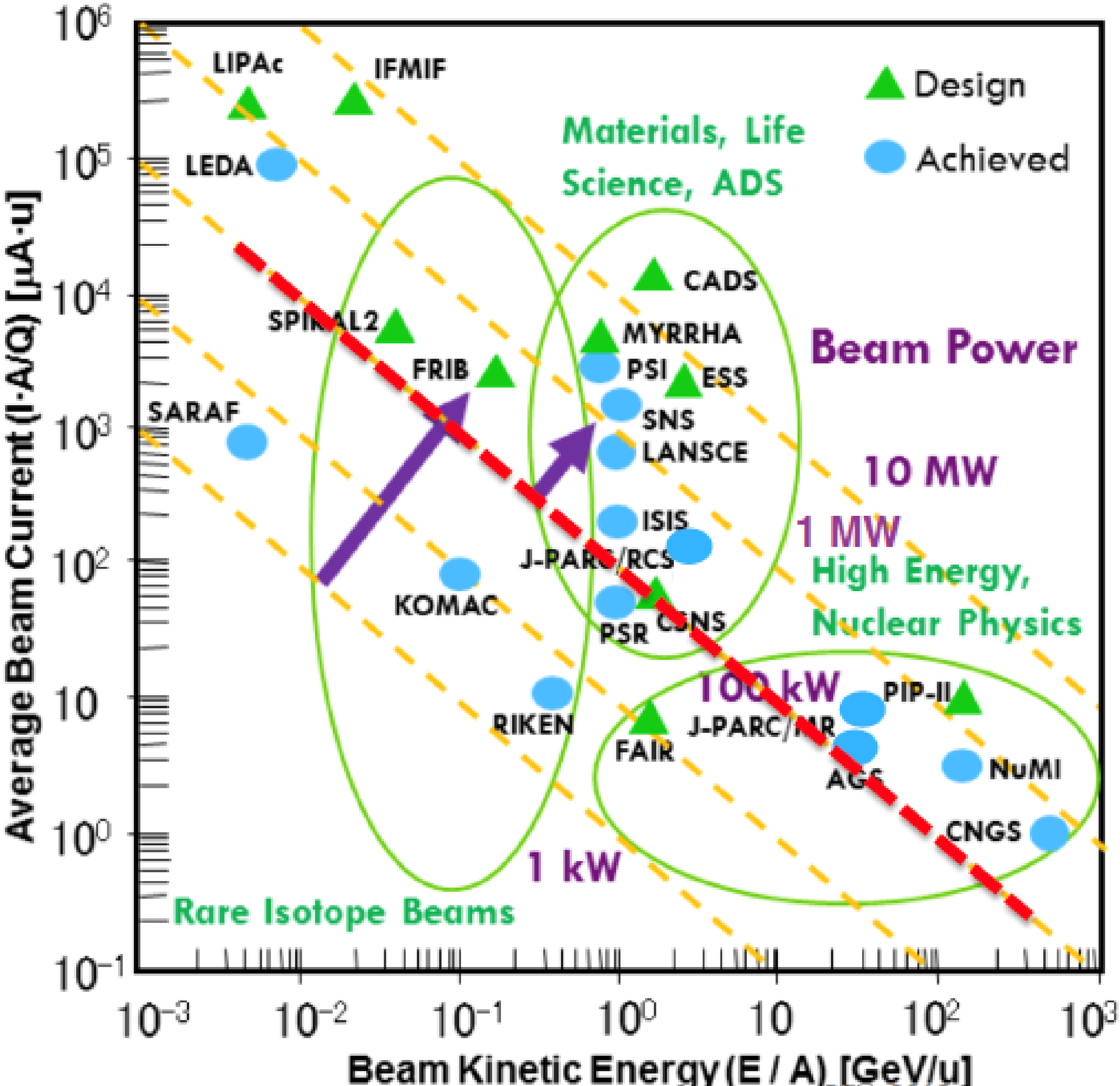
Acceleration of High-Brightness Heavy Ion Beams for Research into Heavy Ion Nuclear Physics

Boris Sharkov - *JINR, Dubna*
- *MEPhI, Moscow*

A Quest for High Intensity



High Intensity

High Statistics

- More Precision
- More Rare Searches
- More Materials

Discovery!

Low and medium energy HI accelerators E < N GeV

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+}

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 .

Common accelerator Technology Issues

High current front end

Multiturn injection

Fast Acceleration

Stacking / Accumulation

Beam Cooling

IBS and vacuum instabilities

Fast extraction

Beam transport and focusing

ФАИР (FAIR) – новый, крупнейший в мире, строящийся, международный исследовательский центр *в г. Дармштадт, ФРГ*

new international research laboratory to explore the nature of matter in the Universe

Primary Beams

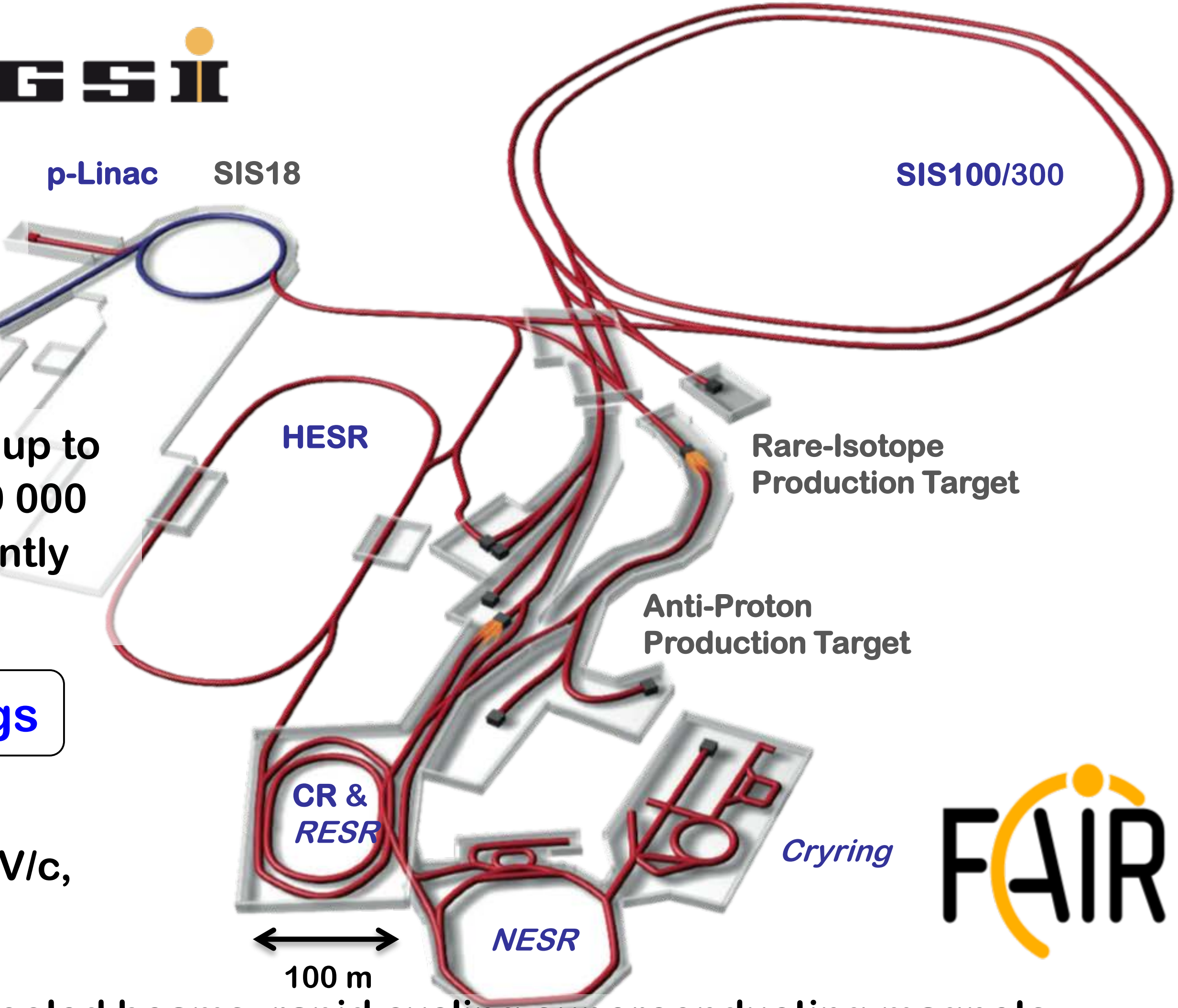
- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- $3x10^{13}$/s 30 GeV protons

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

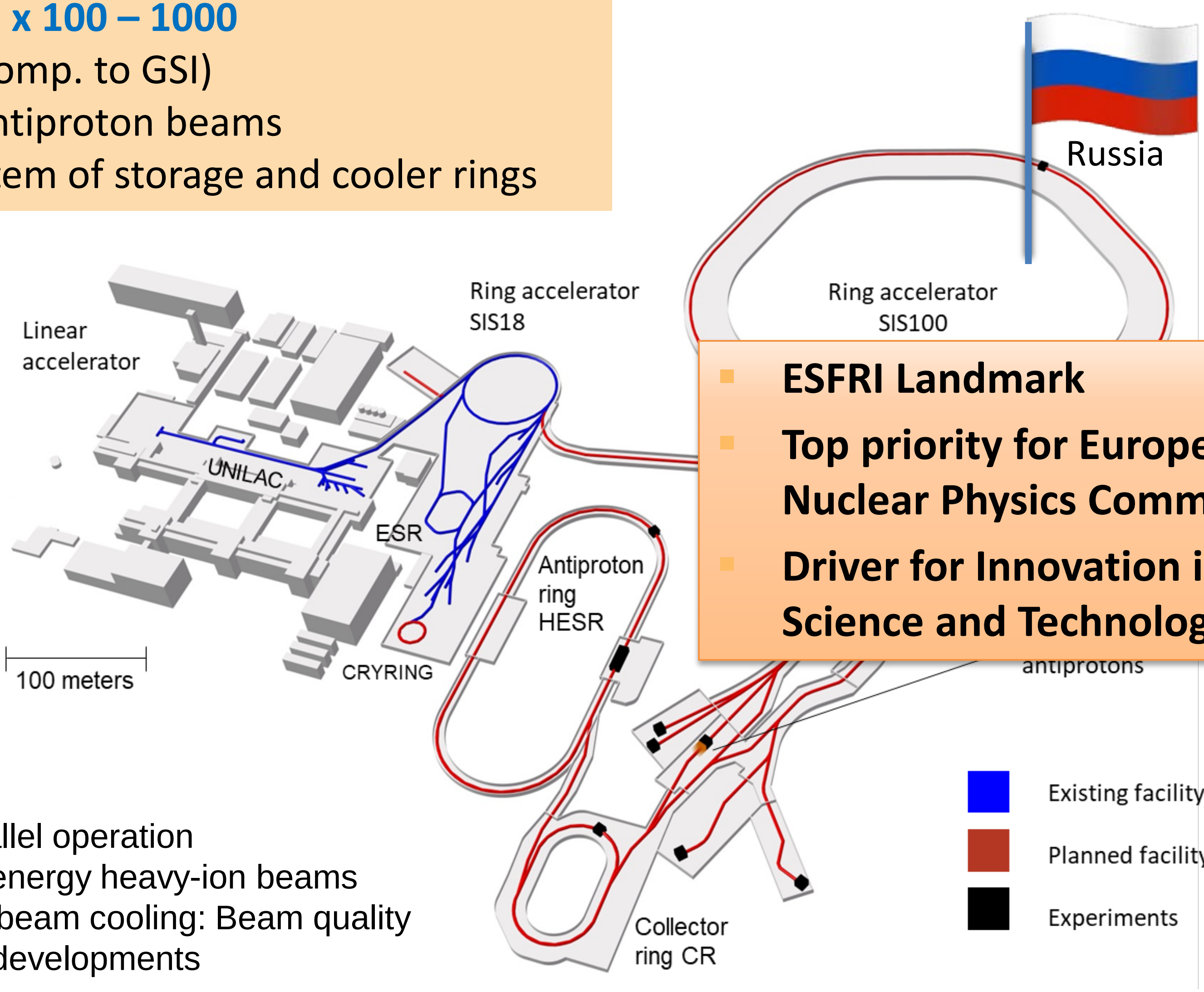


Technical Challenges

- cooled beams, rapid cycling superconducting magnets

FAIR: Facility for Antiproton and Ion Research
– a World-Wide Unique Accelerator Facility

