Present and future accelerators for nuclear physics

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

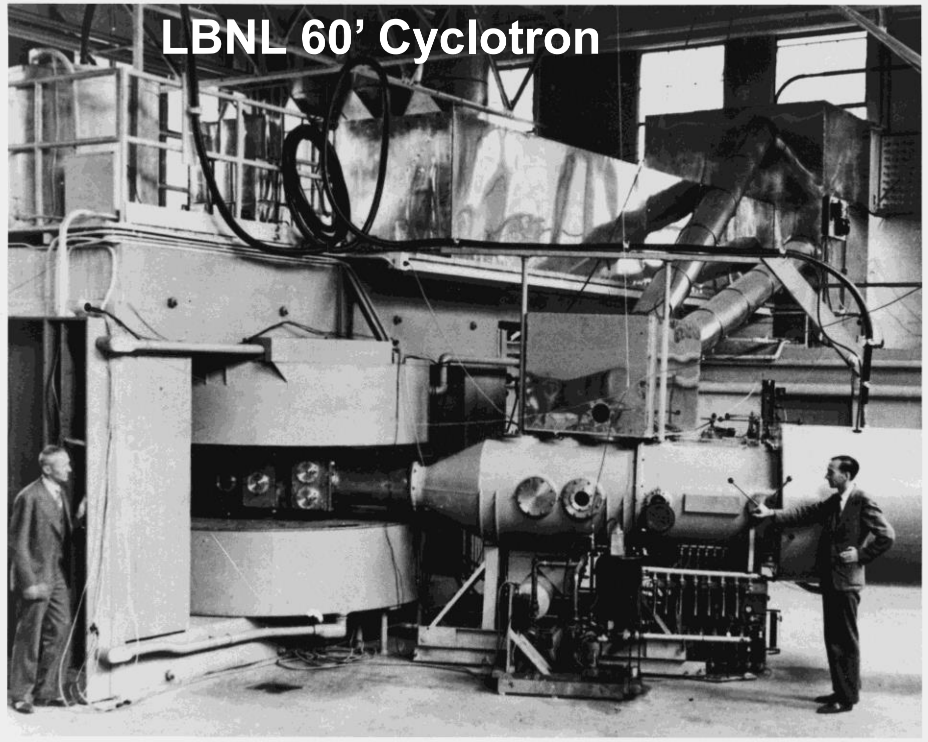
Wolfram Fischer
Brookhaven National Laboratory

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)

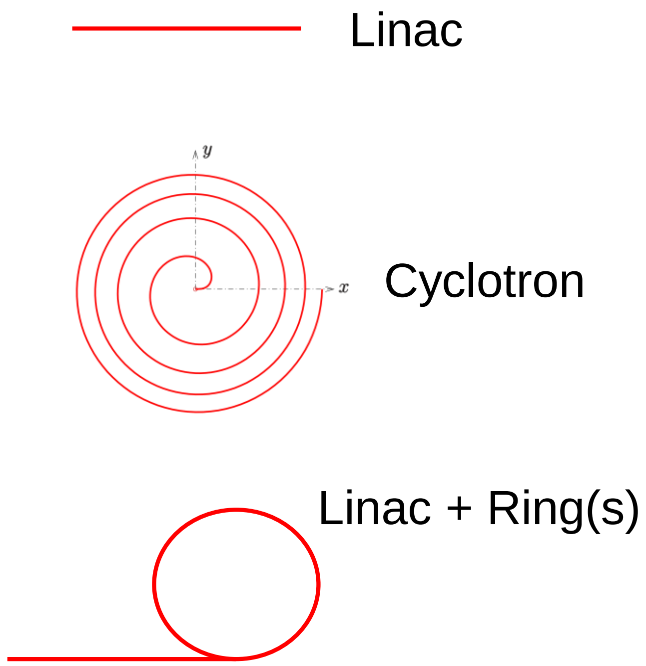
=> Accelerators with

- $\geq$ 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

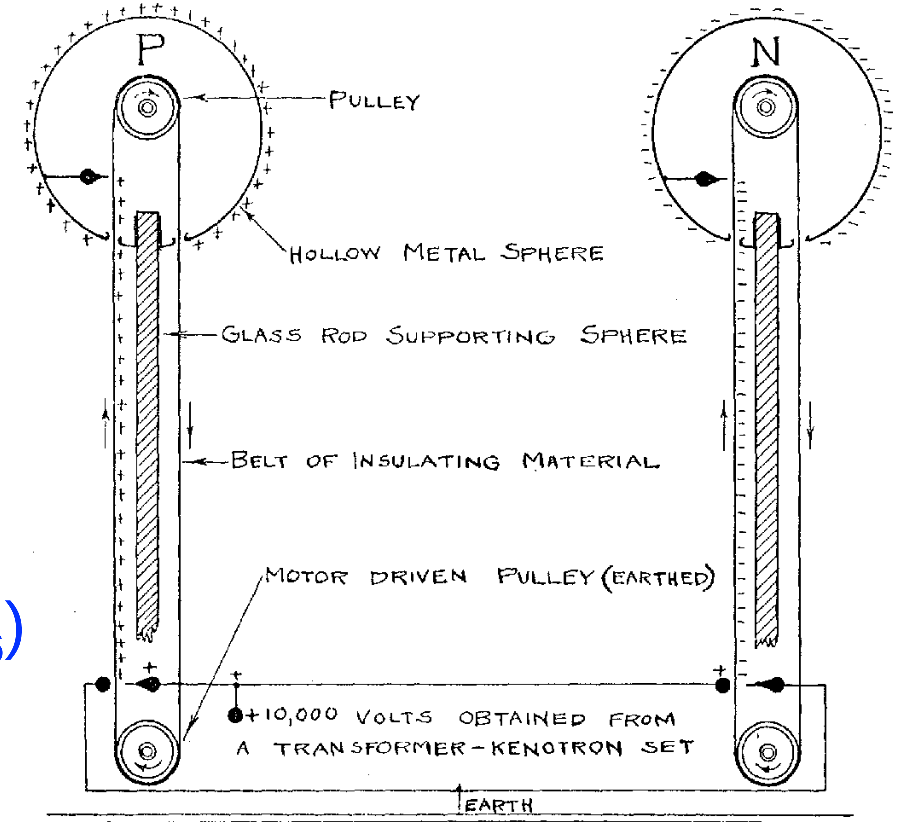
Single voltage drop: E = q V

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)


BNL Tandem Van de Graaff (28 MeV)

Cyclotrons

Energy : to ~600 MeV

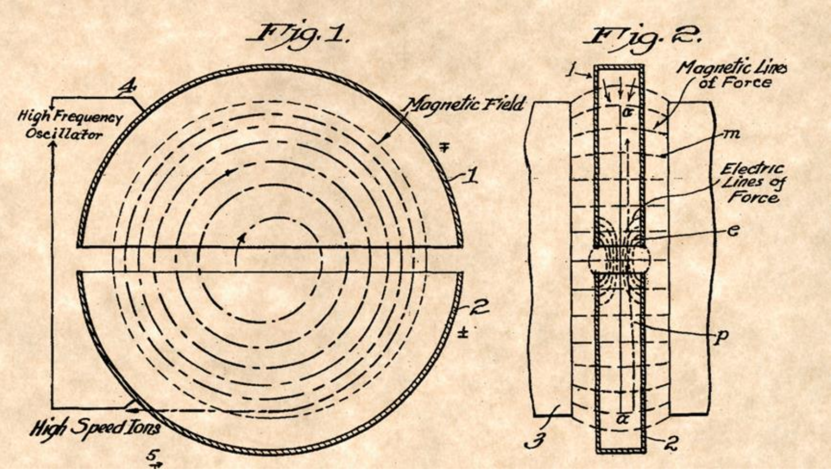
Species: p, H⁻, d, …, heavy ions

- 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)



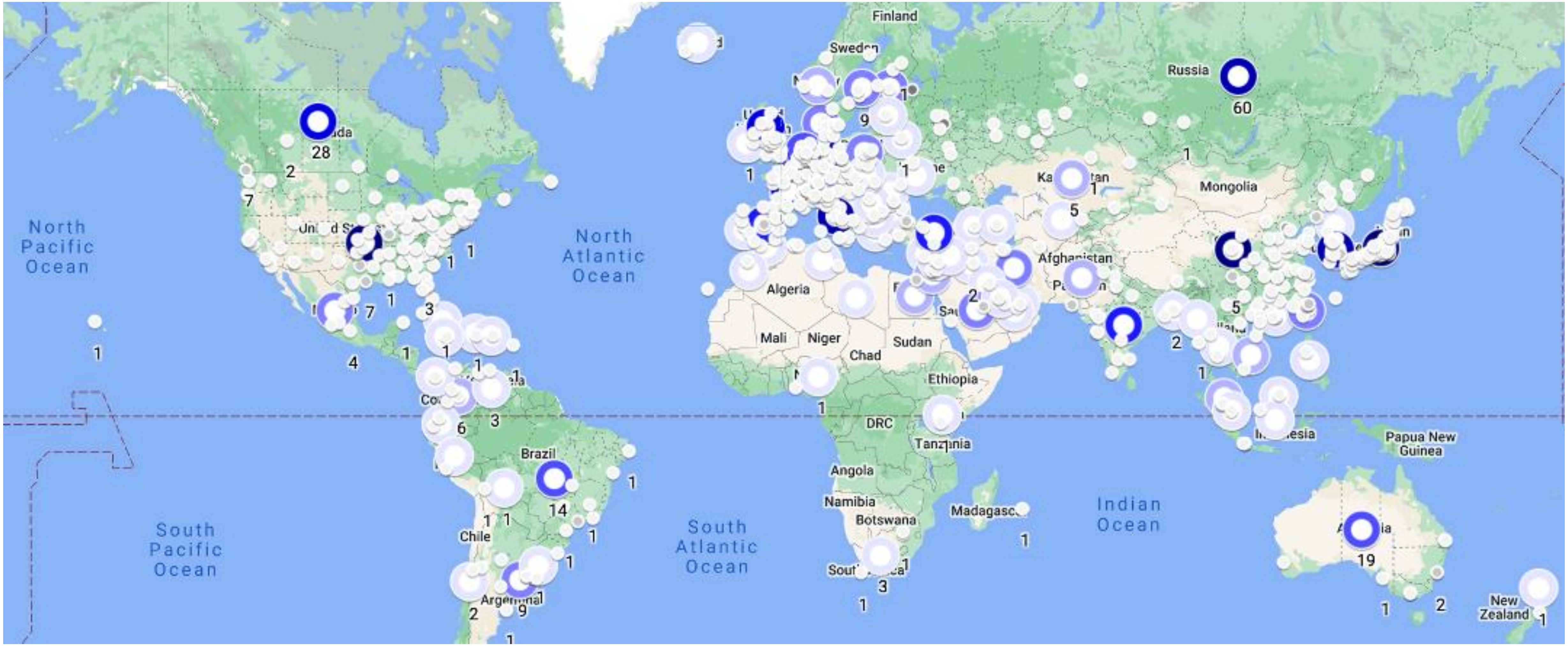
Cyclotron patent application, Ernest Lawrence (1932)

