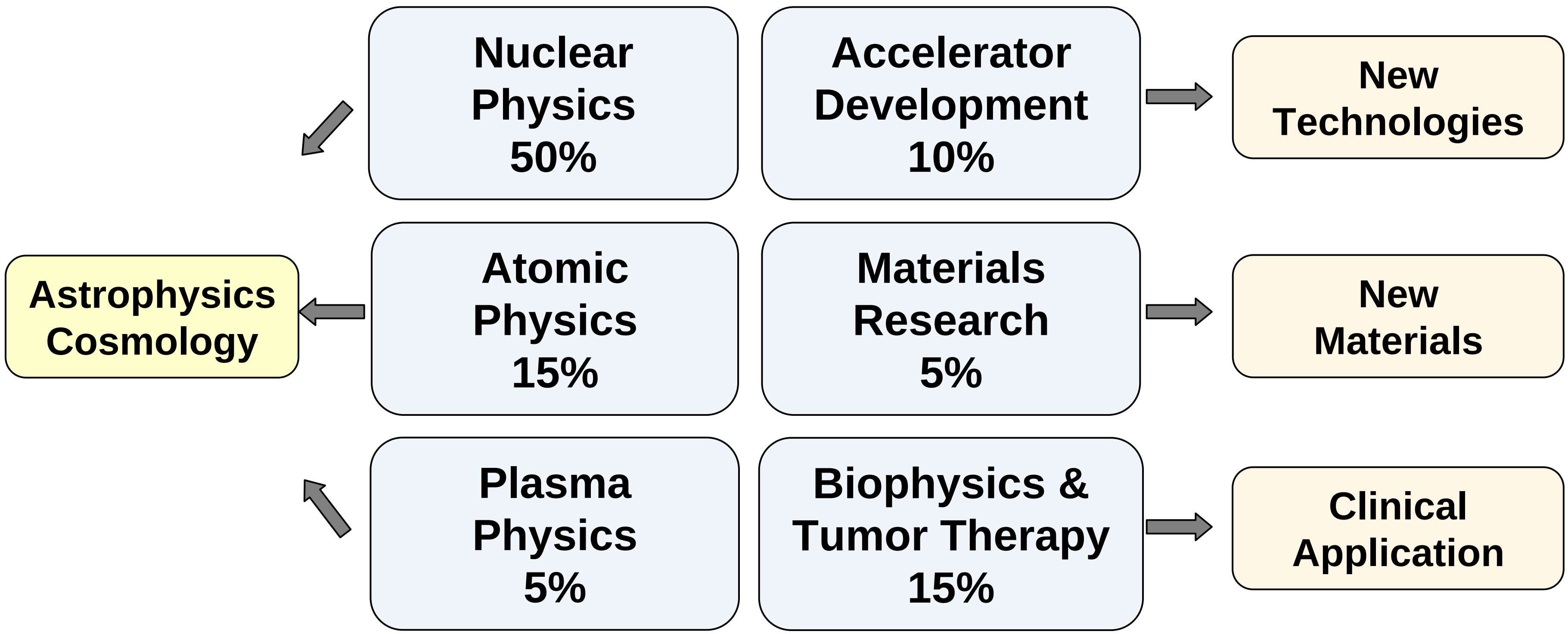
H.-Jürgen Kluge

GSI/Darmstadt and University of Heidelberg, Germany

FAIR: The GSI New Facility

1. **Present GSI: Research Program and Facilities**
2. **Present GSI Specialties: Clean Beams of Highly-Charged, Stored, and Cooled Heavy Ions, High Efficiency and Sensitivity**
3. **FAIR – Facility for Antiproton and Ion Research**
4. **Summary**

PRESENT GSI: RESEARCH PROGRAM



a very broad scientific program
tumor therapy will be transferred to Heidelberg in 2007

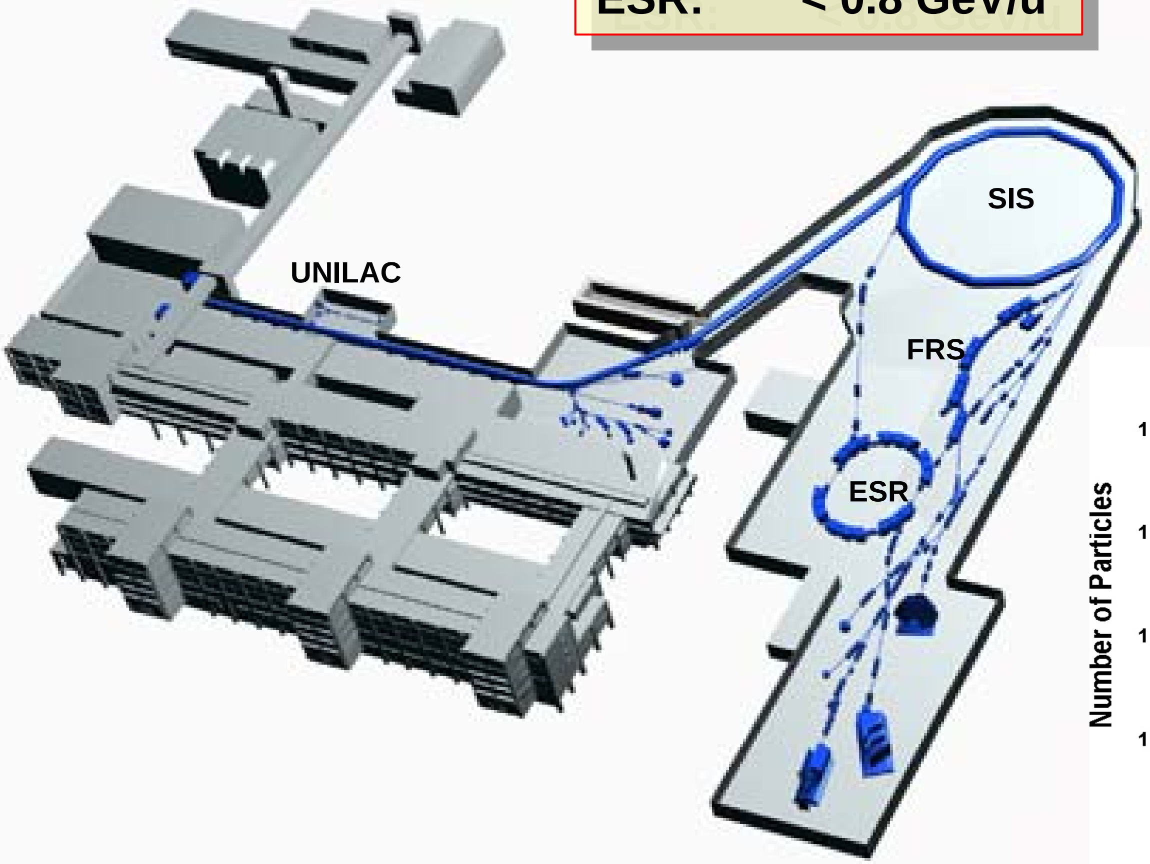
PRESENT GSI HEAVY-ION ACCELERATOR FACILITY

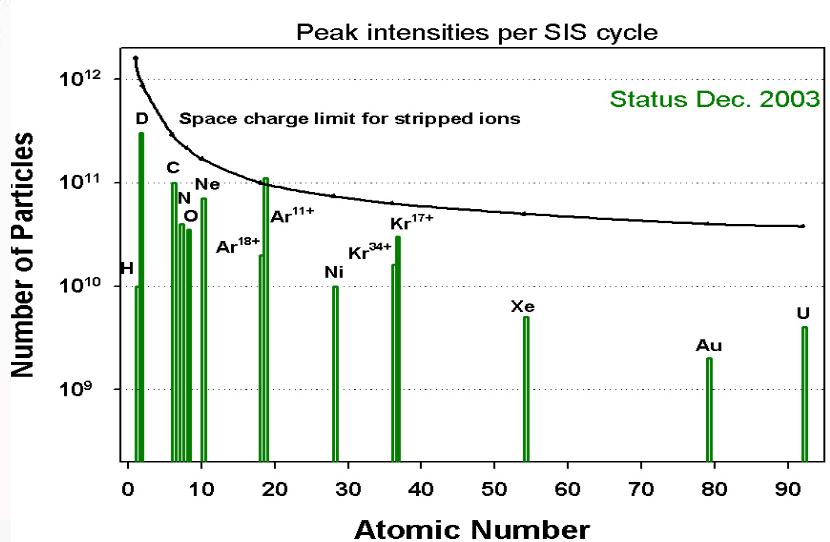
Energies:

Unilac:	< 20 MeV/u
SIS:	1 - 2 GeV/u
ESR:	< 0.8 GeV/u

Three injectors: up to six parallel experiments with three ion species

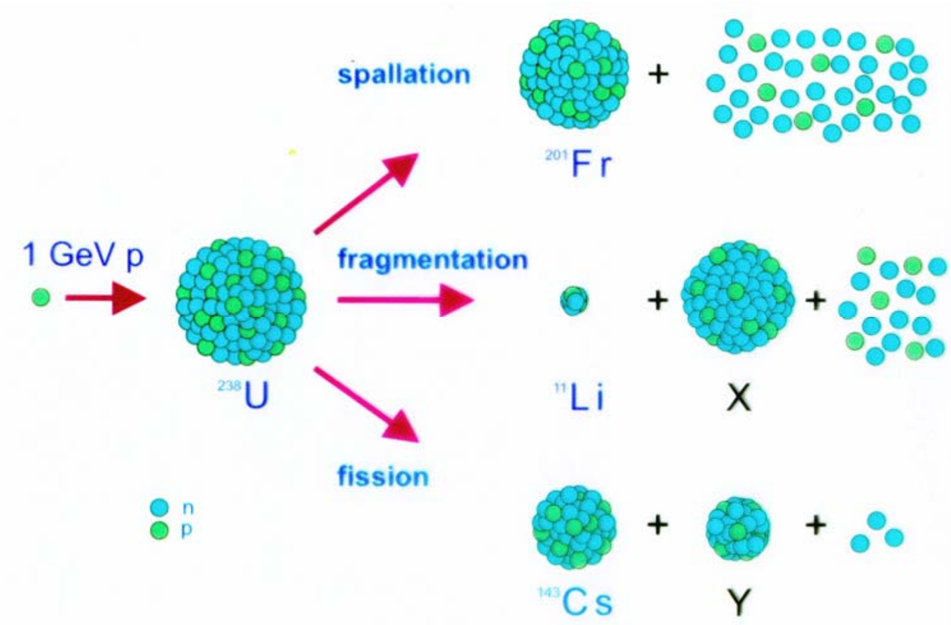
8 mA Ar^{1+}
18 mA Ar^{10+}
15 mA U^{4+}
2.5 mA U^{28+}
0.5 mA U^{73+}



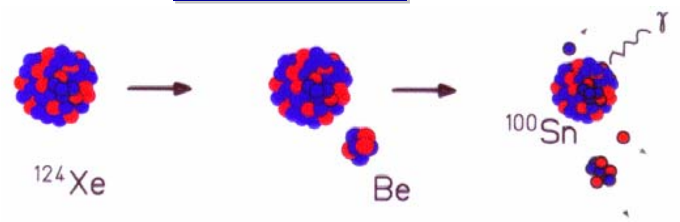


REACTION MECHANISM FOR RADIOACTIVE ION BEAMS

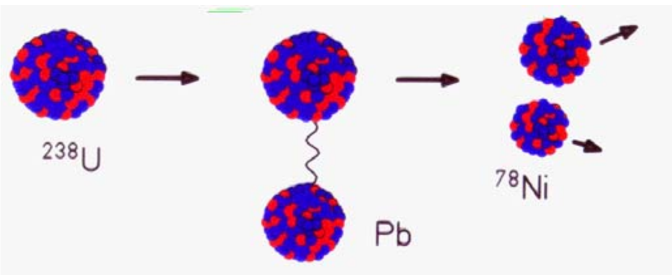
Proton-induced reactions
ISOL



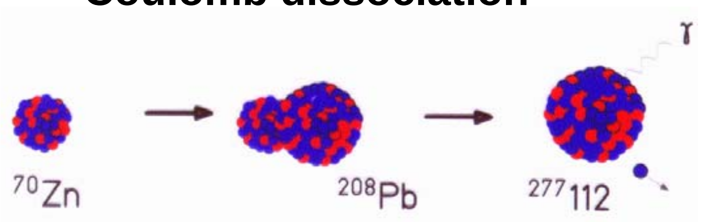
Heavy-ion-induced reactions
in-flight



fragmentation



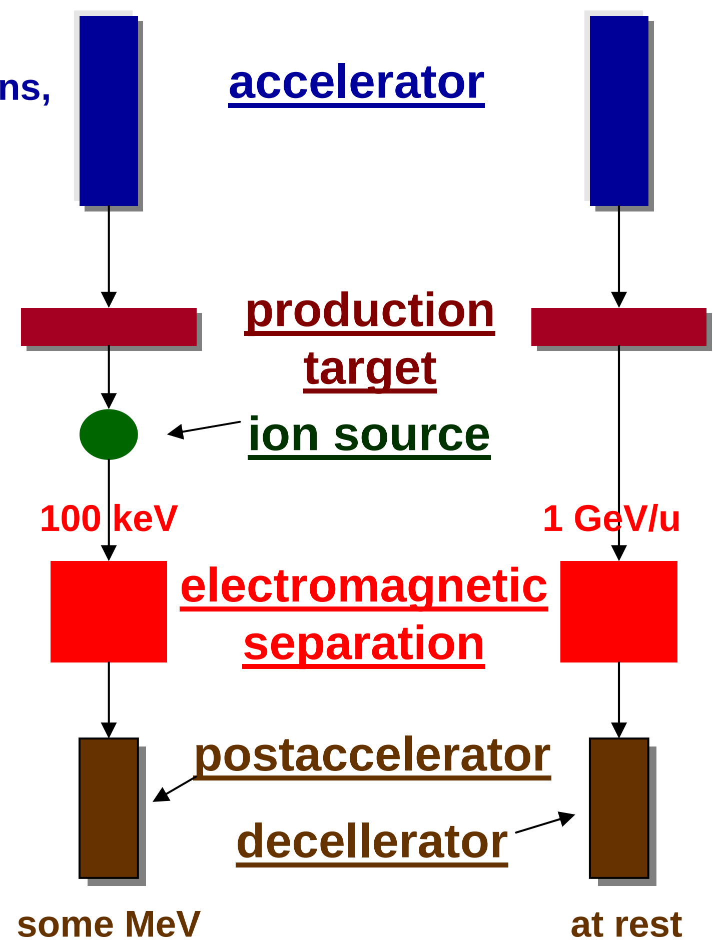
Coulomb dissociation



fusion

RIB PRODUCTION: ISOL vs. IN-FLIGHT

ISOL | IN-FLIGHT



high intensities for long-lived isotopes

limitation at $T_{1/2} < 10$ ms

high beam quality

no refractory elements

low intensities

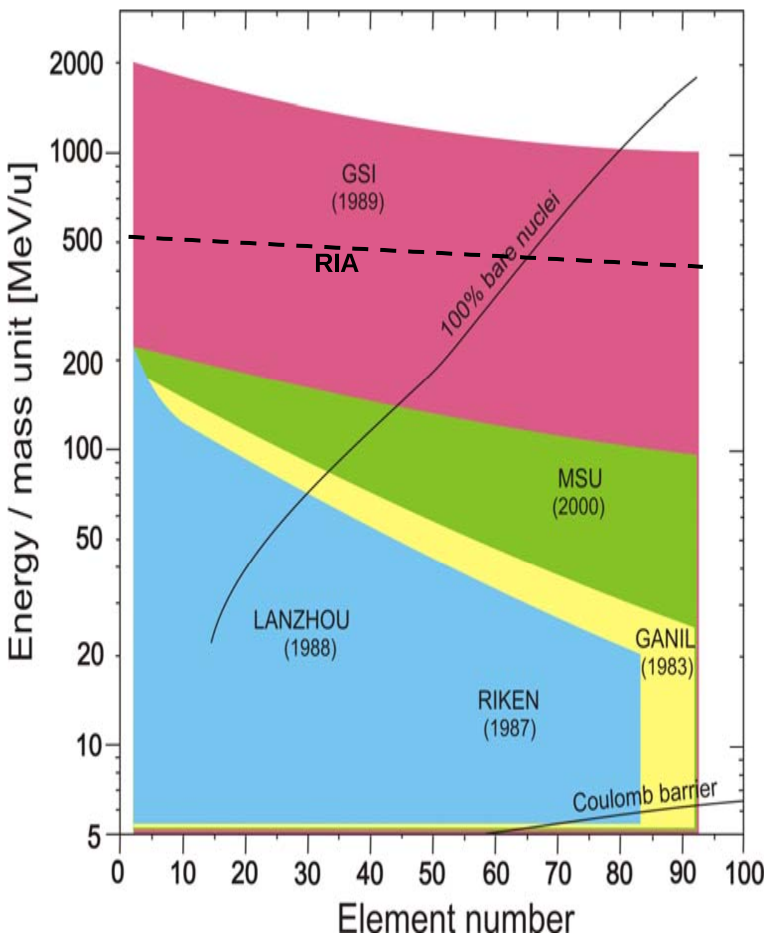
limitation at $T_{1/2} < 10$ µs

low beam quality

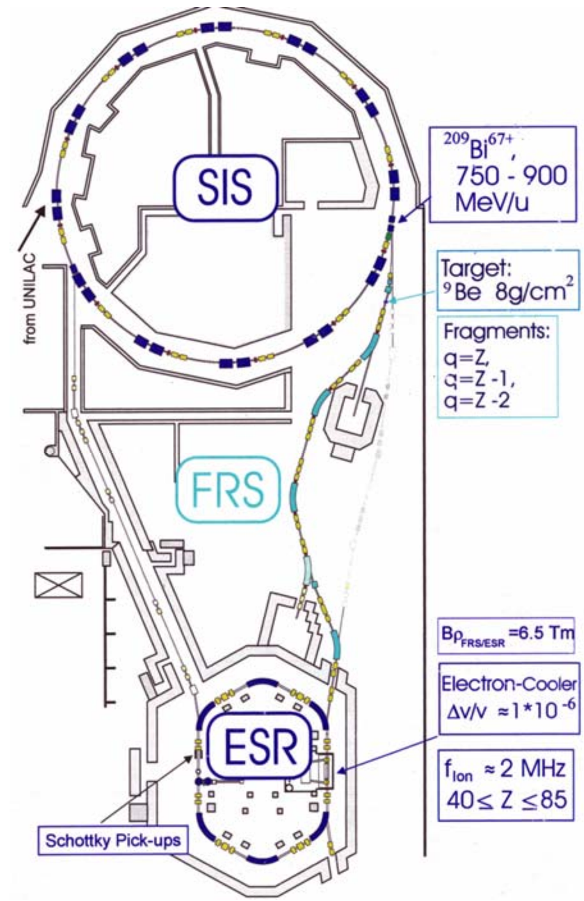
all elements

ISOL and fragmentation facilities have unique and complementary features

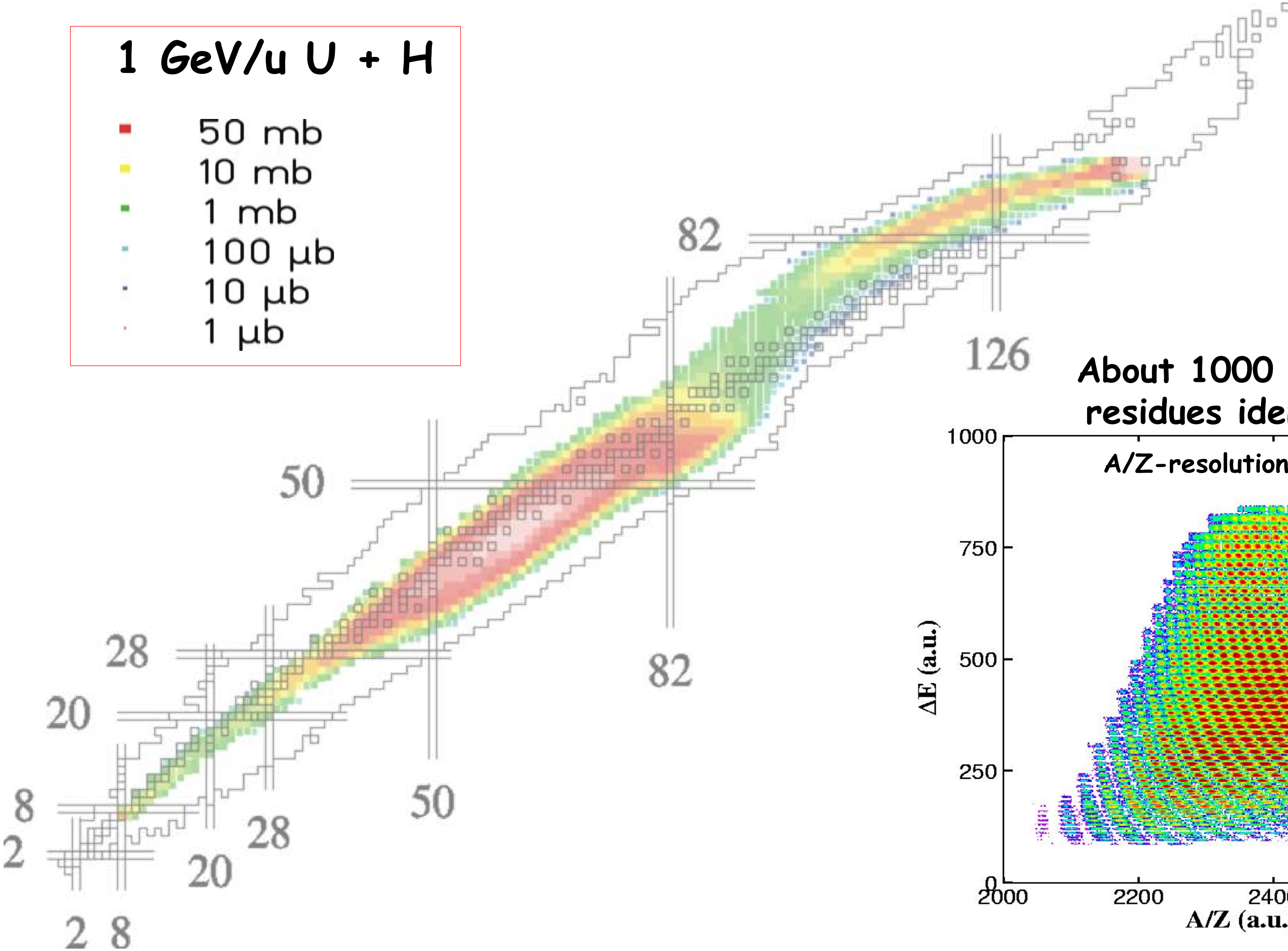
PRESENT GSI: HIGH-ENERGY PRIMARY ION BEAMS



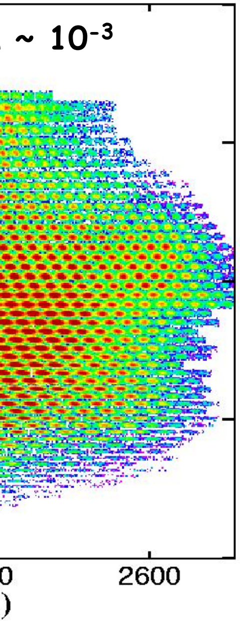
- High energies
- Highly-charged ions
- Clean beams
- Radioactive isotopes by fragmentation and Coulomb dissociation
- Universal
- Fast separation
- Efficient
- Short bunches
- Extreme static and dynamic electromagnetic fields



