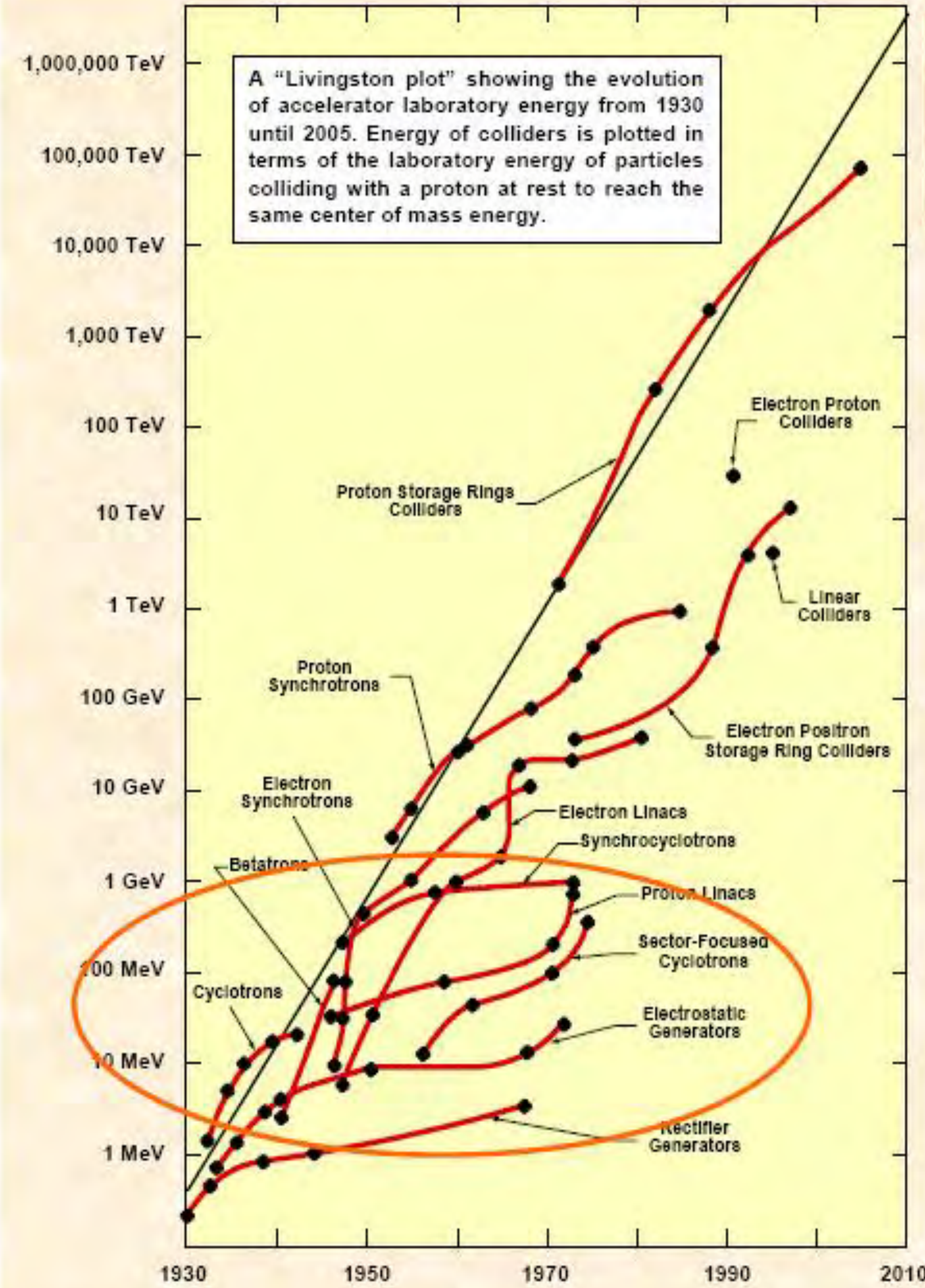
Large Scale Accelerator Facilities for Nuclear Research and Practical Applications

Boris Sharkov JINR, Dubna

IAEA   23/05/2022



Livingston chart

From 1 MeV P+ cyclotron (E.O.Lawrence 1931) 12,7 cm to LHC 14 TeV (2012) 8,5 km:
cyclotron > RF linac > synchrotron

Charged particle accelerators are one of the main tools of modern nuclear physics and elementary particle physics

The vast majority of fundamental results in particle physics and nuclear physics have been obtained in experiments on accelerators

Large scale accelerators for Nuclear Physics :

low and medium enegy accelerators E $\leq$N x GeV, cost ≥ N x 100 kEuro

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

- **Full range of ion beam species:** p+ - 239U , e^- , e+
- **Highest beam intensities & luminosities;**
- **Generation of ‘Precision beams’:** sophisticated beam manipulation methods-stochastic and electron cooling, 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

Key Questions in modern Nuclear Physics

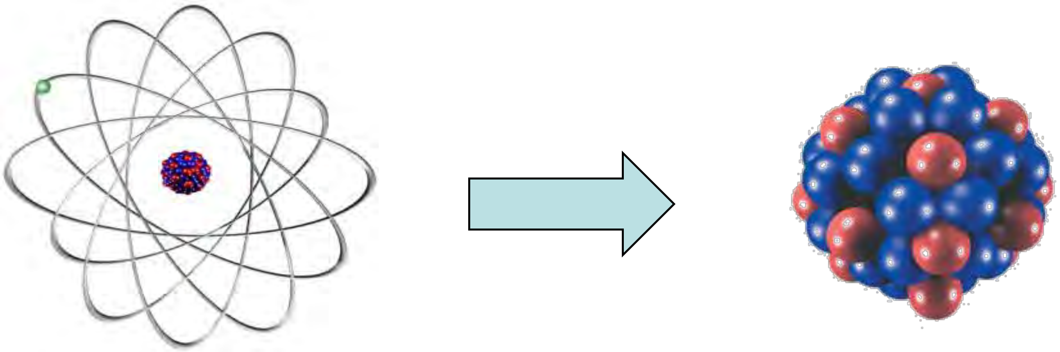
Nuclear Stucture Physics:

- In what ratio of protons to neutrons can nuclei exists? What new properties do highly unstable nuclei reveal?

- What are the limits of nuclear existence?

- What fundamental symmetries govern the laws of nature? When and with what consequences do violations of such symmetries occur?

- How do heavier than iron nuclei come into being?

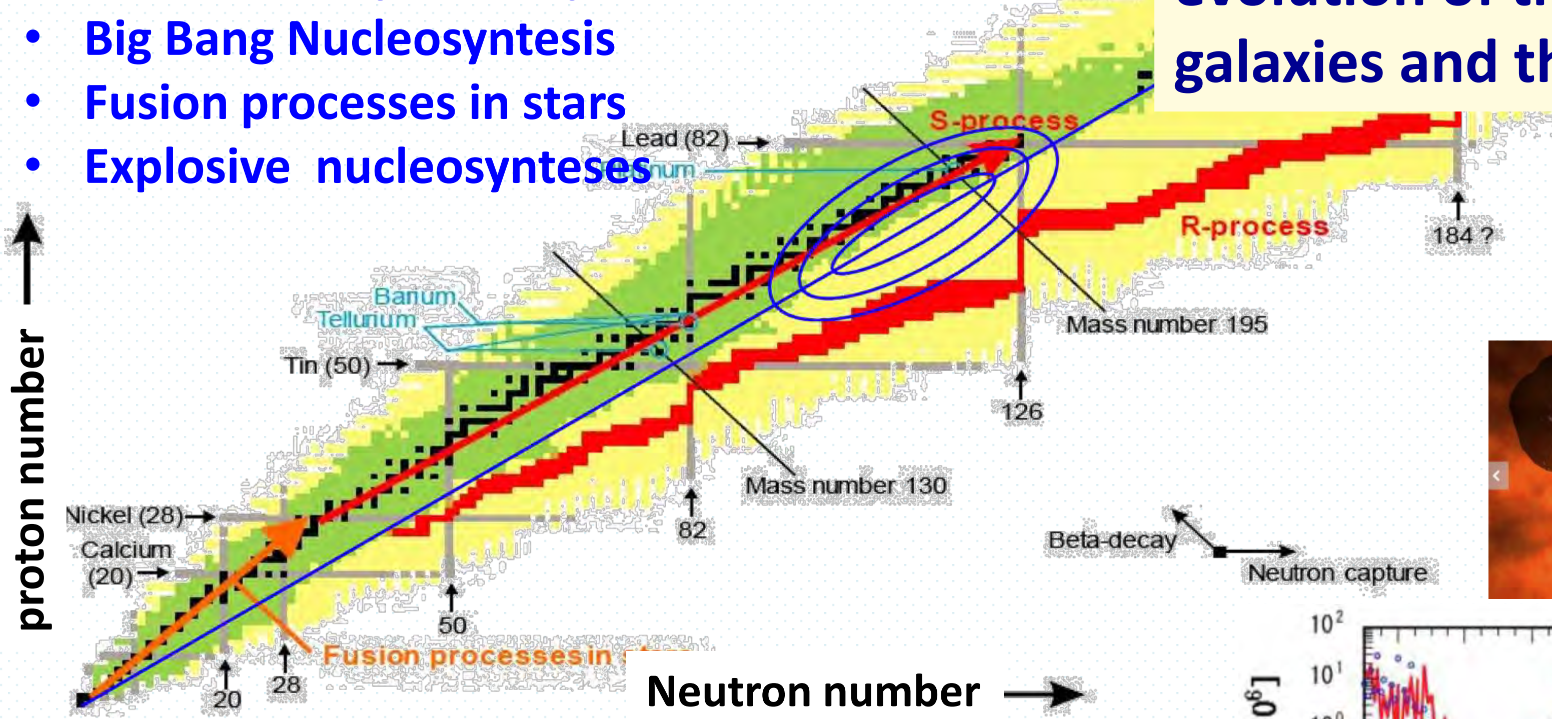


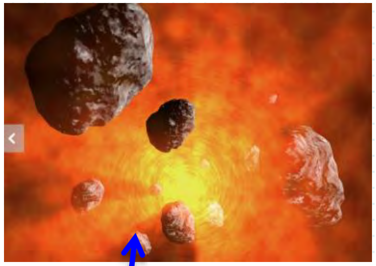
Nuclear astrophysics

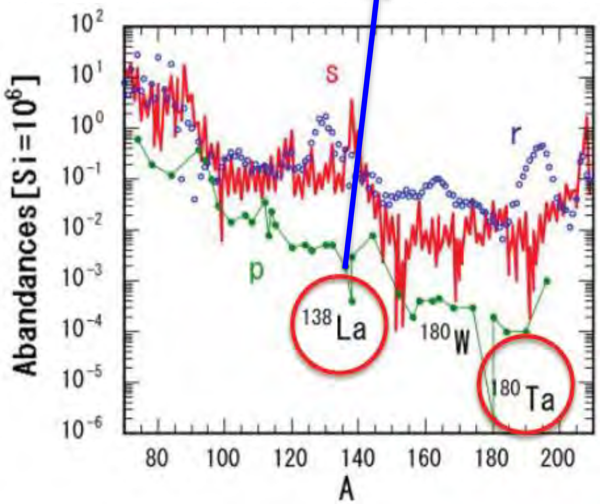
What are the nuclear processes that drive the evolution of the stars, galaxies and the Universe?

Various nucleosynthesis processes

- Big Bang Nucleosyntesis
- Fusion processes in stars
- Explosive nucleosynteses







Interplay of:

- nuclear structure
- nuclear decays
- half-lives
- nuclear reactions
- nucler masses

Proton and neutron rich side nuclei – our precursors need to be investigated with different tools

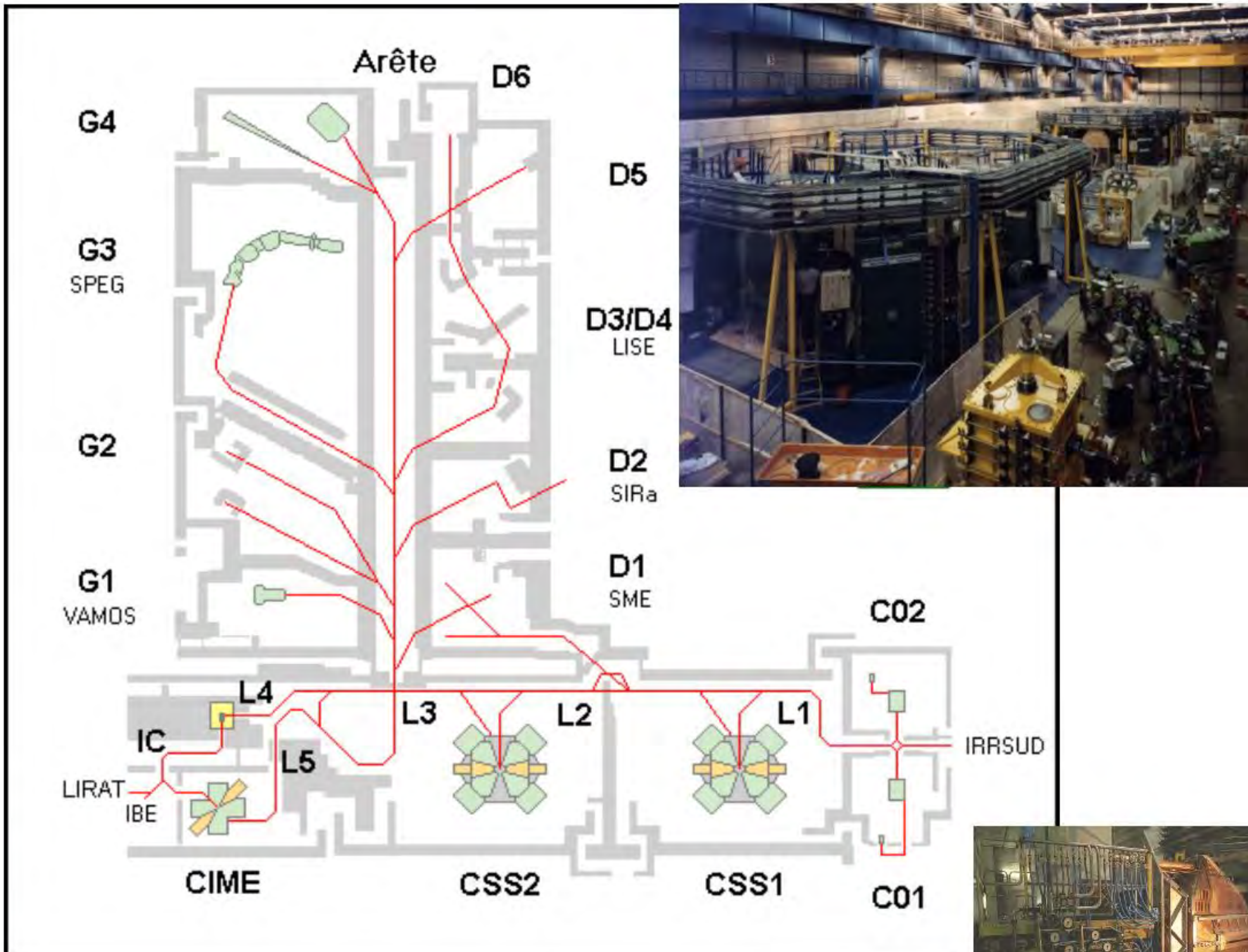
GANIL Accelerators and Experimental Area

