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Accelerator Technologies and Science: *Progress and Outlook*

Vladimir SHILTSEV (Fermilab)

PANIC'2021

September 10, 2021

Content: Progress Since 2017

- **New Accelerators:**
  - for Nuclear Physics
  - for Basic Sciences
  - for Neutrinos
  - for Energy Frontier
- **Technologies:**
  - magnets
  - RF acceleration
  - targets
- **Beam Physics:**
  - cooling
  - colliding beams
  - plasma acceleration

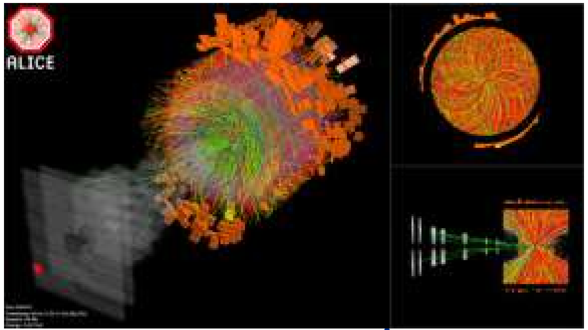
Accelerators for NP

Outstanding success of STAR/PHERNIX and ALICE operations at RHIC and LHC – since 2017:

RHIC: >10 nb-1 4-100 GeV/u ions (Au, Zr, …)

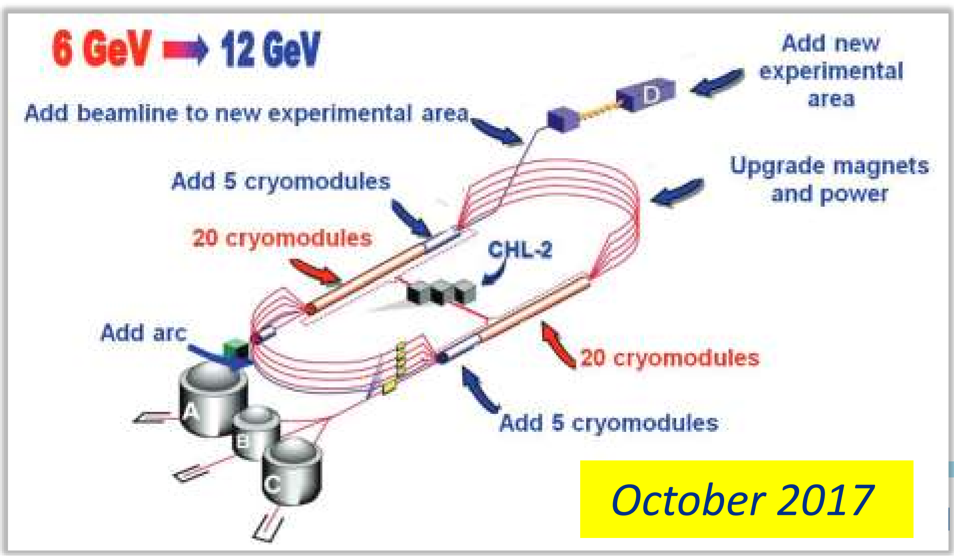
RHIC: >0.5 fb-1 in 510 GeV cme polarized *pp* (*P*=55%)

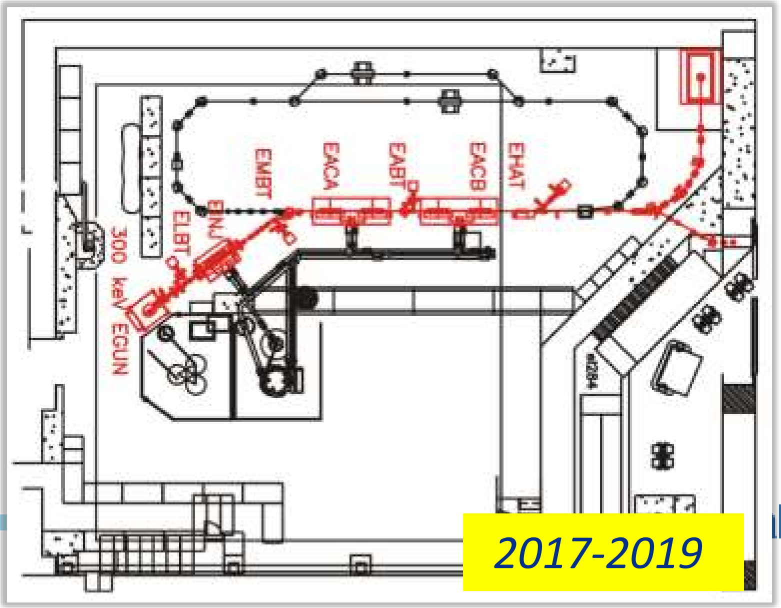
ALICE: ~1nb-1 in 5TeV cme Pb-Pb, 0.3ub-1 in Xe-Xe (comparable luminosity also to CMS, ATLAS and LHCb)



Continuous Electron Beam Accelerator Facility (CEBAF) at TJNAF : 12 GeV electron beam energy upgrade (cw SRF linac)

Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF : 30 MeV 10 mA cw SRF electron linac





Facility for Rare Isotope Beams (FRIB)

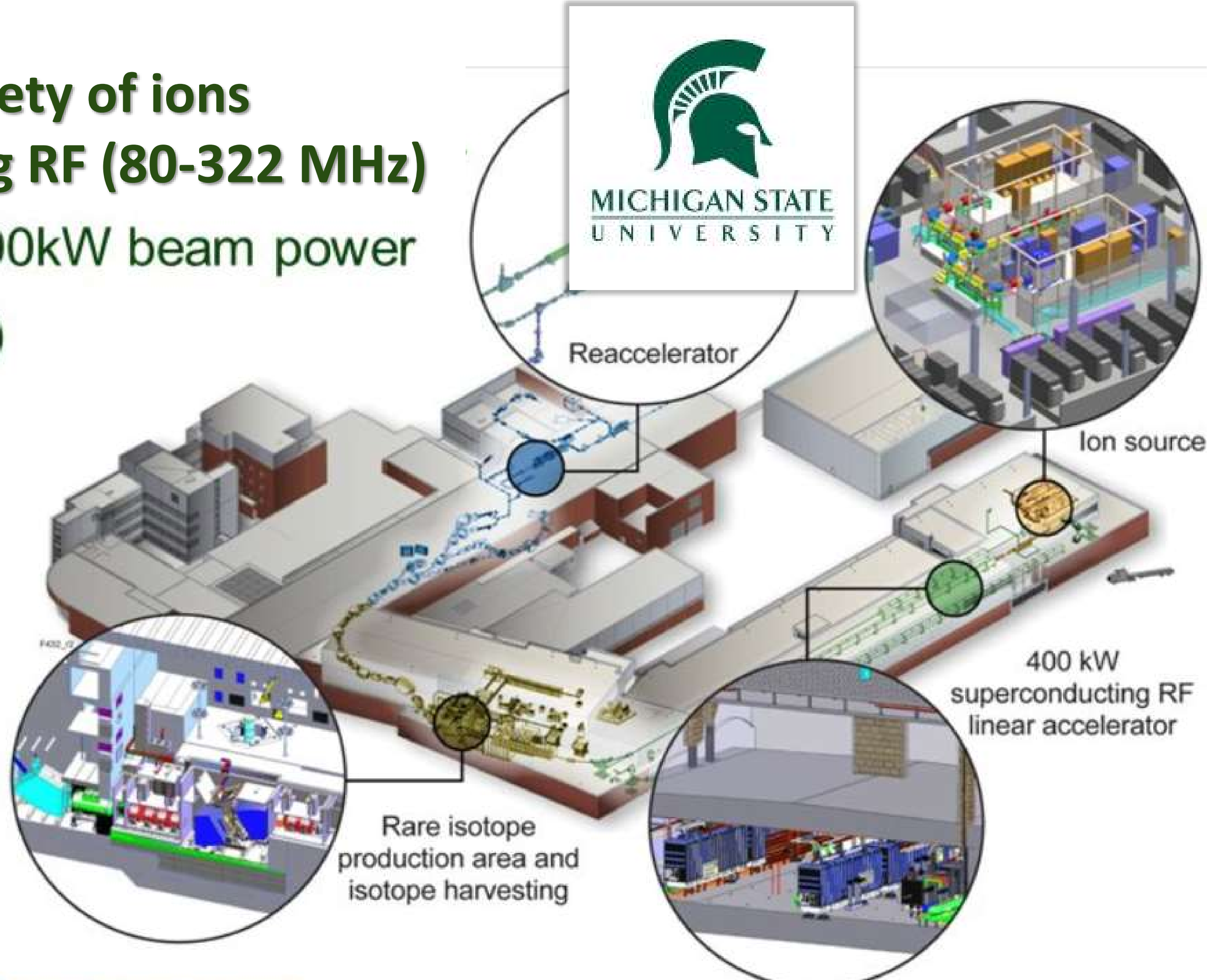
- **200 MeV/u, variety of ions**
  Superconducting RF (80-322 MHz)
- Key Feature is 400kW beam power
  (5×10^{13} ^{238}U/s)

Apr. 2021:
all 46 CMs
212 MeV/u

Separation of isotopes "In-flight"

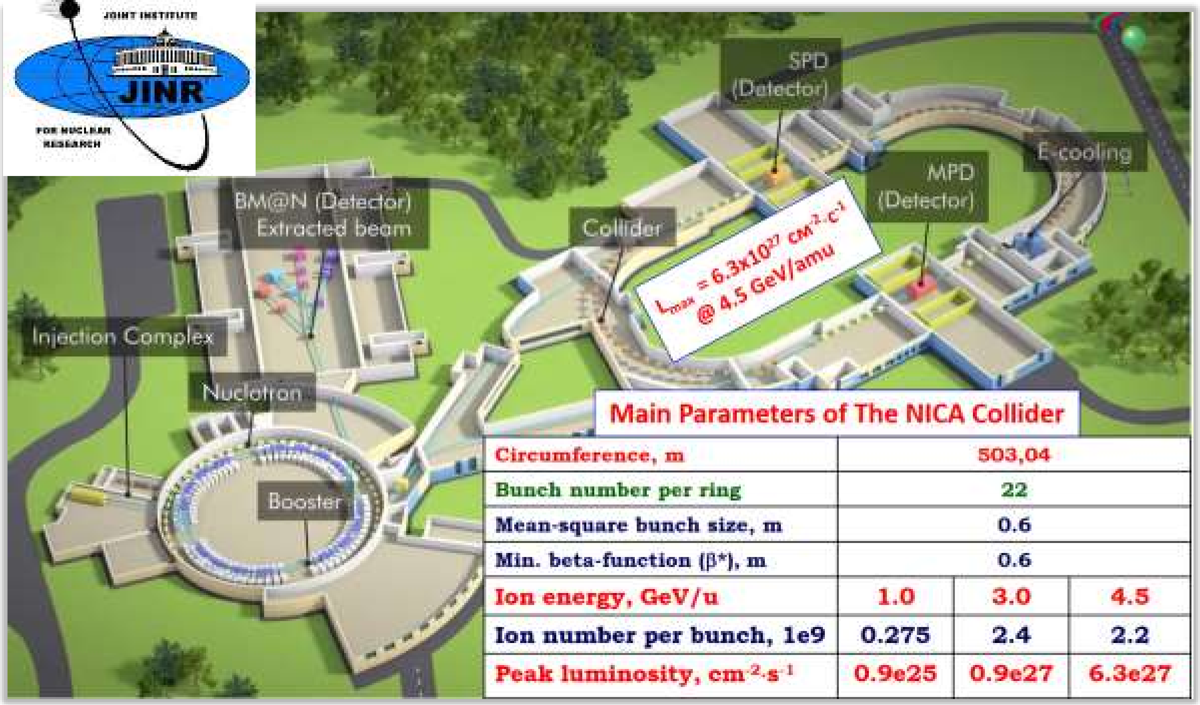
Suited for all elements and short half-lives

