Future Particle Accelerators

Frank Zimmermann
International Teacher Programme 2024
15 August 2024

outline

- **accelerators**
- **particle colliders, including luminosity & beam-beam**
- **next and next-next(-next) generation high-energy machines**
  - **hadron colliders, both circular and linear electron-positron colliders, and muon colliders**, along with 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.

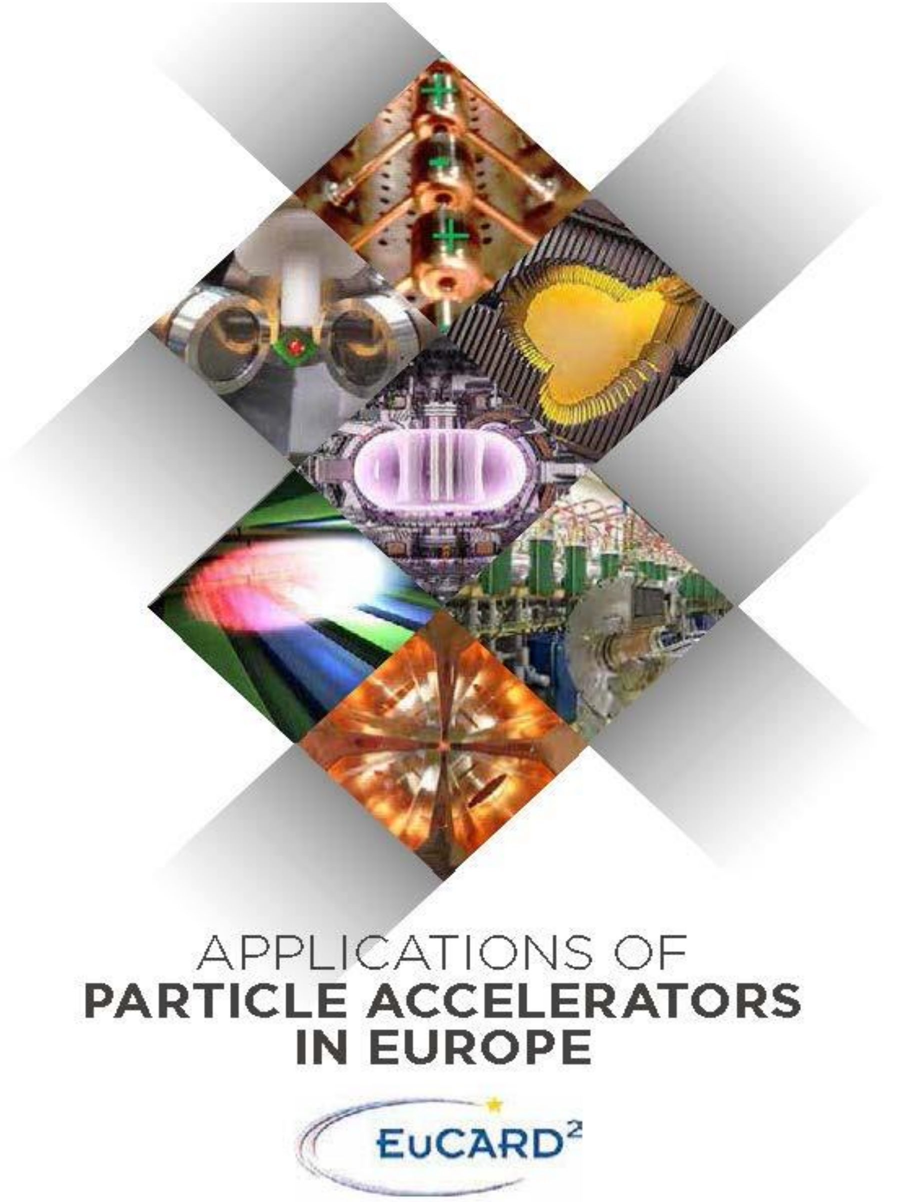
Cutting-edge industrial equipment: analysis and modification of surfaces across many fields (ion implantation, polymer treatment, sterilization, environment, etc.).

Applications of Particle Accelerators

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

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

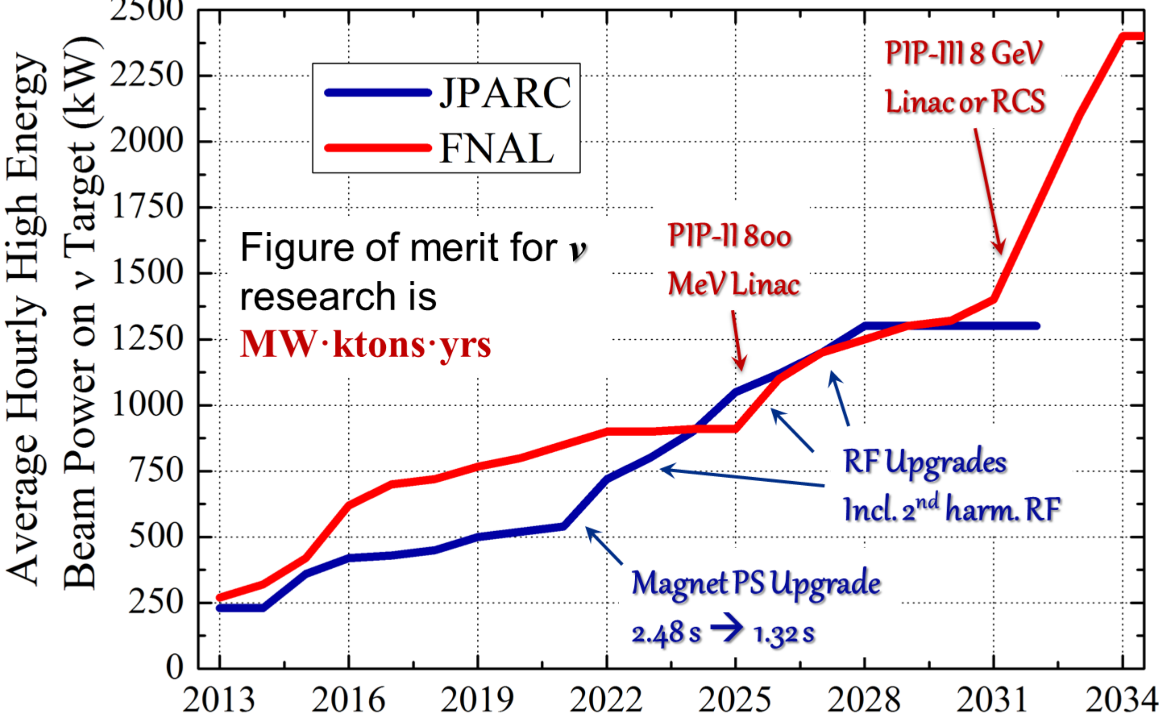
CERN-ACC-2020-0008 http://cds.cern.ch/record/2716155



APPLICATIONS OF
PARTICLE ACCELERATORS
IN EUROPE

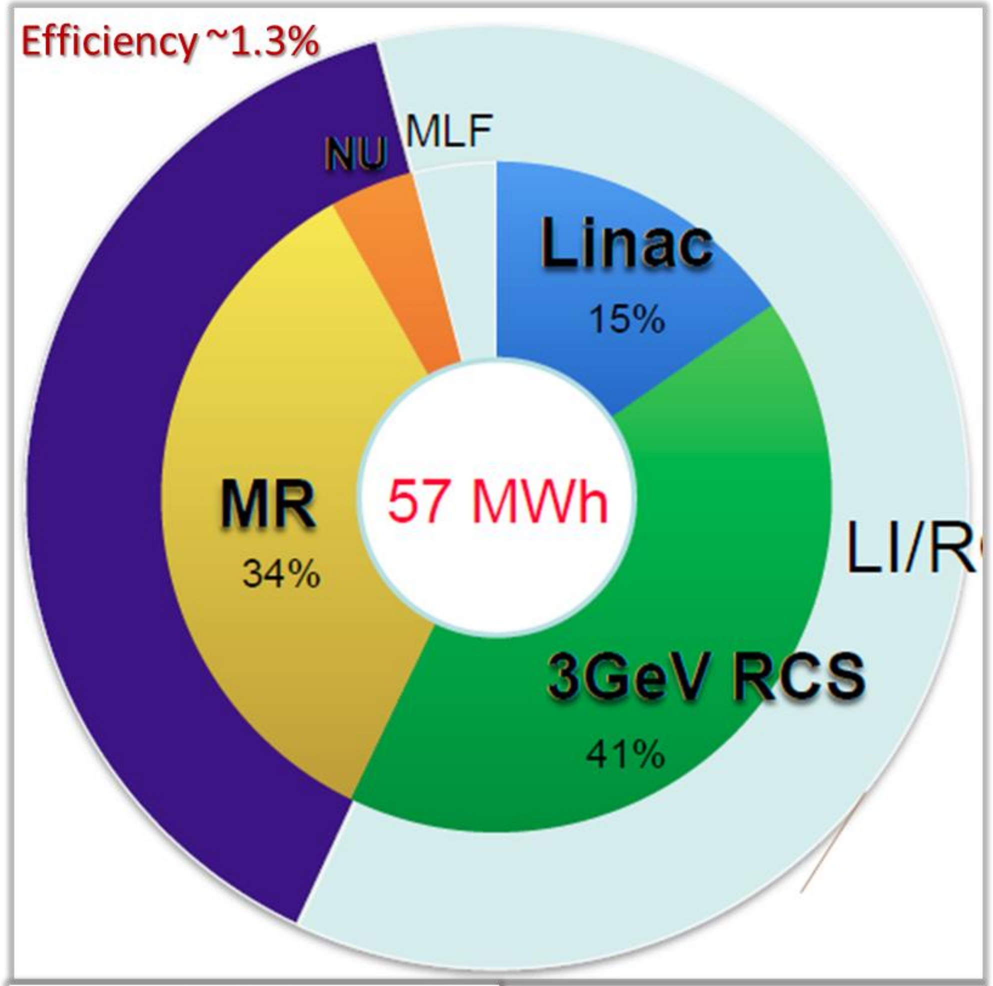
example: super-beam facilities & upgrades

Fermilab & J-PARC Power Upgrades



power efficiency challenge

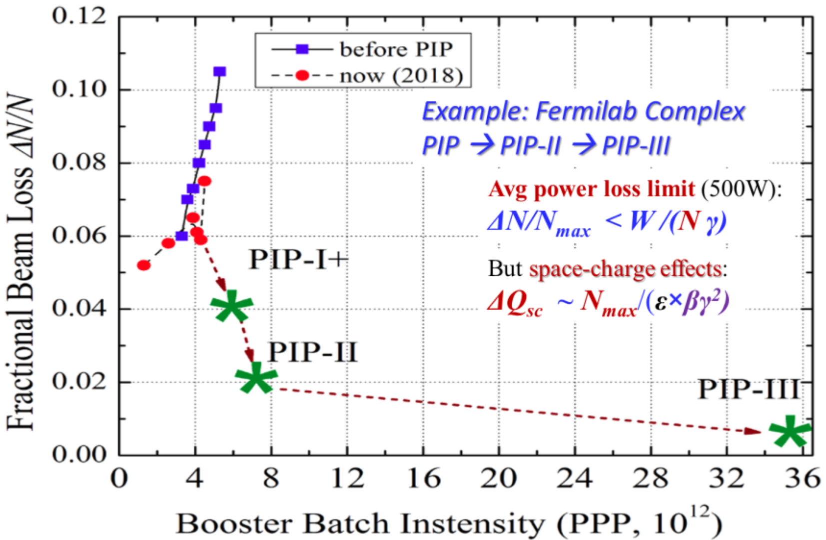
J-PARC : 0.5 MW beams vs ~40 MW site power



- MR Magnets: 10.4 MWh per hour
- MR RF: 3.8 MWh per hour

- RCS Magnets: 9.6 MWh per hour
- RCS RF: 7 MWh per hour

protons per pulse challenge



V. Shiltsev

examples: 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

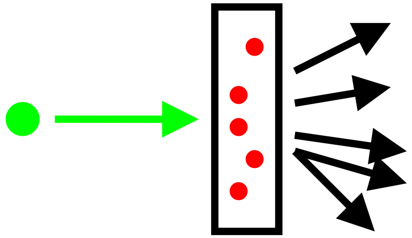
why colliders ? - energy

colliders were invented (1943) and patented (1953) by Rolf Wideröe

centre-of-mass energy:

