Present and approved accelerator facilities

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U.S. DEPARTMENT OF ENERGY

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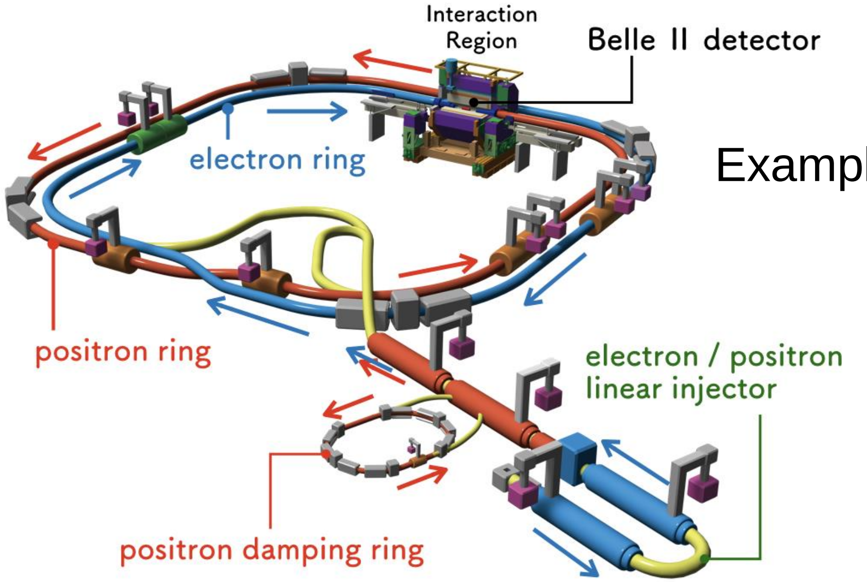
Particle Physics Accelerator Facilities

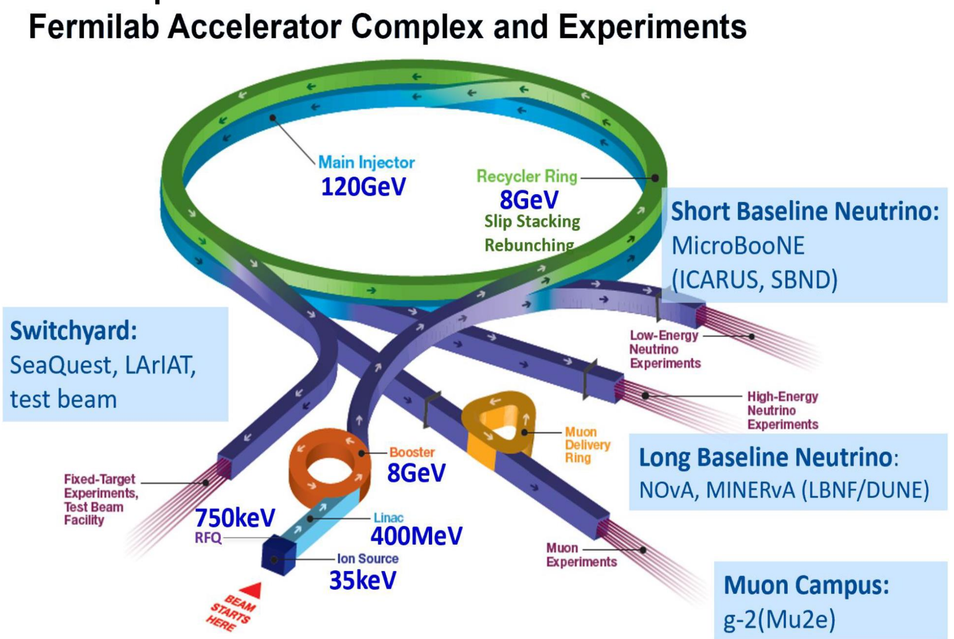
- Colliders
- High-intensity accelerators
  - Targets
- Specialty beams like

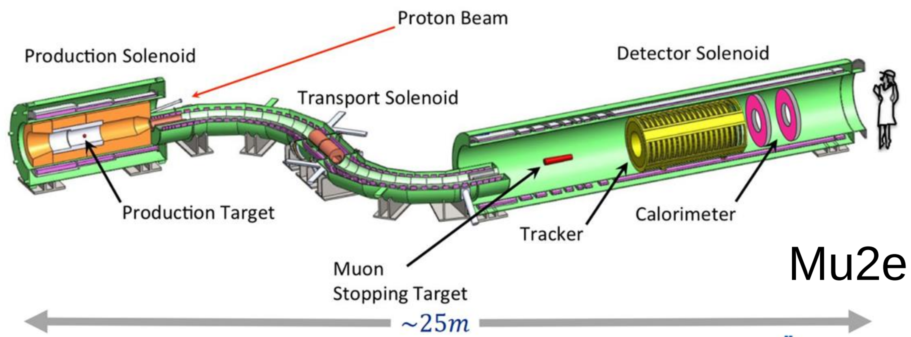
  Muon g-2, pEDM, antiprotons



Example: SuperKEKB

Example:





Mu2e

Many thanks to colleagues:

Mike Lamont (CERN)

Tadashi Koseki (KEK)

Alexander Valishev and Mary Convery (Fermilab)

Wolfram Fischer (BNL)

Catia Milardi (INFN)

Valeri Lebedev (JINR)

Chenghui Yu (IHEP)

Summary up front

Colliders are focused of achieving the highest average luminosity through reliable operations and continuous implementation of innovations:

- Nano beams;
- Crab waist;
- Crab cavities;
- Beam screens and vacuum coatings to suppress electron cloud;

For high-intensity beams, the focus is on delivering >1 MW proton beams for neutrino experiments and on developing and operating high-power beam targets for high-radiation and high-stress environments

Colliders

For factories and high-energy collisions

e^+e^-, hh, eh

Colliders – Important considerations

- Energy
- Luminosity
  - Target density in collider >10 orders of magnitude lower than in fixed target
- Interaction Region design
  - Detector space
  - Experimental background
  - Forward particles
  - …

Also

- Cost
- Reliability
- Flexibility (energy, species for ion colliders)
- Energy efficiency / operating cost
- …

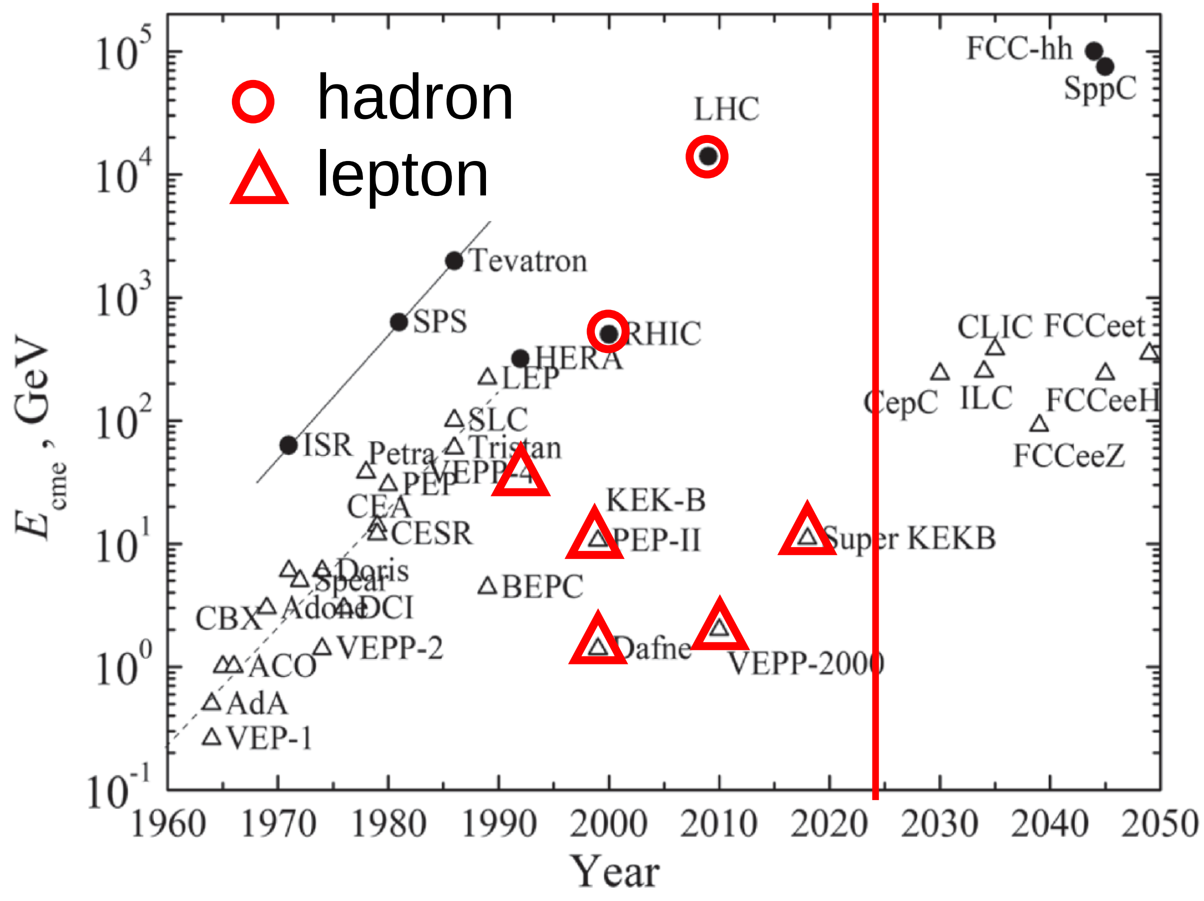
Colliders	Species	E_{cm}, GeV	C, m	$\mathcal{L}$, 10^{32}	Years	Host lab, country
AdA	e^+e^-	0.5	4.1	10^{-7}	1964	Frascati/Orsay
VEP-1	e^-e^-	0.32	2.7	5×10^{-5}	1964-68	Novosibirsk, USSR
CBX	e^-e^-	1.0	11.8	2×10^{-4}	1965-68	Stanford, USA
VEPP-2	e^+e^-	1.34	11.5	4×10^{-4}	1966-70	Novosibirsk, USSR
ACO	e^+e^-	1.08	22	0.001	1967-72	Orsay, France
ADONE	e^+e^-	3.0	105	0.006	1969-93	Frascati, Italy
CEA	e^+e^-	6.0	226	0.8×10^{-4}	1971-73	Cambridge, USA
ISR	pp	62.8	943	1.4	1971-80	CERN
SPEAR	e^+e^-	8.4	234	0.12	1972-90	SLAC, USA
DORIS	e^+e^-	11.2	289	0.33	1973-93	DESY, Germany
VEPP-2M	e^+e^-	1.4	18	0.05	1974-2000	Novosibirsk, USSR
VEPP-3	e^+e^-	3.1	74	2×10^{-5}	1974-75	Novosibirsk, USSR
DCI	e^+e^-	3.6	94.6	0.02	1977-84	Orsay, France
PETRA	e^+e^-	46.8	2304	0.24	1978-86	DESY, Germany
CESR	e^+e^-	12	768	13	1979-2008	Cornell, USA
PEP	e^+e^-	30	2200	0.6	1980-90	SLAC, USA
$Sp\bar{p}S$	$p\bar{p}$	910	6911	0.06	1981-90	CERN
TRISTAN	e^+e^-	64	3018	0.4	1987-95	KEK, Japan
Tevatron	$p\bar{p}$	1960	6283	4.3	1987-2011	Fermilab, USA
SLC	e^+e^-	100	2920	0.025	1989-98	SLAC, USA
LEP	e^+e^-	209.2	26659	1	1989-2000	CERN
HERA	ep	30+920	6336	0.75	1992-2007	DESY, Germany
PEP-II	e^+e^-	3.1+9	2200	120	1999-2008	SLAC, USA
KEKB	e^+e^-	3.5+8.0	3016	210	1999-2010	KEK, Japan
VEPP-4M	e^+e^-	12	366	0.22	1979-	Novosibirsk, Russia
BEPC-I/II	e^+e^-	4.6	238	10	1989-	IHEP, China
DAΦNE	e^+e^-	1.02	98	4.5	1997-	Frascati, Italy
RHIC	p, i	510	3834	2.5	2000-	BNL, USA
LHC	p, i	13600	26659	210	2009-	CERN
VEPP2000	e^+e^-	2.0	24	0.4	2010-	Novosibirsk, Russia
S-KEKB	e^+e^-	7+4	3016	6000*	2018-	KEK, Japan
NICA	p, i	13	503	1*	2024(tbd)	JINR, Russia
EIC	ep	10+275	3834	105*	2032(tbd)	BNL, USA

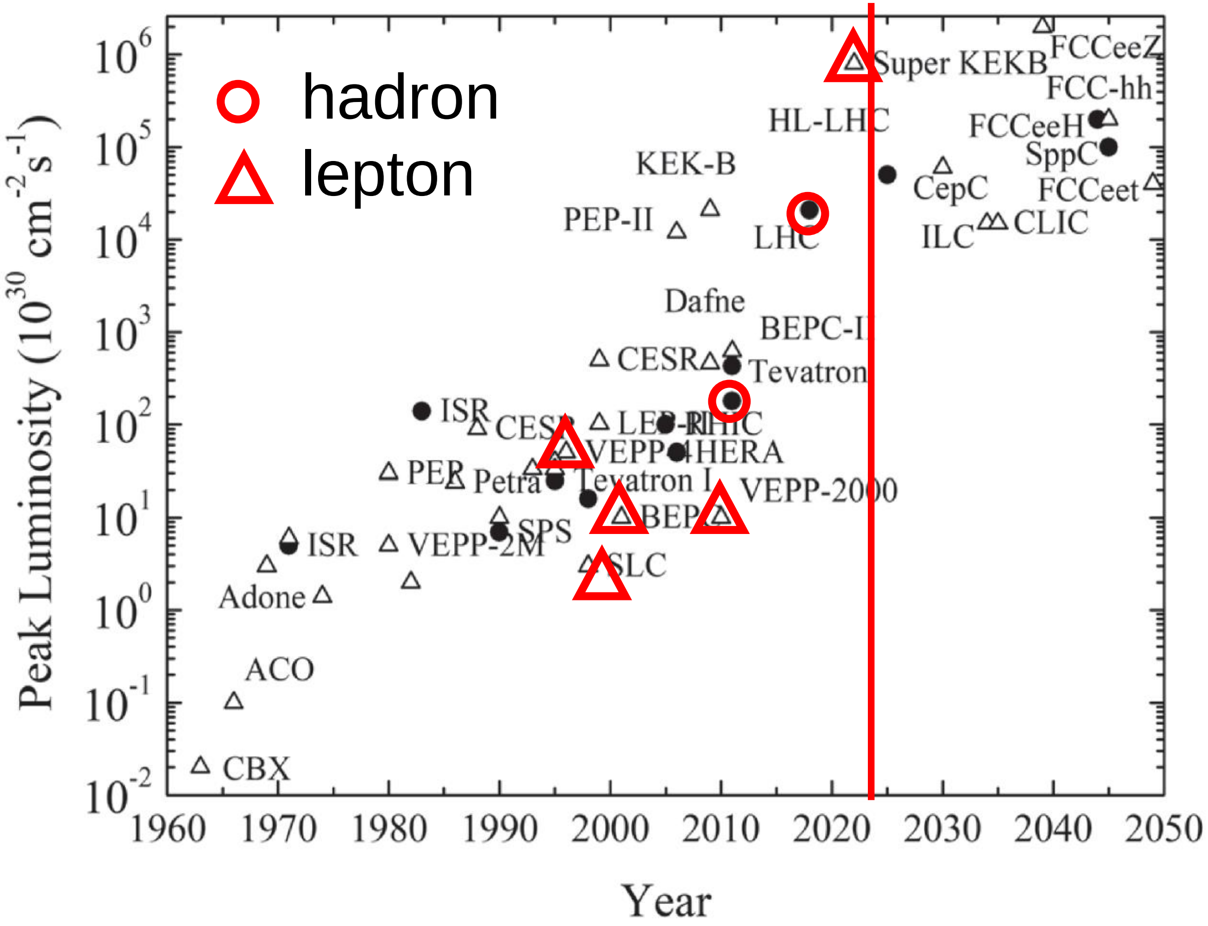
Present (7)

Approved

(adapted from [Shiltsev and Zimmermann, 2021]).