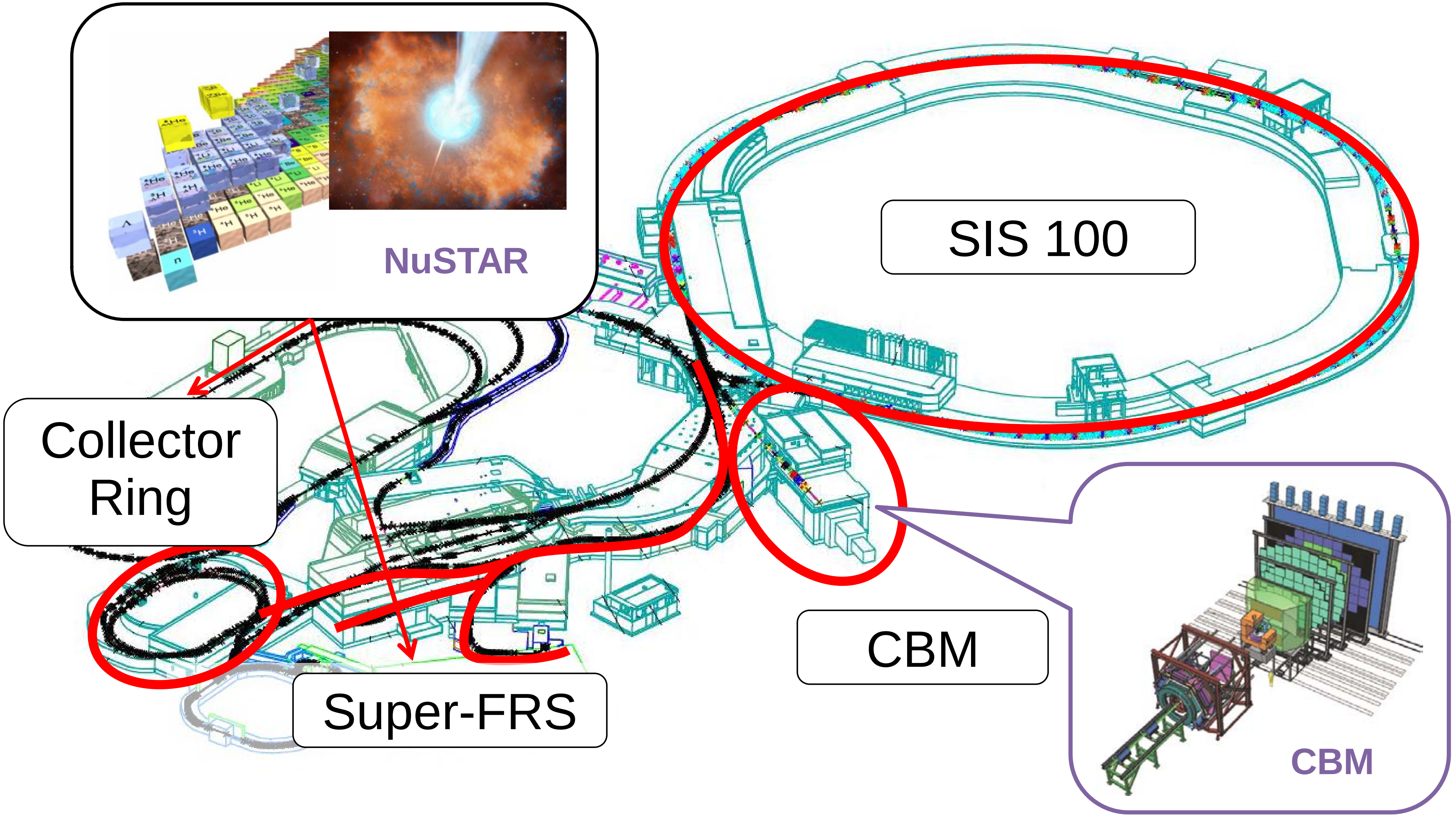
- **Intensity gain: x 100 – 1000**
- 10 x energy (comp. to GSI)
- **Antimatter:** antiproton beams
- **Precision:** System of storage and cooler rings



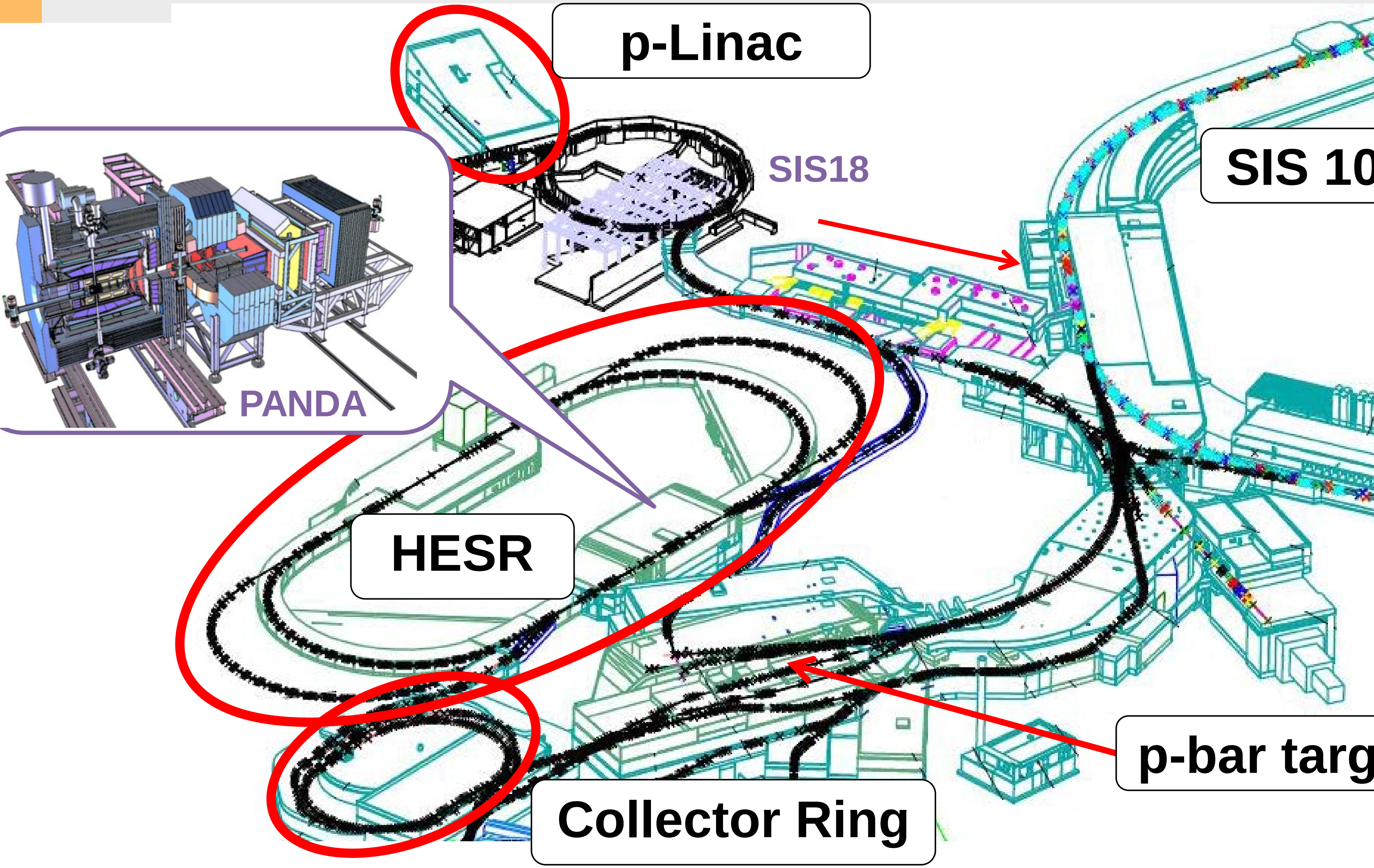
- **ESFRI Landmark**
- **Top priority for European Nuclear Physics Community**
- **Driver for Innovation in Science and Technology**

Unique features:
- Flexibility and parallel operation
- **Intense** and high-energy heavy-ion beams
- Storage rings and beam cooling: Beam quality
- Major accelerator developments

