

Present and future accelerators for nuclear physics

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Present and future accelerators for nuclear physics



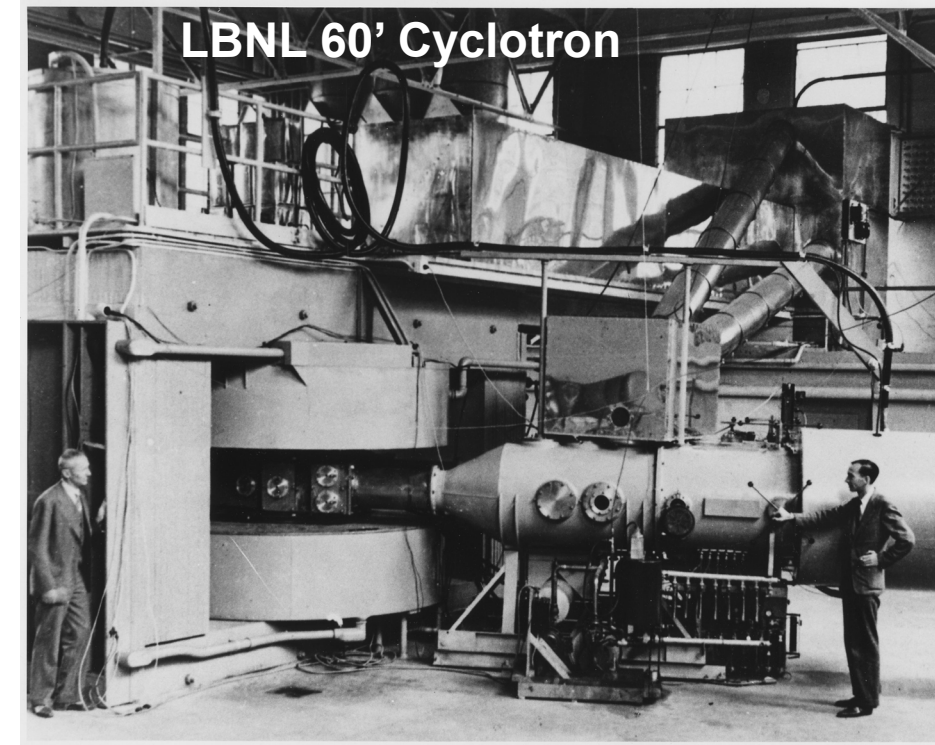
Wolfram Fischer
Brookhaven National Laboratory

European Nuclear Physics Conference 2022
University of Santiago de Compostela
24 October 2022

Content

- Introduction – acceleratory types
- Electrostatic accelerators and cyclotrons
most common low-energy accelerators
- Electron accelerators
- High-intensity accelerators
secondary/tertiary particles and rare isotopes
- Colliders
high energy nuclear physics

... also need high-intensity and polarized sources, efficient charge strippers, targets, charge breeders, post-acceleration, spectrometers, detectors



Accelerators for nuclear physics

- Nuclear physics is the field of [physics](#) that studies [atomic nuclei](#) and their constituents and interactions, in addition to the study of other forms of [nuclear matter](#). (Wikipedia)

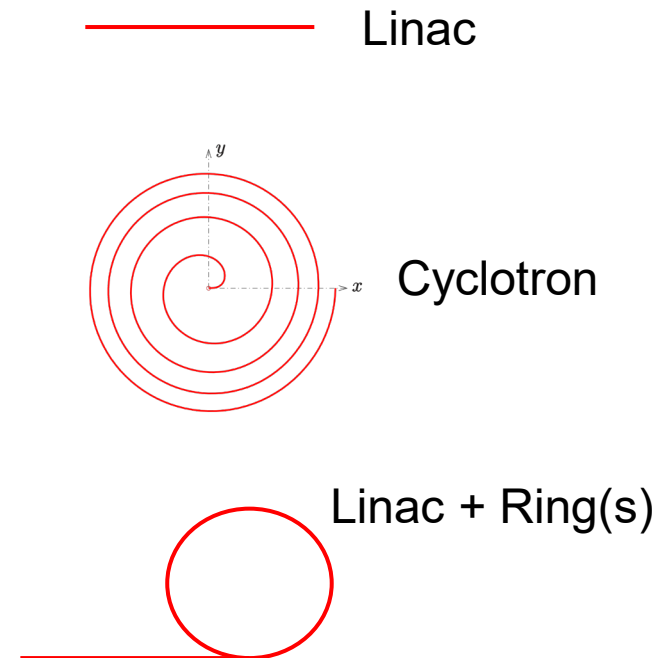
=> Accelerators with

- $\geq$ MeV hadron beams
- electron or positron beams that penetrate nuclei ($\geq$ GeV)
- high-intensity accelerators for rare isotopes and secondary/tertiary particles (e.g. n and μ^-/μ^+)
- polarized beams ($e^- \uparrow / e^+ \uparrow$, $p \uparrow / d \uparrow / h \uparrow$)
- colliders for high-energy NP

Large number of NP accelerators in the world (~hundreds)

Accelerator types (Accelerator Handbook)

- Betatron – to ~300 MeV
- Electrostatic accelerators – Tandem to ~25 MeV
- RF and Induction Linacs
- Cyclotron – to ~600 MeV
- Microtron
FFA = Fixed Field Alternating gradient
- Rings (synchrotrons) – to ~TeV range
- Colliders (RHIC, LHC, NICA, EIC) – to ~TeV range
- Energy Recovery Linacs (ERL)
- Wakefield Plasma and Dielectric Accelerators
- ... many variations



NP Accelerator labs often hosting multiple different accelerators

Electrostatic accelerators and cyclotrons

Electrostatic accelerators

Single voltage drop: $E = q V$

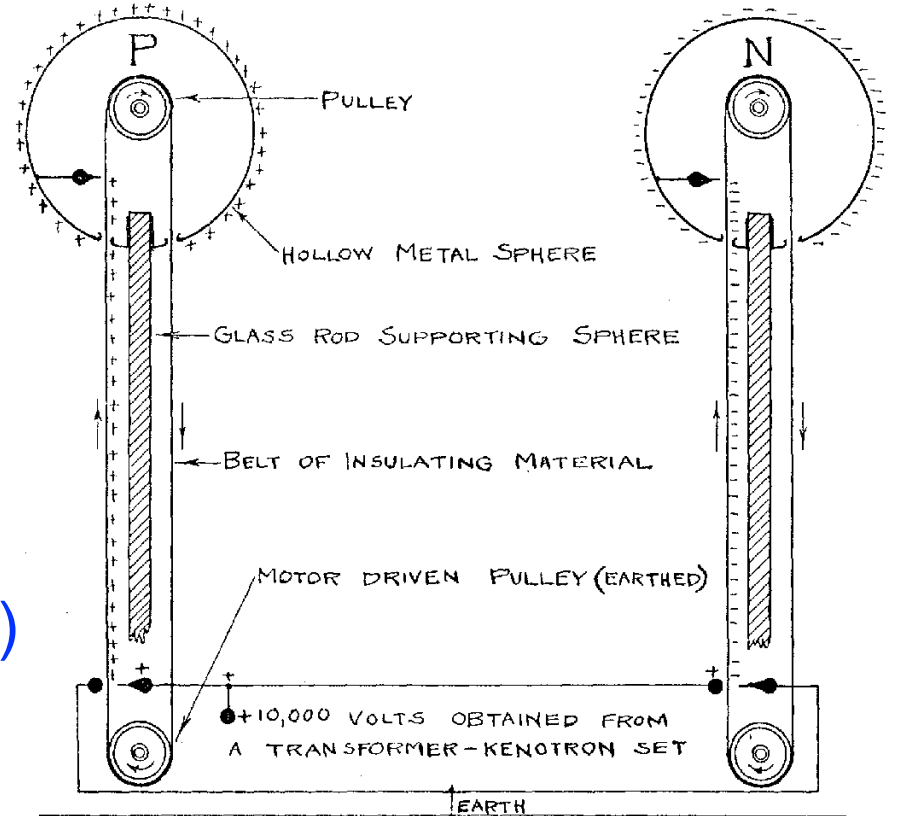
Energy: max ~25 MeV (2x for Tandem)

Van de Graaff, Cockcroft-Walton
voltage limited by breakdown (use vacuum or SF_6)

Many in Tandem configuration
accelerate negative ion, strip $2 e^-$
in middle, accelerate again

Small transverse beams and energy
spread compared to RF acceleration

Commercially available
(eg NEC Peletron ~1 MV)



R.J. Van de Graaff et al, Phys. Rev. 43, 149 (1933)



Cyclotrons

Energy : to ~600 MeV

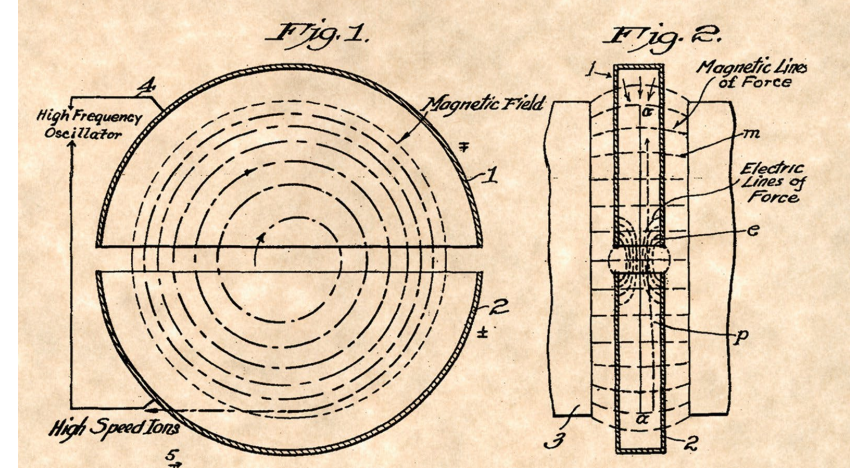
Species: p, H⁻, d, ..., heavy ions

H⁻ for multiple extractions through stripping
high power cyclotrons limited by extraction losses

Relatively recent development: small cyclotrons
with superconducting magnets for compactness
to be mounted on a gantry

Large numbers in service worldwide

Commercially available for low to medium E
(eg IBA Belgium 9-70 MeV, ACSI Canada 19-33 MeV,
Best USA 15-70 MeV)



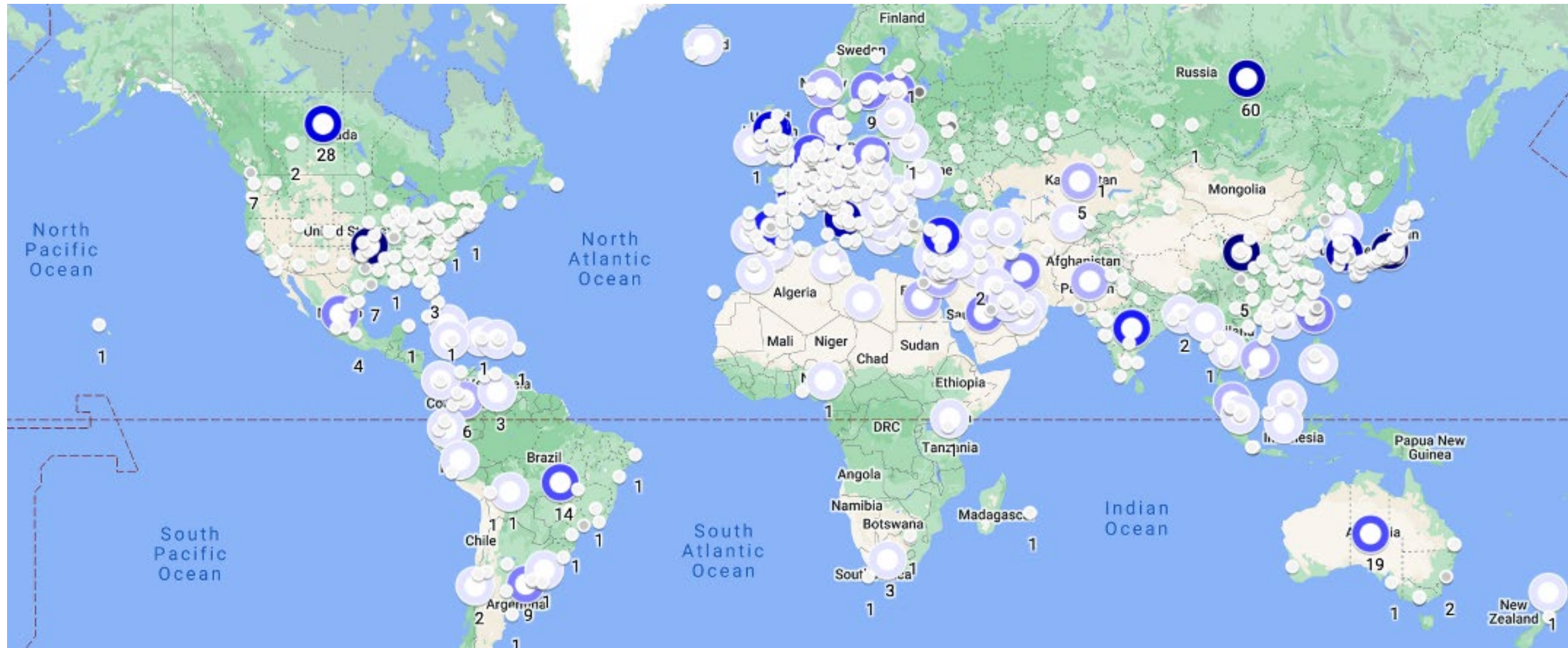
Cyclotron patent application,
Ernest Lawrence (1932)