18 MeV cyclotron at CNA, Sevilla

Brookhaven National Laboratory

Over 1500 cyclotrons in the world

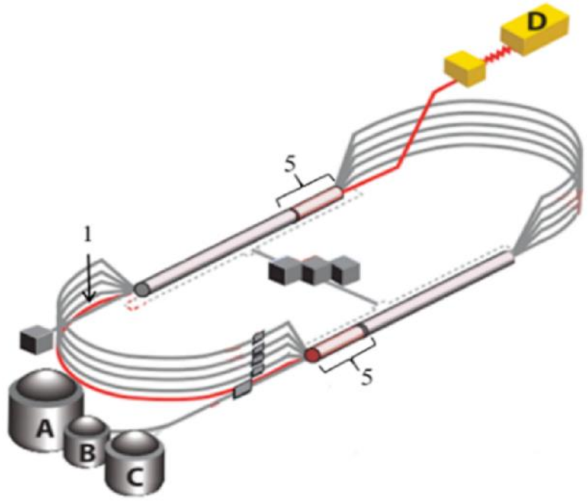
IAEA interactive database: >1300 in 95 countries



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

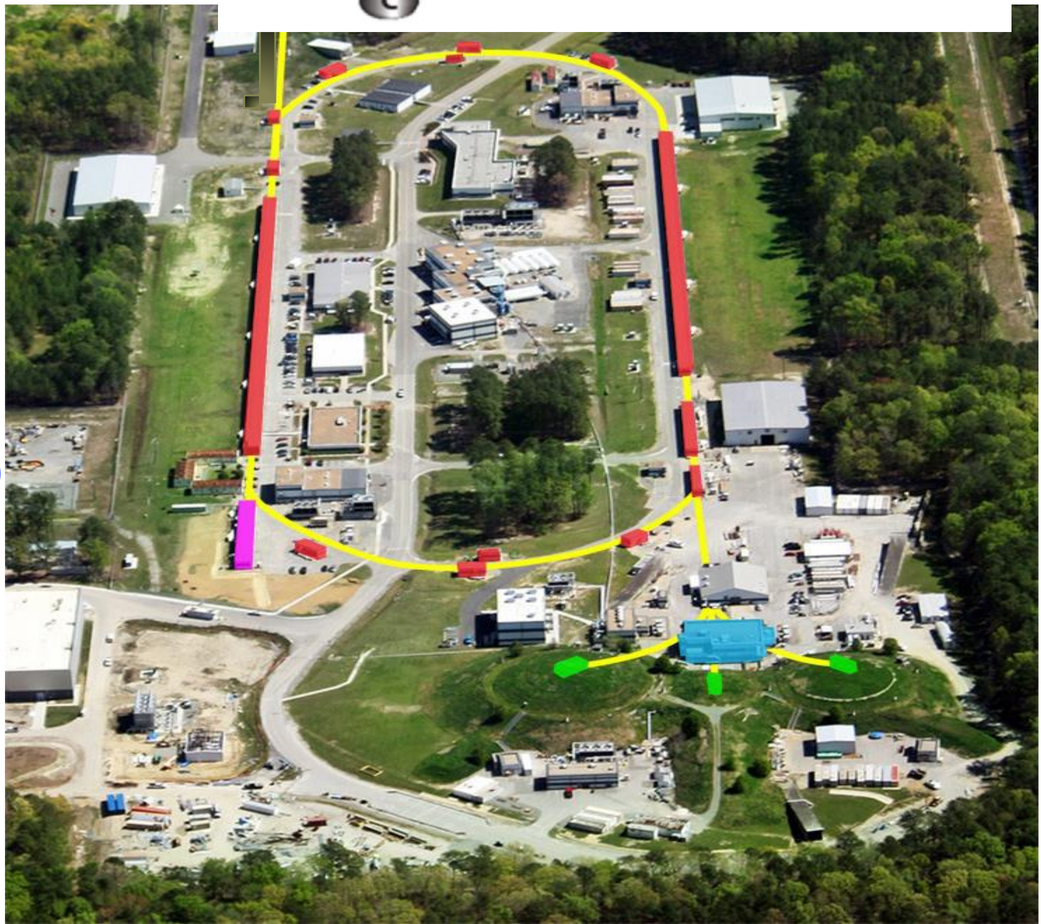
Energy upgrade 2017: 12 GeV
linac extensions, 1 new arc, Hall D

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

Current: up to ~100 μA (~1 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

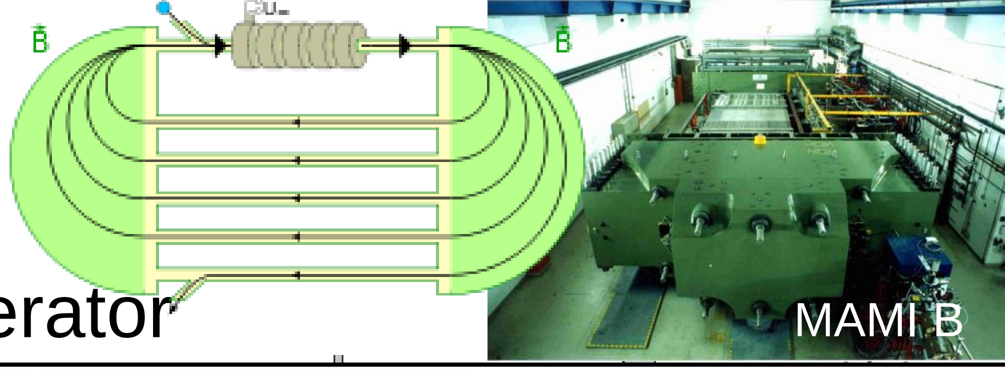
Upgrade option 2: Energy to ~22 GeV
2 Fixed Field Alternating gradient (FFA) arcs (permanent magnets) replace highest energy arc – FFA arcs with ~2x momentum acceptance



Brookhaven National Laboratory

MAMI and MESA, Uni Mainz

MAinzer MIcrotron and Mainz
Energy-recovering Superconducting Accelerator

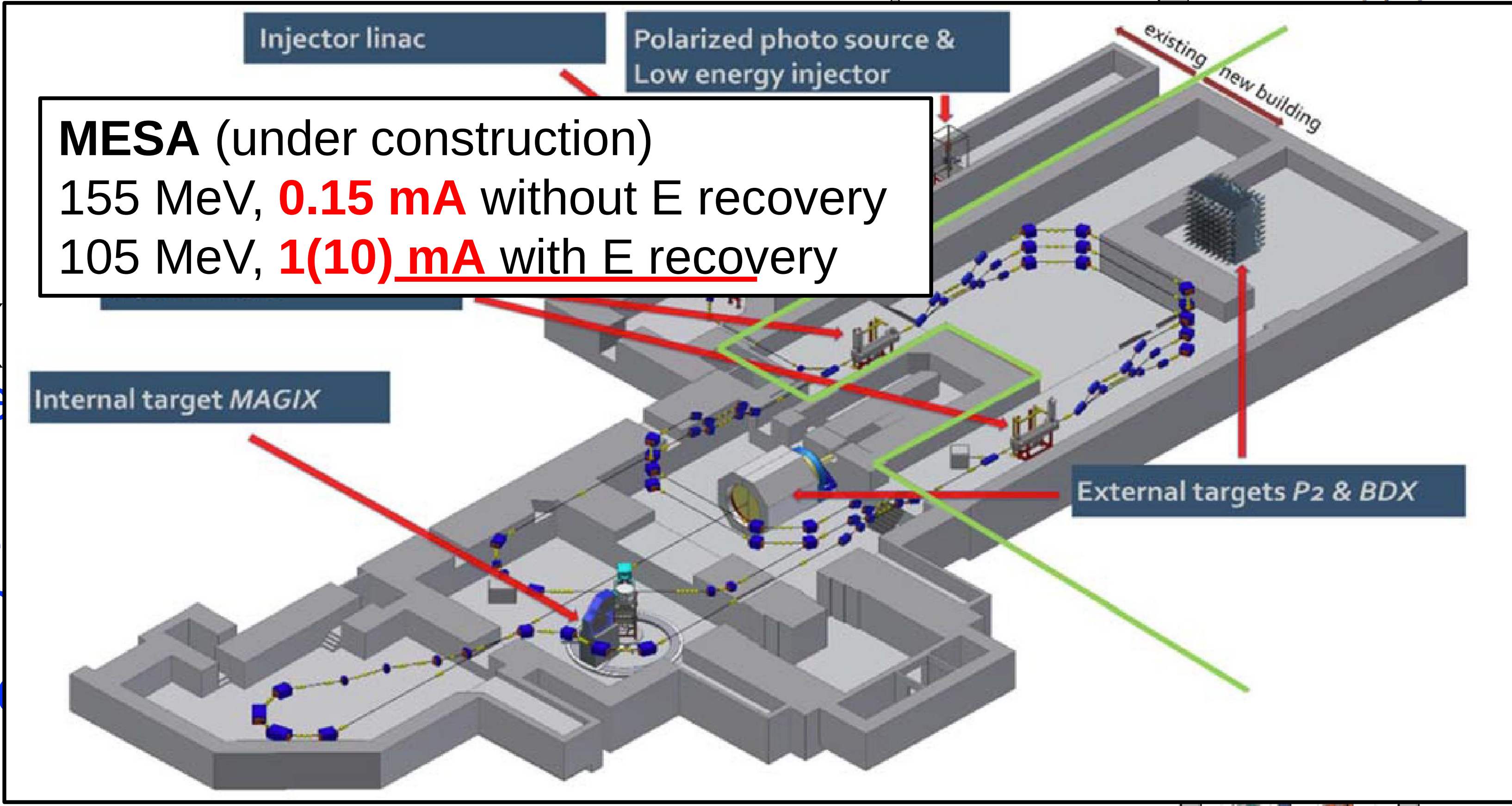


Mictrotron = racetrack type accelerator
(separated cyclotron)

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

⇒ beam quality determine
by source / acceleration

⇒ allows for much higher
with non-dense targets



MESA (under construction)
155 MeV, **0.15 mA** without E recovery
105 MeV, **1(10) mA** with E recovery

Brookhaven National Laboratory

High-intensity machines

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

For rare isotopes (including radioactive and SHE)

High-intensity accelerators – Important considerations

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

Limited by beam dynamics

Limited by funding

Power

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

Energy efficiency (grid-to-beam)

Beam loss / component activation

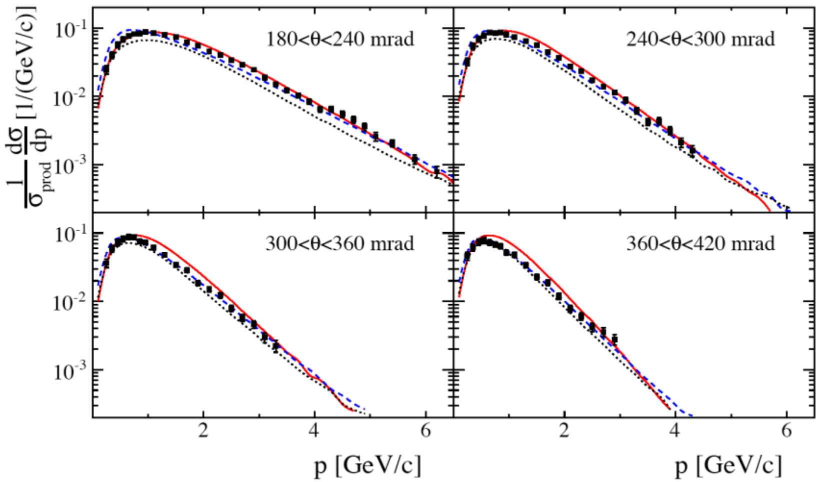
Targets

For heavy ions:

low charge state at low E (space charge reduction)
high charge state at high E (efficient acceleration)

