Geneva

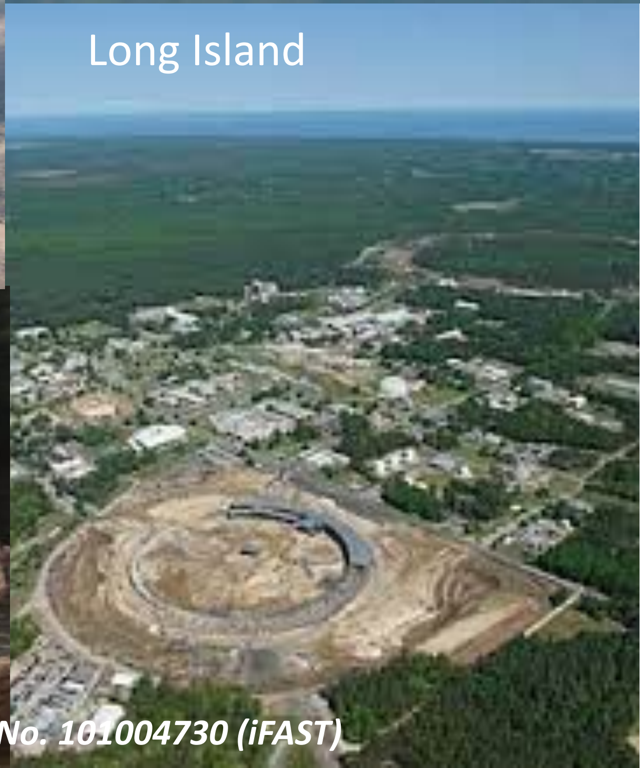
Accelerator Overview

Frank Zimmermann, CERN

ICTS, Bengaluru, 14 November 2022

including slides from M. Benedikt, D. Contardo, A. Faus-Golfe, D. Kaplan, K. Oide, M. Palmer, D. Schulte, V. Shiltsev, F. Willeke et al.

Many thanks to Rohini Godbole and Swapan Chattopadhyay

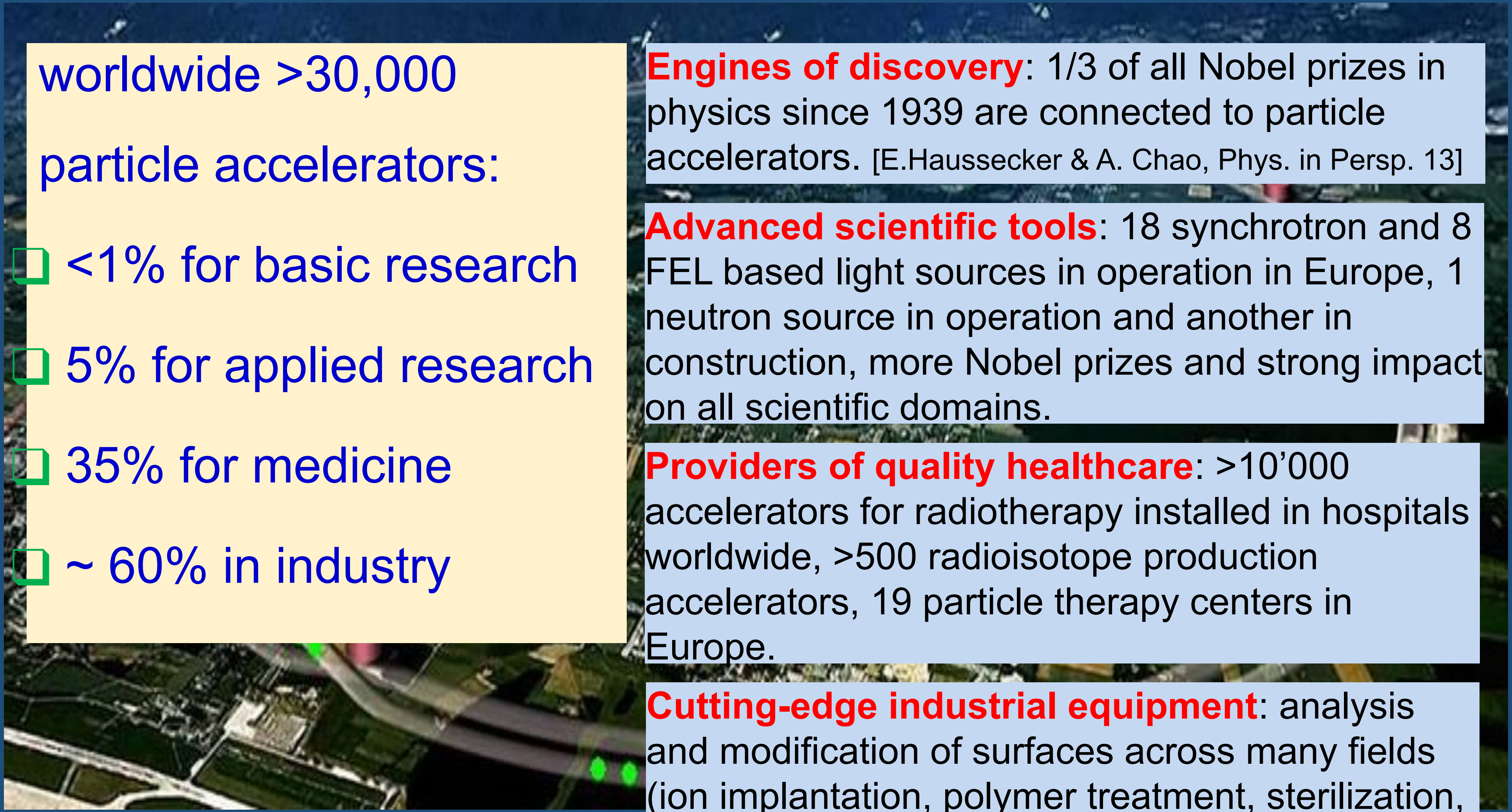


Work supported by ***the Eruopean Union's Horizon 2020 Research and Innovation programme under Grant Agreement No. 101004730 (iFAST)***

outline

- **accelerators**
- **particle colliders**
- **next and next-next(-next) generation high-energy machines**
  - **hadron colliders, both circular and linear electron-positron colliders, and muon colliders**, along with some challenges and merits
  - collider energy efficiency, including **energy recovery**
  - **advanced accelerators incl. accelerators for the dark sector**
  - **elements of the recent US Snowmass process**
  - **approximate technical timelines**
- **brief outlook** to the far future
- **back to next generation**

accelerator landscape in the 21st century



worldwide >30,000 particle accelerators:

- <1% for basic research
- 5% for applied research
- 35% for medicine
- ~ 60% in industry

Engines of discovery: 1/3 of all Nobel prizes in physics since 1939 are connected to particle accelerators. [E.Haussecker & A. Chao, Phys. in Persp. 13]

Advanced scientific tools: 18 synchrotron and 8 FEL based light sources in operation in Europe, 1 neutron source in operation and another in construction, more Nobel prizes and strong impact on all scientific domains.

Providers of quality healthcare: >10’000 accelerators for radiotherapy installed in hospitals worldwide, >500 radioisotope production accelerators, 19 particle therapy centers in Europe.

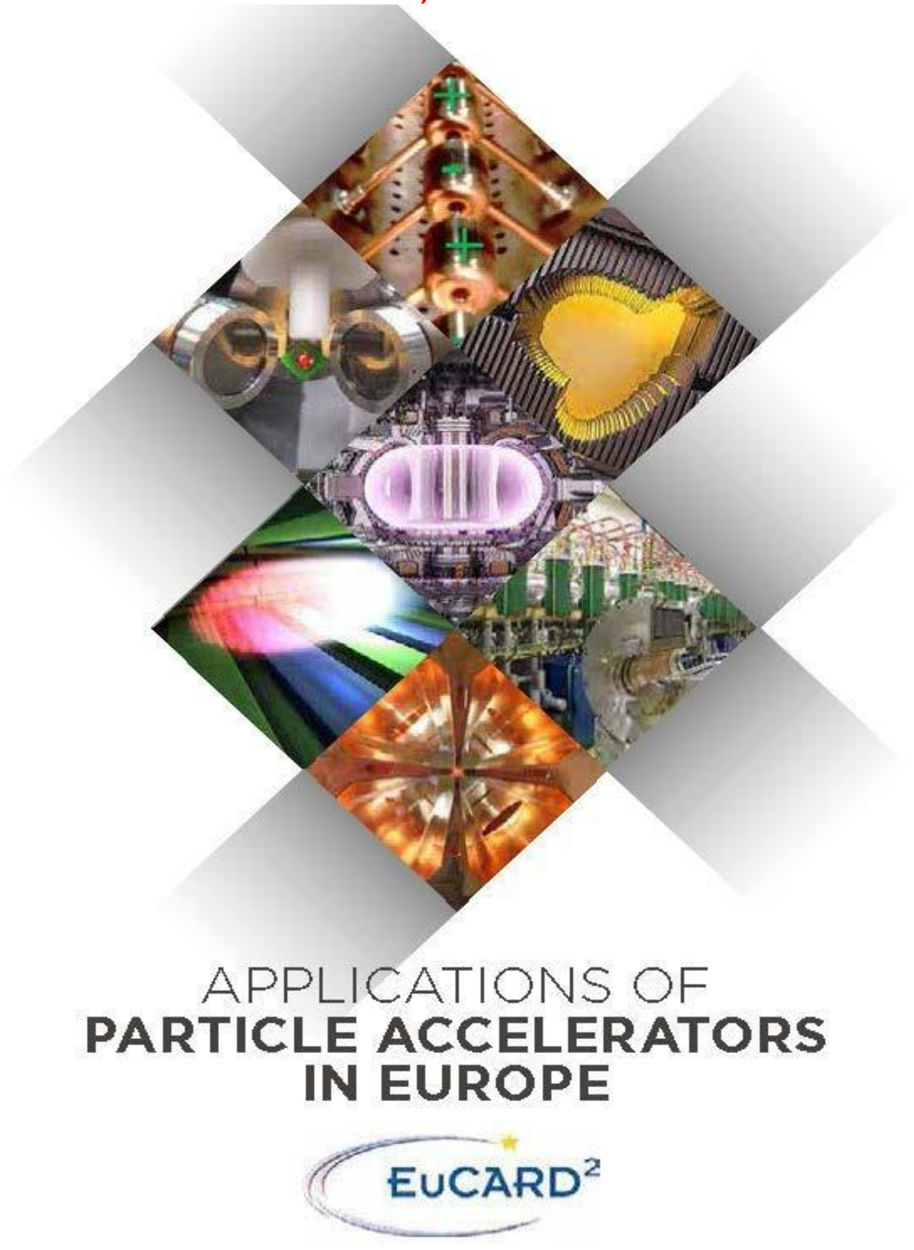
Cutting-edge industrial equipment: analysis and modification of surfaces across many fields (ion implantation, polymer treatment, sterilization, environment, etc.).

M. Vretenar

Applications of Particle Accelerators

Source: R. Edgecock, A. Faus Golfe, EuCARD-2, 2017

Area	Application	Beam	Accelerator	Beam energy/MeV	Beam current/ mA	Number
Medical	Cancer therapy	e	linac	4-20	10^{-2}	>14000
		p	cyclotron, synchrotron	250	10^{-6}	60
		C	synchrotron	4800	10^{-7}	10
	Radioisotope production	p	cyclotron	8-100	1	1600
Industrial	Ion implantation	B, As, P	electrostatic	< 1	2	>11000
	Ion beam analysis	p, He	electrostatic	<5	10^{-4}	300
	Material processing	e	electrostatic, linac, Rhodatron	≤10	150	7500
	Sterilisation	e	electrostatic, linac, Rhodatron	≤10	10	3000
Security	X-ray screening of cargo	e	linac	4-10	?	100?
	Hydrodynamic testing	e	linear induction	10-20	1000	5
Synchrotron light sources	Biology, medicine, materials science	e	synchrotron, linac	500-10000		70
Neutron scattering	Materials science	p	cyclotron, synchrotron, linac	600-1000	2	4
Energy – fusion	Neutral ion beam heating	d	electrostatic	1	50	10
	Heavy ion inertial fusion	Pb, Cs	Induction linac	8	1000	Under development
	Materials studies	d	linac	40	125	Under development
Energy – fission	Waste burner	p	linac	600-1000	10	Under development
	Thorium fuel amplifier	p	linac	600-1000	10	Under development
Energy – bio-fuel	Bio-fuel production	e	electrostatic	5	10	Under development
Environmental	Water treatment	e	electrostatic	5	10	5
	Flue gas treatment	e	electrostatic	0.7	50	Under development



high energy particle accelerators

G. Hoffstaetter

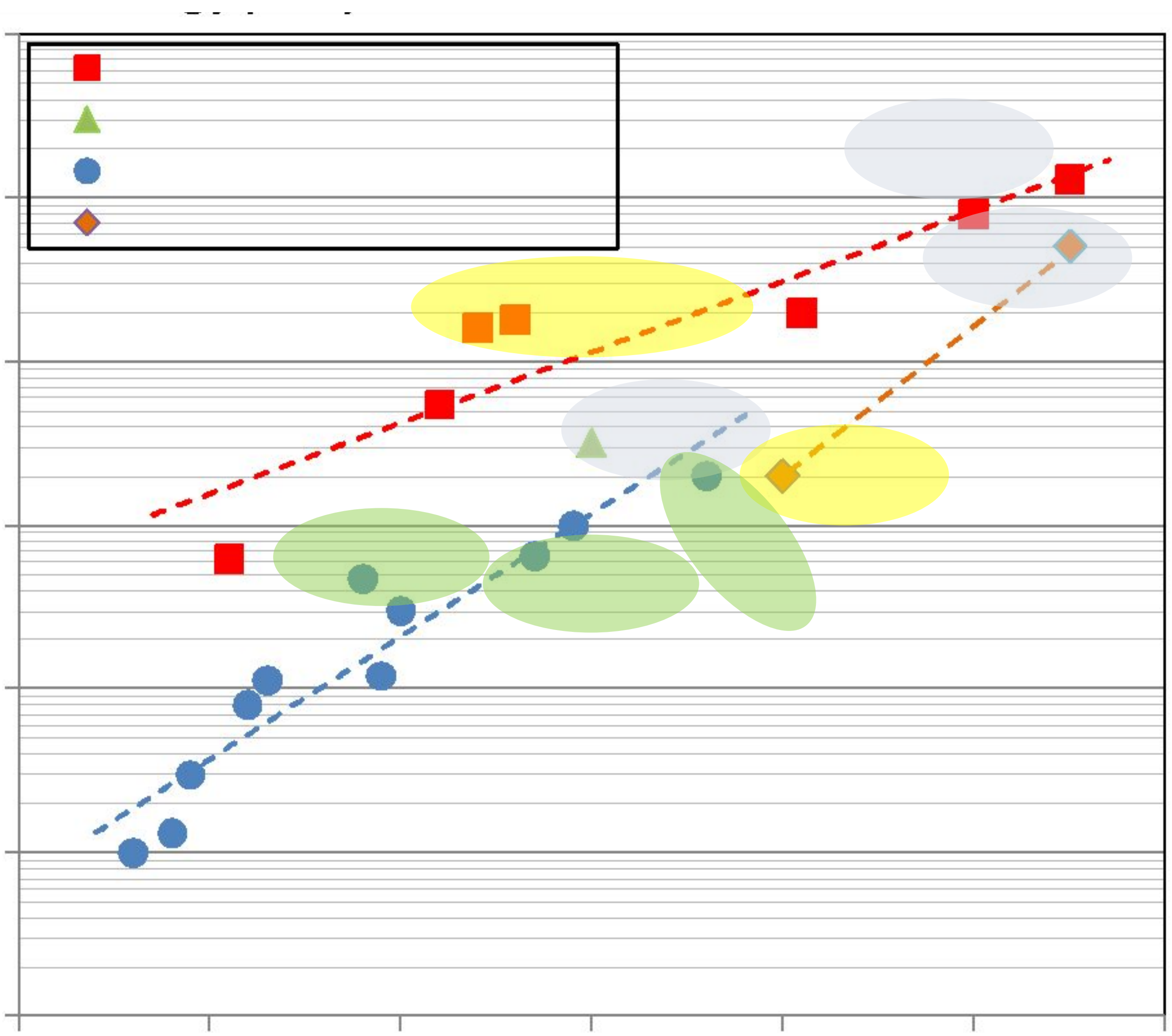
then ~1930

first cyclotron
E.O. Lawrence
11 cm diameter
1.1 MeV protons

now

Large Hadron Collider
9 km diameter, 7 TeV protons

particle colliders constructed and operated



A. Ballarino

Colliders with superconducting RF system

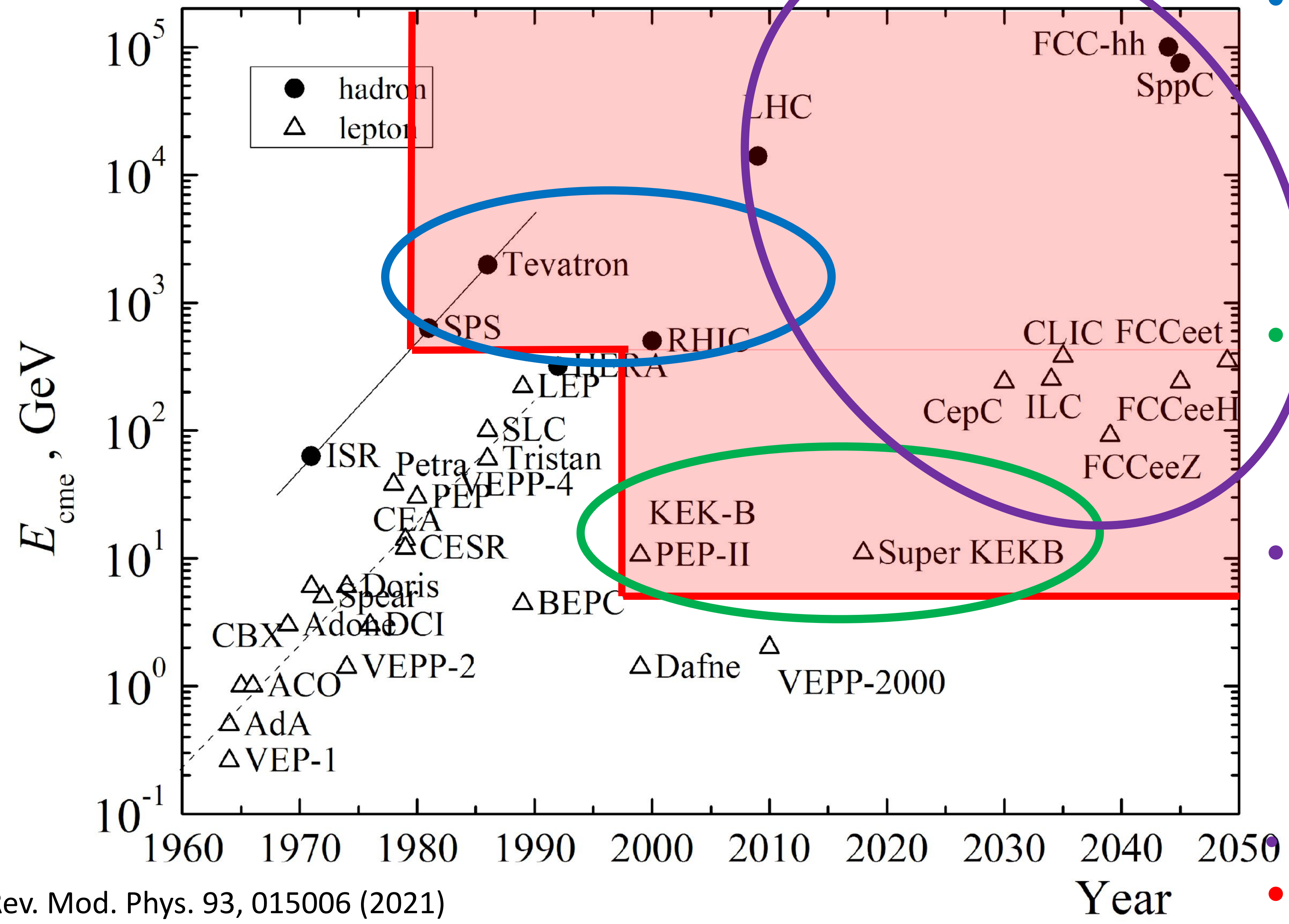
Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF

advances by new technologies and new materials

(important example SC)

more key collider technologies & concepts -
Swapan Chattopadhyay's contributions to colliders: past, present & future

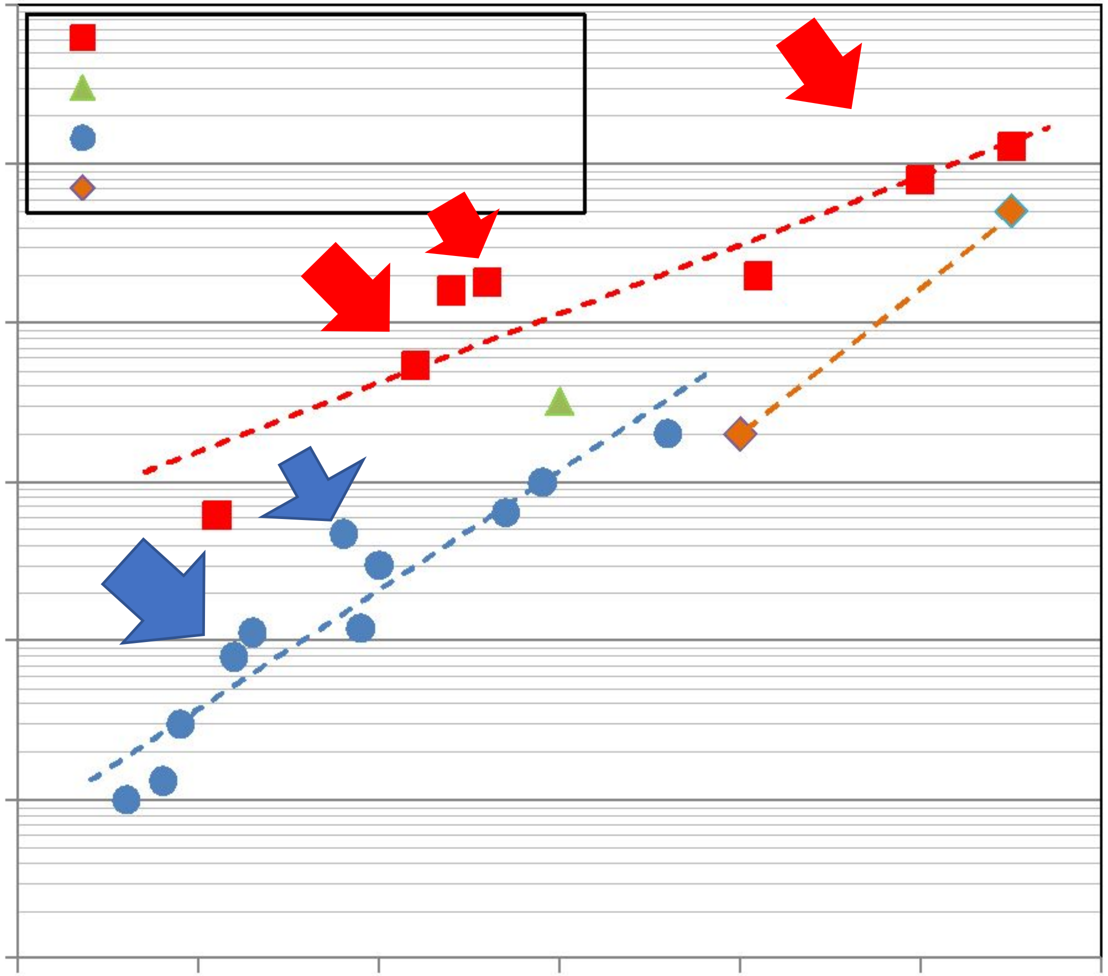


Rev. Mod. Phys. 93, 015006 (2021)

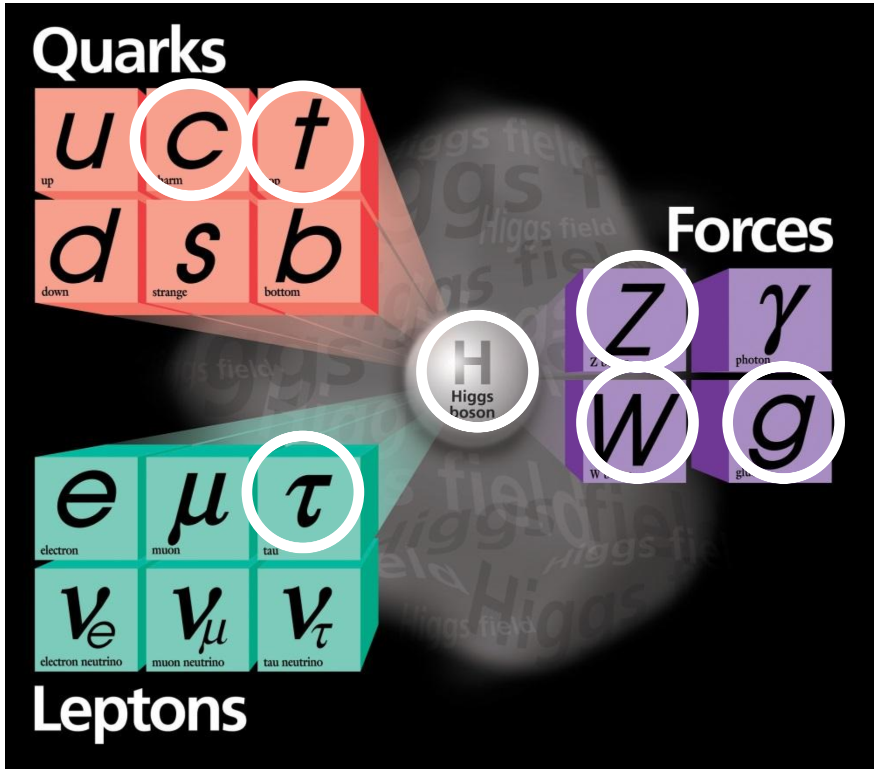
- **stochastic cooling and <u>bunched beam stochastic cooling</u> of antiprotons and heavy ions:**
  SPS, Tevatron, RHIC + … ?
- **development of <u>asymmetric B factories</u>:** PEP-II, KEKB, SuperKEKB
- **<u>highest energy hadron and lepton colliders</u>:** LHC, HL-LHC, FCC, CLIC, ILC, μ colliders, γγ colliders, plasma-based colliders
- **+ <u>energy recovery</u> for colliders**

colliders and discoveries

A. Ballarino



Standard Model
Particles and forces

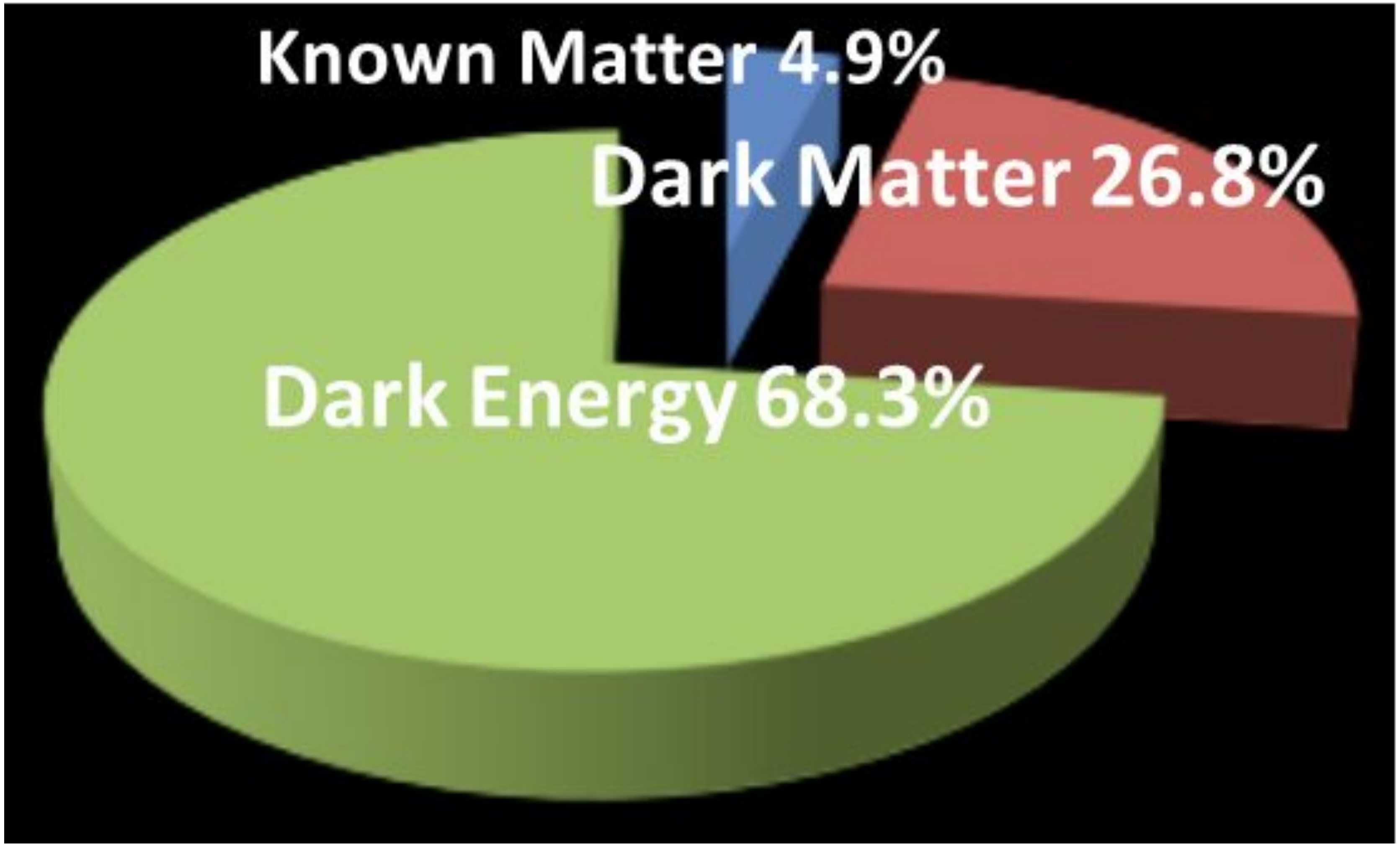


powerful instruments for discovery and precision measurement

still many open questions

Known matter is only 5% of universe!