18 MeV cyclotron at CNA, Sevilla

Over 1500 cyclotrons in the world

IAEA interactive database: >1300 in 95 countries



Electron accelerators

For fixed target experiments (colliders later)

CEBAF – Jefferson Lab USA

Start of operation 1994: 6 GeV

2 superconducting linacs (new), used multiple times

Energy upgrade 2017: 12 GeV

linac extensions, 1 new arc, Hall D

4 experimental halls (A,B,C,D)

Current: up to $\sim 100 \mu\text{A}$ ($\sim 1 \text{ MW}$)

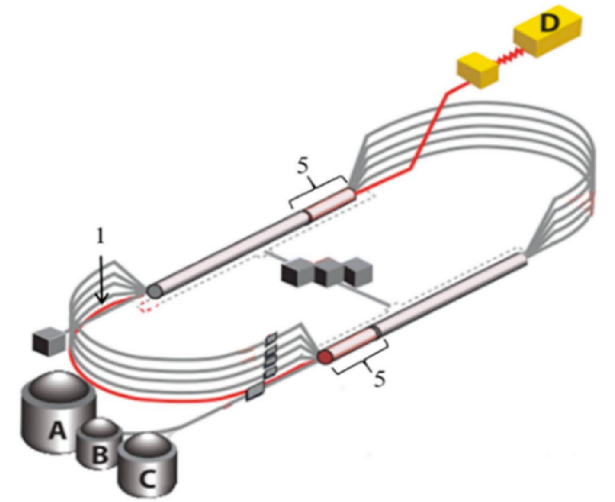
polarized electron beam $>85\%$, shared between halls

Upgrade option 1: Positions

$>60\%$, use polarized e- for conversion (PEPPo Collaboration)
depends on conversion energy and intensity trade-off

Upgrade option 2: Energy to $\sim 22 \text{ GeV}$

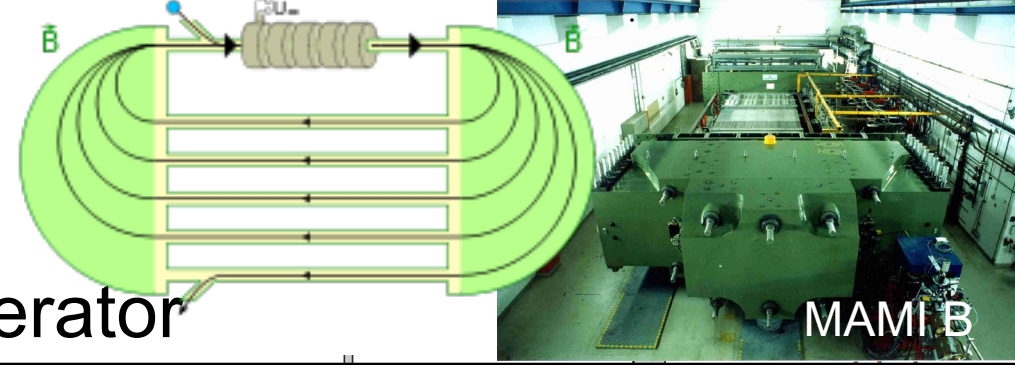
2 Fixed Field Alternating gradient (FFA) arcs (permanent magnets) replace highest energy arc – FFA arcs with $\sim 2\times$ momentum acceptance



MAMI and MESA, Uni Mainz

MAinzer Microtron and Mainz

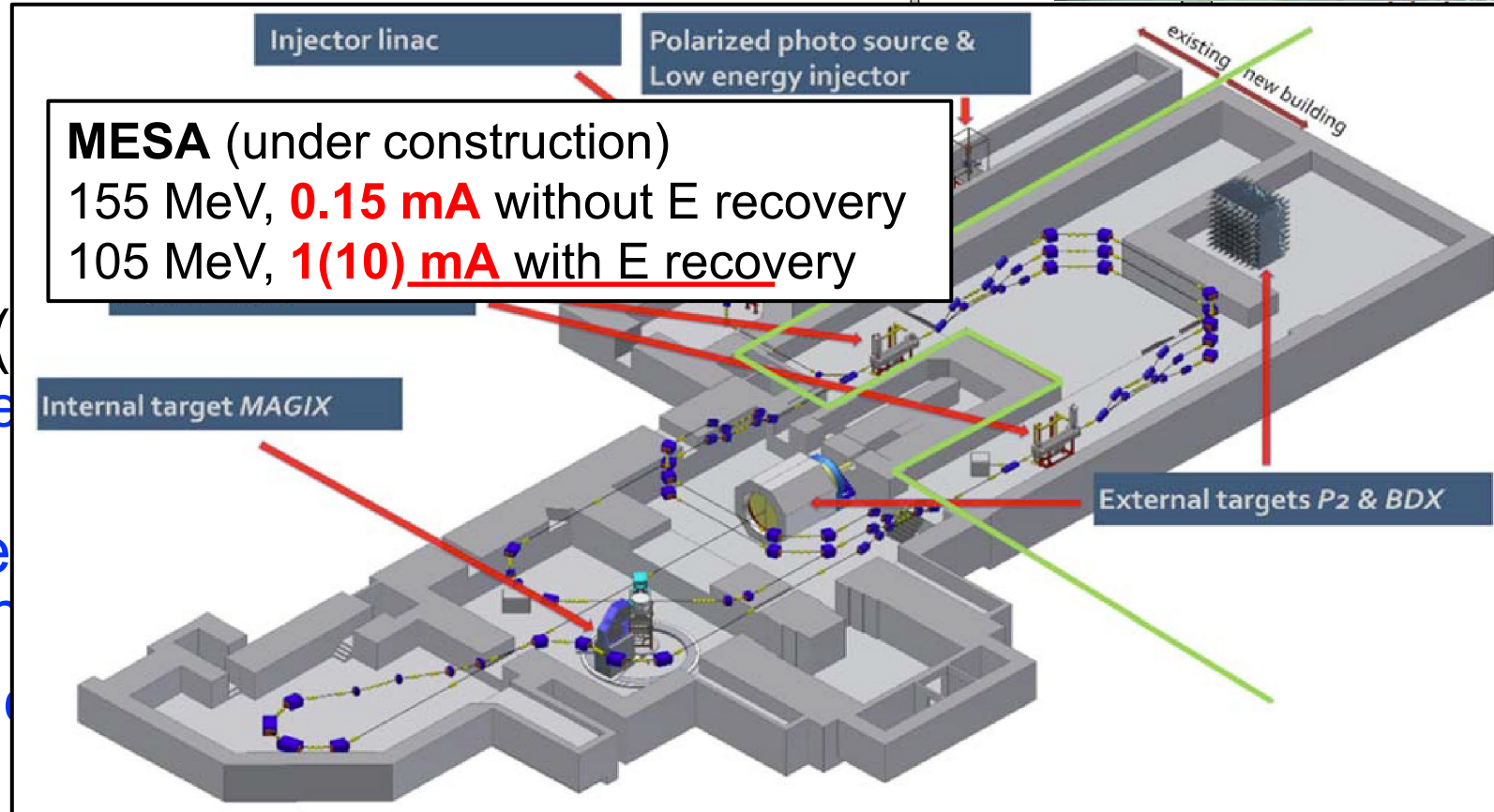
Energy-recovering Superconducting Accelerator



Microtron = racetrack
type accelerator
(separated cyclotron)

Energy Recovery Linac (
electron beam is decelerated
after use to extract energy

- ⇒ beam quality determined
by source / acceleration
- ⇒ allows for much higher
currents with non-dense targets



High-intensity machines

Secondary/tertiary particles (n and μ^-/μ^+)

For rare isotopes (including radioactive and SHE)

High-intensity accelerators – Important considerations

Power

Energy

- used to increase power
- used to maximize production cross section

Energy efficiency (grid-to-beam)

Beam loss / component activation

Targets

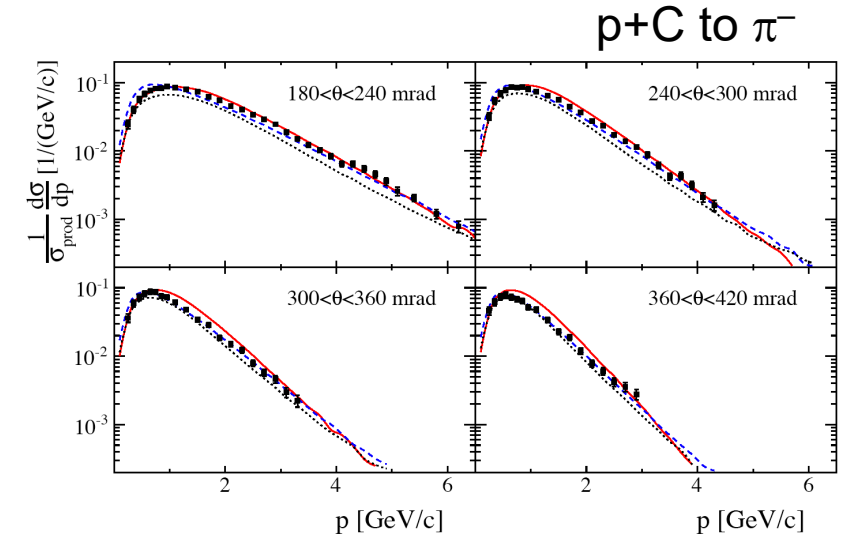
For heavy ions:

- low charge state at low E (space charge reduction)
- high charge state at high E (efficient acceleration)
- => efficient charge strippers

$$P_{\text{beam}} = (1/e) I_{\text{beam}} * E_{\text{beam}}$$

Limited by beam dynamics

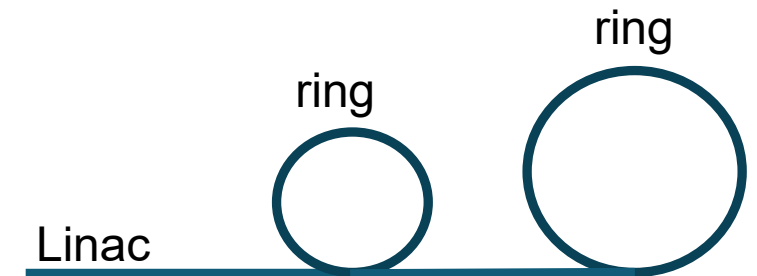
Limited by funding



[N. Abgrall et al., Phys. Rev. C 84, 034604 (2011)]

Cyclotrons, Linacs, Rings

- Cyclotrons
 - Limited to ~600 MeV
(extension: Fixed Field Alternating (FFA) gradients machines)
 - Present power frontier: PSI cyclotron 1.4 MW
 - Best energy efficiency
- Linacs
 - Space charge limit at source
 - Present power frontier: ORNL SNS 1.4 MW
 - Good energy efficiency with SRF and CW
- Accelerator rings
 - Highest energy reach
 - Space charge limit at injection
 - Low power efficiency