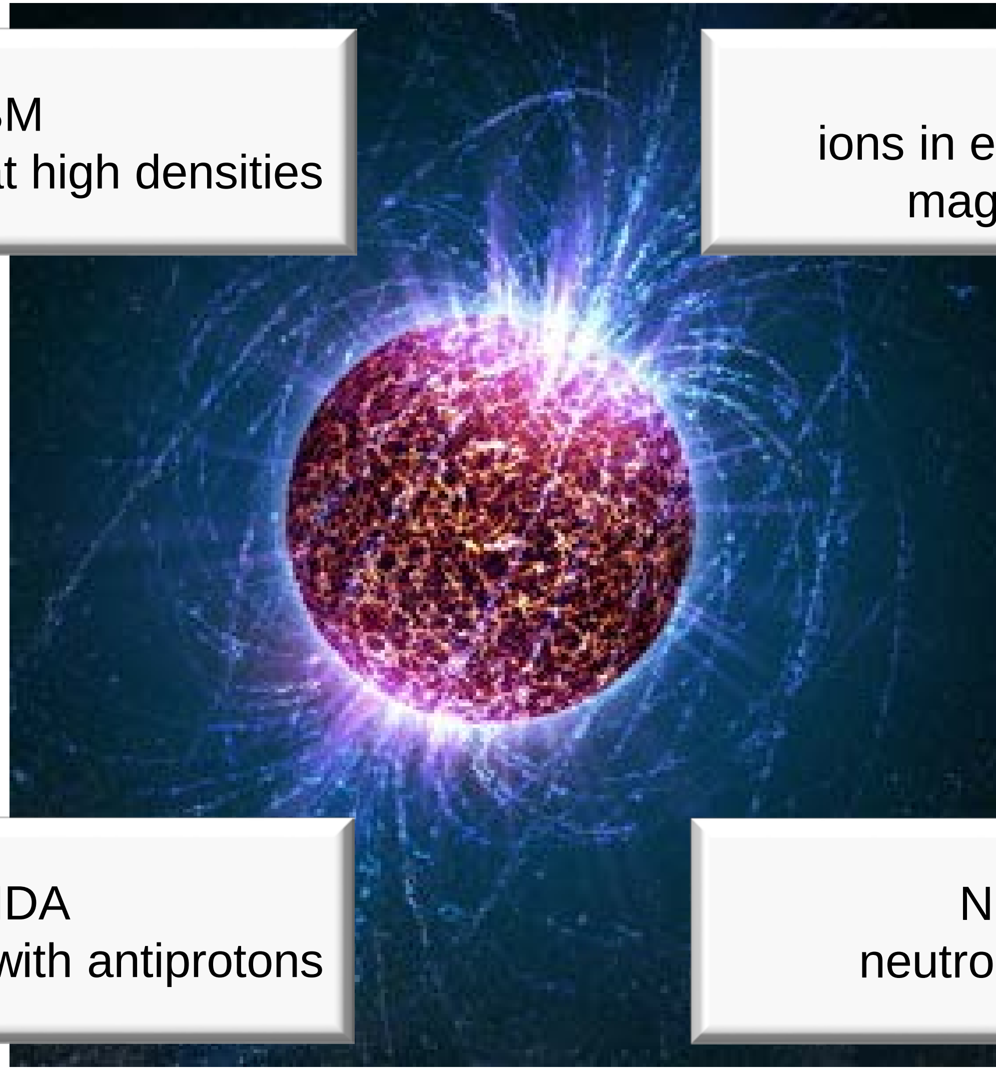
Ускорительный комплекс



Anti proton accelerator chain



4 Research Pillars of FAIR



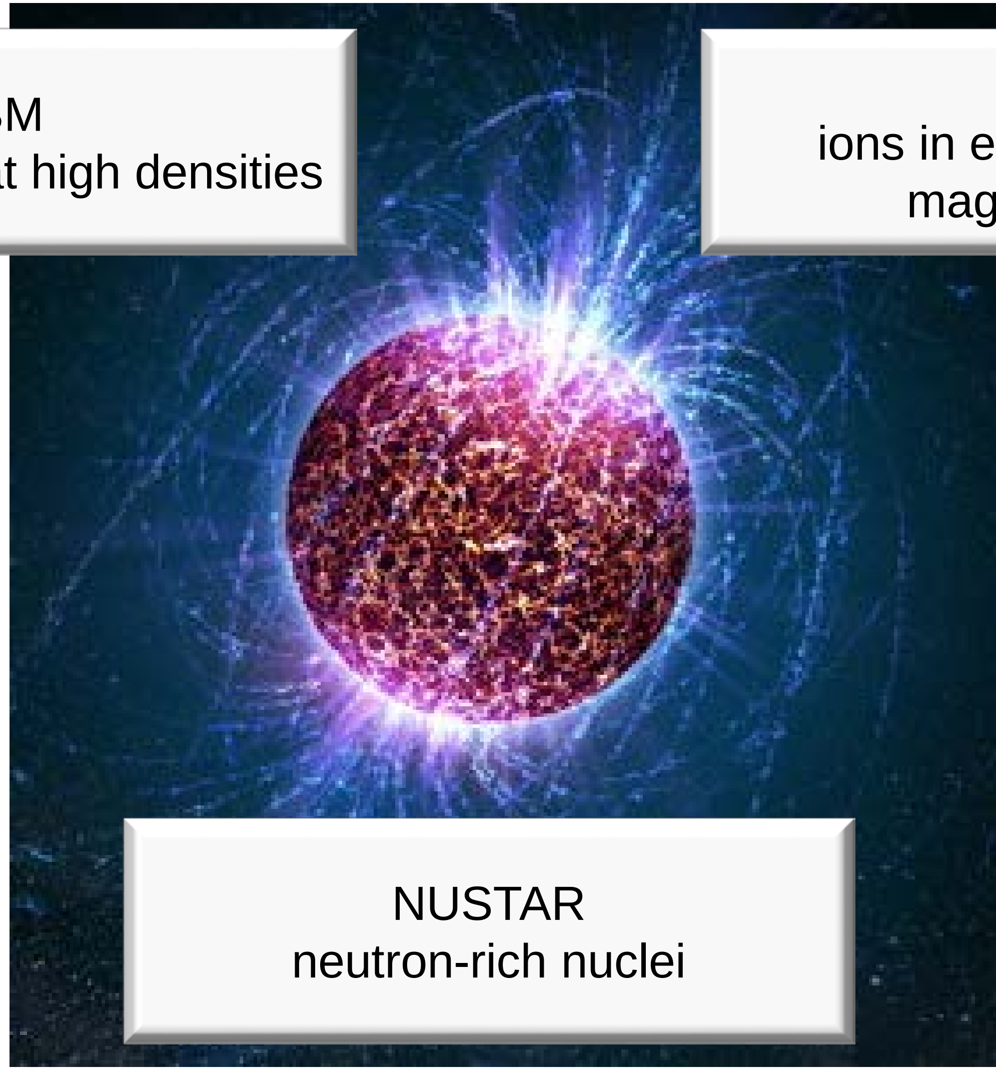
CBM
nuclear matter at high densities

APPA
ions in extreme electro-magnetic fields

PANDA
hadron physics with antiprotons

NUSTAR
neutron-rich nuclei

2015 :   3 Research Pillars of FAIR



CBM
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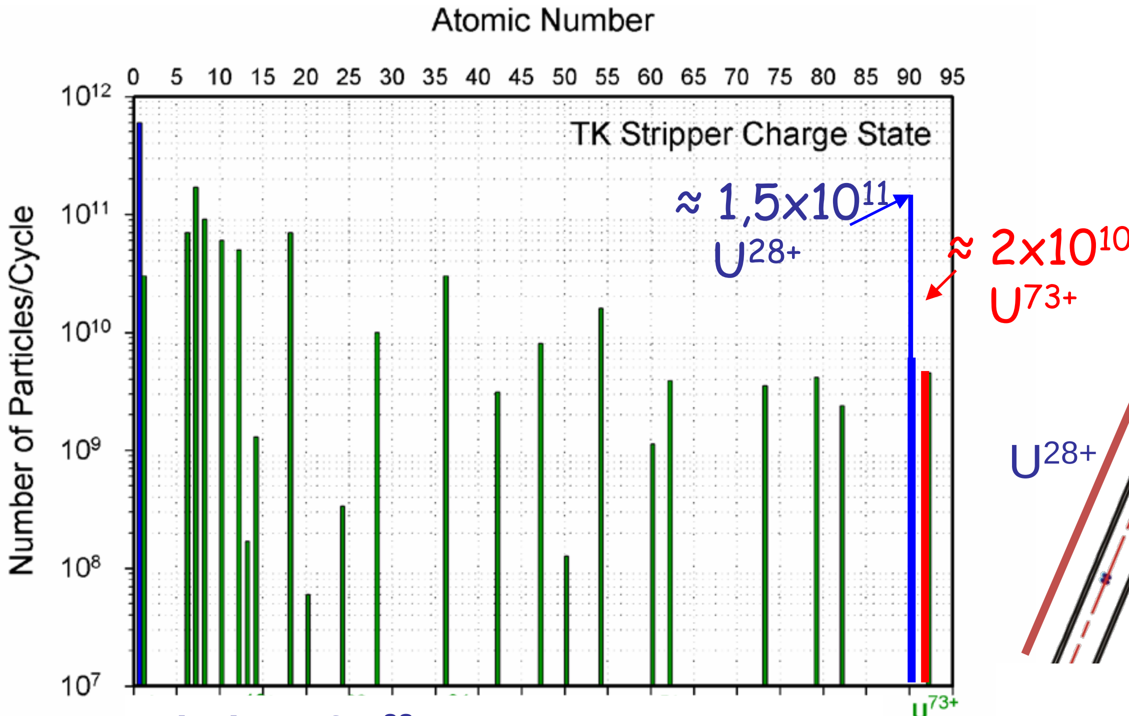
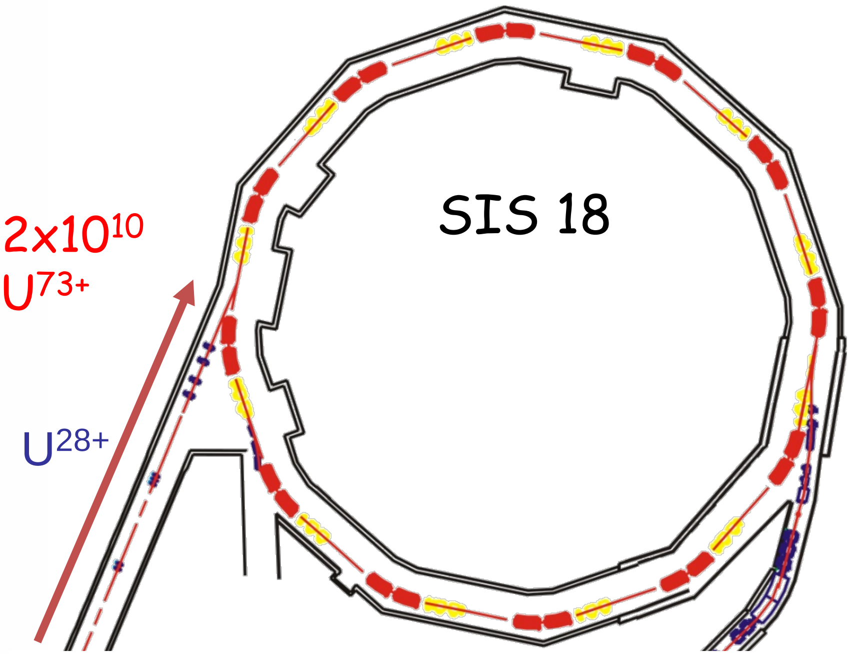
SIS 18 as Injector for SIS 100





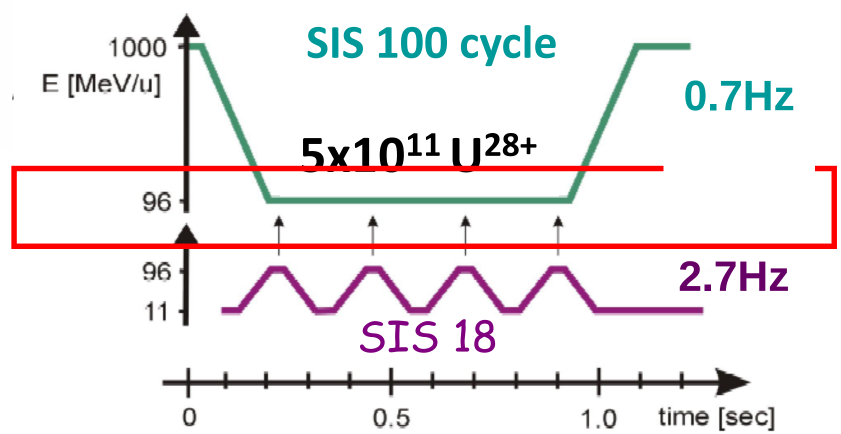
Choice of U^{28+}

+ Lower space charge

→ higher intensity N_{max}~A/Q^2

+ No stripping losses

- Lower beam lifetime

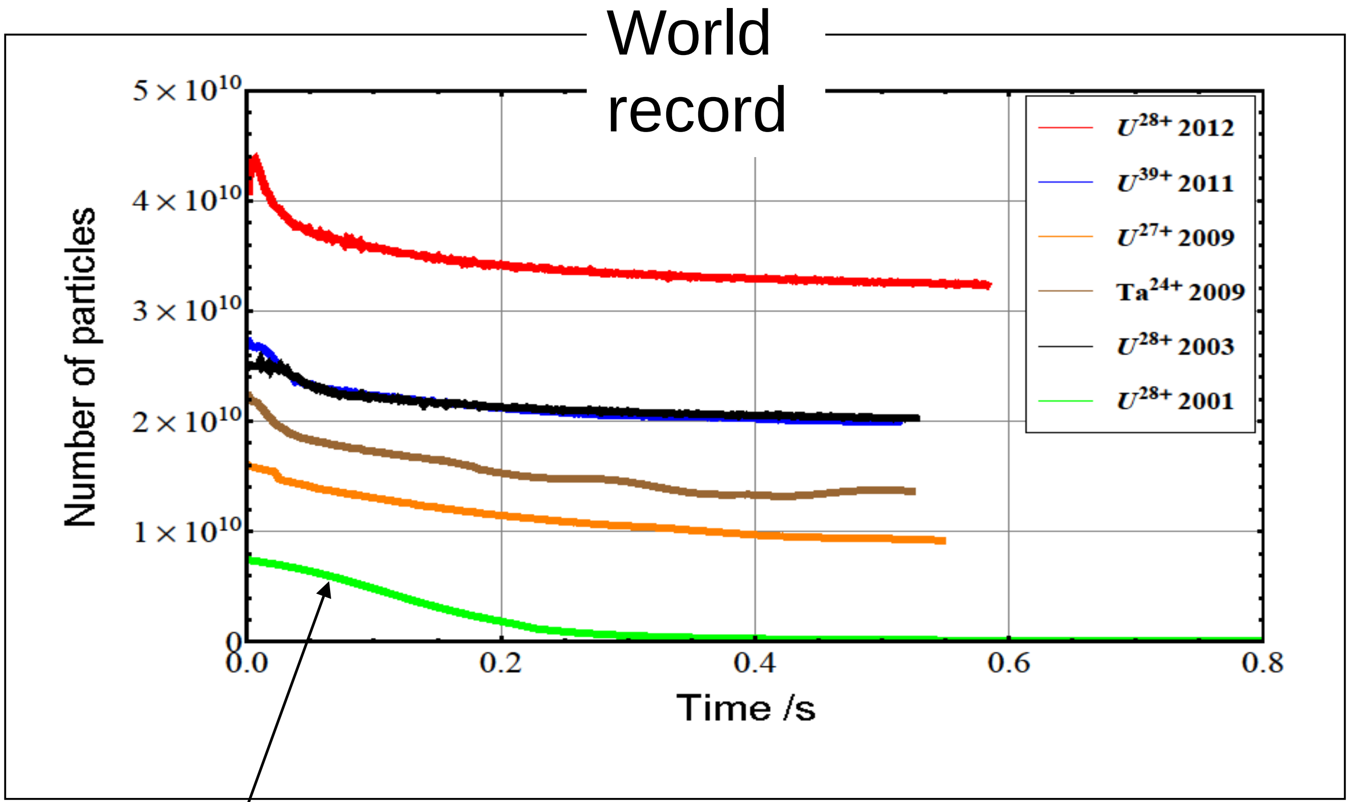


U^{28+} - Beam Intensity

Results of the combined upgrade measures for SIS18

World record intensity for intermediate charge state heavy ions.

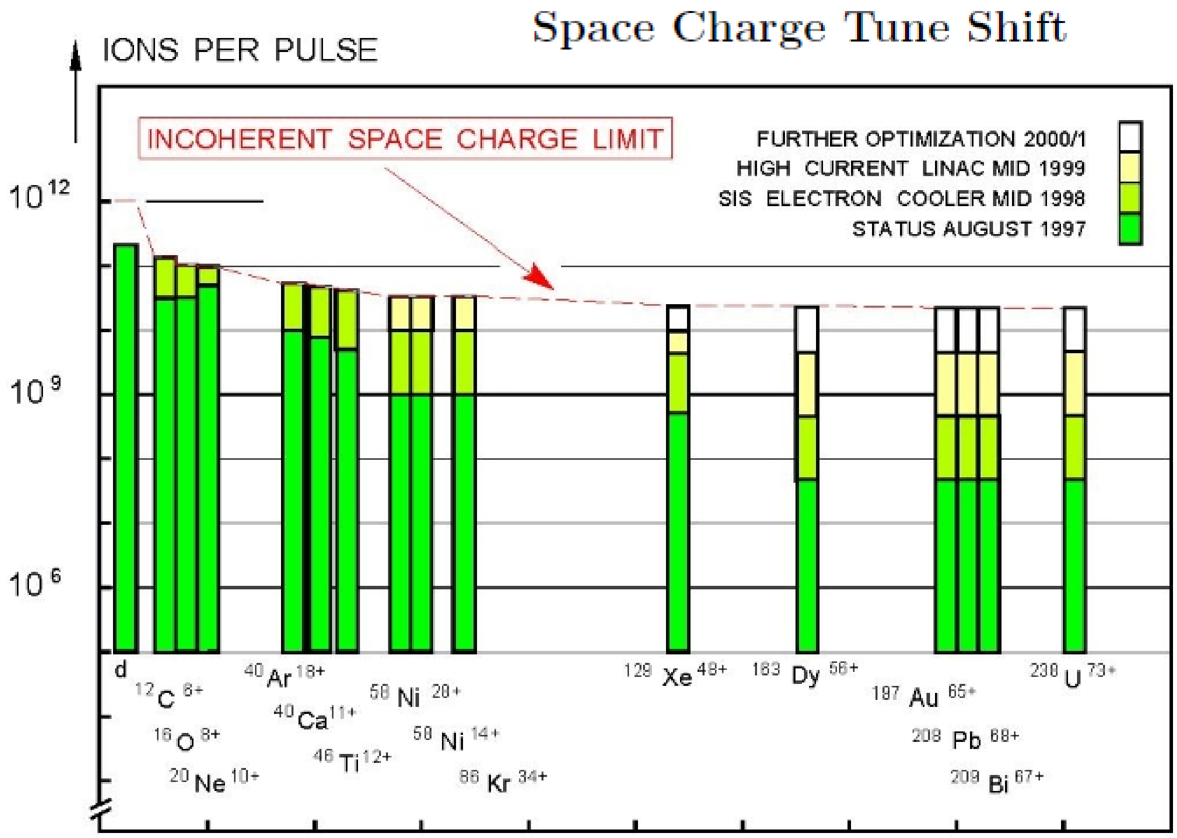
The feasibility of high intensity beams of intermediate charge state heavy ions has been demonstrated.