F. Gianotti



- what is dark matter?
- what is dark energy?
- why more matter than antimatter?
- what about gravity?

also QCD,
quark-gluon plasma,
proton spin, etc.

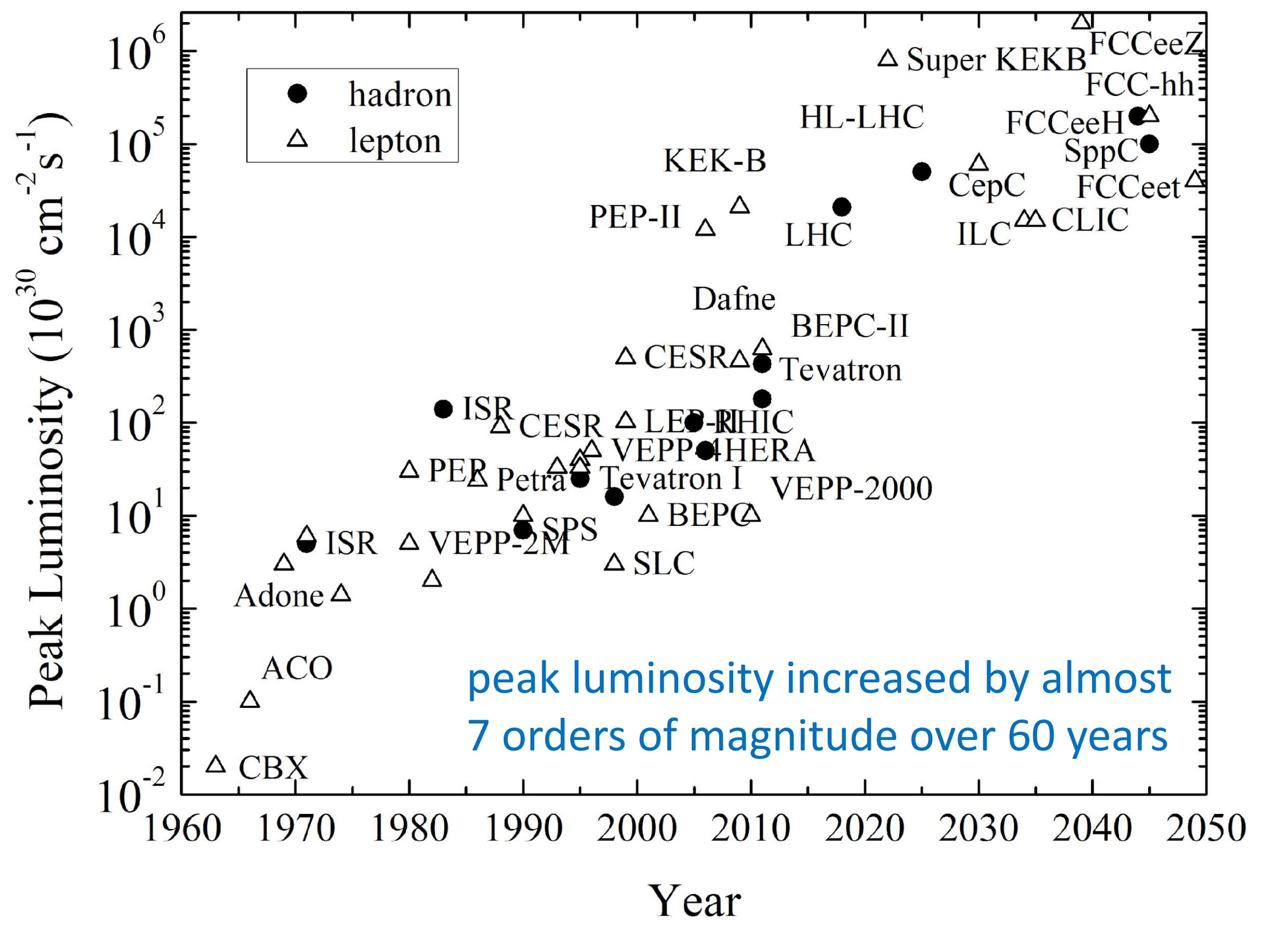
collider figure of merit: luminosity

$$R = \sigma L$$

reaction rate **cross section** **luminosity**

σ tends to decrease as energy^{-2}

V. Shiltsev & F.Z., arXiv:2003.09084, submitted to RMP



geometric factor (crossing angle, hour glass, pinch, ...)

bunch population

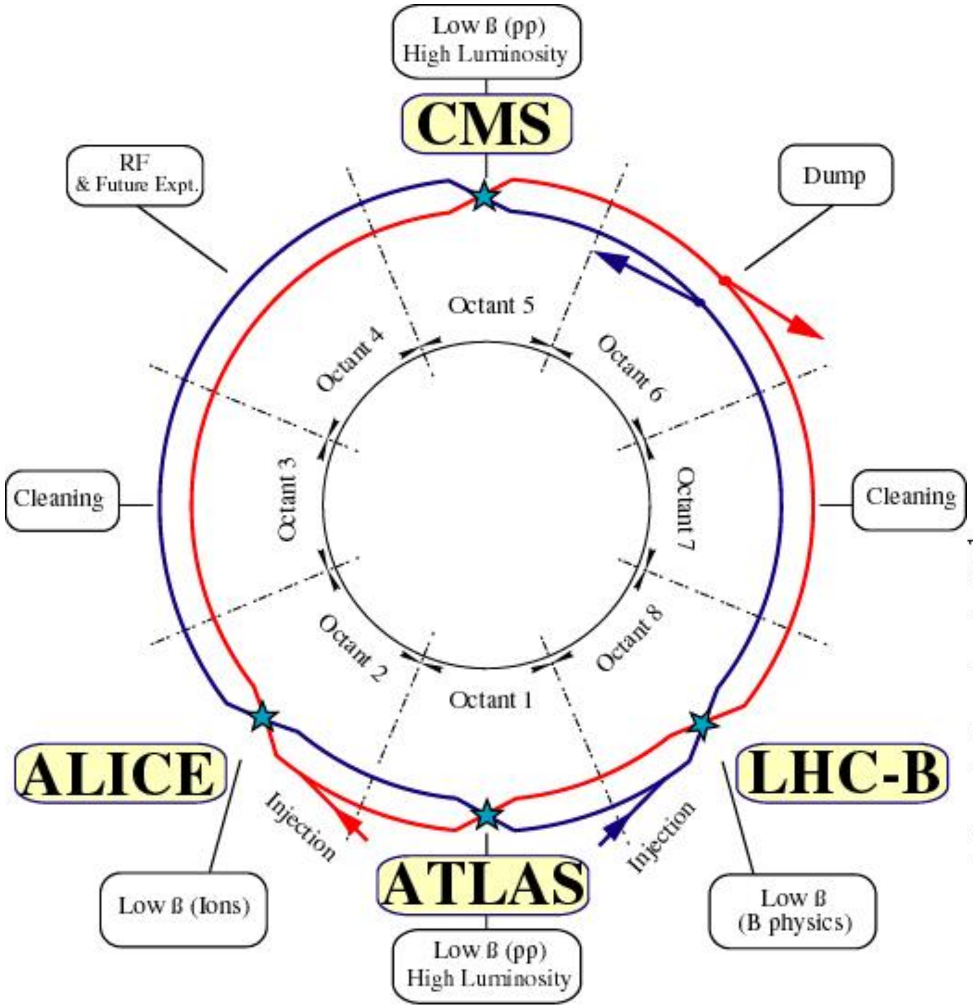
$$L = f_{\text{coll}} \frac{N_b^2}{4\pi\sigma_x^*\sigma_y^*} F$$

bunch collision rate

horizontal & vertical rms beam size at collision point

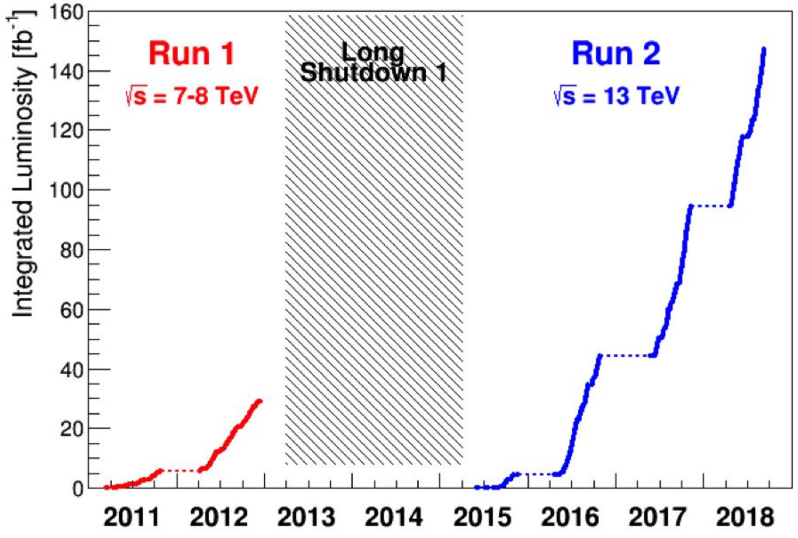
Large Hadron Collider (LHC)

circumference 27 km

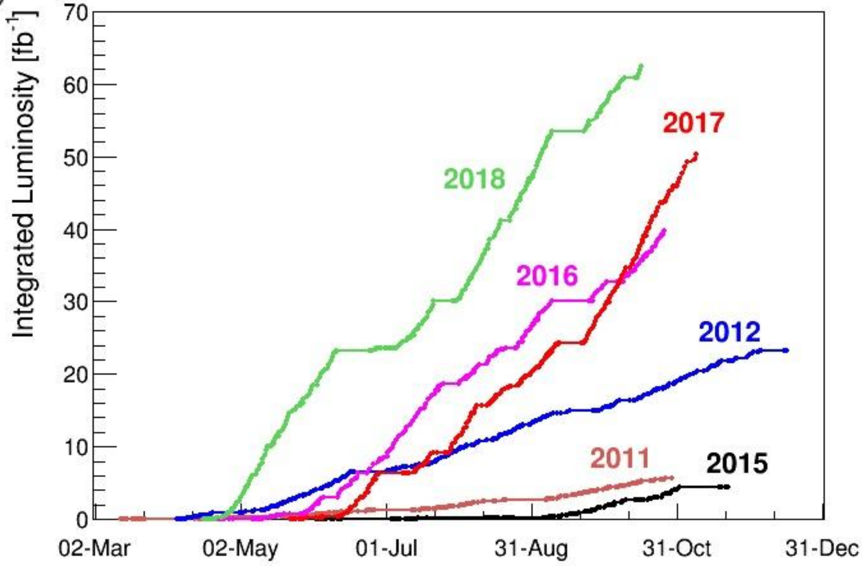


world's highest energy p-p collider at CERN/Geneva

running
extremely well



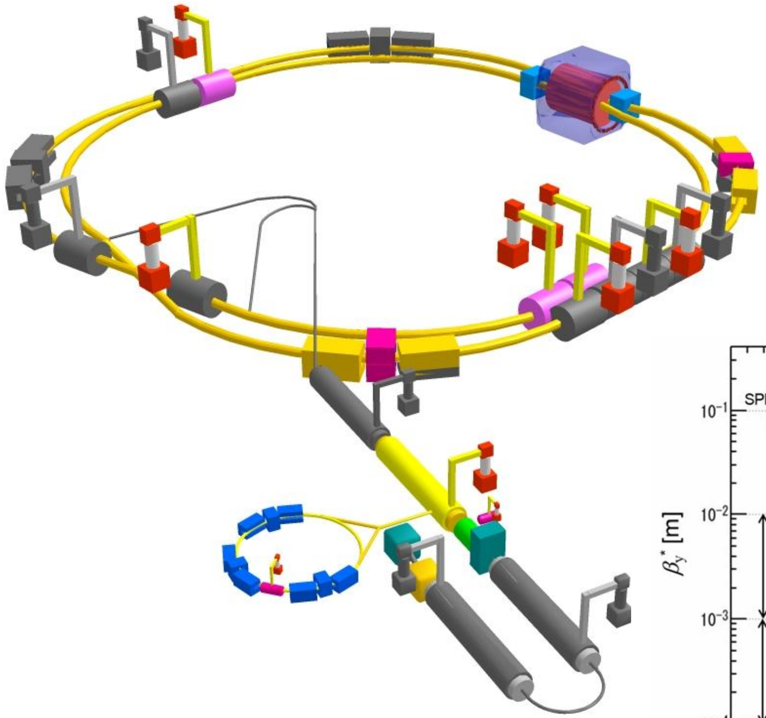
total integrated luminosity so far ~200 fb^{-1} over ~10 years



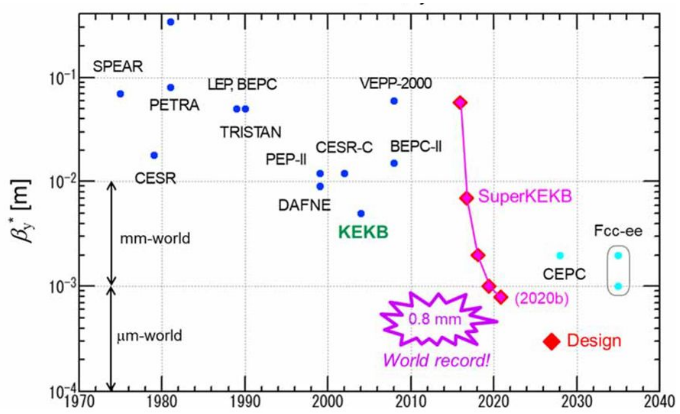
peak luminosities up to **~2.2x10^{34} cm^{-2}s^{-1}**, levelled to 1.5x10^{34} cm^{-2}s^{-1}

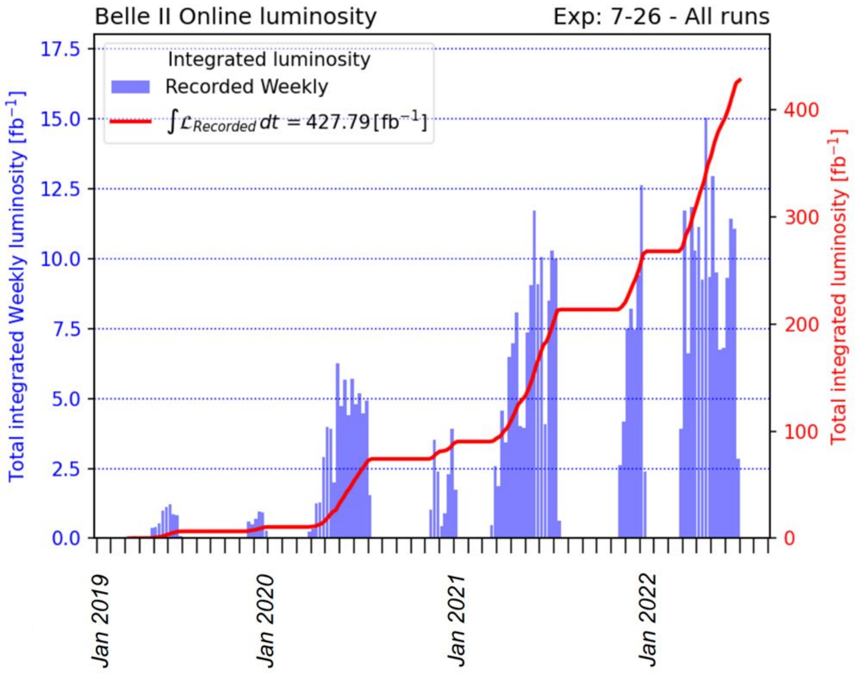
SuperKEKB

circumference 3 km

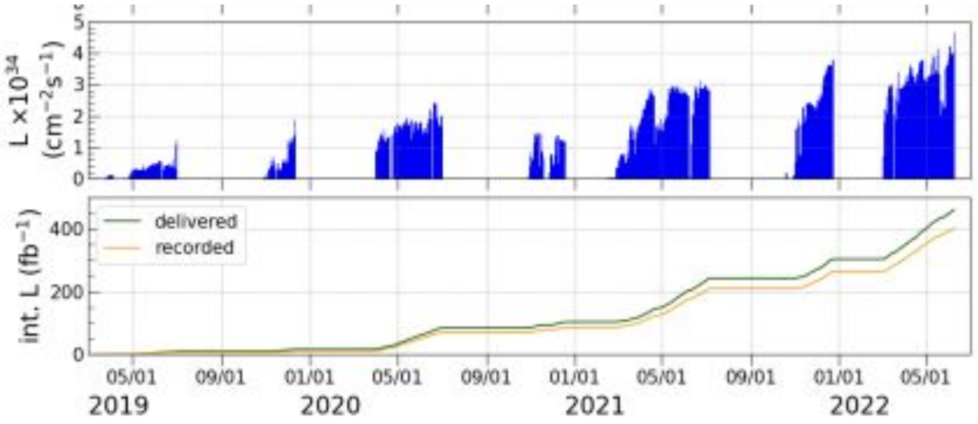


world's highest luminosity & lowest β^* e^+e^- collider at





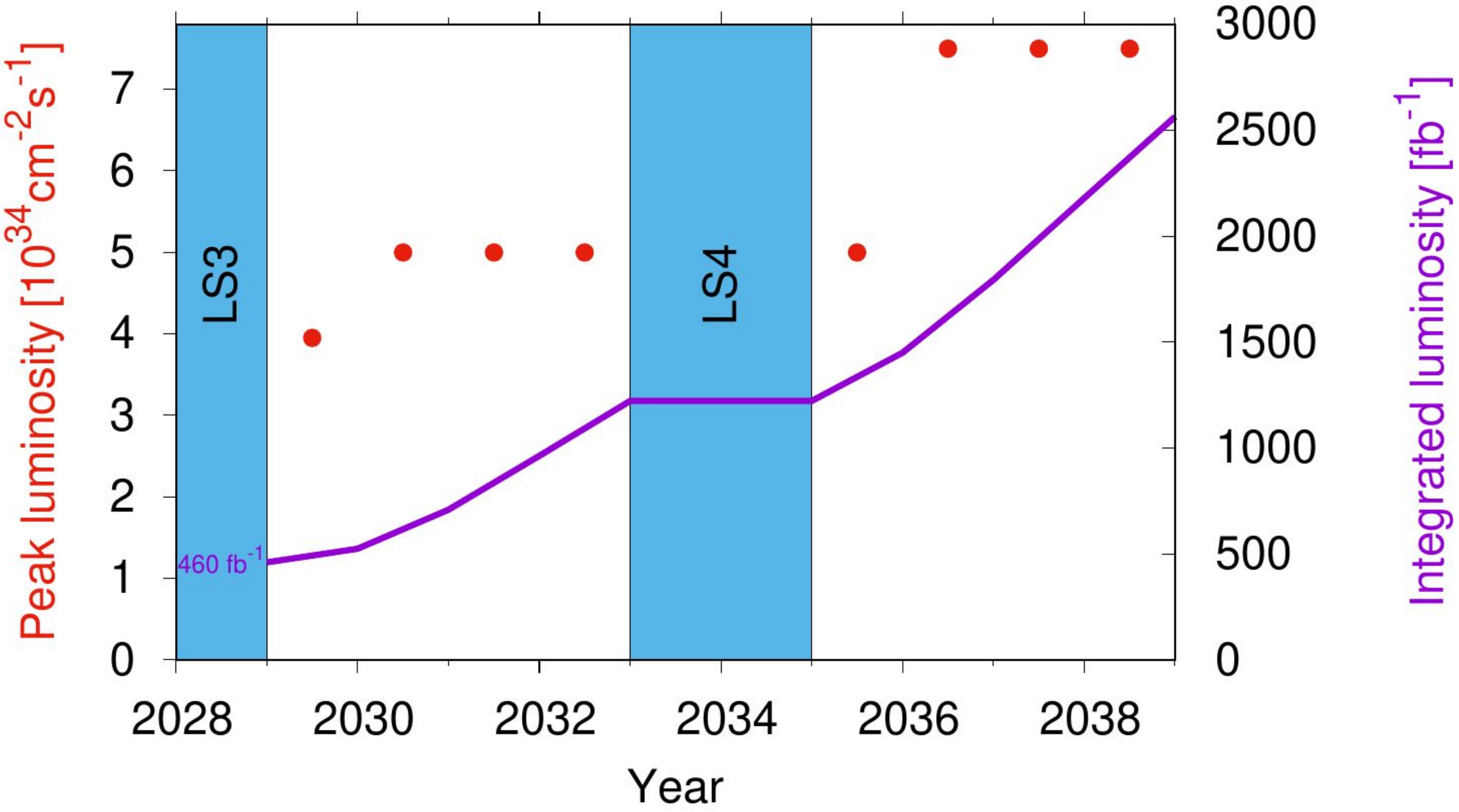
total integrated luminosity so far ~430 fb^{-1} over ~3 years



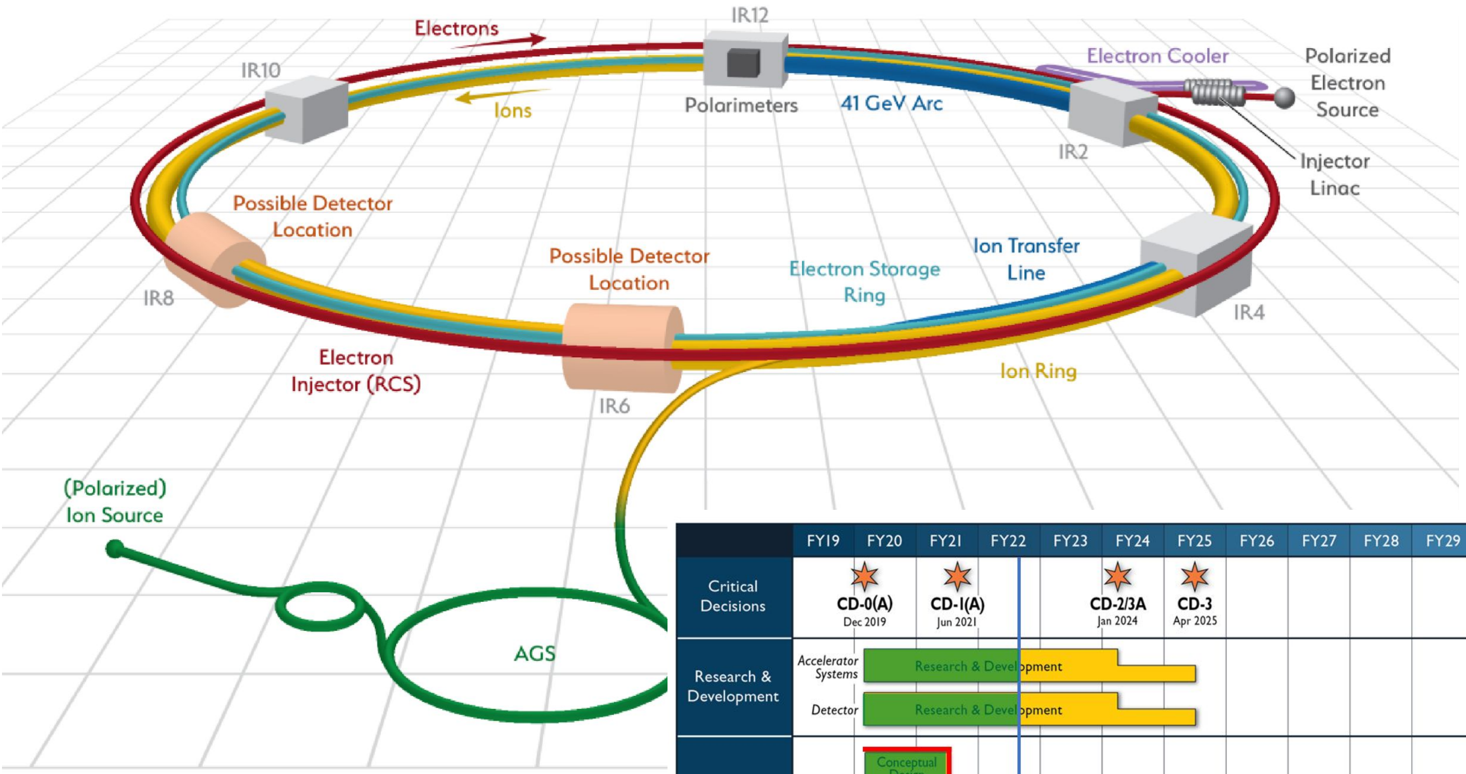
world record luminosity of 4.71x10^{34} cm^{-2}s^{-1},
β_y^* = 1.0 mm routinely, also β_y^* = 0.8 mm shown
– with "virtual" crab-waist collision scheme originally developed for FCC-ee (K. Oide)

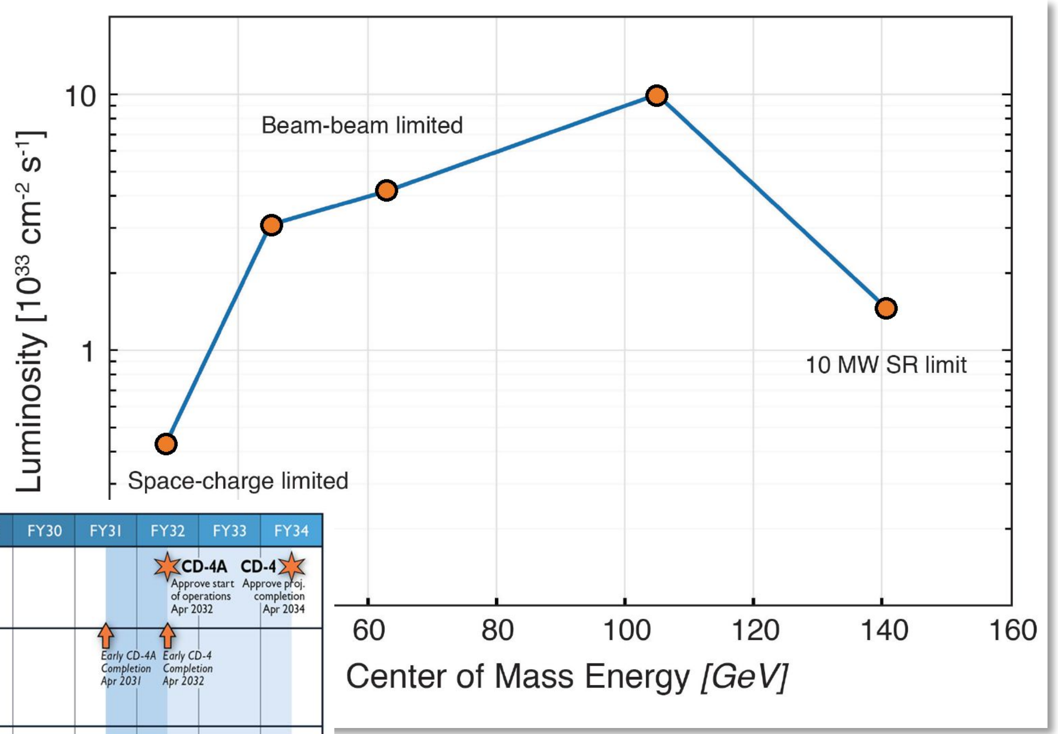
near-future collider 1: High-Luminosity LHC