=> efficient charge strippers

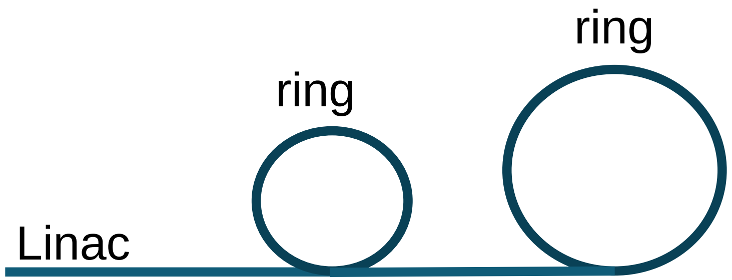
p+C to π^-



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

Cyclotrons, Linacs, Rings

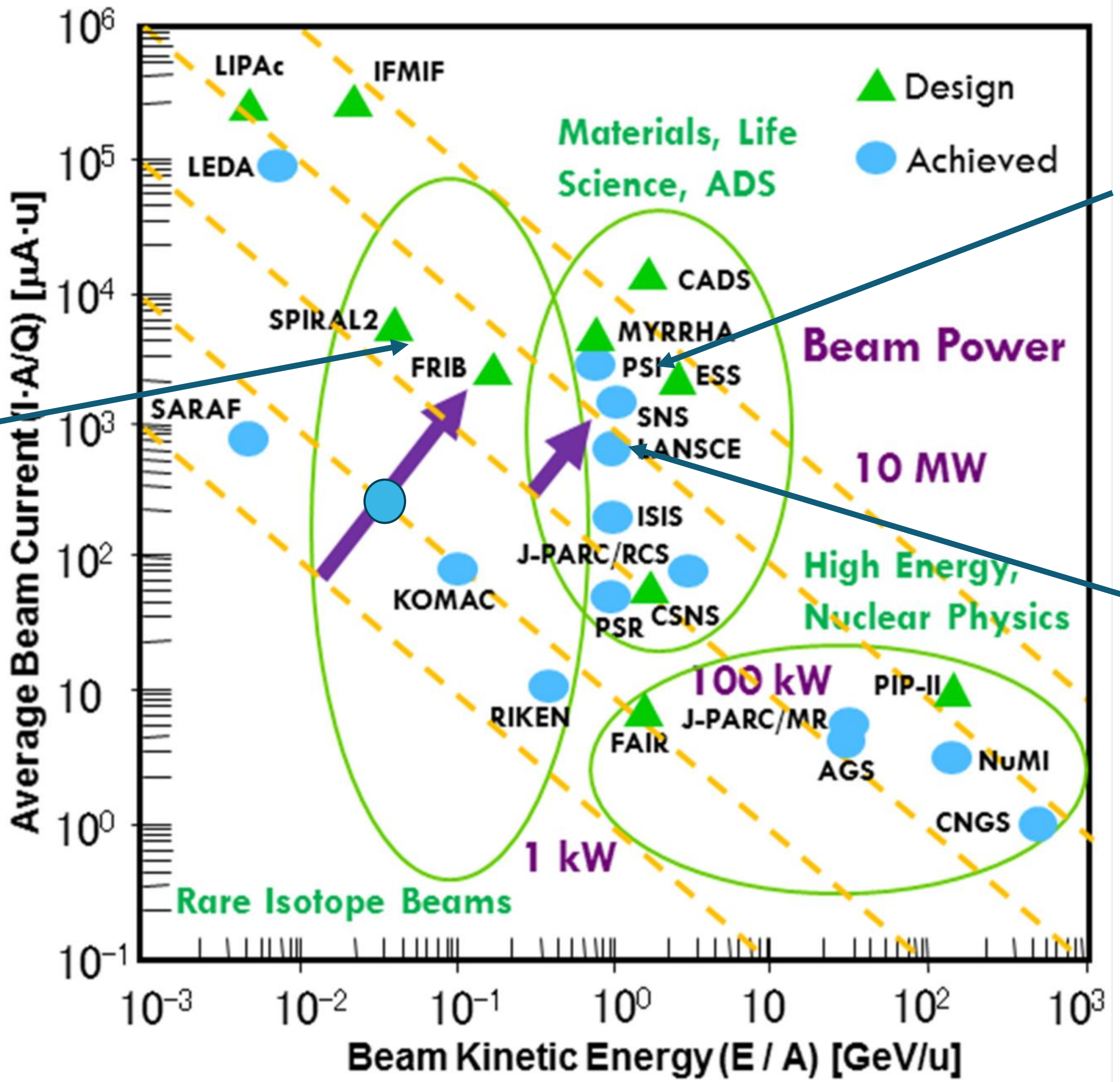
- Cyclotrons
  - Limited to ~600 MeV
    (extension: Fixed Field Alternating (FFA) gradients machines)
  - Present power frontier: PSI cyclotron 1.4 MW
  - Best energy efficiency
- Linacs
  - Space charge limit at source
  - Present power frontier: ORNL SNS 1.4 MW
  - Good energy efficiency with SRF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



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

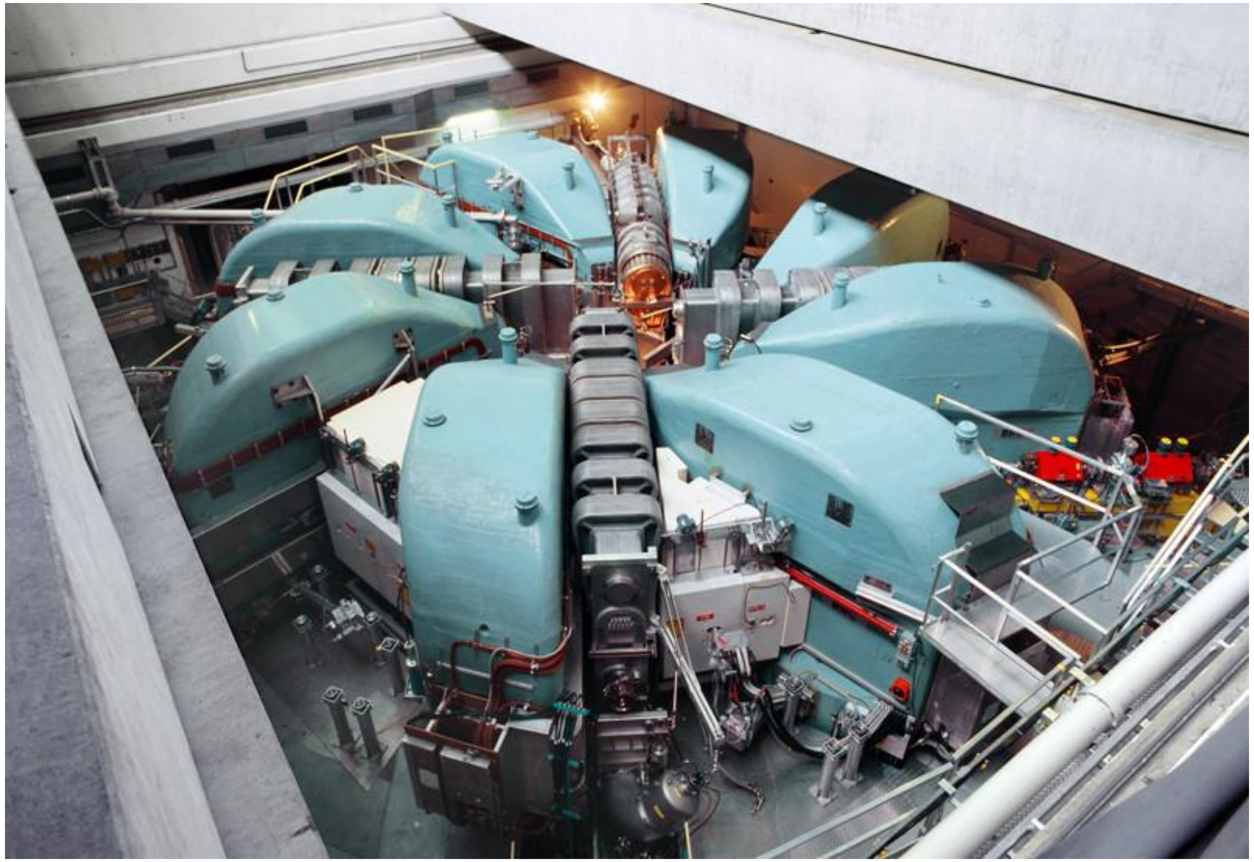


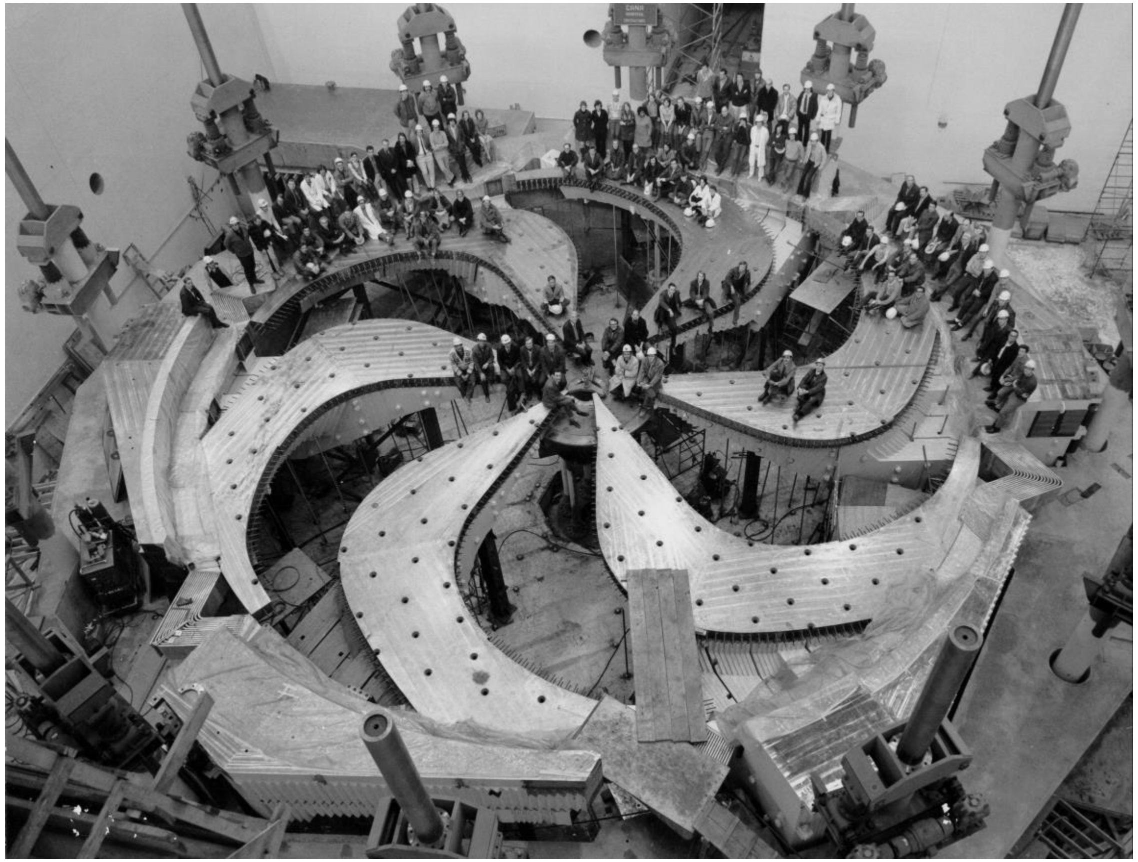
present power frontier:
PSI Cyclotron 1.4 MW
ORNL SNS 1.4 MW
(SNS 2x by 2025)

neutron sources
(often also μ sources)

[J. Wei, "Particle accelerator development: selected examples," Modern Physics Letters A, vol. 31, no. 10, pp. 1630010-1-13, Mar. 2016.]