Heavy Ions
from Carbone
to Uranium

High Energy
(CSS2):
from 24 AMeV
up to 95 AMeV

Medium energy
(CSS1):
from 4 AMeV
up to 13,7 AMeV

Low energy(C0):
from 0,3 AMeV
up to 1 AMeV



http://u.ganil-spiral2.eu/chartbeams/

SHE Factory Flerov Laboratory of Nuclear Reactions JINR

SHE Factory Building

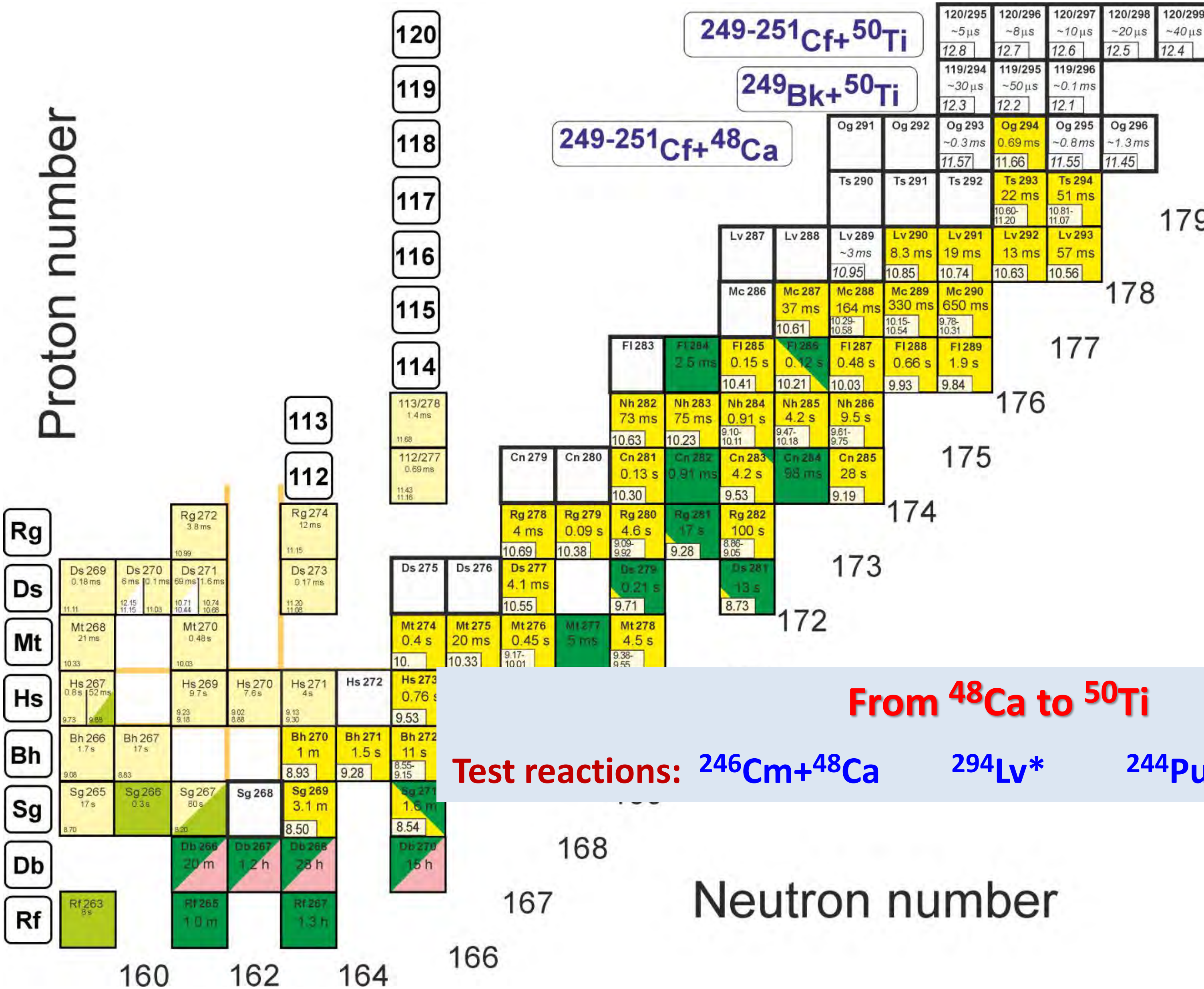
High-current cyclotron DC-280

DC-280 E=4÷8 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	$0{,}6\text{-}1{,}2\times10^{14}$
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{124}Sn	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

- **Synthesis and study of properties of superheavy elements.**
- **Search for new reactions for SHE-synthesis.**
- **Chemistry of new elements.**

First experiments at SHE Factory

Synthesis of new elements 119 and 120



From ^{48}Ca to ^{50}Ti

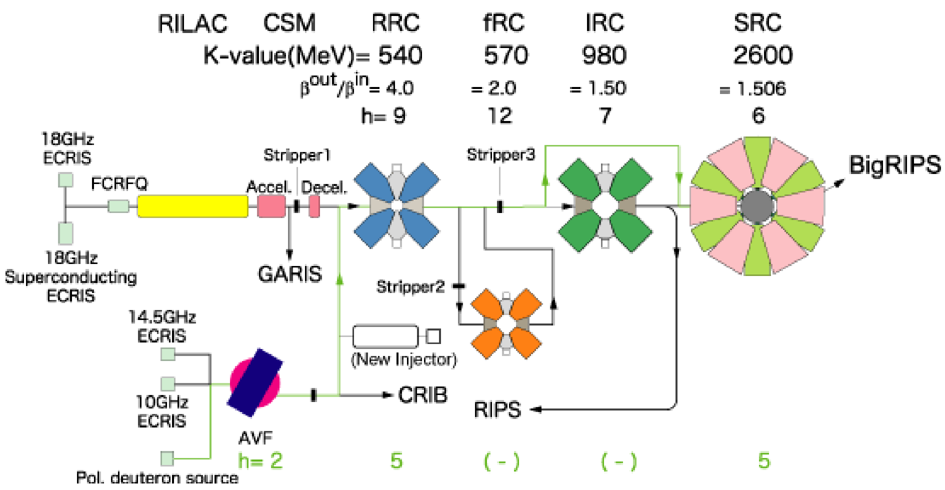
Test reactions: $^{246}Cm+^{48}Ca$ $^{294}Lv^*$ $^{244}Pu+^{50}Ti$ $^{294}Lv^*$

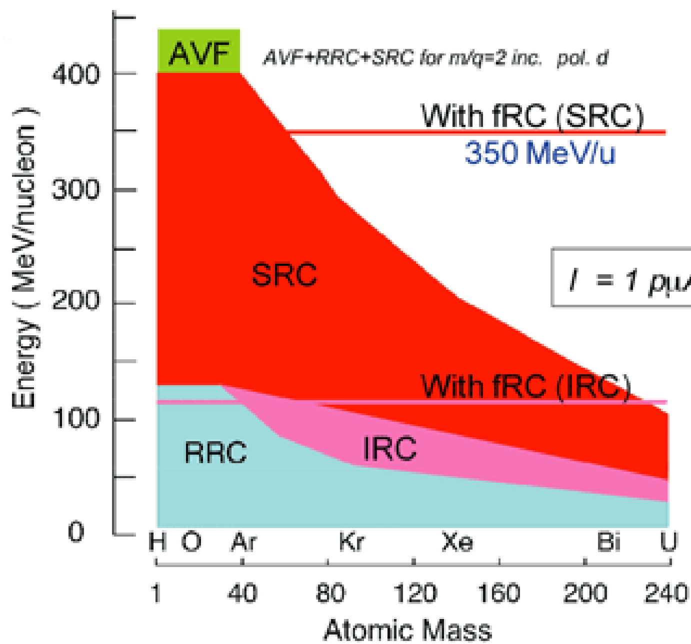
Common solution – cascades of accelerators

Operates	In construction	Upgrade plans
RIKEN: LINAC+4xCyc/ LINAC+3xCyc/3xCyc		RIBF+: +Cyc
GSI: LINAC+Sync	FAIR: LINAC+Sync+Sync	FAIR+: LINAC+Sync
	HIAF: LINAC+Sync	
GANIL: Cyc+Cyc	SPIRAL2: LINAC	
MSU: Cyc+Cyc	FRIB: LINAC	FRIB+: LINAC
	RISP: LINAC	
K4/K10: Cyc+Sync		
Lanzhou: Cyc+Sync		Lanzhou: LINAC+Sync

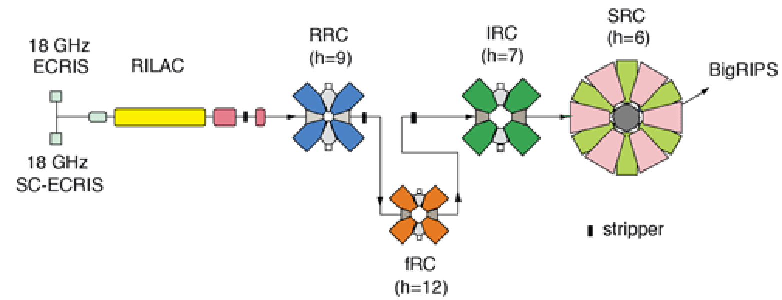
RIKEN RIBF cyclotron layout and operation

Schematic diagram of the RIBF heavy-ion accelerator system

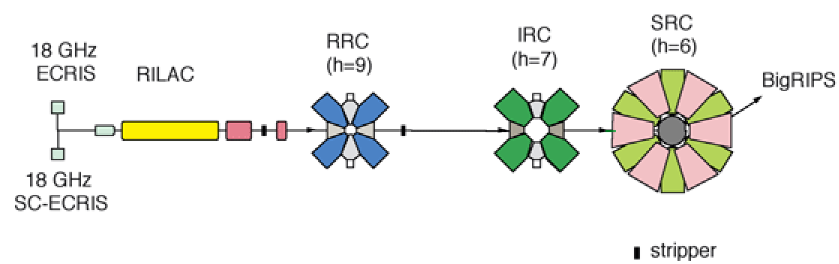




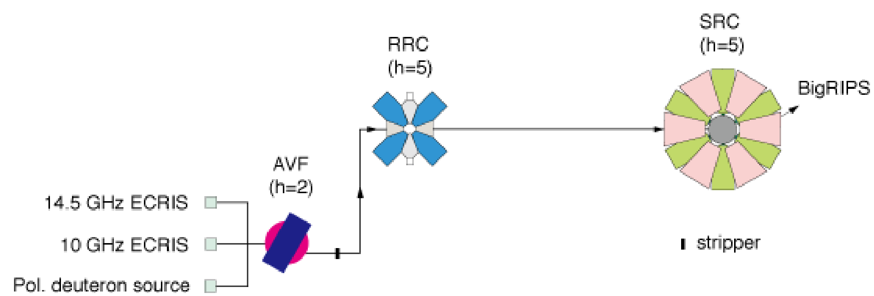
Mode (1): RILAC + RRC + (stripper2) + fRC + (stripper3) + IRC + SRC



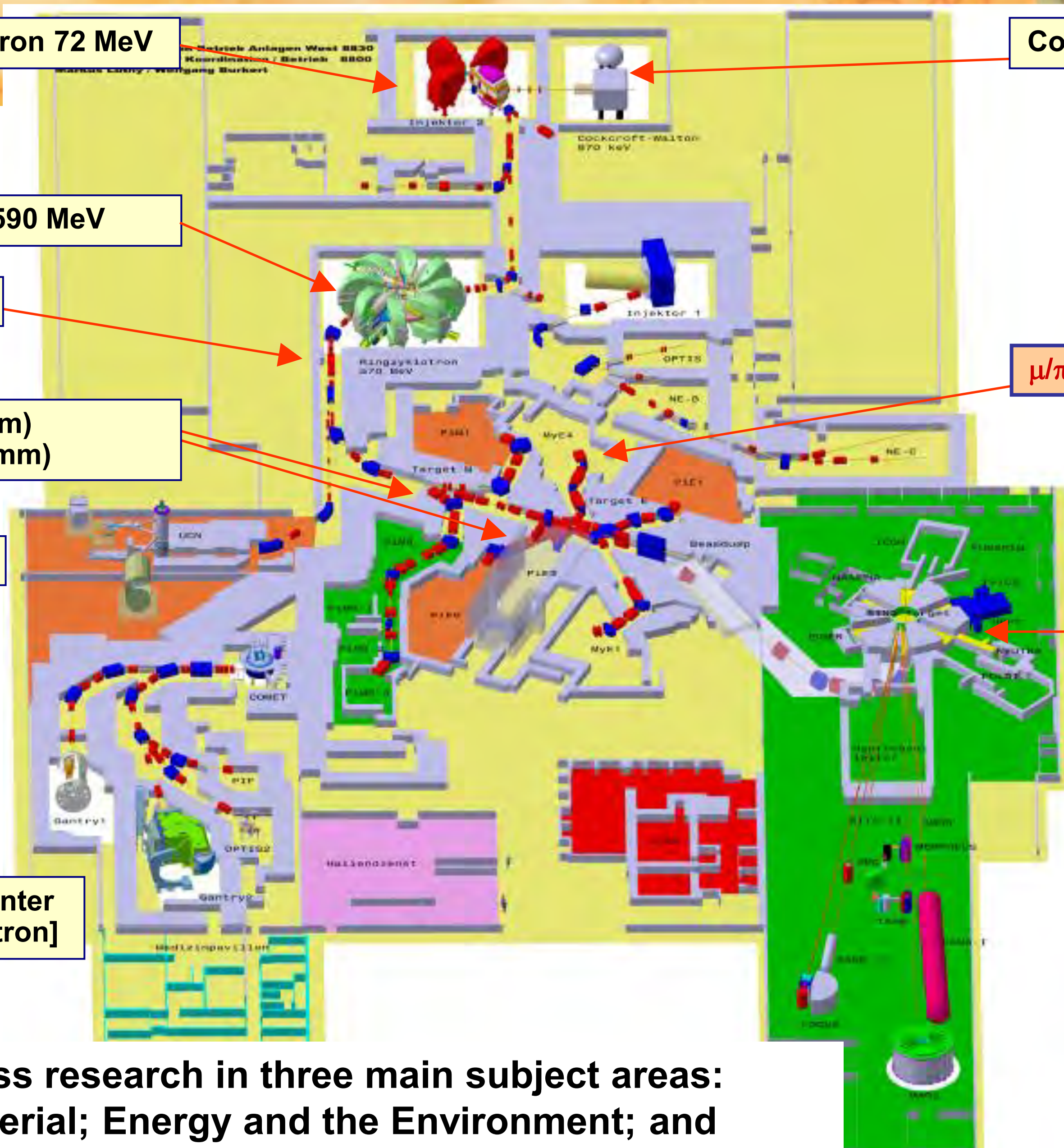
Mode (2): RILAC + (stripper1) + RRC + (stripper3) + IRC + SRC



Mode (3): AVF + RRC + SRC



Good example: (CW) PSI Facility @ 1.3 MW



dimensions:
120 x 220m^2

PSI world-class research in three main subject areas: Matter and Material; Energy and the Environment; and Human Health

GSI

From nuclear physics to nuclear medicine

IBA is the world leader for the supply of PET & SPECT cyclotrons from 18 to 70 MeV for radiopharmaceuticals production