Fast, stopped, and reaccelerated radioactive beams



see Artemis Spyrou's talk today

NICA: Nuclotron-based Ion Collider fAcility)



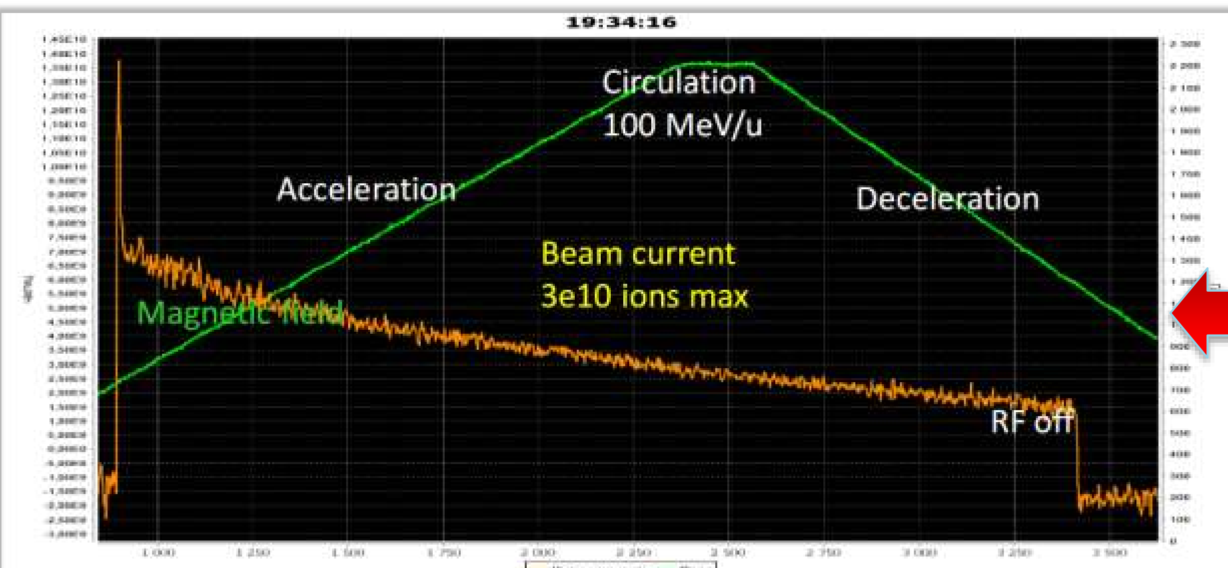
Main Parameters of The NICA Collider

Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, $cm^{-2} \cdot s^{-1}$	0.9e25	0.9e27	6.3e27

- Protons to ions (Au)

$$\sqrt{s_{NN}} = 4\text{–}11 \text{ GeV}$$

- Polarized *p* and *d*
- Superconducting magnets
- Stochastic and electron cooling for high luminosity 10^{27}



- Construction start in 2013
- About 80% done
- Booster beam (2021)
- Collisions in 2024

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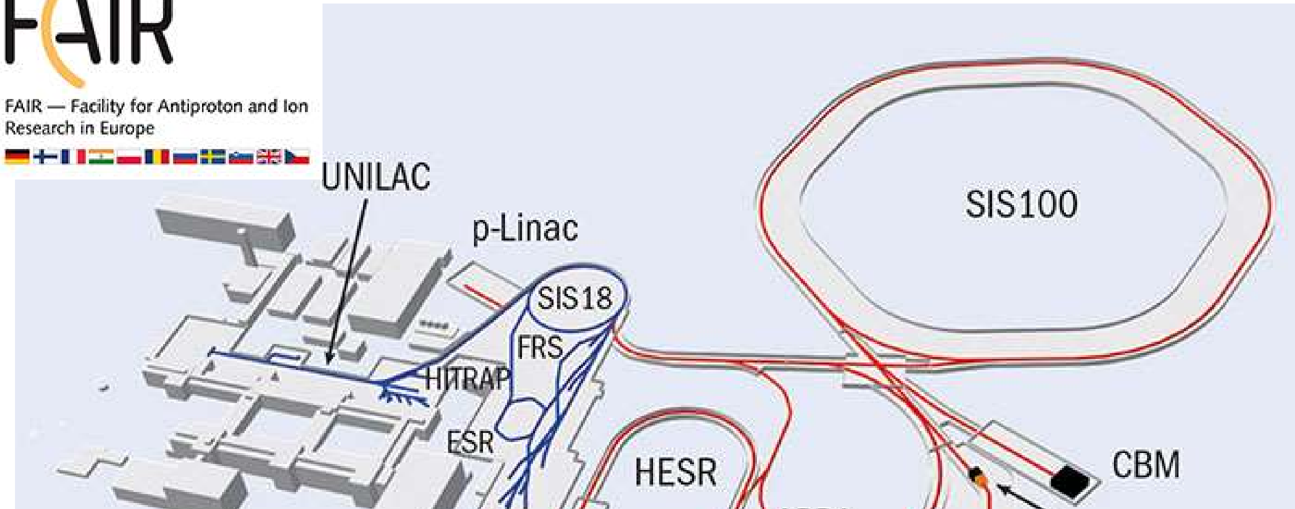
Facility for Antiproton and Ion Research (FAIR@GSI)

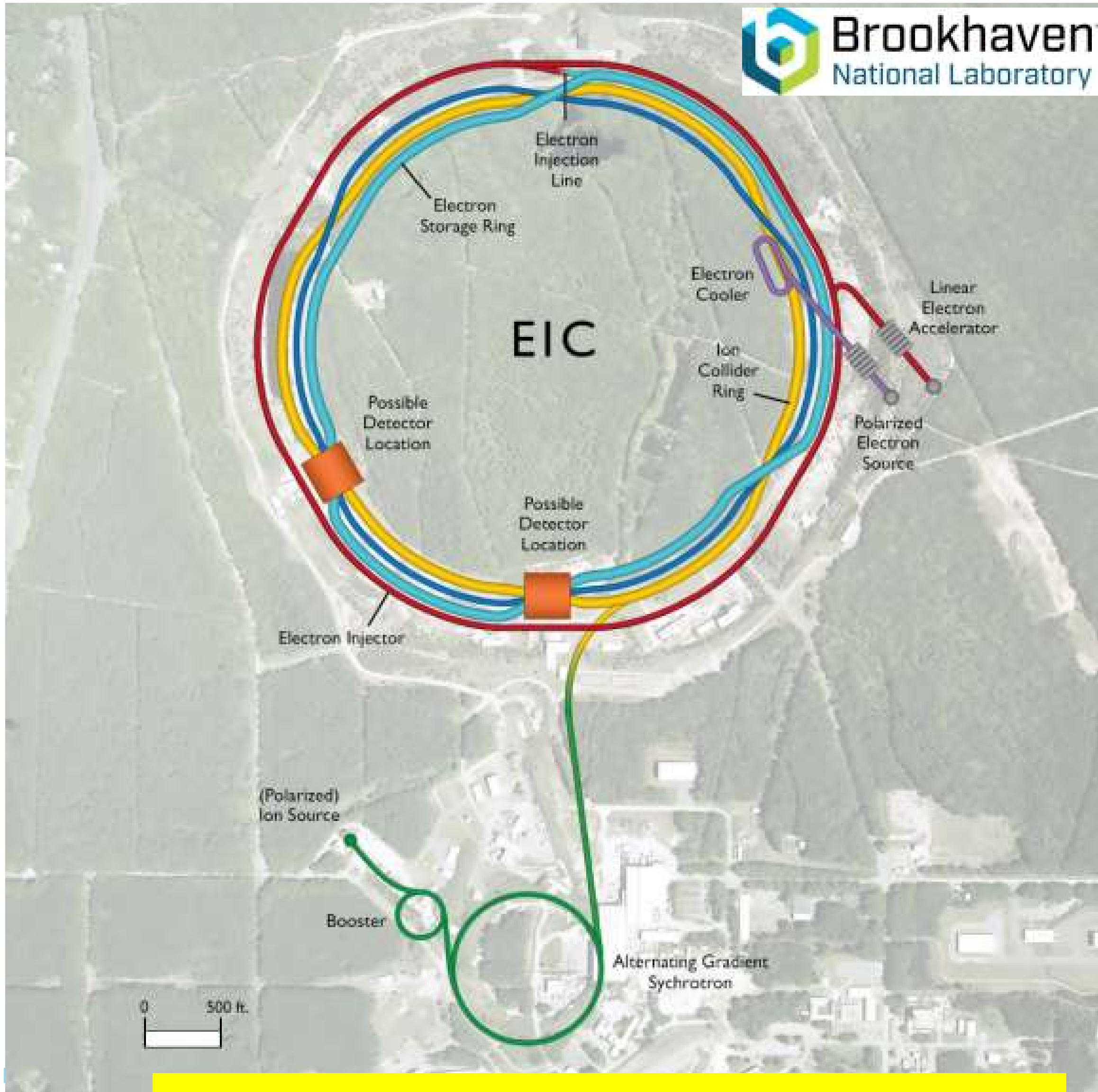
FAIR — Facility for Antiproton and Ion Research in Europe



- Complex of rings and beamlines
- SIS-100: C=1.1 km, 29 GeV *p*, 2.9 GeV/u ions, SC superferric 1.9 T magnets

- Groundbreaking in 2017
- Impressive civil construction
- SIS-100 machine installation in 2022

Electron Ion Collider (EIC)
Brookhaven National Laboratory



- 275 GeV protons, 100 GeV/u (existing RHIC, upgraded)
- 10 GeV electrons (5-18 GeV storage ring, new)

