HIGH-ENERGY HEAVY-ION ACCELERATORS

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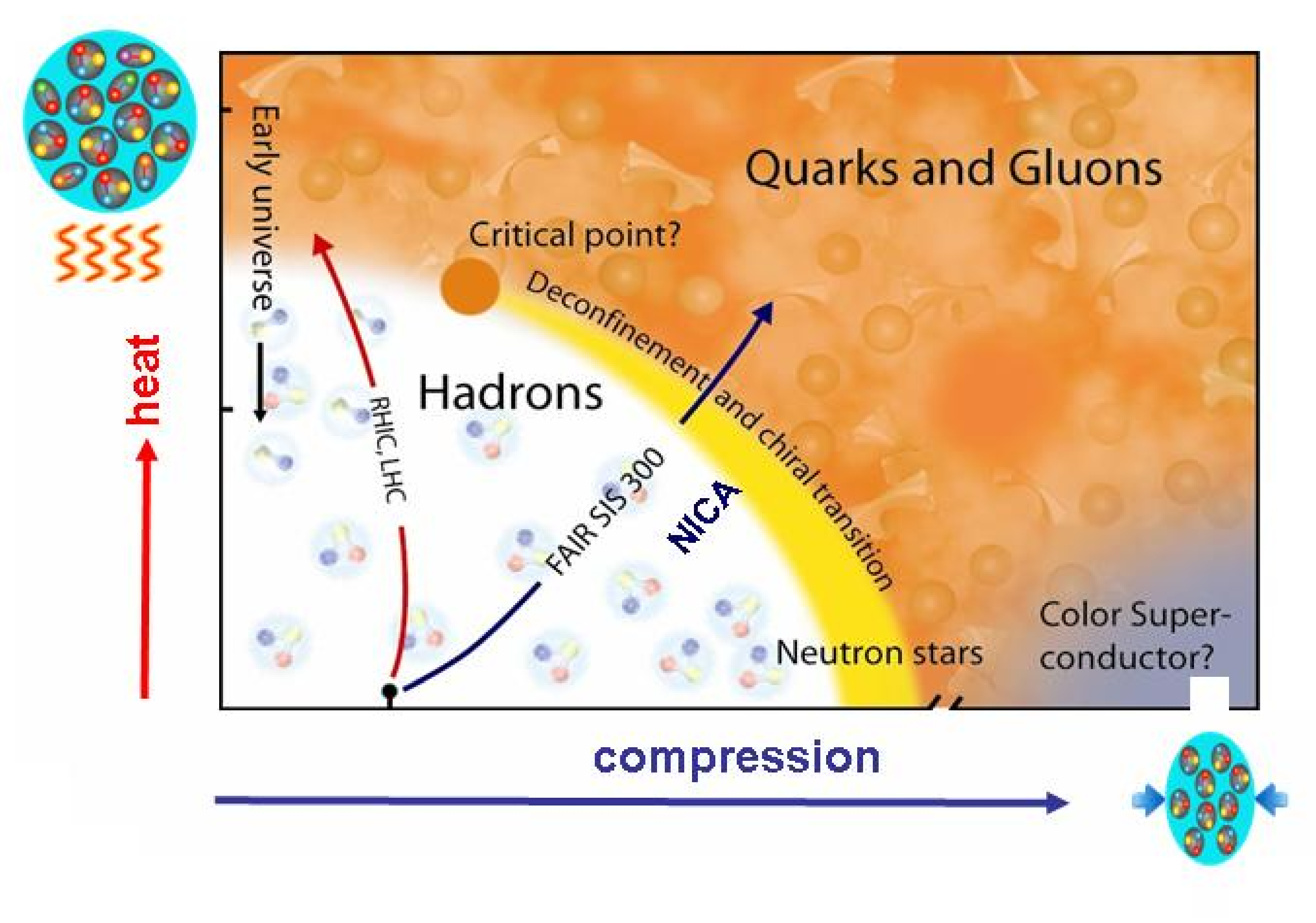
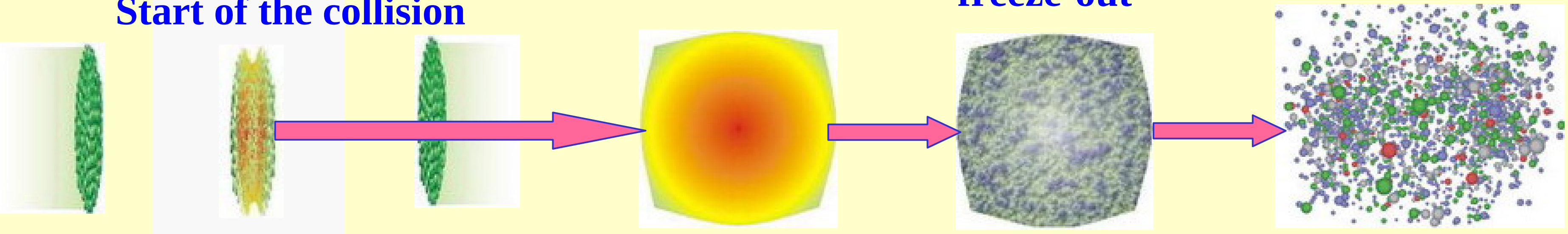
Why heavy ions accelerated to high energies ?



QCD phase diagram (Artist’s view)

Nucleus-nucleus collisions
at relativistic energies



Start of the collision

pre-equilibrium

QGP formation
and
hydrodynamic
expansion

Hadronisation,
hadronic phase
& chemical
freeze-out

Hadronic phase &
kinetic freeze-out

Mixed phase = mixture of QGP and hadronic matter

QUESTIONS

- **To what extent the nuclei could be regarded as hadron systems?**
- **In which way the quark-gluon structure of hadrons manifests itself in nuclear matter?**
- **What is the behavior of strongly interacting matter under extremely high temperatures and baryon densities?**

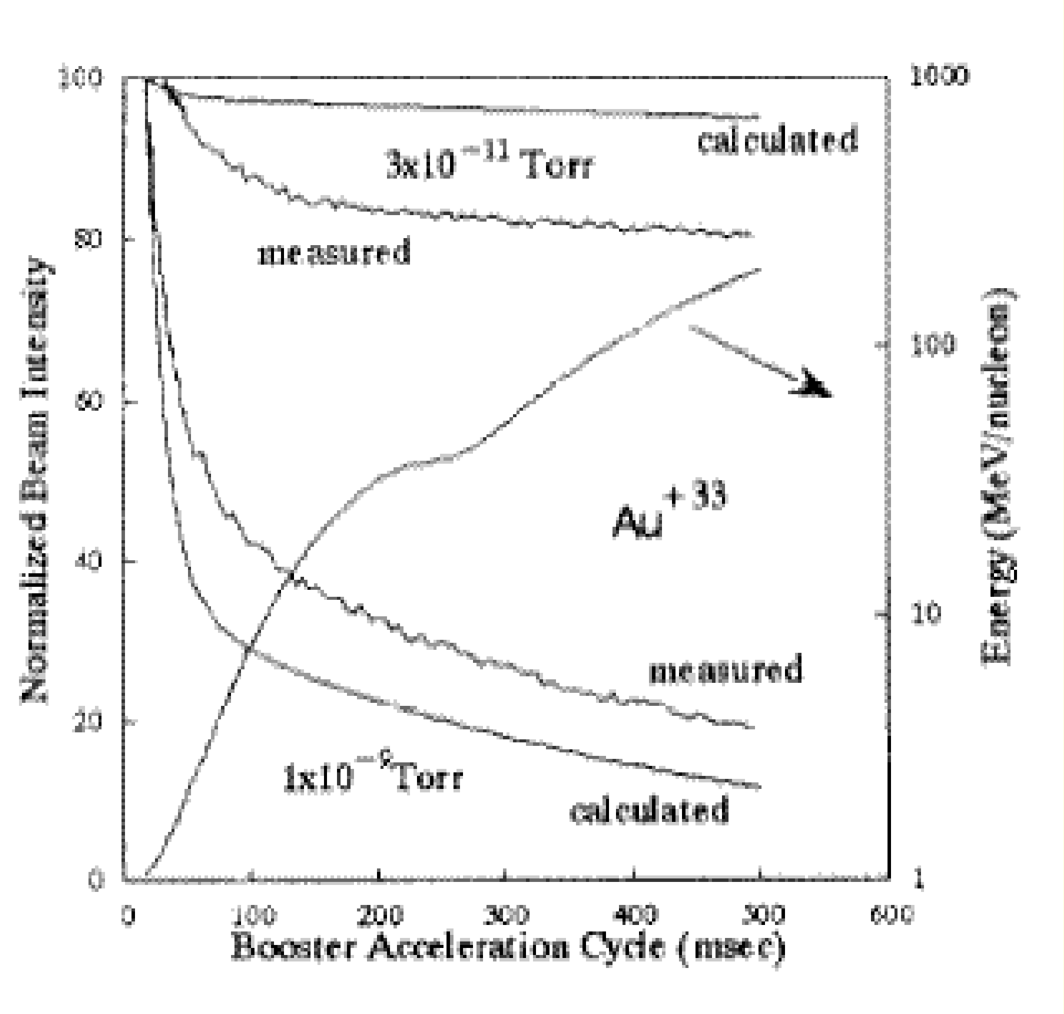
ACCELERATION OF HEAVY IONS TO HIGH ENERGY

High charge state ions → more compact and sufficiently cheaper accelerator

$$B\rho = \frac{A}{300\,Z}\sqrt{T_n^2 + 2\,E_{0n}\,T_n}$$

Vacuum related beam losses

→The partially stripped ions are subject to charge exchange processes with the residual gas in the machine vacuum chamber and could be lost



The fraction of survival Au^{33+} ions during the AGS booster acceleration.

Electron loss cross section by fast ions:

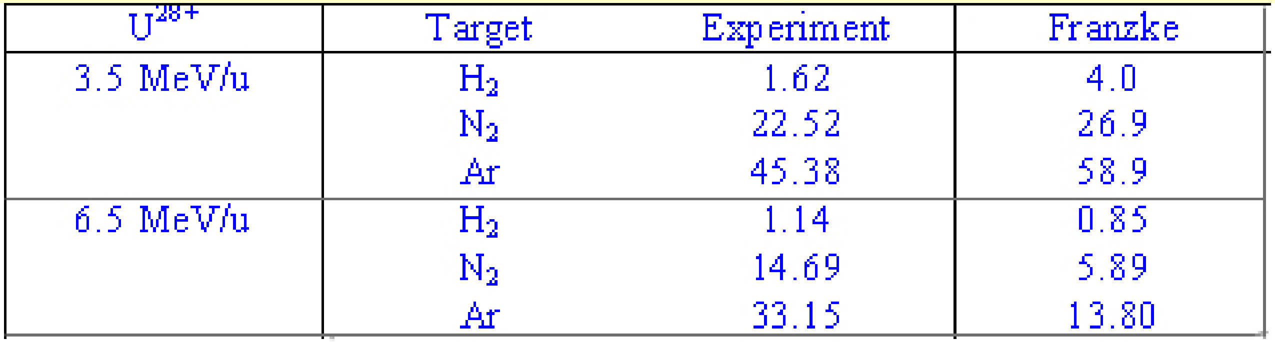
$$\sigma_{i,i+1} \quad = \quad 3.5.10^{-18+(0.71\lg Z_{pr})^{3/2}} \frac{\bar{q}_t}{\bar{q}_{pr}\sqrt{\gamma^2-1}}\left(\frac{q_{pr}}{\bar{q}_{pr}}\right)^{-4}$$

$$\bar{q} \quad = \quad Z\left(1-e^{-\frac{137\beta}{Z^{0.67}}}\right)$$

(B. Franzke)

Comparison of the experimental cross sections and Franzke’s formula;

cross sections in 10^{-18} cm^2/atom

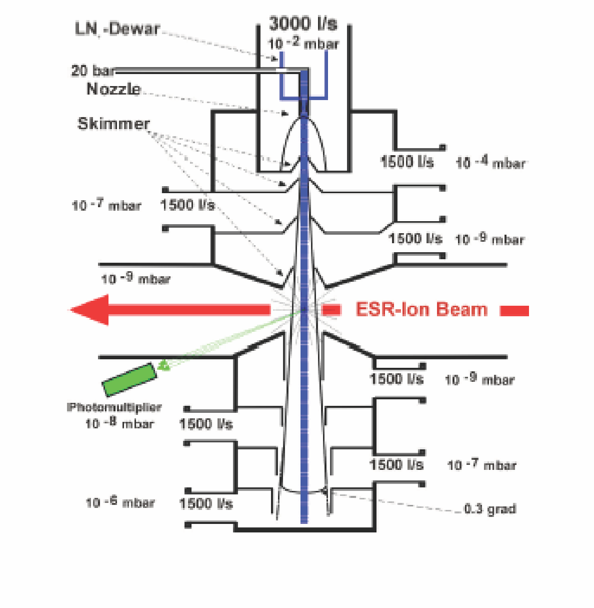


U^{28+}	Target	Experiment	Franzke
3.5 MeV/u	H_2	1.62	4.0
	N_2	22.52	26.9
	Ar	45.38	58.9
6.5 MeV/u	H_2	1.14	0.85
	N_2	14.69	5.89
	Ar	33.15	13.80

CURE:

→stepwise ionizing of ions along the chain of accelerators

→ ion stripping

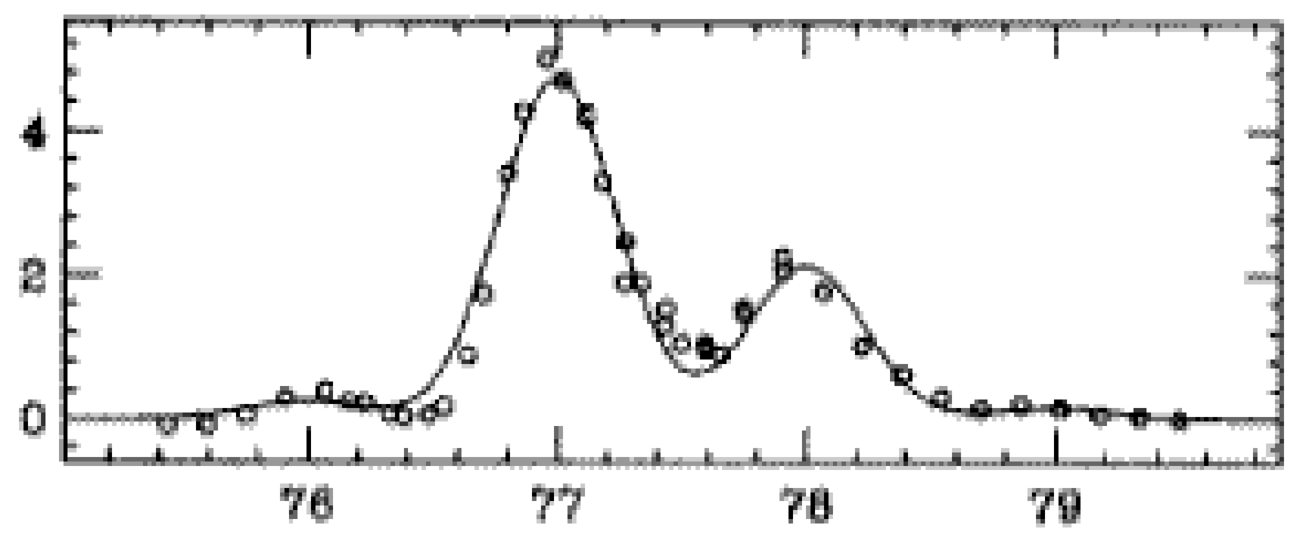


Supersonic gas jet target (10^{14} p/cm^3), GSI

Rotating carbon disk stripper, thickness of the foil 100 μg/cm^2, RIKEN

AGS booster: Au^{33+} ions, 192 MeV/u + 56 mg/cm^2 carbon stripping foil → Au^{77+}.

Stripping efficiency = 65%.



