Accelerator facility @ FAIR Project
and NICA project

Grigory Trubnikov
Joint Institute for Nuclear Research (JINR), Dubna

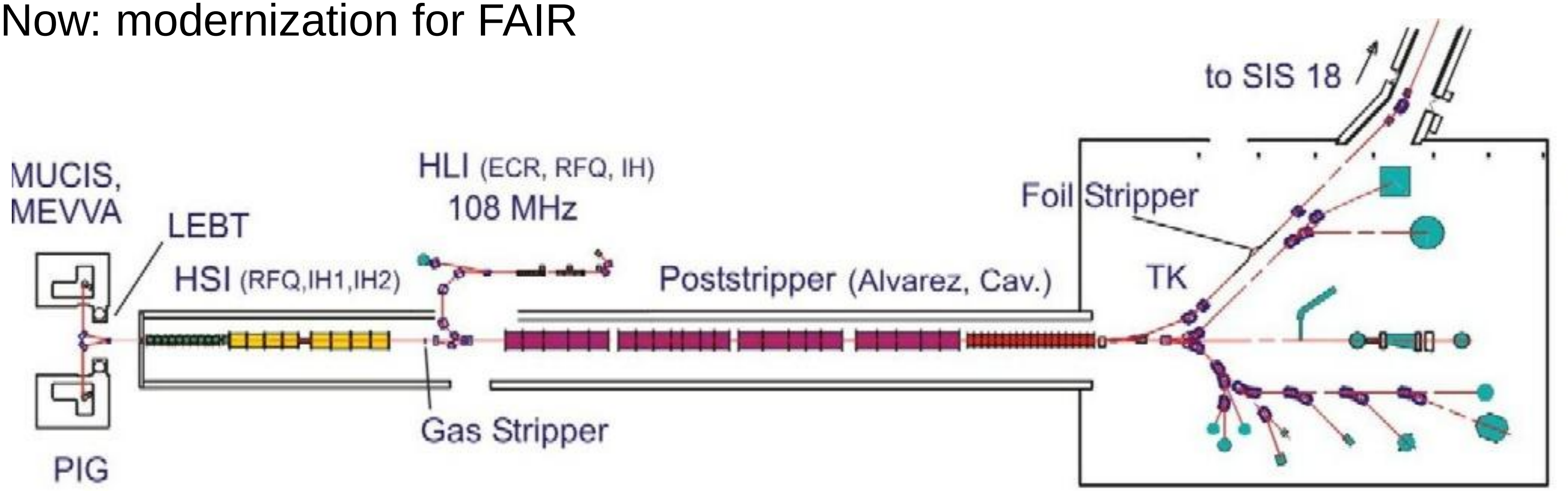
Helmholtz-FRRC-ITEP Winter School, Bekasovo, Feb.2012

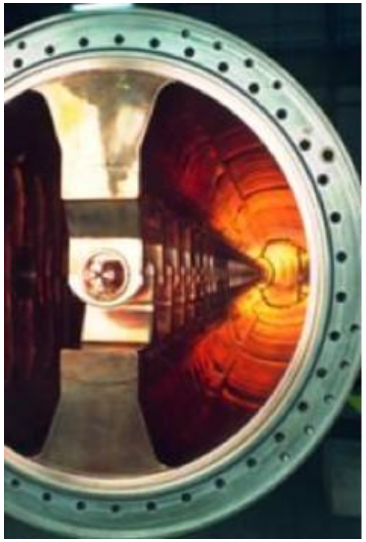
UNILAC - the Universal Linear Accelerator (1975).

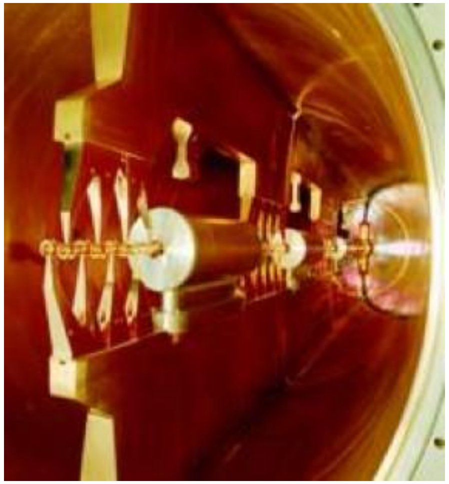
from Hydrogen to Uranium, E=11.4 MeV/u

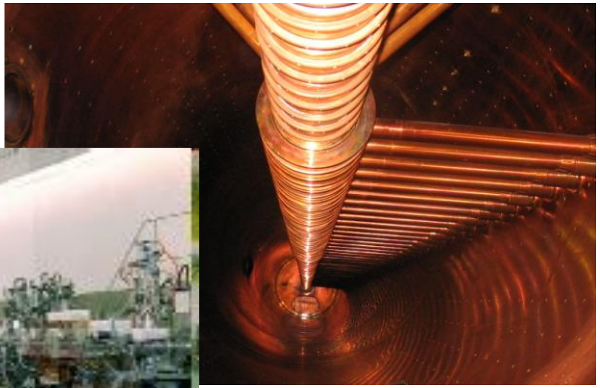
1990: modernization for operation together with ESR and SIS

Now: modernization for FAIR

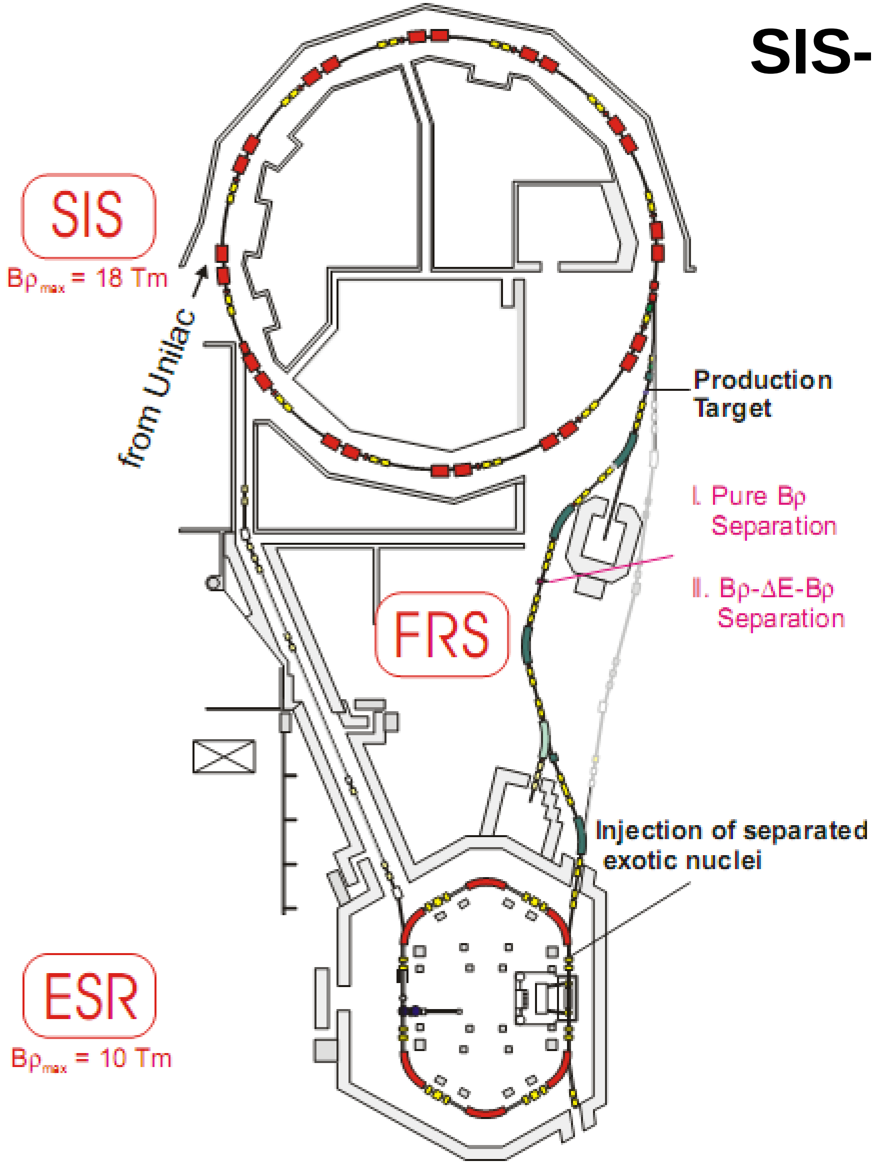




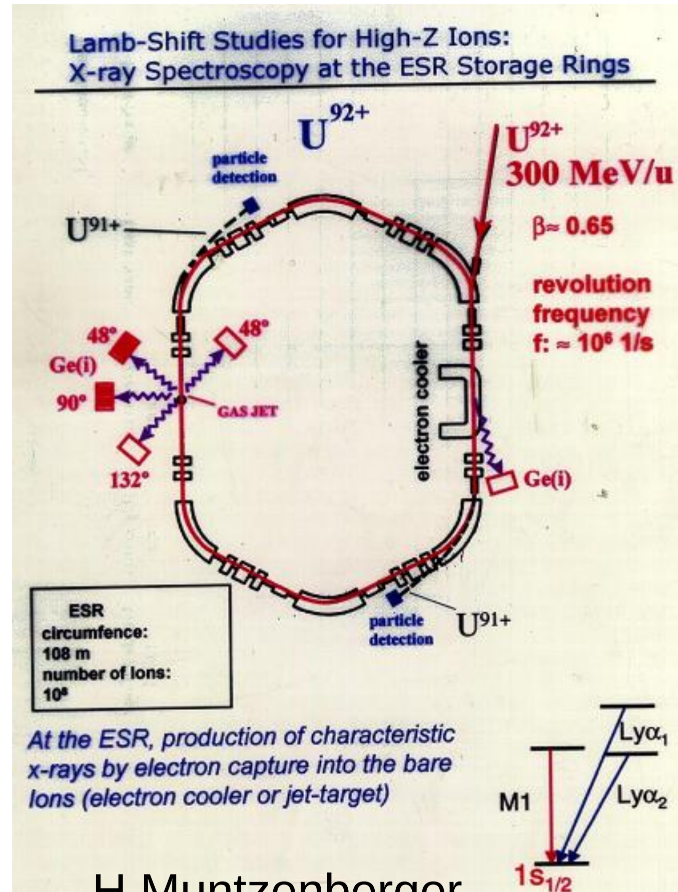




SIS-ESR at 1990

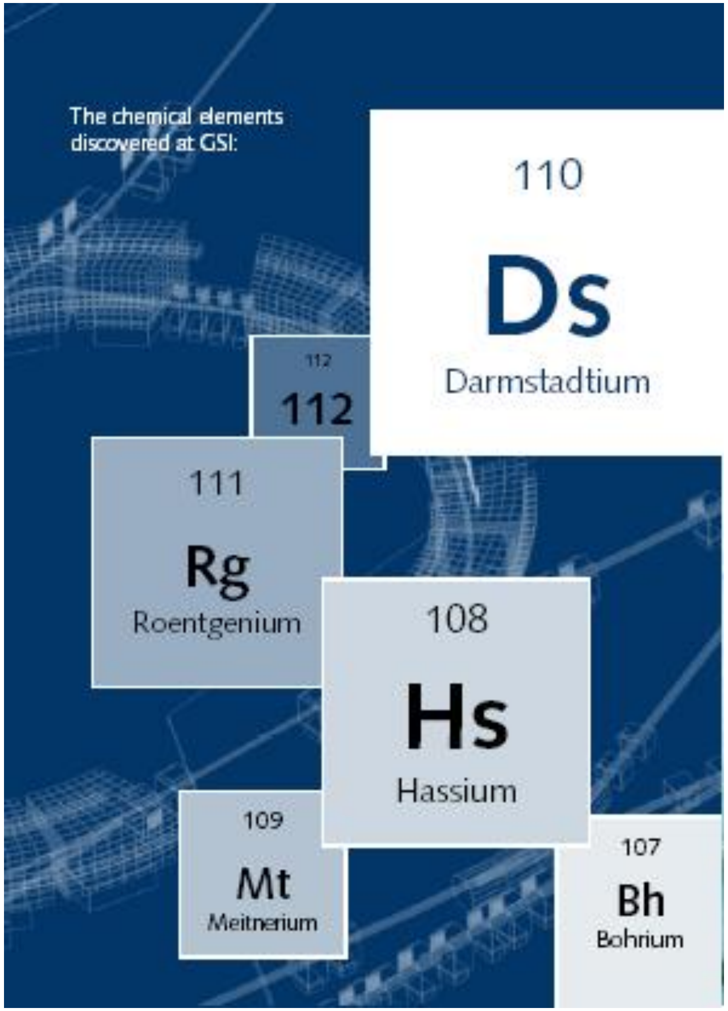


18 T·m:
4.5 GeV - protons
196 MeV/u - $^{238}U^{+28}$



Precise measurements of masses and lifetime of rare isotopes

H.Muntzenberger



To enlarge experimental possibilities it is required to increase energy of the primary beam:

SIS100 - 2.7 GeV/u U^{28+}
Wide spectra of secondary particles with enough intensity to create e-i collider with high luminosity

SIS100 economical and efficient synchrotron with magnets of "Nuclotron" type (made in JINR)

But SIS100 - 29 GeV protons
$\rightarrow$ p-bar production is required…

Norbert Angert for the Study Group, May 2001, Conference on Bean cooling, Bad Honnef, Germany

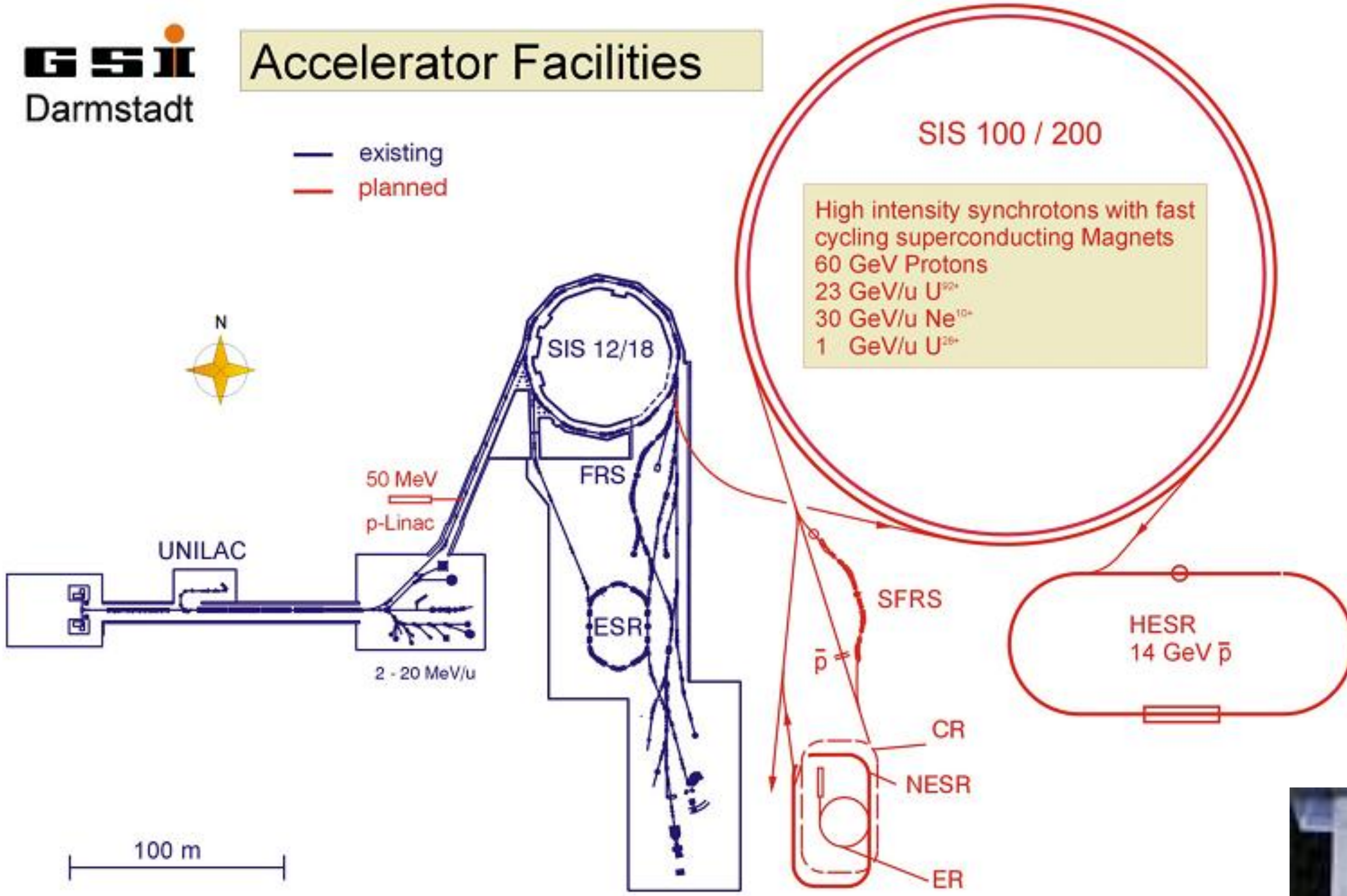
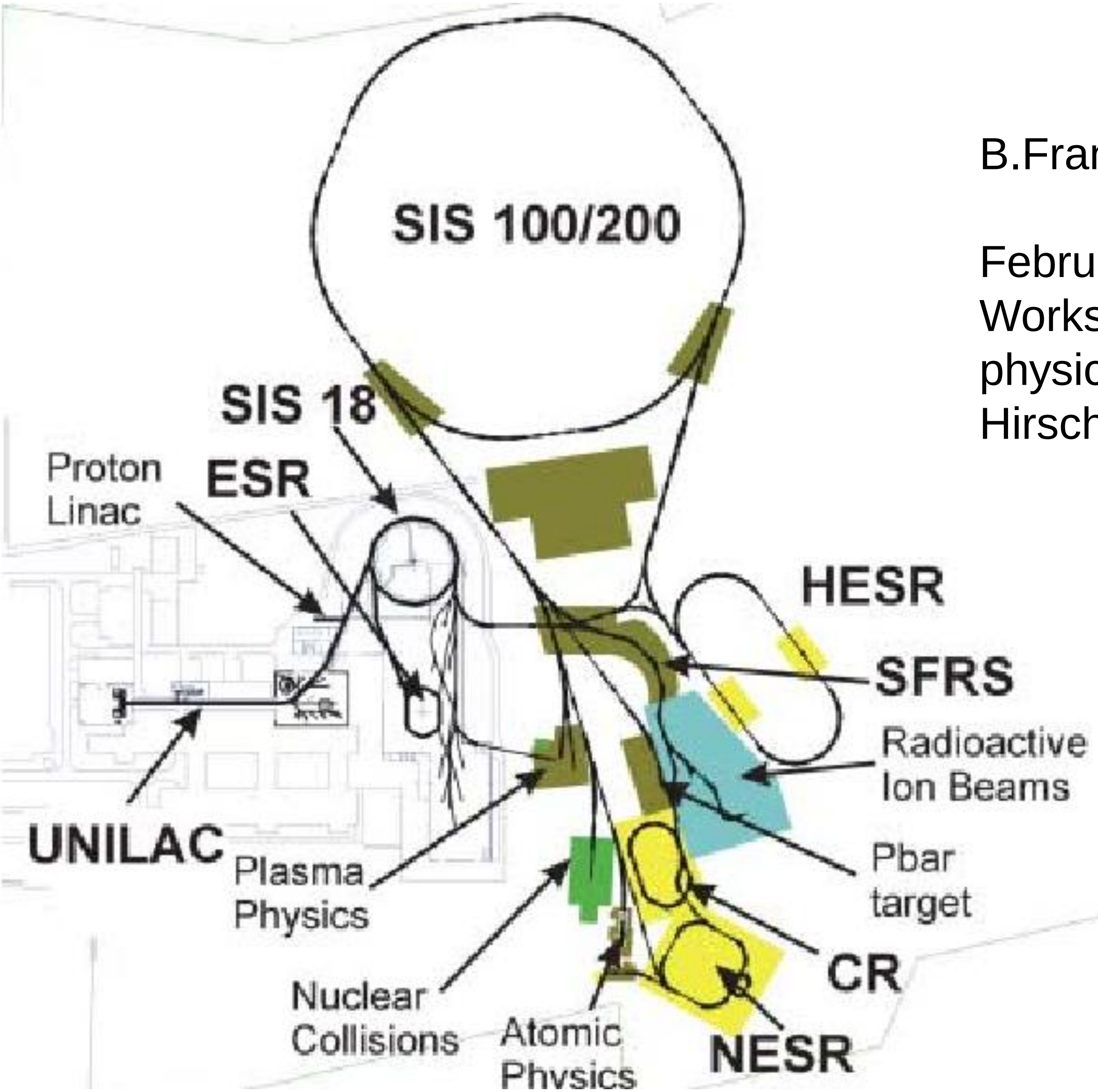


Fig.: Present Layout of the existing and planned facilities

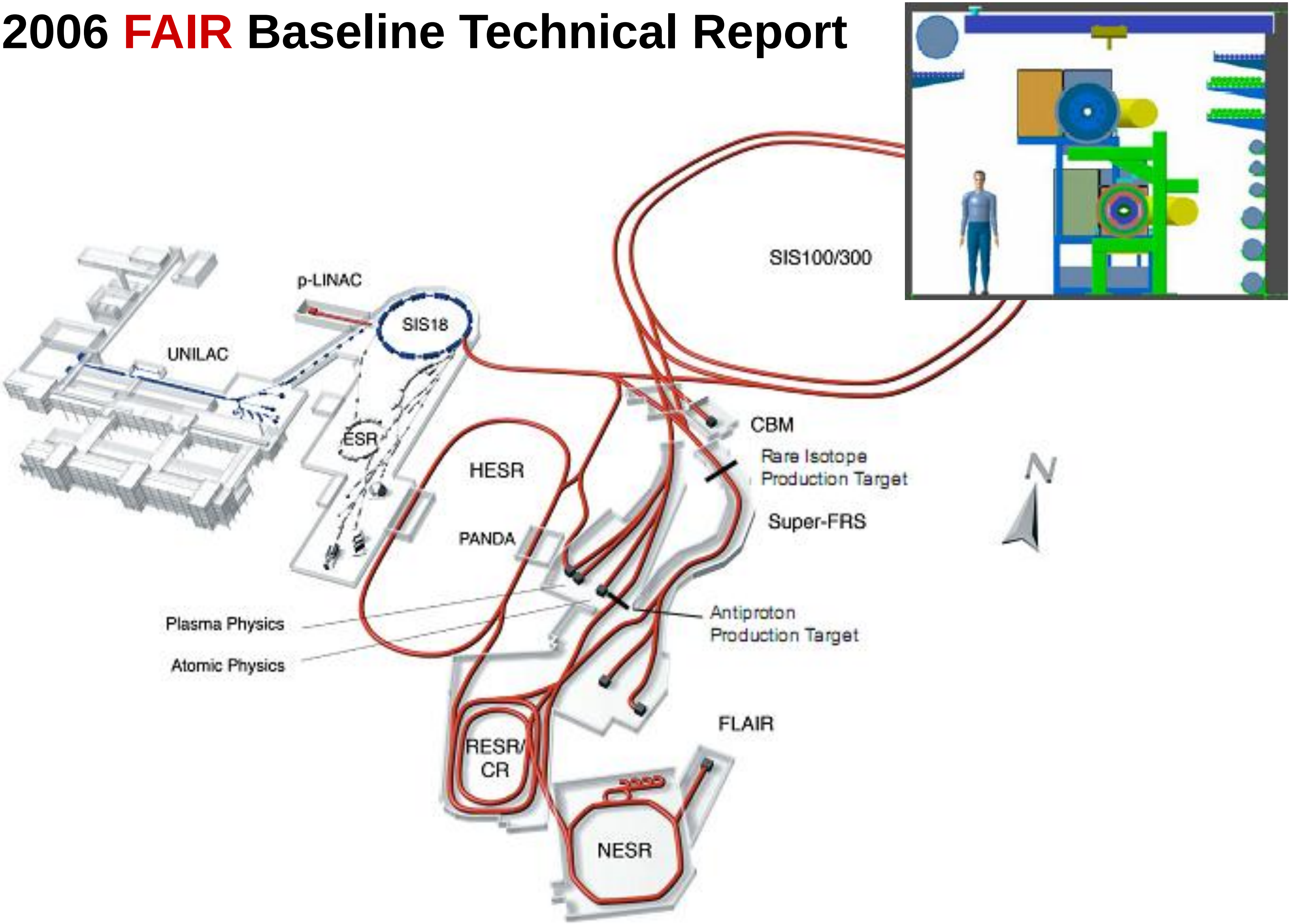
«New experimental complex»



B.Franzke,

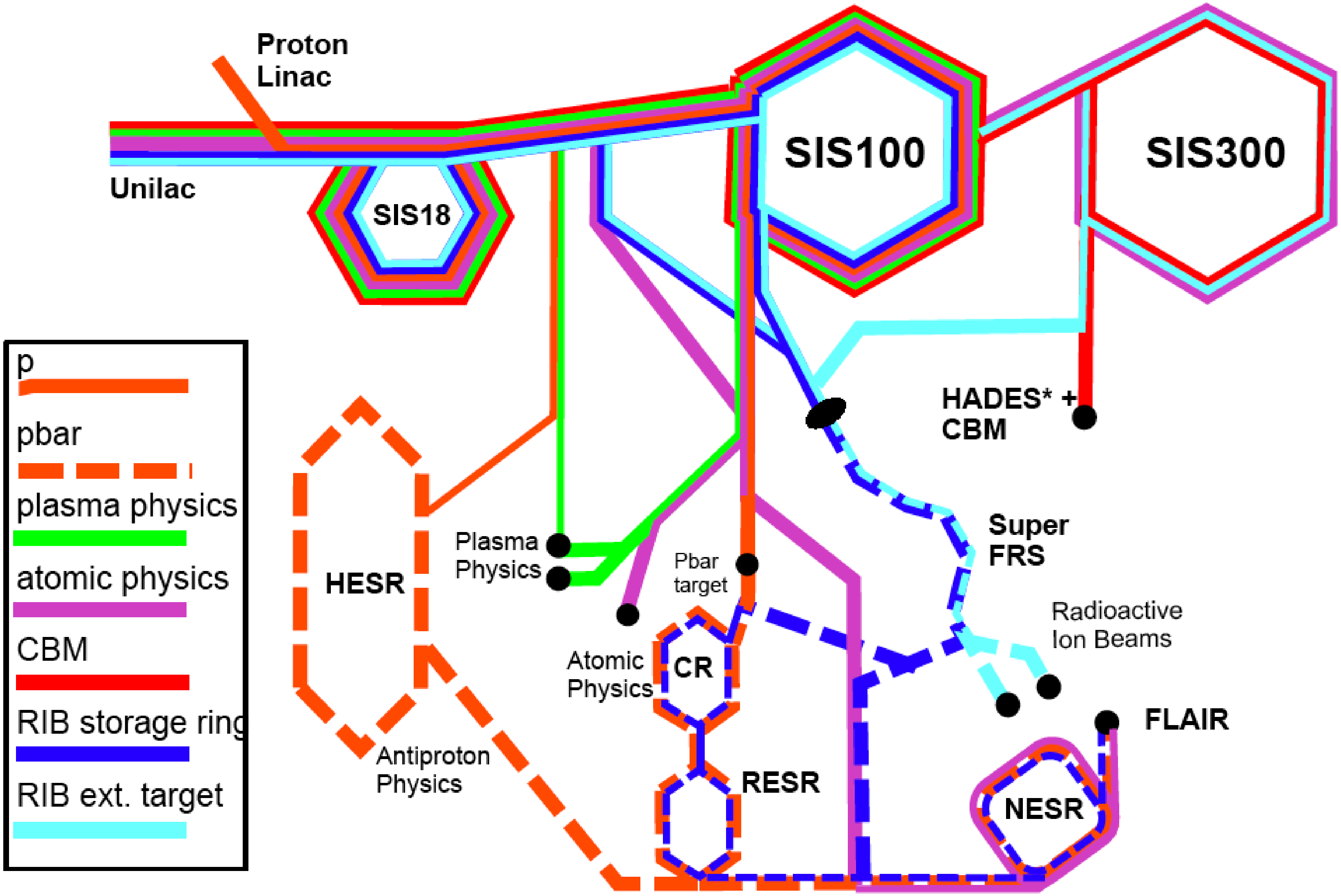
February 2002,
Workshop on rare isotop physics, GSI – RIKEN, Hirschegg, Austria

2006 FAIR Baseline Technical Report



http://www.gsi.de/fair/index_e.html

Up to 4 fold Parallel Operation at FAIR !



