



Accelerator Technologies and Science: *Progress and Outlook*

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Content: Progress Since 2017



The 21st Particles & Nuclei International Conference

1-5 September 2017, IHEP, Beijing, China



- **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

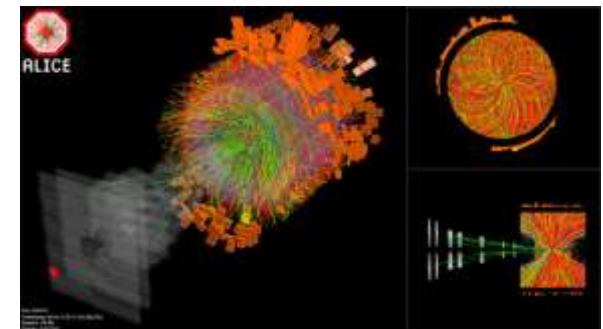
Accelerators for NP

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, ...)

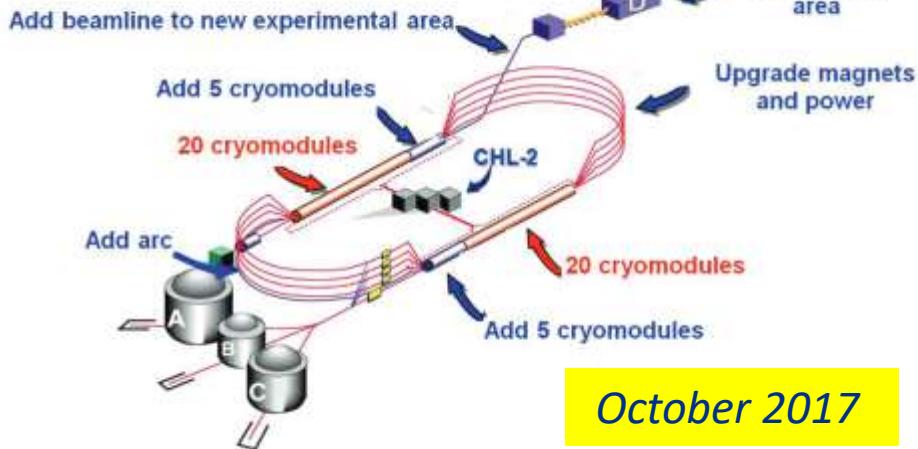
RHIC: >0.5 fb-1 in 510 GeV cme polarized $p\bar{p}$ ($P=55\%$)

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

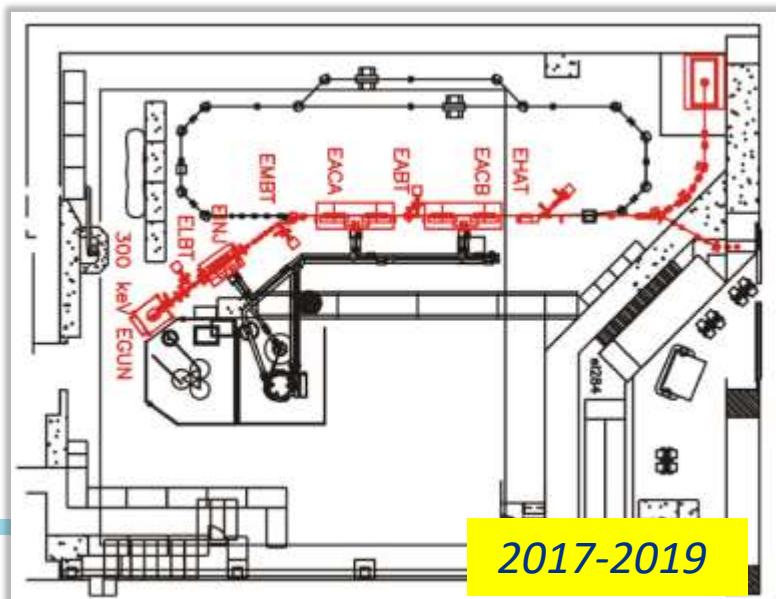


Continuous Electron Beam Accelerator Facility (CEBAF) at TJNAF : 12 GeV electron beam energy upgrade (cw SRF linac)

6 GeV → 12 GeV



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



Facility for Rare Isotope Beams (FRIB)

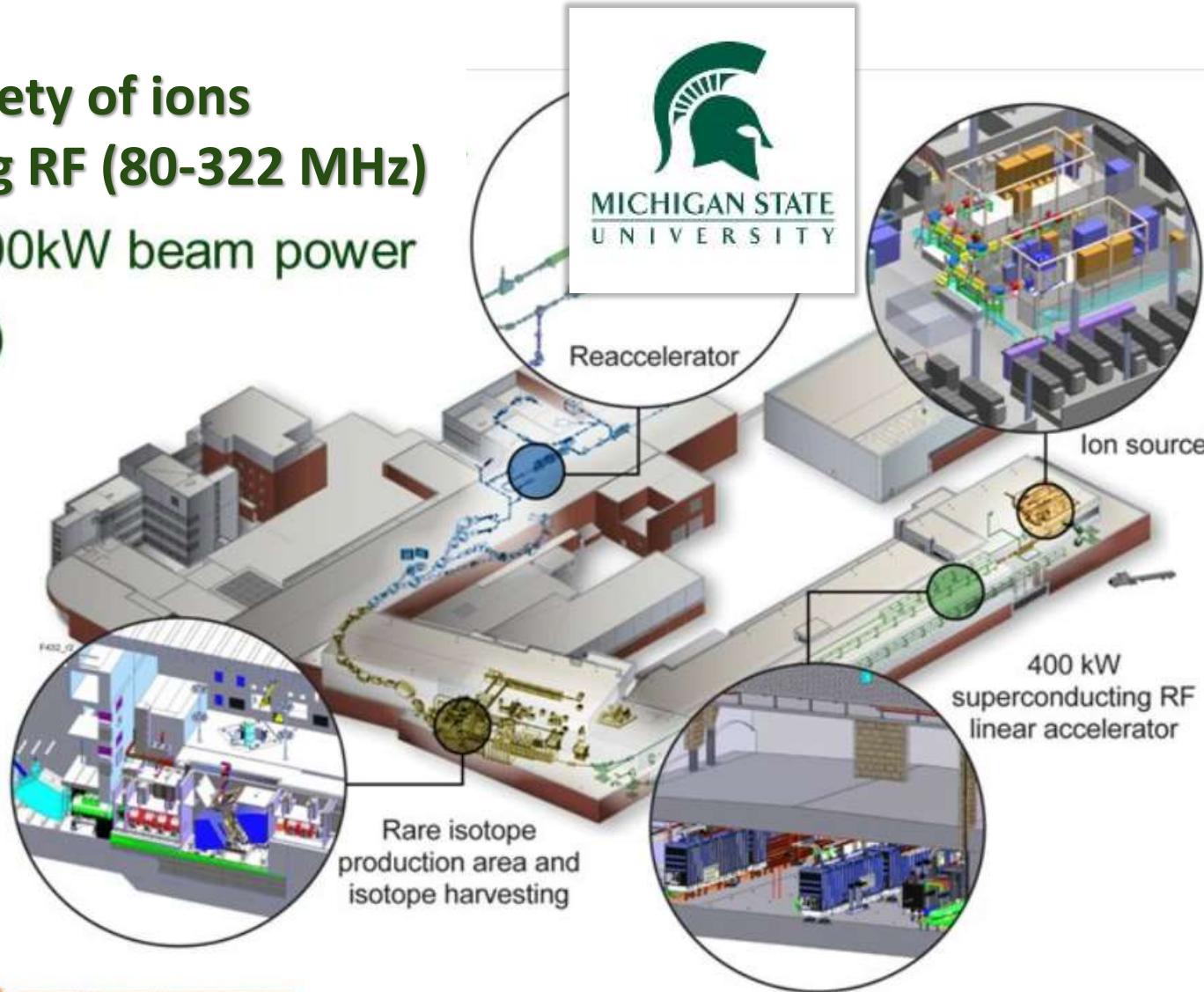
- 200 MeV/u, variety of ions
Superconducting RF (80-322 MHz)
- Key Feature is 400kW beam power
(5×10^{13} $^{238}\text{U}/\text{s}$)

Apr. 2021:
all 46 CMs
212 MeV/u

Separation of isotopes
“In-flight”

Suited for all elements
and short half-lives

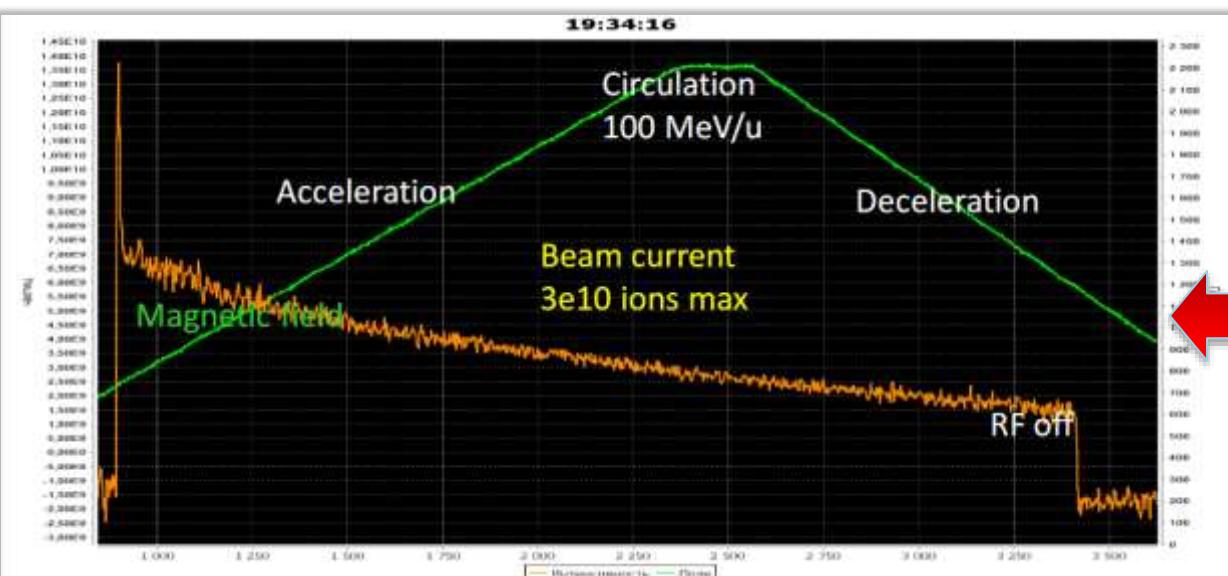
Fast, stopped, and
reaccelerated radioactive beams