Best Cyclotron Systems

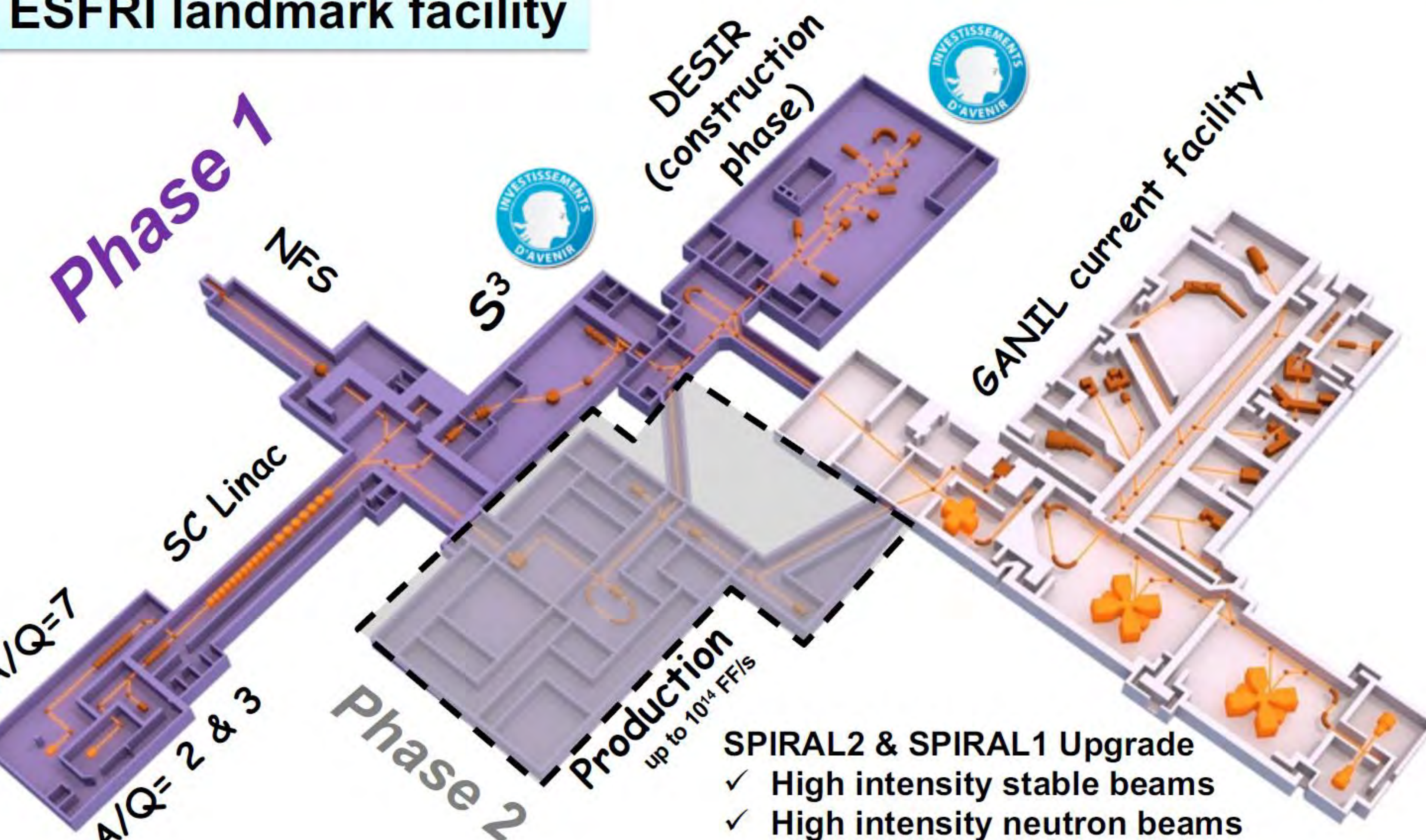
Turnkey solutions for radioisotope production in nuclear medicine

Cyclotron vs. LINAC – pro et contra

	Cyclotron	LINAC
Basic	Injection <50% transmission Acceleration of 1 charge state	RFQ ~99% transmission Acceleration of 3 to 5 charge states **Factor 6 - 10**
Plus	Compact Easy to operate	"No loss" operation Flexible acceleration strategy Upgradable Easy to repair Variable energy
Minus	Could be hard to repair HI Injection/extraction problems Superconductivity for U > 50 AMeV	Length Cost per AMeV Superconductivity for CW

GANIL-SPIRAL2 layout

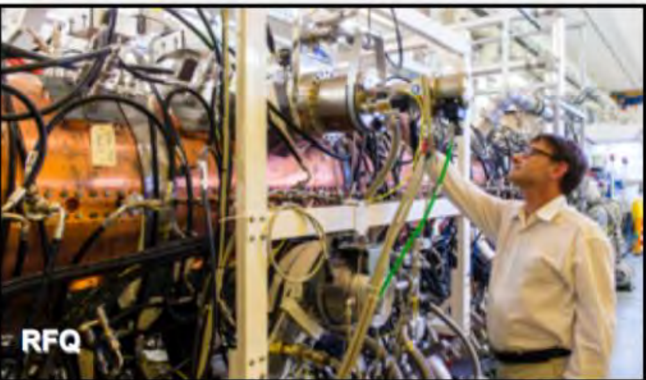
ESFRI landmark facility

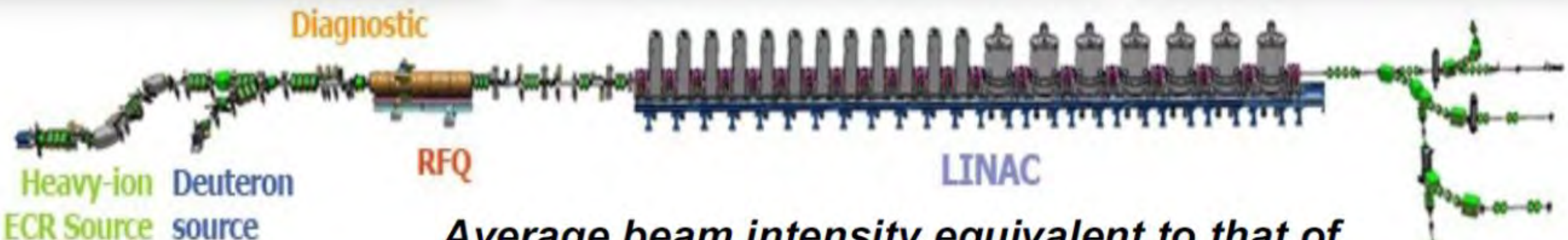


SPIRAL2 & SPIRAL1 Upgrade
- ✓ High intensity stable beams
- ✓ High intensity neutron beams
- ✓ High intensity RIBs

SPIRAL2

Very-high intensity Super Conducting Heavy-Ion LINAC





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

Facility for Rare Isotope Beams (FRIB) - USA

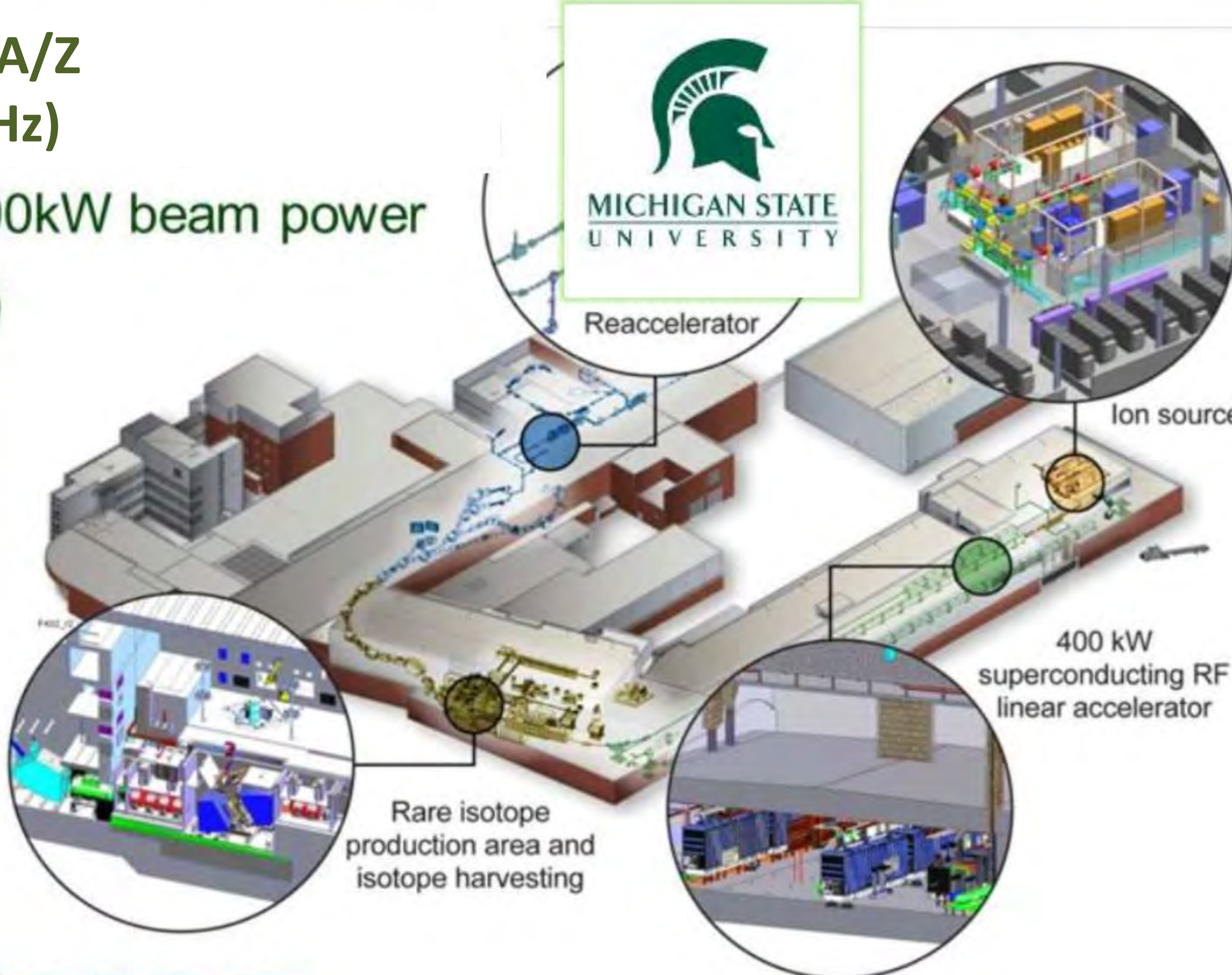
- **200 AMeV, verity A/Z**
  SC RF (80- 322 MHz)
- Key Feature is 400kW beam power
  ($5x10^{13}$ $^{238}U/s$)

Apr. 2021:
all 46 CMs
212 MeV/u

Separation of isotopes "In-flight"

Suited for all elements and short half-lives

Fast, stopped, and reaccelerated radioactive beams



Primary beams for RIB production

RIBF (RIKEN)	370 AMeV
FAIR (Darmstadt)	1800 AMeV
FRIB (MSU)	240 AMeV
RAON (S.Korea)	200 AMeV
HIAF (China)	800 AMeV

RACING IN “ENERGY DOMAIN”

Possible strategy of RIB production

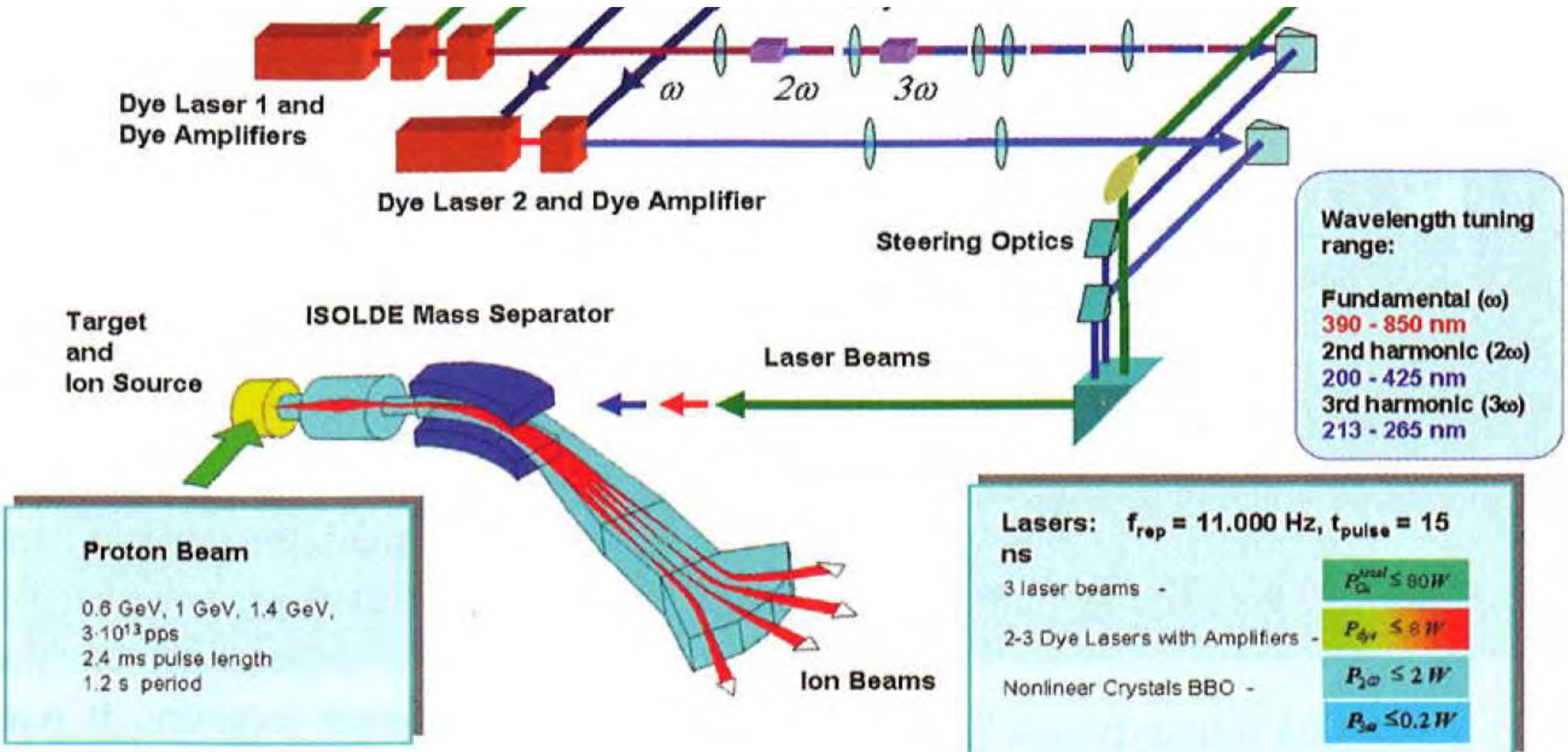
To focus on the INTENSITY of primary beam for modest energy 100-150 AMeV

Enjoy the advantages of relatively low-energy RIBs:

- **Easier to study reactions in 20-70 AMeV energy range**
- **Easier to operate stopped RIBs**

The ISOLDE Facility (CERN) ....where radioactive beam production started long ago

At ISOLDE, radioactive nuclides are produced via spallation, fission, or fragmentation reactions in a thick target, irradiated with a proton beam from the PSB at an energy of 1.4 GeV and an intensity up to 2 microA.