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





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

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

Brookhaven National Laboratory

Also done with Linacs (SNS, ESS, RAON/RISP) and rings (ISIS, J-PARC)

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

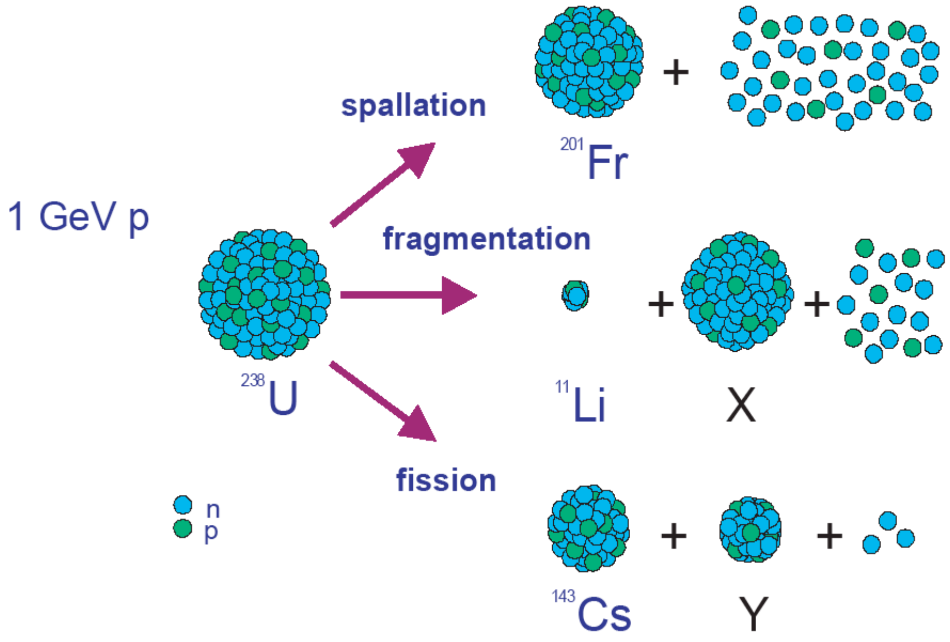
thick target

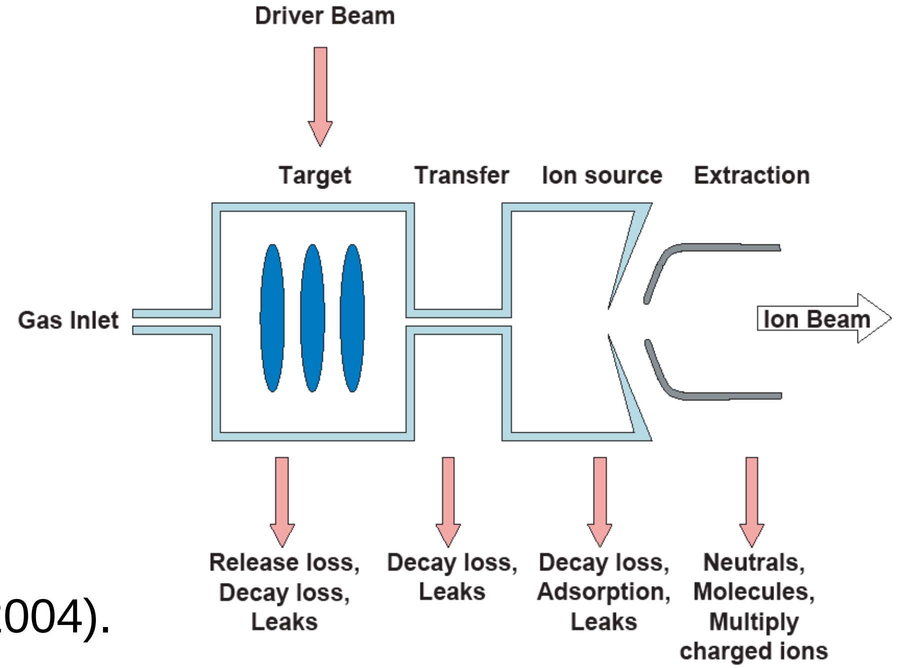
high production rate at rest / low energy

- good for low-energy experiments

difficult to achieve high purity

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



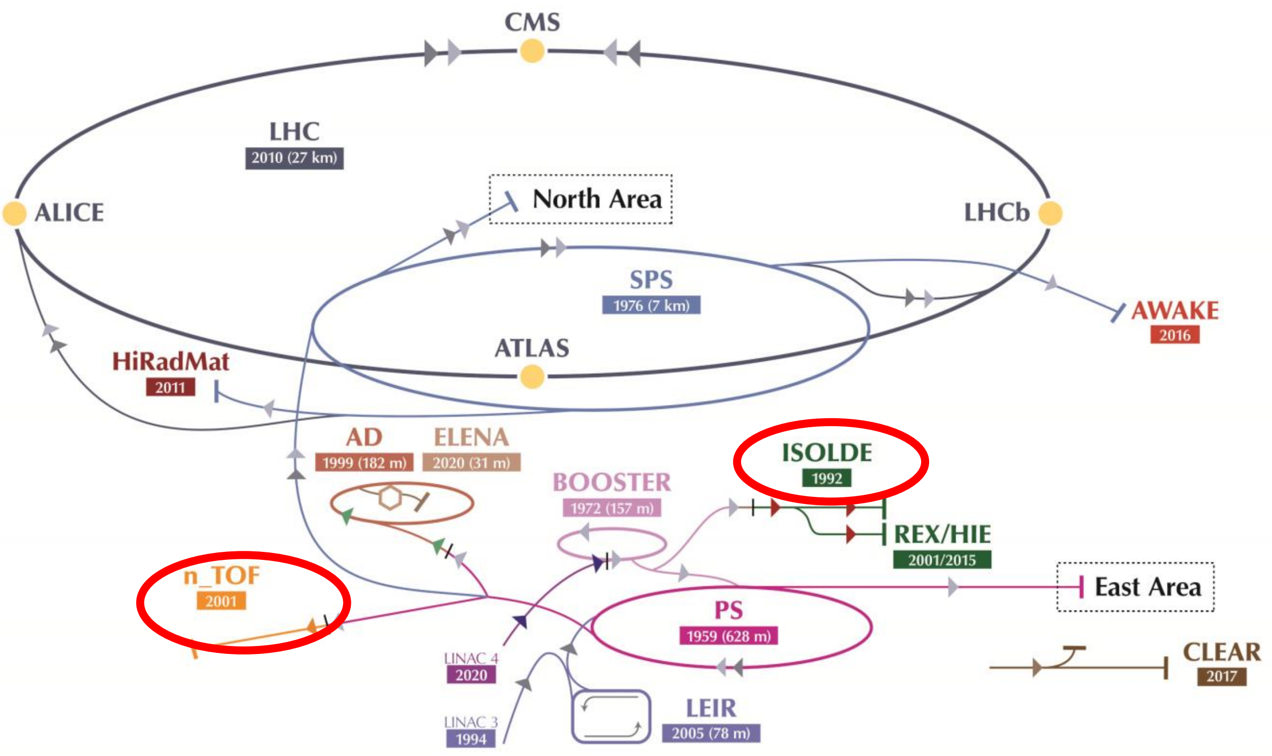


Brookhaven National Laboratory

M. Lindros, EPAC2004 Lucerne (2004).

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 μs pulse
- Lead : 173.5 GeV/nucleon, max 3.64×10^{9} ions/pulse, max 21 kJ/pulse, 5.2 μs pulse