NICA: Nuclotron-based Ion Collider fAcility)



- 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}

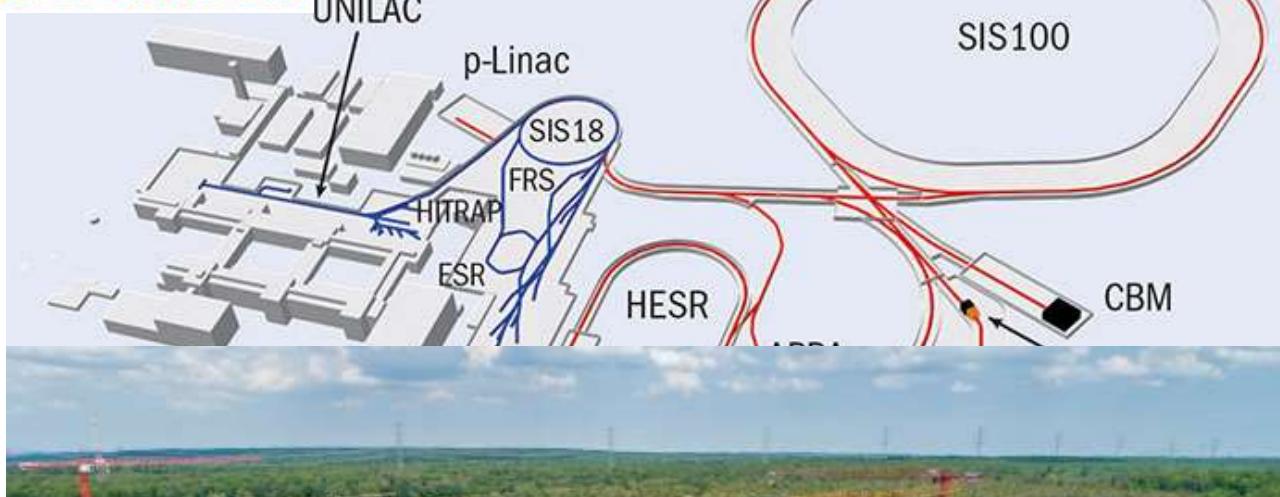


- Construction start in 2013
- About 80% done
- Booster beam (2021)
- Collisions in 2024

Facility for Antiproton and Ion Research (FAIR@GSI)



FAIR — Facility for Antiproton and Ion Research in Europe

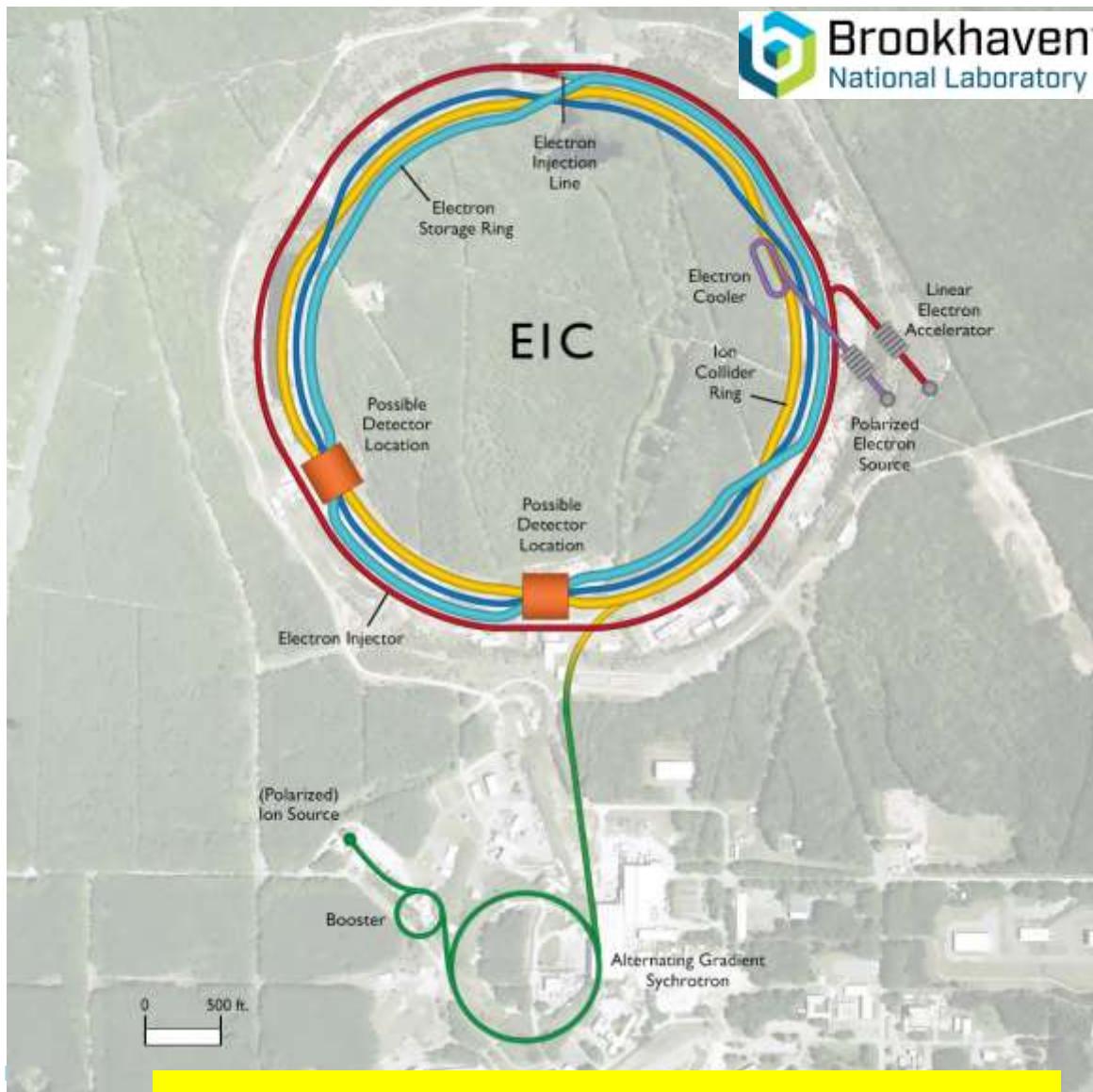


- Complex of rings and beamlines
- SIS-100: C=1.1 km, 29 GeV p , 2.9 GeV/u ions, SC superferric 1.9 T magnets

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

Electron Ion Collider (EIC)

Brookhaven National Laboratory



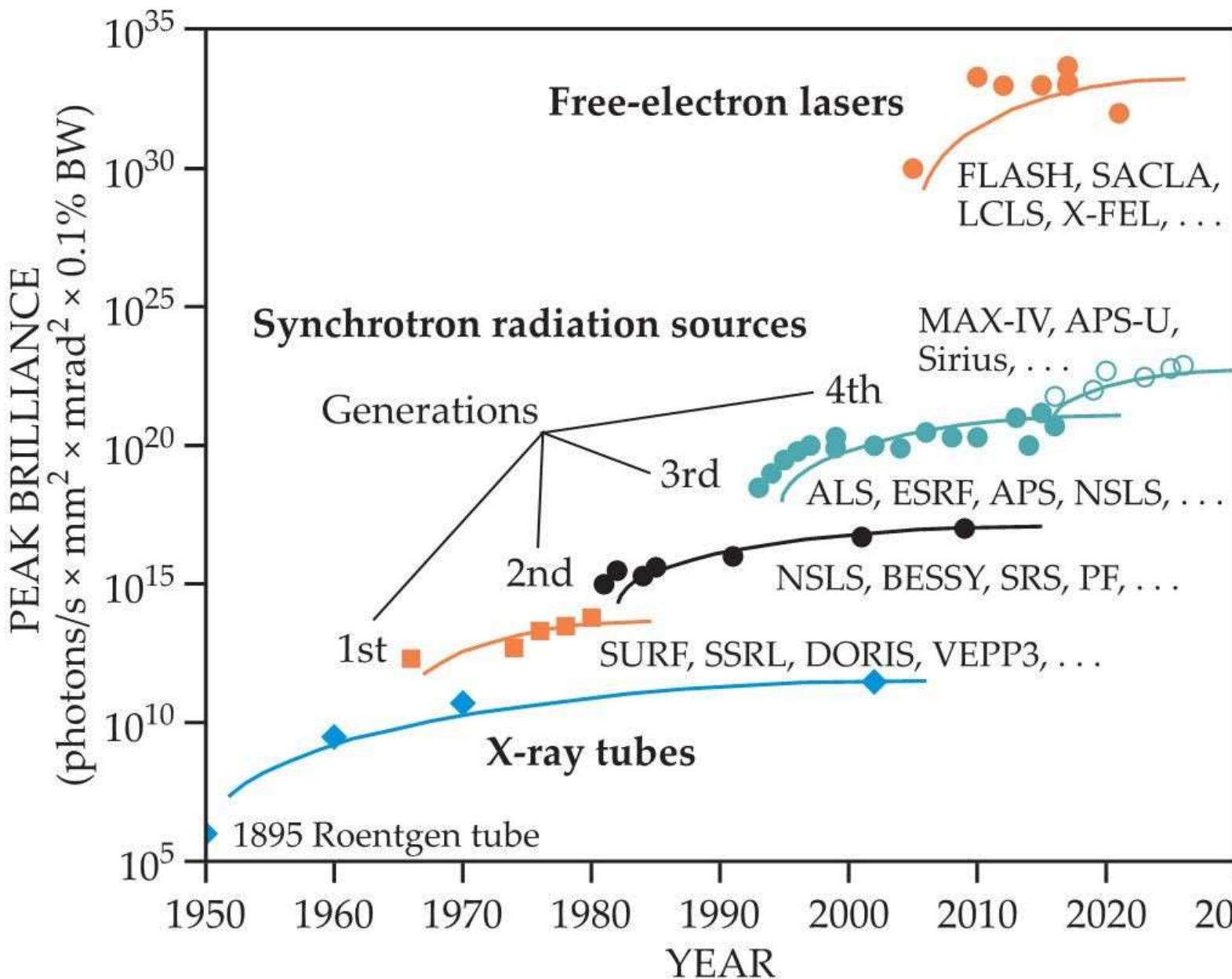
- 275 GeV protons, 100 GeV/u (existing RHIC, upgraded)
- 10 GeV electrons (5-18 GeV storage ring, new)