Colliders: history





[V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006 (2021); V. Shiltsev, Phys. Usp. 55, 965 (2012)]

Colliders e^+e^- (factories): VEPP-2000, VEPP-4M, BEPC-II, DAΦNE, SuperKEKB

[Reported numbers, not design]

	DAΦNE	VEPP-2000	BEPC-II	VEPP-4M	SuperKEKB
Start of operation [year]	1999	2010	2008	1994	2018
Species	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-
Circumference [m]	97	24	238	366	3016
Beam energy [GeV]	0.51	1	1.89 (2.474 max)	6	4 / 7
CoM energy [GeV]	1.02	2	3.78 (5.56 max)	12	10.58
Average beam current [mA]	800 / 1250	160	851	80	1400 / 1000
Peak luminosity [10^{30} $cm^{-2}s^{-1}$]	453	50	1000	20	3810
Focus	Φ meson	u,d,s interactions	tau-charm	Υ(1S) meson	B meson

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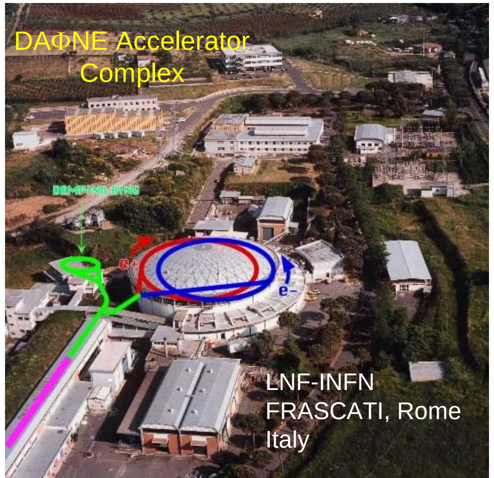
[PDG, Tables 32.1, 32.3;
Q. Qin, "Overview of the low energy colliders", proceedings eeFACT2016, Daresbury (2016)]

DAΦNE

DAΦNE Parameters & Achievements

Energy (each beam MeV)	510
θ_{cross} (mrad)	50
ε_x (mm mrad)	0.28
$\Phi_{Piwinski}$	1.7
$\beta^*_{x/y}$ (mm)	240. / 8.
Maximum Stored Currents e^- / e^+ (A)	2.4 / 1.4
Bunch Spacing (nsec)	2.7
Maximum Luminosity (10^{32} $cm^{-2}s^{-1}$)	4.53
ξ_y max	0.09



The Frascati lepton collider DAΦNE has been powering physics research at the LNF since more than 20 years.

This was possible since in 2008 DAΦNE implemented and successfully tested, with detectors of different complexity, a new collision scheme: the ***Crab-Waist Collision Scheme,*** which has become, de facto, one of the main concept to operate present and future colliders.

Presently, DAFNE has completed a physics run delivering 1.5 fb^{-1} to the SIDDHARDA-2 experiment aiming at performing the first-ever measurement of kaonic deuterium X-ray transitions to the ground state level.

Ongoing discussion concerning DAΦNE future

In the next future DAΦNE might be used for short periods, 4-5 months per year.
Operations might be be dedicated at:

- studying physics problems and innovative technologies,
- testing innovative collision concepts,
- implementing short term experiments about fundamental and applied physics,
- training young generations of particle accelerator physicists.

DAFNE Synchrotron Light Facility could be also operated.

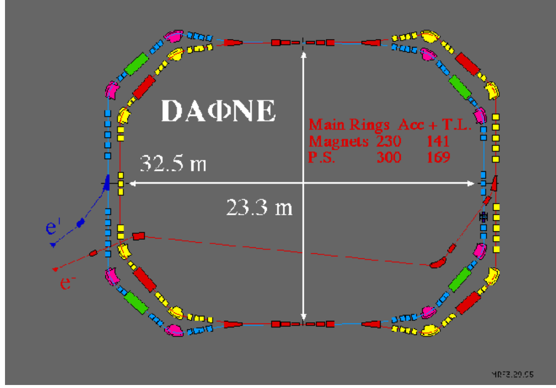
DAΦNE LINAC will continue to power two **Beam Test Facility lines.**

This plan requires a minimal refurbishment of the accelerator complex that can also be implemented progressively

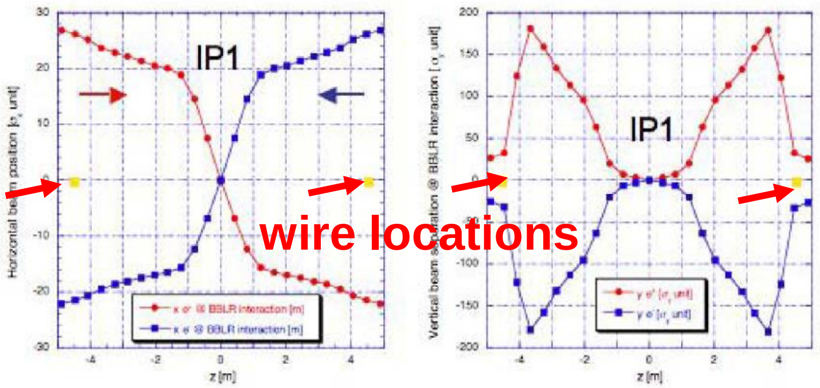
Maintaining DAΦNE infrastructure operative could be also very much synergic with Future CERN developments in the lepton colliders field.

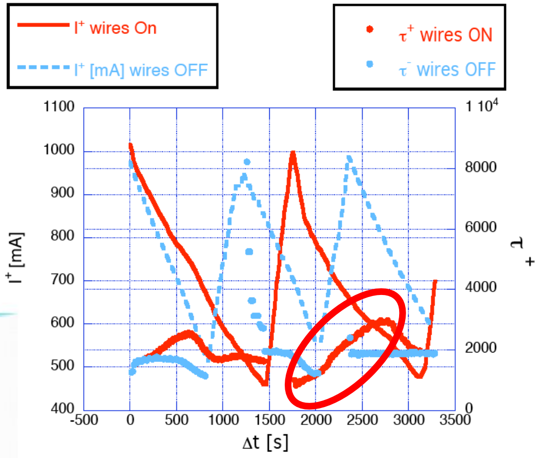
(Courtesy of Catia Milardi)

Innovation at low-energy colliders from INFN DAΦNE

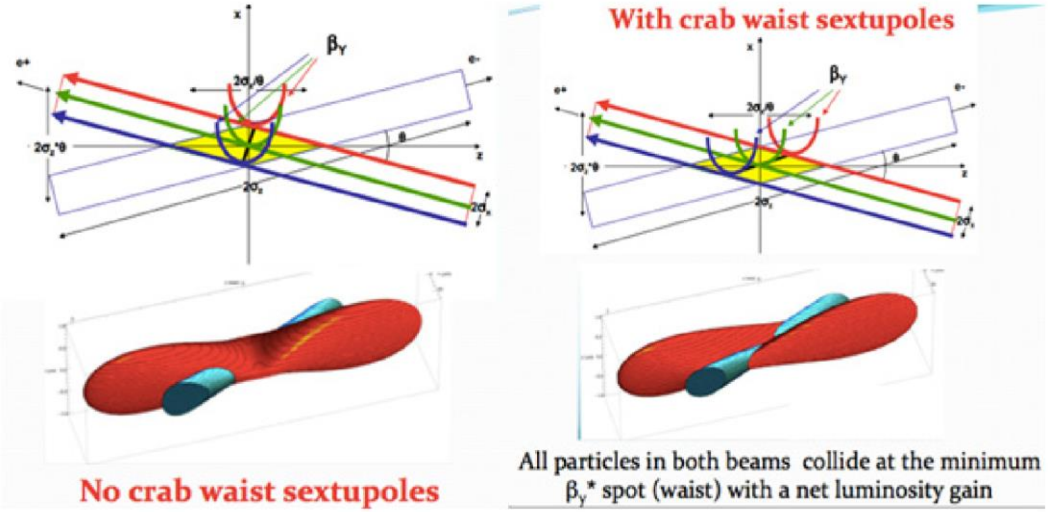


- Long-range beam-beam compensation with wires improves beam lifetime





- Crab waist increases luminosity by x3



[C. Milardi et al, "DAΦNE lifetime optimization with octupoles and compensating wires", CARE-HHH-APD IR'07 Workshop, Frascati (2007); M.Zobov, C. Milardi, P. Raimondi et al., Phys.Rev.Lett. 104 (2010) 174801;
Q. Qin, "Overview of the low energy colliders", proceedings eeFACT2016, Daresbury (2016)]

BINP VEPP-2000/4M

Round beams to mitigate beam-beam
Beam shaking to avoids beam size flip-flip

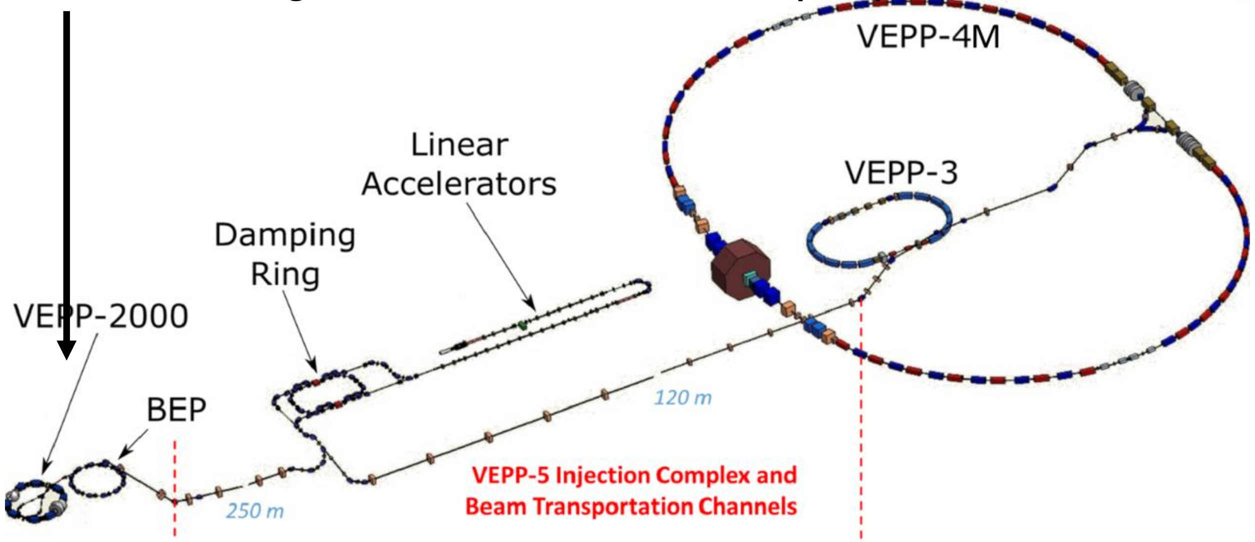


Table 1: VEPP-2000 Design Parameters (at $E = 1$ GeV)

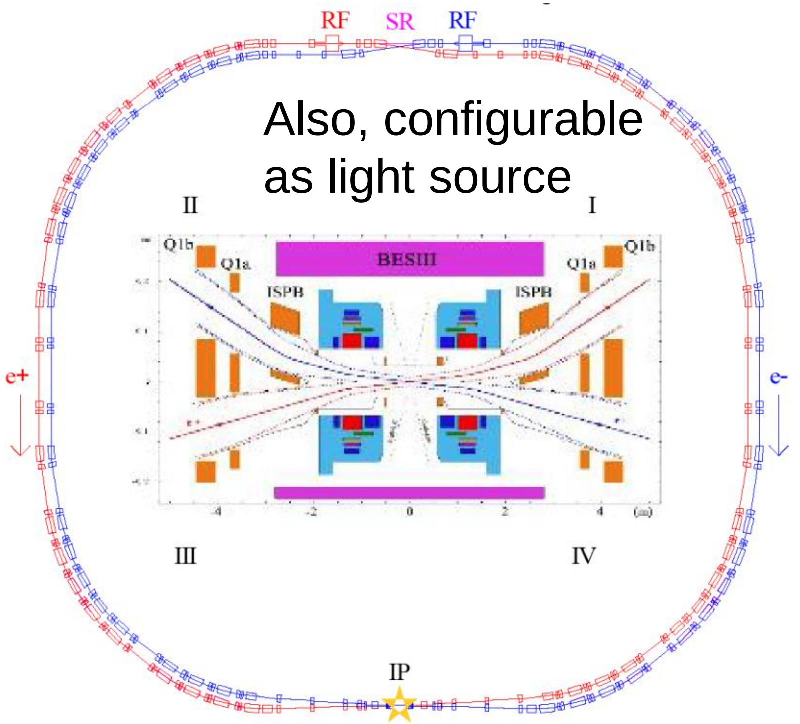
Circumference, C	24.39 m
Energy range, E	150–1000 MeV
Number of bunches	1 × 1
Particles per bunch, N	1×10^{11}
Beta-functions at IP, $\beta^*_{x,y}$	8.5 cm
Betatron tunes, $\nu_{x,y}$	4.1, 2.1
Beam emittance, $\varepsilon_{x,y}$	1.4×10^{-7} m rad
Beam–beam parameters, $\xi_{x,z}$	0.1
Luminosity, L	1×10^{32} cm^{-2} s^{-1}

Table 1: Parameters of VEPP-4M for Different Energies

Energy	2.3	3.5	4.75	GeV
Betatron Tunes		8.54/7.57		
Nat. Chroms		–14/–20		
Comp. Factor		0.0168		
Hor. Emit.	42	100	180	nm·rad
Energy Spread	3.7	6.5	7.5	$\cdot 10^{-4}$
Bunch Length		4		cm
Bunch Current	6	9/15	15	mA
Luminosity	0.5	1.2/2.0	$0.6 \cdot 10^{31}$	$\cdot 10^{31}$ cm^{-2} s^{-1}

[Y. Maltseva, RuPAC 2018; D.B. Shwartz, IPAC2021; P.A. Piminov, IPAC2021]

IHEP BEPC-II



Also, configurable as light source

Table 3: Main Design Parameters of the BEPCII

Parameters	Collision	SR
Beam energy (GeV)	1.89	2.5
Circumference (m)	237.53	241.13
Beam current (A)	0.91	0.25
Bunch current (mA) / No.	9.8 / 93	~1/160-300
Natural bunch length (mm)	13.6	12.0
RF frequency (MHz)	499.8	499.8
Harmonic number	396	402
Emittance (x/y)(nm·rad)	144/2.2	140
β function at IP (x/y) (m)	1.0/0.015	10.0/10.0
Luminosity (cm^{-2}s^{-1})	1×10^{33}	—

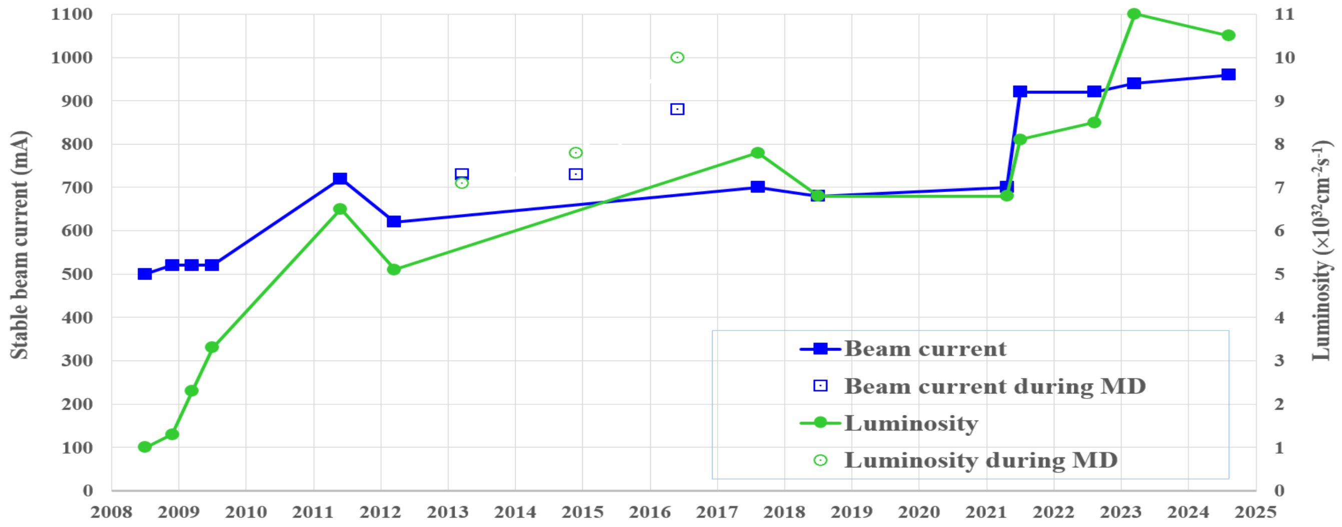
[Q. Qin, eeFACT2016]