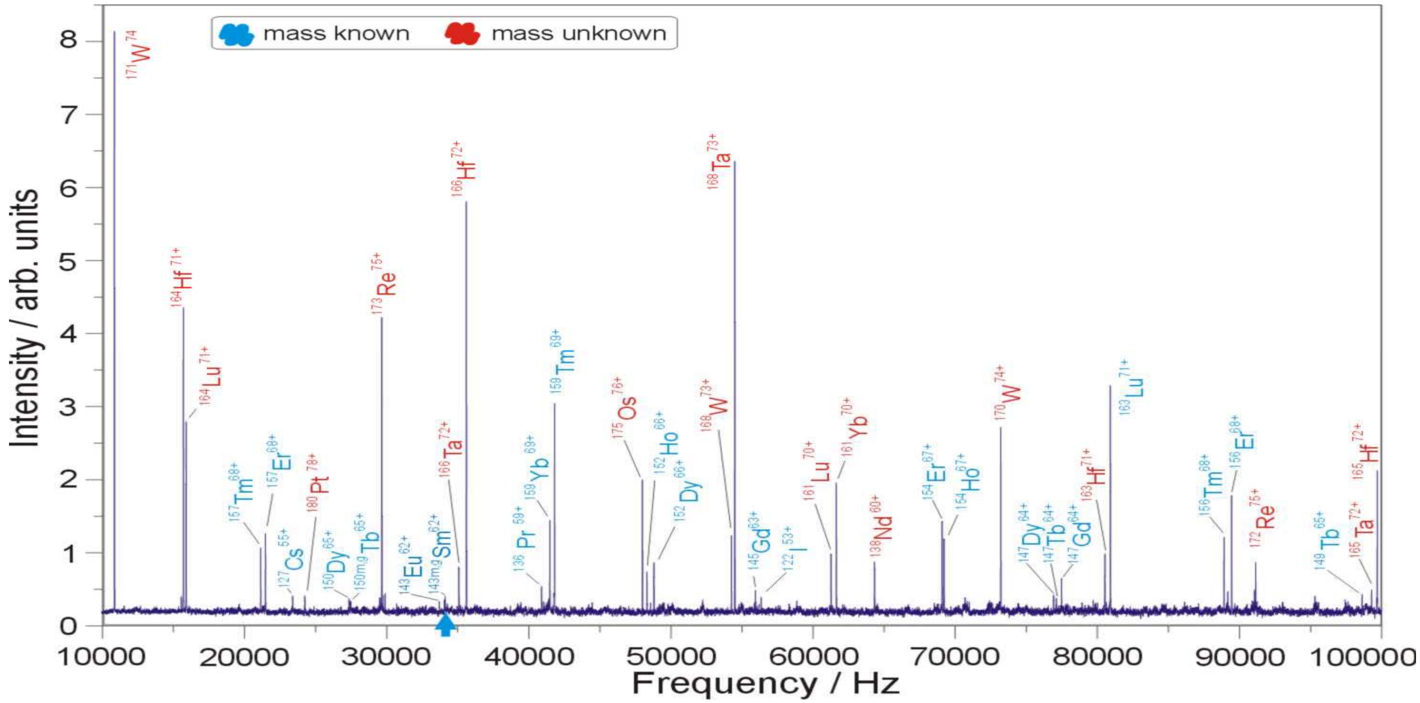
PRODUCTION AND INDENTIFICATION OF RADIOACTIVE BEAMS

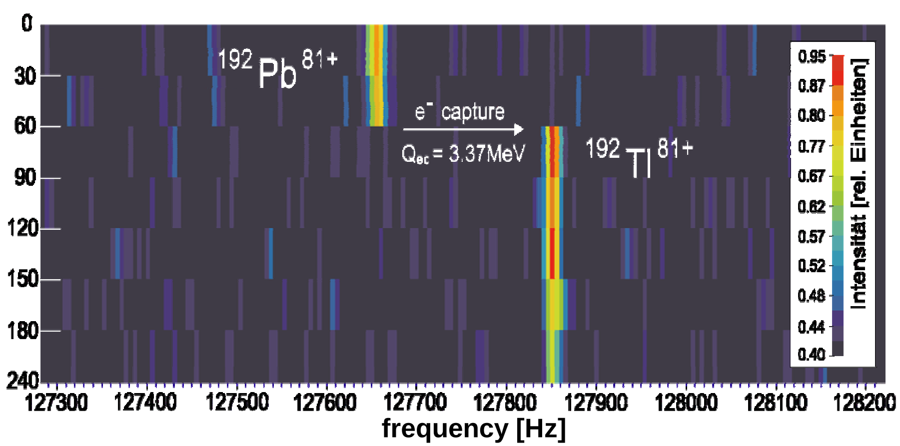


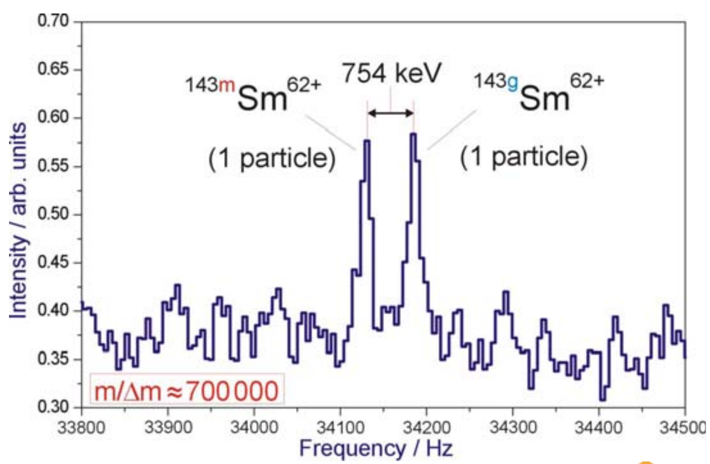
About 1000 nuclear residues identified



MASS SPECTROMETRY WITH SINGLE-ION SENSITIVITY







PREPAIRING FOR FAIR

1996 - 1999
Working Groups on Long-Term Perspectives of GSI

Deep-inelastic electron-nucleon and electron-nucleus scattering at $\sqrt{s}$ = 20 – 30 GeV
Conveners: V. Metag (GSI), D. v. Harrach (Mainz), A. Schäfer (Frankfurt)

X-ray spectroscopy and radiation physics
Conveners: J. Kluge (GSI), H. Backe (Mainz), G. Soff (Dresden)

Nuclear collisions at maximum baryon density
Conveners: P. Braun-Munzinger (GSI), R. Stock (Frankfurt), J. P. Blaizot (Saclay)

Physics with secondary beams
Conveners: U. Lynen (GSI), D. Frekers (Münster), J. Wambach (Darmstadt)

Nuclear structure with radioactive beams
Conveners: G. Münzenberg (GSI), D. Habs (LMU München), H. Lenske (Gießen), P. Ring (TU München)

Plasma physics with heavy ion beams
Conveners: R. Bock (GSI), D.H.H. Hoffmann (Erlangen), J. Meyer-ter-Vehn (IPP München)

Accelerator studies (electron-nucleon/nucleus collider)
Conveners: K. Blasche (GSI), J. Maidment (DESY), B. Autin (CERN), N. S. Dikansky (Novosibirsk)

Accelerator studies (high intensity option)
Convener: D. Böhne (GSI)

Short Pulse/High Power Lasers
Convener: J. Kluge (GSI)

Letter of Intent: ”Construction of a GLUE/CHARM Factory at GSI"

B. Franzke (GSI), P. Kienle (Munich), H. Koch (Bochum), W. Kühn (Giessen), V. Metag (Giessen), U. Wiedner (CERN & Uppsala)

1999 - 2003
24 Workshops on scientific and technical aspects of the new facility

2000
Development of Facility Concept

November 2001
Submission of Conceptual Design Report (700 pages, ca. 500 authors worldwide)

June 2002
Evaluation by the German Scientific Council: Recommendation for Realization

5 February 2003
Decision by the German Government to build the facility: (two conditions: 25% of funding from international sources; technical staging)

THE (APPROVED) WISH LIST

Radioactive Beams for Nuclear Structure Studies & Astrophysics:

in-flight separation
storing and cooling (mass, lifetime, charge radii, reactions)
≈ 2 GeV/u, protons up to U with highest intensities (≈ 100 kW)

Relativistic Heavy Ion Beams for Fixed-Target Collisions:

exploration of the QCD phase diagram in the region of high baryon densities at low temperature, color conducting phase?
heavy ions above the strange particle threshold, up to ≈ 40 GeV/u

High-Energy Antiprotons for a Glue Charm Factory:

exploration of the charm sector
search for charmed hybrid mesons
stored and cooled antiprotons with energies up to ≈ 15 GeV

Short Bunches of Highly-Charged Ions for Plasma Physics:

properties of high density plasmas
phase transitions and equation of state
bunch compressed heavy ion pulses (1 TW)

Highly-Charged Ions and Low-Energy Antiprotons for Atomic Physics:

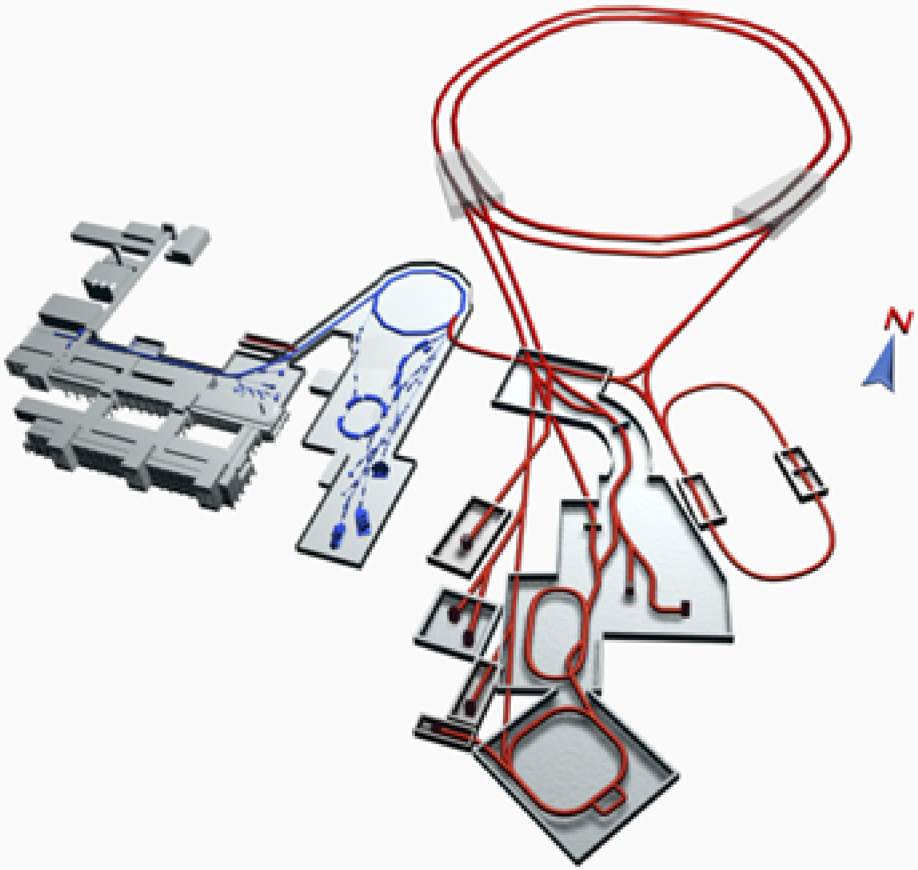
test of QED in extreme fields, fundamental tests and constants
dynamics of relativistic atomic collisions, nuclear ground state properties
stored highly-charged ions at low energy or at rest

THE CONCEPT

- synchrotrons for pulsed injection into storage rings
- present (up-graded) UNILAC/SIS18 as injector
- increase of cycling rate of SIS18 by an order of magnitude
- lower charge states for higher intensities (space charge limit)
- two superconducting rings SIS100, SIS300

- relativistic heavy ion beams:
  - SIS 100, SIS 200, slow extraction to fixed target
- radioactive ion beams:
  - SIS100, fast extraction, SFRS, stochastic cooling in CR (TOF-MS), deceleration in RESR, stochastic and e-cooling in NESR
- high-energy antiprotons:
  - 50 MeV proton linac, SIS100, fast extraction, pbar target, stochastic cooling in CR, accumulation in RESR, acceleration in SIS 100, electron cooling in HESR
- low-energy and ultra-low energy antiprotons and highly-charged ions:
  - experiments in NESR, deceleration in NESR, extraction and further deceleration in FLAIR
    (Facility for Low-Energy Antiproton and Ion Research)

PLANNED LAY-OUT AND FEATURES OF FAIR



Primary Beams

- 10^{12}/s 1.5-2 GeV/u $^{238}U^{28+}$
- factor 100-1000 over present in intensity
- $2.5 \cdot 10^{13}$/s 29 GeV protons
- 10^{9}/s $^{238}U^{92+}$ up to 34 GeV/u

Secondary Beams

- broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- antiprotons 3 - 30 GeV

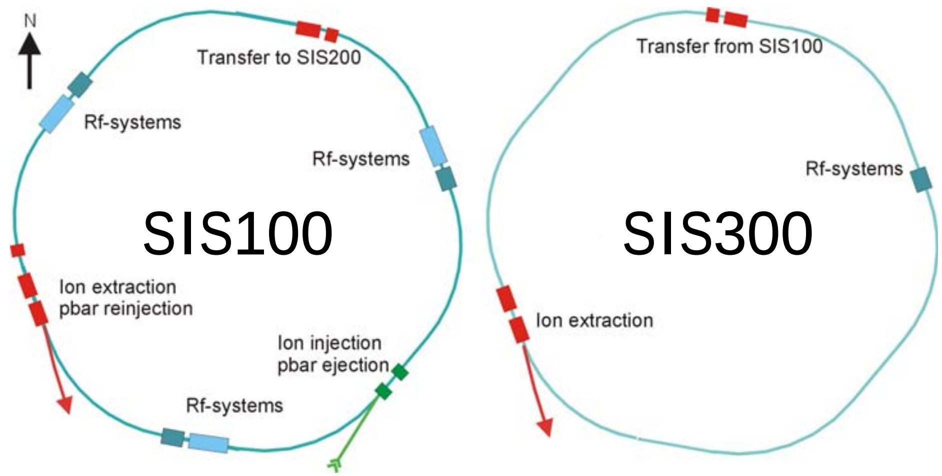
Storage and Cooler Rings

- radioactive beams
- e-A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons
- highly-charged ions and pbar at rest

Key Technical Features

cooled and stored beams
rapidly cycling superconducting magnets
parallel operation

SIS100/300 Design Parameters



First Stage
fast acceleration
compression

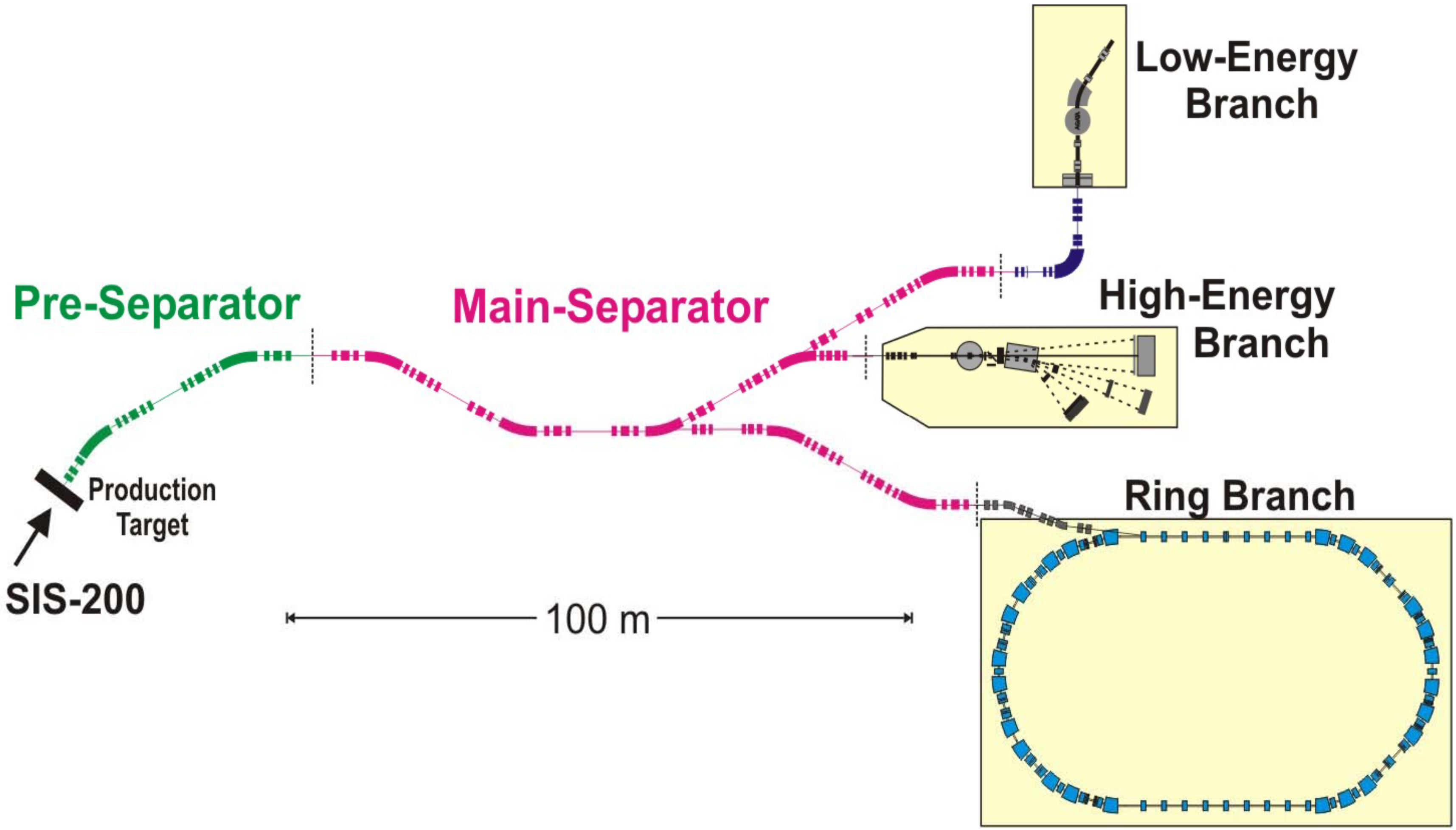
Second Stage
acceleration
stretcher

BR = 100 Tm
Bmax = 2 T
dB/dt = 4 T/s

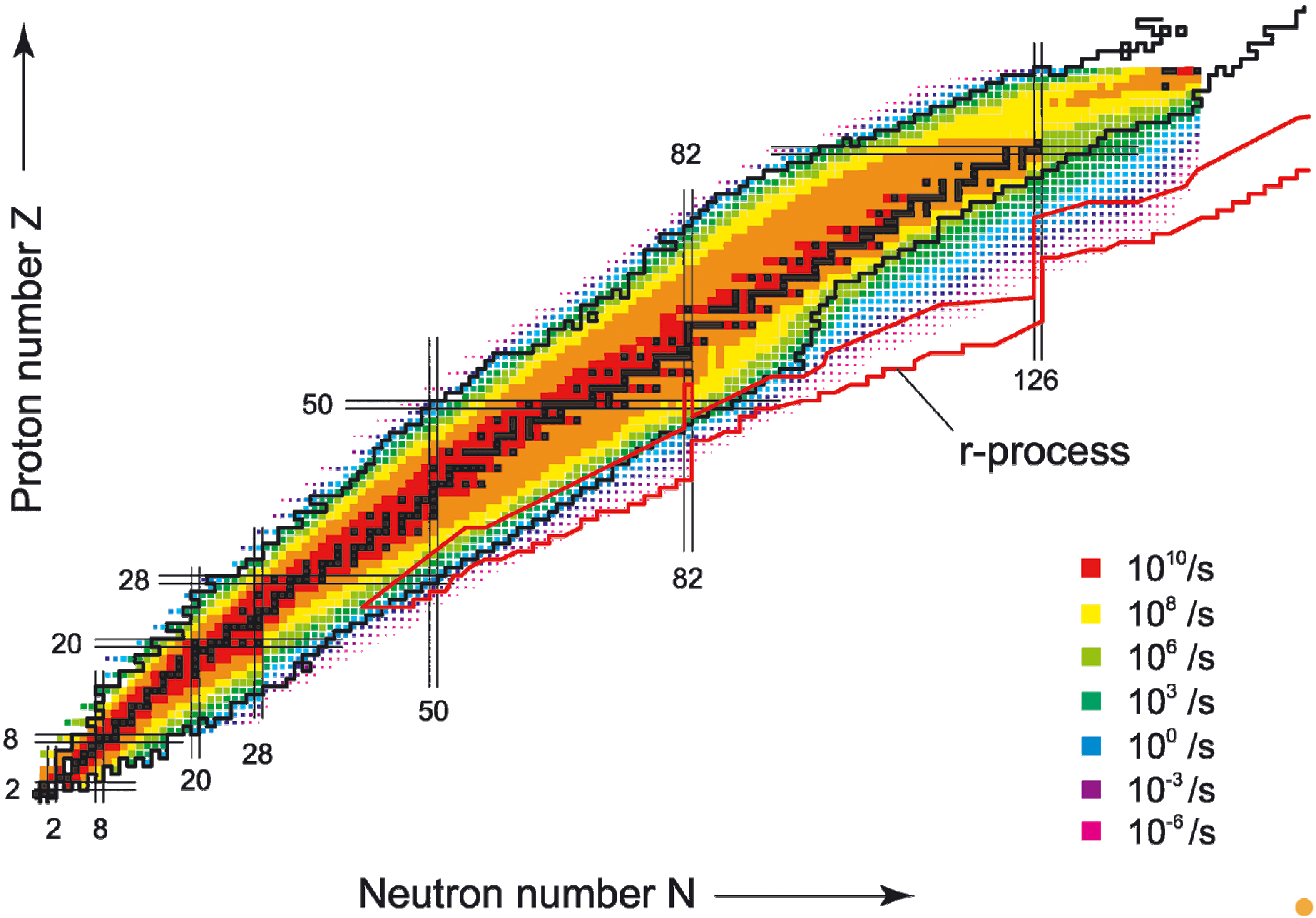
BR = 300 Tm
Bmax = 6 T
dB/dt = 1 T/s

Reference Ions	U^{28+} p	U^{28+} U^{92+}
Rigidity [Tm]	100	300
Circumf. [m]	1083	1083
Intensity	$1\text{-}2 \cdot 10^{12}$ $2.5 \cdot 10^{13}$	$1 \cdot 10^{12}$ /s $1 \cdot 10^{9}$ /s
Energy [GeV/u]	2.7 29	2.7 34
Pulse length [ns]	25 – 90 < 50	d.c. slow ext.
Main Magnets	s.c. wf	s.c. cosΘ

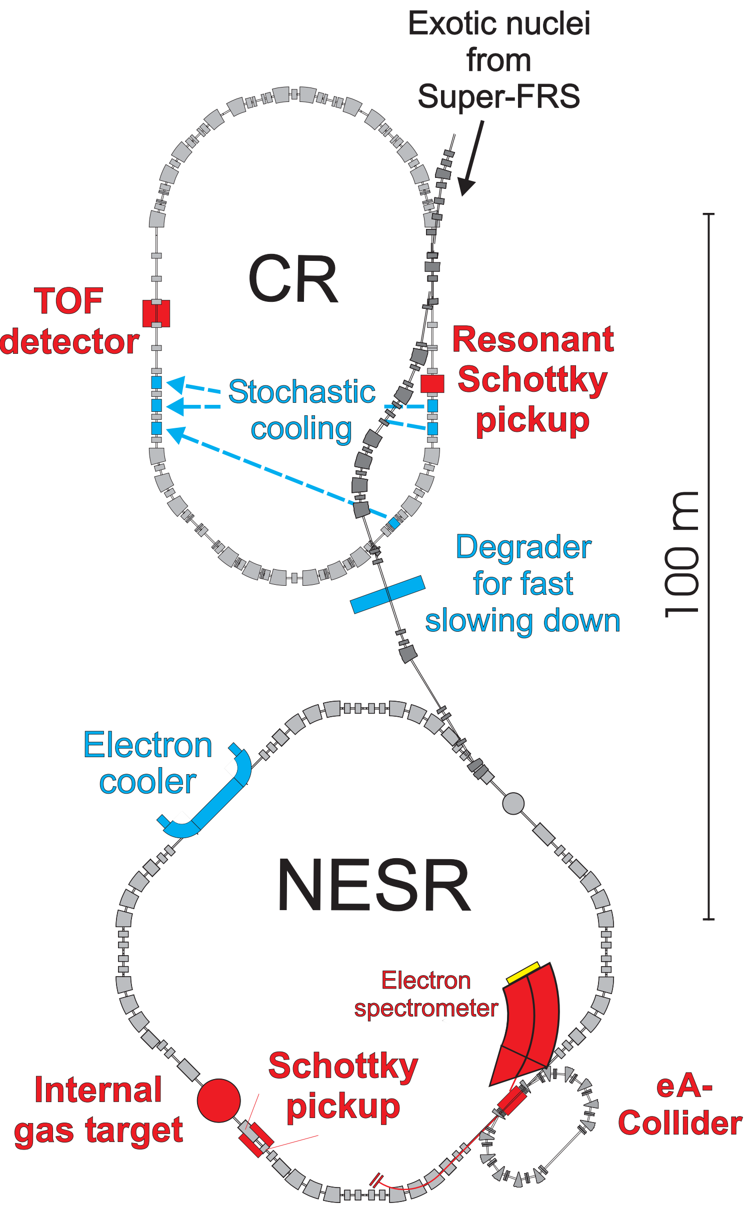
SFRS: LARGE-ACCEPTANCE HIGH-RESOLUTION SPECTROMETER



EXPECTED SFRS YIELDS AT FAIR



FAIR : NEW TECHNIQUES FOR RIB´s AND HCI



- Fast pre-cooling in CR complex
  ➔ very short-lived nuclei
- Combination of two storage rings
  ➔ high acceptance
- Electron-cooled beams in NESR
  ➔ high-accuracy MS, $T_{1/2}$
- Light hadron (p,d,He..) scattering
  ➔ internal-target experiments
- Electron scattering
  ➔ electron-ion collider
- Deceleration of highly-charged ions
  ➔ very high-accuracy spectr., MS ...
- Deceleration of singly-charged ions
  ➔ capture into traps ...