Accelerator	Circumference, m	Magnetic regidity, T·м	Particle energy
Synchrotron SIS100	1084	100	2.7 GeV/u U^{28+} 29 GeV/u, protons
Synchrotron SIS300	1084	300	35 GeV/u U^{92+}
Collector Ring CR	211	13	0.74 GeV/u U^{92+} 3 GeV, antiprotons
Accumulator: Recycled Experimental Storage Ring – RESR	245	13	0.74 GeV/u U^{92+} 3 GeV – antiprotons
New Experimental Storage Ring – NESR	222	13	0.74 GeV/u U^{92+}
P-bar accumulator: High Energy Storage Ring – HESR	574	50	14 GeV – antiprotons

$$(pc)_{[eV]} = 300 B_{[Gs]} R_{[cm]} = 3 B_{[T]} R_{[m]}$$

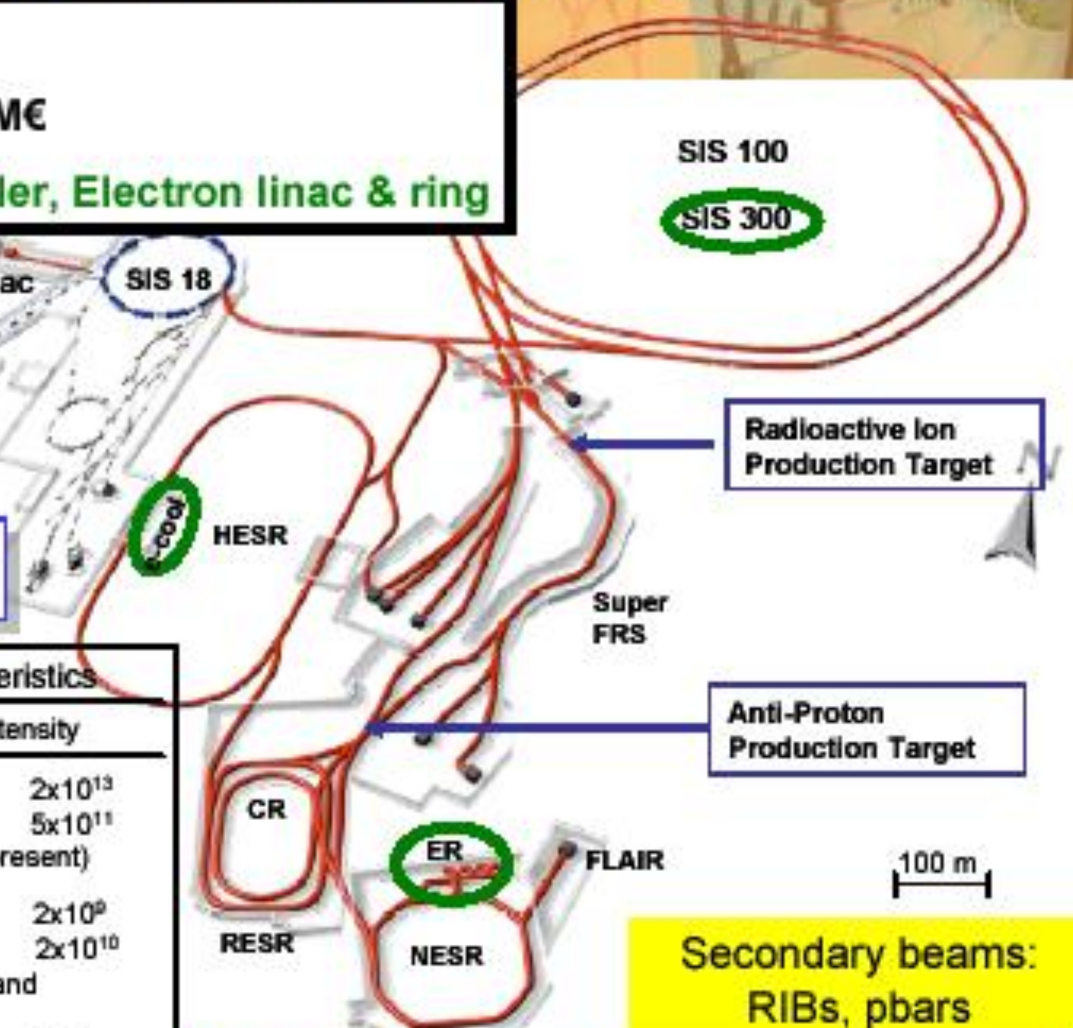
C.Dimopoulou on behalf of FAIR technical division, RuPAC 2008, Zvenigorod, Sept.2008

The FAIR Accelerator Complex

Total project: 1300 M€

Start Version = Phase A: 940 M€

Phase B: SIS 300, HESR ecooler, Electron linac & ring



Primary beams: protons to ^{238}U

Upgraded existing facility: provides ion-beam source and injector for FAIR

Secondary beams: RIBs, pbars

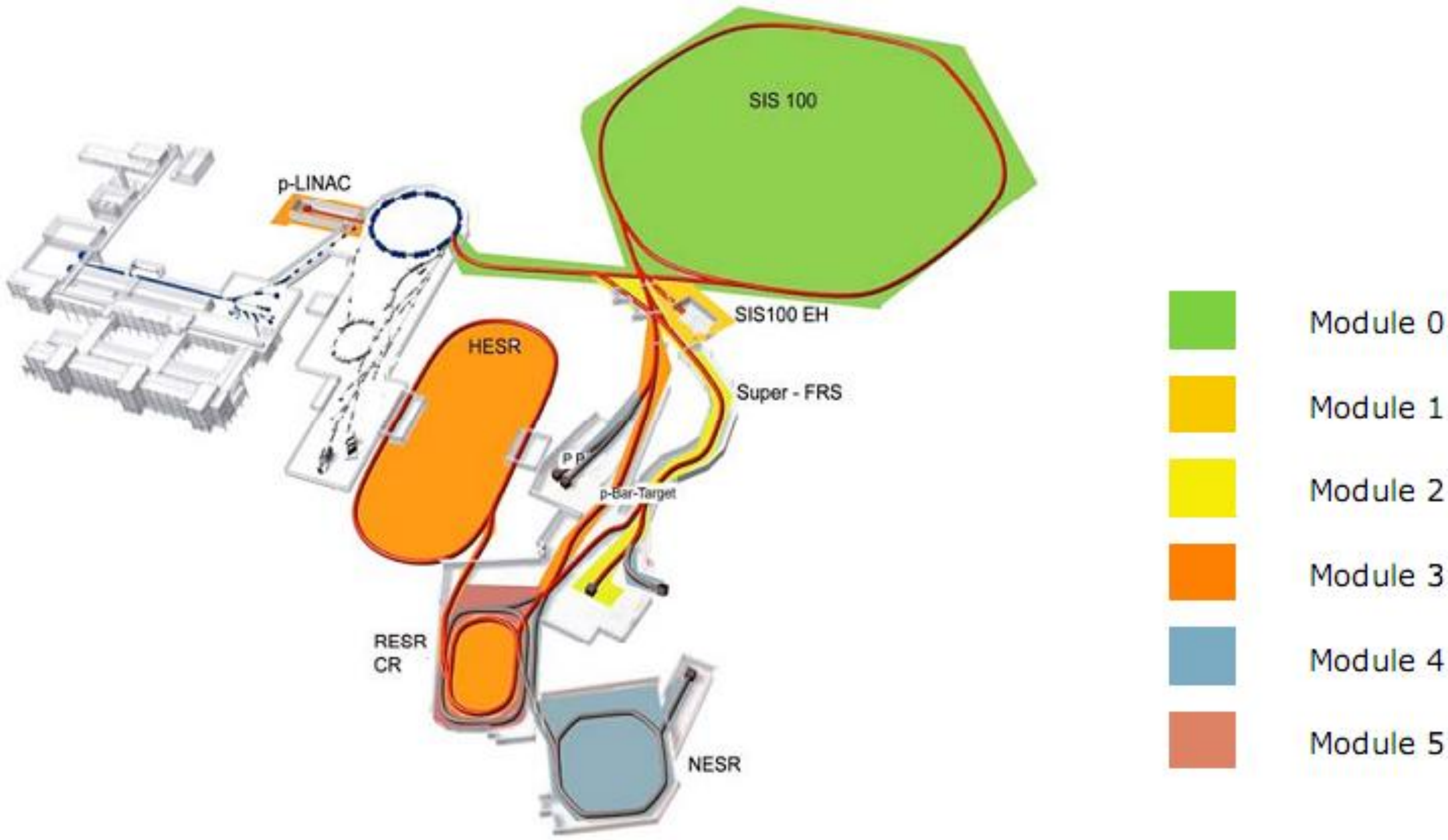
New future facility: provides ion and anti-matter beams of highest intensities and up to high energies

Accelerator Components & Key Characteristics

Ring/Device	Beam	Energy	Intensity
SIS 100 (100Tm)	protons	30 GeV	$2x10^{13}$
	$^{238}U^{28+}$	2.7 GeV/u	$5x10^{11}$
	(intensity factor 100 over present)		
SIS 300 (300Tm)	^{40}Ar	45 GeV/u	$2x10^{9}$
	$^{238}U^{92+}$	34 GeV/u	$2x10^{10}$
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim 10^{11}$
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

FAIR Newsletter No. 13

September 2009



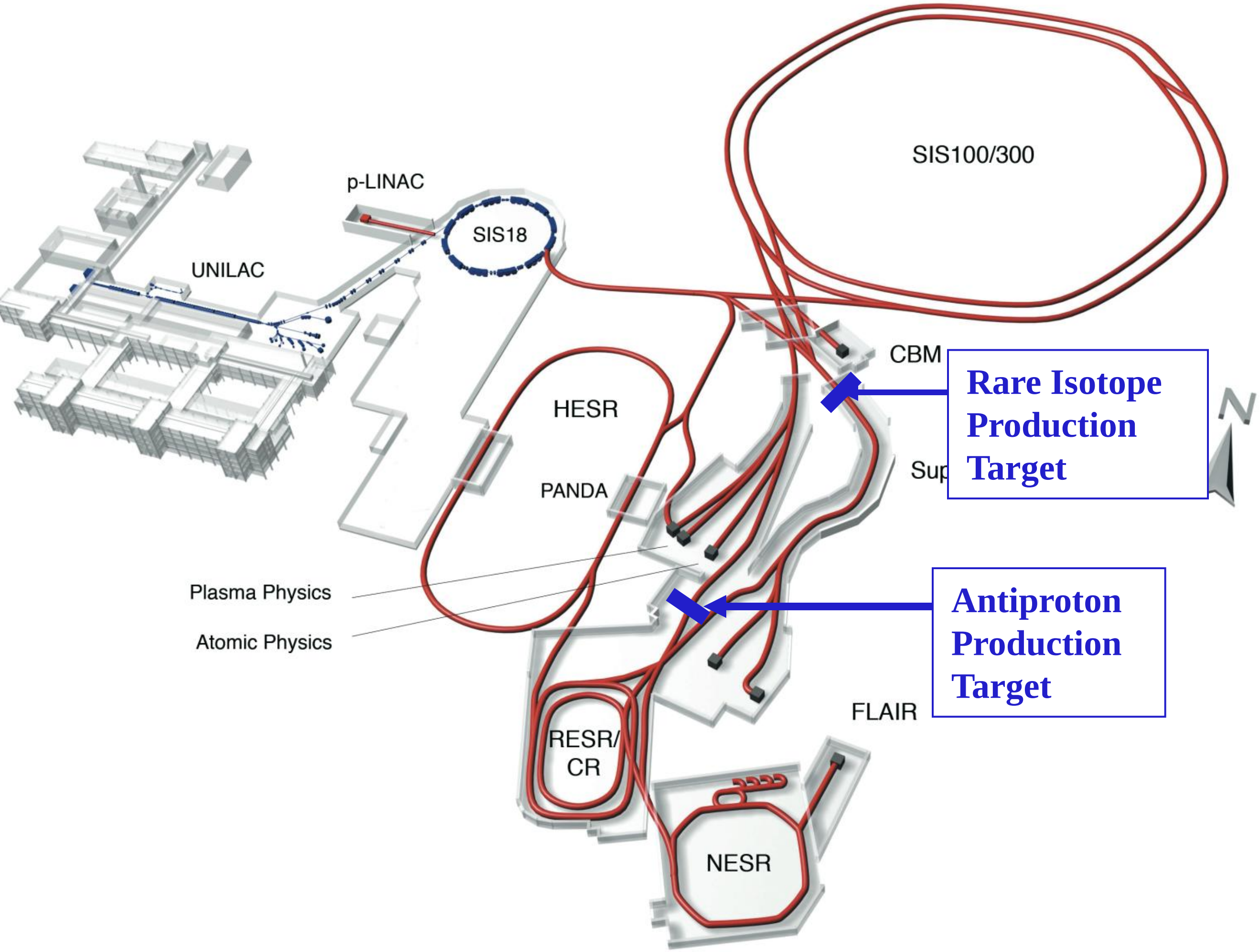
Strategy of staging had been developed: 6 modules (0 – 5). Modules 0 – 3 will be constructed during nearest 5 years, 4 and 5 when additional funding will be supplied.

International FAIR Project: *the Intensity Frontier*

B.Sharkov, 2010

Key Technologies

- Beam cooling
- Rapidly cycling superconducting magnets



Primary Beams

- **All elements** up to Uranium
- Factor 100-**1000** over present intensity
- **50ns bunching**

Secondary Beams

- **Rare isotope beams** up to a factor **of 10 000** in intensity over present
- Low and high energy **antiprotons**

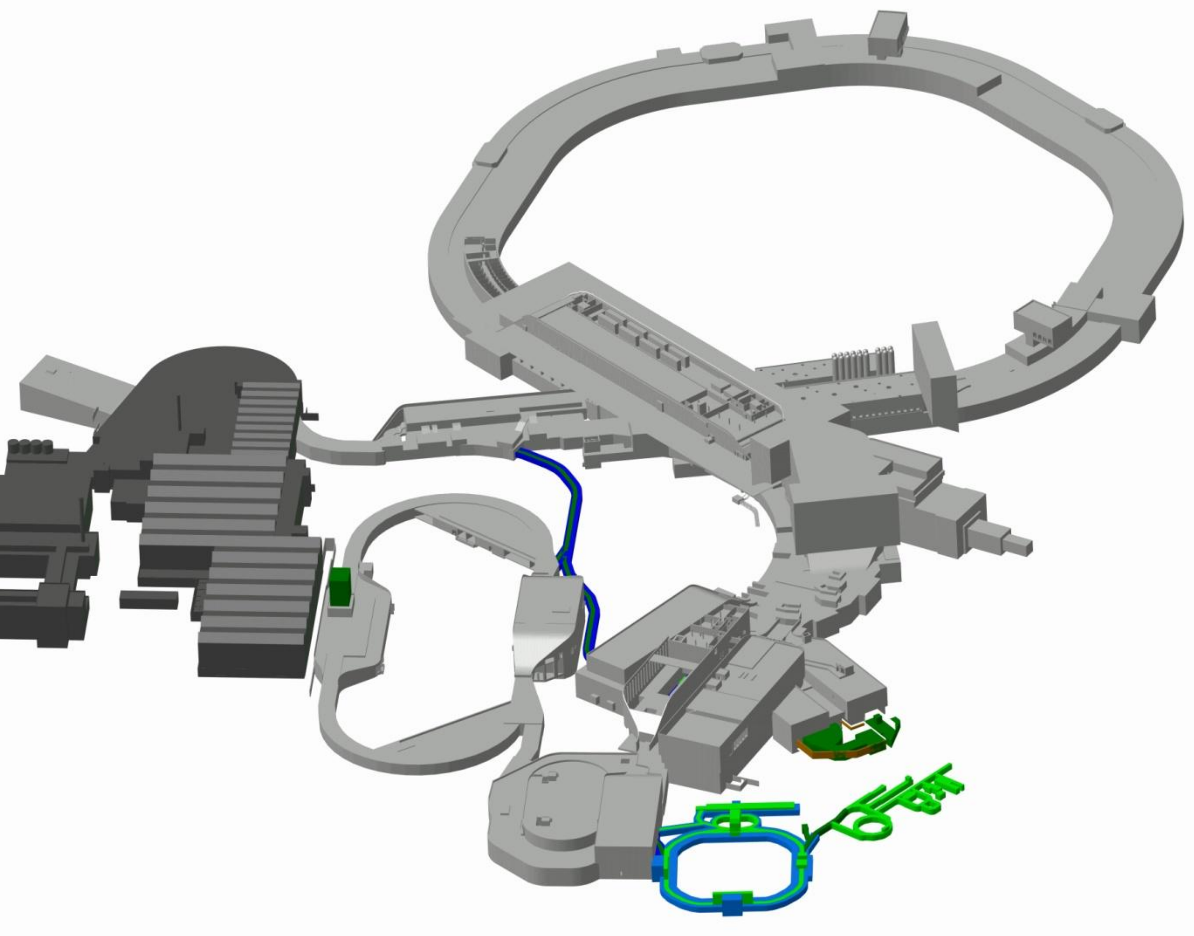
Storage and Cooler Rings

- Rare isotope beams
- **e⁻**– Rare Isotope collider
- **10^{11}** stored and cooled antiprotons for **Antimatter** creation

Collision Checks

Integration of contour model and DMU models into civil construction design

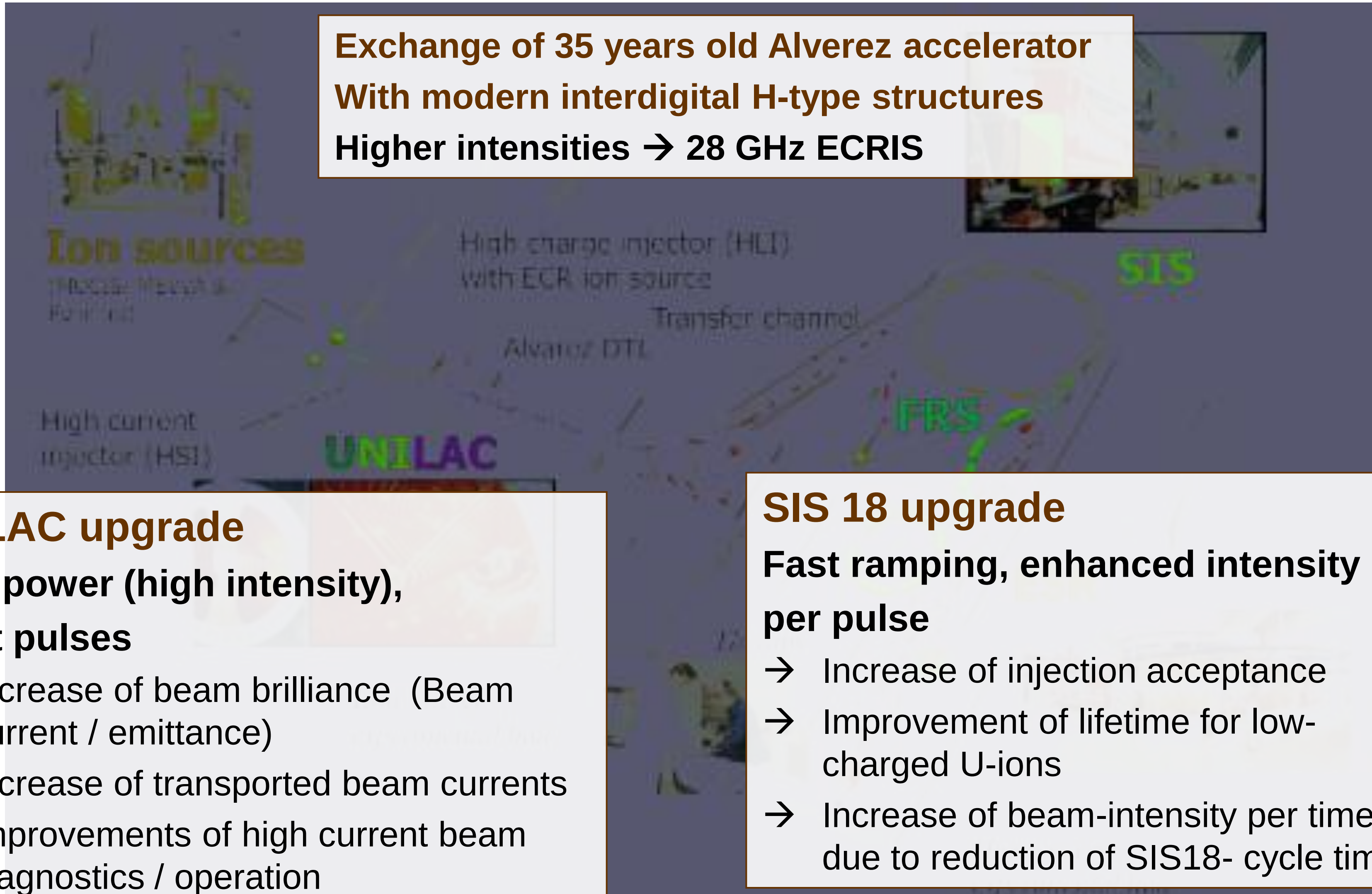
Collision checks with „concrete“ and accelerator infrastructure (started)



Civil construction design

Contour model of FAIR

Preparing the Injector Chain



Exchange of 35 years old Alverez accelerator
With modern interdigital H-type structures
Higher intensities → 28 GHz ECRIS

UNILAC upgrade

High power (high intensity), short pulses

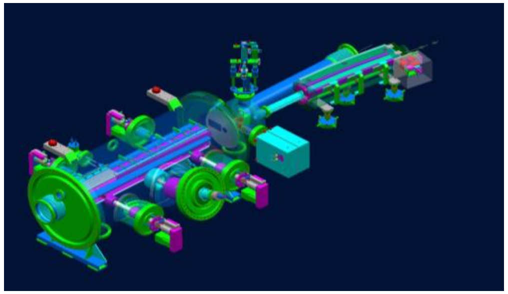
- → Increase of beam brilliance (Beam current / emittance)
- → Increase of transported beam currents
- → Improvements of high current beam diagnostics / operation

SIS 18 upgrade

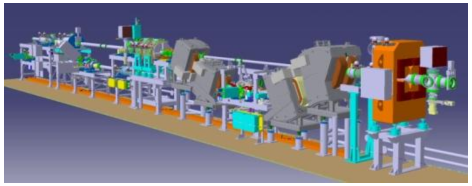
Fast ramping, enhanced intensity per pulse

- → Increase of injection acceptance
- → Improvement of lifetime for low-charged U-ions
- → Increase of beam-intensity per time due to reduction of SIS18- cycle time

SIS18 Upgrade Program

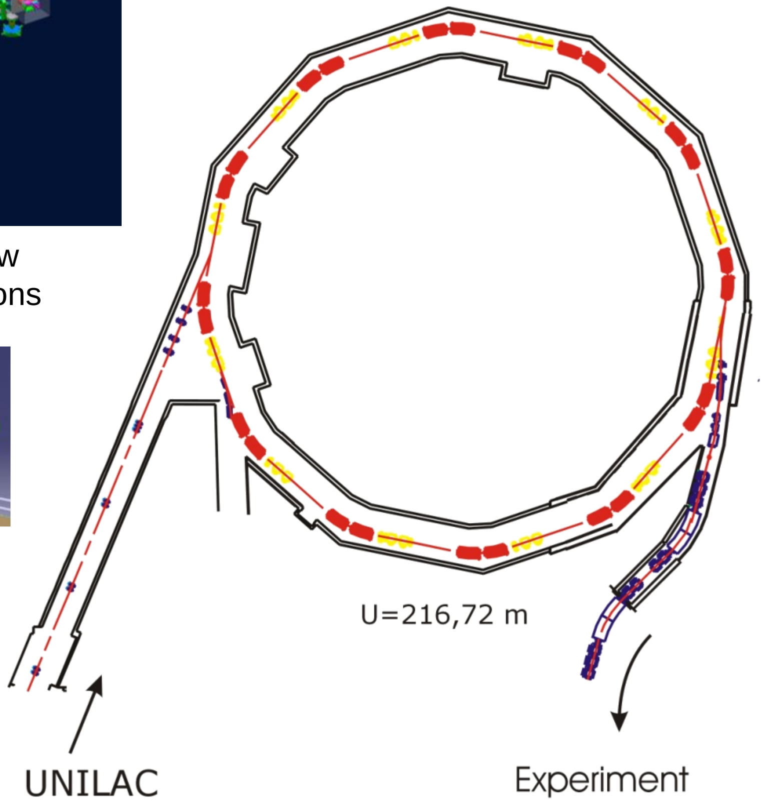


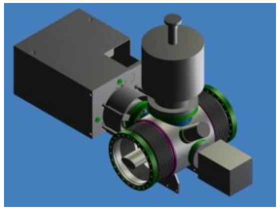
Injection system for low charged state heavy ions



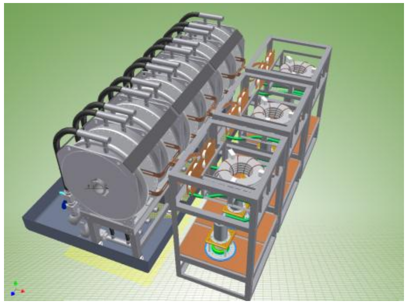
Charge separator for higher intensity and high quality beams

Power grid connection





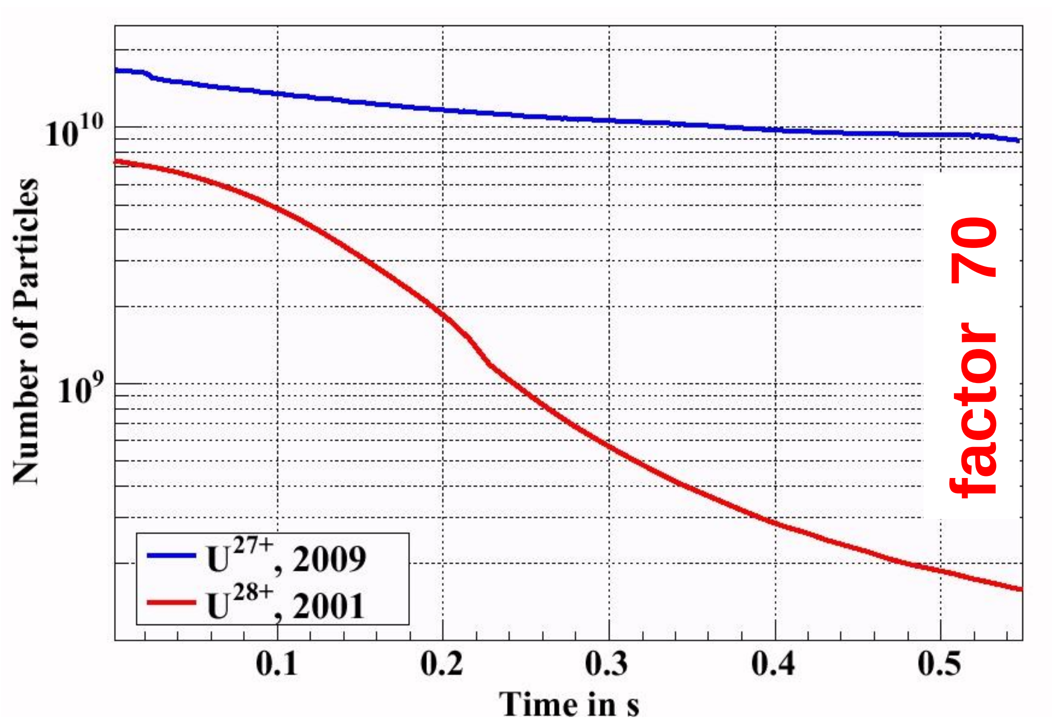
Scrapers and NEG coating for pressure stabilization

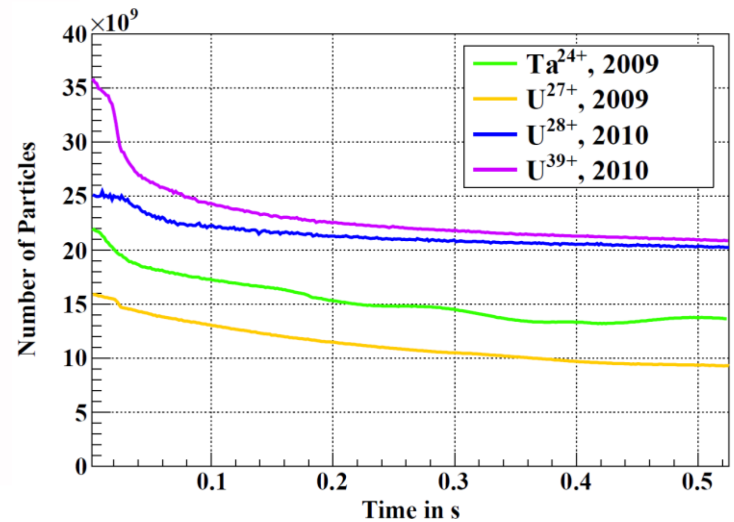


h=2 acceleration cavity for faster ramping

The SIS18upgrade program: Booster operation with intermediate charge state heavy ions

World Record Intensity of Intermediate Charge State Heavy Ions



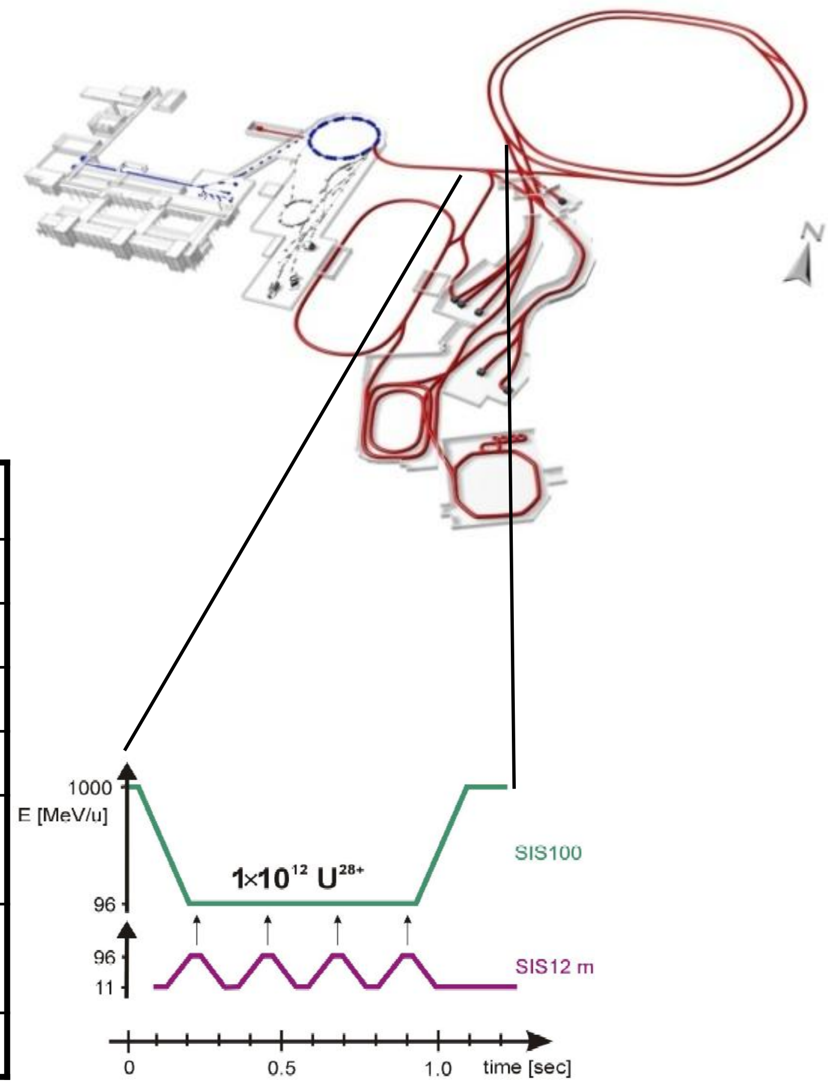


Significantly increased number of accelerated ions (2009 versus 2001)

SIS100 Beam Parameters SIS18/SIS100

SIS18	Protons	Uranium
Number of ions per cycle	5 x 10^{12}	1.5 x 10^{11}
Initial beam energy	70 MeV	11 MeV/u
Ramp rate	10 T/s	10 T/s
Final beam energy	4.5 GeV	200 MeV/u
Repetition frequency	2.7 Hz	2.7 Hz

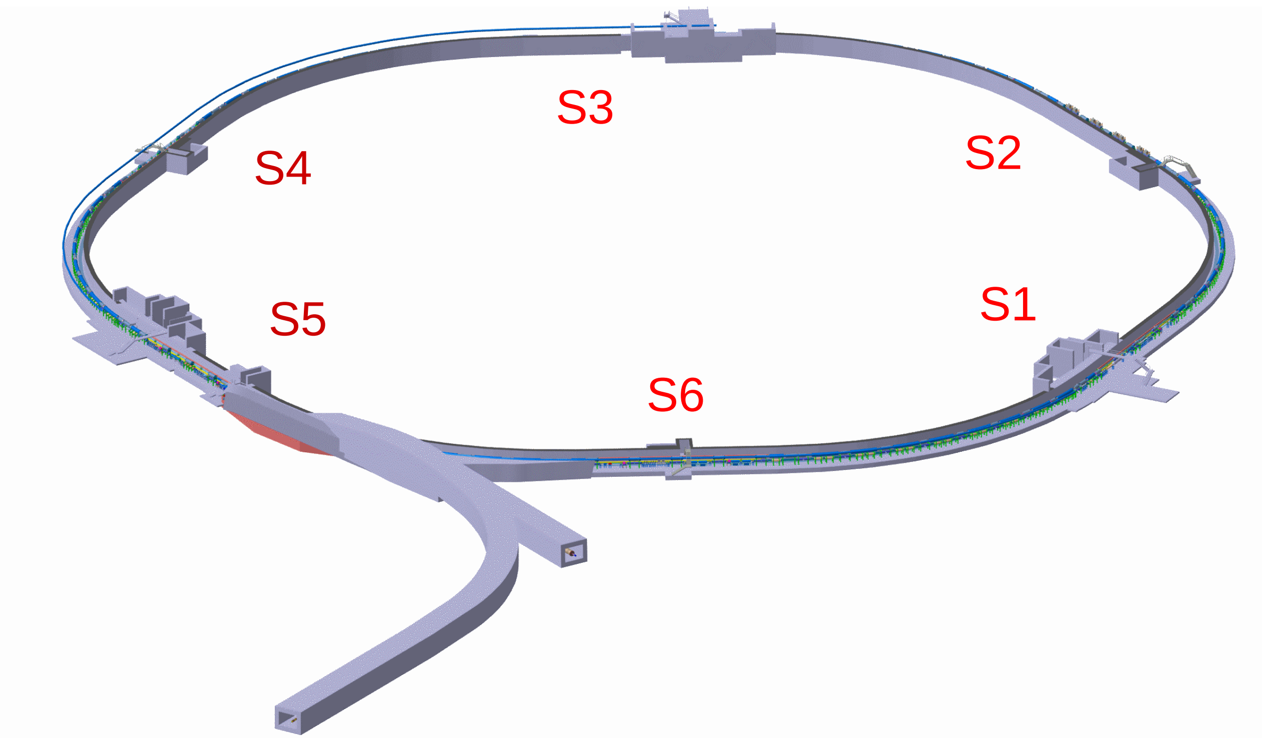
SIS100	Protons	Uranium
Number of injections	4	4
Number of ions per cycle	2.5x 10^{13} ppp	5 x 10^{11}
Maximum Energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.7 Hz	0.7 Hz



