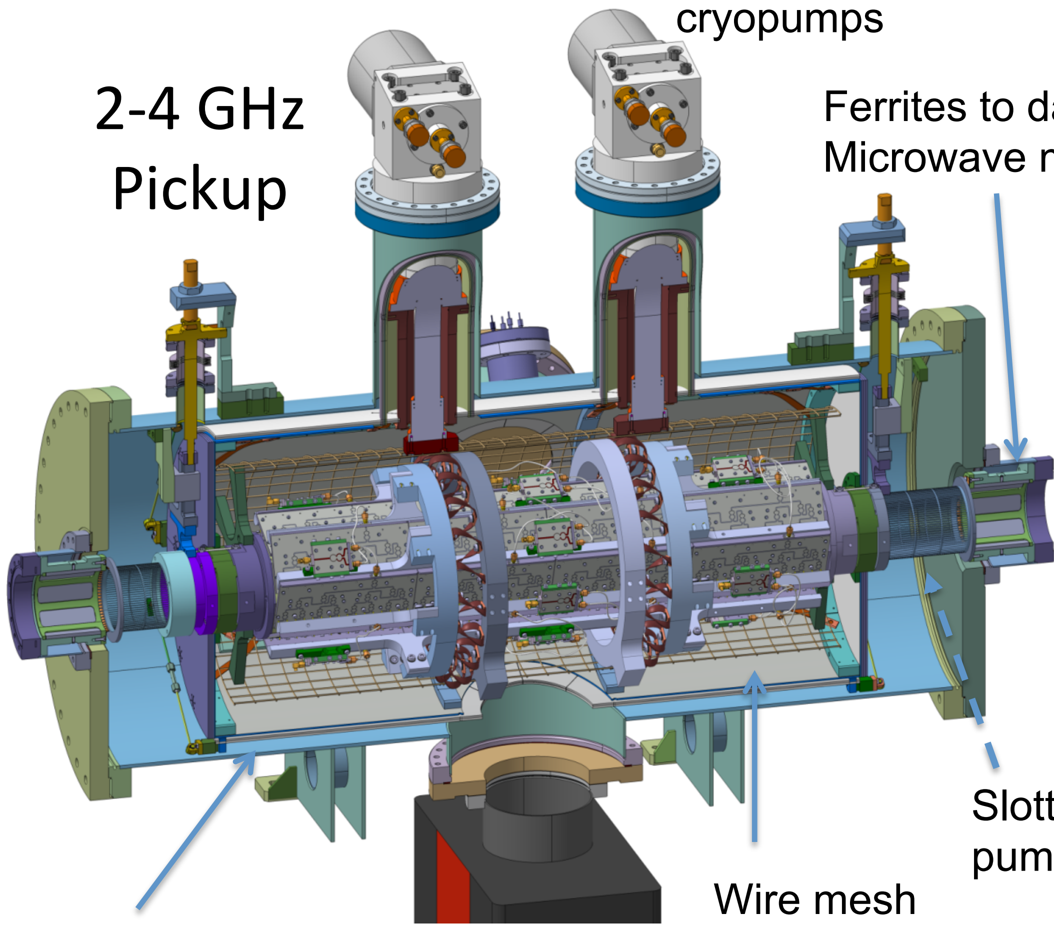


linear motor drives



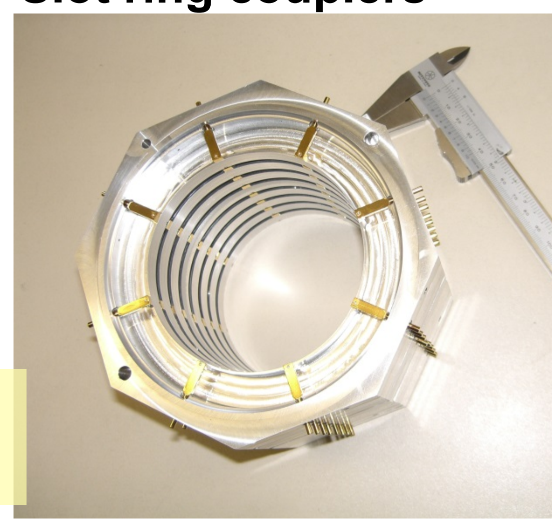
HESR Stochastic Cooling

development at FZ Jülich



16 rings in test-tank cooled down to 30 K