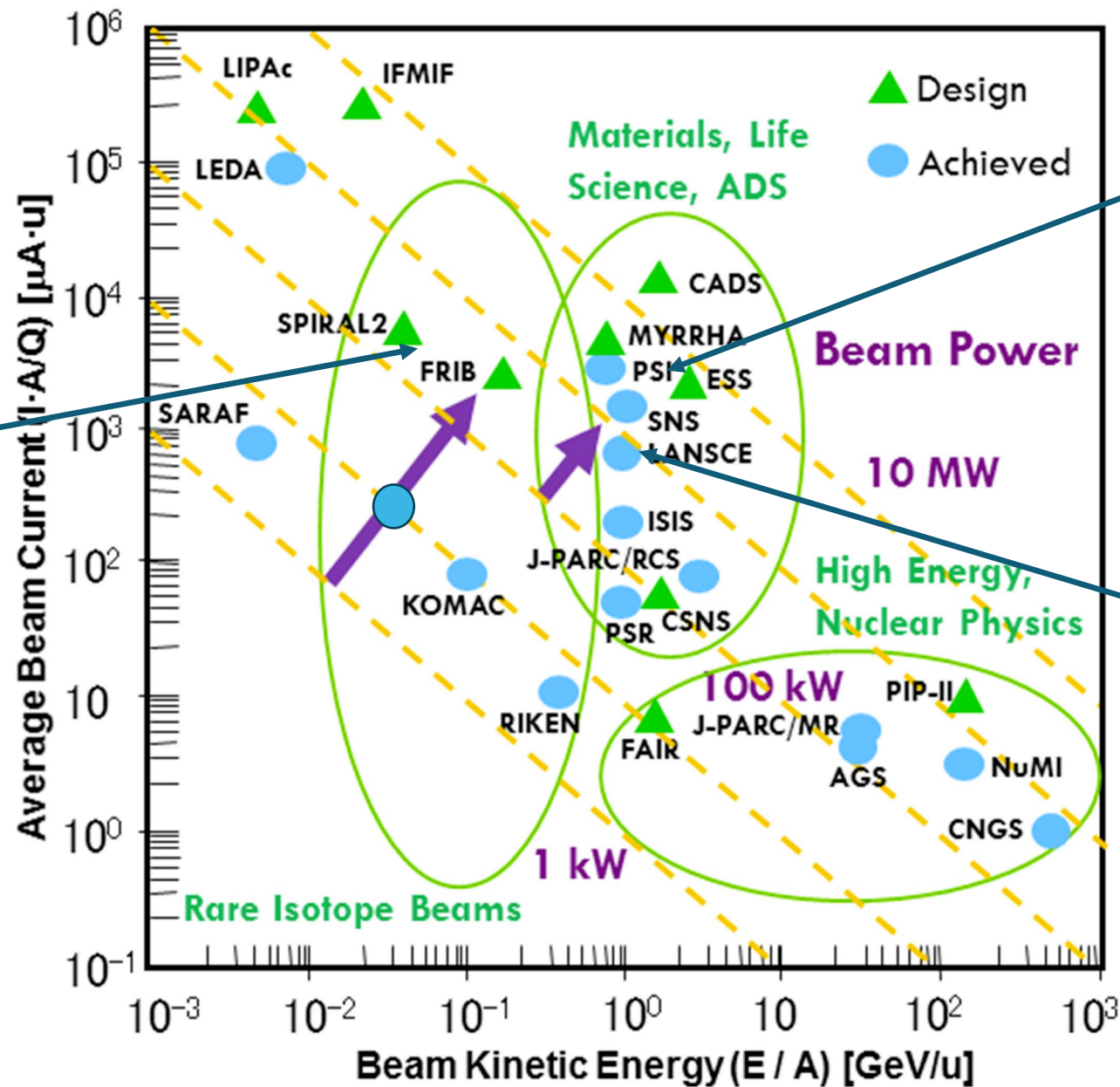
Space charge limits ($\sim 1/\gamma^2$)

- At source
- In rings at injection

Intensity upgrade of rings:

- raise injection energy into ring
eg CERN Linac4, FNAL PIP-II
- reduce cycle time
eg J-PARC Main Ring
- replace ring by linac

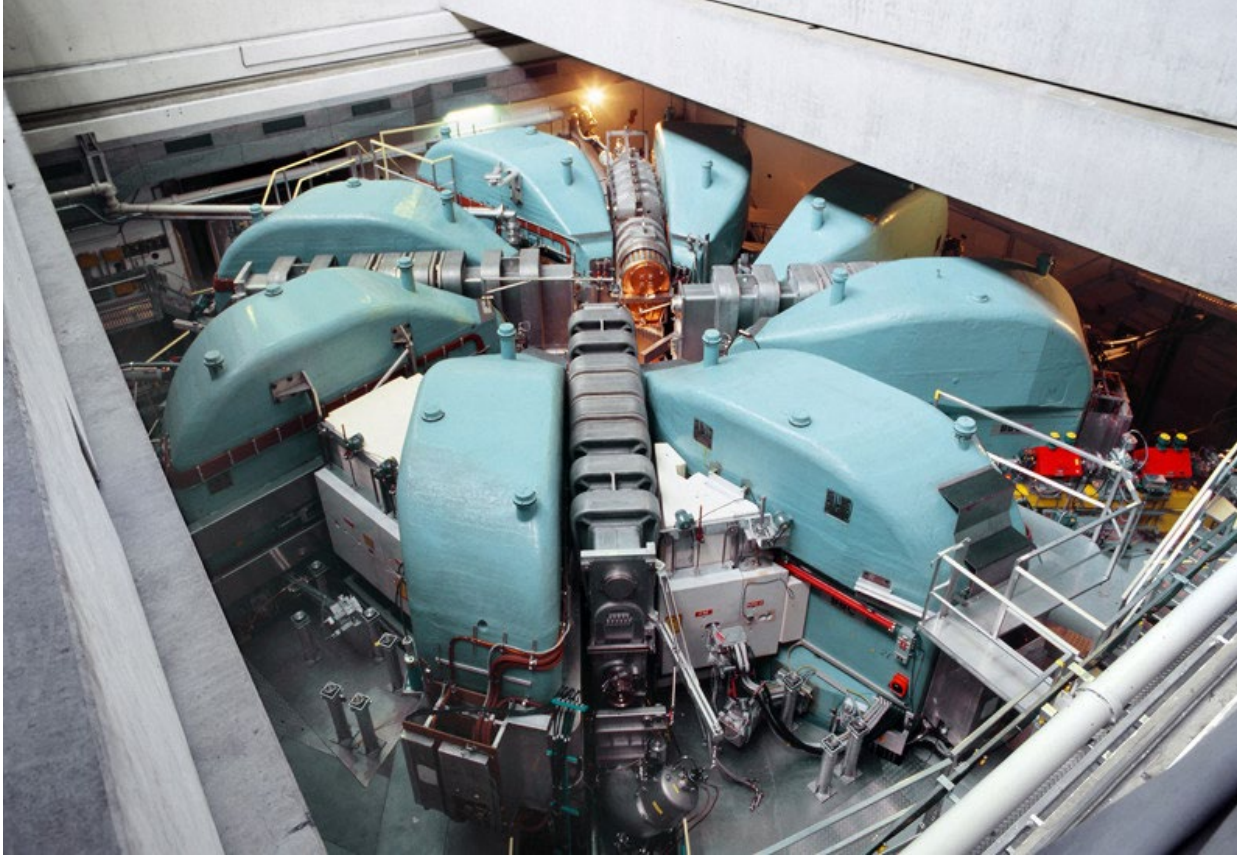
accelerators
for rare
isotopes



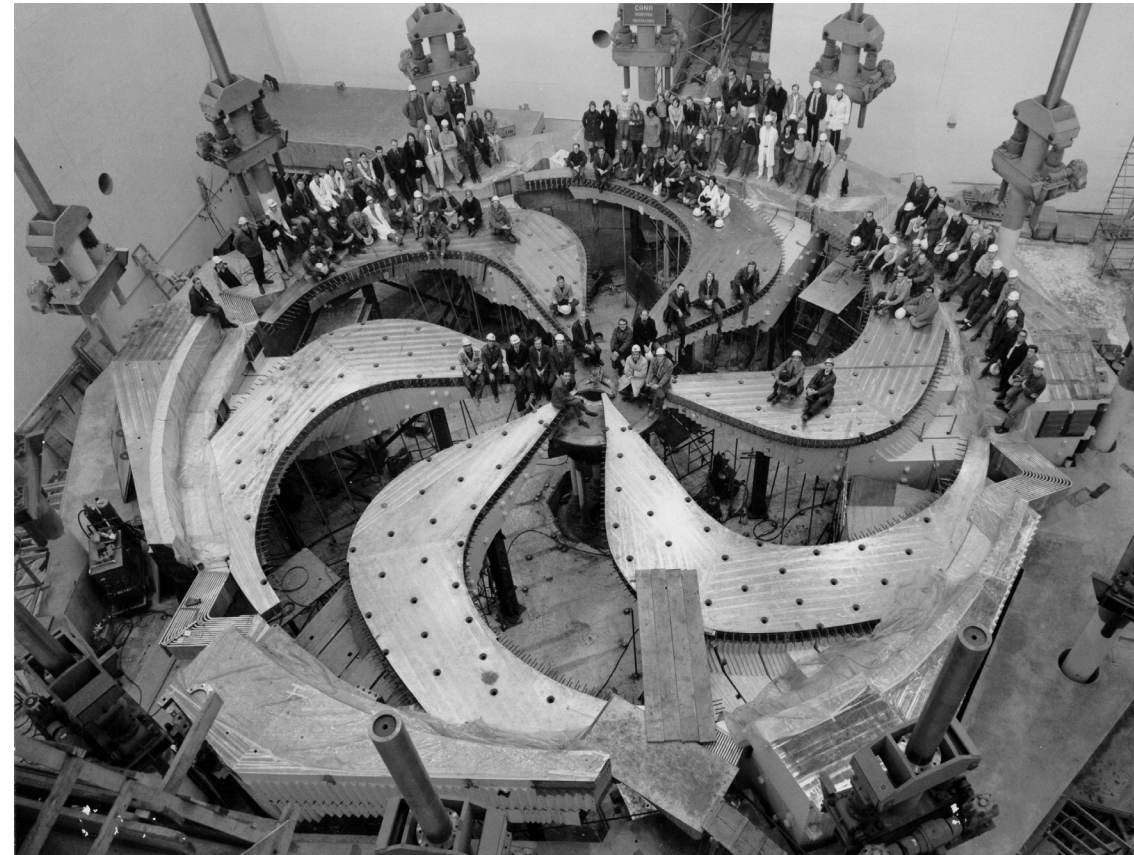
present power frontier:
PSI Cyclotron 1.4 MW
ORNL SNS 1.4 MW
(SNS 2x by 2025)

neutron sources
(often also μ sources)

n and μ^+/μ^- PSI and TRIUMF Cyclotrons for



Paul Scherrer Institute (PSI), Cyclotron
Particle: p, most energy efficient machine today
 $E = 590 \text{ MeV}$, $P = 1.4 \text{ MW}$
Experiments: e.g. mu3e $\mu^+ \rightarrow e^+ e^+ e^-$



TRIUMF, Cyclotron
Particle: H^- , multiple simultaneous extractions
 $E = 520 \text{ MeV}$, $P = 0.2 \text{ MW}$
Experiments: e.g. PIENU $\pi^+ \rightarrow e^+ \nu / \pi^+ \rightarrow \mu^+ \nu$