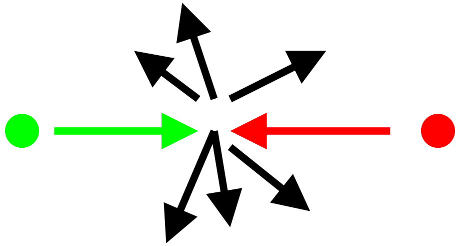
$$E_{\mathrm{c.m.}} = \sqrt{2E_{\mathrm{beam}}M_{\mathrm{target}}c^2}$$

beam hits
a “fixed target”



$$E_{\mathrm{c.m.}} = 2E_{\mathrm{beam}}$$

two equal
beams collide

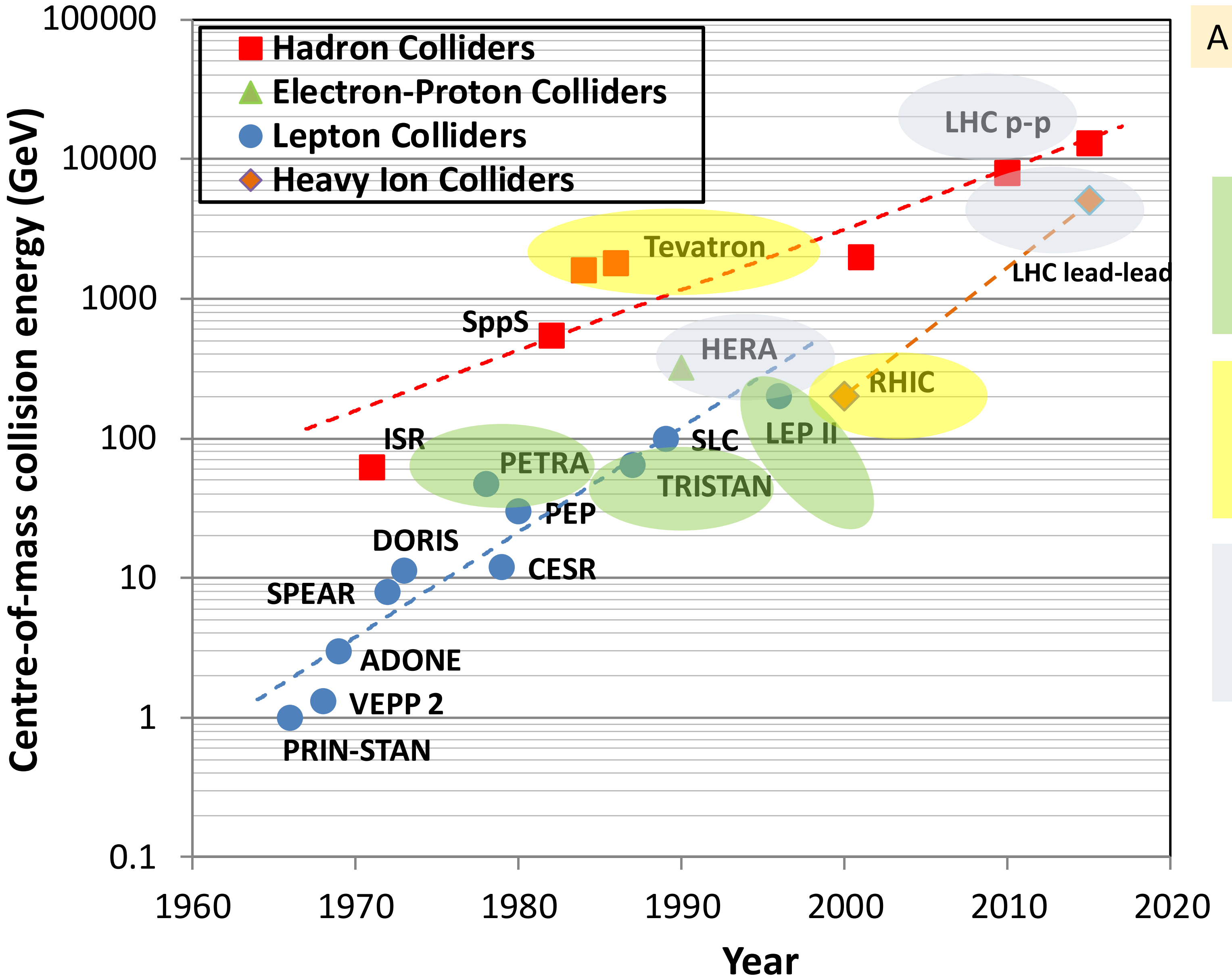


colliding two beams against each other can provide much higher centre-of-mass energies than fixed target!

$$E_{\mathrm{c.m.}} = 2\sqrt{E_1E_2}$$

for two high-energy beams
of unequal energy

particle colliders constructed and operated



A. Ballarino

🟩 Colliders with superconducting RF system

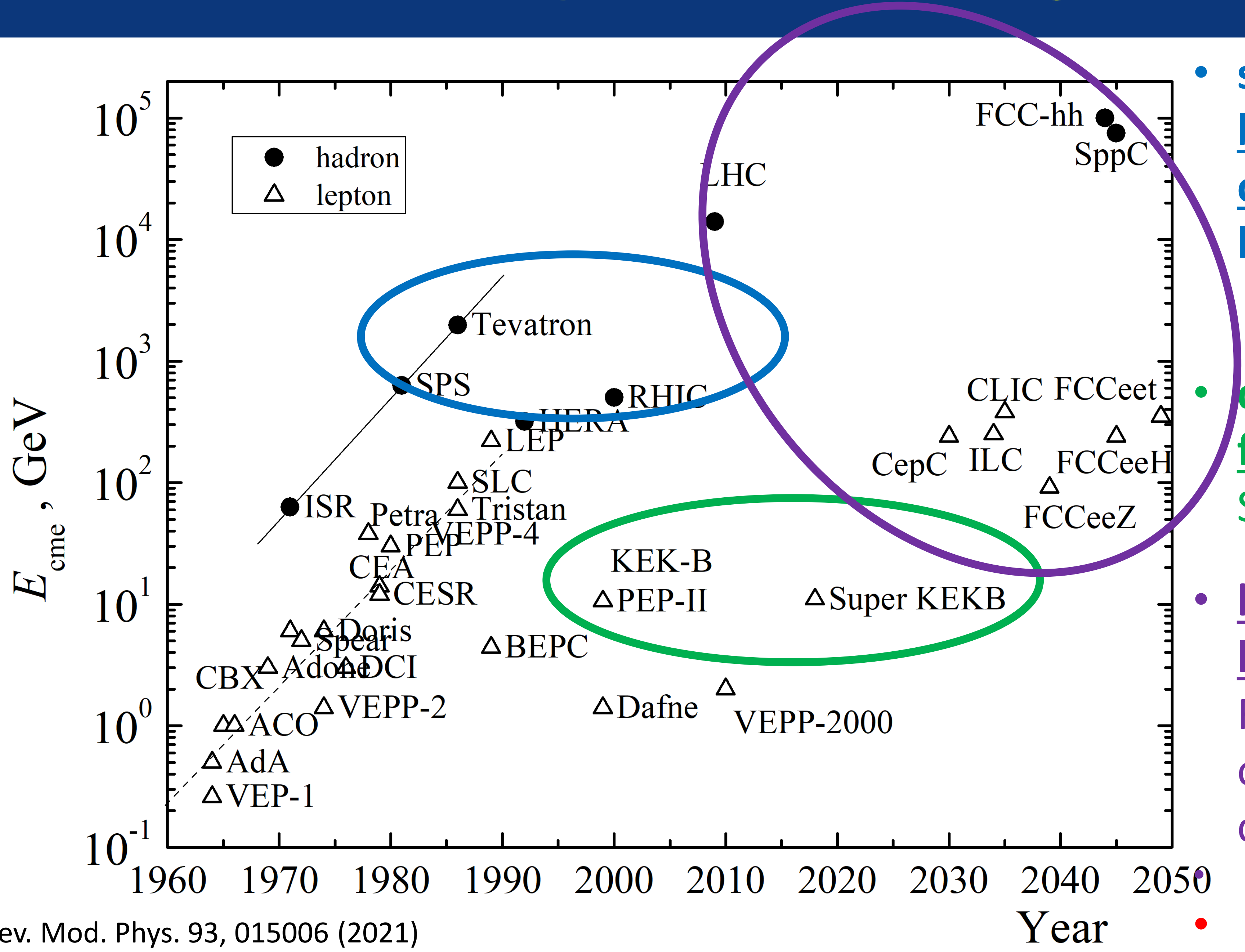
🟨 Colliders with superconducting arc magnet system

⬜ Colliders with superconducting magnet & RF

advances by new technologies and new materials

(important example SC)

more key collider technologies & concepts

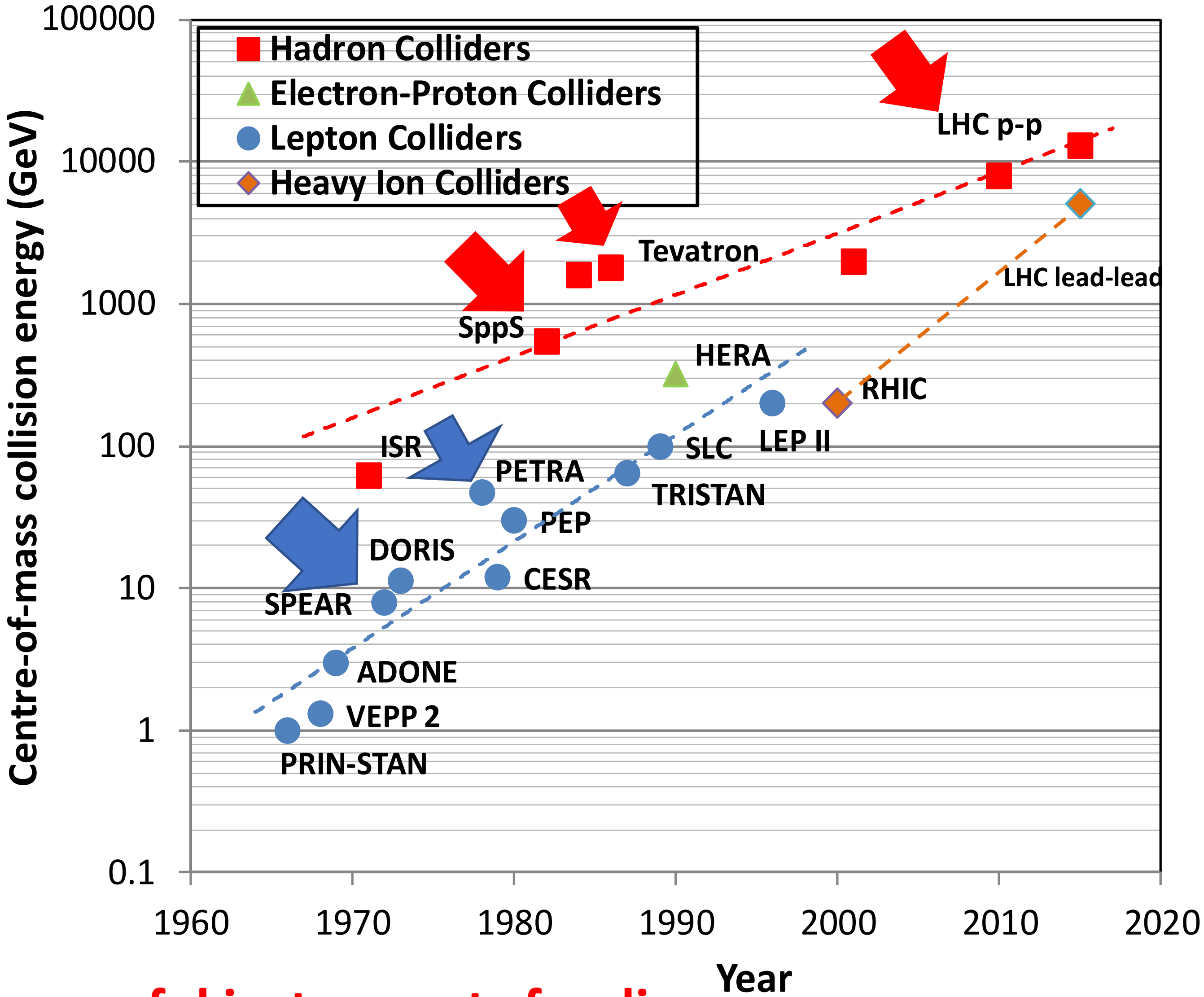


Rev. Mod. Phys. 93, 015006 (2021)