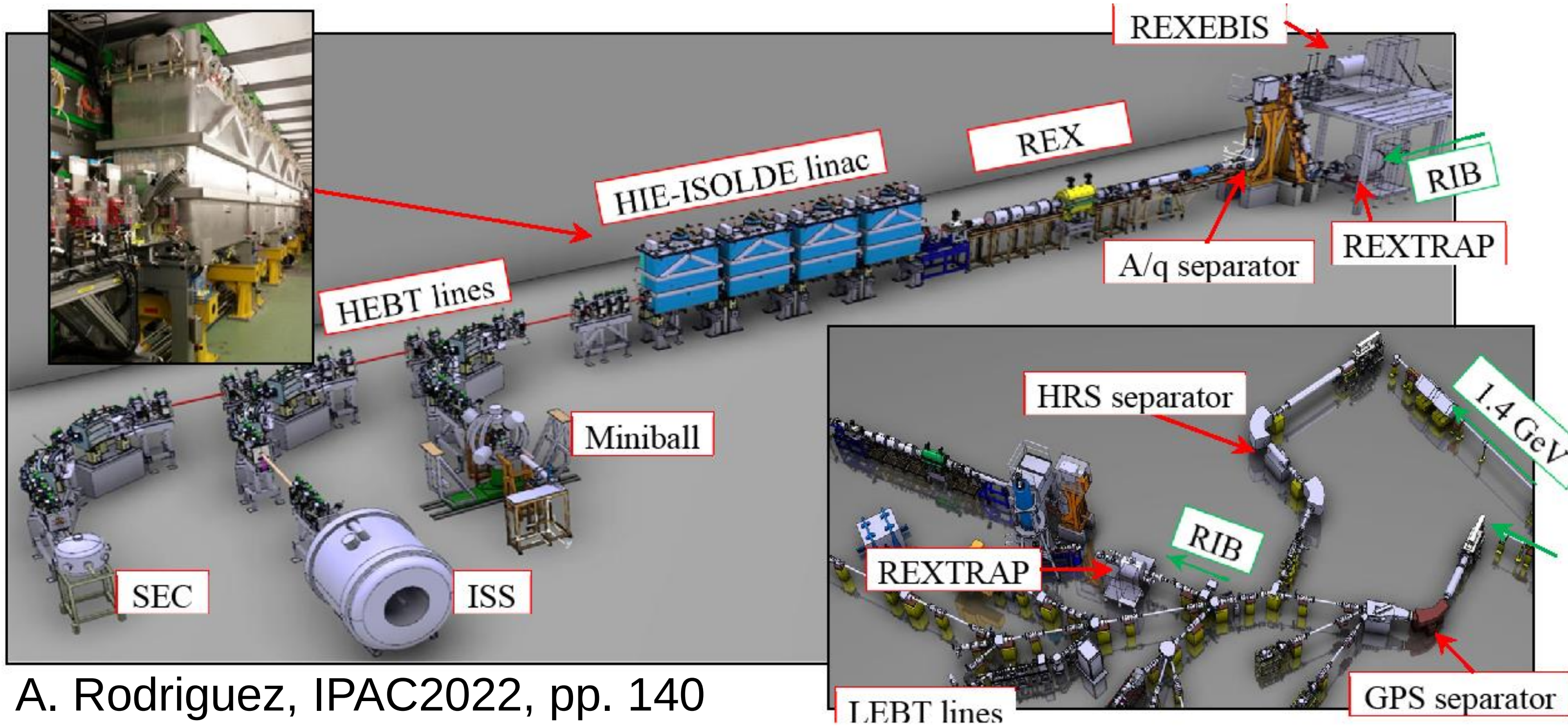
Brookhaven National Laboratory

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

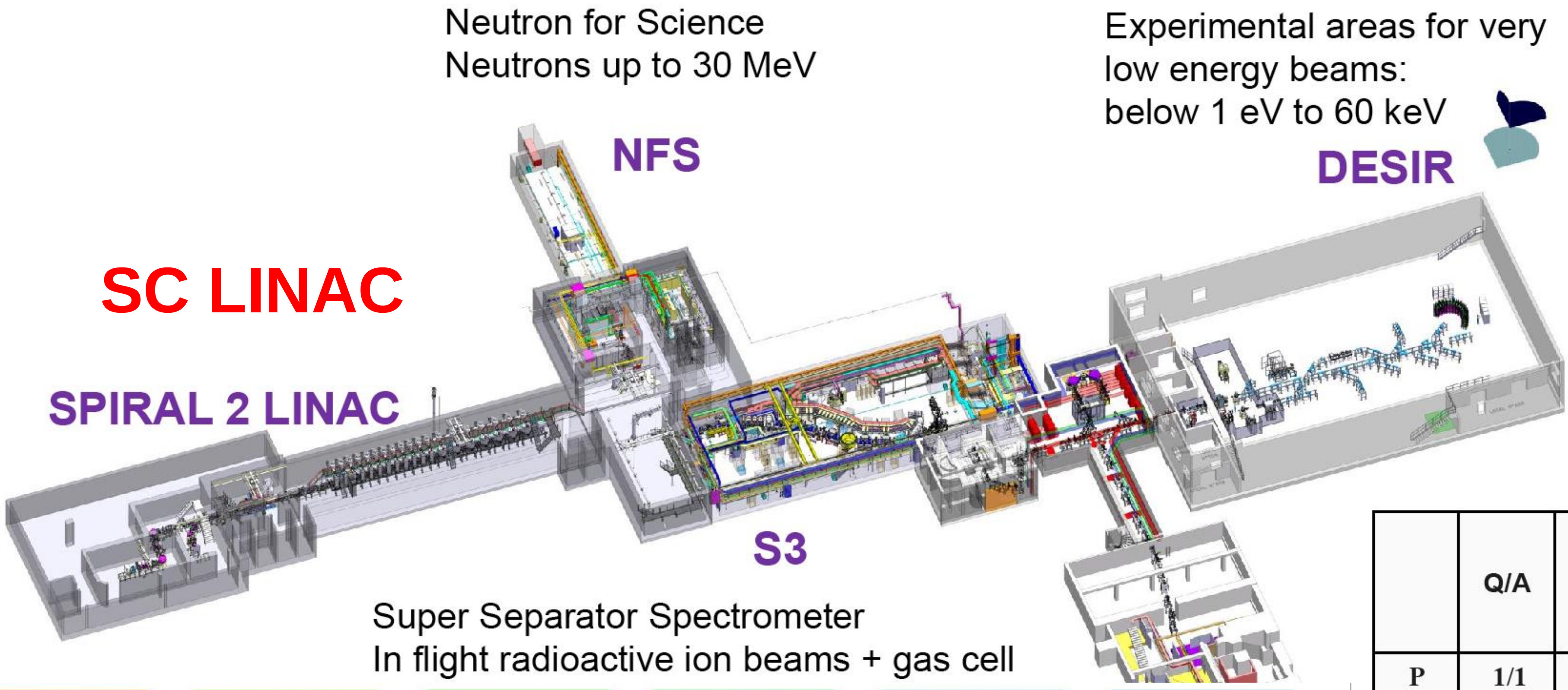
Superconducting RF for high gradient (short linac)



A. Rodriguez, IPAC2022, pp. 140

GANIL-SPIRAL 2

H. Franberg-Delahaye, HIAT2022



2014

P/D source: first beam 2 mA H^+.

December.

2015

Phoenix V2: first beam 230 µA Ar^{9+}.

July.

RFQ: first beam H^+.
December.

2018

Diagnostic plate commissioning end.

April-November.

2019

MEBT @5 mA H^+.
SBS* @ 0.2 mA H^+
SC LINAC @ 0.2 mA H^+
33 MeV H^+
July-December

2020

SBS @ 5 mA H^+. July
SBS* @1.3 mA $^4He^{2+}$
SC LINAC @ 5 mA H^+
16 kW H^+
July – December

2021

SC LIN@1.3 mA $^4He^{2+}$
SBS* @ 5 mA D^+
SC LINAC @ 5 mA D^+
40 MeV D^+
July-September

	Q/A	I max (mA)	Energy (MeV/n)	CW max beam power (kW)
P	1/1	5	2 - 33	165
He	*2/3*	*1*	*2-2 4*	*36*
D	1/2	5	2 - 20	200
Ions	1/3	1	2 - 14.5	45

SPES Legnaro

Selective Prodcution of Exotic Species

Cyclotron 70 MeV, 500 μA

ISOL

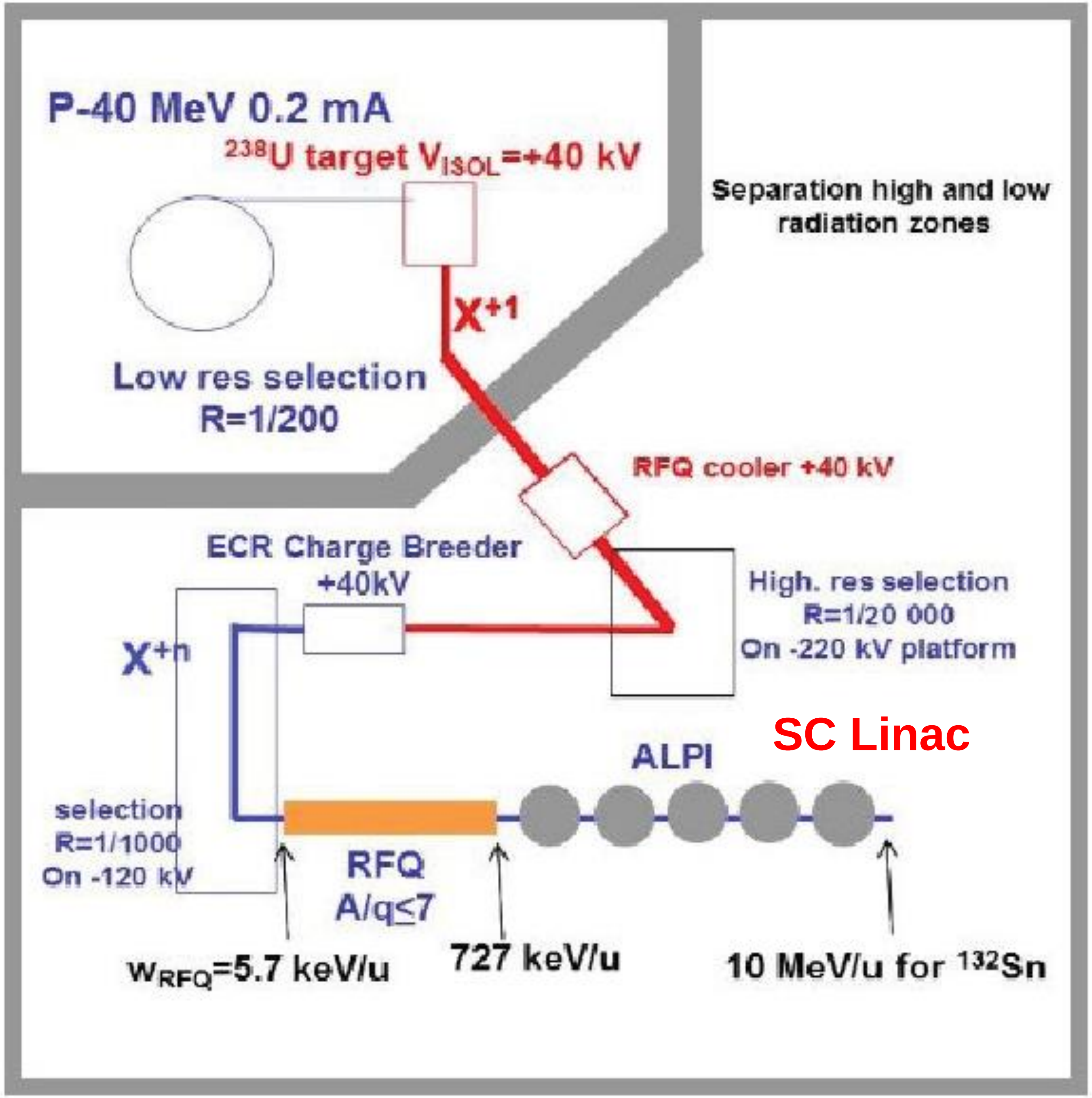
RFQ Cooler

spectrometer

charge breeding

spectrometer

acceleration



Brookhaven National Laboratory

M. Comunian, et al., HIAT2018
T. Marchi et al, INPC2019

FRIB, MSU US

Superconducting Linac

Energy: 200 MeV/nucleon (U)

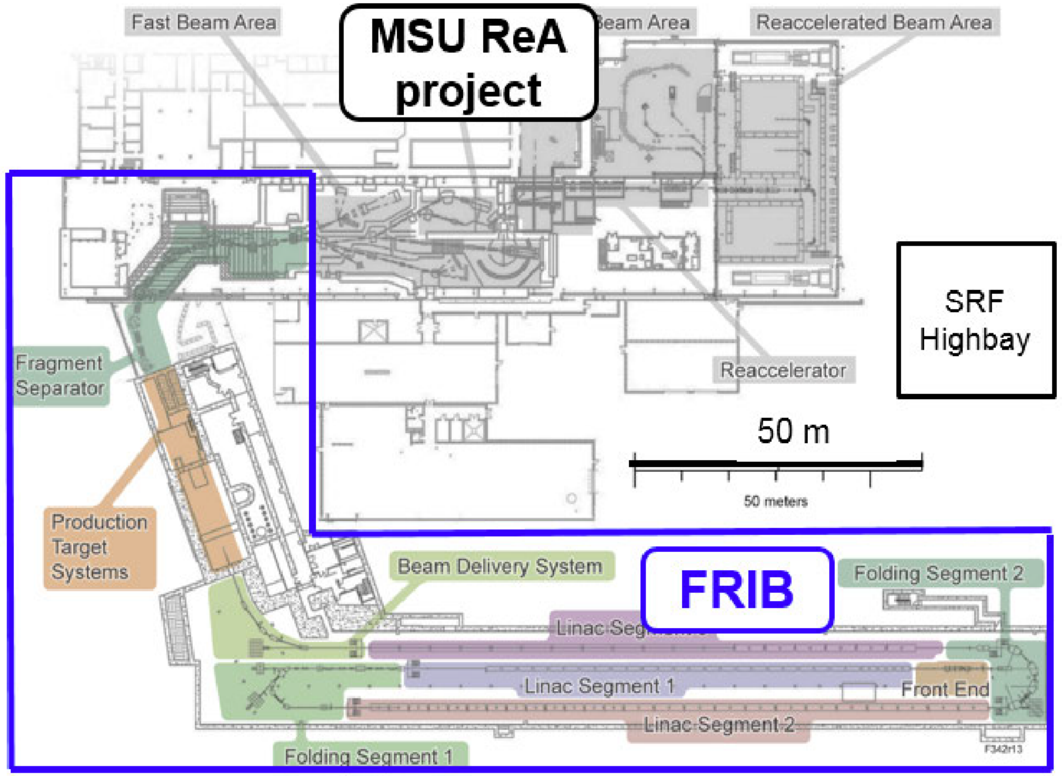
Beam power: 400 kW (design, highest HI beam power) now ~1 kW