Charge state spectrum of Au^{33+} ions at 192 MeV/u stripped by a 56 mg/cm^2 carbon foil, BNL

Equilibrium mean charge after stripping:

$$\bar{i} = Z_{pr}\,[1+(\frac{v}{v'\,Z_{pr}^{\;0.45}})^{-1.67}]^{-0.6}$$

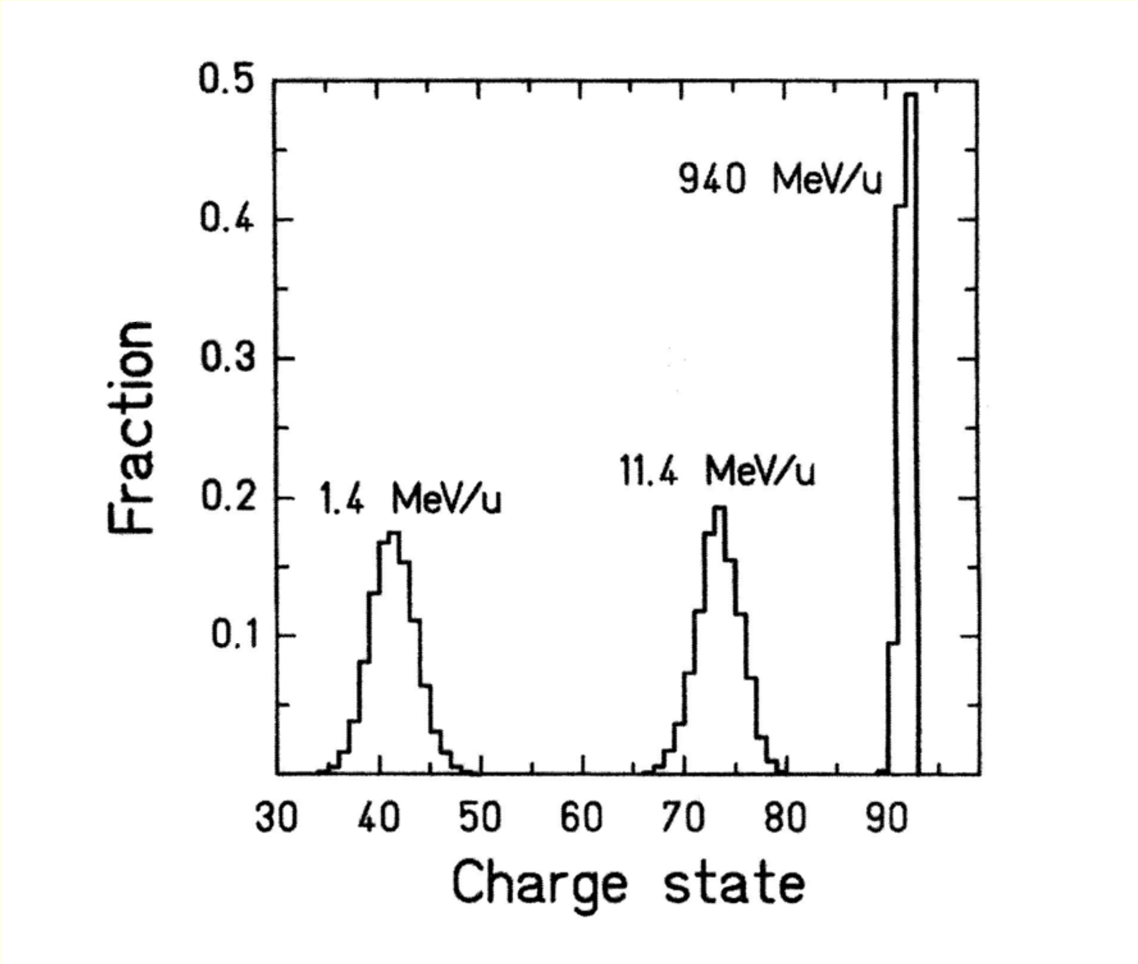
(V. S. Nikolaev, I. S. Dmitriev)

Charge state spectrum:

$$\Phi_q = \frac{1}{\sigma\sqrt{2\pi}}\,e^{-\frac{(q-\bar{q})^2}{2\sigma^2}}$$

$$\sigma = 0.5\sqrt{\bar{q}\,(1-(\frac{\bar{q}}{Z_{pr}})^{1.67}}$$

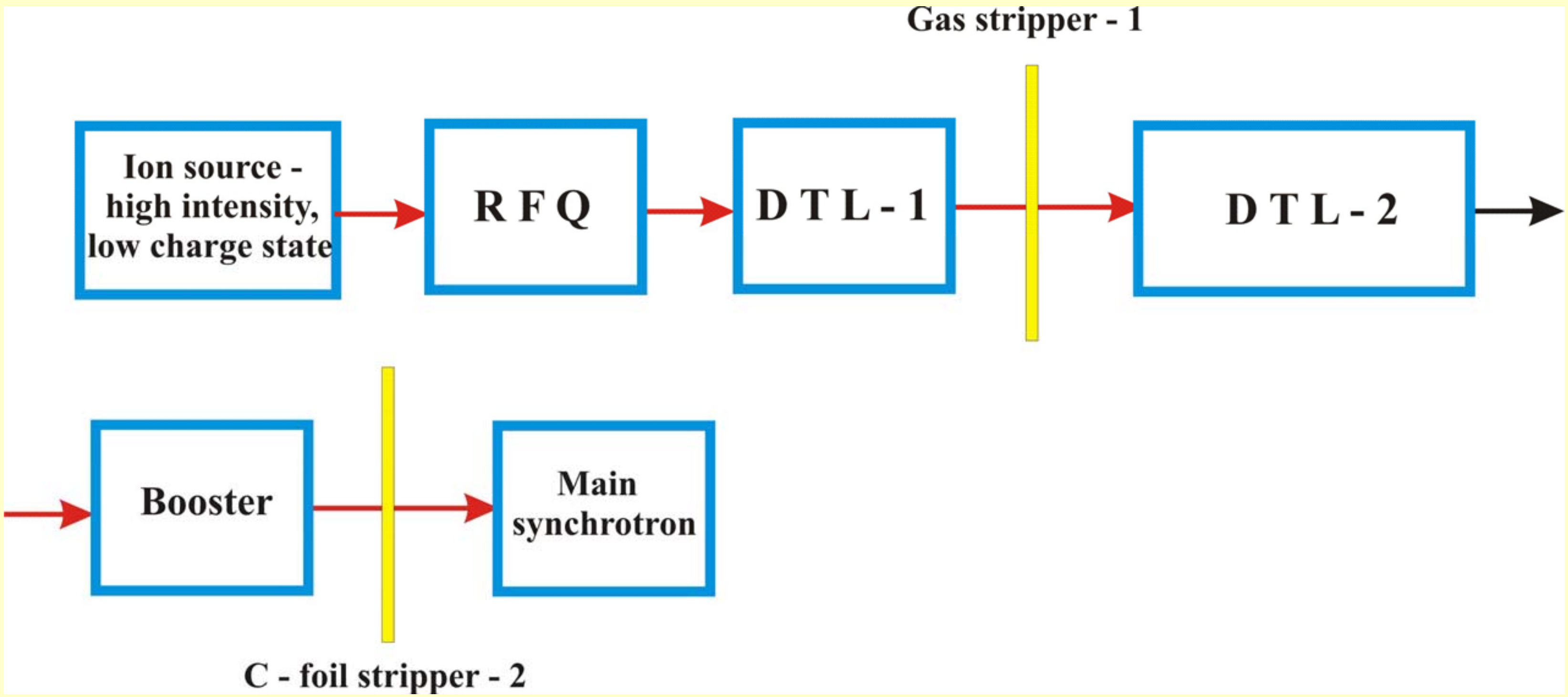
For fast enough (ultra-relativistic) ions the mean charge tends to Z_{pr} (bare ions) and the spectrum becomes very narrow. Stripping efficiency increases.



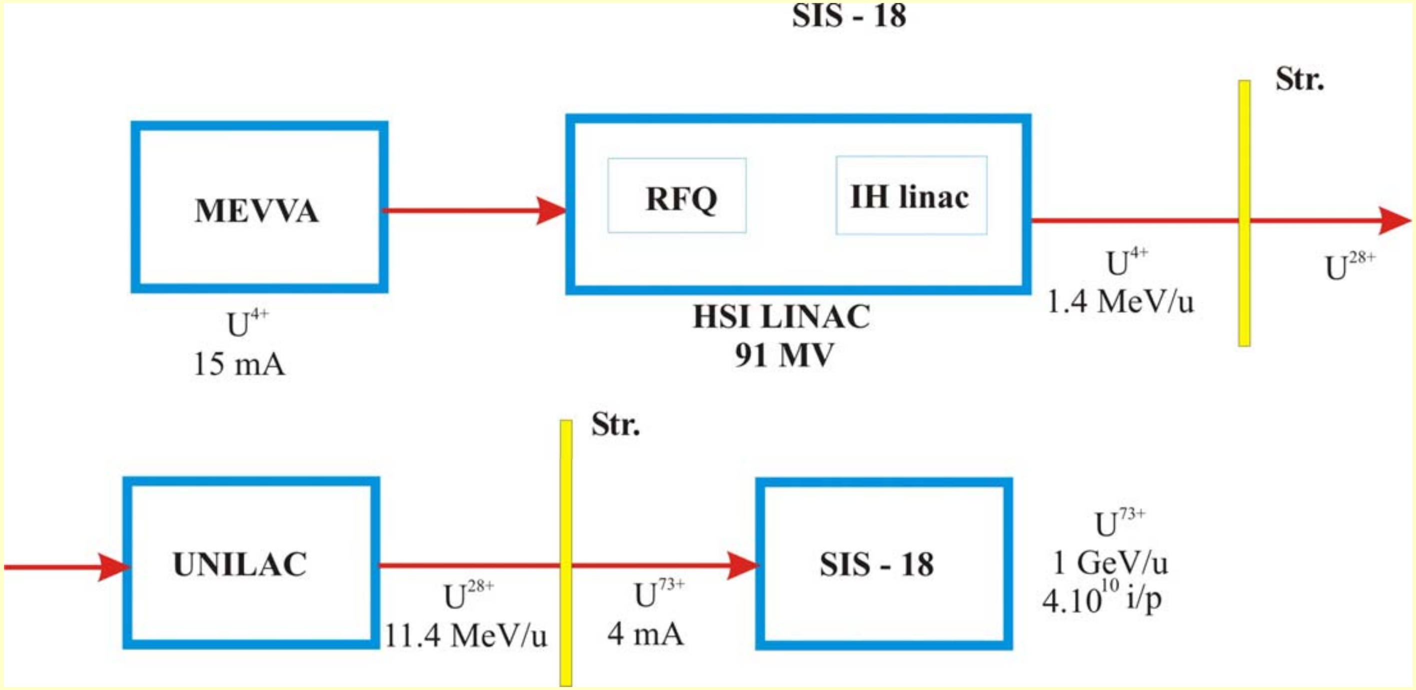
Equilibrium charge state spectra of uranium projectiles behind C–foils, GSI

VARIANTS
OF A HIGH-ENERGY HEAVY- ION ACCELERATOR COMPLEX

Variant with a high current, low charge state injector.



SIS-18 heavy ion synchrotron at GSI, Darmstadt



SIS - 18

MEVVA

U^{4+}
15 mA

RFQ

IH linac

HSI LINAC
91 MV

U^{4+}
1.4 MeV/u

Str.

U^{28+}

UNILAC

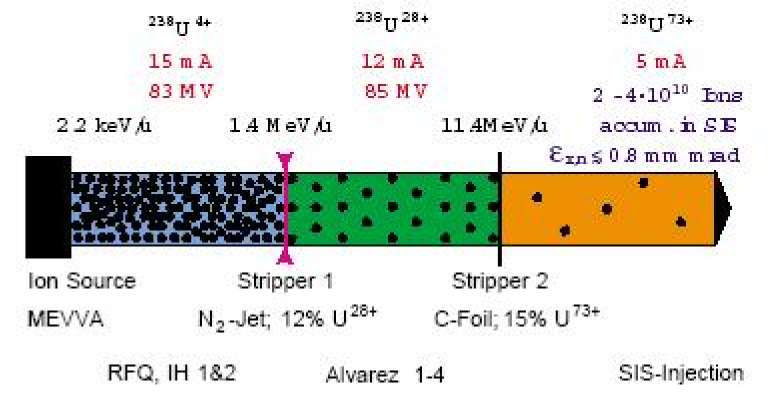
U^{28+}
11.4 MeV/u

Str.

U^{73+}
4 mA

SIS - 18

U^{73+}
1 GeV/u
4.10^{10} i/p



$^{238}U^{4+}$
15 mA
83 MV

$^{238}U^{28+}$
12 mA
85 MV

$^{238}U^{73+}$
5 mA
$2-4 \cdot 10^{10}$ Ions
accum. in SIS
$\varepsilon_{x,n} \leq 0.8$ mm mrad

2.2 keV/u

1.4 MeV/u

11.4MeV/u

Ion Source
MEVVA

Stripper 1
N_2-Jet; 12% U^{28+}

Stripper 2
C-Foil; 15% U^{73+}

RFQ, IH 1&2

Alvarez 1-4

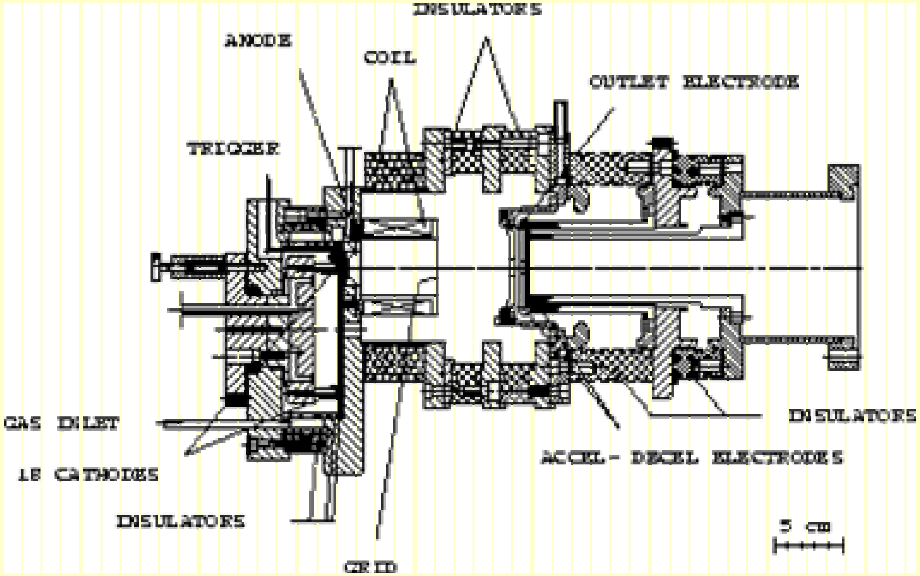
SIS-Injection

Vaccum Arc Ion Sources (GSI): *high intensity, long pulse (>500 µs) → multiturn injection, long lifetime, simple, reliable*

MUCIS – gaseous ions (Ar^{1+}, 38 emA)

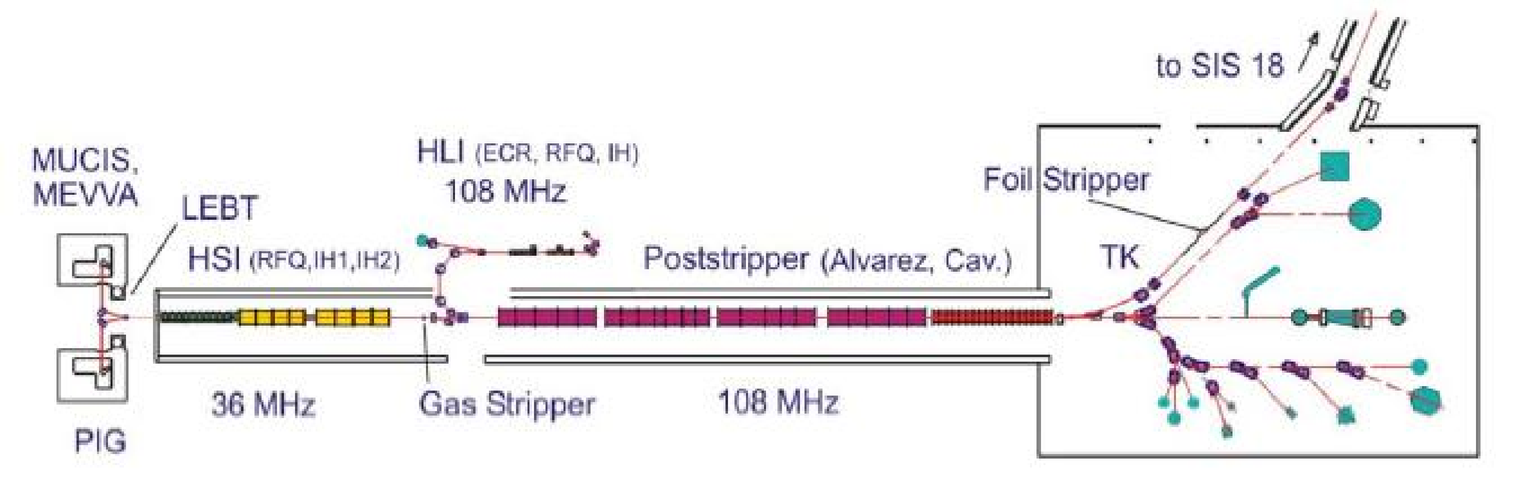
MEVVA – metal ions (total current = 24 emA, 67% U^{4+})

VARIS – uranium beams (U^{4+}, 25 emA)



MEVVA source of uranium ions

High Current Injector (HIS) and UNILAC Alvarez linac

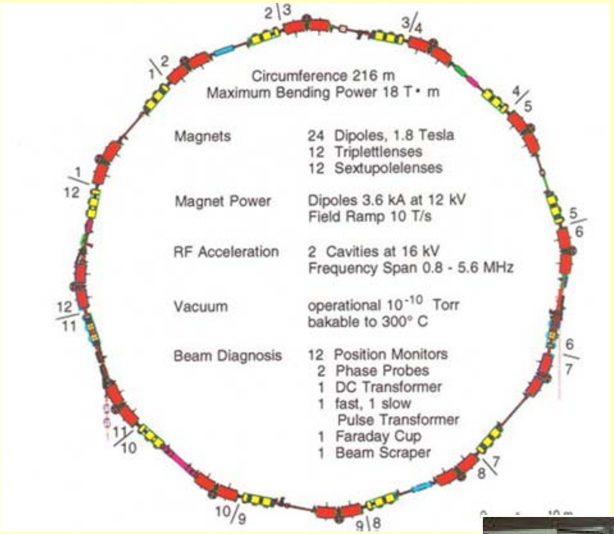


Upgraded UNILAC: **MEVVA ion source (15 mA U^{4+}) + 36 MHz RFQ linac (U^{4+}, 120 keV/U) + 36 MHZ IH-linac (two tanks) → 1.4 MeV/u, U^{28+} (after stripping) + UNILAC Alvarez linac → 4 mA, 11.4 MeV, U^{73+} (after stripping). Efficiency of the two strippers = 12% +15%.**

UNILAC

108 MHz, Alvarez linac with five tanks, 11.4 MeV/u, U^{28+} ions

SIS-18 synchrotron



Circumference 216 m
Maximum Bending Power 18 T • m

Magnets	24 Dipoles, 1.8 Tesla 12 Triplettlenses 12 Sextupolelenses
Magnet Power	Dipoles 3.6 kA at 12 kV Field Ramp 10 T/s
RF Acceleration	2 Cavities at 16 kV Frequency Span 0.8 - 5.6 MHz
Vacuum	operational 10^{-10} Torr bakable to 300° C
Beam Diagnosis	12 Position Monitors 2 Phase Probes 1 DC Transformer 1 fast, 1 slow Pulse Transformer 1 Faraday Cup 1 Beam Scraper

Combination of multiturn injection + e-cooling (15 cycles, 1s) → 4.10^{10} ions/pulse