Technical Subsystems

Sixfold Symmetry

- Sufficiently long and number of straight sections
- Reasonable line density in resonance diagram
- Good geometrical matching to the overall topology



S1: Transfer to SIS300

S2: Rf Compression (MA loaded)

S3: Rf Acceleration (Ferrite loaded)

S4: Rf Acceleration (Ferrite loaded)

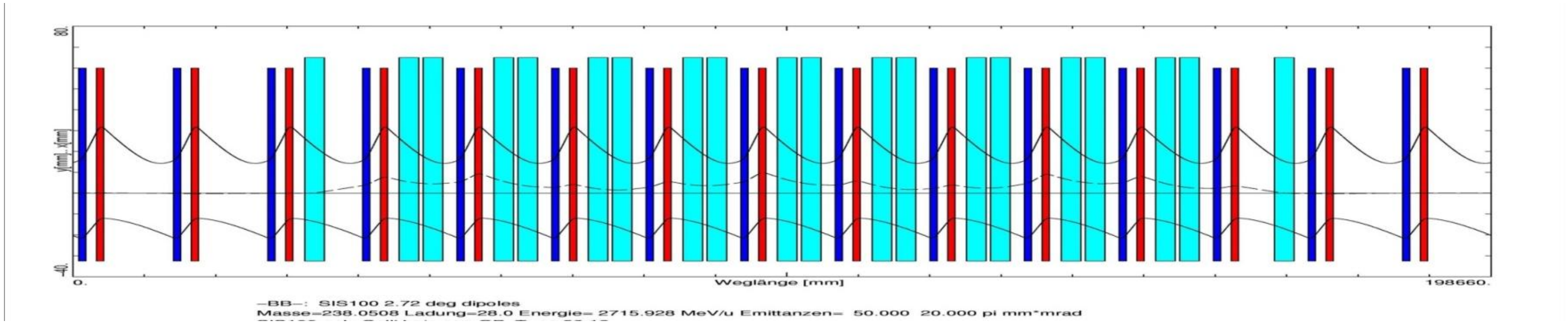
S5: Extraction Systems (slow and fast)

S6: Injection System plus RF Acceleration and Barrier Bucket

The SIS100 technical subsystems define the length of the straight sections of both synchrotrons

SIS100 Lattice Characteristics

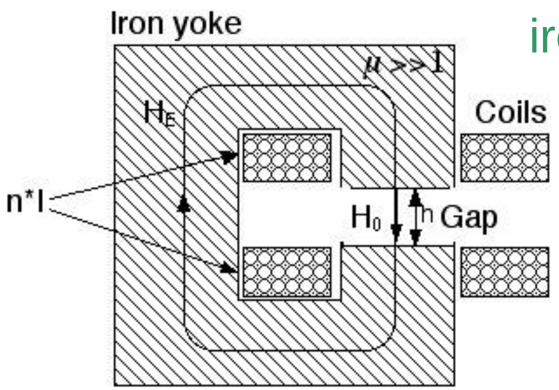
- Maximum transverse acceptance (minimum 3x emittance at injection)
  at limited magnet apertures (problems: pulse power, AC loss etc.)
- Vanishing dispersion in the straight sections for high dp/p during compression
- Low dispersion in the arcs for high dp/p during compression
- Sufficient dispersion in the straight section for slow extraction with Hardt condition
- Shiftable transition energy (three quadrupole power busses) for p operation
- Sufficient space for all components and efficient use of space
- Enabling slow, fast and emergency extraction and transfer within one straight.
- Peaked distribution and highly efficient collimation system for ionization beam loss



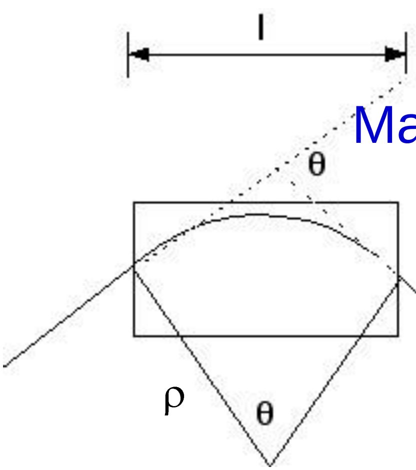
Charged Particle Motion in Magnetic Fields

Bending in dipole magnet

iron dominated magnets



$$nI = \oint \vec{H} d\vec{s} = H_E l_E + H_0 h \approx H_0 h \quad \Rightarrow \quad B = \mu_0 \frac{nI}{h}$$



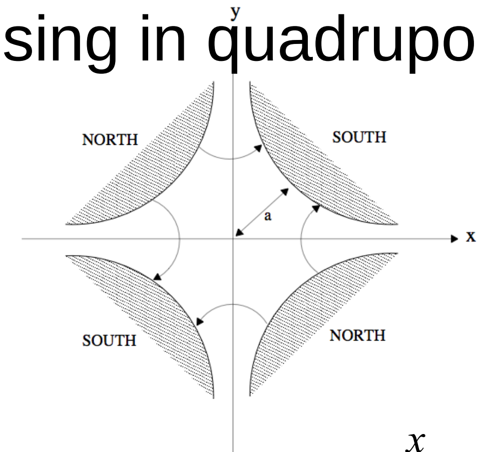
$$p = qB\rho$$

Magnetic rigidity Bρ

short dipole

$$\theta = \frac{\int B_y ds}{B\rho}$$

Focusing in quadrupole magnet



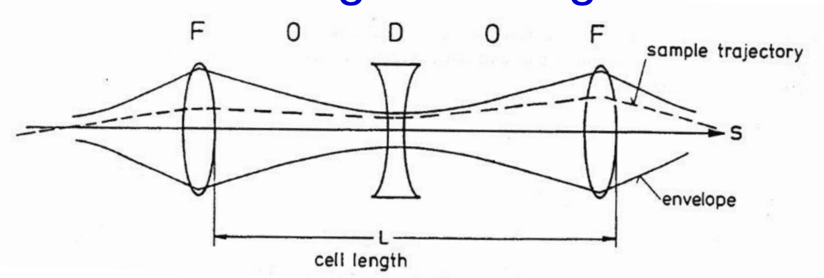
Magnetic field: $B_y = B_0 \frac{x}{a}, \quad B_x = B_0 \frac{y}{a}$

Force: $F_x = -qv_0 B_y = -qv_0 B_0 \frac{x}{a}, \quad F_y = qv_0 B_x = qv_0 B_0 \frac{y}{a}$

Focusing in one plane, defocusing in perpendicular plar

$\Rightarrow$ Combine focusing and defocusing qaudrupole

´Strong Focusing´



Rf Cycle in SIS100 (temporary concepts)

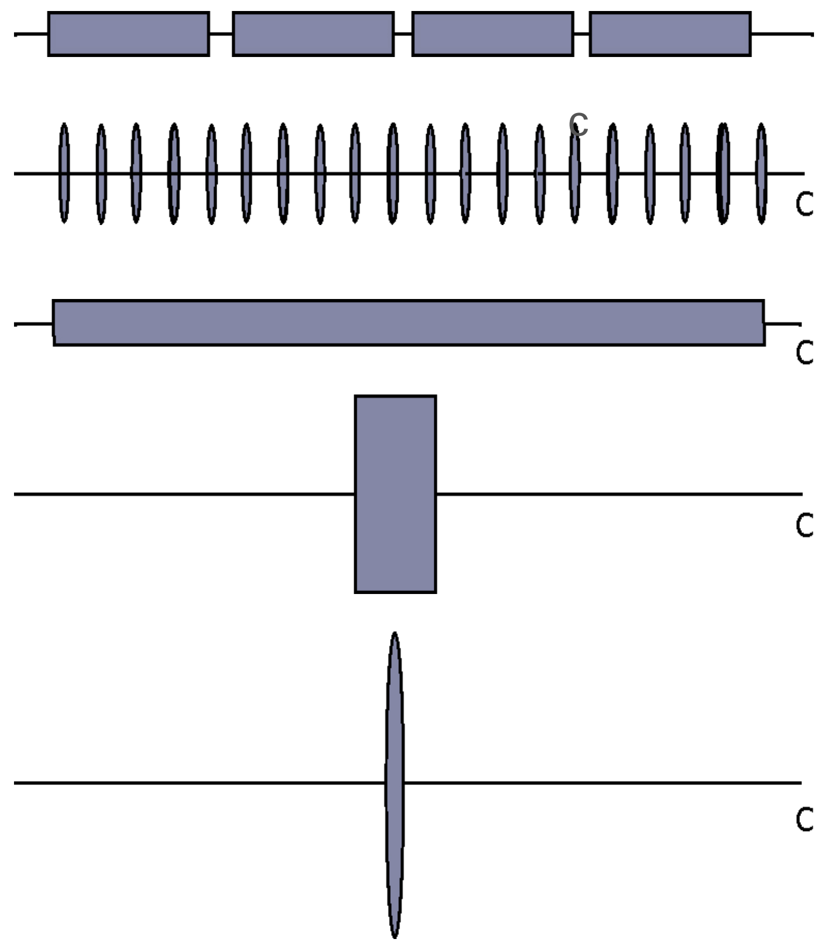
Barrier Bucket Injection
(RF System 1)

Acceleration at h = 20
(RF System 2)

Debunching in Barrier Bucket
(RF System 1)

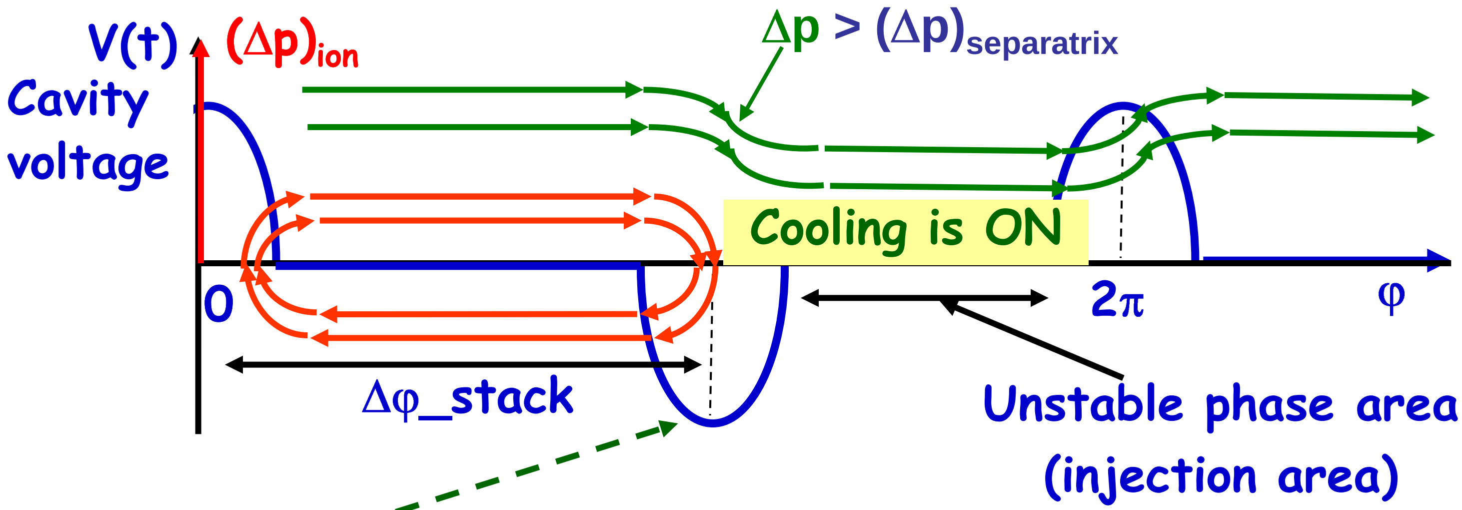
Precompression in Barrier Bucket
or Harmonic Potential
(RF system 1/2)

Compression at h = 2
(RF system 3)



Barrier Bucket Method

Ion trajectory in the phase space (Δp, φ)



In reality RF voltage pulses can be (and are actually) of nonrectangular shape

The first proposal: Fermilab, J. Griffin et.al., IEEE Trans. on Nuclear Science, v.NS30 No.4, 3502 (1983)

The particle storage with barrier buckets method was tested at ESR (GSI) with electron cooling (2008).

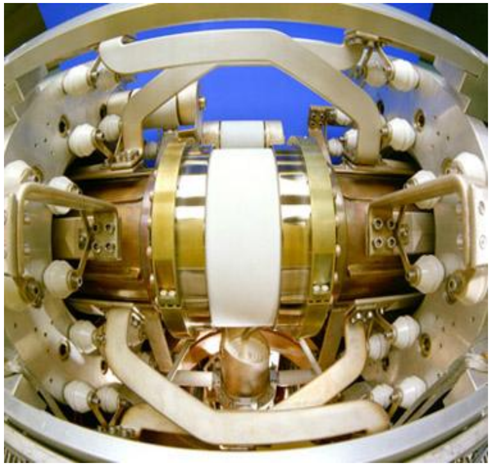
RF Systems in SIS100

- ***Acceleration Systems***
  18 ferrite loaded Cavities
  $V_{a,tot}$ = 300 kV - Frequency Range : 2.28 – 5.34 MHz

- ***Compression Systems***
  38 MA-loaded Cavities
  $V_{c,tot}$ = 1.3 MV – Frequency Range : 465 kHz (±70)

- ***Barrier Bucket Systems***
  Broad band MA-loaded Cavities
  V_b = 2x 15 kV – Frequency = 2.4 MHz.

Total Length of RF-Systems ~ 120 m
(11% of Circumference)

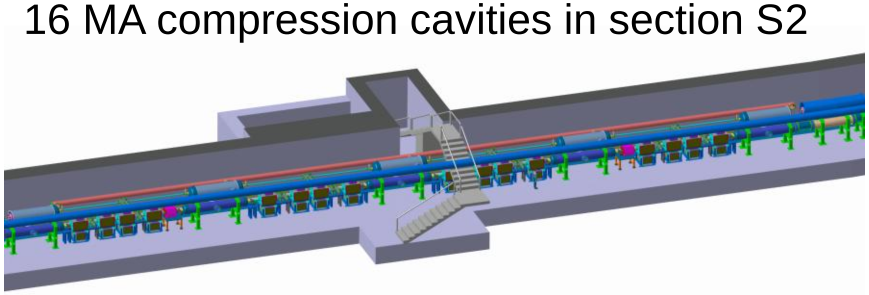


Bunch Compression Systems

Short pulse (500 μs), high power bunch compressor developed at GSI

World wide MA core material survey

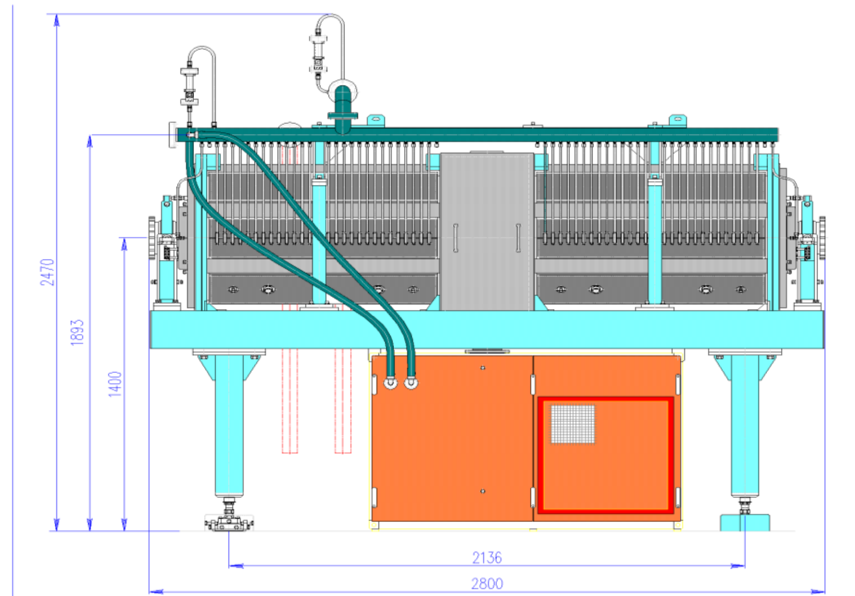
16 MA compression cavities in section S2



RF: Acceleration Sections

Acceleration Cavities:

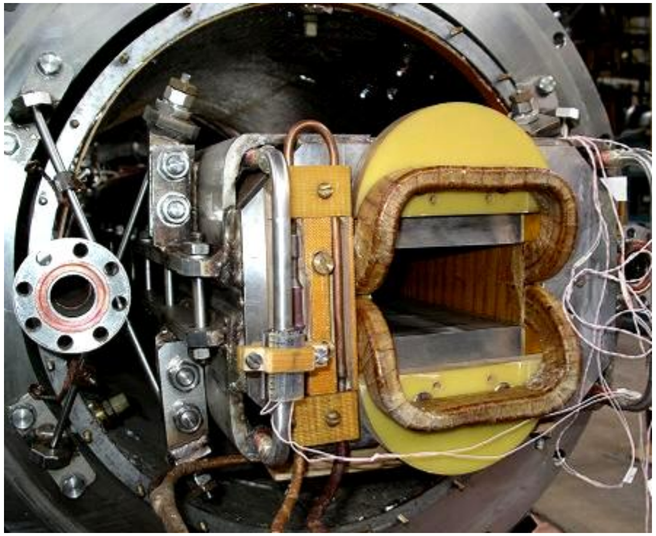
- Design study completed (BINP)



Minimization of shunt impedance:

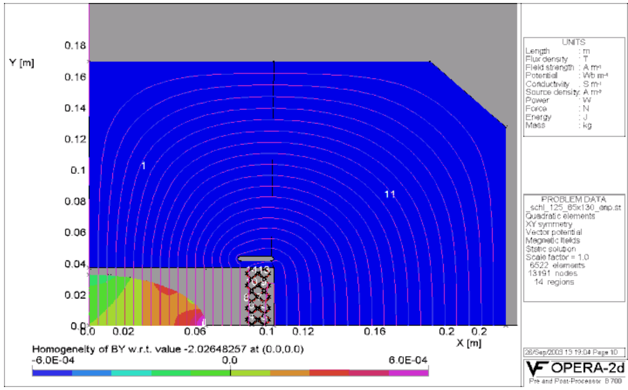
Fast semi-conductor gap switch R&D

SIS100 Fast Ramped S.C. Magnets



R&D Goals

- **Reduction of eddy / persistent current effects at 4K (3D field, AC loss)**
- **Improvement of DC/AC-field quality**
- **Guarantee of long term mechanical stability** ($\geq 2 \cdot 10^8$ cycles)



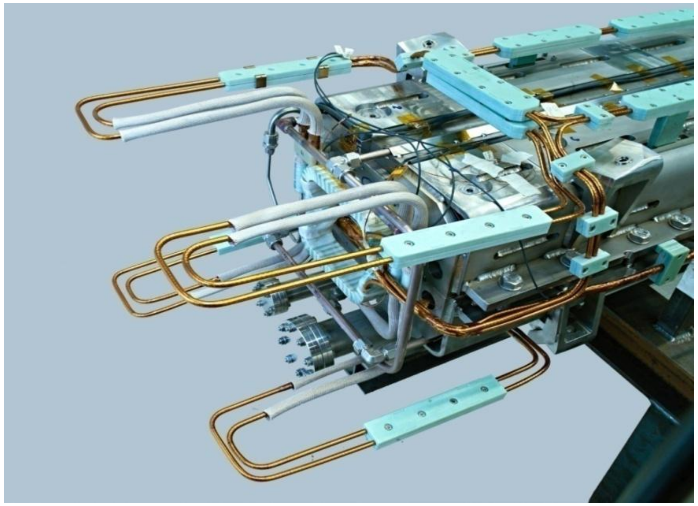
Activities

- AC Loss Reduction (exp. tests, FEM)
- 2D/3D Magnetic Field Calculations (OPERA, ANSYS, etc.)
- Mechanical Analysis and Coil Restraint (design, ANSYS) (>Fatigue of the conductor and precise positioning)

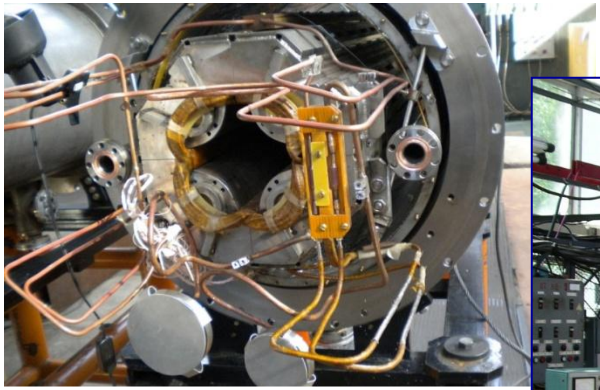
Experimental studies with modified Nuclotron magnets in JINR

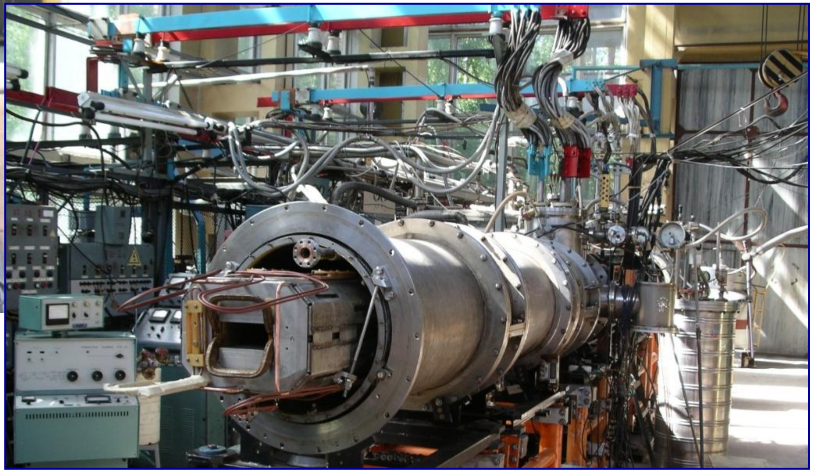
Full Length SIS100 Prototype Dipole

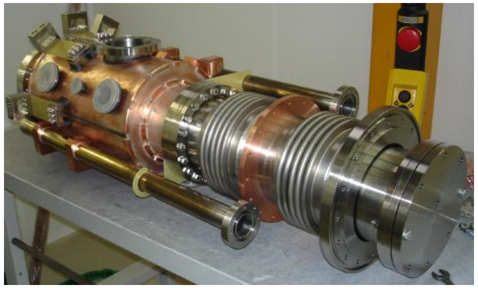
One - manufactured by BNG (Würzburg)



- Second straight dipole and quadrupole had been manufactures at JINR
- Curved dipole manufactured at BINP



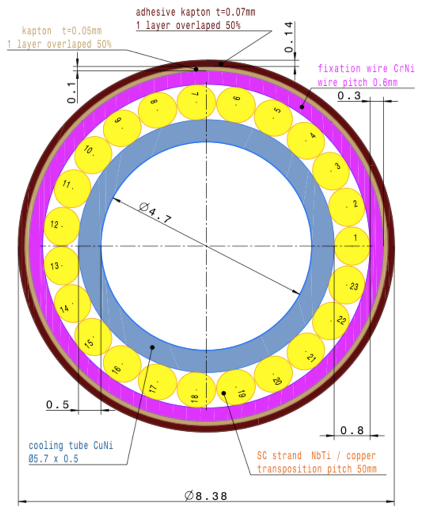


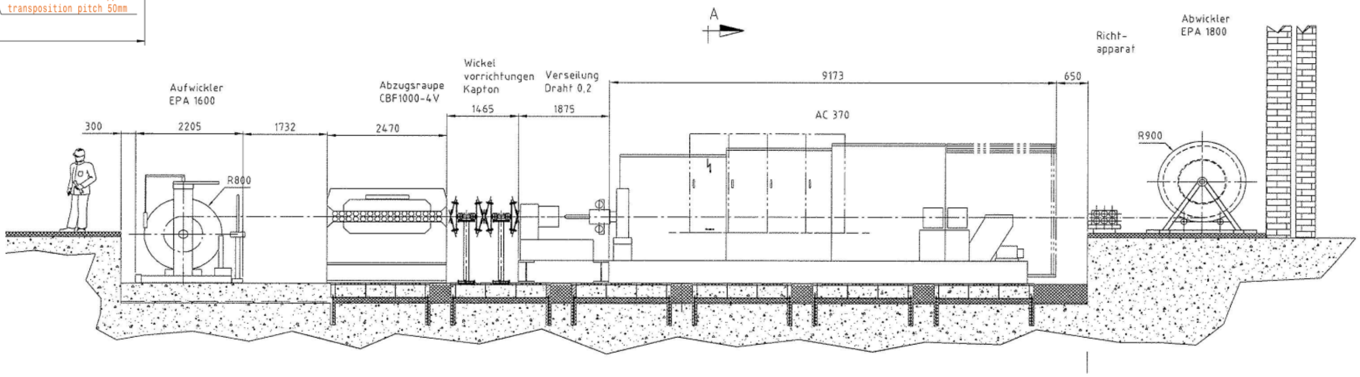


Cryocatcher prototype

Nuclotron Cable Production at BNG

Second Nuclotron type cable production capability set-up at BNG in Würzburg





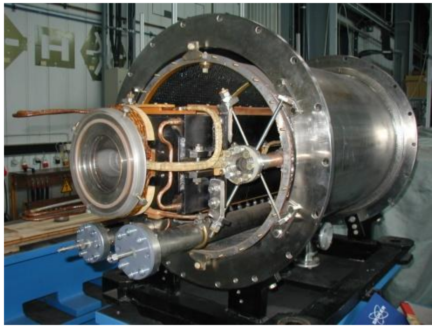
Two Stage Synchrotron SIS100/300

- **1. High Intensity- and Compressor Stage**

SIS100 with fast-ramped superconducting magnets and a strong bunch compression system.

Intermediate charge state ions e.g. U^{28+}-ions up to 2.7 GeV/u
Protons up to 30 GeV

$B\rho$= 100 Tm - B_{max}= 1.9 T - dB/dt= 4 T/s (curved)

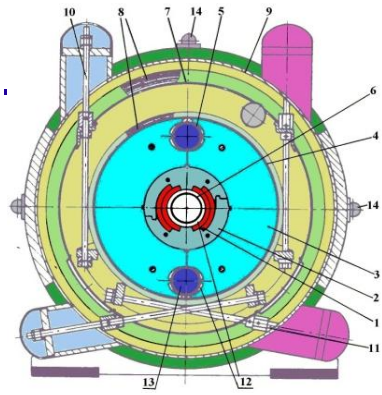


- **2. High Energy- and Stretcher Stage**

SIS300 with superconducting high-field magnets and stretcher function.

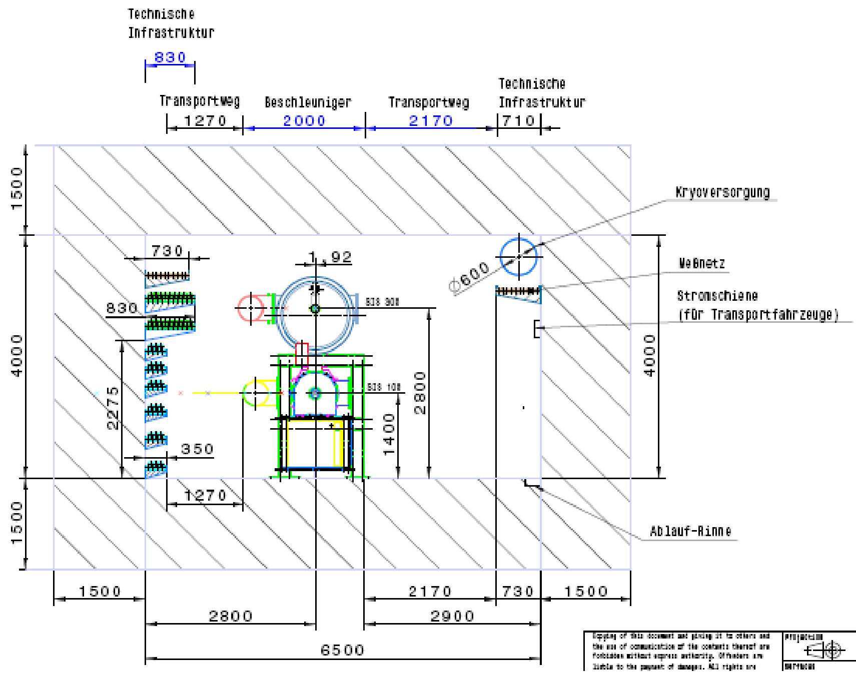
Highly charges ions e.g. U^{92+}-ions up to 34 GeV/u
Intermediate charge state ions U^{28+}- ions at 1.5 to 2.7 GeV/u with 100% duty cycle

$B\rho$= 300 Tm - B_{max}= 4.5 T - dB/dt= 1 T/s (curved)



System and Ion Optical Design

Realisation of two-stage SIS100 and SIS300 concept in one tunnel is challenging:

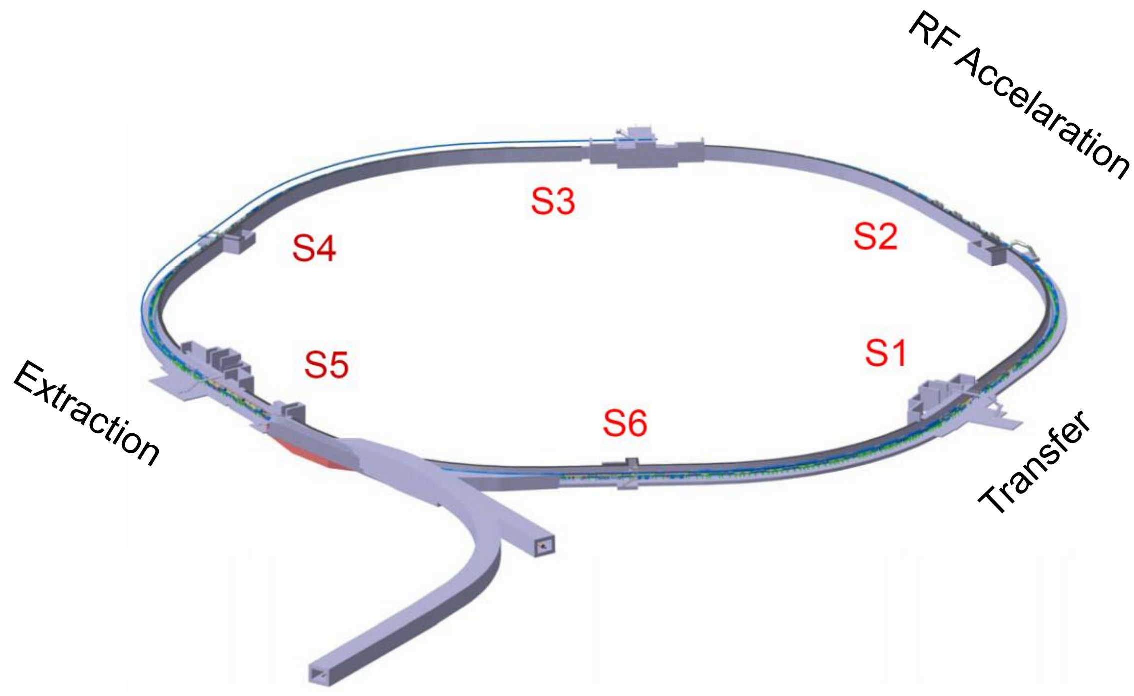


- Geometrical matching of both synchrotrons with different lattice structures (Doublet and FODO) and different magnet technologies (superferric and cosθ)
- Ratio between straight section length and arc length with fixed circumference defined by the warm straight section requirements of SIS100
- Fast, slow and emergency extraction in one short straight and precisely at the same position, with the same angle and fixed distance between the SIS100 and SIS300 extraction channel
- Vertical extraction of SIS100 bypassing SIS300 (on top of SIS100)
- Transfer between SIS100 and SIS300, 1.4 m difference, many geometrical constraints