Accelerators for rare isotopes

Isotope Separation On-Line:

light beam (~ 1 GeV p) on thick target

Fragmentation Facility:

high-Z beam on thin target

ISOL

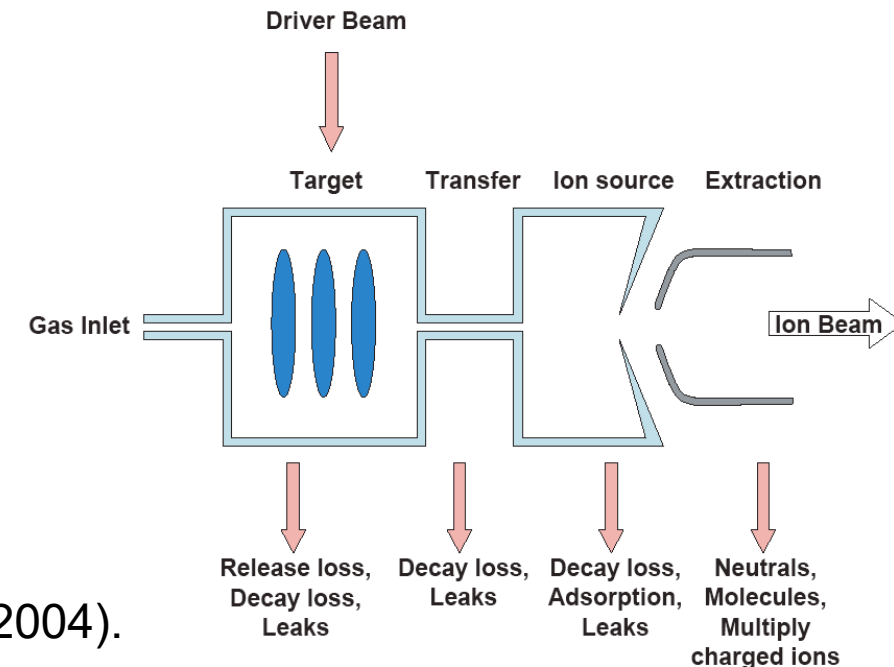
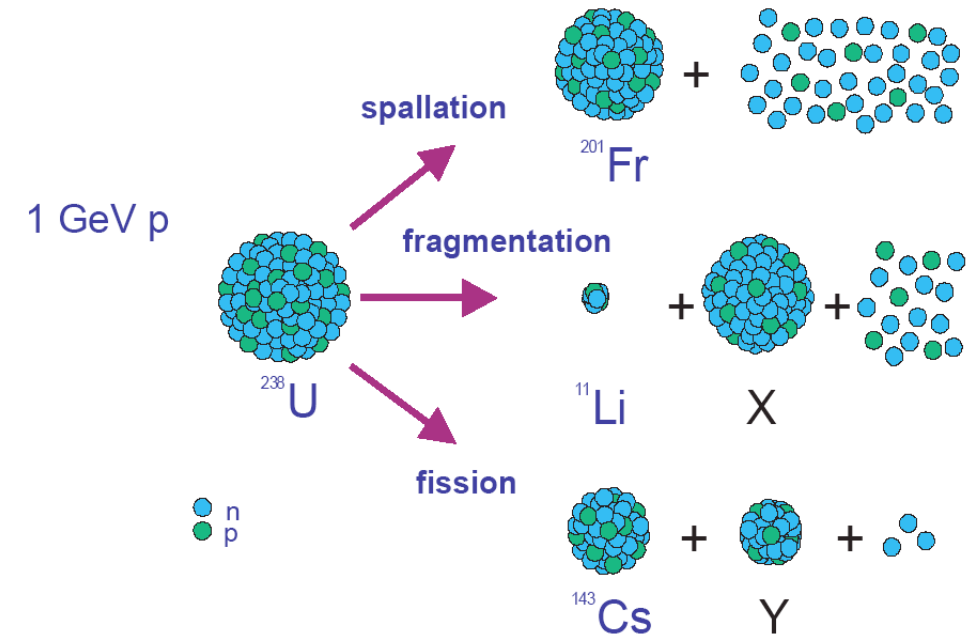
high-intensity proton beam ~ 1 GeV
thick target

high production rate at rest / low energy

good for low-energy experiments

difficult to achieve high purity

re-acceleration possibly, charge breeding
(increased charge $q \Rightarrow F = qE$
need sufficient lifetime for breeding)



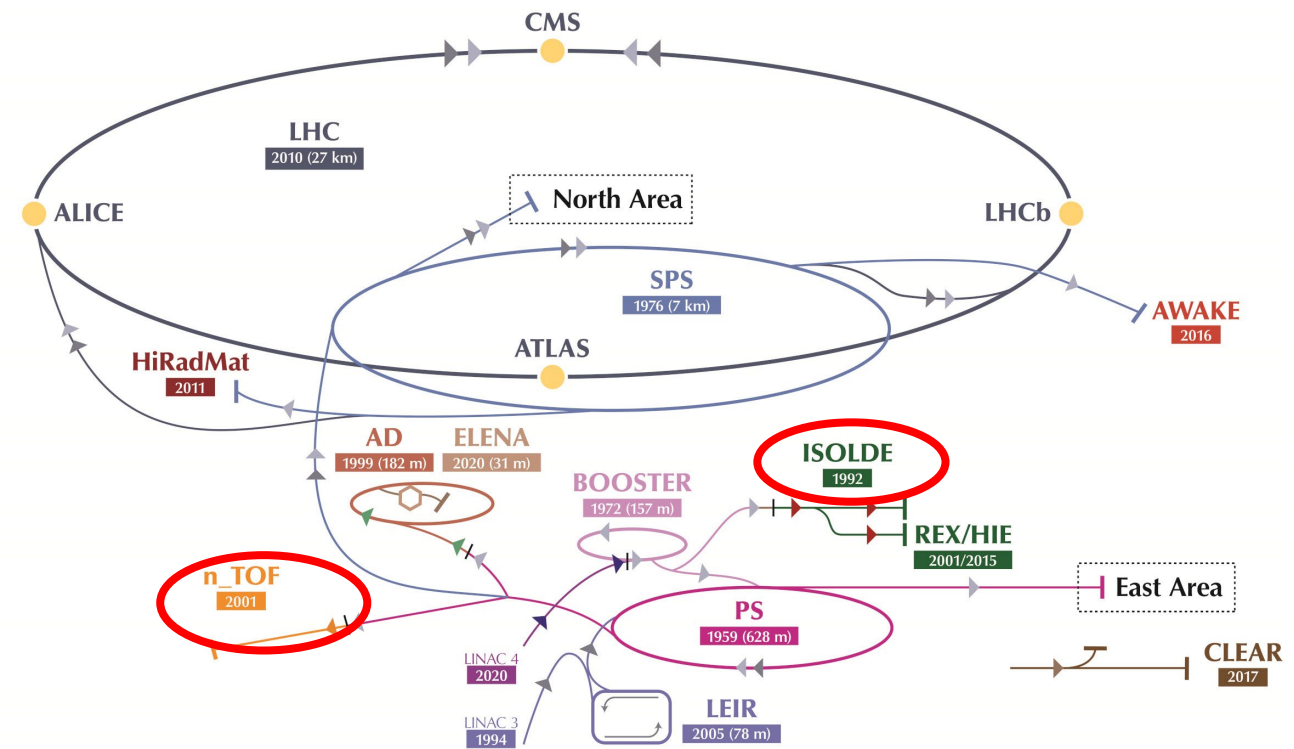
CERN PS and SPS

Extensive LHC Injector Upgrade (LIU) recently completed - increased Linac and Booster energy

PS Booster to **ISOLDE**

PS to East Area and **n_TOF**

SPS to North Area



HiRadMat = High-Radiation to Materials

Protons: 440 GeV, max 3.46×10^{13} p/pulse, max 2.4 MJ/pulse, 7.95 μ s pulse

Lead : 173.5 GeV/nucleon, max 3.64×10^9 ions/pulse, max 21 kJ/pulse, 5.2 μ s pulse

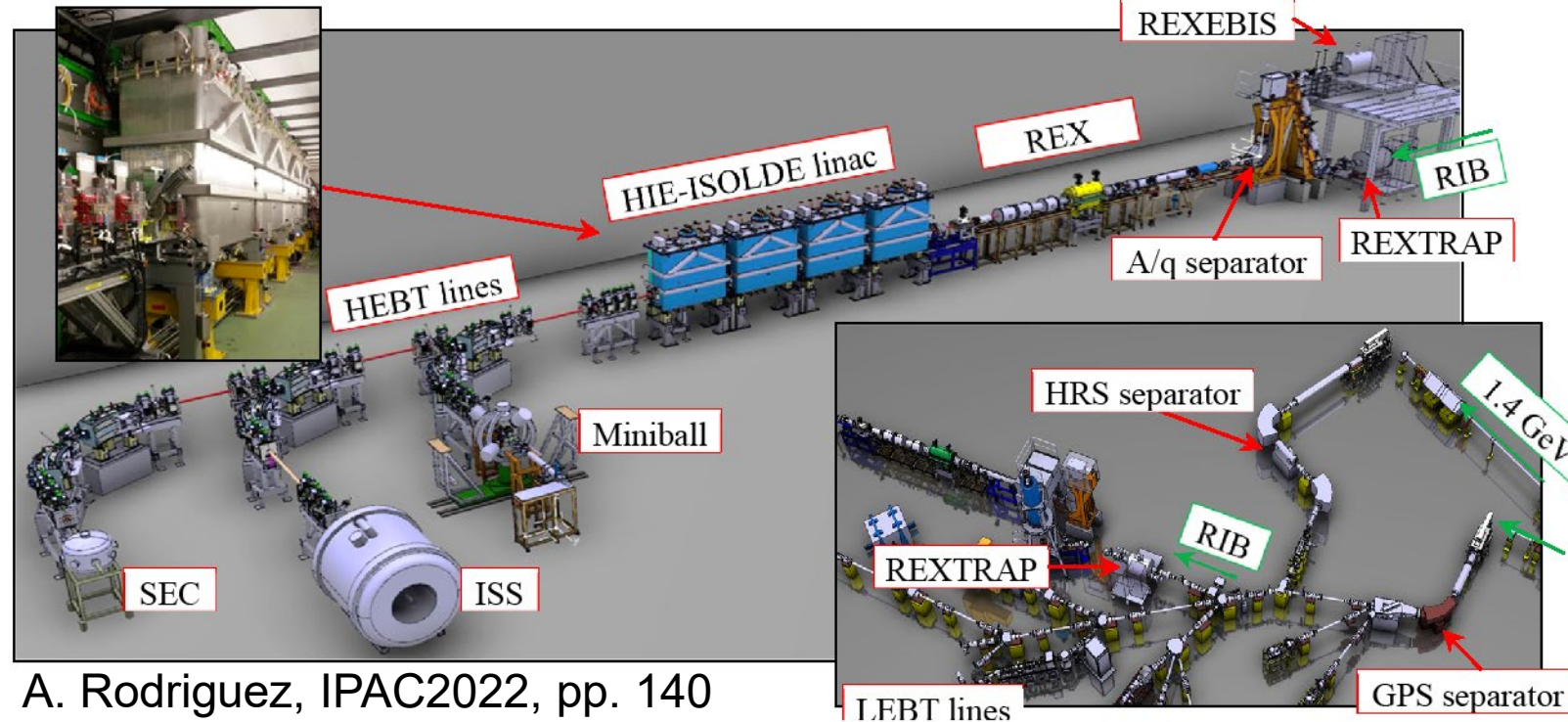
REX/HIE-ISOLDE, CERN

Energy: 1.4 GeV proton
from PS Booster

REX/HIE-ISOLDE

RIB in trap
charge breeding in
Electron Beam Ion Source
reacceleration to
10 MeV/nucleon

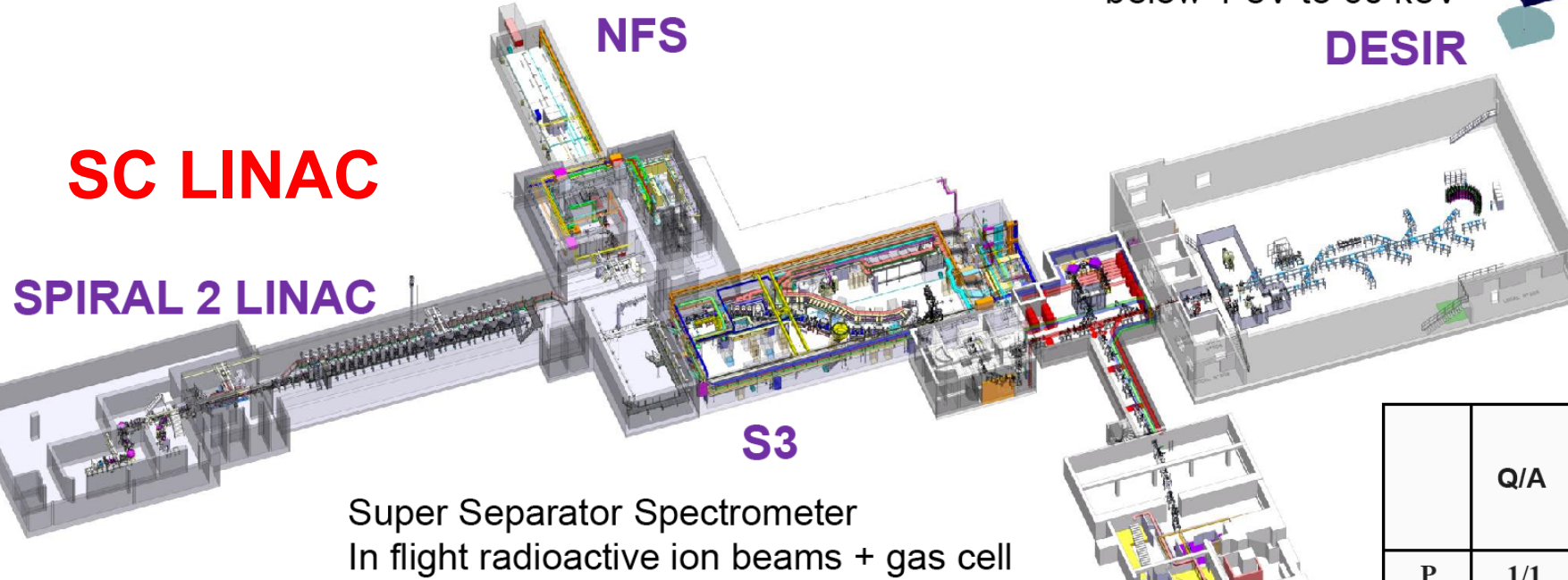
Superconducting RF
for high gradient (short linac)