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

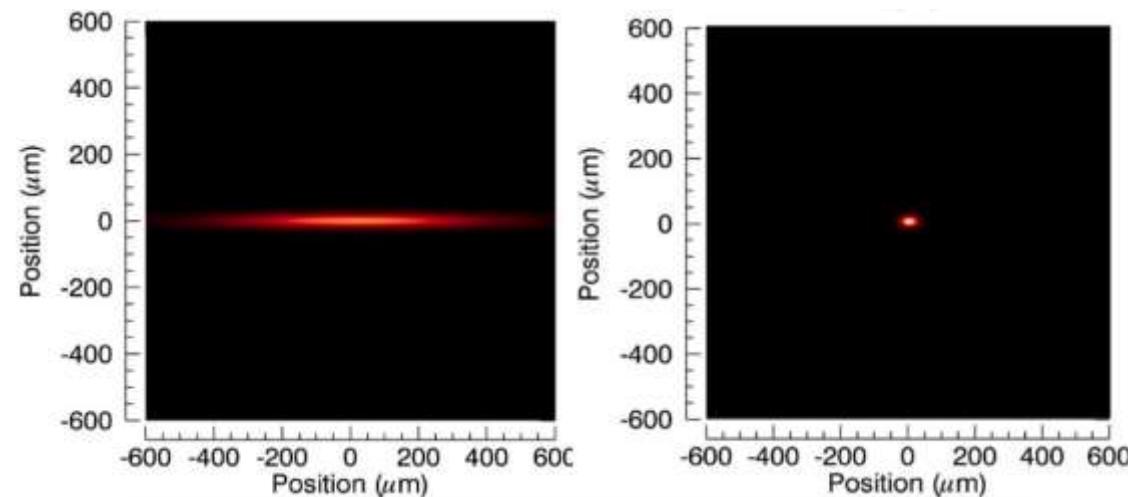
- ~70% polarization
- Luminosity ~x100 HERA (with Strong Hadron Cooling)
- CD-1 in July 2021
- Construction is expected to begin in 2024
- Operations early in the next decade.

see Bernd Surrow's talk Thursday

Revolution in Light Sources /X-ray Sources



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



- 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

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

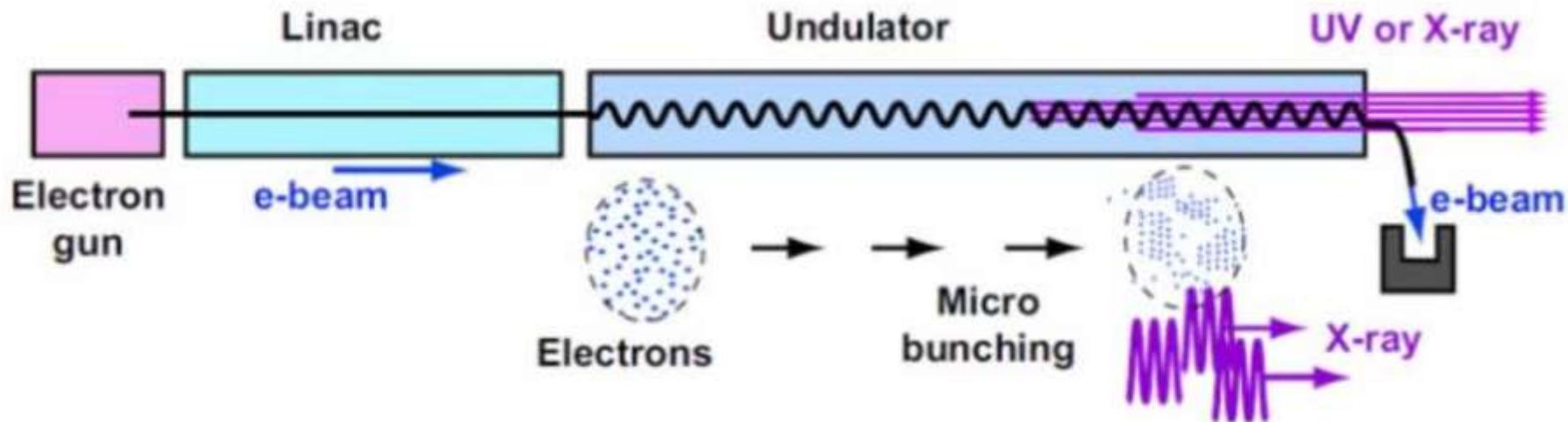


Self-Amplified Spontaneous Emission (SASE) Free Electron Lasers (FEL)