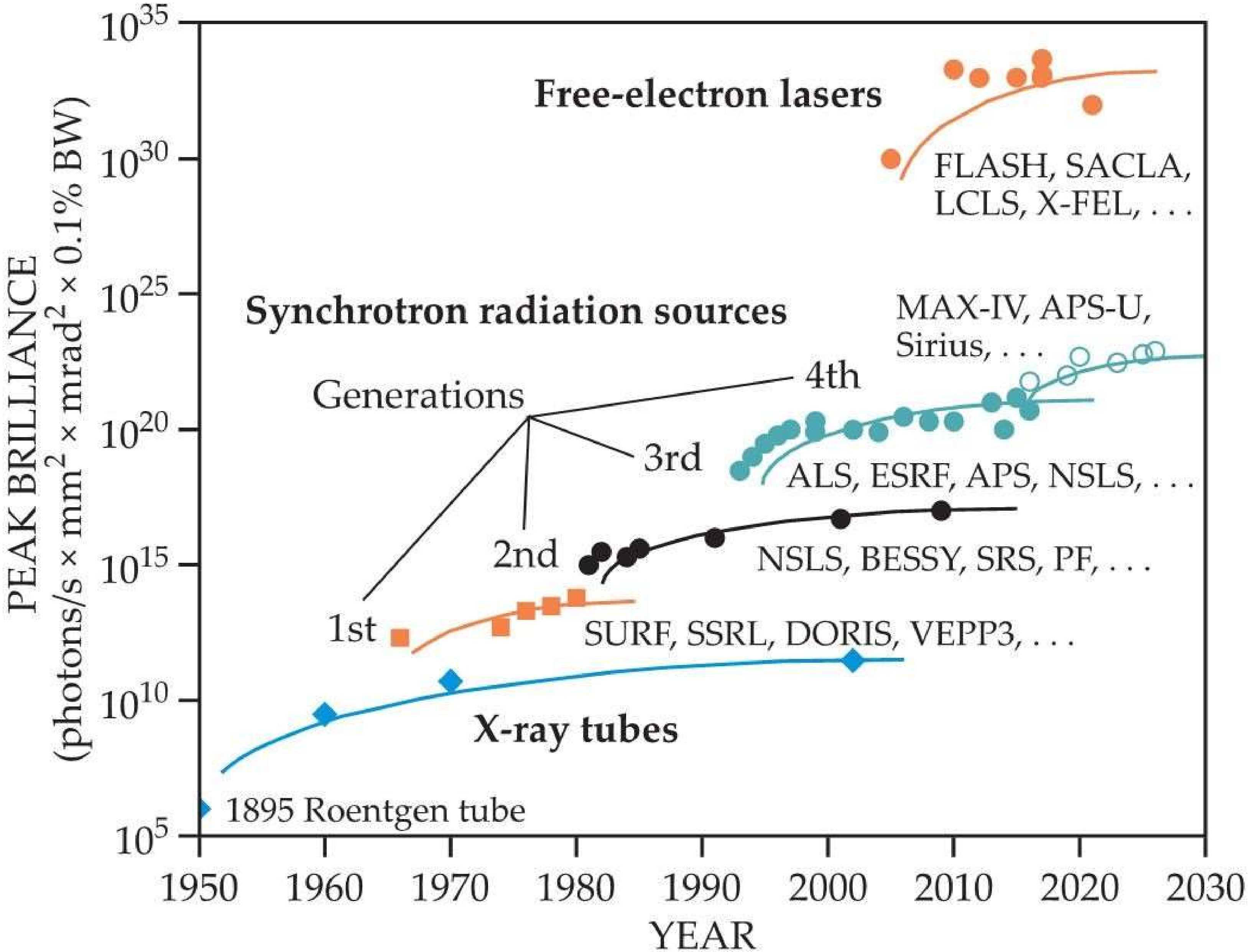
$$\sqrt{s} = 20 \text{ GeV to } 100 \text{ GeV}$$

- ~70% polarization
- Luminosity ~x100 HERA (with Strong Hadron Cooling)

- CD-1 in July 2021
- Construction is expected to begin in 2024
- Operations early in the next decade.

see Bernd Surrow's talk Thursday

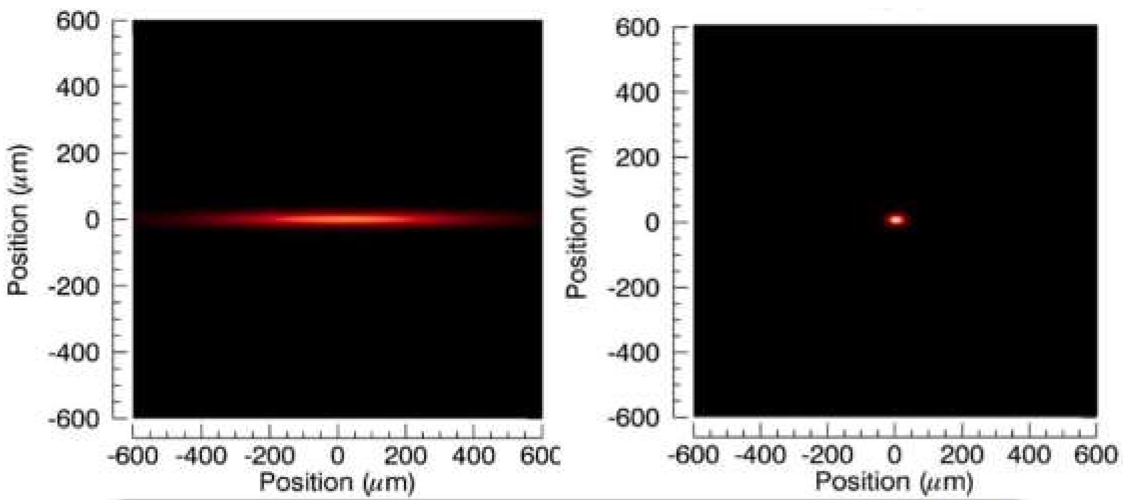
Revolution in Light Sources /X-ray Sources



V.Shiltsev, Physics Today **73** (4), 32 (2020)

milab

4^{th} Generation Light Sources
aka *diffraction-limited storage rings*



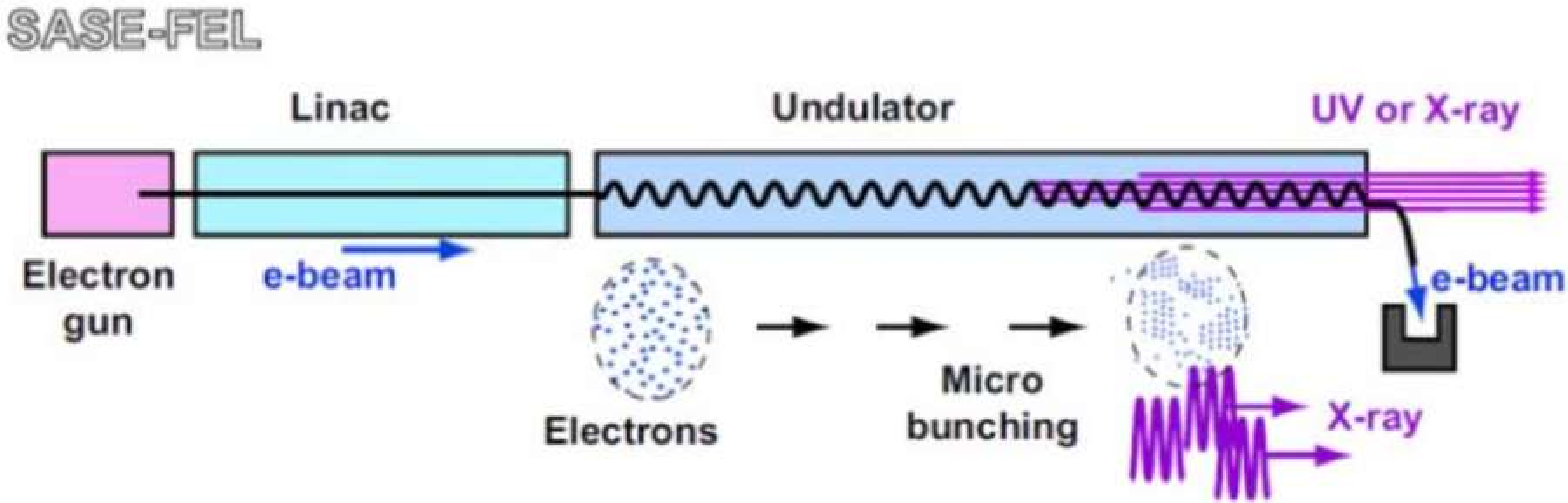
“Multi-Band Achromat” (MBA) - advanced beam optics lattice → ***x100 brightness increase (1996)*** **→**

- 2024 – APS-Upgrade @ Argonne 6 GeV, 70 pm
- 2024 – SKIF @ Novosibirsk 3 GeV, 75 pm
- 2025 – SLS @ Swiss-PSI 2.7 GeV, 135 pm
- 2026 – ALS-Upgrade @ Berkeley, 2 GeV, 70 pm
- 2026 – HEPS @ Beijing 6 GeV, 60 pm
- 2027 – HALF @ Hefei 2.2. GeV, 85 pm
- 2027 – PETRA-IV @ Hamburg 6 GeV, 8 pm

Self-Amplified Spontaneous Emission (SASE) Free Electron Lasers (FEL)

aka

X-FELs



- High energy (0.1-10’s of GeV) AND High brightness electron beam
- Exponential growth of radiation power while in (10’s of m) undulator
- Proposed in 1980, proof-of-principle demonstrations 1985-1998

XFELs


PAL-XFEL
Pohang PAL-XFEL 10 GeV (2017)

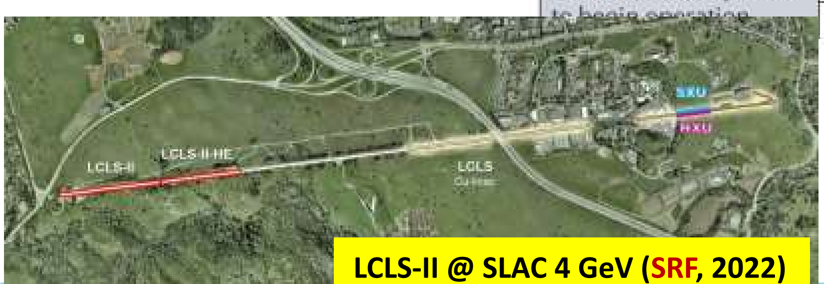

1992
2005
2009
2011
2012
2017
2019
2021
2022
2025
FERMI@Elettra (Italy) begins user operation
SACLA (Japan) begi
user operation
PAL-XFEL (South Korea) begins user operation
Completion of the DCLS VUV FEL (China)
European XFEL (Ge
begins user operati
SwissFEL (Switzerla
begins user operati
SXFEL (China) expe
to begin user opera
LCLS-II (USA) expected


European XFEL 17.5 GeV (SRF, 2017)


SwissFEL 5.8 GeV (2017)


Commissioned, 2021
Shanghai X-ray FEL User Facility
530m, 1.6GeV, 2-10nm


DCLS 0.3 GeV (2017)
Seed laser
LINAC

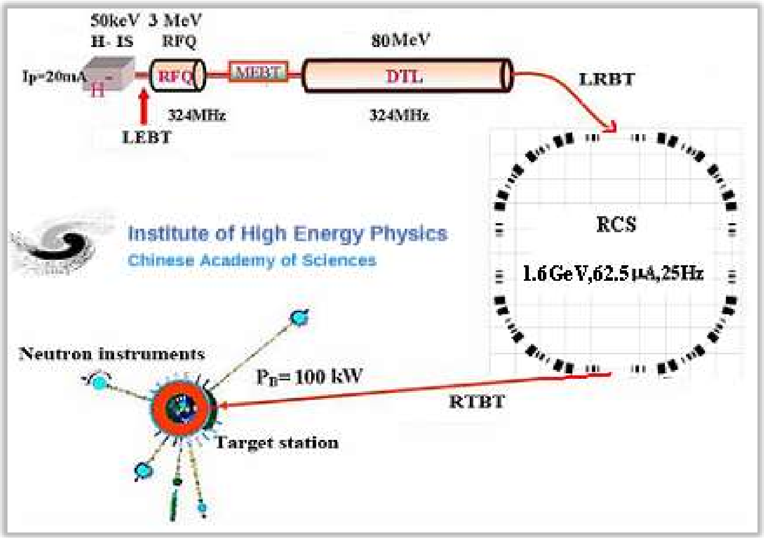

SXU
HXU
LCLS-II
LCLS-II-HE
LCLS
LCLS-II @ SLAC 4 GeV (SRF, 2022)


e-beam: 8 GeV
Photon energy: 0.4-25 keV
Pulse duration : 1-100fs
Repetition : 1MHz
Total length : 3.1km
ca 30m underground
Shanghai SHINE 8 GeV (SRF, 2025)
Near Exp.Hal
Far Exp.Hall
Undulators
Beamlines
Switchyard
SC Linac
Injector

Neutron Sources

Spallation Neutron Source (SNS) at ORNL:

- 1.4 MW 1 GeV SRF linac+ring since 2007
- Upgrade to 2MW on target in 2025
- Followed by 2nd target station and 2.8 MW