SIS300 Basic Requirements

- The SIS300 will be installed on top of SIS100 in the same tunnel.
- The maximum magnetic rigidity is 300 Tm in high energy mode
- The magnetic rigidity is up to 100 Tm in stretcher mode
- Bent super conducting cos(θ)-type magnets will be used with a maximum field of 4.5 T in the dipoles.
- The injection into SIS300 is performed via a vertical transfer line from SIS100.
- The design injection energy is 1500 MeV (64 Tm). The expected beam emittance is 10x4 pi mm mrad. Lower injection rigidities are possible with reduced intensity down to 27 Tm in stretcher mode.
- The slow extraction is performed vertically into an extraction beamline parallel to the one of SIS100.
- In case of emergency the beam is dumped into an internal target

SIS300 Overview

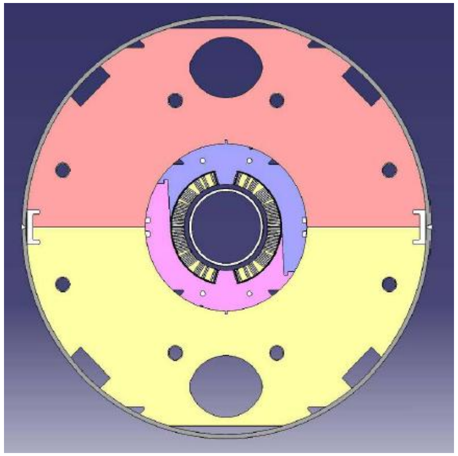


Sixfold symmetry

SIS100 technical subsystems define the length and number of the straight sections of both synchrotrons

Good geometrical matching to the overall geometry

A parallel supply tunnel at the inner shell of the synchrotron

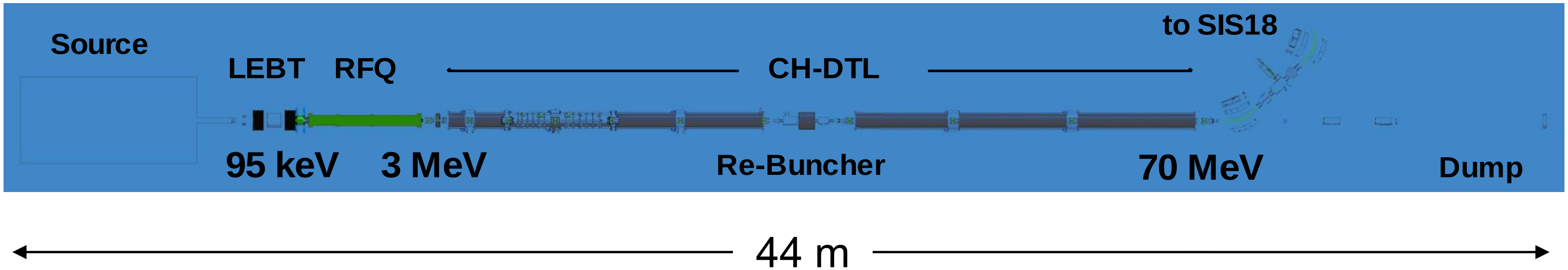


Main Dipoles

Block number	5
Turn number/quadrant	34 (17+9+4+2+2)
Operating current	8924 A
Yoke inner radius	98 mm
Peak field on conductor (with self field)	4.90 T
Bpeak / Bo	1.09
Working point on load line	69%
Current sharing temperature	5.69 K
Inductance/length	2.9 mH/m
Stored energy/length	116.8 kJ/m

Discorap-Project by INFN
Magnet finished in 2010

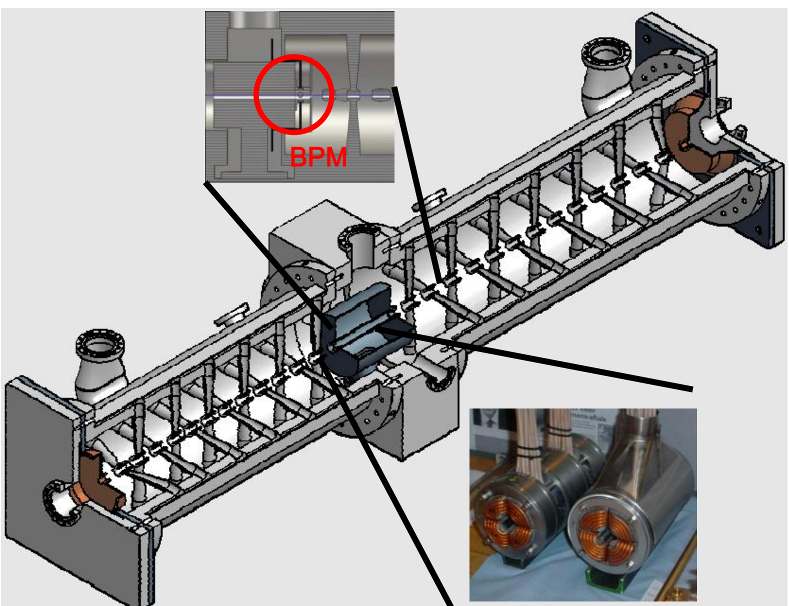
Proton Linac Overview



Beam energy	70 MeV
Beam current (op.)	35 mA
Beam current (des.)	*70 mA*
Beam pulse length	36 µs
Repetition rate	4 Hz
Rf-frequency	325.224 MHz
Tot. hor. emit. (norm.)	2.1 / *4.2* µm
Tot. mom. spread	$\leq \pm 10^{-3}$
Linac length	≈ 33 m

Developments for the Proton Linac

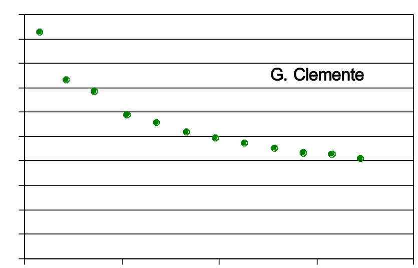
DTL-Energy	70 MeV
# cavities+bunchers	6+3
# internal quads	11 triplets
# internal BPMs	4



internal quad triplet

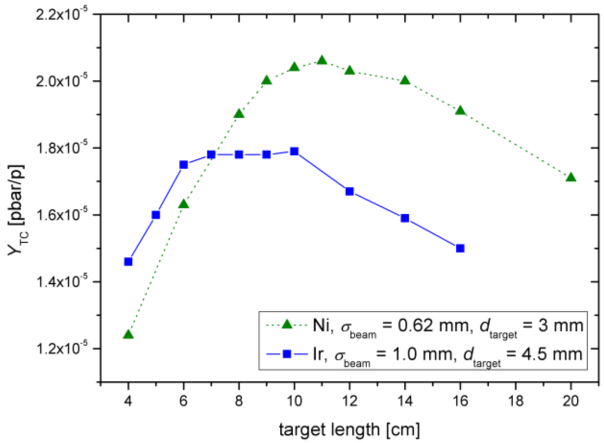
- Final cavity assembly comprises:
    - rf-coupled CH-cavity
    - internal quad triplet lens
    - one BPM (partly)

- Challenges:
    - CH-cavities never built before
    - BPM R&D ongoing (primary-rf suppression)
    - many interfaces w.r.t. system design:
        - beam dynamics
        - quad design
        - cavity design
        - BPM design

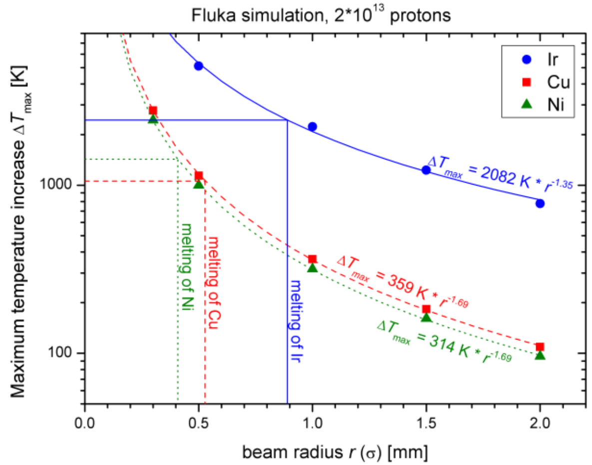


Antiproton Target and Separator

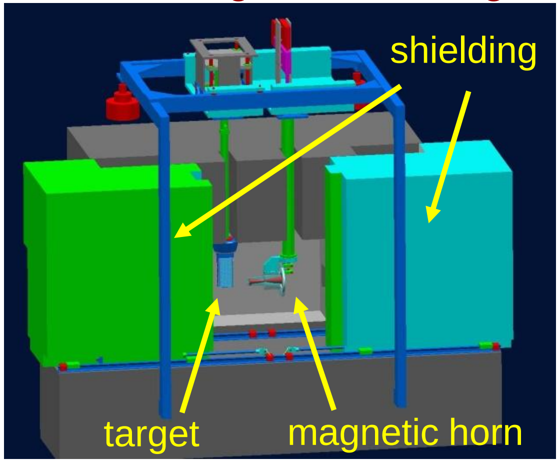
production rate of antiprotons
primary beam 29 GeV protons



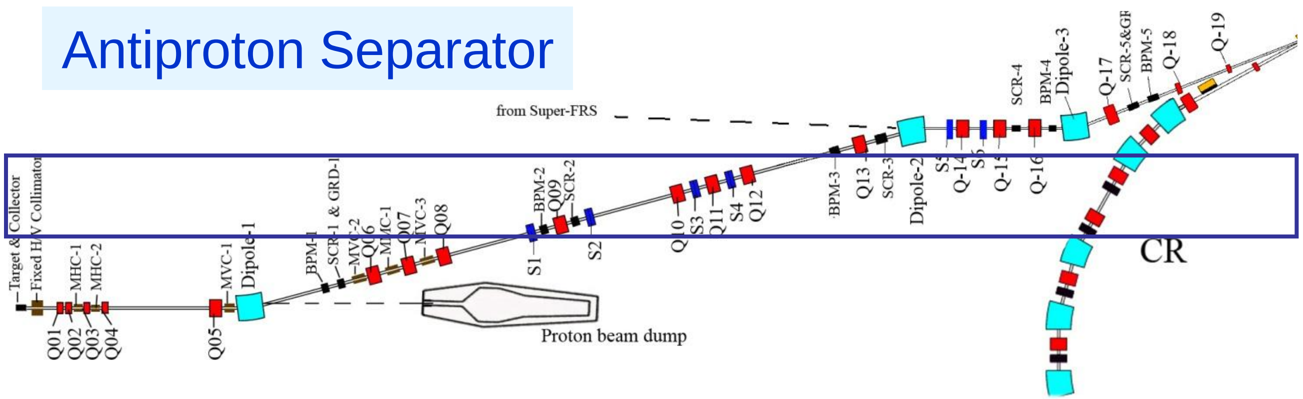
temperature of target
⇒ choice of nickel



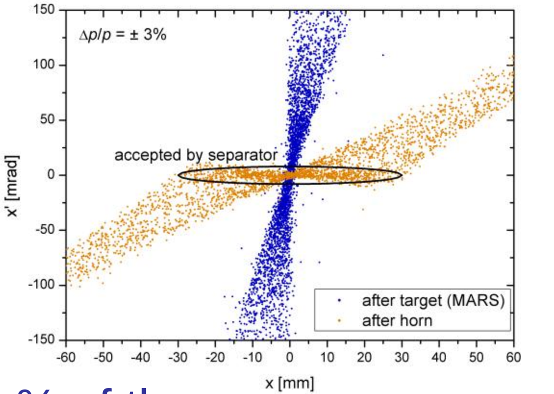
target station
shielding and handling



Antiproton Separator

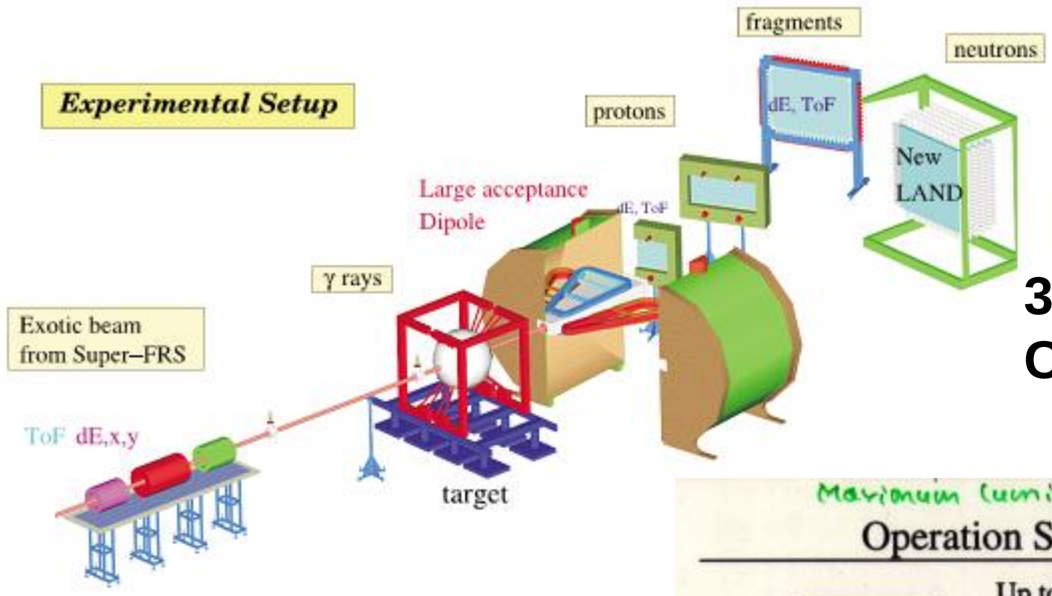


Particle tracking in separator

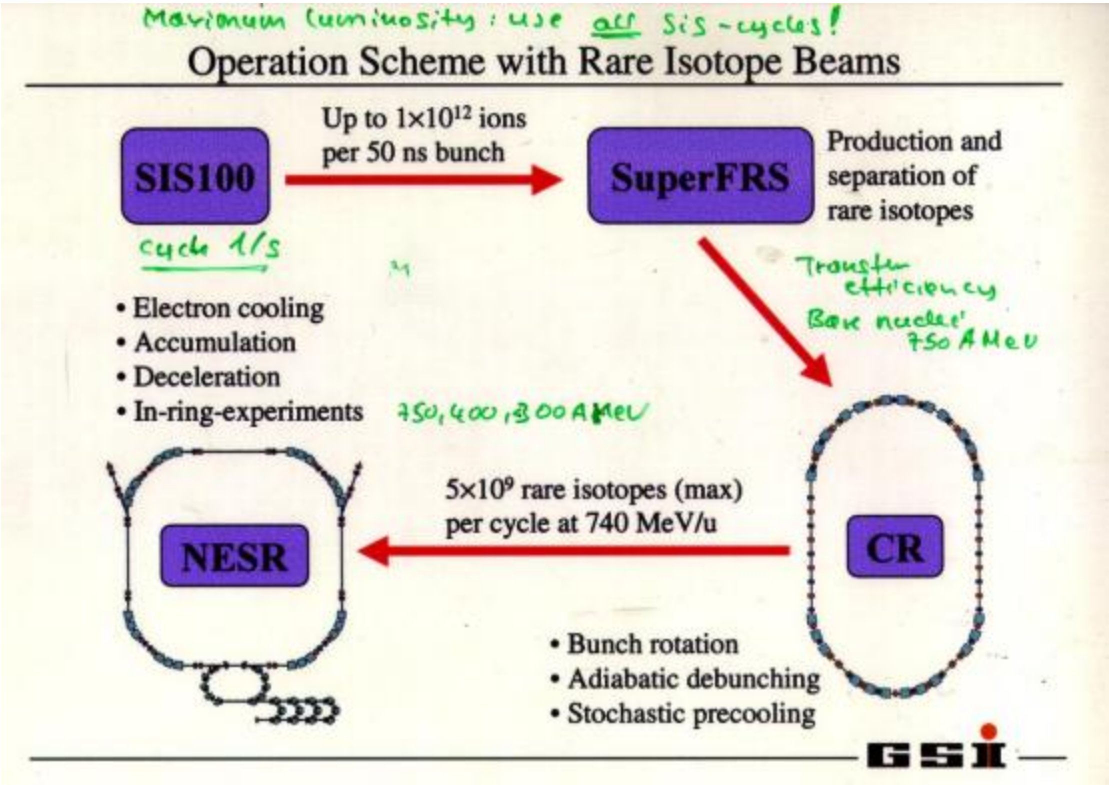


according to tracking calculations about 70 % of the produced antiprotons will be stored in the CR

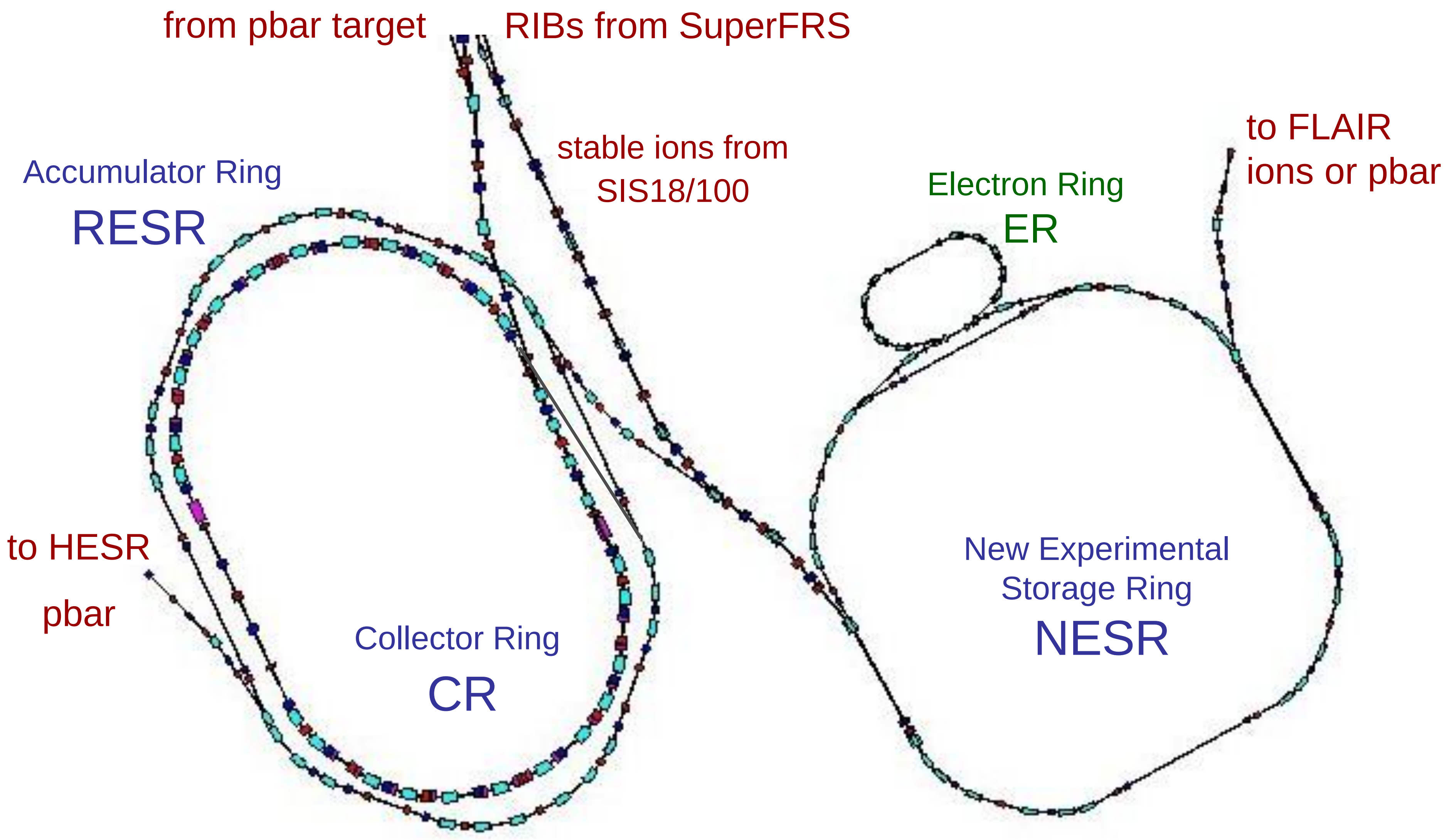
3.1. Fixed target experiments (module 2)



3.2. Experiments with Circulating beam (module 4)



The FAIR 13 Tm Storage Rings



Benefits of Beam Cooling

- Improved beam quality
  - Precision experiments
  - Luminosity increase

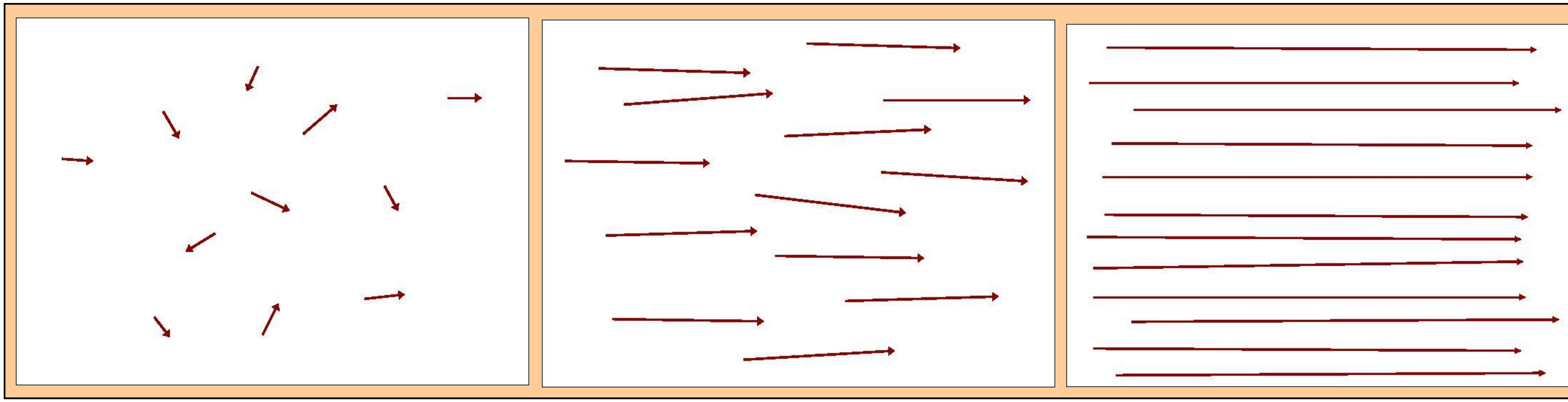
- Compensation of heating
  - Experiments with internal target
  - Colliding beams

- Intensity increase by accumulation
  - Weak beams from source can be increased
  - Secondary beams (antiprotons, rare isotopes)

Courtesy to M.Steck

Beam Temperature

Thermal particle motion (temperature is conserved)



at rest (source) | low energy | high energy

In a standard accelerator the beam temperature is not reduced
(thermal motion is superimposed the average motion after acceleration)
but: many processes can heat up the beam

temperature

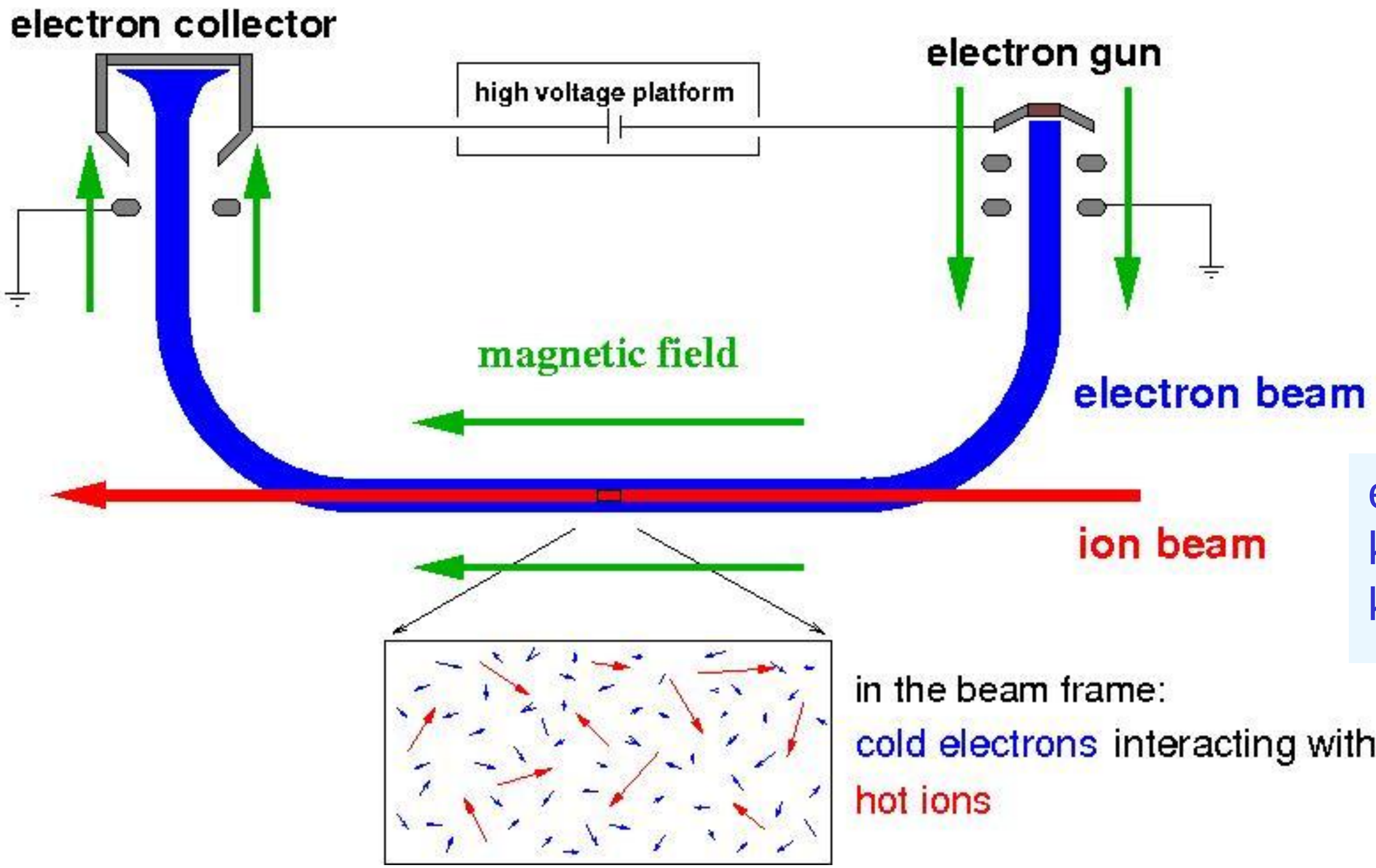
longitudinal $$\frac{1}{2}k_B T_{\parallel} = \frac{1}{2}m v_{\parallel}^2 = \frac{1}{2}mc^2\beta^2\left(\frac{\delta p_{\parallel}}{p}\right)^2$$

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

$$\theta_{\perp}(s) = \sqrt{\frac{\epsilon}{\beta_{\perp}(s)}}$$

Courtesy to M.Steck

Electron Cooling



$v_{e//} = v_{i//}$

$E_e = m_e / M_i \cdot E_i$

e.g. :220 keV electrons
cool 400 MeV/u ions

electron temperature
$k_B T_\perp \approx 0.1$ eV
$k_B T_{//} \approx 0.1 - 1$ meV

superposition of a cold intense electron beam with the same velocity

momentum transfer by Coulomb collisions

cooling force results from energy loss in the co-moving gas of free electrons

Courtesy to M.Steck

Electron Cooling Time

first estimate:
(Budker 1967)

$$\tau = \frac{3}{8\sqrt{2\pi} n_e Q^2 r_e r_i c L_C} \left(\frac{k_B T_e}{m_e c^2} + \frac{k_B T_i}{m_i c^2}\right)^{3/2}$$

for large relative velocities

cooling time $\tau_z \propto \frac{A}{Q^2} \frac{1}{n_e \eta} \beta^3 \gamma^5 \theta_z^3$ $\begin{cases} \theta_{x,y} = \frac{v_{x,y}}{\gamma \beta c} \\ \theta_{\parallel} = \frac{v_{\parallel}}{\gamma \beta c} \end{cases}$

<u>cooling rate:</u>

- slow for hot beams $\propto \theta^3$
- decreases with energy $\propto \gamma^{-2}$ ($\beta\gamma\theta$ is conserved)
- linear dependence on electron beam intensity n_e and cooler length $\eta = L_{ec}/C$
- favorable for highly charged ions Q^2/A
- independent of hadron beam intensity

for small relative velocities

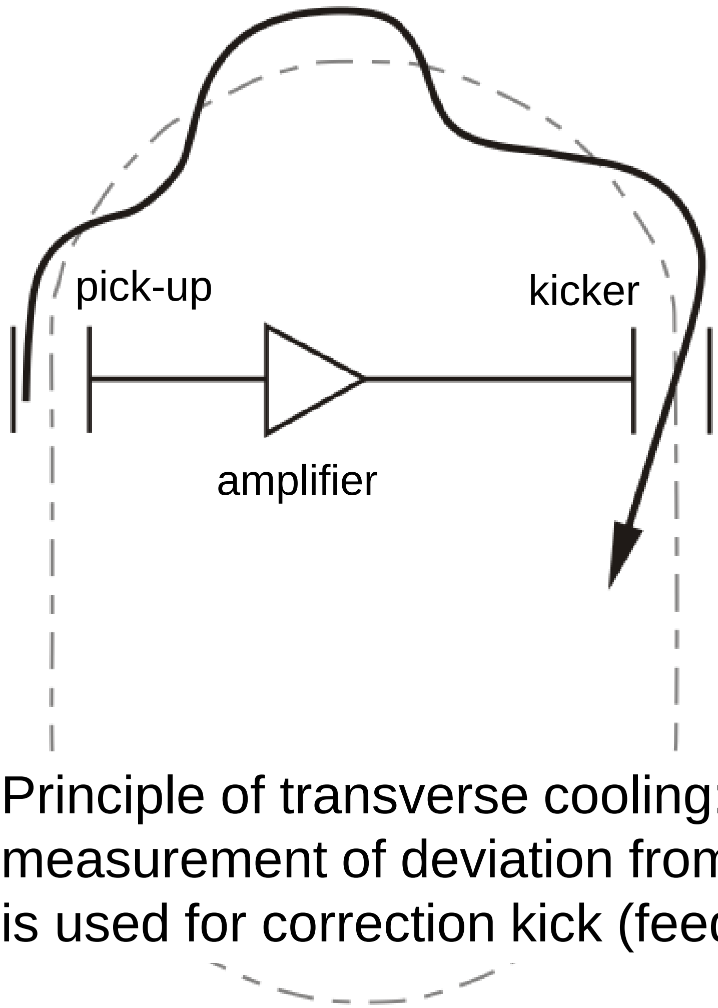
cooling rate is constant and maximum at small relative velocity

$F \propto v_{rel} \Rightarrow \tau = \Delta t = p_{rel}/F =$ constant

Courtesy to M.Steck

Stochastic Cooling

First cooling method which was successfully used for beam preparation



S. van der Meer, D. Möhl, L. Thorndahl et al.

Conditions:
Betatron phase advance
(pick-up to kicker): $(n + \frac{1}{2})\,\pi$

Signal travel time = time of flight of particle
(between pick-up and kicker)