2001 FAIR conceptual design report (FAIR proposal)

Intensity limitation in synchrotrons - Laslett tune shift

Intensity limits in synchrotron accelerators



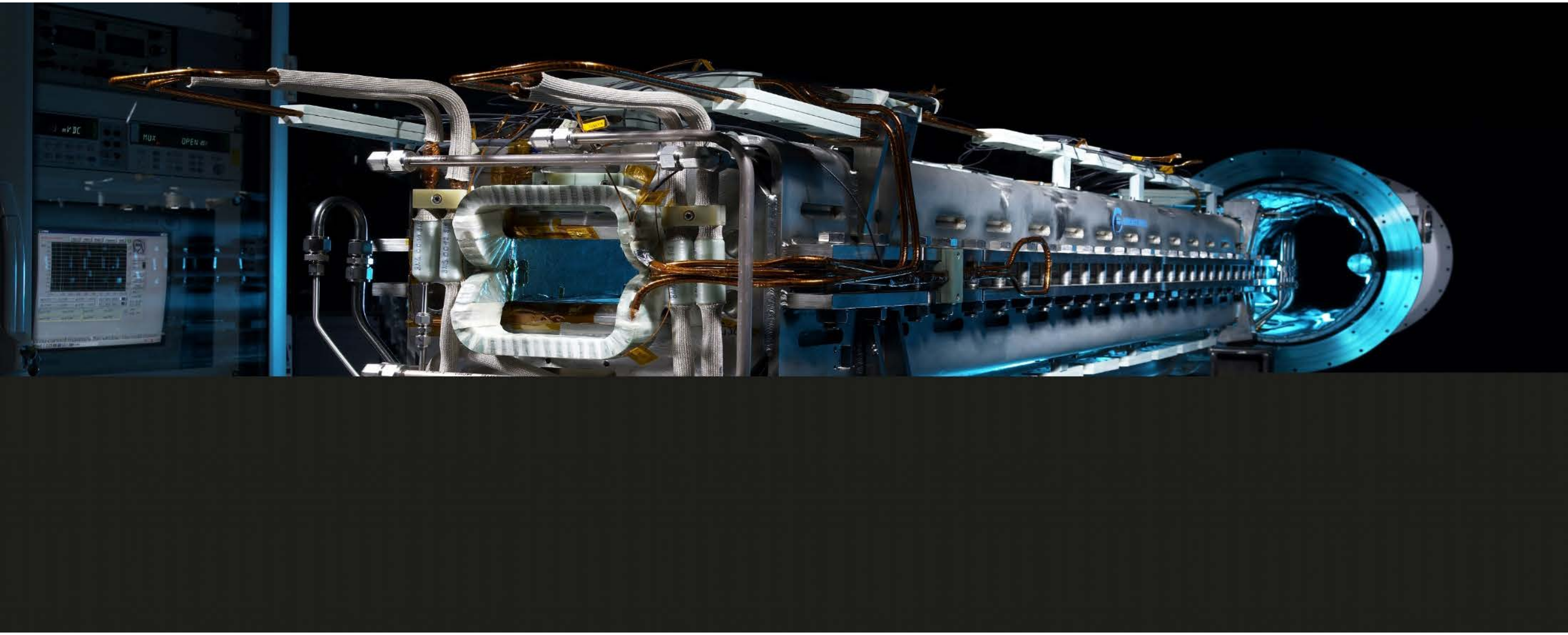
$$\Delta Q = -\frac{1}{4\pi}\oint \frac{K}{\epsilon_x} ds = -\frac{KR}{2\epsilon_x}$$

perveance

$$K = \frac{qI}{2\pi\epsilon_0 mc^3\beta^3\gamma^3}$$

12

Forefront Technologies



- **Applications in accelerator science, detector instrumentation, materials research, radiation biology, therapy...**

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

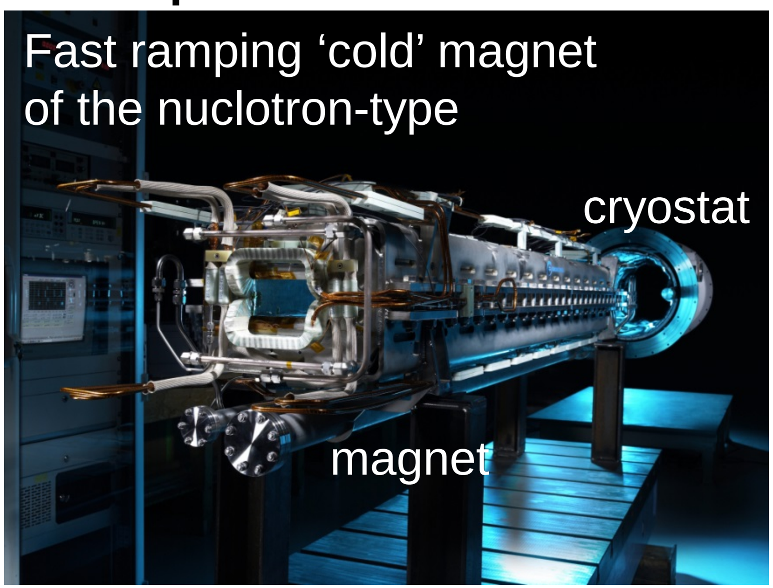
SIS-18: 1.8 T

J-PARC RCS: 1.1 T

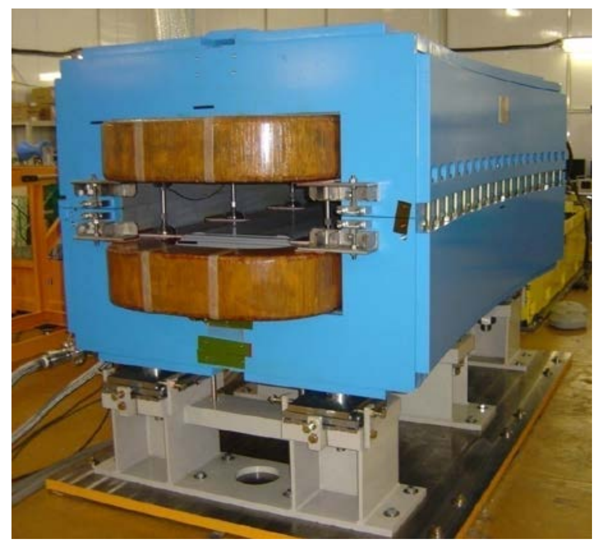
Fast ramping (3 Hz) SIS-18 dipoles

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)



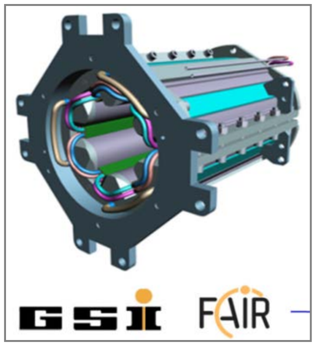
J-PARC RCS (25 Hz) dipole

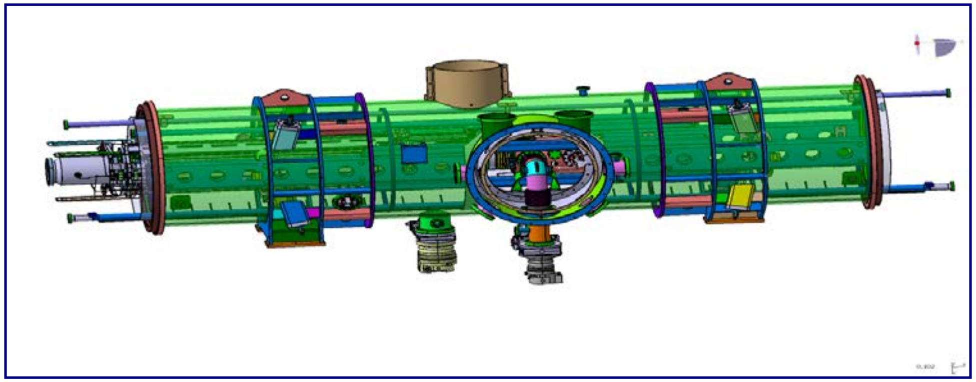


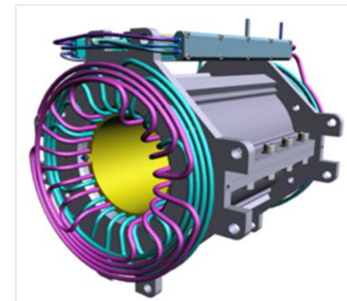
Experimental studies with modified Nuclotron magnets in JINR

Cryomagnetic Quadrupole Modules for SIS100 (JINR)

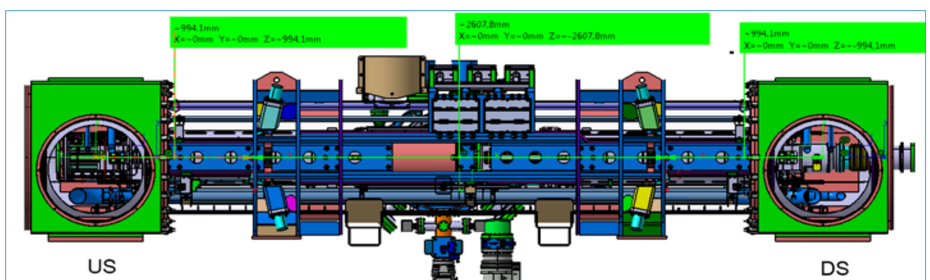
- Manufacturing design of first of series module, completed by GSI design department
- Design service contract for overall cryomagnetic quadrupole module system signed and progressing
- In-kind & R&D contract for production and testing of quadrupole units with JINR signed
- **Production of FoS unis until end of 2018 in JINR**







Design of FoS modul and components by GSI Design Office

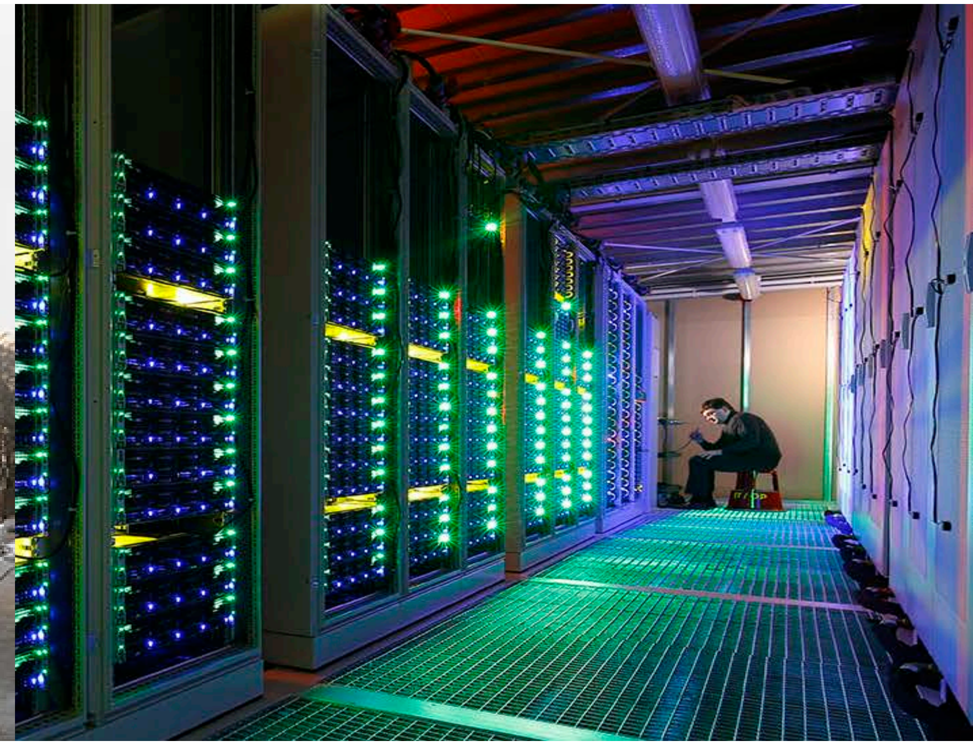


Design of QM module including end boxes (link to local cryogenics)