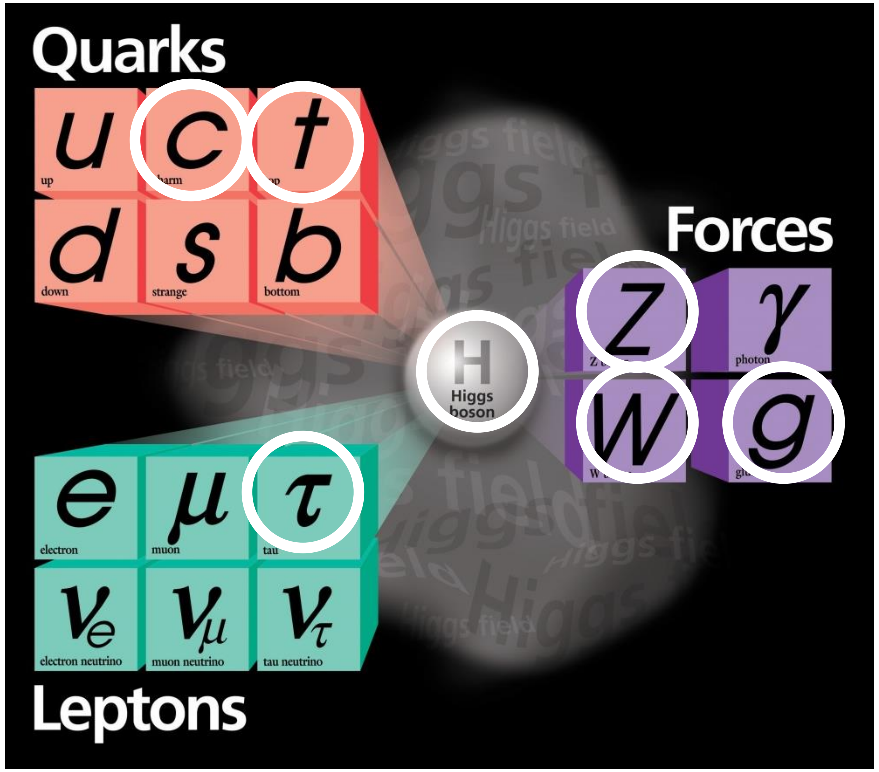
- **stochastic cooling and bunched beam stochastic cooling of antiprotons and heavy ions:**
  SPS, Tevatron, RHIC + … ?
- **development of asymmetric B factories:** PEP-II, KEKB, SuperKEKB
- **highest energy hadron and lepton colliders:** LHC, HL-LHC, FCC, CLIC, ILC, μ colliders, γγ colliders, plasma-based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

colliders and discoveries

A. Ballarino



Standard Model
Particles and forces

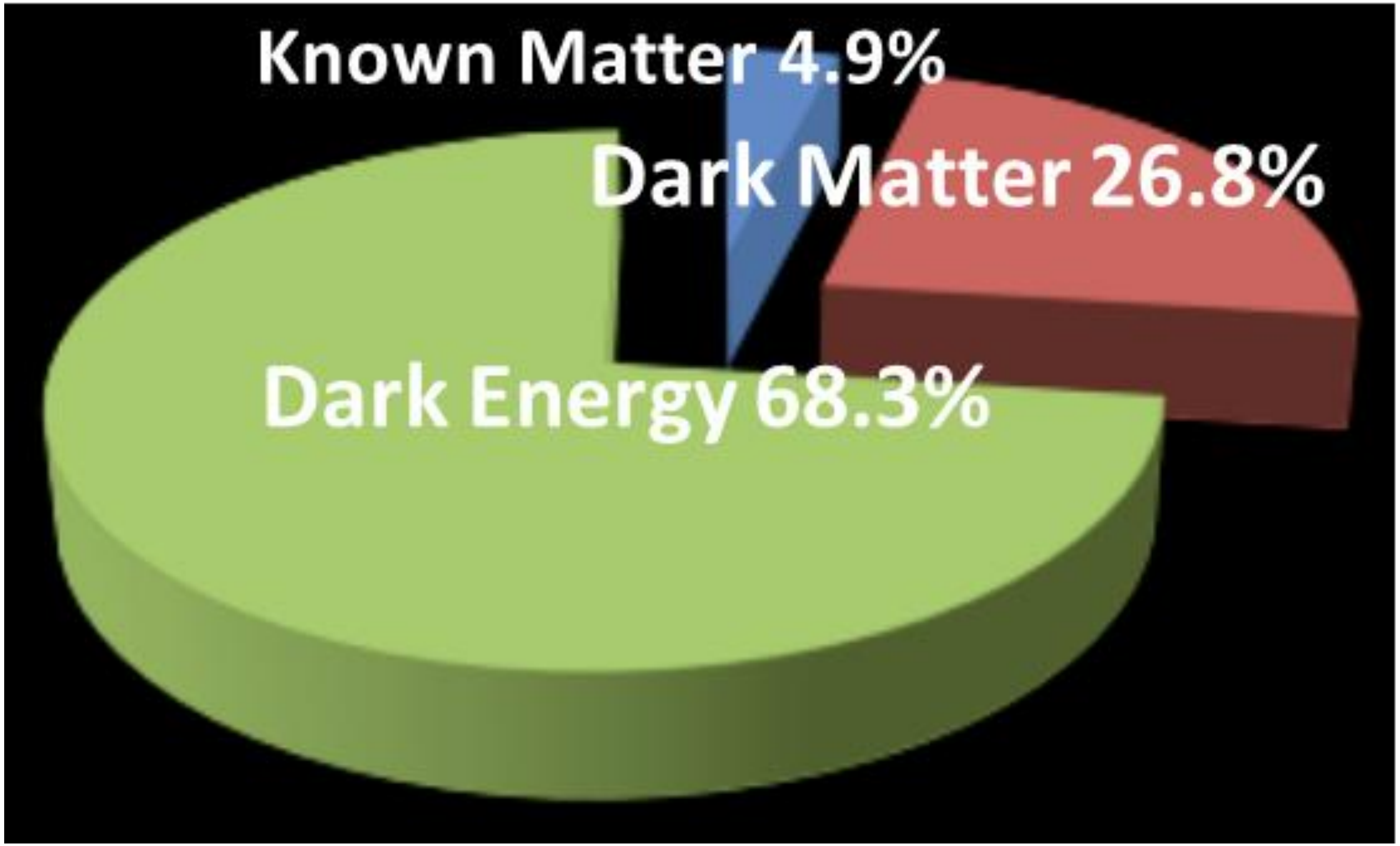


powerful instruments for discovery
and precision measurement

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}

bunch population

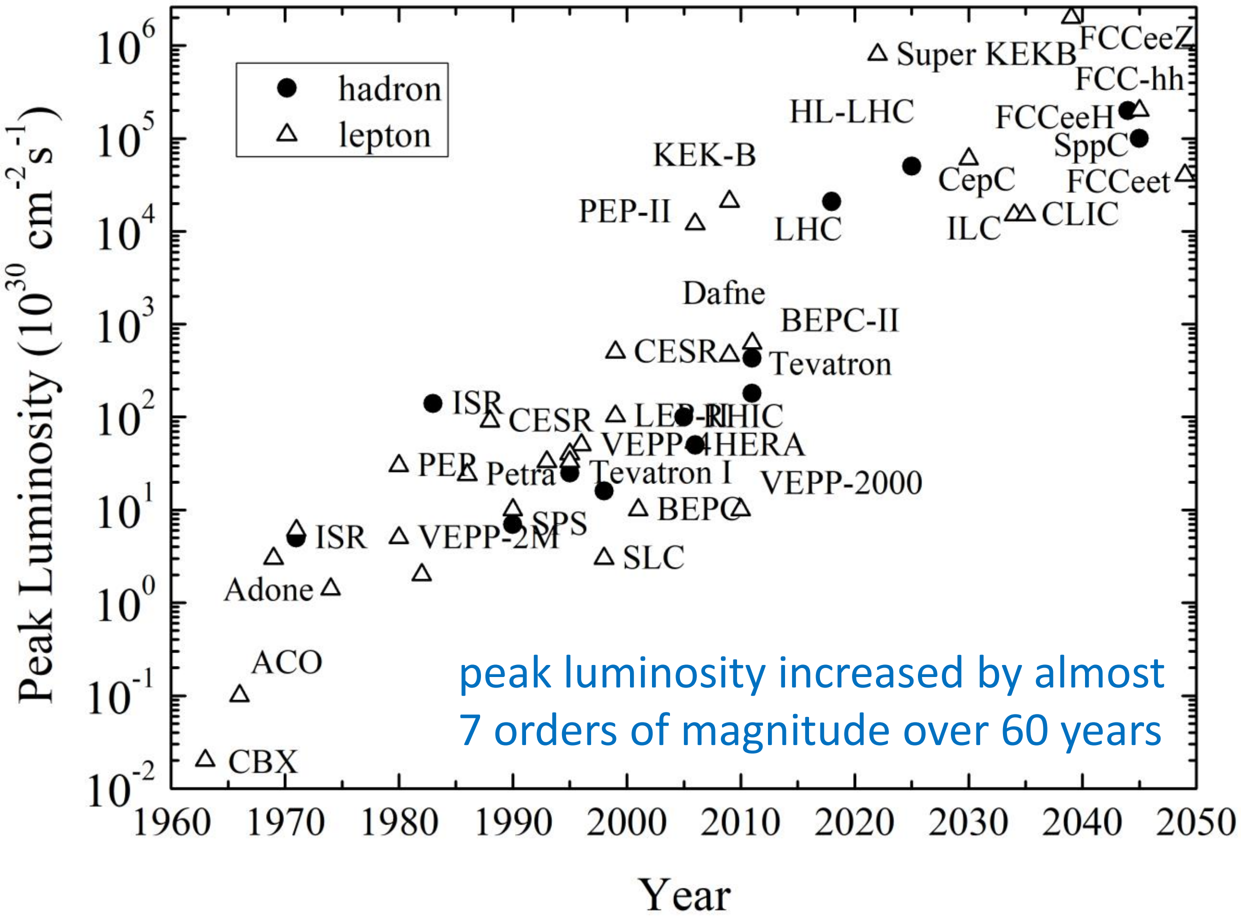
geometric factor (crossing angle, hour glass, pinch, …)

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

bunch collision rate

horizontal & vertical rms beam size at collision point

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



peak luminosity increased by almost 7 orders of magnitude over 60 years

collider figure of merit: integrated luminosity

Example: hadron collider energy reach with *M* the mass of new particle to be discovered

$$\sigma \propto \frac{1}{E^2} f(M/E) \qquad f\left(\frac{M}{E}\right) \sim \left(\frac{M}{E}\right)^{-6}$$

$$\longrightarrow \quad M \propto E^{2/3} L_{\mathrm{int}}^{1/6}$$

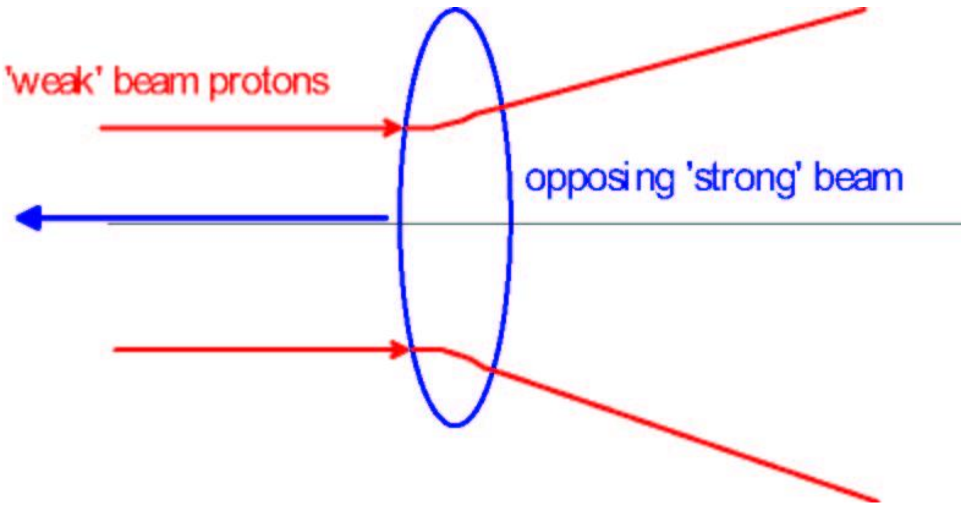
Lee Teng, APAC 2001
also V.Shiltsev, F.Z., RMP **93**, 015006 (2021)

proposed figure of merit

$$\mathrm{FoM}_{\mathrm{hadron\ collider}} = \frac{E^{2/3} L_{\mathrm{int}}^{1/6}}{\int P_{\mathrm{wall}}\, dt}$$