aka

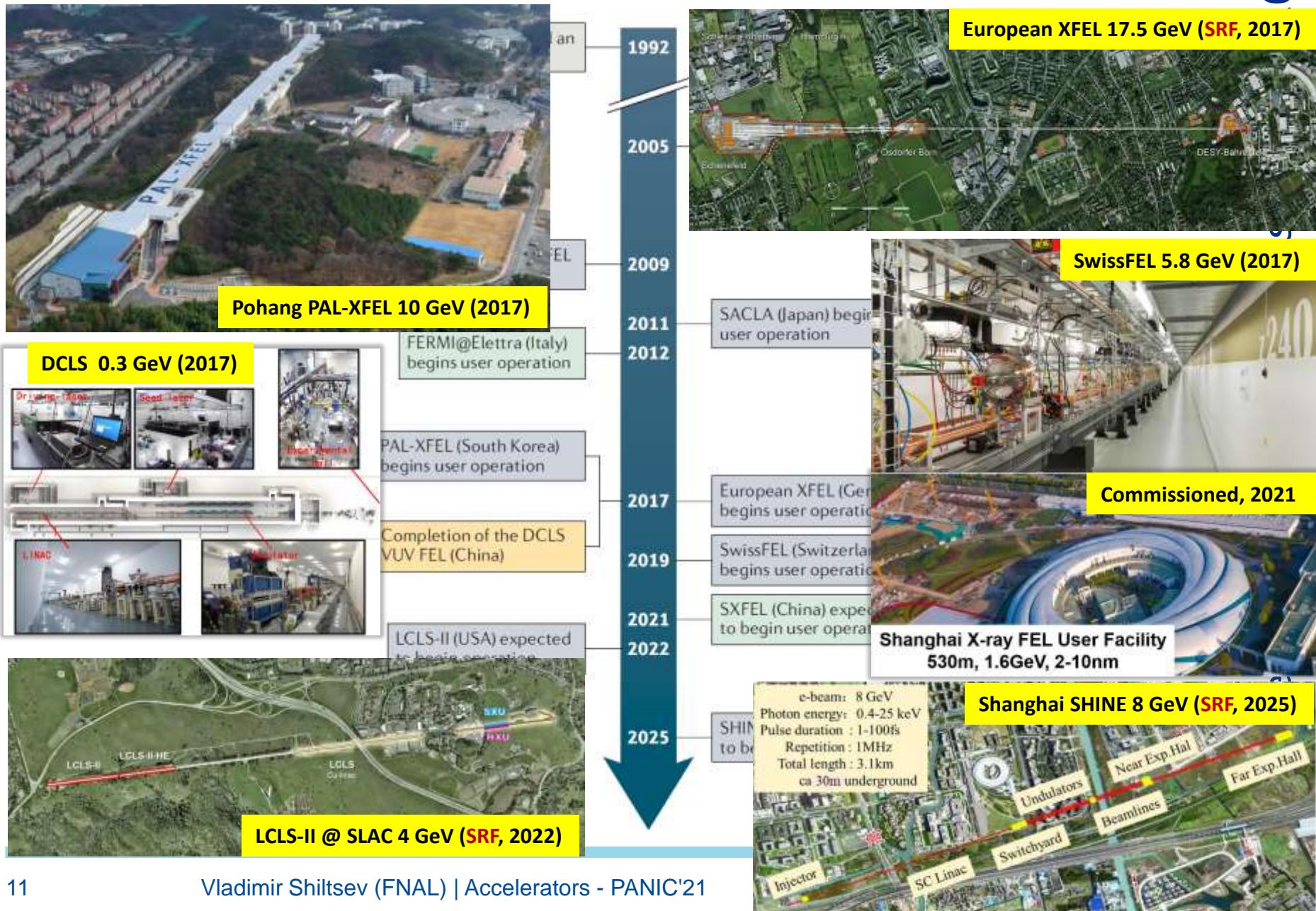
X-FELs

SASE-FEL



- 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

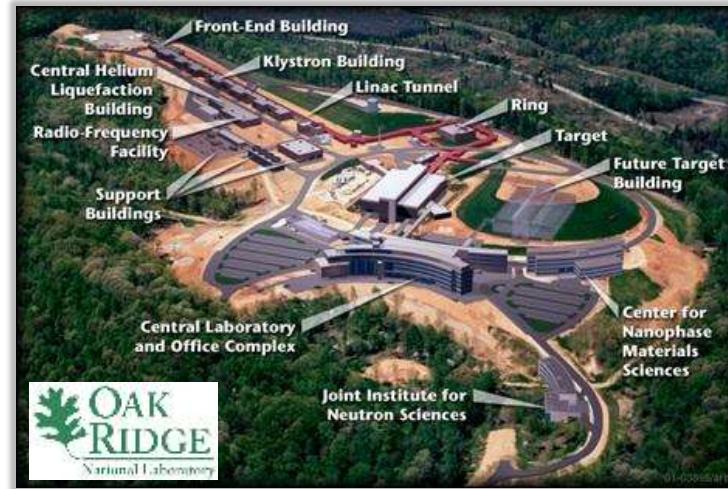
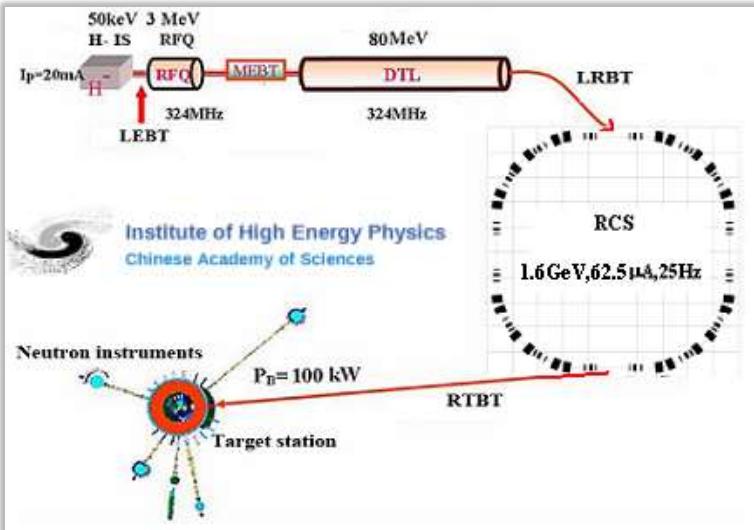
XFELs



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):

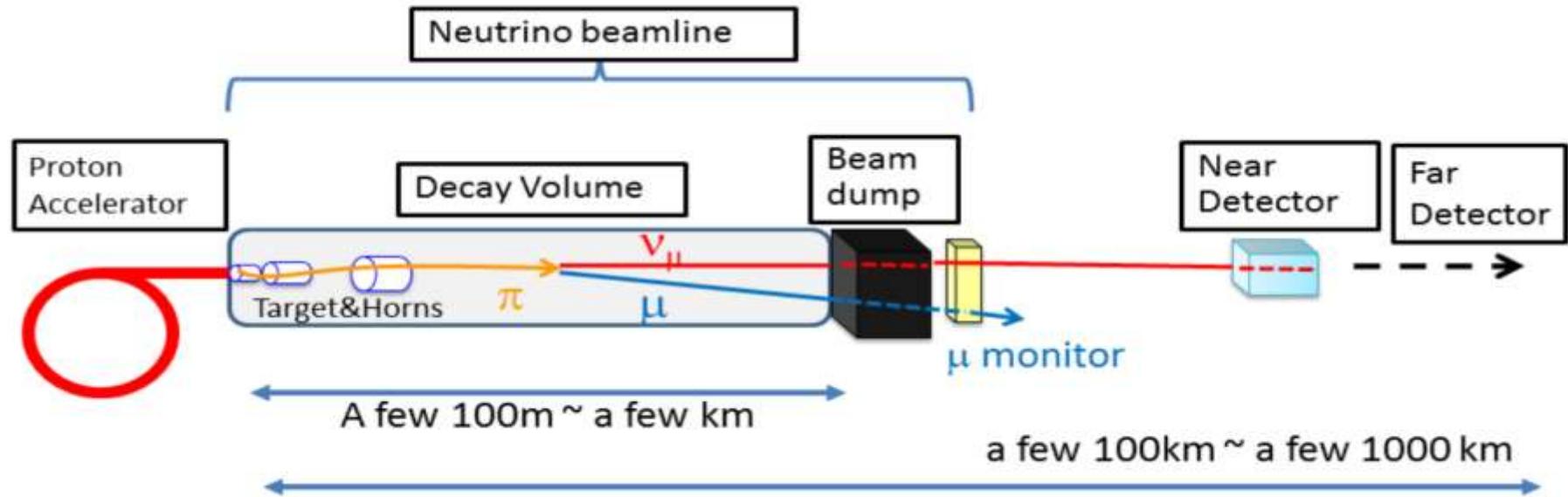
- 80 MeV linac and 1.4 GeV ring → target
- First neutrons Aug'2017, 0.1 MW Feb'2020
- Planned upgrades to 0.2MW, then 0.5MW

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



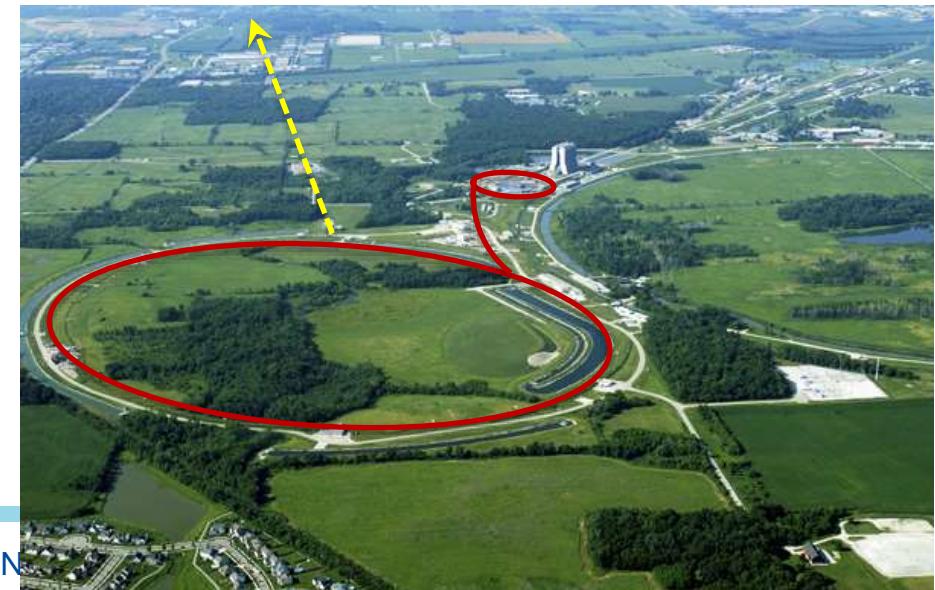
Neutrino Superbeams – ν Oscillations



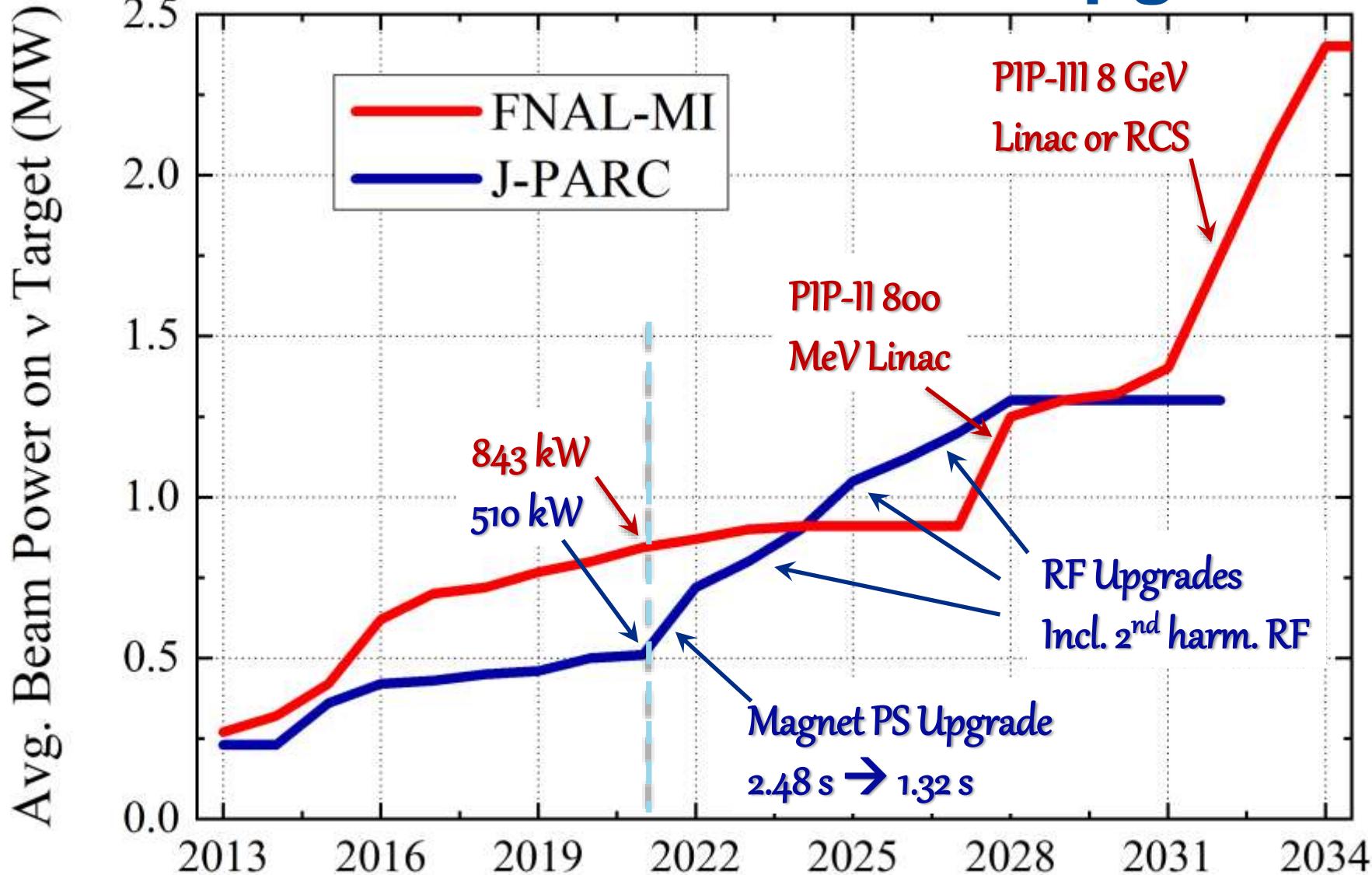
Japan Proton Accelerator Research Complex – 3/30 GeV (295 km to SuperK)