SIS100 Quad. Units Collaboration Contract with JINR

Dubna 20.02.2015

Forefront Technologies



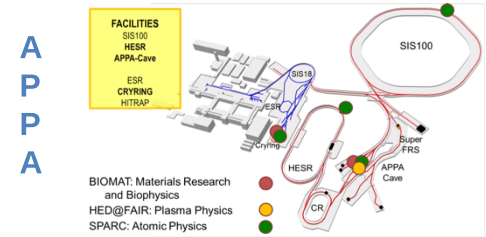
- **Technological advancements in high-performance & scientific computing, Big Data, Green IT**

Schedule for FAIR Science

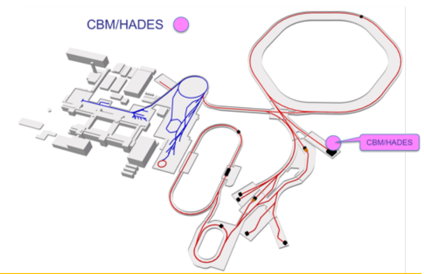
- Working towards the completion of FAIR by 2025
- Major thrust is on construction of FAIR accelerators and experiments.
- At the same time ***staged approach to FAIR science and progressive commissioning of accelerators and detectors***:
  - ***FAIR Phase-0 : start in 2019***
  - FAIR Day-1 configurations/ Phase-1 experiments with FAIR accelerators progressively approaching design parameters → 2024/25 …
  - Full FAIR operation 2025+

FAIR Phase 0 Research Program

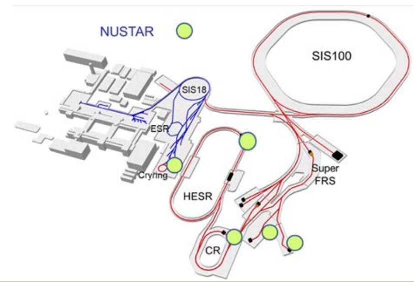
A P P A



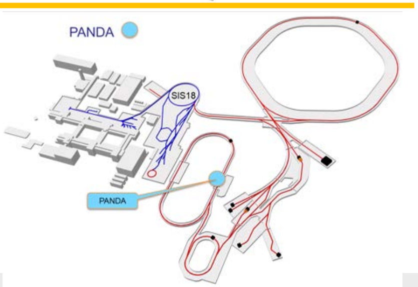
C B M



N U S T A R



P A N D A



Status of FAIR: Accelerators:
construction / procurement progress

~ 60 sc dipole SIS100 modules manufactured at BNG and **55** shipped to GSI and tested

SIS100 quadrupole units shipped from JINR to BNG for integration into FoS module

All 51 HEBT vacuum chambers of batch 1 delivered (BINP, Russia)

The series production of RF – debunchers

All HESR Dipoles are produced, in Jülich and 65% are delivered to FAIR

Delivery of 1st 6 series Power Converter from India, (ECIL, India)

Status of FAIR: Accelerators:
construction / procurement progress

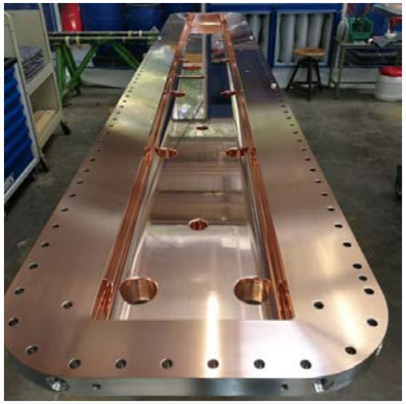
Two FoS vacuum chambers for the quadrupole doublet modules of the SIS100 arrived from China. They will be installed by the integrator in the quadrupole units

First-of-Series of the Super-FRS short SC Multiplet arrived in February 2019 at CERN test facility for execution of the Site Acceptance Test

First HESR Stochatic cooling pick-up and kicker in operation at COSY

Successfully First-of-Series FAT for the Super-FRS short SC Multiplet took place in Italy at January 2019

Copper plating and first tests of the RFQ accelerator cavity for the pLinac have been completed and match specifications



Three new MA acceleration cavities installed and commissioned with beam

Distributed testing infrastructure for the FAIR superconducting magnets

GSI: Series test facility for the SIS100 s.c. dipole magnets, string test, current leads and local cryogenics components.

CERN: Test facility completed for the Super-FRS s.c. dipoles and multipletts

INFN: Test facility in Salerno for testing the series of SIS100 quadrupole modules

JINR, Series test facility in Dubna for testing of the series of SIS100 s.c. quadrupole units

Status of FAIR Project: Civil Construction
Progress since official start on 4th of July 2017

FAIR Progress and Cost Review - Report

See: www.gsi.de/en/start/news/details/2019/04/30/expertengruppe_abschlussbericht_zum_fair_projekt0.htm

Final report on the FAIR project

Evaluation of the project in spring 2019.
More information and final report.

Report

of the

FAIR Progress and Cost Review Board:

Detailed Review of Progress and Financial Status of the FAIR Project

April 2019

I. Executive Summary

The FAIR Project is based on the scientific pillars APPA, CBM, NUSTAR and PANDA. Their programmes will enable unique and world leading discovery science. **The breadth and reach of these programmes will remain unsurpassed at the planned start of FAIR operation in 2025 and for many decades beyond.**

With foresight and adequate planning of resources, the different parts of the Project can be brought on sequentially, beginning to produce world-leading science before the end of 2025. However, it will be very challenging to finish the whole Project by the end of 2025 with the available resources, even if the additionally required funds will be available.

...

...Delaying or reducing part of the MSV's scope is not recommended, for scientific and also cost reasons.

...

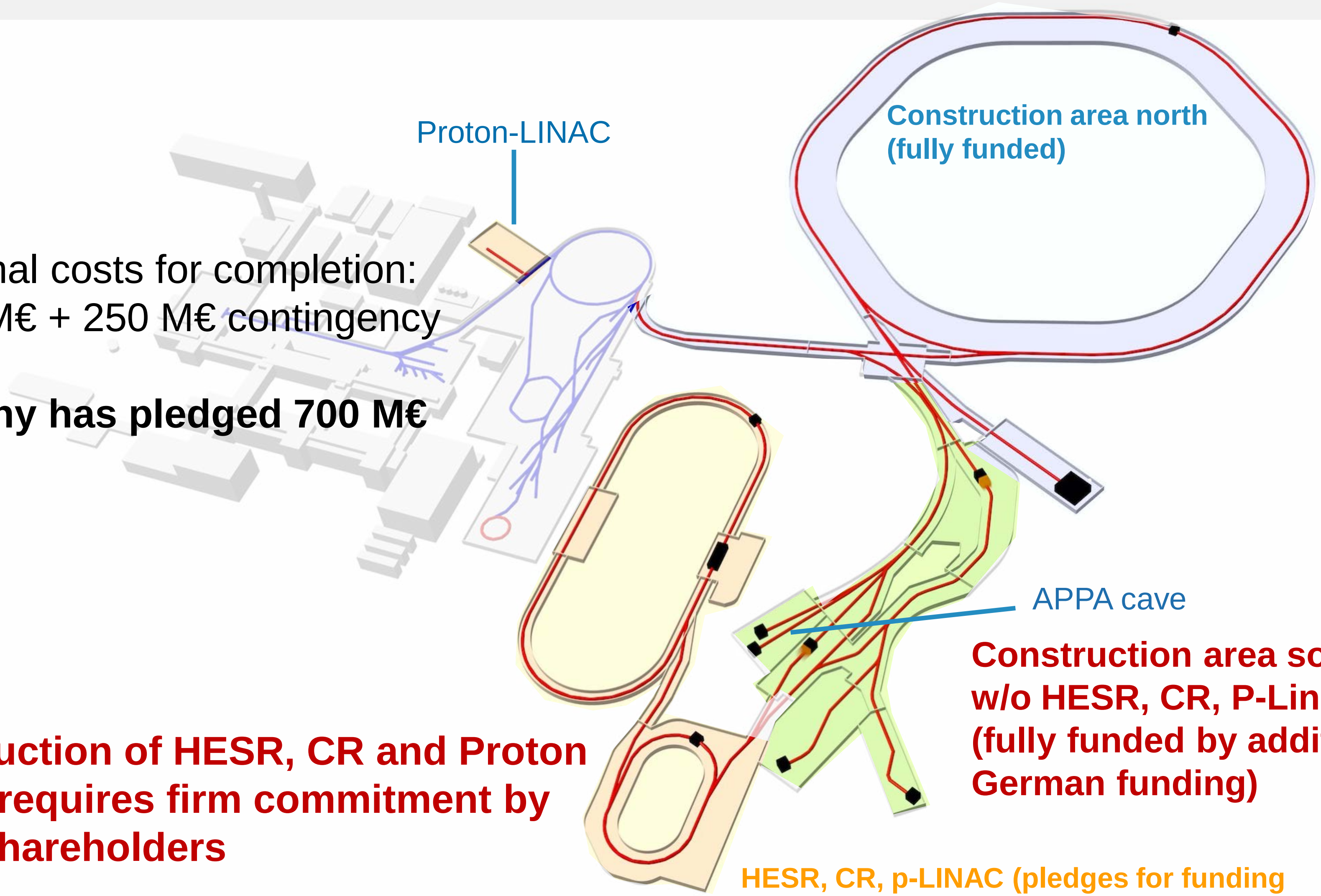
...

In summary, the FAIR Modularized Start Version (MSV) is to be constructed and completed in full as soon as possible. All else would be an extreme loss of science and waste of resources.

The FAIR Council has approved the additional costs for the Modularized Start Version

Additional costs for completion:
~880 M€ + 250 M€ contingency

Germany has pledged 700 M€



Construction of HESR, CR and Proton LINAC requires firm commitment by other shareholders

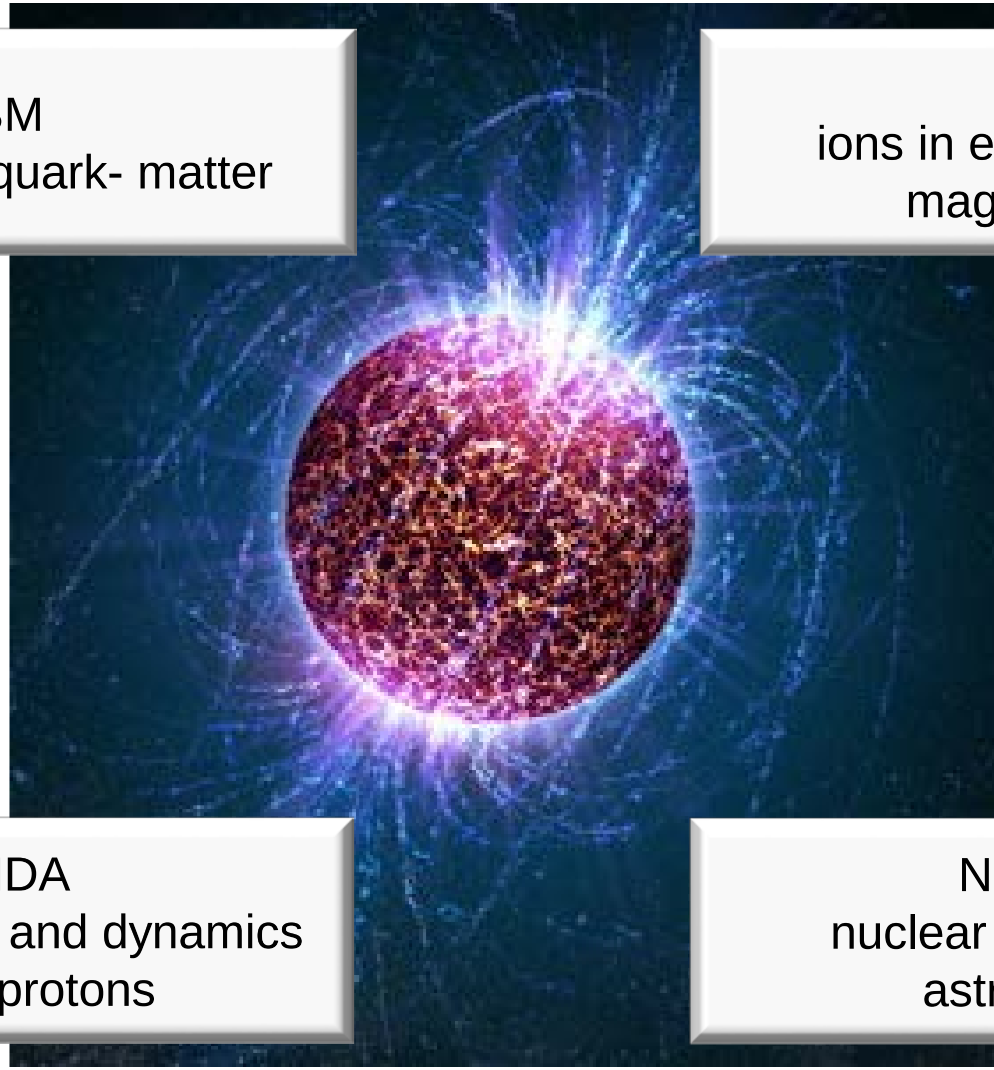
Conclusions

- **FAIR Phase-0** is now starting and research activities are coming back to the GSI/FAIR campus
- **The preparations for the FAIR MSV are in full swing**
- In particular civil – which had been a stumbling block for quite a while – is progressing very well and close to schedule
- **Despite the large funding needs, the shareholders have declared their wish to complete the FAIR MSV**