A. Rodriguez, IPAC2022, pp. 140

Neutron for Science
Neutrons up to 30 MeV

Experimental areas for very
low energy beams:
below 1 eV to 60 keV



	Q/A	I max (mA)	Energy (MeV/n)	CW max beam power (kW)
P	1/1	5	2 - 33	165
He	2/3	1	2-24	36
D	1/2	5	2 - 20	200
Ions	1/3	1	2 - 14.5	45

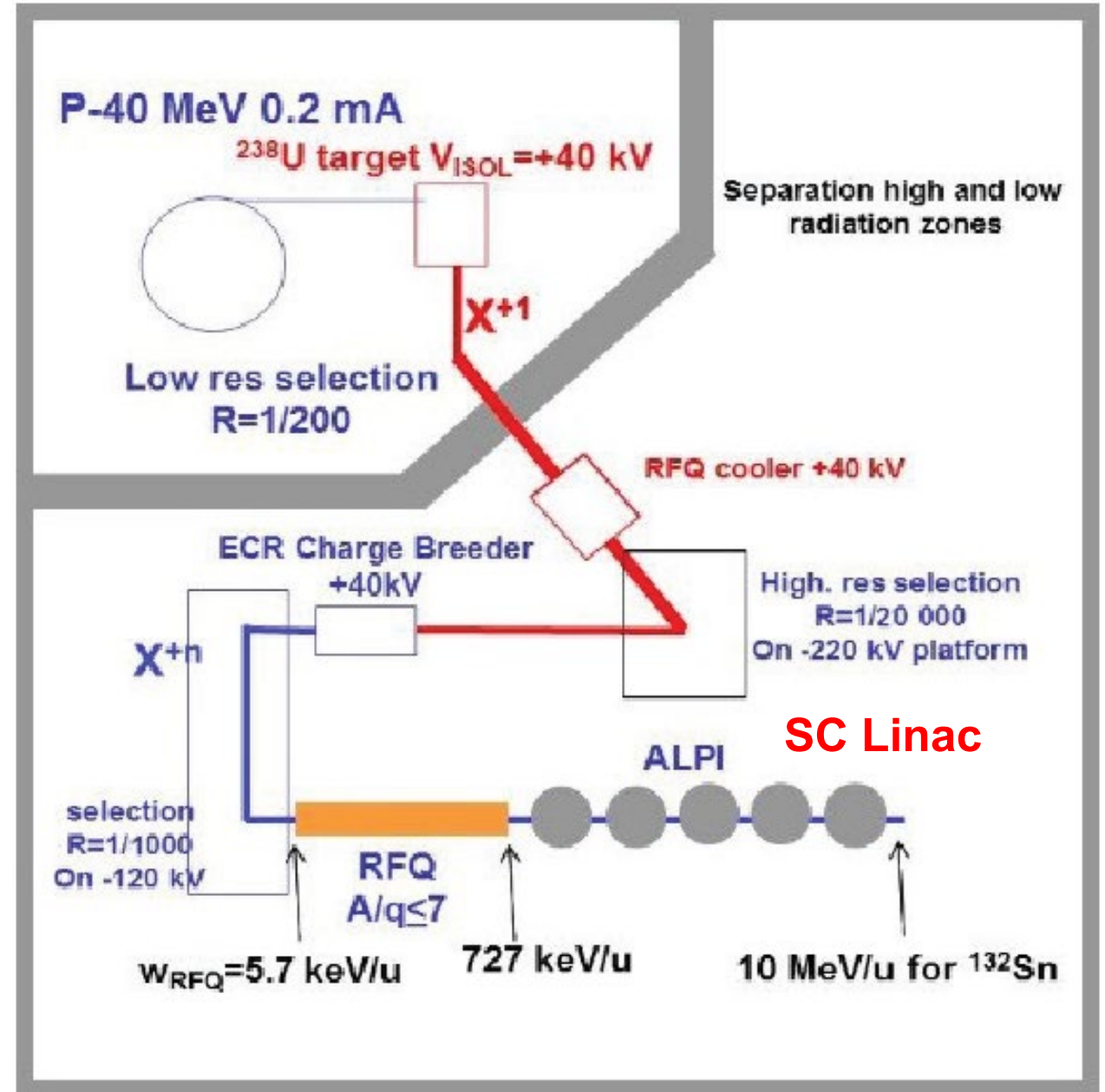


SPES Legnaro

Selective Production of Exotic Species

Cyclotron 70 MeV, 500 μ A
ISOL

RFQ Cooler
spectrometer
charge breeding
spectrometer
acceleration



FRIB, MSU US

Superconducting Linac

Energy: 200 MeV/nucleon (U)

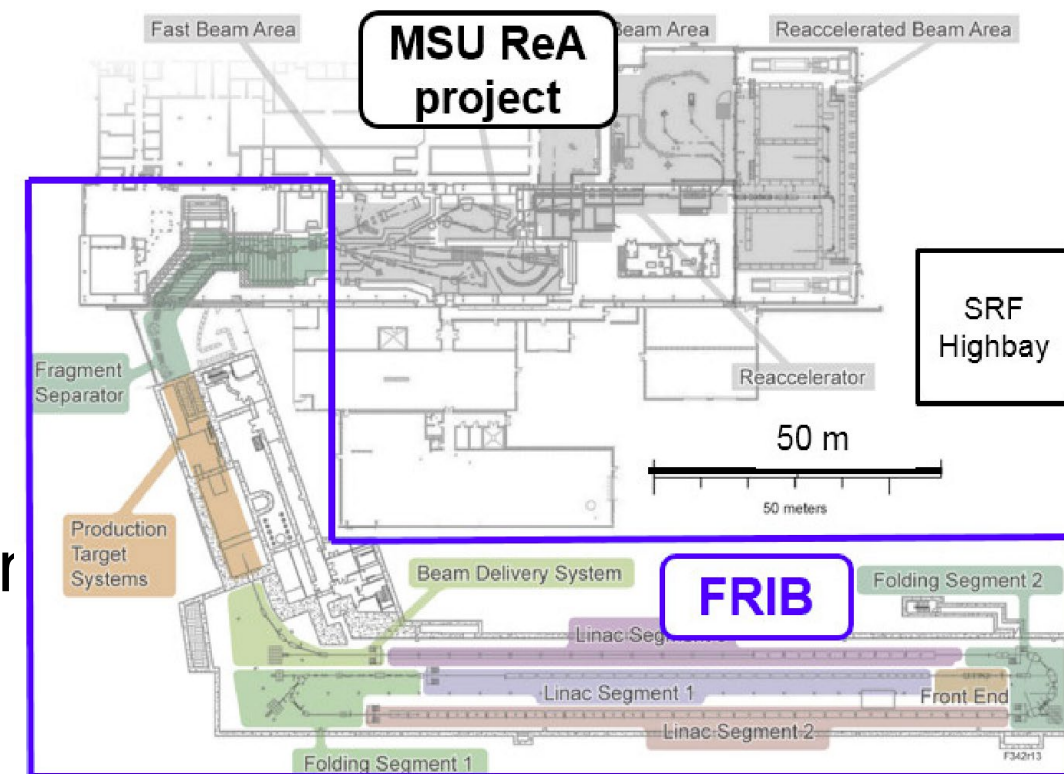
Beam power: 400 kW (design, **highest
HI beam power**) **now ~1 kW**

Operation: started in 2022

**SRF cavities and folded
geometry for small footprint**

Liquid Li charge stripper

Possible upgrade: E to 400 MeV/nucleon



RIBF, Japan (FF)

First Superconducting Ring Cyclotron (SRC)

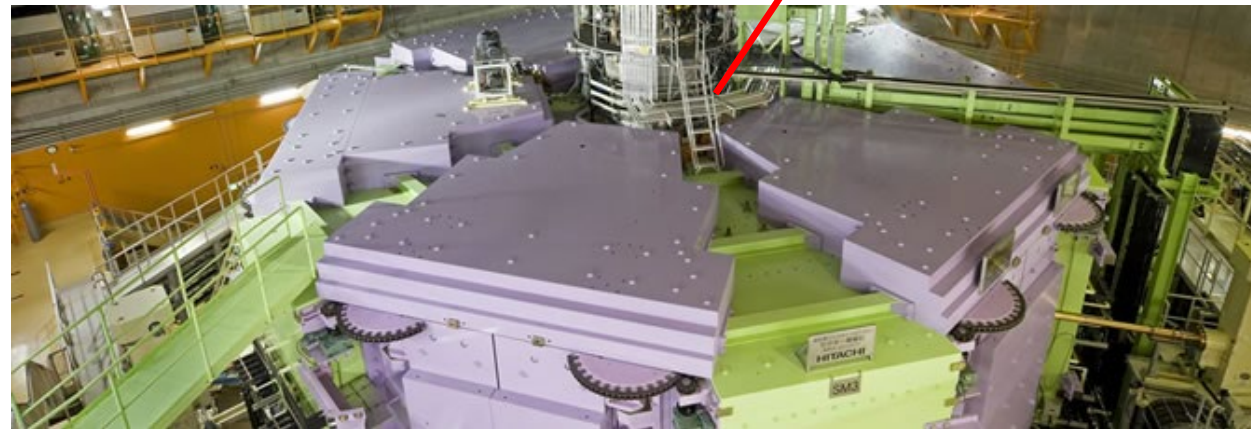
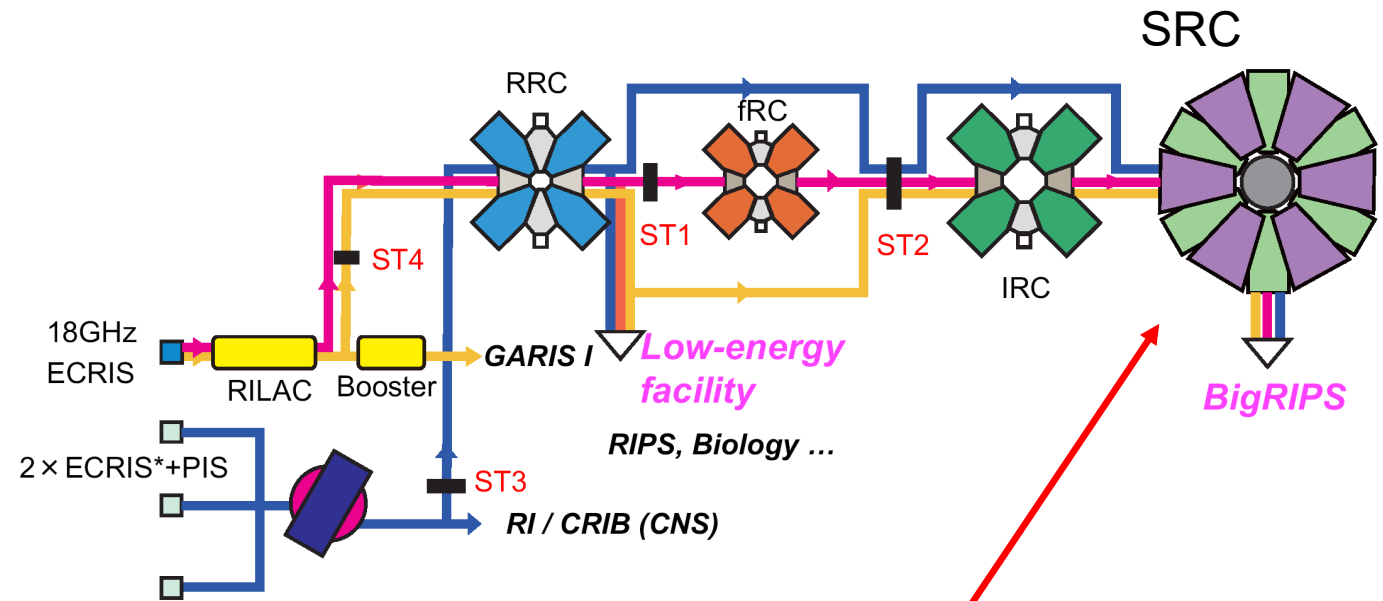
Energy: 345-440 MeV/n

Beam power: 20 kW

Superconducting magnet 3.8 T
($B\rho$) = 8 Tm, 8300 t

Upgrades:

Charge stripper ring between cyclotrons for increased U intensity – keeps partially stripped ions for further stripping



FAIR - Facility for Antiprotons and Ion Research, Darmstadt (FF)

SIS100 Energy:

Intensity:

5×10^{11} U^{28+} /cycle (50 kW)

$\sim 100 \times$ BNL AGS Au^{77+} /cycle

Fast cycling superferric magnets

(Nucletron type); ring designed to reduce dynamic vacuum rise from charge-exchange

Super Fragment Separator (SFRS)

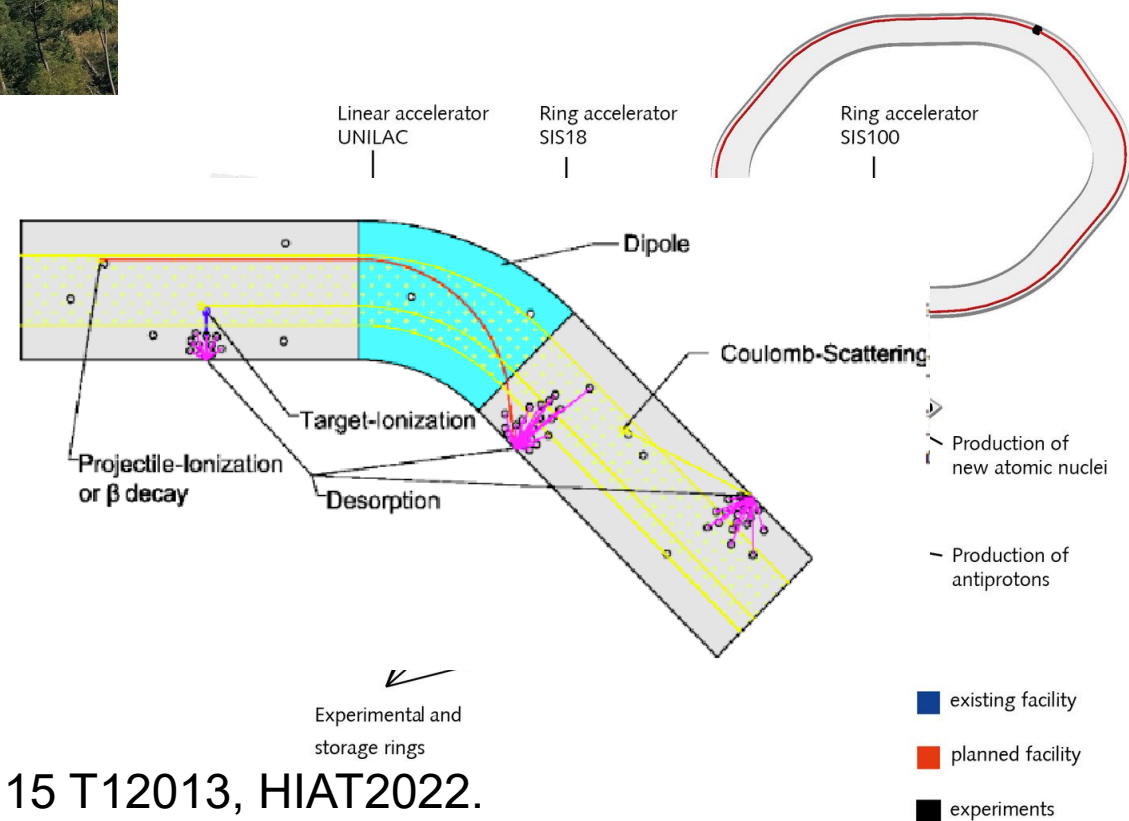
Storage rings: CR, HESR (pbar)

Commissioning start ~ 2024



P. Spiller, P. Spiller et al 2020 JINST 15 T12013, HIAT2022.

SIS100 covered again, Sep 2022



Factory for SHE, Dubna

Cyclotron DC-280

Energy: 4-8 MeV/n

High current: up to 10 pμA

Synthesis of elements $Z > 118$

(double-magic ^{48}Ca with neutron-rich $^{242,244}\text{P}$, ^{243}Am , ^{249}Cm , ^{249}Bk , and ^{249}Cf)

Note: SHE search at GSI with Linac (UNILAC, possibly SRF linac in future)

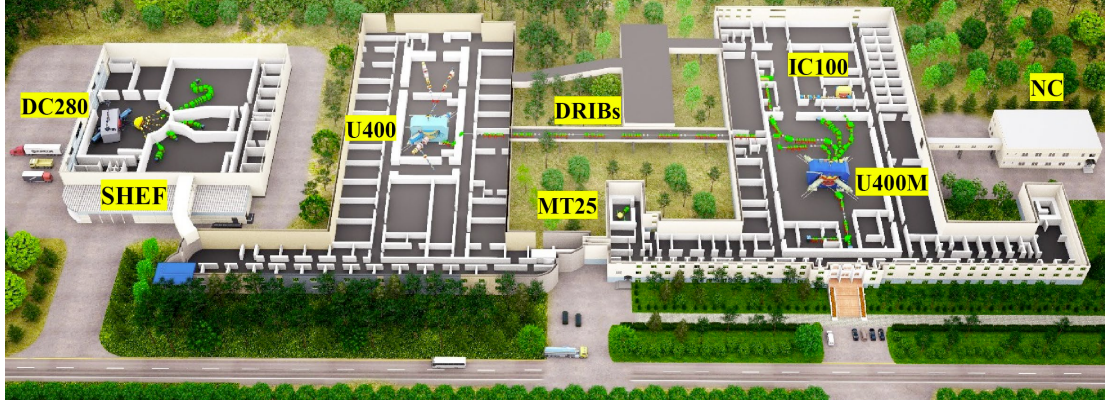
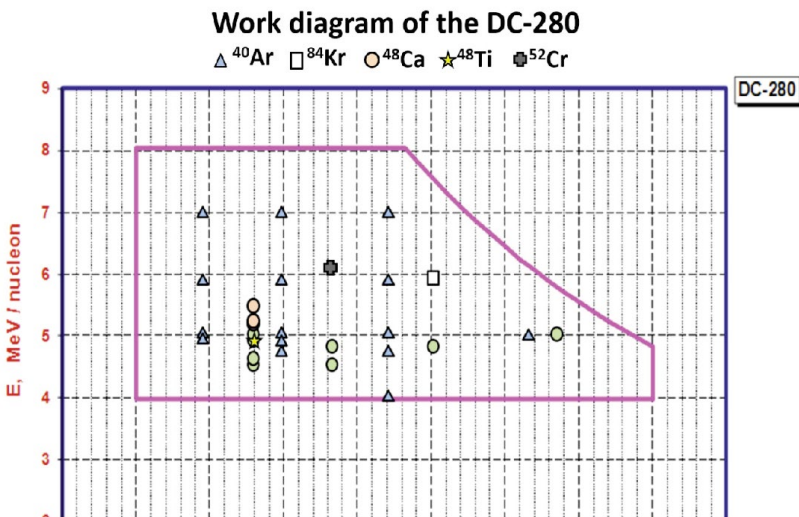


Figure 2: Layout of the Flerov Laboratory buildings, where: U400, U400M, IC100, DC280 are heavy ion cyclotrons, MT25 is the microtron, SHEF is the Super Heavy Element Factory, NC is the Nanotechnology Centre.

Table 1: Main Parameters of DC-280 Cyclotron

Parameters	Design	Achieved
Injecting beam energy	Up to 80 keV/Z	38,04 – 72,89 keV/Z
A/Z	4÷7.5	4,4($^{40}\text{Ar}^{+7}$) ÷ 6,9($^{48}\text{Ca}^{+7}$)
Energy	4÷8 MeV/n	4,01 – 7 MeV/n
Ion (for DECRIS-PM)	4-136	12 ($^{12}\text{C}^{+2}$) – 84 ($^{84}\text{Kr}^{+14}$)
Intensity (A~50)	>10 pμA	10,4 pμA ($^{40}\text{Ar}^{+7}$);
Magnetic field level	0.6÷1.3 T	0.8÷1.23 T
K factor		280
Dee voltage	2x130 kV	130 kV
Power of RF generator	2x30 kW	
Accelerator efficiency	>50%	51,9 % ($^{48}\text{Ca}^{+10}$ 5 pμA)



Colliders

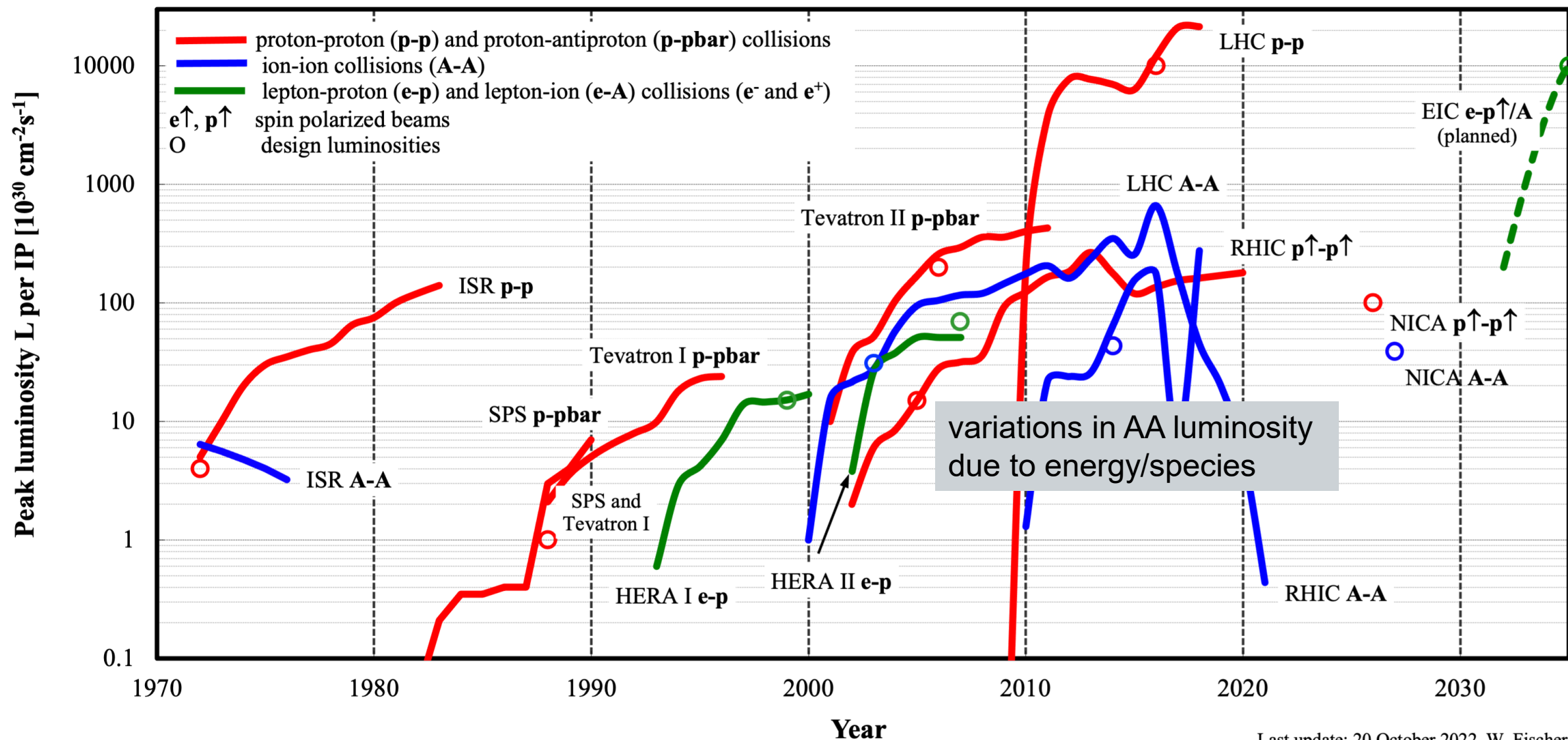
High-Energy Physics and
high-energy Nuclear Physics

Colliders hh and eh: RHIC, LHC, NICA, EIC

[Reported numbers or design]