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

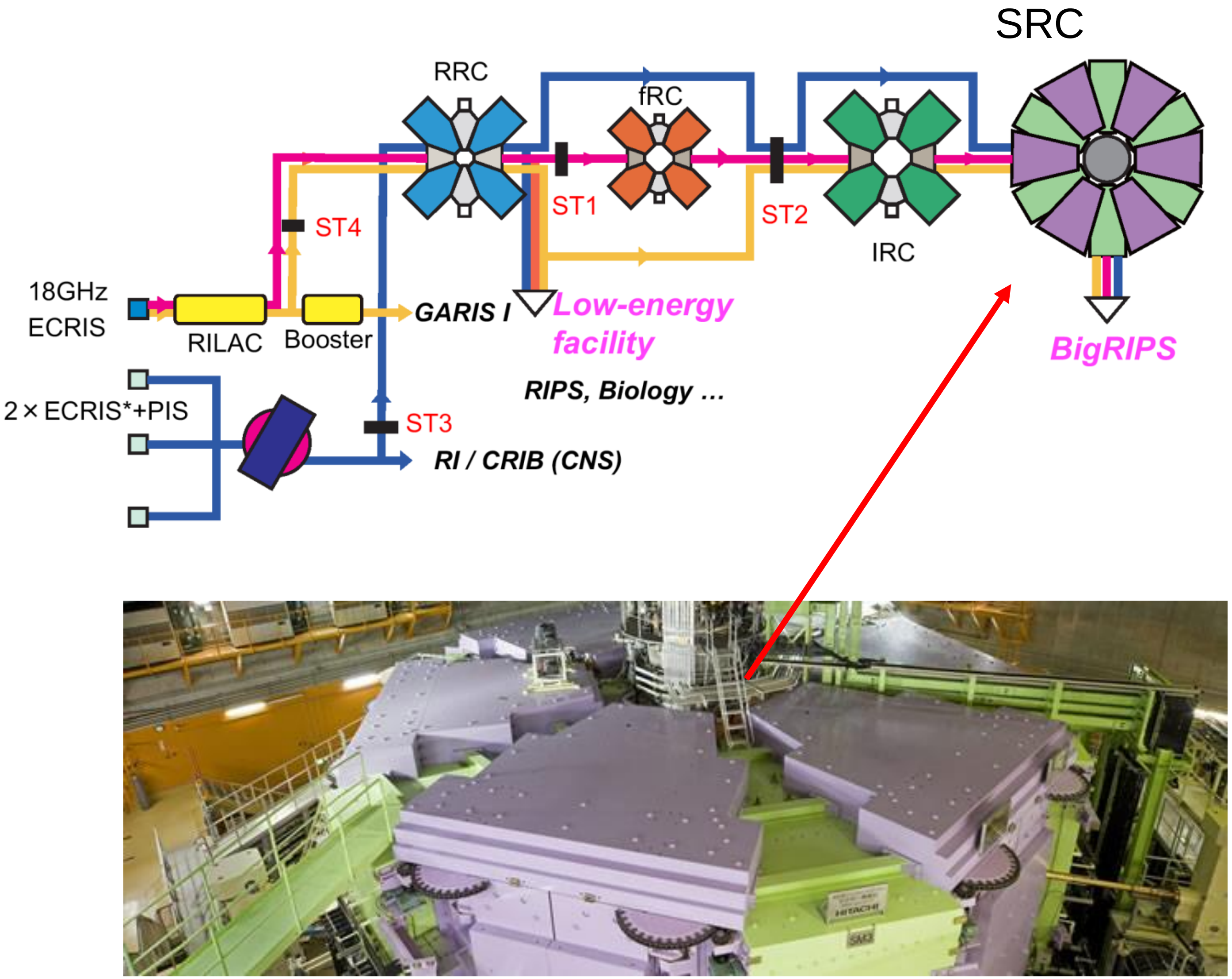
Beam power: 20 kW

Superconducting magnet 3.8 T

(Bρ) = 8 Tm, 8300 t

Upgrades:

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



Brookhaven National Laboratory

O. Kamigaito, HIAT2022, Darmstadt (2022)

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

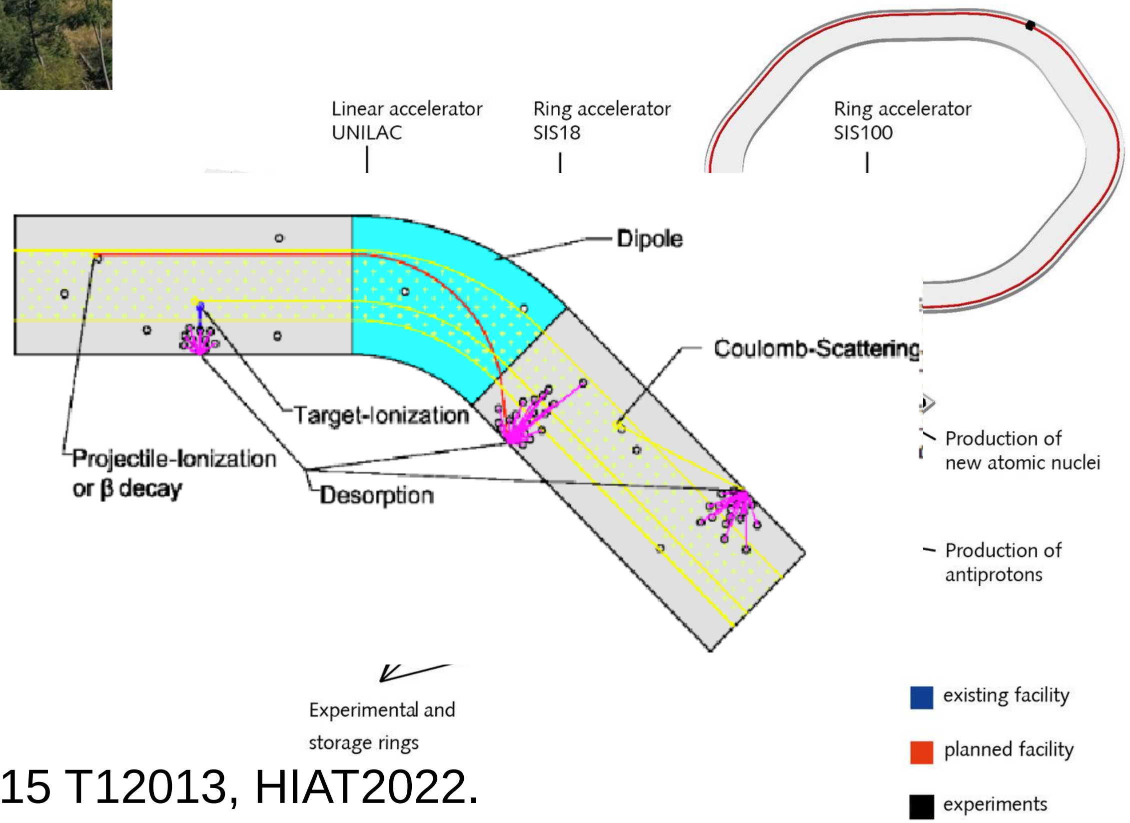
SIS100 Energy:

Intensity:
  $5x10^{11}$ U^{28+}/cycle (50 kW)
  ~100x 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



Brookhaven National Laboratory

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

Factory for SHE, Dubna

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.

Cyclotron DC-280

Energy: 4-8 MeV/n

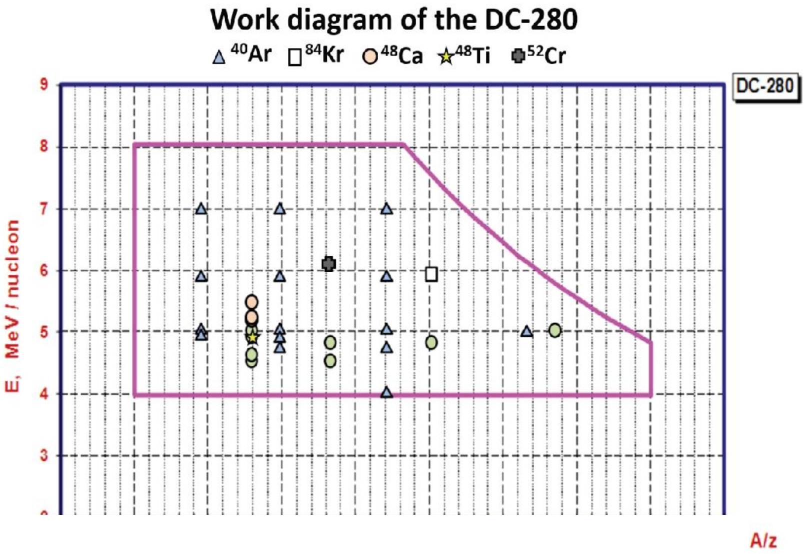
High current: up to 10 pμA

Synthesis of elements Z > 118
(double-magic ^{48}Ca with neutron-rich ^{242,244}P, ^{243}Am, ^{249}Cm, ^{249}Bk, and ^{249}Cf)

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($^{40}Ar^{+7}$) ÷6,9($^{48}Ca^{+7}$)
Energy	4÷8 MeV/n	4,01 – 7 MeV/n
Ion (for DECRIS-PM)	4-136	12 ($^{12}C^{+2}$) – 84 ($^{84}Kr^{+14}$)
Intensity (A~50)	>10 pμA	10,4 pμA ($^{40}Ar^{+7}$);
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 % ($^{48}Ca^{+10}$ 5 pμA)

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



G.G. Gulbekian et al., Cyclotrons2016 (2016)
G.G. Gulbekian et al., Physics of Particles and Nuclei Letters, 2019, Vol. 16, No. 6, pp. 866–875 (2019)
V.A. Semin et al., IPAC2021, Campinas (2021).

odes.

Colliders

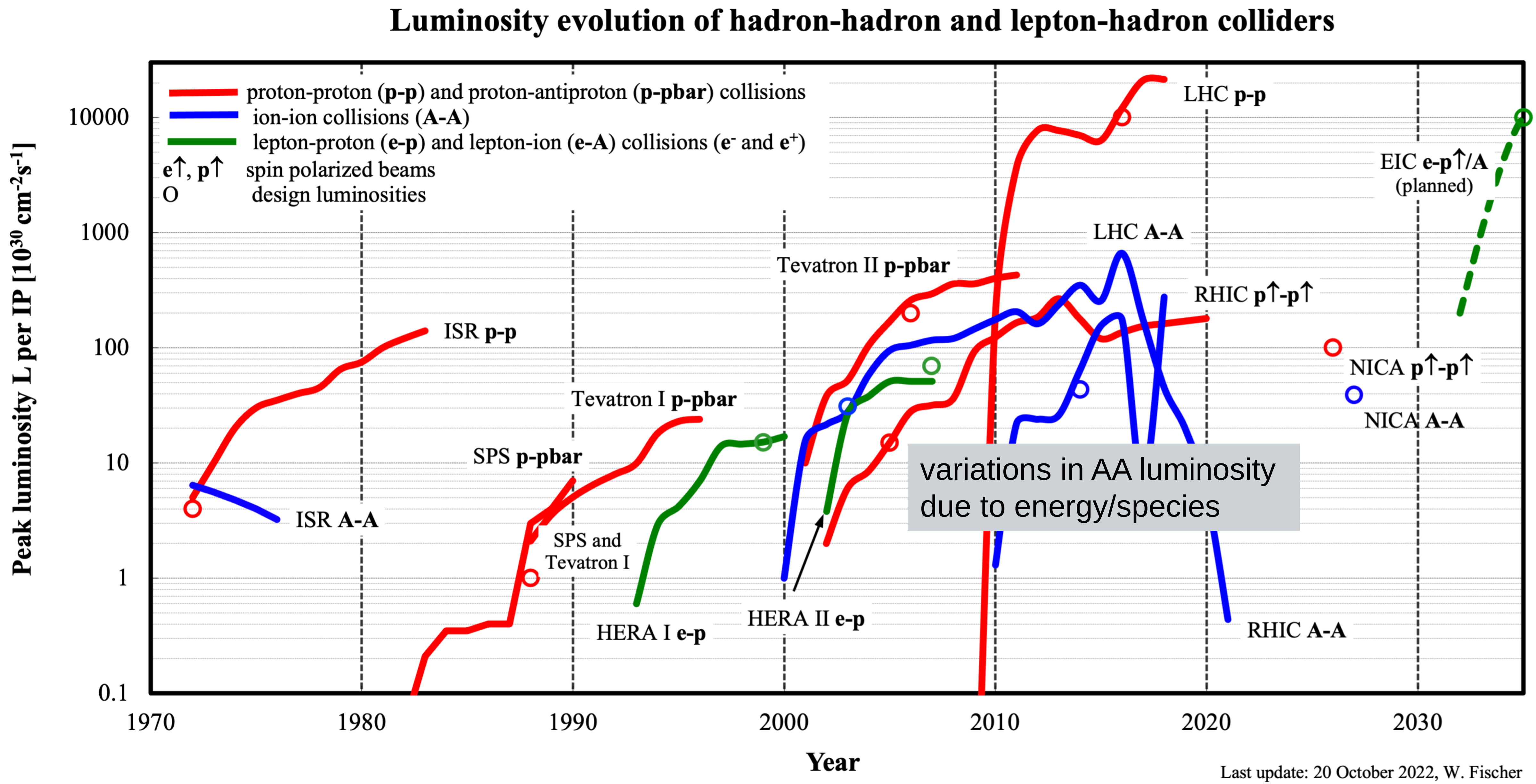
High-Energy Physics and
high-energy Nuclear Physics