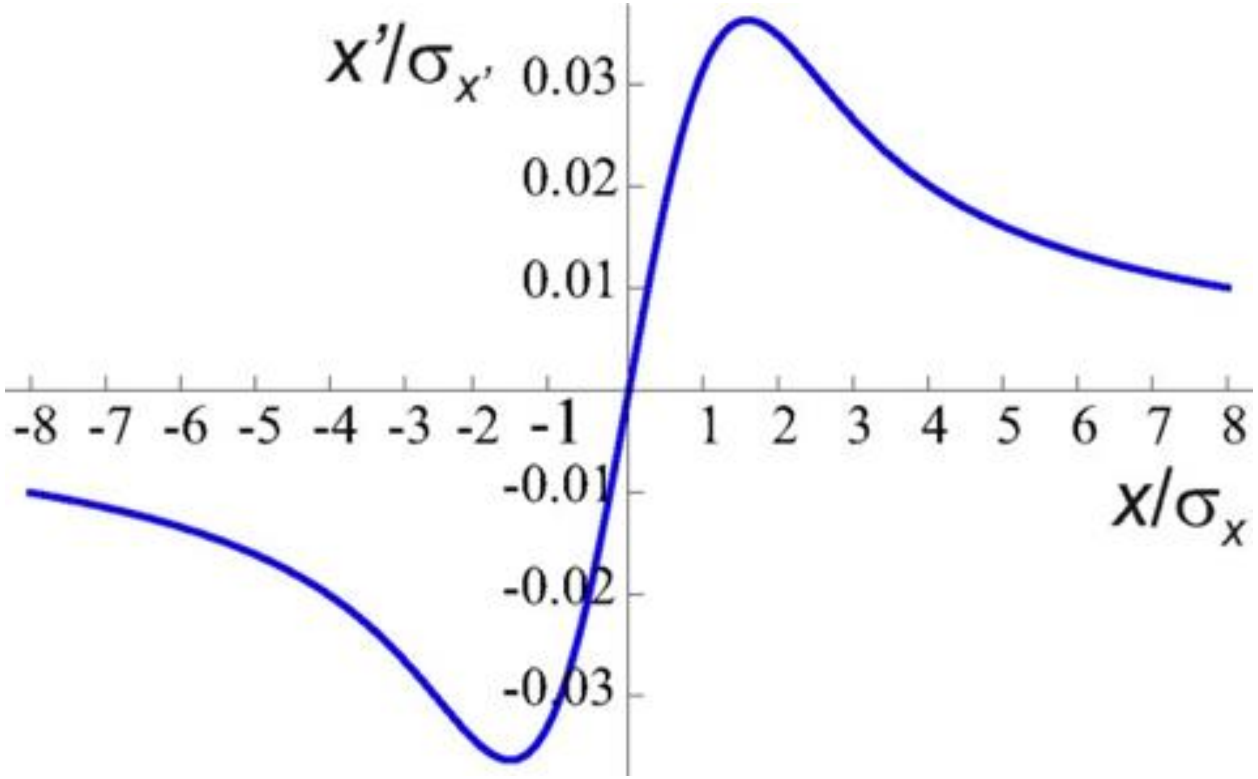
another
collider figure of merit

collider figure of merit: beam-beam tune shift



head-on beam-beam collision in the LHC

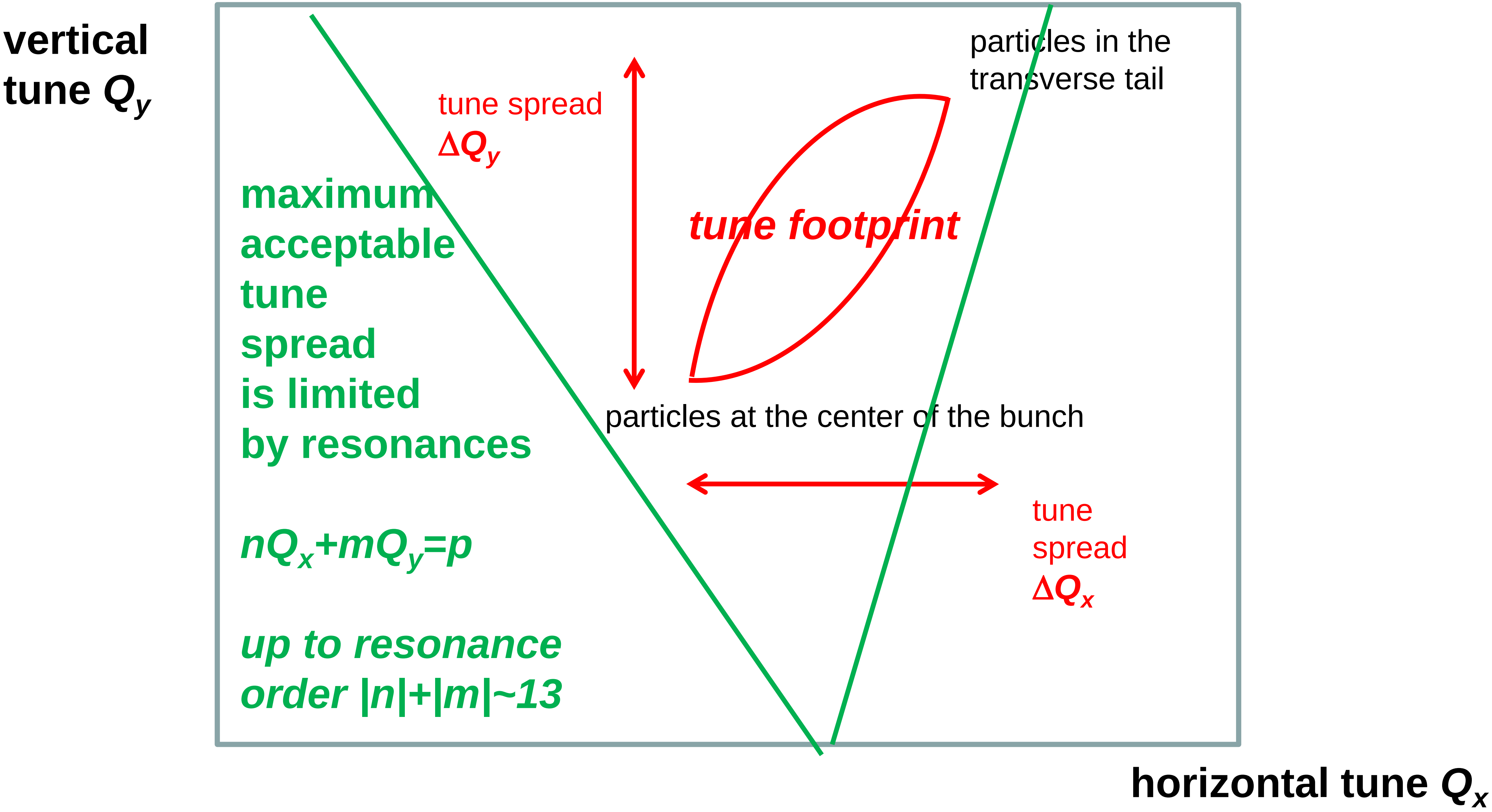
(nonlinear) beam-beam force



at small amplitude similar to effect of defocusing quadrupo

for pure head-on collision $$\Delta Q_{x.y;\mathrm{max}} = \xi_{x,y} = \frac{2N_b r_0 \beta^*}{4\pi\gamma\left(2\sigma^{*2}\right)} = \frac{N_b}{\varepsilon_N}\frac{r_0}{4\pi}$$ for single collision (nominal LHC ~0.0033)

