Acceleration of High-Brightness Heavy Ion Beams for Research into Heavy Ion Nuclear Physics

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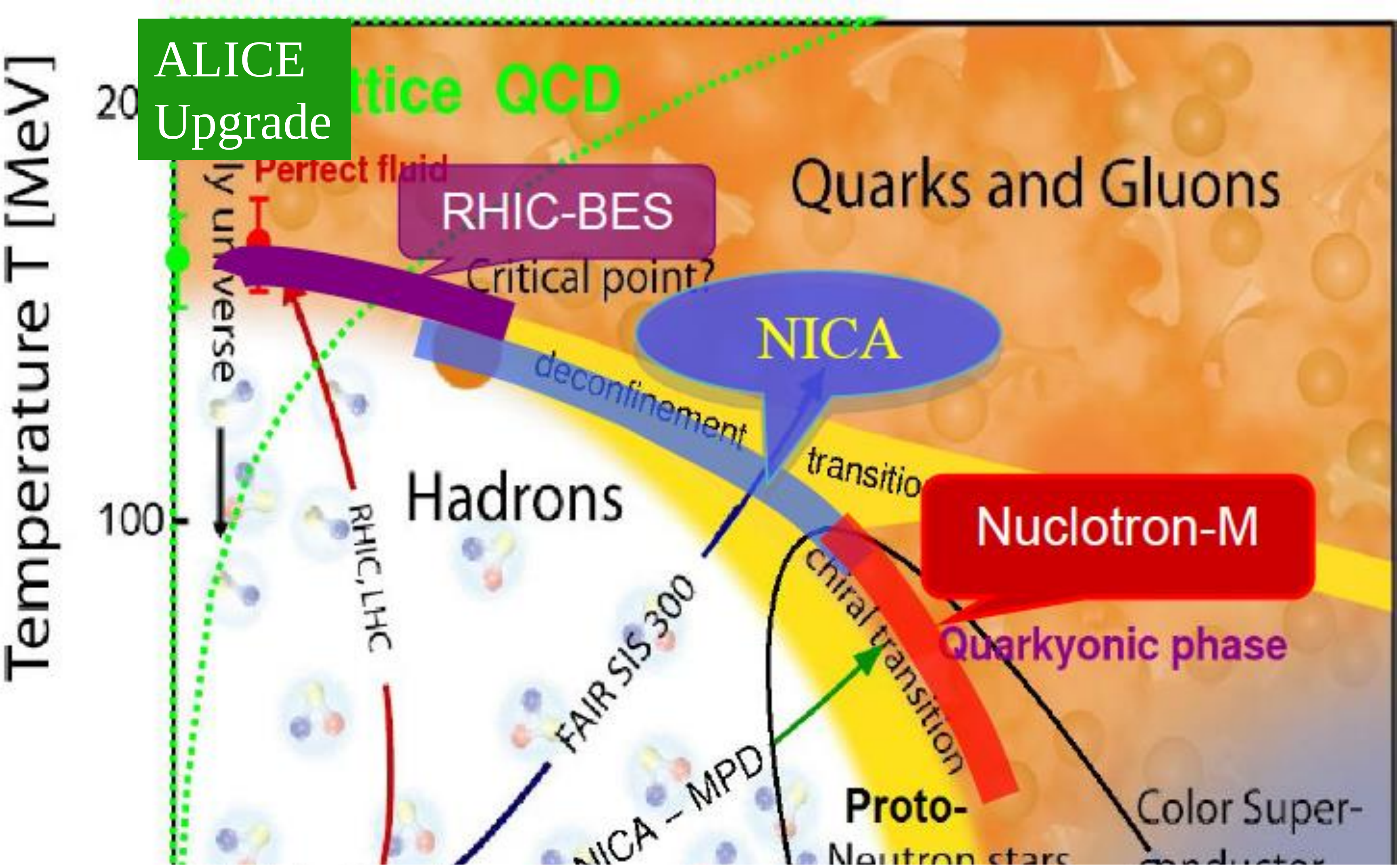
Facilities goals : pushing the “intensity” and the “precision frontiers” to the extremes – not “energy frontier”!

- **Full range of ion beam species:** p+ - 239U ;
- **Highest beam intensities & luminosities;**
- **Generation of ‘Precision beams’:** sophisticated beam manipulation methods-stochastic and electron cooling of ion beams, *also applicable to the secondary radioactive and antiproton beams*;
- **Rings as accelerator structures of choice:** capability to store, cool, bunch, and stretch beams ;
- **Substantial increase in beam energy variation:** by a factor of 20 in energy for beams as heavy as Uranium .

Accelerator Technology Issues

- **High current injection,**
- **Acceleration -> Stacking**

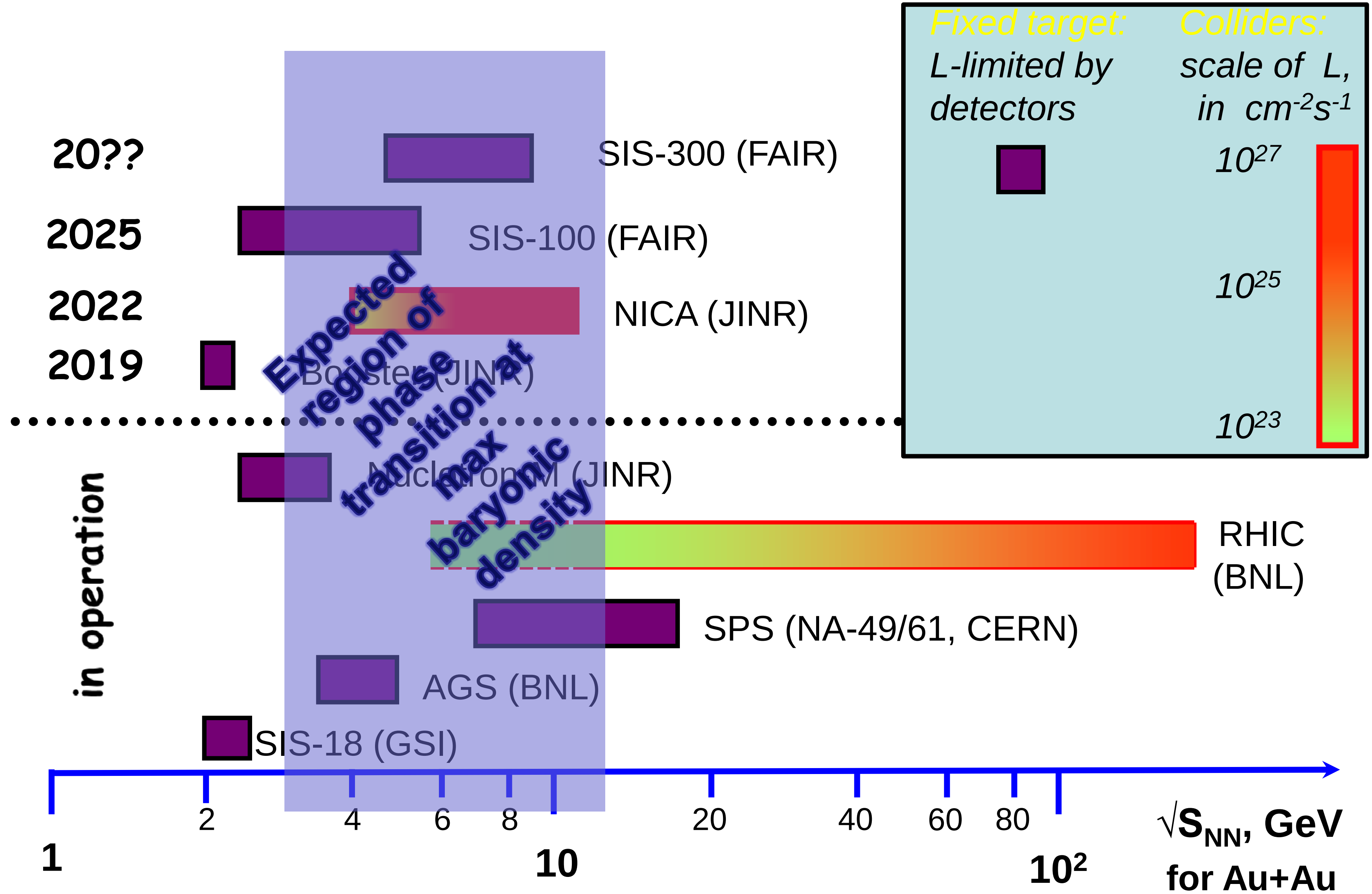
  Accumulation + Beam Cooling
- **Instabilities - space charge, IBS , vacuum**
- **Fast extraction**
- **Beam transport and focusing**
- **Collider mode issues**



Probing the QCD diagram at very high T and $\rho_B \sim 0$ (early universe):
ALICE, ATLAS, CMS at LHC
STAR, PHENIX at top RHIC energies

Probing the QCD diagram at moderate T and very high ρ_B (neutron star):
BES at RHIC, NA61 at CERN SPS, CBM at FAIR, MPD at NICA, J-PARC, NA60+

Existing and future HI accelerators



CBM – NICA co-operation agreement

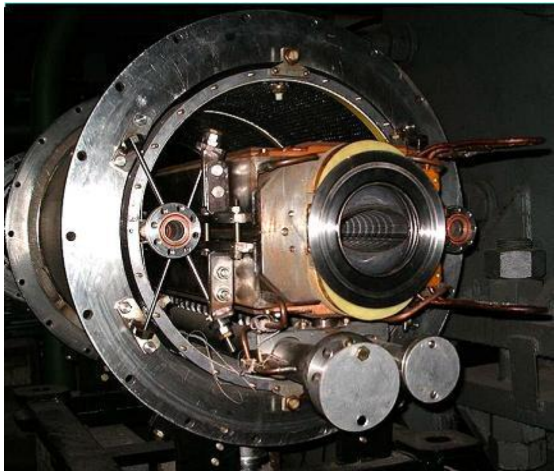
Intermediate Charge State Heavy Ions

Existing and planned Heavy Ion Accelerators operated with intermediate charge states worldwide

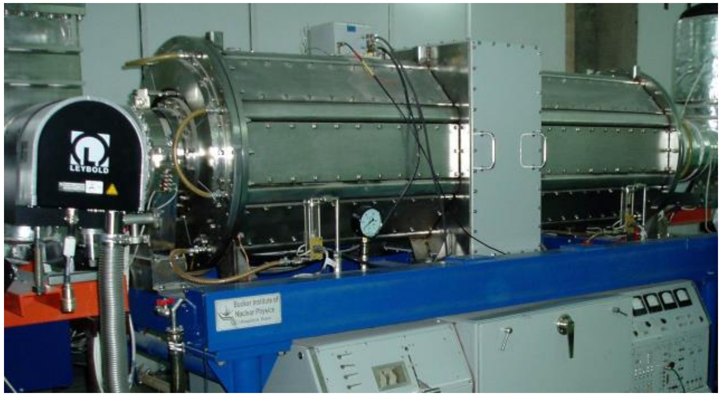
AGS Booster	BNL	5x10^{9}	Au^{31+}
LEIR	CERN	1x10^{9}	Pb^{54+}
Nuclotron	JINR	4x10^{9}	Au^{32+}
SIS18	GSI/FAIR	1.5x10^{11}	U^{28+}
HIFL	IMP	$> 10^{9}$	U^{34+}
SIS100	**FAIR**	5x10^{11}	U^{28+}
HIAF	**HIAF**	$>10^{11}$	U^{72+}
NICA (collider)	**JINR**	2×10^{9}	Au^{79+}

Accelerator Challenges

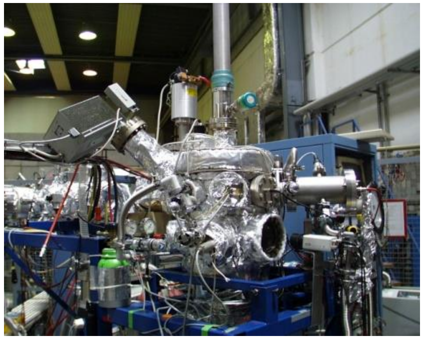
Compact & cost effective accelerators
Fast cycling superconducting magnets
dB/dt ~ 4T/s