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} $cm^{-2}s^{-1}$]	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

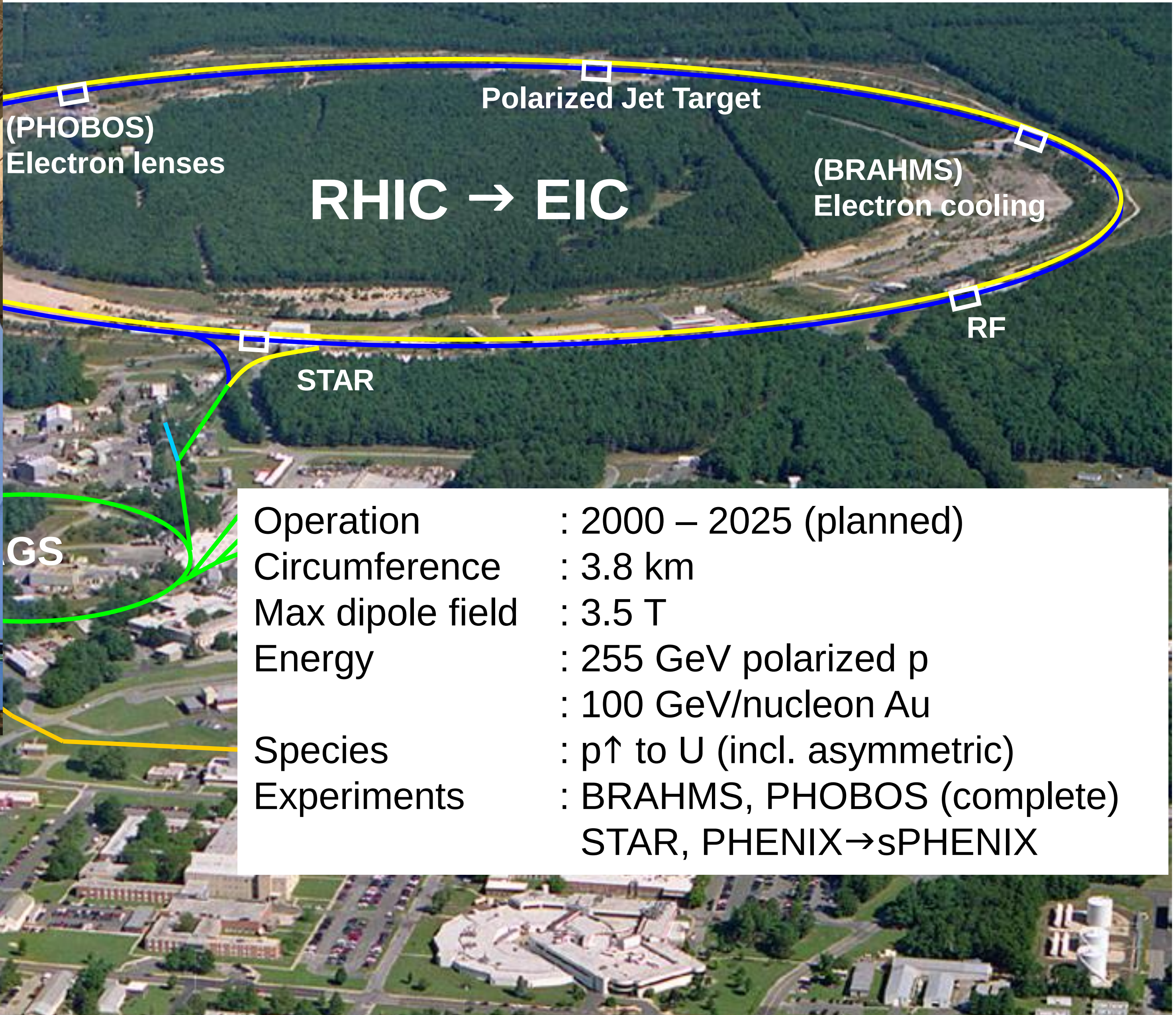
[PDG, Tables 32.4, 32.5; NICA, EIC]



Luminosity evolution of hadron-hadron and lepton-hadron colliders
proton-proton (p-p) and proton-antiproton (p-pbar) collisions
ion-ion collisions (A-A)
lepton-proton (e-p) and lepton-ion (e-A) collisions (e⁻ and e⁺)
e↑, p↑ spin polarized beams
O design luminosities
Peak luminosity L per IP [10^30 cm^-2s^-1]
Year
ISR p-p
ISR A-A
SPS p-pbar
SPS and Tevatron I
Tevatron I p-pbar
HERA I e-p
HERA II e-p
Tevatron II p-pbar
LHC p-p
LHC A-A
RHIC p↑-p↑
RHIC A-A
EIC e-p↑/A (planned)
NICA p↑-p↑
NICA A-A
variations in AA luminosity due to energy/species
Last update: 20 October 2022, W. Fischer

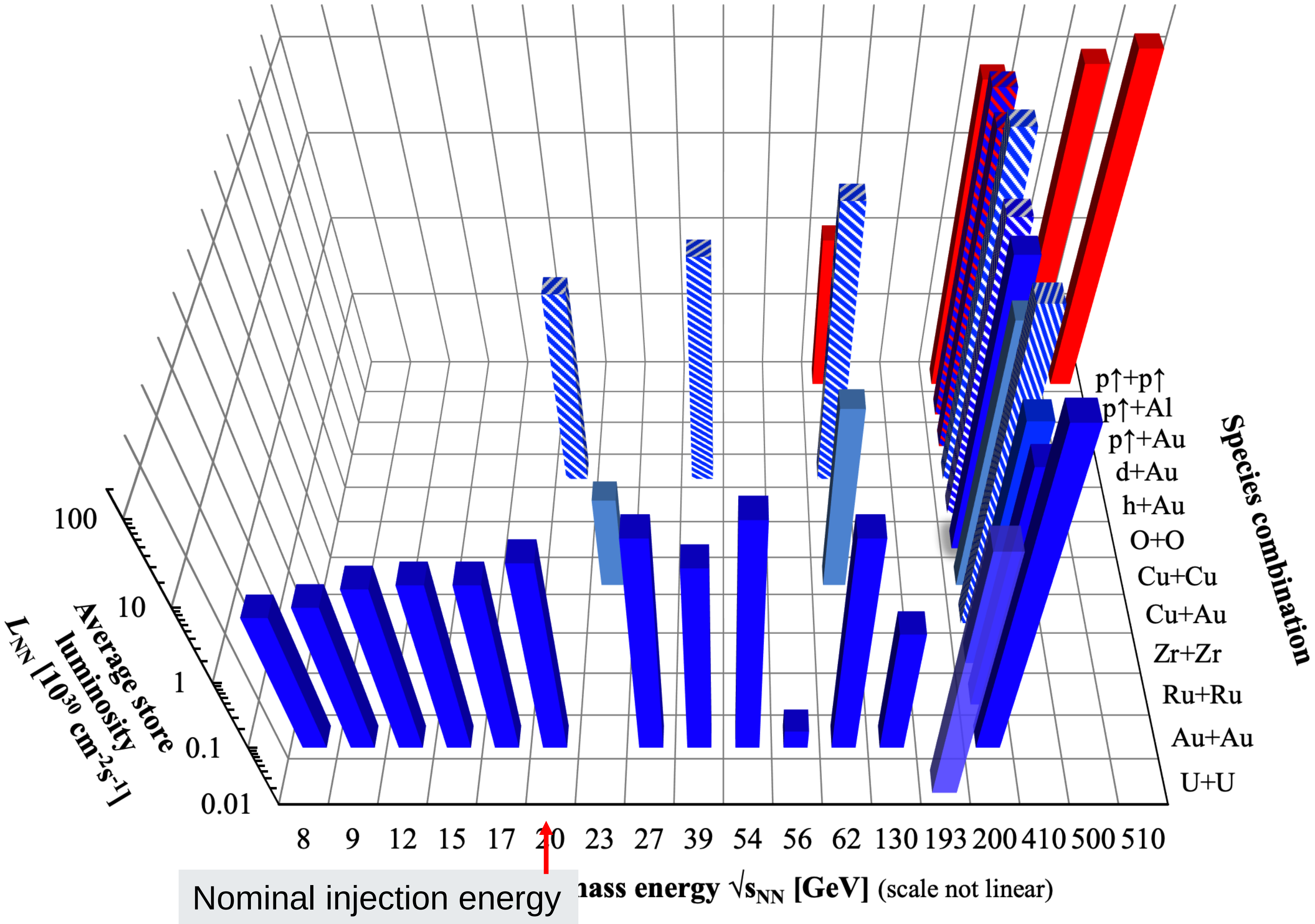
Relativistic Heavy Ion Collider at Brookhaven National Lab

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)