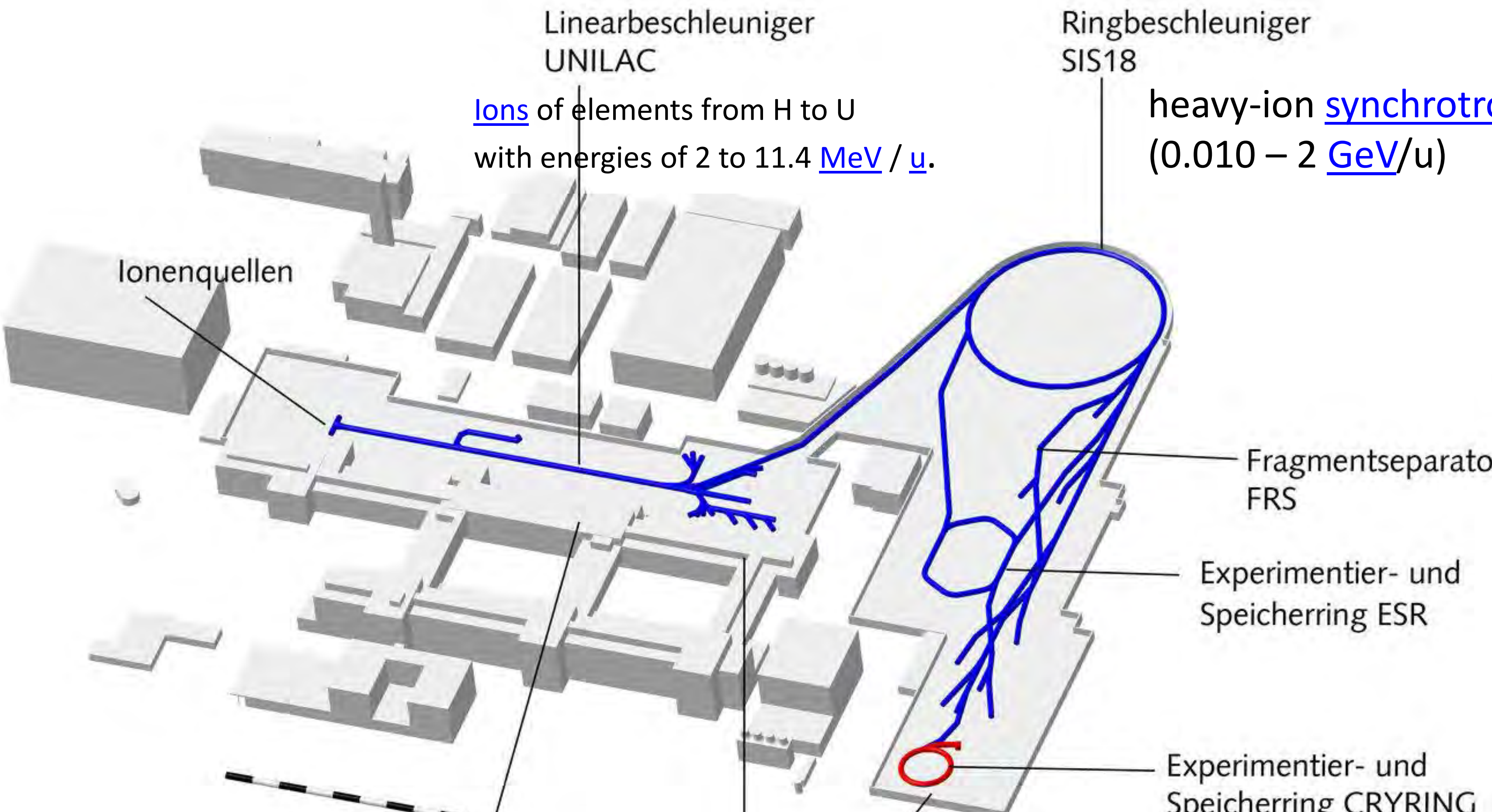


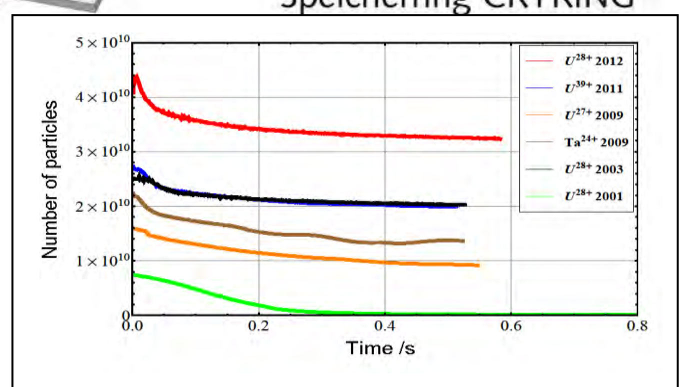
- 500 Users from 100 Institutions, 50 experiments / year, 50 years of experiments and breakthroughs and many more with HIE-ISOLDE

GSI - Darmstadt

Ions of elements from H to U with energies of 2 to 11.4 MeV / u.

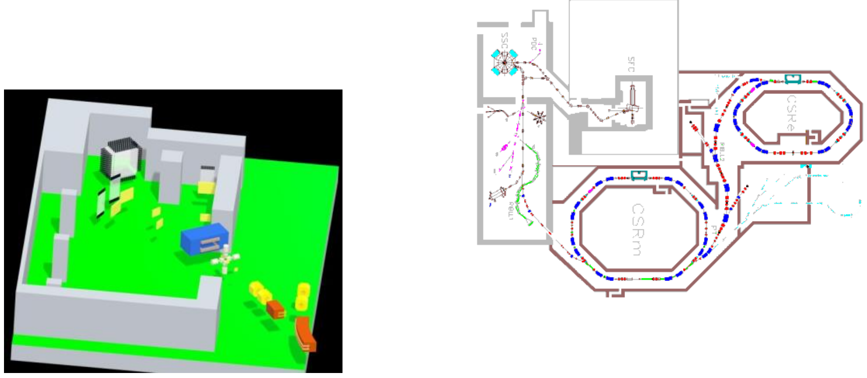
heavy-ion synchrotron (0.010 – 2 GeV/u)

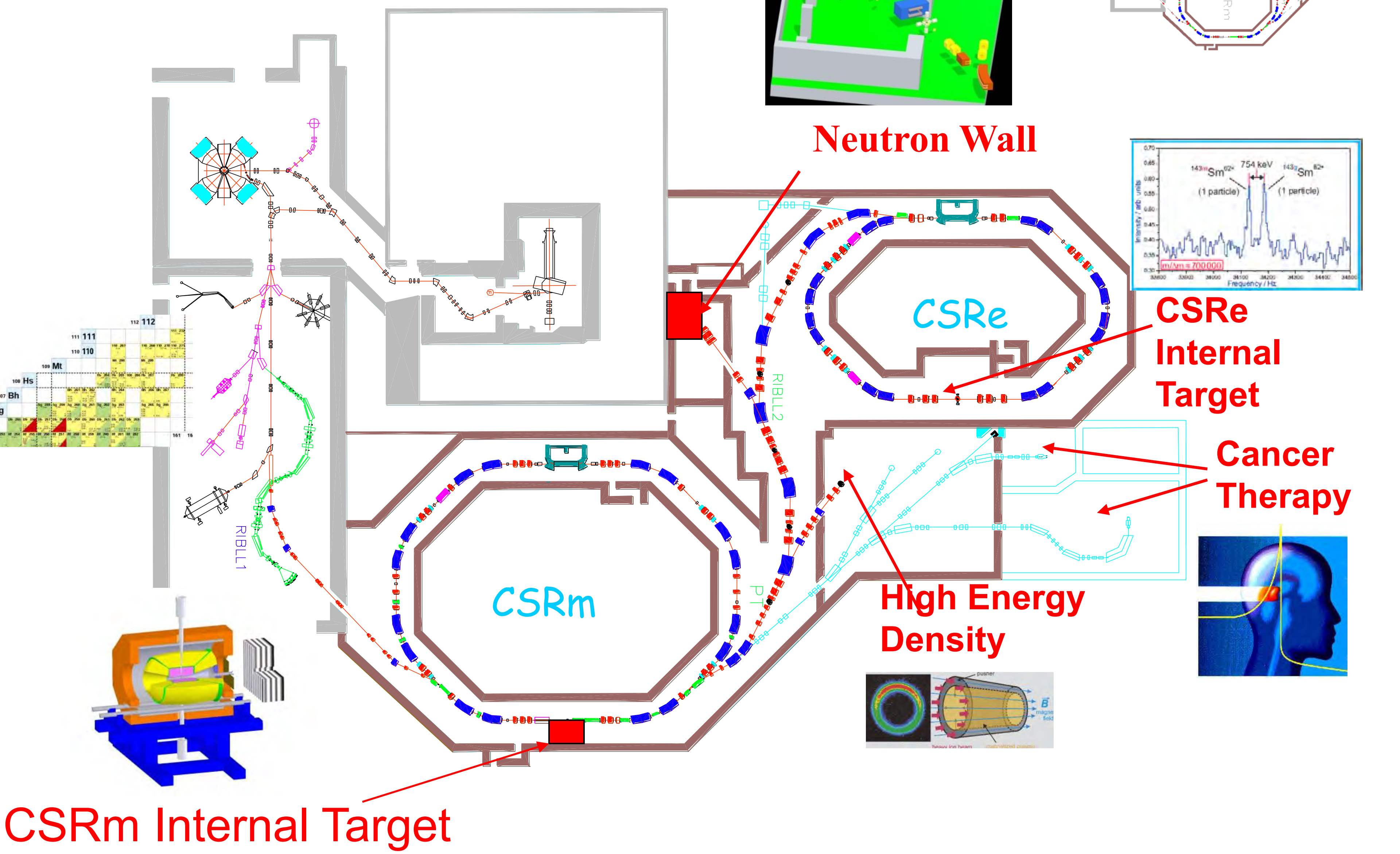




World record intensity for intermediate charge state heavy ions

HIRFL-CSR experiment stations Lanzhou





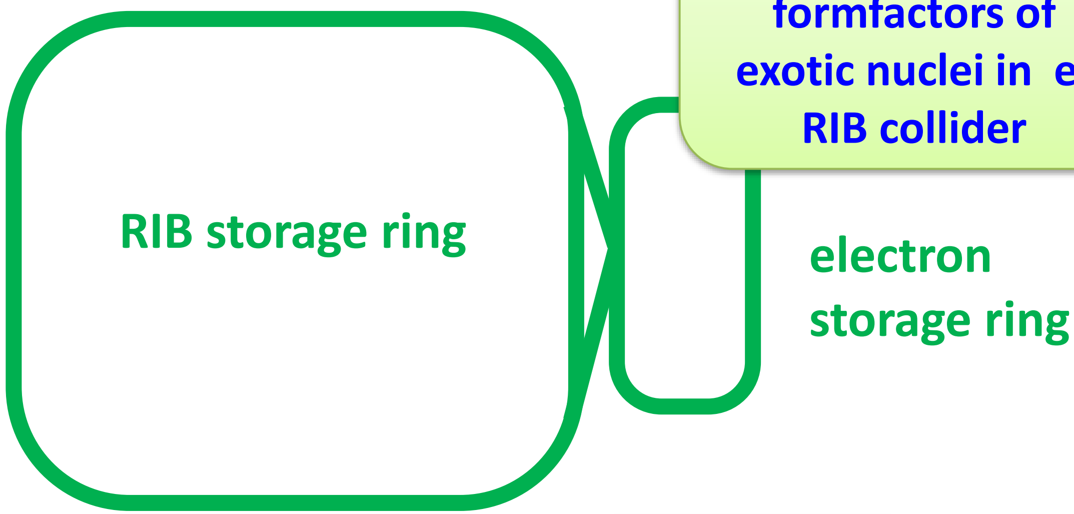
Empty "thematic niche"

Non-explored field: studies of RIBs in electron-RIB collider

Storage ring physics with RIBs

Isochronous mass spectromentry

Studies of electromagnetic formfactors of exotic nuclei in e-RIB collider



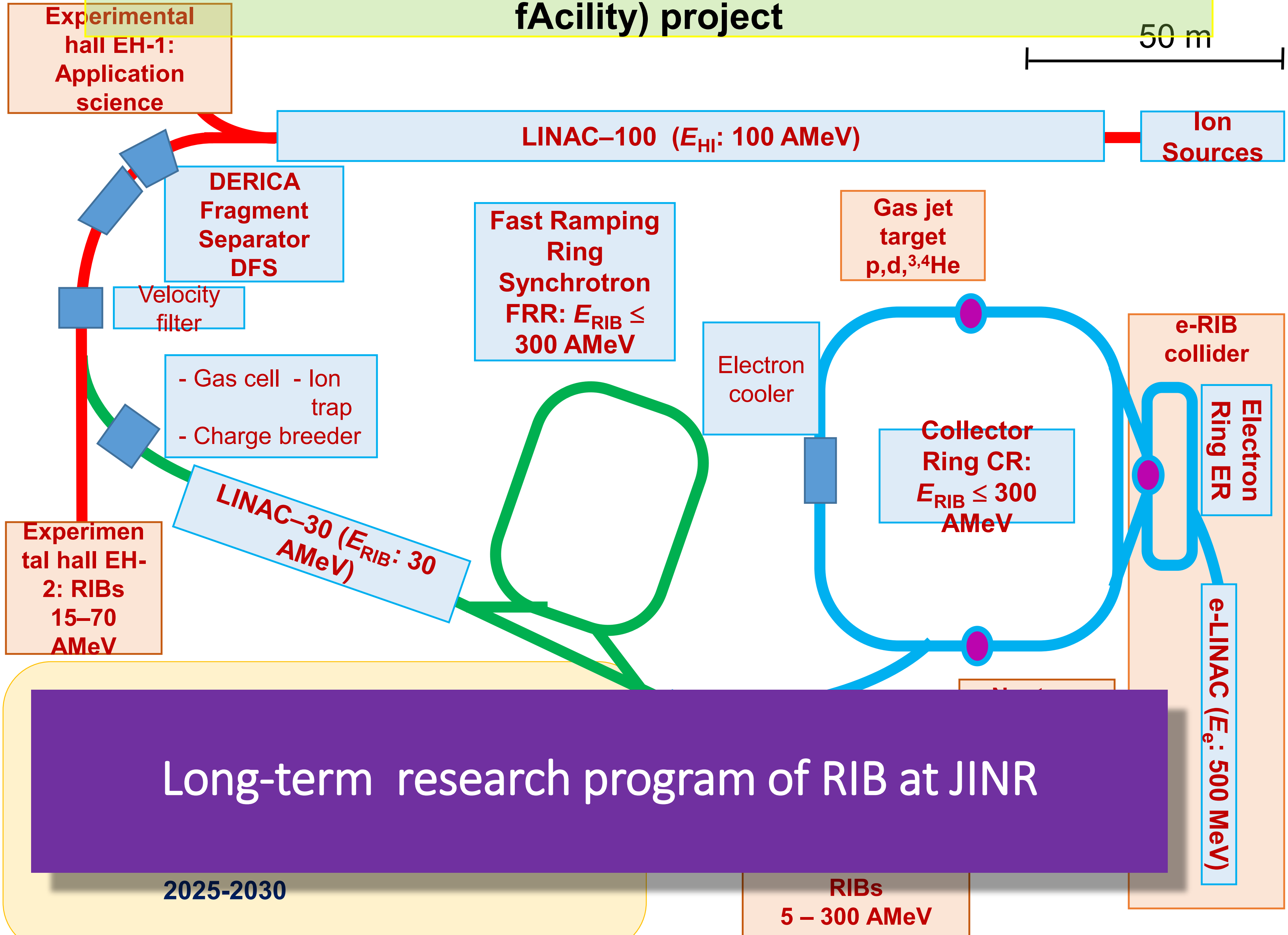
Precision reaction studies on internal gas jet target

Atomic physics studies with striped ions

Radioactivity studies with striped ions

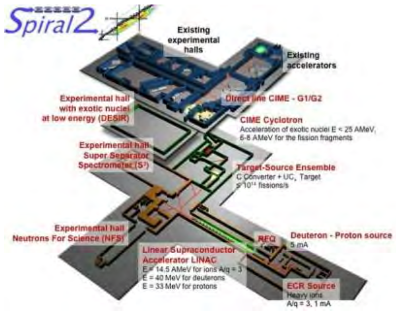
Etc….