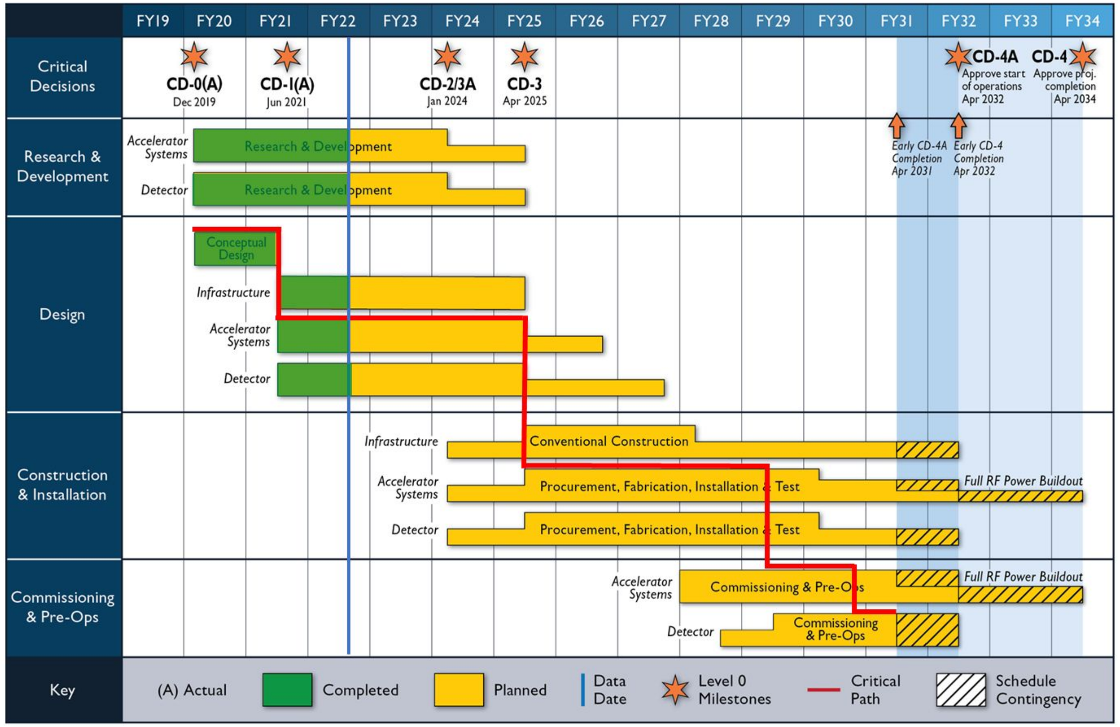
High-Luminosity LHC at CERN: $E_{p\text{-}p,cm}$=14 TeV, L=5 or $7.5\times10^{34}cm^{-2}s^{-1}$ levelled
goal: increase LHC integrated luminosity x10 to >3 ab^{-1} around 2040



near-future collider 2: Electron-Ion Collider

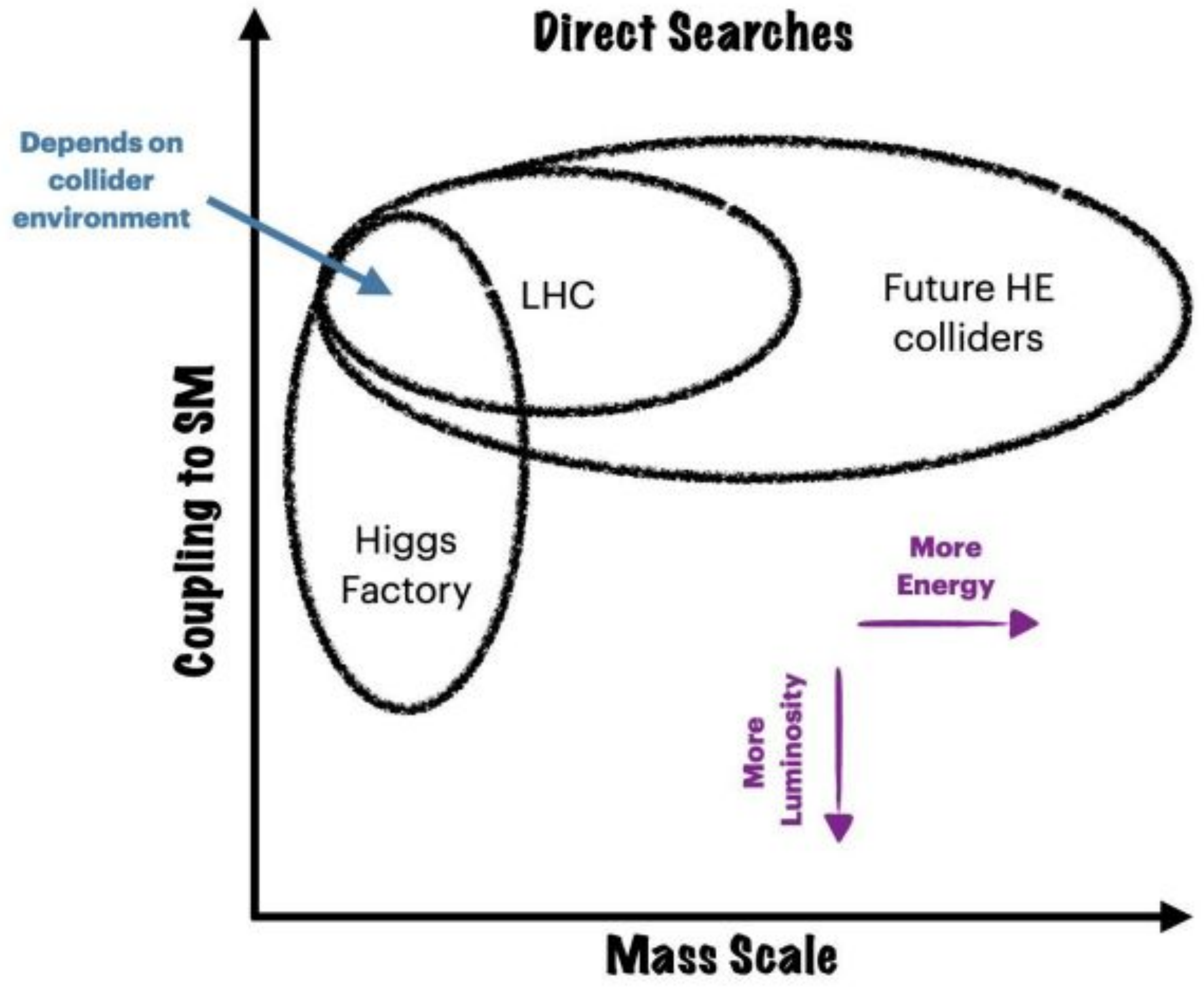






3.83 km double ring,
polarized beams
full-energy e^- injection,
injection rate 1 Hz

Energy Frontier Machines – Energy & Precision

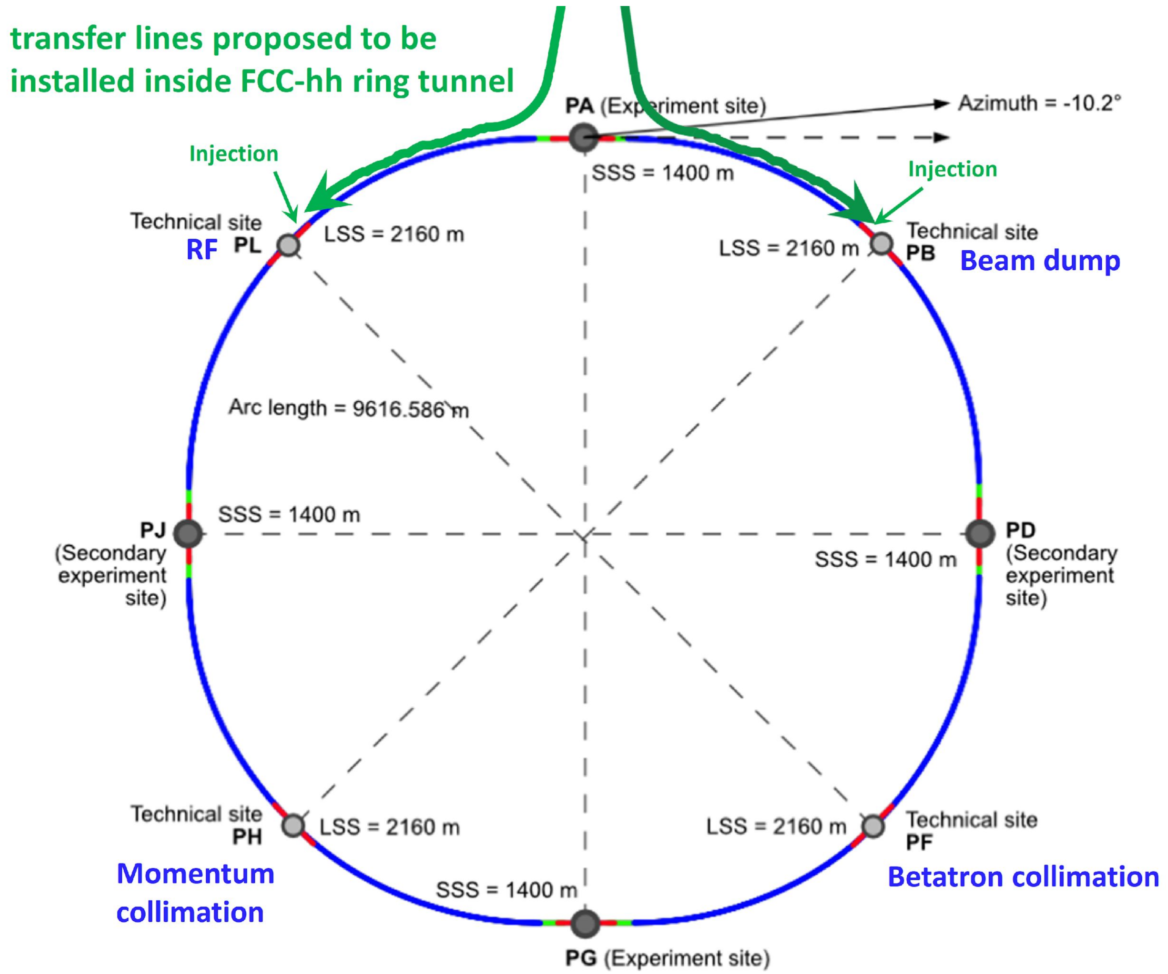


L. Reina, Snowmass'21 (22)

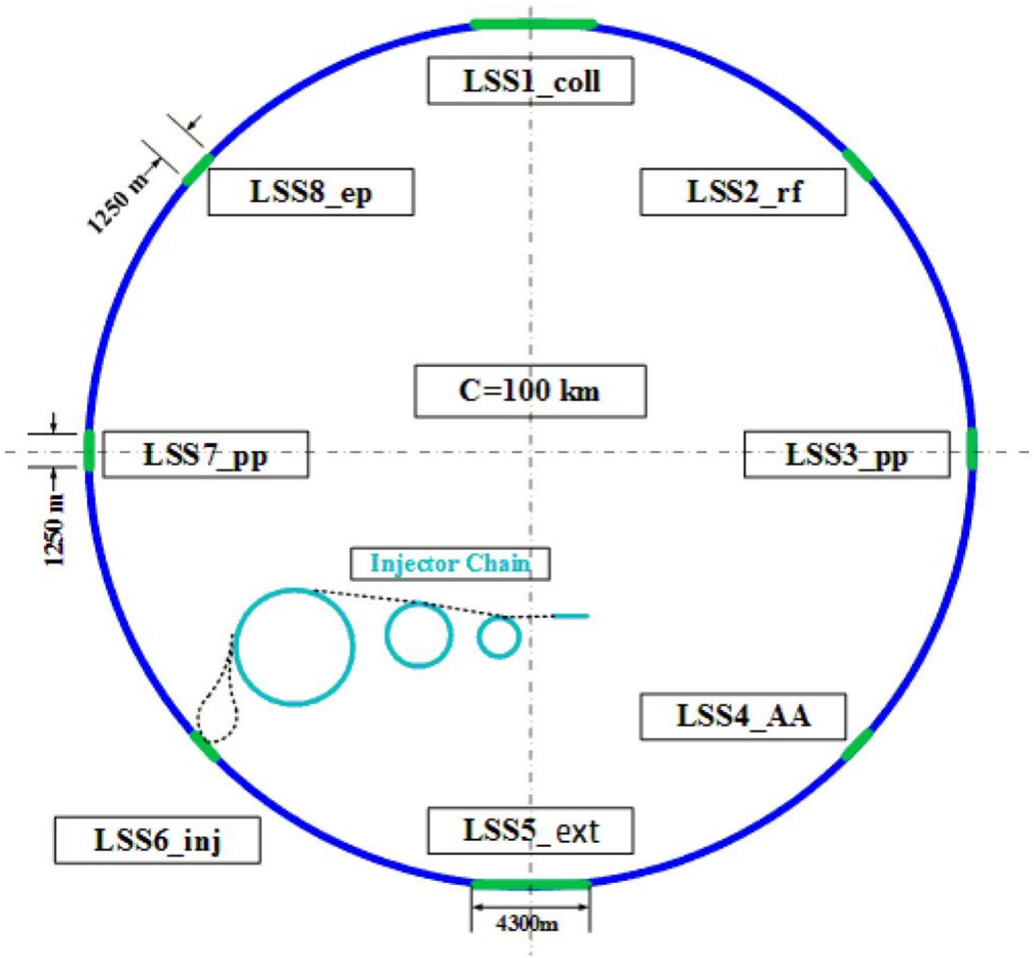
Proposed Higher-Energy Hadron Colliders

Snowmass '21

FCC-hh

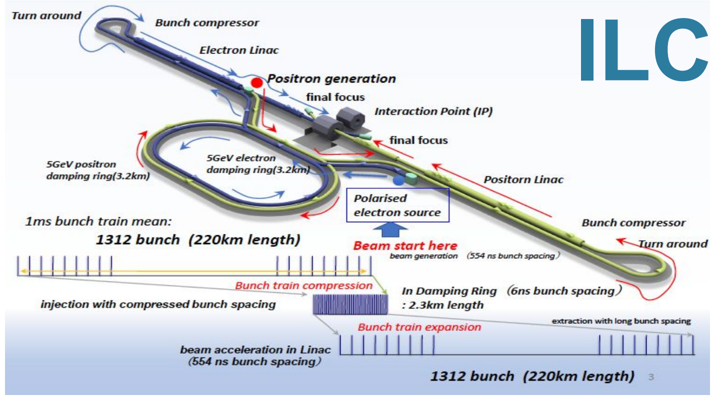


SPPC

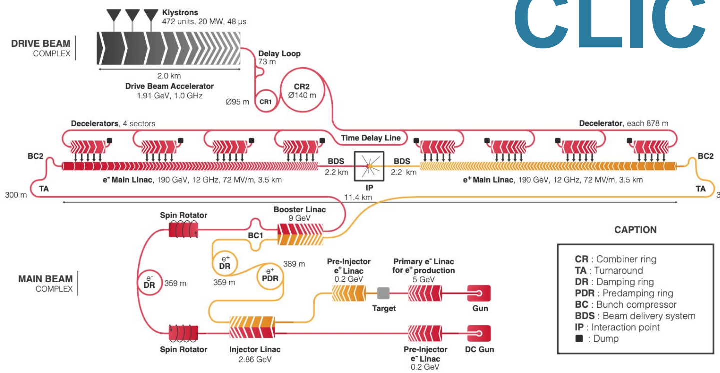


Proposed e⁺e⁻ Higgs & EW Factories

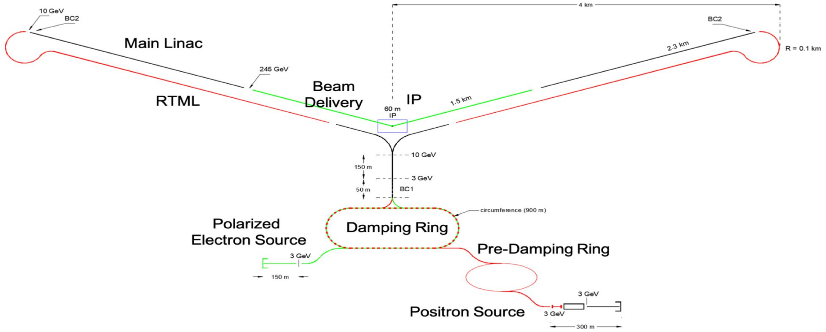
ILC



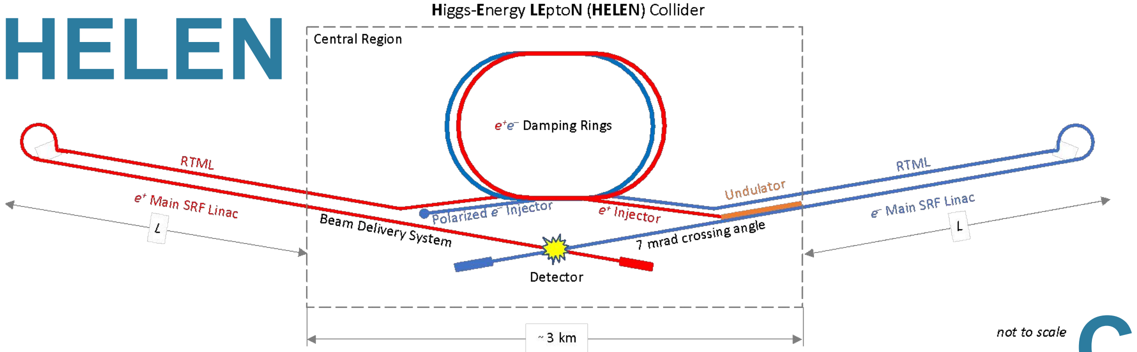
CLIC



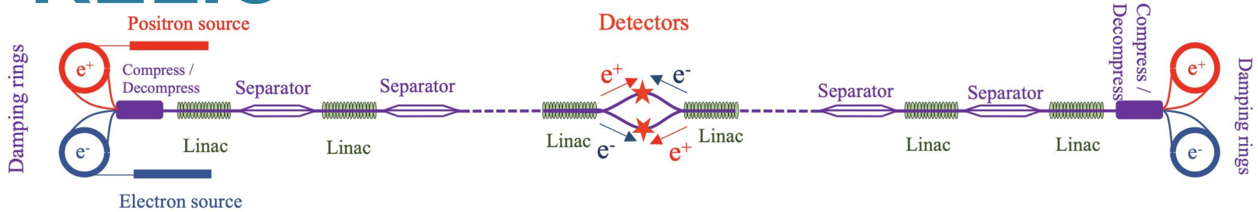
C³



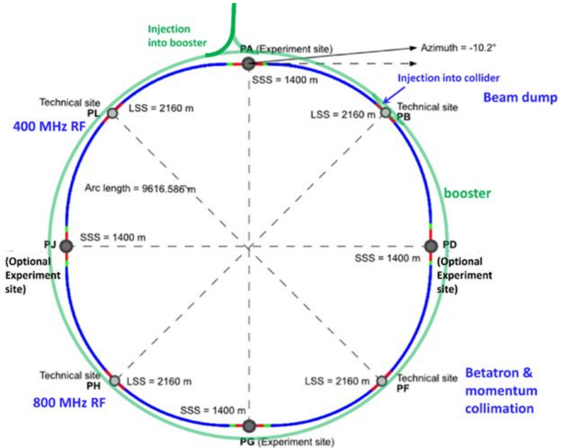
HELEN



RELIC

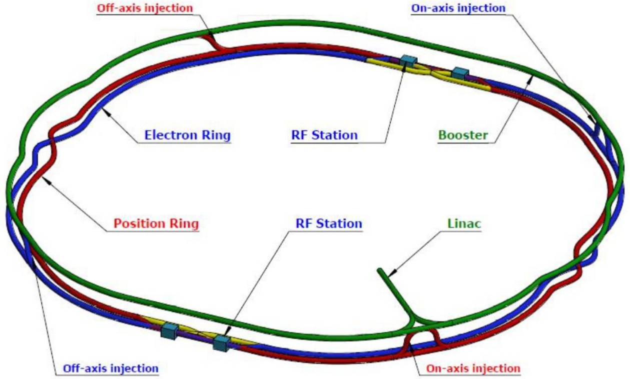


FCC-ee

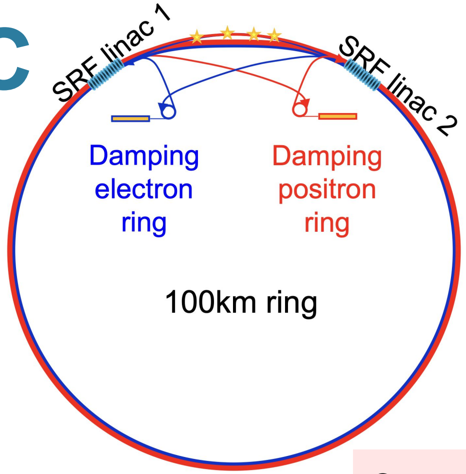


not to scale

CEPC



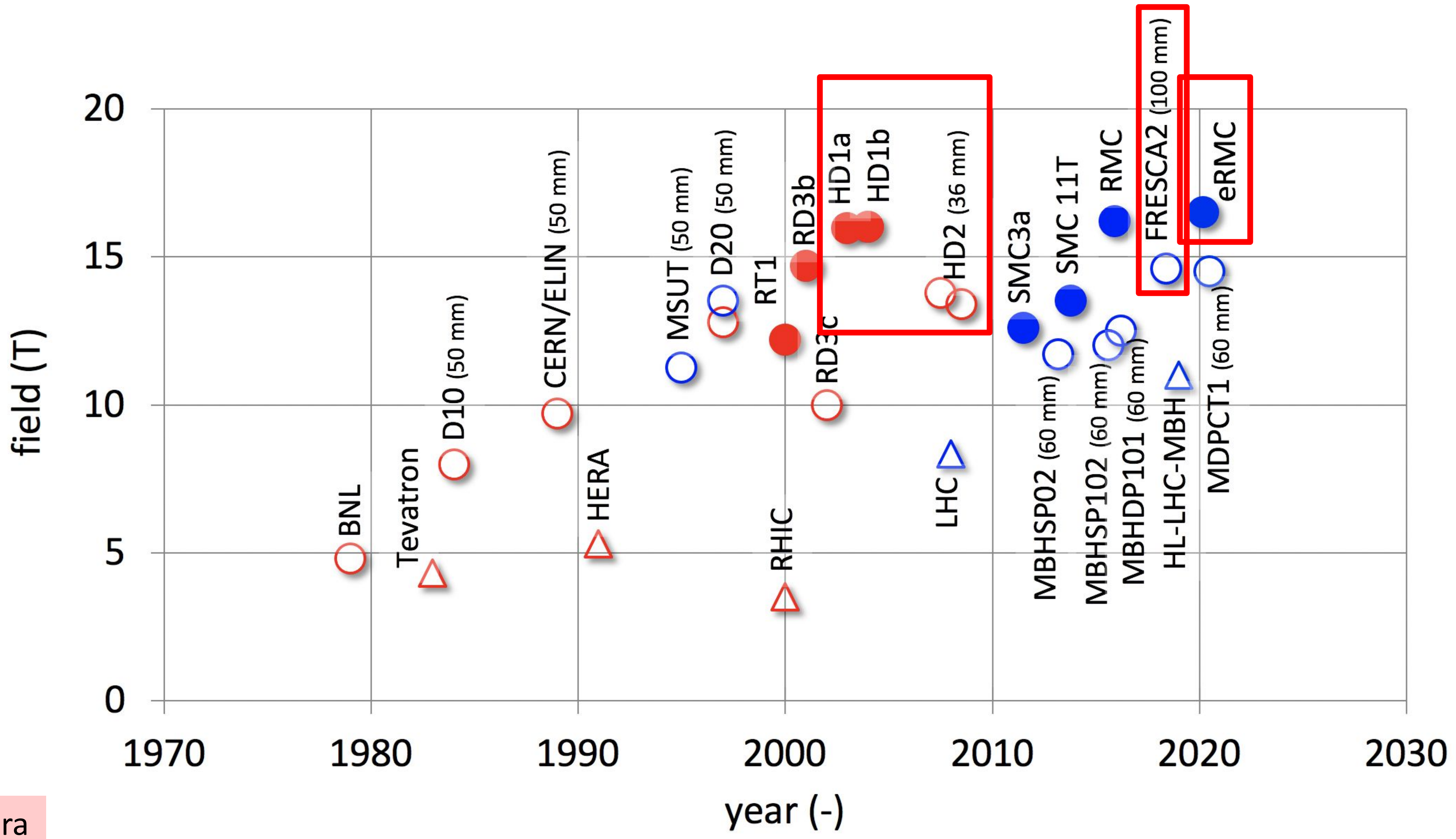
CERC



Towards the next, next-next and next-next-next generation of accelerators – main themes

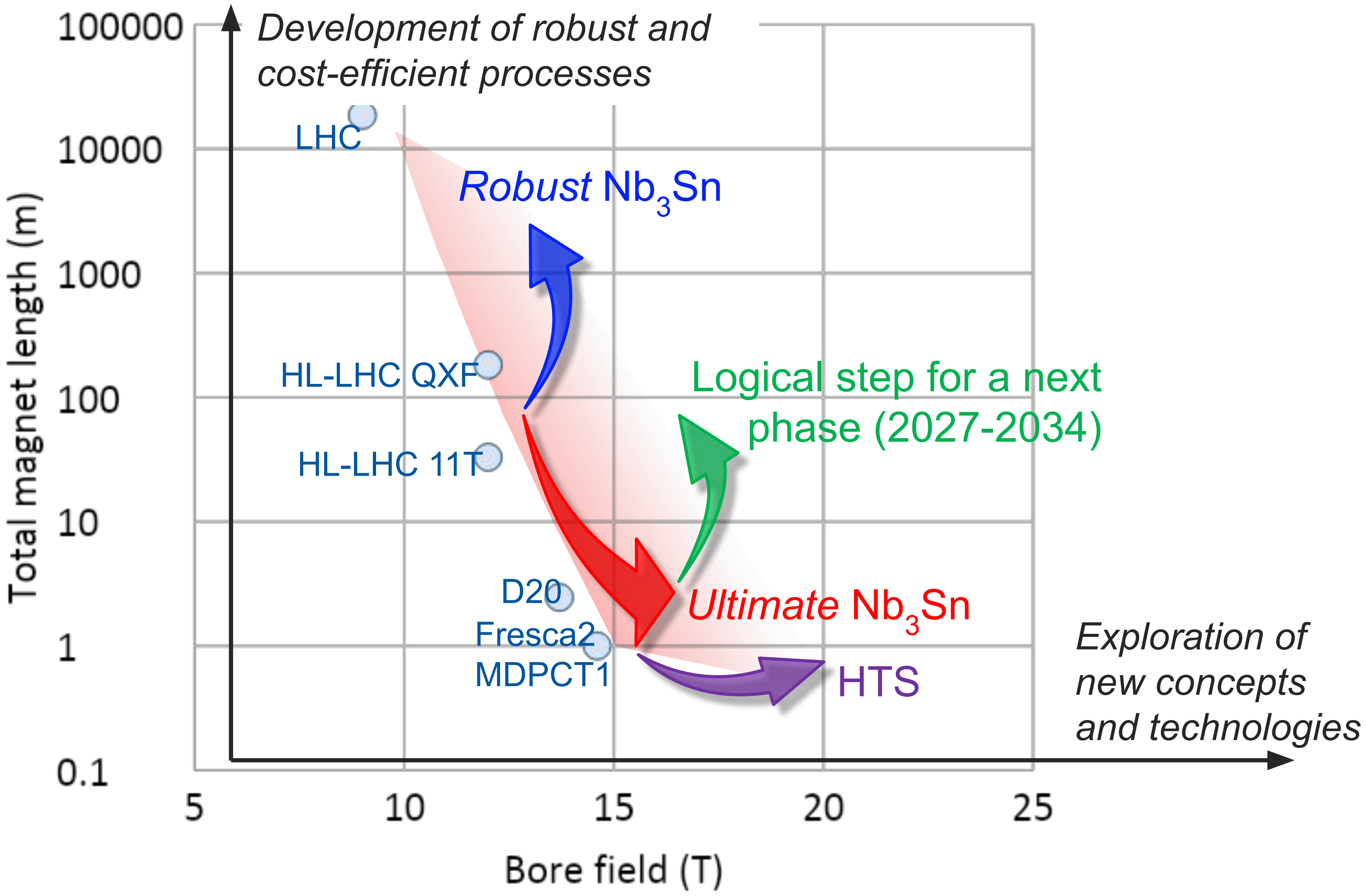
- High-field magnets
- SC Radiofrequency systems
- Efficient RF power sources
- e^+ production
- Gamma Factory
- Monochromatization
- Energy Recovery Linacs
- $\gamma\gamma$ colliders
- Muon Collider(s)
- Advanced Accelerator Concepts
- Sustainability