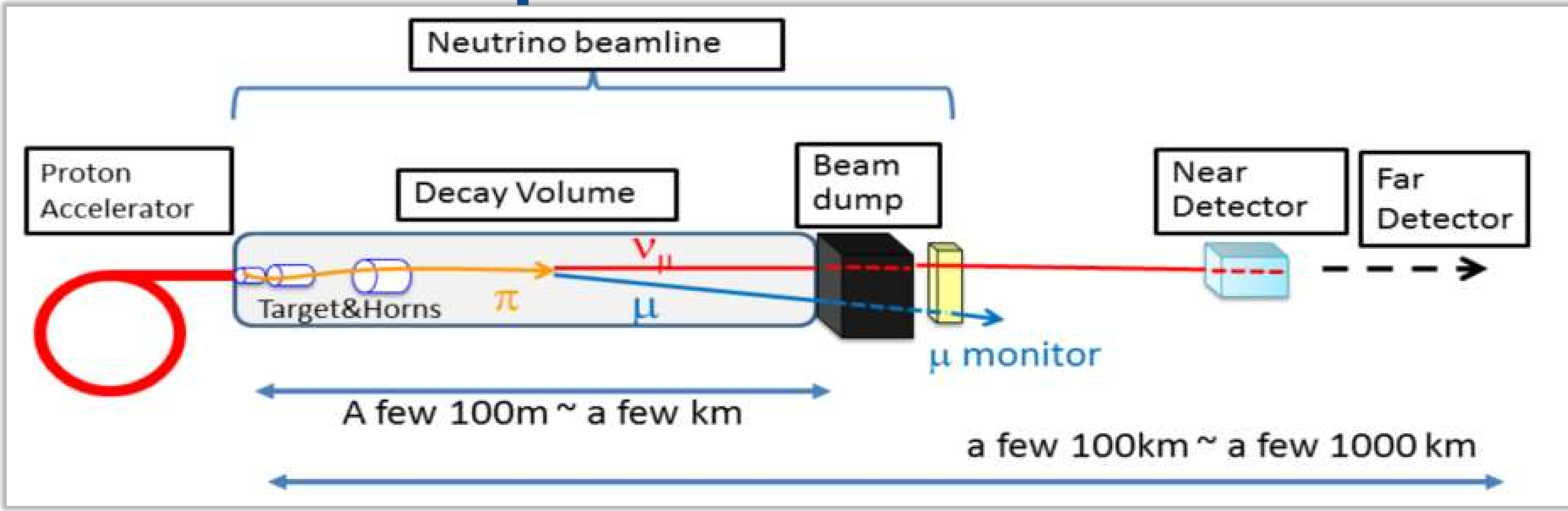
China Spallation Neutron Source (CSNS):

- 80 MeV linac and 1.4 GeV ring → target
- First neutrons Aug'2017, 0.1 MW Feb'2020
- Planned upgrades to 0.2MW, then 0.5MW

European Spallation Source (ESS), Lund:

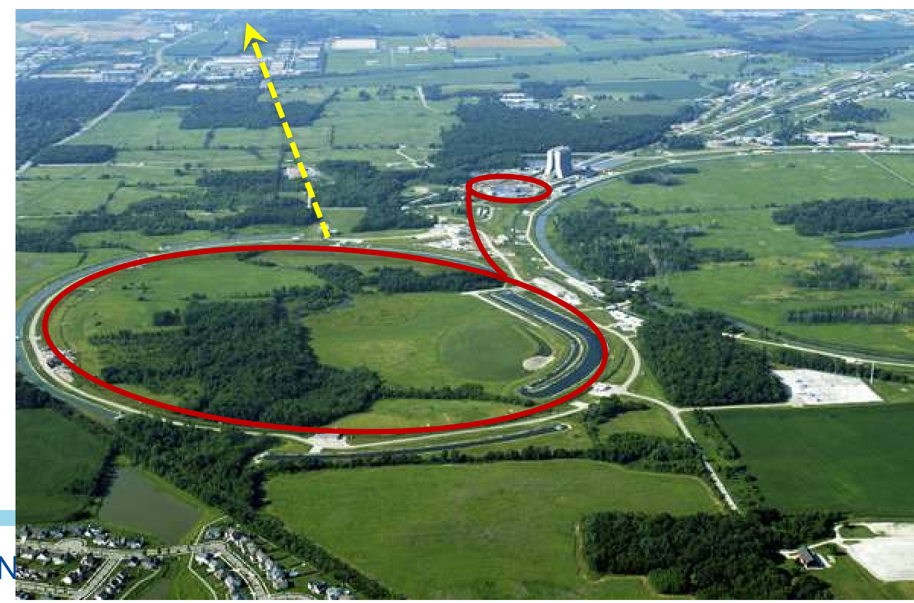
- 5 MW 2 GeV pulsed SRF linac → target
- Construction started 2014, 80% complete
- Beam thru RFQ this Fall
- Users program in 2023

Neutrino Superbeams – ν Oscillations

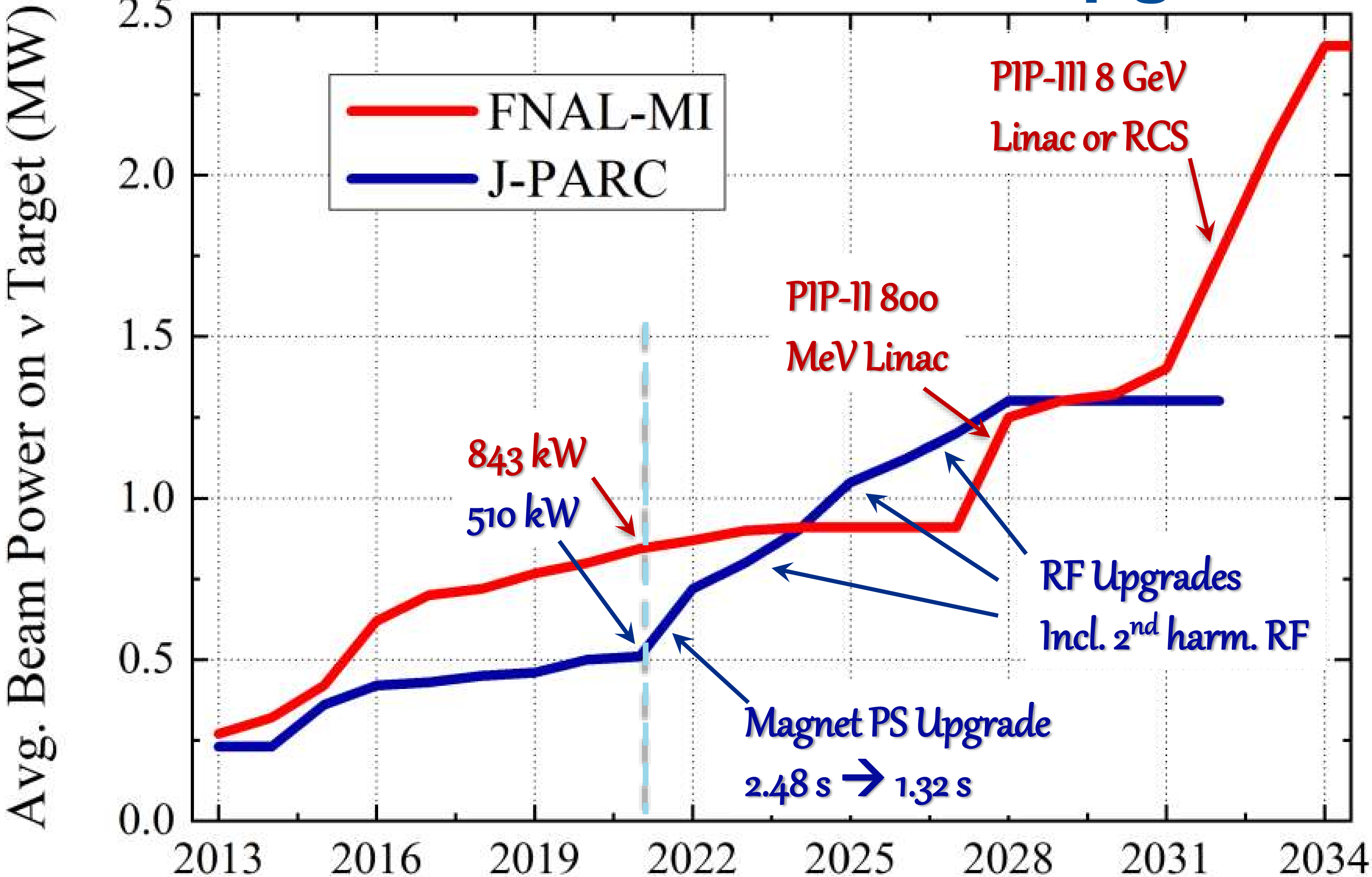


Japan Proton Accelerator Research Complex – *3/30 GeV (295 km to SuperK)*

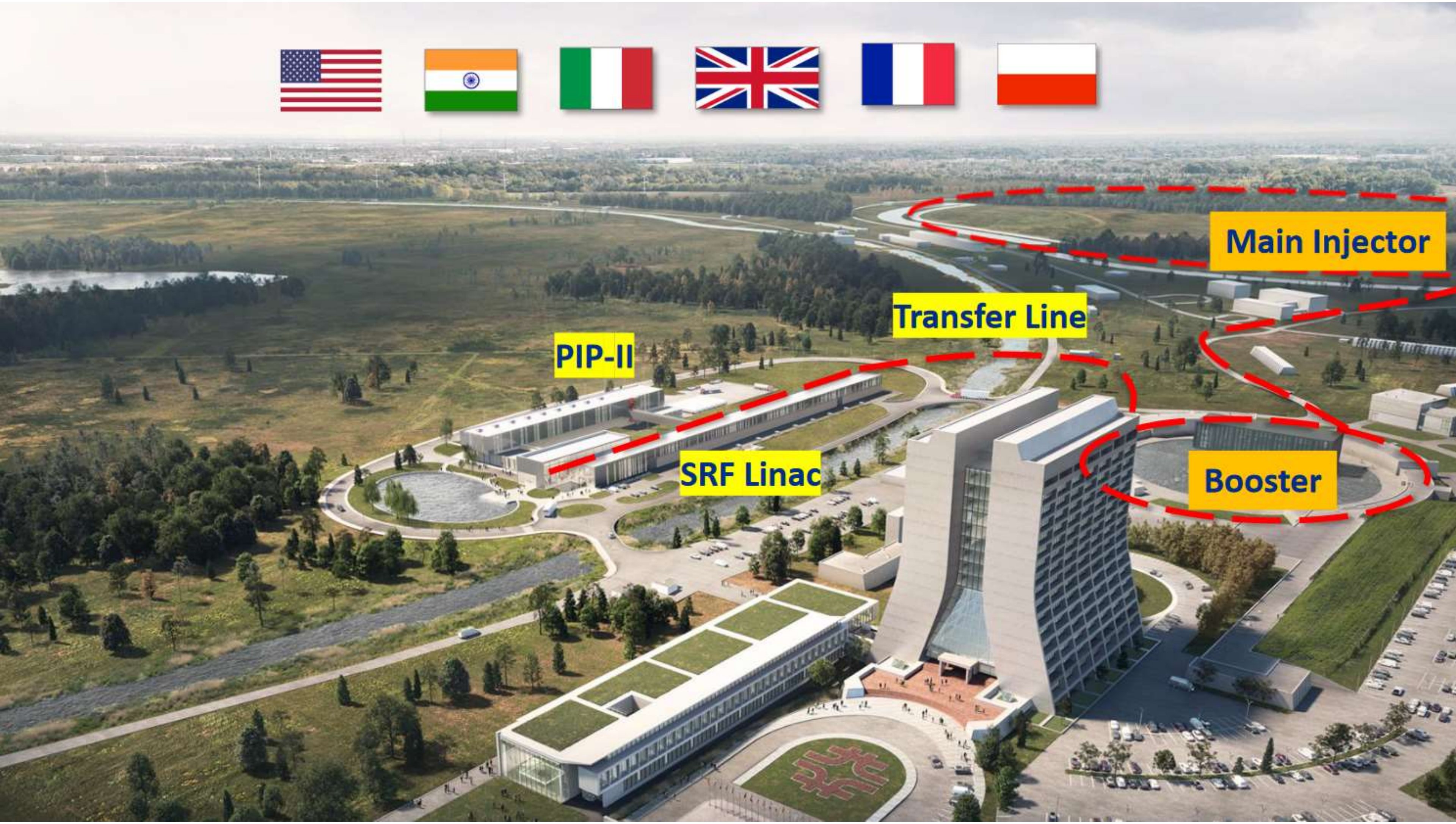
Fermilab Proton Accelerator Complex – *8/120 GeV (810 km to MINOS)*