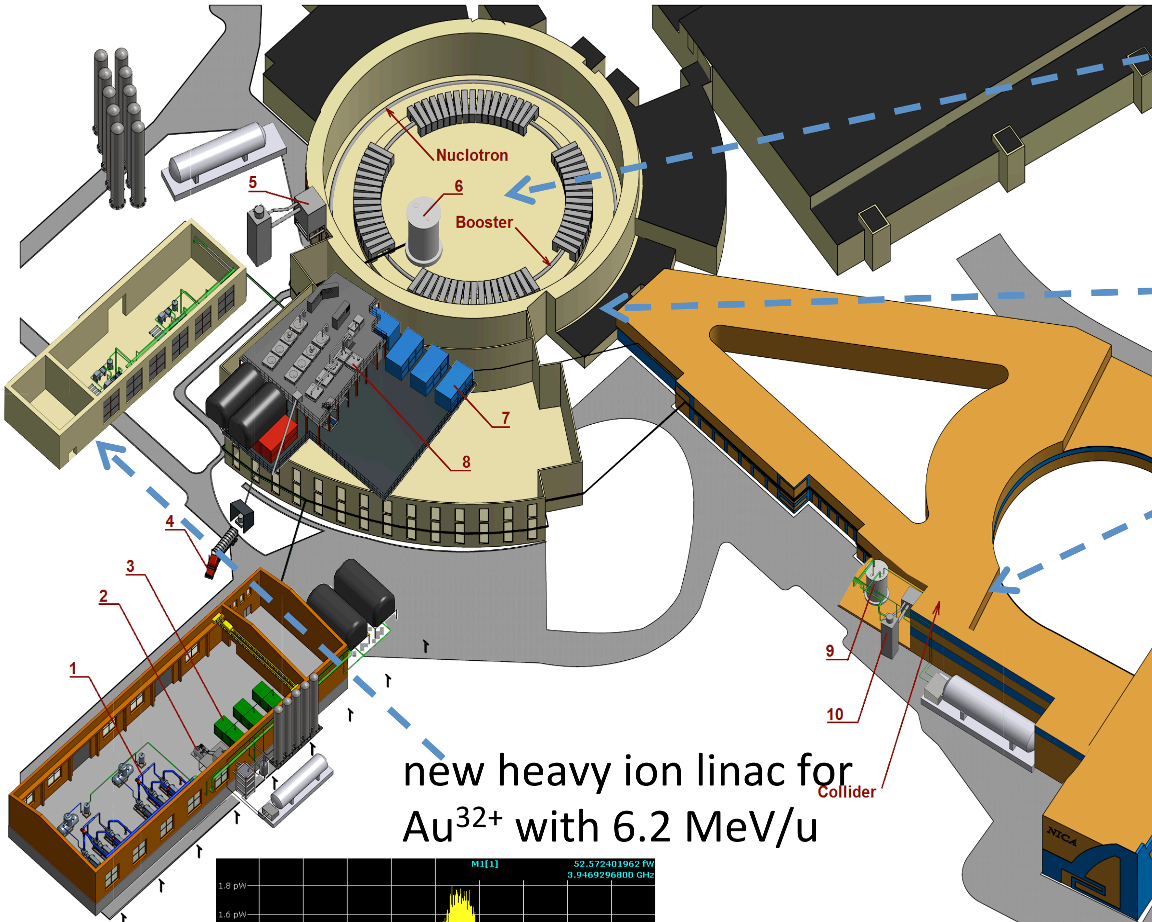
Slot ring couplers



cooling (3-14 GeV) and accumulation (3 GeV): antiprotons
cooling and accumulation: stable ions, RIBs (option)