beam-beam tune spread



vertical tune Q_y

maximum acceptable tune spread is limited by resonances

$nQ_x+mQ_y=p$

up to resonance order $|n|+|m|$~13

tune spread ΔQ_y

tune footprint

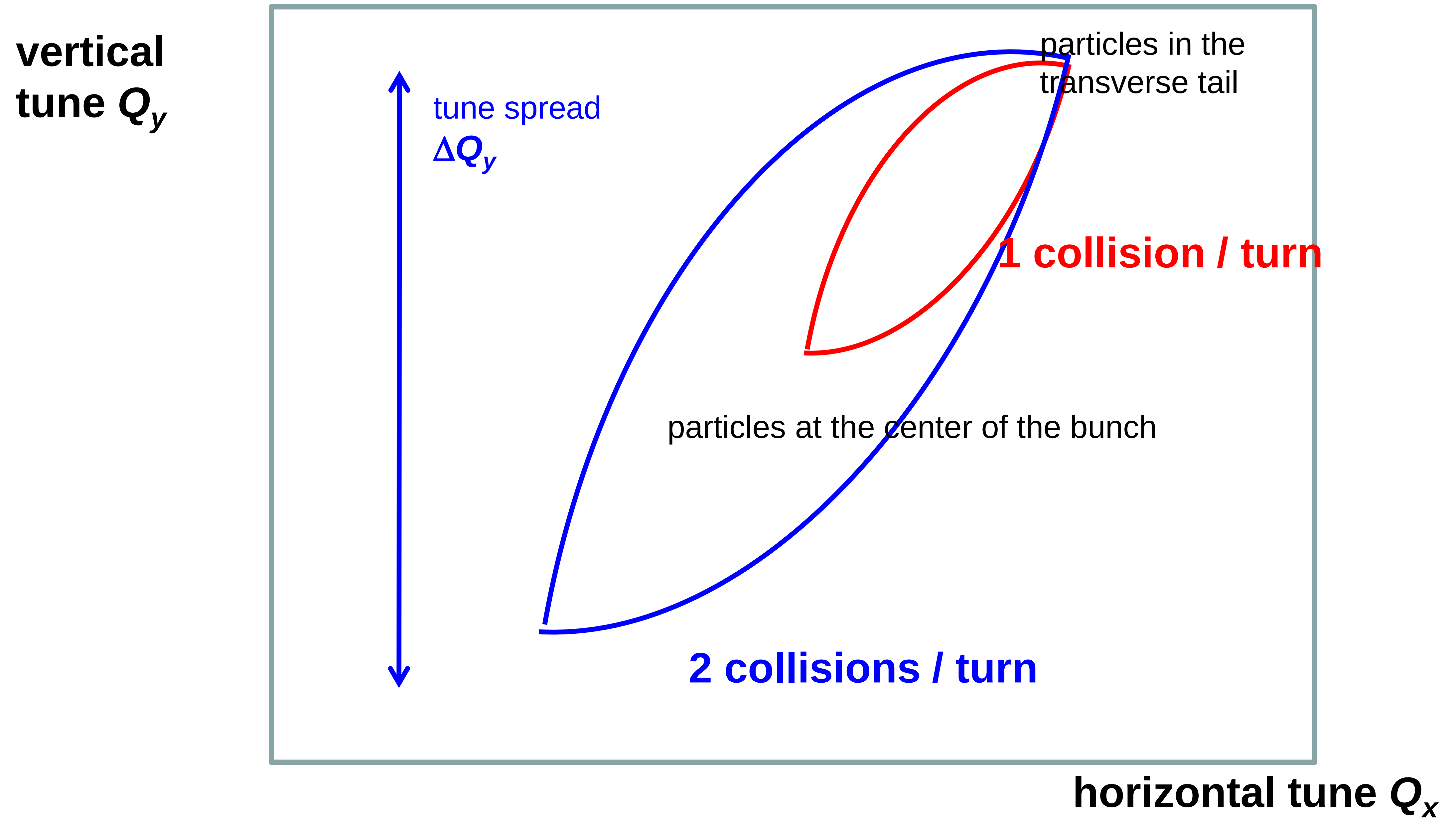
particles in the transverse tail

particles at the center of the bunch

tune spread ΔQ_x

horizontal tune Q_x

multiple interaction points



vertical tune Q_y

tune spread ΔQ_y

particles in the transverse tail

1 collision / turn

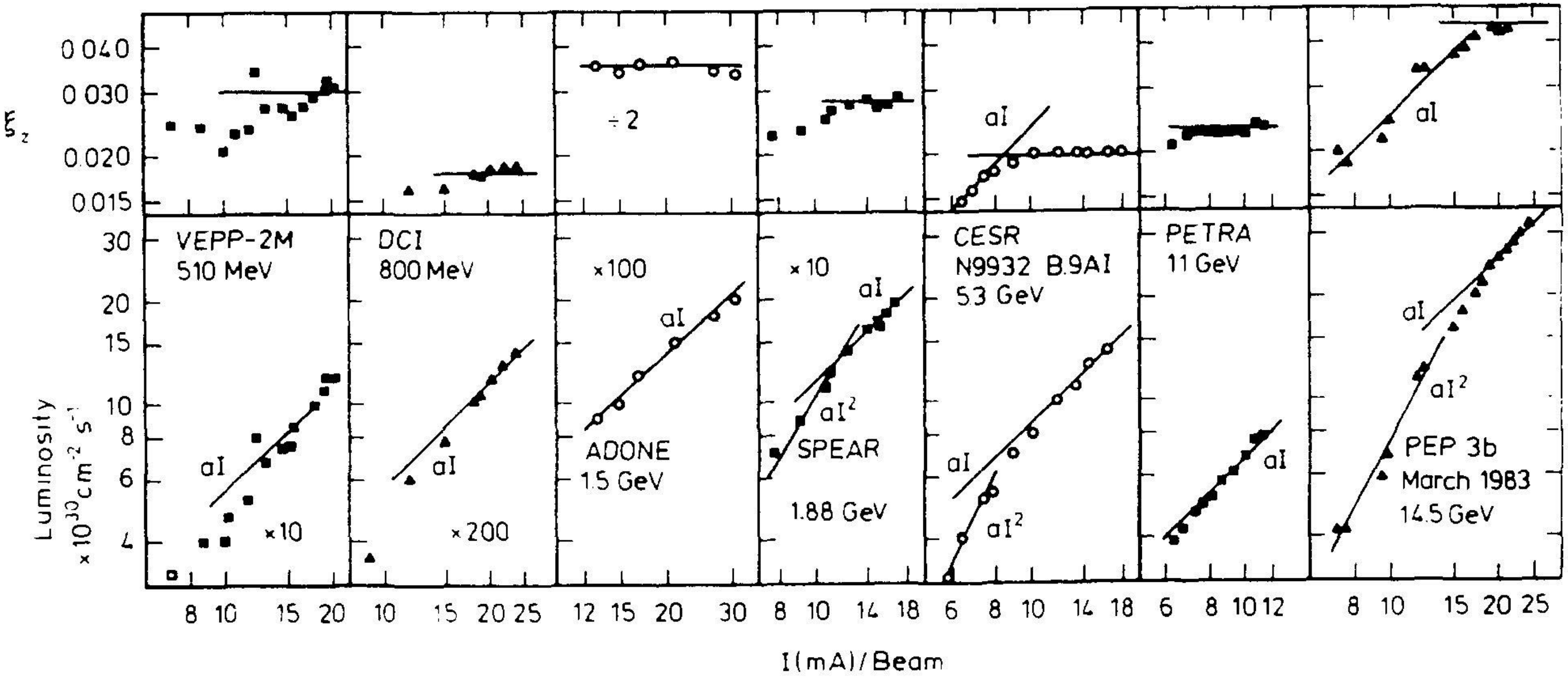
particles at the center of the bunch

2 collisions / turn

horizontal tune Q_x

beam-beam limit in e$^+$e$^-$ colliders

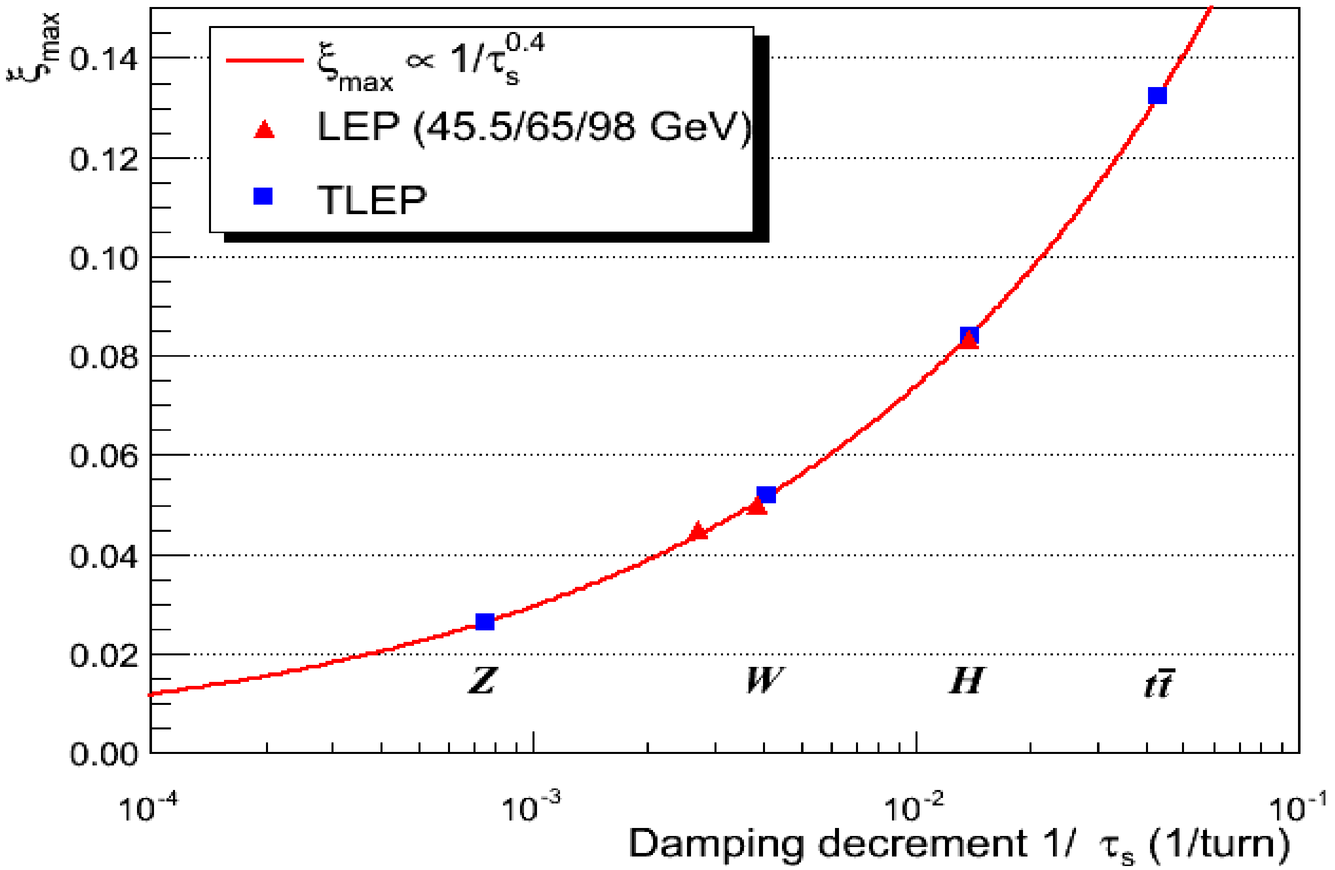
J. Seeman



luminosity and vertical tune-shift parameter versus beam current for various electron-positron colliders; the tune shift saturates at some current value, above which the luminosity grows linearly

beam-beam limit w strong SR damping

R. Assmann



$$\lambda_d = 1/(f_{rev} \cdot \tau \cdot n_{ip})$$

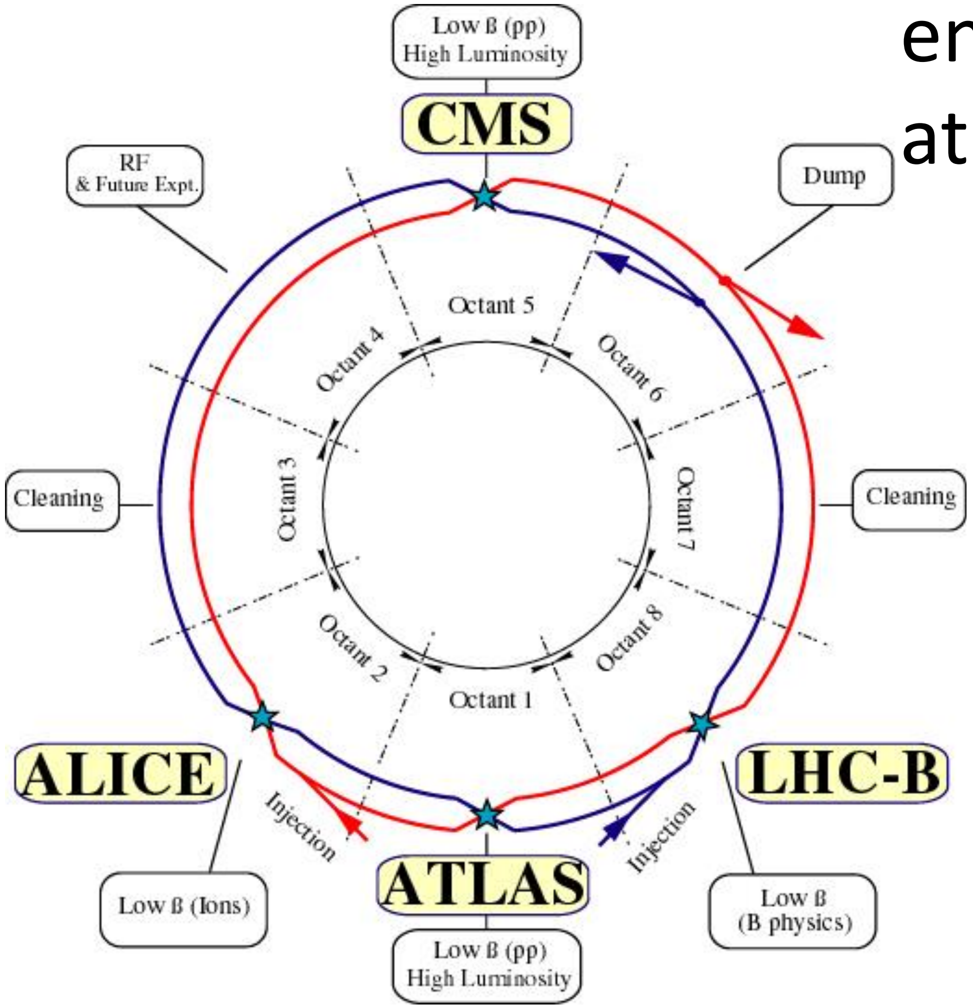
damping decrement per IP

$$\xi_y^{\infty} \propto (\lambda_d)^{0.4}$$

Modern Colliders

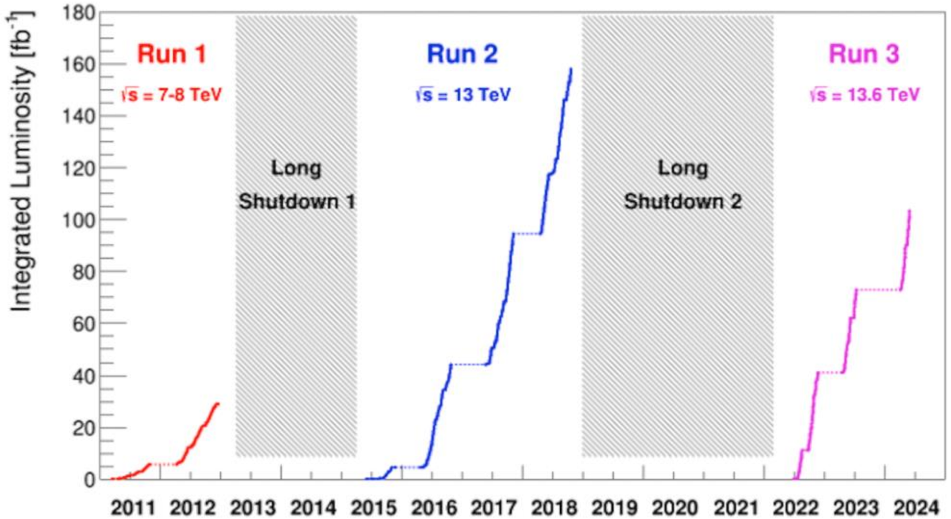
Large Hadron Collider (LHC)

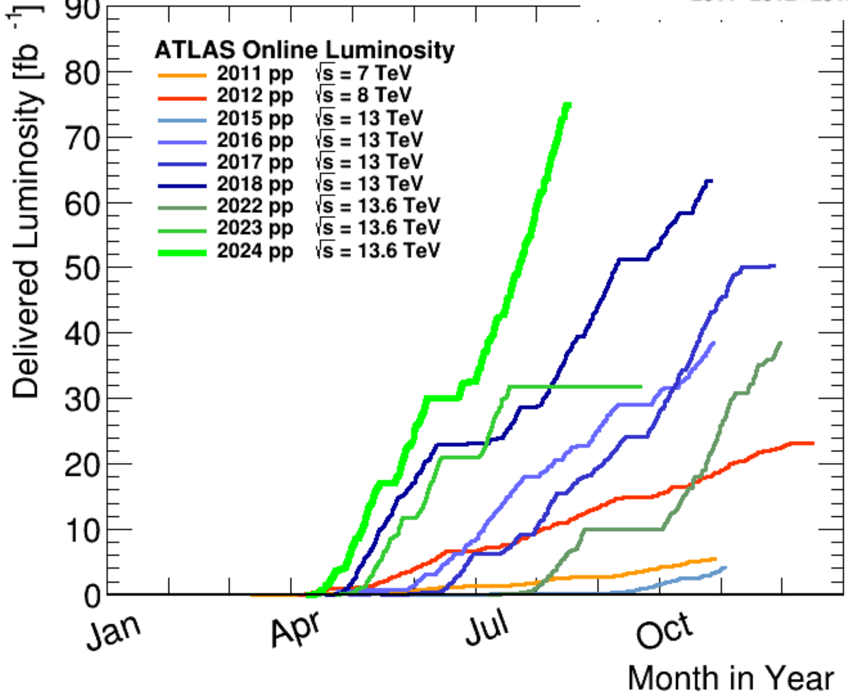
circumference 27 km



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

running extremely well



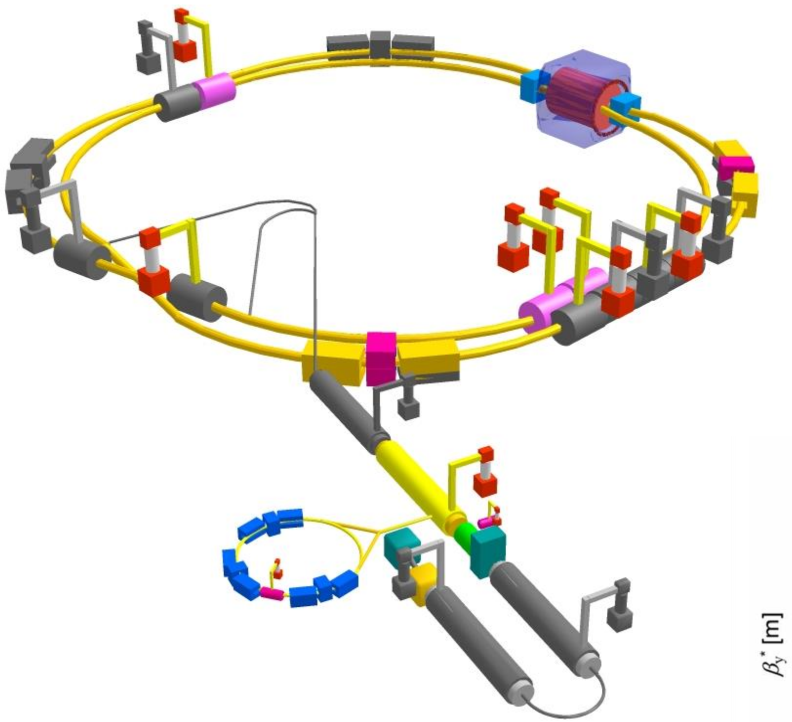


total integrated luminosity so far ~400 fb^{-1} over ~14 years

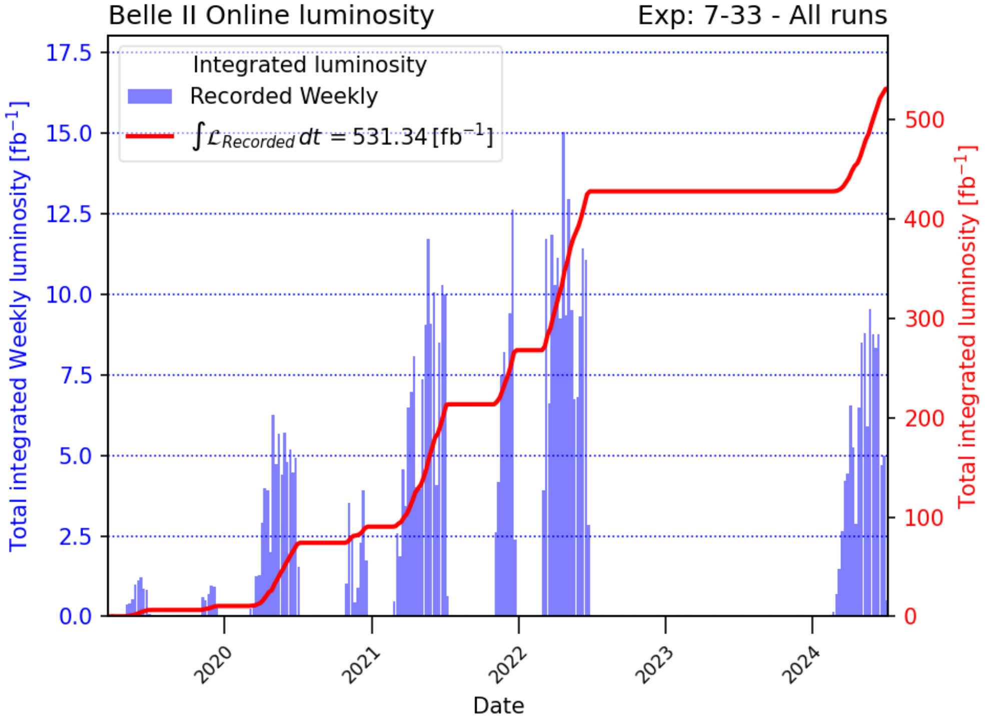
peak luminosities up to **~$2.2\text{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$**, levelled to $1.5\text{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