High-Field Magnet – historical progress



Luca Bottura

CERN High-Field Magnet Program

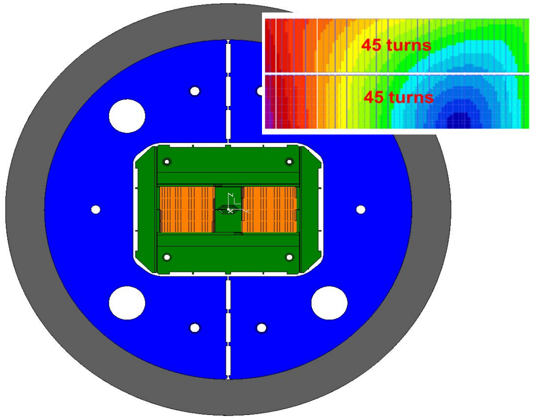


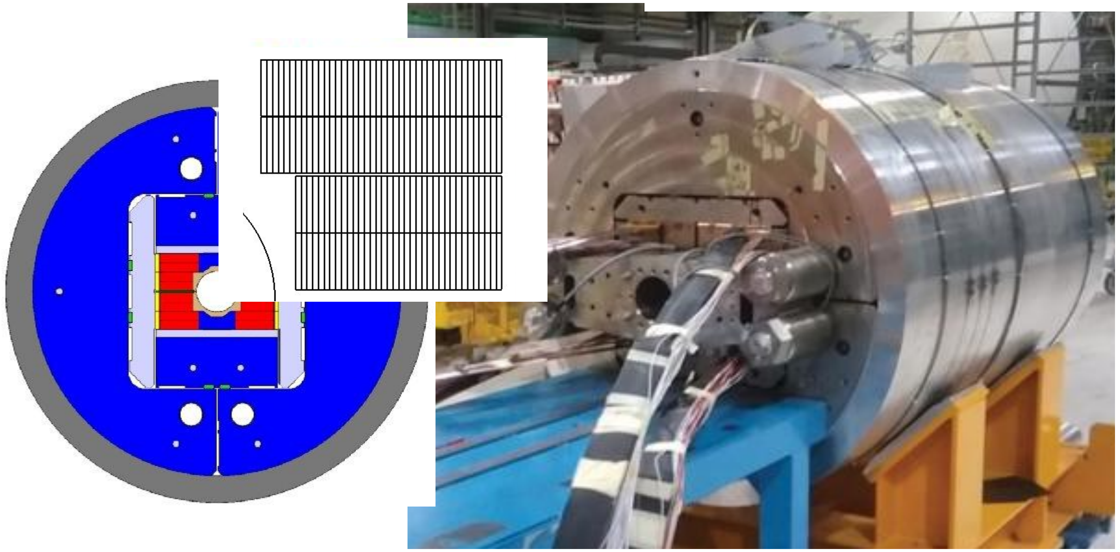
Luca Bottura

High-Field Nb_3Sn Magnets

CERN

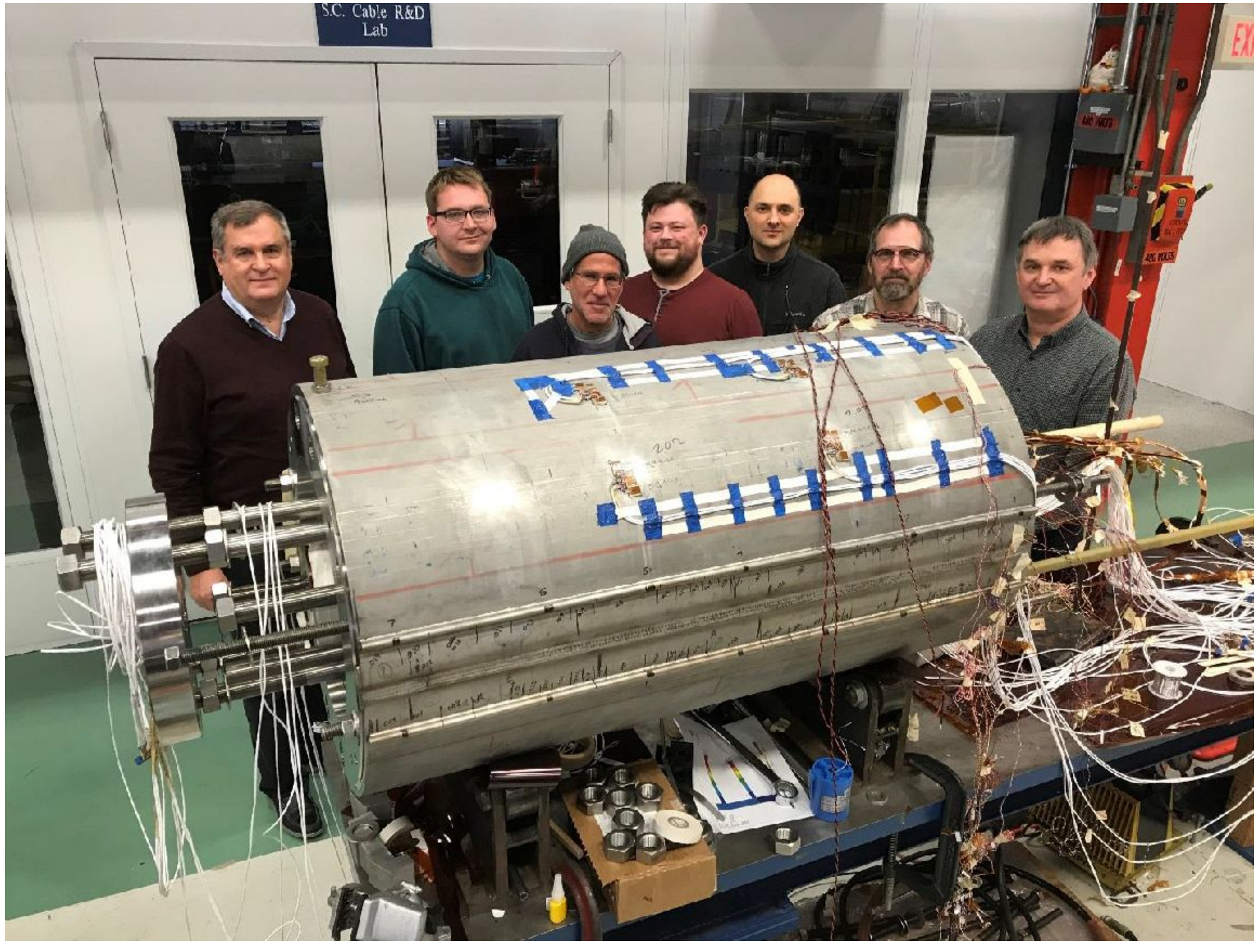
RMC/eRMC (2-decks, no aperture), 16.5 T





FRESCA2 (4-decks, 100 mm), 14.6 T

FNAL



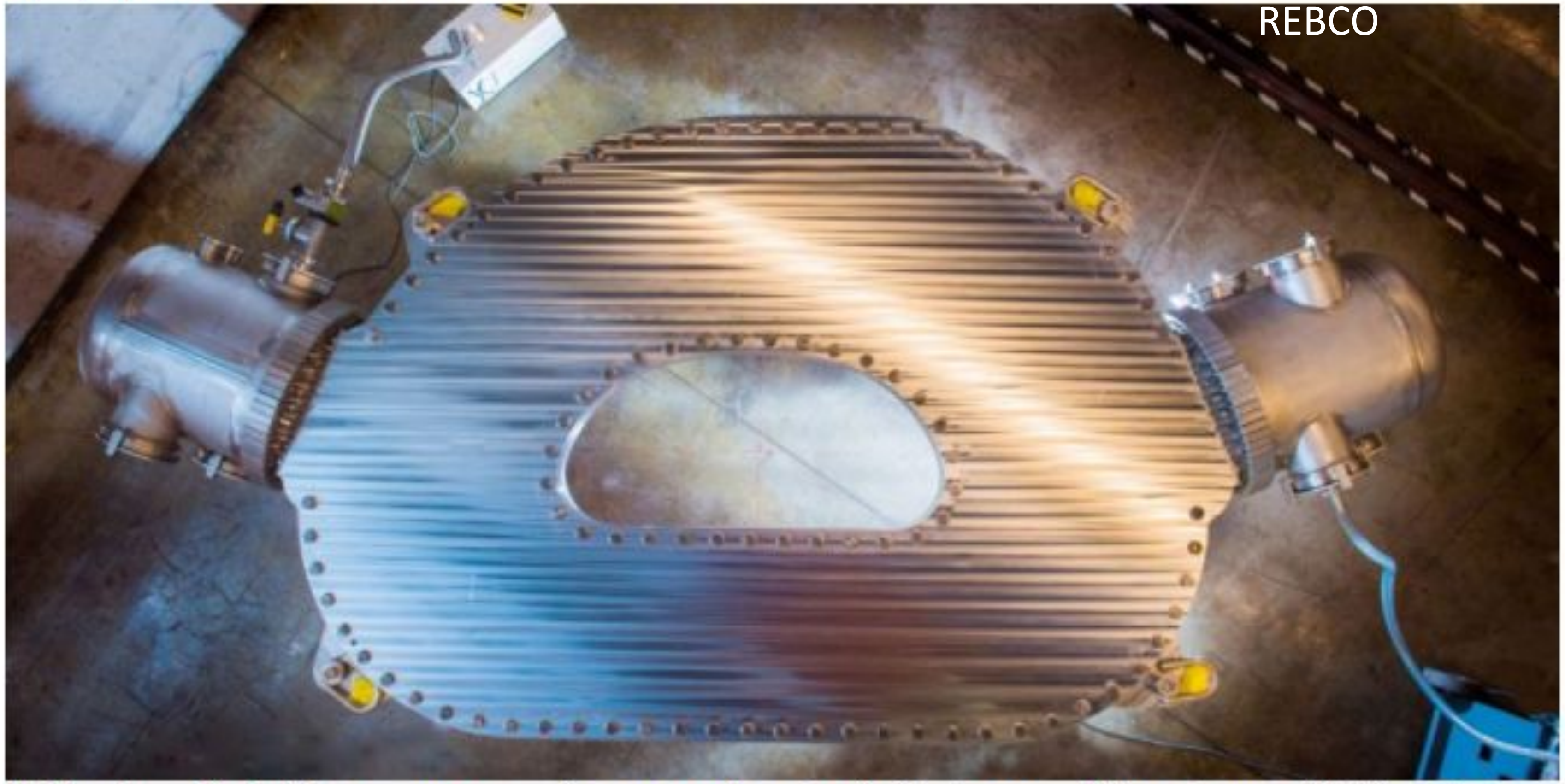
MDPCT1 (4-layer graded coil, 60 mm), 14.5 T

Nuclear Fusion HTS Magnet Progress

RESEARCH & APPLICATIONS

MIT ramps 10-ton magnet up to 20 tesla in proof of concept for commercial fusion

Fri, Sep 10, 2021, 6:59PM | Nuclear News



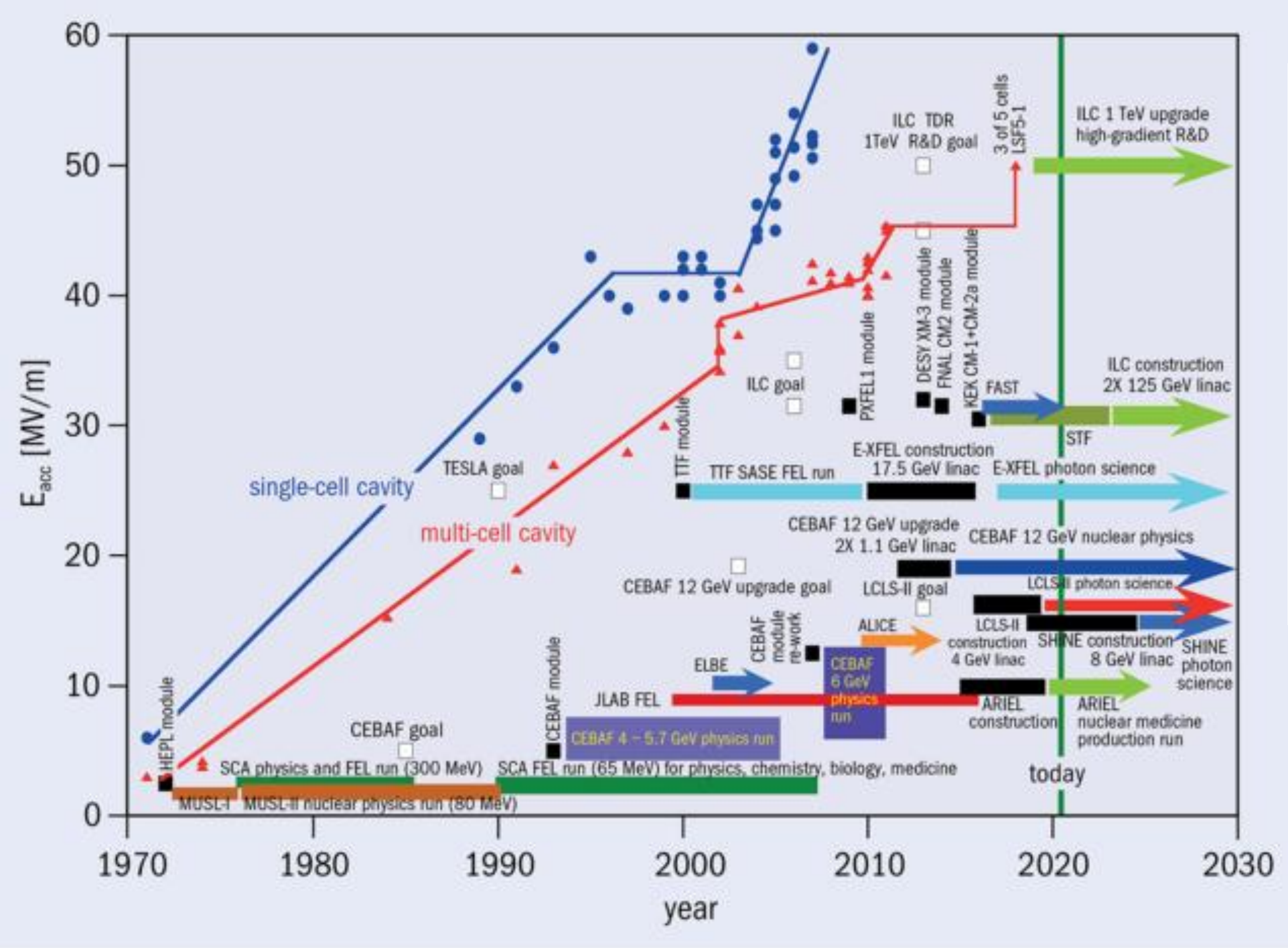
This large-bore, full-scale high-temperature superconducting magnet designed and built by Commonwealth Fusion Systems and MIT's Plasma Science and Fusion Center is the strongest fusion magnet in the world. (Photo: Gretchen Ertl, CFS/MIT-PSFC)

September 2021

toroidal model coil

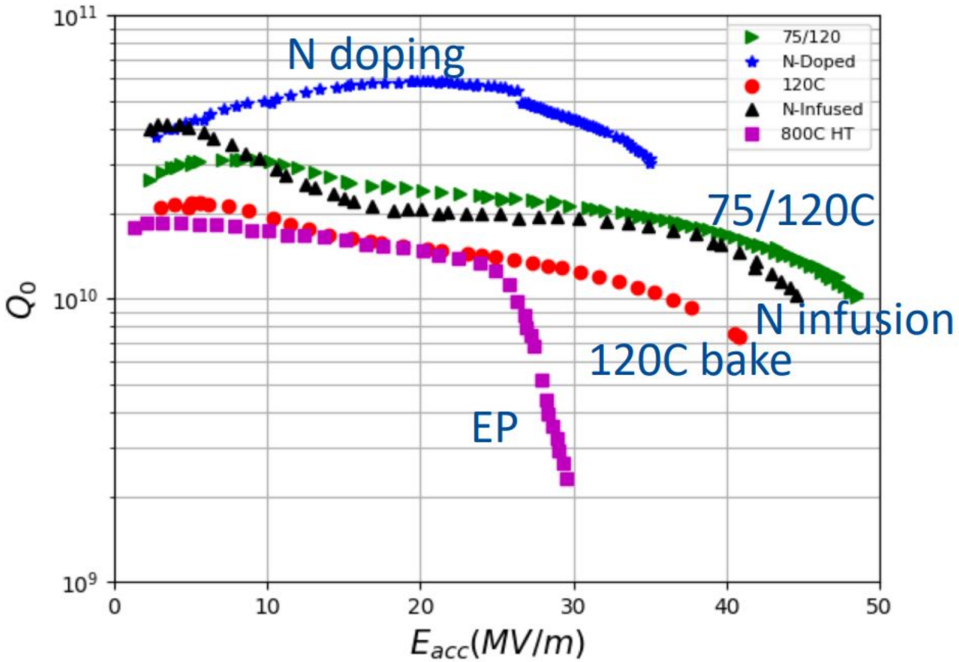
synergies with accelerator magnet developments

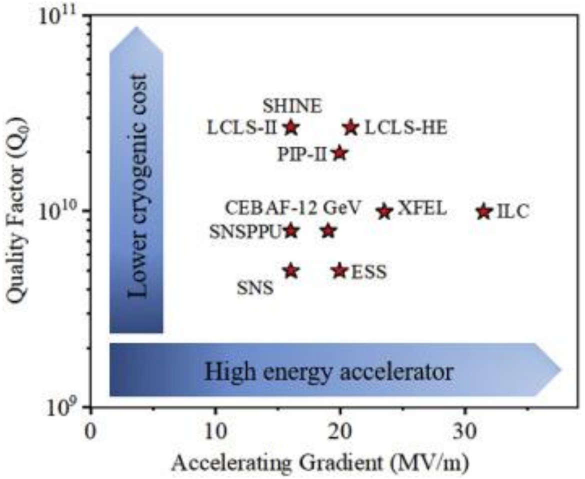
SC Radiofrequency Systems



Gradient growth SRF linac accelerating gradient achievements and application specifications since 1970 (CERN Courier., Nov. 2020)

Anna Grasselino

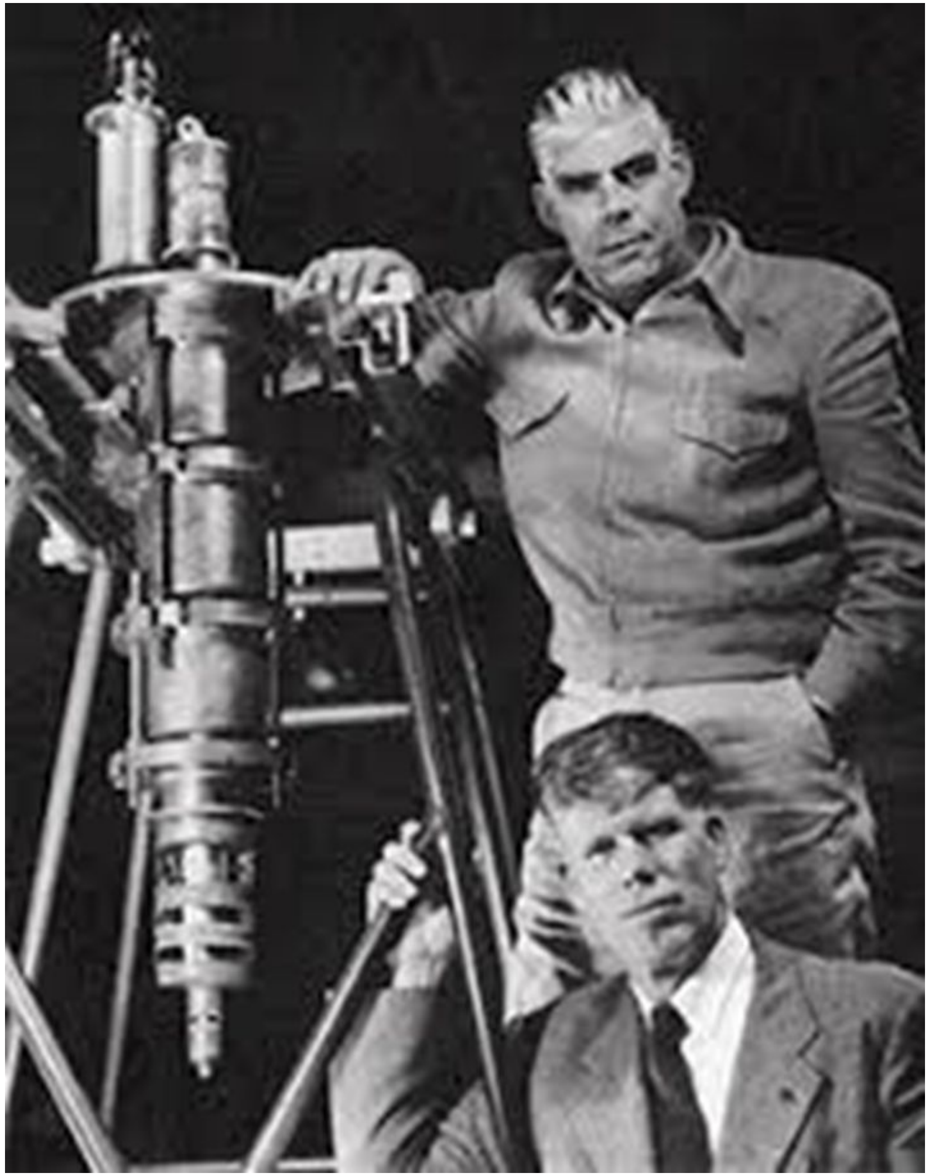




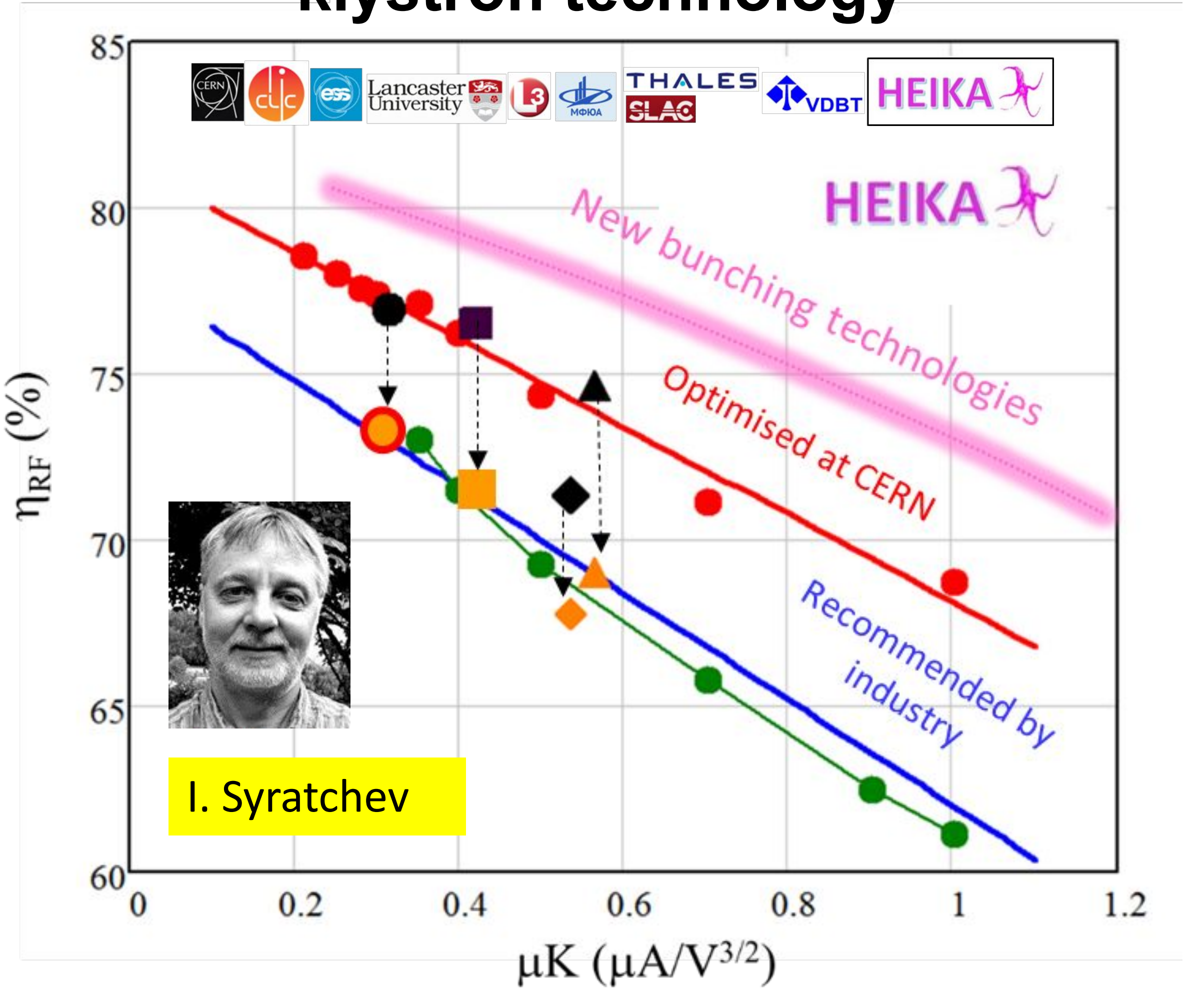
P. Dhakal

More Efficient RF Power Sources

1937: the Varian brothers of Palo Alto invent the klystron

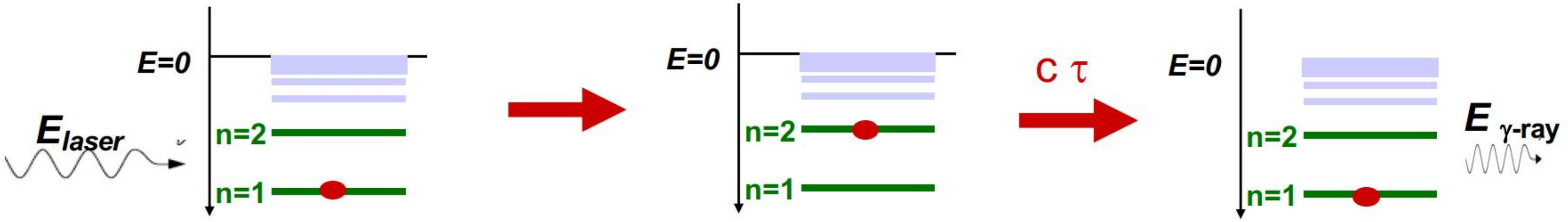


80 years later, another breakthrough in klystron technology



New bunching technologies

Gamma Factory concept



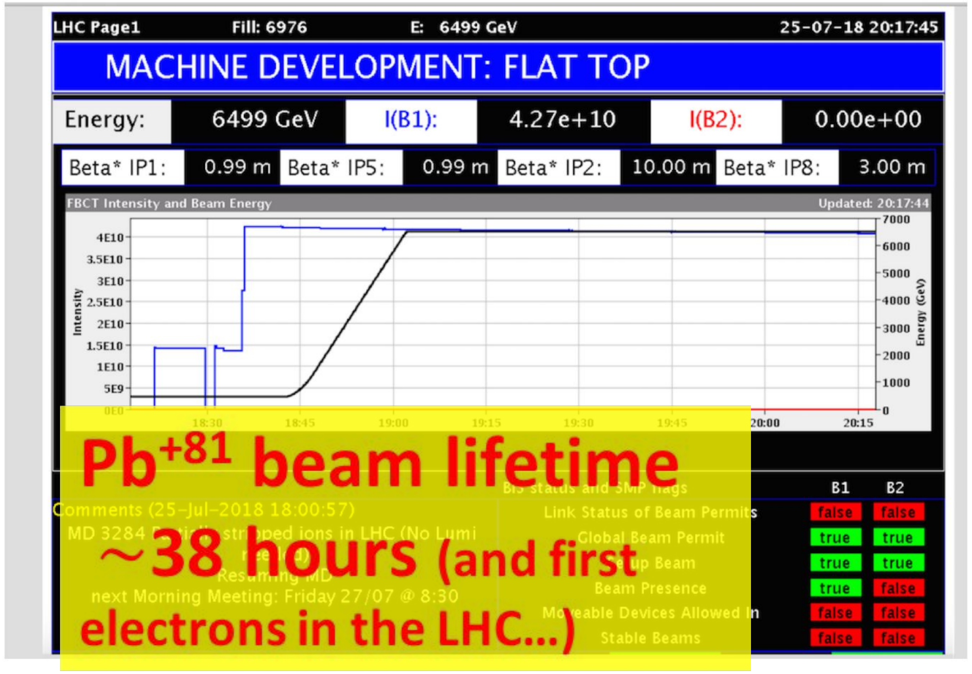
Witek Krasny

arXiv:1511.07794

partially stripped heavy-ion beam in LHC (or FCC):
resonant scattering of laser photons off ultrarelativistic atomic beam; high-stability laser-light-frequency converter

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\,\nu_{Laser}$$

Gamma Factory proof-of-principle experiment in the LHC



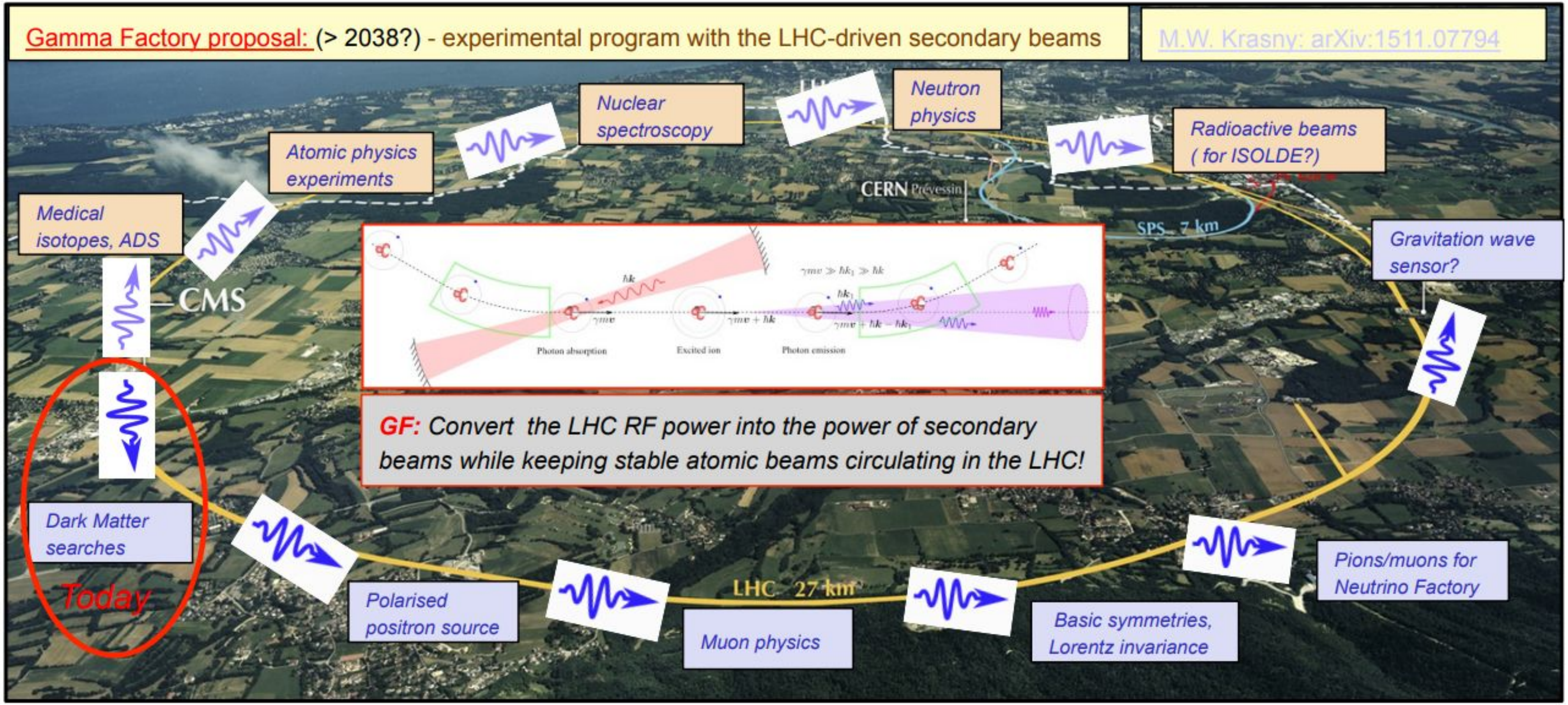
<u>proposed applications:</u>

intense source of e^+ (10^{16}-10^{17}/s), π, μ etc

doppler laser cooling of high-energy beams

HL-LHC w. laser-cooled isocalar ion beams

The LHC as a driver of secondary beams



Schematic transformation of the LHC into a Gamma-Factory-based driver of secondary beams [Witek Krasny].