FAIR IN THE WORLD-WIDE CONTEXT

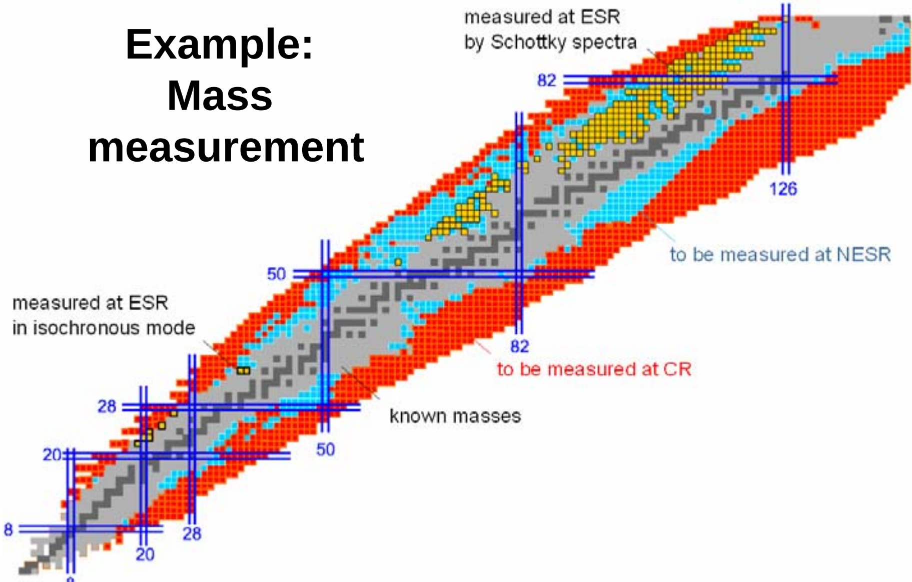
Other Large-Scale In-Flight Facilities

- **RIKEN (Japan)**
  - ➔ Cyclotrons: 350 MeV/u
  - ➔ Multi-use storage rings
  - ➔ Status: phase I construction started
- **RIA (USA)**
  - ➔ Superconducting linac: 400 MeV/u
  - ➔ ISOL/in-flight hybrid; no storage rings, 10 - 50 times higher yields
  - ➔ Status: proposed (NSAC priority)
- **ISOL-Facilities**

  Complementary approach

Lower primary beam intensity at GSI as compared to RIA is partly compensated by higher energy. In addition, higher energy eases identification by full stripping.

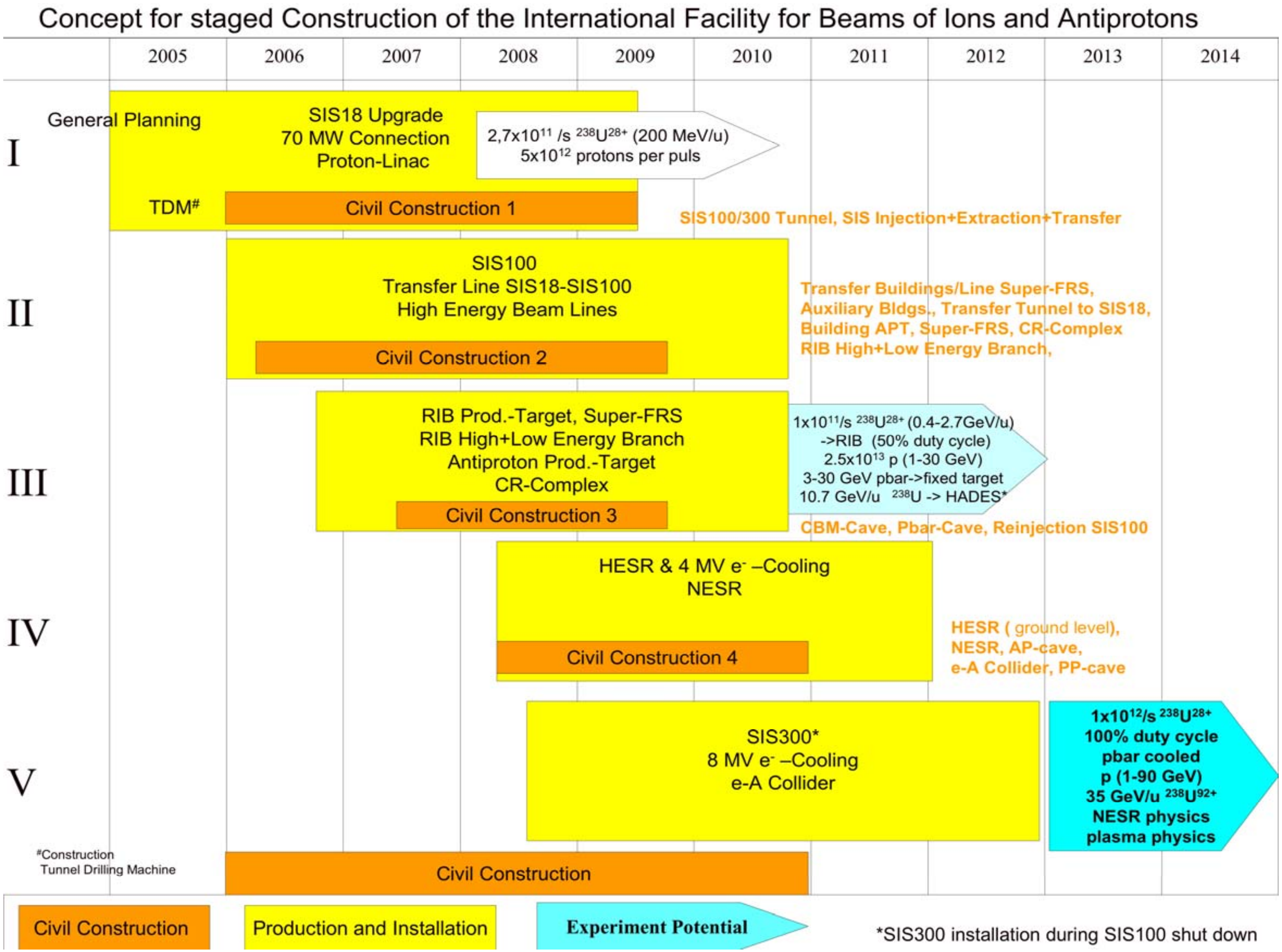
Example: Mass measurement



Nucleus	Yield / cycle	Half life $T_{1/2}$ [s]
$^{11}Be^{4+}$	6.0×10^8	13.8
$^{46}Ar^{18+}$	3.2×10^8	7.8
$^{71}Ni^{28+}$	6.7×10^6	2.6
$^{91}Kr^{36+}$	4.2×10^7	8.6
$^{132}Sn^{50+}$	4.0×10^7	39.7
$^{133}Sn^{50+}$	4.0×10^6	1.4
$^{187}Pb^{82+}$	1.0×10^7	15.0
$^{207}Fr^{87+}$	3.2×10^7	14.8
$^{227}U^{92+}$	1.6×10^6	66

^{132}Sn: $3\cdot10^9$ acc. in NESR

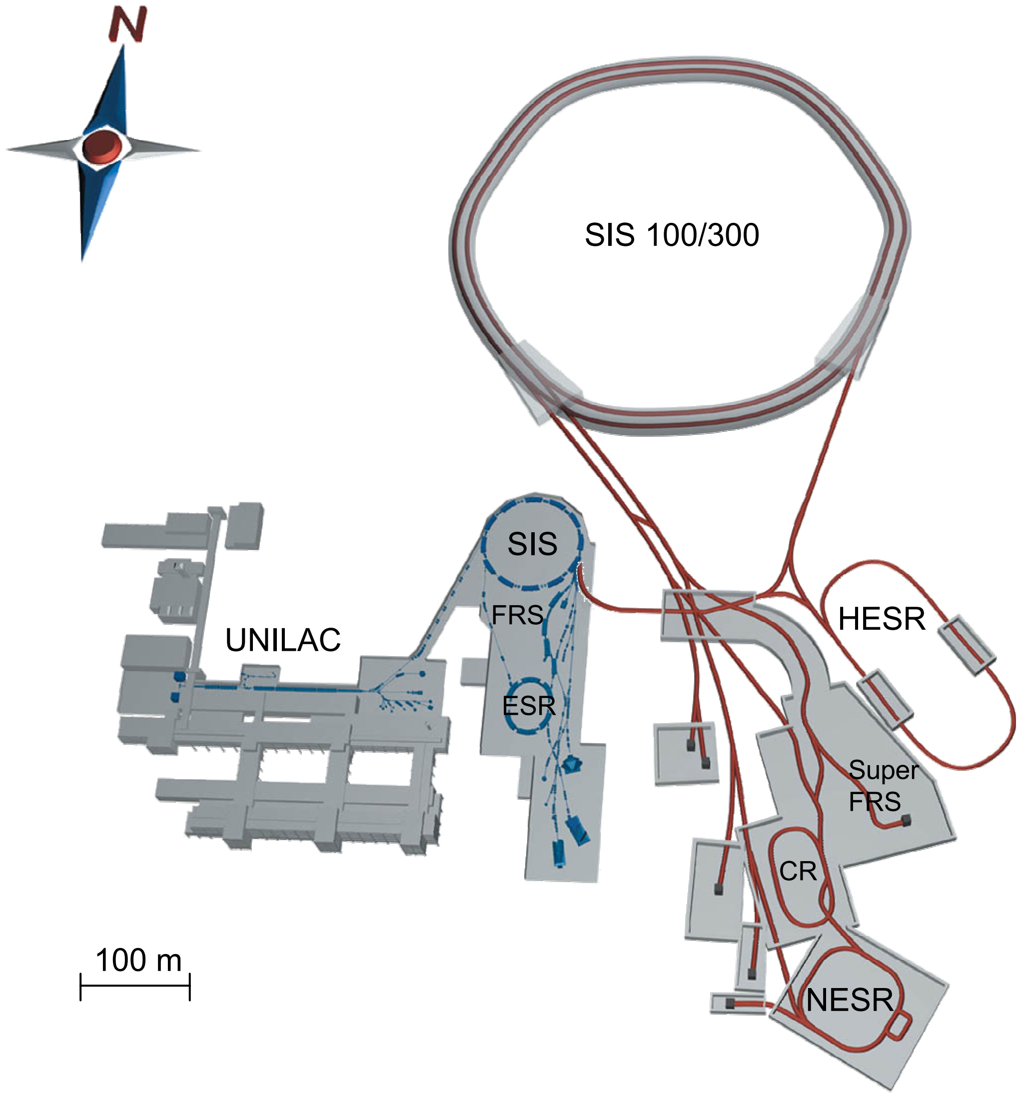
CONCEPT FOR STAGED CONSTRUCTION OF FAIR



ACCELERATOR ASPECTS: TECHNOLOGICAL CHALLENGES

- Superconducting magnets for cost-effective construction and operation of the new synchrotron rings SIS100/300
- Fast cycling magnets
- Bunch compression
- Collector and storage rings with efficient stochastic cooling for radioactive ions and antiproton beams
- Electron cooling of heavy ions up to 900 MeV/u
- Electron cooling of antiprotons up to 15 GeV
- Ultra high vacuum in synchrotrons (10^{-12} mbar)
- Losses of high intensity beams

SUMMARY



Gain Factors

- **Primary beam intensity: Factor 100 – 1000**
- **Secondary beam intensities for radioactive nuclei: up to factor 10,000**
- **Beam energy: Factor 15**

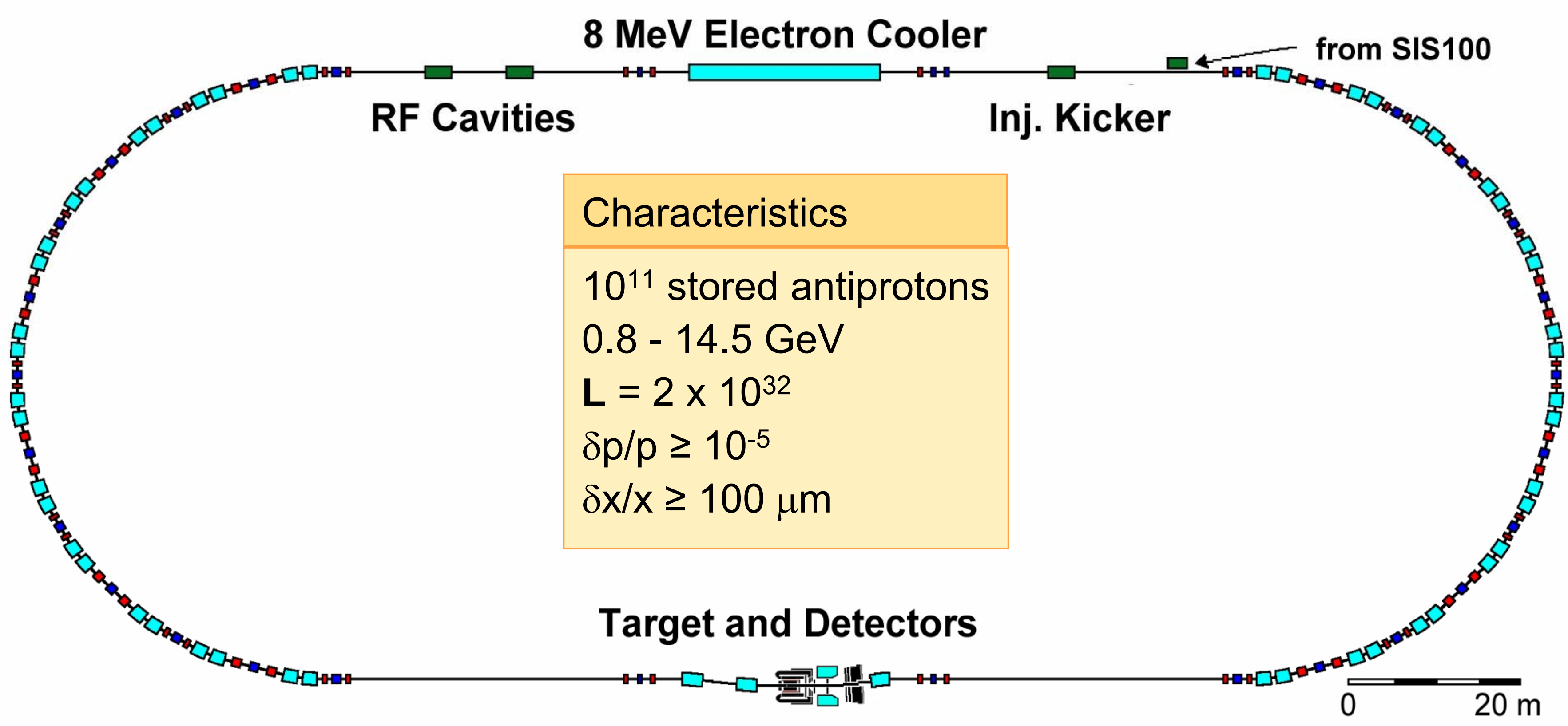
Special Properties

- **Intense, fast cooled energetic beams of exotic nuclei**
- **Cooled antiprotons up to 15 GeV and down to rest**
- **Internal targets for high-luminosity in-ring experiments**
- **Parallel operation and time sharing**

New Technologies

- **Fast cycling superconducting magnets**
- **Electron cooling at high ion intensities and energies**
- **Fast stochastic cooling**

HESR - High Energy Storage Ring



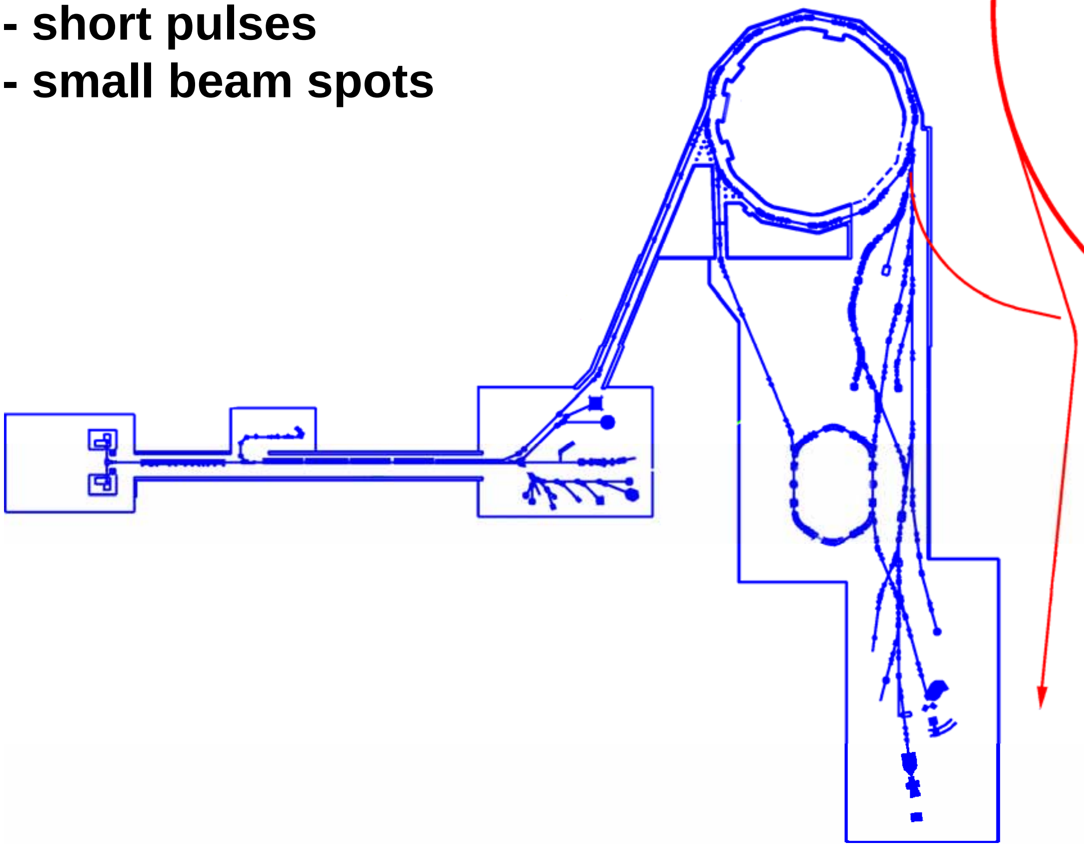
Characteristics

- 10^{11} stored antiprotons
- 0.8 - 14.5 GeV
- **L** = 2×10^{32}
- $\delta p/p \geq 10^{-5}$
- $\delta x/x \geq 100\ \mu m$

FAIR: HIGH-ENERGY DEPOSITION IN MATTER

Requirements for plasma physics experiments:

- high intensity (12 000 GW/g)
- short pulses
- small beam spots



SIS 100

100 Tm
all elements: H to U
$2 \cdot 10^{12}$ ions per cycle
1 s cycle length
400 MeV/u U^{28+} (ref.)
(pulsed 100 ns)

FAIR: NUCLEUS - NUCLEUS COLLISIONS AT HIGH ENEGY

Requirements for nucleus - nucleus collision experiments at high energy:

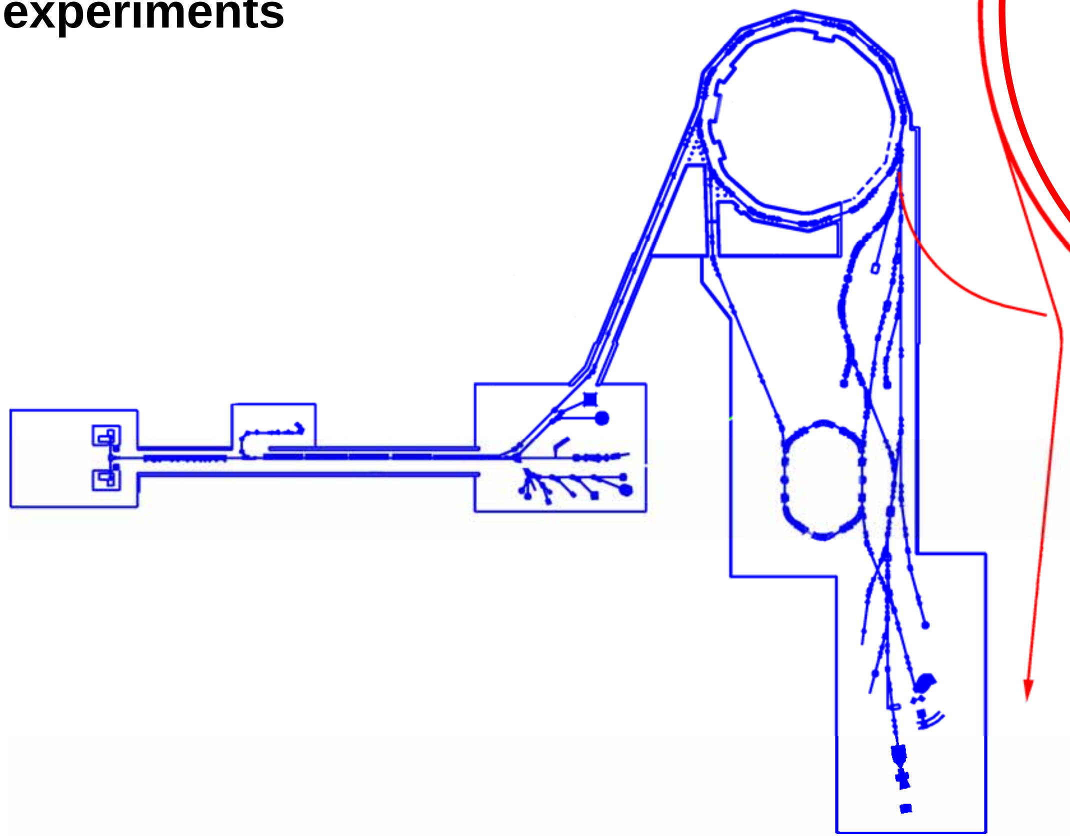
- 10 – 40 GeV/u for highest baryon densitiy
- moderate intensities
- high duty cycle for fixed target experiments