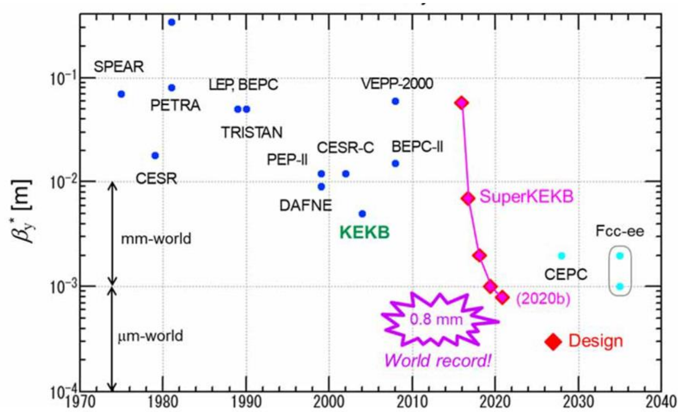
SuperKEKB

circumference 3 km



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





total integrated luminosity so far ~535 fb^{-1} over ~5 years

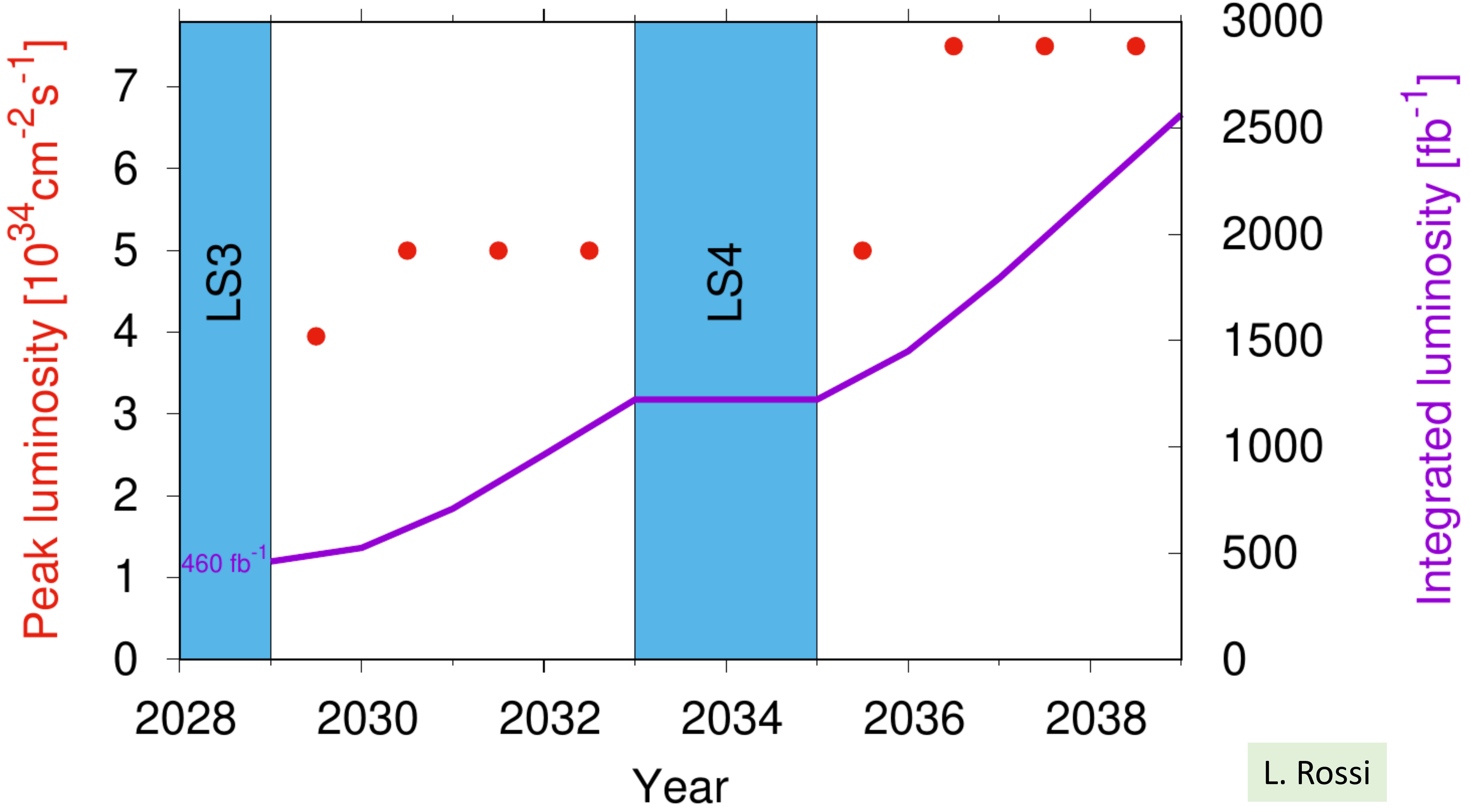
world record luminosity of $4.71\mathrm{x}10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, β_y^* = 1.0 mm routinely, also β_y^* = 0.8 mm shown

– with "virtual" crab-waist collision scheme originally developed for FCC-ee (K. Oide)

near-future collider 1: High-Luminosity LHC

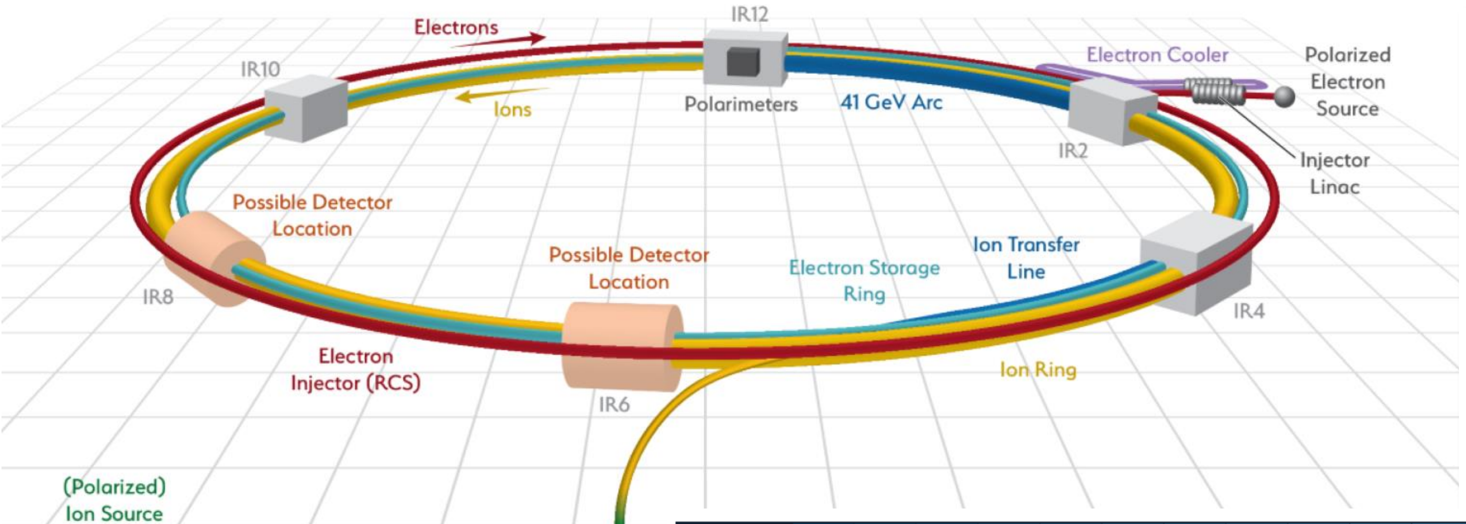
High-Luminosity LHC at CERN: $E_{p\text{-}p,\mathrm{cm}}$=14 TeV, L=5 or 7.5x10^{34}cm^{-2}s^{-1} levelled

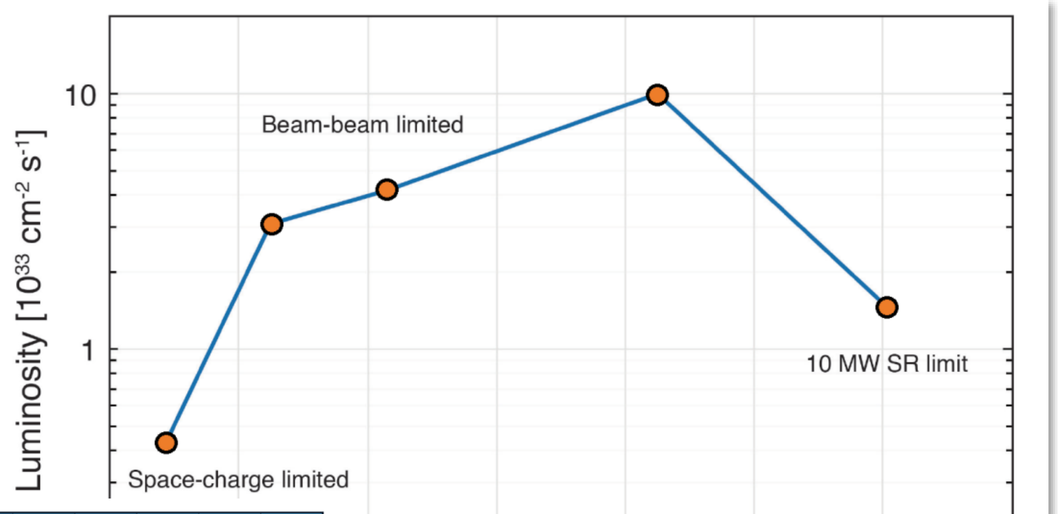
goal: increase LHC integrated luminosity x10 to >3 ab^{-1} around 2040