	RHIC pp (actual)	LHC pp (actual)	RHIC AA (actual)	LHC AA (actual)	NICA AA (design)	EIC ep, eA (design)
Start of operation [year]	2001	2009	2000	2010	2023 (planned)	2032 (planned)
Species	p↑+p↑ (polarized p)	p+p	p↑+Al, p↑+Au, d+Au, h+Au, O+O, Cu+Cu, Cu+Au, Zr+Zr, Ru+Ru, Au+Au, U+U	Pb+Pb, p+Pb, Xe+Xe	p↑+p↑ to Au+Au (polarized p, d)	e↑+p↑ to e↑+U (polarized e,p, He-3)
Circumference [km]	3.8	26.7	3.8	26.7	503	3.8
Beam energy [total, GeV]	255	6800	100 A	2560 A	5.5-13 GeV	5-18 / 40-275
CoM energy [GeV]	510	13600	200 A	5120 A	27, 11A	28-140 (e↑+p↑)
Average beam current [mA]	257	510	224 (Au+Au)	24 (Pb+Pb)	~300 (Au)	2500 / 1000
Peak luminosity [$10^{30} \text{ cm}^{-2} \text{ s}^{-1}$]	245	2100	0.015 (Au+Au)	0.006 (Pb+Pb)	100 (p+p), 0.001 (Au+Au)	10000 (e↑+p↑)
Spin polarization	55-60%	0	0	0	>50% p,d	70% e,p,h

Luminosity evolution of hadron-hadron and lepton-hadron colliders

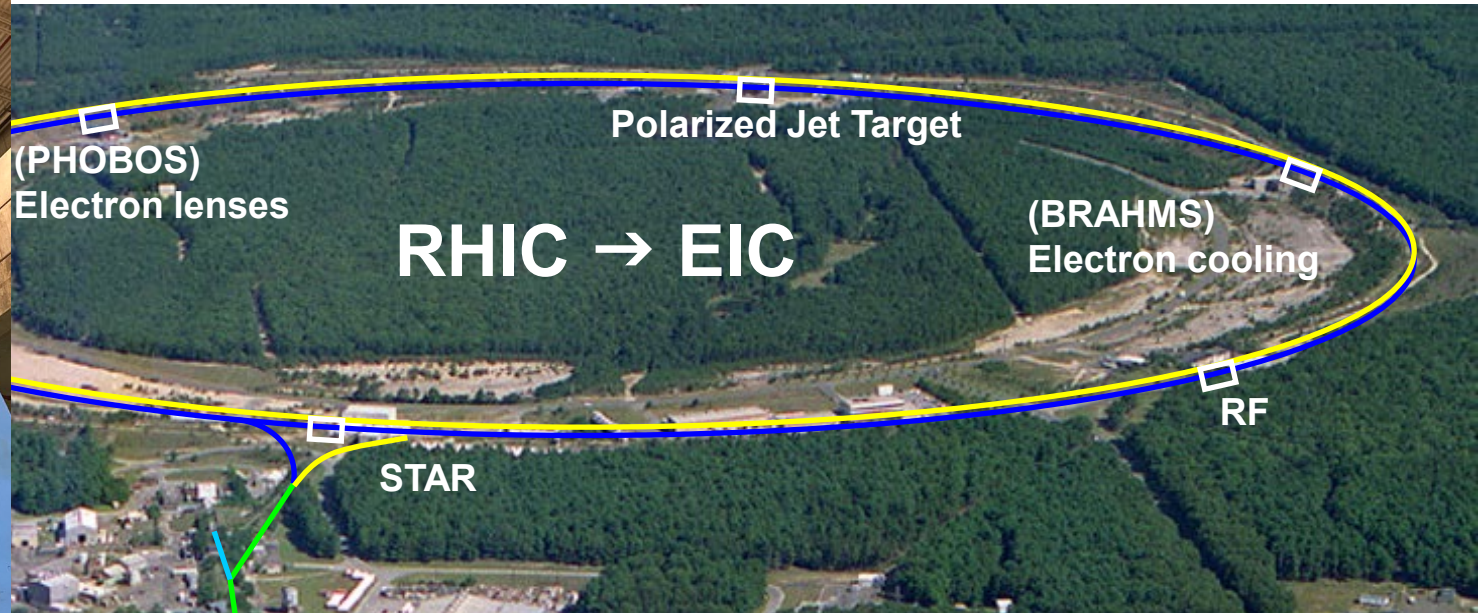


Last update: 20 October 2022, W. Fischer

Relativistic Heavy Ion Collider at Brookhaven National Lab

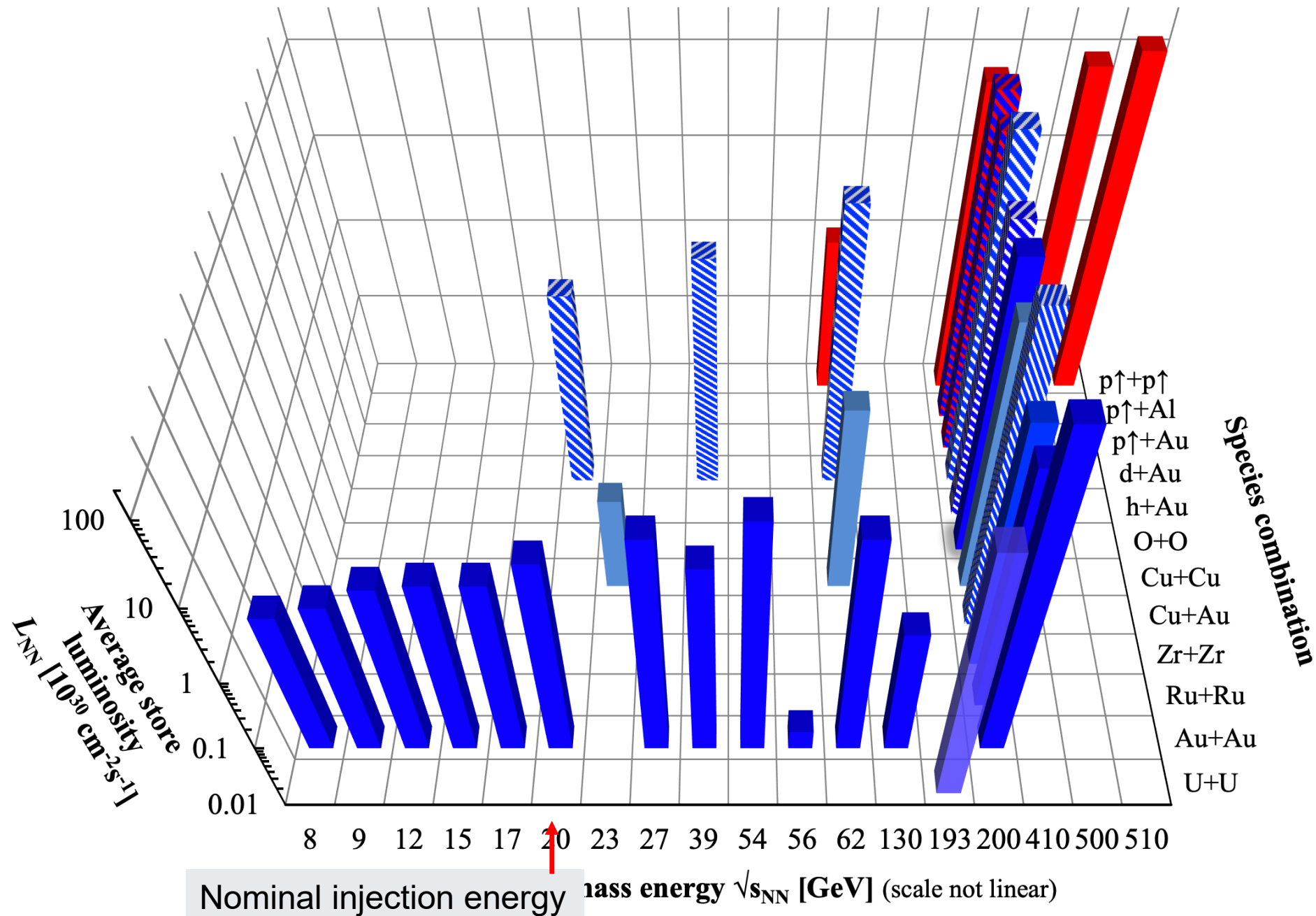


New sPHENIX detector
to be completed for
operation 2023-2025
(uses former BaBar magnet)



Operation	: 2000 – 2025 (planned)
Circumference	: 3.8 km
Max dipole field	: 3.5 T
Energy	: 255 GeV polarized p : 100 GeV/nucleon Au
Species	: p↑ to U (incl. asymmetric)
Experiments	: BRAHMS, PHOBOS (complete) STAR, PHENIX→sPHENIX

RHIC energies, species combinations and luminosities (Run-1 to 22)



Ion programs require high flexibility in

- Species
- Energy

also in LHC ion program

To date did not have same species combination in RHIC and LHC (apart from p+p)

O+O likely also in LHC in the future

LHC AA

Operation since 2011 (p since 2010)

Energy: 2560 A GeV (Pb)

Species to date: p+p, Pb+Pb, p+Pb, Xe+Xe

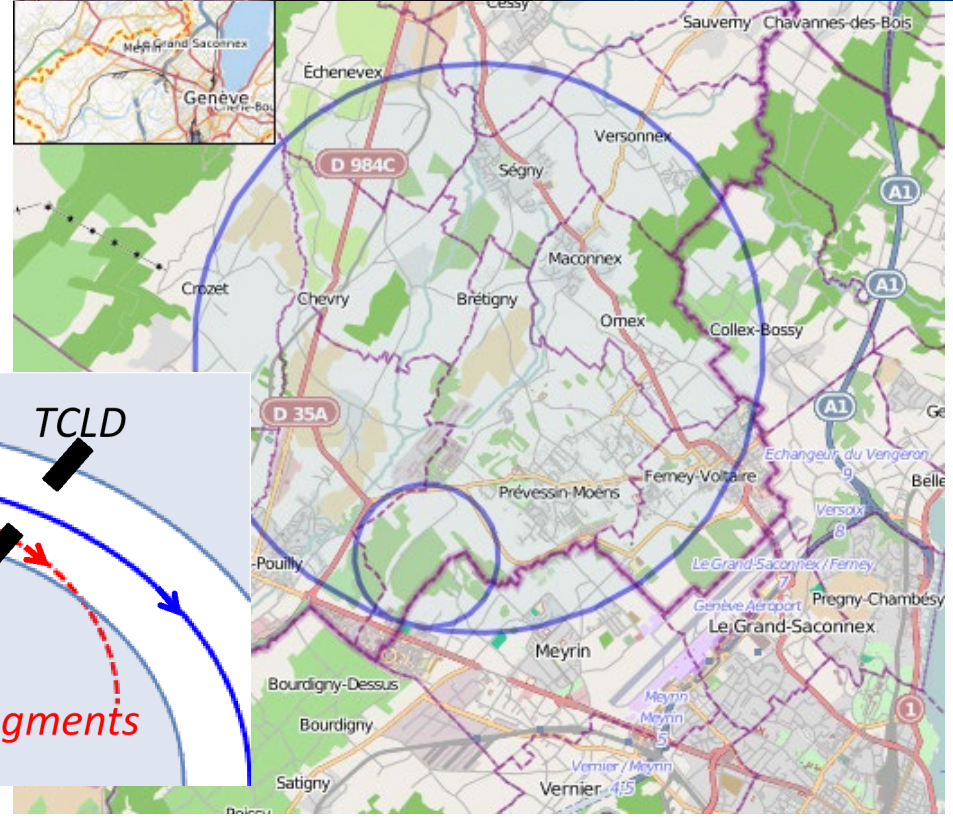
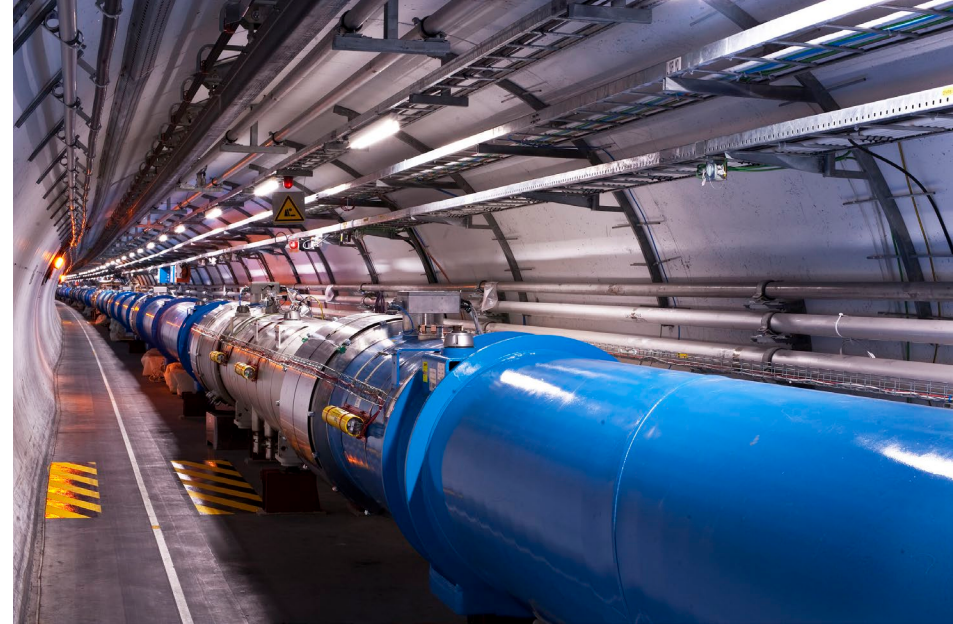
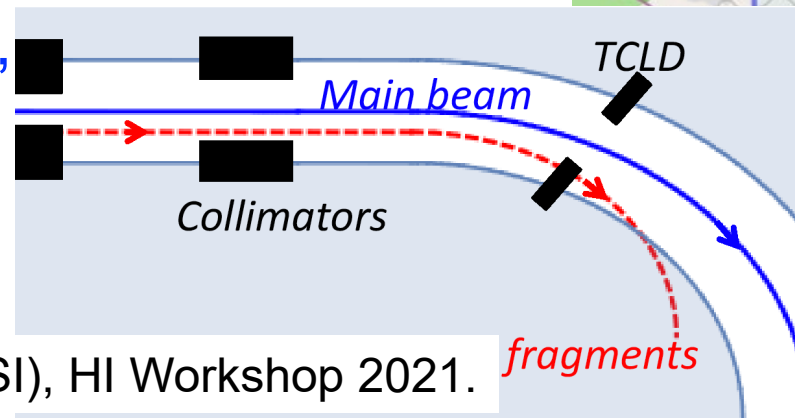
Detector optimized for ion program: ALICE