Fast acceleration
High gradient, variable frequency
Ferrite & MA loaded cavities



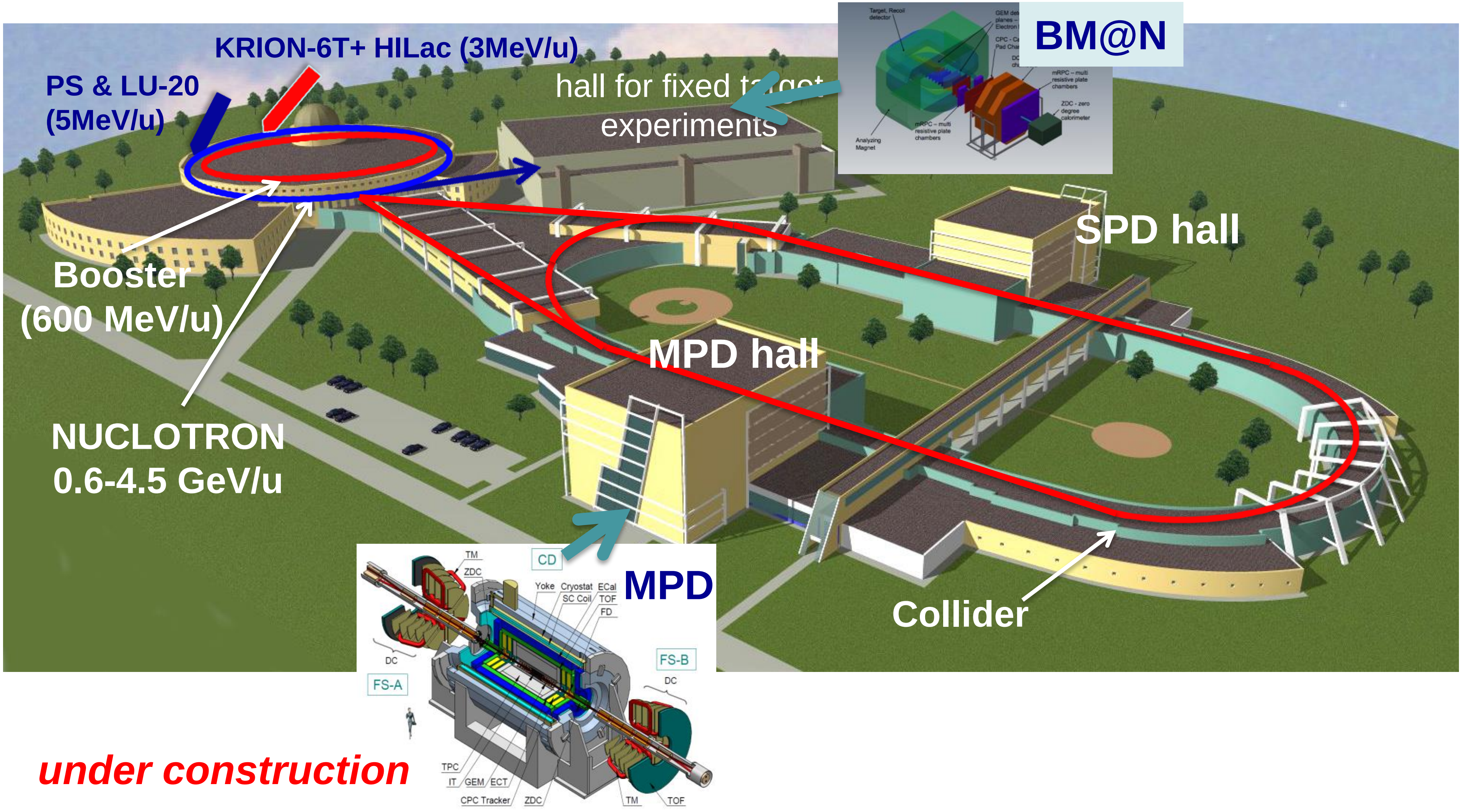
XHV @ high beam intensities
Extremely high vacuum $\sim 10^{-12}$ mbar



Precision beams
Electron & stochastic cooling

The NICA Complex - JINR

existing facility



KRION-6T+ HILac (3MeV/u)

PS & LU-20 (5MeV/u)

hall for fixed target experiments

BM@N

SPD hall

Booster (600 MeV/u)

MPD hall

NUCLOTRON 0.6-4.5 GeV/u

Collider

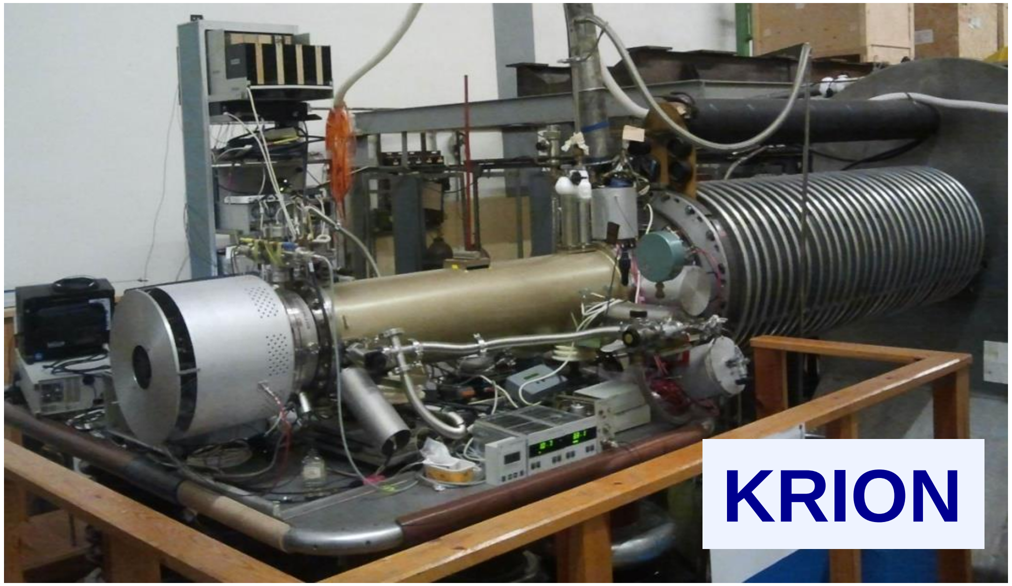
MPD

under construction

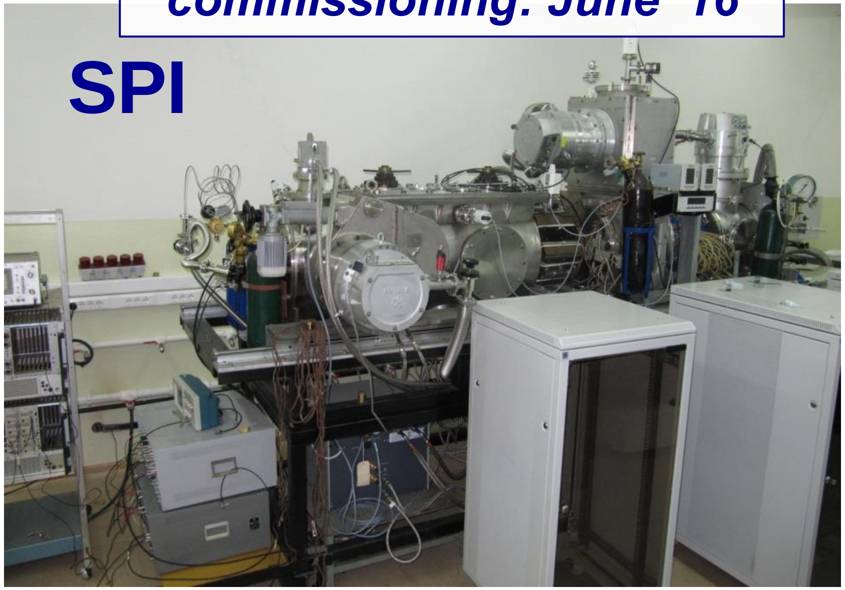
Injection complex: 4 ion sources

Source	**KRION-6T**	**Laser**	**Douplasmatron**	**SPI new !**
particles	Au^{31+}	up to Mg^{10+}	p, d, He^{2+}	↑p, ↑d
particle/cycle	~2.5 10^9	~10^{11}	p, d ~5 10^{12} He^{2+} ~10^{11}	5 10^{11}
repetition, Hz	10	0,5	1	0,2

to be commissioned



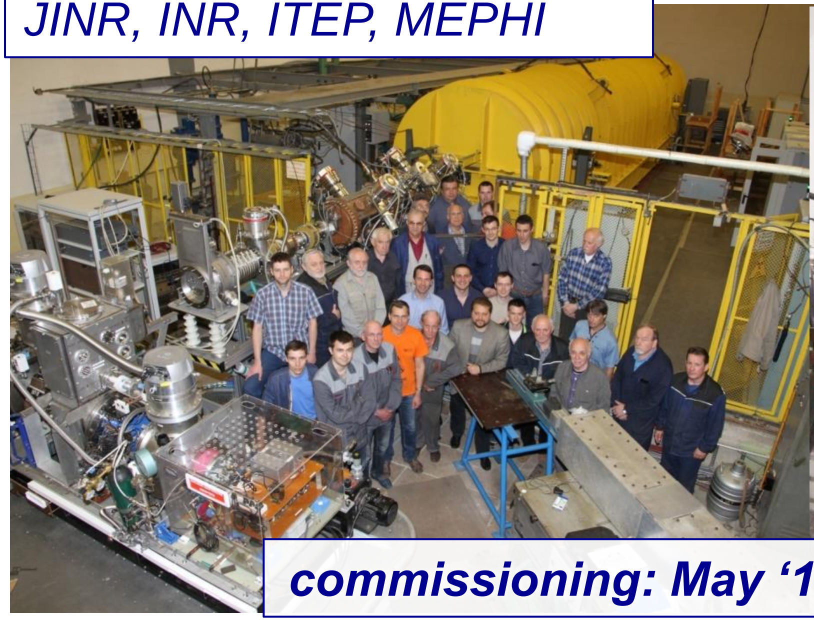
commissioning: June '16



Injection complex: 2 Linacs

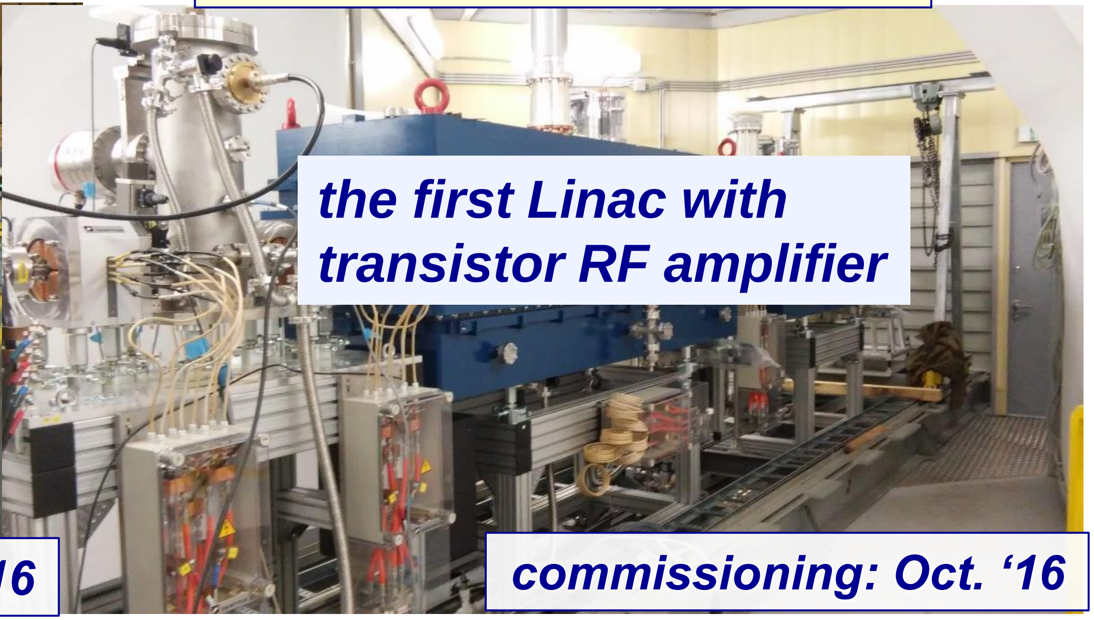
Linac	LU-20	HILAC **new !**
structure (section number)	RFQ + Alvarez type	RFQ + IH DTL(2)
mass to charge ratio A/Z	1-3	1-6
injection energy, keV/amu	150 for A/Z 1-3	17
extraction energy, MeV/amu	**5** (A/Z 1-3)	**3.24** (A/Z=6)
input current, mA	up to 20	up to 10