NICA

all circular accelerators in NICA employ superconducting magnet technology

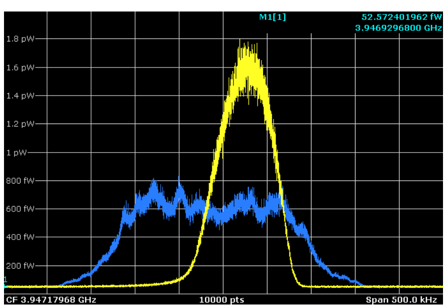


new 25 Tm booster
(installed inside Synchrophasotron)
with **electron cooling**

existing Nuclotron
serves as full energy injector

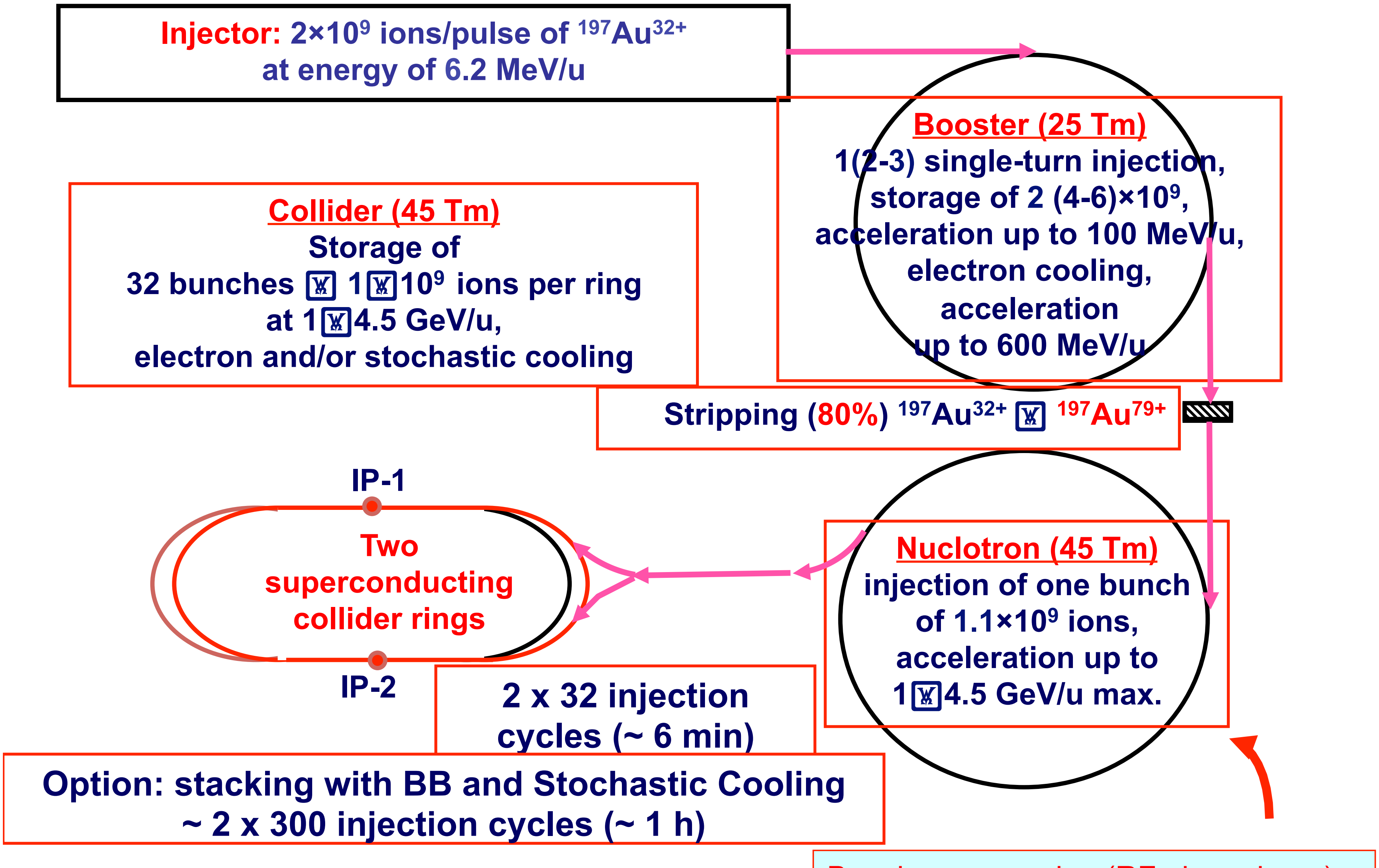
45 Tm ion collider
2 x 4.5 GeV/u gold (79+) beams
polarized protons (2 x 12.6 GeV)
polarized deuterons (2 x 5.9 GeV/u)
accumulation of 32 single bunches
by combination of
barrier bucket rf system
and **stochastic cooling**
option: **electron cooling**
(recombination problem)