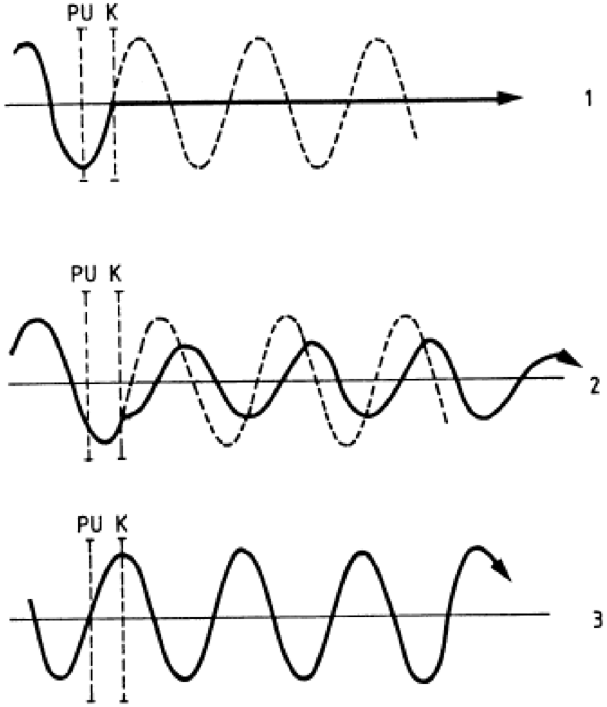
Sampling of sub-ensemble of total beam

Principle of transverse cooling:
measurement of deviation from ideal orbit
is used for correction kick (feedback)

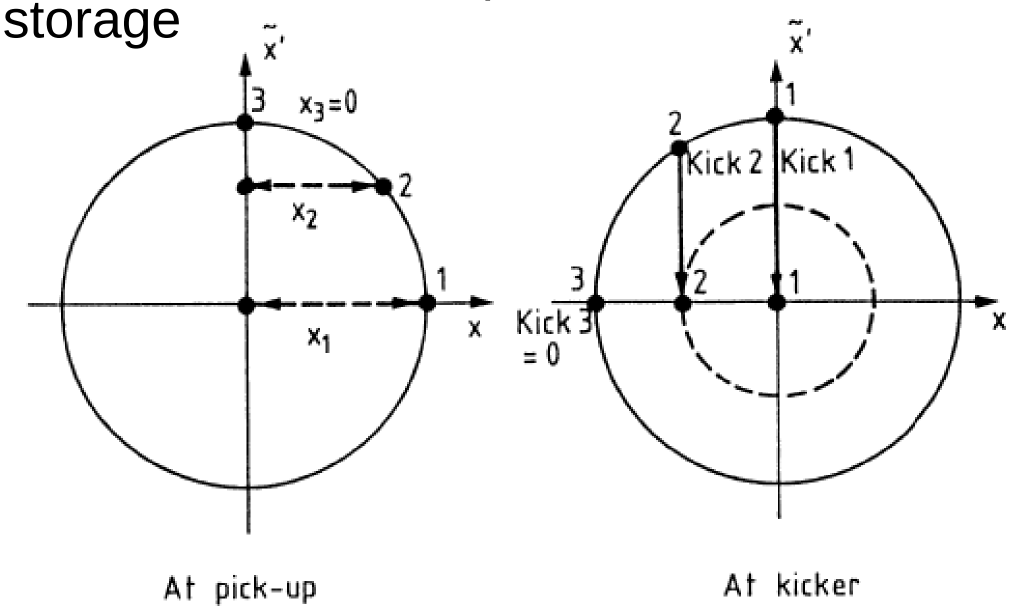
Courtesy to M.Steck

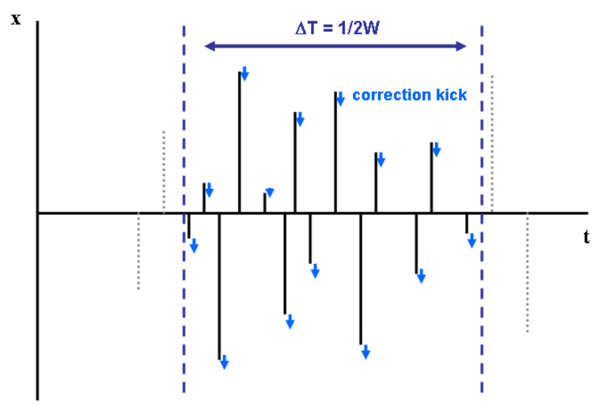
Stochastic Cooling

single particle betatron motion along storage ring without and with correction kick



projection to two-dimensional horizontal phase area





Nyquist theorem:
a system with a band-width Δf = W in frequency domain can resolve a minimum time duration ΔT=1/(2W)

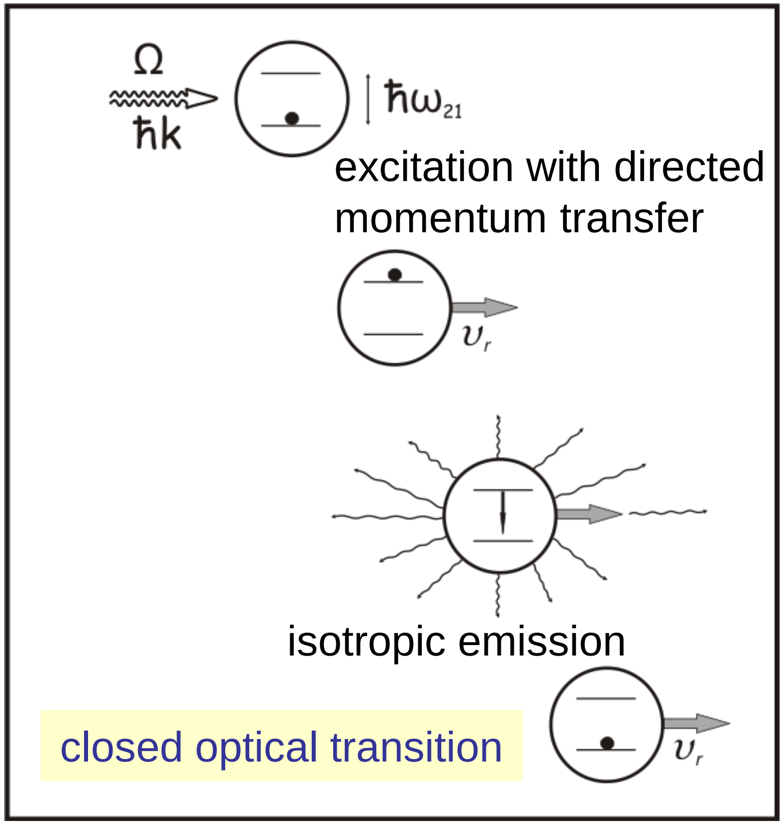
$$\tau^{-1} = T_0^{-1} \times \frac{\Delta x}{x} = \frac{g2W}{N},\ if \sum_{i=1..N_s} x_i = x$$

$$\tau^{-1} \leq \frac{2W}{N},\ if\ g \leq 1$$

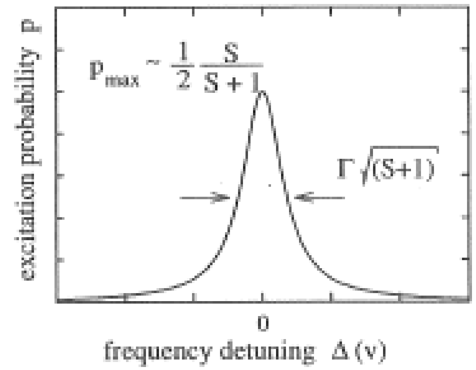
Courtesy to M.Steck

Laser Cooling

$$\Omega = \gamma\omega_{21}(1 \pm \beta\cos\theta)$$



the directed excitation and isotropic emission result in a transfer of velocity v_r



cooling force

$$\vec{F}(\vec{v},\vec{k}) = \frac{\hbar\vec{k}}{2} S\Gamma \frac{(\Gamma/2)^2}{(\omega - \omega_{21} - \vec{v}\vec{k}) + (\Gamma/2)^2(1+S)}$$

Lorentzian with width $\Gamma/k \sim 10$ m/s

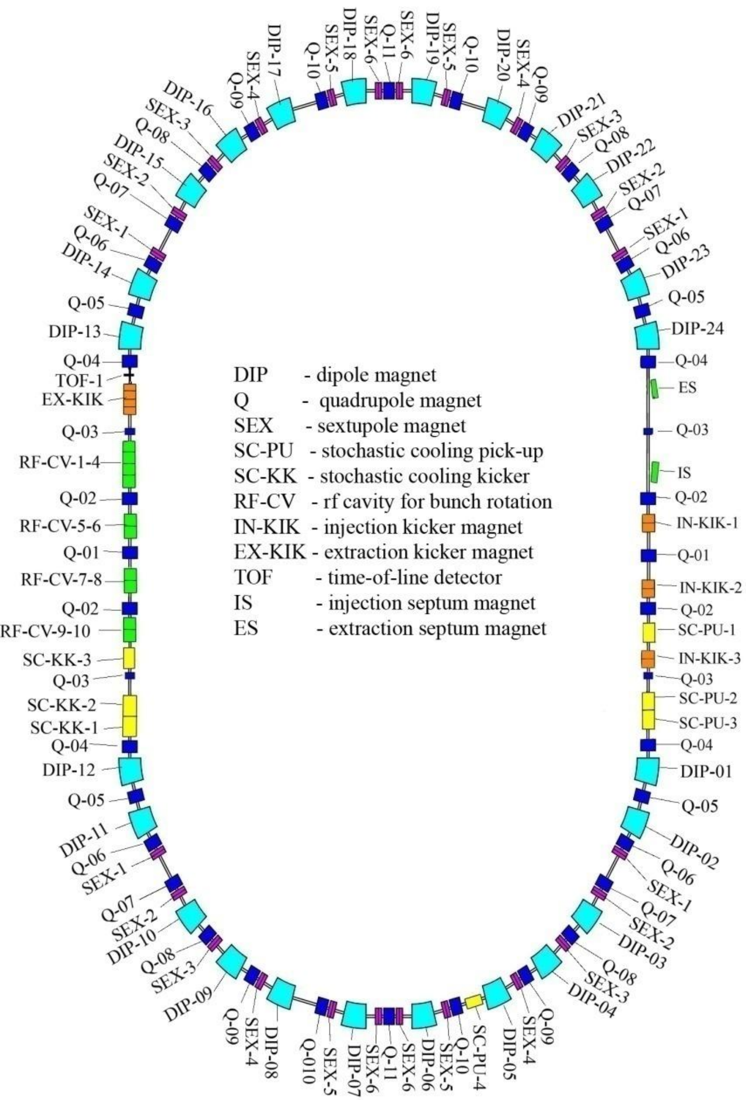
minimum temperature $T_D = \frac{\hbar\Gamma}{2k_B}$ (Doppler limit)
typical $10^{-5} – 10^{-4}$ K

typical cooling time ~ 10 μs

only longitudinal cooling

Courtesy to M.Steck

The Collector Ring CR



circumference 216 m
magnetic bending power 13 Tm
large acceptance $\varepsilon_{x,y}$ = 240 (200) mm mrad
$\Delta p/p = \pm$ 3.0 (1.5) %

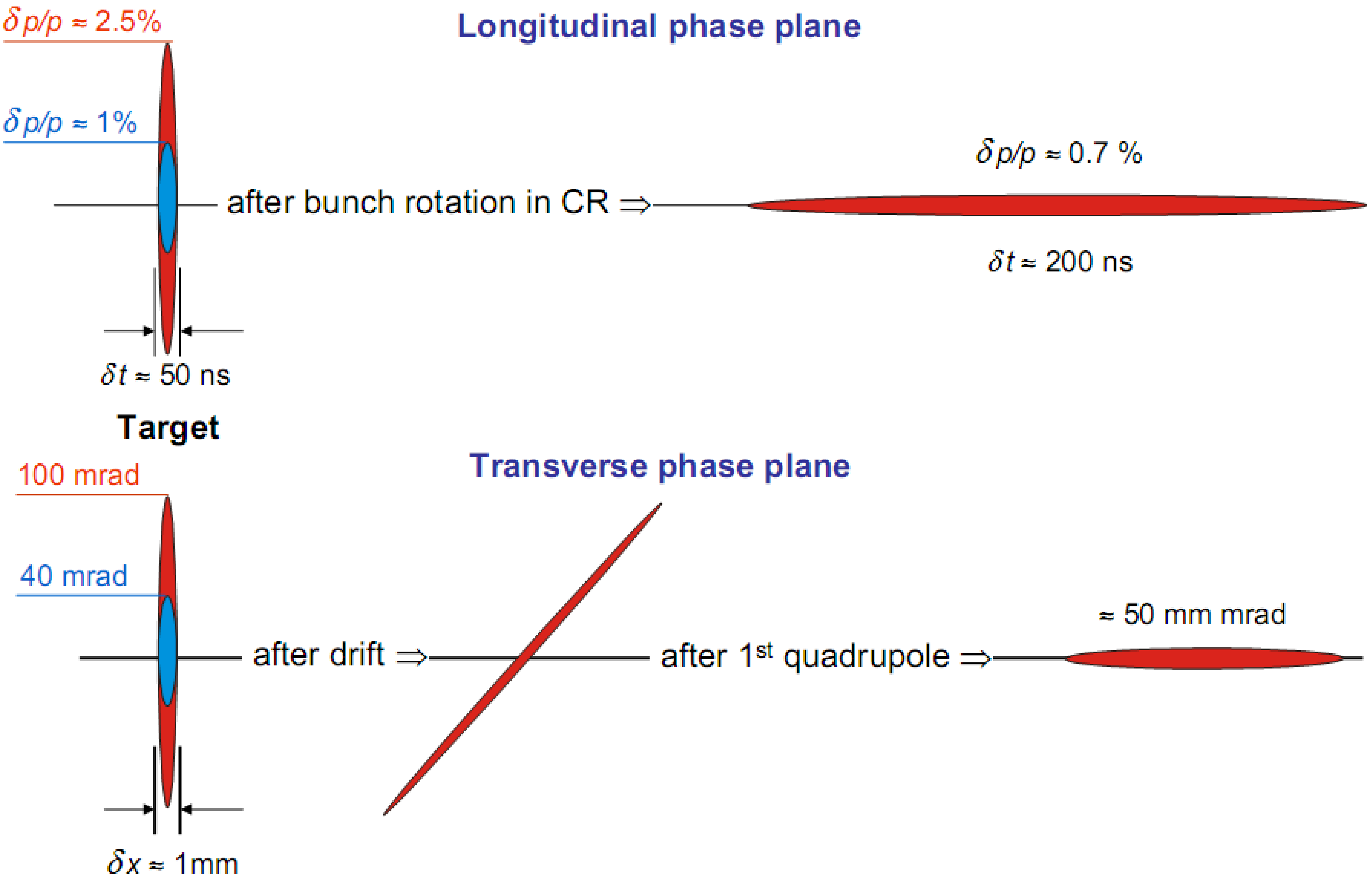
fast stochastic cooling (1-2 GHz)
of antiprotons (10 s) and
rare isotope beams (1.5 s)

fast bunch rotation at h=1
with rf voltage 200 kV
adiabatic debunching
optimized ring lattice (slip factor)
for proper mixing
large acceptance magnet system

additional feature:
isochronous mass measurements
of rare isotope beams

option: upgrade of rf system to 400 kV
and stochastic cooling to 1-4 GHz

Fast decreasing of the dP/P and angular spread is provided at CR:



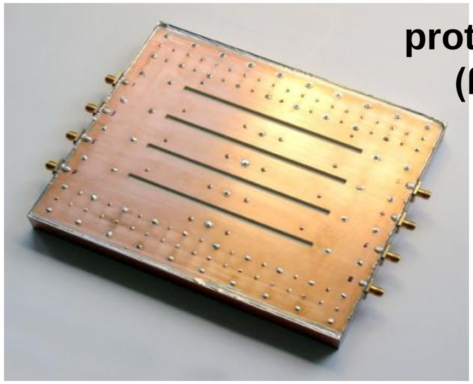
After that beam is stochastically cooled

Developments for the Storage Rings

Challenges of the Stochastic Cooling Systems :

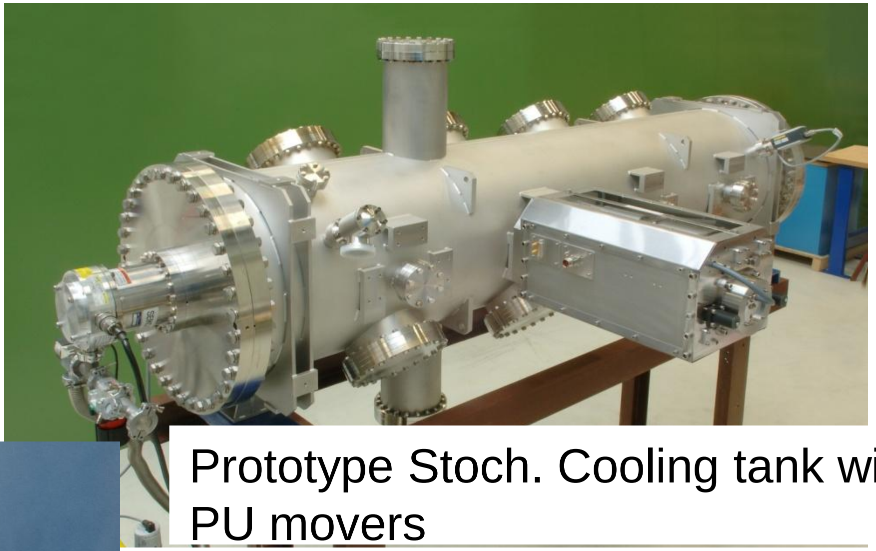
- 2 GHz band (large bandwidth required)
- UHV conditions and on 20 K temperature level
- Mounted on movable feedthroughs

CR: fast stochastic cooling (1-2 GHz) of antiprotons (10 s) and RIBs (1.5 s)

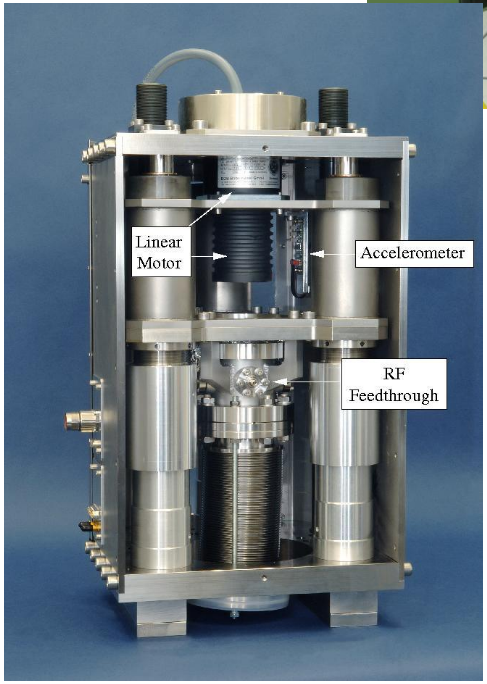


prototype electrode (ß = 0.83-0.97)

Mechanics for Stochastic cooling PU and Kickers



Prototype Stoch. Cooling tank with PU movers



Move PU and kicker electrodes at 5 sec cycle time in CR

Criteria for the Layout of the HESR

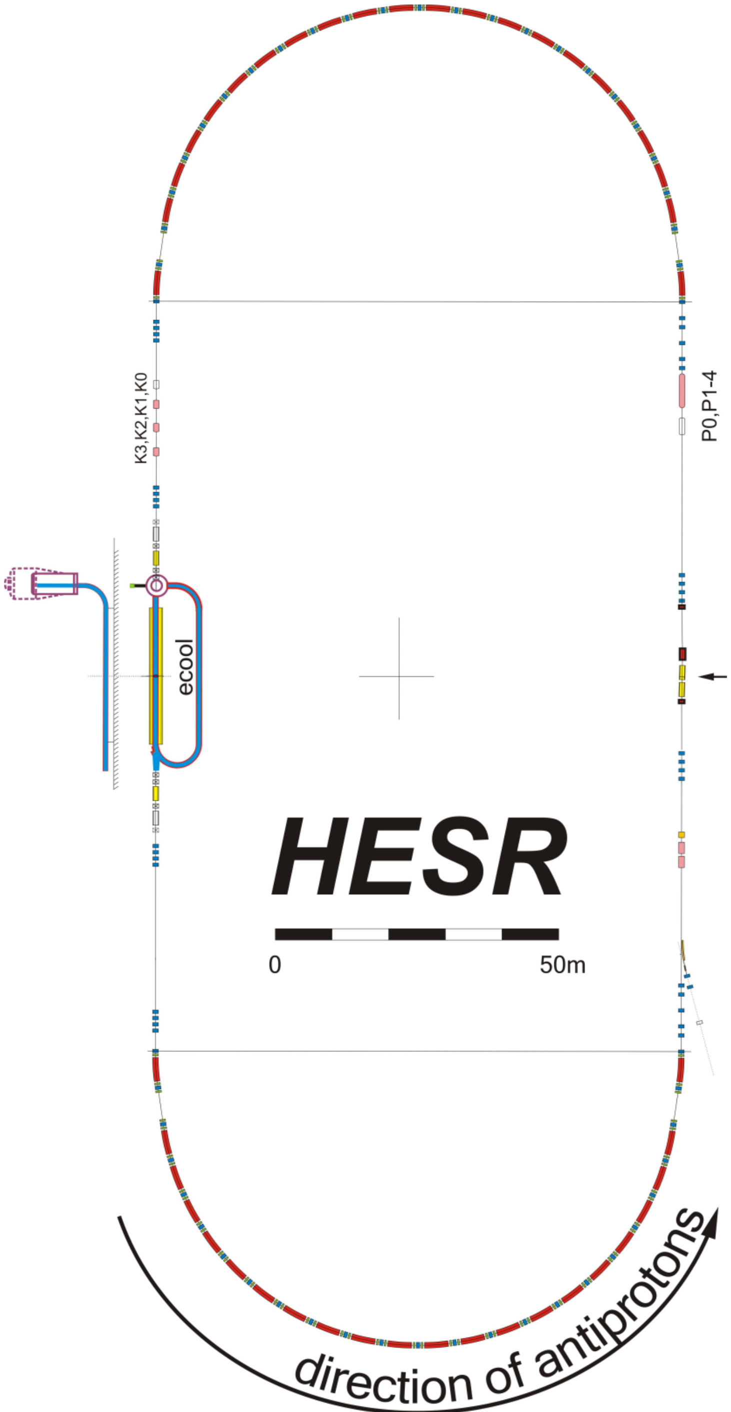
- HESR design driven by the requirements of PANDA:

- Antiprotons with 1.5 GeV/c ≤ p ≤ 15 GeV/c
- High luminosity: $2 \cdot 10^{32}$ $cm^{-2}s^{-1}$
  - -Thick targets: $4 \cdot 10^{15}$ cm^{-2}

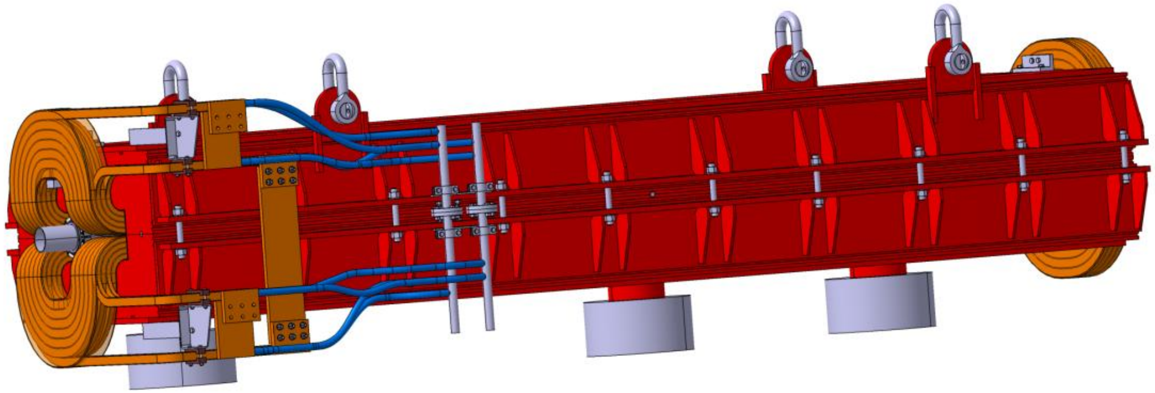
- High momentum resolution: $\Delta p/p \leq 4 \cdot 10^{-5}$
  - -Phase space cooling

- Long beam life time: >30 min

Basic Data of HESR

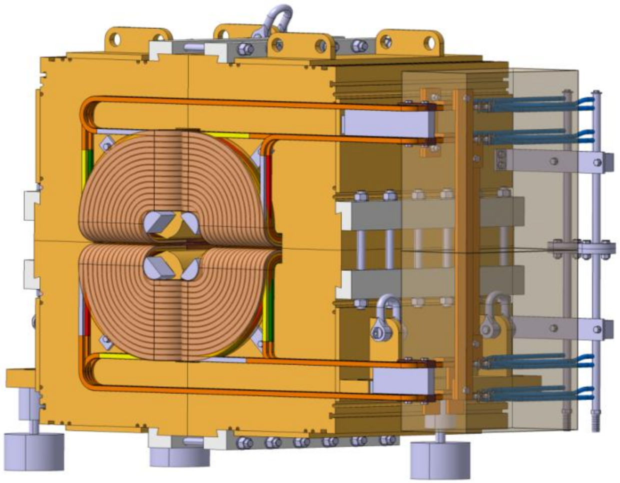


- Circumference 574 m
- Momentum (energy) range 1.5 to 15 GeV/c (0.8-14.1 GeV)
- Injection of (anti-)protons from RESR at 3.8 GeV/c
- Maximum dipole field: 1.7 T
- Dipole field at injection: 0.4 T
- Dipole field ramp: 0.025 T/s
- Acceleration rate 0.2 (GeV/c)/s



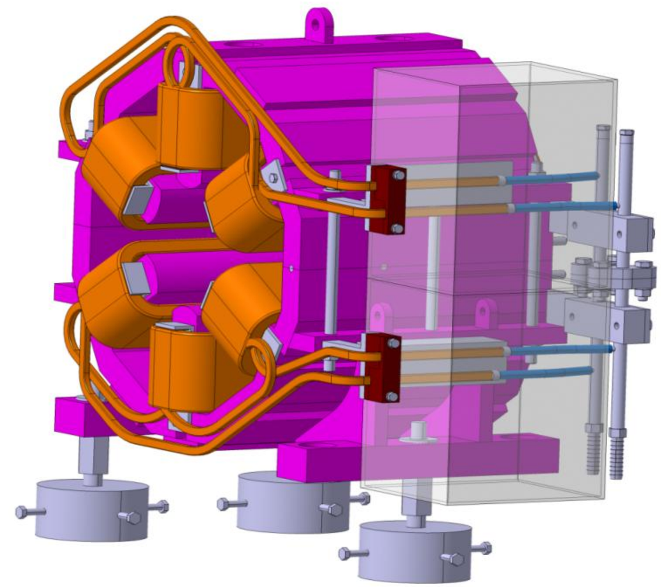
Number	44
Magnetic length	4.2 m
Iron length (arc)	4.126 m
Deflection angle	8.182°
Max B-field	1.7 T
Min B-field	0.17 T
Aperture	100 mm
Number of turns per coil	24
Current	2922 A
Current density	4.4 A/mm^2
UDC	36 V
R (dipole)	12.3 mΩ
L (dipole)	40 mH

Quadrupoles



Number	**84**
Magnetic length	**0.6 m**
Iron length (arc)	**0.58 m**
Max gradient	**20 T/m**
Aperture	**100 mm**
Number of turns per coil	**100**
Current	**300 A**
Current density	**6.8 A/mm^2**
UDC	**55.3 V**
R (quadrupole)	**184 mΩ**

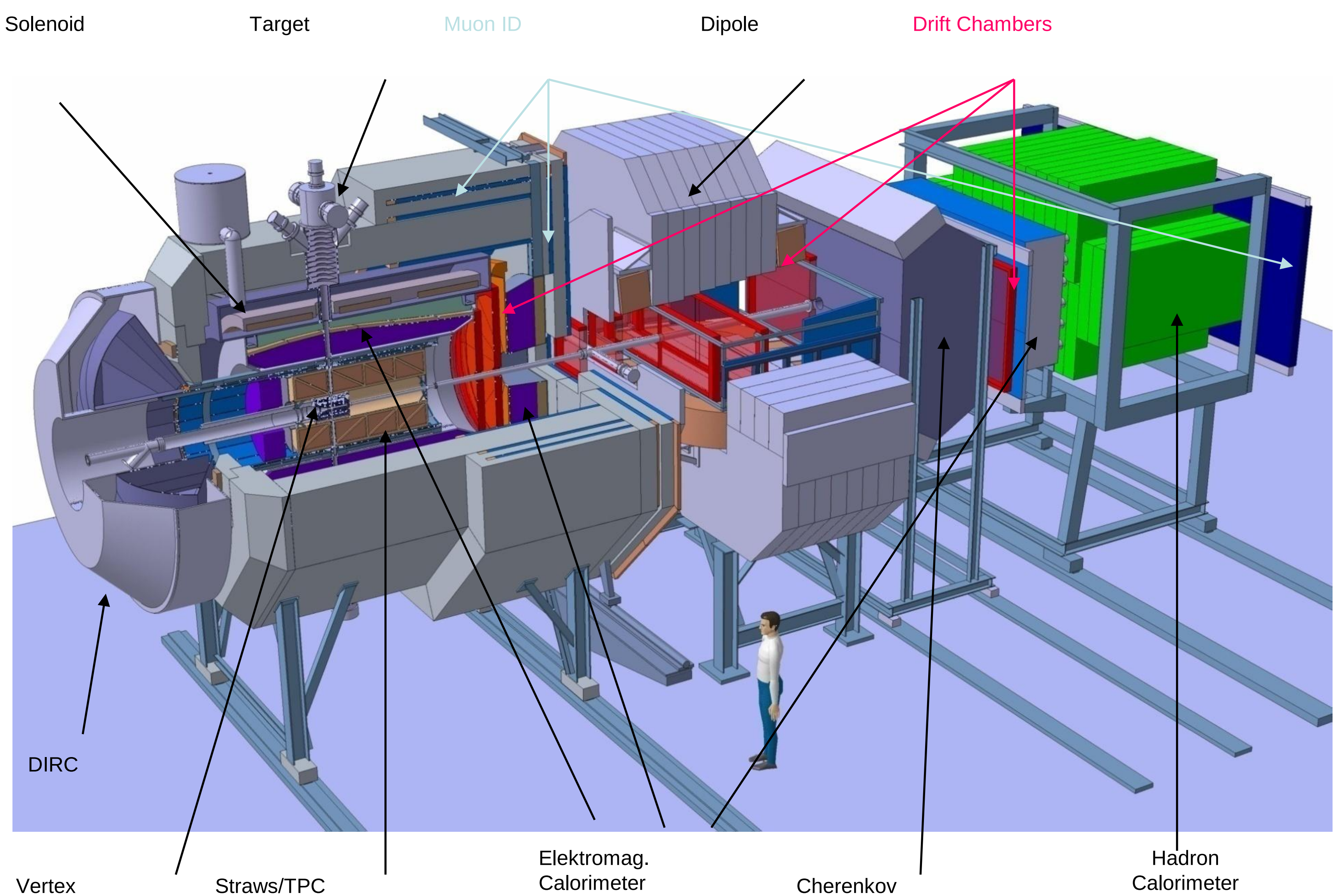
Sextupoles



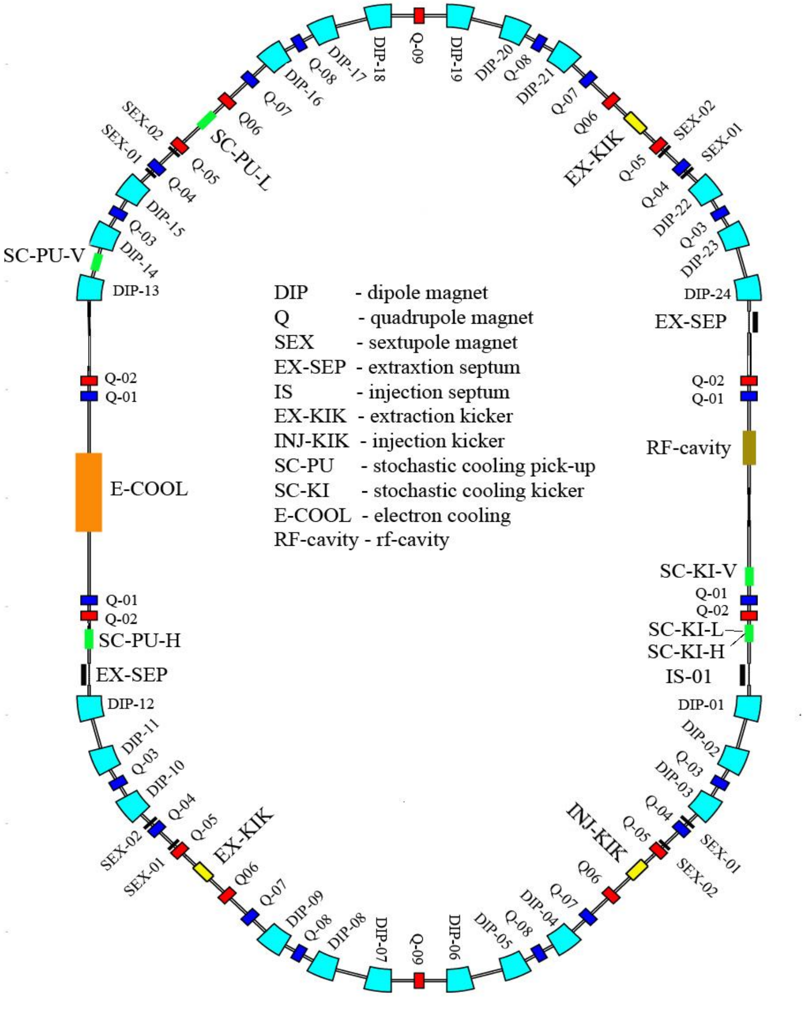
Number	52 in arcs
	8 in straights
Magnetic length	0.3 m
Max d^2B/dx^2	42.5 T/m^2
Aperture	135 mm