***LU-20 – new fore-injector**:*
JINR, INR, ITEP, MEPHI



commissioning: May ‘16

HILAC: “BEVATECH OHG”

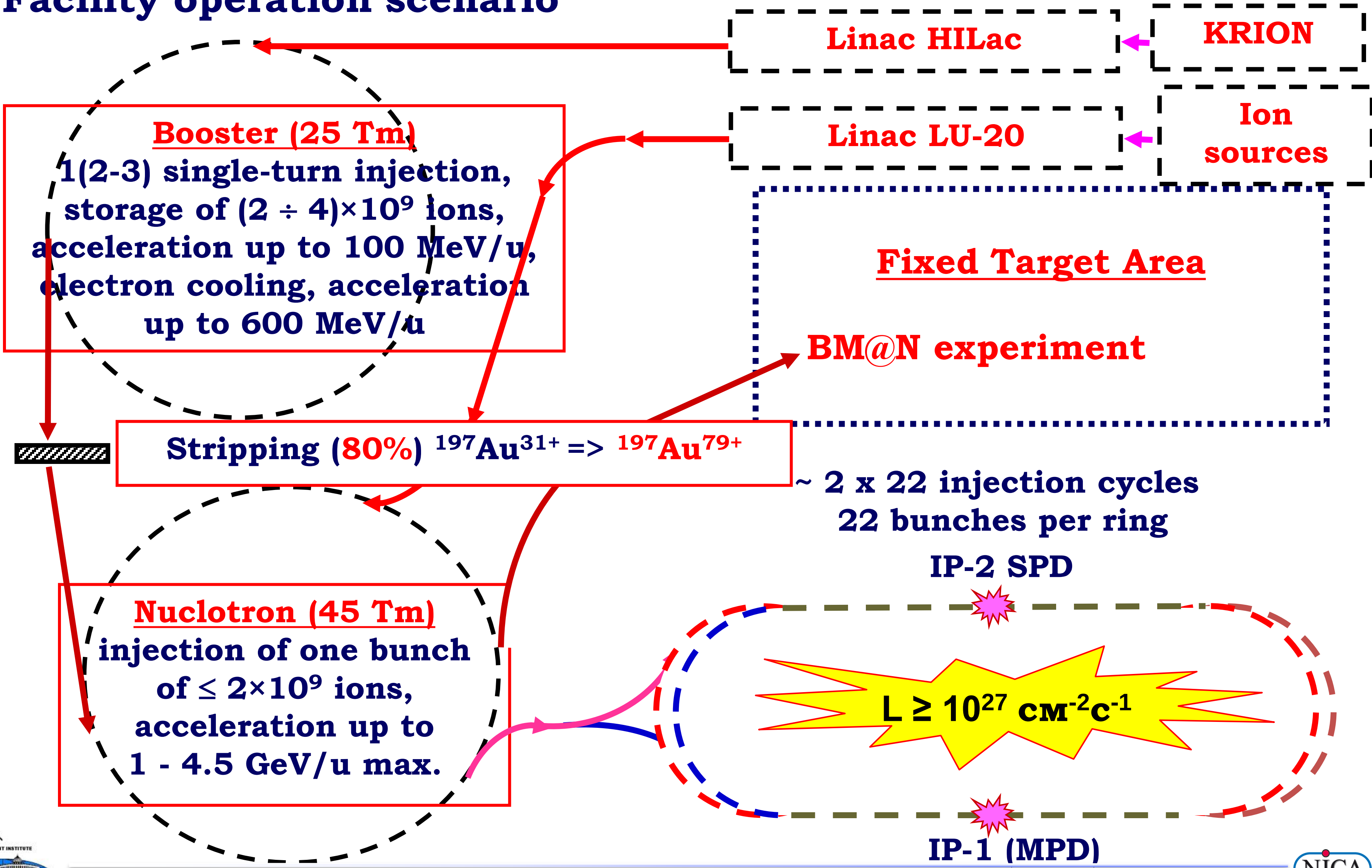


the first Linac with transistor RF amplifier

commissioning: Oct. ‘16

NICA – Heavy Ion Collider

Facility operation scenario



Linac HILac

KRION

Linac LU-20

Ion sources

Booster (25 Tm)

1(2-3) single-turn injection, storage of $(2 \div 4)\times 10^9$ ions, acceleration up to 100 MeV/u, electron cooling, acceleration up to 600 MeV/u

Fixed Target Area

BM@N experiment

Stripping (80%) $^{197}\mathrm{Au}^{31+}$ => $^{197}\mathrm{Au}^{79+}$

~ 2 x 22 injection cycles
22 bunches per ring

IP-2 SPD

Nuclotron (45 Tm)

injection of one bunch of $\leq 2\times 10^9$ ions, acceleration up to 1 - 4.5 GeV/u max.

$L \geq 10^{27}\ \text{см}^{-2}\text{с}^{-1}$

IP-1 (MPD)

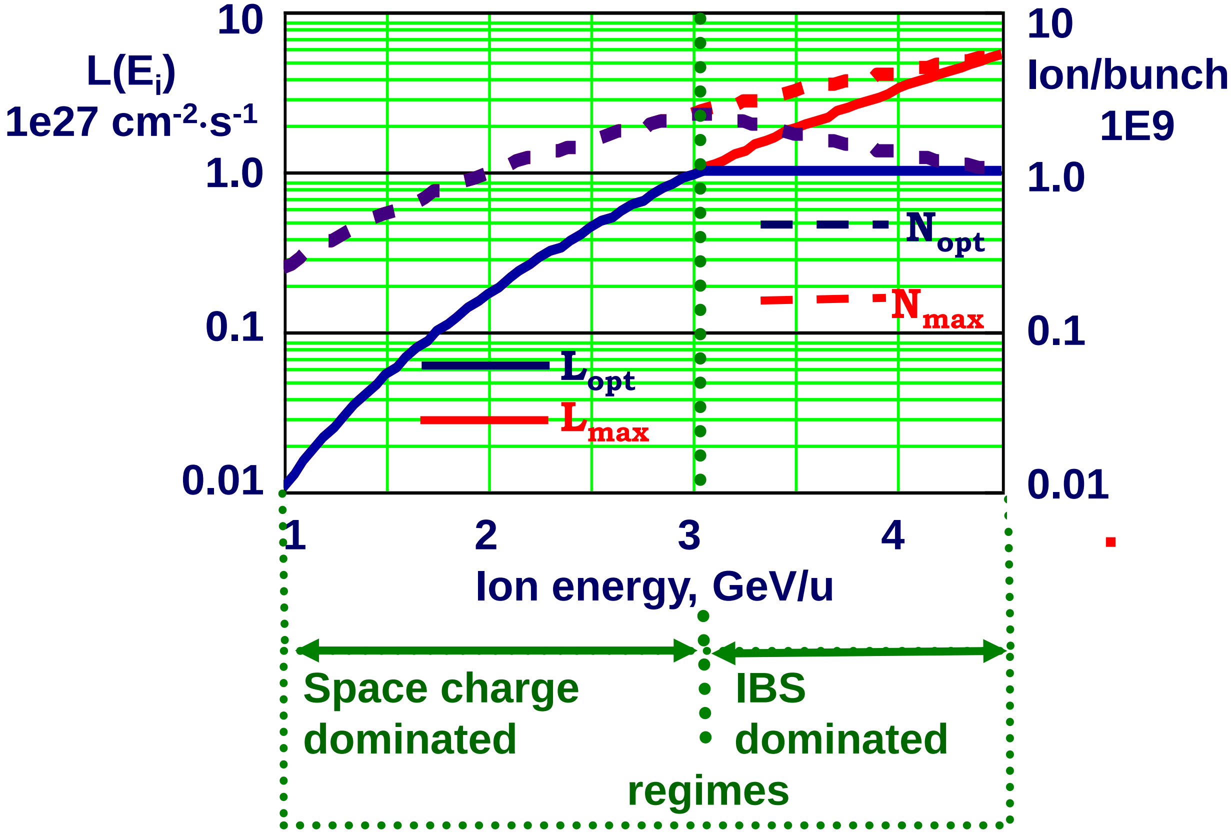
Key Parameters of The NICA Collider

Collider lattice: FODO, 12 cells x 90^0 each arc,

Ring circumference, m	**503,04**		
Number of bunches	**22**		
R.m.s. bunch length, m	**0.6**		
Ring acceptance, $\pi\cdot$mm$\cdot$mrad	**40.0**		
Long. Acceptance, $\Delta p/p$	**$\leq$ 0.01**		
$\gamma_{transition}$ ($E_{transition}$, GeV/u)	**7.091 (5.72)**		
β^*, m	**0.35**		
Ion Energy, GeV/u	**1.0**	**3.0**	**4.5**
Ion number/bunch, 1e9	**0.275**	**2.4**	**2.2**
R.m.s. emittance, h/v $\pi\cdot$mm$\cdot$mrad	**1.1/1.0**	**1.1/0.9**	**1.1/0.76**
R.m.s. $\Delta p/p$, 1e-3	**0.62**	**1.25**	**1.65**
IBS growth time, s	**190**	**700**	**2500**
Peak luminosity, $cm^{-2}\cdot s^{-1}$	**1.1e25**	**1e27**	**1e27**

NICA – Luminosity

Two operation regimes



Space charge dominated

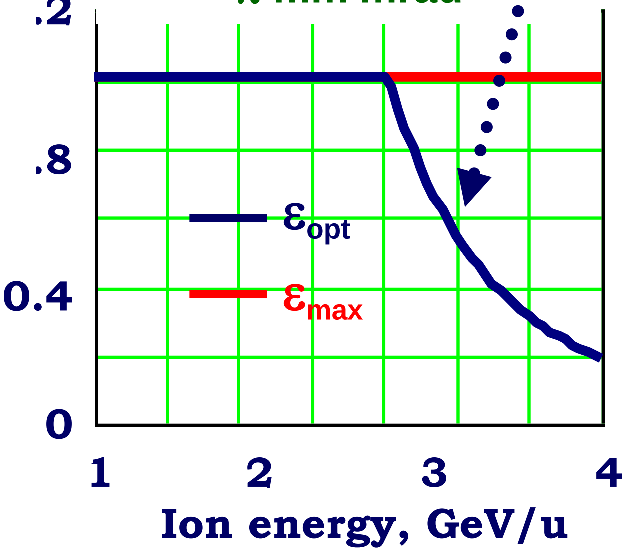
IBS dominated

regimes

Electron and stochastic cooling application!