2020 : 4 Research Pillars of FAIR

CBM
nuclear- and quark- matter

APPA
ions in extreme electro-magnetic fields



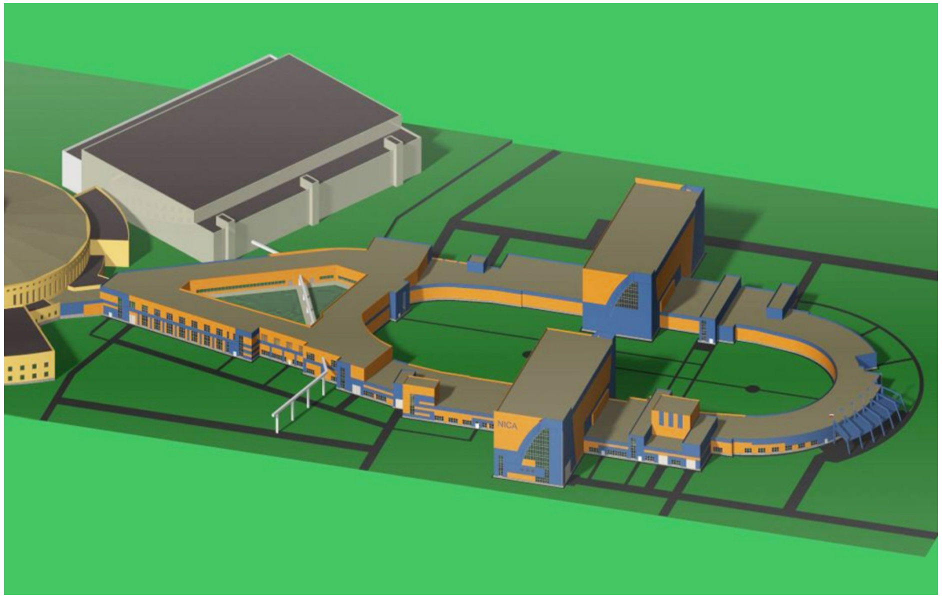
PANDA
hadron physics and dynamics with antiprotons

NUSTAR
nuclear structure and astrophysics

FAIR + ОИЯИ : взаимно дополняющие исследования экстремального состояния ядерной материи

NICA/MPD

***N**uclotron-based **I**on **C**ollider f**A**cility*



FAIR/CBM

E_{lab} < 60 GeV/n

√sNN = 4 ÷ 11.0 GeV/n

Average luminosity
$10^{27} sm^{-2} s^{-1}$ Au x Au

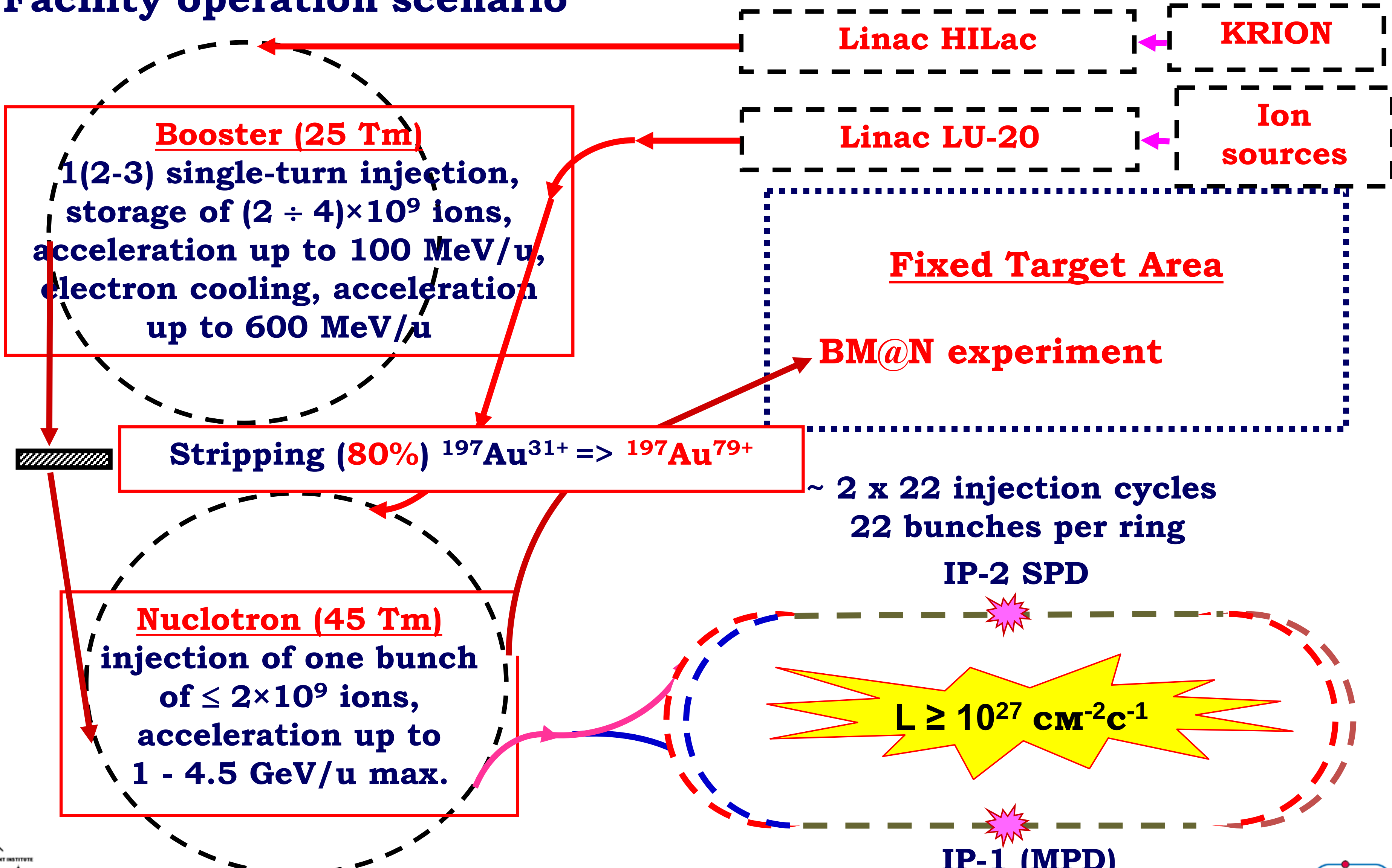
E_{lab} ~ 34 GeV/n

√sNN = 8.5 GeV

Particle intensity
(for U) up to 10^{11} ppp

NICA – Heavy Ion Collider

Facility operation scenario

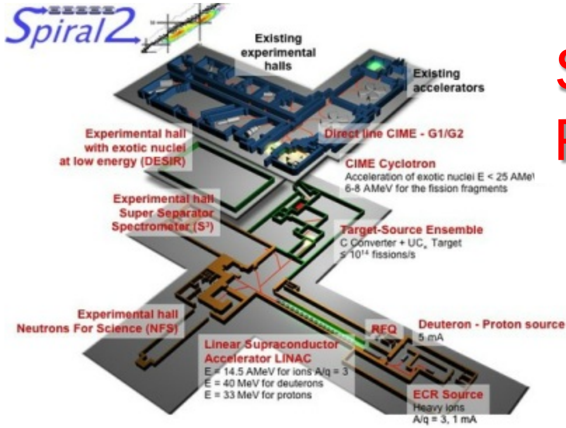


Key Parameters of The NICA Collider

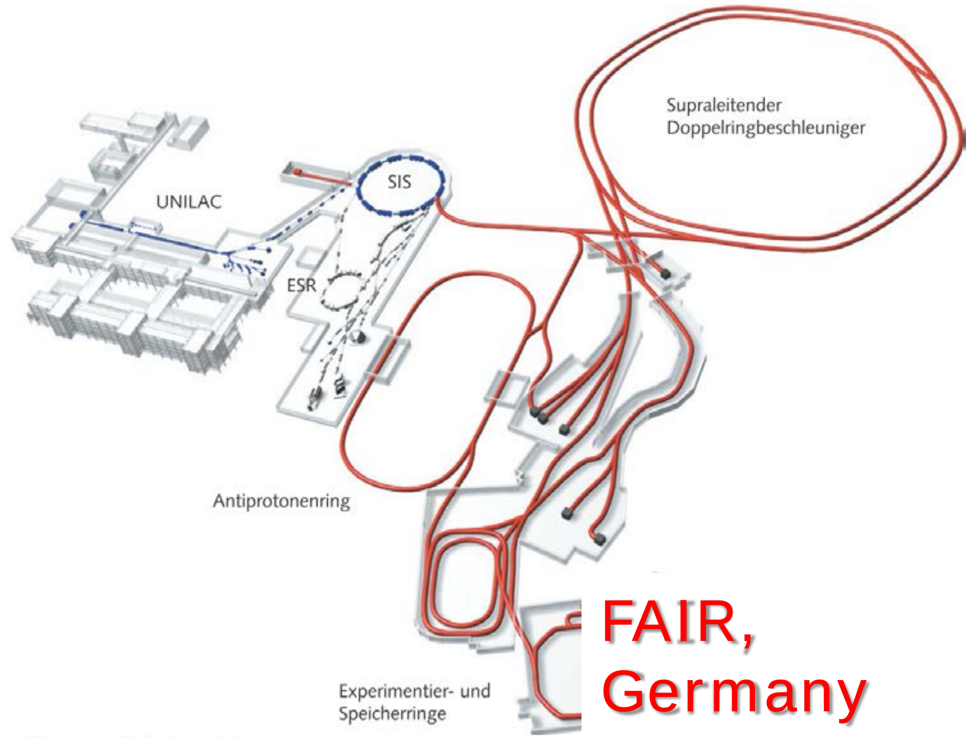
Collider lattice: FODO, 12 cells x 90^0 each arc,

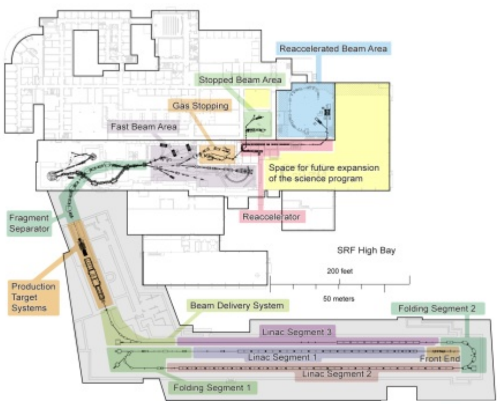
Ring circumference, m	503,04		
Number of bunches	22		
R.m.s. bunch length, m	0.6		
Ring acceptance, π·mm·mrad	40.0		
Long. Acceptance, Δp/p	≤ 0.01		
$\gamma_{transition}$ ($E_{transition}$, GeV/u)	7.091 (5.72)		
β*, m	0.35		
Ion Energy, GeV/u	1.0	3.0	4.5
Ion number/bunch, 1e9	0.275	2.4	2.2
R.m.s. emittance, h/v π·mm·mrad	1.1/1.0	1.1/0.9	1.1/0.76
R.m.s. Δp/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