$B\rho_{max}$ = 18 Tm

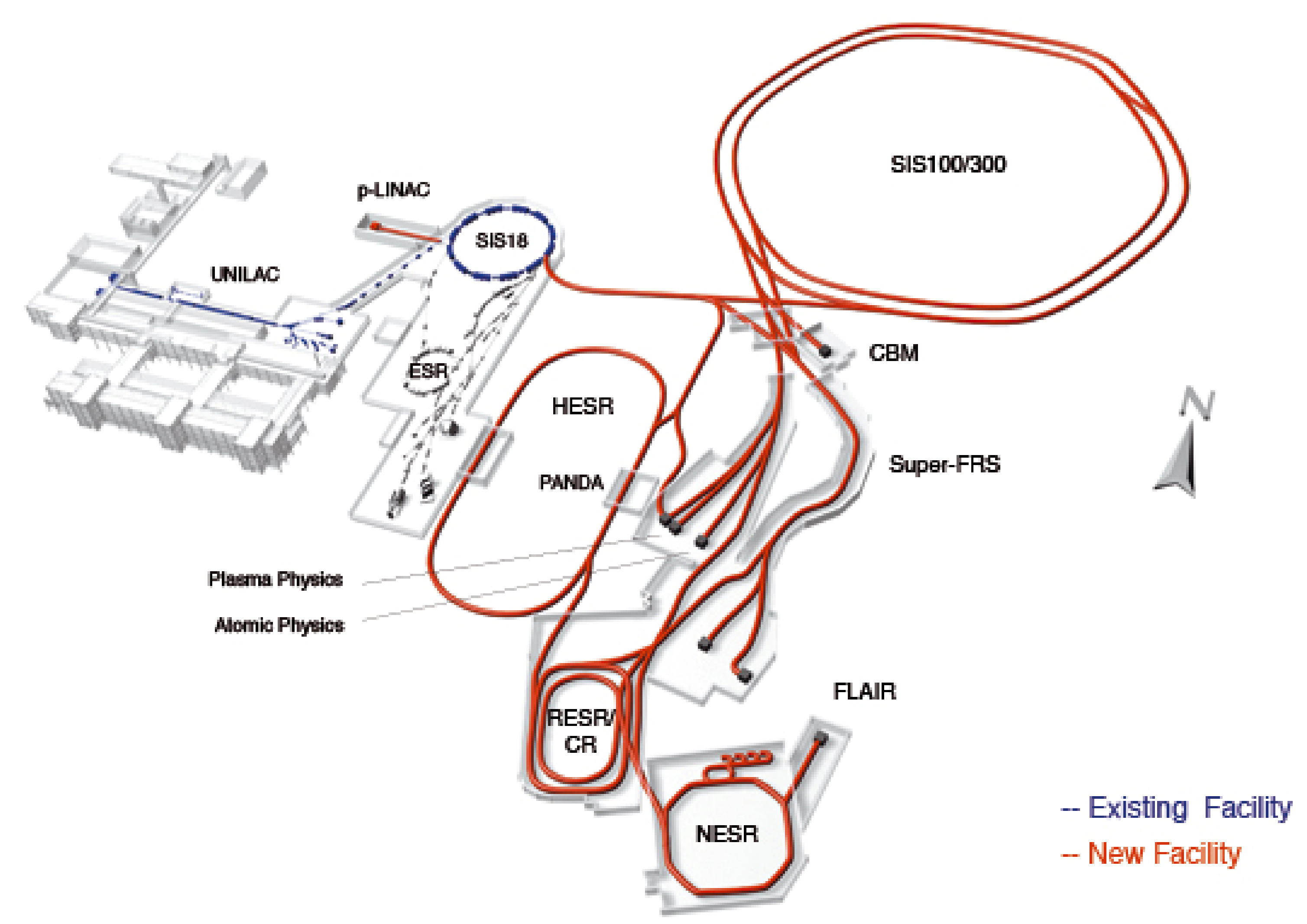
C = 216 m

B_{max} = 1.8 T

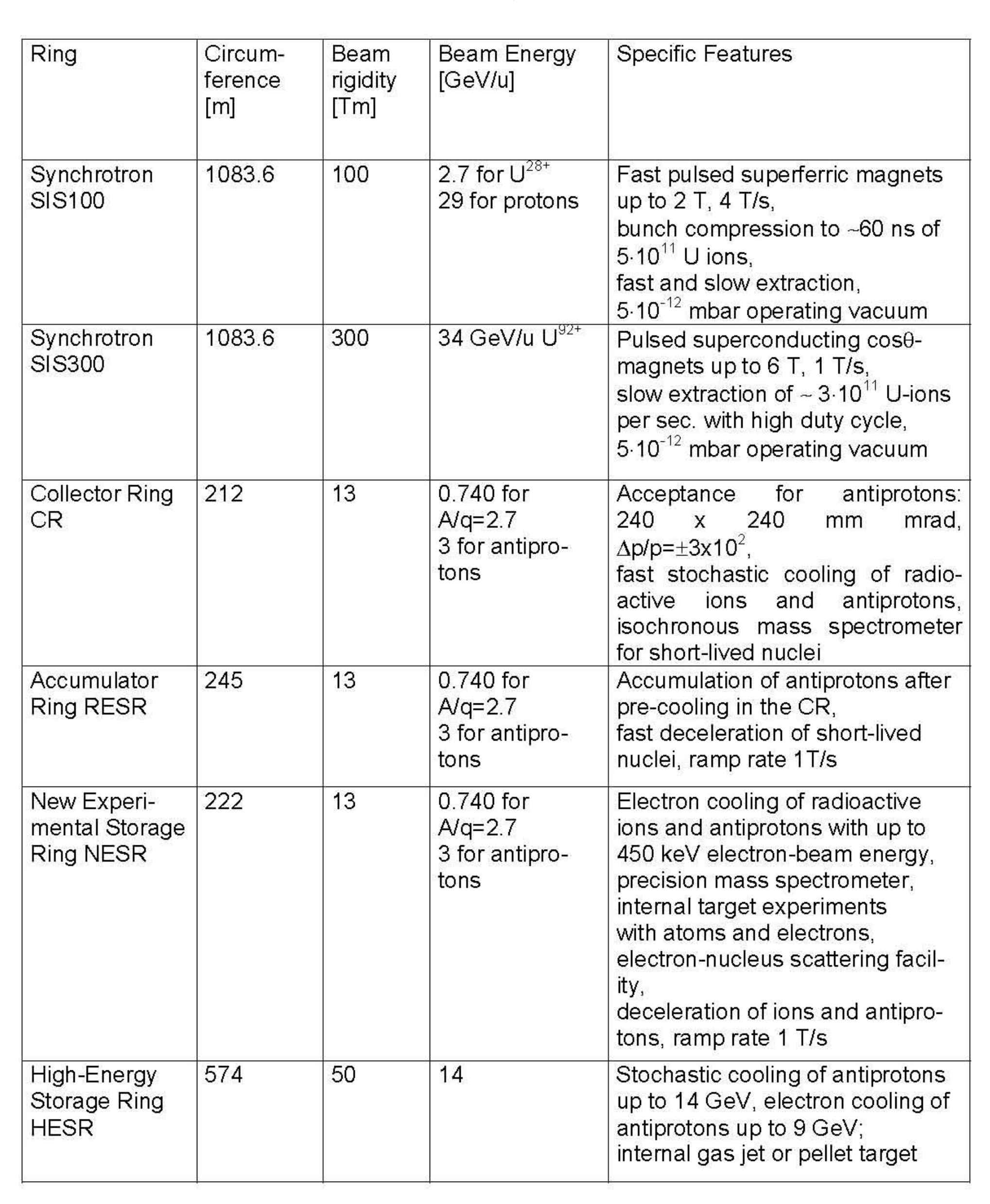
T = 1 GeV/u

P = $1.8.10^{-11}$ Torr

FAIR - Facility for Antiproton and Ion Research

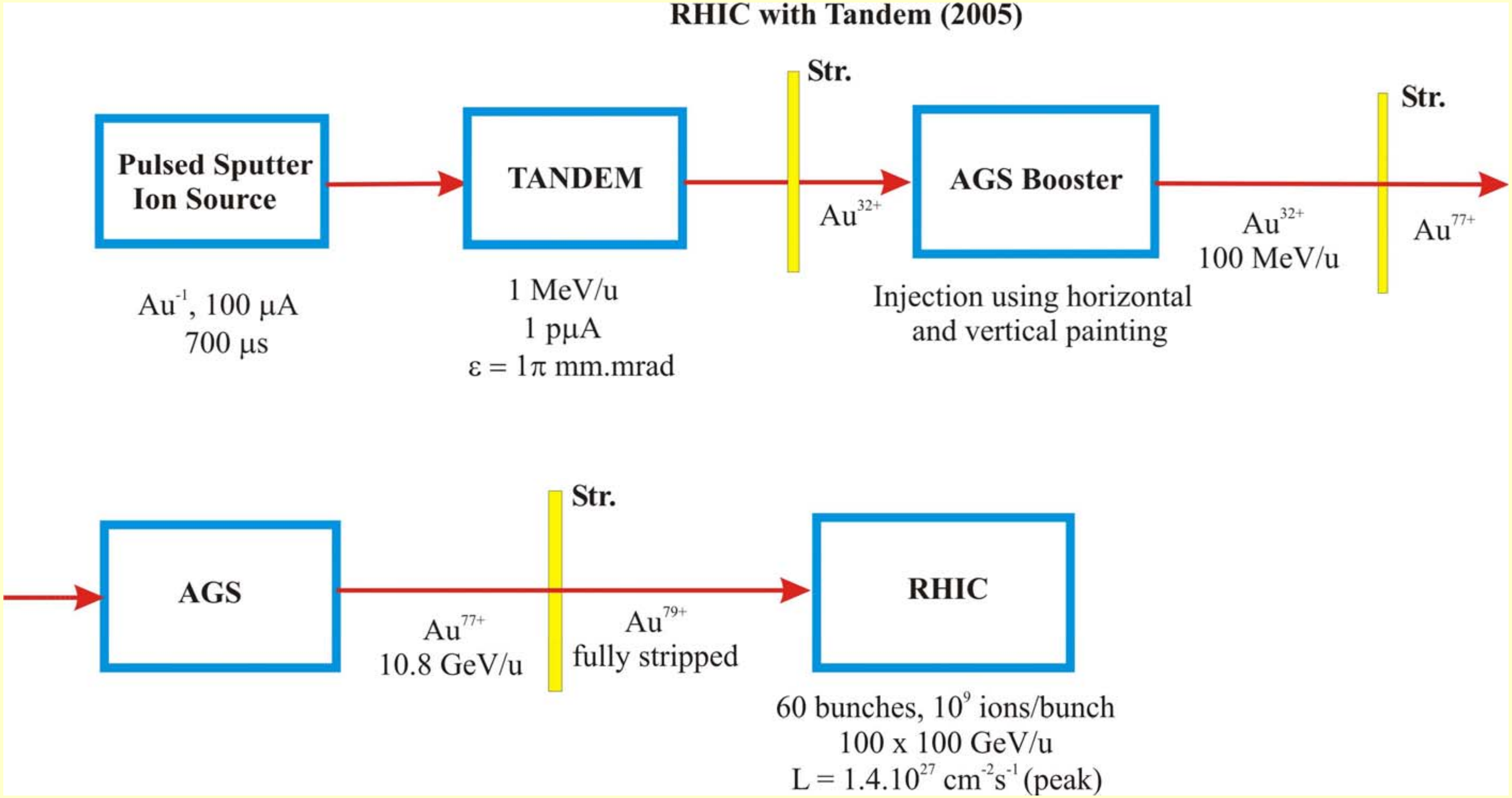


FAIR at GSI, Darmstadt



Ring	Circum-ference [m]	Beam rigidity [Tm]	Beam Energy [GeV/u]	Specific Features
Synchrotron SIS100	1083.6	100	2.7 for U^{28+} 29 for protons	Fast pulsed superferric magnets up to 2 T, 4 T/s, bunch compression to ~60 ns of $5{\cdot}10^{11}$ U ions, fast and slow extraction, $5{\cdot}10^{-12}$ mbar operating vacuum
Synchrotron SIS300	1083.6	300	34 GeV/u U^{92+}	Pulsed superconducting cosθ-magnets up to 6 T, 1 T/s, slow extraction of ~ $3{\cdot}10^{11}$ U-ions per sec. with high duty cycle, $5{\cdot}10^{-12}$ mbar operating vacuum
Collector Ring CR	212	13	0.740 for A/q=2.7 3 for antiprotons	Acceptance for antiprotons: 240 x 240 mm mrad, $\Delta p/p=\pm 3x10^{2}$, fast stochastic cooling of radioactive ions and antiprotons, isochronous mass spectrometer for short-lived nuclei
Accumulator Ring RESR	245	13	0.740 for A/q=2.7 3 for antiprotons	Accumulation of antiprotons after pre-cooling in the CR, fast deceleration of short-lived nuclei, ramp rate 1T/s
New Experimental Storage Ring NESR	222	13	0.740 for A/q=2.7 3 for antiprotons	Electron cooling of radioactive ions and antiprotons with up to 450 keV electron-beam energy, precision mass spectrometer, internal target experiments with atoms and electrons, electron-nucleus scattering facility, deceleration of ions and antiprotons, ramp rate 1 T/s
High-Energy Storage Ring HESR	574	50	14	Stochastic cooling of antiprotons up to 14 GeV, electron cooling of antiprotons up to 9 GeV; internal gas jet or pellet target

RHIC – Relativistic Heavy Ion Collider at BNL, Brookhaven



RHIC with Tandem (2005)

Pulsed Sputter Ion Source

Au^{-1}, 100 μA
700 μs

TANDEM

1 MeV/u
1 pμA
ε = 1π mm.mrad

Str.

Au^{32+}

AGS Booster

Injection using horizontal
and vertical painting

Au^{32+}
100 MeV/u

Str.

Au^{77+}

AGS

Au^{77+}
10.8 GeV/u

Str.

Au^{79+}
fully stripped

RHIC

60 bunches, 10^{9} ions/bunch
100 x 100 GeV/u
L = $1.4.10^{27}$ $cm^{-2}s^{-1}$ (peak)

BNL, Brookhaven

Tandem Van de Graaff

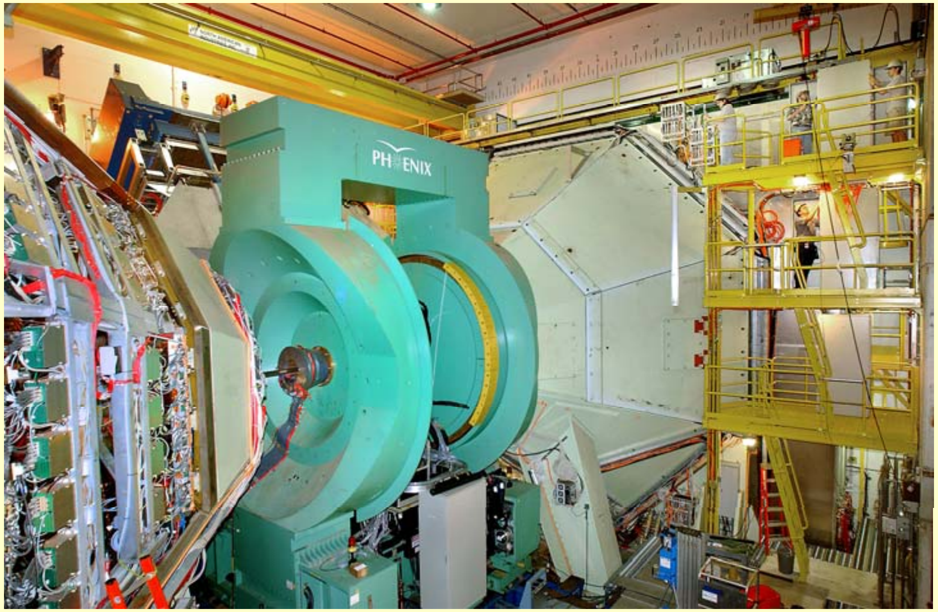
1 MeV/u, 5.4.10^9 gold ions/pulse, $\varepsilon = 1\pi$ mm.mrad

AGS – Alternating Gradient Synchrotron

1960, B_{max}=1.31T, C= 805m, protons 33 GeV, 6.3.10^{13}ppp(1998); gold ions 14.5 GeV/u, 2.10^{9} i/p,

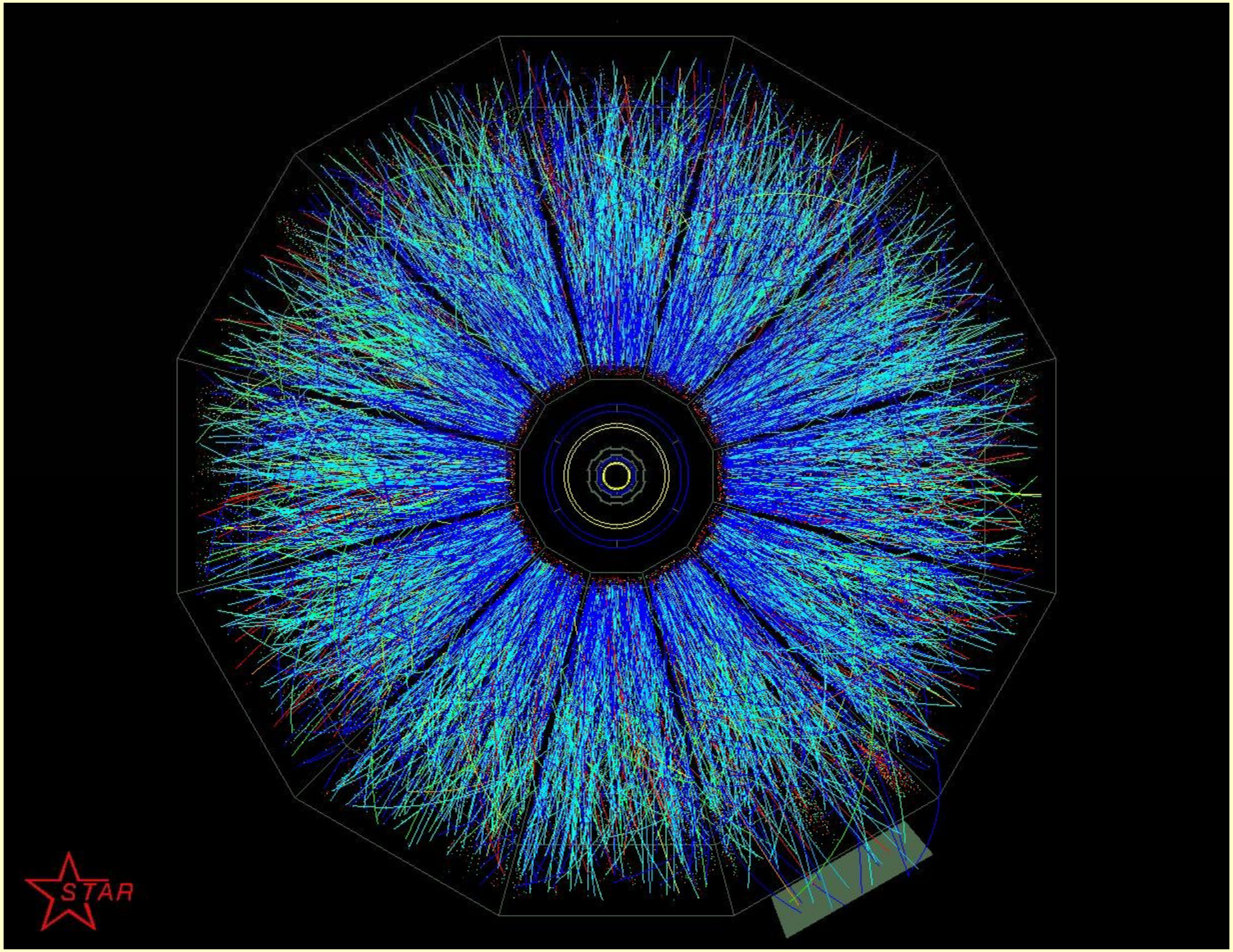
RHIC

Au^{79+} 100 x 100 GeV/u, 60 bunches, 1.10^{9} ions/bunch, L = $1.4.10^{27}$ $cm^{-2}s^{-1}$



Detector PHENIX

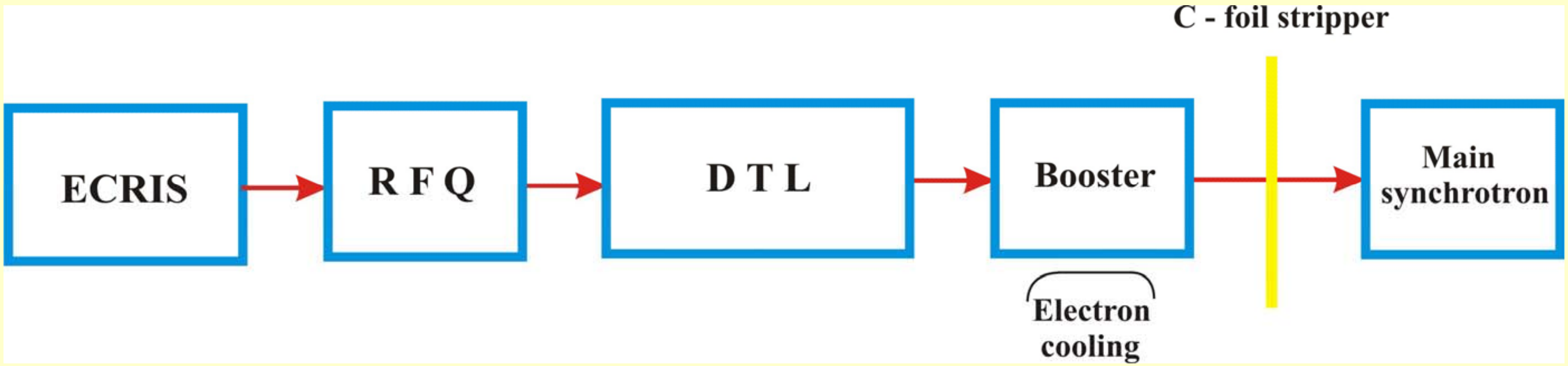
Detector STAR



First gold beam-beam collision event at RHIC at 100 x 100 GeV/u

recorded by STAR detector.