(to allow insertion of beam position monitors)

PANDA detector



RESR The Antiproton Accumulator Ring



circumference	240 m
magnetic bending power	13 Tm
tunes Q_x/Q_y	3.12/4.11
momentum acceptance	$\pm$1.0 %
transverse accept. h/v	25×10^{-6} m
transition energy	3.3-6.4

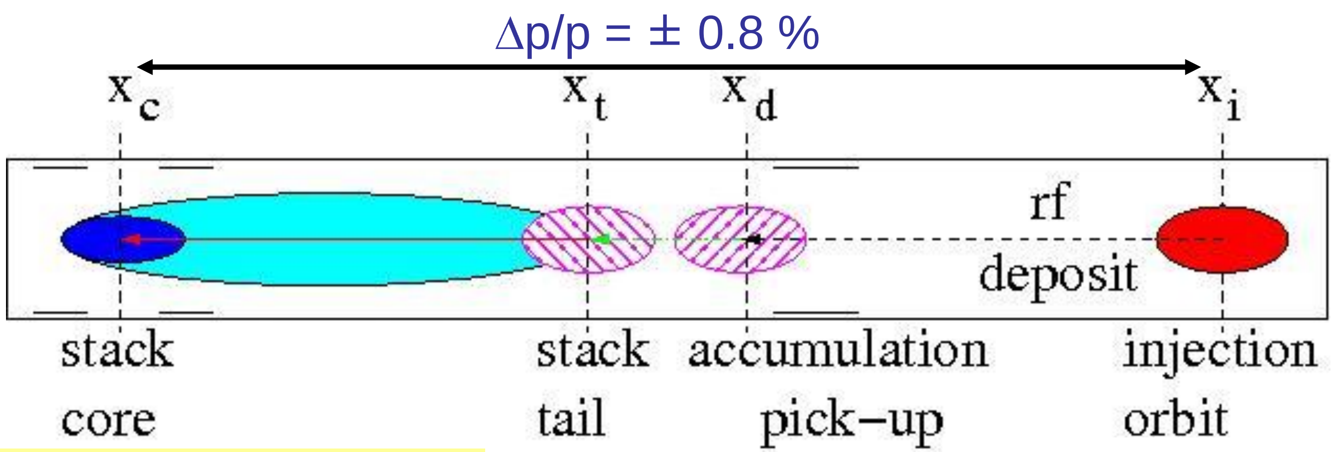
accumulation of antiprotons by a combination of rf and stochastic cooling

max. accumulation rate 3.5 (7)$\times10^{10}$/h

max. stack intensity ~ 1 $\times$ 10^{11}

additional mode:
fast deceleration of RIBs (antiprotons) to a minimum energy of 100 MeV/u
for injection into NESR (ER)
for collider mode experiments

Antiproton Accumulation in RESR

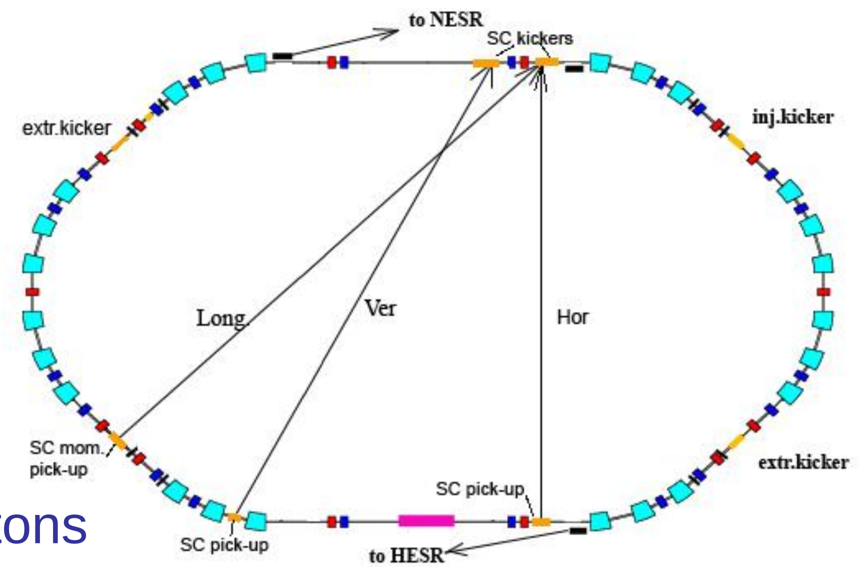


core cooling 2-4 GHz

longitudinal
horizontal
vertical

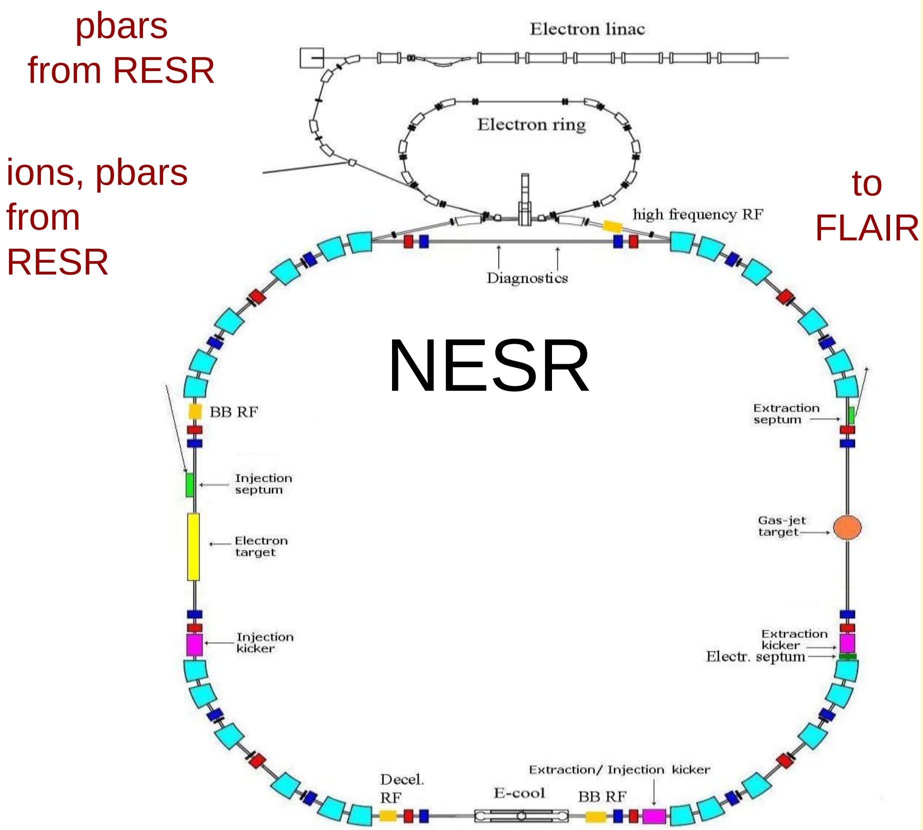
tail cooling 1-2 GHz

longitudinal



injection of 1×10^{8} antiprotons every 10 s
pre-cooling in CR provides
$\delta p/p = 1\times10^{-3}$, $\varepsilon_{x,y}$= 5 mm mrad
maximum stack intensity: 1×10^{11} antiprotons
pre-cooling after injection considered as option

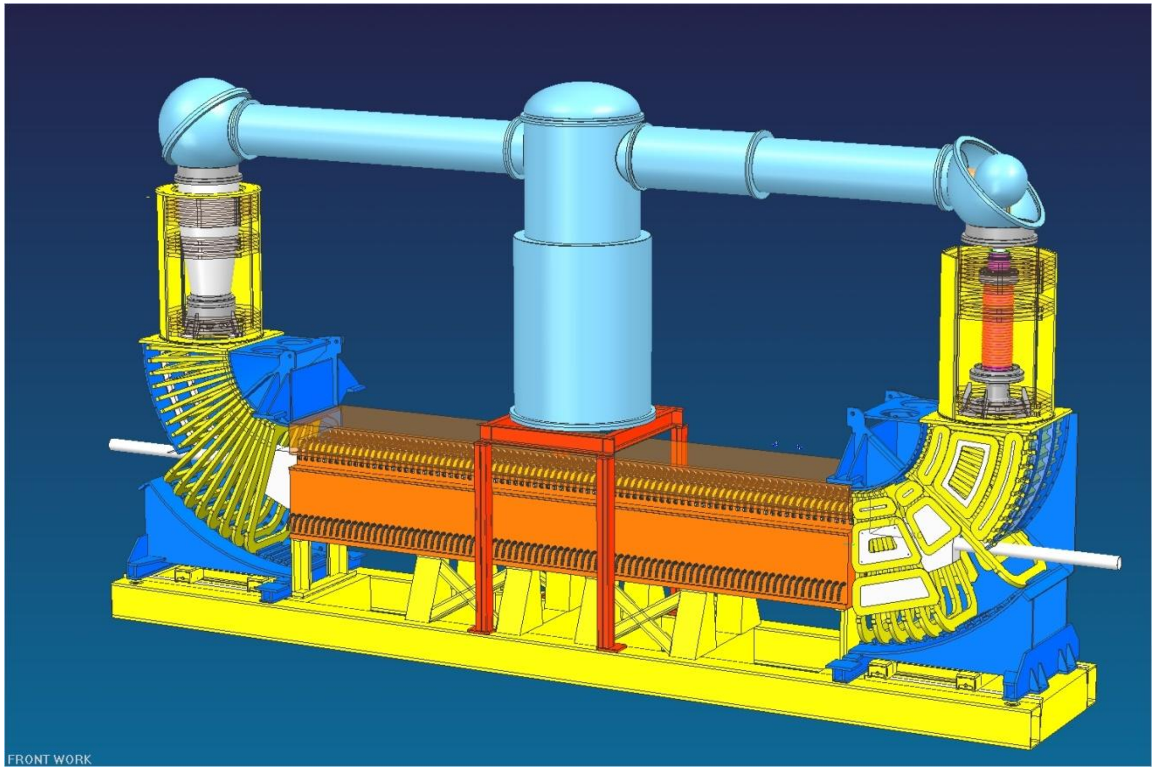
The New Experimental Storage Ring



- Electron cooling of ions and antiprotons
- Fast deceleration of ions to 4 MeV/u
  and antiprotons to 30 MeV
- Fast extraction (1 turn)
- Slow (resonance) extraction
- Ultraslow (charge changing) extraction
- Longitudinal accumulation of RIBs
- Electron-Ion collisions (bypass mode)
- Antiproton-ion collisions
- Internal target
- Electron target
- High precision mass measurements

NESR Electron Cooler

design by BINP, Novosibirsk



Electron Cooler Parameters	
energy	2 - 450 keV
max. current	2 A
beam radius	2.5-14 mm
magnetic field	
gun	up to 0.4 T
cool. sect.	up to 0.2 T
straightness	2×10^{-5}
vacuum	$\leq 10^{-11}$ mbar

Issues:
- high voltage up to 500 kV
- fast ramping, up to 250 kV/s
- magnetic field quality

Layout and Design parameters for the Super-FRS

Projectile:
- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to 10^{12} /s (depending on element)
- DC or pulsed operation

Design Parameters:

$\varepsilon_x = \varepsilon_y =$ 40 π mm mrad

$\Phi_x = \pm 40$ mrad

$\Phi_y = \pm 20$ mrad

$\Delta P/P = \pm 2.5$ %

$B\rho$ = 2 - 20 Tm

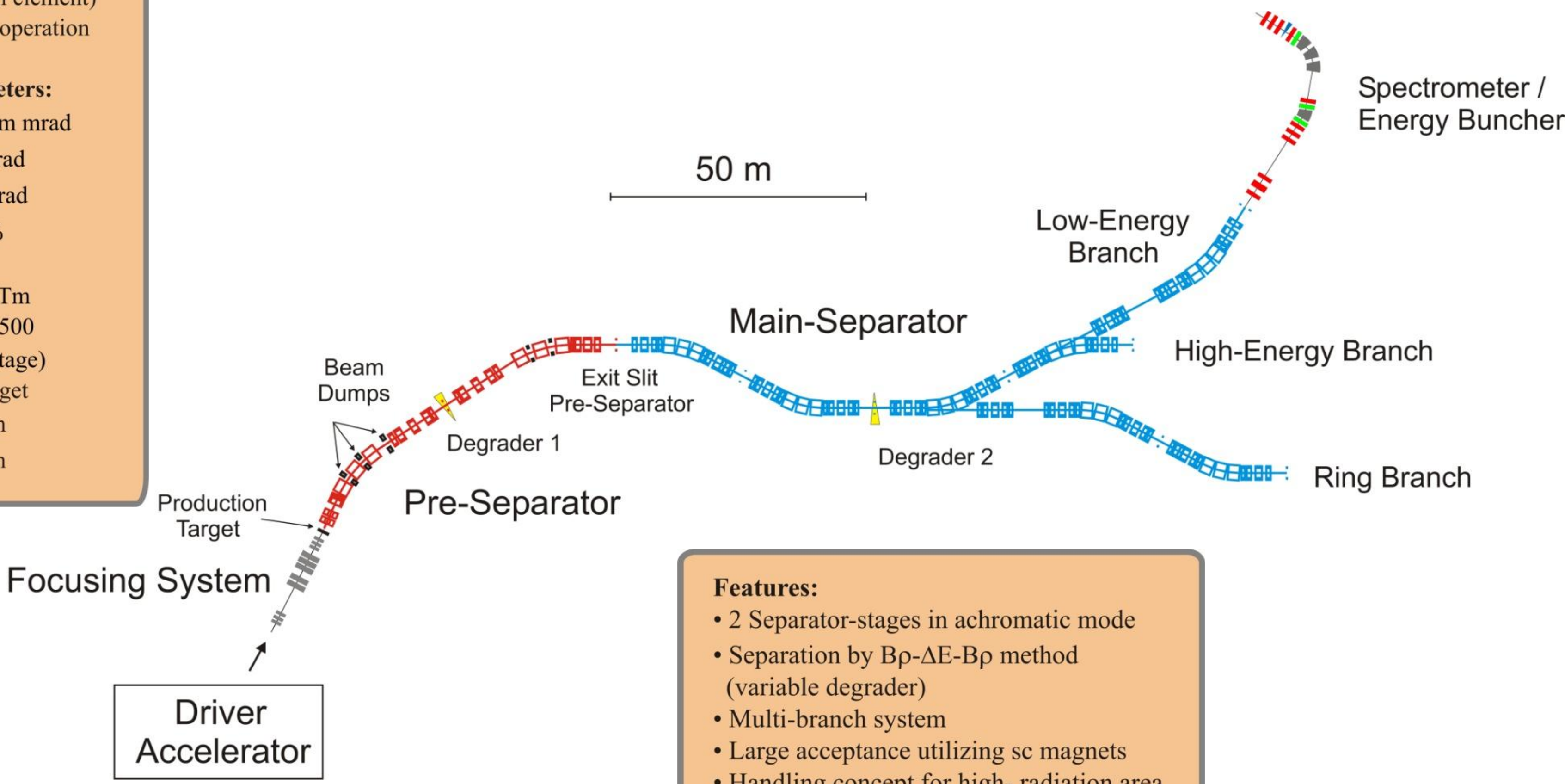
R_{ion} = 750 / 1500 (first / second stage)

Spot size on target

$\sigma_x = 1.0$ mm

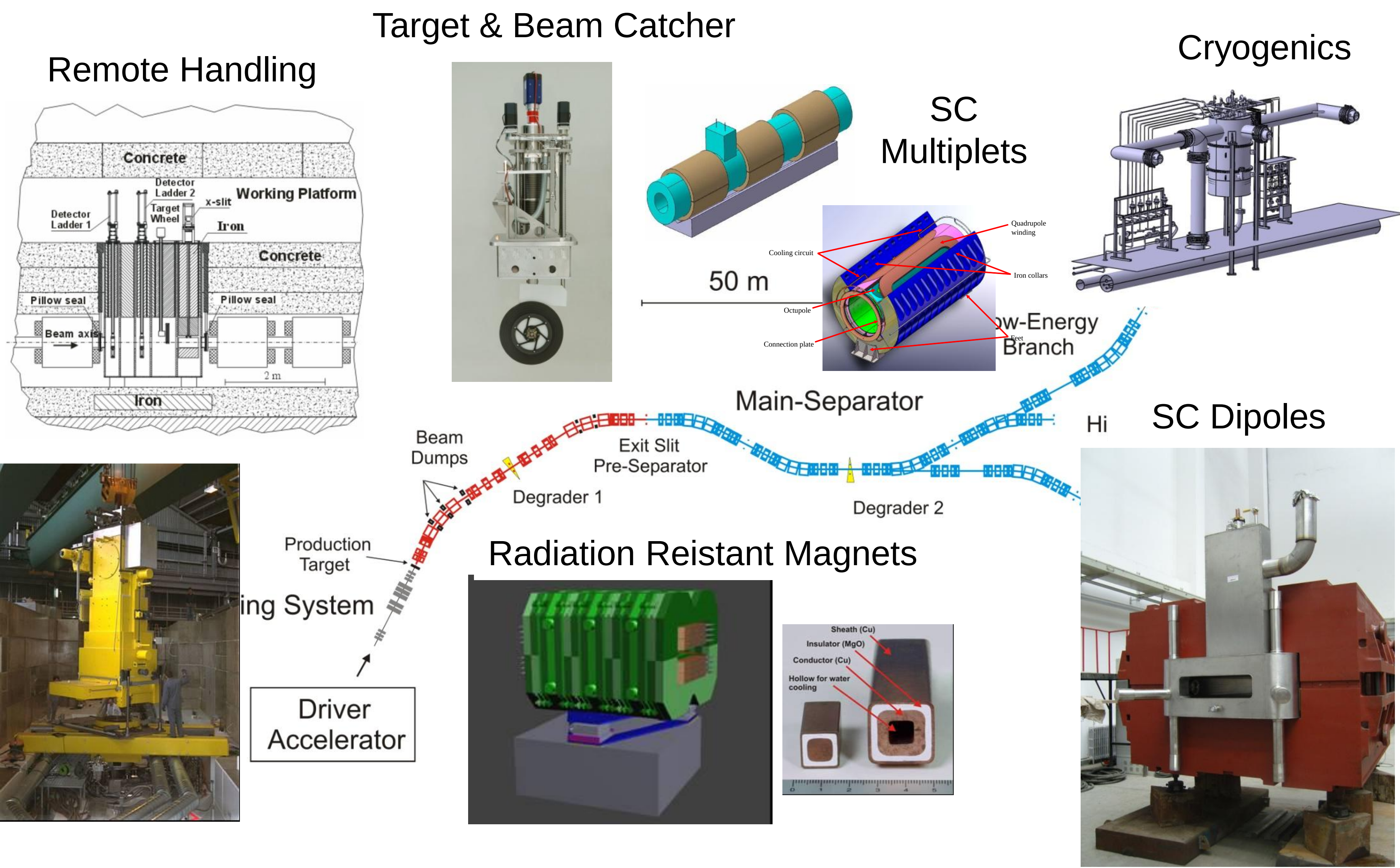
$\sigma_y = 2.0$ mm

Goal: Larger Acceptance



Features:
- 2 Separator-stages in achromatic mode
- Separation by $B\rho$-ΔE-$B\rho$ method (variable degrader)
- Multi-branch system
- Large acceptance utilizing sc magnets
- Handling concept for high- radiation area

Technical Challenges



Study of nuclei at NESR

- Precise measurements of masses and lifetime
- RMS radius and PDF inside nucleus: elastic scattering of protons in the scheme with inverse kinematics on the internal target
- RMS radius and charge distribution function inside nucleus: elastic scattering of electrons: e-i collider
- Deviation of the nucleus shape from spherical: hyperfine structure splitting – experiment on internal target, laser spectroscopy
- Matter distribution – pp-bar collider

Similar program under realisation: FLNR (JINR, Dubna), GANIL (France), TRIUMF (Canada), RIKEN (Japan), IMP (China)

Solid-state gamma laser:
Managing with nuclear processes…

1926, Arthur Eddington:
«Radium decay is spontaneous if atom of Ra is isolated system. But also this decay could be initiated with gamma radiation field at the same frequency as radiated Ra gamma rays».

1971, Vitaly Ginzburg:
«Creation of gamma-laser is one of the most important and principal physics problem»

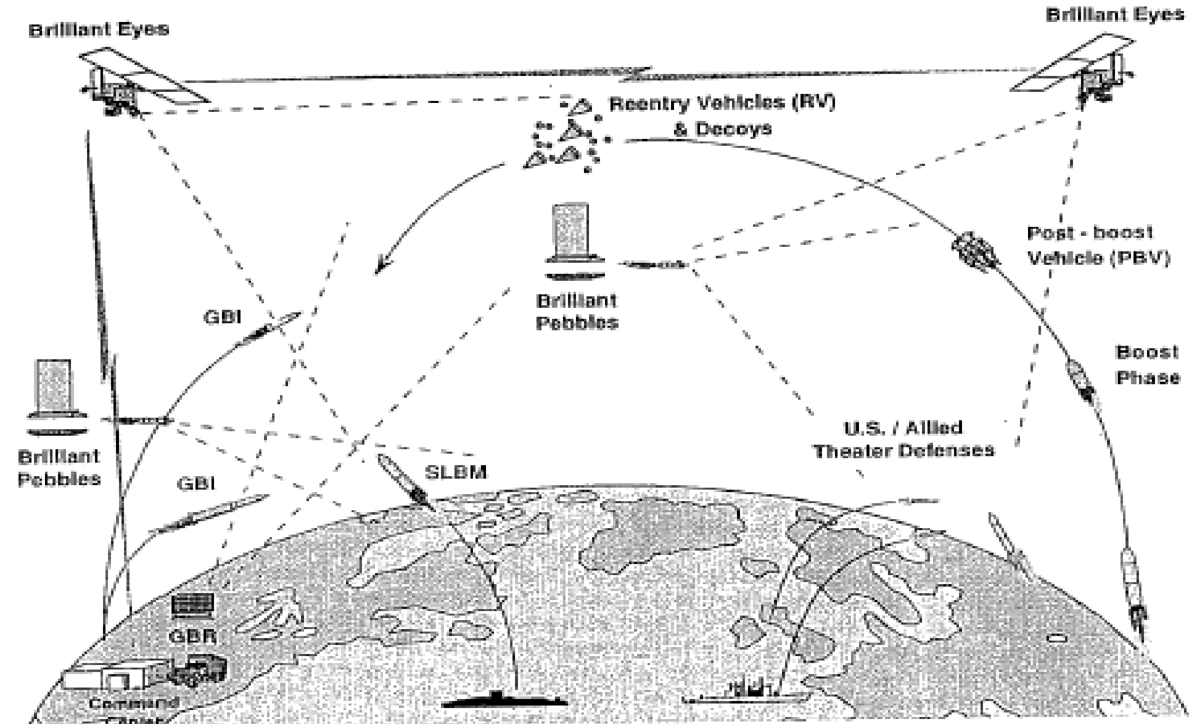
In analogy to usual laser one can artificialy make the inverse population of nuclei between two levels of excitation of **nuclei** (no atoms or molecules)

The best candidate now is Os isotop (187) which has anomalyous long life time of nucleus at excited state.

1983, R.Reigan «Strategic Defence Initiative»:
Usage of solid-state gamma laser with pumping from nuclear explosion for anti-missile defence

UNCLASSIFIED

GPALS ELEMENTS
STRATEGIC AND THEATER

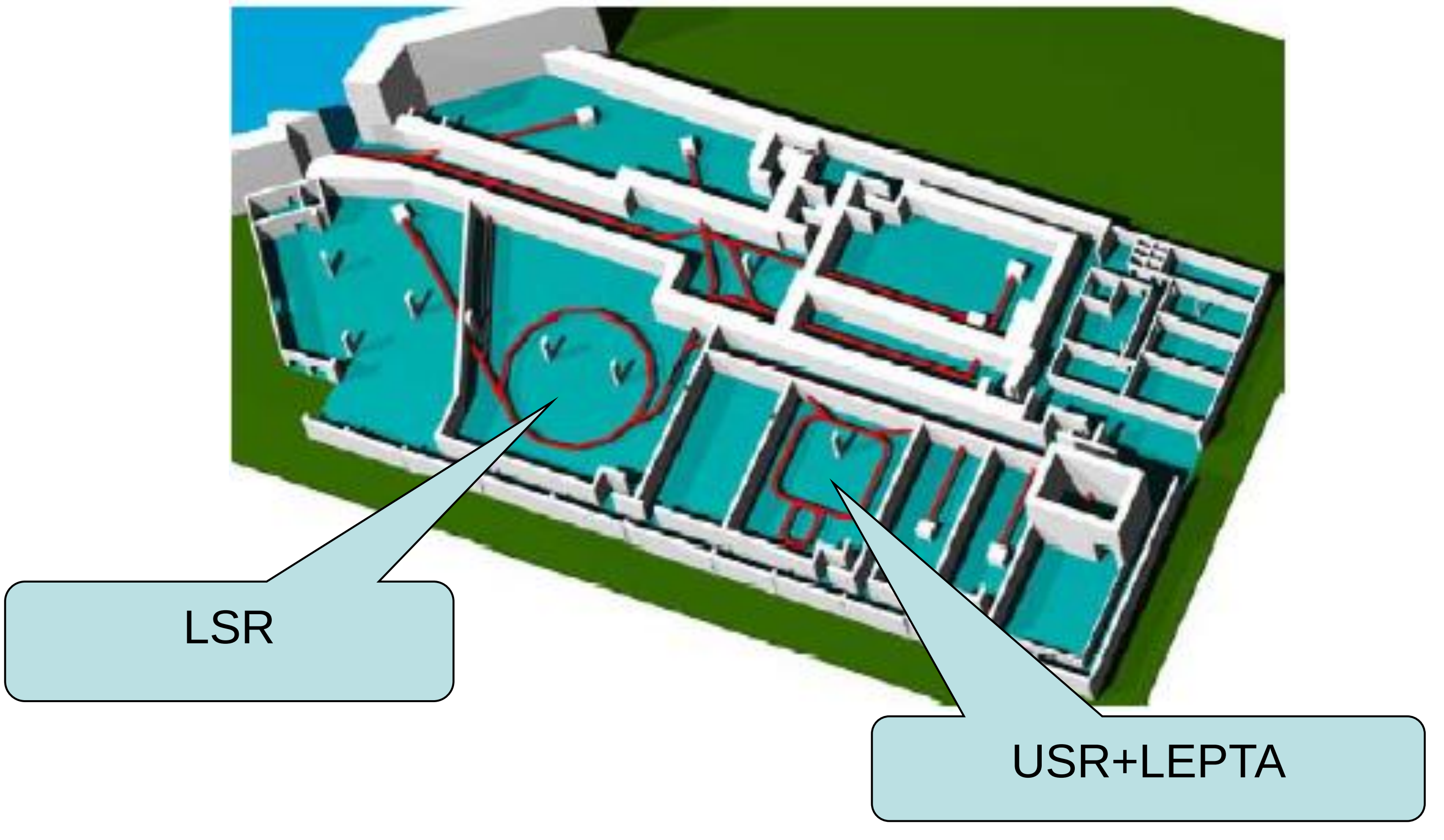


SIFIED

FOI 92-1262

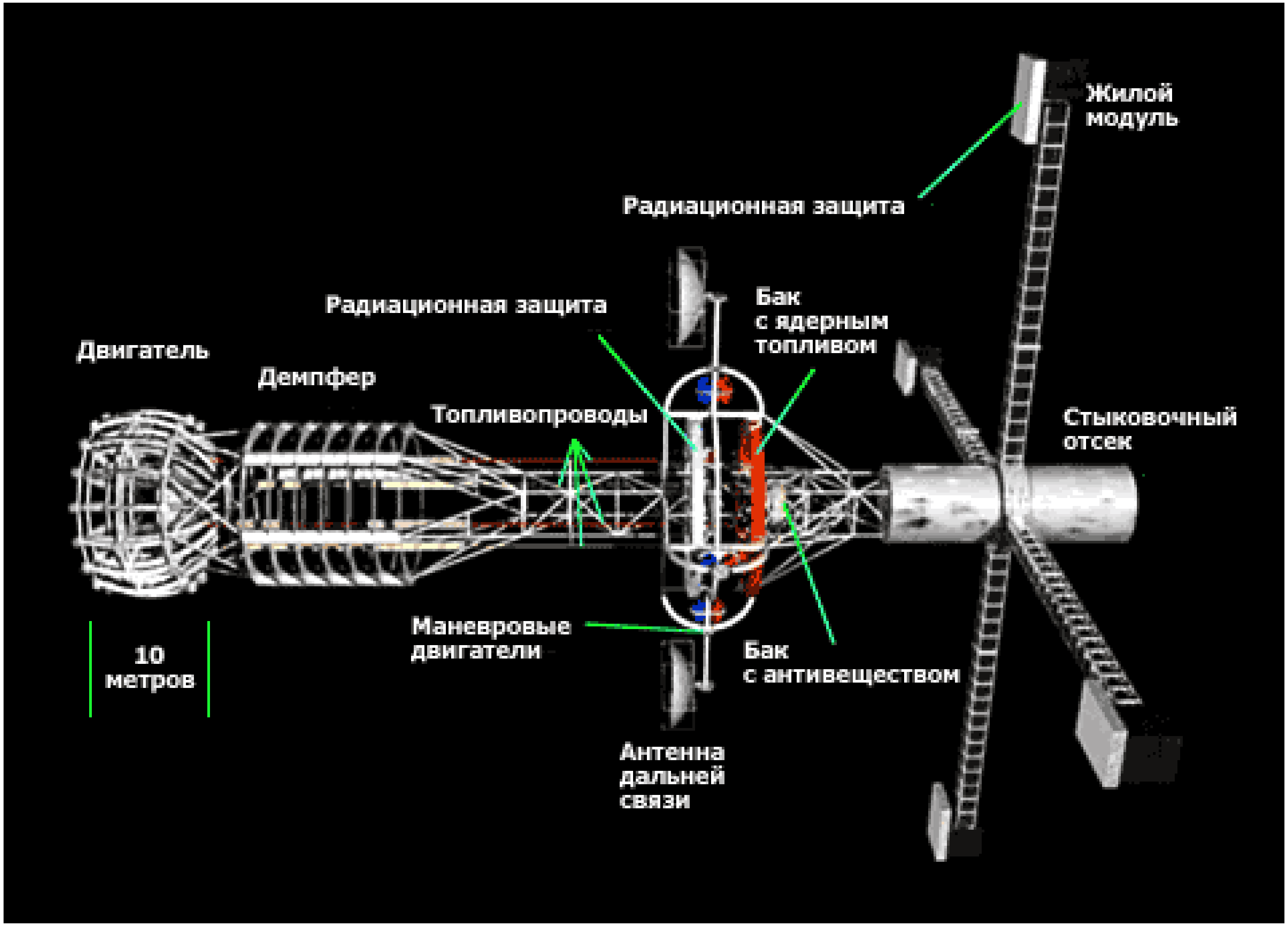
FLAIR

Atomic physics, antiHydrogen generation in-flight and in-traps



Facility for Low energy Antiproton and Ion Research

Space shuttle ICAN-II: mission to Mars only for 40 days



Engine is based on ACMF (Antiproton catalyzed microfission),
140 nanograms of antymatter + 1 tone of Uranium

Pensilvania Univ, USA, AIMStar project

140 nanogramm ~ 10^{17} antiprotons ~ 0.01 Coulomb:
Only antihydrogen

Nowdays cost of antiprotons:
~ 10 B$ per gramm,
Cost of antihydrogen ~ x1000

Projects: ATHENA, ATRAP (CERN), LEPTA (JINR)

In the beginning of XX century it was considered, that solar energy is generated due to chemical reactions.