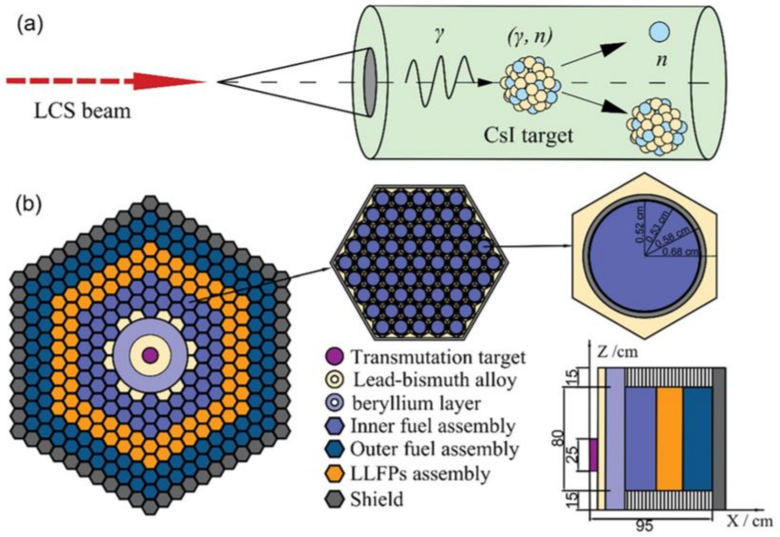
Gamma Factory driving subcritical nuclear reactor?

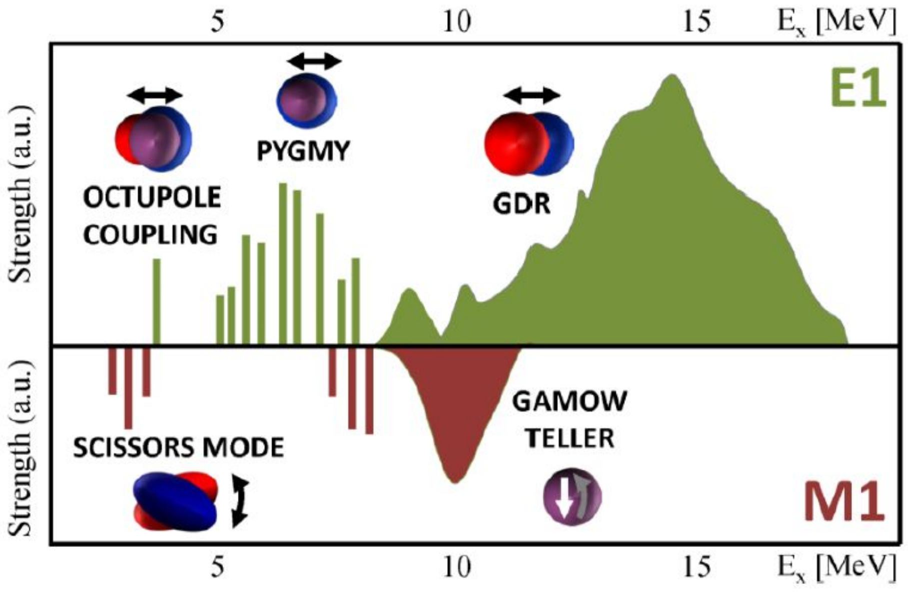
Article | Open Access | Published: 09 February 2022

Transmutation of long-lived fission products in an advanced nuclear energy system

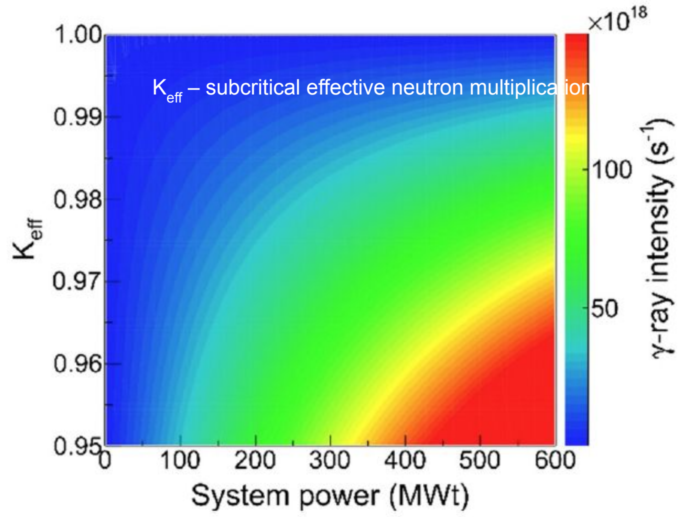
X. Y. Sun, W. Luo, H. Y. Lan, Y. M. Song, Q. Y. Gao, Z. C. Zhu, J. G. Chen & X. Z. Cai

Scientific Reports **12**, Article number: 2240 (2022) | Cite this article



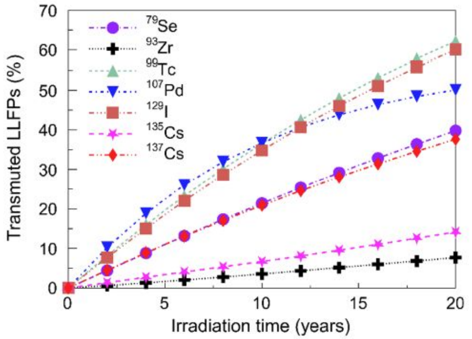


Required photon-beam energy:
5-20 MeV -- He(H)- like Ca or Kr beams + commercial ~ 1 μm lasers



Required beam intensity:
O(10 MW) power

LLFP loaded material: Uranium dioxide pellets-fast breeder reactor core at 50 GWd/t
Fuel: ^{235}U



Witek Krasny

https://indico.cern.ch/event/1137276

LLFPs	Transmutation in CsI target (g/year)		
	in photon field	in neutron field	in hybrid field
^{129}I	1.88×10^3	1.24×10^3	3.12×10^3
^{135}Cs	3.85×10^2	-0.70×10^2	3.15×10^2
^{137}Cs	9.25×10^2	-1.07×10^2	8.18×10^2

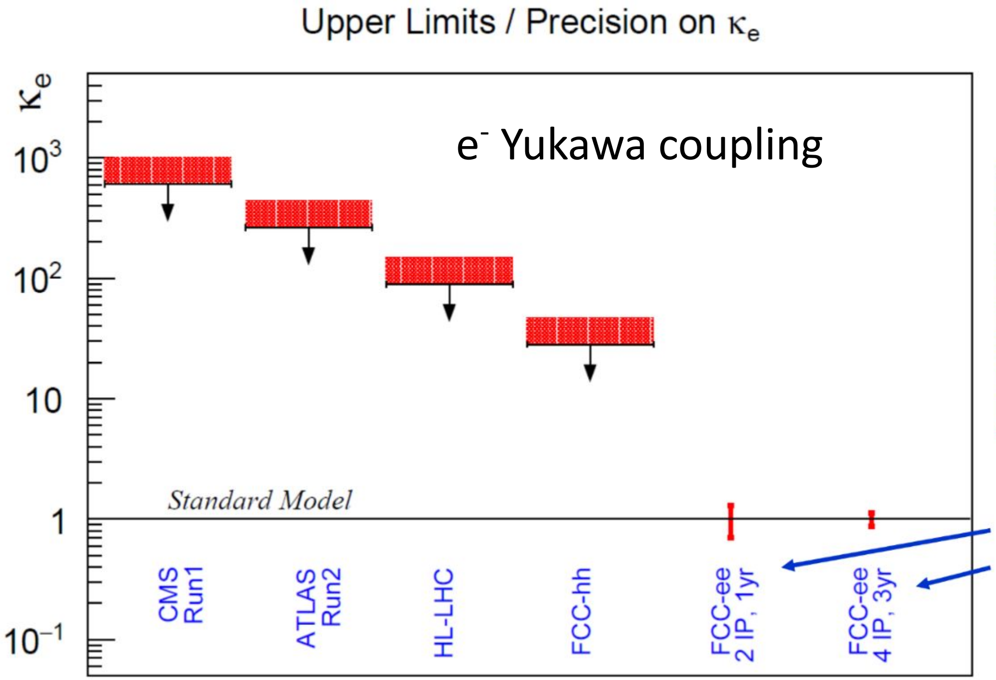
case for a GF based photon driver

Proton beam J-PARC | Photon beam CERN-GF

Efficiency = 1.3 % | Efficiency ~ 20 %

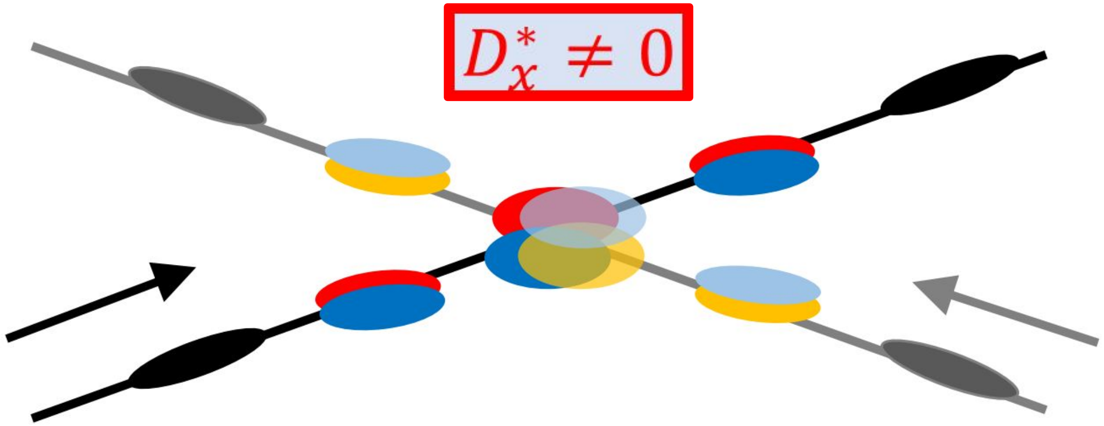
plus targeting specific isotopes and transitions

Monochromatization for $e^+e^- \longrightarrow H$ at FCC-ee

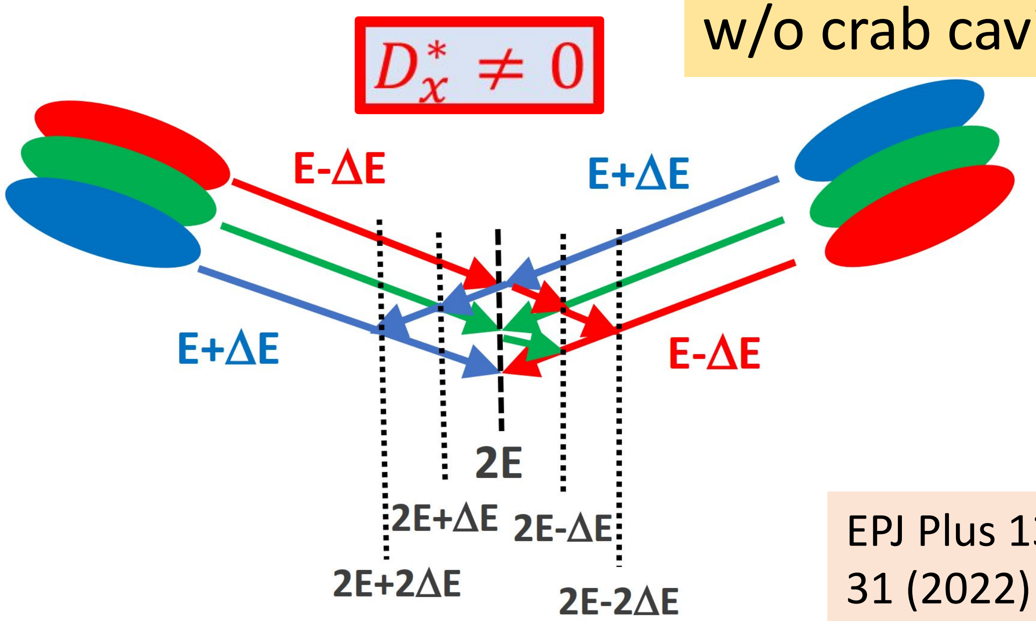


nonvanishing IP dispersion

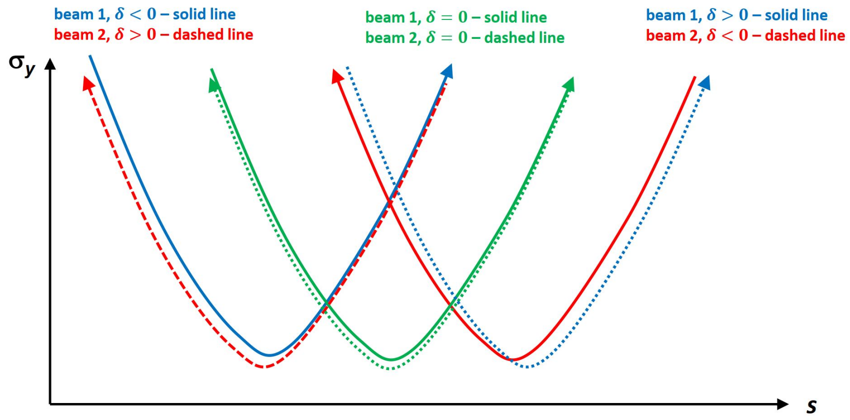
w crab cavities



w/o crab cavities



chromatic waist shift

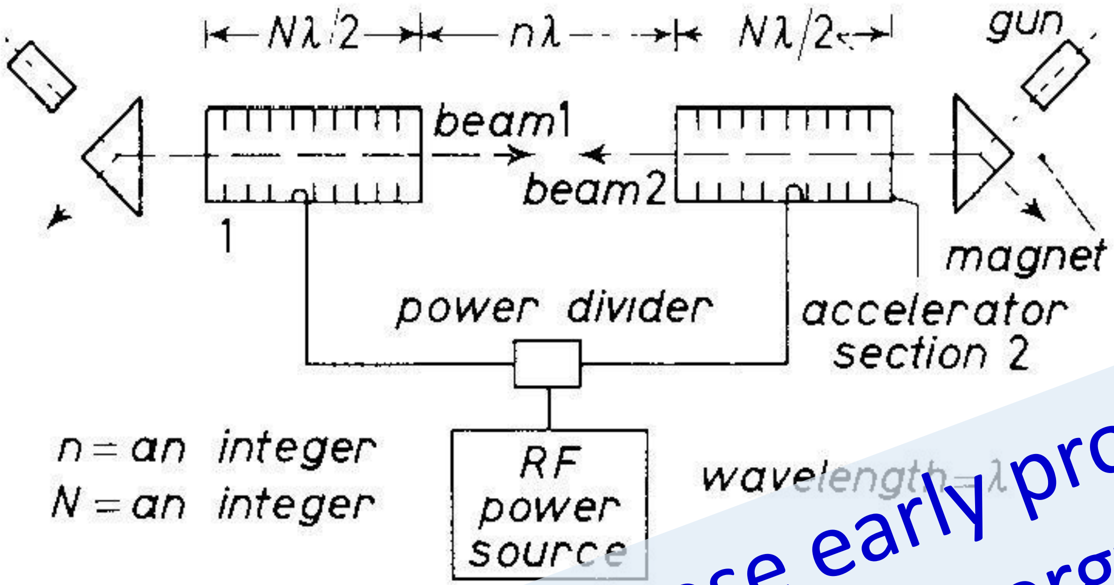


Pantaleo Raimondi

EPJ Plus 137, 31 (2022)

Energy Recovery Linacs - Historical Proposals 1960s & 70s

early linear-collider proposals

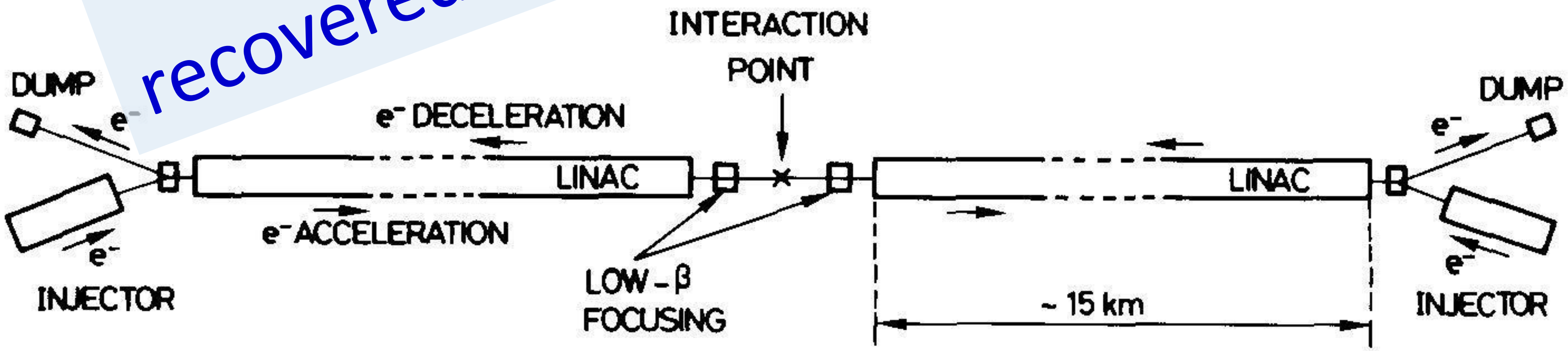


1-6 GeV c.m.

Maury Tigner, "*A Possible Apparatus for Clashing-Beam Experiments*", Nuovo Cimento 37, 1228 (**1965**)

these early proposal always recovered the energy of the spent beam!

Ugo Amaldi, "*A possible scheme to obtain e-e- and e+e- collisions at energies of hundreds of GeV*", Physics Letters B61, 313 (**1976**)



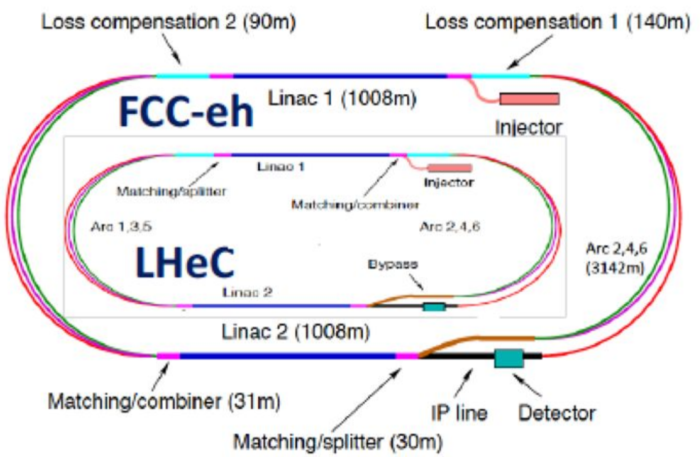
300 GeV c.m.

Energy Recovery Linacs : recent revival

European LDG roadmap

Main advances: flat instead of round beams, much smaller (vertical) beam sizes, higher beam current → ~10,000x higher luminosity

Energy Frontier Collider Applications of Energy Recovery Linacs

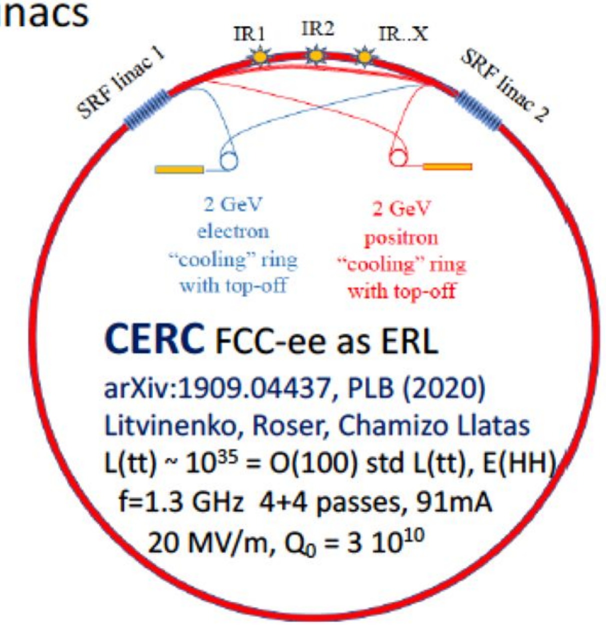


$\sqrt{s_{ep}}$ = 1-4 TeV

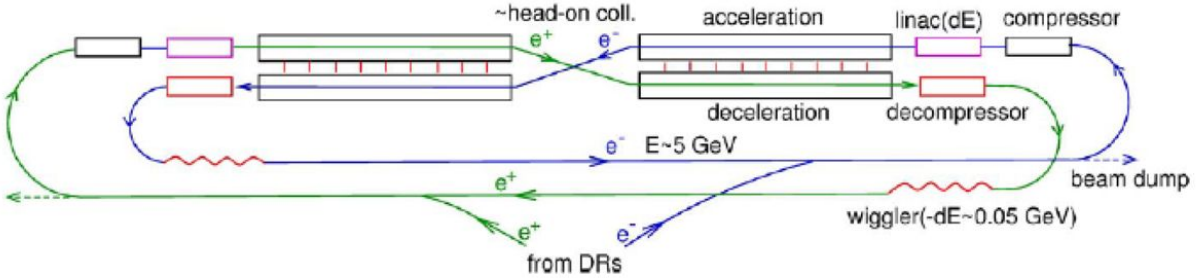
L(HERA) x 1000
(ERL and LHC)

1206.2913, JPhysG
2007.14491, JPhysG

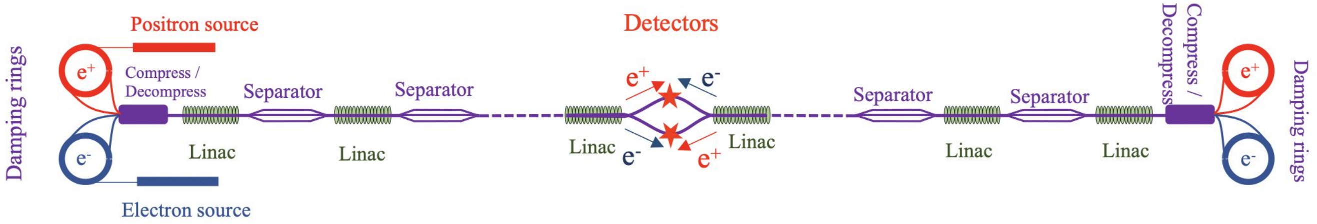
f=802Mz,
3+3 passes: 20mA x 6
20 MV/m, $Q_0 > 10^{10}$



LHeC ERL was first proposed by Swapan Chattopadhyay

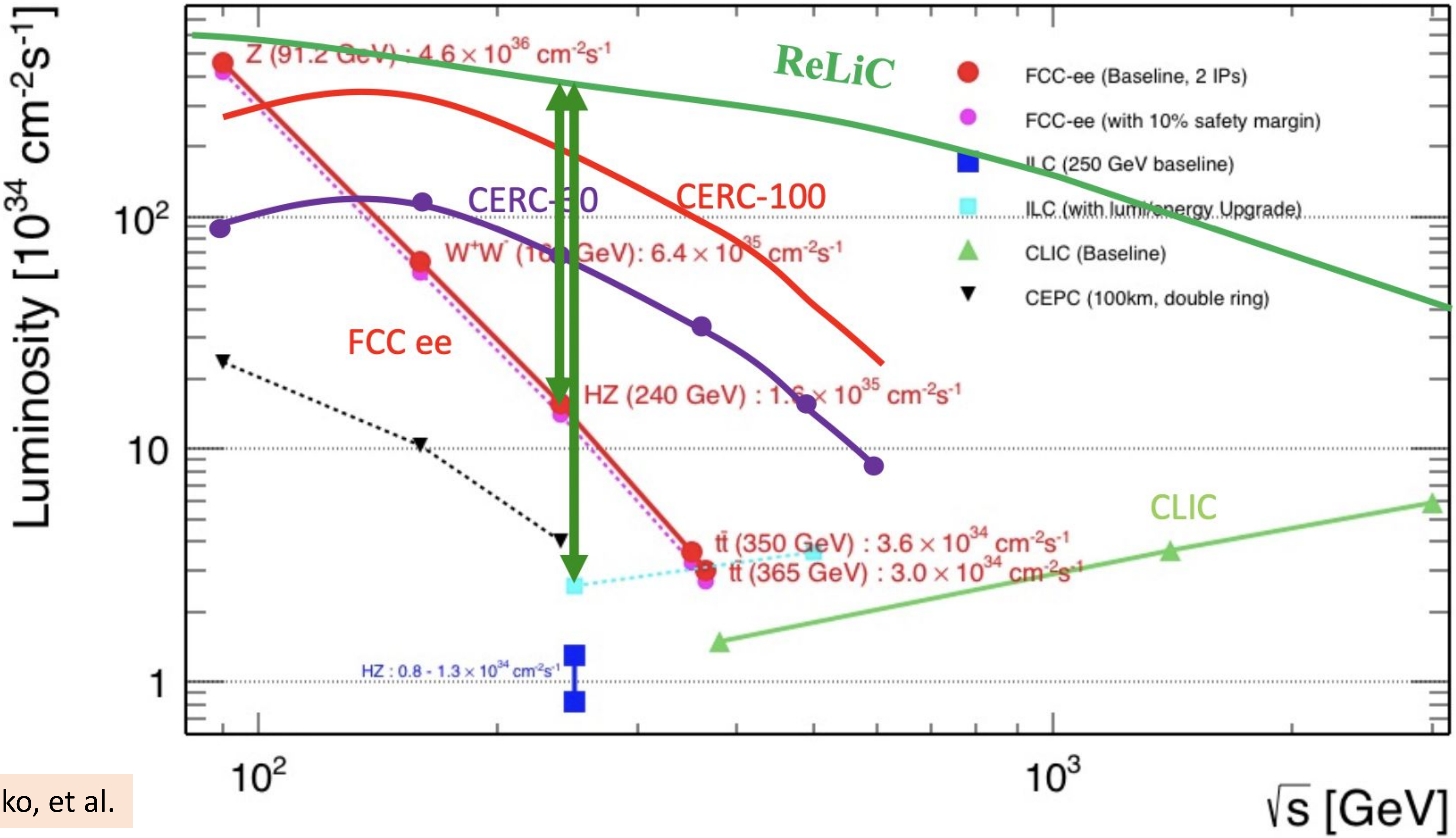


ERLC ILC as ERL
V. Telnov at LCWS → arXiv:2105.11015
L(ERLC) ~ 10^{36} = O(100) std L(ILC)
This yields O(10^7) HZ events in 3 years.
1+1 passes. ...
650 MHz coll rate, 20 MV/m, Q~10^{11}



ReLiC
Litvinenko
L~4x10^{36} , 21 km,
3 MHz coll rate
1.5 GHz RF, Q~10^{11}

ERL prospects & promises

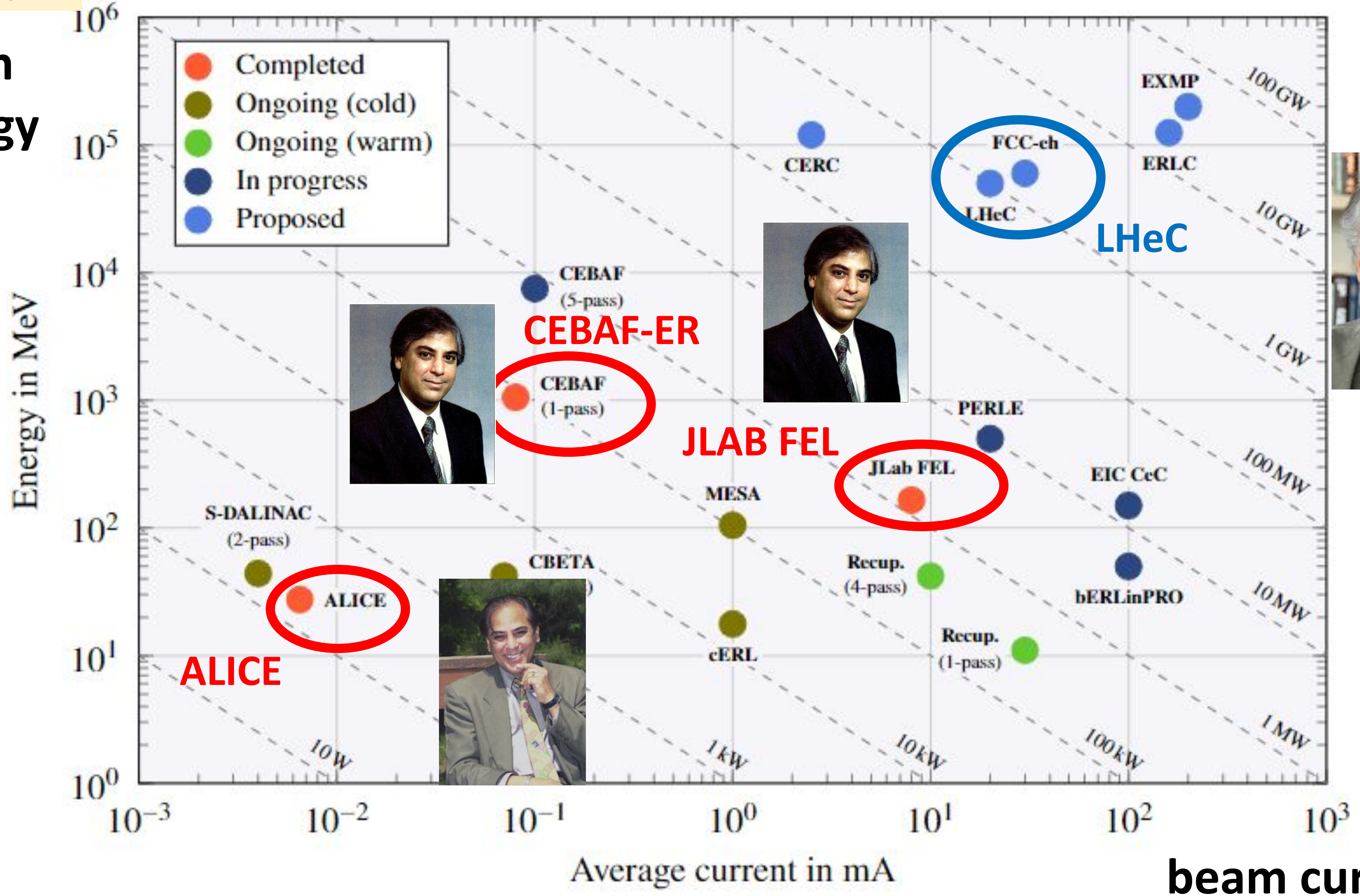


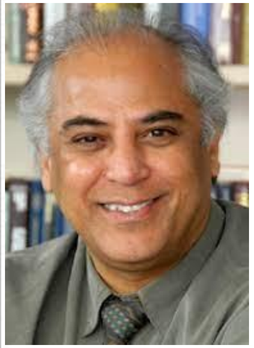
V. Litvinenko, et al.