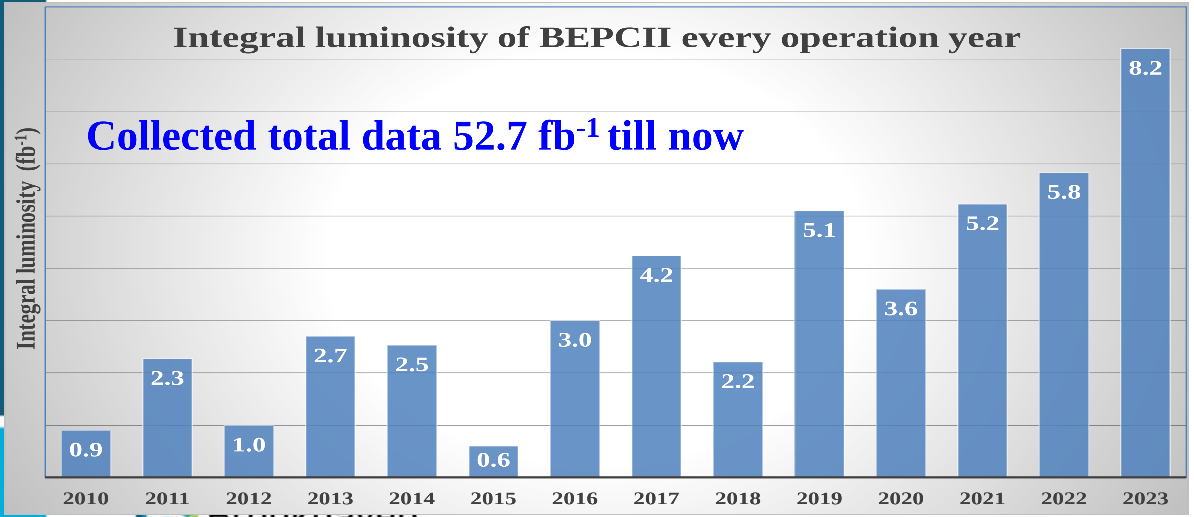
Status of BEPCII

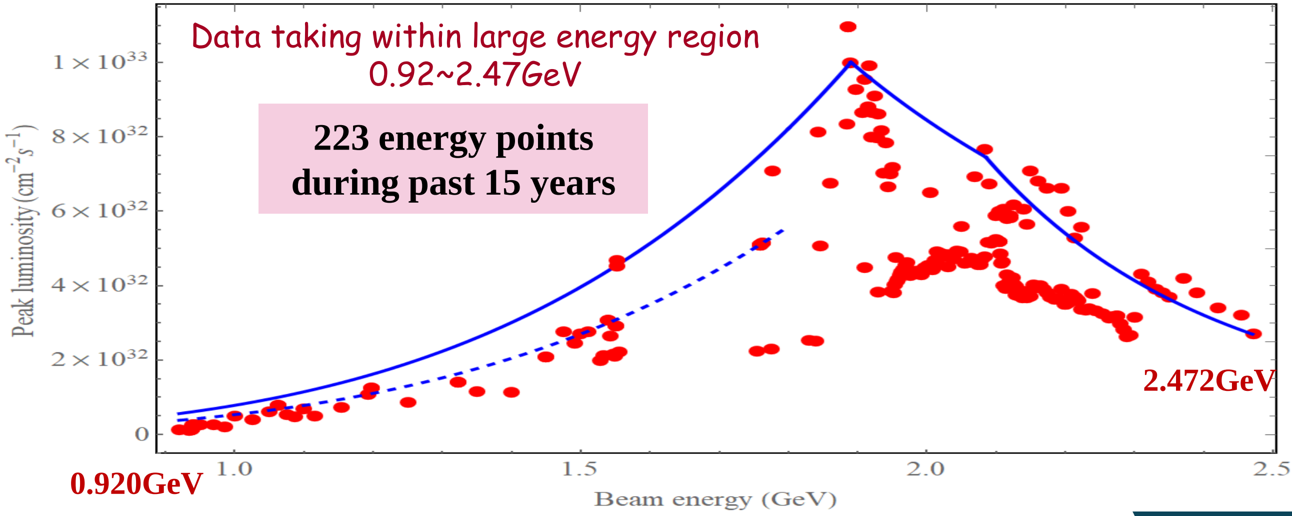
Main parameters of BEPCII

Parameters	Design	Achieved	
		BER	BPR
Beam energy (GeV)	1.0-2.1， 1.89	0.92-2.47， 1.89	0.92-2.47， 1.89
Beam current (mA)	910	950	950
Bunch number	93	118	118
Beam-beam parameter	0.04	0.041	
β_x^*/β_y^* (m)	1.0/0.015	1.0/0.0135	1.0/0.0135
Inj. Rate (mA/min)	200 e^- / 50 e^+	>1000	>200
Lum. ($\times 10^{33}cm^{-2}s^{-1}$)	1.0	1.1	

History of peak luminosity and beam current of BEPCII







Courtesy of Chenghui Yu

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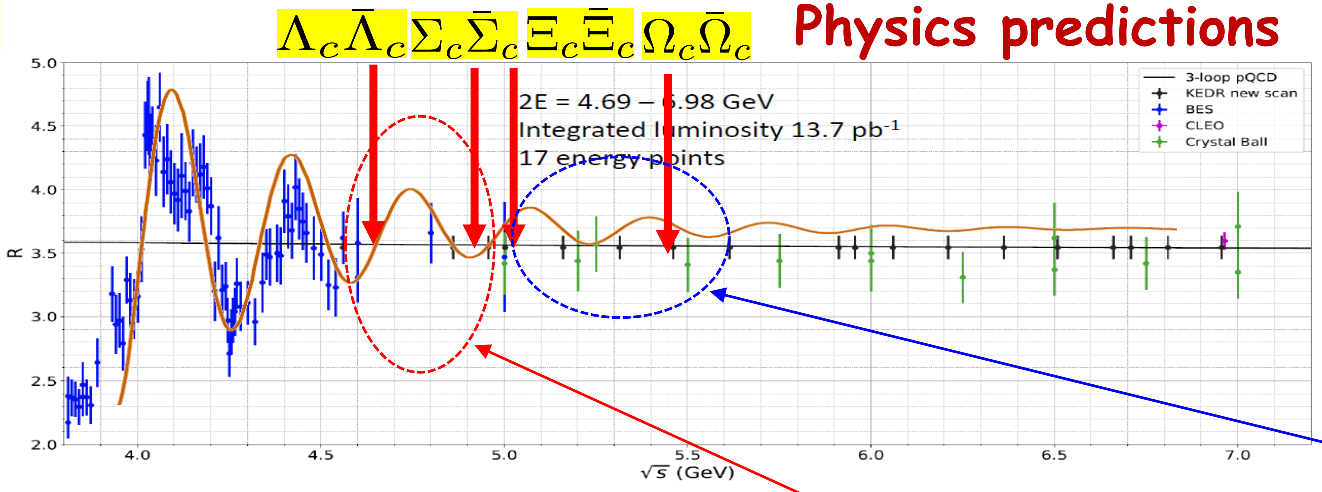
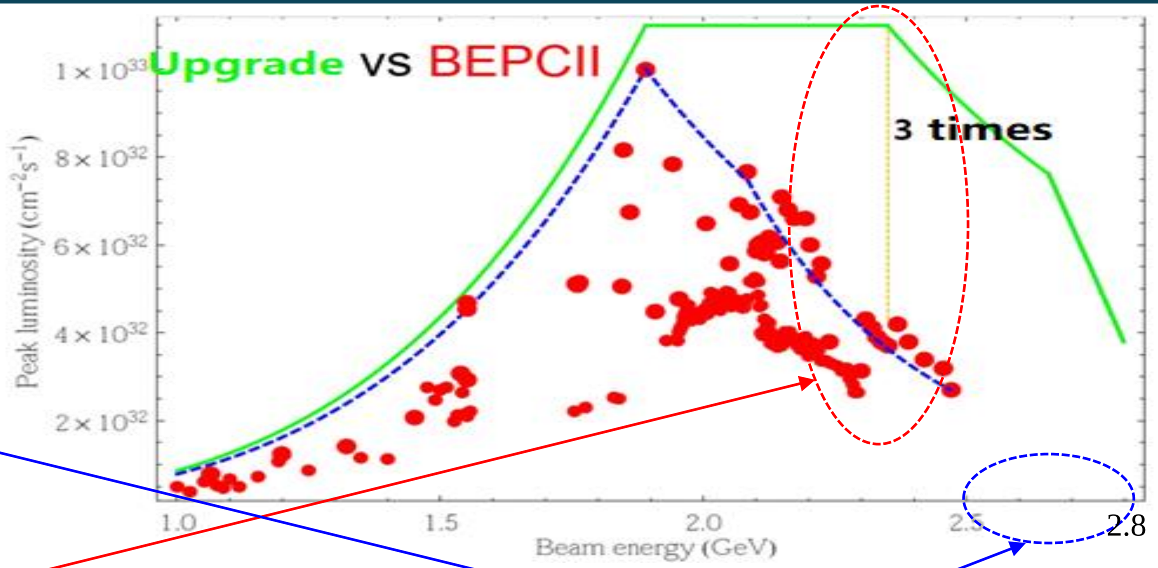
Institute of High Energy Physics Chinese Academy of Sciences

Status pf BEPCII upgrade project



* KEDR new scan points positions are fixed at pQCD predictions
Expected total uncertainty is about 3 % (systematic uncertainty about 2.5%)



BEPCII upgrade aims at: **Increase luminosity by a factor of 3** & **Increase beam energy to 2.8GeV**

Key Technologies: Double beam power & Optics upgrade & New high gradient of magnets

- **2020** White Paper of BESIII
- **May. 2020** Internal Review of Accelerator
- **Jun. 2021** Feasibility Study Report
- **Jul. 2021** Project Approved
- ***Apr. 2022*** *Design Finished*
- **Jun. 2024** Fabrication Finished
- **Jul. 2024** Shutdown for Installation
- **Jan. 2025** Commissioning

BEPCII keep running

Timeline of BEPCII operation and its upgrade

Courtesy of Chenghui Yu

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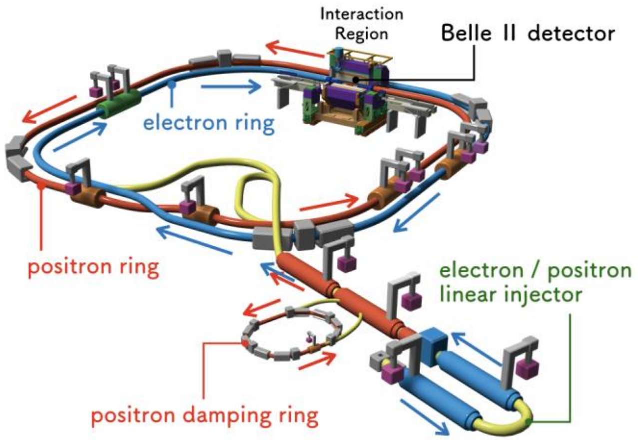
SuperKEKB - design

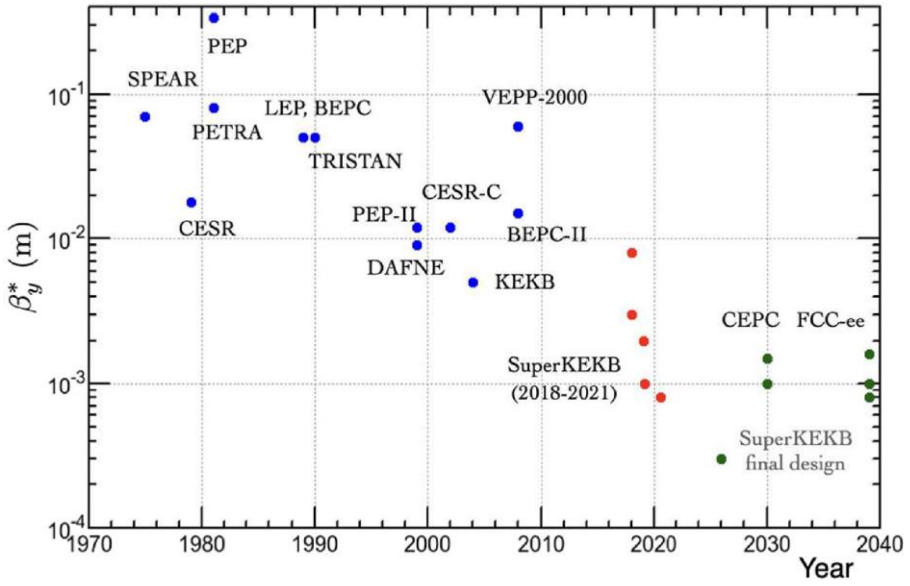
- 40x KEKB luminosity

“Nano-beam” collision scheme with

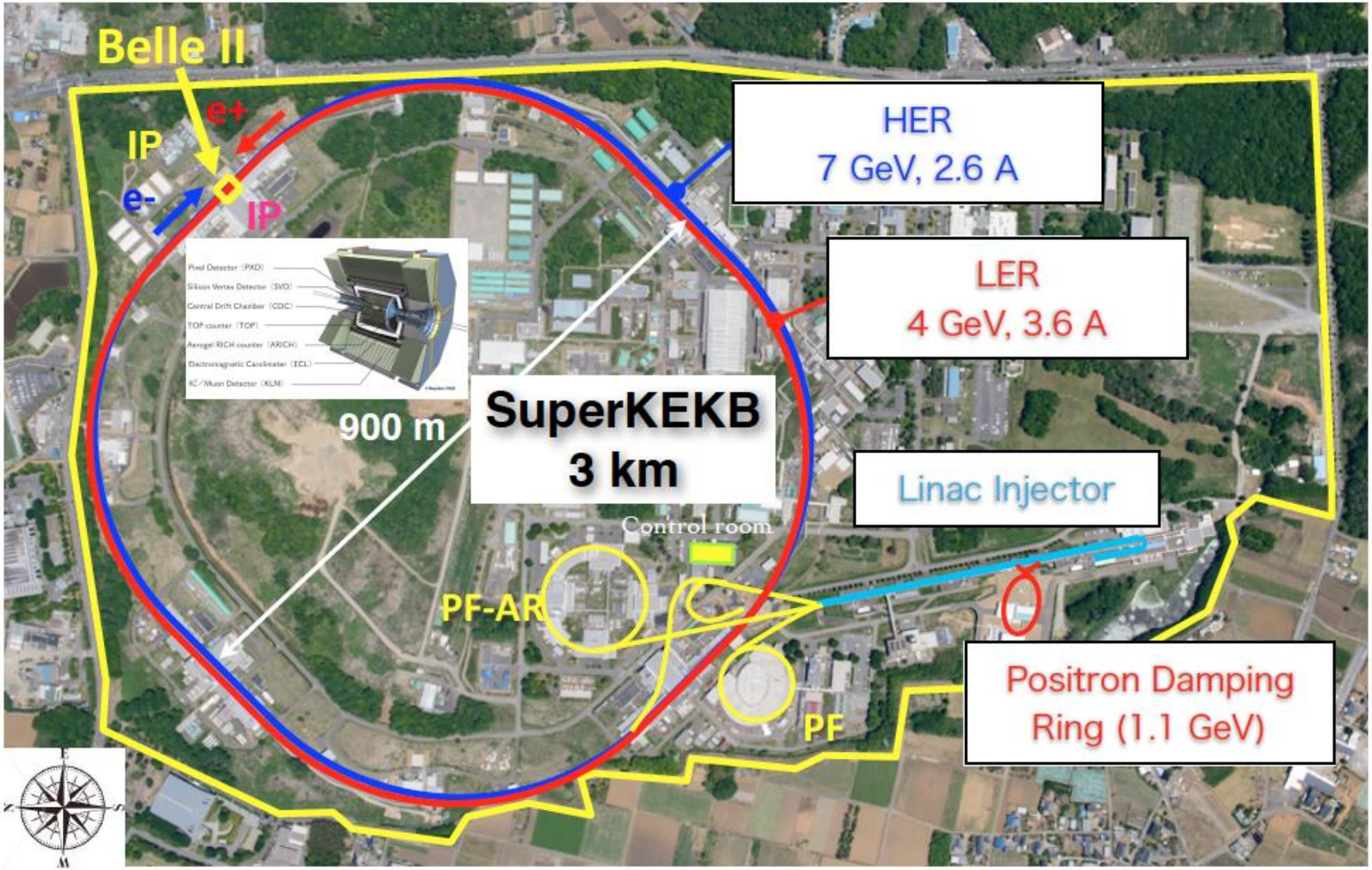
- Low emittance, new e^+ damping ring
- Large Piwinski angle
- Crab waist

	SuperKEKB design	
	LER	HER
I_{beam} [A]	3.6	2.6
# of bunches	2500	
I_{bunch} [mA]	1.440	1.040
βy^* [mm]	0.27	0.30
ξy	0.0881	0.0807
Luminosity [$10^{34}cm^{-2}s^{-1}$]	80	
Integrated Luminosity [ab^{-1}]	50	