Variant with a source of heavy ions in medium charge state, working in dc mode



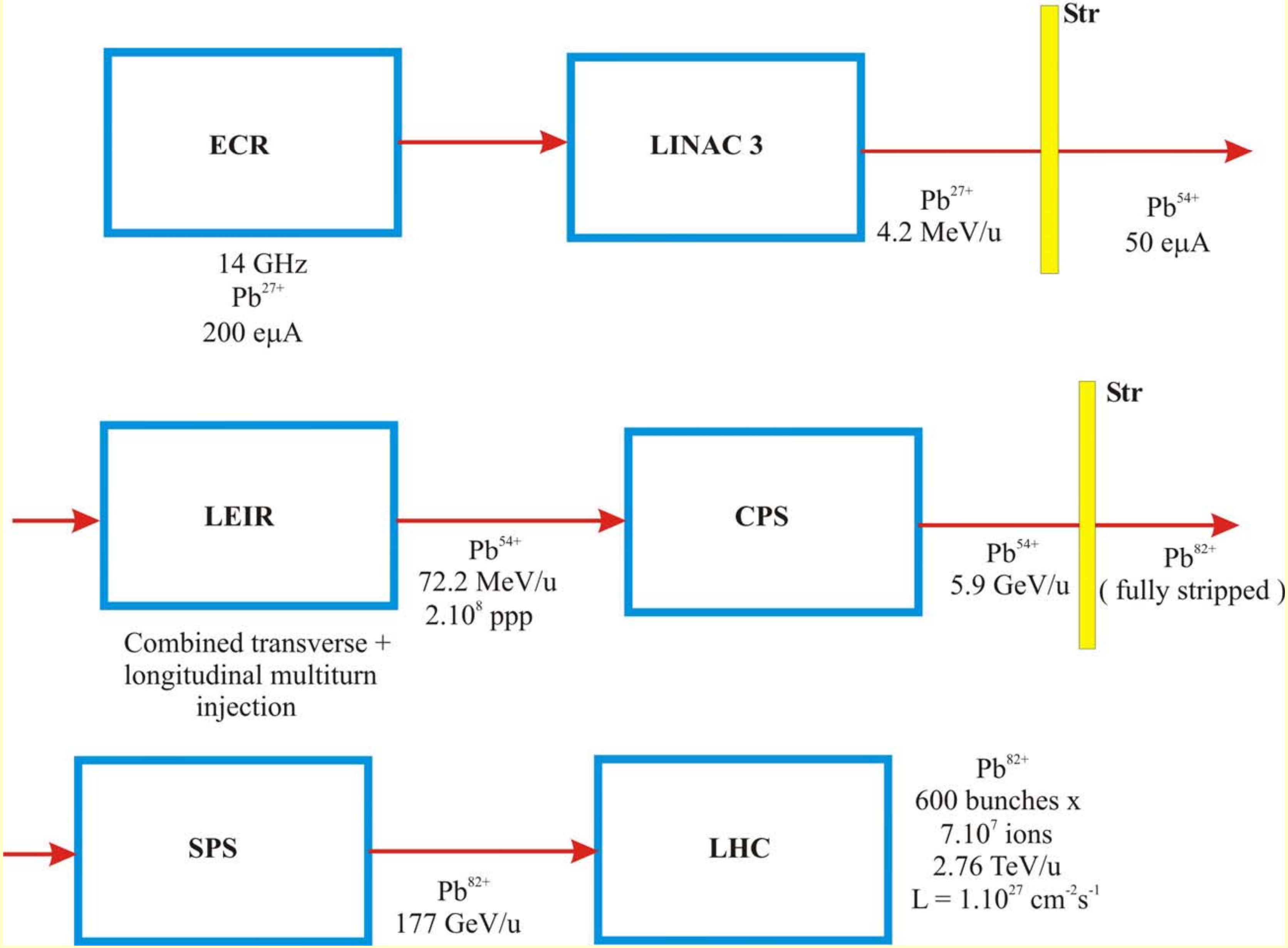
ECRIS - Electron Cyclotron Resonance Ion Source

dc or long pulses (~200 μs) modes.

ECRIS – VENUS at LBNL: U^{30+} 240 eμA , U^{48+} 5 eμA

28 GHz, 4T

LHC - Lead Program



ECR

14 GHz
Pb^{27+}
200 eμA

LINAC 3

Pb^{27+}
4.2 MeV/u

Str

Pb^{54+}
50 eμA

LEIR

Combined transverse +
longitudinal multiturn
injection

Pb^{54+}
72.2 MeV/u
2.10^{8} ppp

CPS

Pb^{54+}
5.9 GeV/u

Str

Pb^{82+}
(fully stripped)

SPS

Pb^{82+}
177 GeV/u

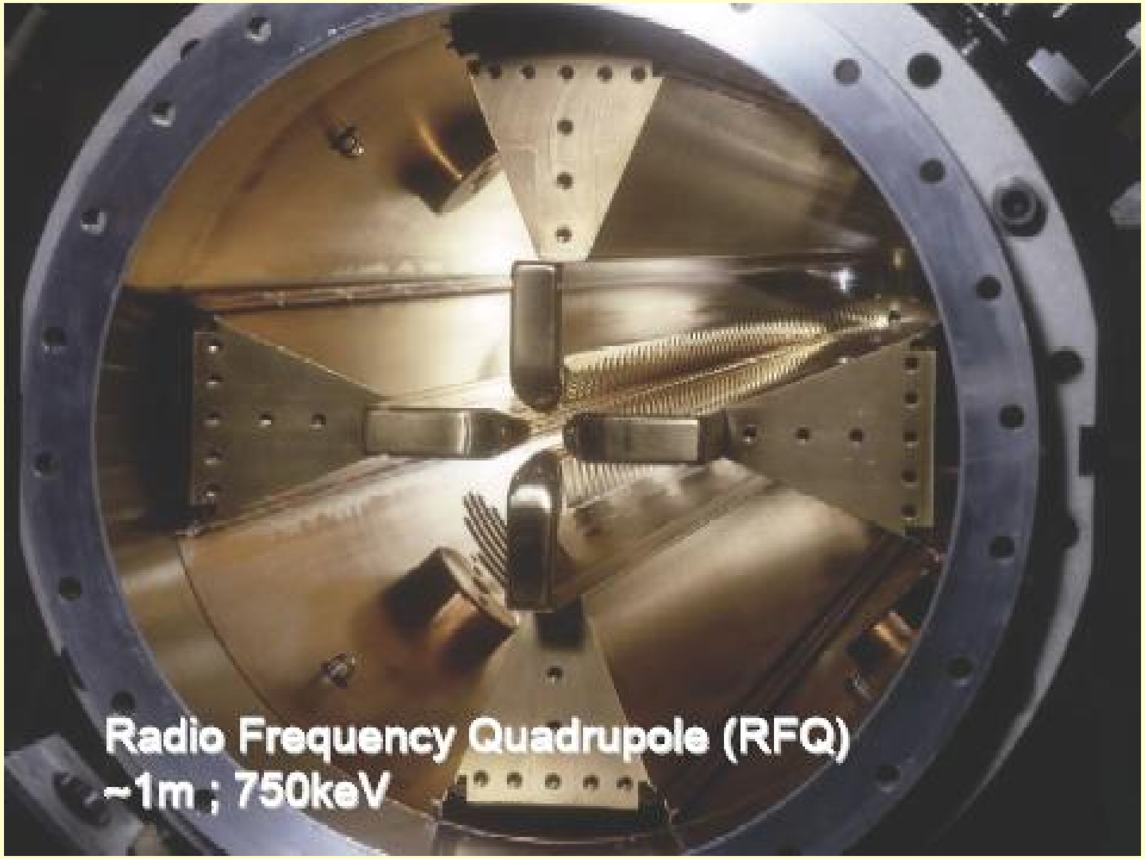
LHC

Pb^{82+}
600 bunches x
7.10^{7} ions
2.76 TeV/u
$L = 1.10^{27}$ cm^{-2}s^{-1}

Linac 3

100 MHz RFQ section, Pb^{27+}, 250 keV/u, 90 eμA

3 tanks IH βλ/2 linac, L=8.1 m, Pb^{54+}(after 100 μg/cm^2 C-foil), 4.2 MeV/u, 50 eμA



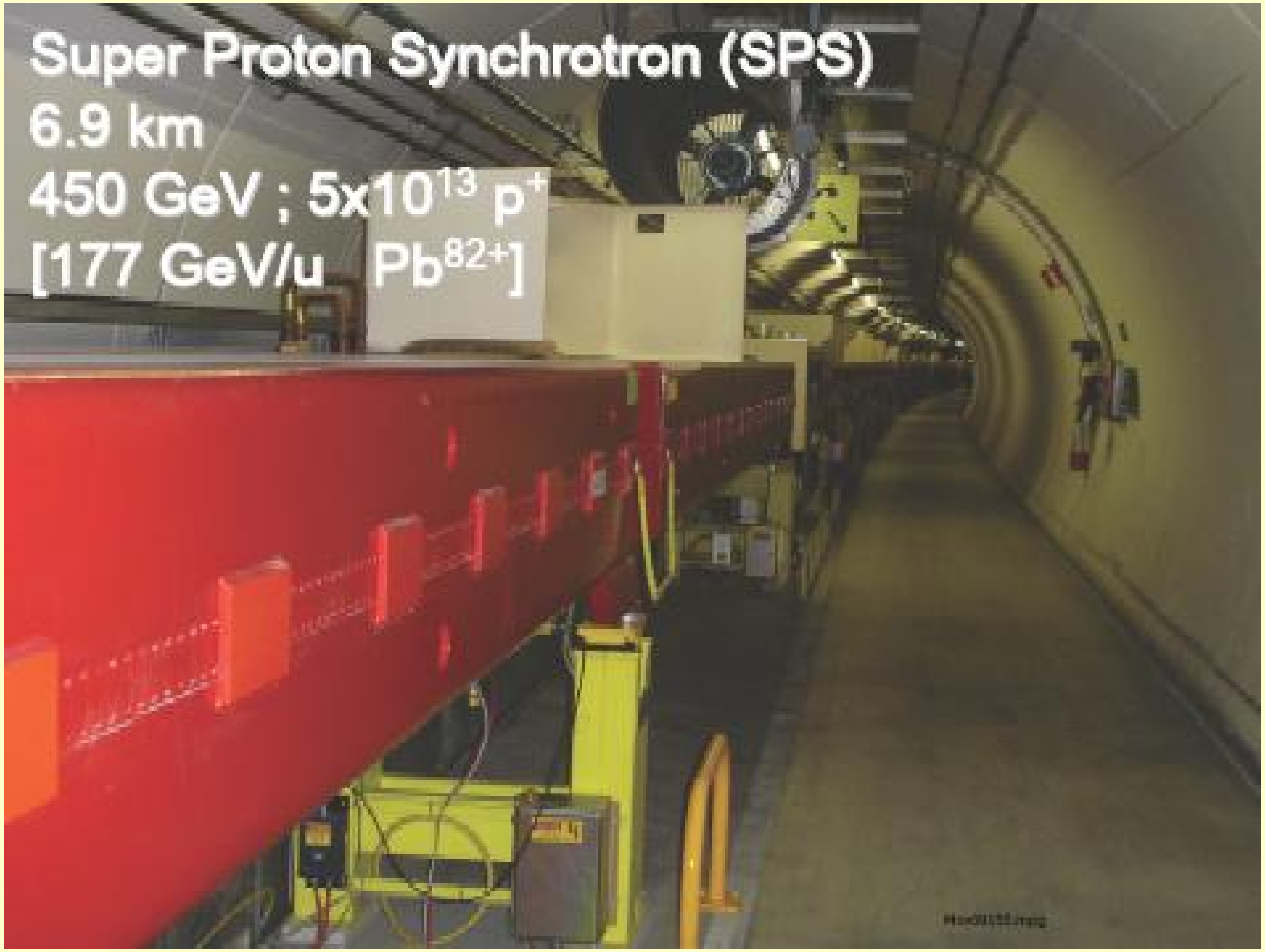
LEIR – Low Energy Ion Ring

Bρ=4.8 Tm, Pb^{54+}, 72.2 MeV/u, 2.10^{8} ions/pulse, Combined longitudinal + transverse multiturn injection (n$_{eff}$=25) + e-cooling (12x) → 1.2.10^{9} ions/pulse

PS – Proton Synchrotron

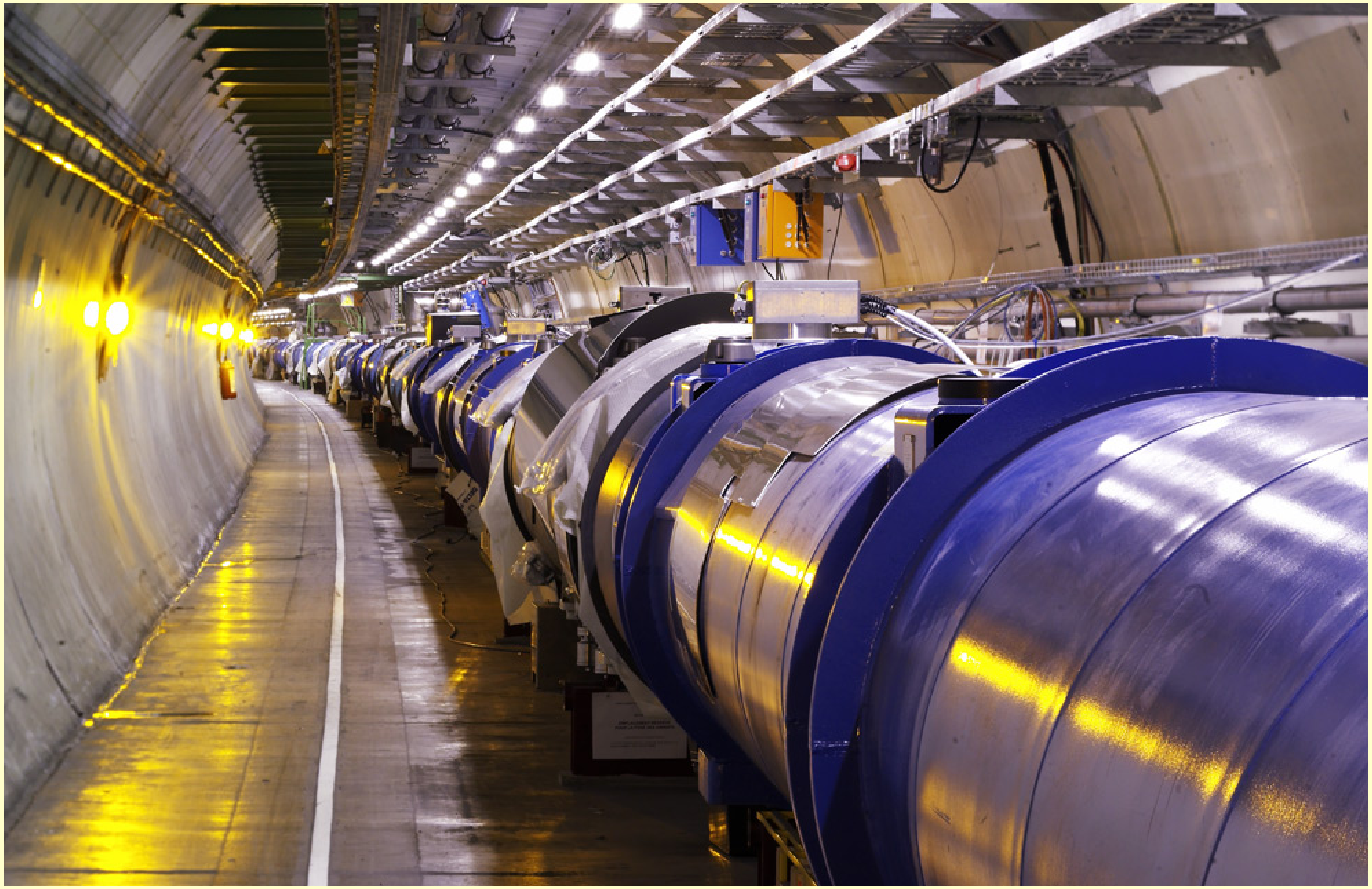
1959, C= 628 m, Bρ=86.7 Tm, combined function, protons: 28 GeV, 3.1.10^{13} ppp, ions: Pb^{54+}, 5.9 GeV/u