The Rare Isotope Factories become larger and more and more expensive



SPIRAL2
France

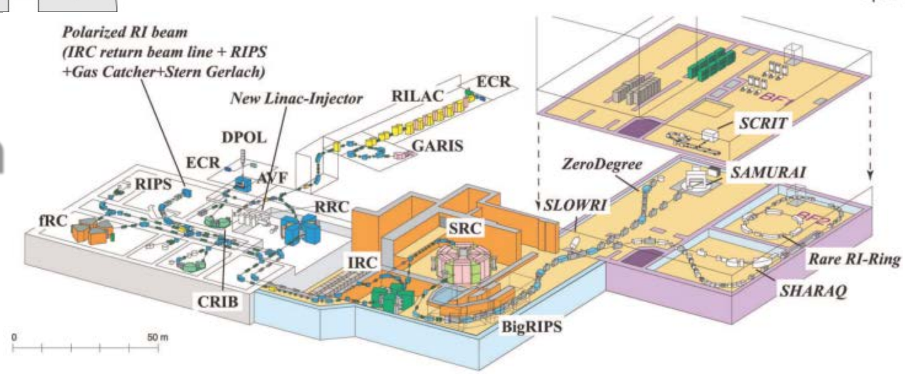




FRIB USA

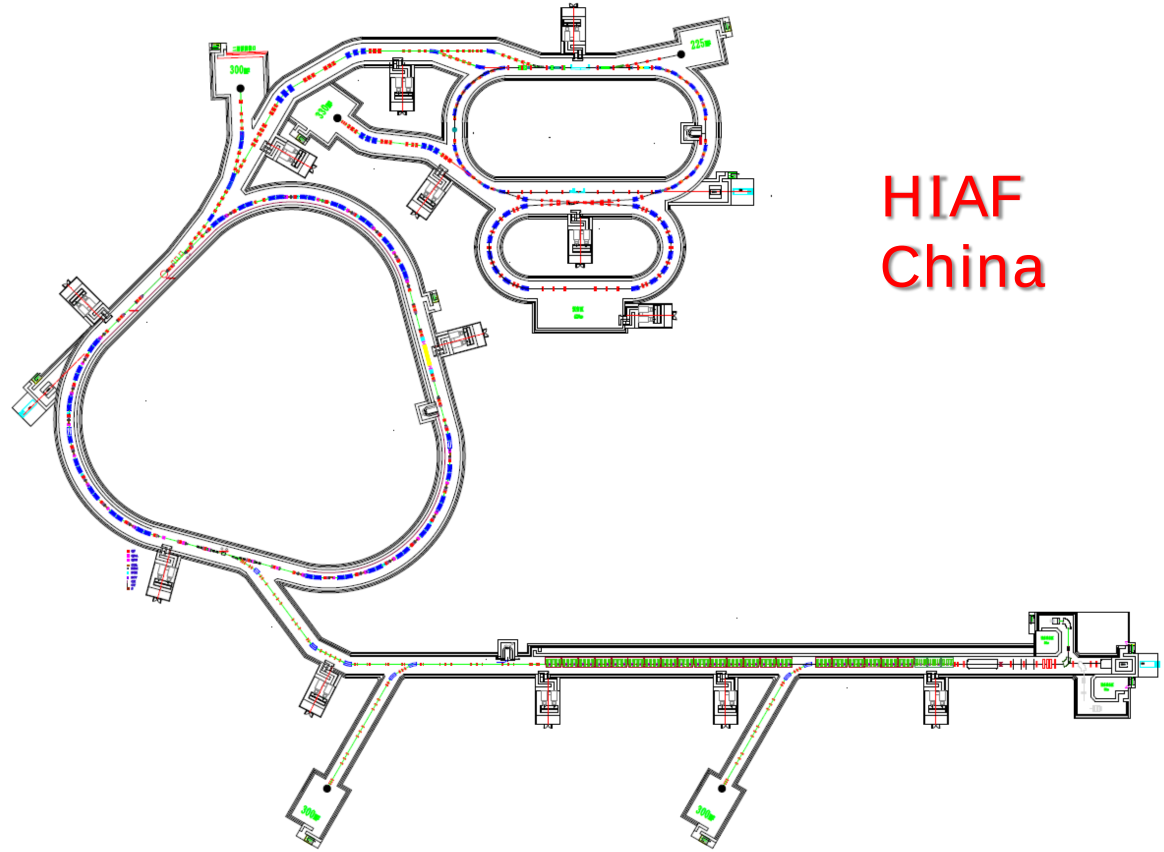
FAIR,
Germany

RIBF Japan

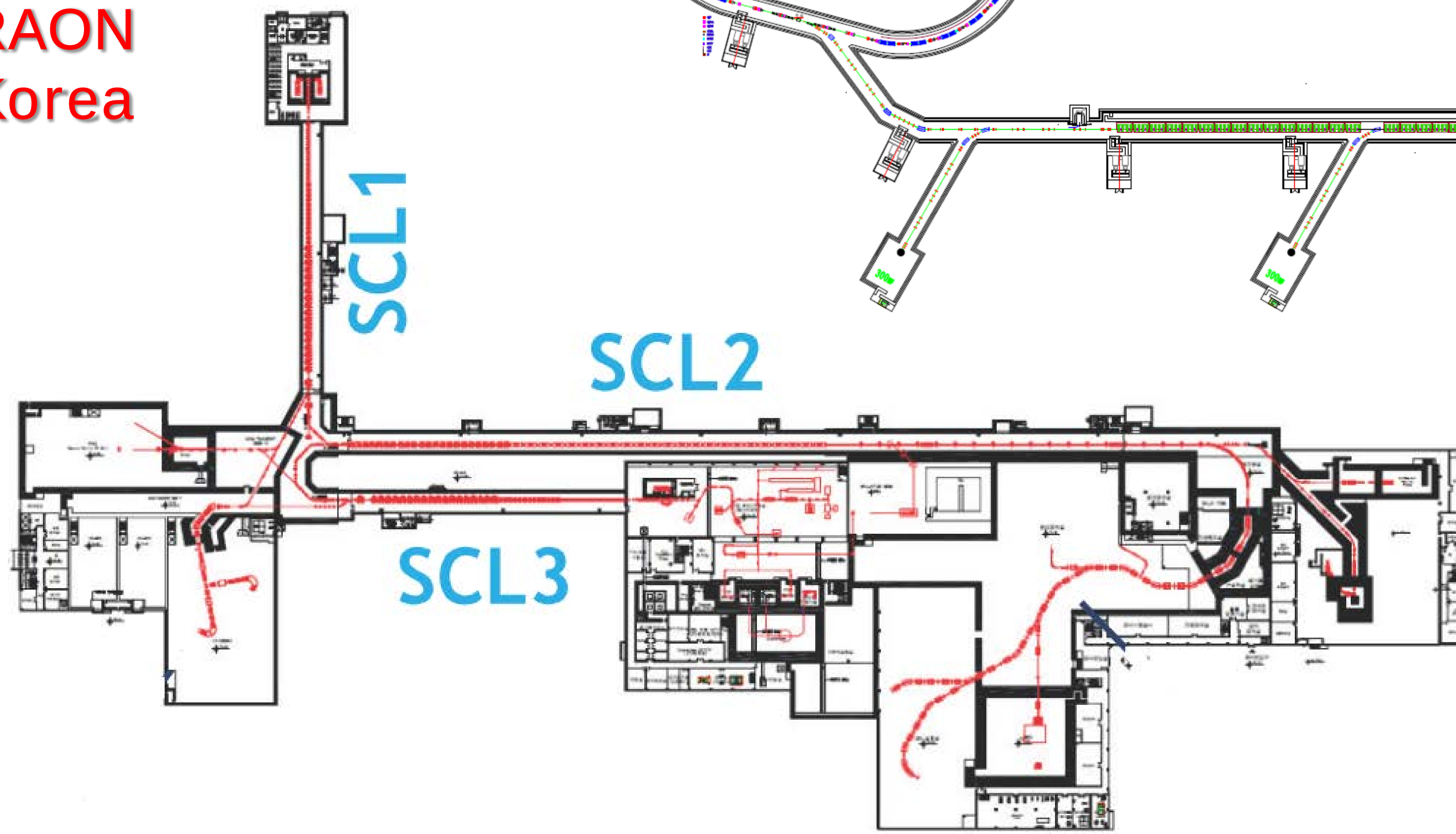


Horizontal scale of the slide ~1 km

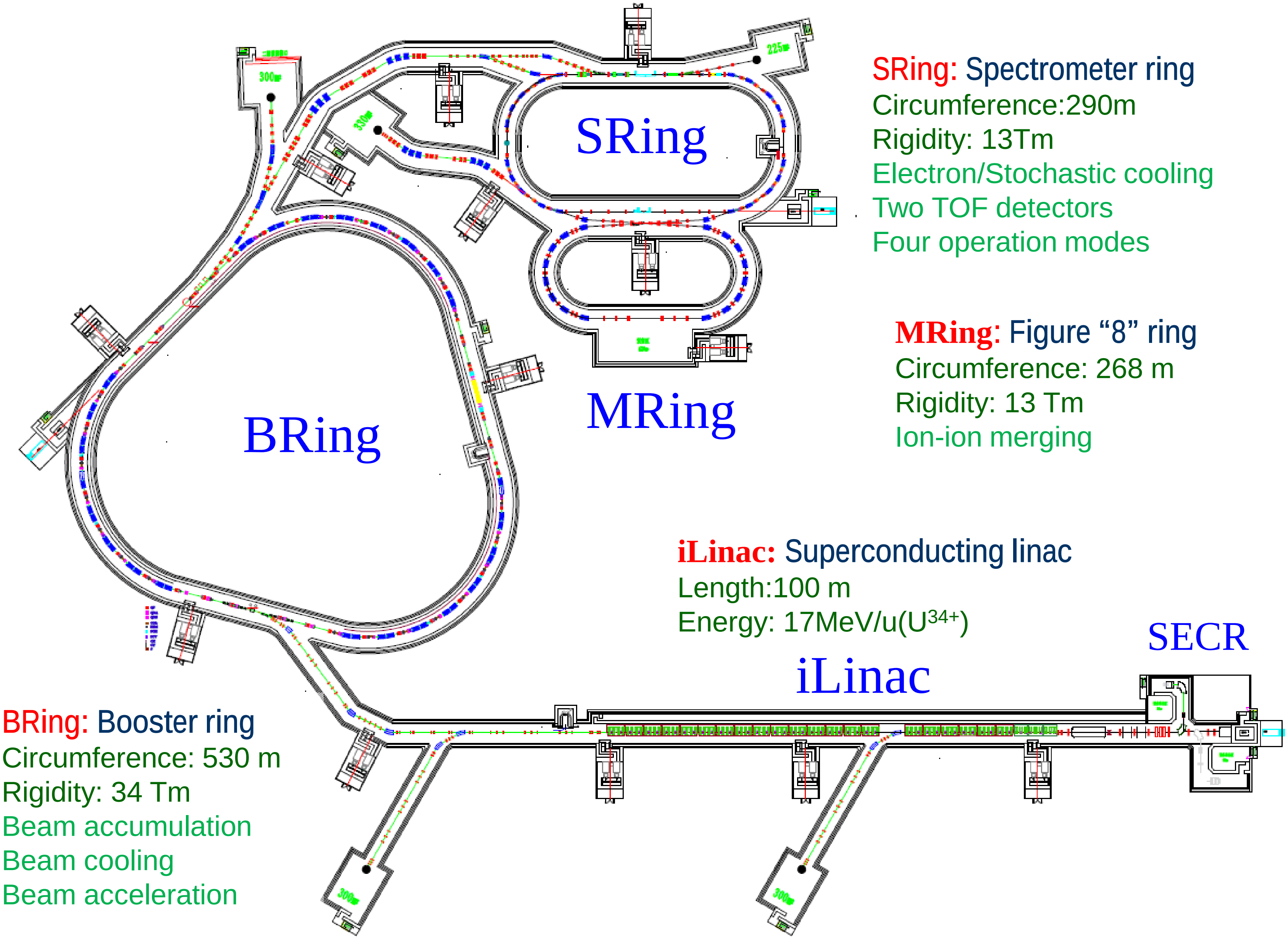
HIAF
China



RAON
Korea



HIAF General description – main components



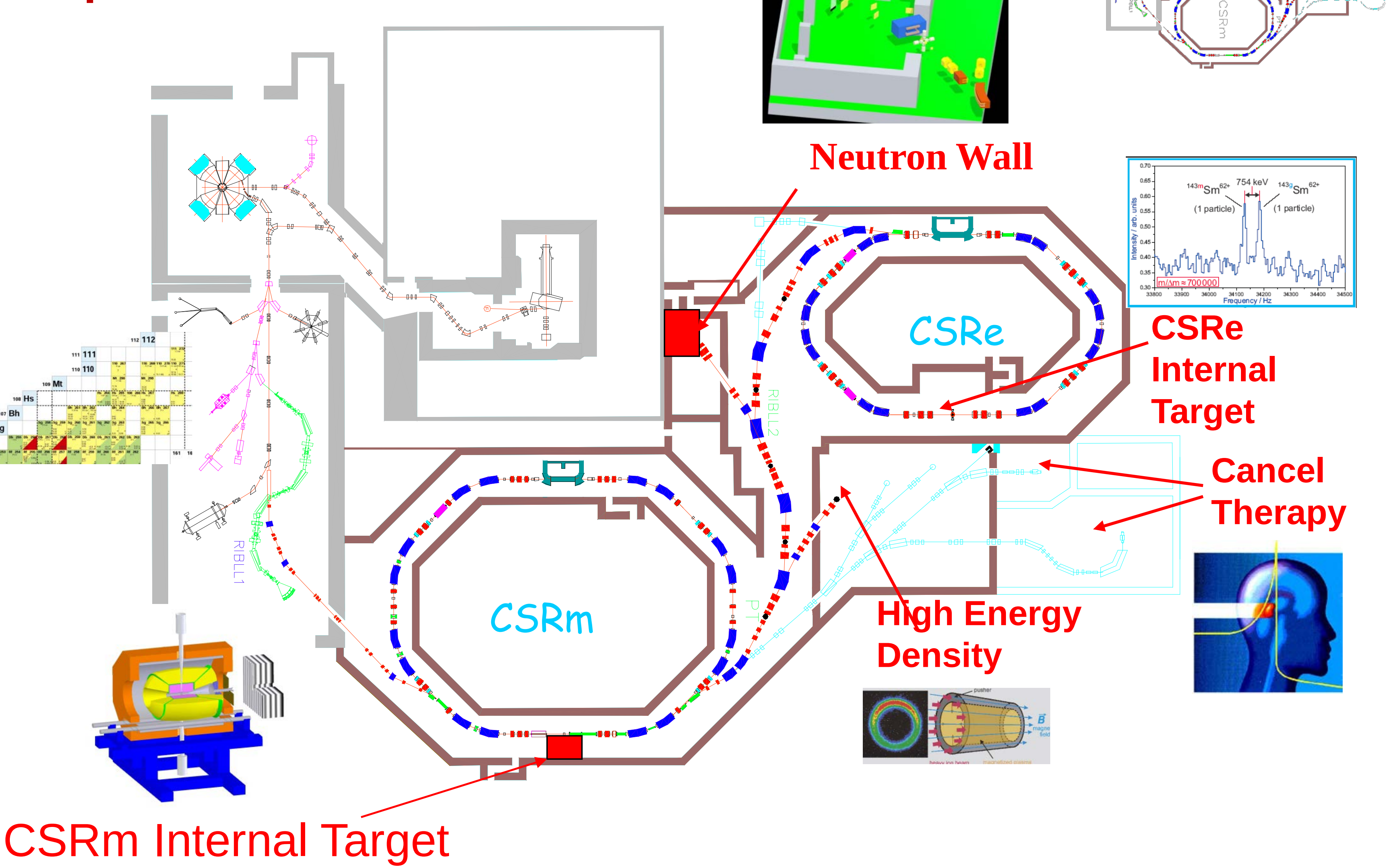
SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