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



Fermilab and J-PARC Power Upgrades



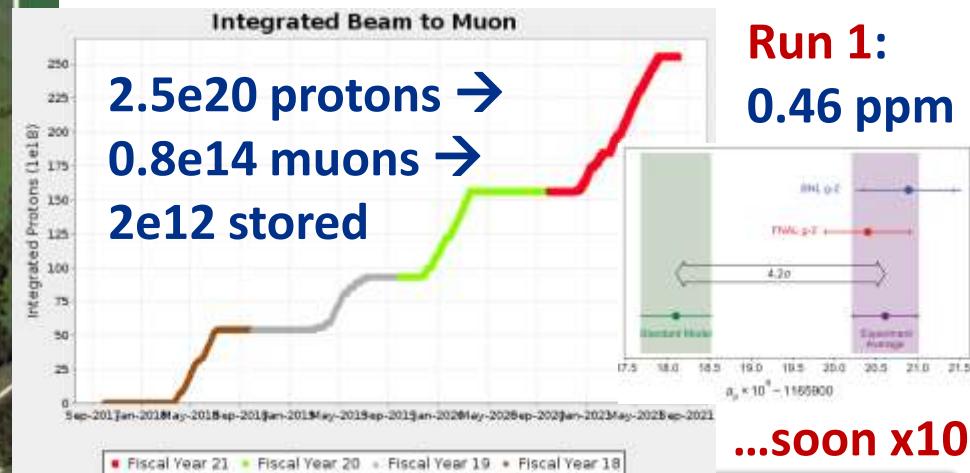
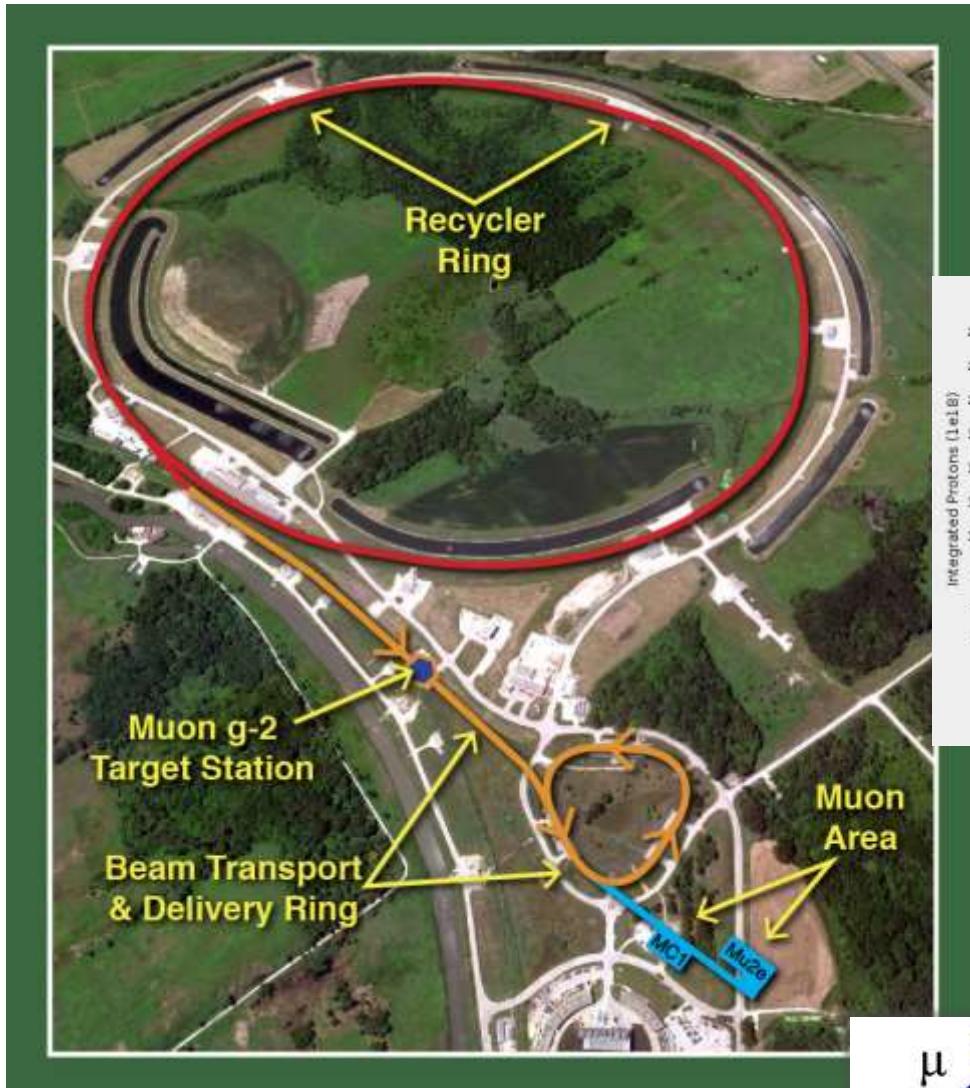
800 MeV SRF p Linac – Proton Improvement Plan-II



Fermilab Accelerator Complex



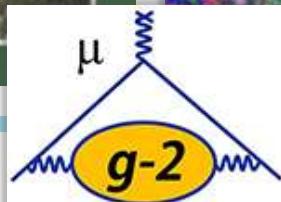
Muon g-2 – 2021 !



...soon x10



see Martin Ferti's talk Tuesday

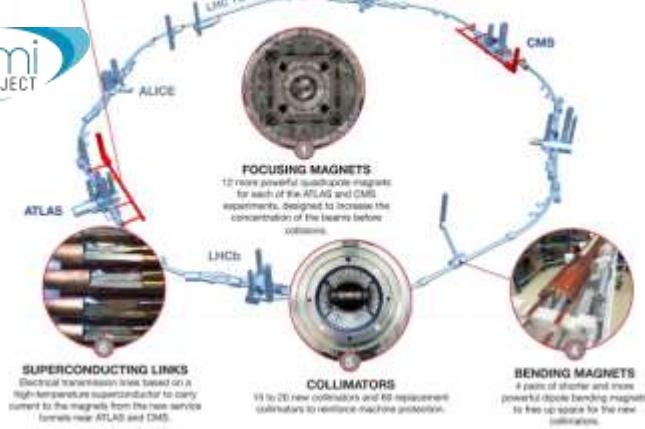
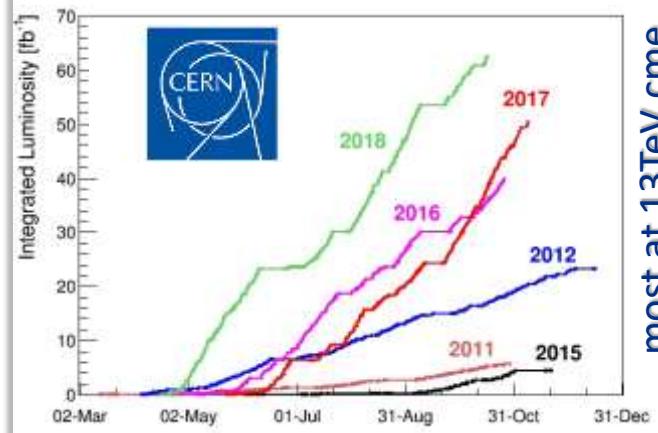


HEP Colliders

Seven in operation now

	Species	E_b (GeV)	C (m)	$\mathcal{L}_{\text{peak}}^{\max}$	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	26659	2.1×10^{34}	2009–present
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010–present
S-KEKB	e^+e^-	7 + 4	3016	$8 \times 10^{35}^a$	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 Nb₃Sn IR magnets), “crabbing”, leveling @14 TeV → 250 fb⁻¹/yr
- Followed by ~decade of ops to 3-4 ab⁻¹

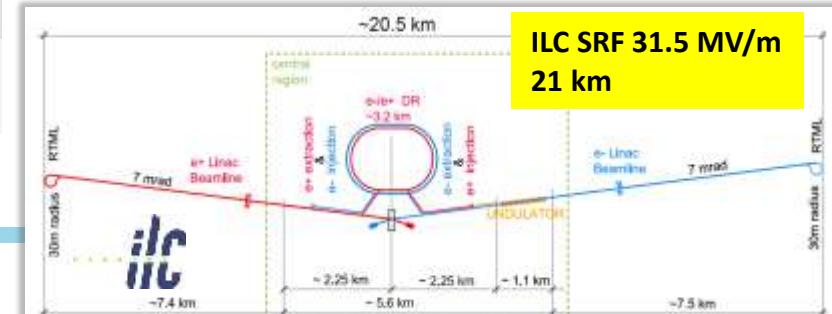
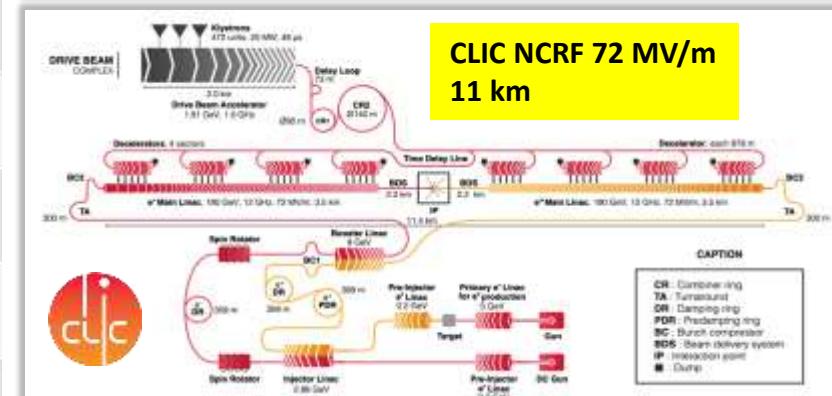
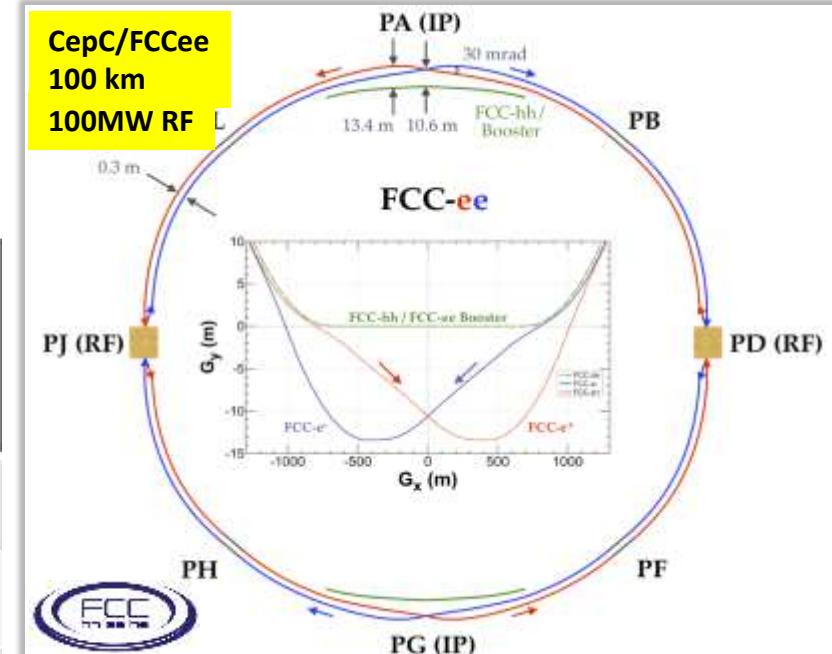
Highlights – Super-KEKB: e+e- 7+4 GeV