ERL landscape

LDG ERL report

beam energy

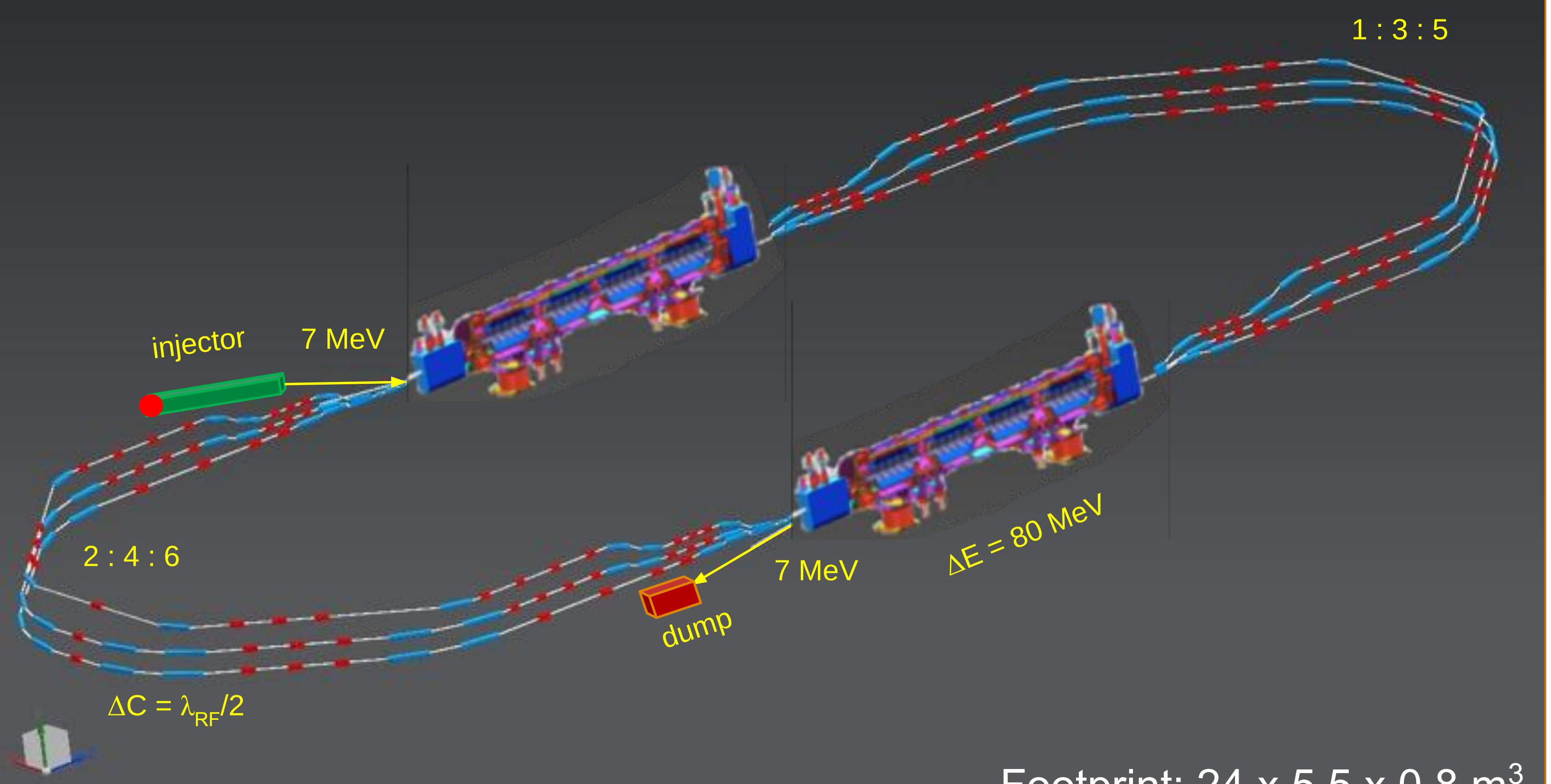




beam current

PERLE

Multi-pass high-current ERL test facility for LHeC (and FCC-ee-ERL) under construction at IJClab



Footprint: 24 x 5.5 x 0.8 m^3

W. Kaabi,
A. Bogacz,
O. Bruning,
M. Klein

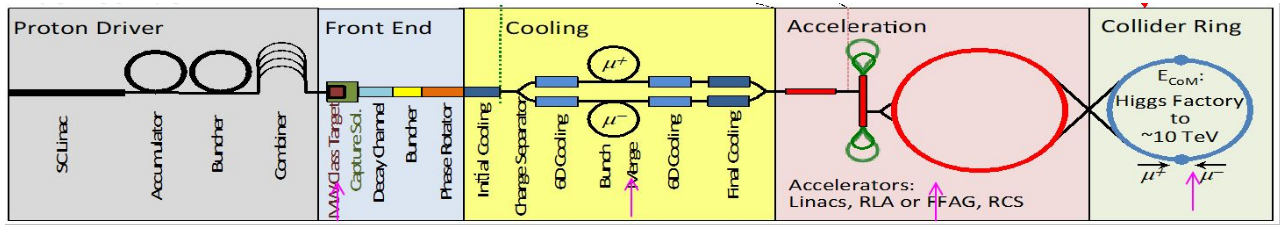
arXiv:1705.08783

Muon Colliders

~1.6x10^9 x less SR than e$^+$e$^-$, no beamstrahlung problem

two production schemes proposed

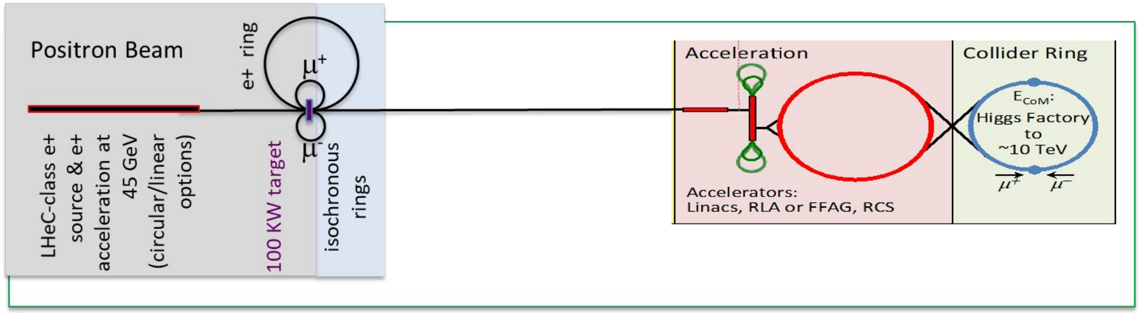
US-MAP (2015) *p*-driven



key challenges

~10^{13}-10^{14} μ / sec tertiary particle $p \to \pi \to \mu$:	fast cooling (τ=2μs) by 10^6 (6D)	fast acceleration mitigating μ decay	background from μ decay

Italian LEMMA (2017) *e*$^+$-annihilation



key challenges: ~10^{11} μ / sec from $e^+e^- \to \mu^+\mu^-$

key R&D: 10^{15} e$^+$/sec, 100 kW class target, NON destructive process in e+ ring

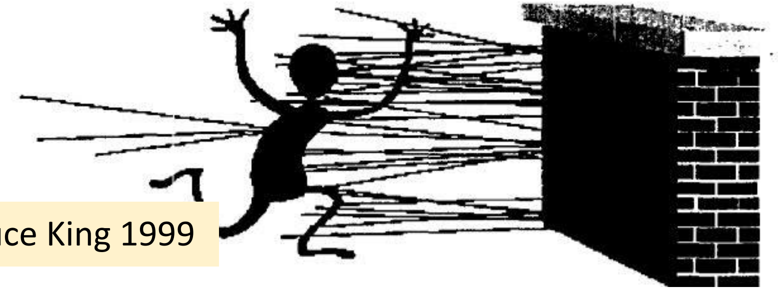
μ's decay within a few 100 - 1000 turns:

$\rightarrow$ rapid acceleration

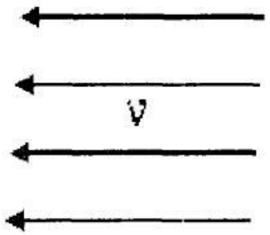
(perhaps plasma?)

$\rightarrow$ ν radiation hazard

(limits maximum μ energy)



Bruce King 1999



$\sigma_\nu \propto E$, flux $\propto E^2$ (Lorentz boost)

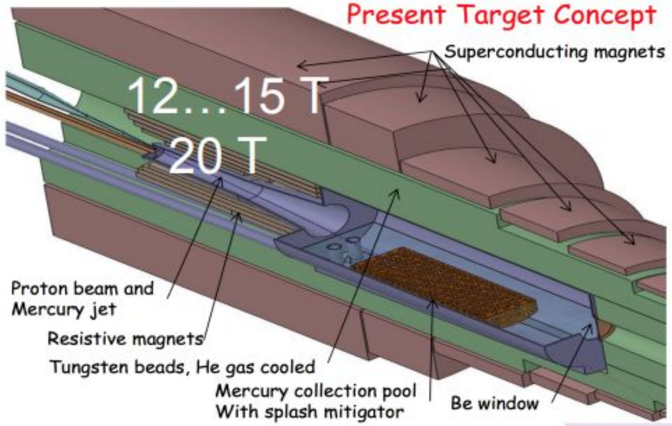
solution beyond 10 TeV unclear

needs large 45 GeV e$^+$ ring like FCC-ee, possible upgrade path to **FCC-$\mu\mu$**

Muon Colliders – Example Challenges

target design for *p* driven μ collider

MAP target design, K. McDonald, et al.



Two approaches:

- 15 T outer superconducting + 5 T inner resistive solenoid
- O(20 T) HTS solenoid

Shield superconducting solenoid
⇒ larger aperture
Synergy with ITER

A. Lechner et al.
L. Bottura et al.

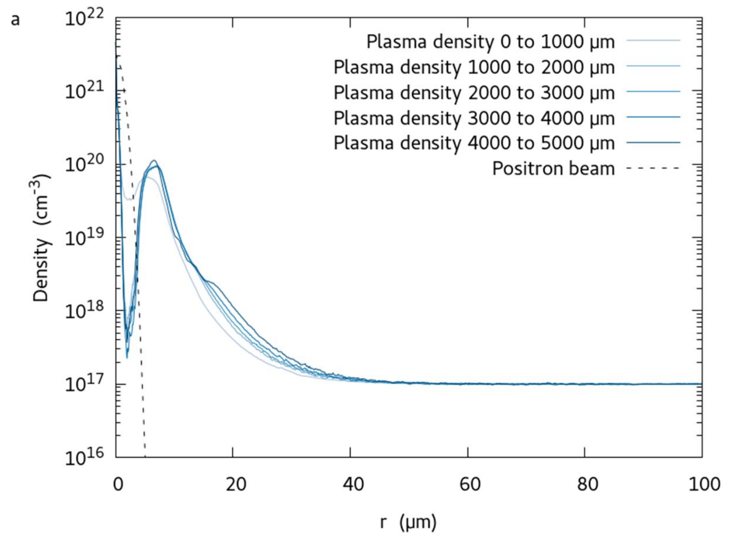
Rui Franqueira Ximenes et al.

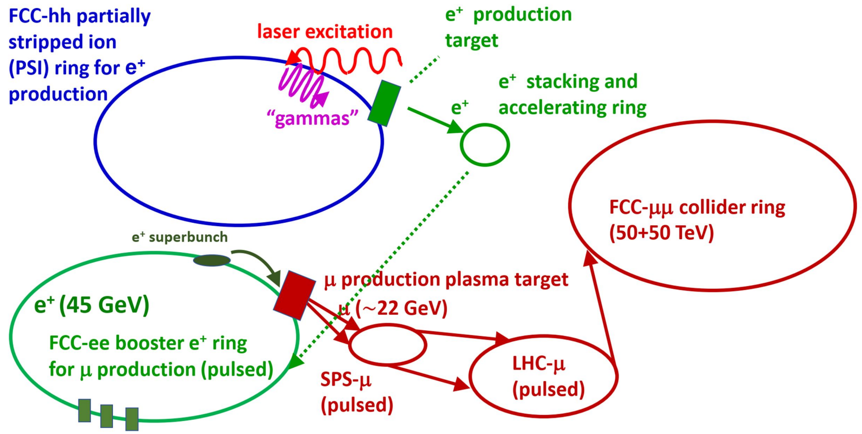
Shock in target: Simulations of graphite target indicate 2 MW could be acceptable

STFC will also study alternatives

Operation at 2000 °C to maximise stress resistance

plasma target for *e*⁺ driven μ collider



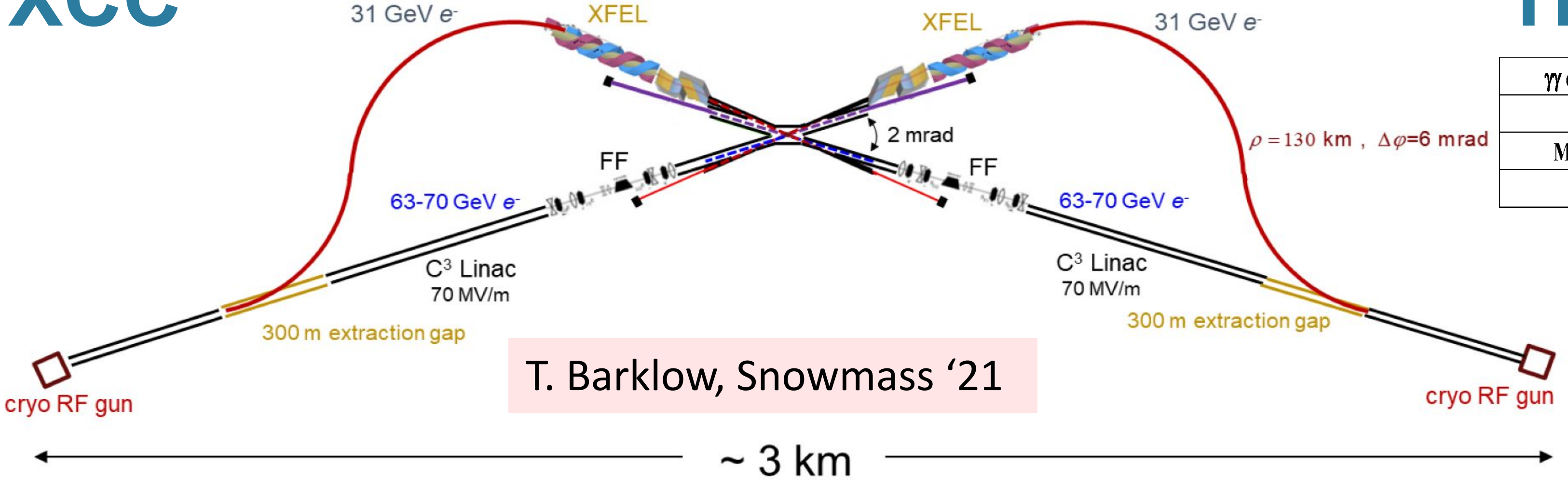


D. Schulte, IPAC'22

J. Farmer et al., IPAC'22

γγ colliders

XCC



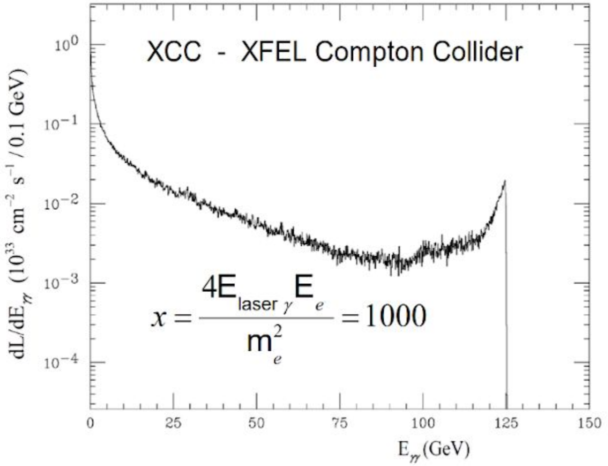
T. Barklow, Snowmass '21

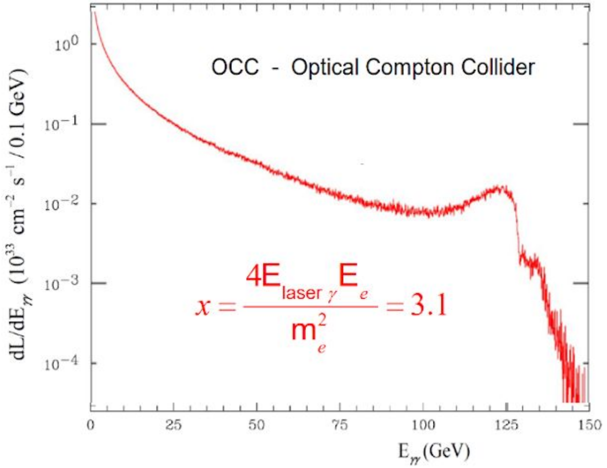
HE - HL γγ Collider

γγ collider parameters	0.5 TeV	1.0 TeV	3.0 TeV	10 TeV	Units
x-factor	2 (4)	4	12	40	
Max. photon energy	0.17 (0.20)	0.40	1.38	4.88	TeV
$L_{\gamma\gamma}$ / L_{ee}	≤ 10	≤ 10	≤ 6	≤ 3	%

E. Barzi, Snowmass '21

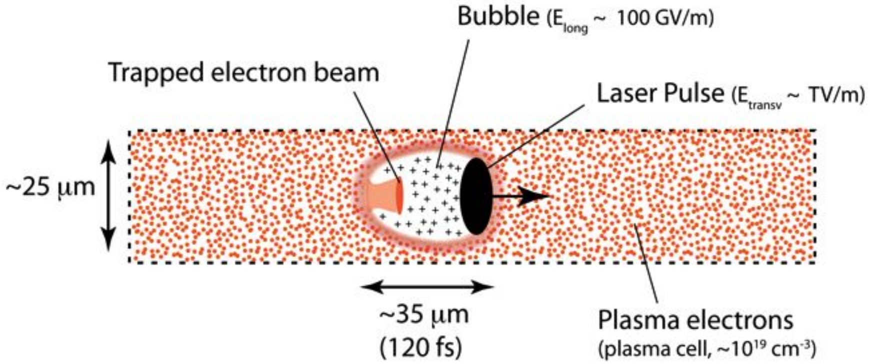
Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	5.4/5.4 nm	bunch charge	1 nC
σ_z	20 μm	Linac-to-XFEL curvature radius	133 km
bunch charge	1 nC	Undulator B field	$\gtrsim$ 1 T
Rep. Rate at IP	240 × 38 Hz	Undulator period λ_u	9 cm
σ_x/σ_y at IPC	12.1/12.12 nm	Average β function	12 m
$\mathcal{L}_{geometric}$	9.7×10^{34} cm^2 s^{-1}	x-ray λ (energy)	1.2 nm (1 keV)
δ_E/E	0.05%	x-ray pulse energy	0.7 J
L^* (QD0 exit to e^- IP)	1.5m	pulse length	40 μm
d_{cp} (IPC to IP)	60 μm	$a_{\gamma x}/a_{\gamma y}$ (x/y waist)	21.2/21.2 nm
QD0 aperture	9 cm diameter	non-linear QED ξ^2	0.10
Site parameters	**Approx. value**		
crossing angle	2 mrad		
total site power	85 MW		
total length	3.0 km		





Machine	E_{e^-} (GeV)	N_{e^-} (nC)	Polarization	N_H/yr	$N_{Hadronic}/N_H$	$N_{minbias/BX}$
XCC	62.8	1.0	90% e^-	34,000	170	9.5
OCC	86.5	1.0	90% e^-	30,000	540	50
ILC	125	3.2	-80% e^- +30% e^+	42,000	140	1.3
ILC	125	3.2	+80% e^- -30% e^+	28,000	60	1.3

Advanced Accelerators: Plasma



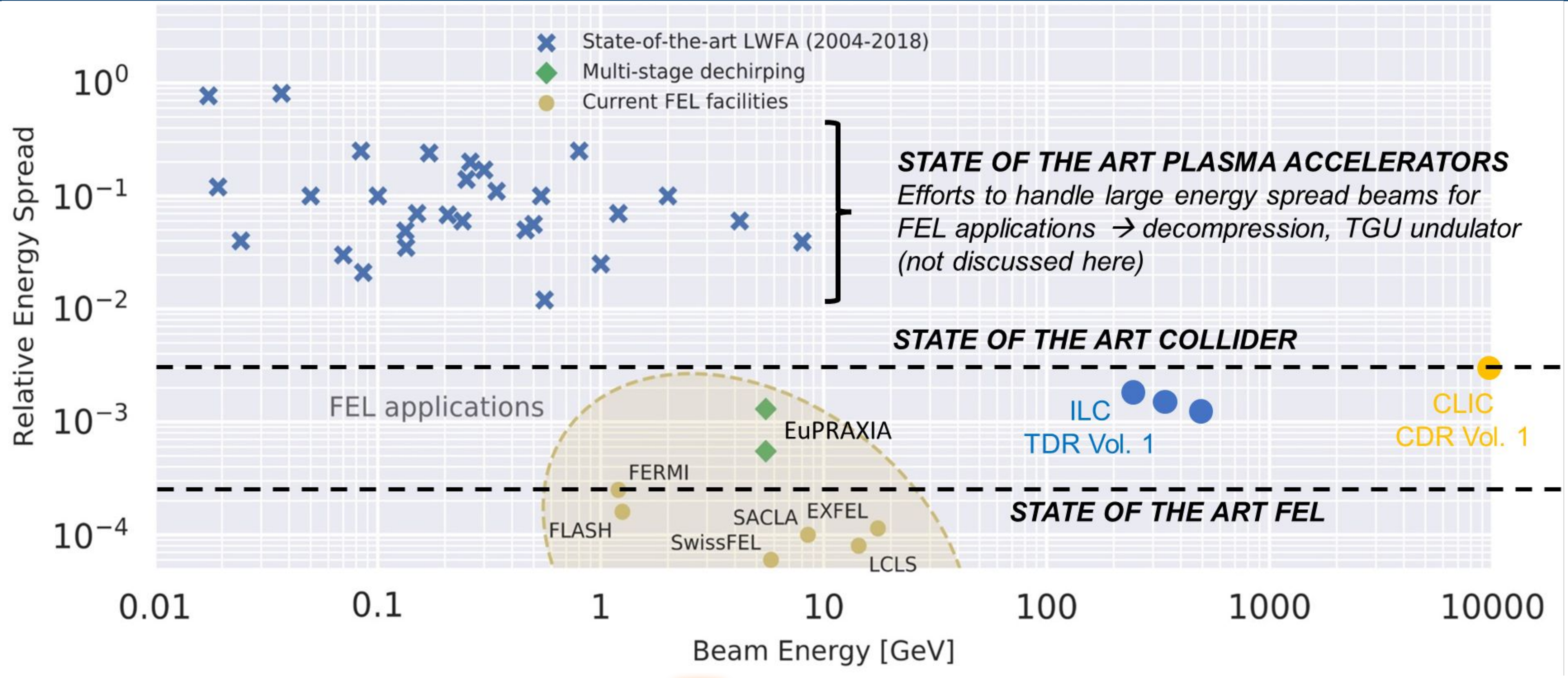
R. Assmann

A plasma cell compared with the superconducting accelerator FLASH (credit DESY)

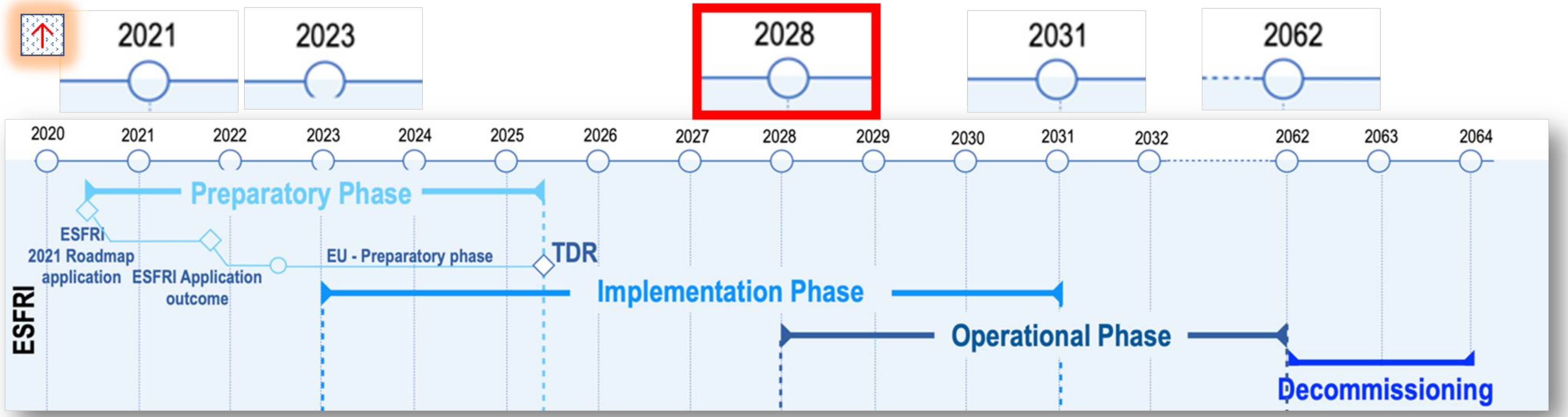
R. Assmann, E. Gschwendtner, R. Ischebeck, LDG Draft

Advanced Accelerator "Demonstrator" EuPRAXIA

R. Assmann,
iFAST BWS2022



construction
at INFN-LNF



Plasma Accelerator Challenge: Positron Acceleration

"ballistic injection": a ring-shaped laser beam and a coaxially propagating Gaussian laser beam are employed to create donut and center bubbles in the plasma, resp.