MRing: Figure “8” ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

HIRFL-CSR Lanzhou experiment stations

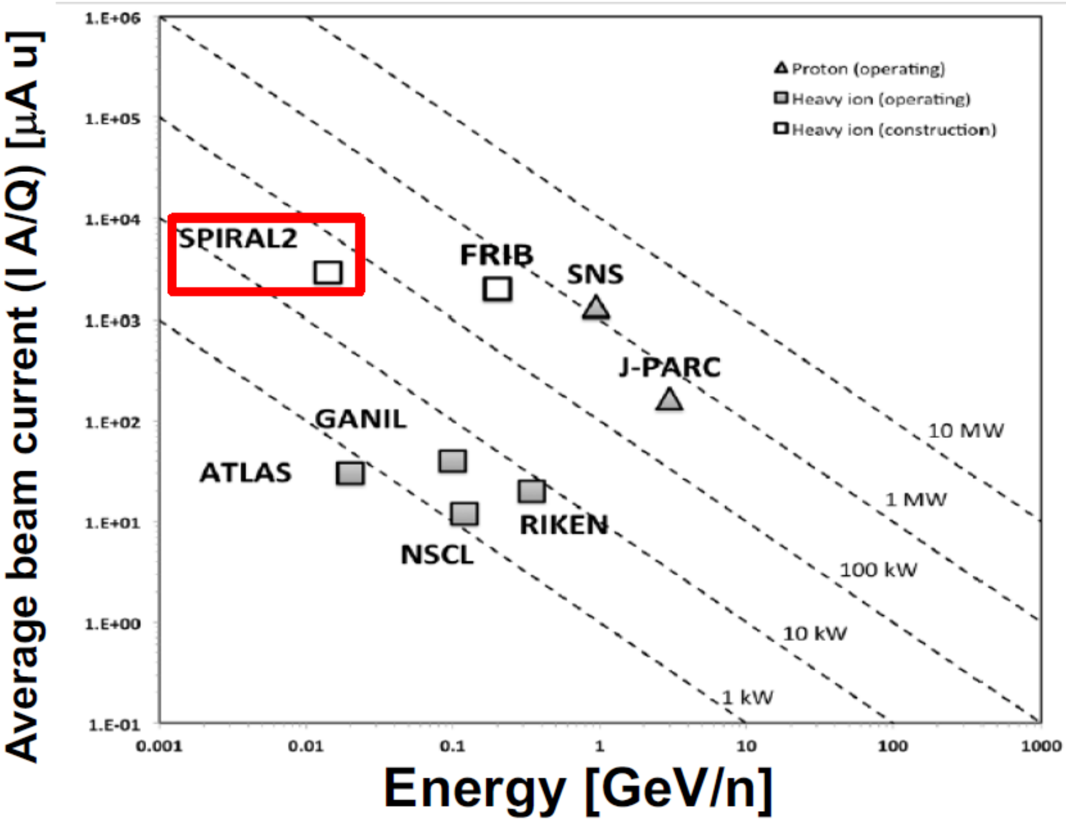


SPIRAL 2 SC LINAC beams

SPIRAL2 LINAC
33 MeV p,
40 MeV d (5mA)
14.5 A.MeV HI (1mA)

1000 µAp $^{4}He^{2+}$
150 µAp $^{18}O^{6+}$
3,2 µAp $^{40}Ar^{14+}$ (60 kV)

5 mA protons (Q/A=1)
500 µAp $^{4}He^{2+}$ (Q/A=1/2)
100 µAp $^{18}O^{6+}$ (Q/A=1/3)

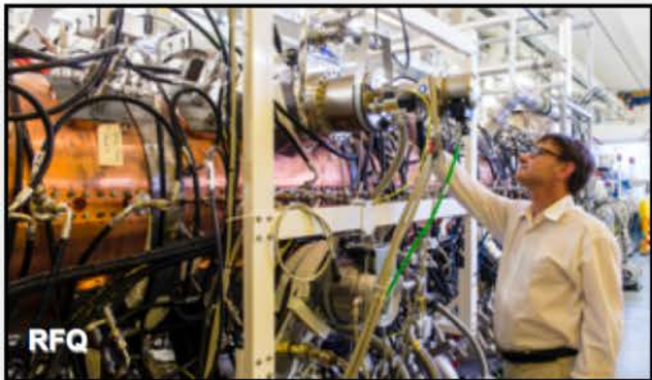


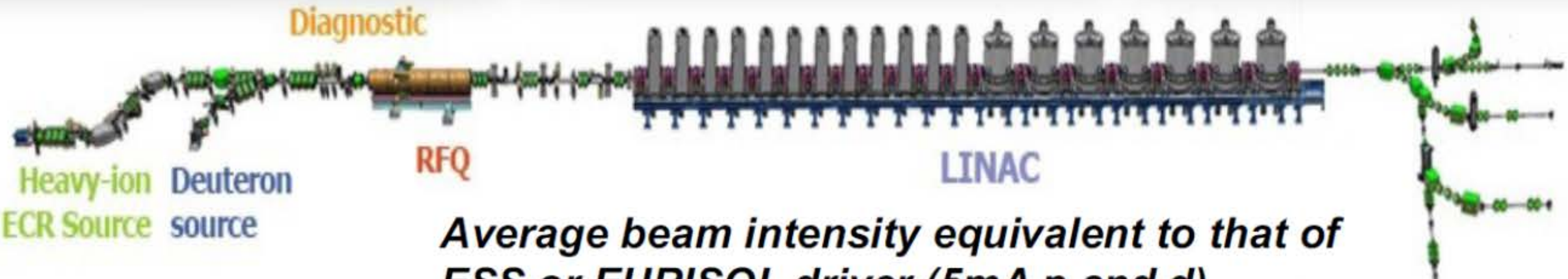
Ions	Intensity (pµA) [A/Q=3]	High Intensity (pµA) [A/Q=6-7]
^{18}O	216	375
^{19}F	28,6	50
^{36}Ar	17.5	40
^{40}Ar	2.9	30
^{36}S	4.6	30
^{40}Ca	3	20
^{48}Ca	1.25	15
^{58}Ni	1.1	10
^{84}Kr	0	20
^{124}Sn	0	10
^{139}Xe	0	10
^{238}U	0	2.5

$\times$5-10

$\times 10^{x}$

SPIRAL2 Very-high intensity Super Conducting Heavy-Ion LINAC





Average beam intensity equivalent to that of ESS or EURISOL driver (5mA p and d)

Installation is almost complet

Summary - for HI accelerators

- **A number of modern international research facilities are under construction;**
- **Generation of intense "precision beams" :** sophisticated beam manipulation methods-stochastic and electron cooling of ion beams;
- **Rings as accelerator structures of choice:** capability to store, cool, bunch, and stretch beams ;
- **Full range of ion beam species:** p+ - 239U ;
- **Ultimate goal : highest beam intensities & luminosities;**
- **Superconducting magnets and RF structures** are widely used in modern accelerators.
- **Superconducting CW linac machines** reach high acceleration efficiency in their RF structures (>50% efficiency from wall plug to beam is possible in SC CW linacs).

Projects for High Energy Accelerators

LHC High Luminosity, High Energy (?)

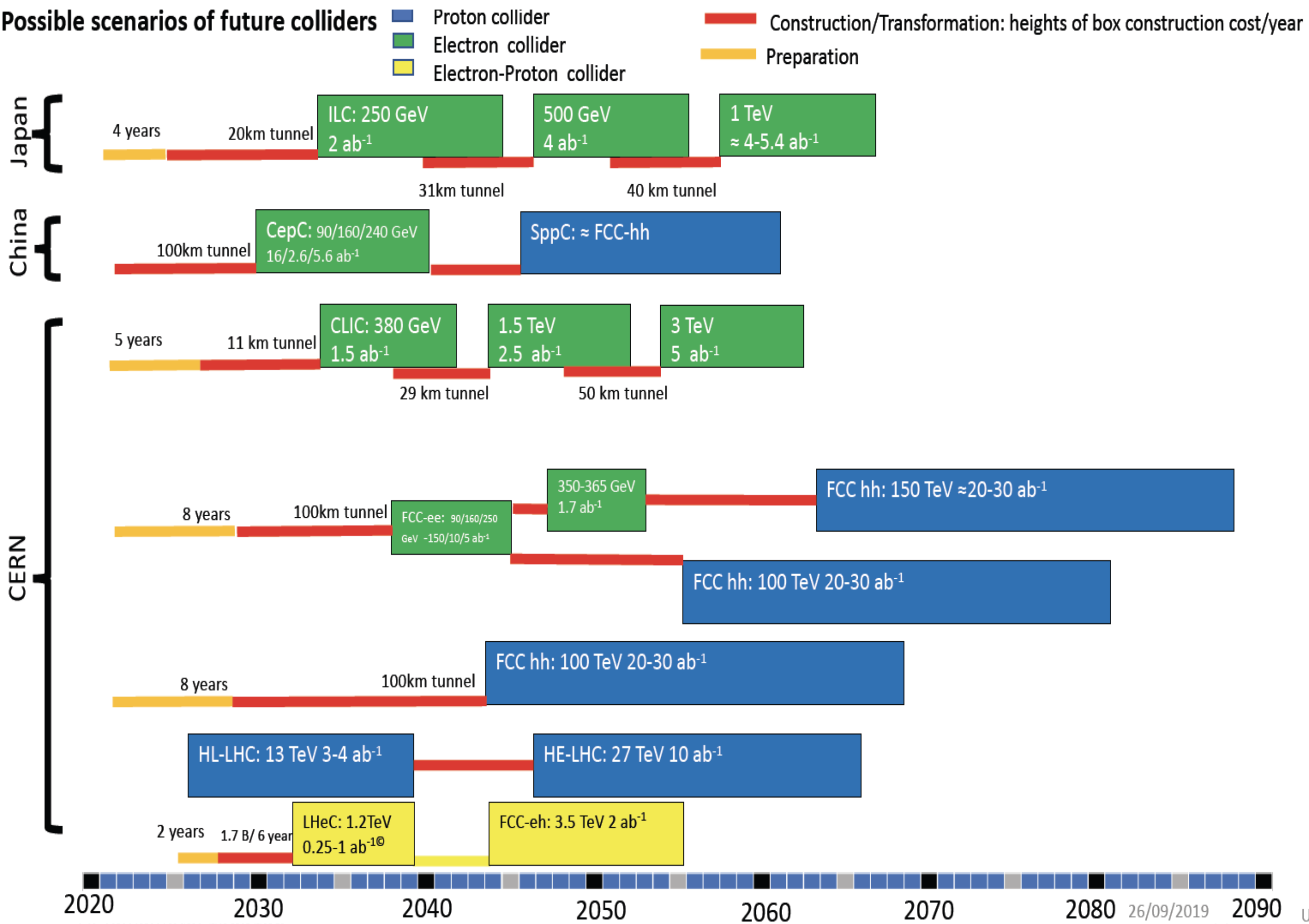
Linear Colliders
(International Linear Collider, Compat Linear Collider)

Electron – Ion Colliders

FCC (Future Circular Colliders ee, eh, hh)

Plasma Wake-field Accelerators for HEP

Muon Collider


Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/year
Preparation
Japan
4 years
20km tunnel
ILC: 250 GeV 2 ab-1
31km tunnel
500 GeV 4 ab-1
40 km tunnel
1 TeV ≈ 4-5.4 ab-1
China
100km tunnel
CepC: 90/160/240 GeV 16/2.6/5.6 ab-1
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
CLIC: 380 GeV 1.5 ab-1
29 km tunnel
1.5 TeV 2.5 ab-1
50 km tunnel
3 TeV 5 ab-1
8 years
100km tunnel
FCC-ee: 90/160/250 GeV -150/10/5 ab-1
350-365 GeV 1.7 ab-1
FCC hh: 150 TeV ≈20-30 ab-1
FCC hh: 100 TeV 20-30 ab-1
8 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
HE-LHC: 27 TeV 10 ab-1
2 years
1.7 B/ 6 year
LHeC: 1.2TeV 0.25-1 ab-1©
FCC-eh: 3.5 TeV 2 ab-1
2020
2030
2040
2050
2060
2070
2080
26/09/2019
2090

Conclusion

Success of experiments is granted by three basic factors :

- **High performance of accelerators**
- **Advanced detector technologies**
- **High performance computing**