new heavy ion linac for
Au^{32+} with 6.2 MeV/u

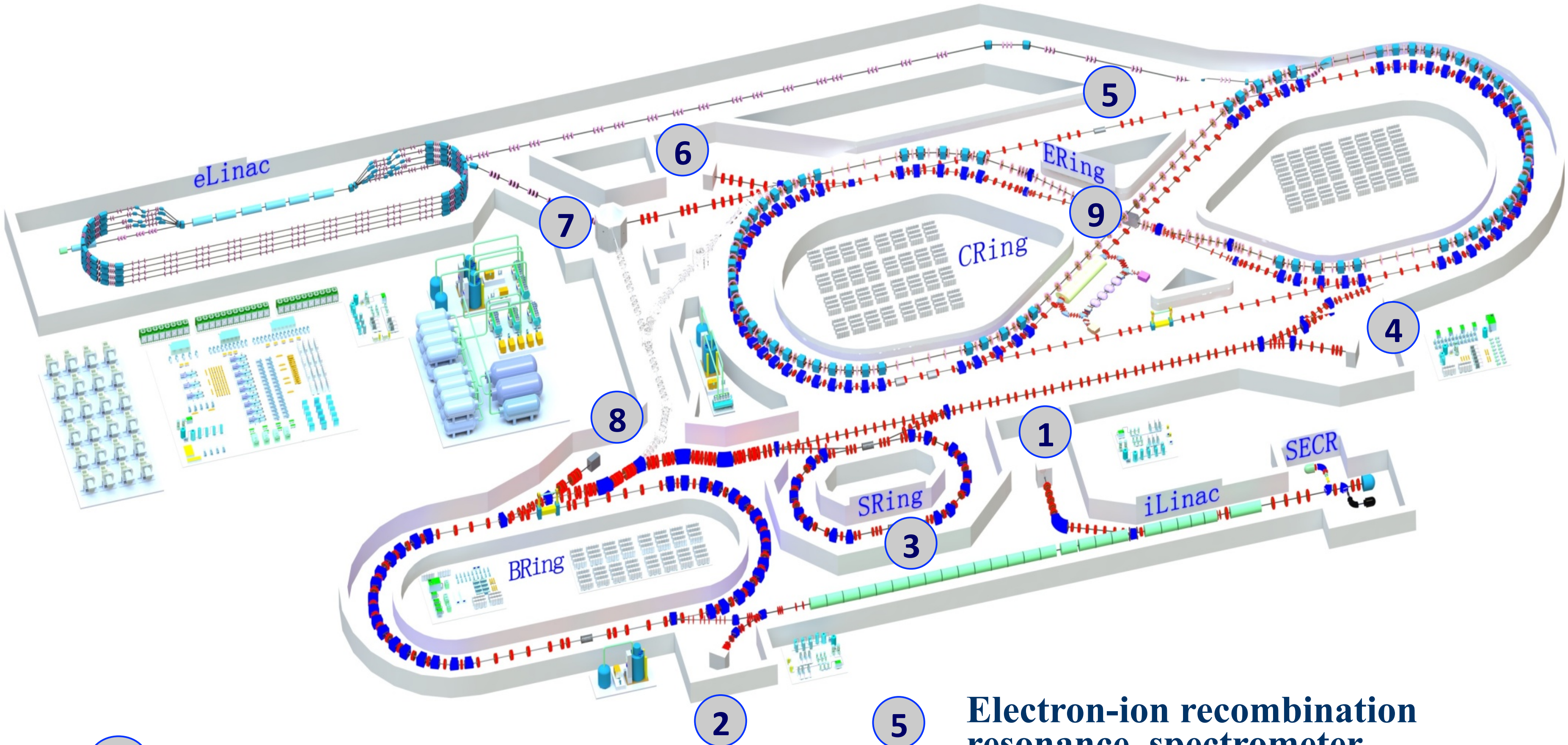


successful test of stochastic cooling in the Nuclotron (collaboration FZJ-JINR)