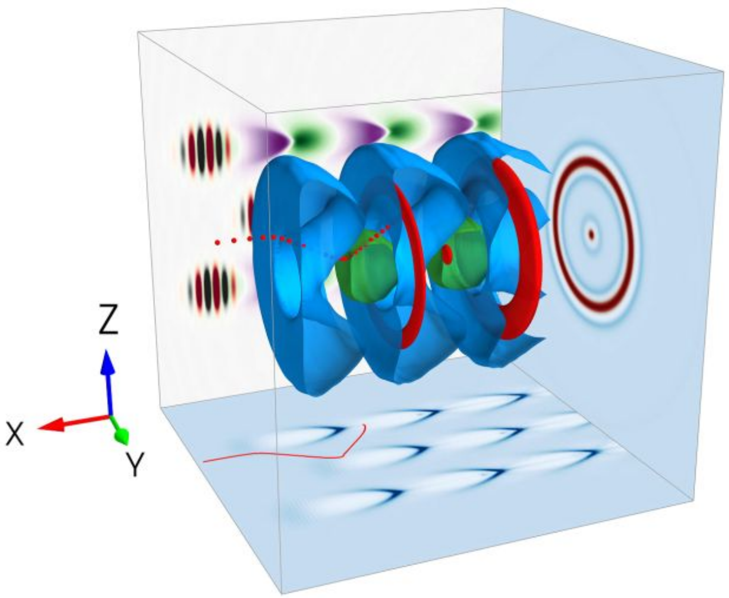
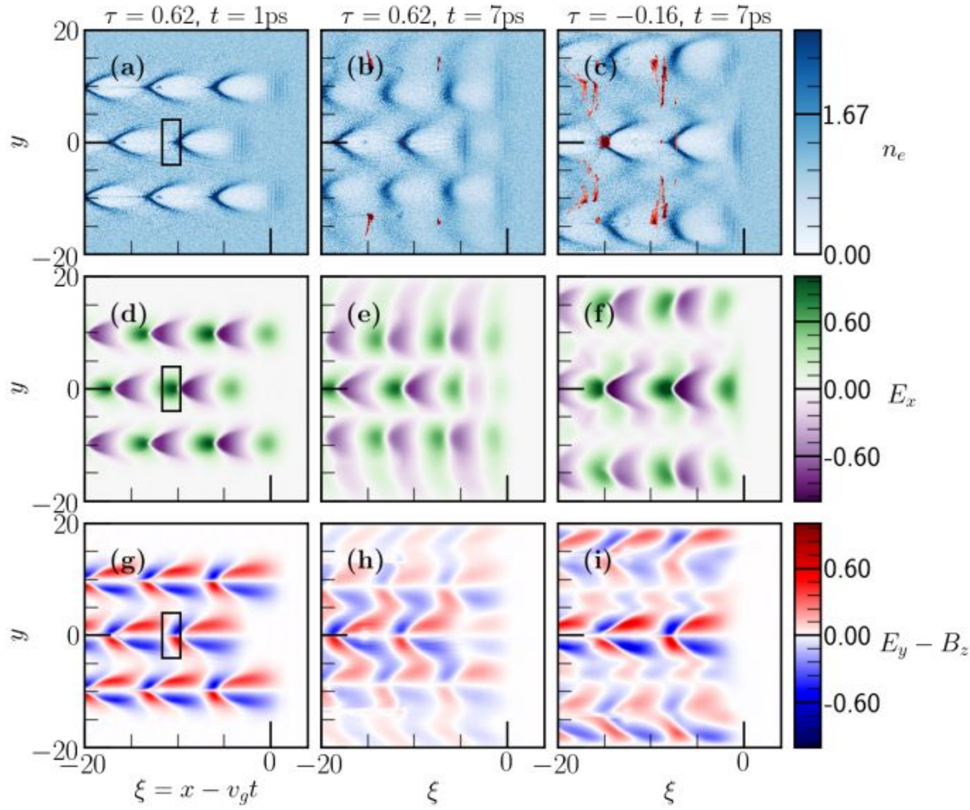


FIG. 1. The concept of the positron ballistic injection scheme. The blue and green colors are contour surfaces of electron densities of donut and center bubbles, respectively. The red color represents injected positrons. The x–y and x–z planes are transverse slices of the density distribution and the longitudinal electric field E_x. The red curve in the x–y plane is the trajectory of an injected positron (corresponding to the projection of red balls in the 3D model). The leading oscillating colors (amber and grey) denote the laser beams in the x–z plane. The y–z plane is the projection of electron density (blue) and injected positron density (red).



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 091301 (2020)

New injection and acceleration scheme of positrons in the laser-plasma bubble regime

Z. Y. Xu,[1] C. F. Xiao,[1] H. Y. Lu,[1,2,3,*] R. H. Hu,[1,†] J. Q. Yu,[1,‡] Z. Gong,[1] Y. R. Shou,[1] J. X. Liu,[1] C. Z. Xie,[1] S. Y. Chen,[1] H. G. Lu,[1] T. Q. Xu,[1] R. X. Li,[4] N. Hafz,[5] S. Li,[5] Z. Najmudin,[6] P. P. Rajeev,[7] D. Neely,[7] and X. Q. Yan[1,3]

Z.Y. Xu

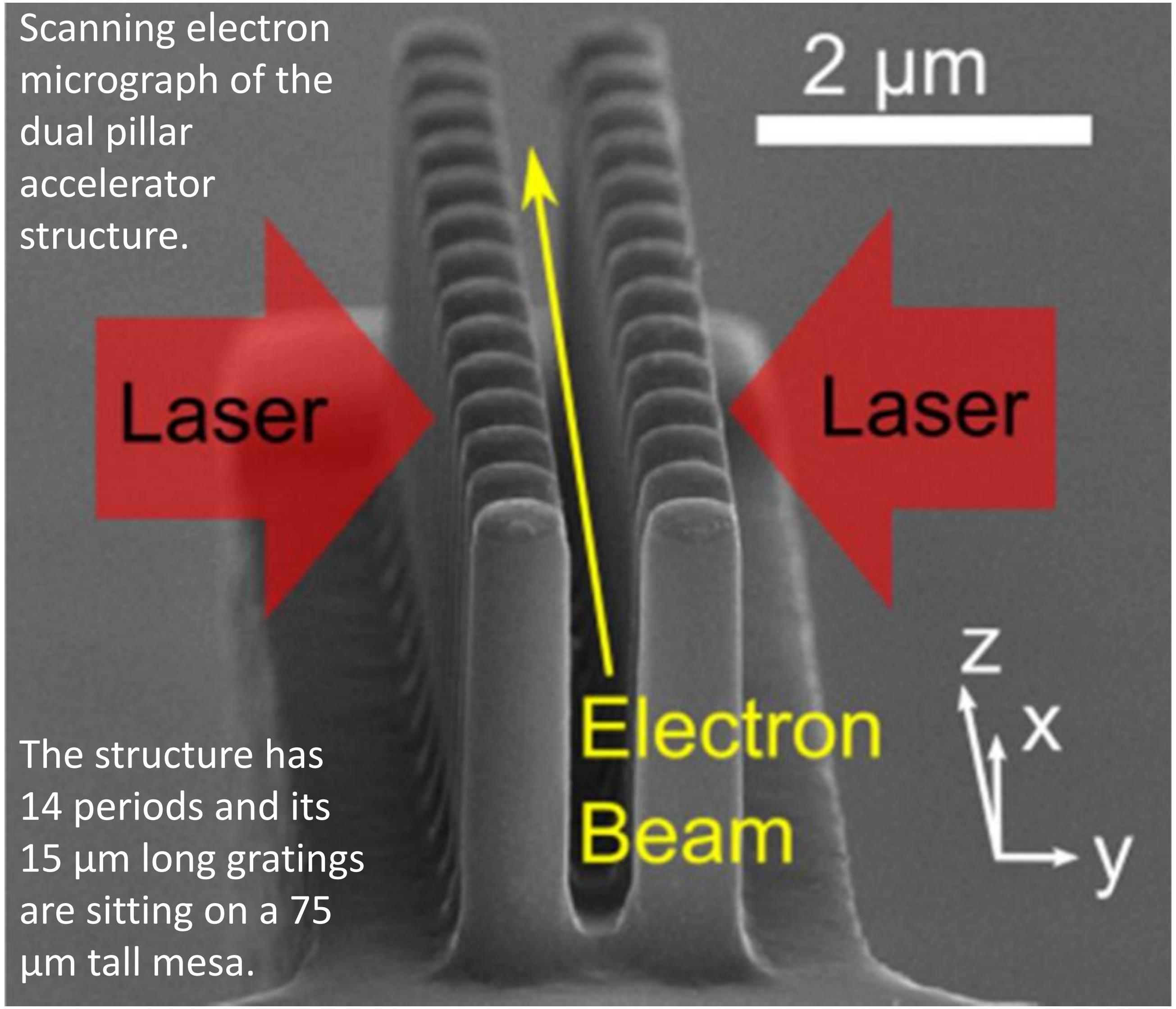
Advanced Accelerator Types

Required parameters for a linear collider with advanced high gradient acceleration [R. Assmann]. Three published parameter cases are listed. This table is taken from the LDG report [N. Mounet (ed.), “European Strategy for Particle Physics - Accelerator R&D Roadmap”, arXiv:2201.07895 CERN-2022-001]

Parameter	Unit	PWFA	LWFA	DLA
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.1	1.0	1.9

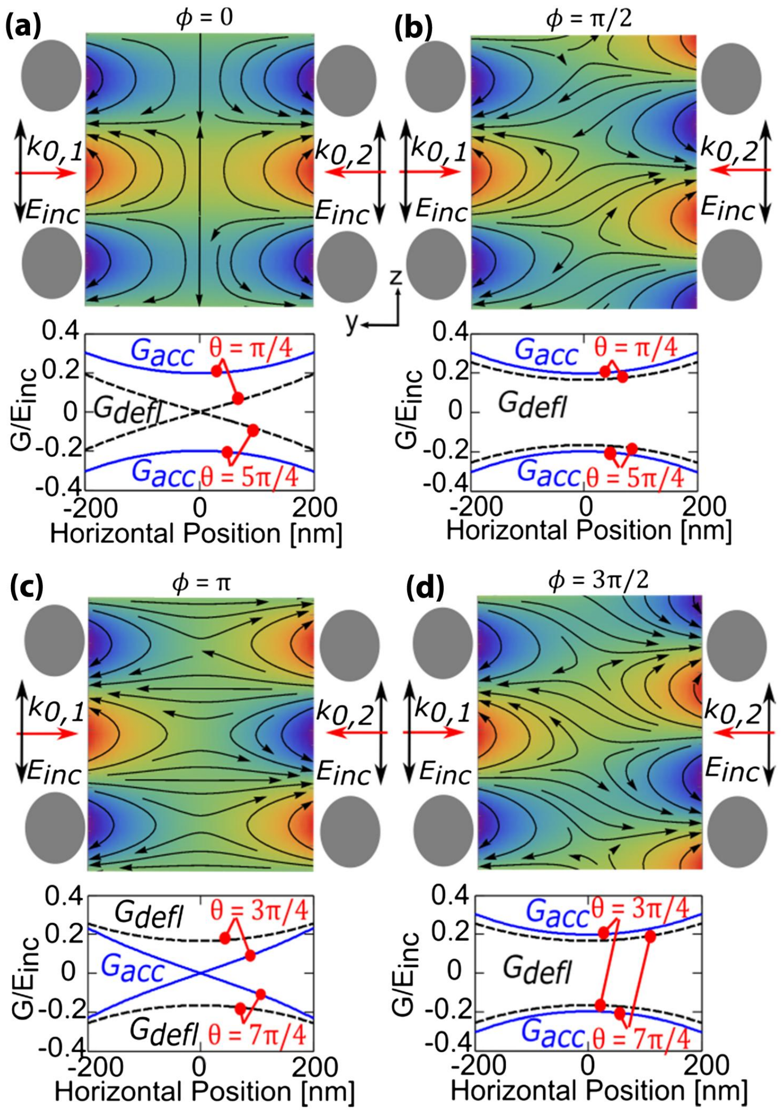
Dielectric Laser Accelerators (DLAs) may help explore the dark sector

Dielectric Laser Accelerators



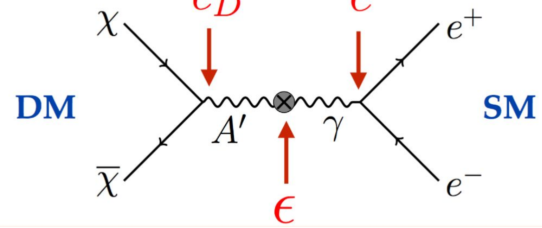
Scanning electron micrograph of the dual pillar accelerator structure.

The structure has 14 periods and its 15 µm long gratings are sitting on a 75 µm tall mesa.



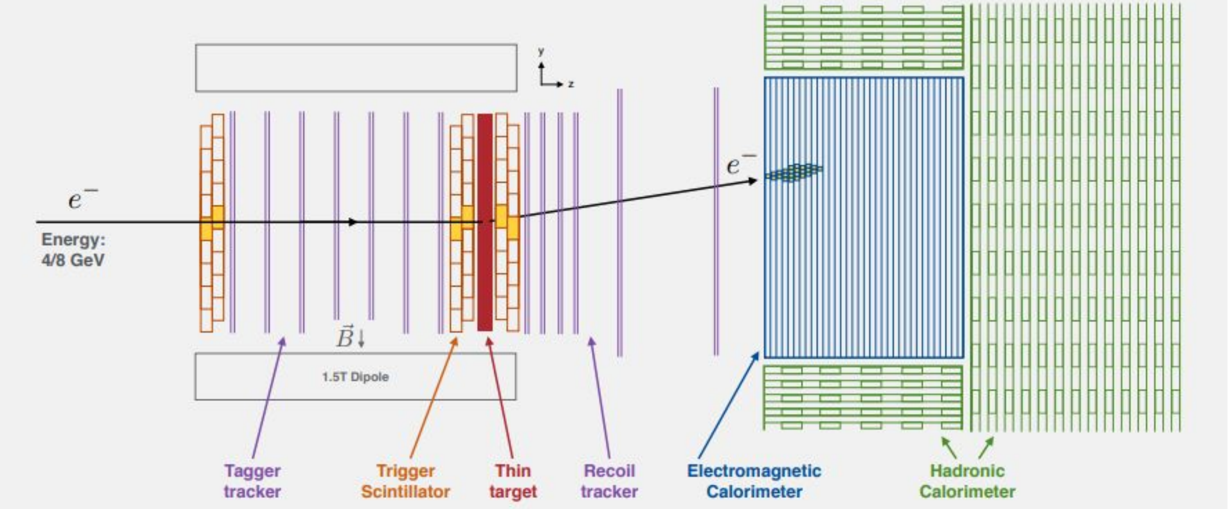
Dual pillar dual-drive mode profiles with force vectors superimposed on the E_z acceleration field color map at different relative drive phases. Insets show accelerating and deflecting gradients across channel for illustrated optical phases θ.

Kenneth J. Leedle, Dylan S. Black, Yu Miao, Karel E. Urbanek, Andrew Ceballos, Huiyang Deng, James S. Harris, Olav Solgaard, Robert L. Byer, "Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings," Opt. Lett. **43,** 2181-2184 (2018); https://www.osapublishing.org/ol/abstract.cfm?uri=ol-43-9-2181

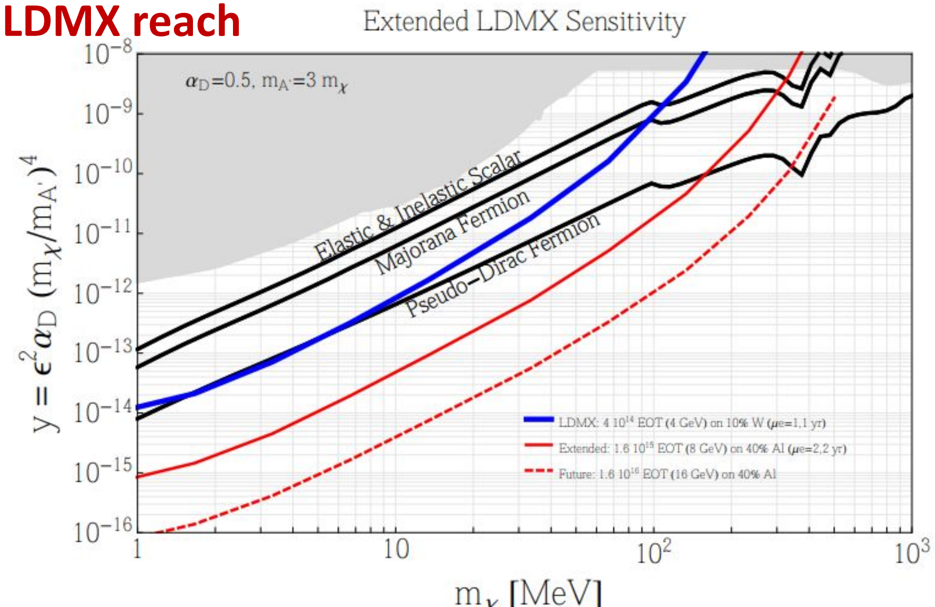


accelerators for indirect dark sector searches

Reference: LDMX at SLAC LCLS-II, baseline 4×10^{14} EOT, 4 GeV

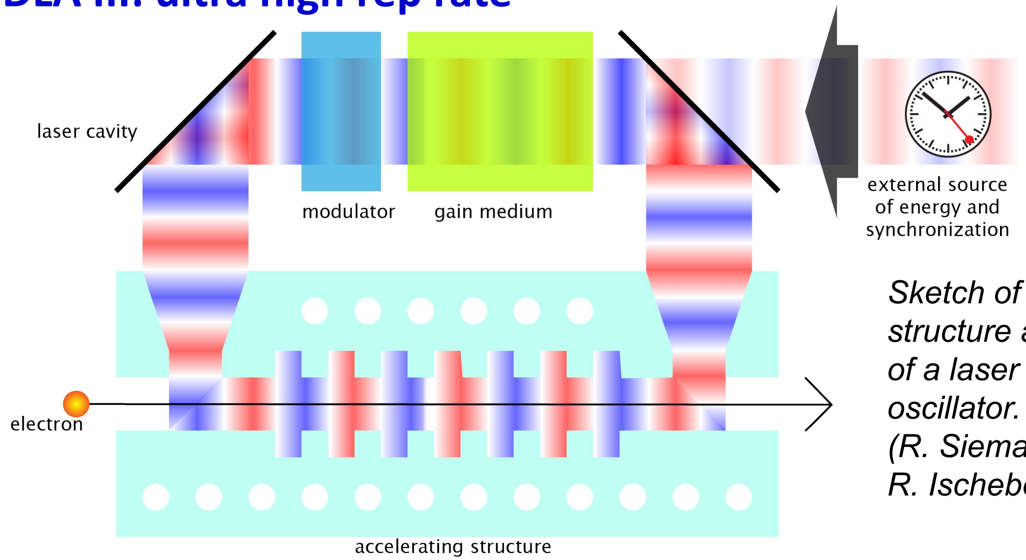


LDMX reach



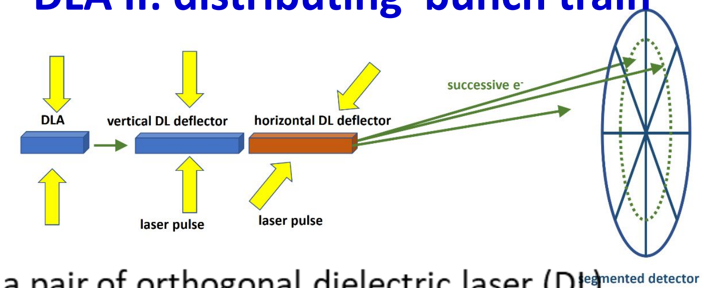
Proposal: high rep. rate DLA based searches, up to 10^{18} EOT/yr

DLA III: ultra high rep rate



Sketch of DLA structure as part of a laser oscillator. (R. Siemann, R. Ischebeck)

DLA II: distributing bunch train



a pair of orthogonal dielectric laser (DL) deflectors sends each electron in a train of ~160 onto a separate segment of the detector, thereby overcoming the time resolution limit and allowing bunch spacing of less than 10 ps within a train.

iFAST MS17

DLA	I	II	III
Beam energy [GeV]	10	10	10
Gradient [GV/m]	1	1	1
Active length [m]	10	10	10
Rep. rate [GHz]	0.06	0.06	100
Pulse length [ps]	0.1	1	0.1
Single e's / pulse	1	159	1
Average current [pA]	1	150	
Pulse time sep. [ns]	17	17	0.01
e^- on target / yr			
Energy cons./ yr [GWh]	1	10	~2

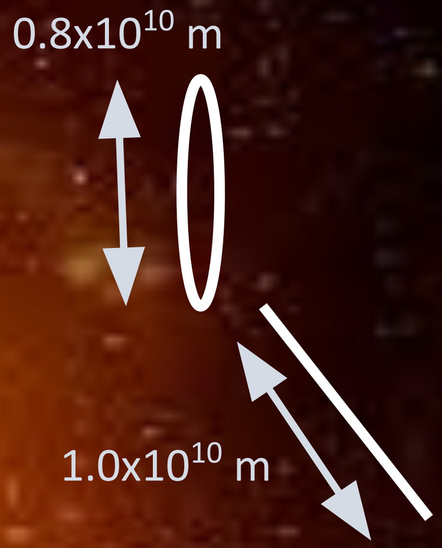
ultimate limit on electromagnetic acceleration

Schwinger critical fields $E_{cr} \approx 10^{12}$ MV/m, B_{cr}=4.4 x10^9 T

Planck scale: 10^{28} eV

“not an inconceivable task for an advanced technological society”

P. Chen, R. Noble,
SLAC-PUB-7402, April 1998

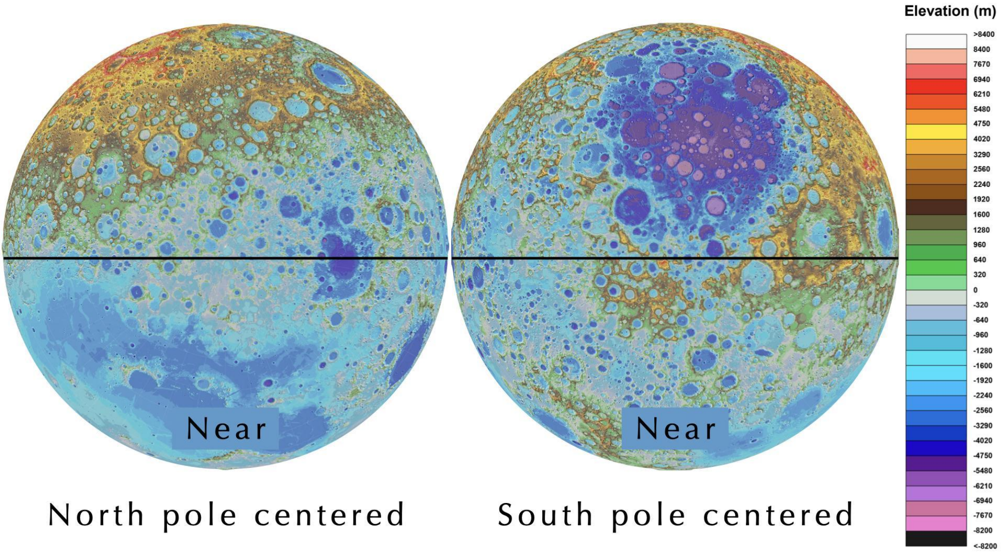


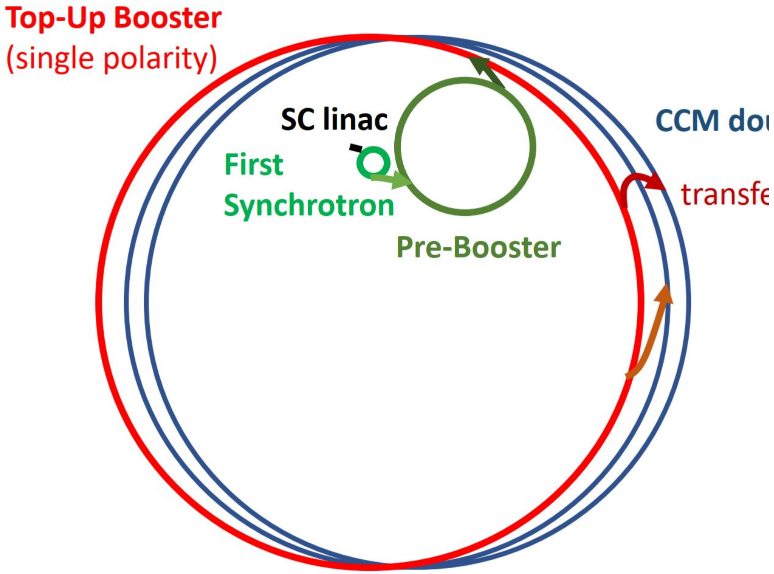
circular & linear Planck-scale colliders

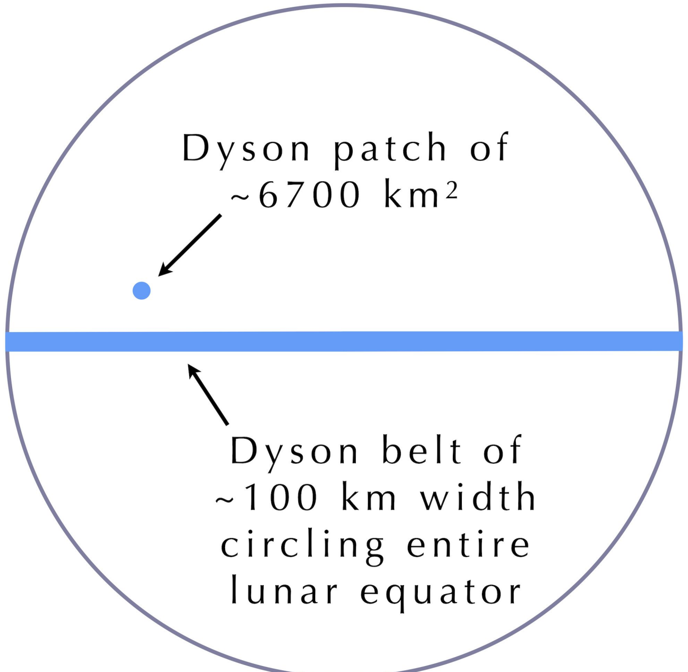
~1/10^{th} for distance earth-sun

stepping stone towards Planck scale collider ?

Very large hadron collider on the Moon (CCM), $C \sim 11$ Mm, $E_{c.m.} \sim 14$ PeV (1000x LHC's), 6x10^5 dipoles with **20 T field**, either ReBCO, requiring ~7-13 k tons rare-earth elements, or IBS, requiring ~a million tons of IBS. **Many of the raw materials required to construct machine, injector complex, detectors, and facilities can potentially be sourced directly on the Moon. 11000-km tunnel a few 10 to 100 m under lunar surface** to avoid lunary day-night temperature variations, cosmic radiation damage, and meteoroid strikes. **Dyson band or belt to continuously collect sun power.** Required: <0.1% sun power incident on Moon surface.