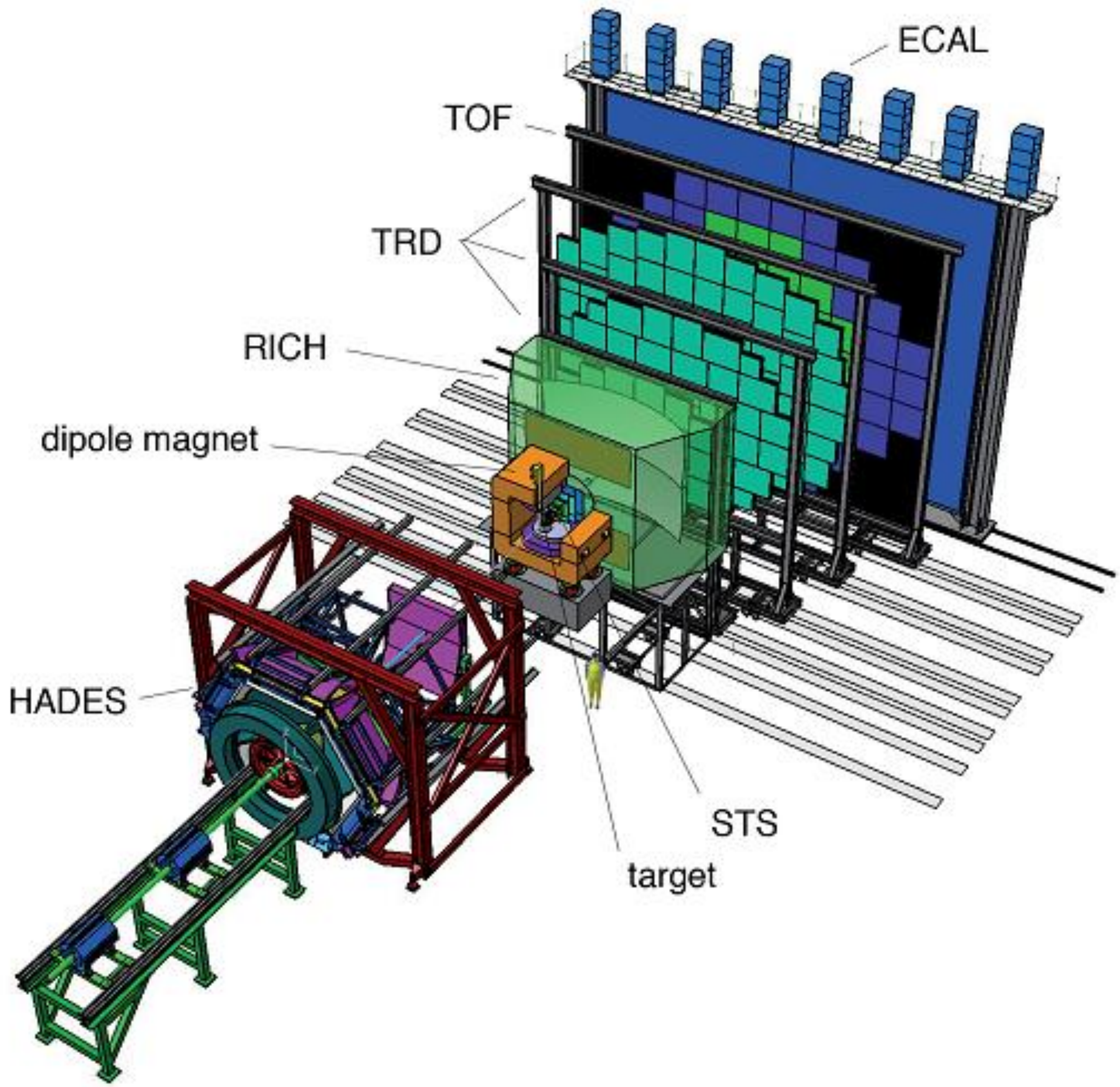
1938 г. - H.Bethe theoreticaly predicted mechanism of energy generation connected to thermonuclear fusion

1943 г. - K.Seifert discovered galactics with active cores:

Active core – object with <1 parsec size (3.25 light year), radiates energy more than all stars of our galaxy

Possible source – phase transitions in hot and dense strongly interacting (baryonic) matter

CBM detector



	CERN	BNL	JINR	FAIR
Facility:	**SPS**	**RHIC**	**NICA**	**SIS-300**
Exp.:	**NA61**	**STAR** **PHENIX**	**MPD**	**CBM**
Start:	**2009**	**2010**	**2017**	**2017**
Pb Energy: **(GeV/(N+N))**	**4.9-17.3**	**4.9-50**	**≤9**	**≤8.5**
Event rate: **(at 8 GeV)**	**100 Hz**	**1 Hz(?)**	**≤10 kHz**	**≤10 MHz**
Physics:	**CP&OD**	**CP&OD**	**OD&HDM**	**OD&HDM**

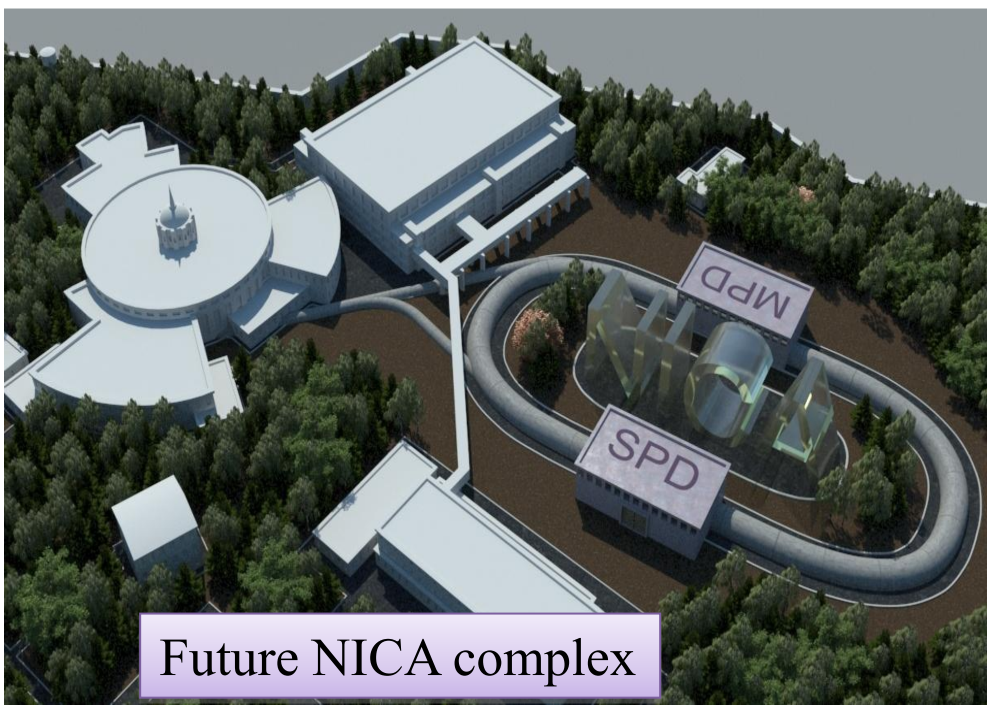
CP – critical point
OD – onset of deconfinement, mixed phase, 1st order PT
HDM – hadrons in dense matter

NICA

NICA: Nuclotron based Ion Collider fAcility


Nuclotron


LHEP JINR


MPD
SPD
Future NICA complex


Synchrofazotron

The goal of the project is

<u>construction at JINR of a new accelerator facility</u> that provides

1a) Heavy ion colliding beams 197Au79+ x 197Au79+ at

$\sqrt{s_{NN}}$ = 4 ÷ 11 GeV (1 ÷ 4.5 GeV/u ion kinetic energy)

at $L_{average}$= 1E27 cm-2·s-1 (at $\sqrt{s_{NN}}$ = 9 GeV)

1b) Light-Heavy ion colliding beams of the same energy range and luminosity

2) Polarized beams of protons and deuterons in collider mode:

p↑p↑ $\sqrt{s_{pp}}$ = 12 ÷ 27 GeV (5 ÷ 12.6 GeV kinetic energy)

d↑d↑ $\sqrt{s_{NN}}$ = 4 ÷ 13.8 GeV (2 ÷ 5.9 GeV/u ion kinetic energy)

$L_{average}$ ≥ 1E30 cm-2·s-1 (at $\sqrt{s_{pp}}$ = 27 GeV)

3) The beams of light ions and polarized protons and deuterons for fixed target experiments:

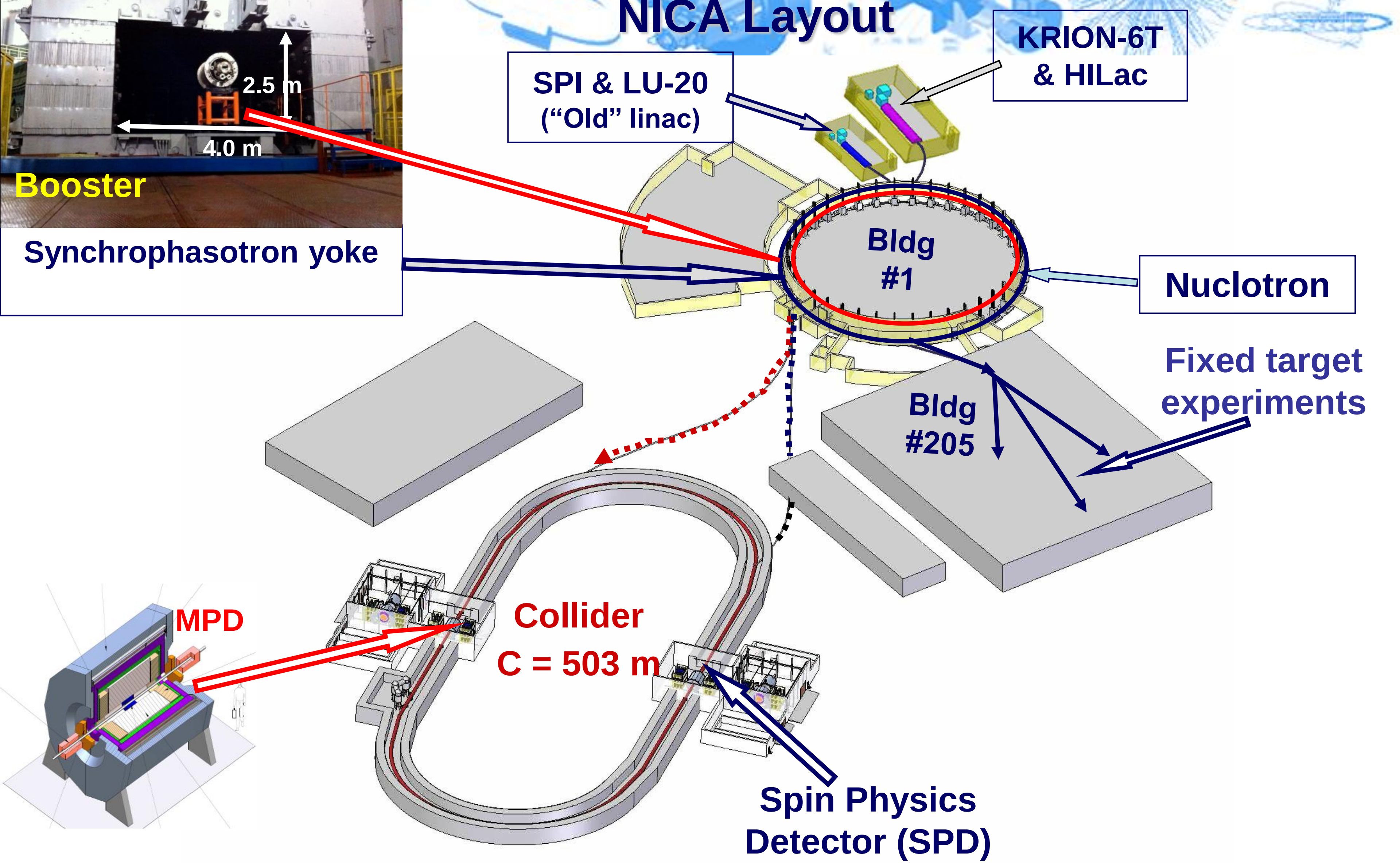
Li ÷ Au = 1 ÷ 4.5 GeV /u ion kinetic energy
p, p↑ = 5 ÷ 12.6 GeV kinetic energy
d, d↑ = 2 ÷ 5.9 GeV/u ion kinetic energy

4) Applied research on ion beams at kinetic energy

from 0.5 GeV/u up to 12.6 GeV (p) and 4.5 GeV /u (Au)

NICA Project Concept & Status

NICA Layout

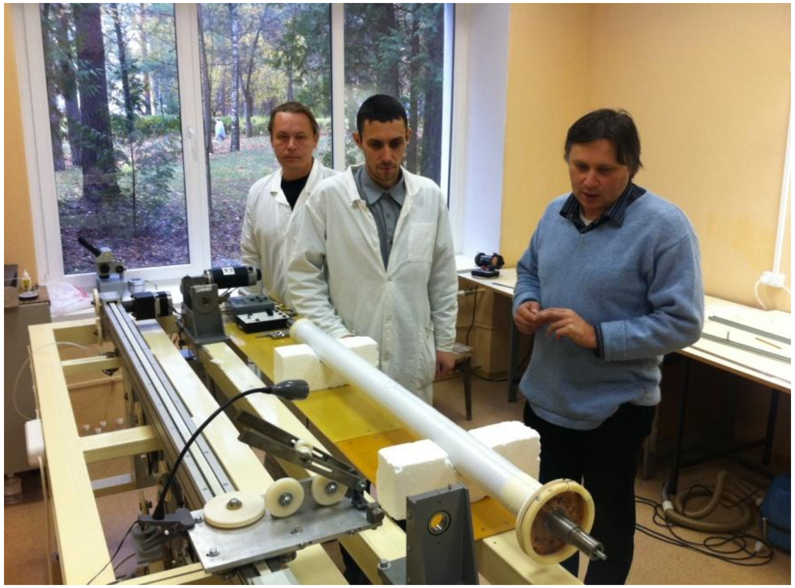


Injection complex

Cryogenic Ion Source KRION-6T ("EBIS type")

(2÷4) E9 197Au31+ ions per pulse at repetition frequency up to 20 Hz

Assembling of electron/ion optics system (view from the "ion extraction" side



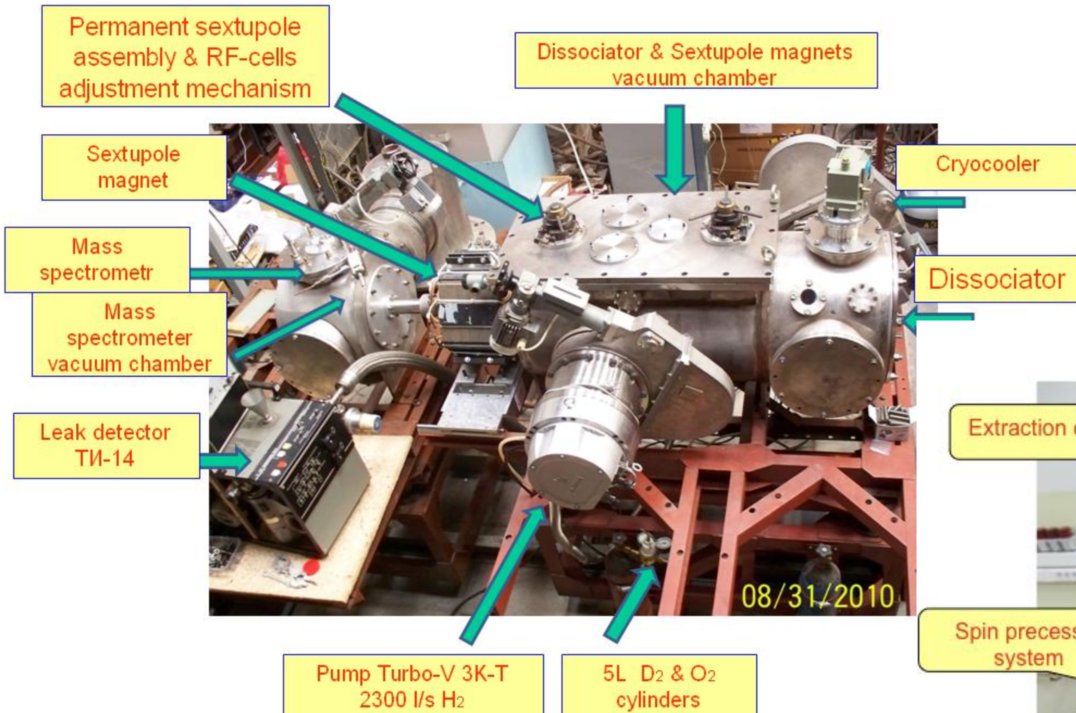
Superconducting test coil 6T

197Au65+

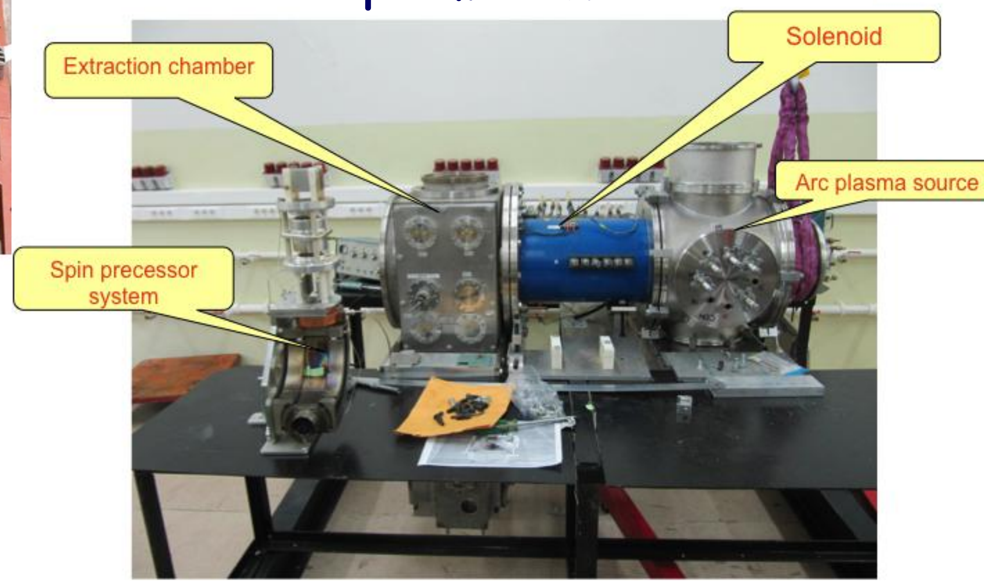
Injection complex

Source of polarized protons/deuterons (JINR/INR RAS)

The source general view

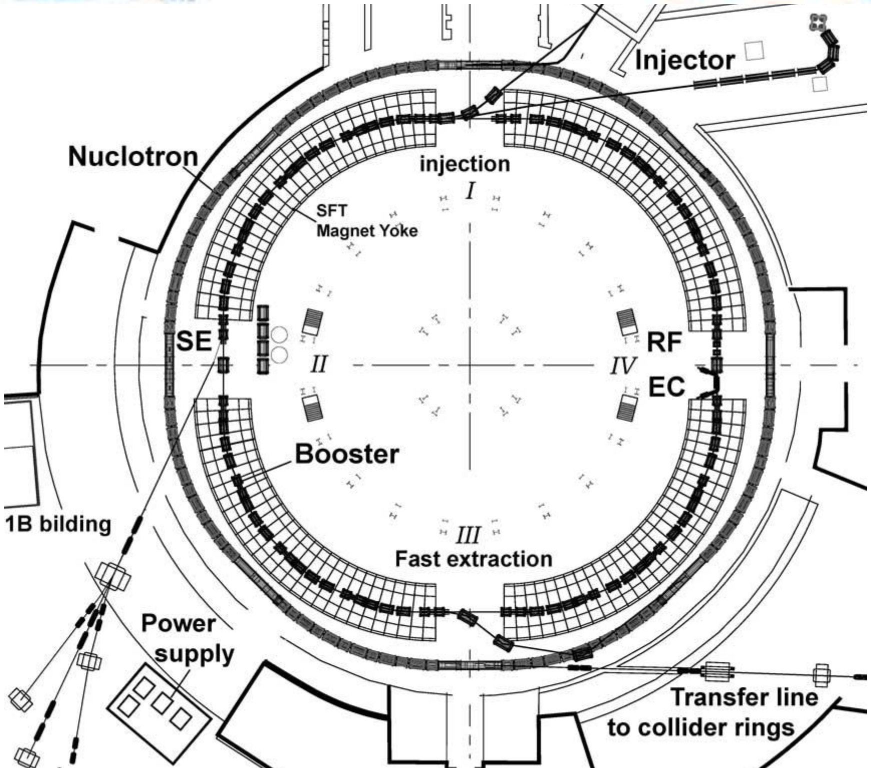


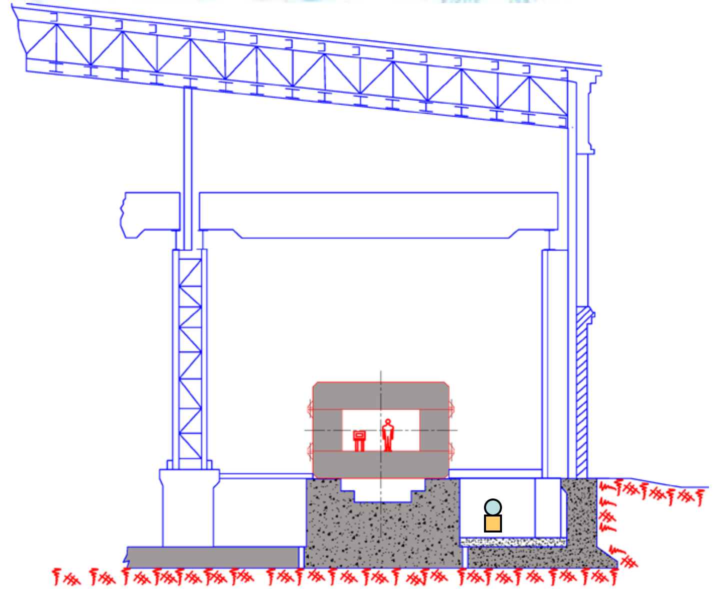
Assembled charge-exchange plasma ionizer

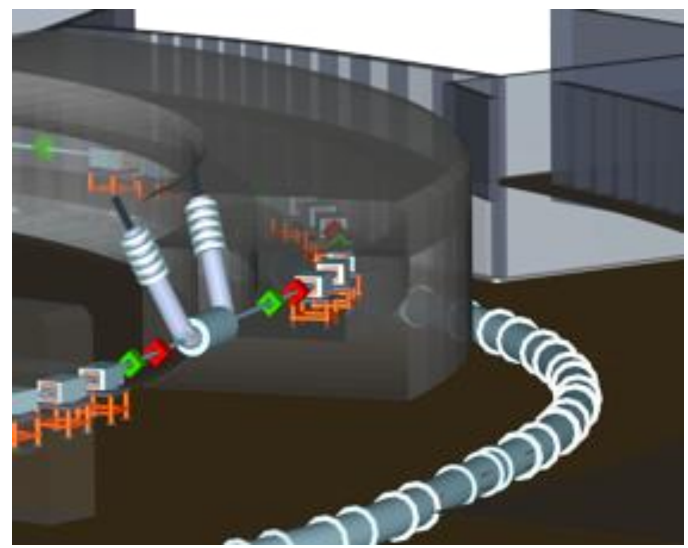


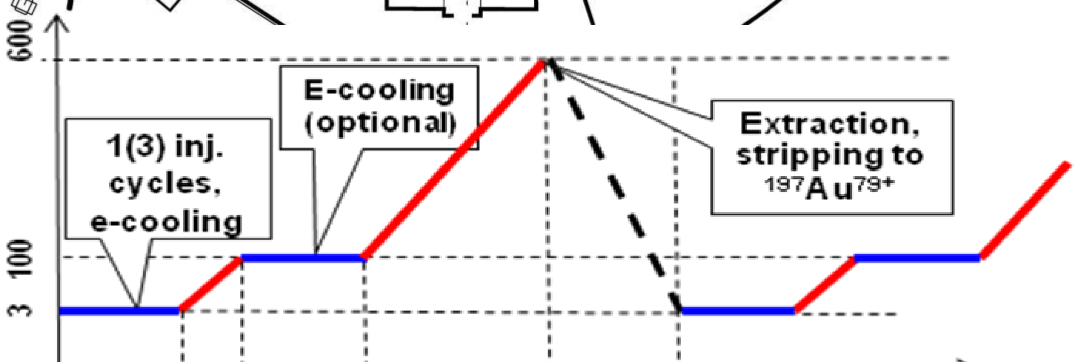
Vladimir I. Veksler

NICA Booster

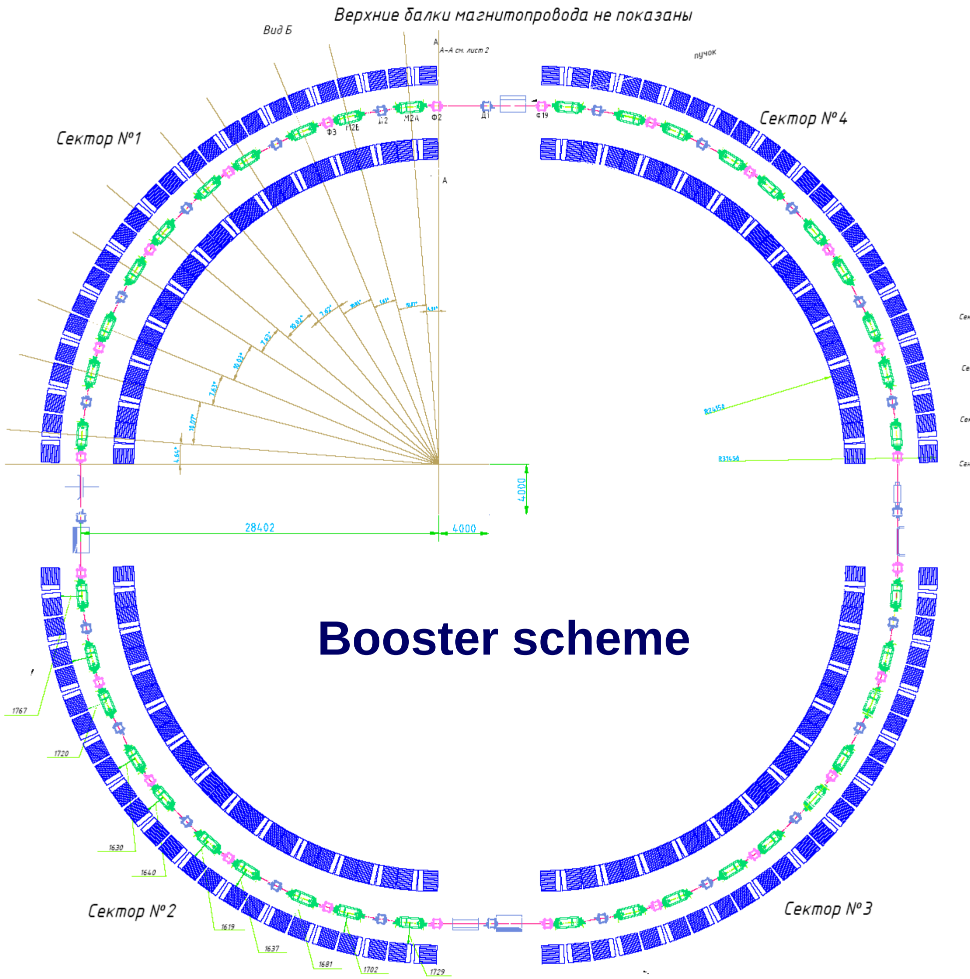








SC Booster-Synchrotron



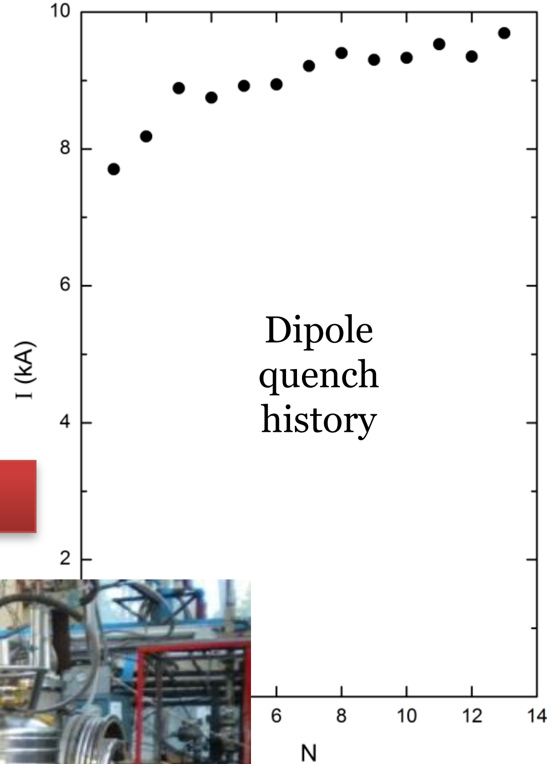
Booster scheme

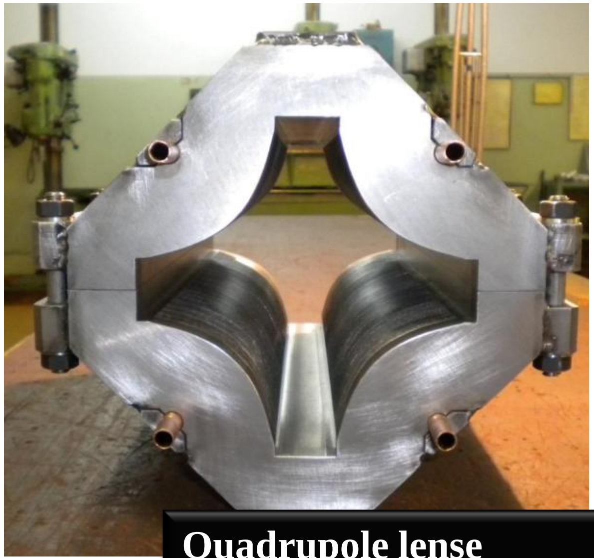
Booster Parameters

Particles	ions A/Z≤3
Injection energy, MeV/u	3
Maximum energy, GeV/u	0.6
Magnetic rigidity, T·m	1.55 ÷ 25.0
Circumference, m	211.2
Fold symmetry	4
Quadrupole periodicity	24
Betatron tune	5.8/5.85