- Startup in 2018, world record $L=3.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Design luminosity goal x40 of KEK-B
- Now ~4% of the goal, steady progress

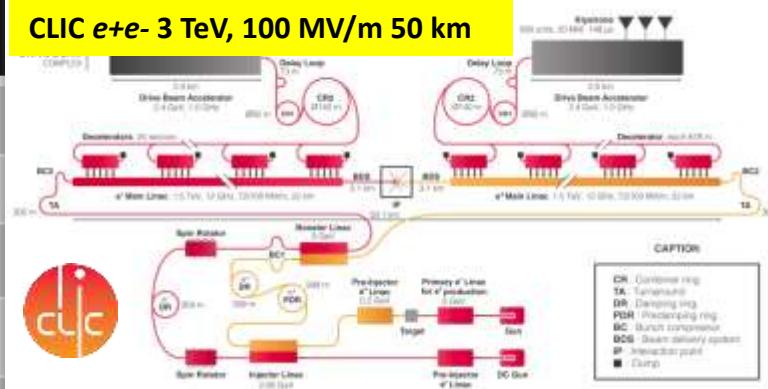
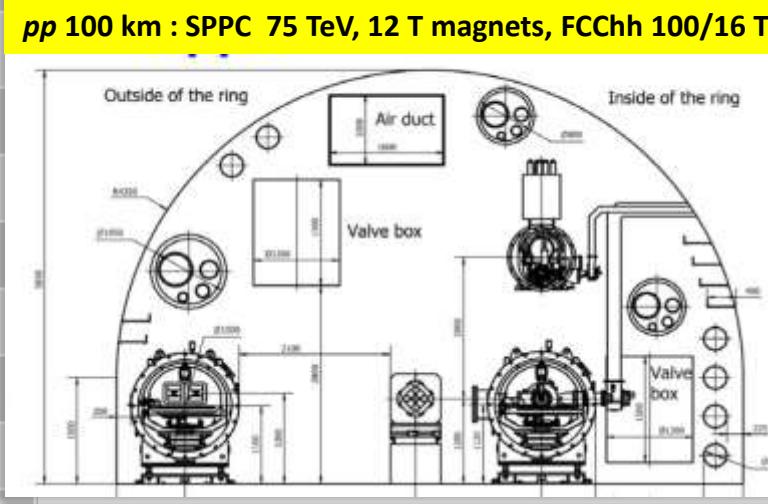
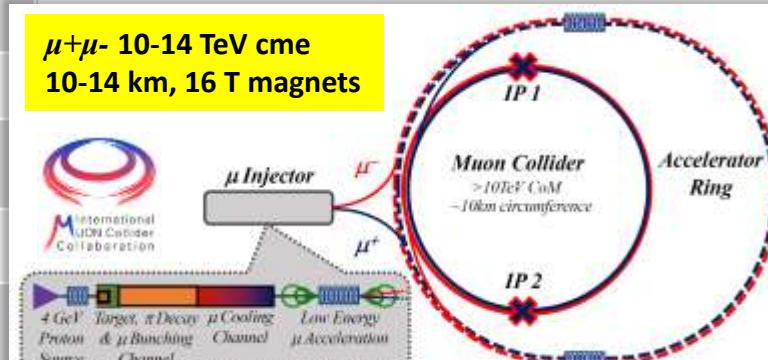
most at 13TeV cme

Future Collider Proposals: 8 Higgs/EW factories

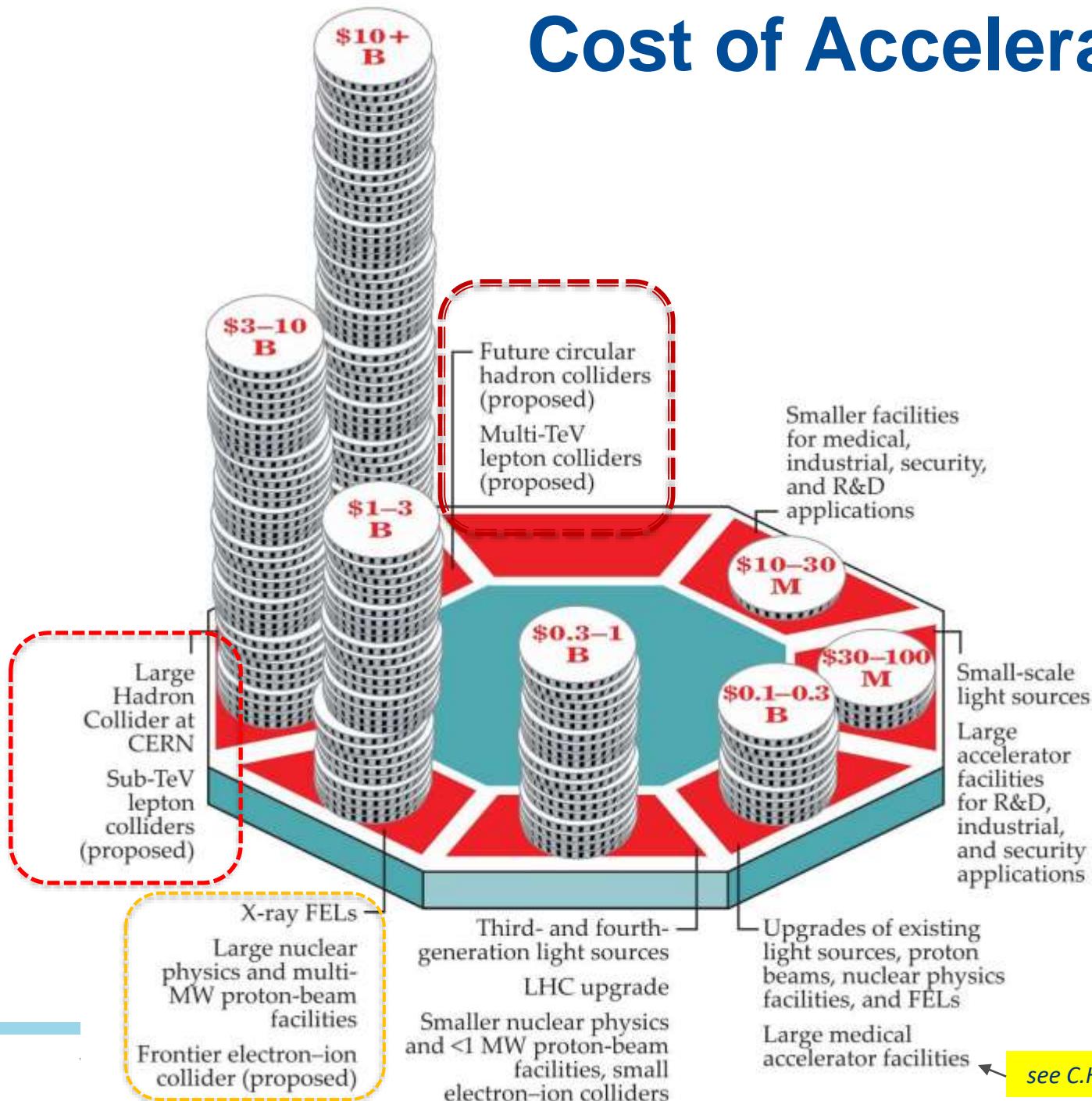
Name	Details
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, $L = 3.0 \times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, $L = 1.5 \times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, $L = 73 \times 10^{34}$
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, $L = 17 \times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ 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	$e+e-$, $\sqrt{s} = 2 \text{ TeV}$, $L = 4.5 \times 10^{34}$	
High Energy CLIC	$e+e-$, $\sqrt{s} = 1.5 - 3 \text{ TeV}$, $L = 5.9 \times 10^{34}$	CLIC $e+e-$ 3 TeV, 100 MV/m 50 km 
High Energy ILC	$e+e-$, $\sqrt{s} = 1 - 3 \text{ TeV}$	
FCC-hh	pp , $\sqrt{s} = 100 \text{ TeV}$, $L = 30 \times 10^{34}$	
SPPC	pp , $\sqrt{s} = 75/150 \text{ TeV}$, $L = 10 \times 10^{34}$	pp 100 km : SPPC 75 TeV, 12 T magnets, FCChh 100/16 T 
Collider-in-Sea	pp , $\sqrt{s} = 500 \text{ TeV}$, $L = 50 \times 10^{34}$	
LHeC	ep , $\sqrt{s} = 1.3 \text{ TeV}$, $L = 1 \times 10^{34}$	
FCC-eh	ep , $\sqrt{s} = 3.5 \text{ TeV}$, $L = 1 \times 10^{34}$	
CEPC-SPPpC-eh	ep , $\sqrt{s} = 6 \text{ TeV}$, $L = 4.5 \times 10^{33}$	
VHE-ep	ep , $\sqrt{s} = 9 \text{ TeV}$	
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5 \text{ TeV}$, $L = 1 \times 10^{34}$	
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3 \text{ TeV}$, $L = 2 \times 10^{34}$	
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14 \text{ TeV}$, $L = 20 \times 10^{34}$	
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14 \text{ TeV}$, $L = 20 \times 10^{34}$	
LWFA-LC ($e+e-$ and $\gamma\gamma$)	Laser driven; $e+e-$, $\sqrt{s} = 1 - 30 \text{ TeV}$	$\mu+\mu-$ 10-14 TeV cme 10-14 km, 16 T magnets 
PWFA-LC ($e+e-$ and $\gamma\gamma$)	Beam driven; $e+e-$, $\sqrt{s} = 1 - 30 \text{ TeV}$	
SWFA-LC	Structure wakefields; $e+e-$, $\sqrt{s} = 1 - 30 \text{ TeV}$	