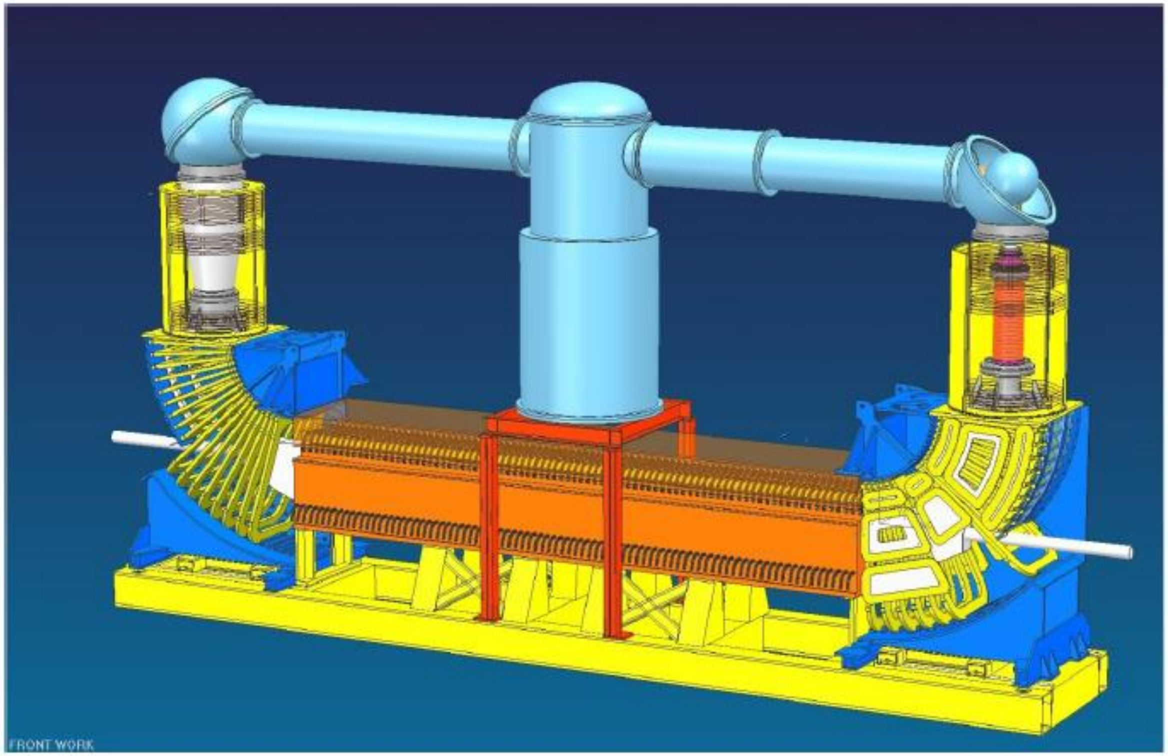
Emittance reduction with energy:

Equilibrium beam emittance vs E_{ion}, π·mm·mrad



NESR Electron Cooler

design by BINP, Novosibirsk



Electron Cooler Parameters

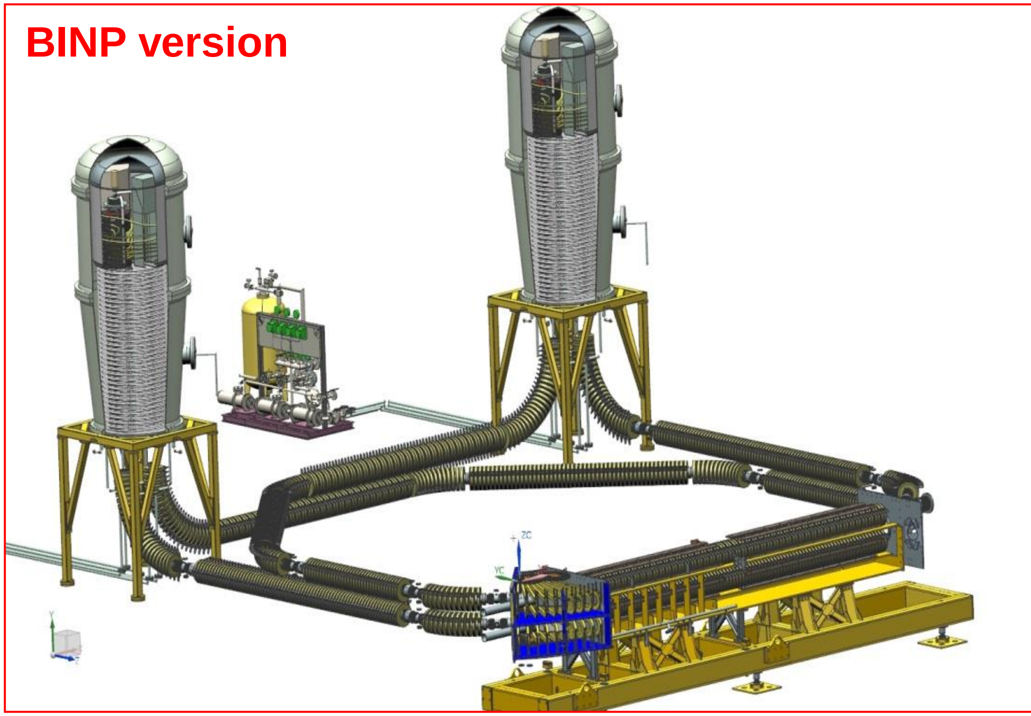
energy	2 - 450 keV
max. current	2 A
beam radius	2.5-14 mm
magnetic field	
gun	up to 0.4 T
cool. sect.	up to 0.2 T
straightness	$2\ 10^{-5}$
vacuum	$\leq 10^{-11}$ mbar

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

NICA – Electron Cooling System (Budker Inst.)

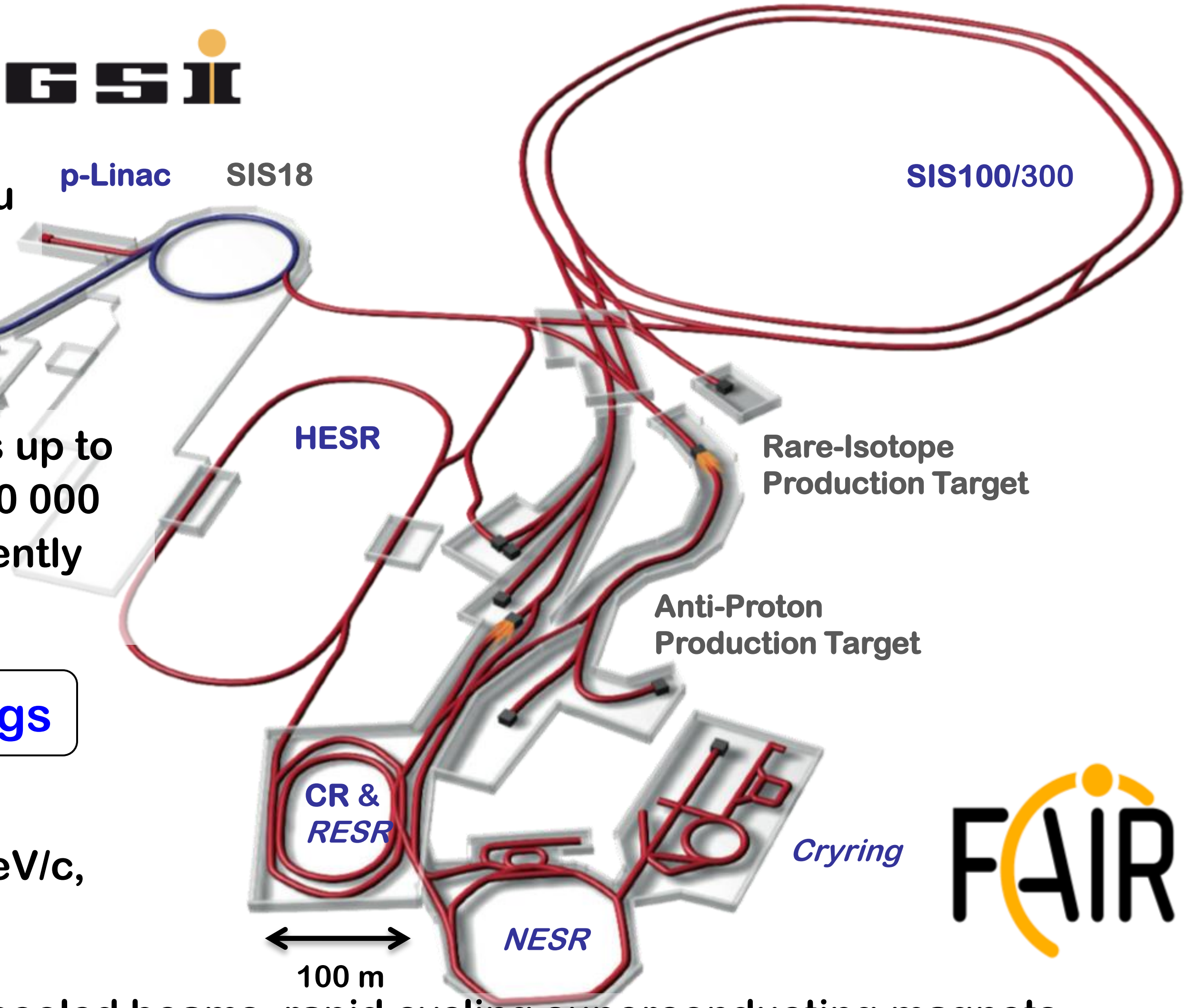
The Electron Cooler design is based on the e-cooling system constructed by the Budker INP team for COSY (Cooler-Synchrotron) at FZ Jülich (Germany).

BINP version



Main parameters of The Electron Cooler	
Maximum electron energy, MeV	2.5
Electron beam current, A	0.1 – 1.0
Solenoids' magnetic field, T	0.2

Facility for Antiproton and Ion Research



Primary Beams

- 5×10^{11}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

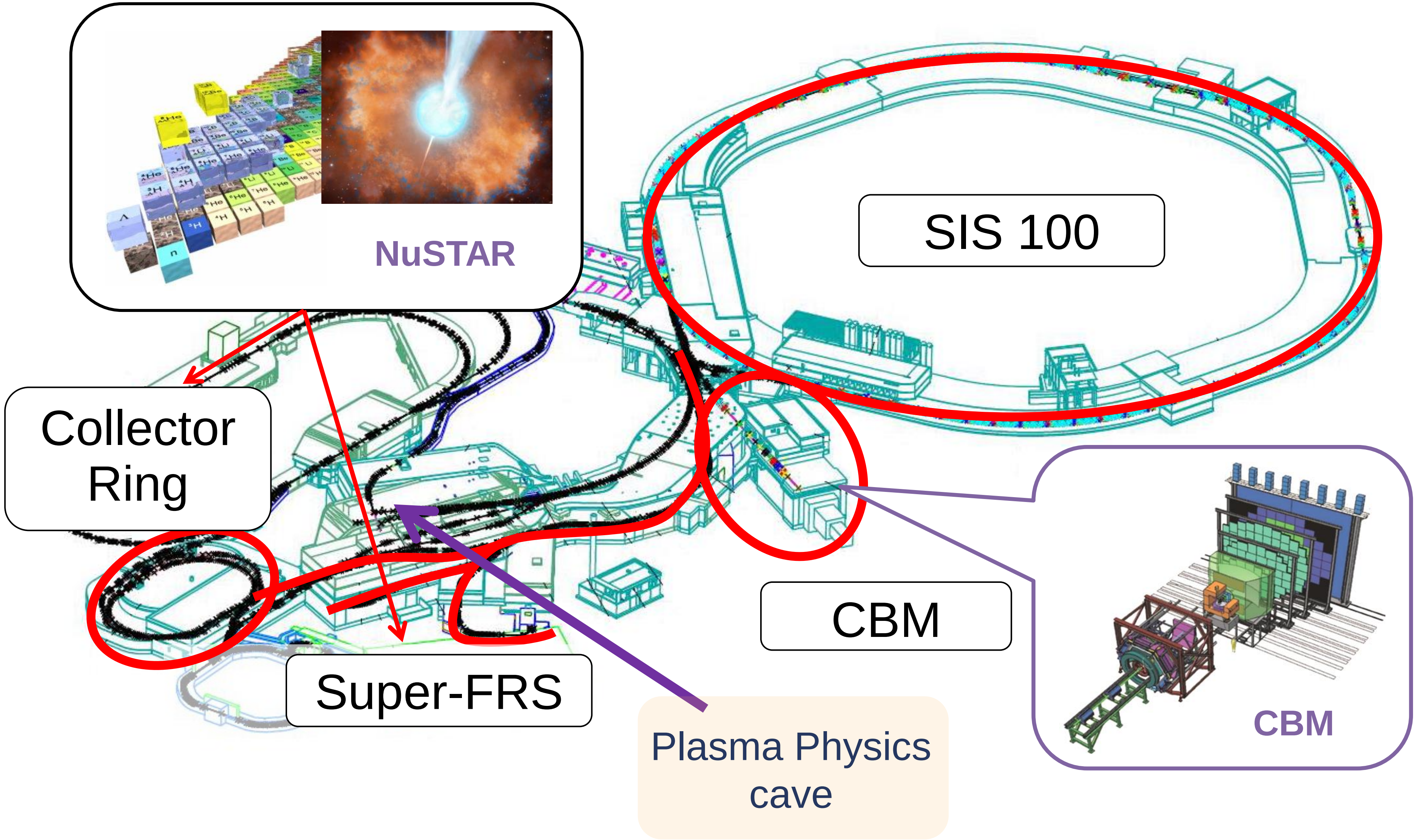
Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled

Technical Challenges

- cooled beams, rapid cycling superconducting magnets

Heavy ion accelerator chain

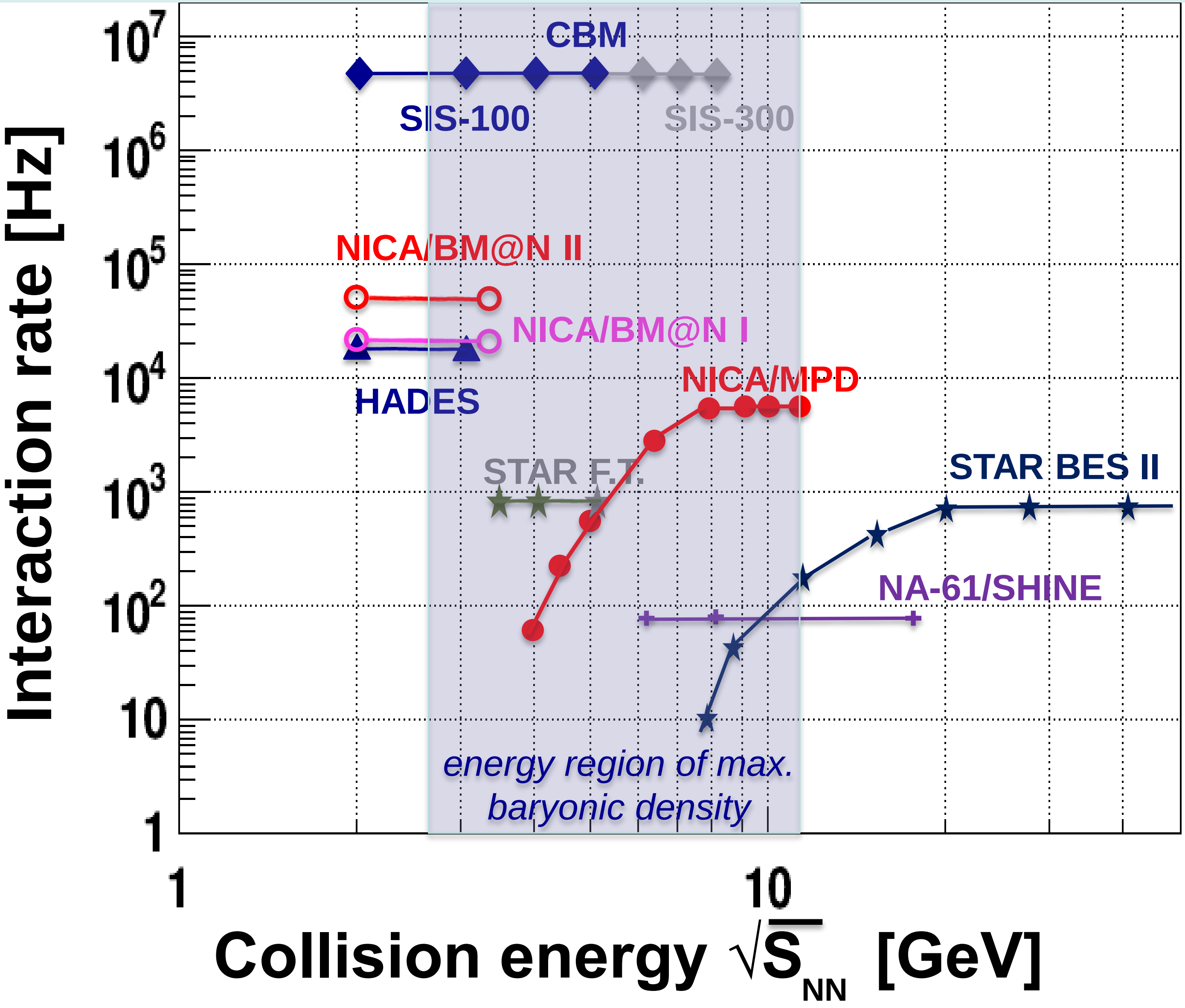


Experiments on superdense nuclear matter

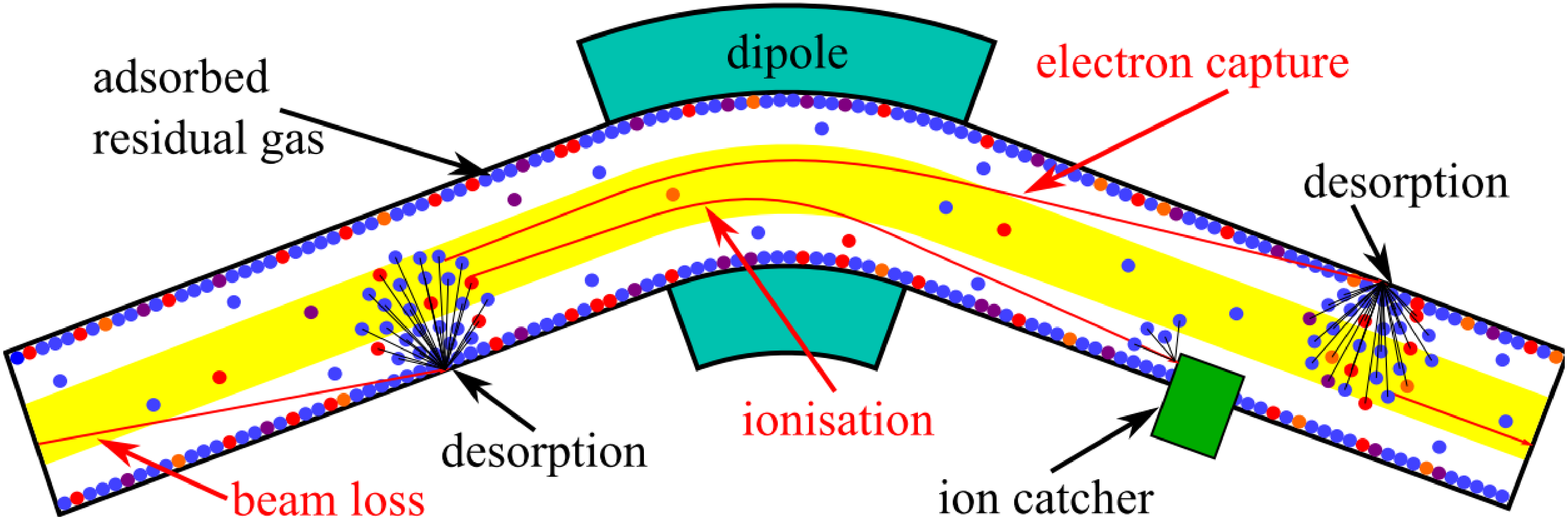
Experiment	Energy range (Au/Pb)	Reaction rates (Hz)
STAR@RHIC (BNL)	$\sqrt{s_{NN}} = 7 – 200$ GeV	1 – 800
NA61@SPS (CERN)	$\sqrt{s_{NN}} = 6.4 – 17.4$ GeV	80
MPD@NICA	$\sqrt{s_{NN}} = 4.0 – 11.0$ GeV	~6000
BM@Nuclotron	$E_{kin} = 2.0 – 4.5$ A GeV	10^5
CBM@FAIR	$\sqrt{s_{NN}} = 2.7 – 8.3$ GeV $E_{kin} = 2.0 – 35$ A GeV	$10^5 – 10^7$

Experiment	Observables (Au+Au at $\sqrt{s_{NN}} = 8$ GeV)
STAR@RHIC (BNL)	Pions, kaons, protons, hyperons
NA61@SPS (CERN)	Pions, kaons, protons, hyperons
MPD@NICA	Pions, kaons, protons, gammas, (multi-strange) hyperons, electron pairs ?
CBM@FAIR	Pions, kaons, protons, gammas, (multi-strange) hyperons, electron pairs, open charm, charmonium

Present and future HI experiments/machines for super-dense nuclear matter physics



Dynamic vacuum - What happens ?



No cure by good initial vacuum or pumping power alone!

Dynamic Pressure Stabilization - Recipe

- Short cycle times, short sequences and short injection plateau

  Fast ramping (SIS18: 10 T/s, SIS100: 4 T/s)

  (power connection, power converters, Rf system,

  fast ramped (superconducting) magnets)

- XHV and huge pumping power

  (NEG-coating, cryo pumping - local and distributed)

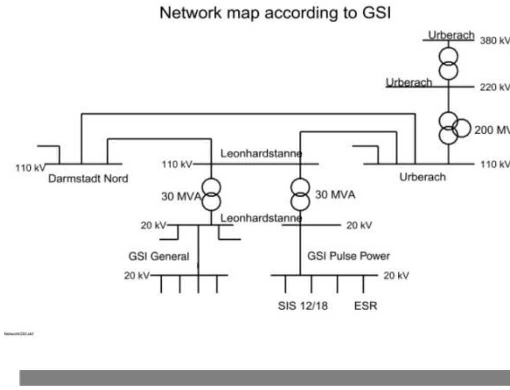
- Localizing beam loss and controle/suppression of desorption gases

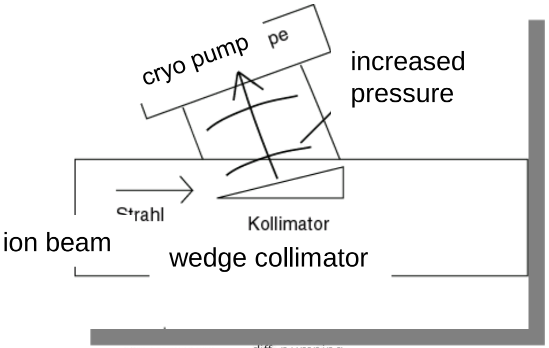
  (Ion catcher system with low desorption yield surfaces,

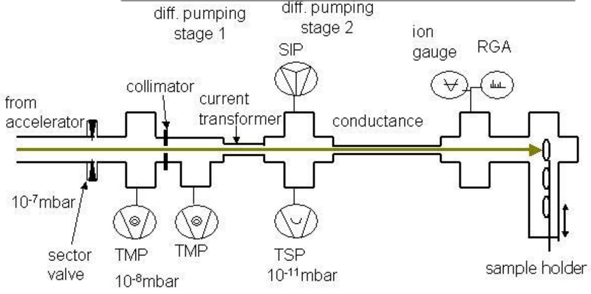
  Synchrotron optics and lattice design)

- Minimum „effective“ initial beam loss

  (TK halo collimation, low desorption yield surfaces)