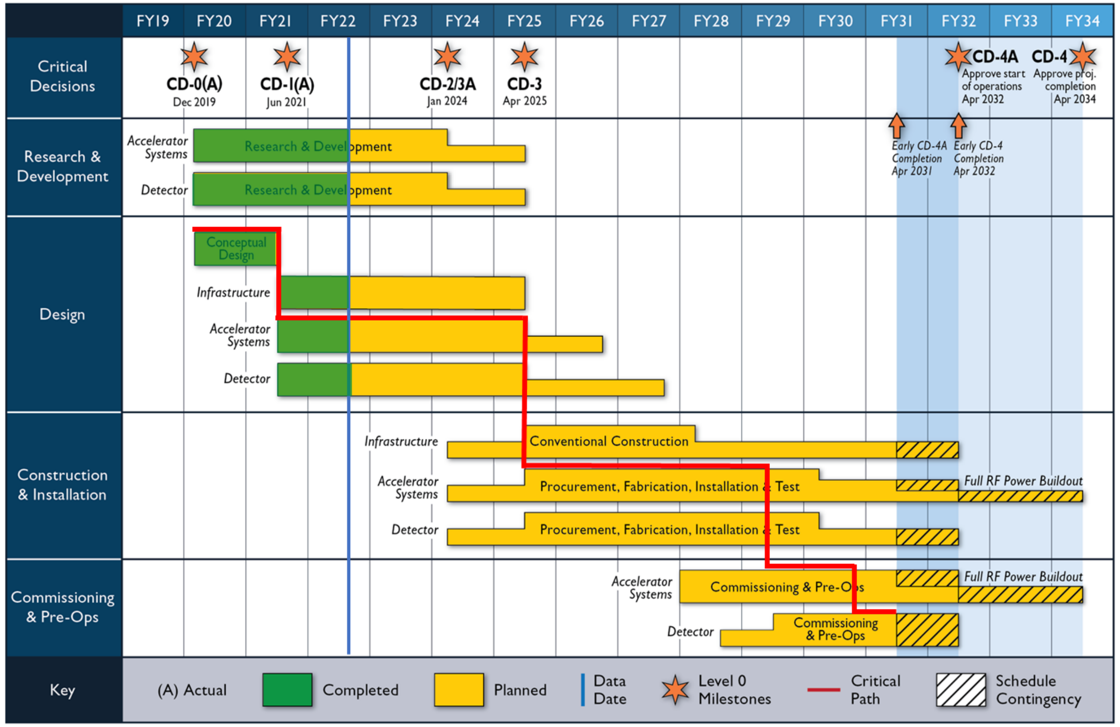


L. Rossi

near-future collider 2: Electron-Ion Collider



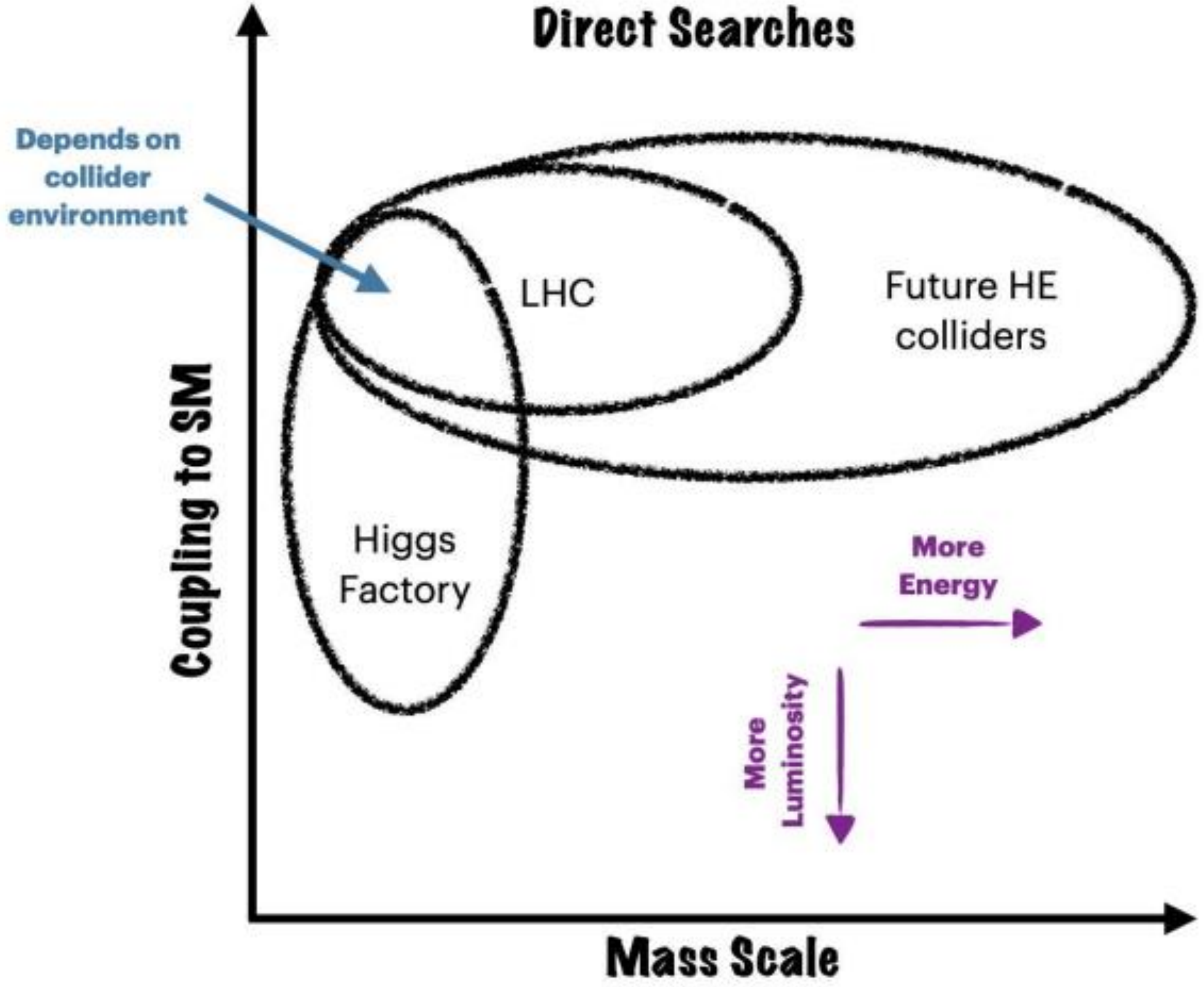




3.83 km double ring,
polarized beams
full-energy e^- injection,
injection rate 1 Hz