NICA operation regime & parameters



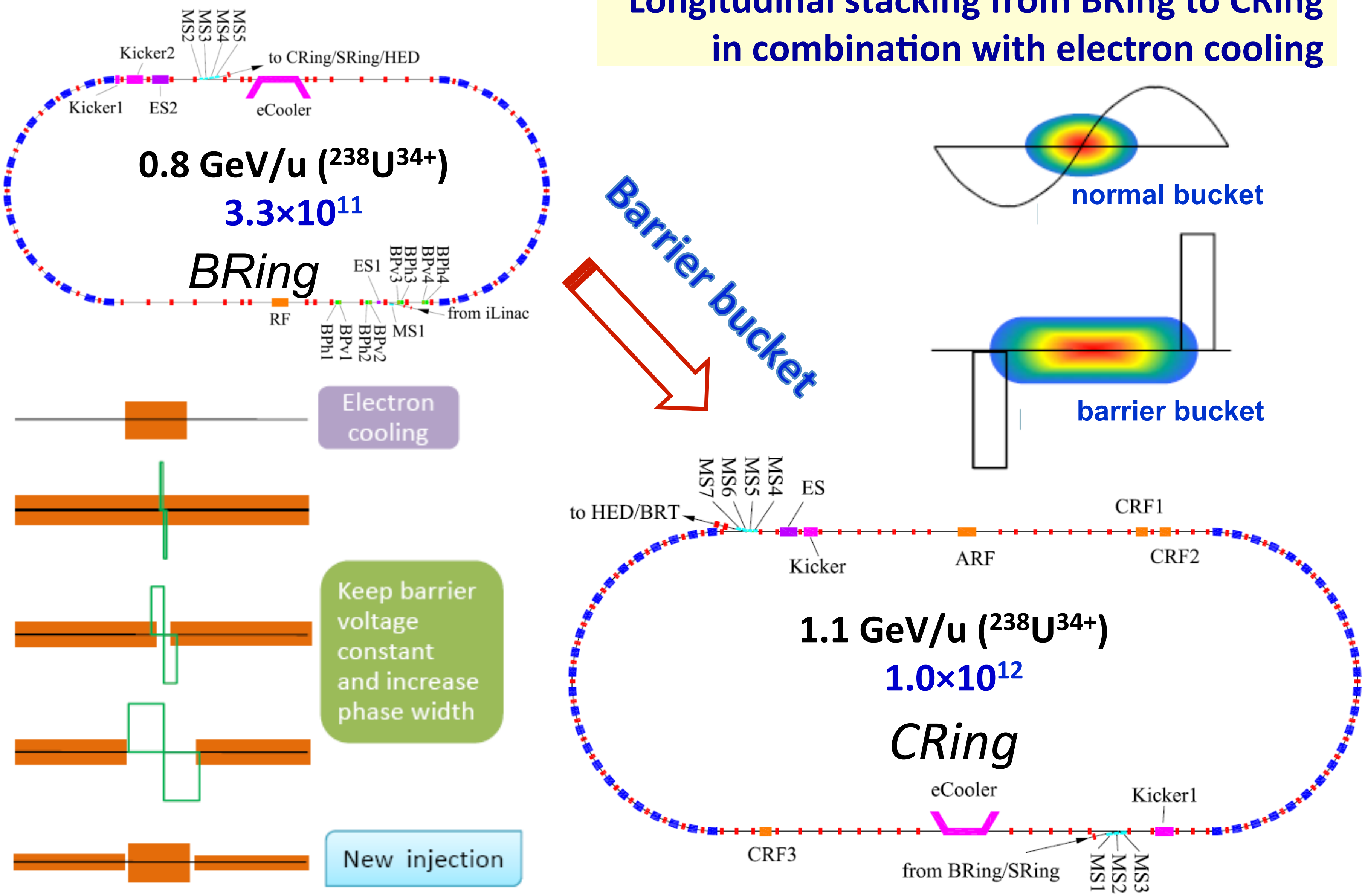
HIAF (incl. EIC)