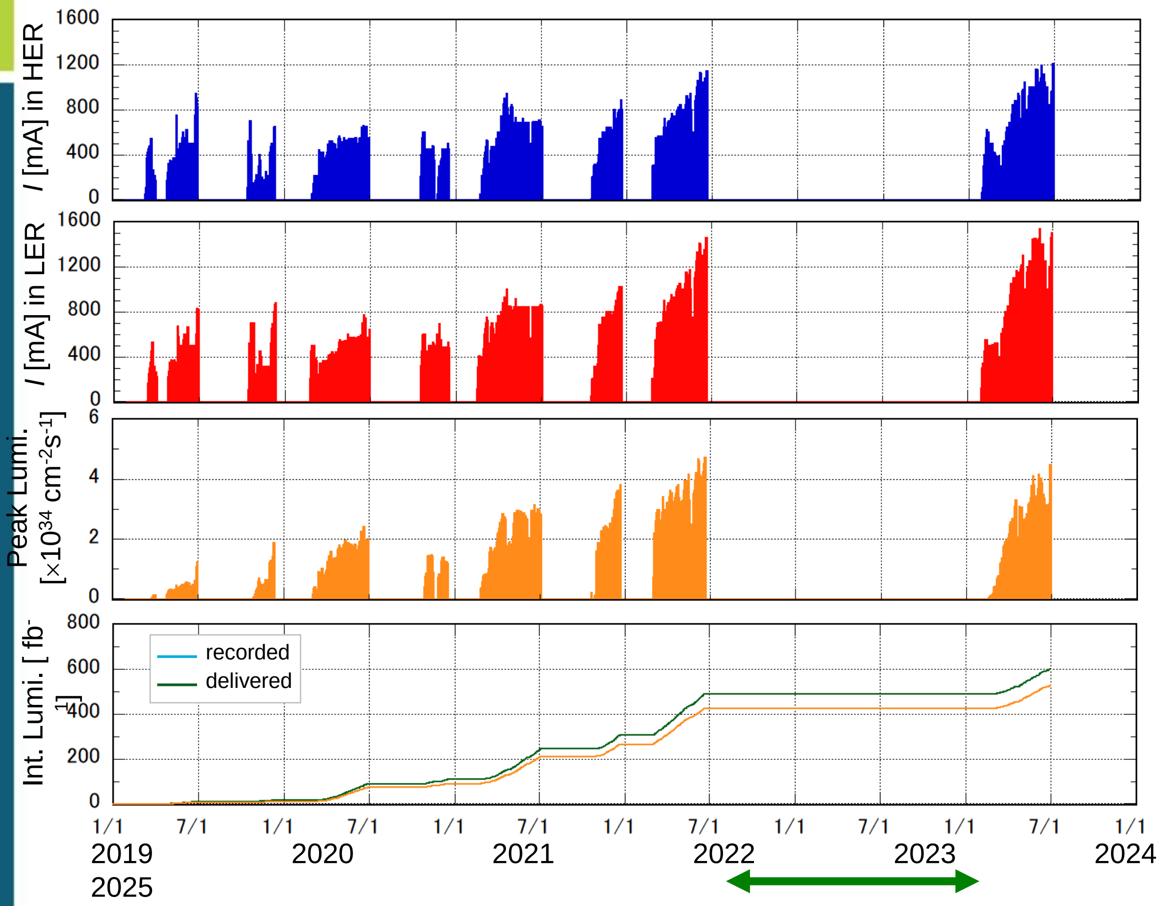


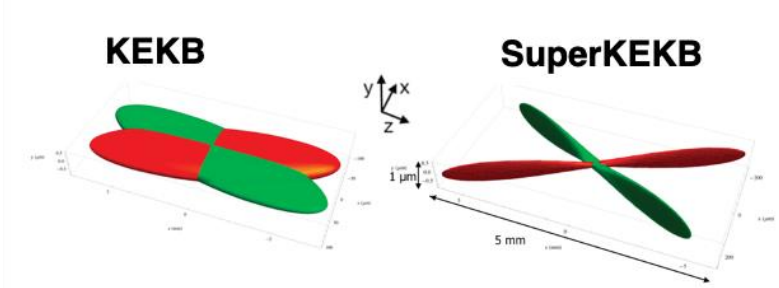
[Y. Ohnishi, et al., Eur. Phys. J. Plus, 136:1023 (2021)
Y. Funakoshi et al., “The SuperKEKB has broken the world record of the luminosity” IPAC 2022 (2022)]

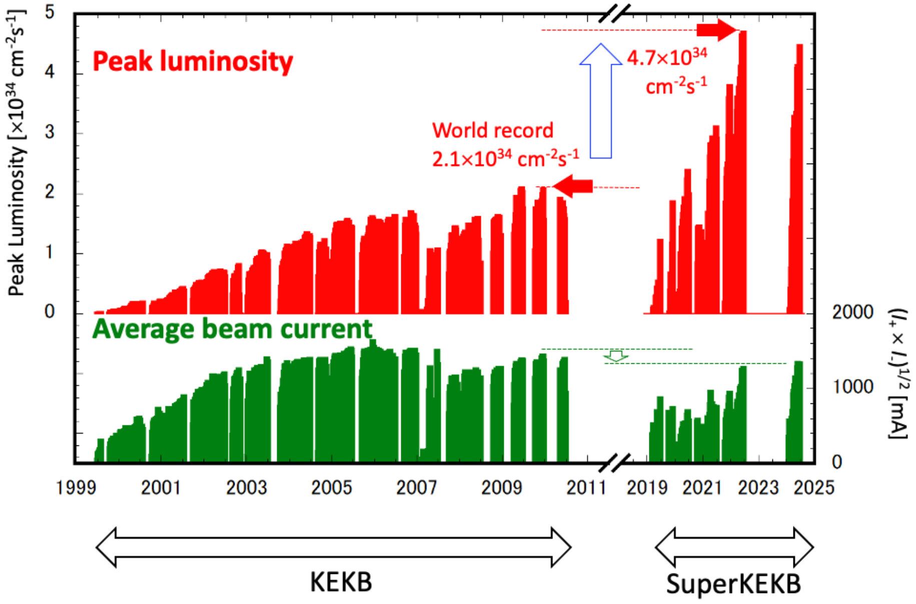

Belle II
e+
IP
e-
IP
Pixel Detector (PXD)
Silicon Vertex Detector (SVD)
Central Drift Chamber (CDC)
TOP counter (TOP)
Aerogel RICH counter (ARICH)
Electromagnetic Calorimeter (ECL)
KL/Muon Detector (KLM)
900 m
SuperKEKB
3 km
HER
7 GeV, 2.6 A
LER
4 GeV, 3.6 A
Linac Injector
Control room
PF-AR
PF
Positron Damping
Ring (1.1 GeV)

Operation Status of SuperKEKB

Design based on “nano-beam” collision scheme:
- Two beams collide at the interaction point (IP) with a large horizontal crossing angle of 83 mrad.
- A very strong vertical focusing is applied at the IP to squeeze the beam.







Long Shutdown 1:
Improvements of the Belle II detector and the SuperKEKB accelerator

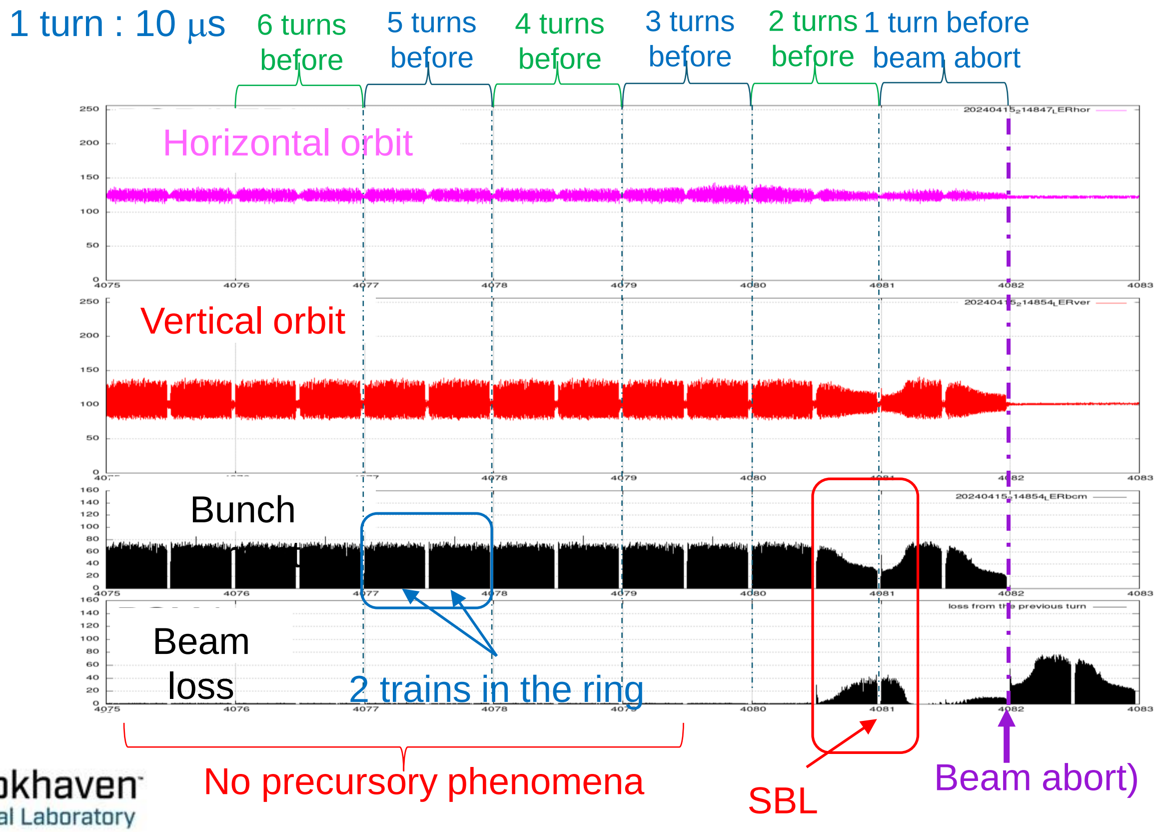
Courtesy of Tadashi Koseki

The nano beam collision scheme is effective to reduce power consumption.

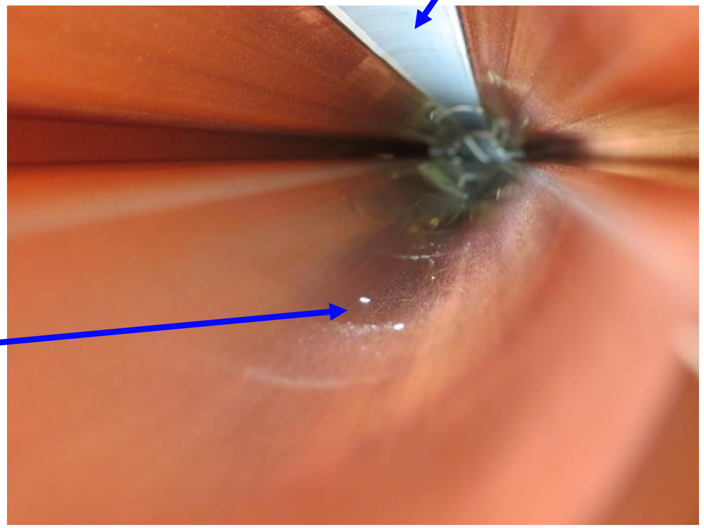
SuperKEKB challenges: Sudden Beam Loss

Sudden Beam Loss - The serious obstacle to increase luminosity

- It has occurred within approximately 2-turn (~20 μs) before the beam abort.
- Small beam orbit displacements (~0.1mm) in horizontal and vertical direction has been observed before 1-2 turns of the beam loss.
- Quick increase in the vertical beam size has been observed by a fast beam size monitor.
- It is more common in LER, but has also occurred in HER.
- It could quench the superconducting coils in QCS, and damage vertical collimator heads and pixel detector system at the innermost part of the Belle II detector.



We have recently found that the most suspicious cause of SBL is the dusts from the clearing electrodes in the wiggler section.
The electrodes are mounted in the beam ducts to mitigate electron cloud. They are very thin electrodes with 0.1 mm tungsten on 0.2 mm Al_2O_3.



Countermeasures to the SBL will be implemented during the 2024 summer maintenance period.

The target luminosity in JFY2024 is ~$1x10^{35}$ $cm^{-2}s^{-1}$.

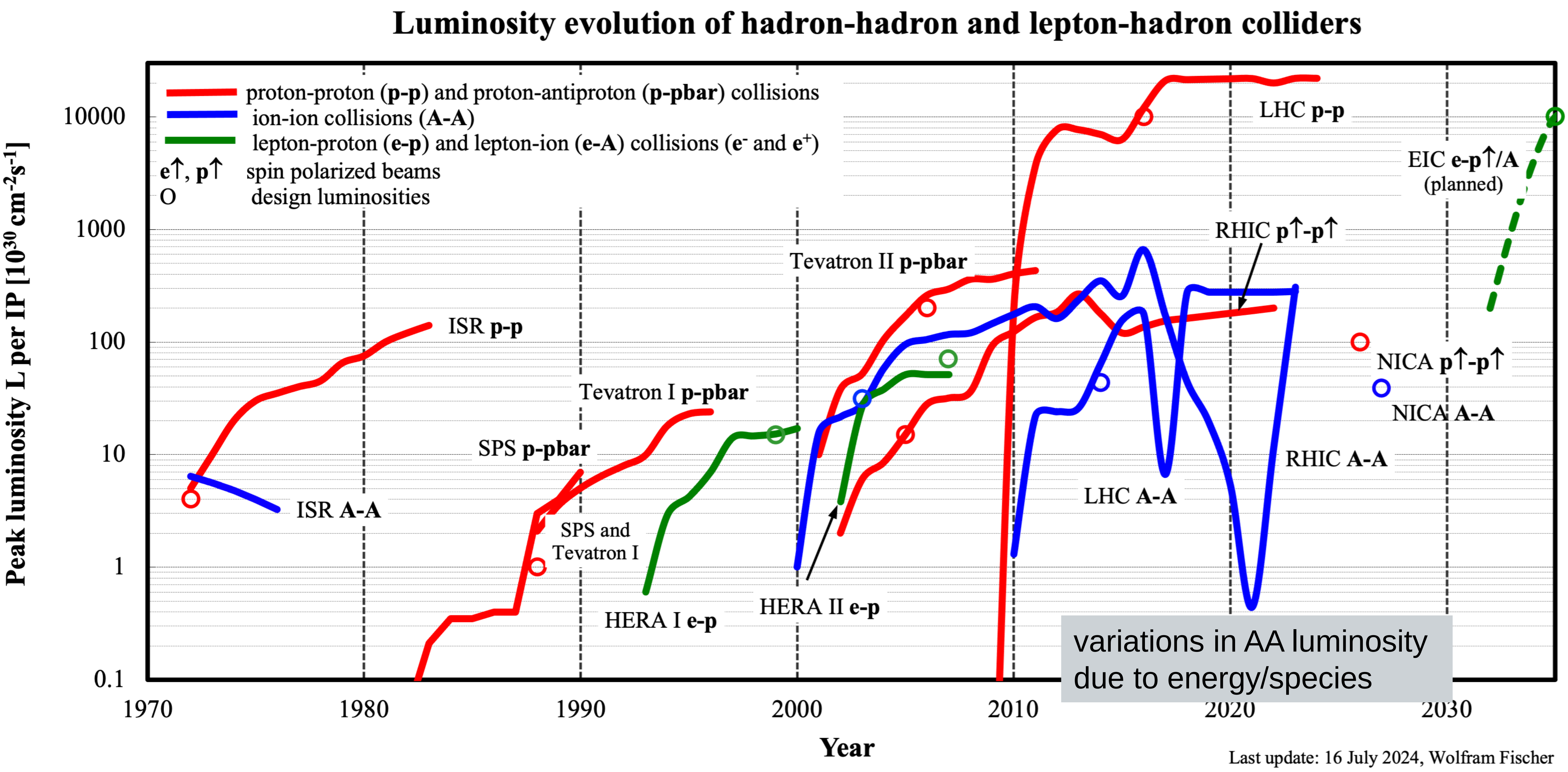
Courtesy of Tadashi Koseki

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

[Reported numbers, EIC – design]

	RHIC **pp** (actual)	**LHC** **pp** (actual)	**RHIC** **AA** (actual)	**LHC** **AA** (actual)	**EIC** **ep, eA** (design)	**NICA** **pp, dd, AA**
Start of operation [year]	2001	2009	2000	2010	2032 (planned)	2025 (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	e↑+p↑ to e↑+U (polarized e,p, He-3)	p↑ d↑ A
Circumference [km]	3.8	26.7	3.8	26.7	3.8	0.5
Beam energy [GeV]	255	6500	100 A	2560 A	5-18 / 40-275	1 – 4.5
CoM energy [GeV]	510	13000	200 A	5120 A	28-140 (e↑+p↑)	4 – 11
Average beam current [mA]	257	510	224 (Au+Au)	24 (Pb+Pb)	2500 / 1000	
Peak luminosity [10^{30} $cm^{-2}s^{-1}$]	245	2100	0.015 (Au+Au)	0.006 (Pb+Pb)	10000 (e↑+p↑)	
Spin polarization	55-60%	0	0	0	70% e,p,h	