Fermilab and J-PARC Power Upgrades

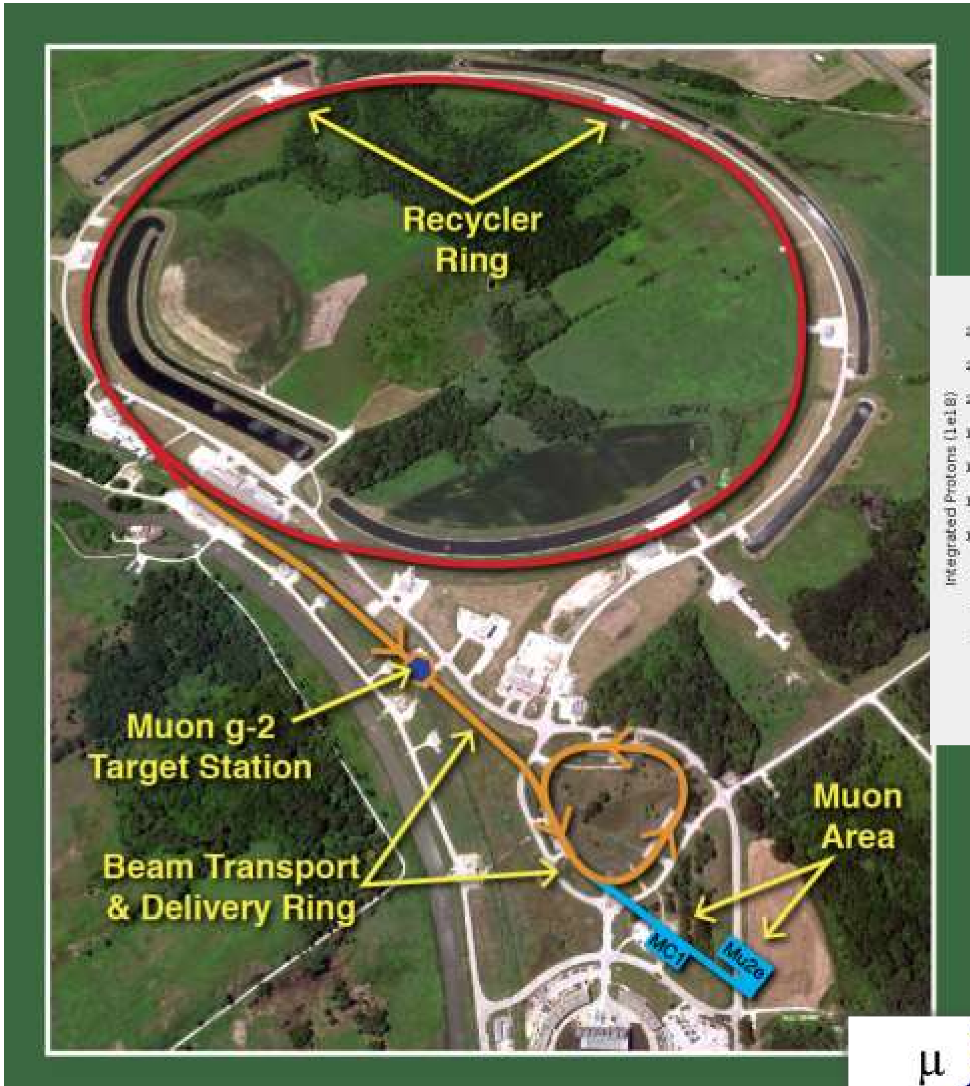


800 MeV SRF *p* Linac – Proton Improvement Plan-II



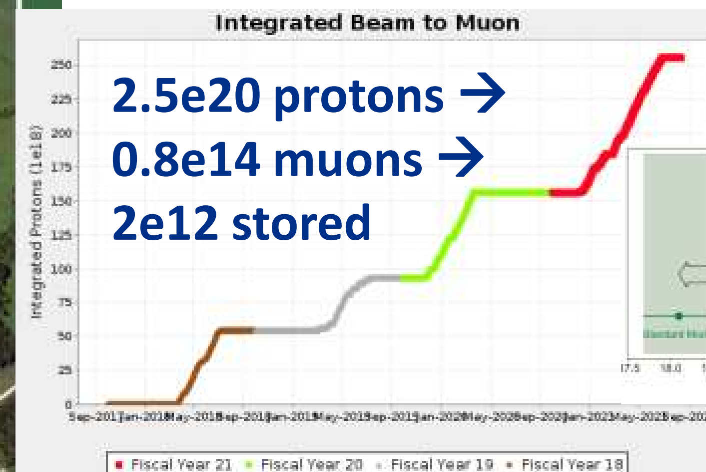
Fermilab Accelerator Complex

Muon *g*-2 – 2021 !

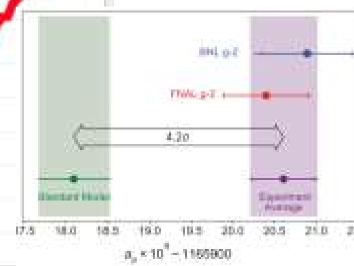



The New York Times @nytimes · Apr 7

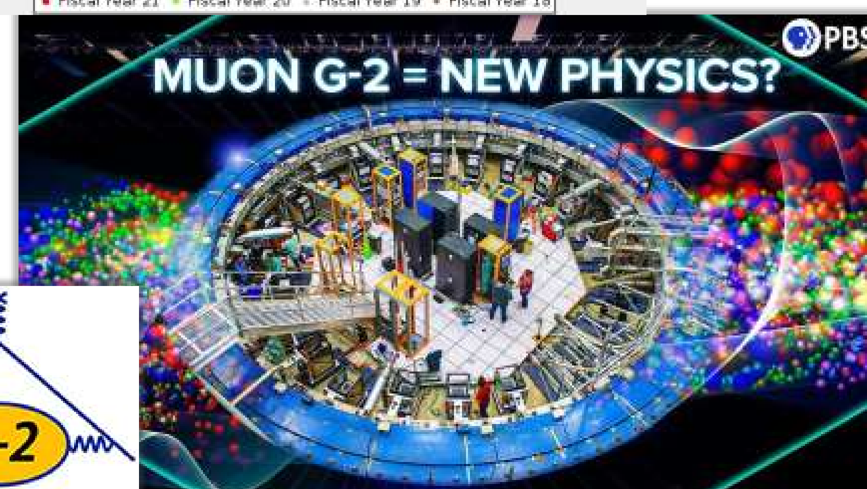
Breaking News: Evidence is mounting that a tiny subatomic particle is being influenced by forms of matter and energy that are not yet known to science but which may nevertheless affect the nature and evolution of the universe.

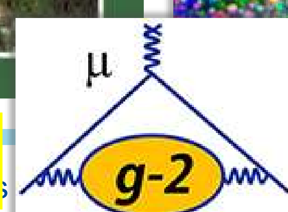


Run 1:
0.46 ppm



...soon x10





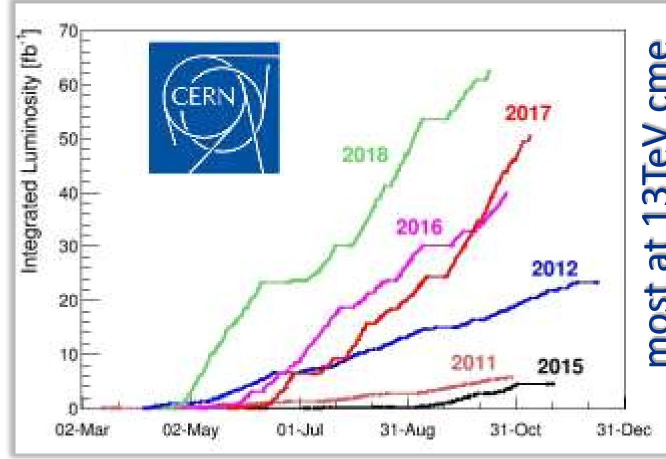
see Martin Ferti's talk Tuesday

HEP Colliders

Seven in operation now

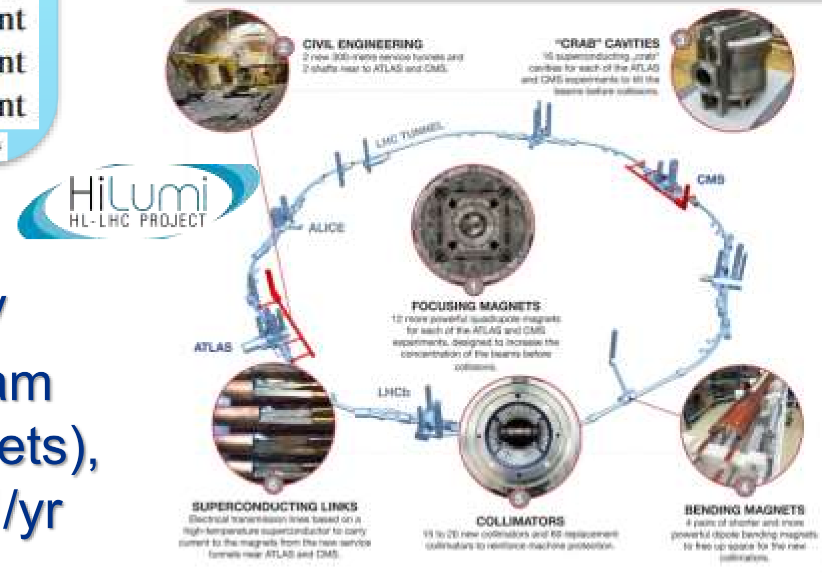
	Species	E_b (GeV)	C (m)	$\mathcal{L}^{max}_{peak}$	Years
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979–present
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989–present
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997–present
RHIC	p, i	255	3834	2.5×10^{32}	2000–present
LHC	p, i	6500	26 659	2.1×10^{34}	2009–present
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010–present
S-KEKB	e^+e^-	7 + 4	3016	8×10^{35a}	2018–present

V. Shiltsev and F. Zimmermann: Modern and future colliders



Highlights – LHC : *pp* 13→14 TeV cme

- 190 fb-1/IP by now, x2 design luminosity
- High-Lumi upgrade by 2028: double beam current, smaller β^* (new Nb_3Sn IR magnets), "crabbing", leveling @14 TeV → 250 fb^{-1}/yr
- Followed by ~decade of ops to 3-4 ab^{-1}