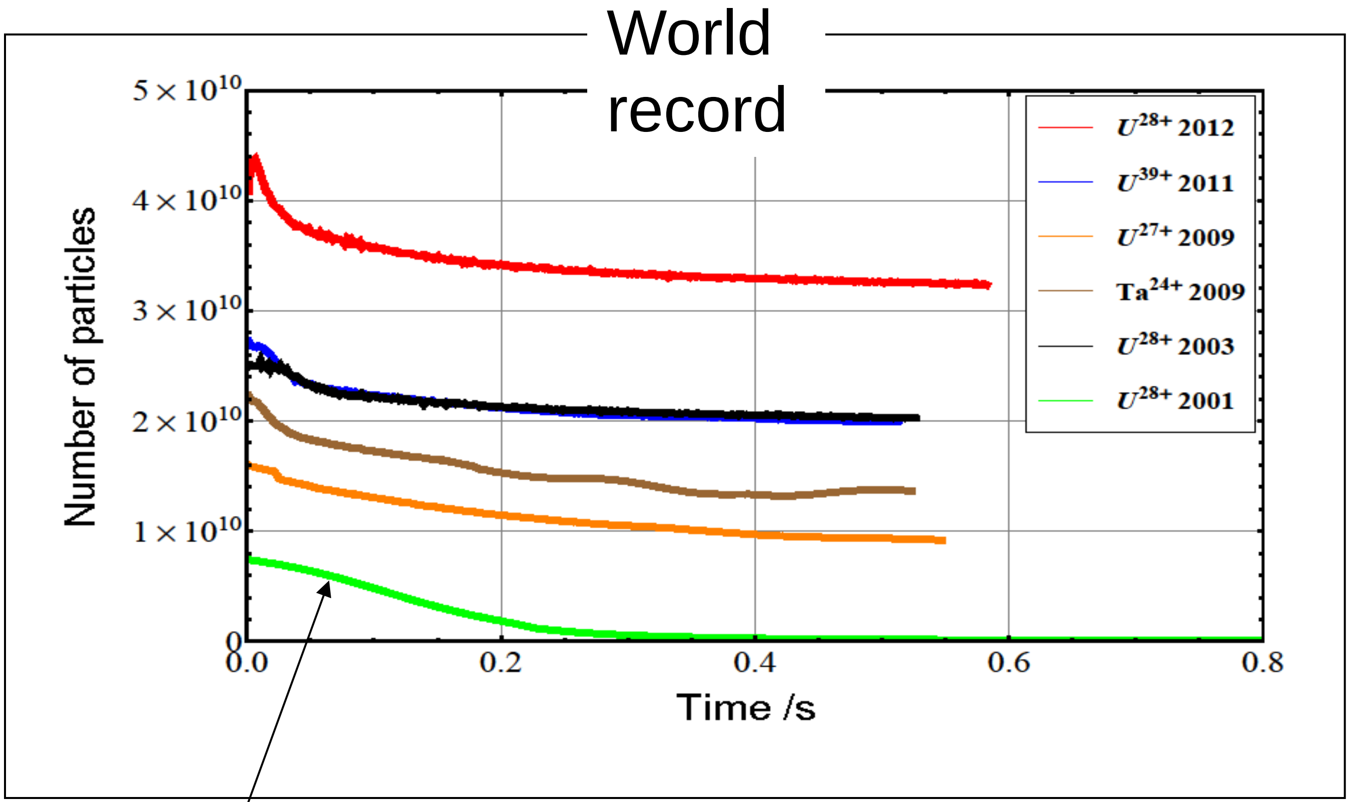


U^{28+} - Beam Intensity

Results of the combined upgrade measures for SIS18

World record intensity for intermediate charge state heavy ions.

The feasibility of high intensity beams of intermediate charge state heavy ions has been demonstrated.



World record

2001 FAIR conceptual design report (FAIR proposal)

Rapid/fast ramping dipole magnets

Examples

Large apertures

SIS-18 dipoles: 20 cm x 8 cm

J-PARC RCS: 25 cm x 19 cm

Ramping rates (Bdot):

SIS-18 dipoles: 10 T/s

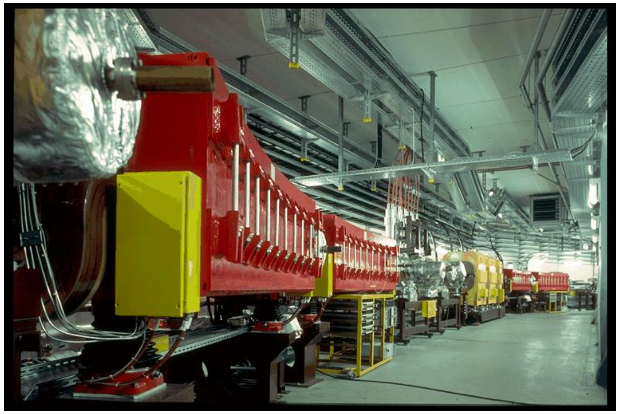
J-PARC RCS dipoles: 40 T/s

Max. B-Field

SIS-18: 1.8 T

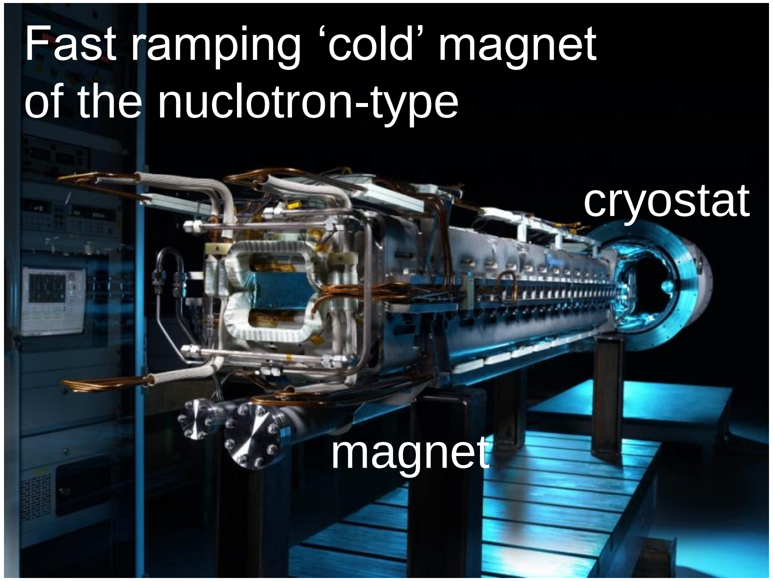
J-PARC RCS: 1.1 T

Fast ramping (3 Hz) SIS-18 dipoles



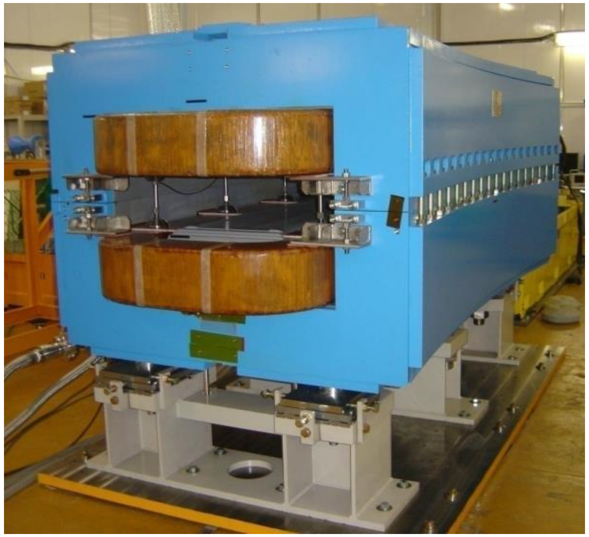
SIS-100 superferric dipole:

13 cm x 6 cm
Bdot = 4 T/s
B_{max}= 1.9 T
pipe at 20 K
(as cryo-pump)



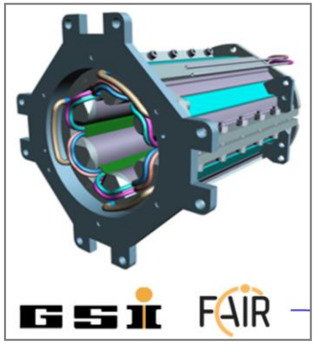
Fast ramping 'cold' magnet of the nuclotron-type

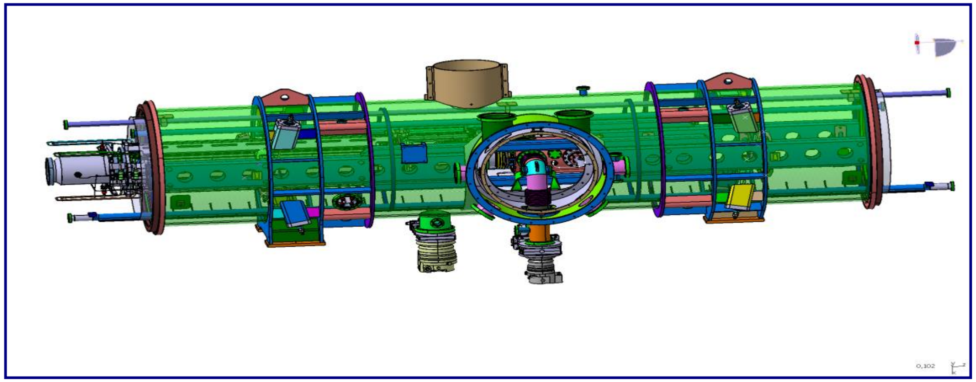
J-PARC RCS (25 Hz) dipole

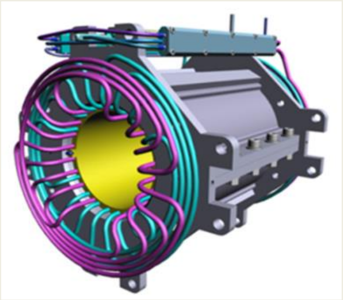


Cryomagnetic Quadrupole Modules for SIS100 (JINR)

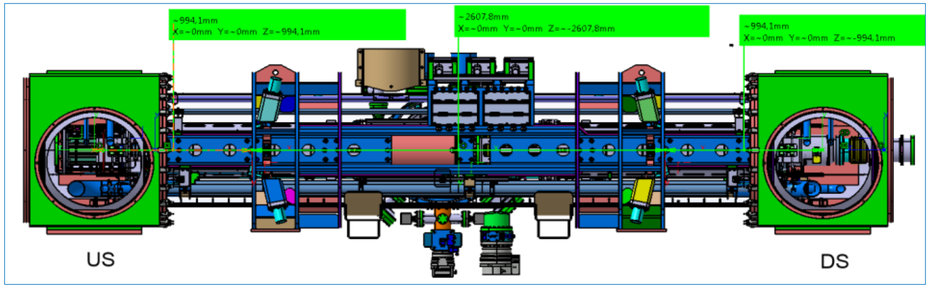
- Manufacturing design of first of series module, completed by GSI design department and JINR
- Design service contract for overall cryomagnetic quadrupole module system signed and progressing
- In-kind & R&D contract for production and testing of quadrupole units with JINR signed
- **Production in JINR**







Design of FoS modul and components by GSI Design Office



Design of QM module including end boxes (link to local cryogenics)

The workshop started magnet production in JINR

cable machine has been put in operation

workshop for coil production

450 SC magnets
for NICA & SIS-100
FAIR

6 arms put in operation

Summary

- FAIR/GSI and JINR-Dubna have conducted successfully major pioneering R&D on HI accelerator key components, providing surpassing and unique performance not only for FAIR and NICA, but also for the next generation of heavy ion particle accelerators world wide.

- Highest intensities of low charge state heavy ion beams with the existing UNILAC and SIS18 was reached and demonstrated in GSI for FAIR and with Nuclotron for NICA.

- Unique modern accelerator technologies are developed in JINR, GSI and BINP and used worldwide.

Summary

- **<u>Generation of intense “precision beams” :</u>** sophisticated beam manipulation methods-stochastic and electron cooling of ion beams, also applicable to the secondary radioactive and antiproton beams;
- **<u>Rings as accelerator structures of choice:</u>** capability to store, cool, bunch, and stretch beams ;
- **Full range of ion beam species:** p+ 239U ;