SIS 100

100 Tm
all elements up to U
$1.2 \cdot 10^{10}$ ions per cycle
1 s cycle length
1.0 – 10.7 GeV/u energy range for U^{92+}

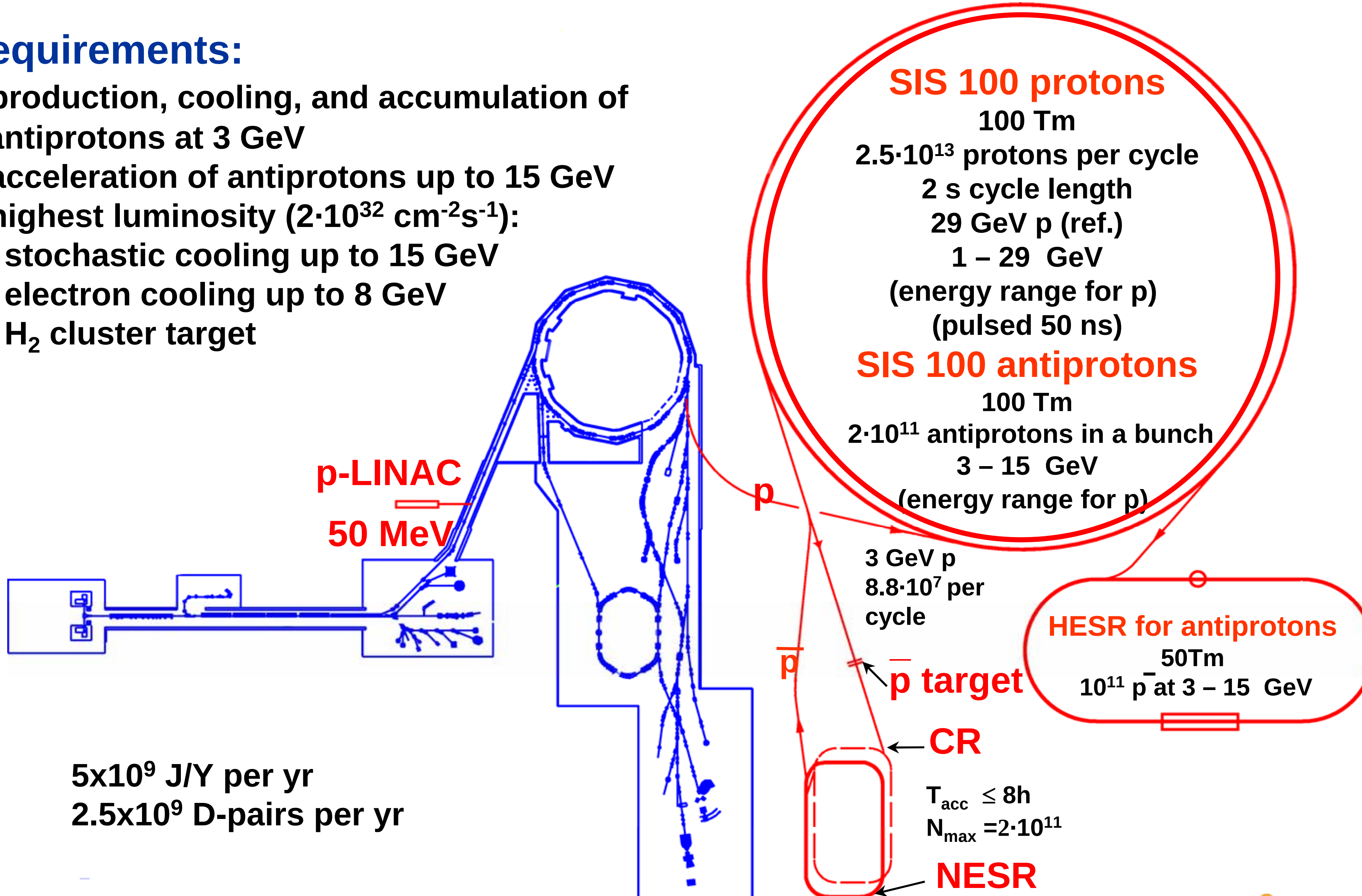
SIS 200

200 Tm
$1.2 \cdot 10^{10}$ ions per cycle
12 s cycle length
$2 \cdot 10^{9}$ ions/s
7.0 – 22.3 GeV/u energy range for U^{92+}
29.1 GeV/u energy for Ne^{10+}



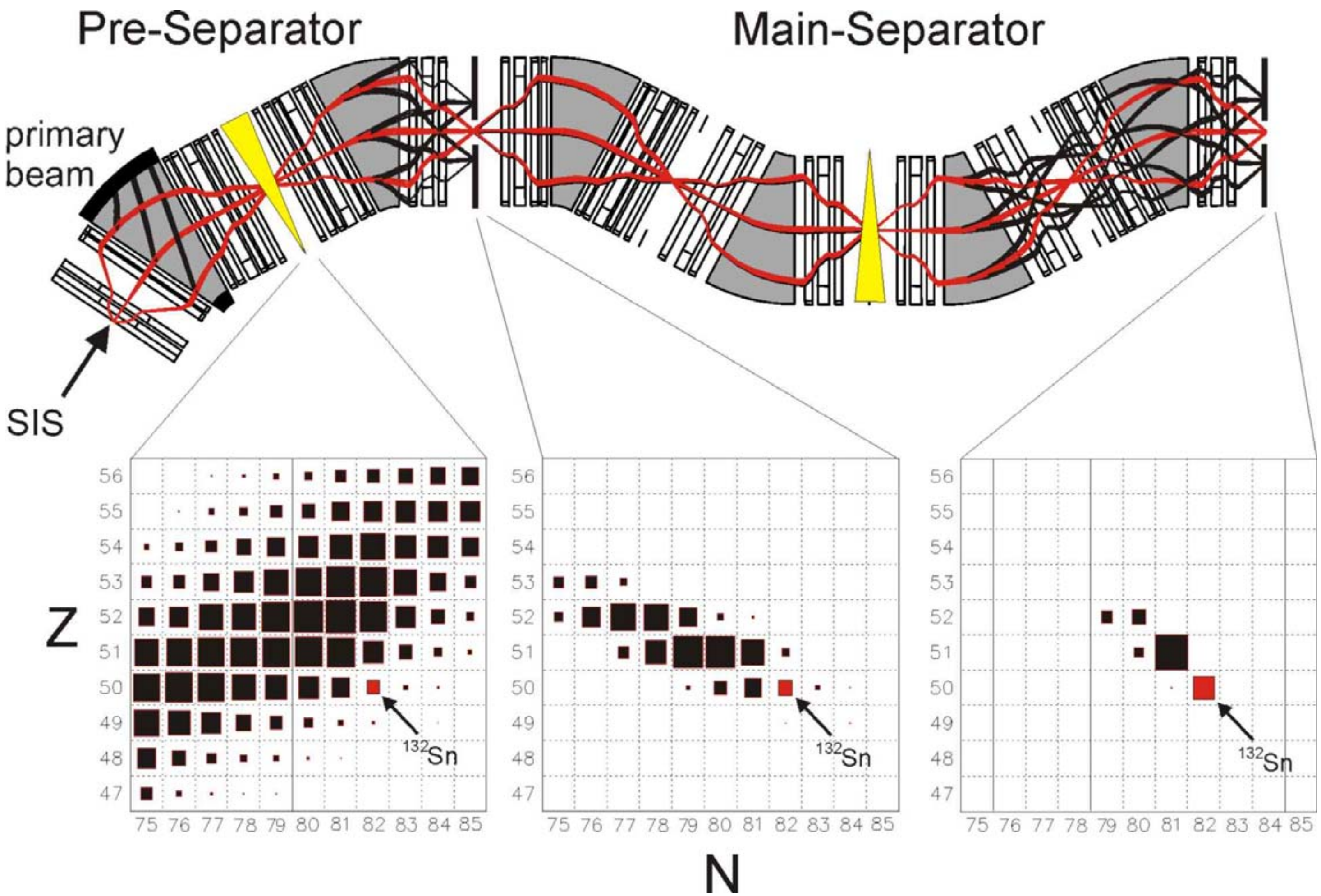
Requirements:

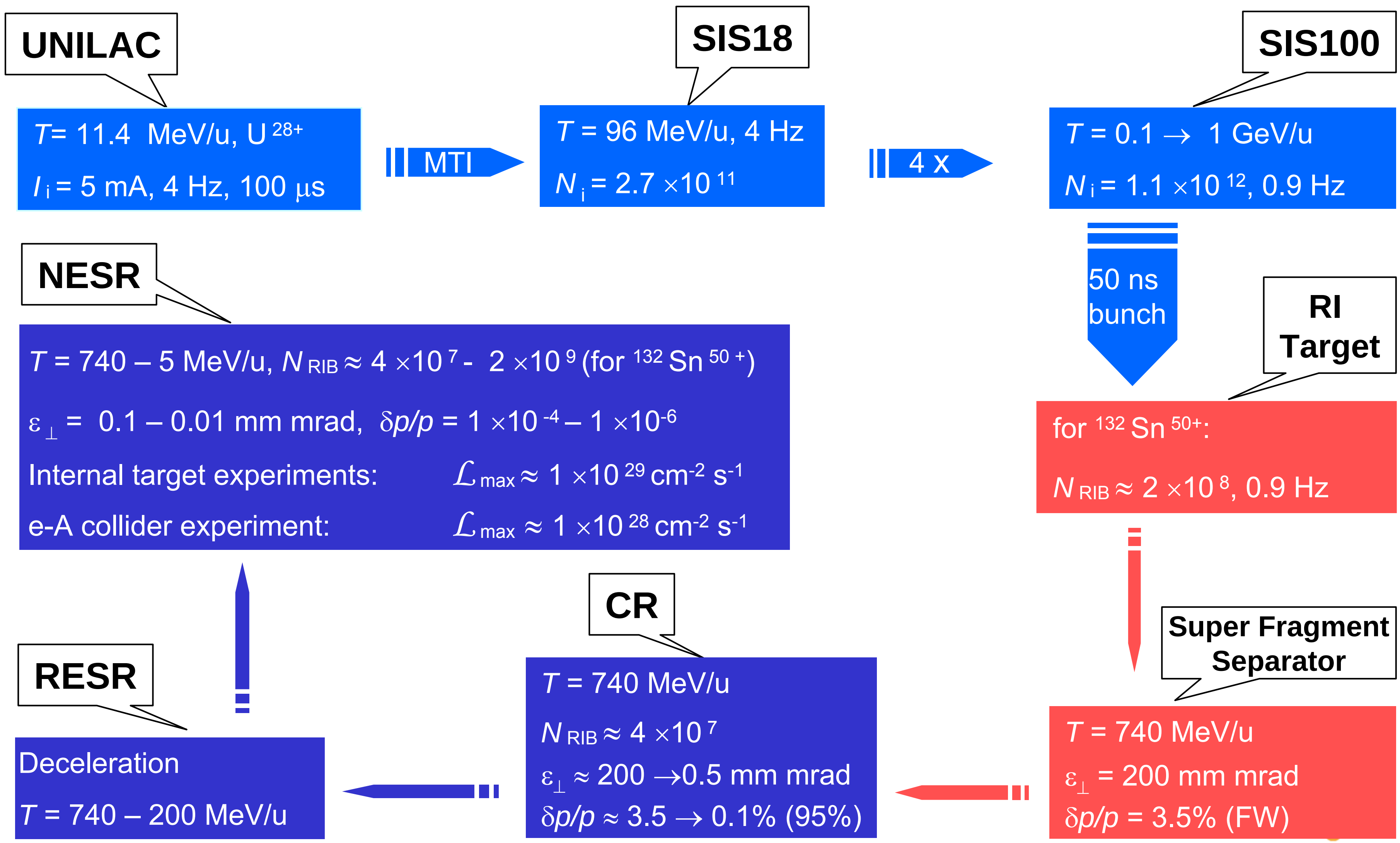
- production, cooling, and accumulation of antiprotons at 3 GeV
- acceleration of antiprotons up to 15 GeV
- highest luminosity ($2 \cdot 10^{32}$ $cm^{-2}s^{-1}$):
  stochastic cooling up to 15 GeV
  electron cooling up to 8 GeV
  H_2 cluster target



5×10^9 J/Y per yr
2.5×10^9 D-pairs per yr

Layout and separation properties




UNILAC
T= 11.4 MeV/u, U^{28+}
I_i = 5 mA, 4 Hz, 100 μs
MTI
SIS18
T = 96 MeV/u, 4 Hz
$N_i = 2.7 \times 10^{11}$
4 x
SIS100
$T = 0.1 \rightarrow$ 1 GeV/u
$N_i = 1.1 \times 10^{12}$, 0.9 Hz
50 ns bunch
RI Target
for $^{132}Sn^{50+}$:
$N_{RIB} \approx 2 \times 10^8$, 0.9 Hz
Super Fragment Separator
T = 740 MeV/u
$\varepsilon_\perp$ = 200 mm mrad
$\delta p/p$ = 3.5% (FW)
CR
T = 740 MeV/u
$N_{RIB} \approx 4 \times 10^7$
$\varepsilon_\perp \approx 200 \rightarrow 0.5$ mm mrad
$\delta p/p \approx 3.5 \rightarrow 0.1\%$ (95%)
RESR
Deceleration
T = 740 – 200 MeV/u
NESR
T = 740 – 5 MeV/u, $N_{RIB} \approx 4 \times 10^7$ - 2×10^9 (for $^{132}Sn^{50+}$)
$\varepsilon_\perp$ = 0.1 – 0.01 mm mrad, $\delta p/p = 1 \times 10^{-4} - 1 \times 10^{-6}$
Internal target experiments: $\mathcal{L}_{max} \approx 1 \times 10^{29}$ cm^{-2} s^{-1}
e-A collider experiment: $\mathcal{L}_{max} \approx 1 \times 10^{28}$ cm^{-2} s^{-1}

Proton linac

T = 50 MeV

I_p = 50 mA, 5 Hz

MTI →

SIS18

T = 2000 MeV, 5 Hz

$N_p = 5 \times 10^{12}$

4 x →

SIS100

$T = 2 \rightarrow 29$ GeV

$N_p = 2 \times 10^{13}$, 0.2 Hz

↓ 25 ns bunch

$\bar{p}$ Target

$N_{pbar} = 1 \times 10^{8}$, 0.2Hz

↓

$\bar{p}$ Separator

T = 3 GeV

$\varepsilon_\perp$ = 240 mm ·mrad

$\delta p/p$ = 6% FW

←

CR

T = 3 GeV

$\varepsilon_\perp \approx 240 \rightarrow 5$ mm mrad

$\delta p/p \approx 6\% \rightarrow 0.2\%$ (95%)

←

RESR

T = 3 GeV

N_{pbar} = up to 1×10^{11}

$T_{accum} \approx 0.25 – 1.5$ h

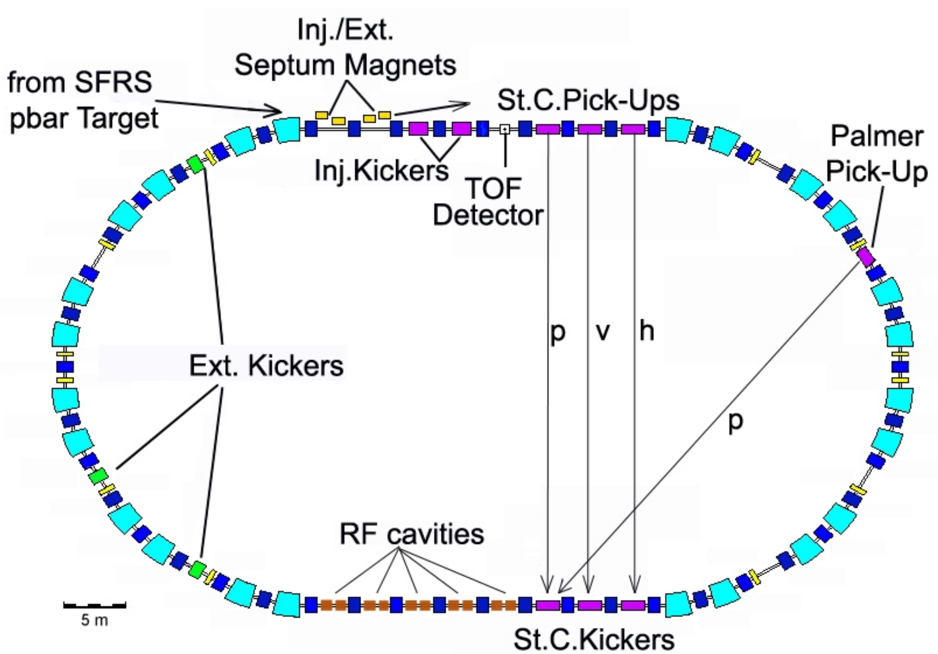
↑ via SIS100

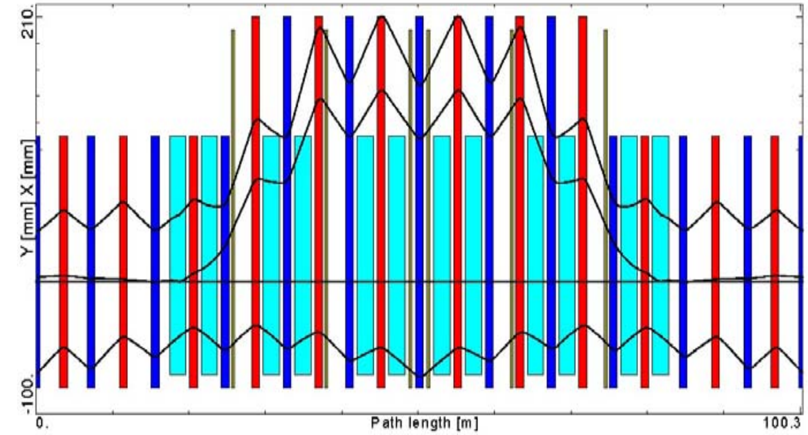
HESR

T = 0.8 – 14.5 GeV

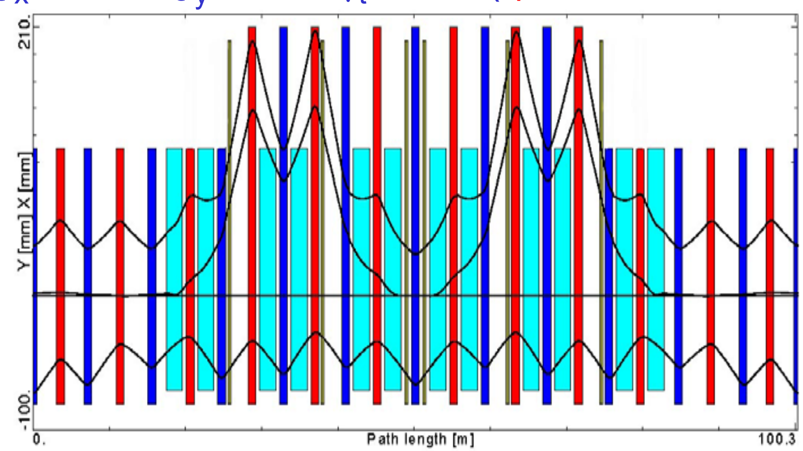
$\varepsilon_\perp$ = 0.1 – 0.01 mm mrad, $\delta p/p = 2 \times 10^{-4} – 1 \times 10^{-5}$

Internal target experiment: $\mathcal{L}_{max} \approx 2 \times 10^{32}$ cm^{-2} s^{-1}





RIB envelopes: $\varepsilon_\perp$=200mm·mrad, $\delta p/p$=±1.75%
Q_x=3.42, Q_y=3.36, γ_t=2.88 ($\eta \approx$ 0.17 at 740 MeV/u)



pbar envelopes: $\varepsilon_\perp$ =240mm·mrad, $\delta p/p$=±3 %
Q_x=4.62, Q_y=4.19, γ_t=4.3 ($\eta \approx$ 0.07 at 3 GeV)

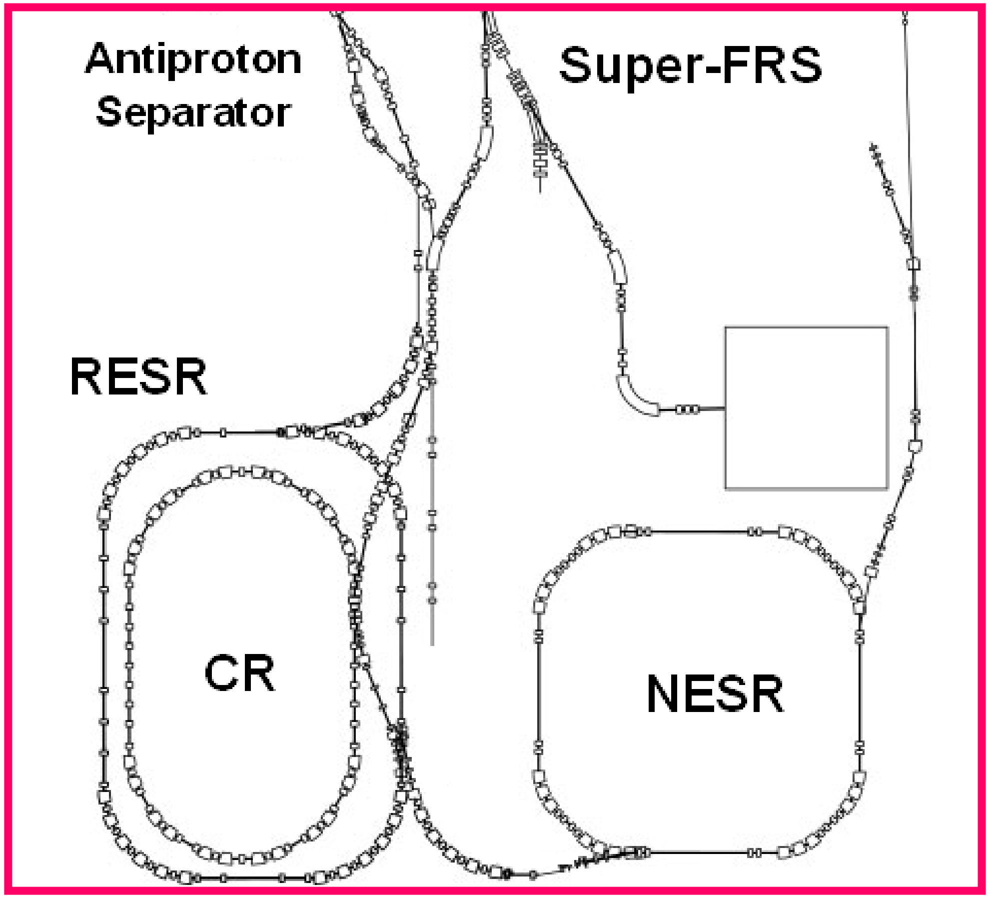
Basic CR Parameters

Circumference	200 m	
Max. $B\times\rho$	13 Tm	
Beams	**RI**	**pbar**
Max. energy	790 MeV/u	3 GeV
Cooling energy	740 MeV/u	3 GeV
Revol. frequency	1.3 MHz	1.5 MHz

See COOL03 Poster by A. Dolinskii et al.