[PDG, Tables 32.4, 32.5; EIC]



variations in AA luminosity due to energy/species

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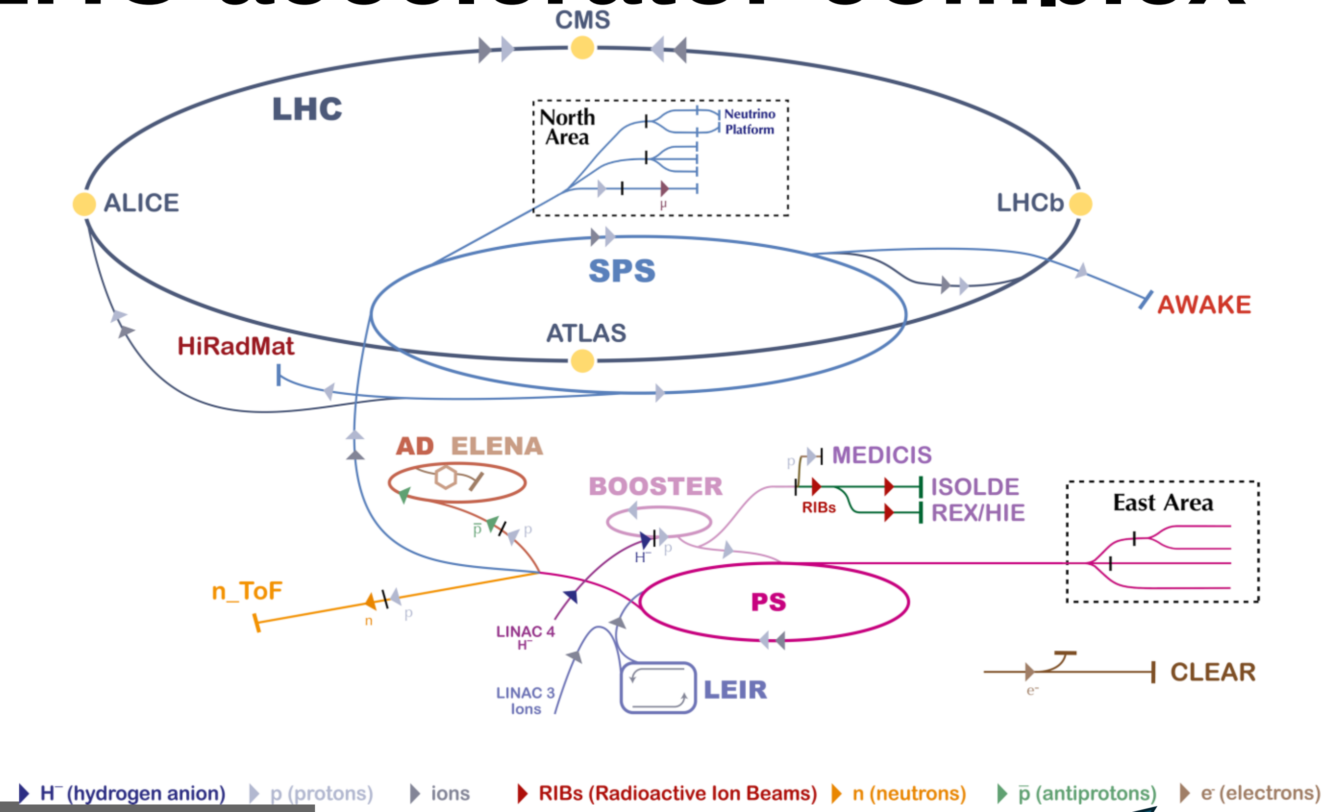
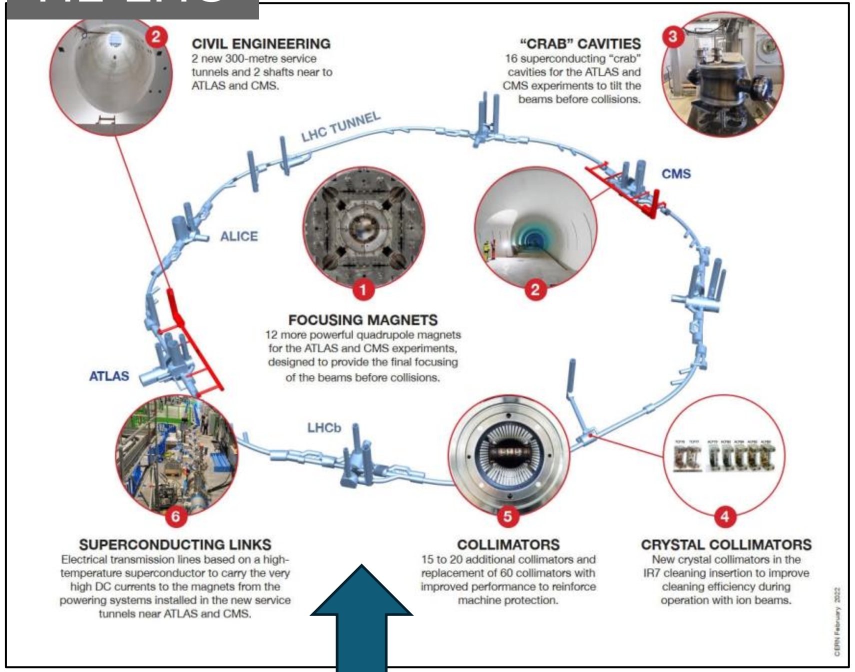
LHC accelerator complex

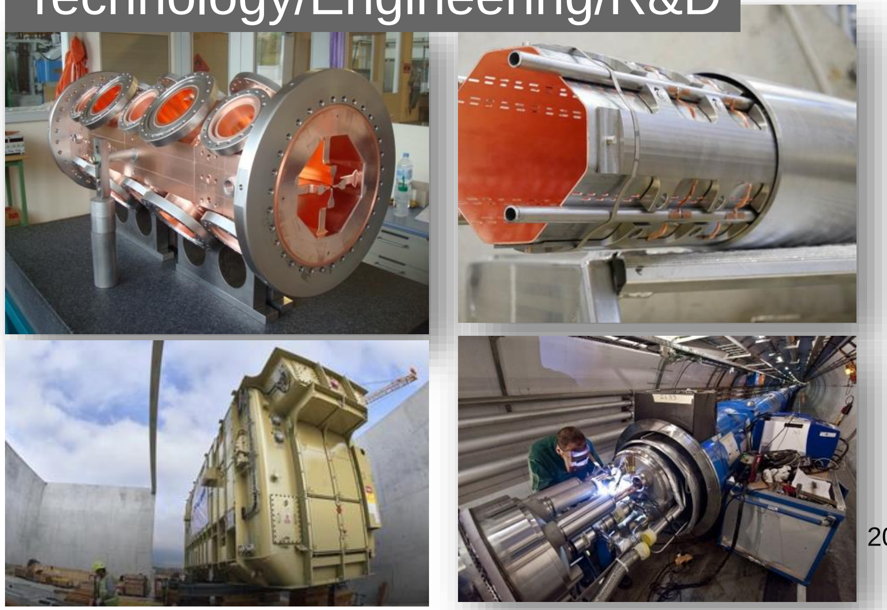


HL-LHC



Future Options

Technology/Engineering/R&D

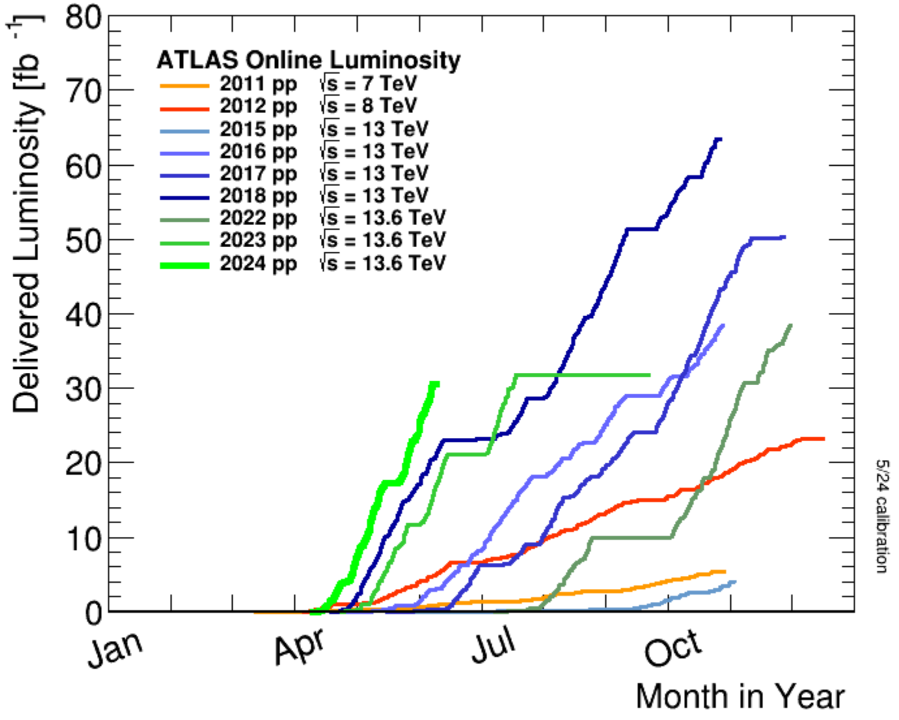


Courtesy of Mike Lamont

LHC Operations

2024 Luminosity target updated from 90 fb^{-1} to 110 fb^{-1}

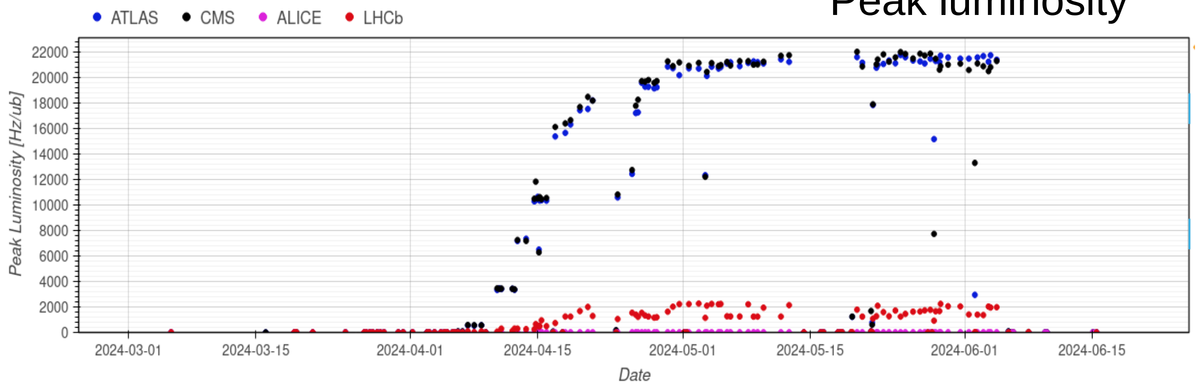
- **Good availability** through the first part of the year
- **~30 fb^{-1}** in ATLAS/CMS (Up to 1.4 fb^{-1} in 24h)
- Achieved **nominal rate** (as 2023)
- **Peak luminosity** at ~2.1×10^{34} $cm^{-2}s^{-1}$
  - >2 factor beyond design value
- **Pile-up** at ~65 in ATLAS/CMS



Present focus

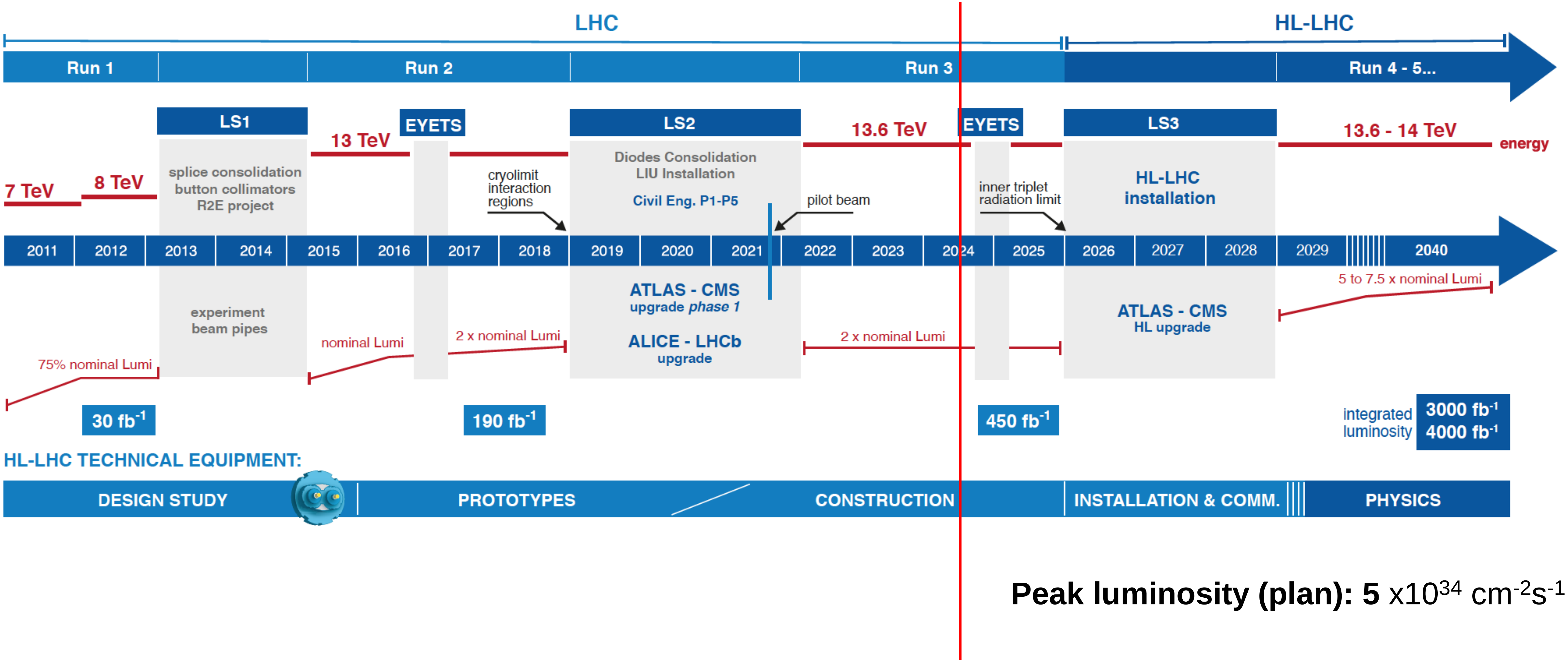
- Long term productive, high availability operation
- Full mastery of considerable inherent operational risks
- Optimal performance to maximize physics output
- Adaptability, reactivity and engagement
- Studies, simulations, tool development to support effective exploitation of the LHC and to prepare for the HL-LHC program

Peak luminosity



Courtesy of Mike Lamont

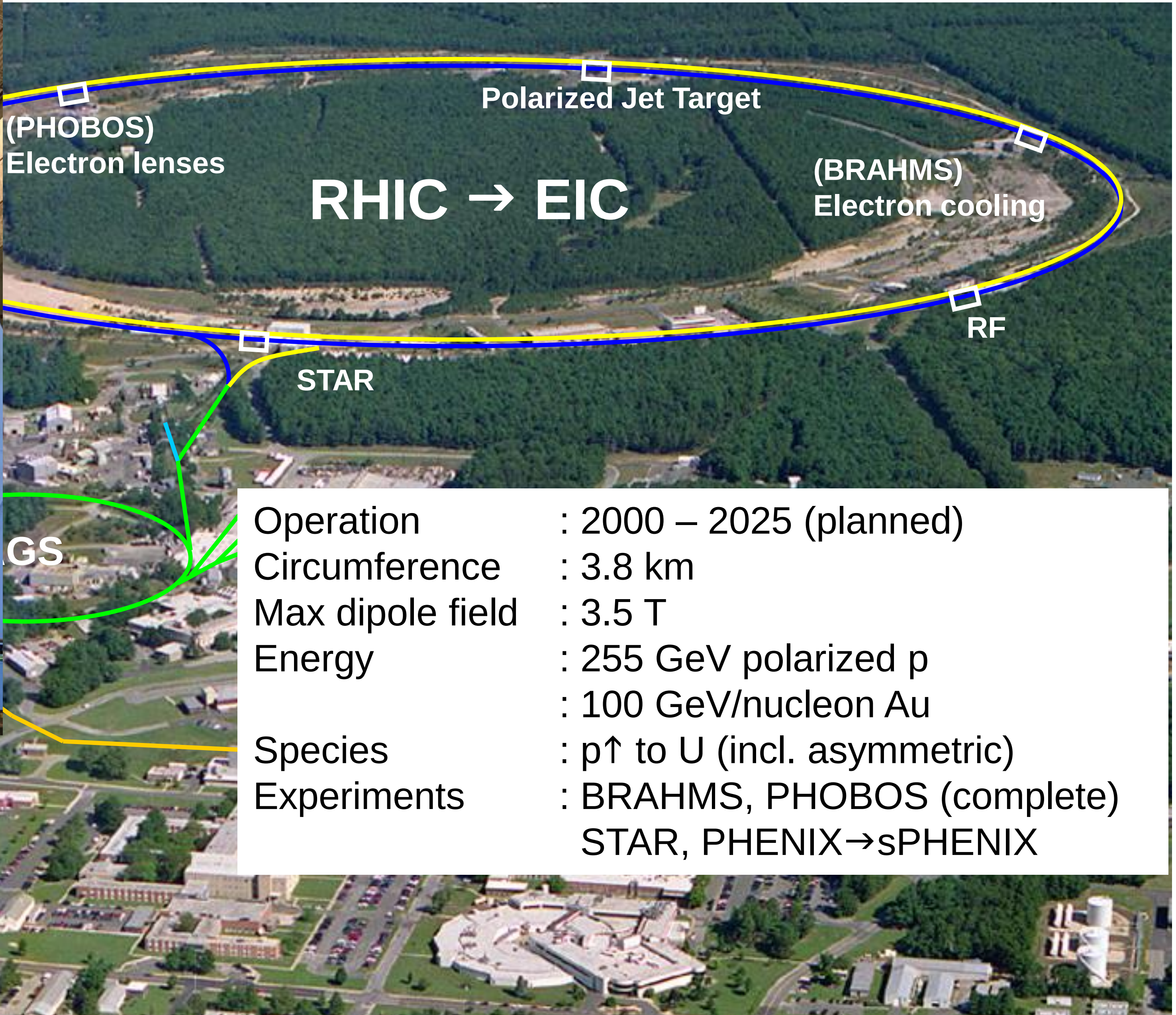
High Luminosity LHC (HL-LHC)