1. Nuclear structure spectrometer
2. Low energy RIBs line
3. High precision Spectrometer
4. External target terminal-1
5. Electron-ion recombination resonance spectrometer
6. High energy irradiation terminal
7. High energy density matter terminal
8. External target terminal-2
9. Electron-Ion Collision (EIC)

HIAF - The First Phase

Longitudinal stacking from BRing to CRing in combination with electron cooling

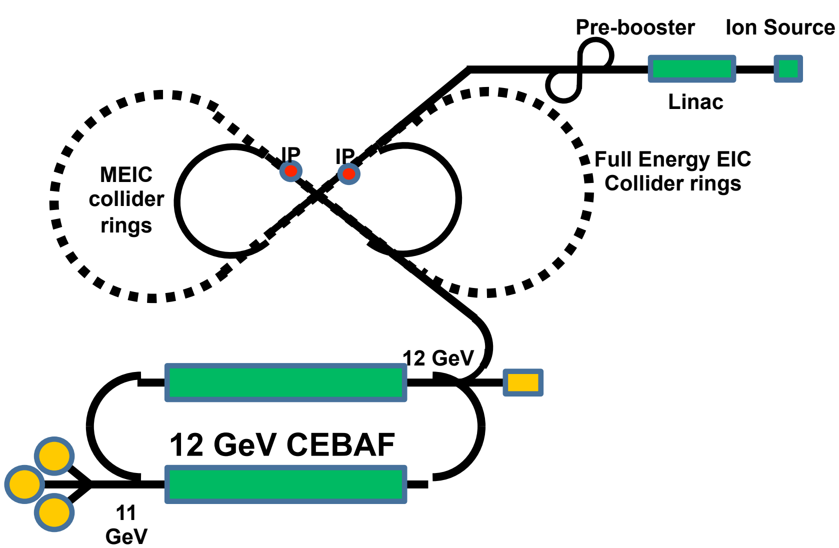


Electron-Ion Colliders

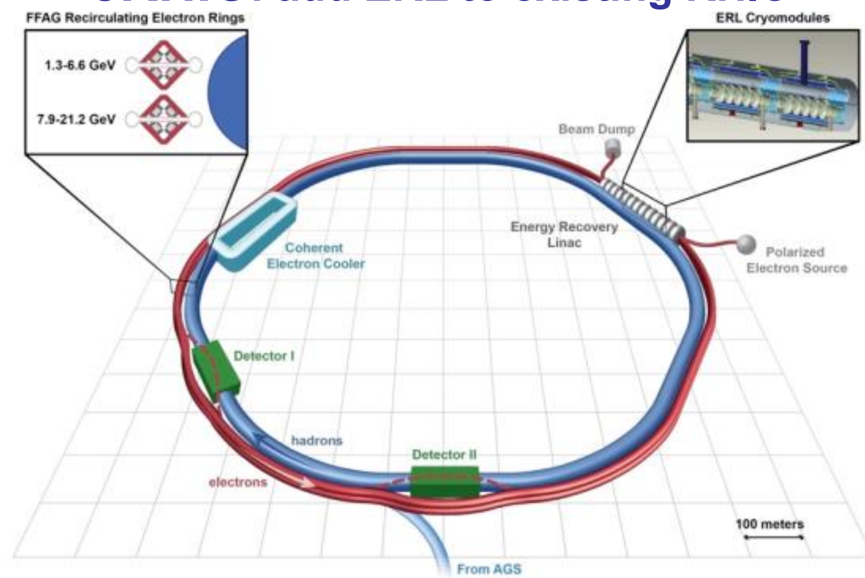
three proposals: **HIAF (IMP Lanzhou, China)**
MEIC (Jefferson Lab, USA)
eRHIC (Brookhaven Lab, USA)

common physics program: high luminosity (10^{34} cm^{-2}s^{-1}) required
center of mass energy (some ten, up to 150 GeV)
need for polarized beams