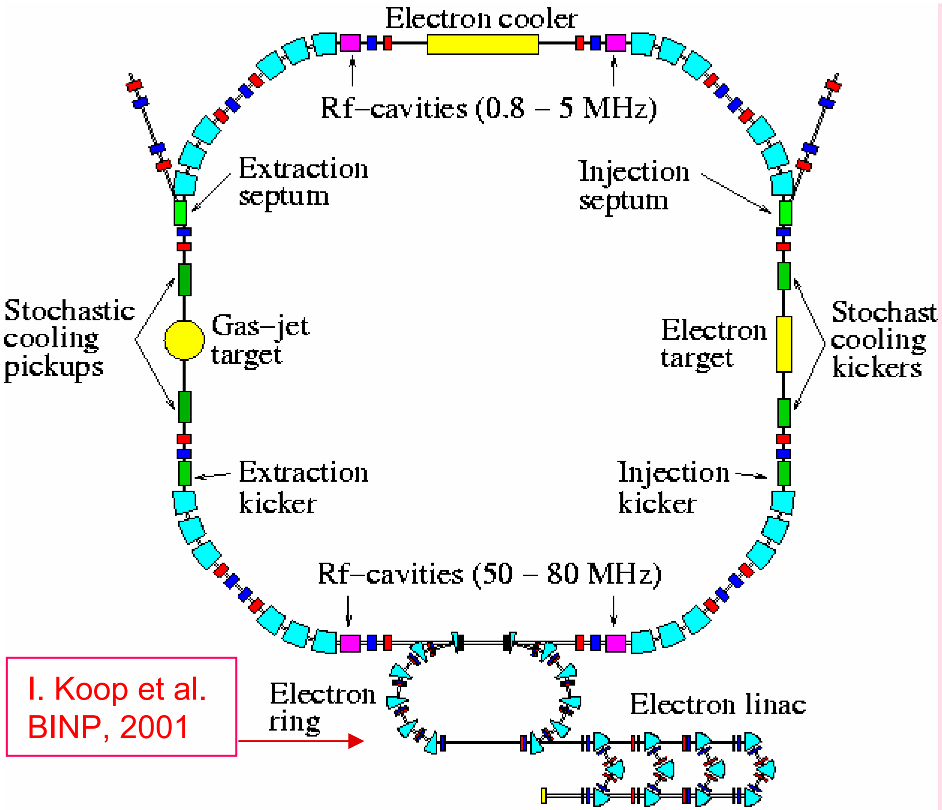
Approach to optimal topology underway

P. Spiller et al.



Requirements

- Injection of RI and pbar beams to CR
- Bunch transfer from CR to RESR
- Bunch transfer from RESR to NESR
- Bunch transfer of pbars to SIS100
- Primary beams to NESR
- Un-cooled RI beams to NESR



I. Koop et al.
BINP, 2001

NESR Cooler Parameters (prelim.)

e^- energy	5-450 keV
e^- current	2 A
e^- temperature	0.1 eV (⊥)
Beam diameter	25 mm
Effective length	4 m

Fast Electron Cooling up to 450 keV

- Find optimal parameters for CR beam for minimized total cooling time.
- Technical design of the cooler with
  high electron density (up to 10^8 cm^{-3}),
  low transverse electron temperature (0.1 eV),
  high longitudinal magnetic field (0.2 T)
  extreme straightness of field ($\Delta B_\perp / B_{||} \leq 5\times10^{-5}$).
- Realization of magnetized cooling for cooling rates of 10 s^{-1} or higher.
- Fast accumulation of RIBs, EC supported.
- EC of decelerated beams (10 MeV/u).
- Improved simulations including
  - electron cooling (EC), intra-beam scattering,
  - internal target effects (heating, dE/dx)
  - rf fields (bunched beam EC),
  - beam-beam effects in e-A-collider mode.

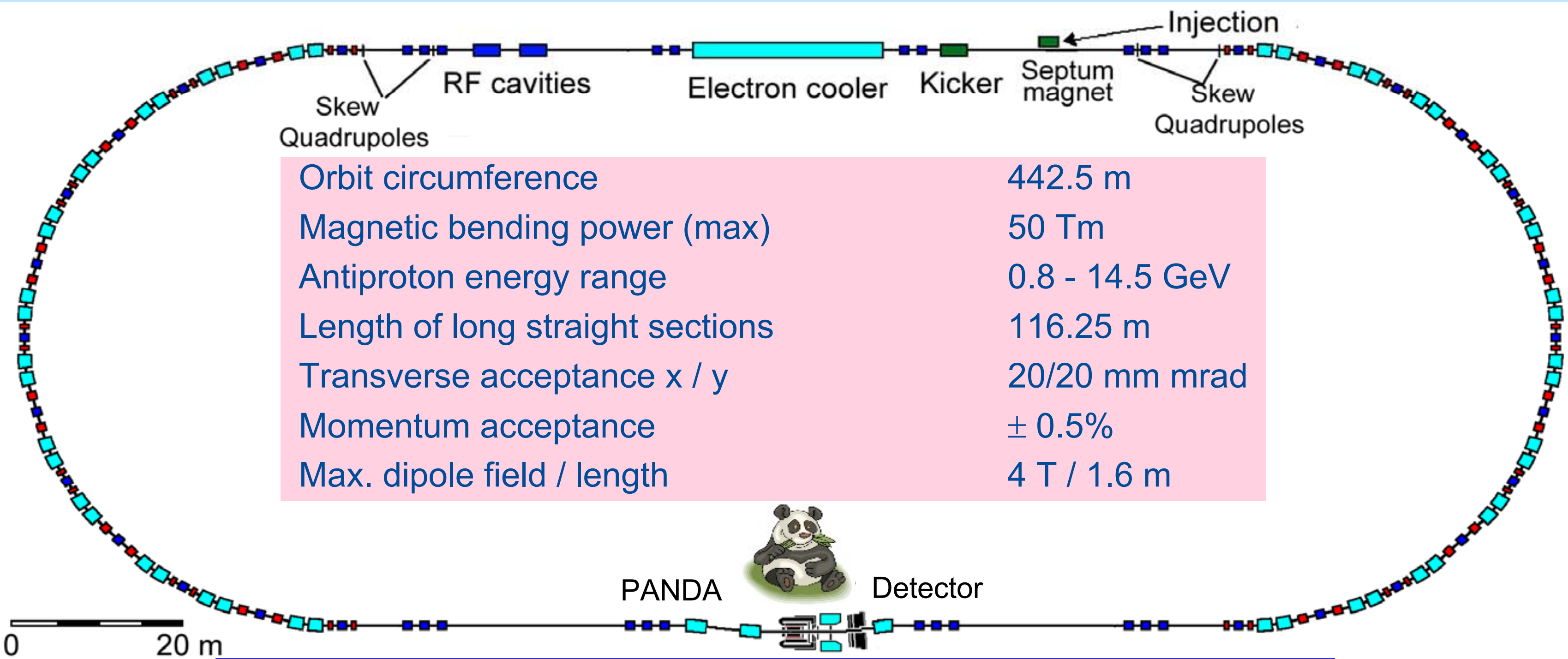
Int. Target: $\mathcal{L}_{max} \approx 1 \times 10^{29}$ cm^{-2} s^{-1}

e-A collider: $\mathcal{L}_{max} \approx 1 \times 10^{28}$ cm^{-2} s^{-1}

$\delta p/p < 1 \times 10^{-4}$, $\varepsilon_\perp < 0.1$ mm mrad

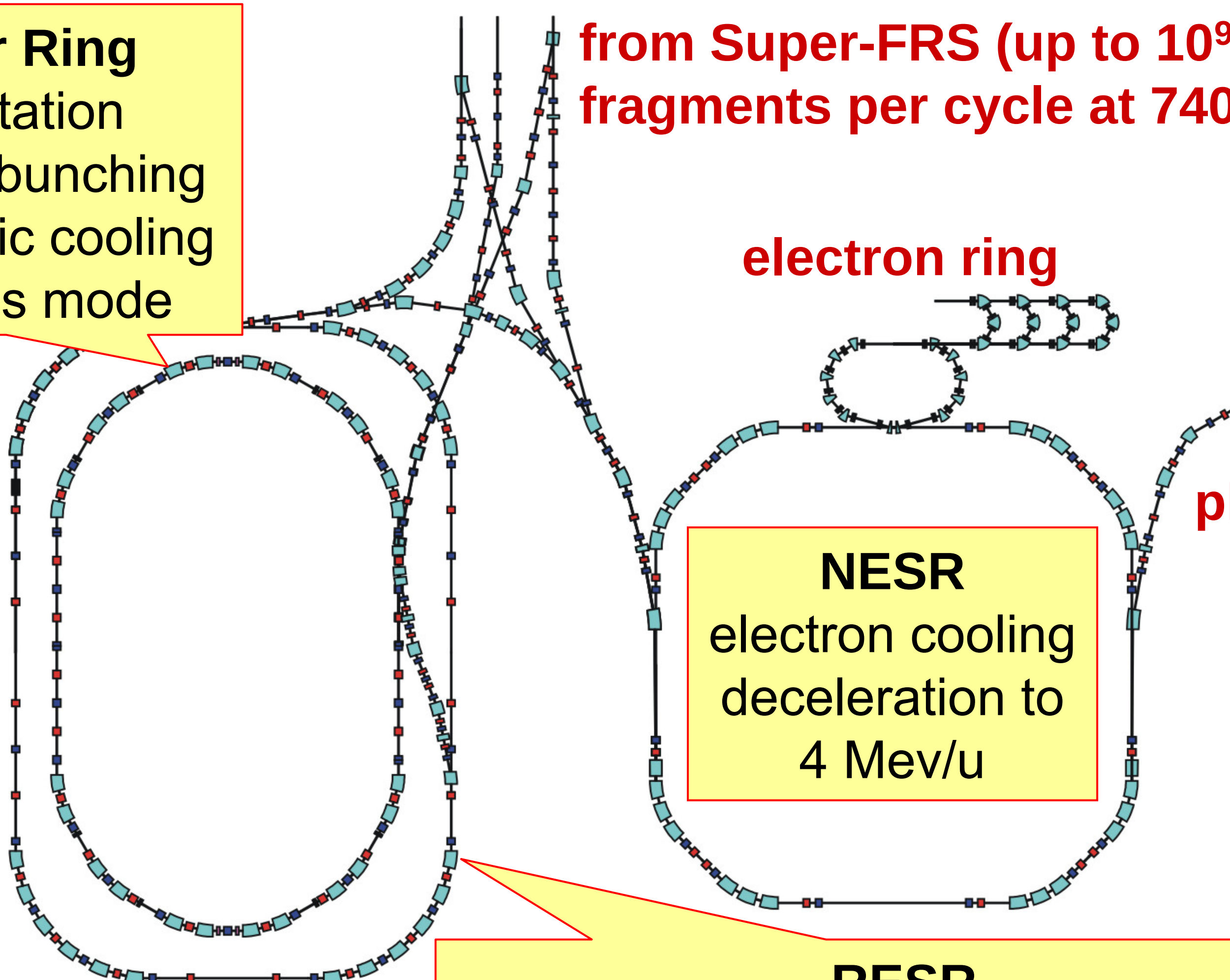
HESR Cooler Parameters (prelim. result of feasibility study by BINP / V. Parkhomchuk et al.)

Electron energy	0.5 -10 MeV	Solenoid field	0.5 T, $\Delta B_{\perp}/B_{\parallel} \leq 1\times10^{-5}$
Electron current	1 A	Electron accelerator	electro-static
Transv. electron temperature	$\leq$ 0.2 eV	Charging method	H^{-}-beam, 1 mA
Beam diameter	3-5 mm	H^{-}-accelerator	10 MeV cyclotron
Effective length	30 m	e^{-} recuperation efficiency	99.99%



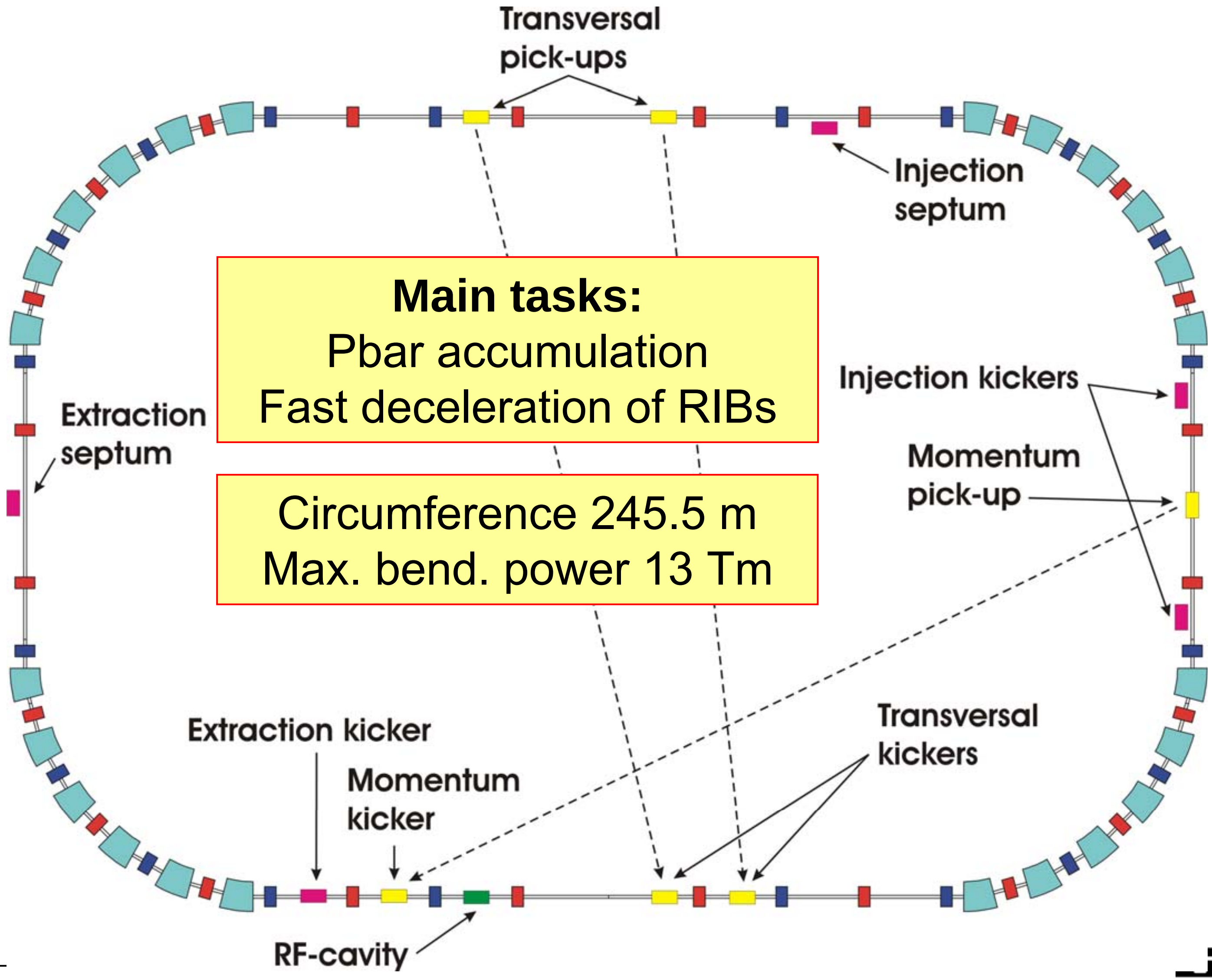
Orbit circumference	442.5 m
Magnetic bending power (max)	50 Tm
Antiproton energy range	0.8 - 14.5 GeV
Length of long straight sections	116.25 m
Transverse acceptance x / y	20/20 mm mrad
Momentum acceptance	$\pm$ 0.5%
Max. dipole field / length	4 T / 1.6 m

Int. Target: $\mathcal{L}_{max} \approx 2 \times 10^{32}$ cm^{-2} s^{-1} $\delta p/p < 1 \times 10^{-4}$, $\varepsilon_{\perp} < 0.1$ mm mrad


Collector Ring
bunch rotation
adiabatic debunching
fast stochastic cooling
isochronous mode
from Super-FRS (up to 10^9 fragments per cycle at 740 MeV/u)
electron ring
to atomic physics cave, HITRAP, FLAIR
NESR
electron cooling
deceleration to 4 Mev/u
RESR
deceleration (1T/s) to 100 - 500 MeV/u

Parameters for RI beams

Reference energy (A/Z=2.7) [MeV/u]	740
Horizontal acceptance [mm mrad]	200
Vertical acceptance [mm mrad]	200
Momentum acceptance	$\pm 1.75 \times 10^{-2}$
Number of fragments per cycle	$< 1 \times 10^{9}$
Cooling time constant (10^7 U^{92+}-ions)	0.1 s
Horizontal emittance after cooling [mm mrad]	0.5
Vertical emittance after cooling [mm mrad]	0.5
Momentum spread after cooling	$\pm 5 \times 10^{-4}$



Main tasks:
Pbar accumulation
Fast deceleration of RIBs

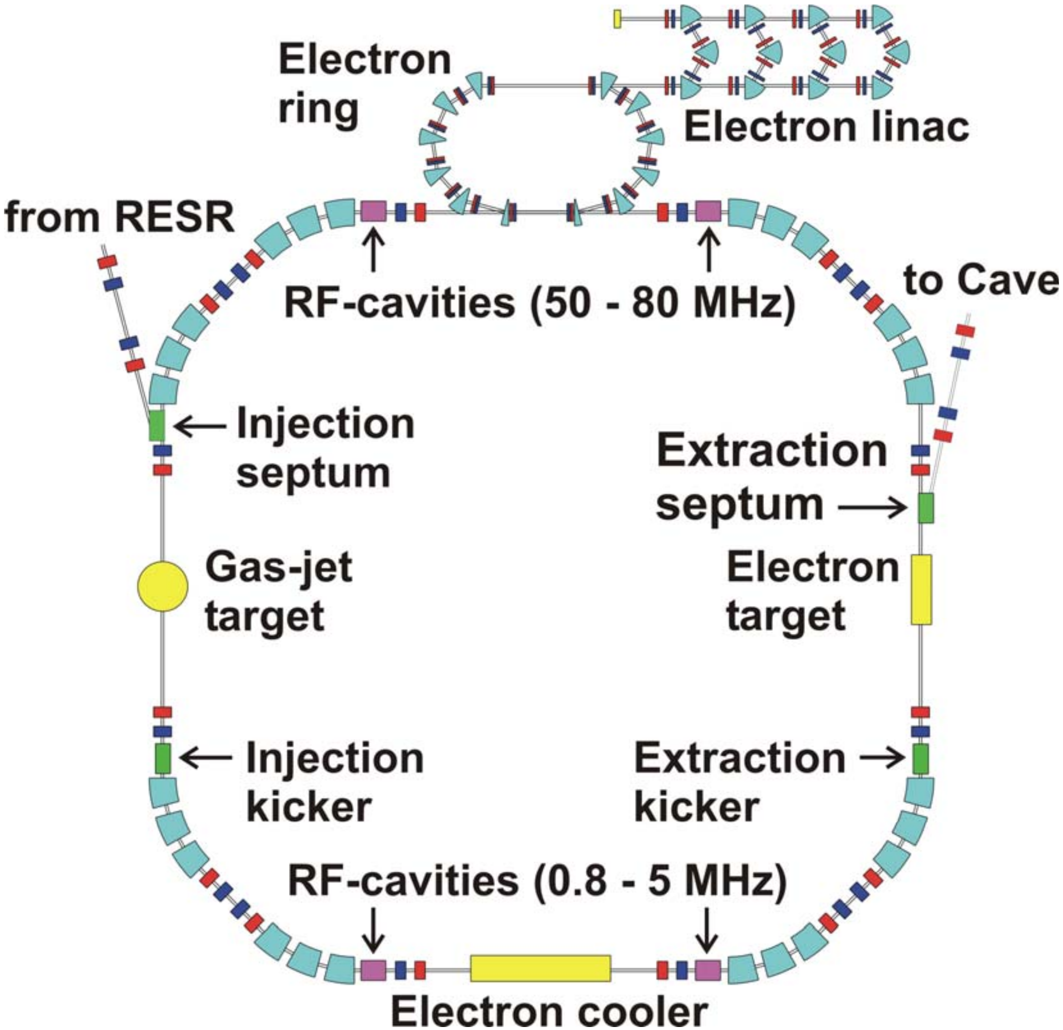
Circumference 245.5 m
Max. bend. power 13 Tm

Ring parameters

Horizontal acceptance [mm mrad]	80
Vertical acceptance [mm mrad]	35
Momentum acceptance [%]	±1
Horizontal tune	3.8
Vertical tune	3.3
Transition energy	3.62

RI Beam parameters

Energy after deceleration (1 T/s) [MeV/u]	100 - 500
Transverse emittance after deceleration [mm mrad]	0.5 - 1.5
Momentum spread after deceleration	$\pm 0.5 - 1.1 \times 10^{-3}$



Circumference 218.75 m
Max. bending power 13 Tm

Tasks

In-ring-experiments at
- **Gas-jet-target**
- **Electron target**
- **Electron ring**

Deceleration to energies > 4 MeV/u

Ring parameters

Horizontal/vertical acceptance [mm mrad]	160/100
Momentum acceptance [%]	±1.75
Horizontal/vertical tune	3.4/3.2
Transition energy	5.74
Maximum dispersion [m]	7.24

RI Beam parameters

Energy range (A/Z=2.7) (Ramp Rate 1 T/s) [MeV/u]	4 - 740
Cooling time constant (for U^{92+}-ions) [s]	0.3 - 0.5
Transverse emittance after cooling [mm mrad]	0.1
Momentum spread after cooling	$\pm 1 \times 10^{-4}$
Luminosity at internal gas target for ^{132}Sn [cm^{-2} s^{-1}]	6×10^{28}

GSI

Outlook

• Electron scattering off radioactive isotopes in a storage ring seems feasible.

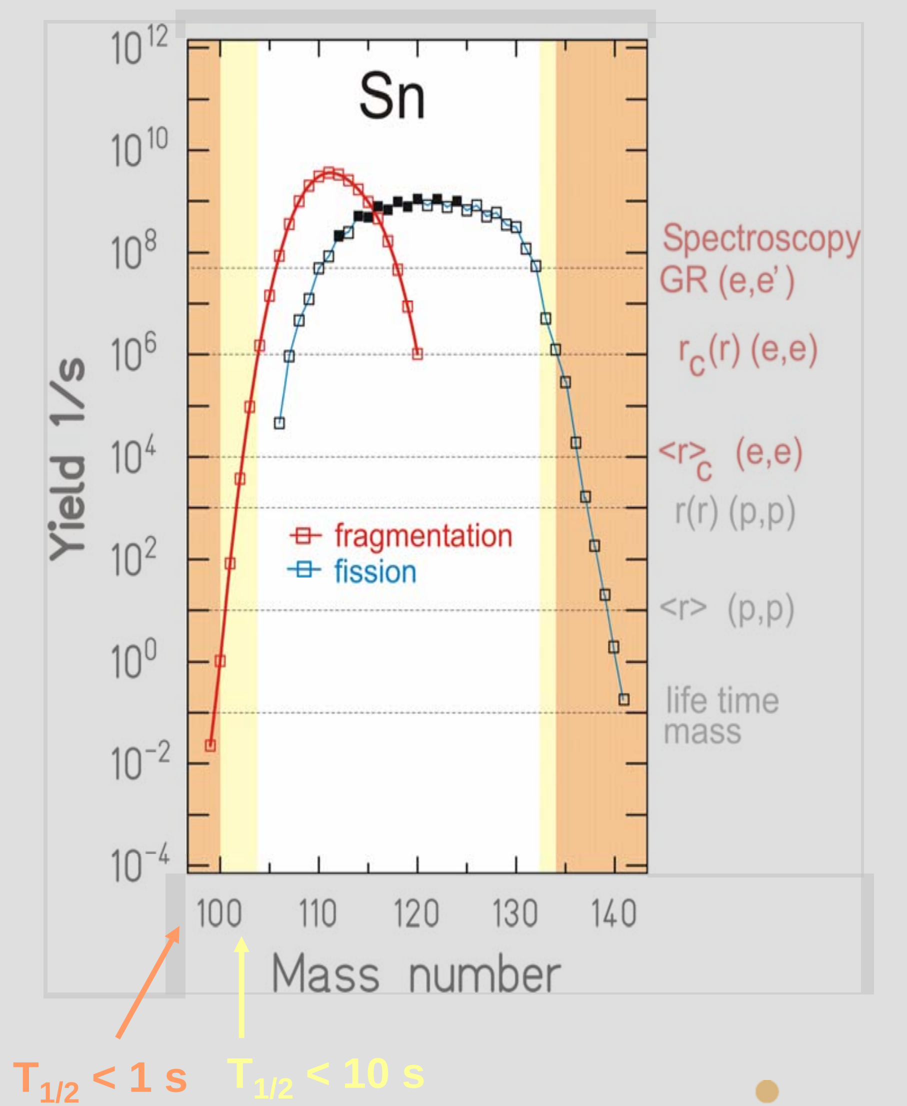
• Charge distributions can be extracted and compared to matter distributions. Charge radii are already accessible in first generation experiments.