Peak luminosity (plan): 5 x10^{34} cm^{-2}s^{-1}

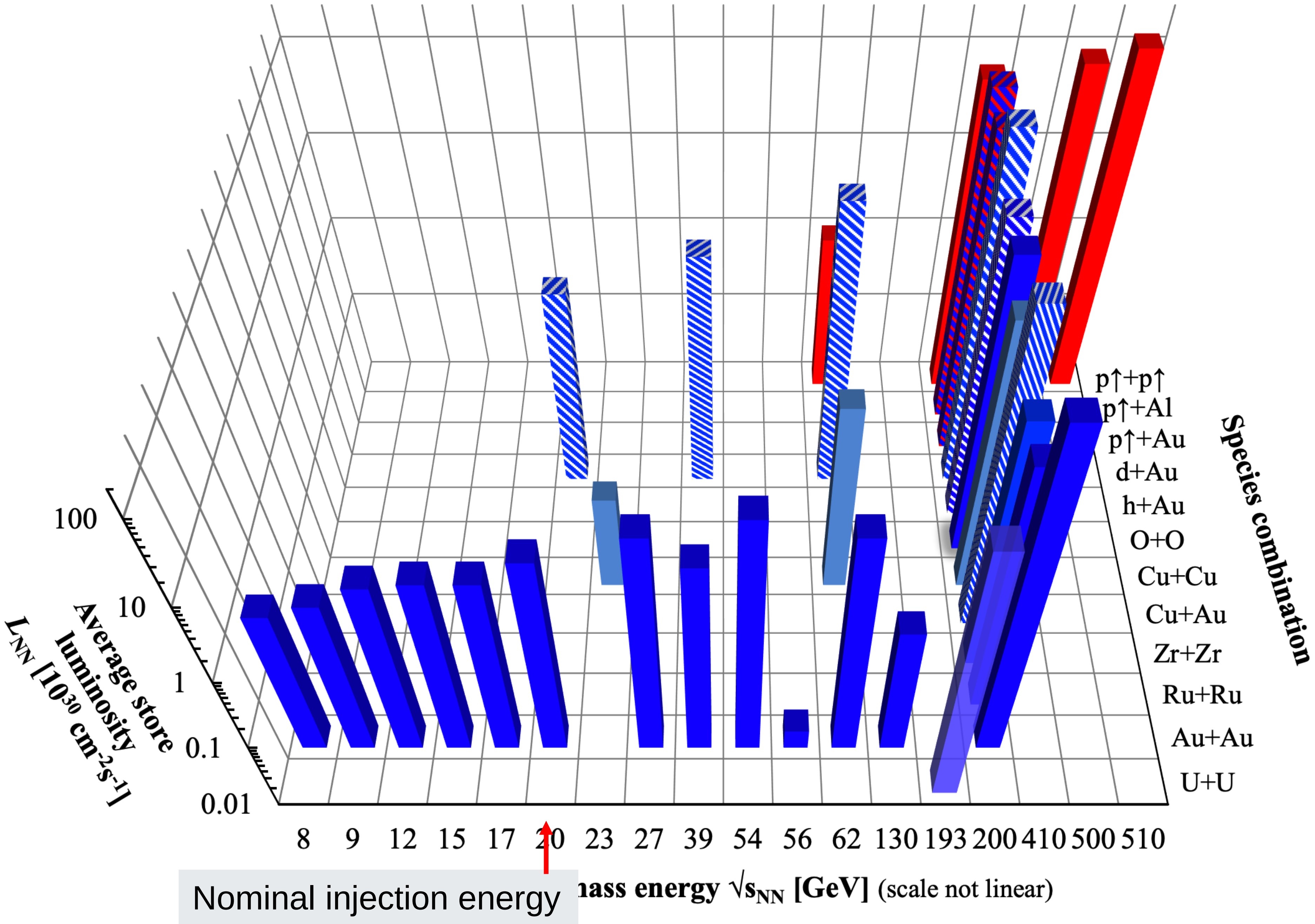
Courtesy of Mike Lamont

Relativistic Heavy Ion Collider at Brookhaven Natl Lab



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

Electron-Ion Collider

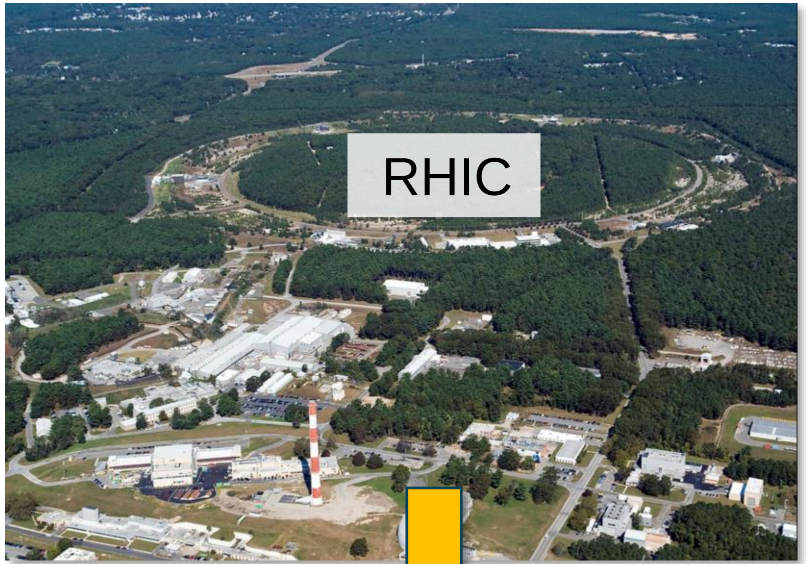
BNL-JLab partnership with national and international contribution
sited at BNL - uses RHIC hadron complex
CD-1 June 2021 (Conceptual Design complete, cost range),
Early Science 2032 (planned)

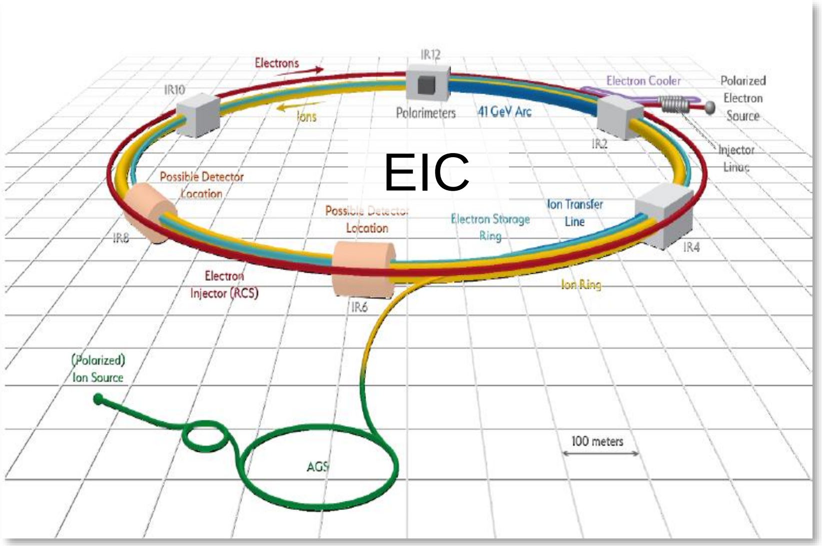
Hadron storage Ring (RHIC Rings) 40-275 GeV **(existing)**
- 1160 bunches, 1A beam current (3x RHIC)
- small vertical beam emittance 1.5 nm
- strong cooling (coherent electron cooling)

Electron storage ring 5–18 GeV (**new**)
- many bunches, large beam current, 2.5 A ➔ 9 MW S.R. power
- SC RF cavities
- Full energy swap-out injection of polarized bunches

Electron rapid cycling synchrotron 3–18 (**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

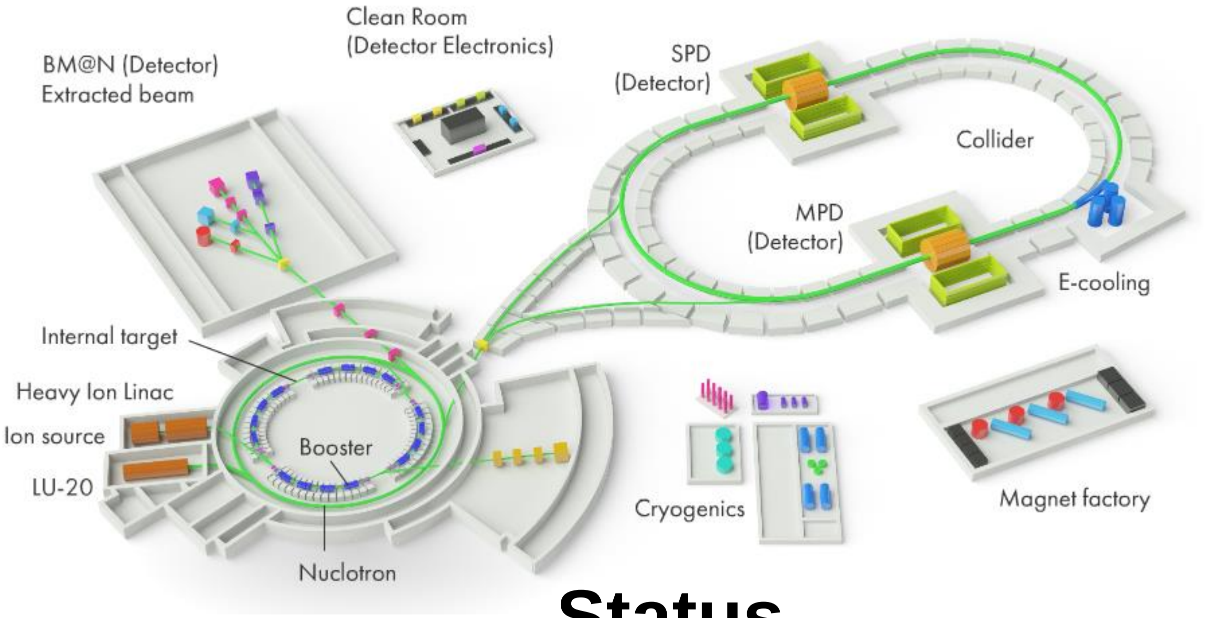




NICA Accelerating Complex

Multipurpose accelerating complex:

- NICA collider
- Injection complex
  - Two linacs
    - HILAC (A/Z >3)
    - LILAC (p, d)
  - Two SC synchrotrons
    - Booster and Nuclotron
    - Heavy ion stripping at Booster-to-Nuclotron transfers
    - Slow and fast extraction from Nuclotron



Status

Collider construction gets to its final stage

- All SC magnets in arcs and their power supplies are installed
- SC solenoid of MPD is installed in its building and is getting to be ready for cryogenic tests and magnetic field measurements

Injection complex has been in commissioning for a few years and should be ready for collider injection in the 1st half of 2025

High-intensity machines

For secondary or tertiary particles

High-intensity accelerators – Important considerations

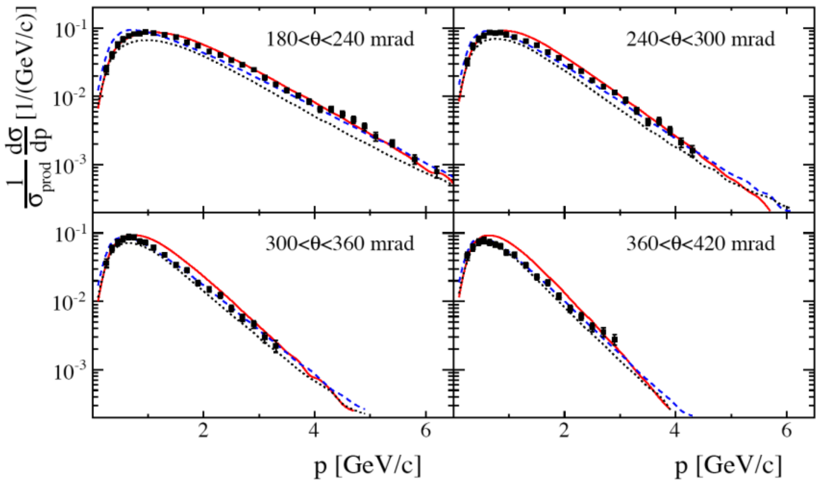
$$P_{beam} = e * N_{beam} * rate * E_{beam}$$

Limited by beam dynamics

Limited by funding

- Beam Power
- Energy
  - used to increase power
  - used to maximize production cross section
- Energy efficiency (grid-to-beam)
- Beam loss / component activation
- Targets

p+C to π^-

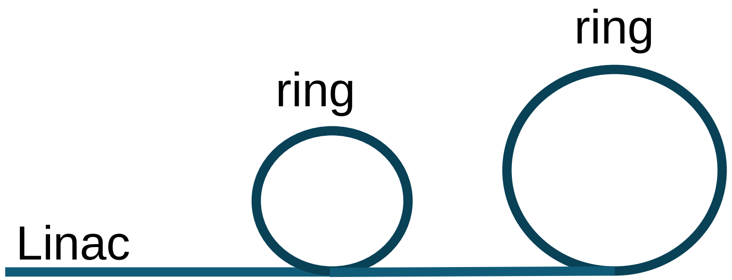


[N. Abgrall et al., Phys. Rev. C 84, 034604 (2011)]

Cyclotrons, Linacs, Rings

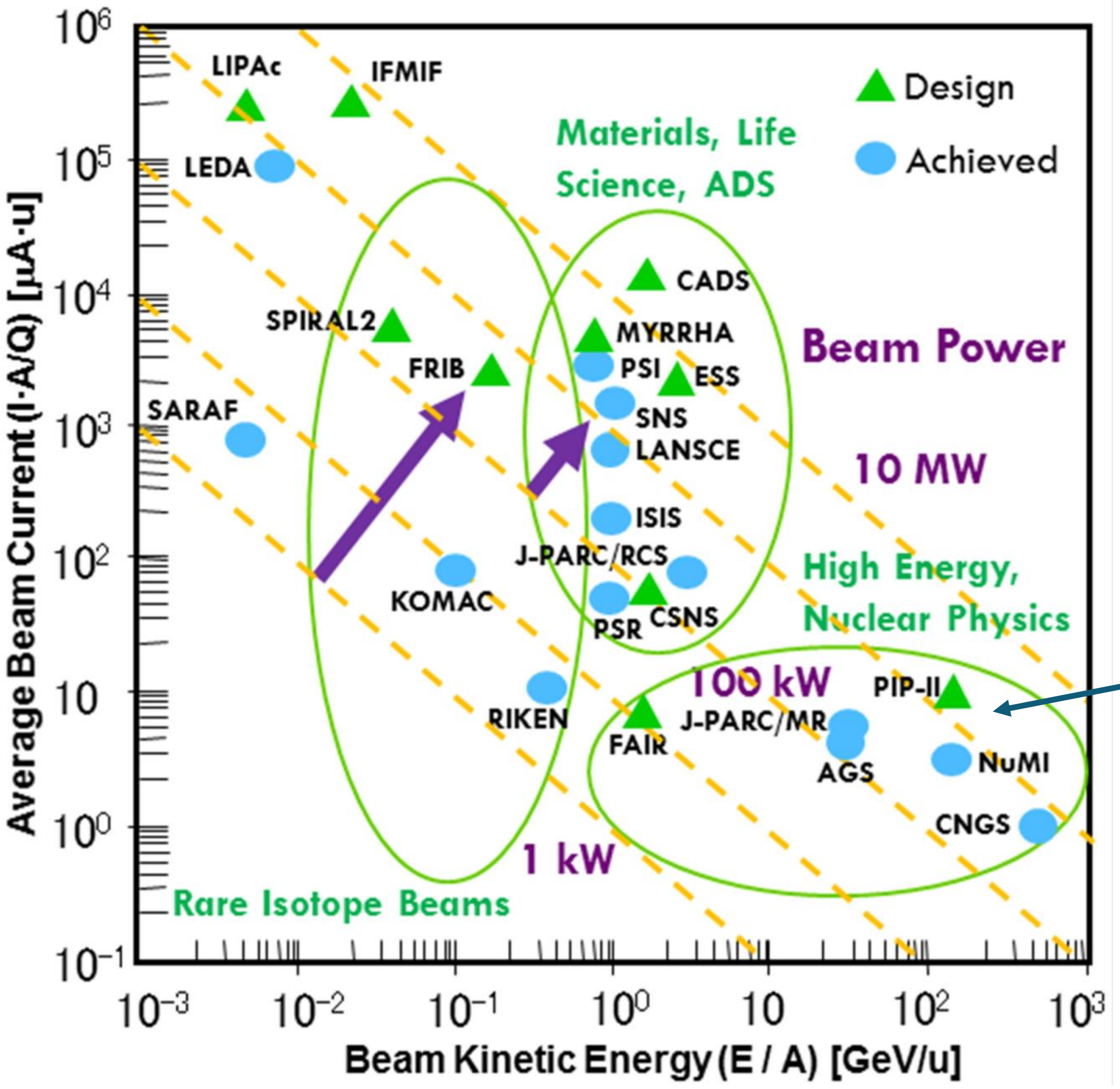
- Cyclotrons
  - Limited to ~600 MeV
    (extension: Fixed Field Alternating (FFA) gradients machines)
  - Present power frontier: PSI cyclotron 1.4 MW
  - Best energy efficiency
- Linacs
  - Space charge limit at source
  - Present power frontier: ORNL SNS 1.7 MW (Jul 2024)
  - Good energy efficiency with SRF and CW
- Accelerator rings
  - Highest energy reach
  - Space charge limit at injection
  - Present power frontier: J-PARC RCS 1.0 MW (Apr 2024)
  - Lower power efficiency