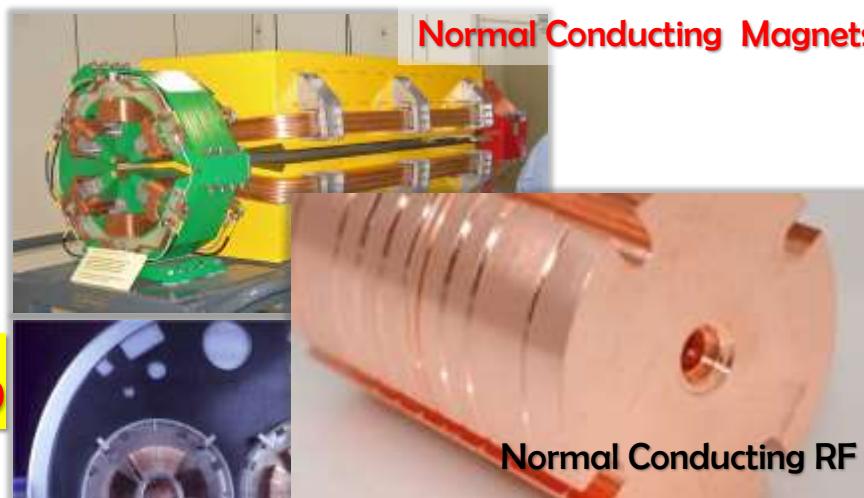
Cost of Accelerators



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

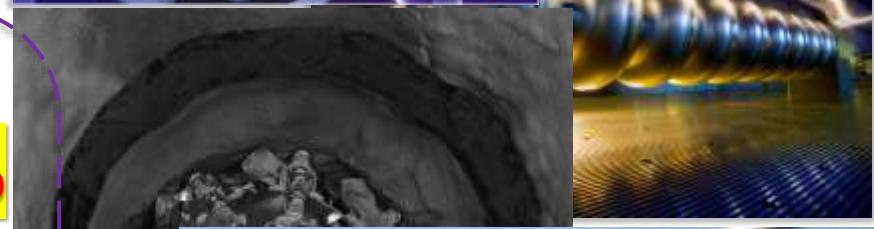
$\sim 50 \pm 10 \%$

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



- Civil construction technology

$\sim 35 \pm 15 \%$



- Power production, delivery and distribution technology

$\sim 15 \pm 10 \%$



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:

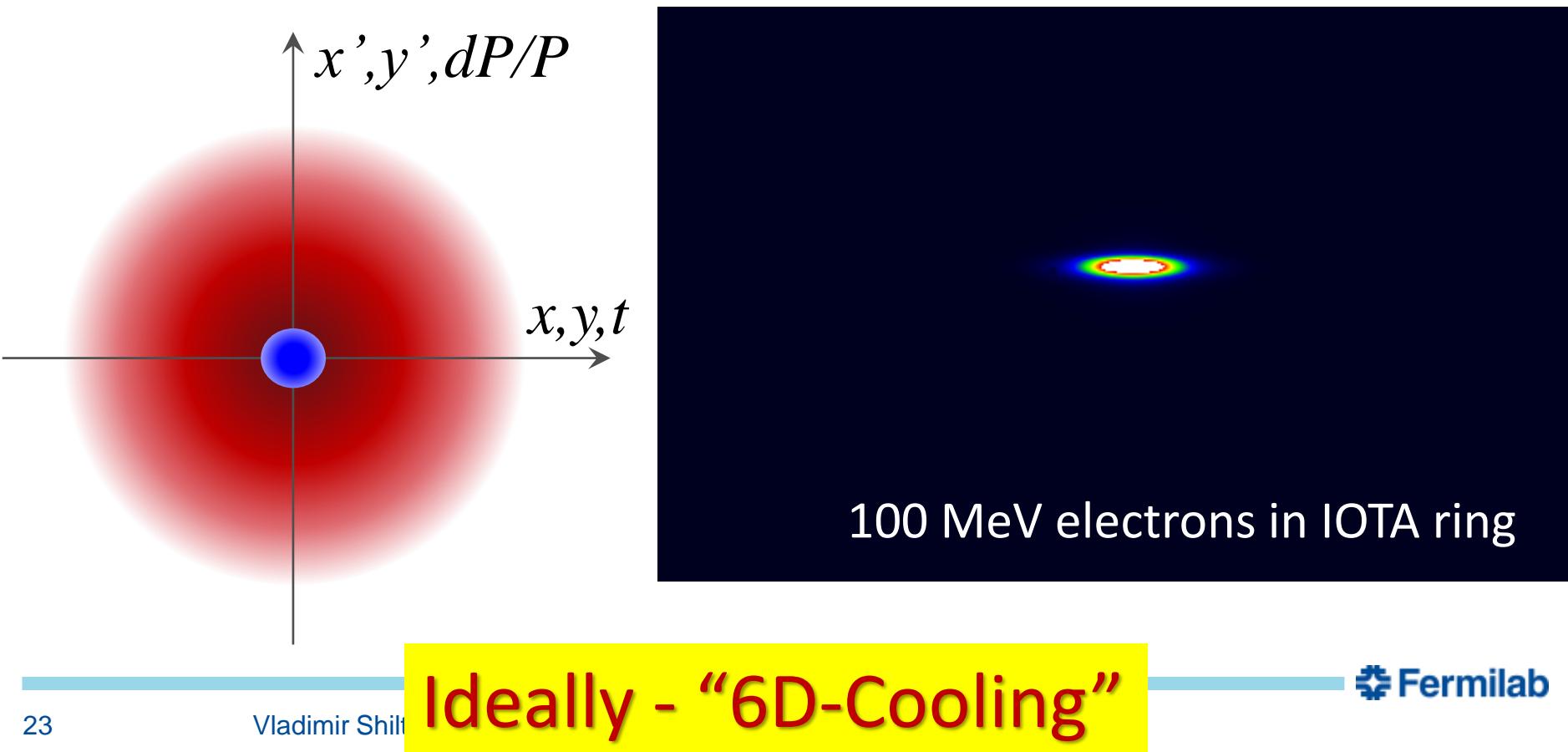
- 25 MV/m at $Q_0=1\text{e}10$ at 1.3 GHz EurXFEL
- ILC specs 31.5MV/m at FNAL
 - Nitrogen doping $\rightarrow Q_0 \sim 3\text{e}10$
 - Aim at $\sim 50\text{MV/m}$ in 1.3GHz

Beam Cooling

Beam Phase Space Density Increase

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

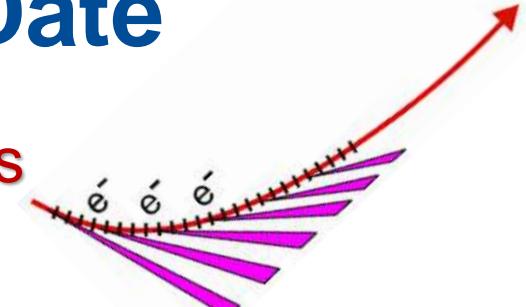
$$\mathcal{L} = f_{\text{coll}} \frac{N_1 N_2}{4\pi\sigma_x^* \sigma_y^*}$$



Beam Cooling Methods to Date

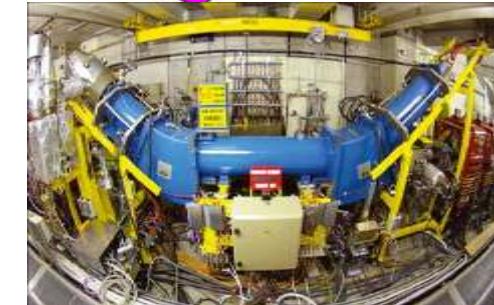
Synchrotron Radiation Damping – since 1960's