• Selective excitation of collective modes in nuclei

• Unique tool

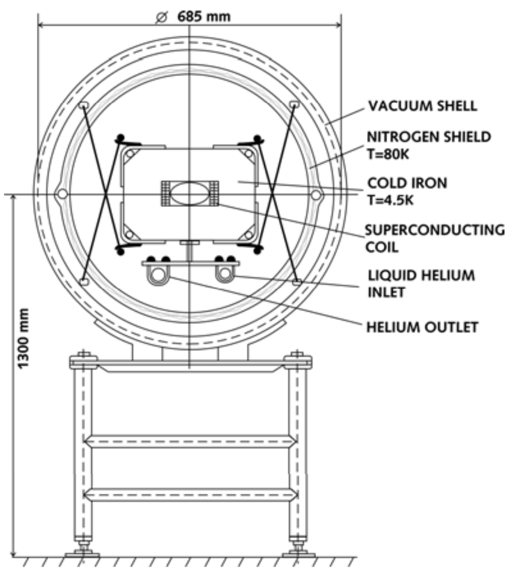
• Other applications ... (PHELIX ...)

→ ***STORIB/ELISE Collaboration***

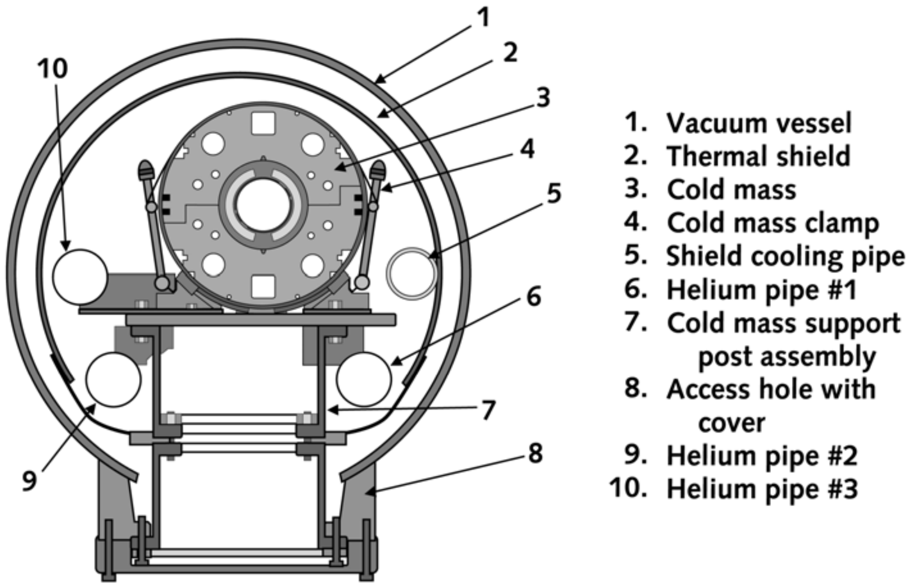


Superconducting Magnets

Nuclotron Dipole



RHIC Arc Dipole



Characteristics:
- 2 Tesla, 4 Tesla/s, limited field quality

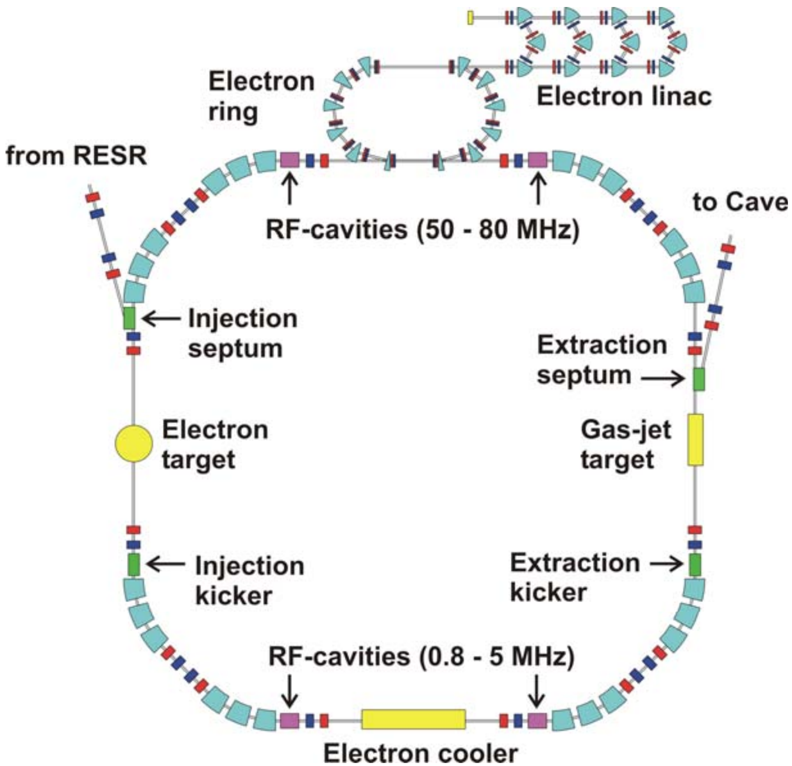
R&D
- Improvement of the field quality
- Reduction of the losses (iron core, vaccum chamber, coil)
- Iron at 80K?

Characteristics:
- 3.5 Tesla, 0,07 Tesla/s, good field quality

R&D
- Reduction of the cable losses (number of strands, increase of interstrand-resitance)
- Reduction of the inductance

NESR

Use for the Deceleration of Antiprotons



circumference	211 m
magnetic bending power	13 Tm
momentum acceptance	±1.8 %
transverse acceptance	$120/100\times10^{-6}$ m
tunes Q_x/Q_y	3.2 / 3.2
length of straight section	18 m

injection at 800 MeV

electron cooling at 800 MeV

deceleration at a maximum ramp rate of 1 T/s

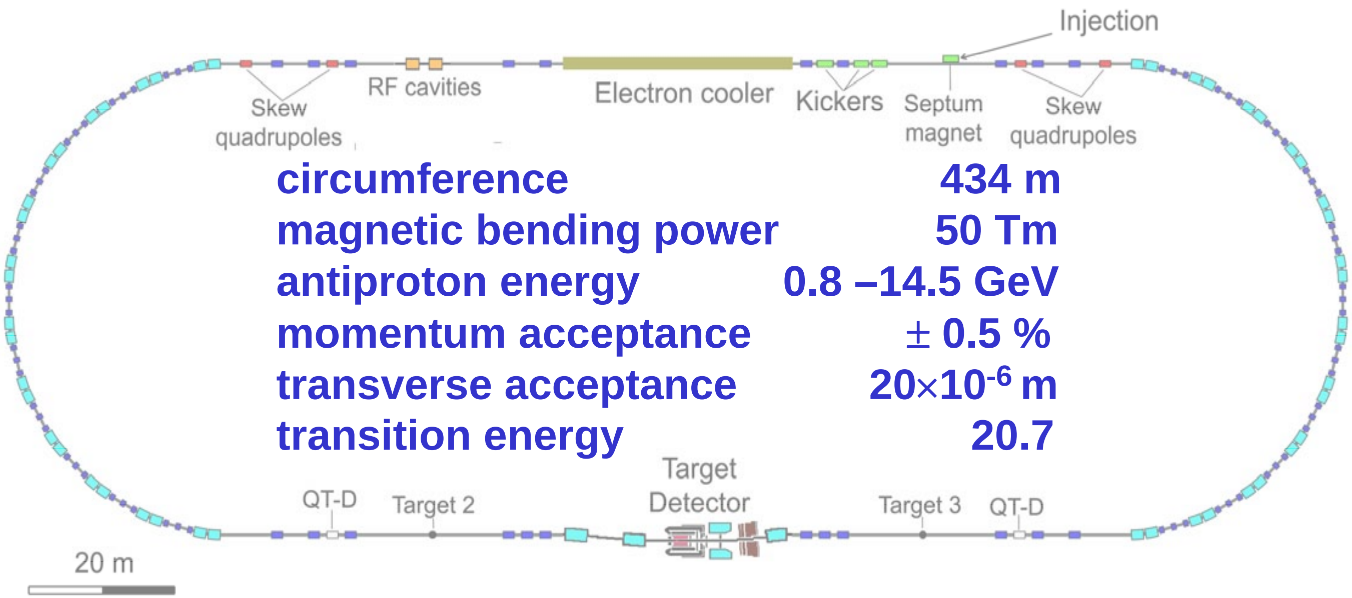
intermediate electron cooling possible (will determine the cycle time)

transfer to low energy storage rings

intensity limited by the lowest energy (space charge limit)

HESR

a storage ring for cooled high energy antiprotons



circumference	434 m
magnetic bending power	50 Tm
antiproton energy	0.8 –14.5 GeV
momentum acceptance	$\pm$ 0.5 %
transverse acceptance	20×10^{-6} m
transition energy	20.7

static operation for highest stability (energy variation from SIS100)

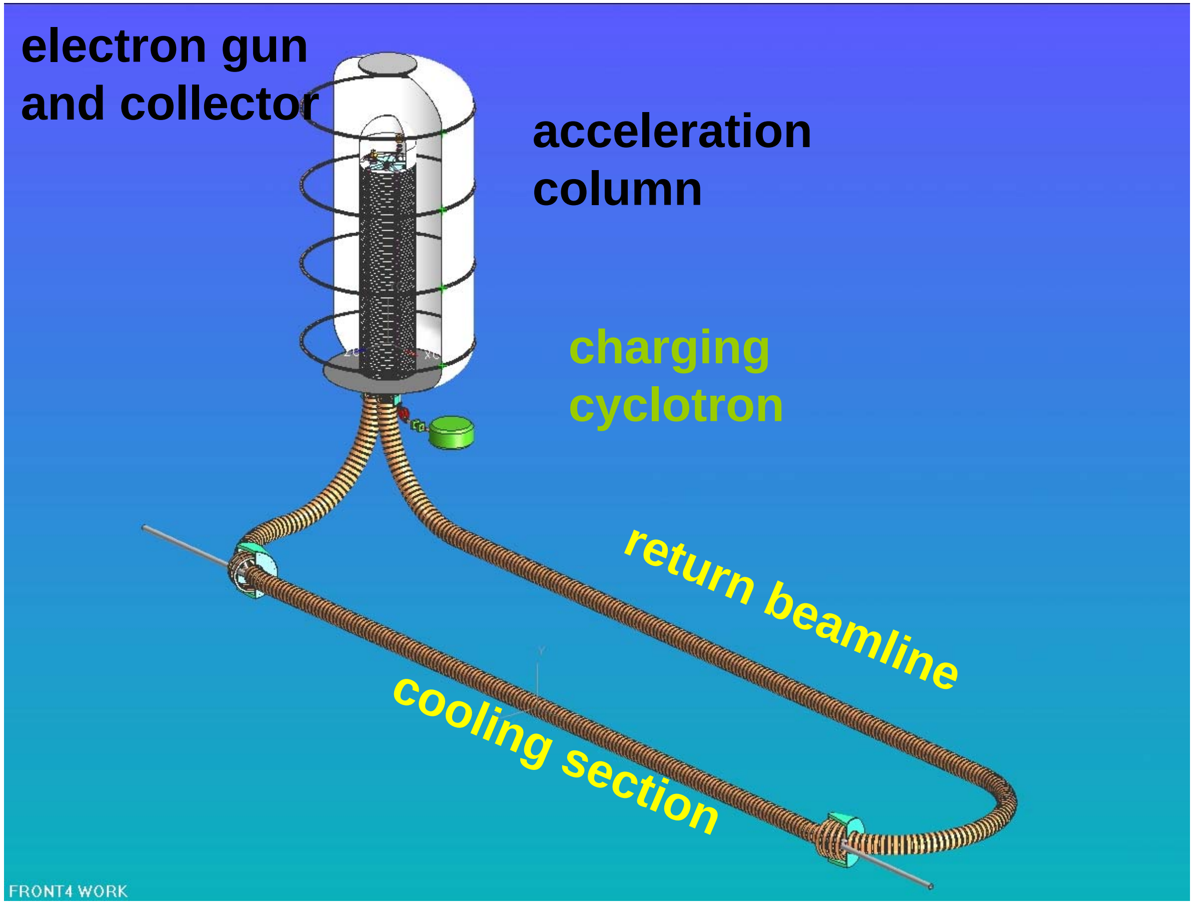
electron cooled antiprotons in the energy range 0.8-14.5 GeV (novel design for powerful cooling)

excellent energy resolution 100 keV with electron cooled antiprotons

internal hydrogen target (pellet, cluster) with density up to 5×10^{15} cm^{-2}

maximum luminosity 2×10^{32} cm^{-2}s^{-1} (consuming all produced antiprotons)

strong magnetized cooling provides highest cooling rates



energy 0.4 - 8 MeV
current up to 2 A

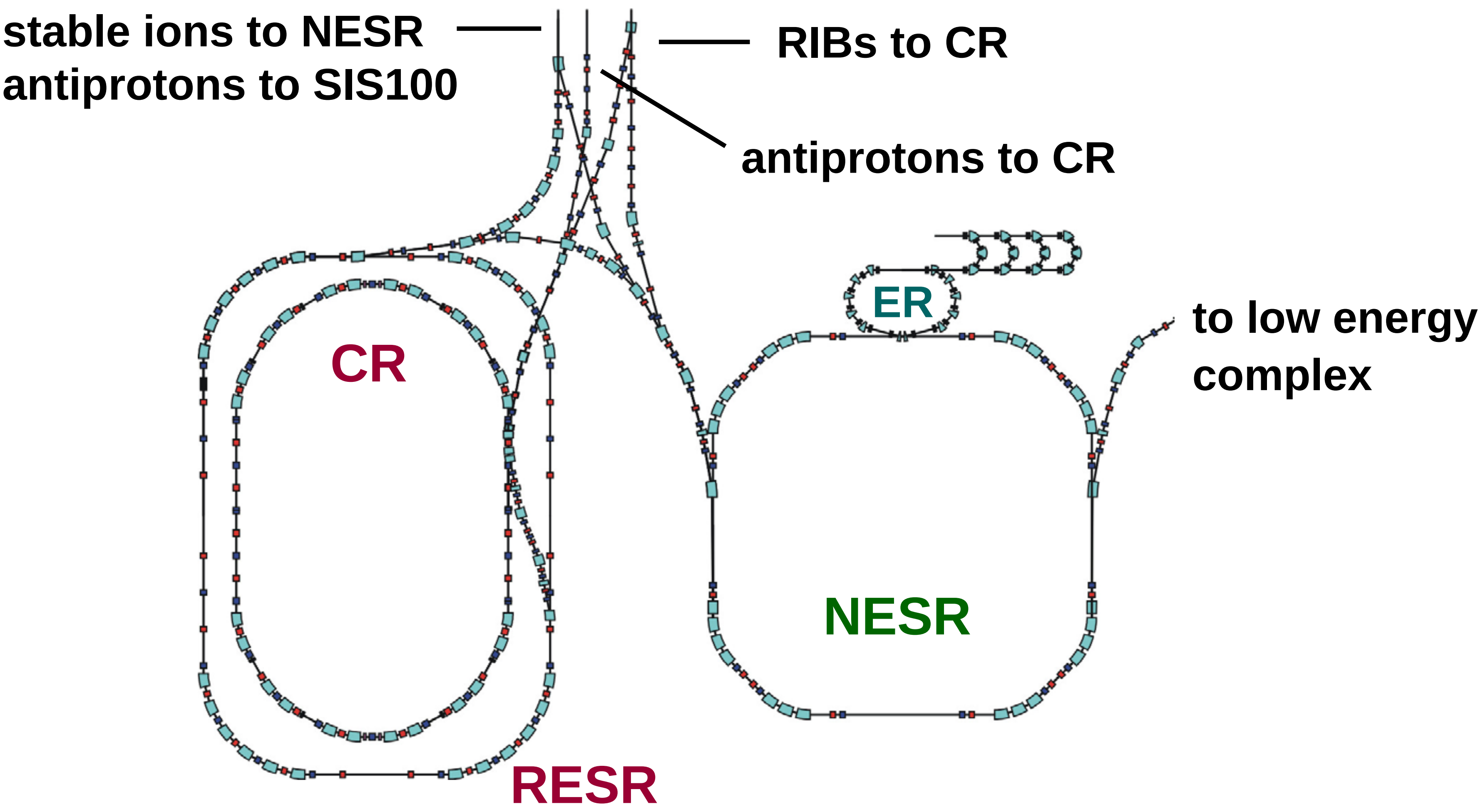
magnetic field 0.2-0.5 T (superconduct. solenoids) in cooling section 30 m

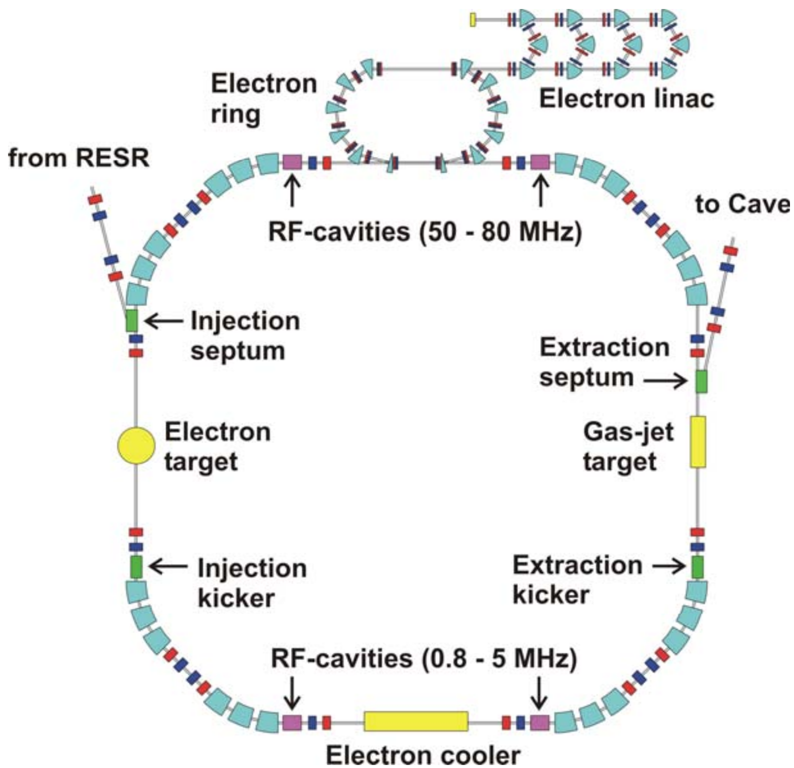
electrostatic accelerator charged by H^--beam

bending by electrostatic fields for highest recuperation efficiency

design study by BINP, Novosibirsk

The New Storage Rings Complex
and the Beam Transport Lines





circumference	211 m
magnetic bending power	13 Tm
momentum acceptance	±1.8 %
transverse acceptance	$120/100 \times 10^{-6}$ m
tunes Q_x/Q_y	3.2 / 3.2
length of straight section	18 m

Ions

storage and cooling of ion beams in the energy range 740 → 4 MeV/u

maximum deceleration rate 1 T/s

electron-nucleus collisions

luminosity up to 10^{28} cm^{-2}s^{-1}

experiments with internal target

target thickness up to 10^{14} cm^{-2}

*⇒ with N = 10^8: **luminosity 10^{28}cm^{-2}s^{-1}***

electron cooling over full energy range (fast cooling, goal: cooling time ≤ 0.1 s)

RIB accumulation by electron cooling

electron target

new: Antiprotons

deceleration from 800 → 30 MeV

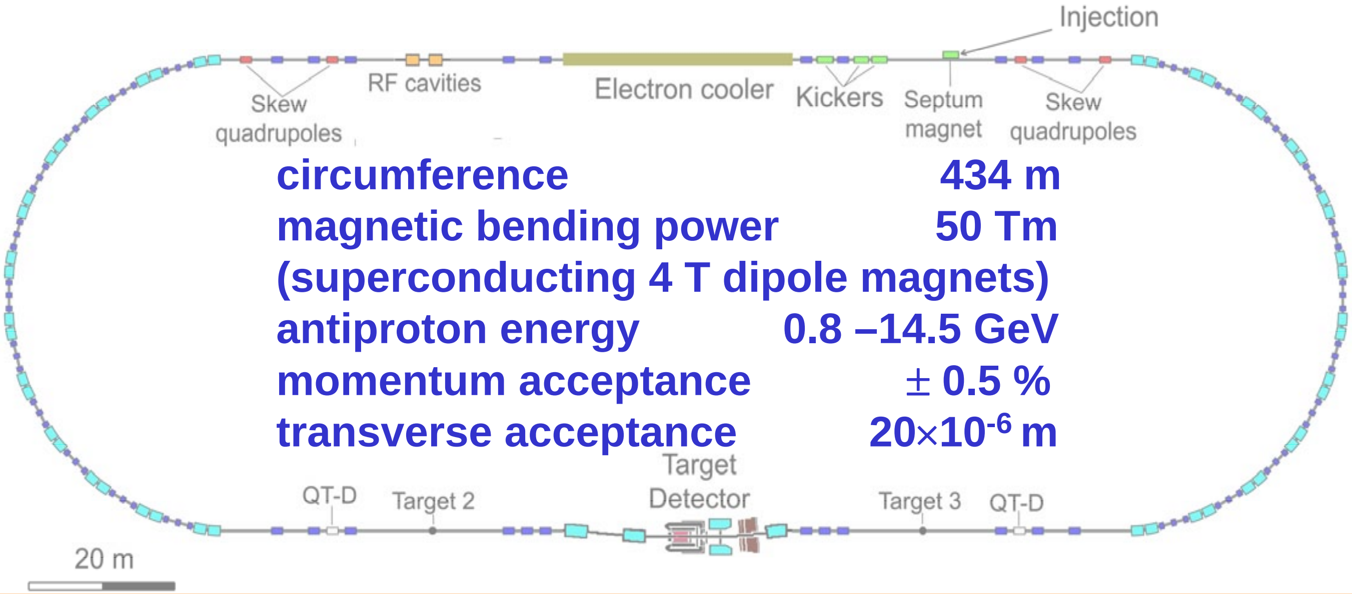
	Electron ring	Ion ring
energy	200 – 500 MeV	100 – 740 MeV/u
circumference	45 m	211 m
number of bunches	6 - 8	40 – 60
particles per bunch	5×10^{10}	$\leq 2 \times 10^{7}$
beam emittance	5×10^{-7} m	5×10^{-7} m
momentum spread	4.0×10^{-4}	3.6×10^{-4}
bunch length	0.04 m	0.15 m
in the interaction point:		
beta functions	1.0 / 0.15 m	
beam radius	0.22 / 0.09 mm	
beam divergence	0.22 / 0.58 mrad	

Luminosity up to a few 10^{28} $cm^{-2}s^{-1}$

study by BINP, Novosibirsk

HESR

Storage Ring for Cooled High Energy Antiprotons



circumference	**434 m**
magnetic bending power	**50 Tm**
(superconducting 4 T dipole magnets)	
antiproton energy	**0.8 –14.5 GeV**
momentum acceptance	**± 0.5 %**
transverse acceptance	**20×10^{-6} m**

static operation for highest stability (energy variation from SIS100)

electron cooled antiprotons in the energy range 0.8-14.5 GeV (novel design for powerful cooling)