Accelerator performance – is progressing well

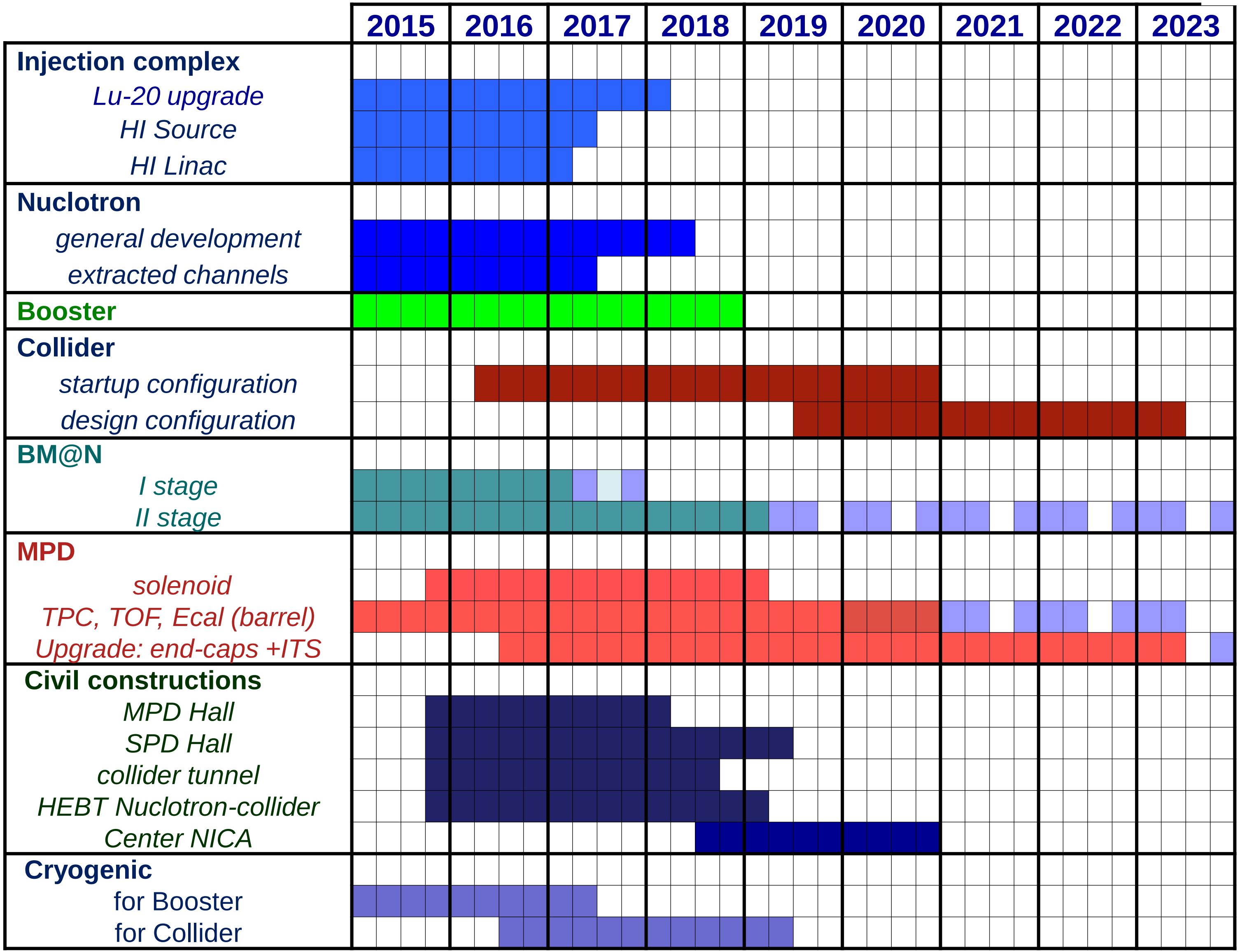
- **<u>Superconducting magnets</u> and RF structures** are widely used in modern accelerators.
- **<u>Superconducting CW linac machines</u>** reach high acceleration efficiency in their RF structures (>50% efficiency from wall plug to beam is possible in SC CW linacs).

Thank you for attention !

Boris Sharkov

- Back up Slides

NICA schedule



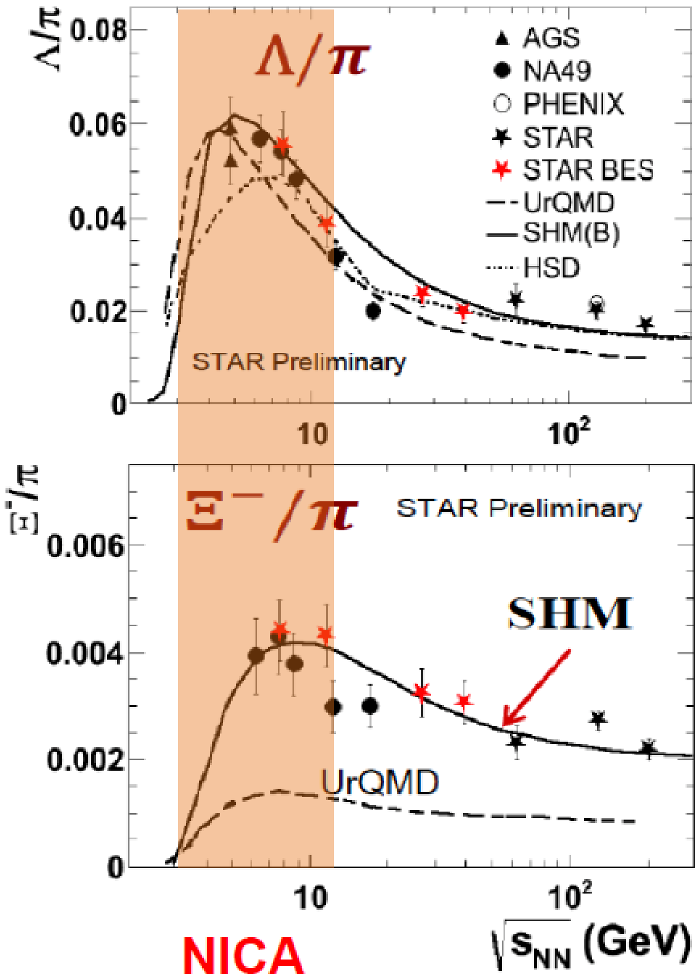
	2015	2016	2017	2018	2019	2020	2021	2022	2023
Injection complex									
Lu-20 upgrade	■■■■	■■■■	■■■■	■□□□	□□□□	□□□□	□□□□	□□□□	□□□□
HI Source	■■■■	■■■■	■■□□	□□□□	□□□□	□□□□	□□□□	□□□□	□□□□
HI Linac	■■■■	■■■■	■□□□	□□□□	□□□□	□□□□	□□□□	□□□□	□□□□
Nuclotron									
general development	■■■■	■■■■	■■■■	■■□□	□□□□	□□□□	□□□□	□□□□	□□□□
extracted channels	■■■■	■■■■	■■□□	□□□□	□□□□	□□□□	□□□□	□□□□	□□□□
Booster	■■■■	■■■■	■■■■	■■■■	□□□□	□□□□	□□□□	□□□□	□□□□
Collider									
startup configuration	□□□□	□■■■	■■■■	■■■■	■■■■	■■■■	□□□□	□□□□	□□□□
design configuration	□□□□	□□□□	□□□□	□□□□	□□■■	■■■■	■■■■	■■■■	■■□□
BM@N									
I stage	■■■■	■■■■	■▨▨▨	□□□□	□□□□	□□□□	□□□□	□□□□	□□□□
II stage	■■■■	■■■■	■■■■	■■■■	■▨▨□	▨▨□▨	▨▨□▨	▨▨□▨	▨▨□▨
MPD									
solenoid	□□□■	■■■■	■■■■	■■■■	■□□□	□□□□	□□□□	□□□□	□□□□
TPC, TOF, Ecal (barrel)	■■■■	■■■■	■■■■	■■■■	■■■■	■■■■	▨▨□▨	▨▨□▨	▨▨□□
Upgrade: end-caps +ITS	□□□□	□□■■	■■■■	■■■■	■■■■	■■■■	■■■■	■■■■	■■□▨
Civil constructions									
MPD Hall	□□□■	■■■■	■■■■	■□□□	□□□□	□□□□	□□□□	□□□□	□□□□
SPD Hall	□□□■	■■■■	■■■■	■■■■	■■□□	□□□□	□□□□	□□□□	□□□□
collider tunnel	□□□■	■■■■	■■■■	■■■□	□□□□	□□□□	□□□□	□□□□	□□□□
HEBT Nuclotron-collider	□□□■	■■■■	■■■■	■■■■	■□□□	□□□□	□□□□	□□□□	□□□□
Center NICA	□□□□	□□□□	□□□□	□□■■	■■■■	■■■■	□□□□	□□□□	□□□□
Cryogenic									
for Booster	■■■■	■■■■	■■□□	□□□□	□□□□	□□□□	□□□□	□□□□	□□□□
for Collider	□□□□	□□■■	■■■■	■■■■	■■□□	□□□□	□□□□	□□□□	□□□□

▨ *running time*

QCD matter at the **NICA** energies:

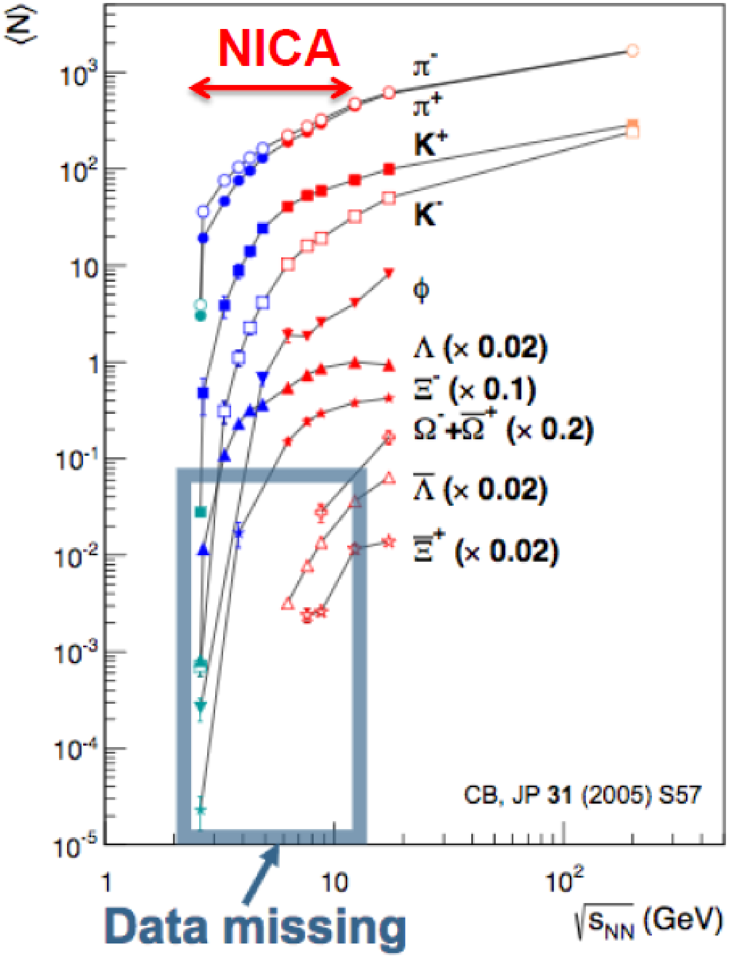
- *maximum in the net baryon density – **density frontier**;*
- *maximum in K^+/π^+ ratio;*
- *maximum in Λ/π ratio;*
- *maximum yield if hypernuclei*
- *transition from a Baryon dominated system to a Meson dominated one;*
- *maximum of the Λ polarization;*
- *1-st order transition & mixed phase creation;*
- *Critical Endpoint ?*

Strange baryon to pion ratios



D. Tlusty, SQM-2017

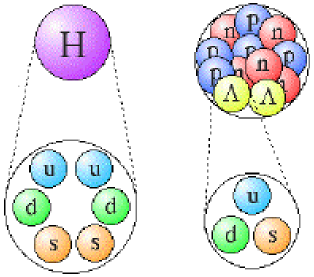
Total yields



Data missing or to be improved!