Concept of DERICA (Dubna Electron – Radioactive Ion Collider fAcility) project



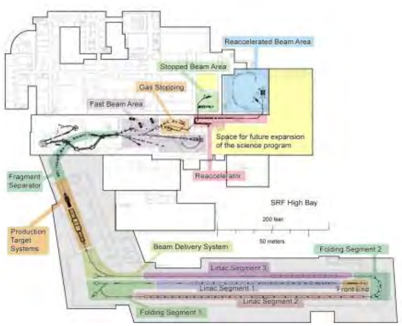
Long-term research program of RIB at JINR

The Rare Isotope Factories become larger and more and more expensive

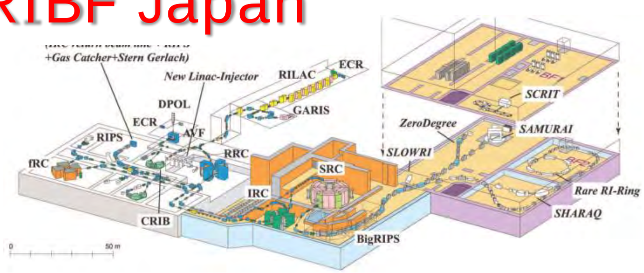


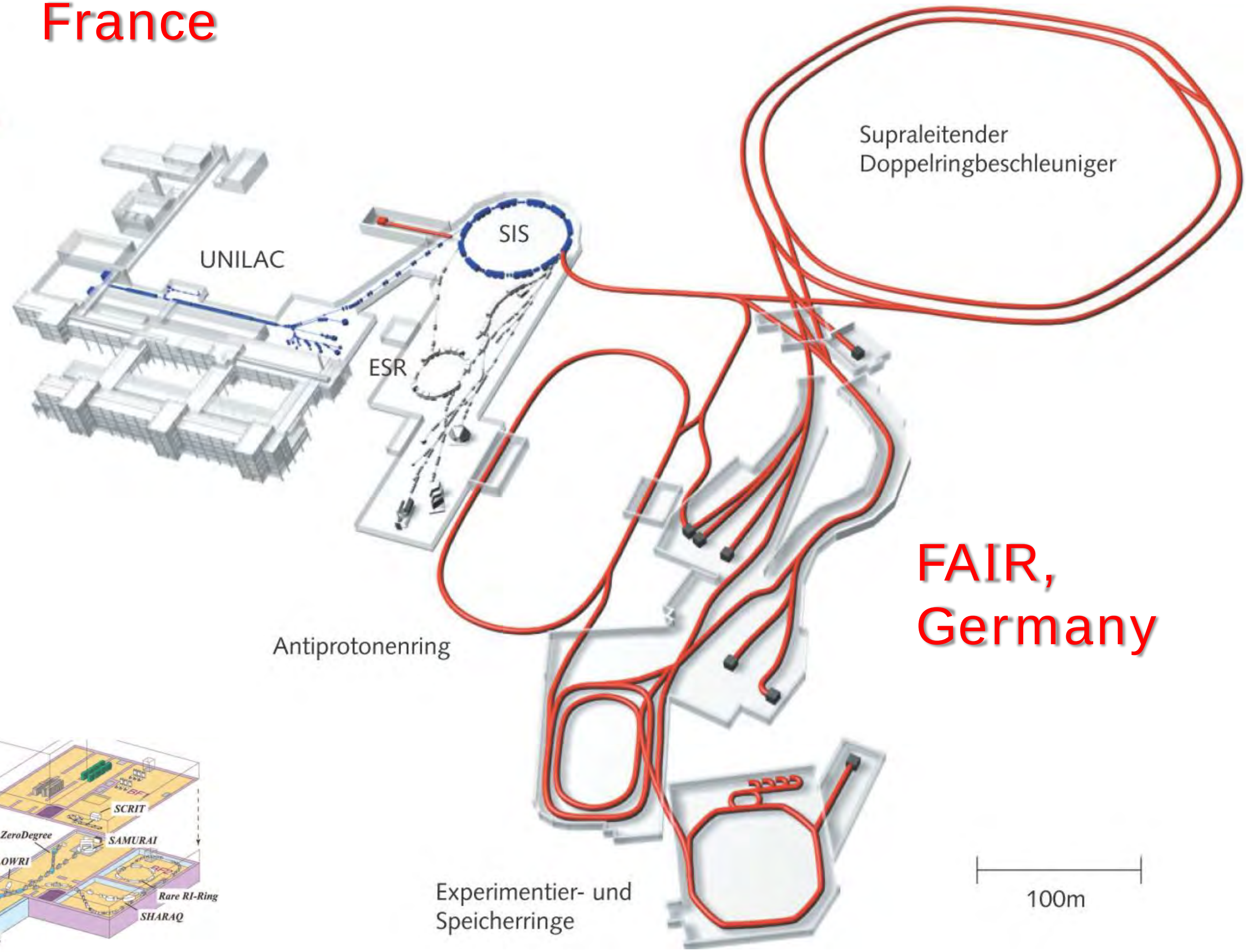
SPIRAL2
France

FRIB USA



RIBF Japan

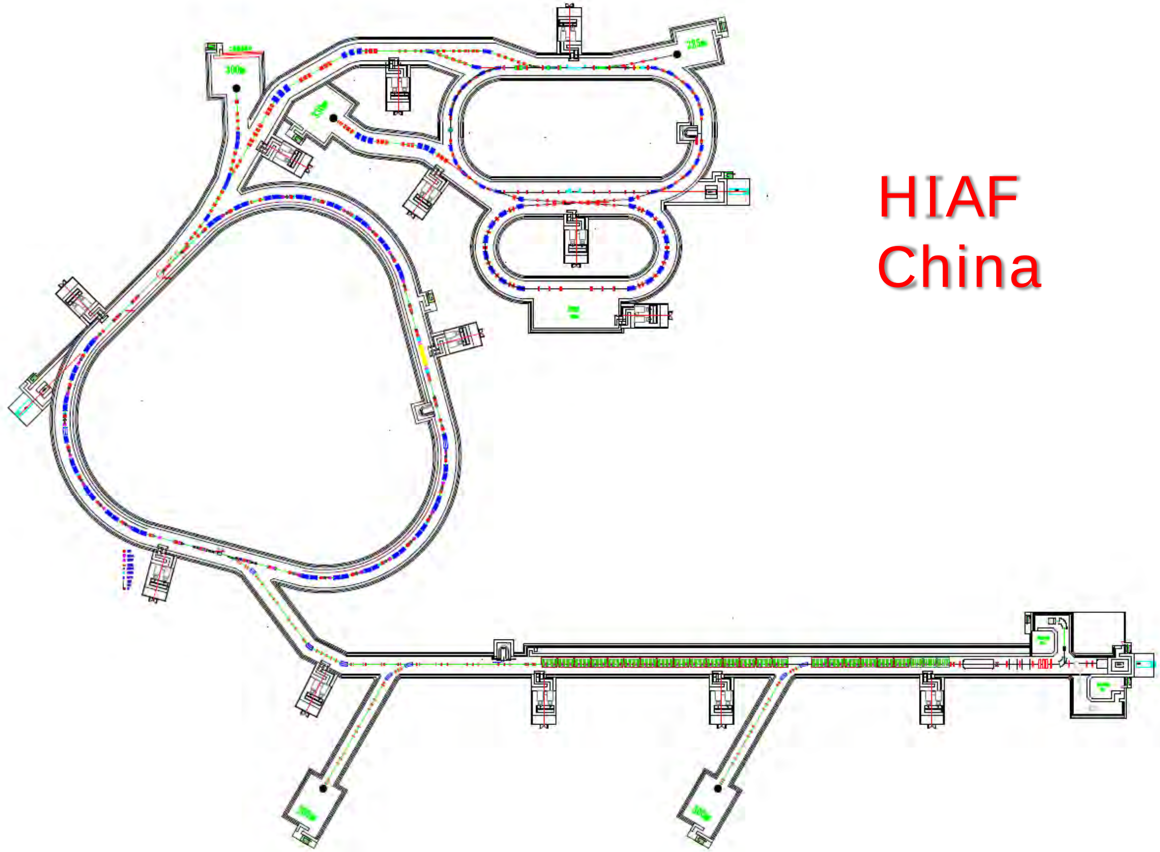




FAIR,
Germany

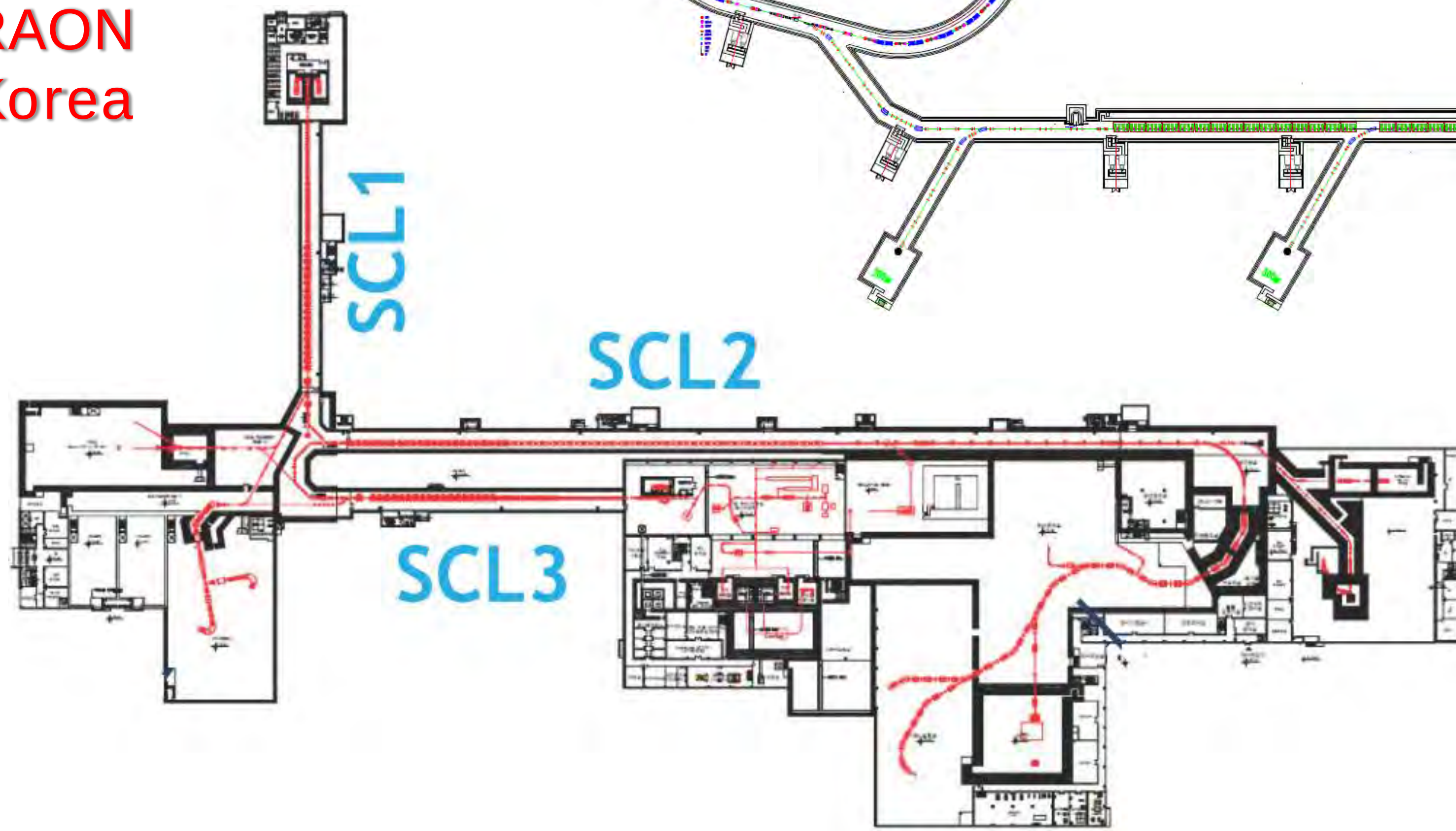
even bigger…

Horizontal scale of the slide ~1 km

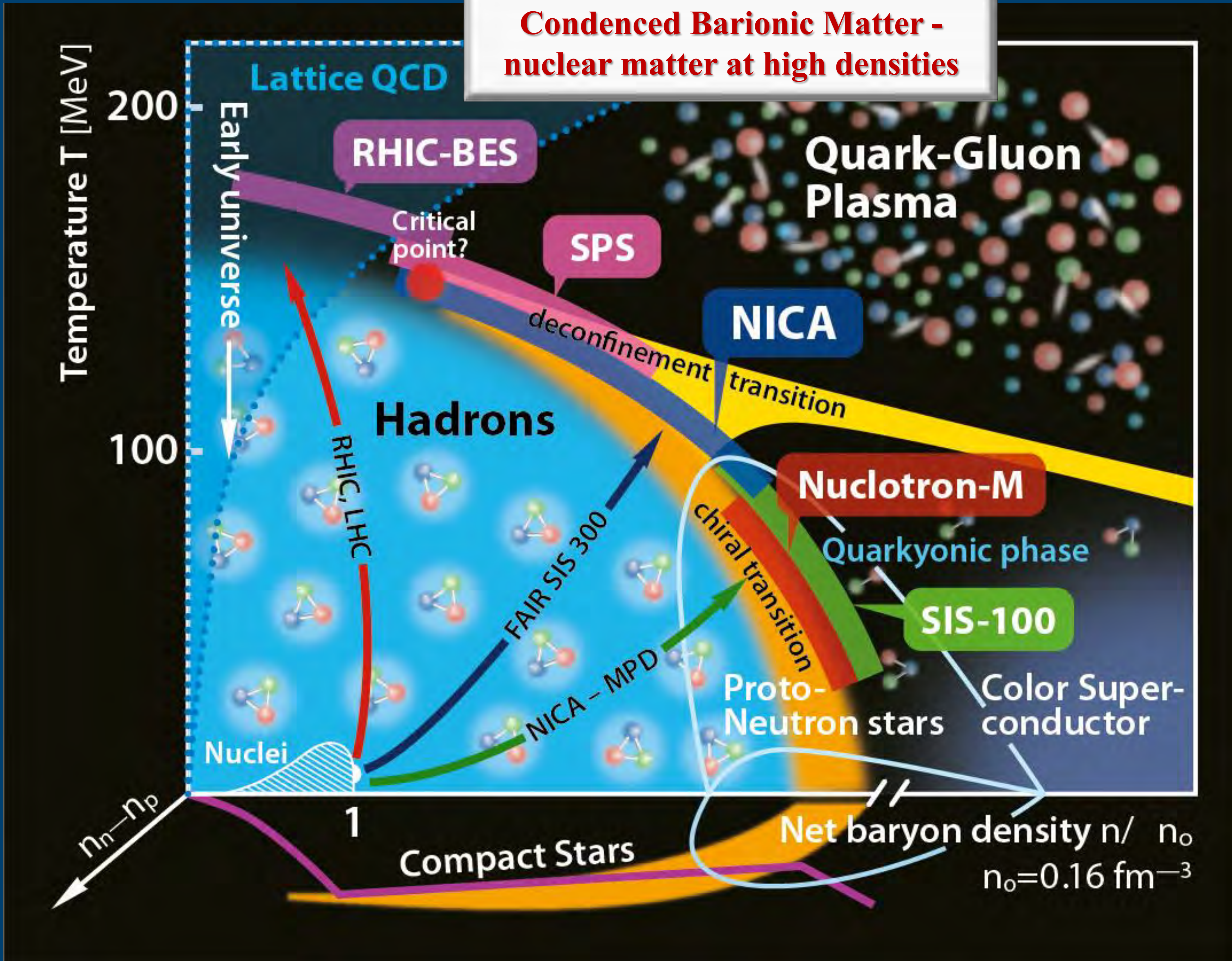