SPS – Super Proton Synchrotron



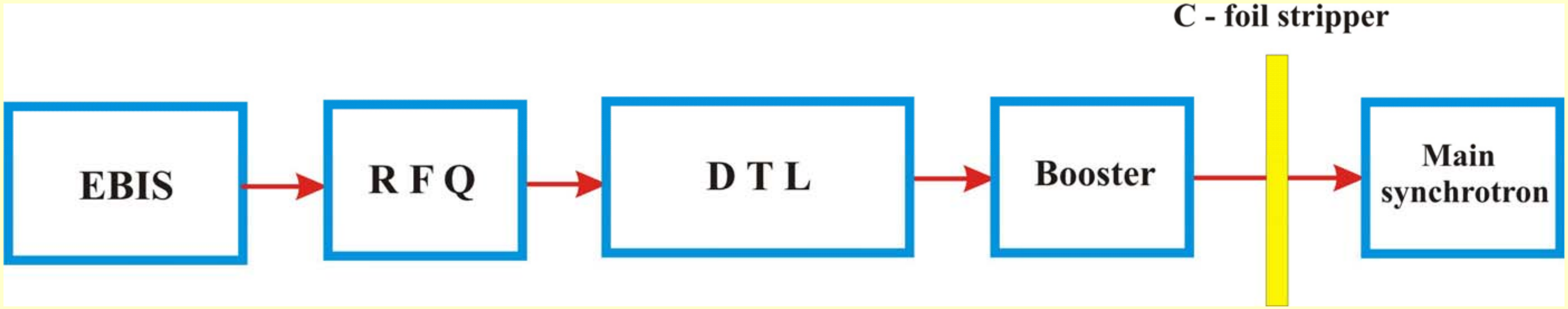
Protons: 450 GeV, $4.8.10^{13}$ ppp, ions: Pb^{82+}, 177 GeV/u, 4.10^{8} ions/pulse

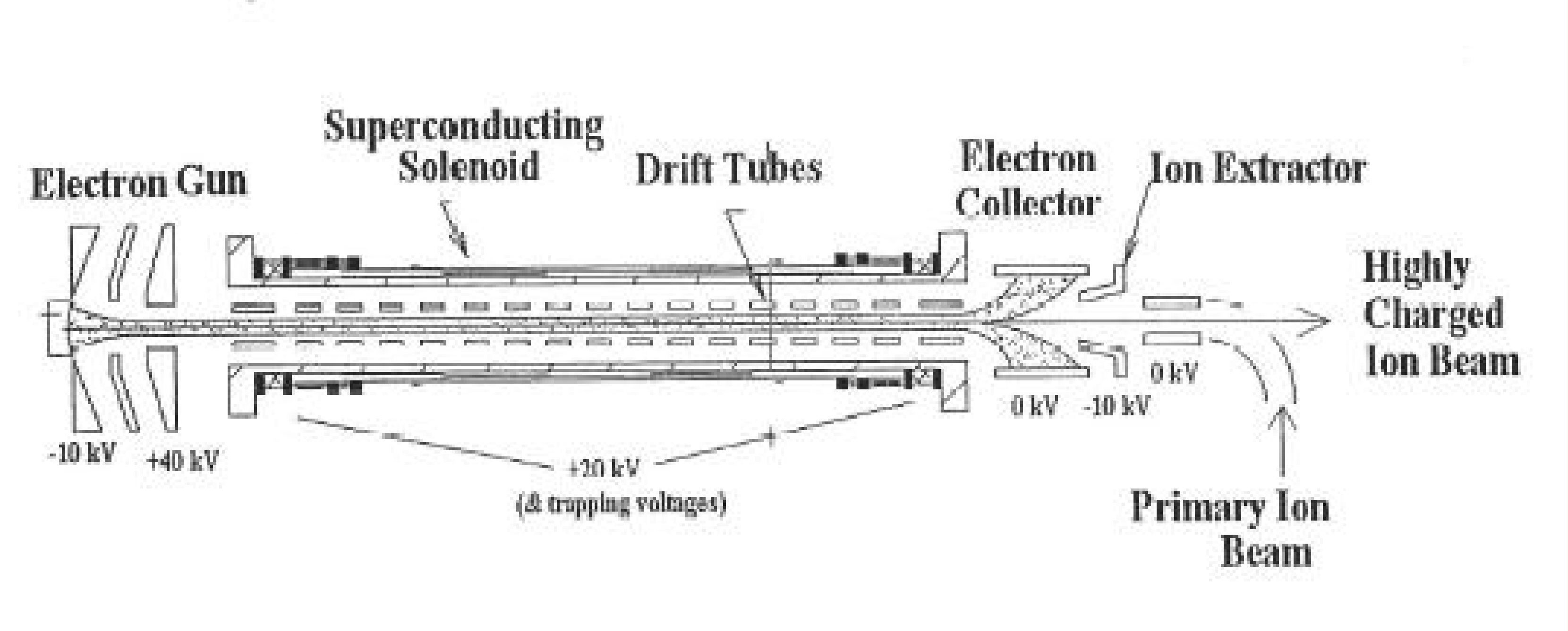
LHC – Large Hadron Collider



Pb^{82+} - Pb^{82+} collisions at 2.76 TeV/u with $L = 1.10^{27}\ cm^{-2}s^{-1}$

Variant with injector of heavy ions in high charge states, working in a short pulses mode.

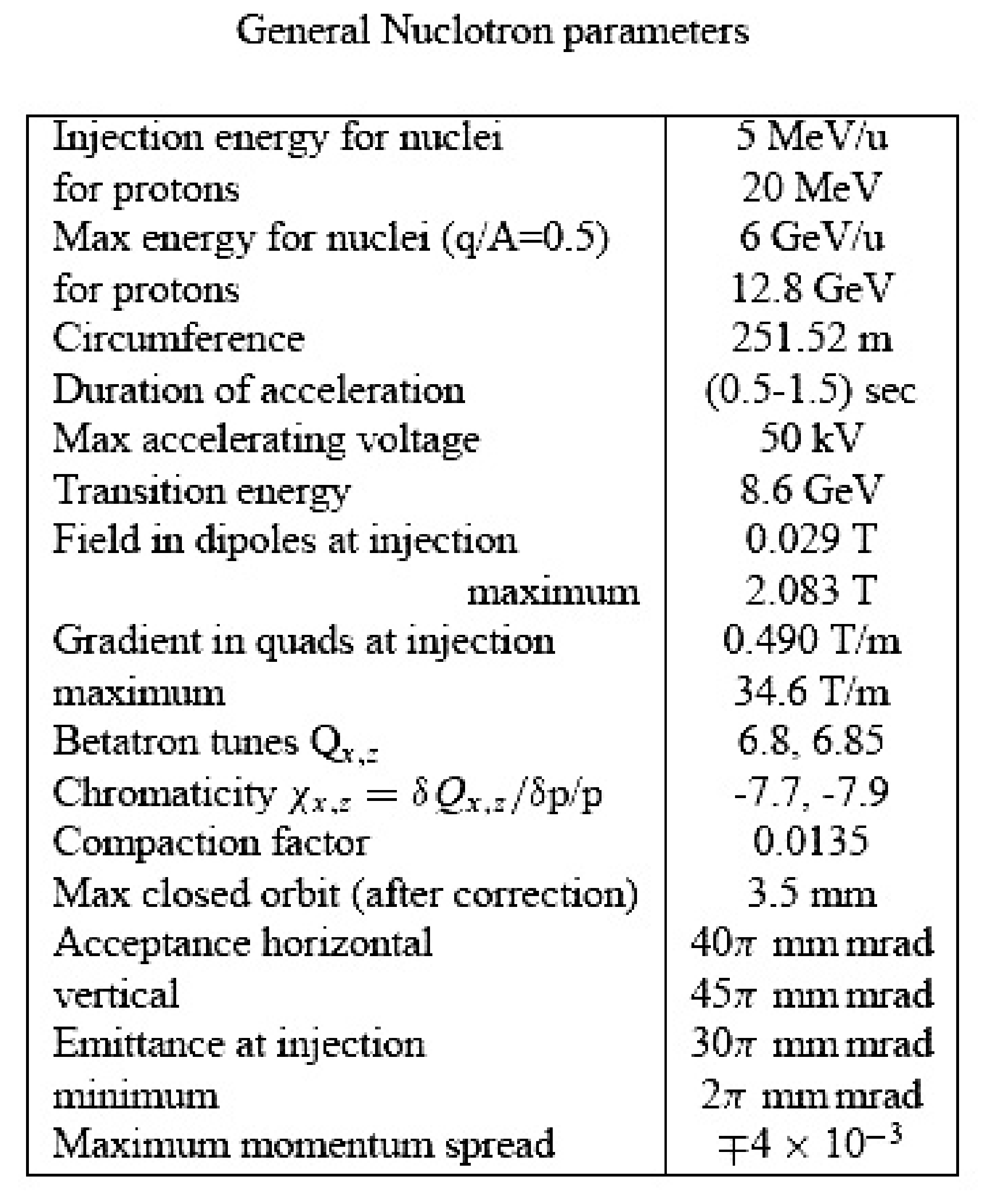




Principle of work of an Electron Beam Ion Source

Superconducting Heavy Ion Synchrotron Nuclotron

at JINR, Dubna



General Nuclotron parameters

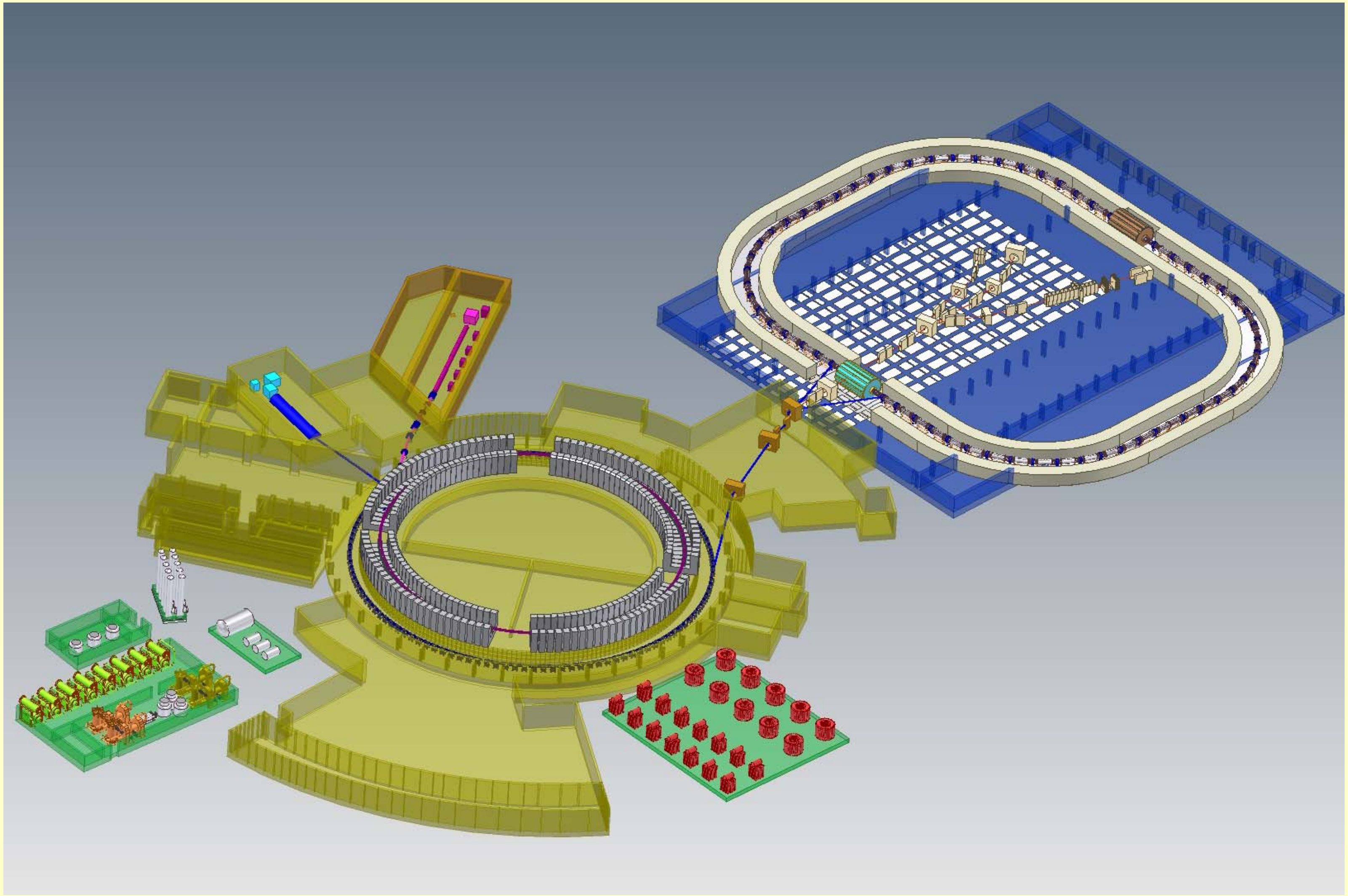
Injection energy for nuclei	5 MeV/u
for protons	20 MeV
Max energy for nuclei (q/A=0.5)	6 GeV/u
for protons	12.8 GeV
Circumference	251.52 m
Duration of acceleration	(0.5-1.5) sec
Max accelerating voltage	50 kV
Transition energy	8.6 GeV
Field in dipoles at injection	0.029 T
maximum	2.083 T
Gradient in quads at injection	0.490 T/m
maximum	34.6 T/m
Betatron tunes $Q_{x,z}$	6.8, 6.85
Chromaticity $\chi_{x,z} = \delta Q_{x,z}/\delta p/p$	-7.7, -7.9
Compaction factor	0.0135
Max closed orbit (after correction)	3.5 mm
Acceptance horizontal	40π mm mrad
vertical	45π mm mrad
Emittance at injection	30π mm mrad
minimum	2π mm mrad
Maximum momentum spread	$\mp 4 \times 10^{-3}$

HEAVY ION COLLIDER NICA

Nuclotron-based Ion Collider fAcility

Project, 2006

Laboratory of High Energy Physics of JINR, Dubna



Heavy ion collider NICA at JINR, Dubna

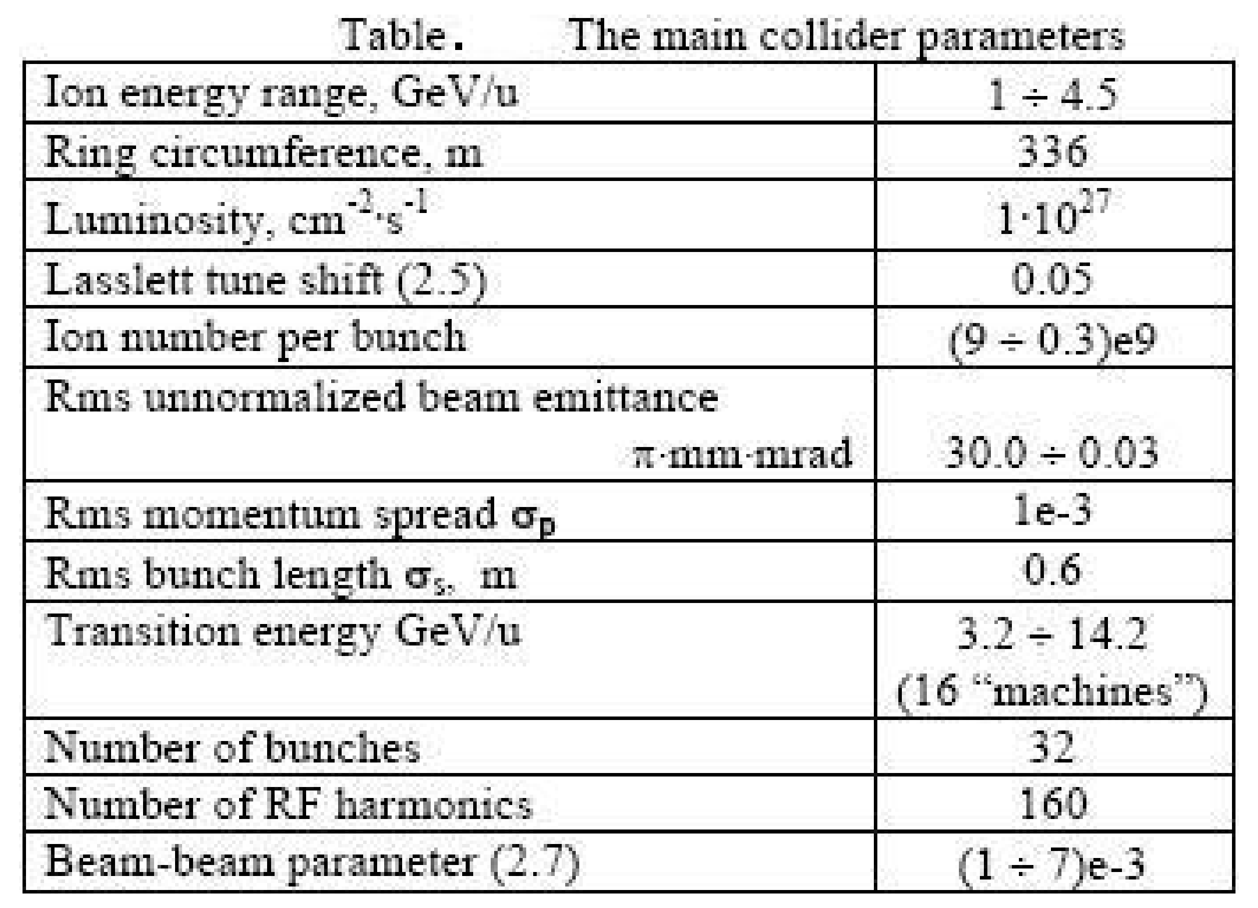
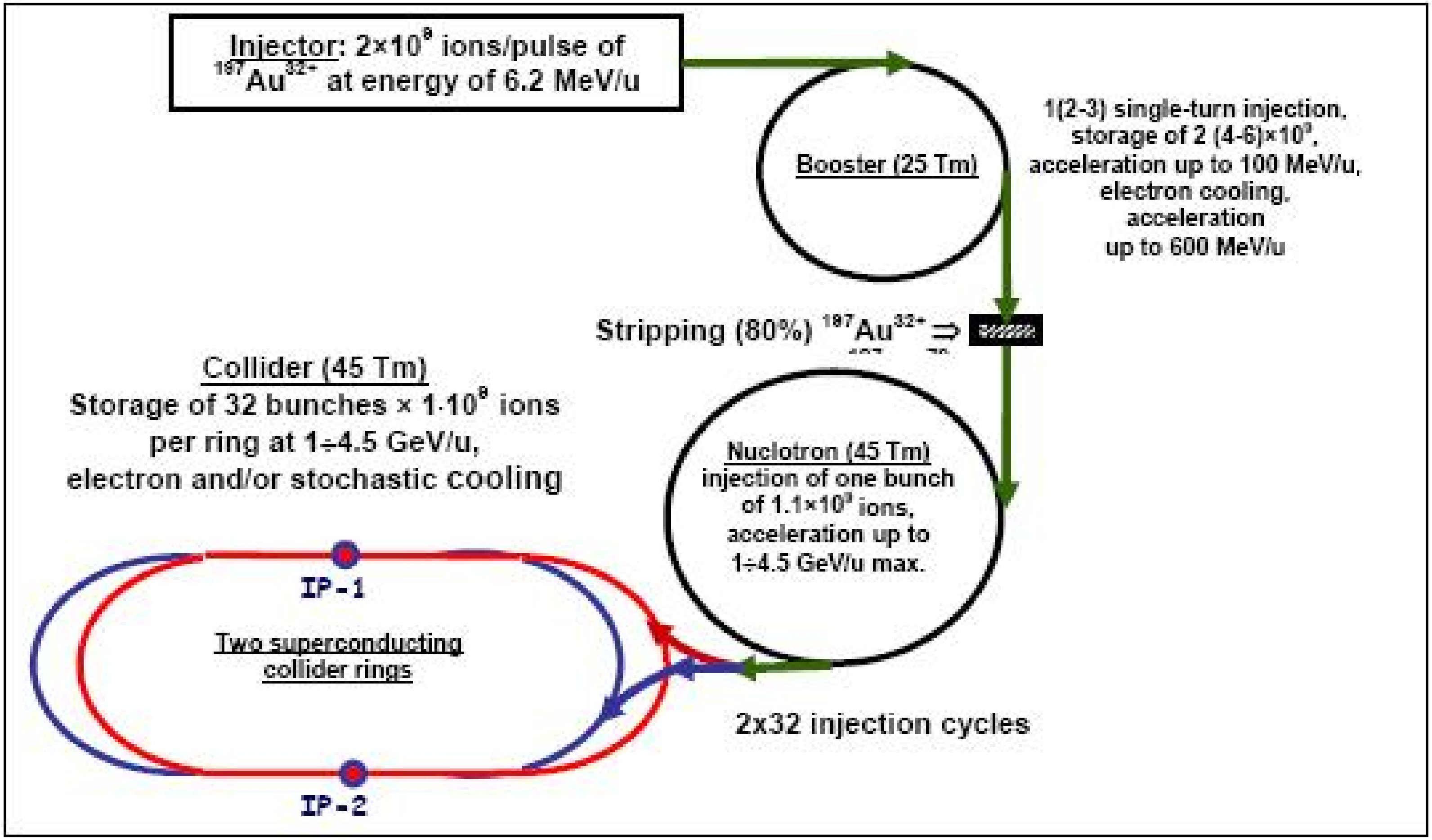