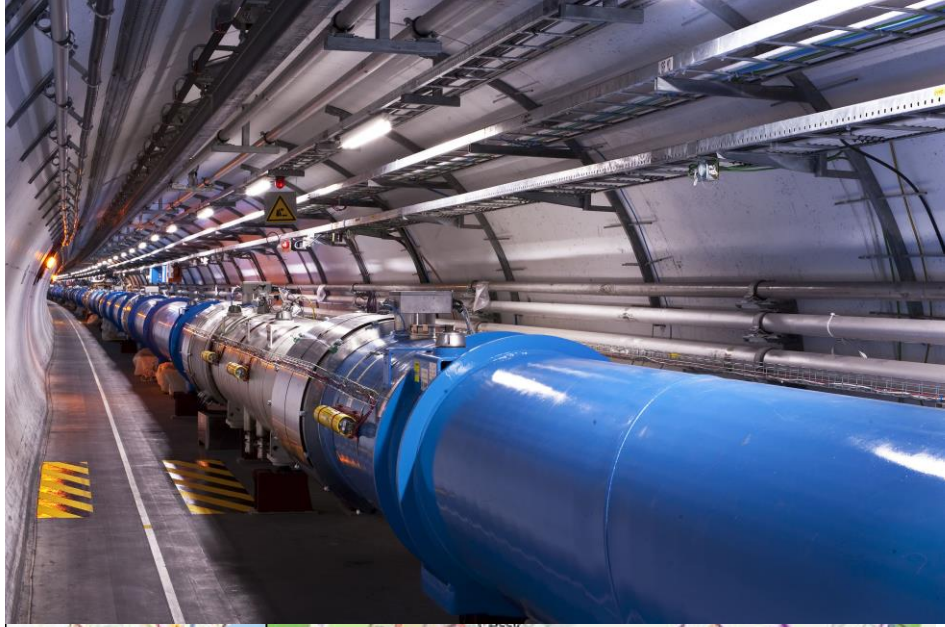
O+O likely also in LHC in the future

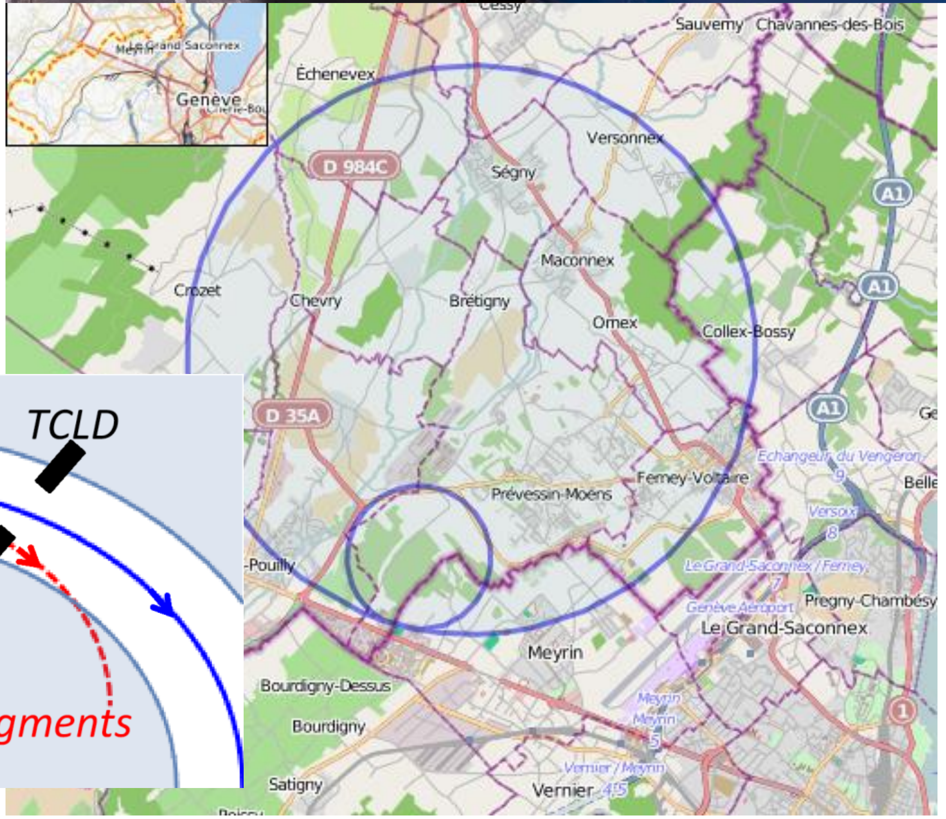
LHC AA

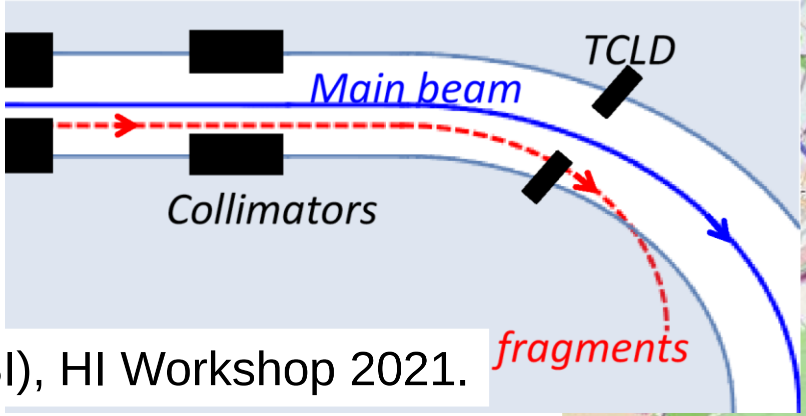
Operation since 2011 (p since 2010)
Energy: 2560 A GeV (Pb)
Species to date: p+p, Pb+Pb, p+Pb, Xe+Xe
Detector optimized for ion program: ALICE

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 ($Pb^{82+} \rightarrow Pb^{81+}$)
EMD = Electro-Magnetic Dissociation ($^{208}Pb \rightarrow {}^{207}Pb$)

=> orbit bumps, new collimators,
crystal collimation







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

LHC AA – present and furture

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

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

Nucletron-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} $cm^{-2}s^{-1}$ for p+p
10^{27} $cm^{-2}s^{-1}$ for Au+Au

~10x RHIC at lowest energy

small circumference reduces space charge:
C = 503 m vs 3834 m in RHIC
ΔQ_{sc} ~ C (space charge) limits storage rings

Figure 5: Installation of magnets in NICA tunnel.

Brookhaven National Laboratory

Electron-Ion Collider

Ferdinand Willeke et al.

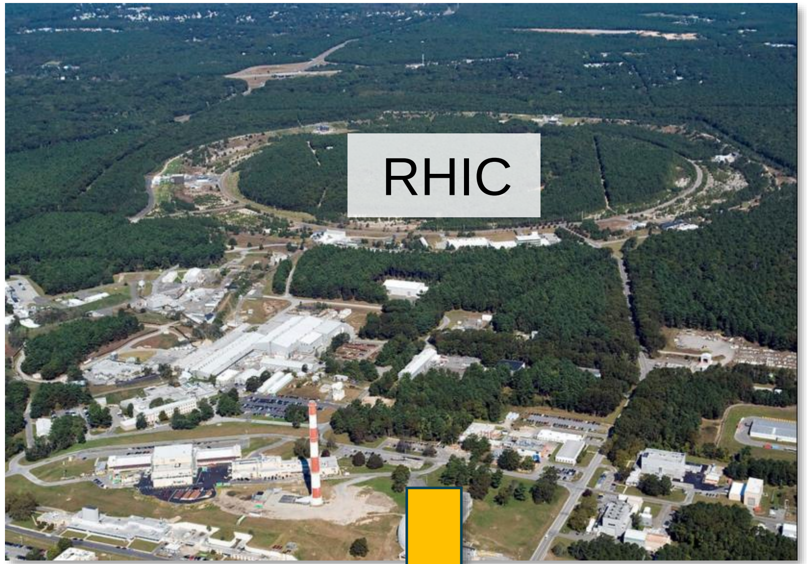
BNL-JLab partnership with national and international contribution
sited at BNL - uses RHIC hadron complex
CD-1 June 2021 (Conceptual Design complete, cost range),
operation 2032 (planned)

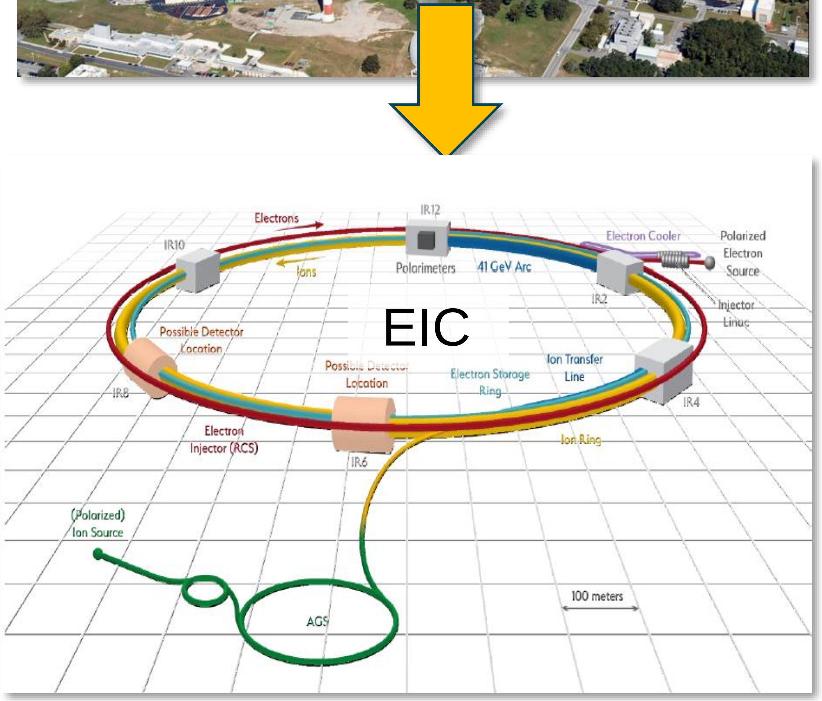
Hadron storage Ring (RHIC Rings) 40-275 GeV (existing)
- 1160 bunches, 1A beam current (3x RHIC)
- small vertical beam emittance 1.5 nm
- strong cooling (coherent electron cooling)

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

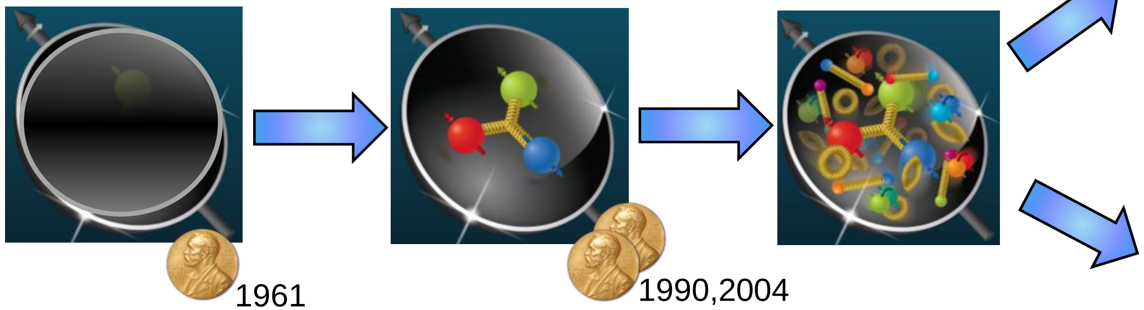




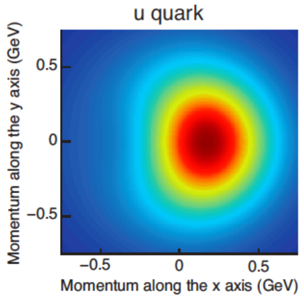
EIC Science Program

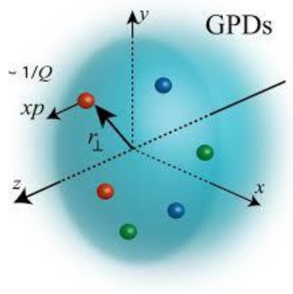
EIC to unravel
the mysteries of visible matter

The Proton

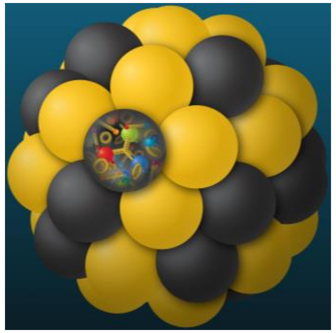


Multidimensional imaging of the structure of the proton: Origin of Mass, Spin, 3d-structure





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)