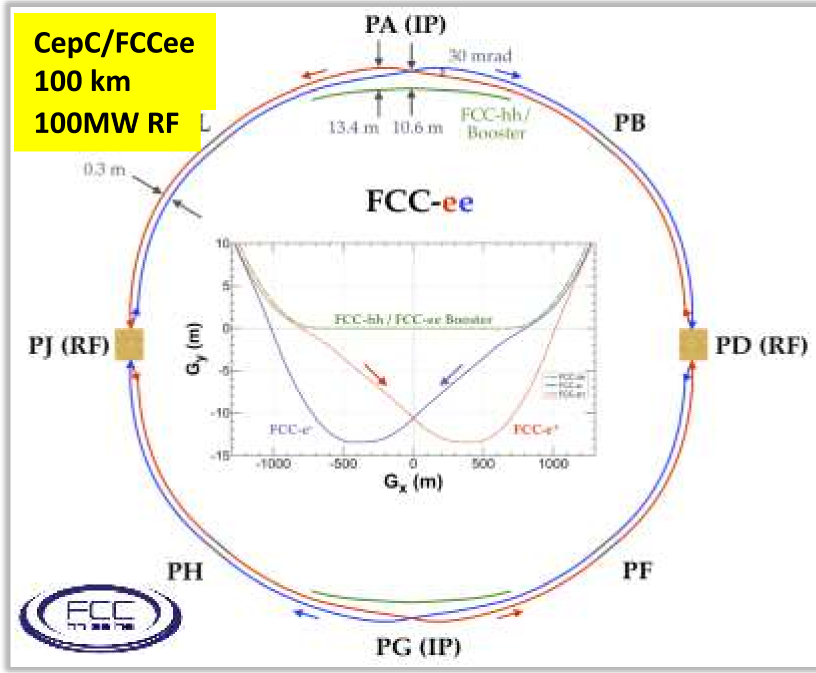


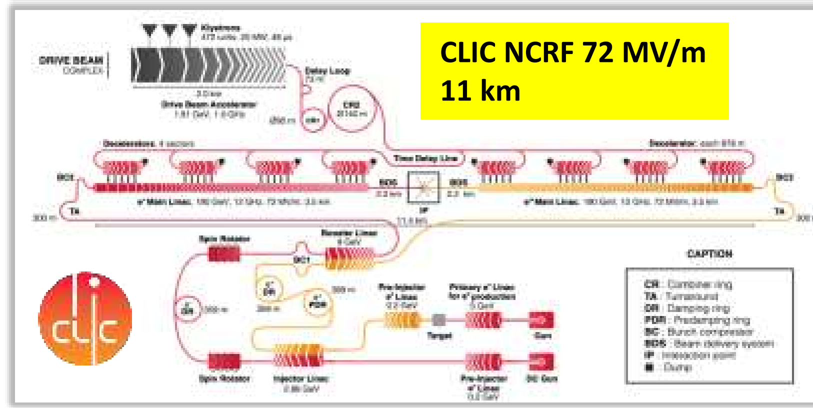
Highlights – Super-KEKB: e+e- 7+4 GeV

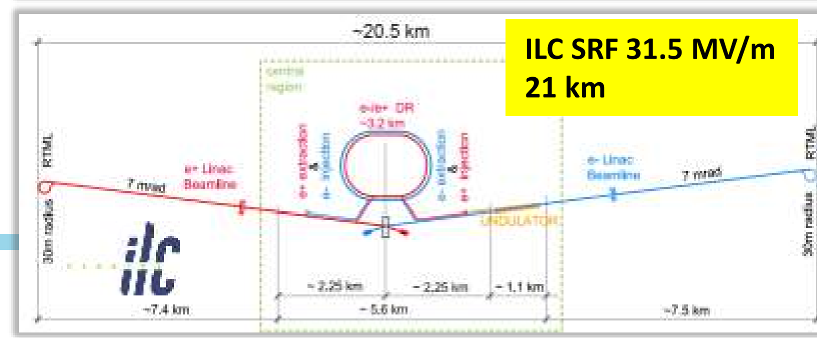
- Startup in 2018, world record L=3.1e34 $cm^{-2}s^{-1}$
- Design luminosity goal x40 of KEK-B
- Now ~4% of the goal, steady progress

Future Collider Proposals: 8 Higgs/EW factories

Name	Details
CepC	e+e-, $\sqrt{s}=0.24$ TeV, L= 3.0 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s}=0.38$ TeV, L= 1.5 $\times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s}=0.24$ TeV, L= 73 $\times 10^{34}$
FCC-ee	e+e-, $\sqrt{s}=0.24$ TeV, L= 17 $\times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e+e-, $\sqrt{s}=0.25$ TeV, L= 1.4 $\times 10^{34}$
LHeC	ep, $\sqrt{s}=1.3$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s}=0.13$ TeV, L= 0.01 $\times 10^{34}$

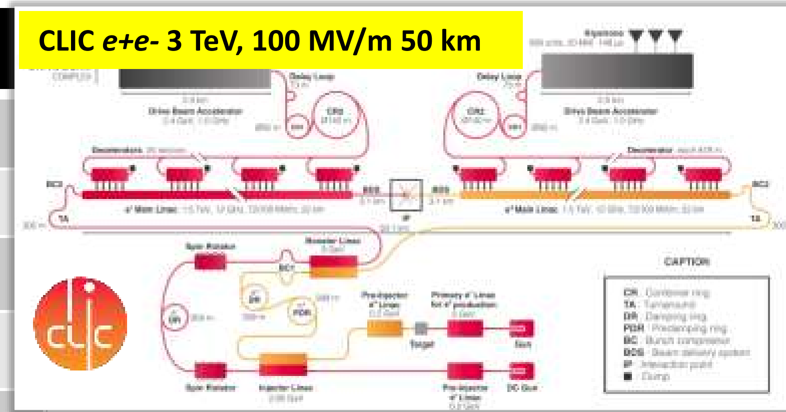


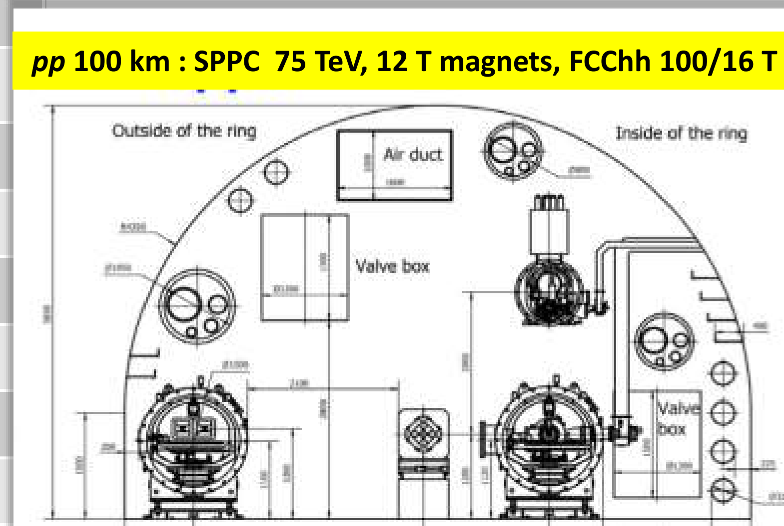


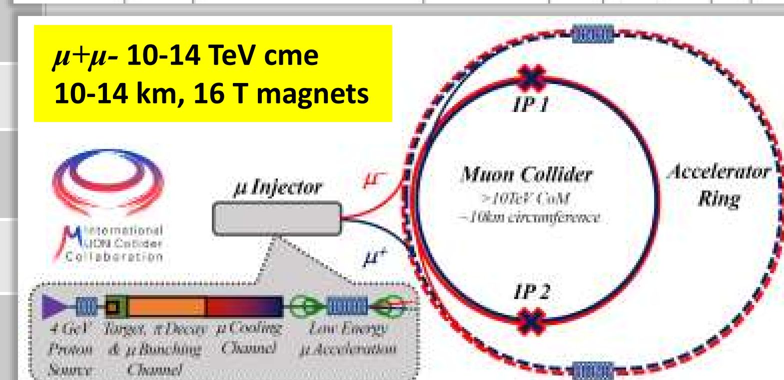


17 (!) High Energy Collider Concepts/Proposals

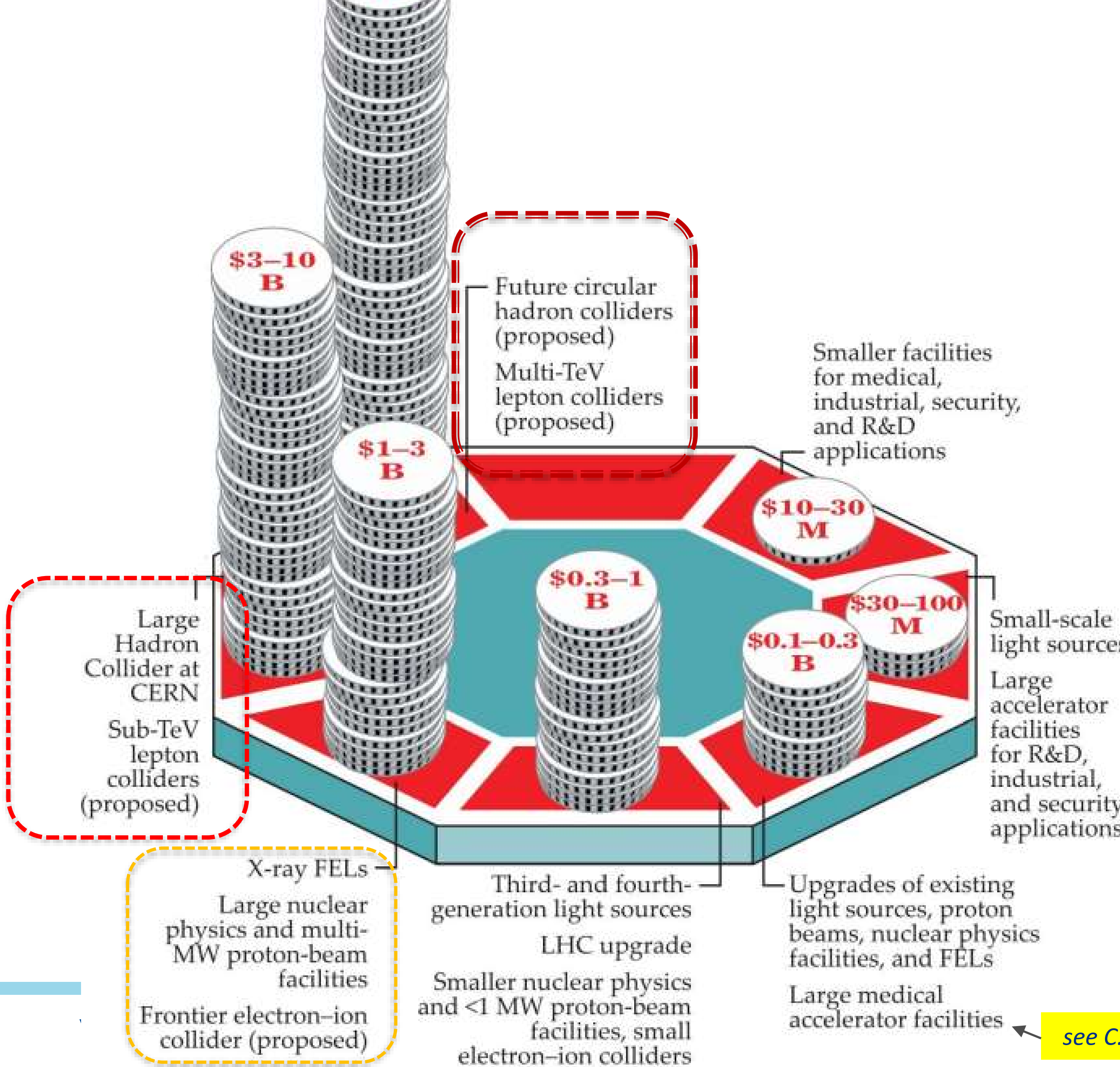
Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV







Cost of Accelerators



V.Shiltsev, Physics Today **73** (4), 32 (2020)

see C.Hoehr's talk today

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Cost is set by the scale (*energy, length, power*) and technology