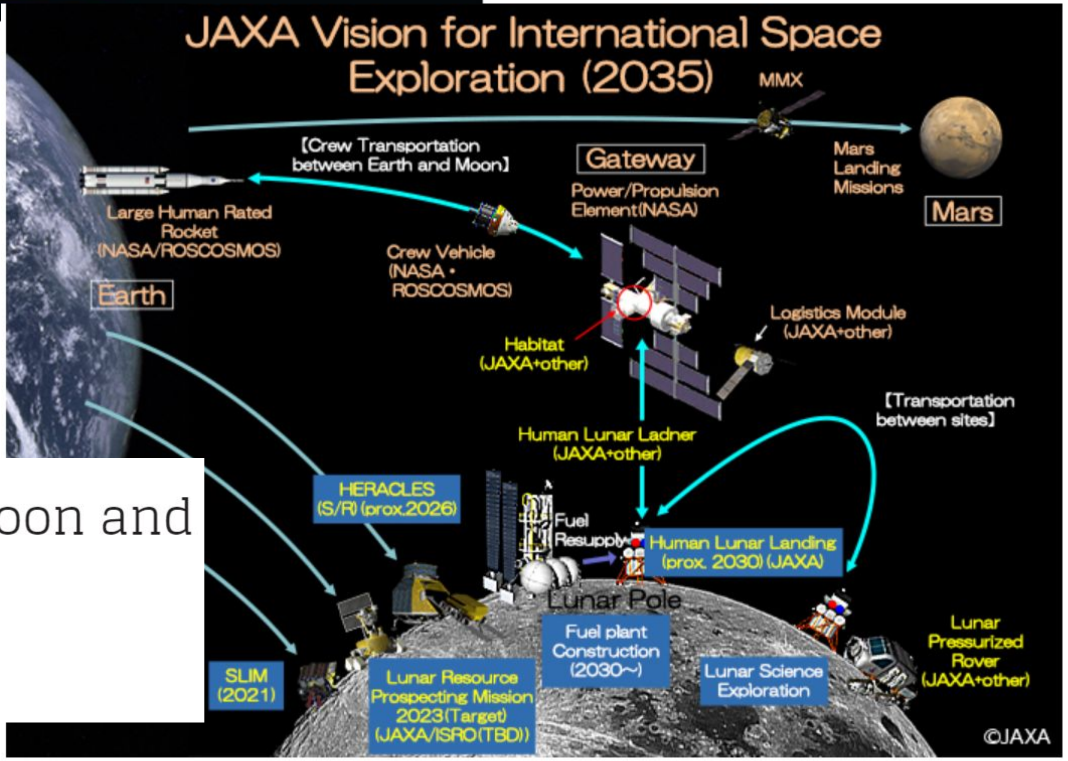
J. Beacham, F. Zimmermann, 2022 *New J. Phys.*, https://doi.org/10.1088/1367-2

a timely consideration ?!

The Economist

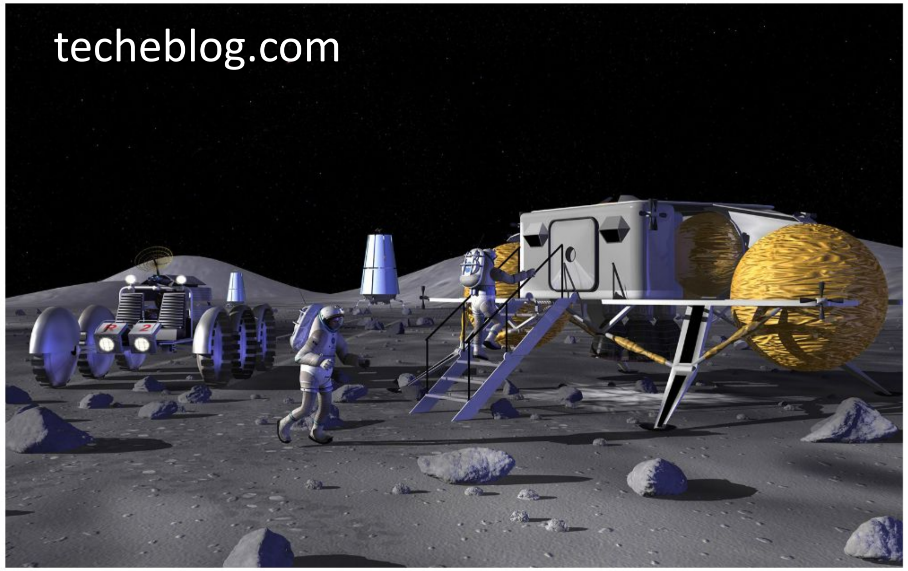
Everyone's going to the moon—a new space race | The Economist

Jan 4, 2022 ... Everyone's going to the moon—a new space race · Our podcast on the science and technology making the news. Also this week: how to avoid conflict ...



NASA Reveals Future Plans for Colonization of the Moon

APRIL 5, 2020



CNRS News

Artemis: To the Moon and beyond

08.26.2022

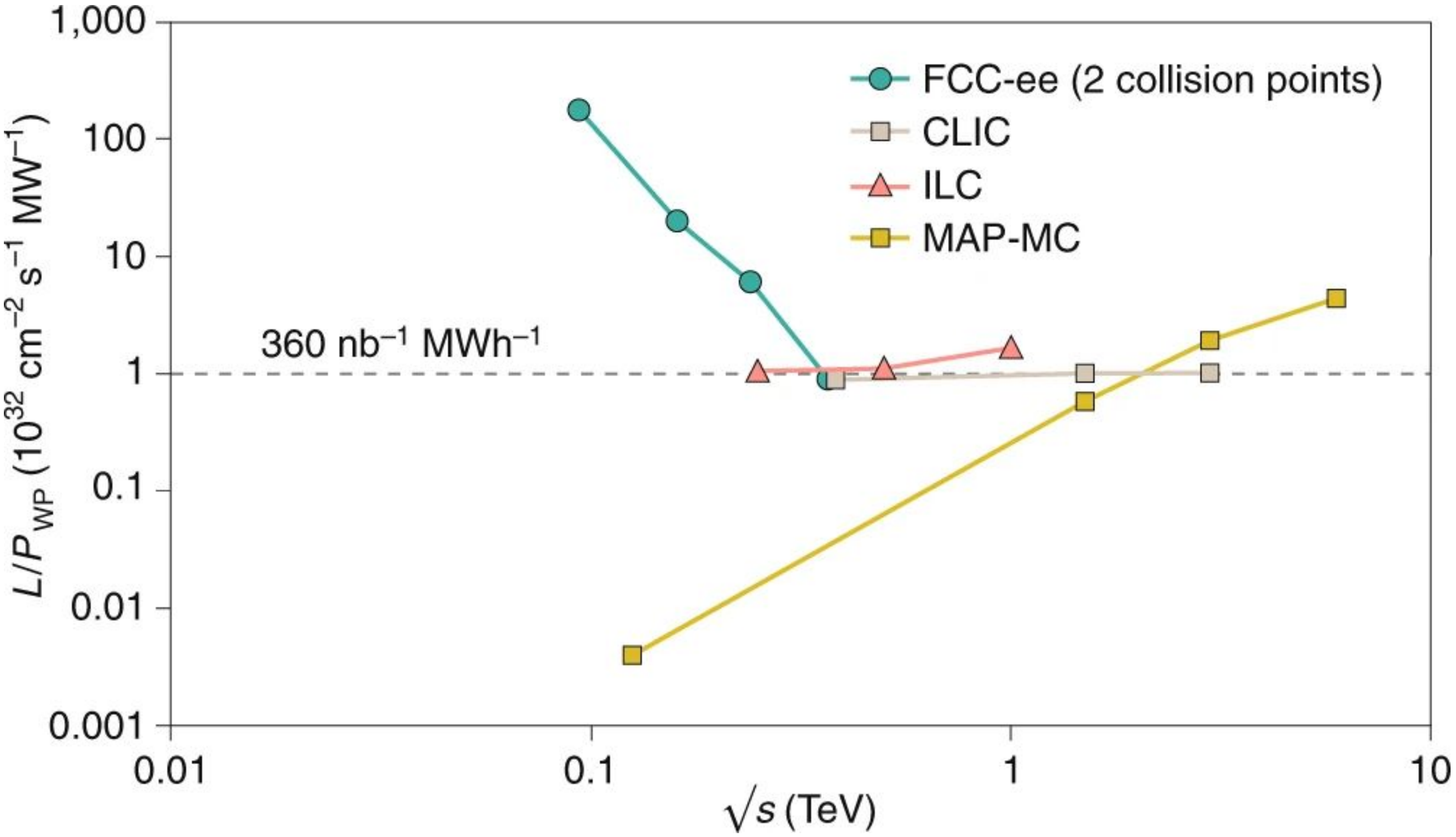
back to the next generation

From Snowmass ITF report*

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st physics	Cost range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
MC-Higgs	0.13	0.01	>10	19-24	4-7	~200
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560

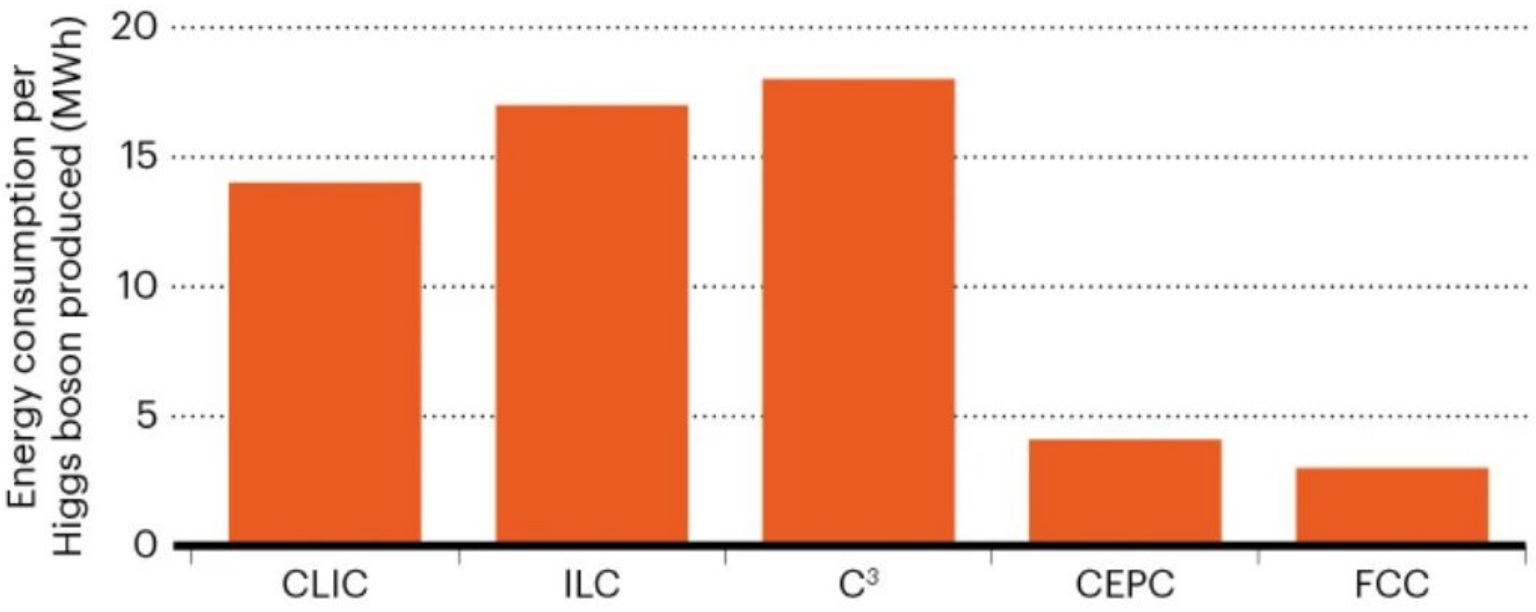
*CEPC missing

Energy efficiency: Higgs factories

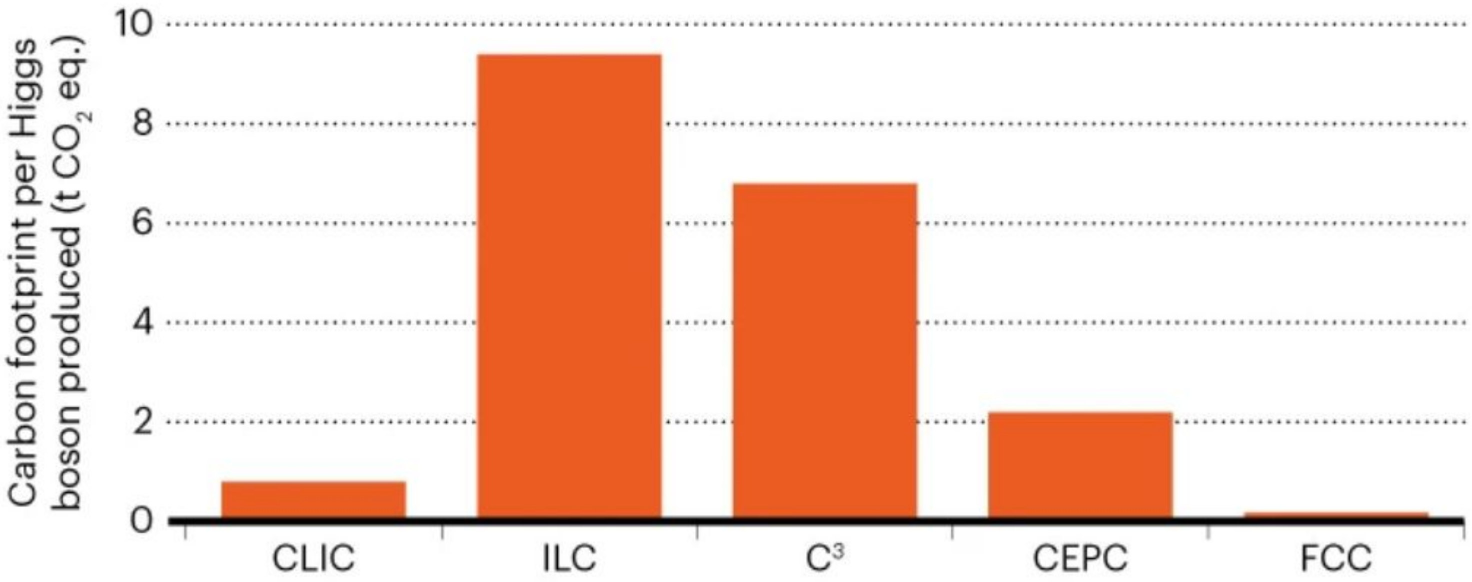


Total luminosity per electrical power. (Nature Physics vol. 16, 402, 2020)

Energy Consumption & Carbon Footprint per Higgs



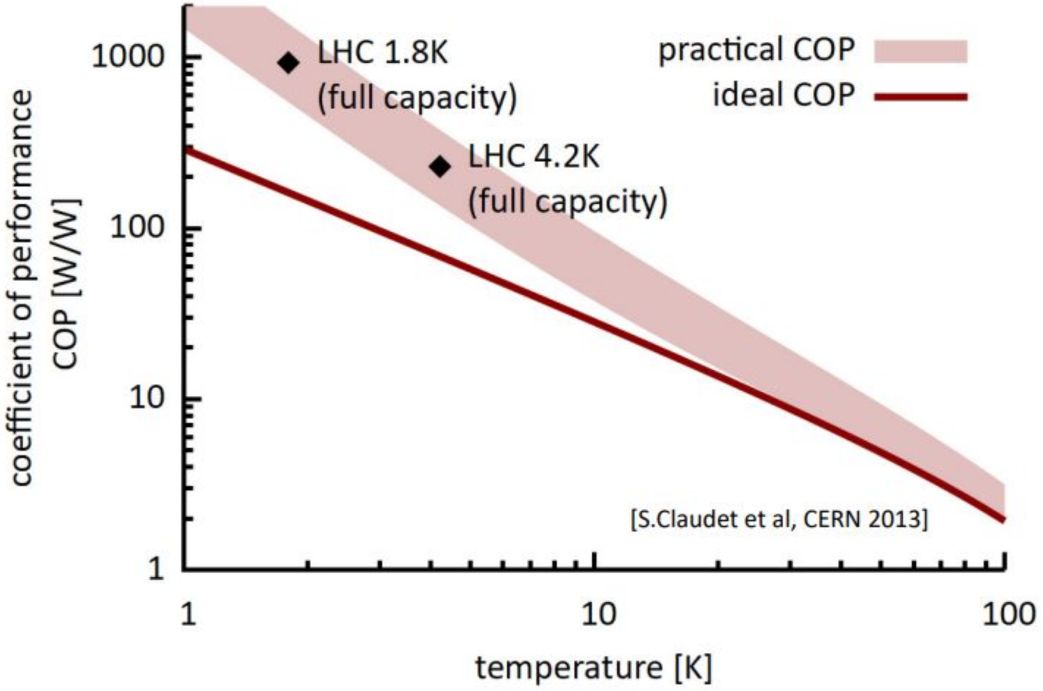
P. Janot and A. Blondel, *The carbon footprint of proposed e^+e^- Higgs factories*, arXiv 2208.10466 (2022); *The European Physical Journal Plus* **volume 137**, Article number: 1122 (2022) https://link.springer.com/content/pdf/10.1140/epjp/s13360-022-03319-w.pdf also see https://www.nature.com/articles/d41586-022-03551-5



Further sustainability considerations

Higher magnet temperature helps

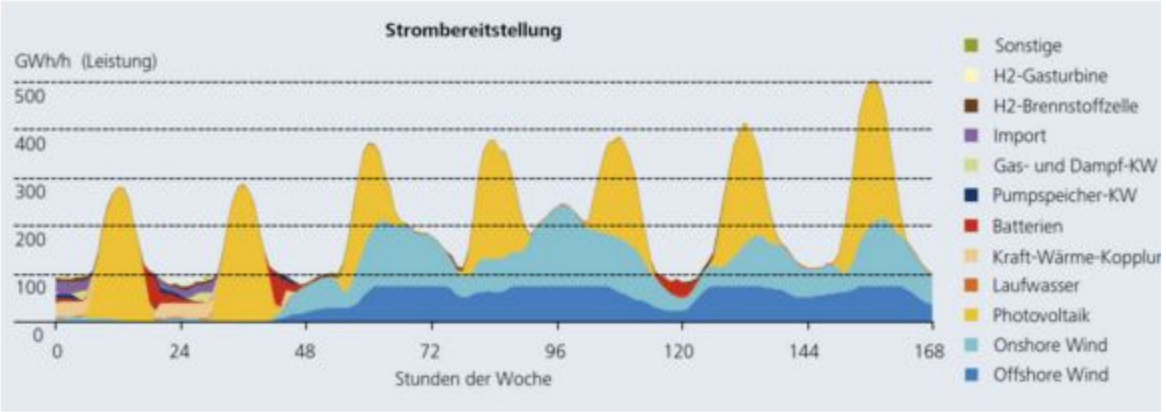
1.9 K Nb-Ti or Nb_3Sn magnets
→ 4.5 K/20 K Nb_3Sn/HTS magnets



still far from ideal Carnot efficiency

Future: fluctuating energy sources

Simulation for Germany 2050



full collider operation at times of high grid production

reduced operation or standby modes with fast L recovery otherwise

varying #bunches in circular colliders

M. Seidel

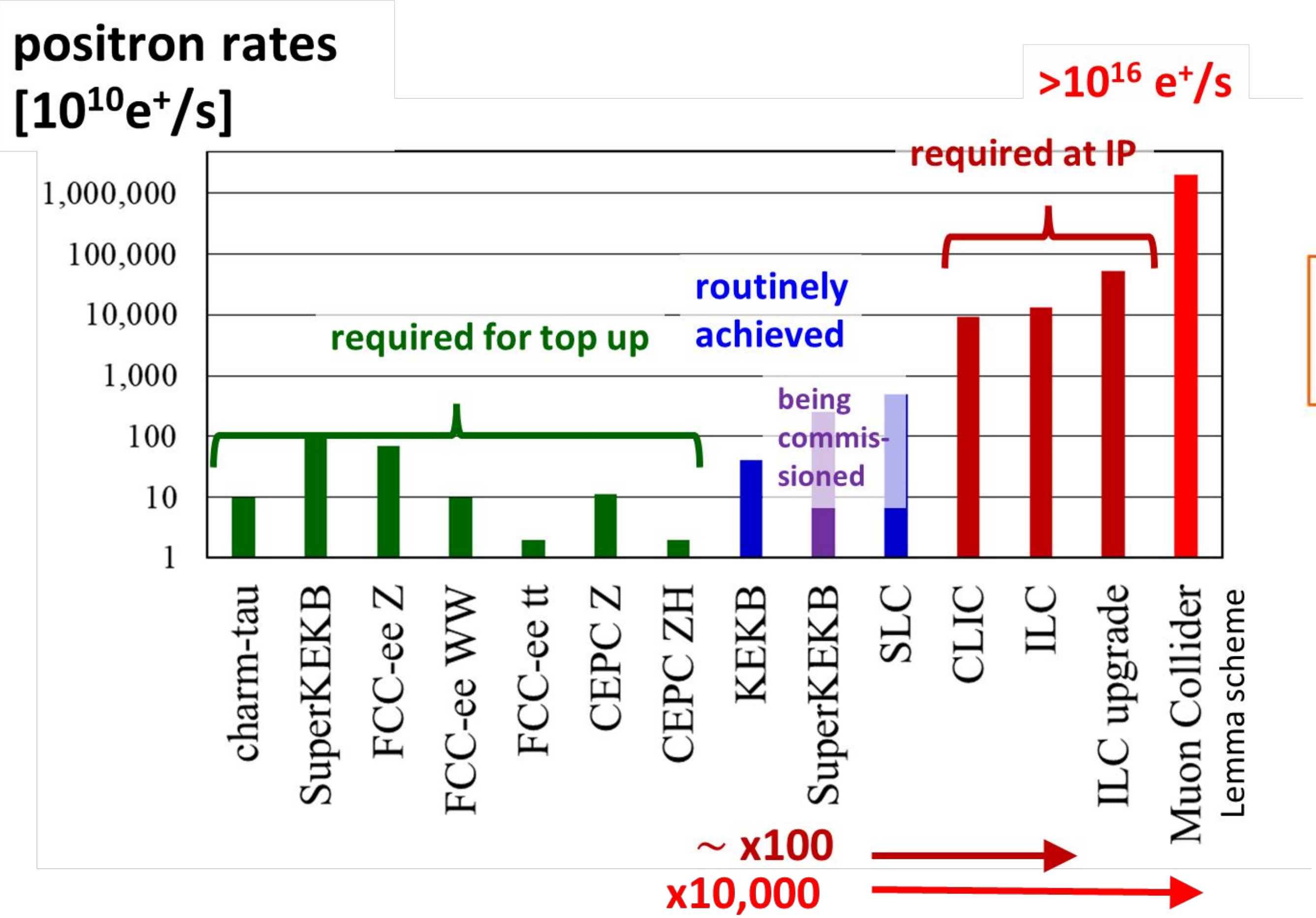
Future e^+e^- Collider Positron Requirements

Collider	Status	Colliding e+ / bunch (x10^10)	Colliding bunches to fill	Injection e+ bunches per pulse	Injection pulses/sec	Injection e+ bunches per second	Replacement e+ fraction per second	Total Inj e+/pulse (x10^10)	Total Inj e+/sec (x10^12)
LEP	Past	43.00	8	1	100	100	Ramped	0.12	0.12
SLC	Past	5.00	120	1	120	120	1.000000	5.00	6.00
PEP-II	Past	8.50	1732	1	30	30	0.001019	0.50	0.15
SuperKEKB	Ongoing	4.10	2151	2	50	100	0.002268	0.20	0.20
FCCee	Designed	20.20	12000	2	200	400	0.002475	1.50	6.00
CEPC	Designed	14.00	19918	2	100	200	0.001348	1.88	3.76
ILC	Designed	2.00	6560	1312	5	6560	1.000000	2.00	131.20
ILC (extend)	Designed	2.00	26250	2625	10	26250	1.000000	2.00	525.00
CLIC	Designed	0.57	17600	352	50	17600	1.000000	0.57	100.32
C3	Concept	0.63	15960	133	120	15960	1.000000	0.63	100.55
CERC	Concept	8.10	800	8	100	800	0.001235	1.00E-02	0.08
ERLC	Concept	0.50	53000	53	100	5300	0.000200	1.00E-03	0.05
ReLiC	Concept	1.00	22000	22	100	2200	0.000100	1.00E-03	0.02
PWFA-LC	Initial	1.00	10000	1	10000	10000	1.000000	1.00	100.00
PWFA-LC (ext)	Initial	1.00	20000	1	20000	20000	1.000000	1.00	200.00
LWFA-LC	Initial	0.12	47000	1	47000	47000	1.000000	0.12	56.40
SWFA-LC	Initial	0.31	23100	231	100	23100	1.000000	0.31	71.61

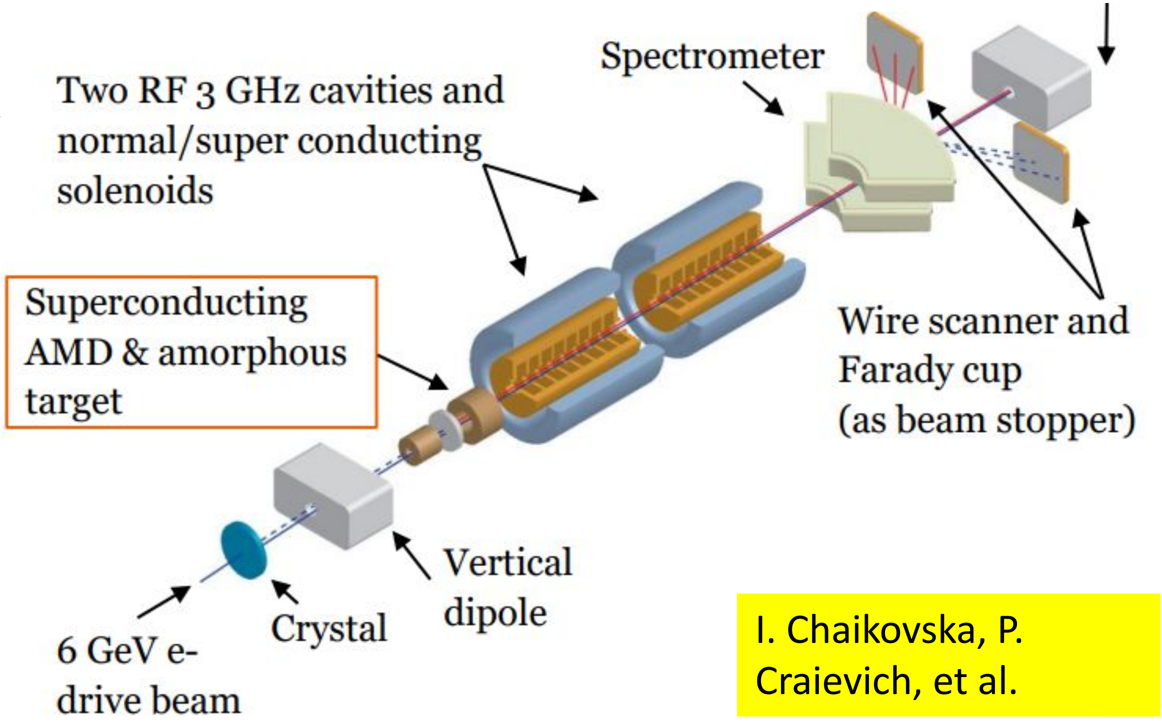
} ?

Positron Production

Challenging demands



Innovative high-yield source



I. Chaikovska, P. Craievich, et al.

P^3: PSI e^+ production experiment with HTS solenoid at SwissFEL

planned for 2024/25

Snowmass'21 (2022) – maturity ranking

arXiv:2209.05827

A. Faus-Golfe et al.

Collider	Design Maturity	R&D Maturity
ILC-250	10	9-10
ILC-500	10	9-10
ILC-1000	6-7	6-7
CLIC-380	9	10
CLIC-1500	8	9-10
CLIC-3000	8	8-9
C3-250	3	3
C3-550	3	2
C3-Nb_3Sn	1	0
HELEN	3 (ML)	2 (SRF)
ReLiC	3	4
ERLC	3	4
XCC γγ	2	2
HE&HL γγ	0	0

Collider	Design Maturity	R&D Maturity
FCC-ee	9	9
CEPC	9	9
CERC	3	4
LEP3	3	8
EPCCF	3	8
MC-HF	3	2

Design Maturity	Maturity Criteria #1 (Design Maturity)	Maturity Criteria #2 (R&D Maturity)
0	No end-to-end design concept prepared	Concept proposed, but no systematic design requirements and/or parameters available.
1	No end-to-end design concept prepared	Concept proposed, proof-of-principle R&D underway
2	End-to-end preliminary design concept under development	Ongoing R&D to address fundamental physics/technical issues.
3	End-to-end preliminary design concept available	Sub-system operating parameters established based on preliminary design concepts for novel/critical sub-systems
4	End-to-end integrated design concept under development	Preliminary design concepts with operating parameters established for all sub-systems. Sub-system design R&D underway.
5	End-to-end integrated design concept available. Enables end-to-end performance evaluation.	Sub-system preliminary designs exist. Sub-system design R&D continues.
6	End-to-end performance evaluation complete. Reference (pre-CDR level) Design Report under development.	Sub-system performance risk assessment complete.
7	Reference Design available. Sub-system parameters and high potential alternatives documented.	Sub-system detailed design and performance R&D for highest risk sub-systems underway.
8	Conceptual Design Report in preparation.	Sub-system specifications with validated operating parameters established. High risk sub-system R&D underway.
9	Conceptual Design Report and detailed cost estimate avaialable.	High risk sub-system R&D ongoing. Risk mitigation strategy for sub-system performance established.
10	Ready for Construction Proposal. Detailed Engineering Design being developed.	Performance Optimization R&D underway.

A few conclusions

- Great progress in SC RF and in high-field magnets
- Accelerators & colliders getting ever more efficient
- Synergies with other applications and other fields
- Numerous innovative concepts and challenges for future colliders
- Advanced DLAs for indirect dark sector searches ?
- Sustainability has become important design criterion
- Several promising paths forward

“The future depends on what we do in the present.“ – Mahatma Gandhi

surely great times ahead !