Table. The main collider parameters

Ion energy range, GeV/u	1 ÷ 4.5
Ring circumference, m	336
Luminosity, $cm^{-2}\cdot s^{-1}$	$1\cdot10^{27}$
Lasslett tune shift (2.5)	0.05
Ion number per bunch	(9 ÷ 0.3)e9
Rms unnormalized beam emittance π·mm·mrad	30.0 ÷ 0.03
Rms momentum spread **σ_p**	1e-3
Rms bunch length σ_s, m	0.6
Transition energy GeV/u	3.2 ÷ 14.2 (16 "machines")
Number of bunches	32
Number of RF harmonics	160
Beam-beam parameter (2.7)	(1 ÷ 7)e-3

Main parameters of NICA collider



Layout of heavy ion collider NICA at JINR, Dubna

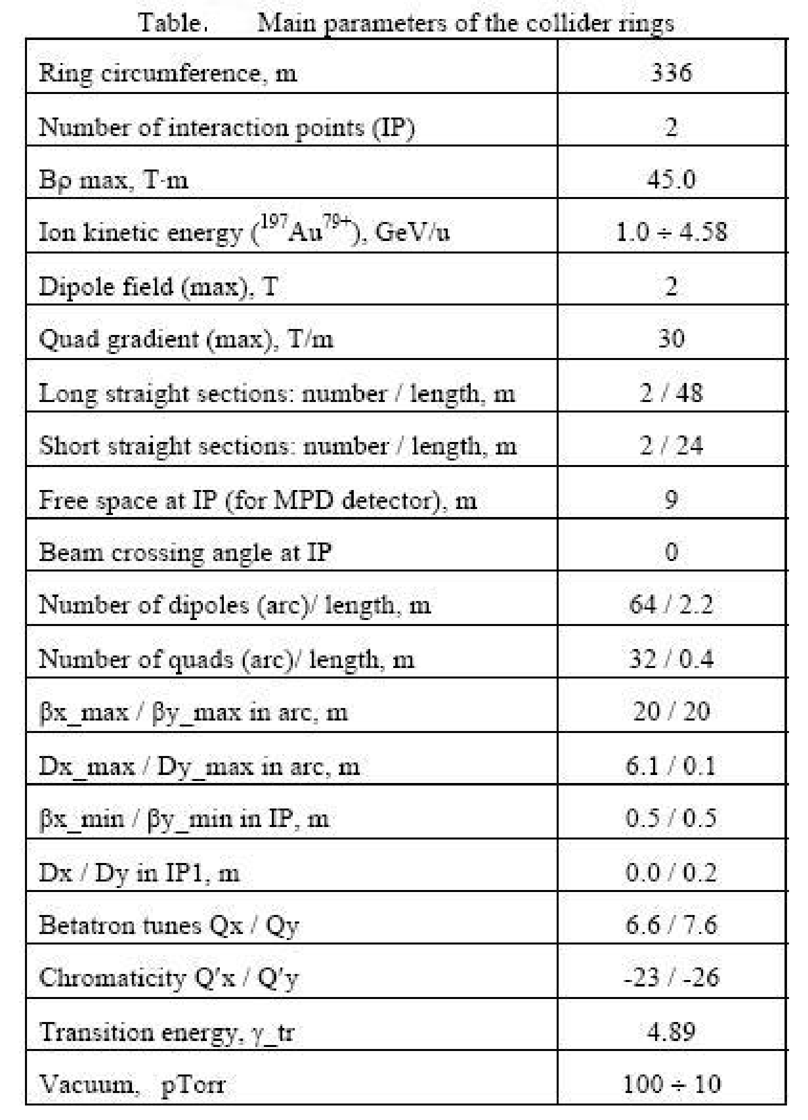
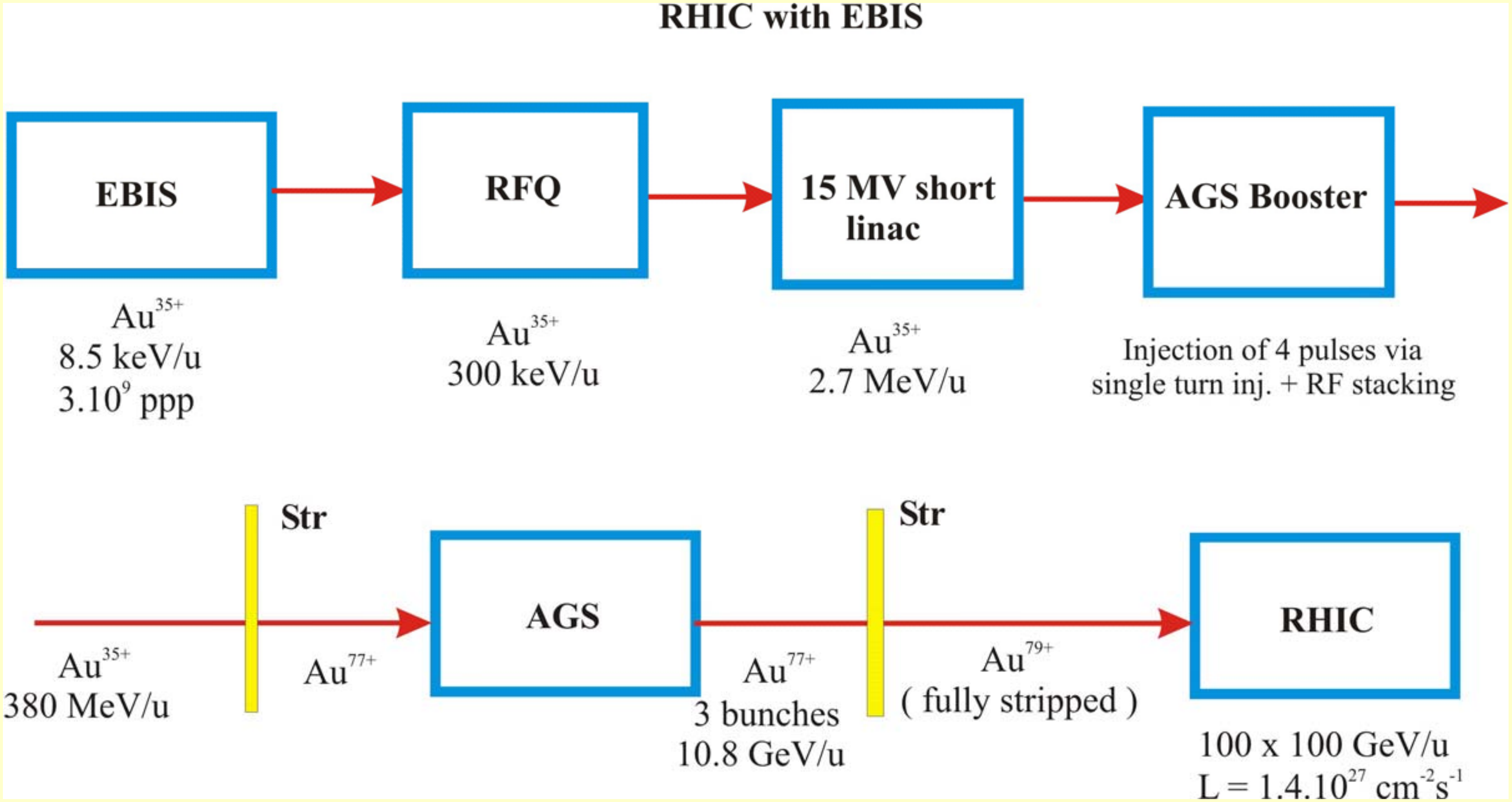


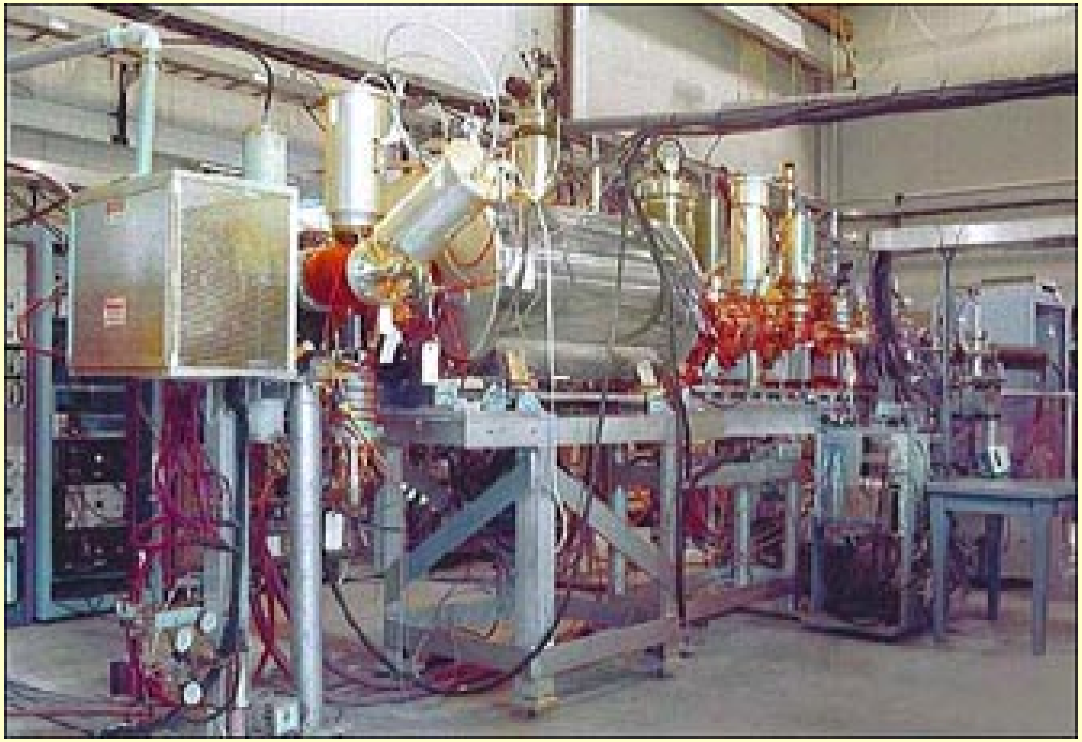
Table. Main parameters of the collider rings

Ring circumference, m	336
Number of interaction points (IP)	2
Bρ max, T·m	45.0
Ion kinetic energy ($^{197}Au^{79+}$), GeV/u	1.0 ÷ 4.58
Dipole field (max), T	2
Quad gradient (max), T/m	30
Long straight sections: number / length, m	2 / 48
Short straight sections: number / length, m	2 / 24
Free space at IP (for MPD detector), m	9
Beam crossing angle at IP	0
Number of dipoles (arc)/ length, m	64 / 2.2
Number of quads (arc)/ length, m	32 / 0.4
βx_max / βy_max in arc, m	20 / 20
Dx_max / Dy_max in arc, m	6.1 / 0.1
βx_min / βy_min in IP, m	0.5 / 0.5
Dx / Dy in IP1, m	0.0 / 0.2
Betatron tunes Qx / Qy	6.6 / 7.6
Chromaticity Q′x / Q′y	-23 / -26
Transition energy, γ_tr	4.89
Vacuum, pTorr	100 ÷ 10

Main parameters of heavy ion collider NICA at JINR, Dubna



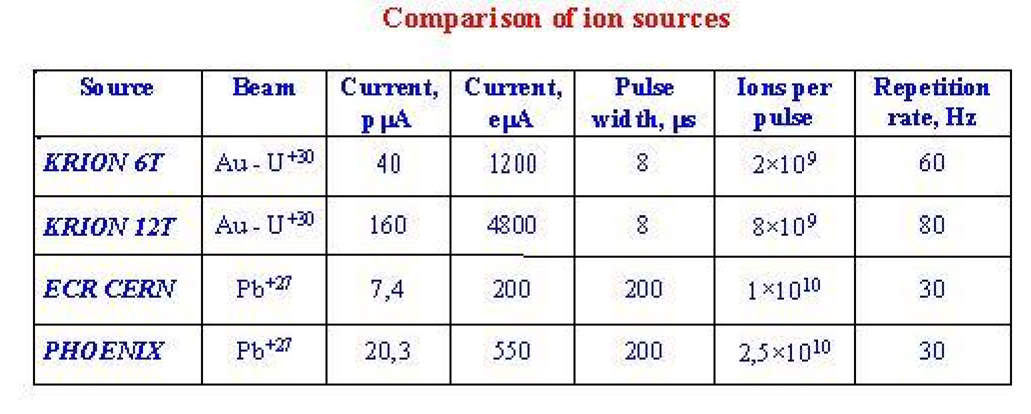
RHIC with EBIS (project)



Test EBIS at BNL, Brookhaven

Parameters: electron current 10 A, length of the trap 0.7 m , 5 T superconducting solenoid, Au^{32+} ions with 550 eμA, 15 μs , U^{30+} ions with 5.10^9 ions, 10 μs, time between the successive pulses = 100 ms

ESIS-Electron String Ion Source at JINR, Dubna



Comparison of ion sources

Source	Beam	Current, p µA	Current, eµA	Pulse width, µs	Ions per pulse	Repetition rate, Hz
KRION 6T	Au - U^{+30}	40	1200	8	2×10^9	60
KRION 12T	Au - U^{+30}	160	4800	8	8×10^9	80
ECR CERN	Pb^{+27}	7,4	200	200	1×10^{10}	30
PHOENIX	Pb^{+27}	20,3	550	200	$2{,}5\times10^{10}$	30