~50±10 %

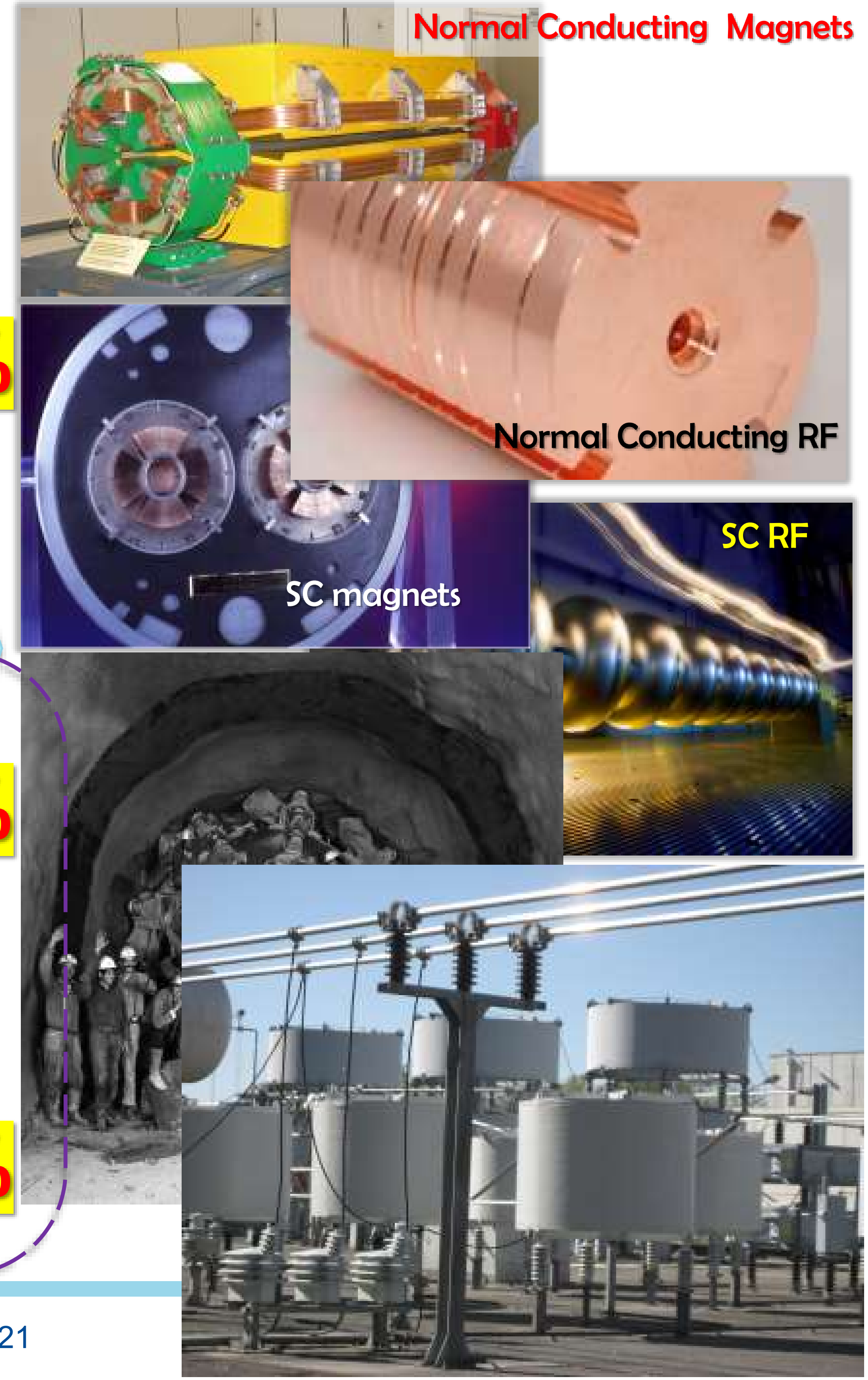
- *Accelerator technology* (magnets NC and SC, RF and SCRF)

- *Civil construction technology*

~35±15 %

- *Power production, delivery and distribution technology*

~15±10 %



State of the art NC (warm) magnets for 4th gen light sources :

- high quality
- buy from industry

NC RF:

- 28 MV/m in SwissFEL (‘17)
- 100MV/m in CLIC structures
- Aim for 117 MV/m in cold copper (LN_2) structures (SLAC)

Supercond. magnets, for colliders and undulators:

- 8.3T in LHC
- 14.5T by US MDP (2020)
- 290 T/s fast cycling HTS (FNAL, 2021)

SC RF:

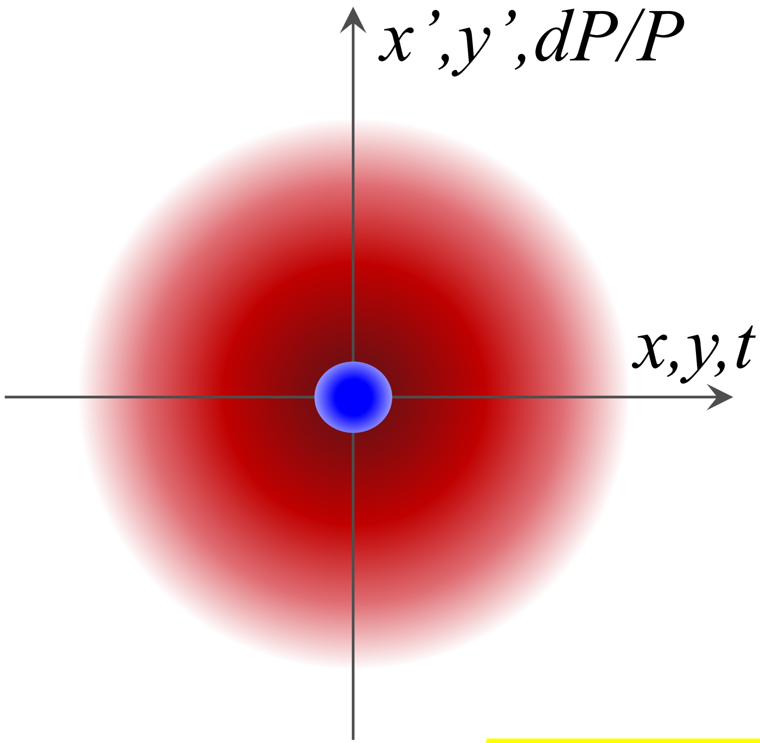
- 25 MV/m at Q_0=1e10 at 1.3 GHz EurXFEL
- ILC specs 31.5MV/m at FNAL
- Nitrogen doping → Q_0~3e10
- Aim at ~50MV/m in 1.3GHz

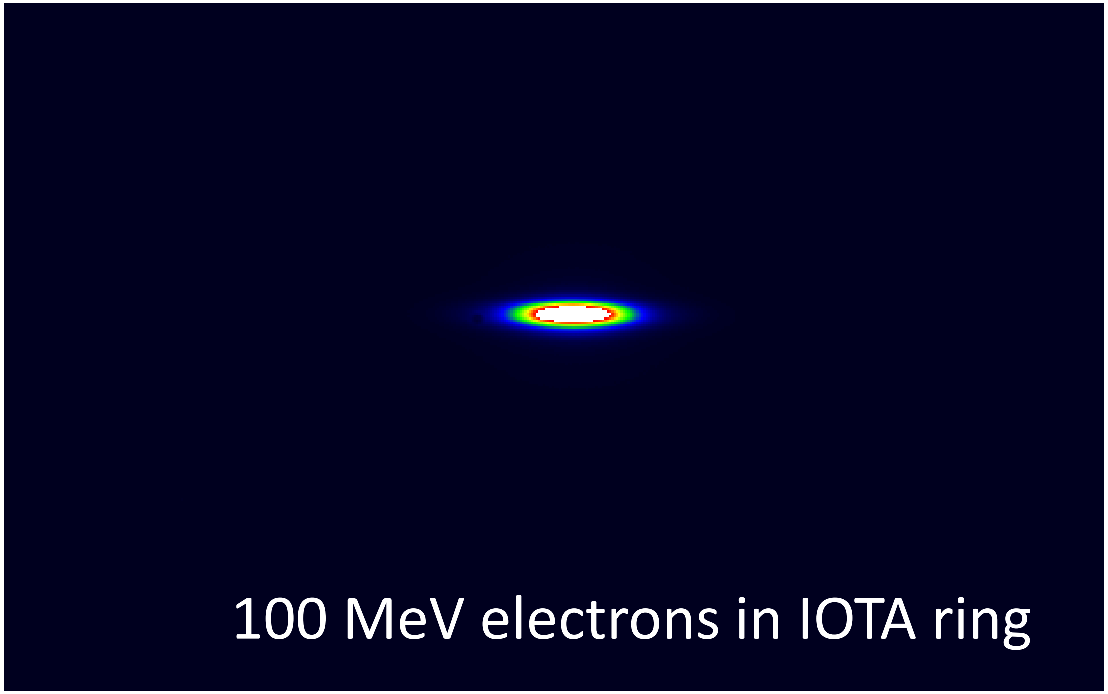
Beam Cooling

$$\mathcal{L} = f_{\text{coll}} \frac{N_1 N_2}{4\pi\sigma_x^* \sigma_y^*}$$

Beam Phase Space Density Increase

- As needed for a collider
- Forbidden by the *Liouville theorem* in non-dissipative systems

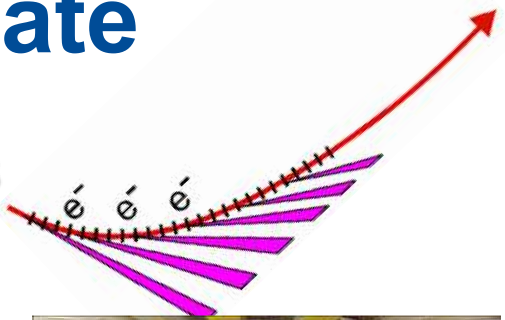




Ideally - "6D-Cooling"

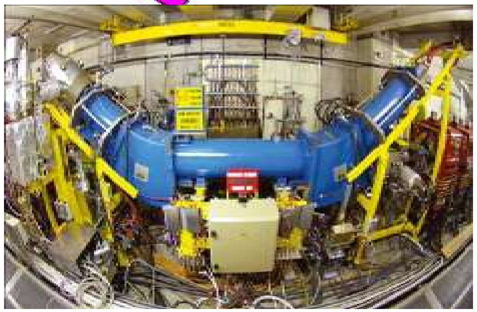
Beam Cooling Methods to Date

Synchrotron Radiation Damping – since 1960's



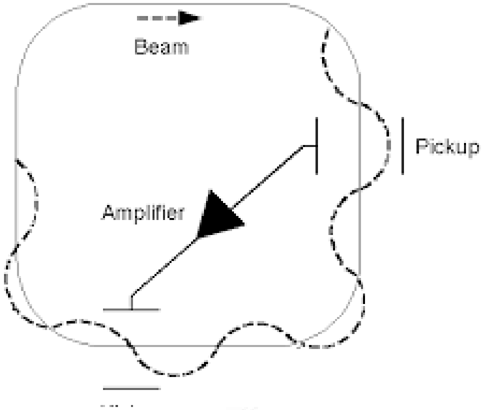
- common in all e+/e- rings

Electron Cooling – since 1970's



- Widely used to cool ions and antiprotons
- 0.1 - 8 GeV/n (50 keV – 4 MeV electrons DC)

Stochastic Cooling – since 1970's

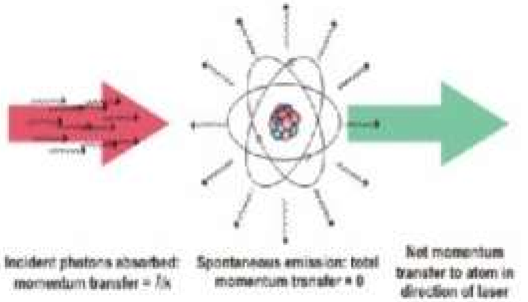


- Widely used to cool ions and antiprotons
- 0.1-100 GeV/n (up to 10 GHz feedback BW)