HIAF
China

RAON
Korea



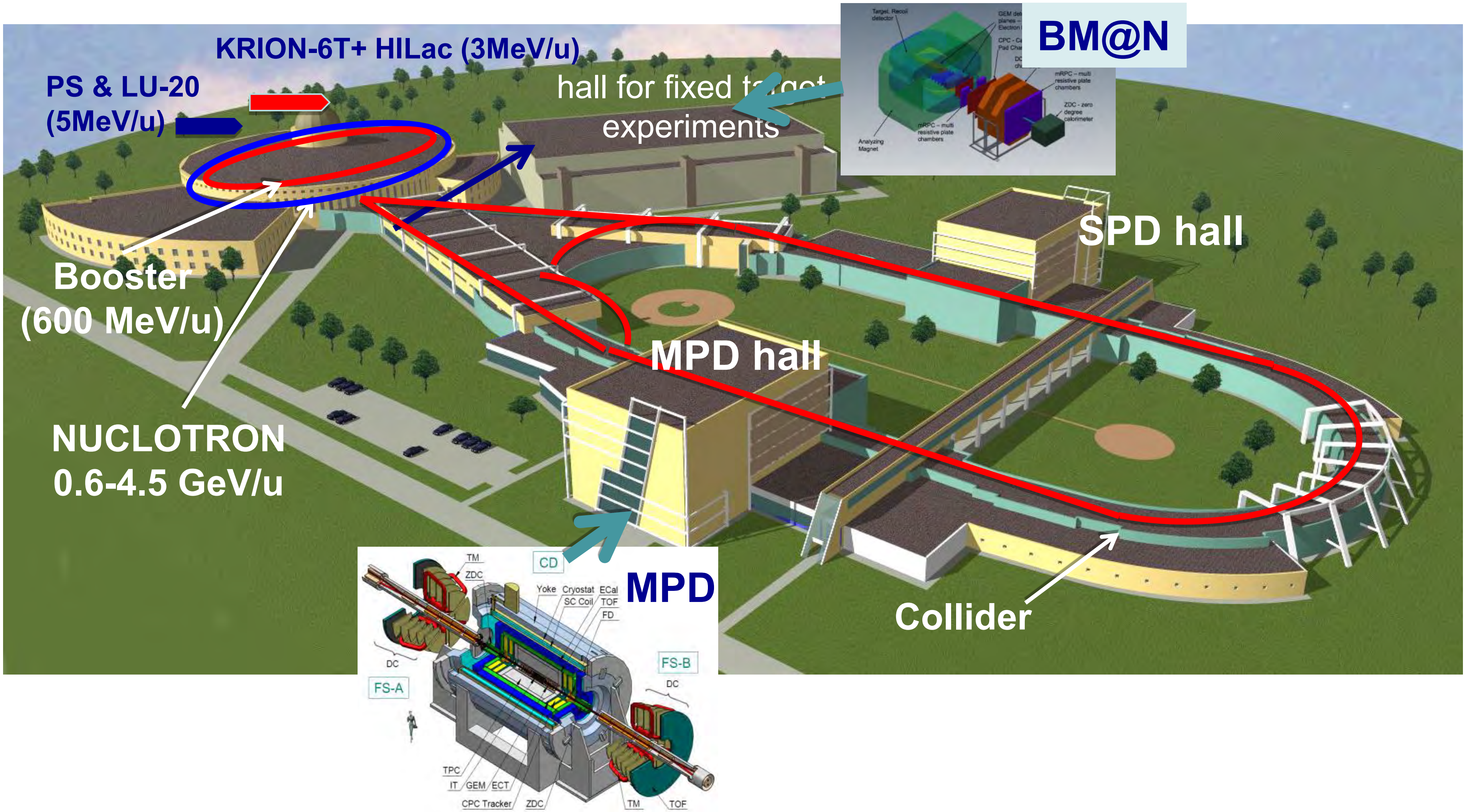
Condenced Barionic Matter - nuclear matter at high densities



The NICA Complex - JINR

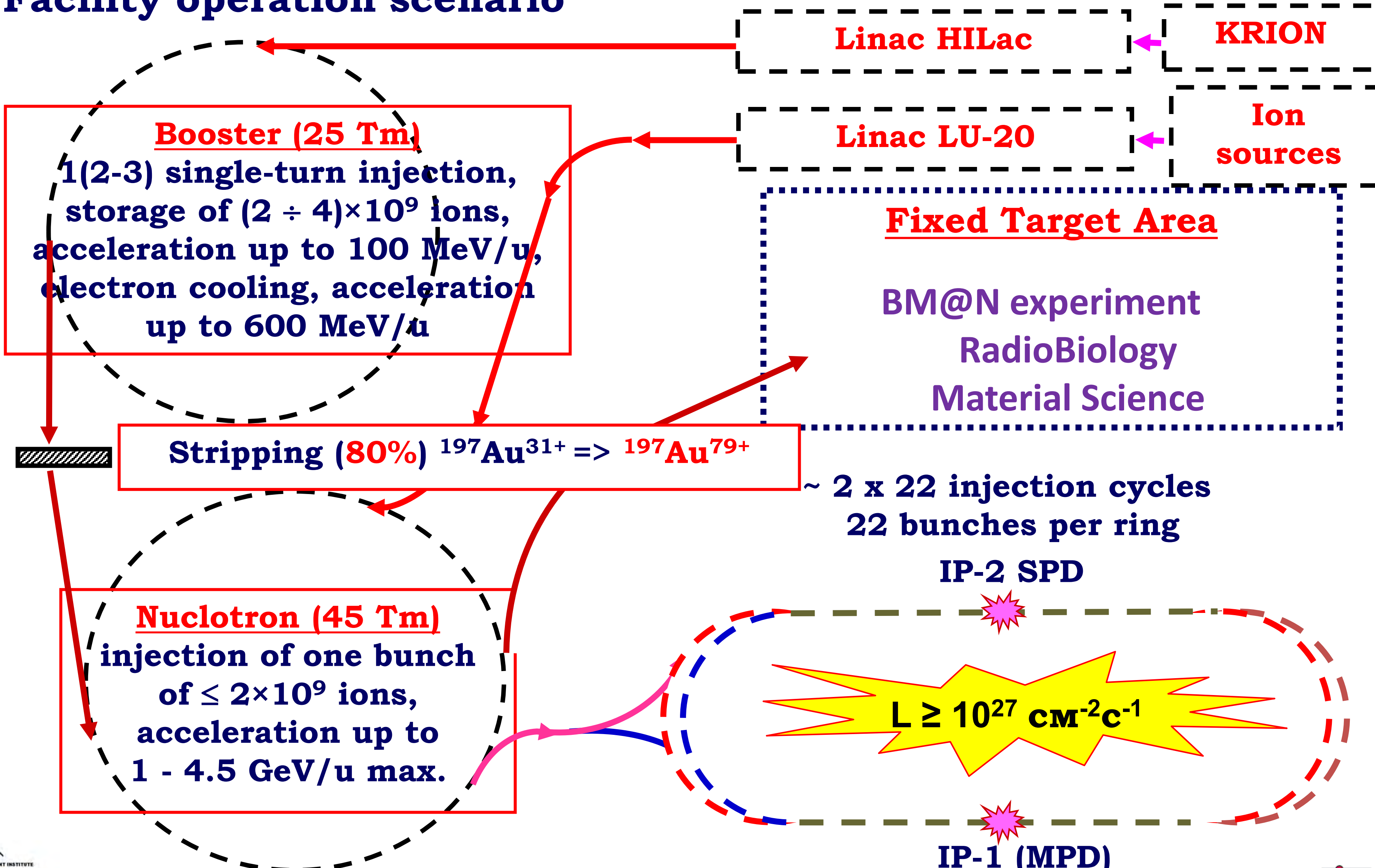
existing facility

under construction



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

Facility for Antiproton and Ion Research
a world-wide unique accelerator facility

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

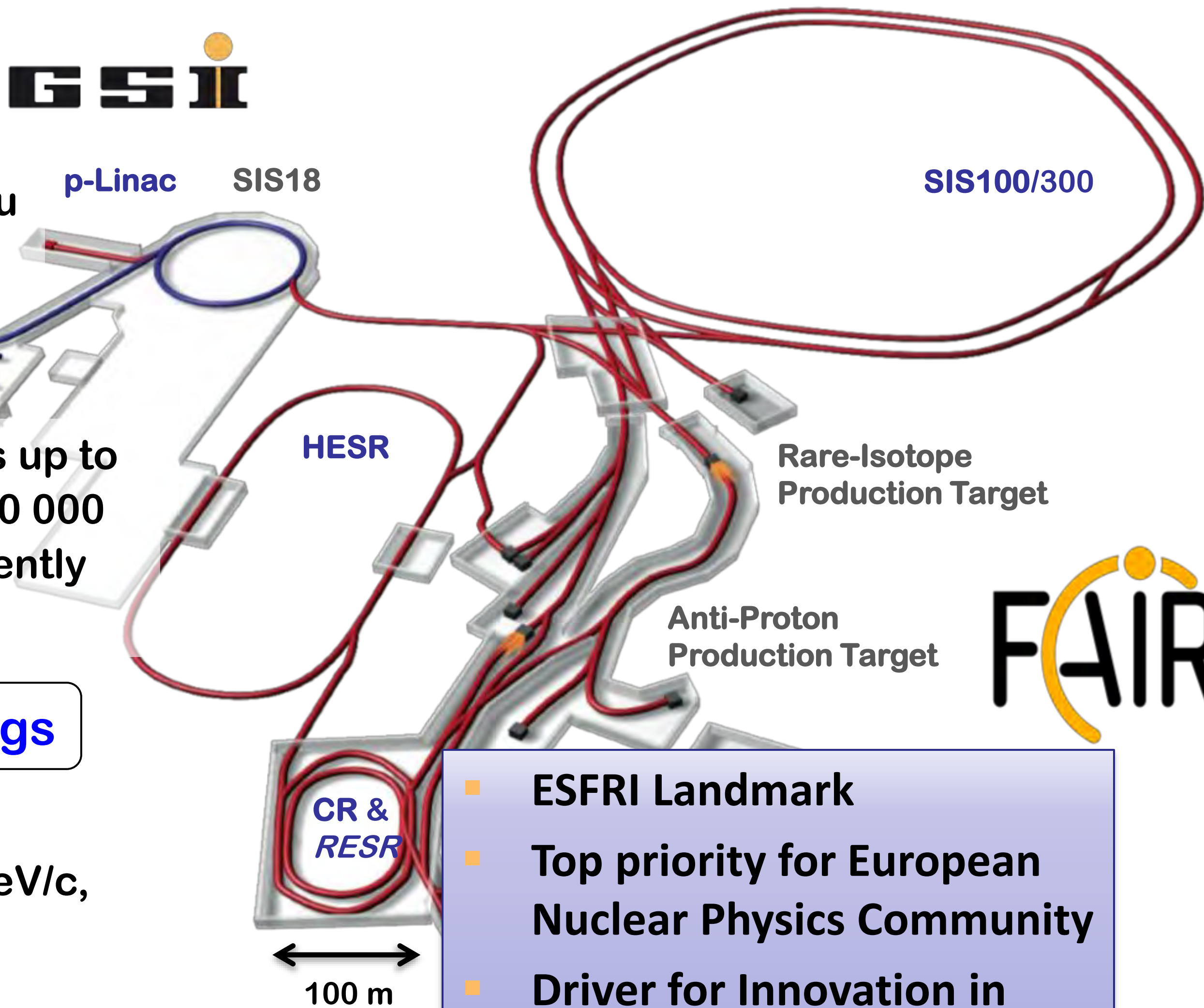
- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