C. Blume, SQM-2017

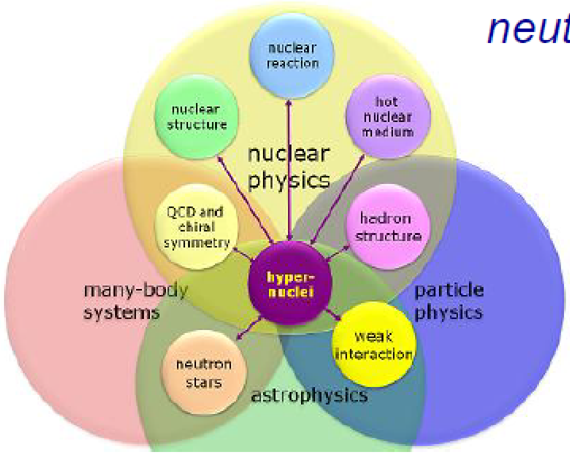
Hypernuclei

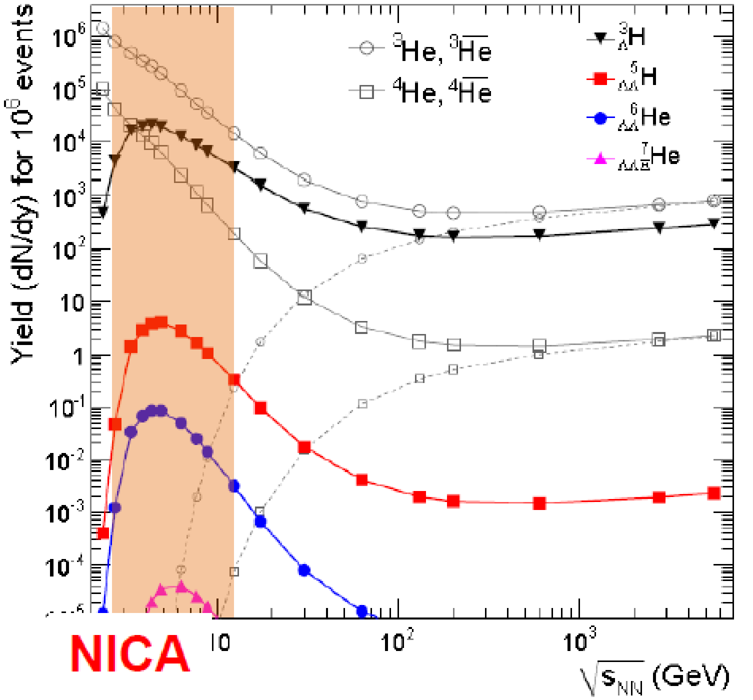


Hypernuclei provides unique opportunity to study the strange particle-nucleus interaction in a many-body environment.

production enhanced at high baryon densities (NICA)

On the astrophysical scale the appearance of hyperons in the dense core of a neutron star has been a subject of extensive studies since the early days of neutron star research



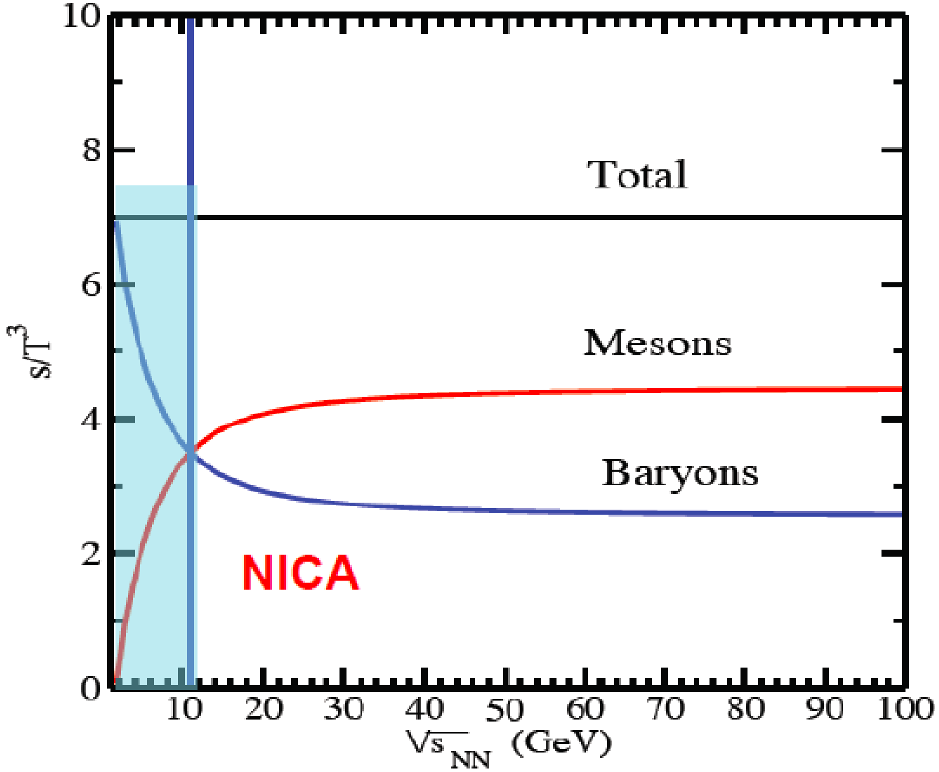


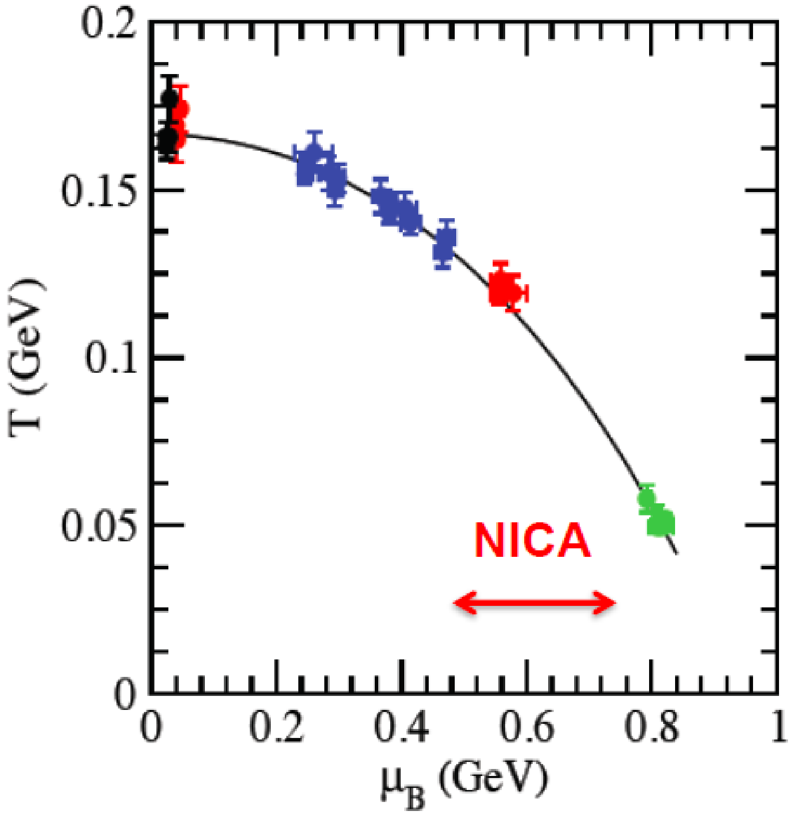
A. Andronic et al., Phys. Lett. B697 (2011) 203

NICA energy region

a transition from a baryon-dominated to a meson-dominated media

less studied region



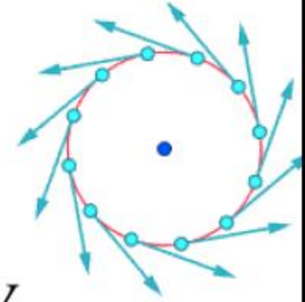


H. Oeschler et al.
Physics Letters B615 (2005) 50-54.

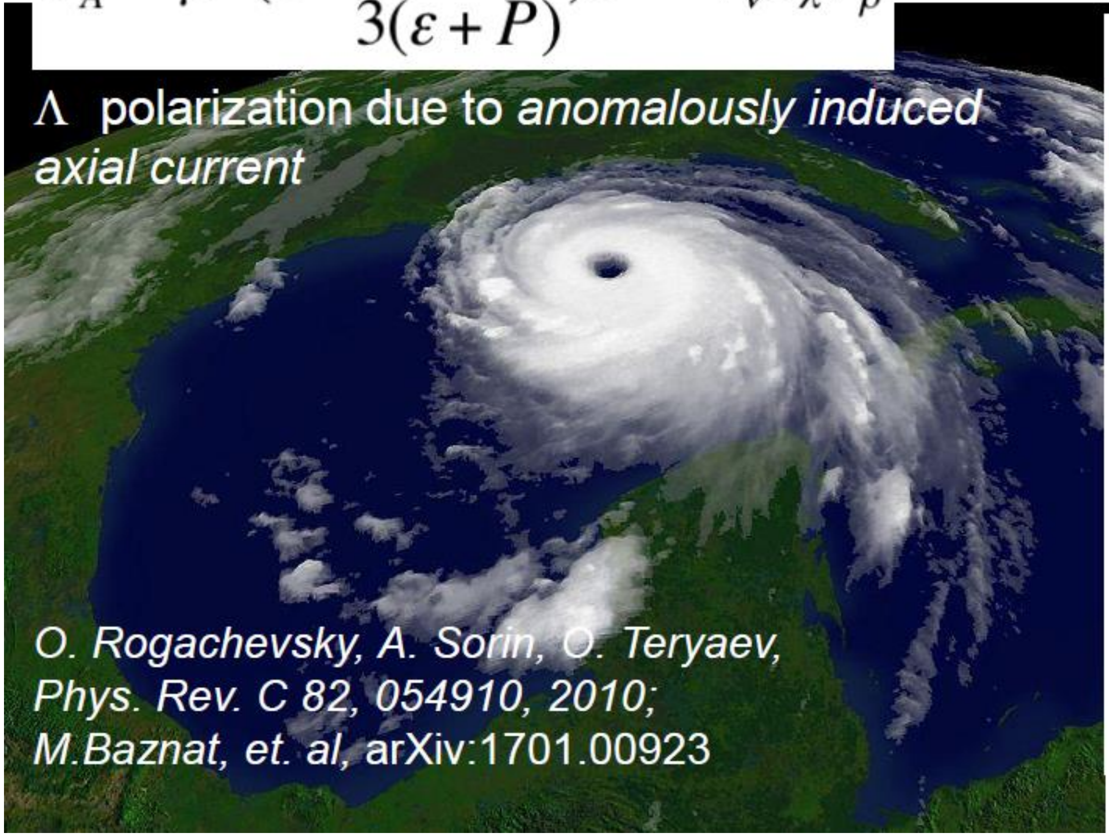
J. Cleymans, SQM-2017.

Vorticity, Λ polarization

$$\vec{J} = \frac{1}{\pi^2}\mu_5\mu\vec{\omega} \quad \vec{\omega} = \frac{1}{2}\vec{\nabla}\times\vec{v}$$

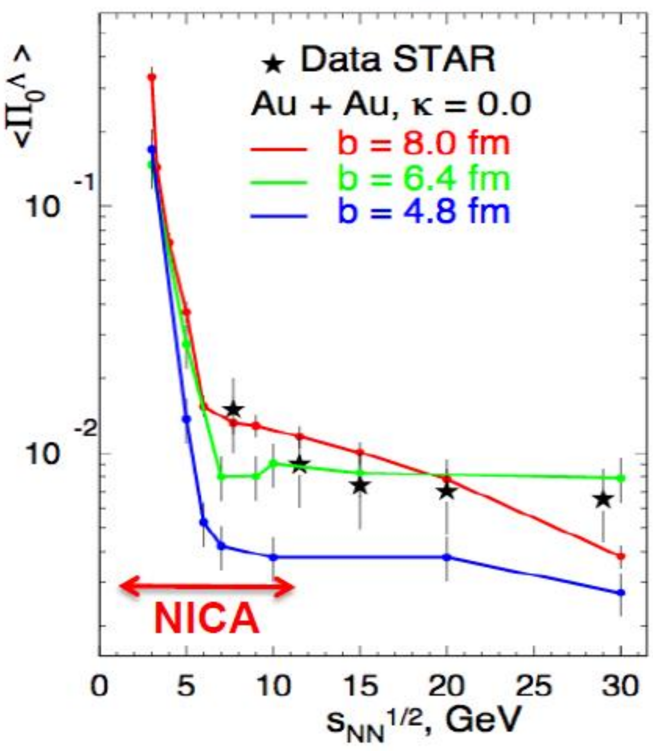


$$J_A^\mu \sim \mu^2\left(1 - \frac{2\mu n}{3(\varepsilon + P)}\right)\varepsilon^{\mu\nu\lambda\rho}V_\nu\partial_\lambda V_\rho$$



Λ polarization due to *anomalously induced axial current*

O. Rogachevsky, A. Sorin, O. Teryaev, Phys. Rev. C 82, 054910, 2010; M.Baznat, et. al, arXiv:1701.00923



STAR Coll.,arXiv:1701.06657

General description – Basic beam parameters

	Ions	Energy	Intensity
SECR	$^{238}U^{34+}$	14 keV/u	0.05 pmA
iLinac	$^{238}U^{34+}$	17 MeV/u	0.028 pmA
BRing	$^{238}U^{34+}$	0.8 GeV/u	$\sim 1.4\times10^{11}$ ppp
SRing	RIBs: neutron-rich, proton-rich	0.84 GeV/u(A/q=3)	$\sim 10^{9\text{-}10}$ ppp
	Fully stripped heavy ions H-like, He-like heavy ions	0.8 GeV/u($^{238}U^{92+}$)	$\sim 10^{11\text{-}12}$ ppp
MRing	$^{238}U^{92+}$	0.8 GeV/u	$\sim 1.0\times10^{11}$ ppp