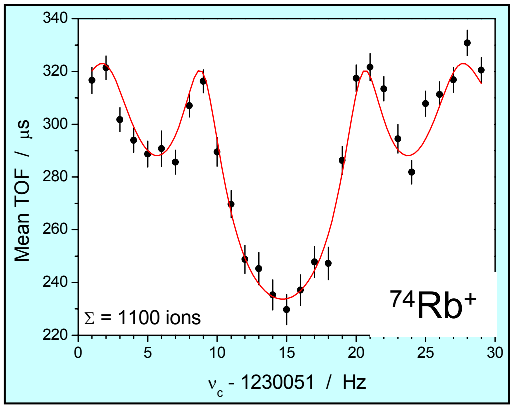
excellent energy resolution 100 keV with electron cooled antiprotons

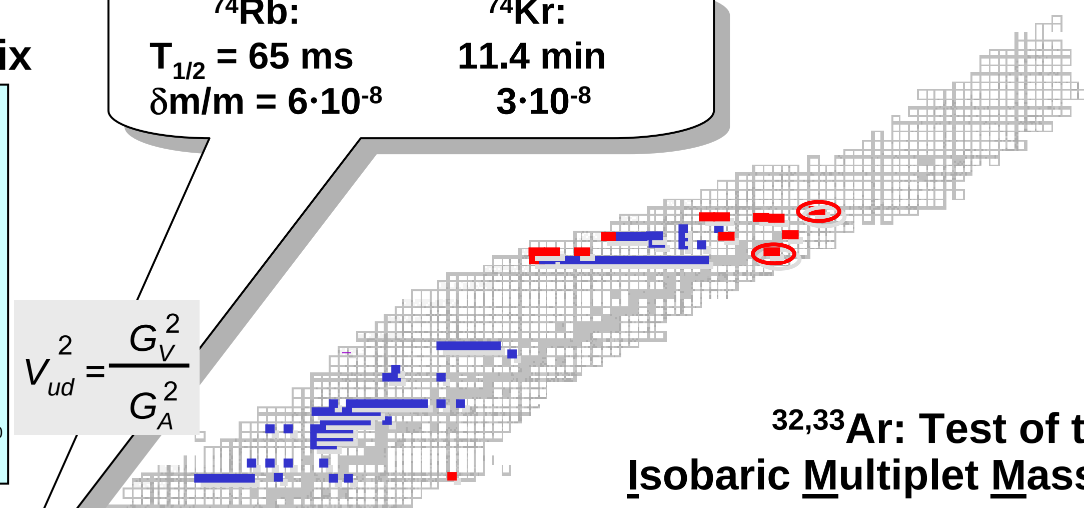
internal hydrogen target (pellet, cluster) with density up to 5×10^{15} cm^{-2}

maximum luminosity 2×10^{32} cm^{-2}s^{-1} (consuming all produced antiprotons)

Symmetry Tests by High-Accuracy Mass Measurements

^{74}Rb, ^{74}Kr: Test of the Unitarity of the CKM matrix



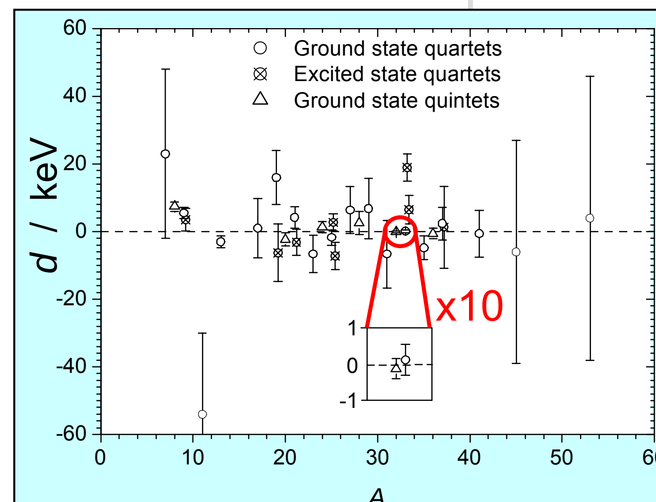


^{74}Rb:	^{74}Kr:
$T_{1/2}$ = 65 ms	11.4 min
$\delta m/m = 6\cdot10^{-8}$	$3\cdot10^{-8}$

$$V_{ud}^2 = \frac{G_V^2}{G_A^2}$$

^{32}Ar:	^{33}Ar:
$T_{1/2}$ = 98 ms	173 ms
$\delta m/m = 5\cdot10^{-8}$	$1\cdot10^{-8}$

^{32,33}Ar: Test of the Isobaric Multiplet Mass Equation



^{32}Ar: Test of scalar contribution to weak interaction

Adelberger et al. 1999:

$a = 0.9989 \pm 0.0052(\text{stat}) \pm 0.0039(\text{syst})$

ISOLTRAP 2003:

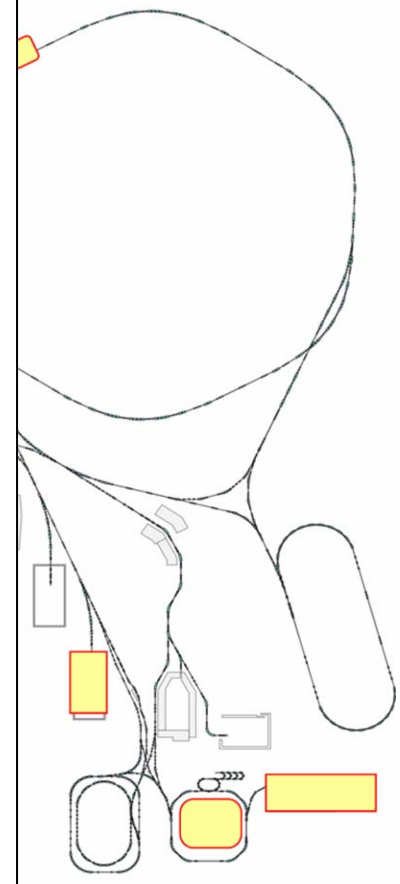
$a = 1.0050 \pm 0.0052(\text{stat}) \pm (\text{syst})$

K. Blaum *et al.*, Phys. Rev. Lett. 91, 260801 (2003)

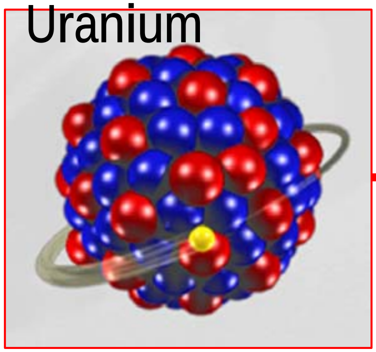
Opportunities and Challenges for Atomic Physics at the Future GSI Facility

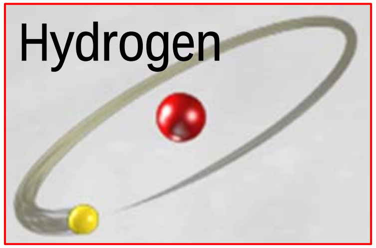
- Stored and Cooled
- - Highly-Charged Ions
- - Exotic Nuclei
- - Antiprotons

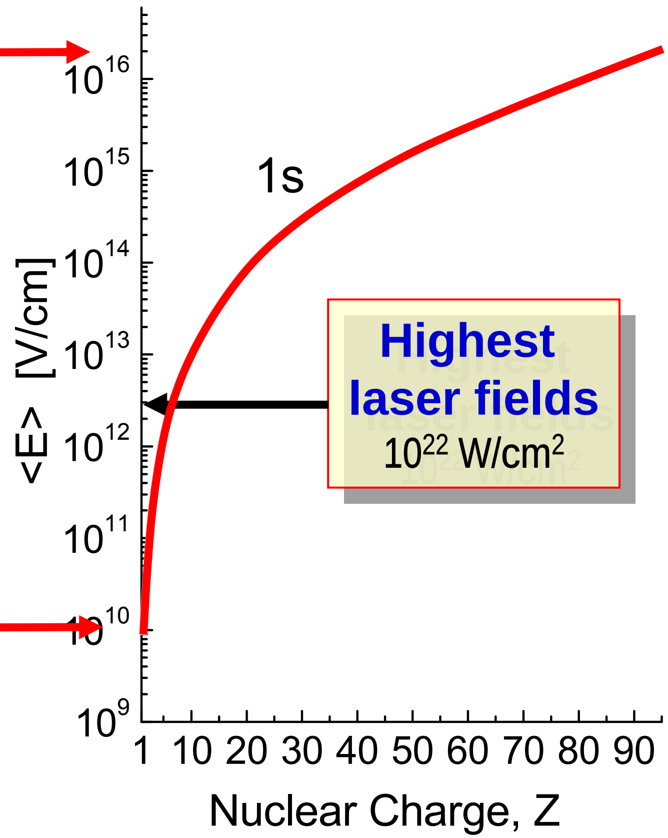
- Fundamental Interactions in
- - Extreme Static Electromagnetic Fields
- - Extreme Dynamic Fields
- Fundamental Tests: Symmetries etc.
- Fundamental Constants
- Nuclear Ground-State Properties



Test of QED in Extreme Electromagnetic Fields







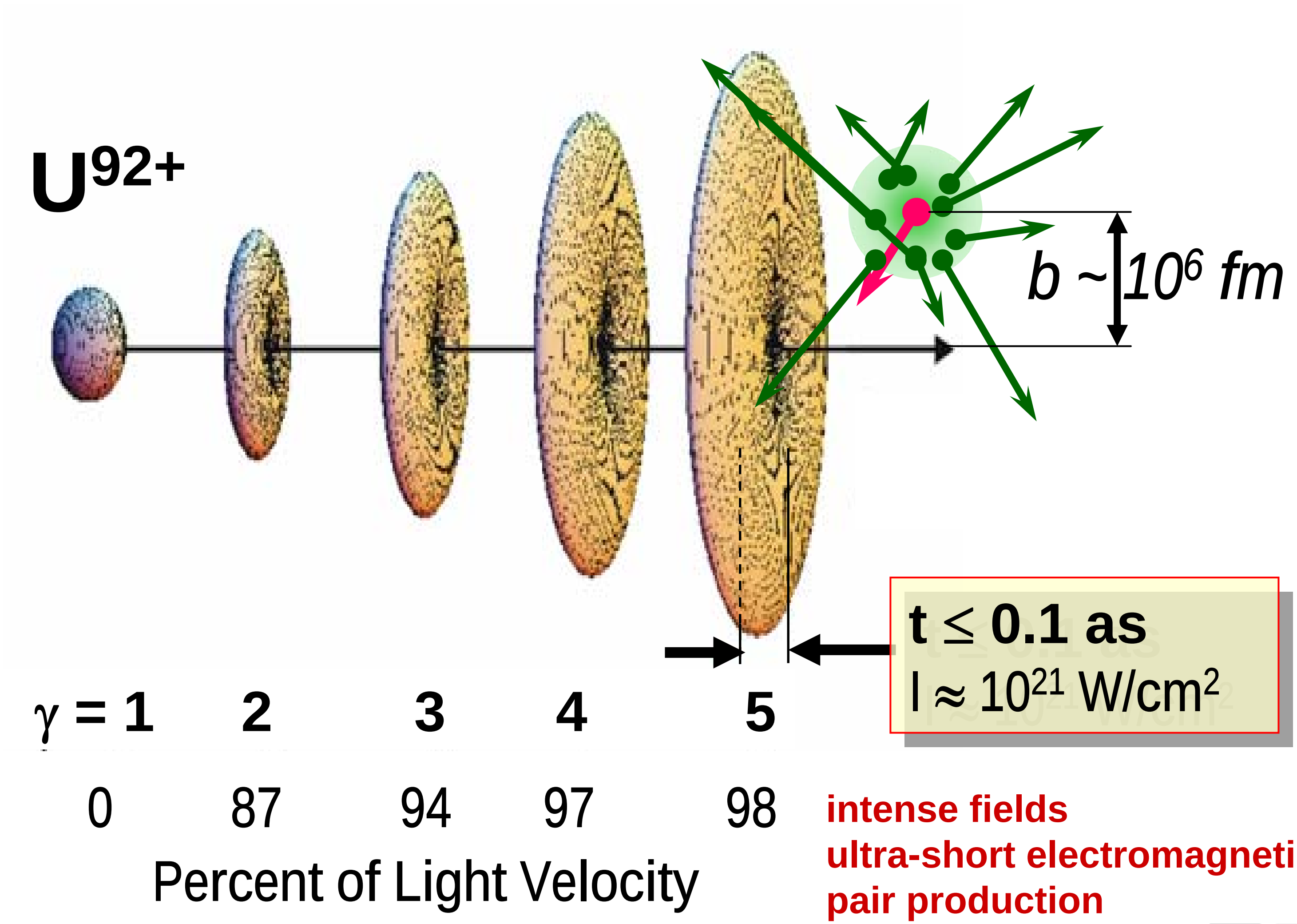
Highest laser fields
10^{22} W/cm^2

H-like Uranium
$\langle E \rangle = 1.8\times10^{16}$ V/cm
$E_K = -132\times10^3$ eV
$\Delta E_{Lamb} \approx 500$ eV
$Z\cdot\alpha \approx 1$

Quantum
Electro-
Dynamics

Hydrogen
$\langle E \rangle = 1\times10^{10}$ V/cm
Ek = -13.6 eV
$\Delta E_{Lamb} \approx 10^{-5}$ eV
$Z\cdot\alpha \approx 10^{-2}$

Reactions of Relativistic Projectiles



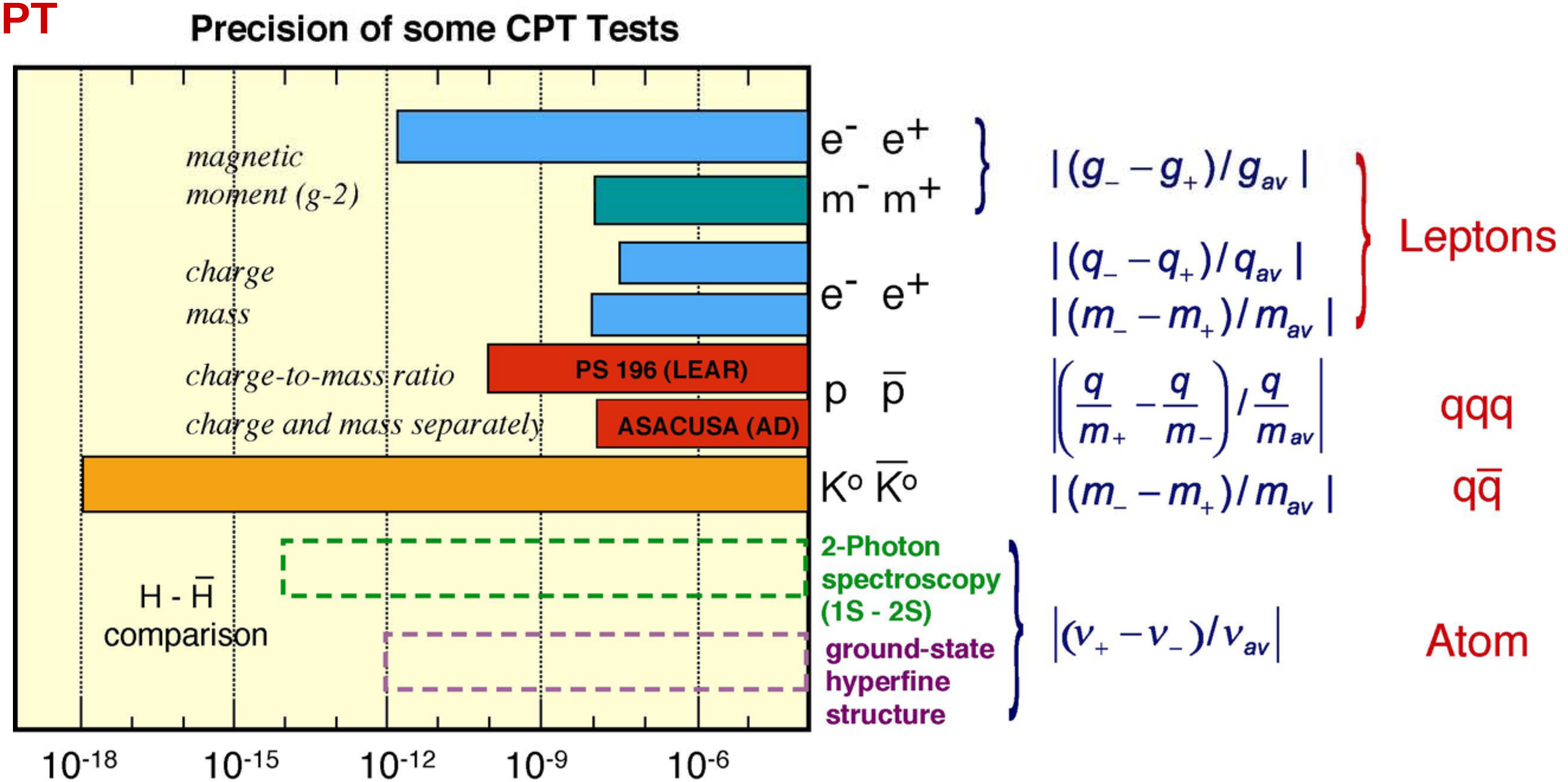
t ≤ 0.1 as

I ≈ 10^{21} W/cm^2

intense fields
ultra-short electromagnetic pulses
pair production

Fundamental Tests

CPT

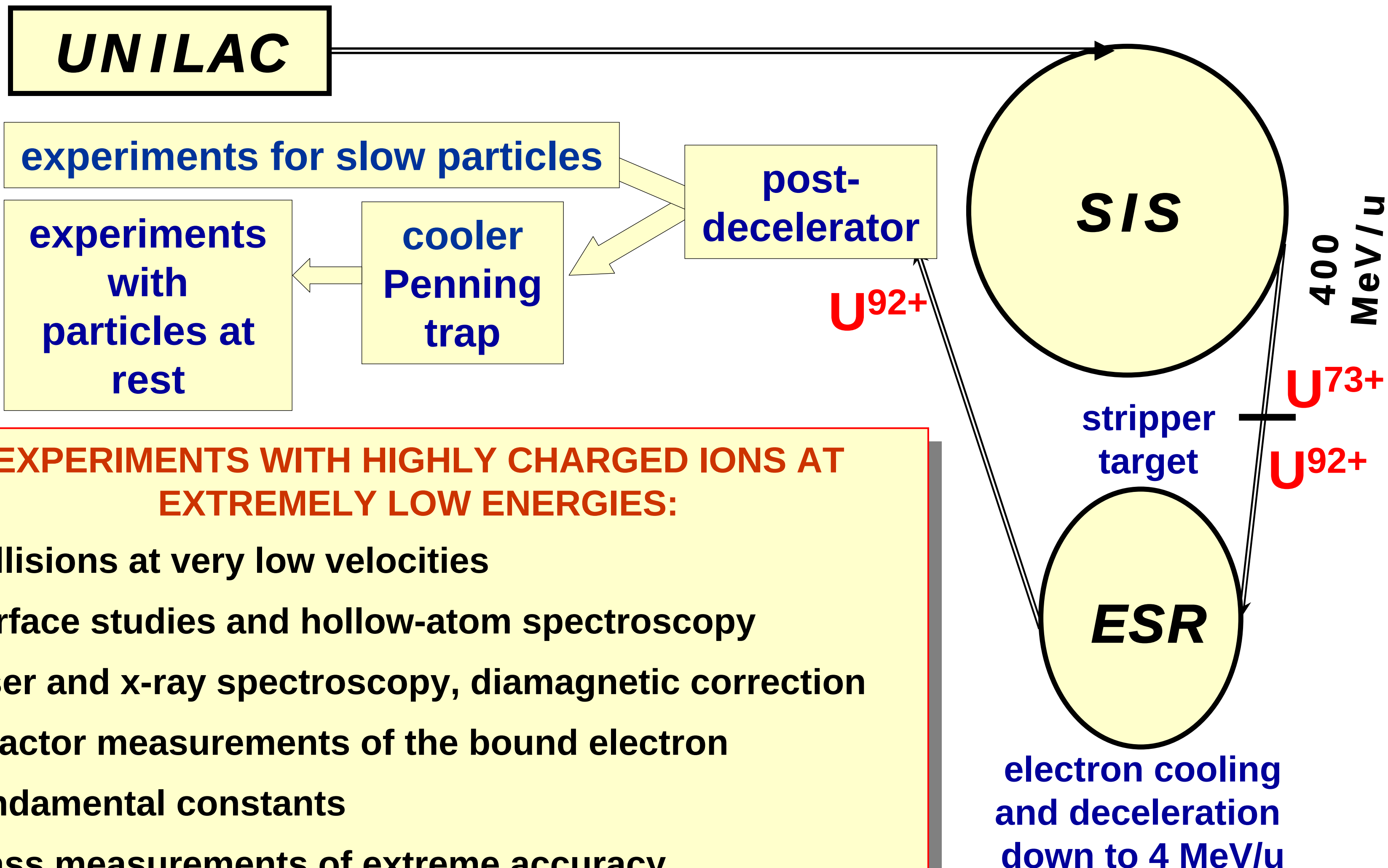


…… gravity of antimatter, parity, unitarity of CKM matrix, CVC hypothesis, validity of IMME, scalar contribution to weak interaction ….