Booster magnets prototypes

Curved dipole magnet



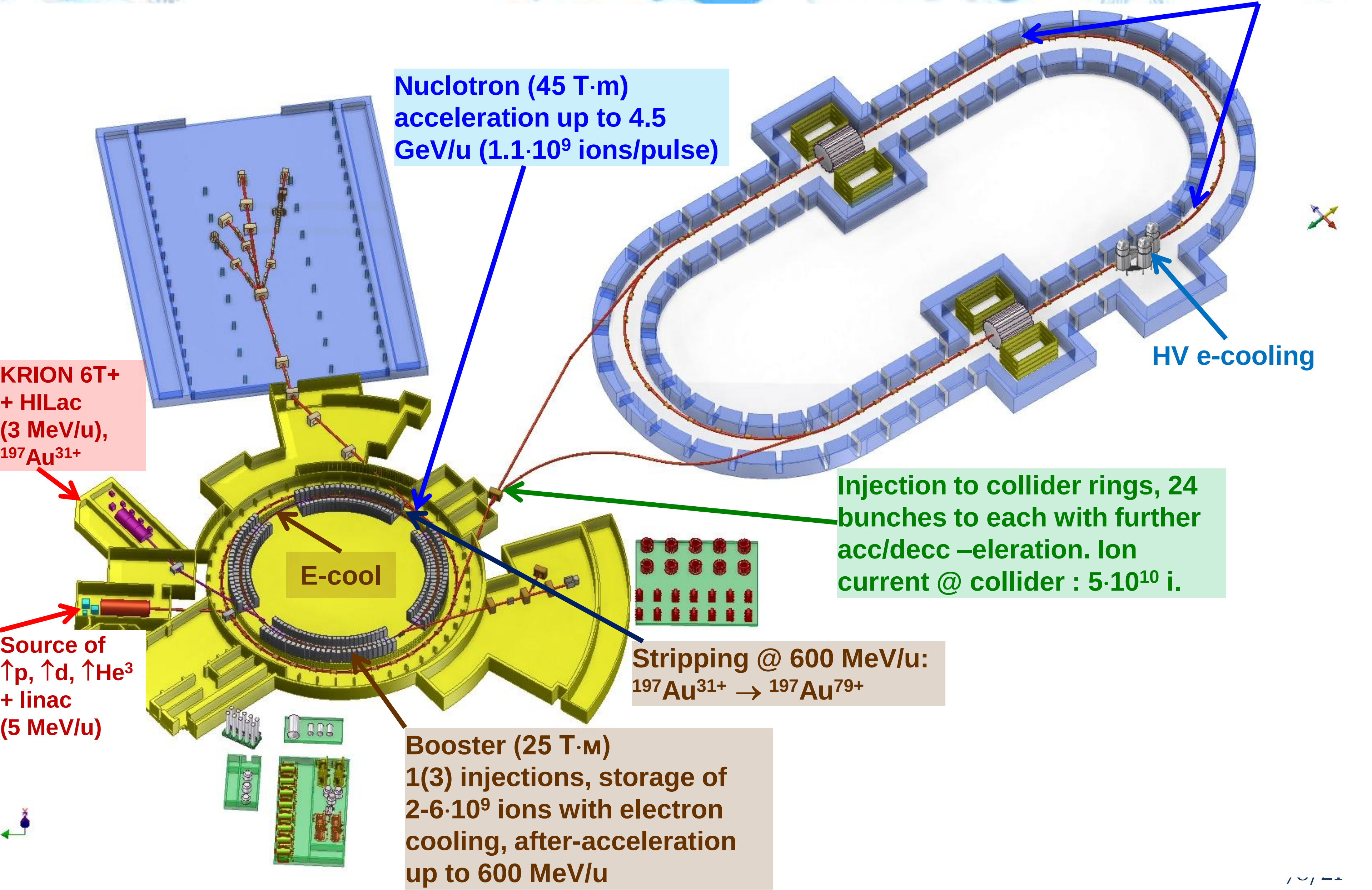


Quadrupole lense

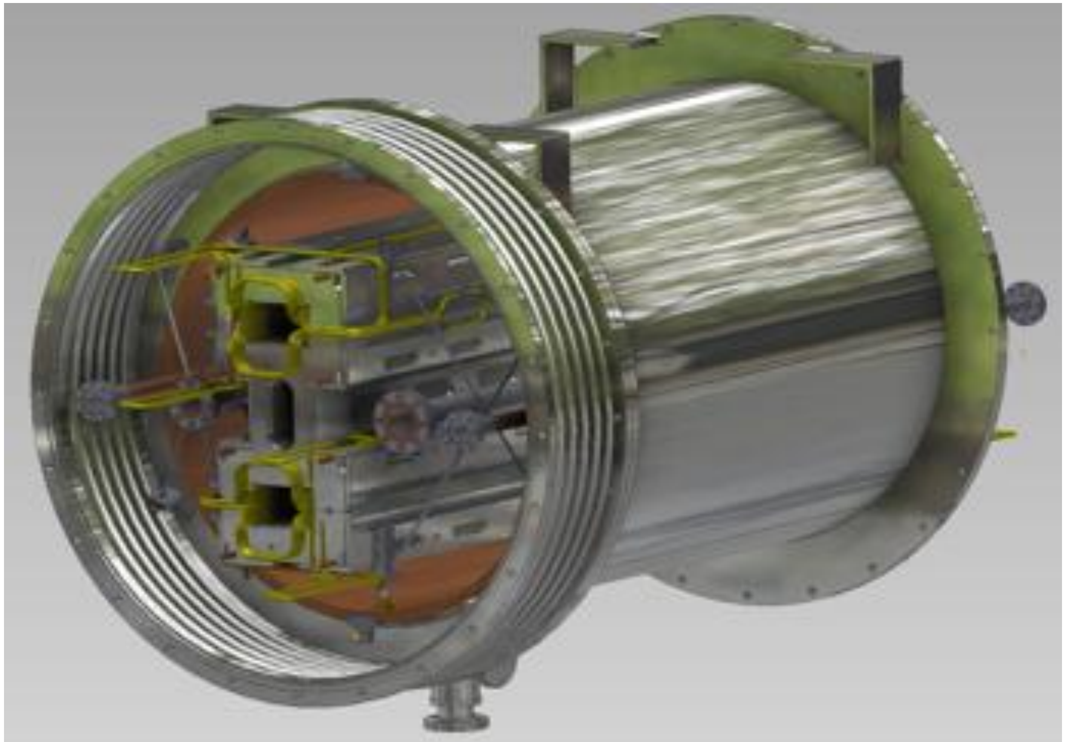
Test bench for cold tests at LHEP JINR

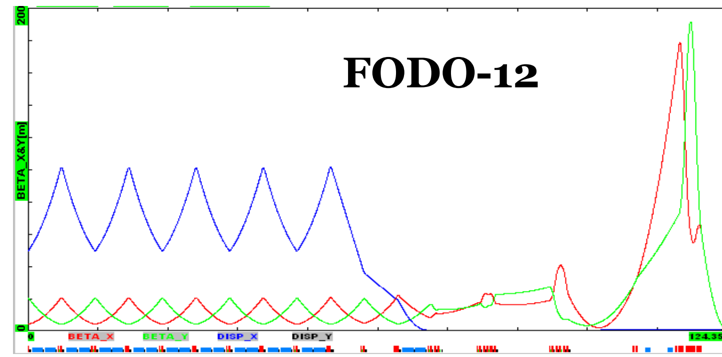
Sextupole corrector

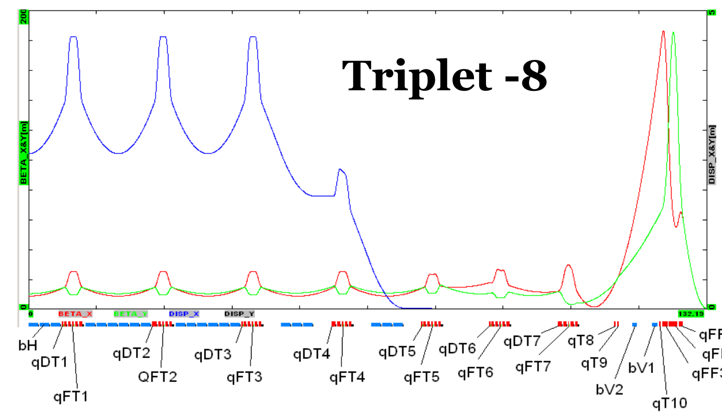
NICA complex



NICA Collider





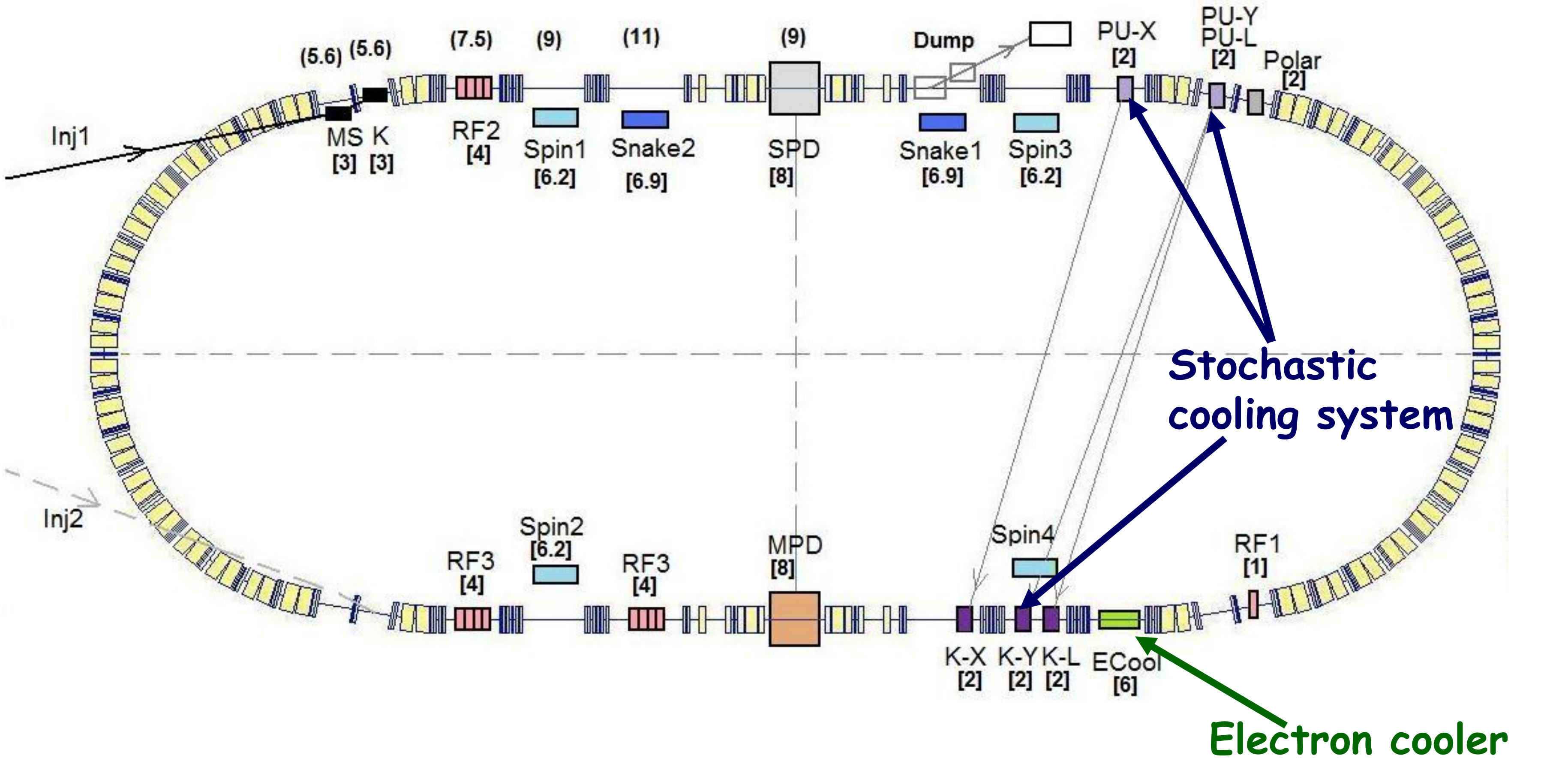


Оптика	Периметр, м	$E_{крит}$, ГэВ/н ($\gamma_{крит}$)	η при 4.5 ГэВ/н	$V_{RF\ макс}$, kV	Число диполей в кольце	Длина диполя, м	T_{IBS},с
FODO-12	497	5.68 (7.05)	0.010	804	80	1.94	1240
FODO-11	489	5.10 (6.43)	0.006	702	72	2.16	1110
FODO-10	503	4.54 (5.89)	0.0006	666	96	1.62	980
Triplets-8	529	4.66 (5.96)	0.002	720	84	1.85	1200
Triplet-10	576	6.16 (7.56)	0.012	995	108	1.44	1610

Part I. NICA Project Concept & Status

I.4. SC Collider

Collider ring principle scheme



Collider general parameters

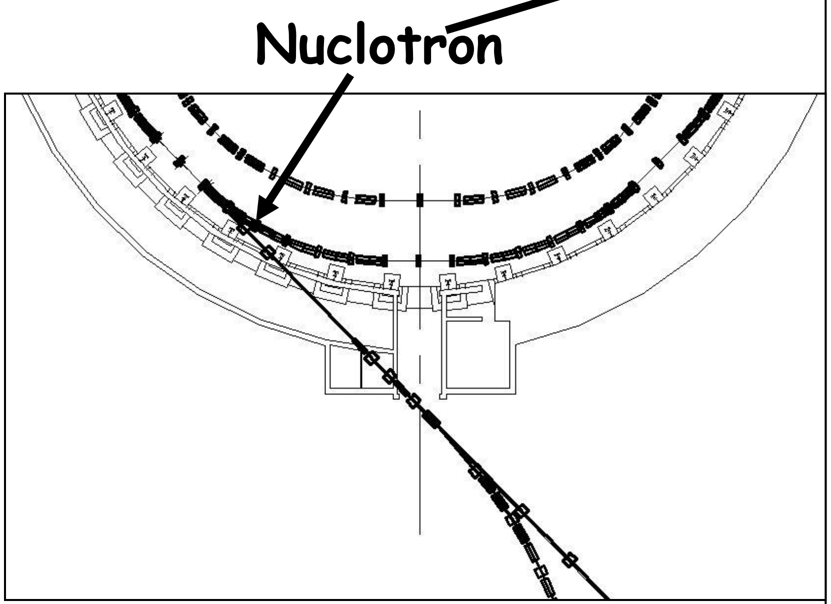
Ring circumference, m	503
Focusing structure	FODO (12 cell x 90^0 each arc)
Number of dipole magnets	80
Number of bunches per ring	24
Ring acceptance, $\pi \cdot$mm$\cdot$mrad	40.0
RMS momentum spread, 1e-3	1.8
Max. Ion number per bunch, 1e9	2.0

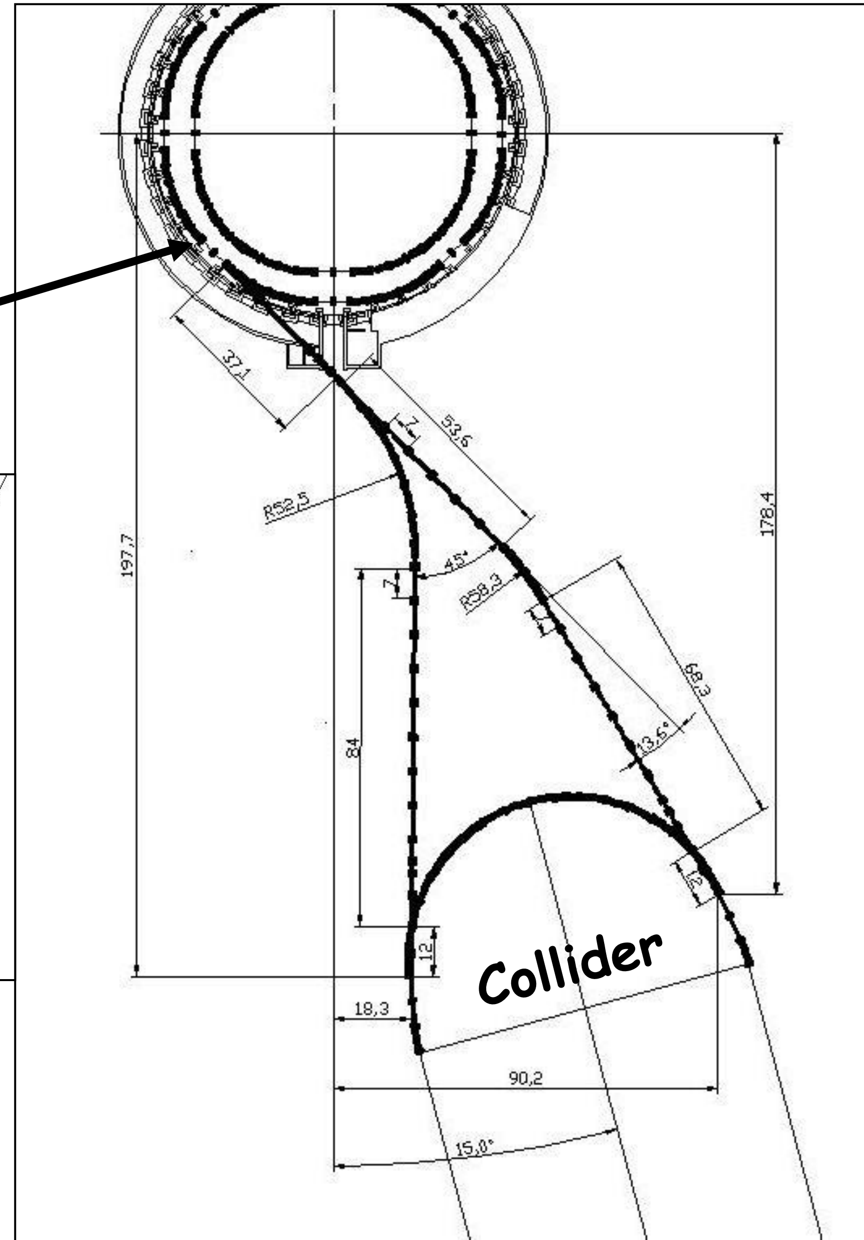
Collider SC magnets

Twin dipole prototype

Cryostat and dipole yoke

Transfer channel Nuclotron - Collider





RF Systems

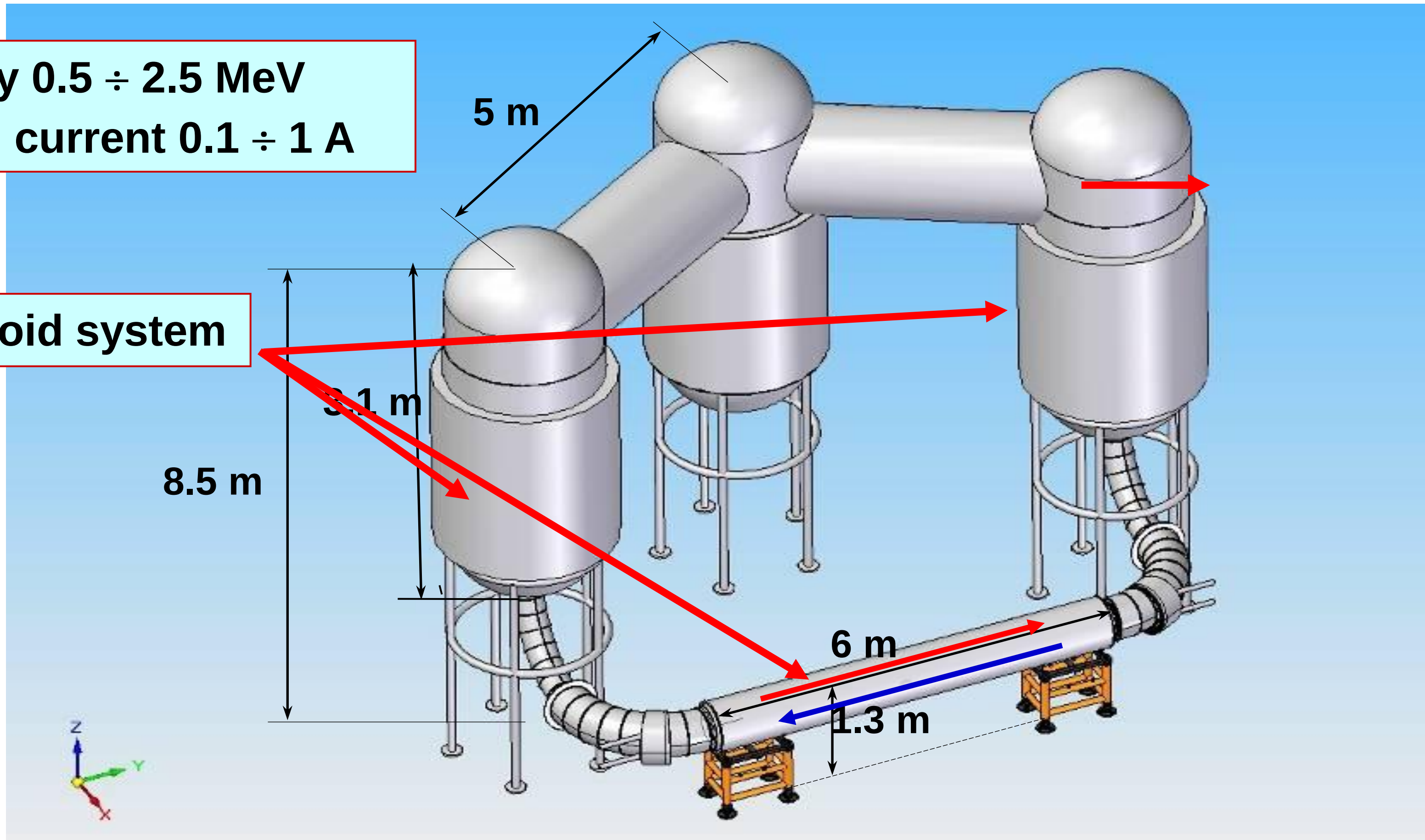
Parameter \ RF system	RF1 (BB*))	RF2	RF3
Frequency, MHz*)	0.529÷0.59	11.4÷12.8	34.2÷38.4
Total voltage amplitude, kV	5	100	1000
Voltage per cavity, kV	5	25	125
Power consumption per cavity	-	25	50
Number of cavities	5	4	8
Total power, kW	-	100	400
Cavity length, m	-	1.1	1.1
Total length, m	-	4.4	8.8

*) Frequency of pulses of the same polarity in RF system of BB type. Rectangular pulses of phase duration $\pi/6$, phase distance between the pulses of opposite polarity is equal to π.

HV Electron cooler: working design

El. energy 0.5 ÷ 2.5 MeV
El. beam current 0.1 ÷ 1 A

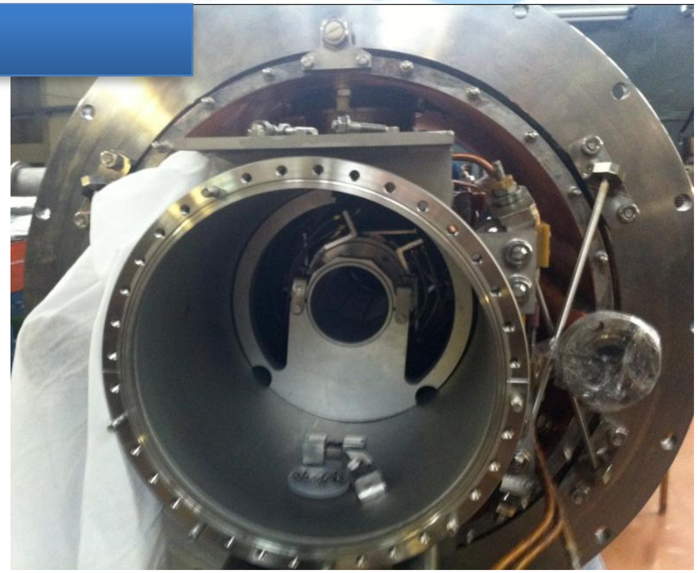
SC solenoid system



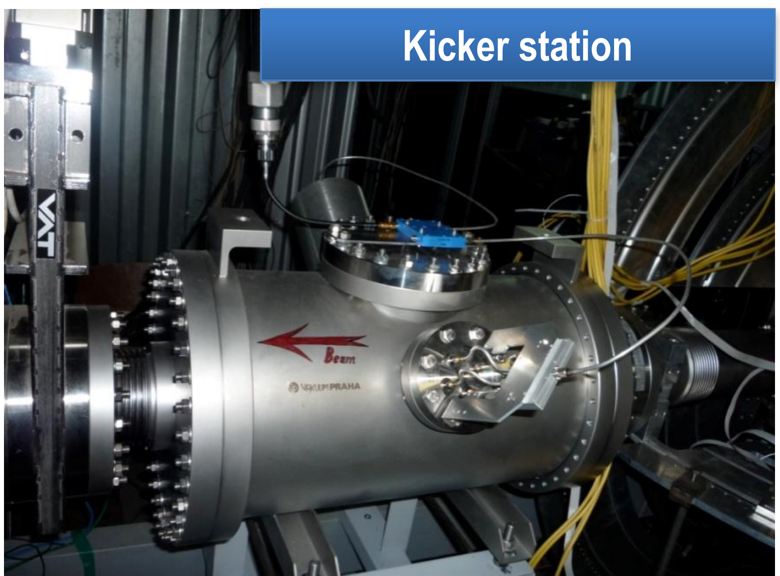
Cooperation with V.I.Lenin All-Russian Electrotechnical Institute

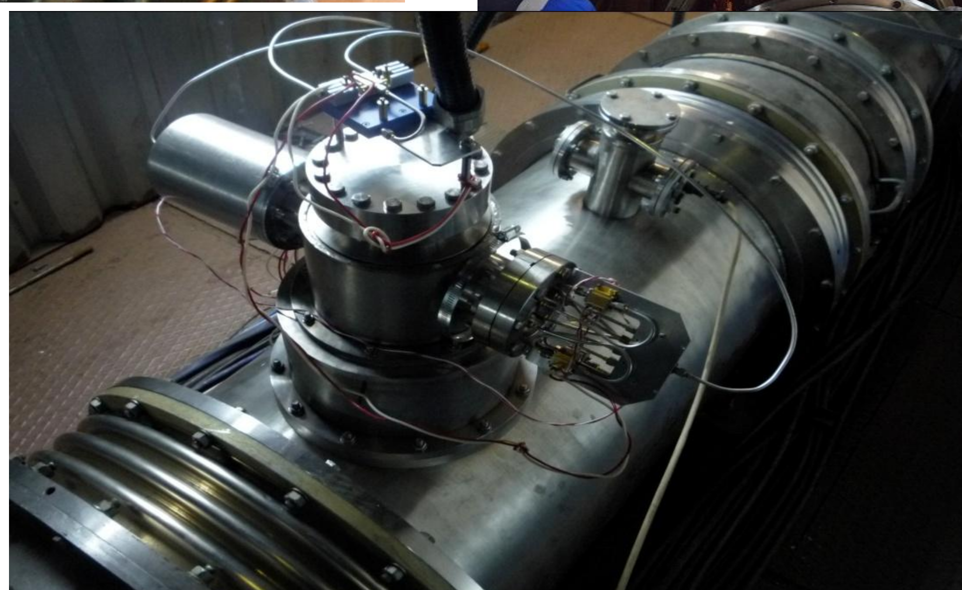
Stochastic cooling system @ Nuclotron – as prototype for Collider

PU station



Kicker station

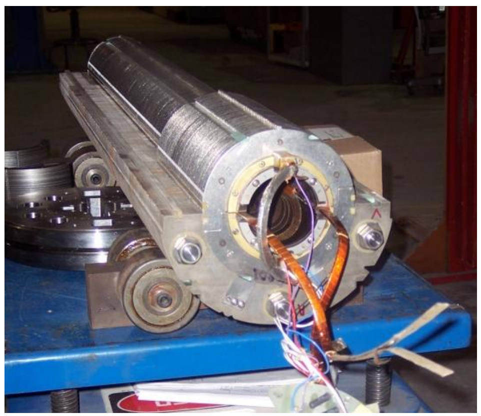




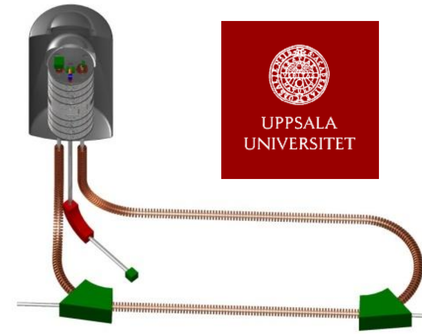
Preparatory Phase R&D by GSI & Partner Institutes since 2001

INFN Istituto Nazionale di Fisica Nucleare

SIS300 magnets



NESR Electron Cooling



UPPSALA UNIVERSITET

Forschungszentrum Jülich in der Helmholtz-Gemeinschaft

BROOKHAVEN NATIONAL LABORATORY

IHEP ИФВЭ

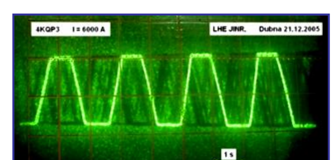
IHEP Protvino

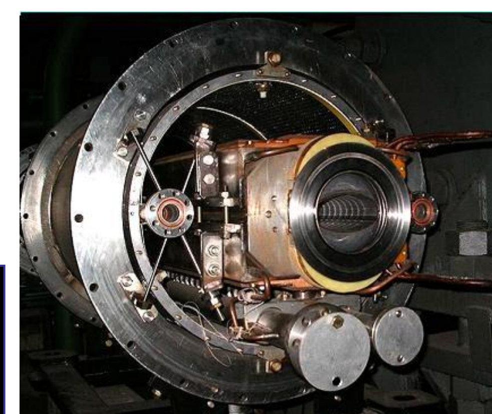
CEA / CNRS

Variable Frequency Cavities

SIS100 rapidly cycling sc magnets

Joint Institute for Nuclear Research





BINP Novosibirsk

Building Readiness

Facility	BOE
HEBT Connection SIS18 - SIS100 (T1S1, T1S2, T1S3, T1S4)	29.04.2016
HEBT-SIS100 (T8DU)	29.04.2016
SIS100	29.04.2016
HEBT - T1X1, T1C1,T1D1-T1C2,TNC1 - T1X2,TXL1,TXL2,TXL3,TXL4,TPP1,TPP2	01.05.2017
Multifunction Cave (CBM HADES)	01.05.2017
HEBT - T1F1,T1F2,TFF1, TSX1, TSF1, FRF, TFC1	28.10.2016
HEBT - TAP1, TAP2, TCR1, THS1	23.01.2017
p-Bar TARGET	28.10.2016
p-LINAC	01.05.2017
CR	23.01.2017
Super FRS	28.10.2016
HESR	23.01.2017

No major staging possible. Installation basically in parallel.
Requires an optimized logistics- and installation planning and a strongly parallel commissioning of devices (without beam).

FAIR – NICA

- Complimentary in some fundamental science goals, but of course FAIR is much multi-disciplinary
- Very similar and close in acceleration technique
- Really friend and dependent (politically and practically) projects
- They NEED you now !


Thank you for attention

Thanks a lot for slides to: B.Sharkov, H.Gutbrod, P.Spiller, M.Steck, H.Khodzhibagiyan, A.Sidorin, N.Pyka, R. Marabotto, P. Fabbricatore, I.Meshkov and others !