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

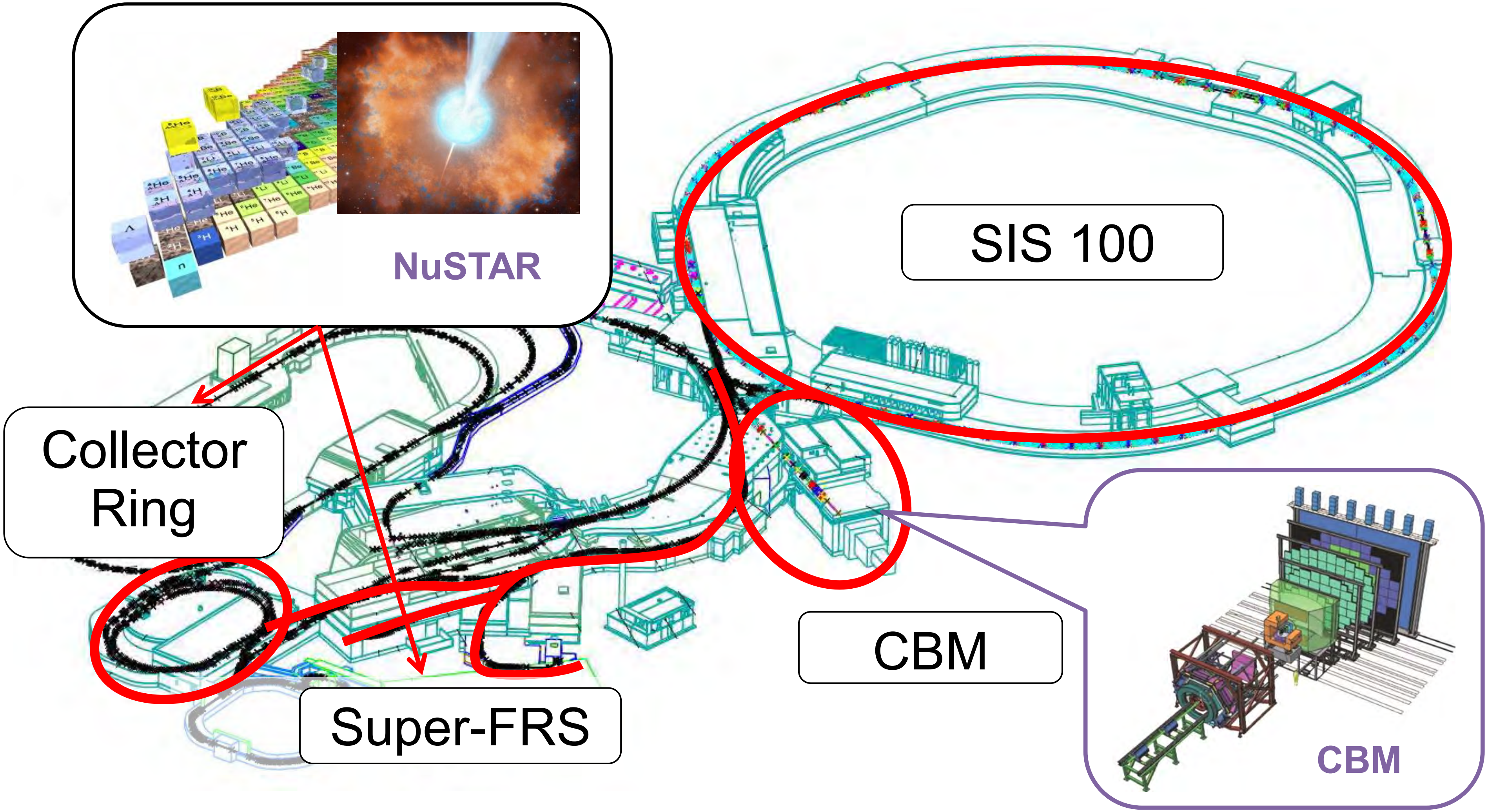
Technical Challenges

- cooled beams, rapid cycling superconducting magnets



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

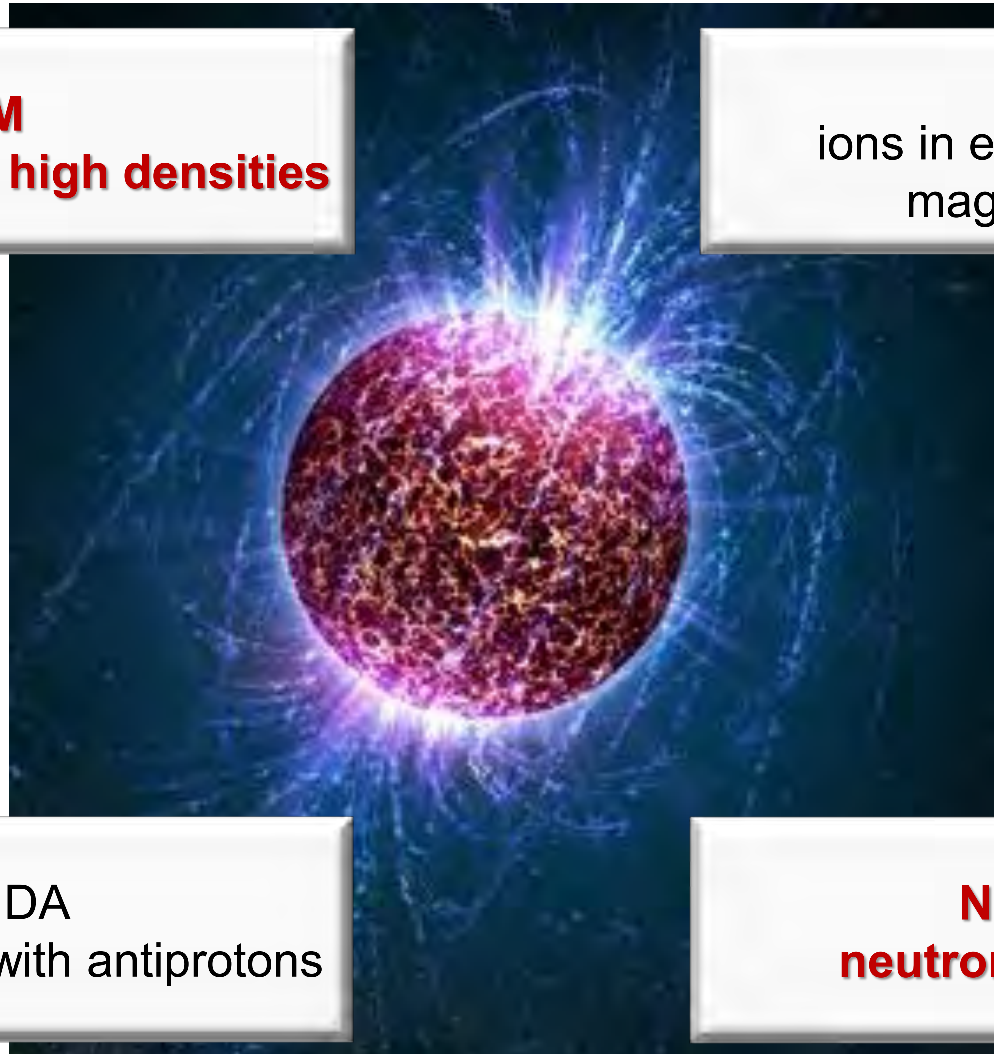
Heavy ion accelerator chain



4 Research Pillars of FAIR

CBM
nuclear matter at high densities

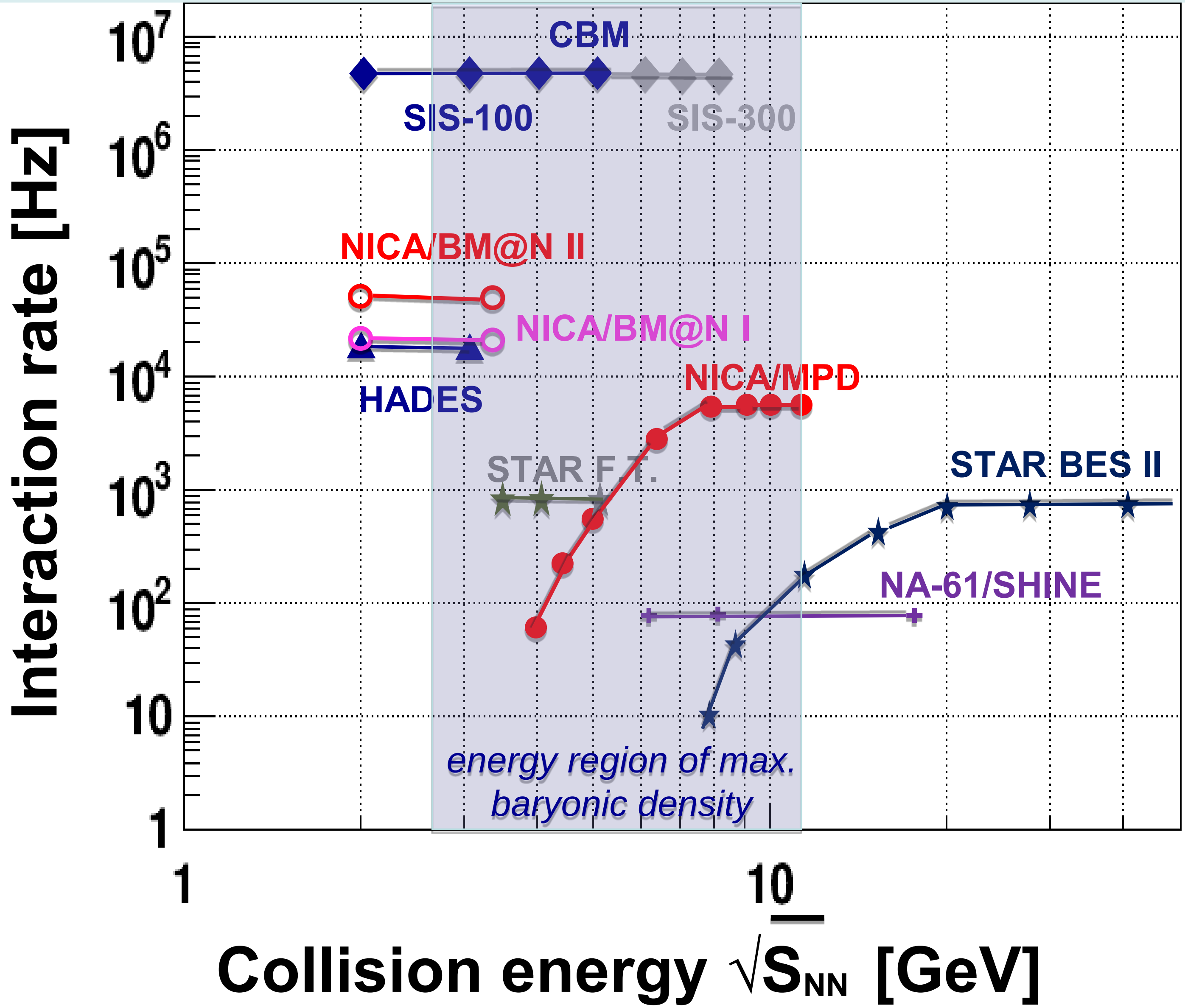
APPA
ions in extreme electro-magnetic fields



PANDA
hadron physics with antiprotons

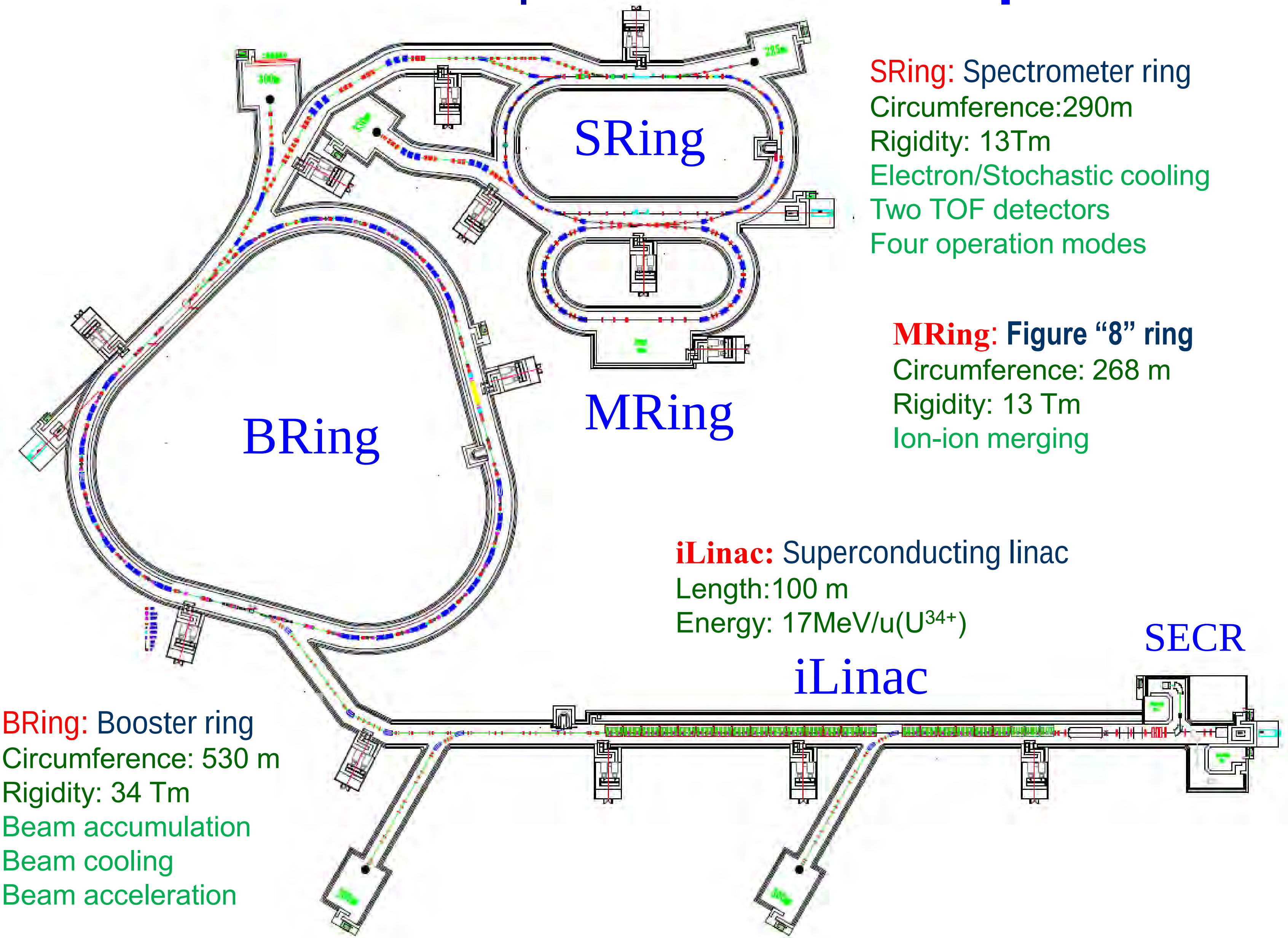
NUSTAR
neutron-rich nuclei

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



High-Intensity Heavy Ion Accelerator Facility

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

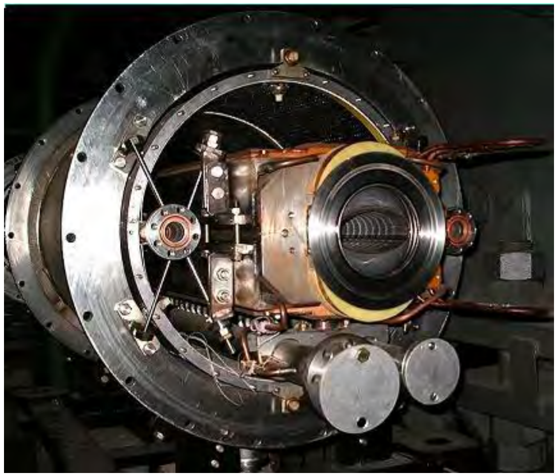
Accelerator Technology Challenges

Be realistic, demand the impossible !

Compact & cost effective accelerators

Fast cycling SC magnets dB/dt ~ 4T/s

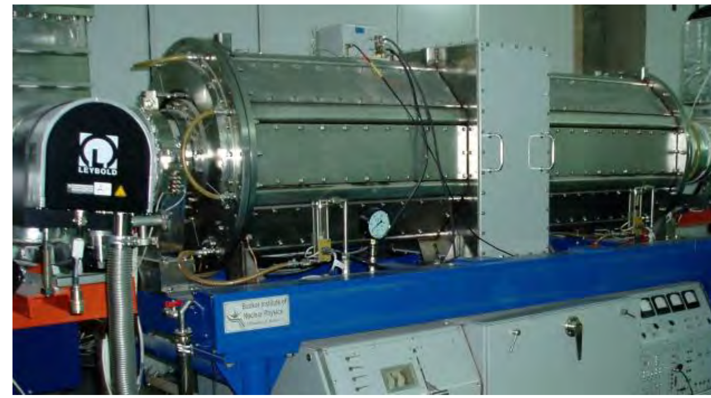
Nb-Ti 8T -> Nb_3Sn 16 T dipoles



Fast acceleration

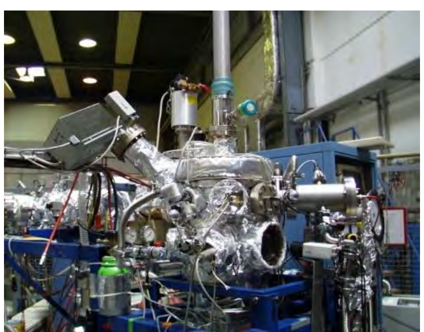
High gradient, variable frequency

SC, Ferrite & MA loaded cavities



XHV @ high beam intensities

Extremely high vacuum ~10^{-12} mbar



Precision beams

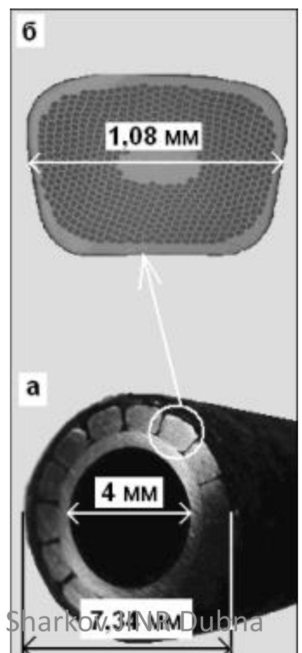
Electron & stochastic cooling

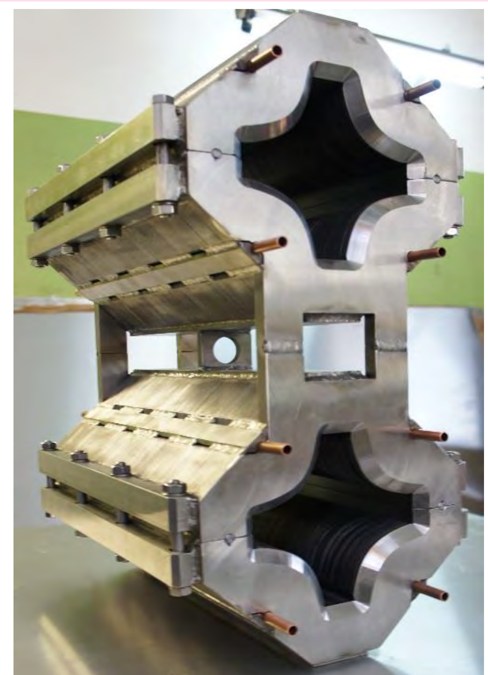
Accelerator performance – is progressing rapidly

Superconducting technologies (T=4.5 K, T=77K)