MEIC: add ion machines to existing CEBAF



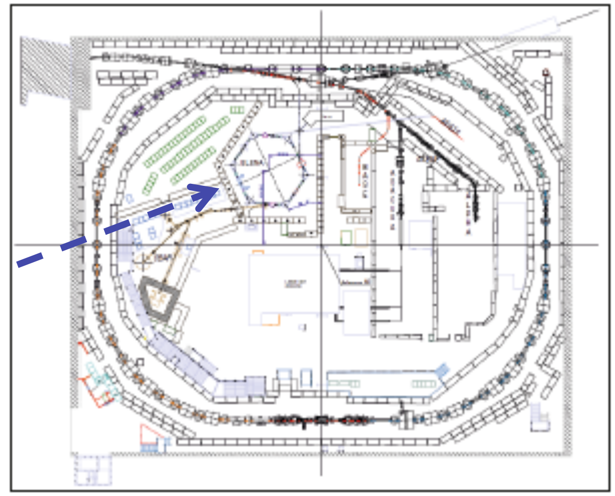
eRHIC: add ERL to existing RHIC

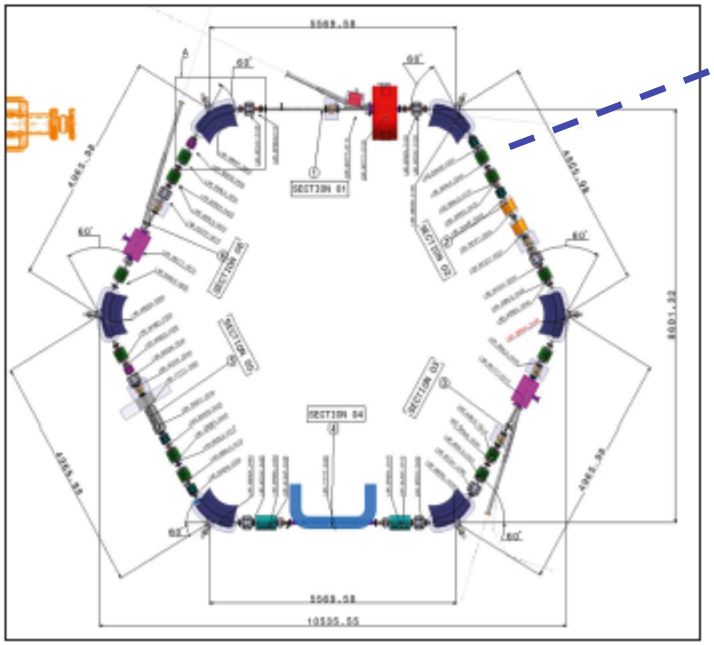


in all three projects:
electron cooling at high energy proposed to provide the required high luminosity

ELENA

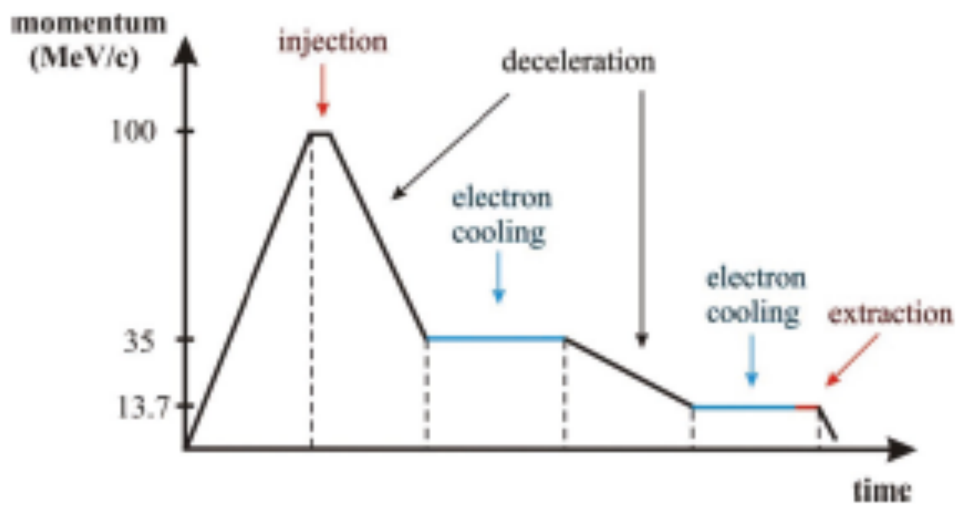
deceleration of antiprotons
after injection from AD
installed inside AD
circumference 30.4 m