PHYSICAL PROCESSES TYPICAL FOR HEAVY ION ACCELERATORS

Interaction with the residual gas and beam lifetime

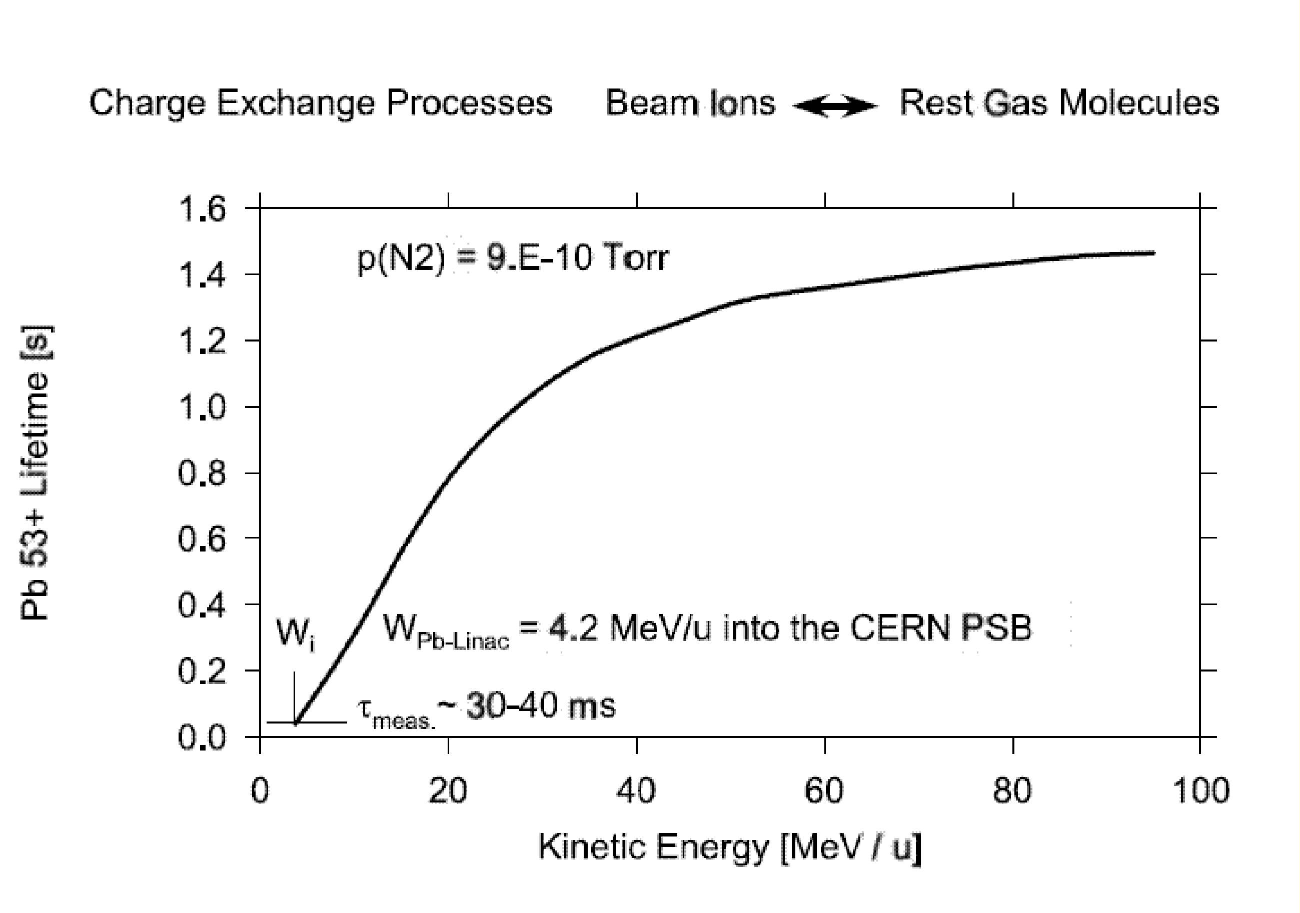
beam lifetime:

$$\frac{1}{\tau} = v_{pr}\,\sigma_{tot}\,n$$

$$n = 9.656.10^{18}\,\frac{p}{T}$$

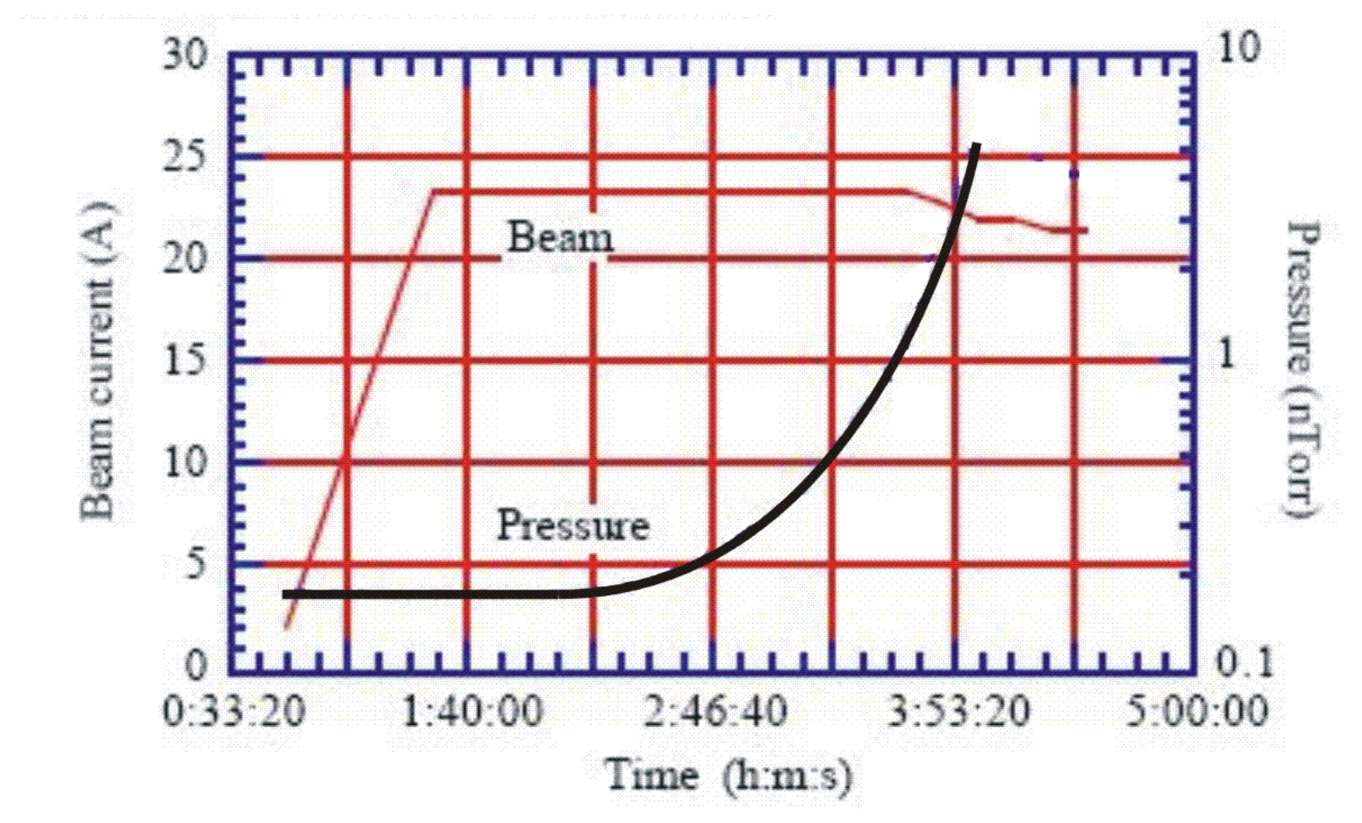
One revolution transparency of the accelerator at 20°C:

$$D = \exp(-3.293.10^{16}\,p\,\sigma_{tot}\,L$$

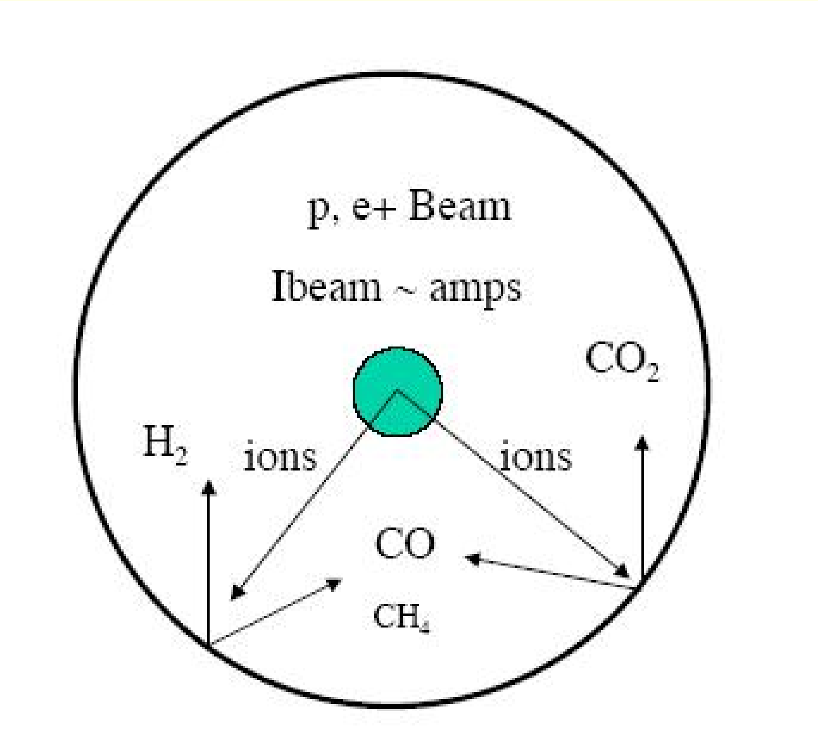


Lifetime of Pb^{53+} ions in PSB, CERN

Dynamic vacuum problems



Pressure instability during beam accumulation in the ISR, CERN



Principle of ion induced pressure instability

Critical beam current:

Warm sections:

$$(\eta I)_{crit} = \frac{\pi^2 e c_0}{\sigma L^2}$$

η - molecular desorption coefficient

σ - the residual gas ionization cross section

I – the total beam current

L – distance between pumps

c_0 - the specific conductance of the vacuum chamber in $m^4.s^{-1}$

Cold sections:

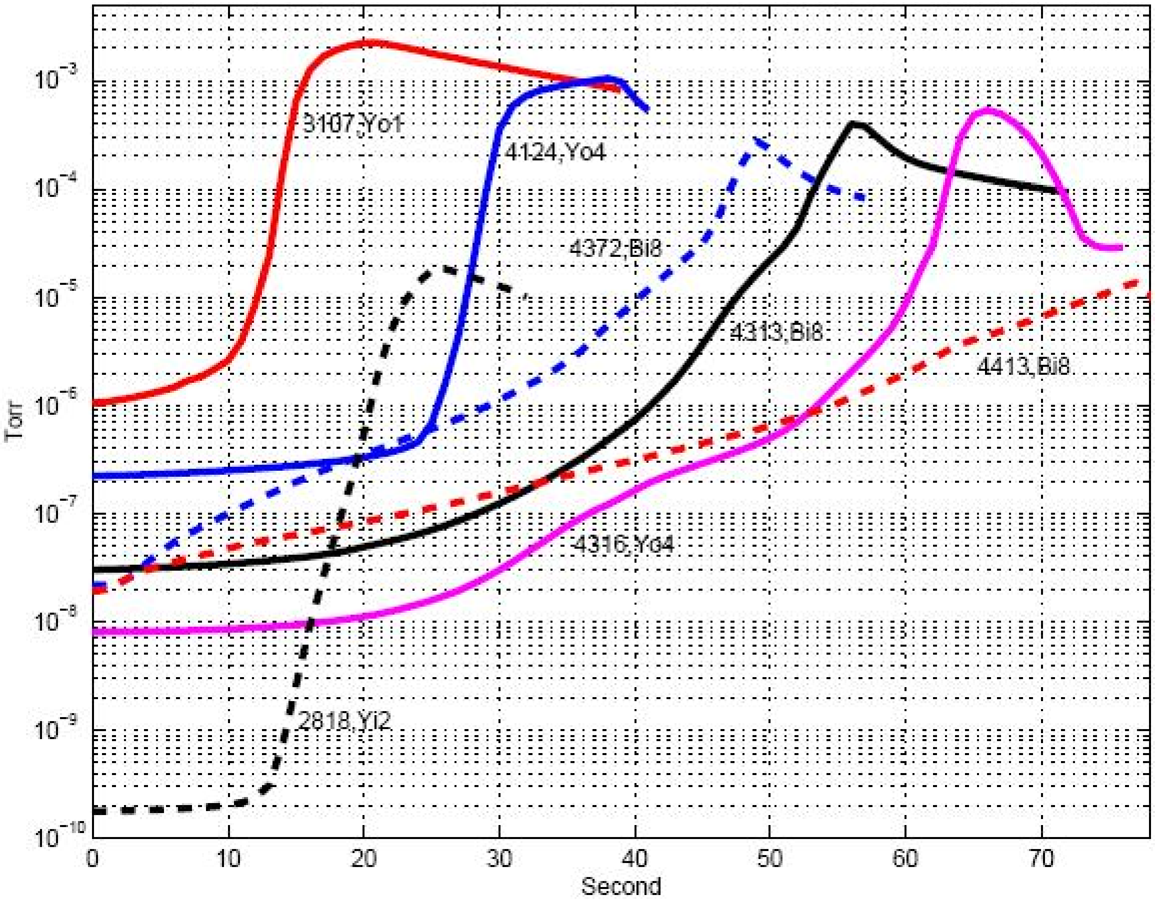
$$(\eta I)_{crit} = \frac{\pi}{2} \bar{v}\, s\, r_p \frac{e}{\sigma}$$

ν - mean molecular velocity

s - sticking probability of molecules on the walls

σ – ionization cross section

r_p –radius of the cold beam pipe.



RHIC pressure bumps; gold beams and unbaked vacuum chamber

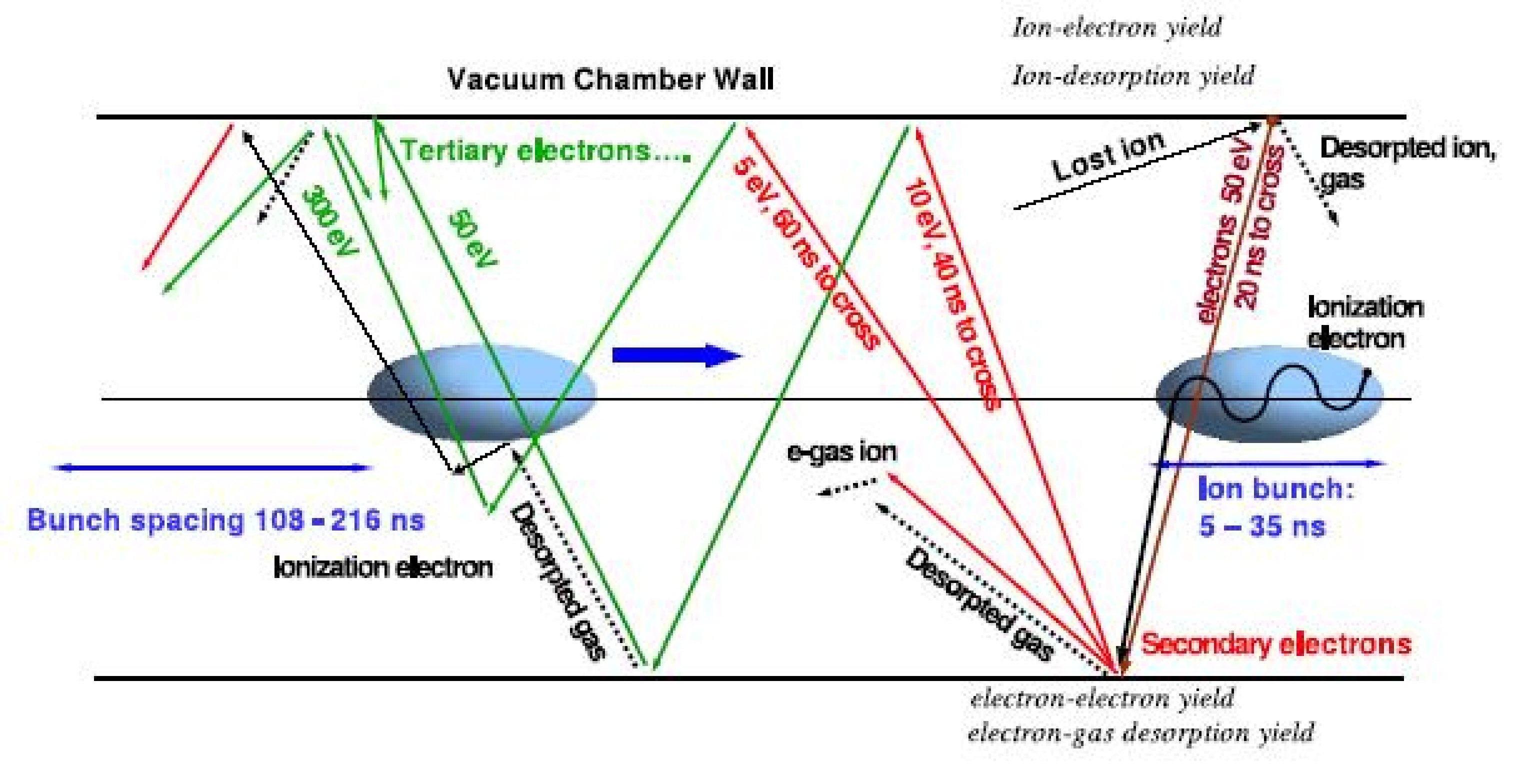
Cures:

- Strict choice of materials and vacuum pumps
- Surface cleaning of the vacuum chamber walls by means of argon glow discharge.
- Provision for bakeout in place up to 200^{o} C for 24 h.
- Beam scrubbing.
- Distributed pumping by ribbons of Non-Evaporable Getters (NEG) for increase the local pumping speed.
- Cooling of vacuum chamber walls.

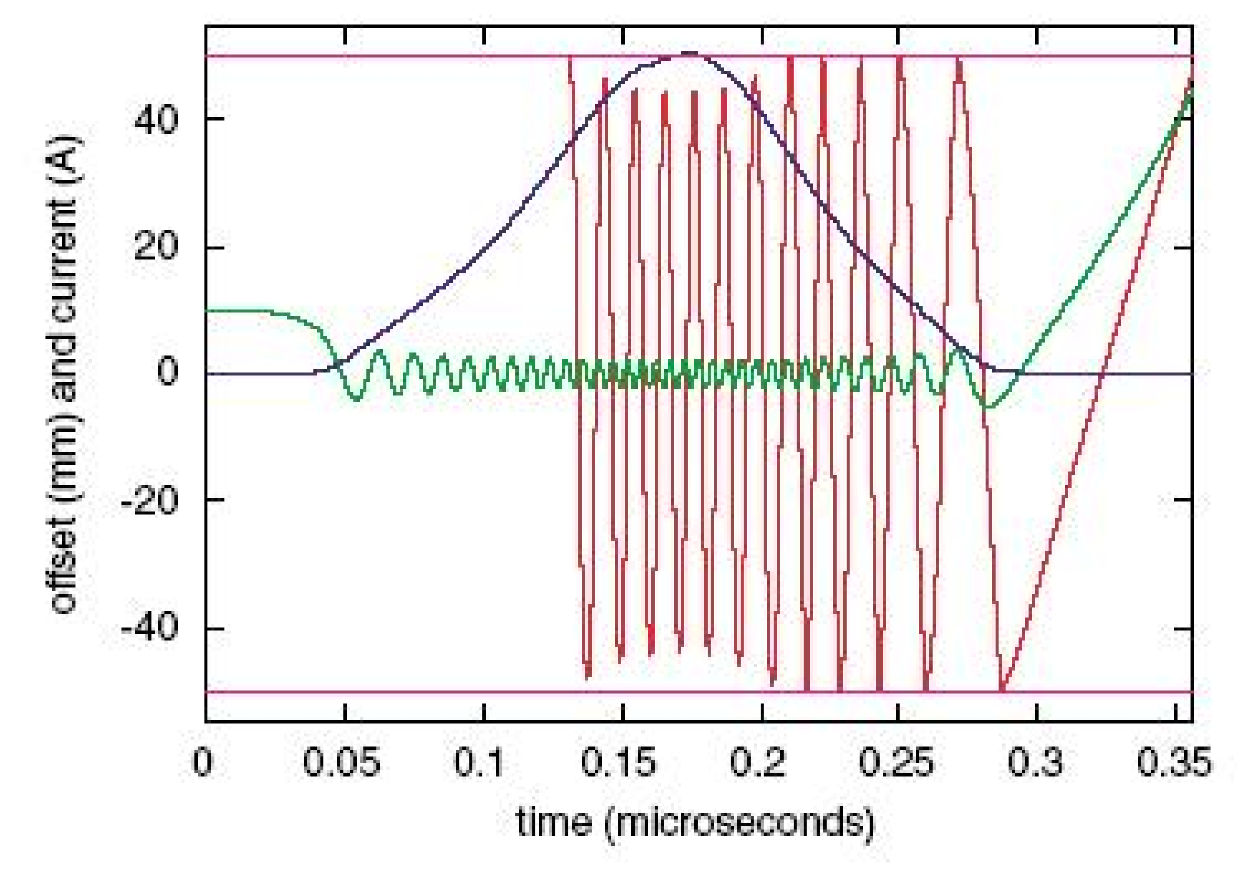
Electron Cloud Effects

Sources of electrons in an accelerator:

- Ionization of residual gas molecules by the beam.
- Generating of electrons in crossing stripping foils.
- Chamber walls bombardment by lost particles.
- Photoelectron production



Electron cloud effects at RHIC. Primary electrons are produced by ionization of the residual gas or by beam lost particles striking the walls. Electrons close to the walls change only their moments (kick); electrons close to the beam are trapped inside the bunch potential and start to oscillate.