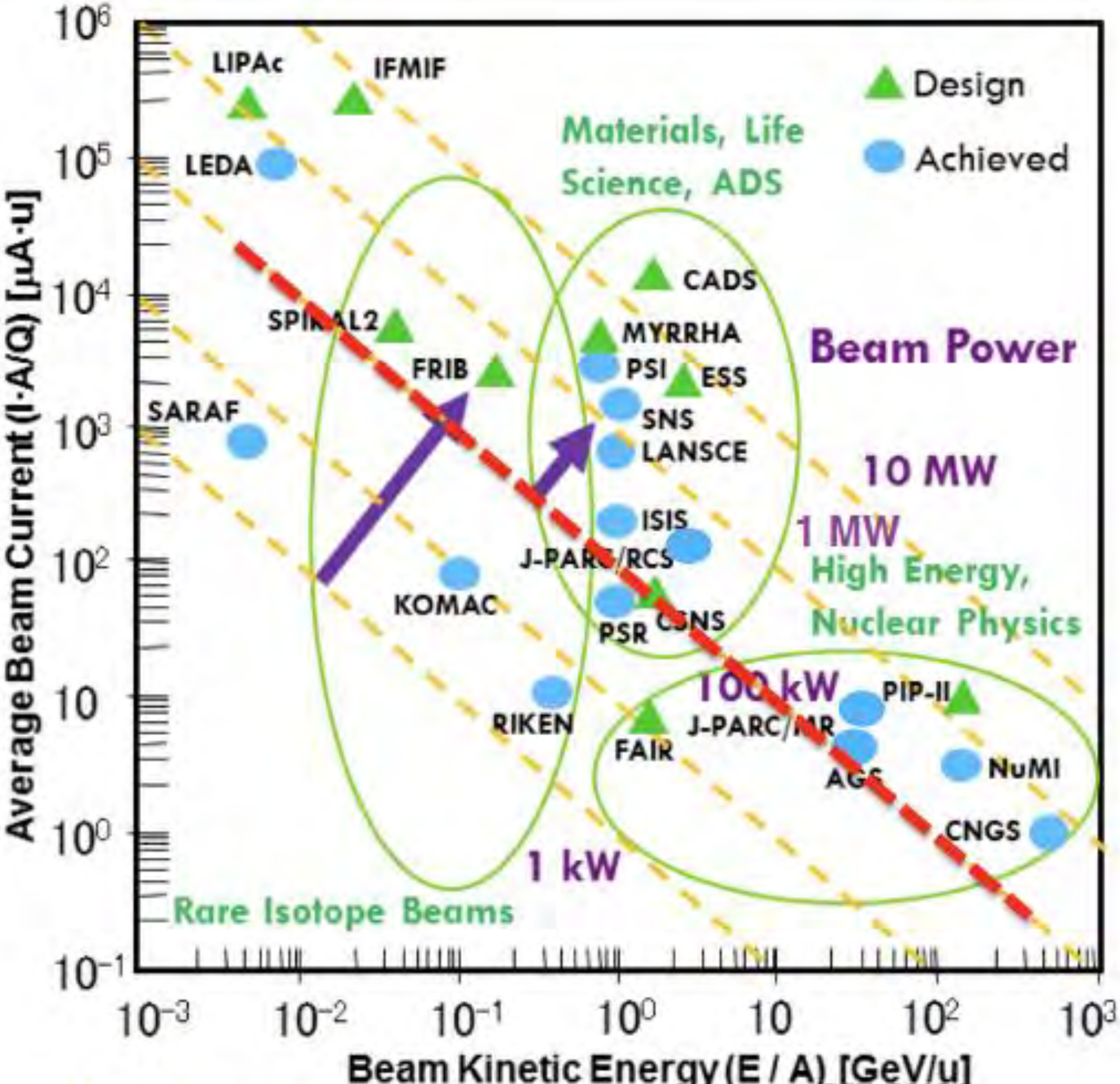
R&D and construction of high-temperature superconducting current leads (HTSC @ 77K), conductors and elements. (20кА x 200 V = 4 MW).
Power saving factor of ~ 20-30

R&D, serial production of compact fast-cycling superconducting (5 Hz, 4-8 T/s) magnets (dipoles, quadrupoles, multipoles). **Compactification with factor of ~2-3 in geometrical sizes in comparison to "warm" magnets.**





A Quest for High Intensity



High Intensity

High Statistics

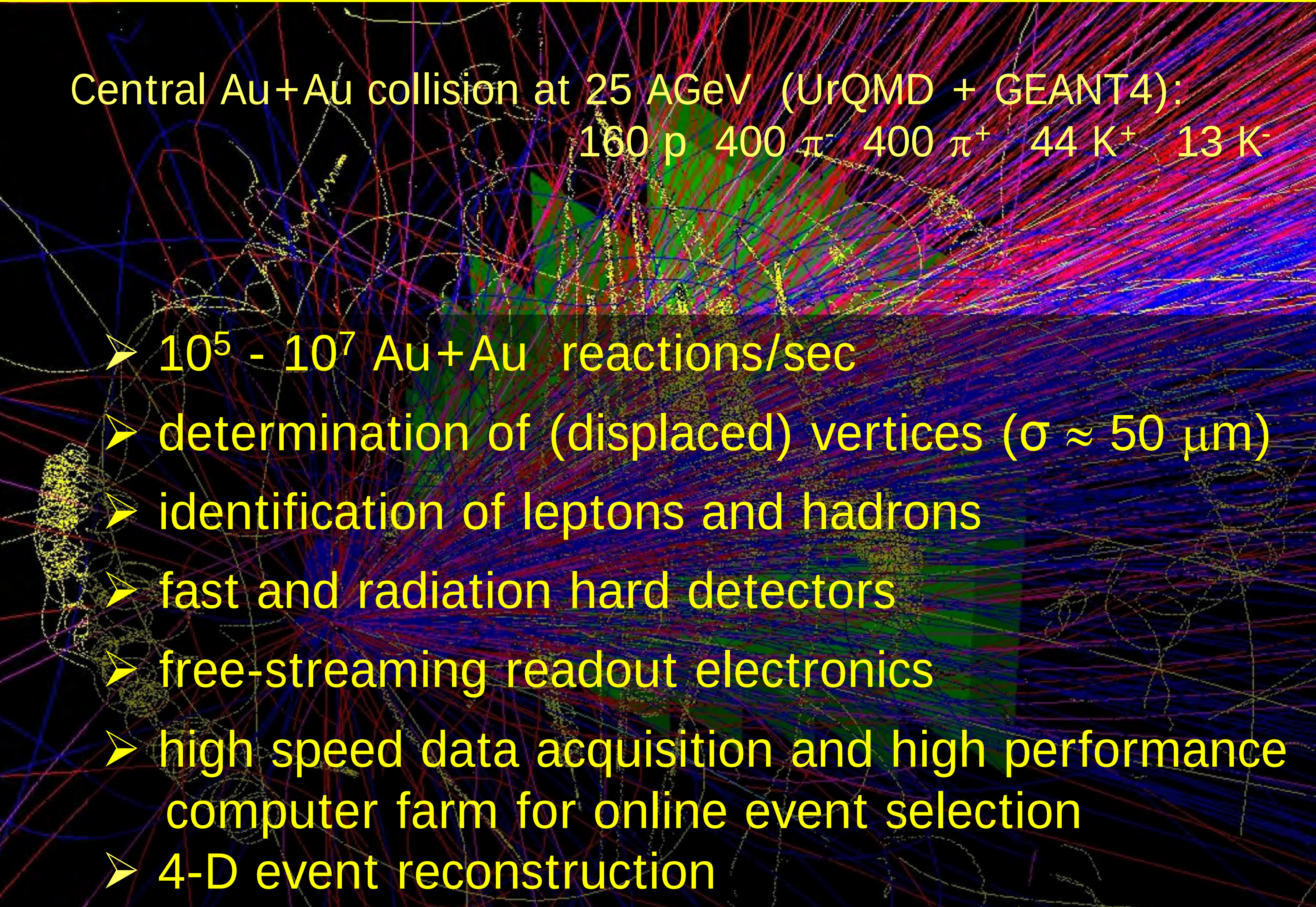
- More Precision
- More Rare Searches
- More Materials

Discovery!

Jie Wei / Y. Yamazaki

PKU 2018

HPC technological challenges

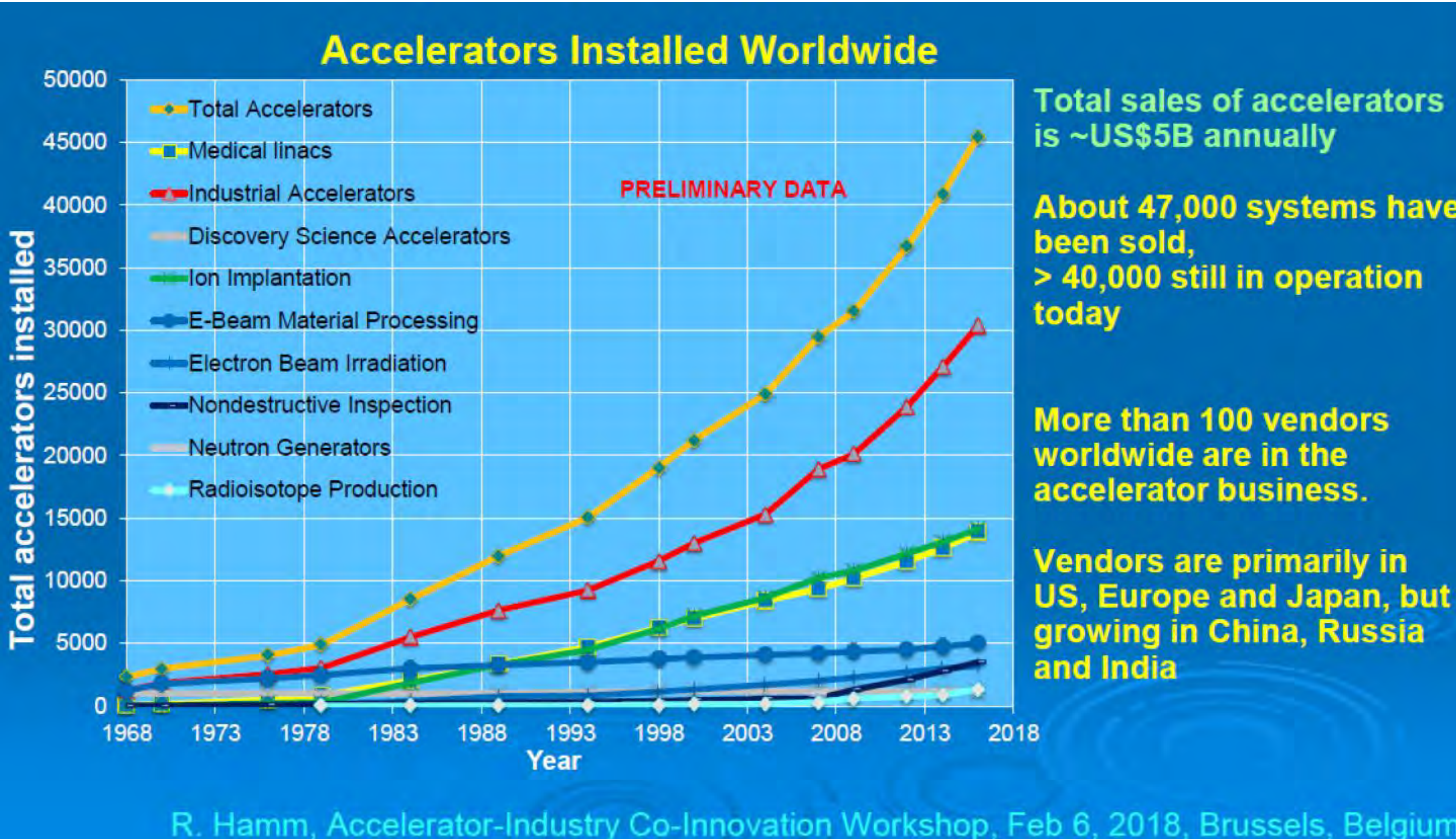


Central Au+Au collision at 25 AGeV (UrQMD + GEANT4):
160 p 400 π^- 400 π^+ 44 K^+ 13 K^-

- 10^5 - 10^7 Au+Au reactions/sec
- determination of (displaced) vertices ($\sigma \approx 50$ μm)
- identification of leptons and hadrons
- fast and radiation hard detectors
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

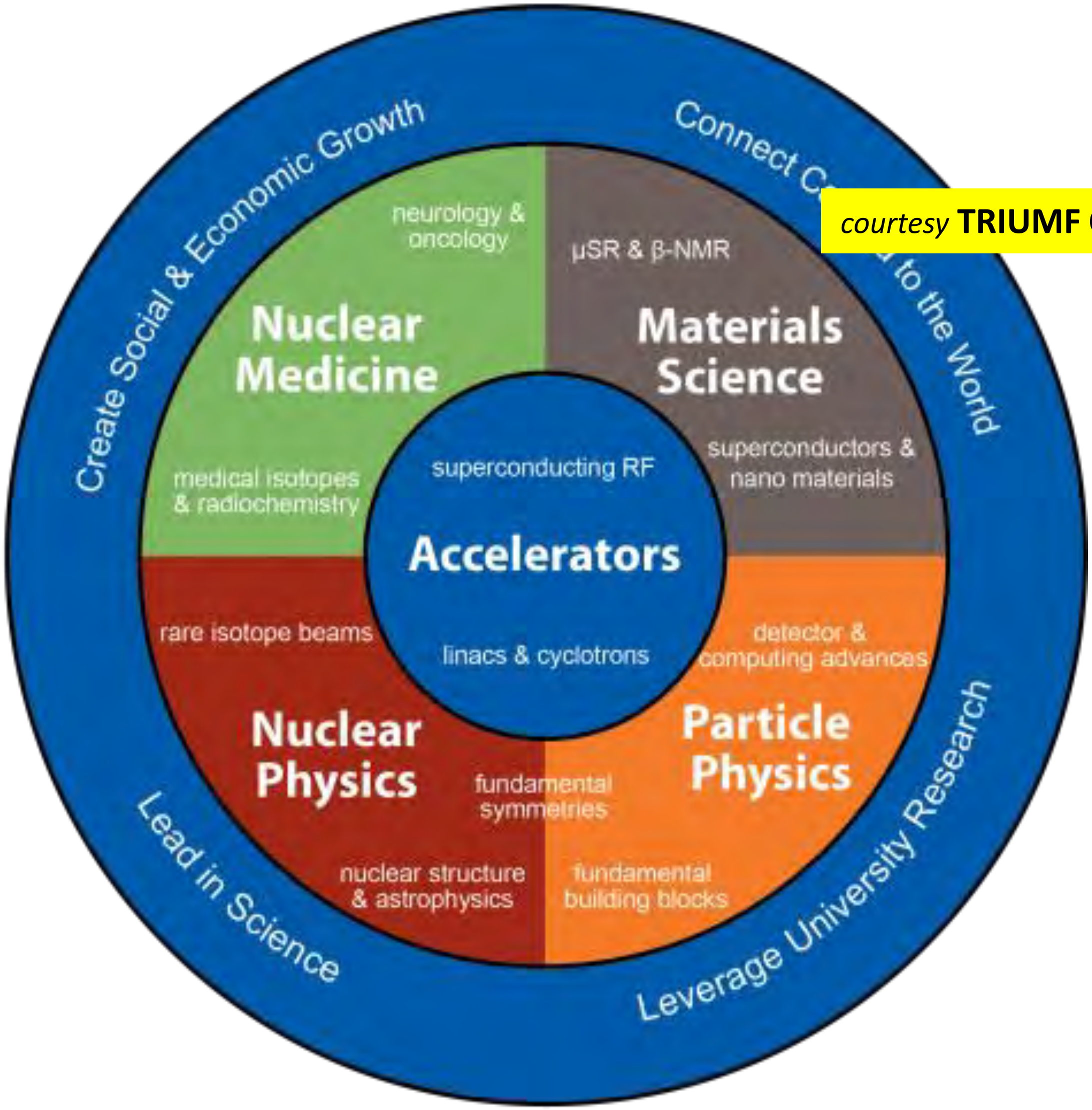
Summary

- A number of **modern international and national research facilities** are operational and/or under construction world wide
- Large scale accelerators for NP have conducted successfully major pioneering R&D on key components, providing surpassing and unique performance for the next generation of particle accelerators including accelerator technologies for practical applications which serve the society at large
- **Generation of intense "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
- **Full range of ion beam species** (p+ - 239U) ; e^- , e^+
- **Highest beam intensities & luminosities**



1/3 - hadron accelerators, 2/3 – electron accelerators, about 3% - for science

Large scale accelerators for humankind - decisive socioeconomic impact



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