- common in all e+/e- rings



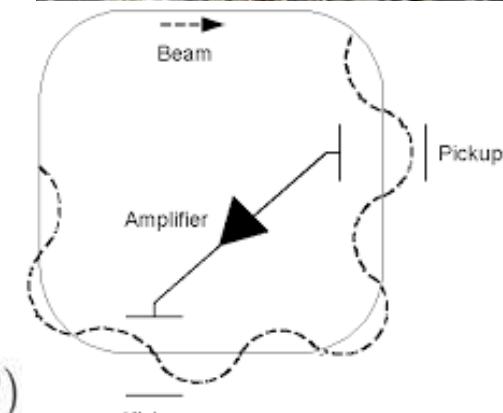
Electron Cooling – since 1970's

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



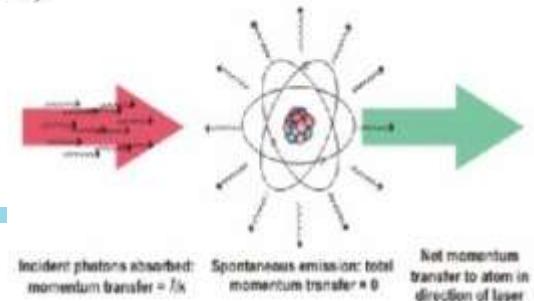
Stochastic Cooling – since 1970's

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



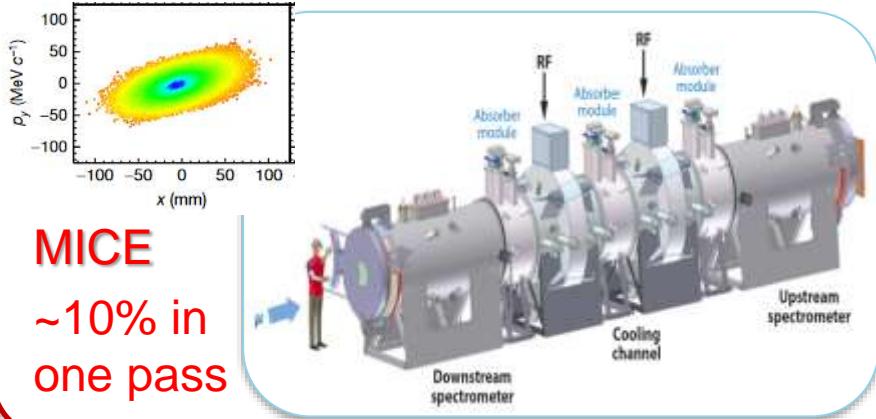
Laser Cooling – since 1990's $\Omega = \gamma\omega_{21}(1 - \beta \cos \theta)$

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

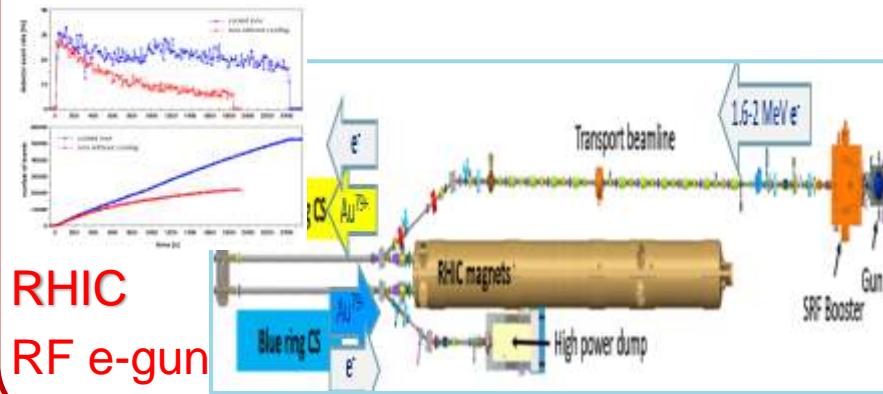


Beam Cooling Breakthroughs

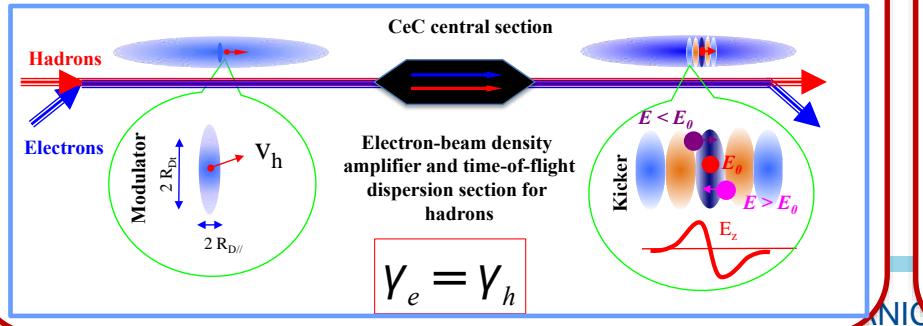
2019 - Ionization cooling of muons (140 MeV/c, RAL, UK)



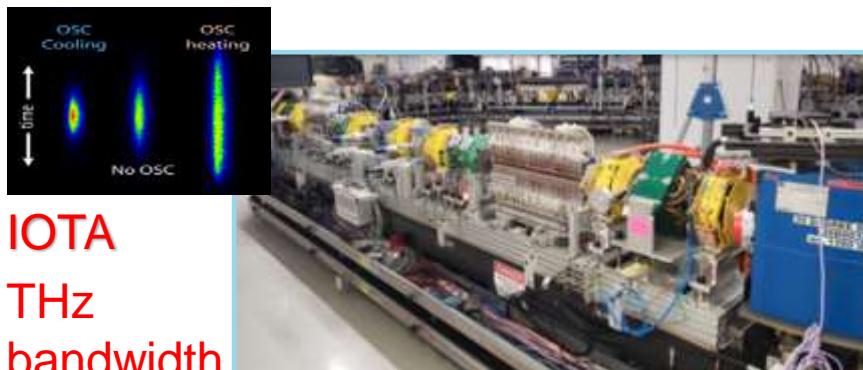
2020 – “Bunched” electron cooling of ions ($\gamma \sim 5$, BNL)



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



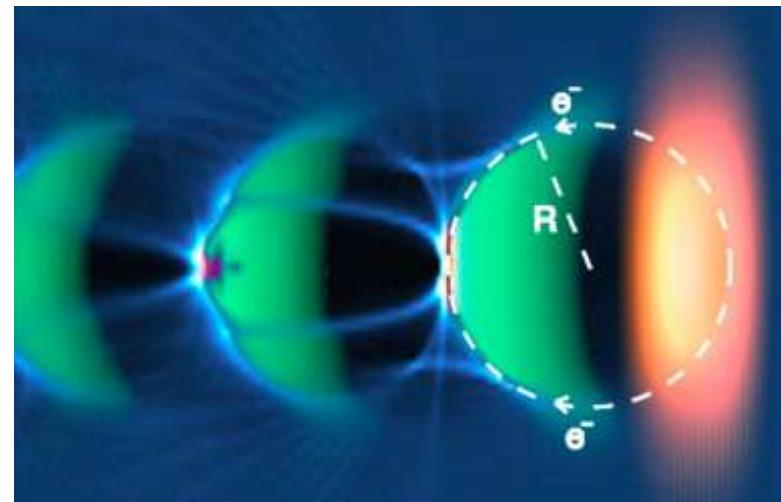
2021 – Optical Stochastic cooling e- (100 MeV, FNAL)



Acceleration in Plasma

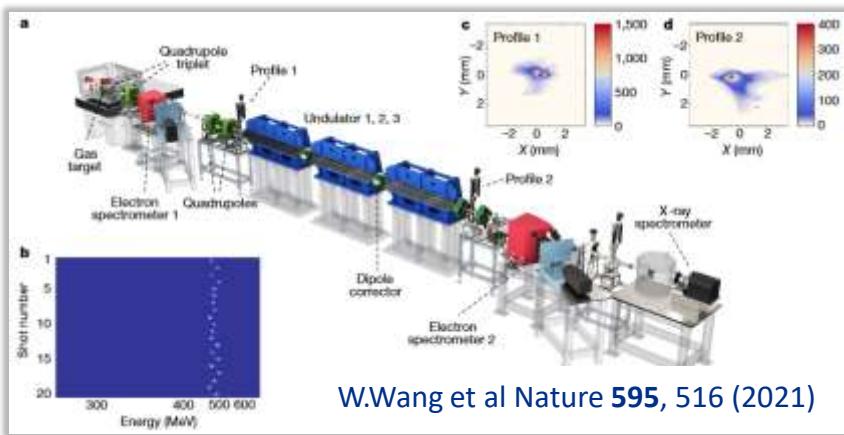
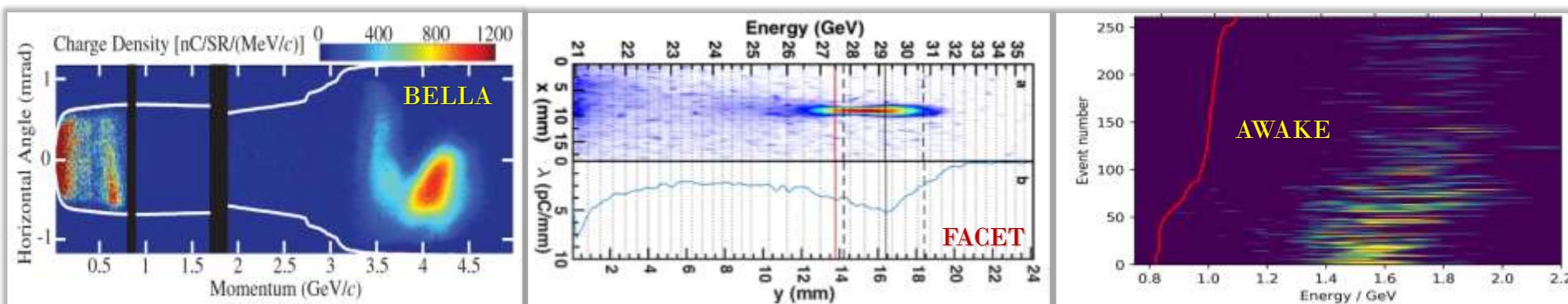
Plasma waves can sustain high fields:

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



Excitation by (smth short and powerful):

laser 4.3 GeV (10^{18} cm^{-3} 9cm) e- bunch 9 GeV ($\sim 10^{17} \text{ cm}^{-3}$ 1.3m) p+ bunch 2 GeV ($\sim 10^{15} \text{ cm}^{-3}$ 10m)



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 ($pp, \mu\mu, ee$)

Thanks for your attention!

Some references



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- XFELs - I.Georgescu *Nature Reviews Physics* **2**, 345 (2020)
- 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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Frank Zimmermann (CERN)

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Meenakshi Narain (UB)



EPPSU-Snowmass'21 input from:

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