PSR proton beam current and trajectories of an electron captured by the bunch and of an electron that undergo large amplitude oscillations.

EC effects:

- The electrons striking the vacuum chamber walls desorb gas molecules and cause a pressure rise. This effect reduces the beam lifetime and could lead to vacuum pressure instability.
- The electron cloud produces a focusing force for the ions and cause a betatron tune shift and emittance blow-up.
- EC could produce a majority of collective effects as a couple bunch instability, fast “head-tail”-type single bunch instability etc.
- EC can enhance the beam-beam effects in colliders and reduce the collider luminosity.
- Electron bombardment of the chamber walls is a source of heat deposition.

EC is a source of noise affecting the proper work of the beam diagnostic devices: pickups, wire scanners, profile monitors etc.

Cures:

- **Applying weak solenoidal magnetic fields.**
- **Reducing of secondary electron yield (SEY) by means of electron irradiation of chamber walls.**
- **SEY can be reduced also by covering the chamber walls by TiN films or by non evaporating getters (TiZrV).**
- **The value of the photoelectron yield can be reduced by use of antechambers, which acsorbs most of the SR photons.**

Intrabeam Scattering

Intra-Beam Scattering (IBS) - small-angle Coulomb scattering of particles within relativistic beams.

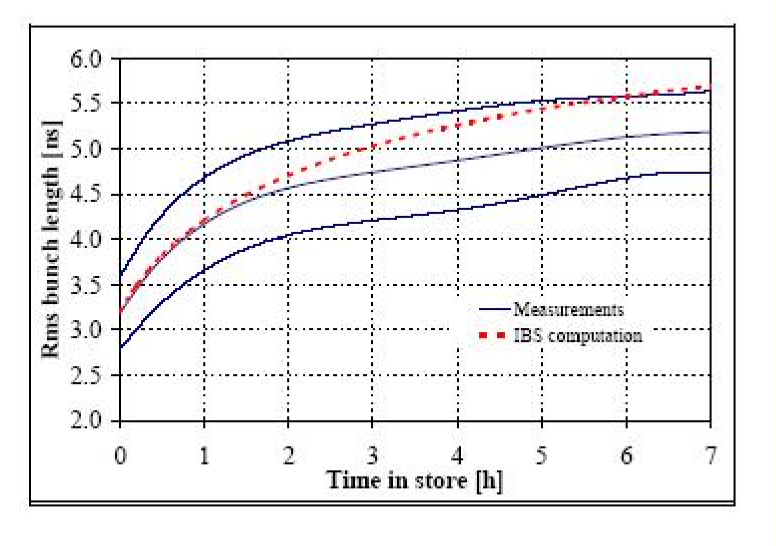
The collisions between the particles in the beam cause longitudinal and transverse emittance growth. IBS is the main limiting factor of the luminosity lifetime in heavy ion colliders.

Emittance growth rates:

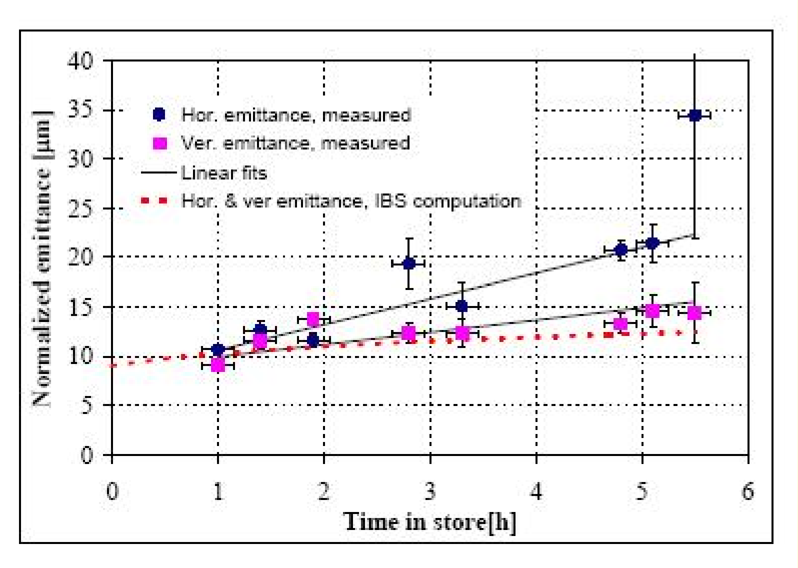
$$\begin{bmatrix} \dfrac{1}{\sigma_p}\dfrac{d\sigma_p}{dt} \\ \dfrac{1}{\sigma_x}\dfrac{d\sigma_x}{dt} \\ \dfrac{1}{\sigma_y}\dfrac{d\sigma_y}{dt} \end{bmatrix} = \frac{Z^4 N}{A^2}\frac{r_0^2 L_c c}{8\pi\gamma\varepsilon_x^*\varepsilon_y^*\varepsilon_l^*}F(\chi)\begin{bmatrix} n_b(1-d^2) \\ -\dfrac{a^2}{2}+d^2 \\ -\dfrac{b^2}{2} \end{bmatrix}$$

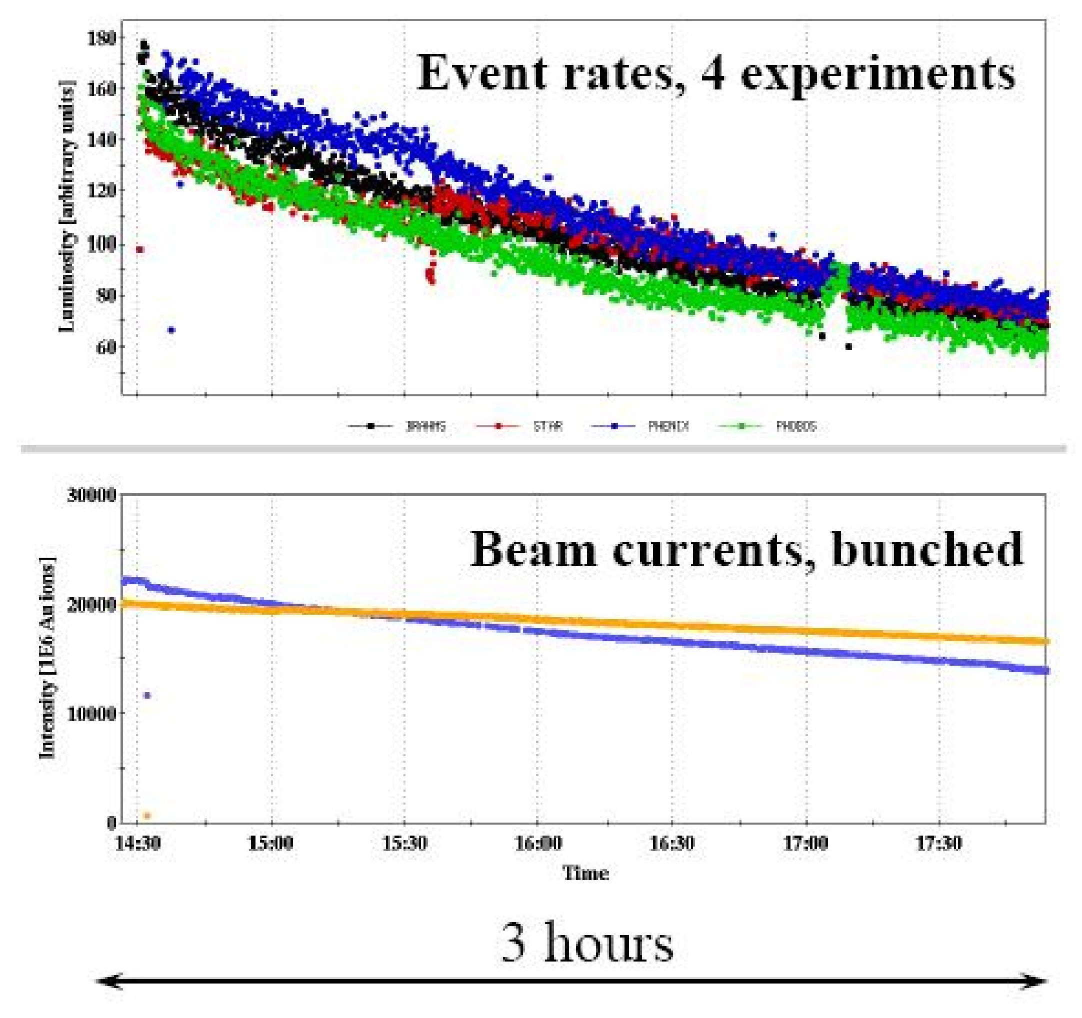
(J. Wei)

RHIC rms bunch length increase during store



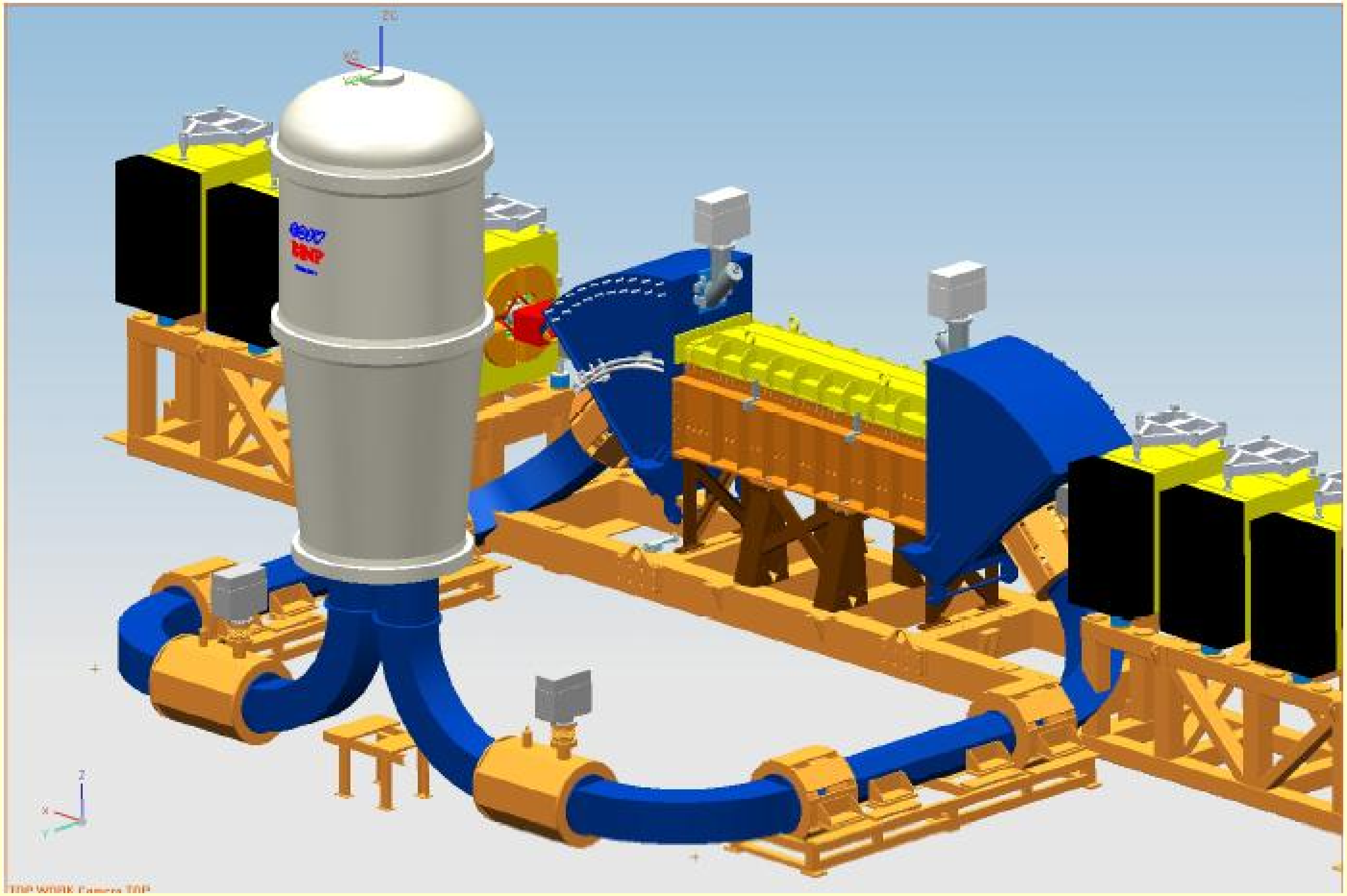
RHIC transverse emittanses growth





RHIC luminosity degradation during store

Electron cooling of high-energy ion beams



High energy electron cooling system

(FZ-Julich, 2 MeV COSY e-cooler)

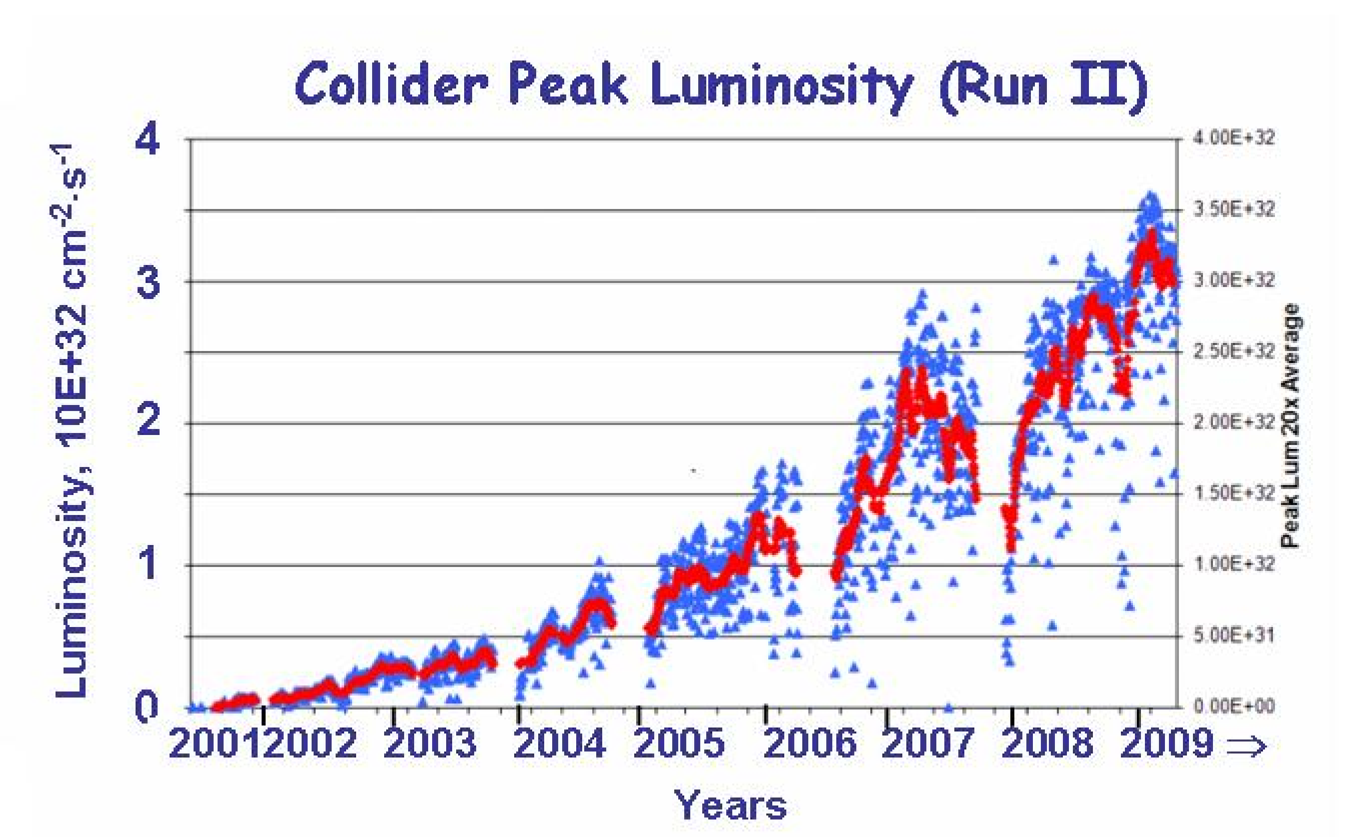
Cooling times:

$$\tau_{\perp} = \frac{2.10^{7}\ \beta^{4}\ \gamma^{5}\ \theta_{\perp}^{3}}{\eta\, i_{e}}\ \frac{A}{Z^{2}}$$

$$\tau_{\parallel} = \frac{2.10^{7}\ \beta^{4}\ \gamma^{5}\ (\frac{\Delta p}{p})^{5}}{\eta\, i_{e}}\ \frac{A}{Z^{2}}$$

High energy electron cooling in FNAL’s antiproton Recycler ring.

8 GeV antiprotons; 4.3 MeV/0.5 A electrons; Pelletron electrostatic electron accelerator.



Increase of Tevatron's luminosity due to electron cooling

THANK YOU FOR YOUR ATTENTION