Laser Cooling – since 1990's

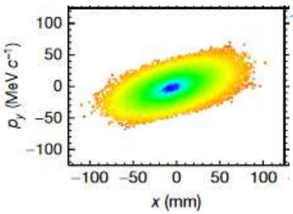
$$\Omega = \gamma\omega_{21}(1 - \beta\cos\theta)$$

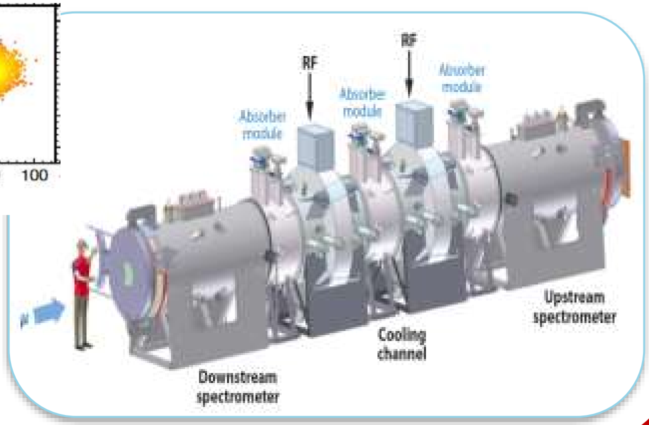
- Works for some highly charged ions
- 0.1-0.5 GeV/n, deep cooling, spectroscopy



Beam Cooling Breakthroughs

2019 - Ionization cooling of muons (140 MeV/c, RAL, UK)

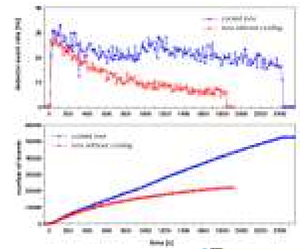


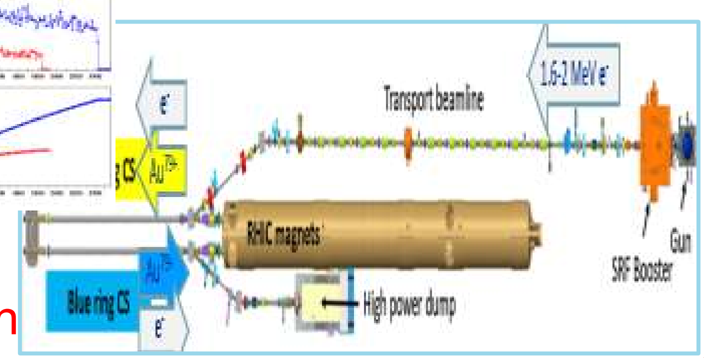


MICE

~10% in one pass

2020 – "Bunched" electron cooling of ions (γ~5, BNL)

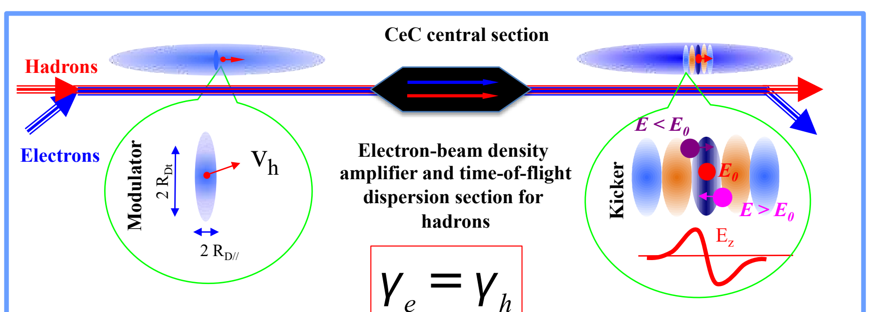




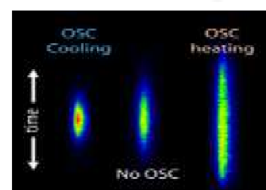
RHIC

RF e-gun

2021 – Coherent Electron cooling of ions (26.5 GeV/n, RHIC) – ongoing PoP exp't at BNL



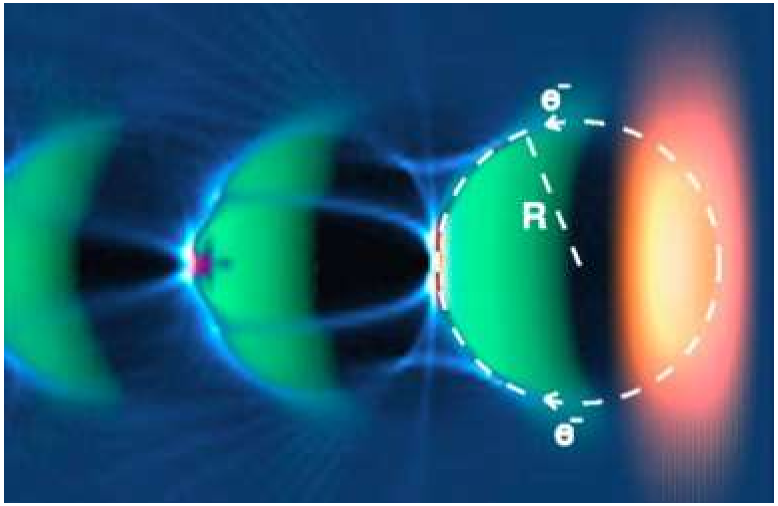
2021 – Optical Stochastic cooling e- (100 MeV, FNAL)



IOTA

THz bandwidth

Acceleration in Plasma

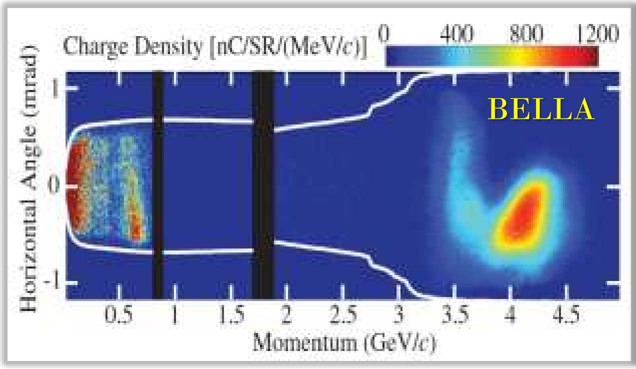


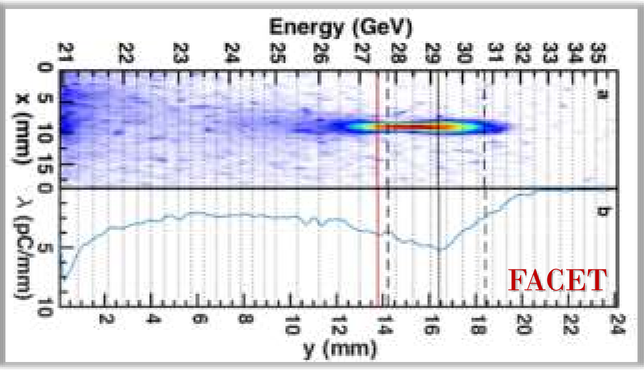
Plasma waves can sustain high fields:

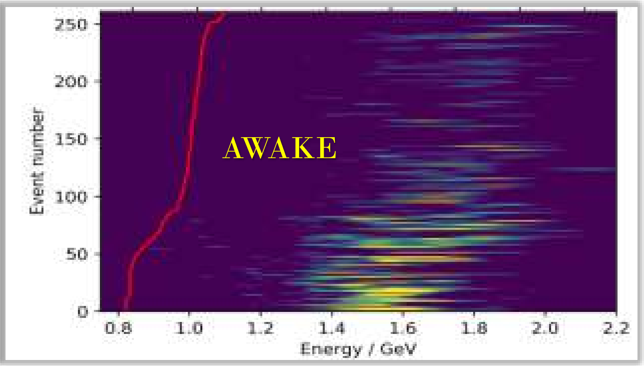
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

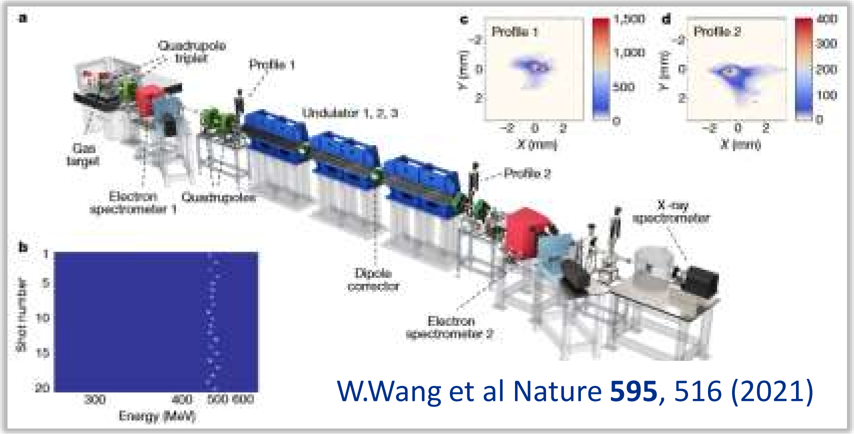
Excitation by (smth short and powerful):

laser 4.3 GeV (10^{18} cm^{-3} 9cm) *e*- bunch 9 GeV (~10^{17} cm^{-3} 1.3m) *p+* bunch 2 GeV (~10^{15} cm^{-3} 10m)









W.Wang et al Nature **595**, 516 (2021)

Latest news – summer 2021:

- EuPRAXIA (European plasma accelerator, 5 GeV *e*- and FELs, 50 institutes in 15 countries, 569M**€**) is included in the **ESRFI** 10-20 yrs roadmap
- First LWFA FEL at SIOM/CAS, Shanghai (6 mm He gas, 200 TW laser → 0.5 GeV e- beam → 27 nm laser)

Take Away Message on Accelerators:

- **Remarkable progress over the past 4 years:**
  - Accelerators for NP, BES, neutrinos and rare processes, colliders
    - e.g., FRIB, XFELs, China SNS, power records at FNAL and JPARC, luminosity records at LHC and SuperKEKB
  - Physics of beams breakthroughs
    - Several new beam cooling schemes, plasma acceleration to *O*(5GeV) – with beams good enough for FELs
  - Core technology advances
    - Records in RF gradients, *B*-field, *dB/dt* rate, MWs beam targets
- **Bright future ahead:**
  - Next: NICA, XFELs, High Lumi LHC, PIP-II, ESS, FAIR, etc
  - Future: Higgs factories (linear or circular), Multi-TeV colliders (*pp,μμ,ee*)

Thanks for your attention!

Some references

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- Modern and Future Colliders - V. Shiltsev, F. Zimmermann *Rev. Mod. Phys.* 93, 015006 (2021)
- RHIC lumi - https://www.rhichome.bnl.gov/RHIC/Runs/
- LHC ions – J.Jowett, IPAC'2019
- MICE - M.Bogomilov et al *Nature,* 578(7793): 53–59 (2020)
- Can the US compete in BES? - https://science.osti.gov/-/media/bes/besac/pdf/Reports/AH_DOE2021-Benchmarking_202108.pdf

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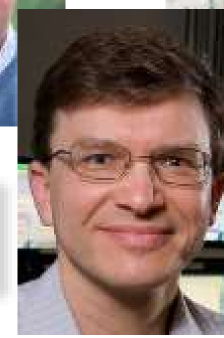

SnowMass2021

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