PSI cyclotron 1.4 MW



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



High-intensity accelerators for HEP

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

High-intensity machines for HEP

Machine	Energy [GeV]	Beam power [MW]	Machine Type	Comment	Used for [examples]
PSI Cyclotron	0.590	1.4	Cyclotron, CW 51 MHz	1974 start	mu3e
TRIUMF Cyclotron	0.520	0.2	Cyclotron, CW 23 MHz	1974 start	PIENU
J-PARC MR	30	0.8	Ring, 2.48 sec, FX/SX	2010 start	Neutrinos FX, HEF SX
… with fast ramping	30	1.3	Ring, 1.16 sec, FX/SX	2028 (planned)	Neutrinos FX, HEFSX
FNAL Booster	8	0.08	Pulsed 15 Hz FX	1970 start	Muon g-2, mu2e
FNAL MI	120	1.0	Pulsed FX/SX	1998 start	Neutrinos
… with PIP-II	120	1.2	Pulsed FX/SX	2030 (planned)	Neutrinos
CERN PS	24	0.03	Pulsed FX/SX	1959 start	CLOUD
CERN SPS	450	0.5	Pulsed FX/SX	1976 start	COMPASS, SHINE, NA62/63/64 AWAKE

FX = Fast eXtraction, SX = Slow eXtraction

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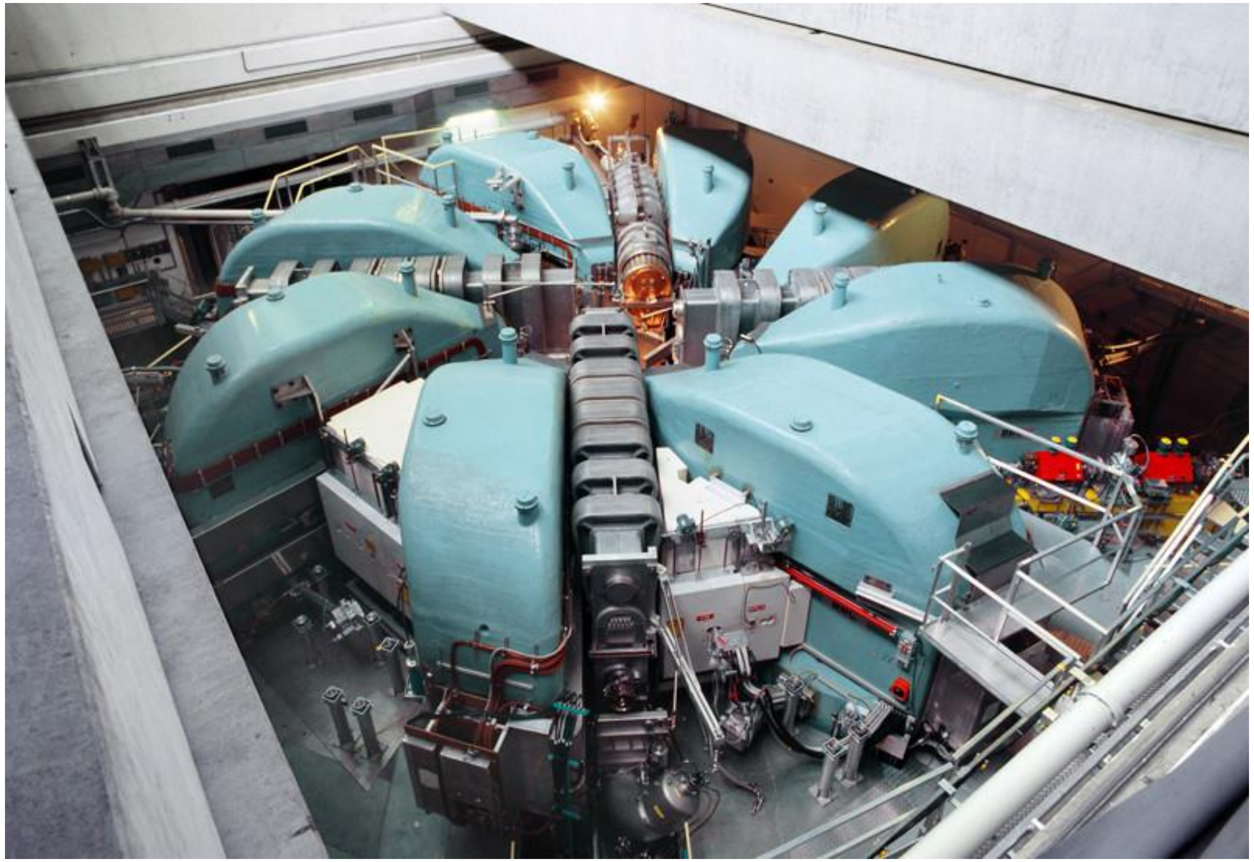
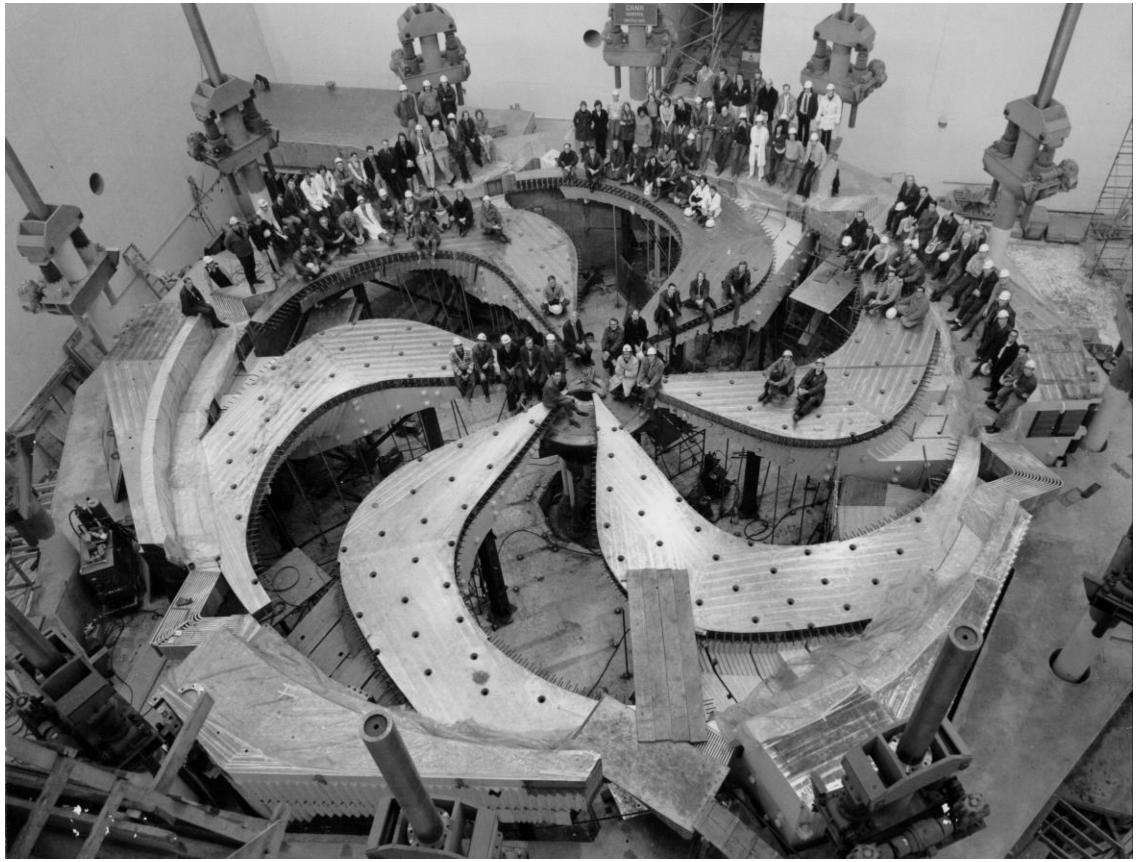
PSI and TRIUMF Cyclotrons





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

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

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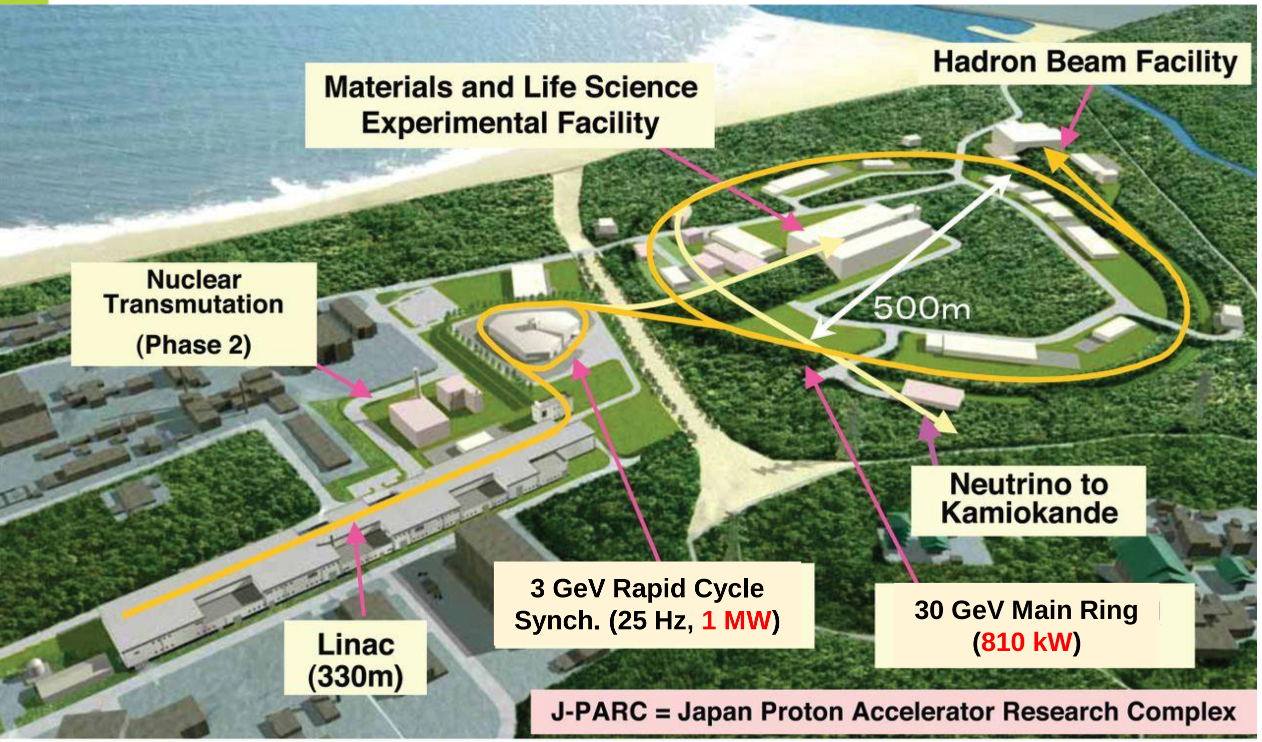
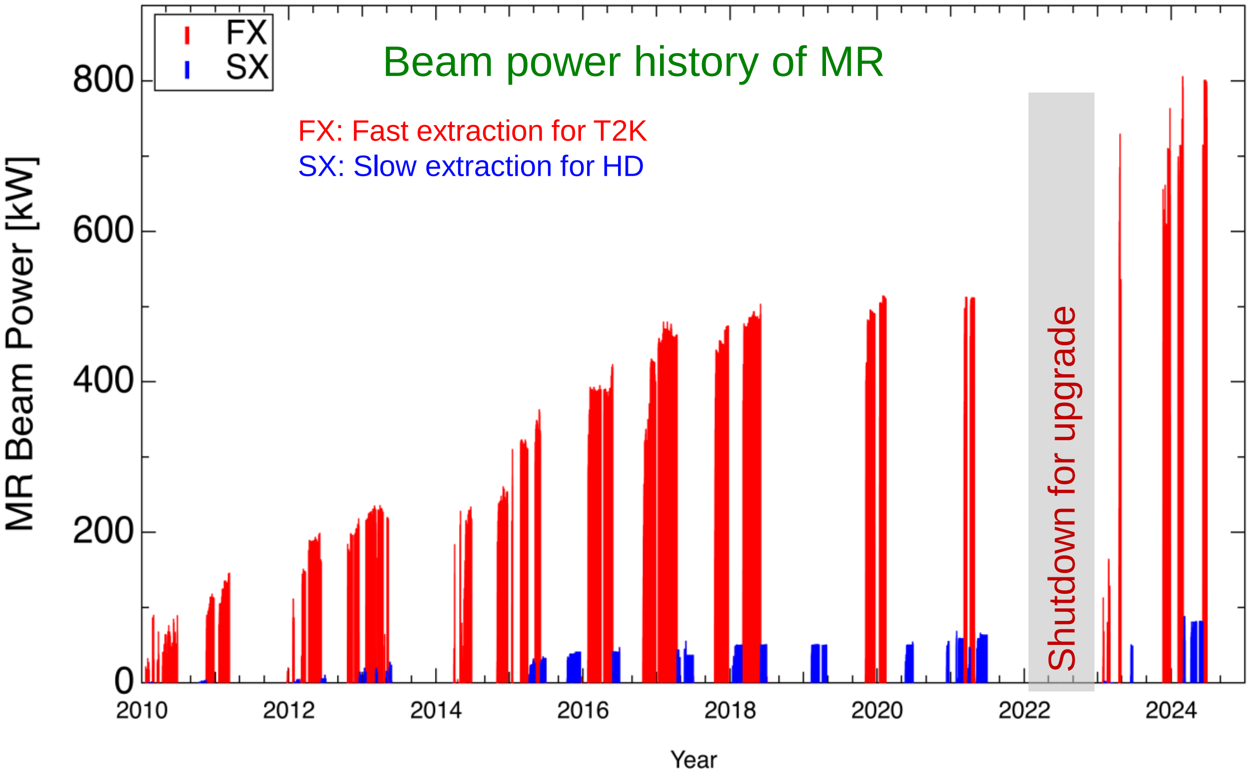
J-PARC Main Ring beam power history



Joint Project between KEK and JAEA

In 2021 and 2022, MR had a long shutdown for hardware upgrade (magnet power supplies, RF systems, injection and FX systems, etc.) to shorten cycle times, 2.48 s →1.36 s for FX , 5.20 s → 4.24 s for SX.



RCS has started 1 MW beam operation since April 2024.