Nuclear Ground-State Properties by Atomic-Physics Techniques

*	MASS	nuclear binding energy
*	NUCLEAR HALF-LIFE	by non-nuclear techniques
*	HYPERFINE STRUCTURE	
	1. Hyperfine Interaction	
	$J + I = F$	nuclear spin
	2. Magnetic Dipole HFS	
	$A = \mu_I \langle H(0) \rangle / I\,J$	nuclear magnetic moment
	3. Electric Quadrupole HFS	
	$B = e_0\, Q_s \langle \varphi_{zz}(0) \rangle$	spectroscopic quadrupole moment
*	ISOTOPE SHIFT	
	Finite Size Effect	
	$\delta \langle r^2 \rangle^{A,A'}$	change of ms charge radius

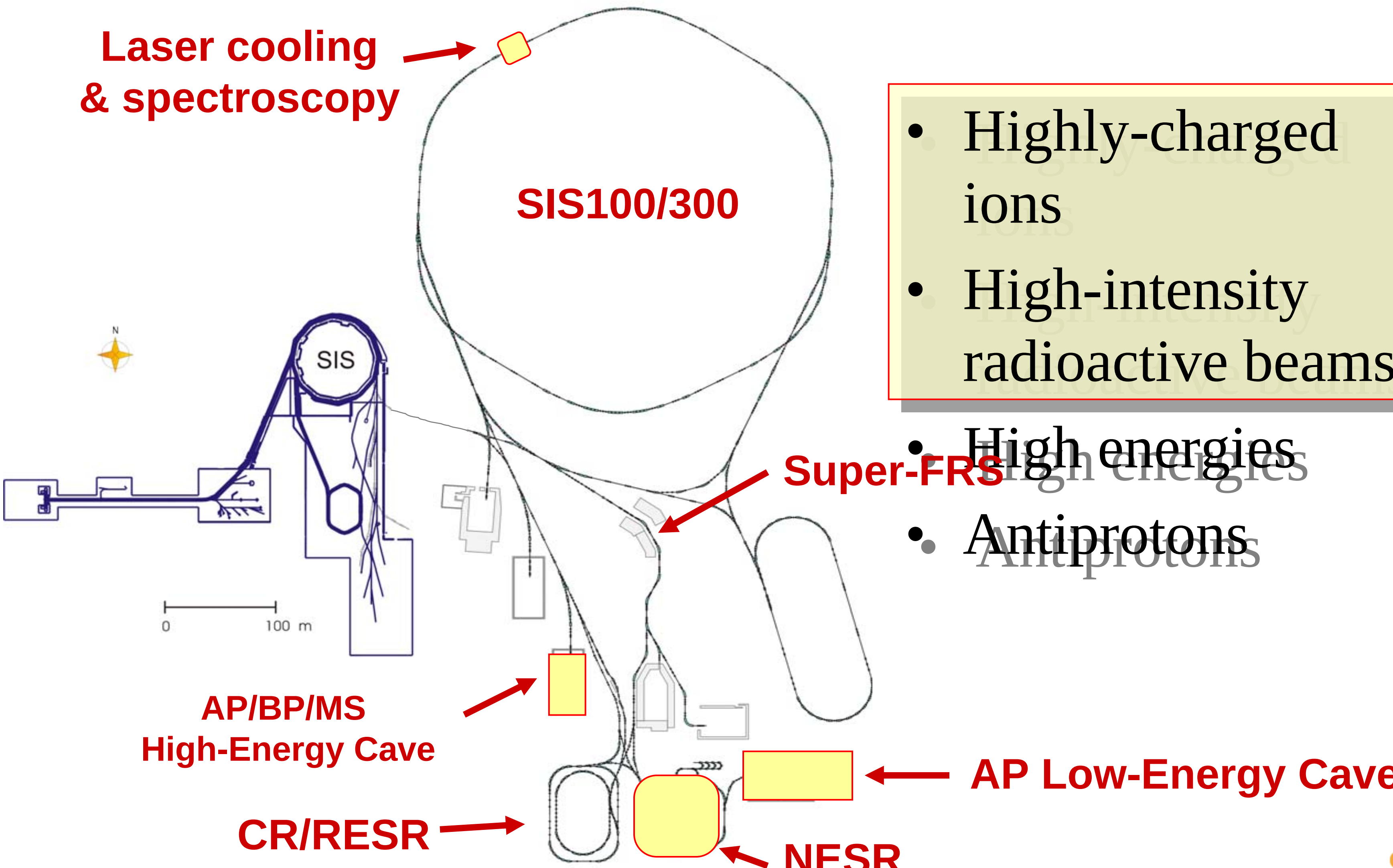
The HITRAP Project for Highly-Charged ions



EXPERIMENTS WITH HIGHLY CHARGED IONS AT EXTREMELY LOW ENERGIES:

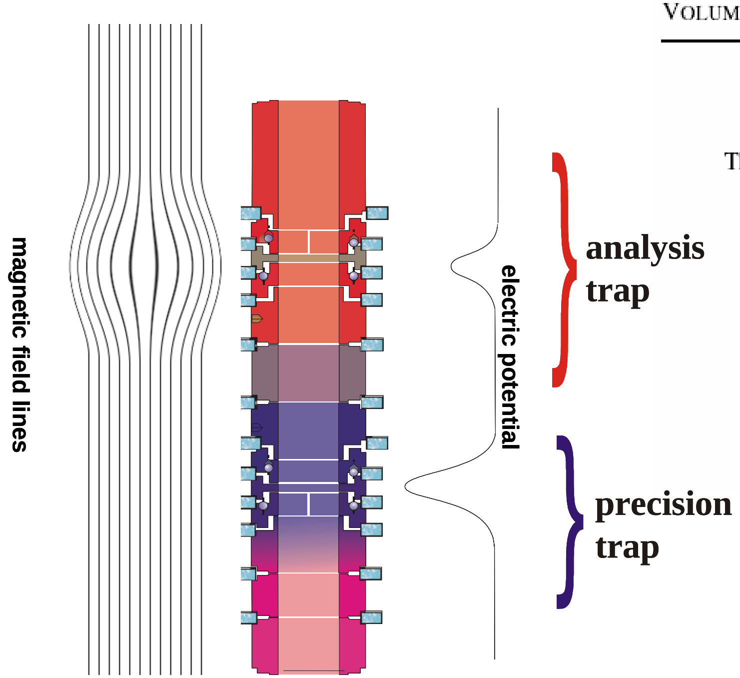
- collisions at very low velocities
- surface studies and hollow-atom spectroscopy
- laser and x-ray spectroscopy, diamagnetic correction
- g-factor measurements of the bound electron
- fundamental constants
- mass measurements of extreme accuracy

The Future GSI Heavy-Ion and Antiproton Accelerator Facility for Atomic Physics



- Highly-charged ions
- High-intensity radioactive beams
- High energies
- Antiprotons

HITRAP - Fundamental Constants: Mass of the Electron



single hydrogen-like ion in a Penning trap: measurement of the cyclotron and Lamor frequency

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

New Determination of the Electron's Mass

Thomas Beier,[1] Hartmut Häffner,[1,2] Nikolaus Hermanspahn,[2] Savely G. Karshenboim,[3,4] H.-Jürgen Kluge,[1] Wolfgang Quint,[1] Stefan Stahl,[2] José Verdú,[1,2] and Günther Werth[2]

[1]*Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany*
[2]*Institut für Physik, Universität Mainz, 55099 Mainz, Germany*
[3]*D.I. Mendeleev Institute for Metrology (VNIIM), 198005 St. Petersburg, Russia*
[4]*Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*

(Received 29 August 2001; published 19 December 2001)

A new independent value for the electron's mass in units of the atomic mass unit is presented, $m_e = 0.000\,548\,579\,909\,2(4)$ u. The value is obtained from our recent measurement of the g factor of the electron in $^{12}C^{5+}$ in combination with the most recent quantum electrodynamical (QED) predictions. In the QED corrections, terms of order α^2 were included by a perturbation expansion in $Z\alpha$. Our total precision is three times better than that of the accepted value for the electron's mass.

theoretical value:	**2.001 041 589 9(9)**
experimental value:	**2.001 041 596 4(10) {44}**
QED correct ⇒	**m_e = 0.000548 579 909 2(4) u**
van Dyck (1995)	**m_e = 0.000548 579 911 1(12) u**
CODATA (1998)	**m_e = 0.000548 579 911 0(12) u**

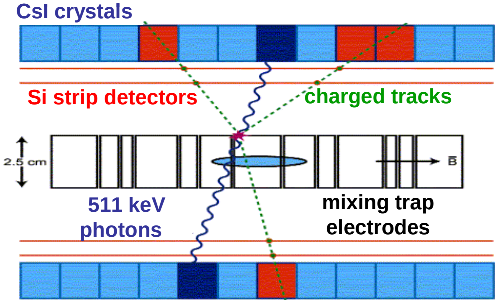
⇒ improvement by a factor of 4*

future: fine-structure constant α

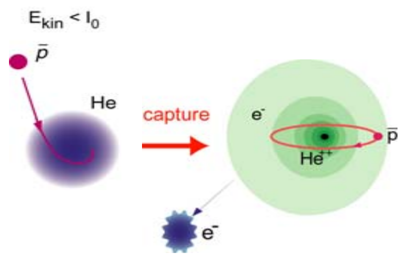
* from $^{12}C^{5+}$ and $^{16}O^{7+}$ g-factor measurement ,J. Verdú et al., PRL 92, 093002 (2004)

EXPERIMENTS WITH ANTIPROTONS AT EXTREMELY LOW ENERGIES

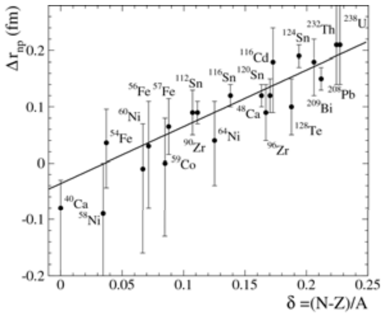
- fundamental interactions
  - CPT (antihydrogen, HFS, magnetic moment)
  - gravitation of antimatter
- atomic collision studies
  - ionization
  - energy loss
  - matter-antimatter collisions
- antiprotonic atoms
  - formation
  - strong interaction and surface effects



ATHENA Nature 419 (2002) 456



M. Hori et al., PRL 92 (2003) 123401



A. Trzcinska, J. Jastrzebski et al.PRL 87 (2001) 082501

Expected production rate:

10^8 $\bar{p}$ every 4 sec

~ 100 x Antiproton Decelerator (AD)

($2\text{-}4 \cdot 10^7$ $\bar{p}$ every 85 sec)

- develop "next generation" technology
- improve performance of most present experiments
- enable experiments that are not feasible at the AD

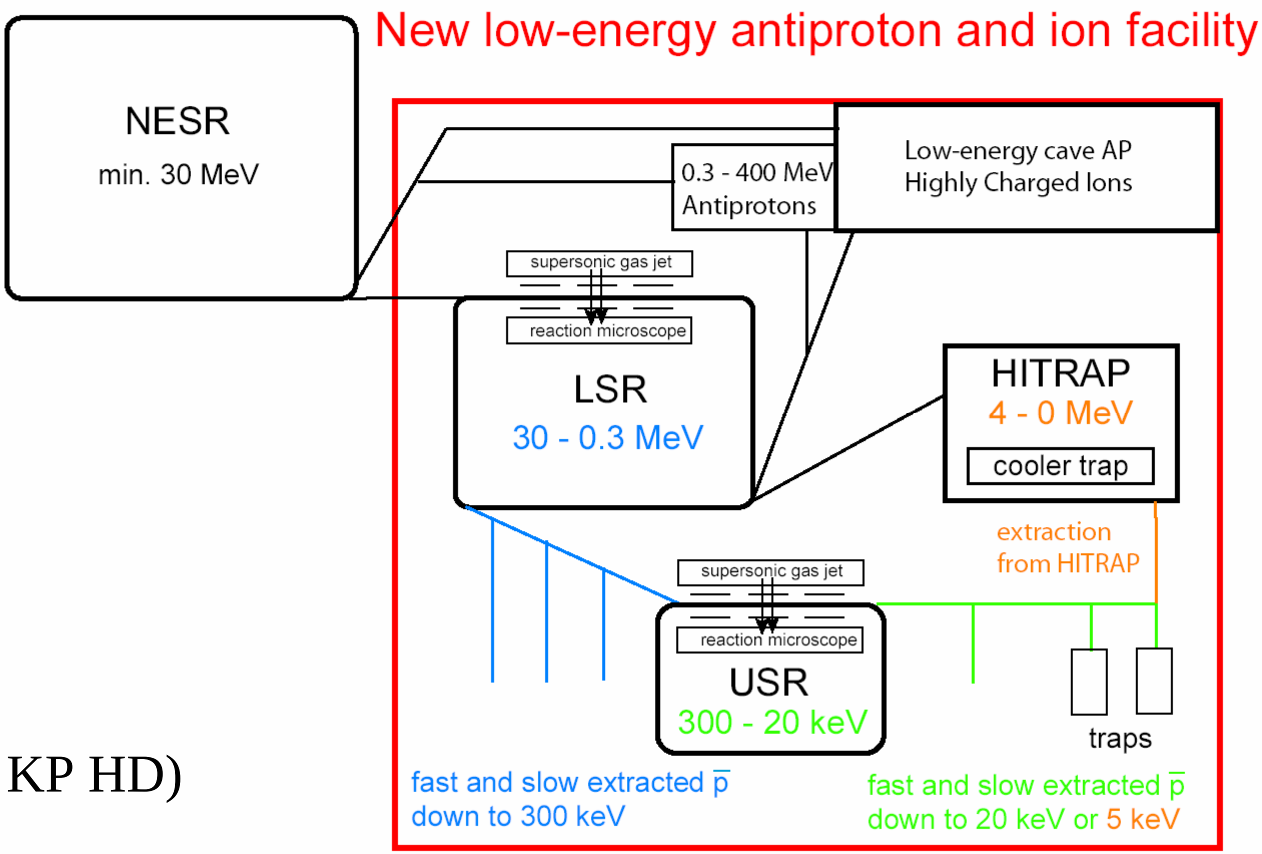
Present $\bar{p}$ collaborations at the AD/CERN:

ATHENA: CPT
ATRAP: CPT
ASACUSA: structure and dynamics

GSI will provide the most intense source of antiprotons

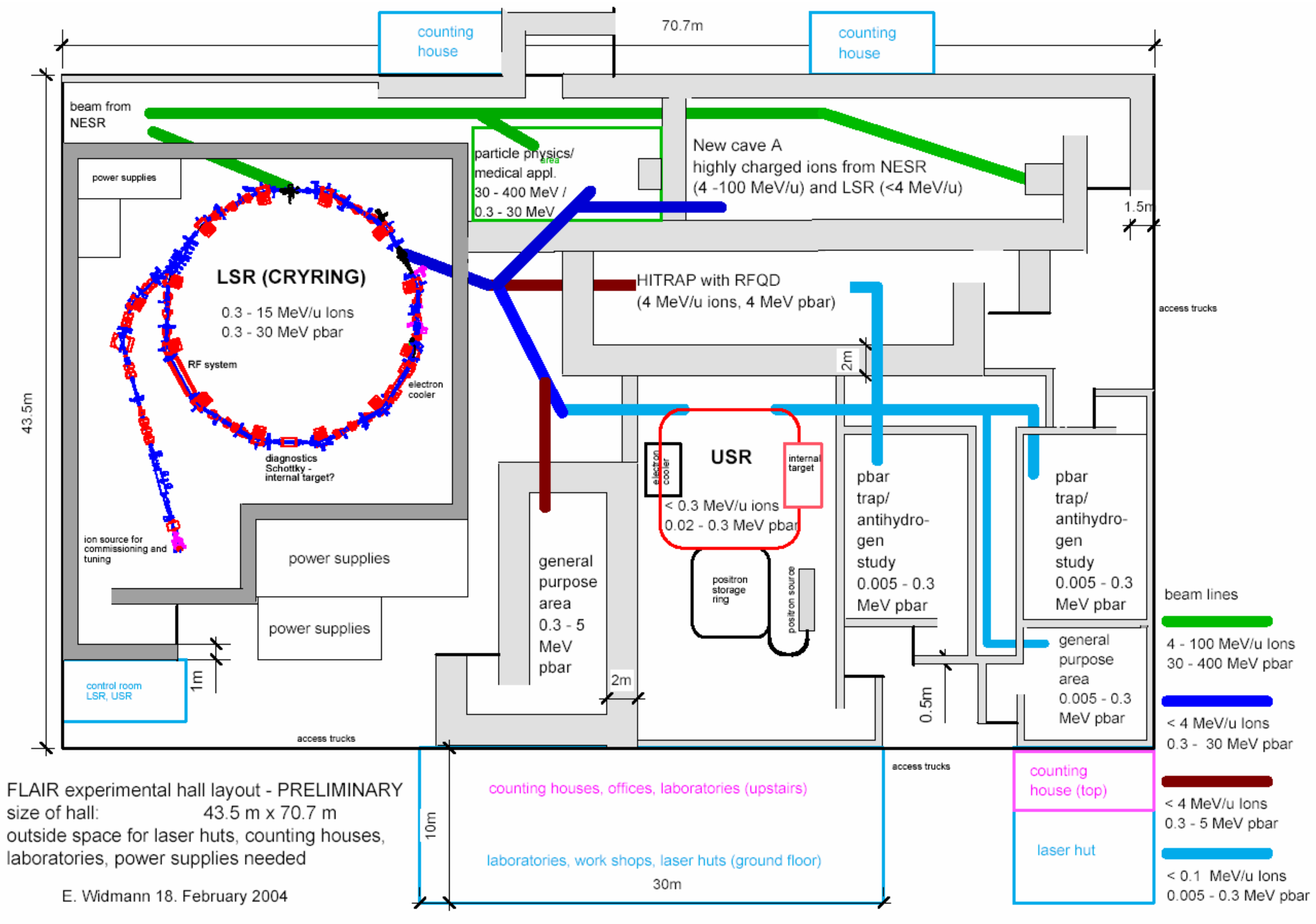
Facility for Research with Antiprotons and Ions

- NESR
  - Pbar & ions
  - 30 – 400 MeV
- LSR:
  - Standard ring
  - Min. 300 keV (CRYRING)
- USR
  - Electrostatic
  - Min 20 keV (MPI KP HD)
- HITRAP
  - Pbar and ions
  - Stopped & extracted @ 5 keV

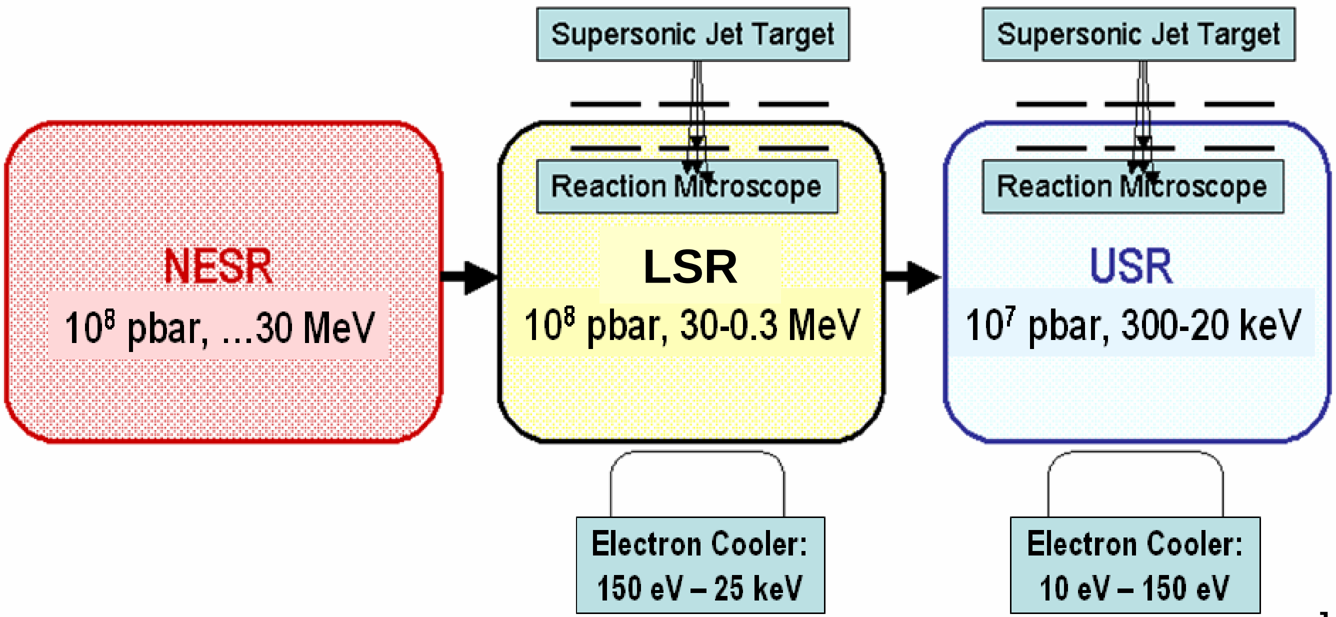


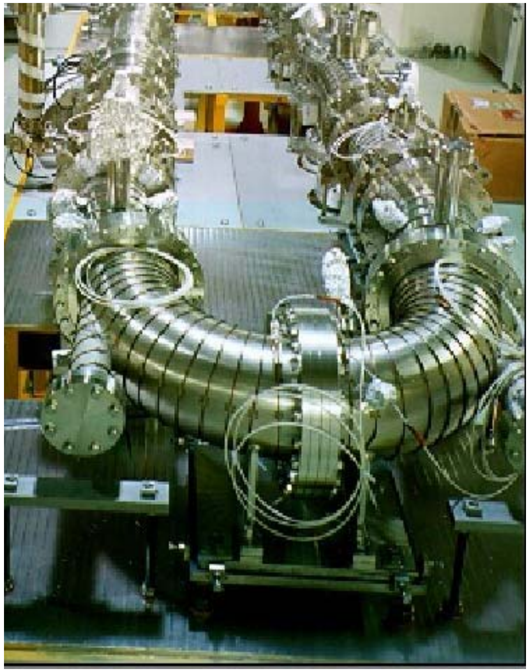
energy range: 400 MeV – 1 meV

FLAIR – Facility for Low-Energy Antiproton and Ion Research



The Electrostatic Storage Ring USR for Antiprotons and Ions at Ultra-Low Energy



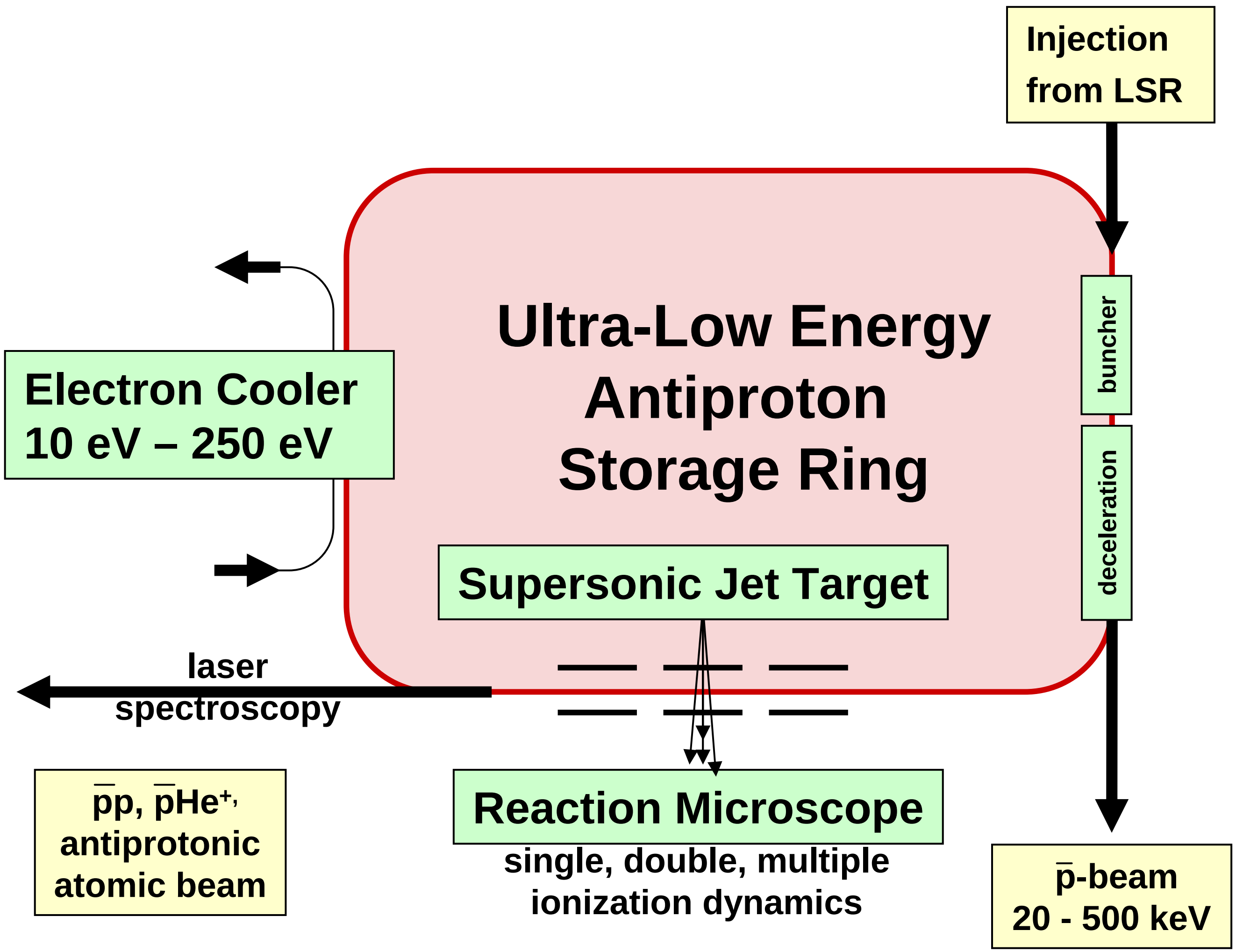


J. Ullrich et al.

USR: A novel electrostatic cooler storage ring:

- **low to ultra-low energies**
- **excellent beam quality and large number of stored $\bar{p}$**
- **high luminosity for in-ring experiments**

Experiments at the USR with Antiprotons



- energy: 300 keV – 20 keV
- length straight sections: 4 m
- circumference: 20 m
- bending radius: 1 m
- mode of operation: electrostatic
- revolution time 700 ns – 12 μs

Experiments at the USR with Antiprotons