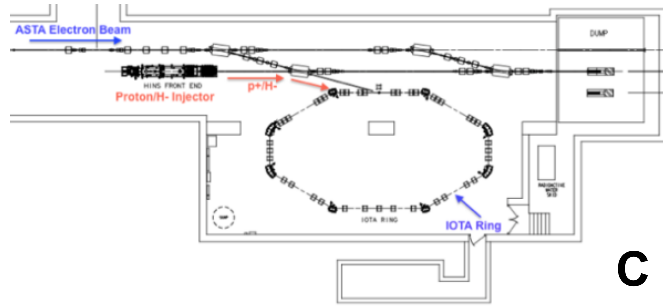
injection momentum 100 MeV/c
lowest antiproton momentum 13.7 MeV/c
minimum electron energy 55 eV

deceleration cycle



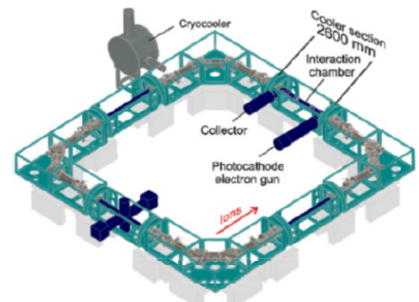
Other New Projects

IOTA Ring (Fermilab)
basic accelerator physics research
option to study optical stochastic cooling



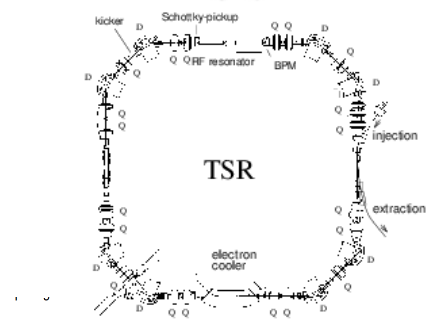
C ≈ 40 m

CSR (MPI Heidelberg)
cryogenic electrostatic storage ring
successful commissioning
plans to install electron cooling



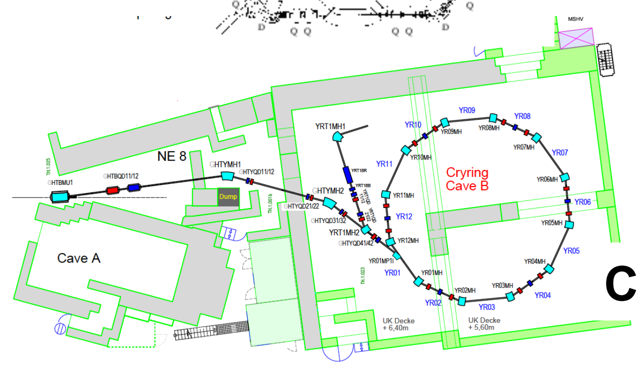
C ≈ 35 m

TSR (MPI Heidelberg/CERN)
decommissioned at MPI Heidelberg
proposal to install it after HIE-Isolde
for experiments with cooled stored secondary beams



C ≈ 55 m

CRYRING@ESR (GSI/FAIR)
installation of CRYRING behind ESR
for experiments with low energy
cooled highly charged ions
e.g. U^{92+} 0.02-10 MeV/u



C ≈ 54 m

Thank you

Enjoy COOL‘15