MAX. Beam Power:
FX: 810kW (2.3 x10^{14} ppp), the world highest extracted ppp
SX: 81 kW (7.2 x10^{13} ppp) with the world highest extraction efficiency of 99.6 %

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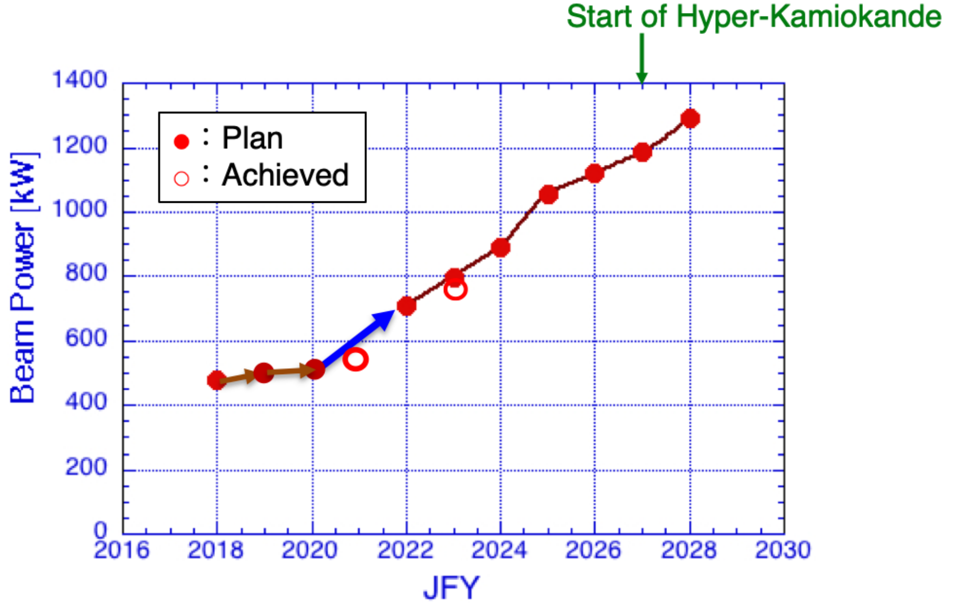
Courtesy of Tadashi Koseki

J-PARC Future Plans

(1) Power upgrade plan of MR-FX for the long-baseline neutrino oscillation experiments

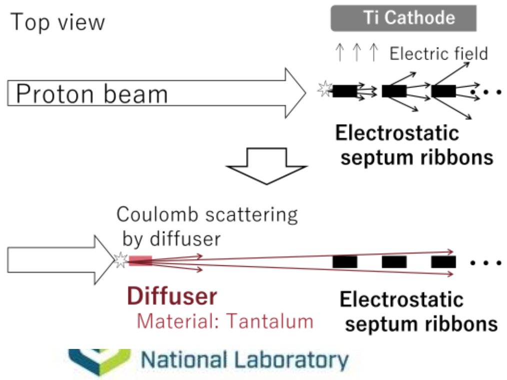
	Beam Power	Cycle Time	Number of protons	Equivalent beam power at RCS
Original Design	750 kW	1.36 s	2.1×10^{14} ppp	640 kW
Goal for HK	1.3 MW	1.16 s	3.3×10^{14} ppp	1 MW

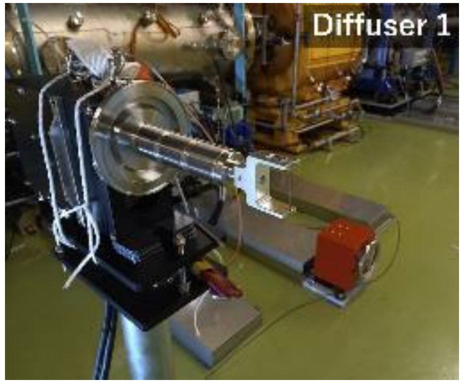


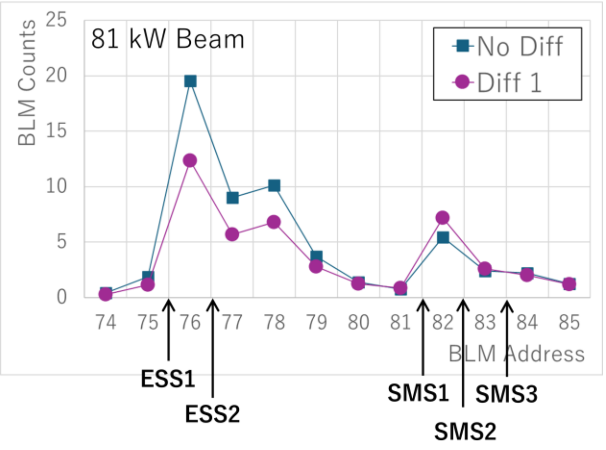
- Further reinforcement of RF system and magnet power supplies
- Further reduction of beam loss using fine tuning of individual quadrupoles and sextupoles
- Installation of new beam dump with a larger capability

(2) Power upgrade of MR-SX > 100 kW

Beam loss reduction at ESS by diffusers







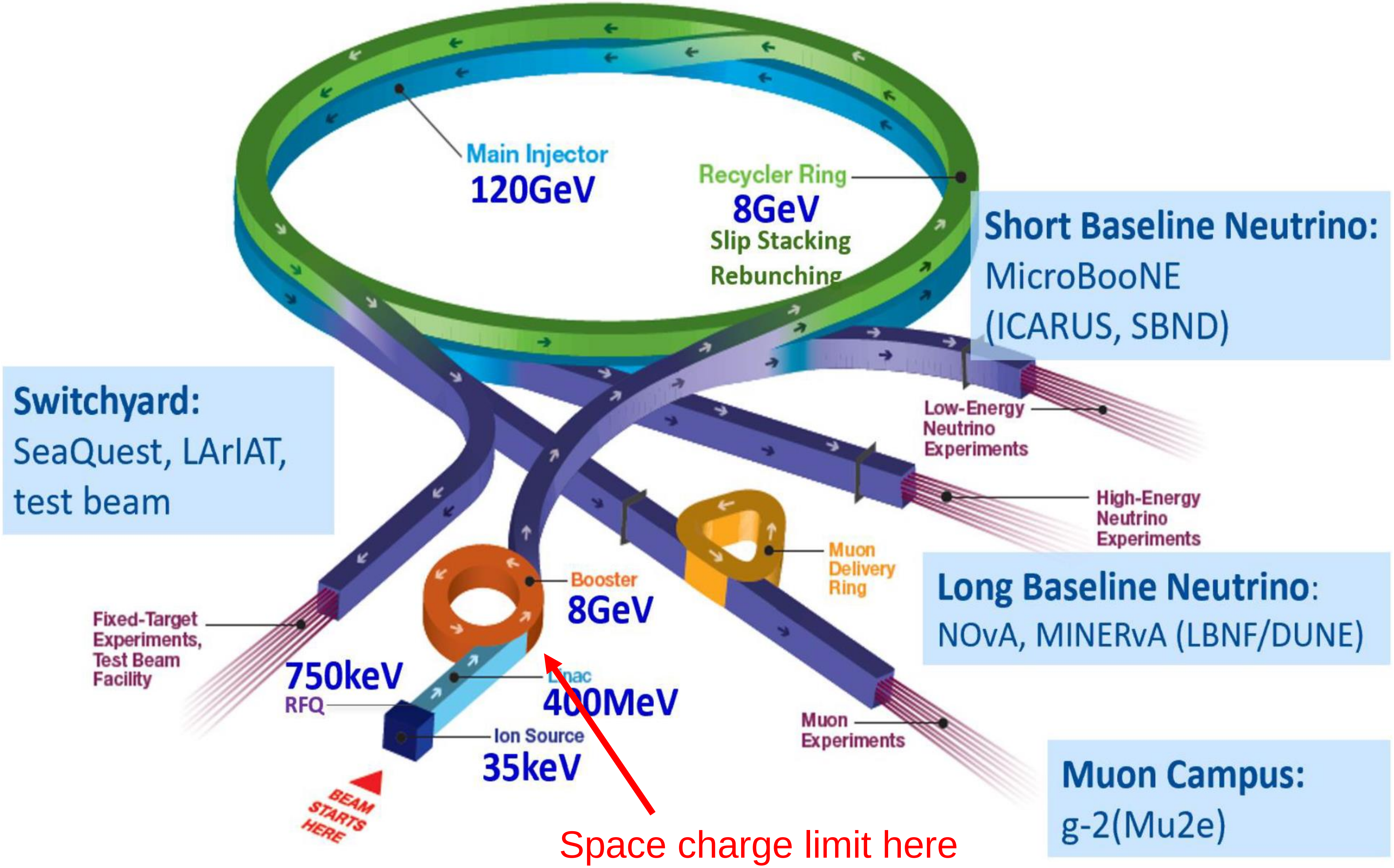
Courtesy of Tadashi Koseki

ESS: Electrostatic Septum
SMS: Septum magnet for SX

(3) MLF second target station

The RCS beam intensity will be increased to 1.5 MW: 1 MW (17 Hz) for TS1 and 0.5 MW (8 Hz) for TS2.

Fermilab accelerator complex



~80 kW

1 MW

Space charge limit here

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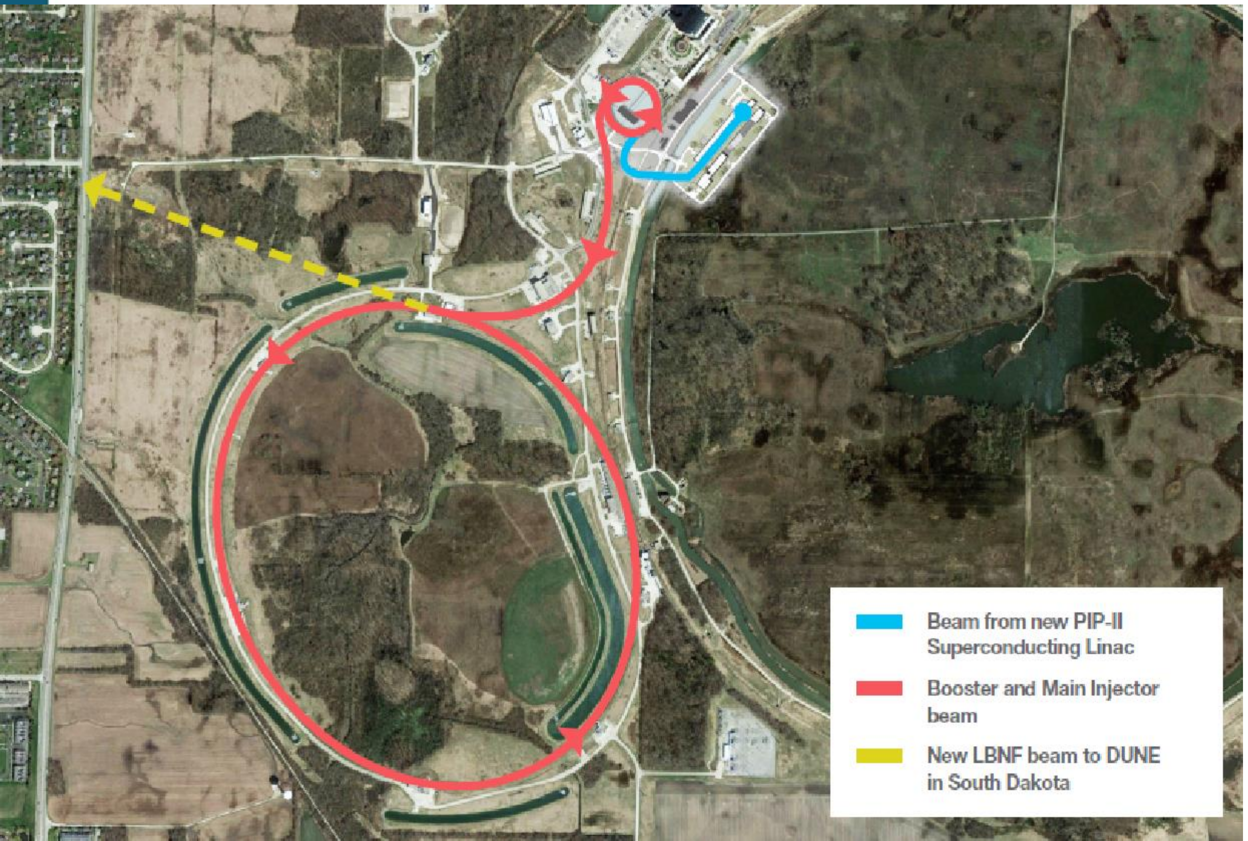
Fermilab Accelerator Complex in PIP-II / LBNF era

- **New PIP-II SRF linac** (to be completed in 2029) provides beam for injection into **Booster at energy increased to 800 MeV** from present 400 MeV
- **Booster cycle rate is upgraded to 20 Hz from 15 Hz (doubling the proton flux)**

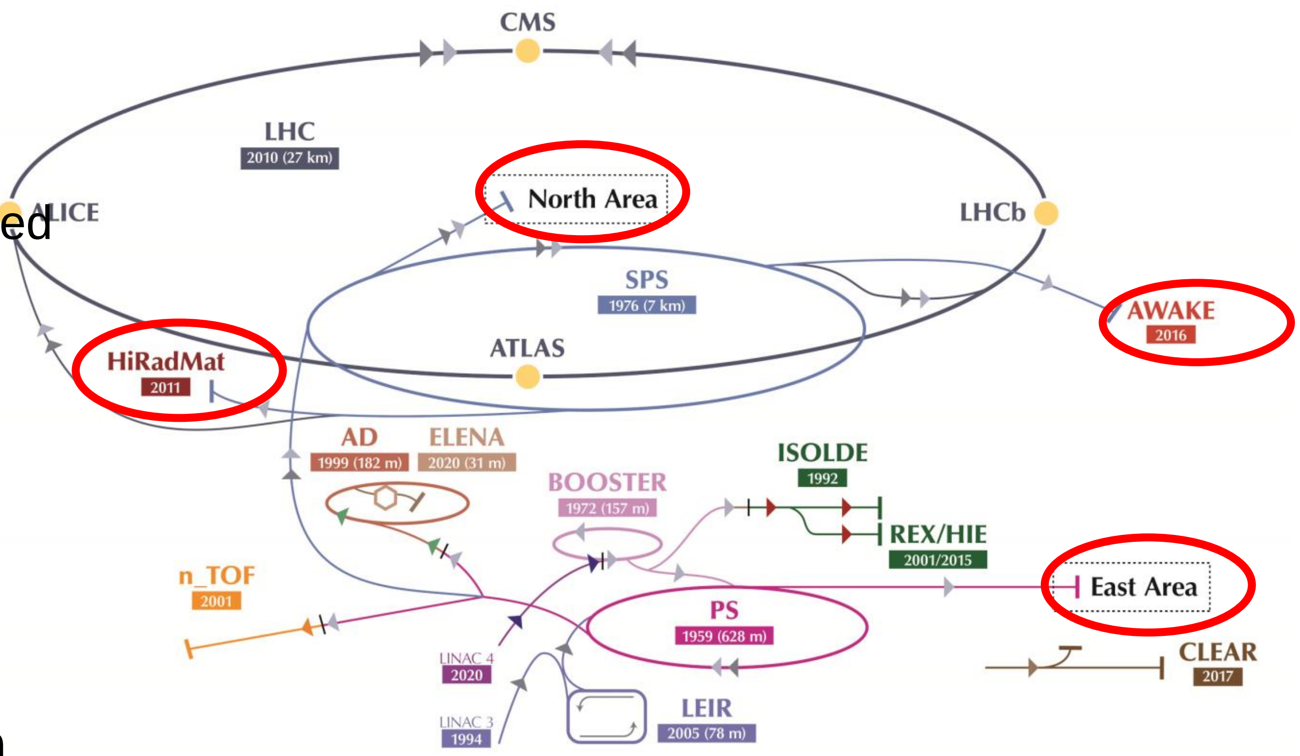


- **New LBNF beam line and target station** for neutrino beam to DUNE
- Wide-reaching modernization campaign and series of upgrades will improve reliability
- **With the present complex enables LBNF power of 1.2 MW**
- **Creates a platform for next-generation upgrades**

Courtesy of A.Valishev

CERN PS and SPS

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



- PS to East Area
  - CLOUD, IRRAD, CHARM
- SPS to North Area
  - COMPASS, SHINE, NA62/63/64
- AWAKE = Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Plasma Wakefield acceleration with proton beam driver, bunch with 19 KJ
  - Rb vapor 10 m long plasma cell, accelerated 18 MeV electrons to ~800 MeV
- 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

[E. Adli et al., “Acceleration of electrons in the plasma wakefield of a proton bunch”, Nature **561**, pages 363–367 (2018)]

Summary – present accelerators and approved facilities

- Present colliders: 5x e^+e^- and 2x hh
  - Low-energy colliders are technology test beds (beam-beam compensation, crab crossing, beam cooling, collimation, …)
  - SuperKEKB (very high L) prototype for future e^+e^- colliders, EIC
  - hh colliders – increasing flexibility (energy, species)
- Colliders under construction:
  - BNL Electron-Ion Collider: ~100x HERA luminosity, polarized e,p,He-3 and heavy ions
  - NICA

- Present high-intensity machines
  - >1 MW beam power available, ν beams drive increases
  - Synergies with other applications: spallation neutron sources, nuclear physics, Accelerator Driven Systems (ADS)
- Present high-intensity projects:
  - FNAL PIP-II goal: 1.2 MW
  - J-PARC MR goal: 1.3 MW

BNL EIC project – working towards baseline collisions 2032 (planned)