Luminosity limited by ion intensity from injectors,
and loss of secondary beams created in collision
and lost in cold magnets

BFPP = bound-free pair production ($\text{Pb}^{82+} \rightarrow \text{Pb}^{81+}$)

EMD = Electro-Magnetic Dissociation ($^{208}\text{Pb} \rightarrow ^{207}\text{Pb}$)

=> orbit bumps, new collimators,
crystal collimation



LHC AA – present and future

- **Pb–Pb at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$, $L_{int} = 13 \text{ nb}^{-1}$ (ALICE, ATLAS, CMS), 2 nb^{-1} (LHCb)**
- **pp at $\sqrt{s} = 5.5 \text{ TeV}$, $L_{int} = 600 \text{ pb}^{-1}$ (ATLAS, CMS), 6 pb^{-1} (ALICE), 50 pb^{-1} (LHCb)**
- **pp at $\sqrt{s} = 14 \text{ TeV}$, $L_{int} = 200 \text{ pb}^{-1}$ with low pileup (ALICE, ATLAS, CMS)**
- **p–Pb at $\sqrt{s_{NN}} = 8.8 \text{ TeV}$, $L_{int} = 1.2 \text{ pb}^{-1}$ (ATLAS, CMS), 0.6 pb^{-1} (ALICE, LHCb)**
- **pp at $\sqrt{s} = 8.8 \text{ TeV}$, $L_{int} = 200 \text{ pb}^{-1}$ (ATLAS, CMS, LHCb), 3 pb^{-1} (ALICE)**
- **O–O at** ← **Only combination that also ran in RHIC (apart from pp)**
- **p–O at $\sqrt{s_{NN}} = 9.9 \text{ TeV}$, $L_{int} = 200 \mu\text{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)**
- **Intermediate AA**, e.g. $L_{int}^{\text{Ar–Ar}} = 3\text{--}9 \text{ pb}^{-1}$ (about 3 months) gives NN luminosity equivalent to Pb–Pb with $L_{int} = 75\text{--}250 \text{ nb}^{-1}$

In Run 3 + Run 4

Proposal for after Run 4

R. Bruce, M. Schaumann (CERN), J. Jowett (GSI), HI Workshop 2021.

Possible future large AA colliders for NP: LHeC, FCC-hh, FCC-eh

NICA, Dubna

Nucleon-based Ion Collider Facility

Under construction

Injector commissioning started

Collider commissioning start 2023

Species: p , d to Au

Energy: 4-27 A GeV (some overlap with RHIC)

Luminosity: $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ for $p+p$
 $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ for Au+Au

~10x RHIC at lowest energy

small circumference reduces space charge:

$C = 503 \text{ m}$ vs 3834 m in RHIC

$\Delta Q_{sc} \sim C$ (space charge) limits storage rings



Figure 5: Installation of magnets in NICA tunnel.

Electron-Ion Collider

BNL-JLab partnership with national and international contribution
sited at BNL - uses RHIC hadron complex
CD-1 June 2021 (Conceptual Design complete, cost range),
operation 2032 (planned)

Hadron storage Ring (RHIC Rings) 40-275 GeV (existing)

- 1160 bunches, 1A beam current (3x RHIC)
- small vertical beam emittance 1.5 nm
- strong cooling (coherent electron cooling)

Electron storage ring 2.5–18 GeV (new)

- many bunches, large beam current, 2.5 A → 9 MW S.R. power
- SC RF cavities
- Full energy injection of polarized bunches

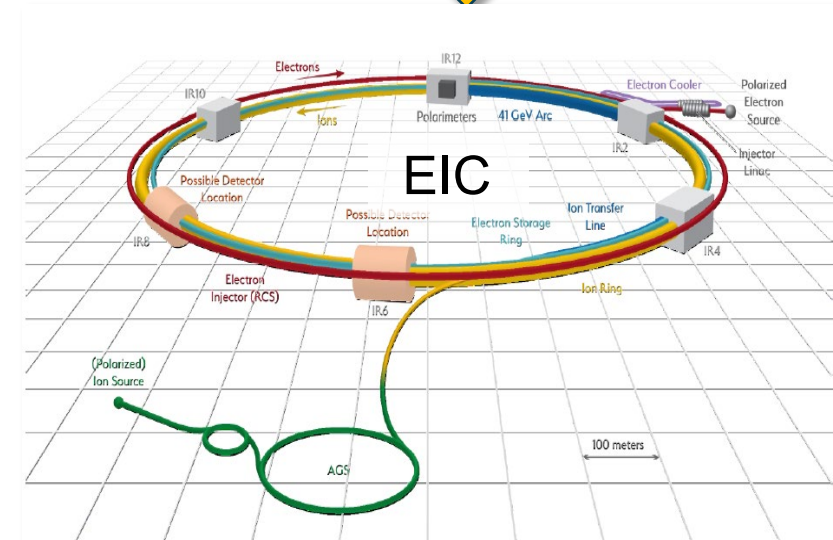
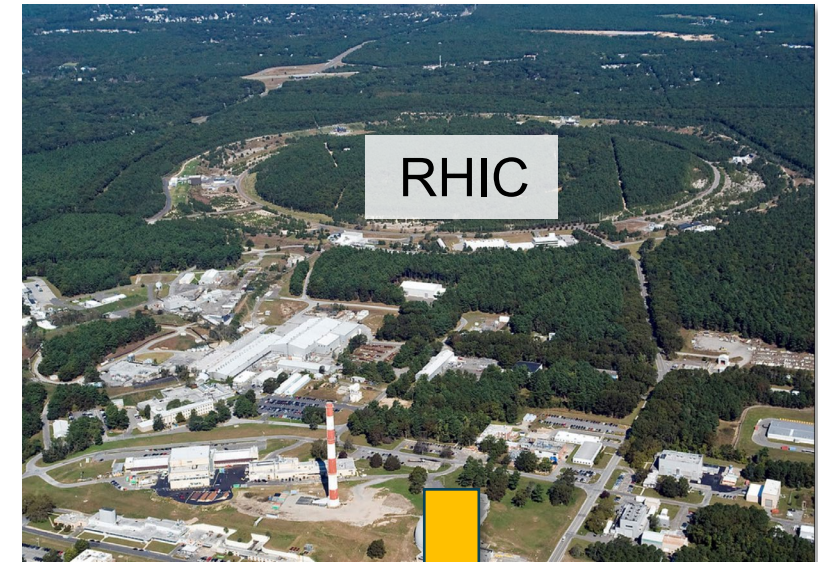
Electron rapid cycling synchrotron 0.4–(new)

- 1-2 Hz
- Spin transparent due to high periodicity

High luminosity interaction region(s) (new)

- $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Superconducting magnets
- 25 mrad full crossing angle with crab cavities
- Spin rotators (longitudinal spin)
- Forward hadron instrumentation

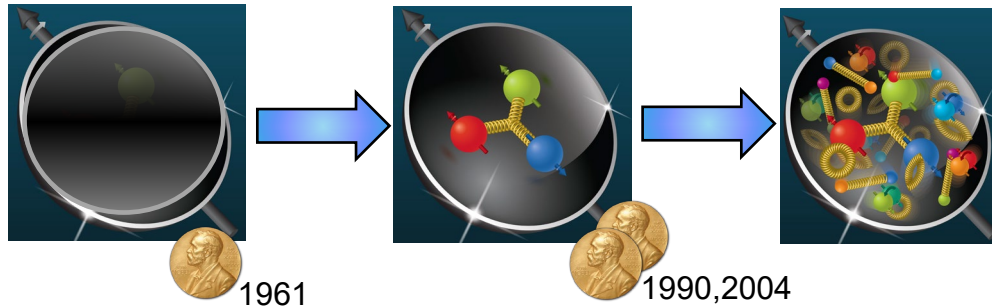
Ferdinand Willeke et al.



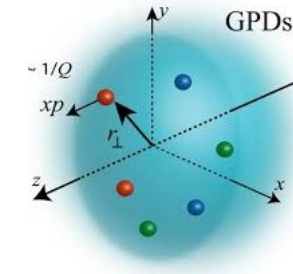
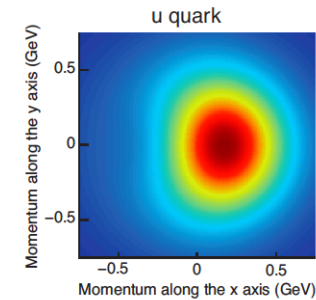
EIC Science Program

*EIC to unravel
the mysteries of visible matter*

The Proton

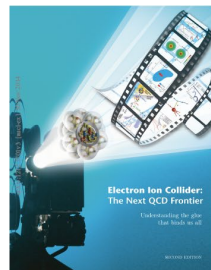
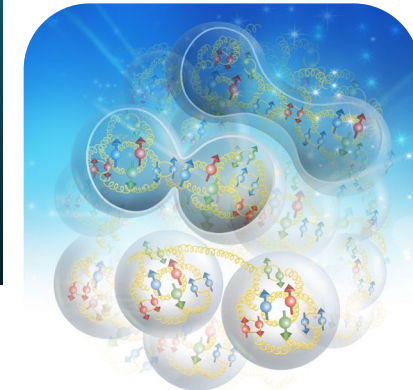
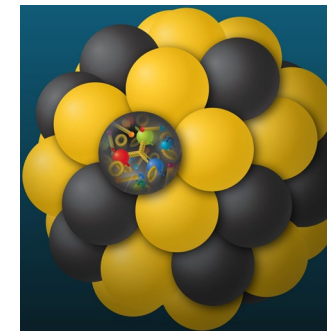


Multidimensional imaging of the structure of the proton: Origin of Mass, Spin, 3d-structure

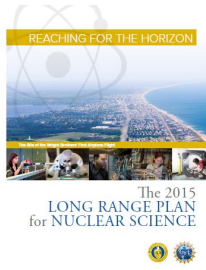


The proton
in a nucleus

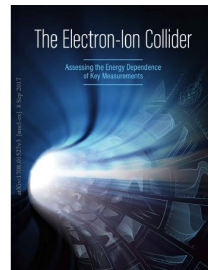
QCD dynamics
that can affect the
identity of
nucleons in a
nucleus



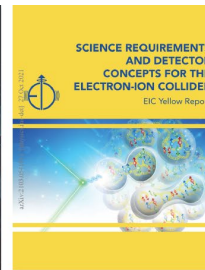
2012



2015



2017



2020

Summary – accelerators for nuclear physics

Large number and many types of accelerators used in NP

Electrostatic and cyclotrons

widely used for lower energies, some commercially available

High-intensity machines for (n, μ , rare isotopes)

~MW beam power machines operating, further power increases planned

Colliders (RHIC, LHC, NICA, EIC)

design and operation driven by
energy, luminosity, flexibility (NP much more than HEP)

Wide use of superconducting RF and magnets

Successful experimental programs also need high-intensity and polarized sources, efficient charge strippers, targets, charge breeders, post-acceleration, spectrometers, detectors (not well covered in talk)