F. Willeke

Energy Frontier Machines – Energy & Precision

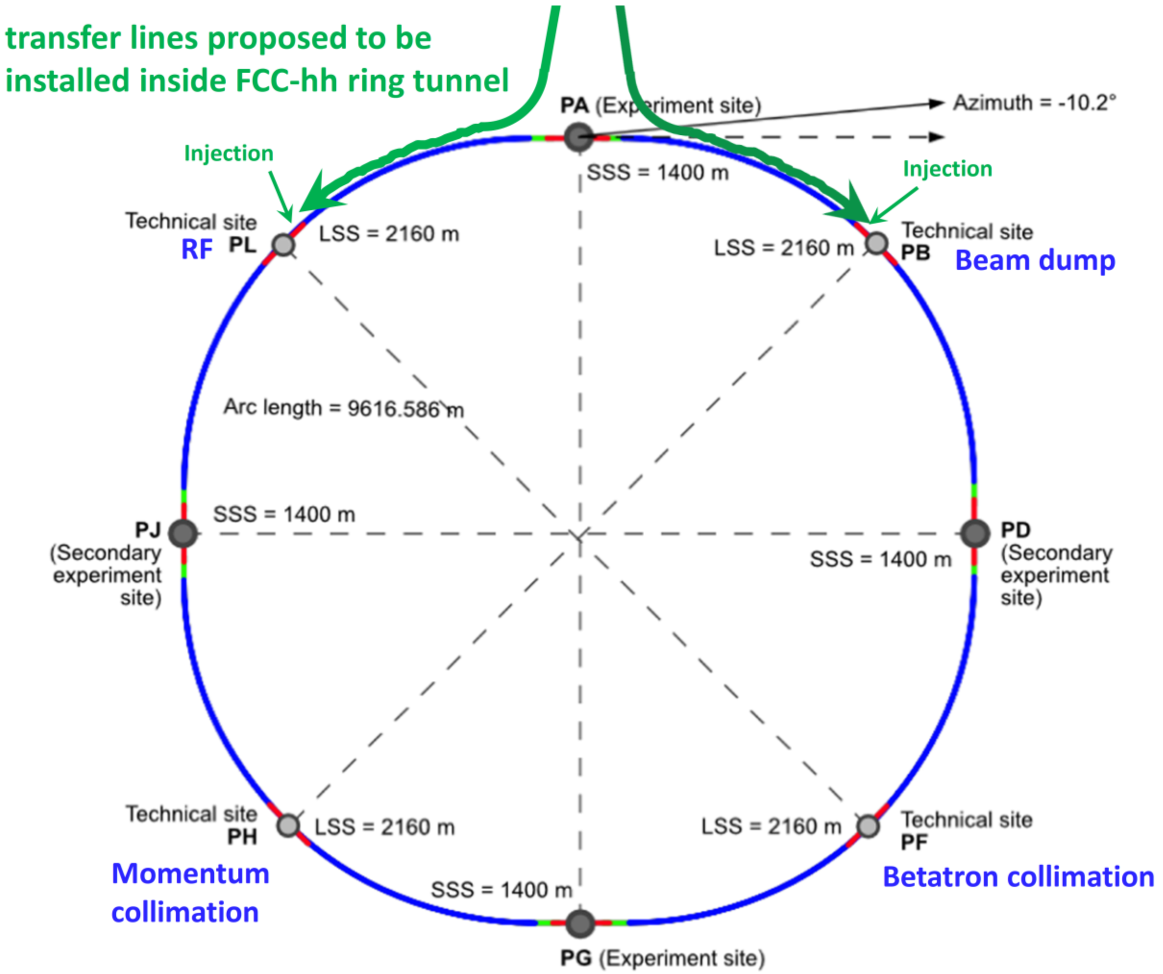


L. Reina,
Snowmass'21 (22)

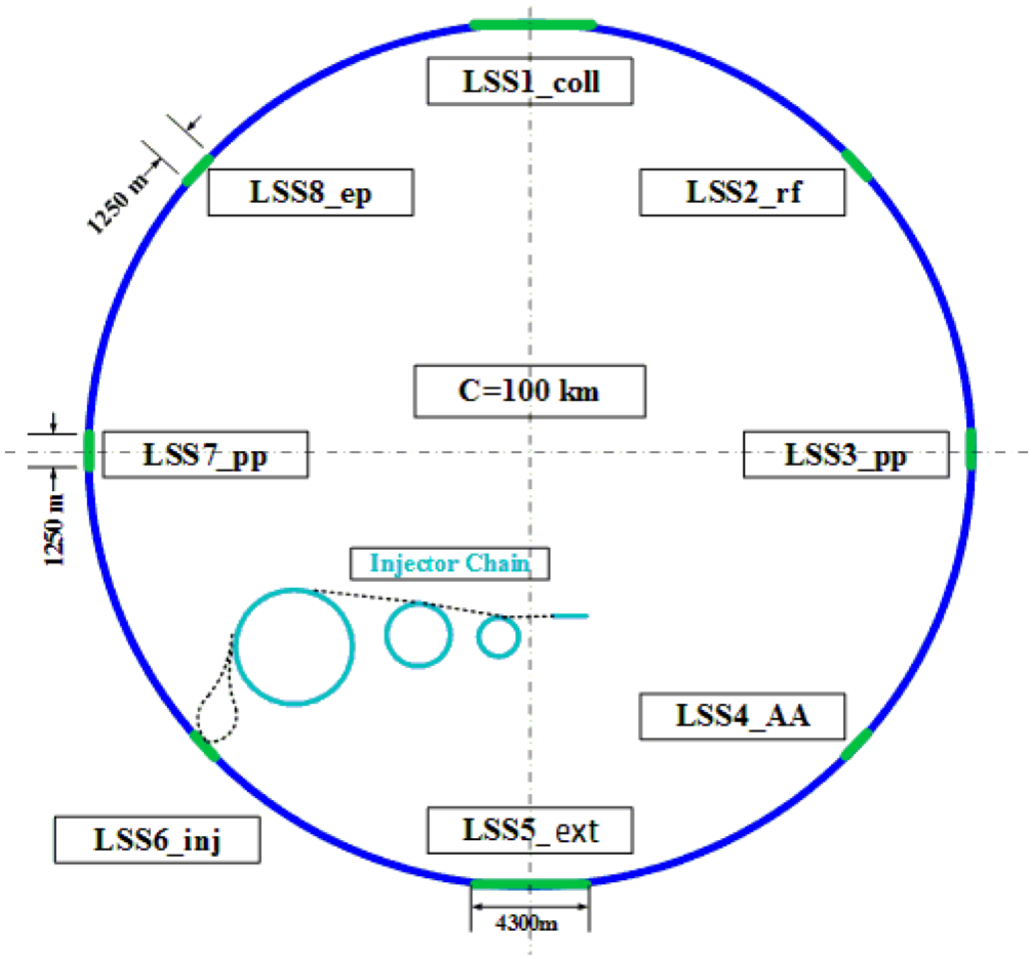
Proposed Higher-Energy Hadron Colliders

Snowmass '21

FCC-hh

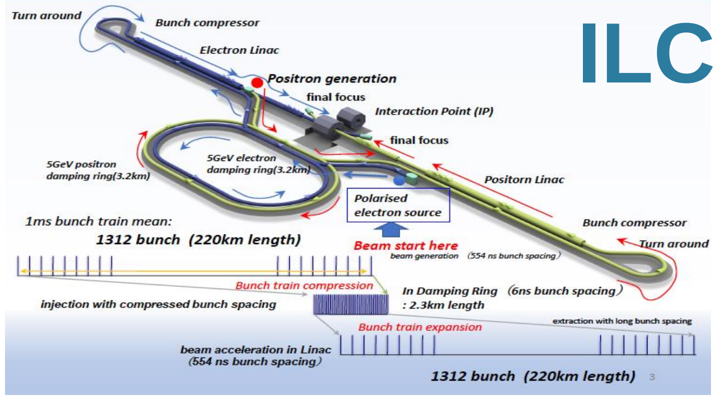


SPPC

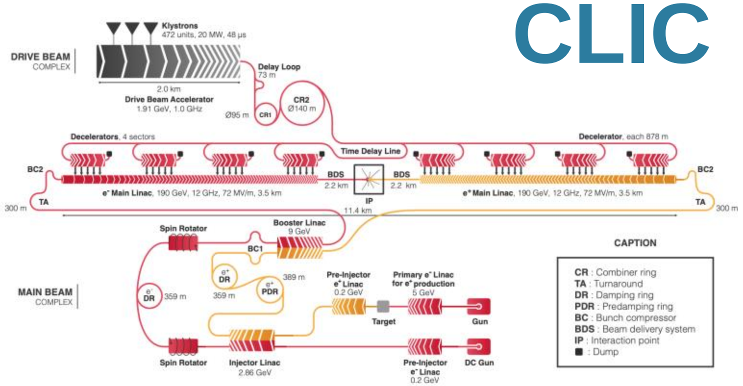


Proposed e^+e^- Higgs & EW Factories

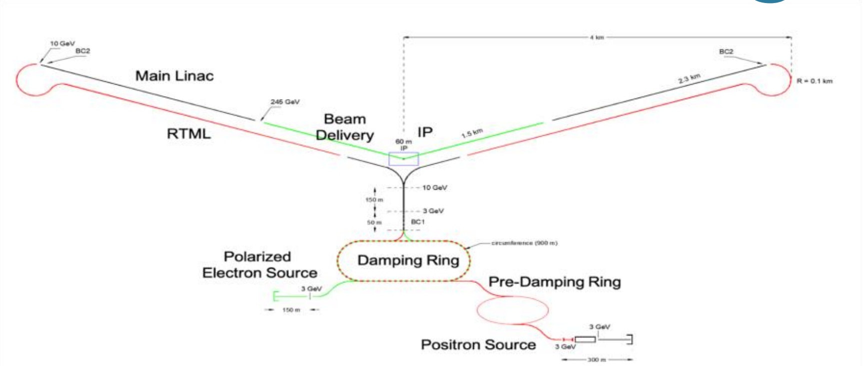
ILC



CLIC

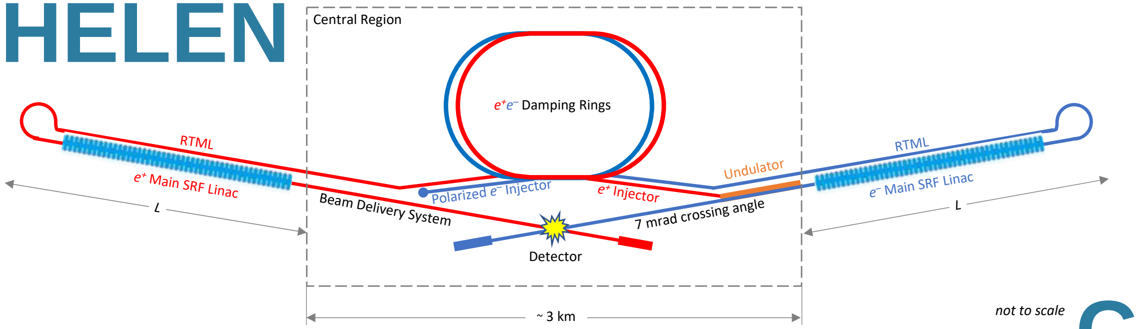


C^3



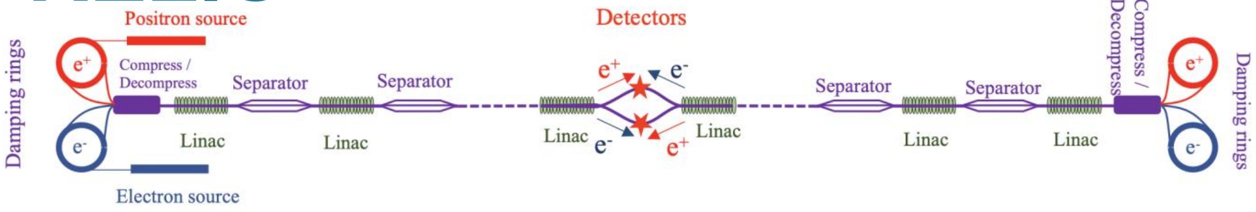
HELEN

Higgs-Energy LEptoN (HELEN) Collider

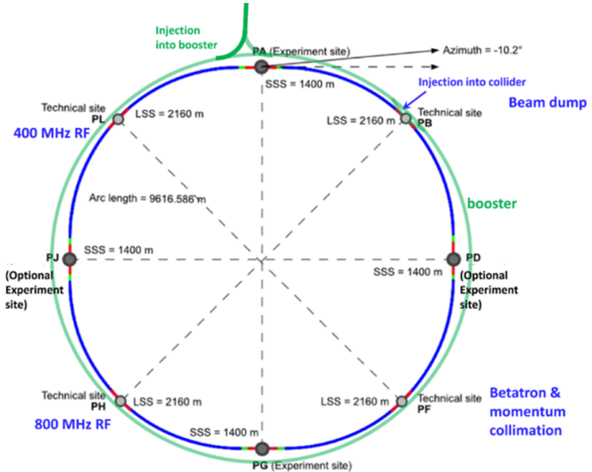


not to scale

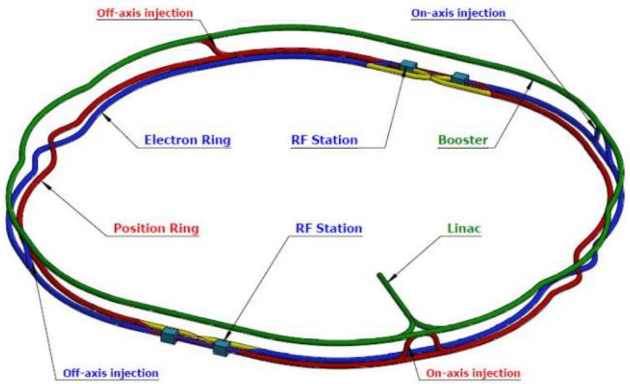
RELIC



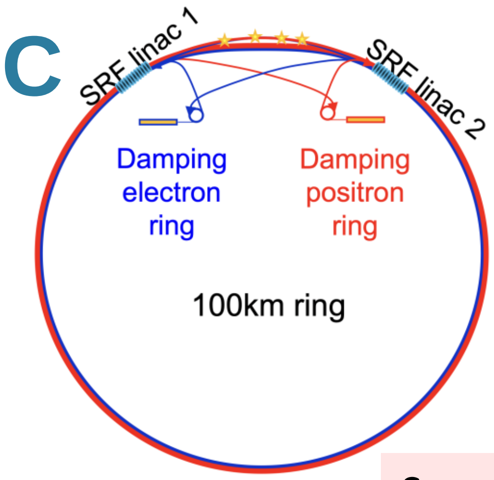
FCC-ee



CEPC



CERC



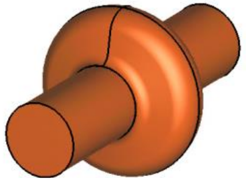
FUTURE
CIRCULAR
COLLIDER

FCC-ee SRF system

Universität Rostock · Traditio et Innovatio · INFN LNL Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro · Jefferson Lab · Fermilab

Z

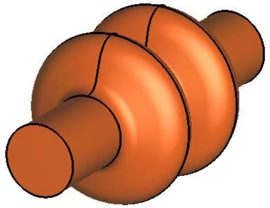
**1-cell
400 MHz,
Nb/Cu**



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

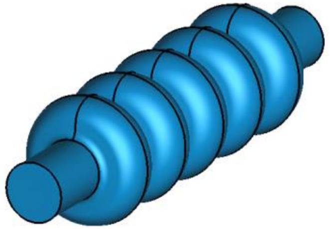
**2-cell
400 MHz,
Nb/Cu**



moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

**ttbar,
booster**

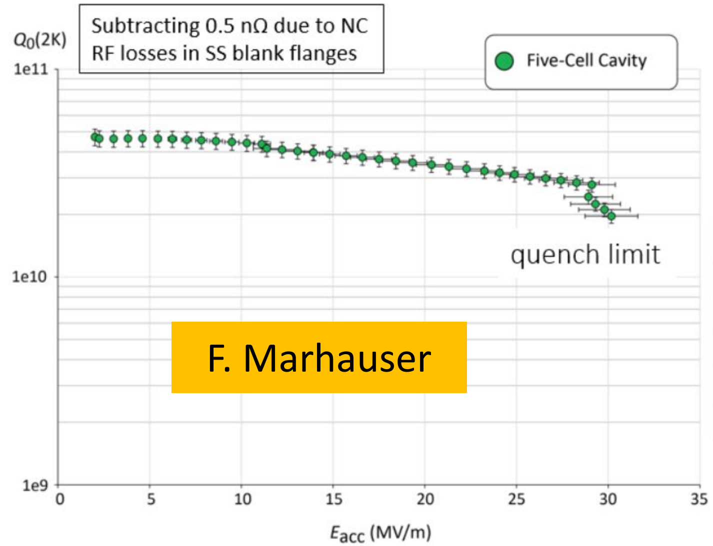
**5-cell
800 MHz,
bulk Nb**



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

F. Peauger,
O. Brunner

5-cell cavity development (2018), successful collaboration with JLAB



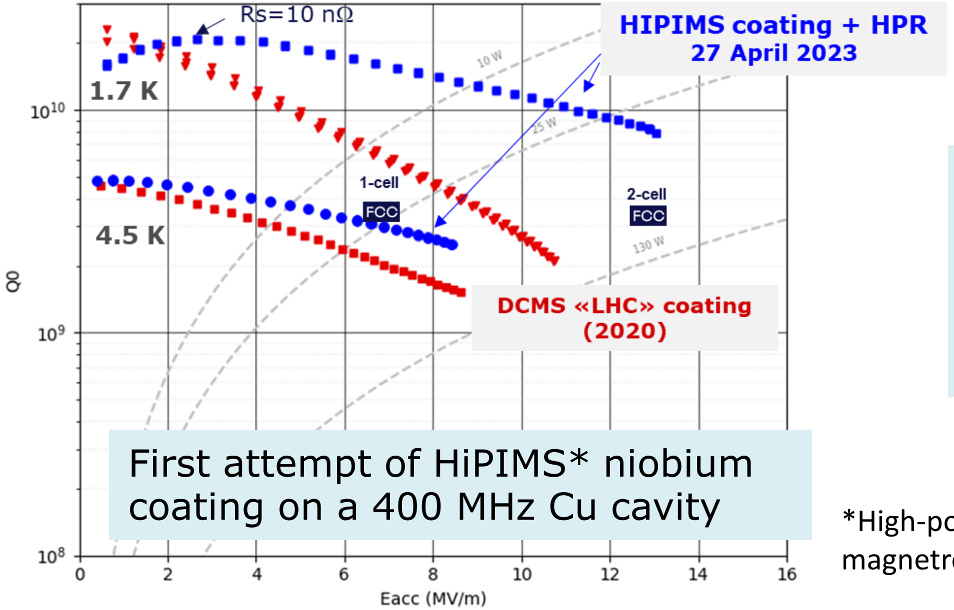
F. Marhauser

Main post-processing steps

	Unit	*CRN5*
Bulk BCP	µm	216
High-T heat treatment	°C, hrs.	800, 3
Final EP	µm	30
HPR cycles		4
Low-T bake-out	°C, hrs.	120, 12

FCC Week 2018, 9-13 April 2018, Beurs van Berlage, Amsterdam, Netherlands

Jefferson Lab 17



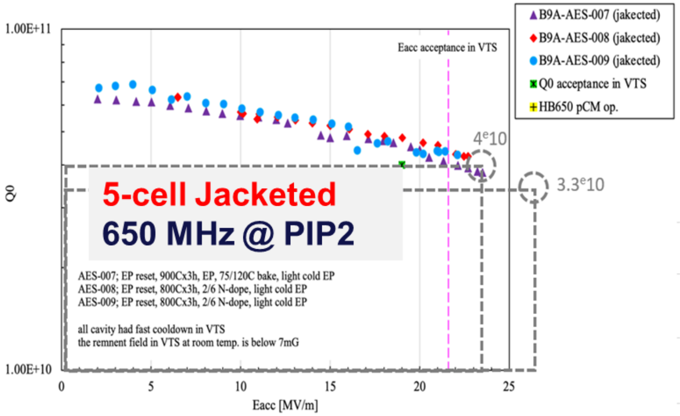
**HIPIMS coating + HPR
27 April 2023**

**DCMS «LHC» coating
(2020)**

First attempt of HiPIMS* niobium coating on a 400 MHz Cu cavity

*High-power impulse magnetron sputtering

Promising R&D towards ultra-high Q_0. Collaboration with FNAL

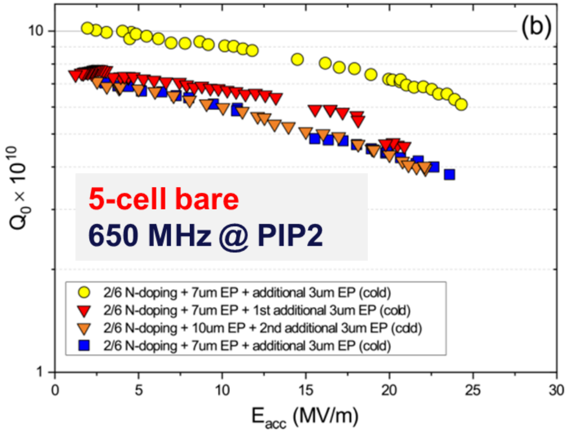


**5-cell Jacketed
650 MHz @ PIP2**

AES-007; EP reset, 900Cx3h, EP, 75/120C bake, light cold EP
AES-008; EP reset, 800Cx3h, 2/6 N-dope, light cold EP
AES-009; EP reset, 800Cx3h, 2/6 N-dope, light cold EP

all cavity had fast cooldown in VTS
the remnent field in VTS at room temp. is below 7mG

**Q0 = 3.5e10 @ 25 MV/m
with 2/6 N-doping or midT bake + EP**



**5-cell bare
650 MHz @ PIP2**

**Q0 = 6e10 @ 25 MV/m
with 2/6 N-doping + EP + cold EP**

FUTURE CIRCULAR COLLIDER

FCC-ee RF parameter table

Number of 800 MHz cavities: 1088
Total number of cavities: 1456

F. Peauger, May 2023

20-Apr-23	Z		W		H		ttbar2		
	Collider per beam	booster	Collider per beam	booster	Collider 2 beams	booster	Collider 2 beams	Collider 2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.93	6.23	10.78	20.76	10.78	20.76	10.78	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.22	5.83	8.08	19.44	8.08	19.44	8.08	18.85	18.83
#cells	54	120	260	270	520	540	520	2440	3000
# cavities	54	24	130	54	260	108	260	488	600
# CM	13.5	6	32.5	13.5	65	27	65	122	150
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	23	0.3	158	4	158	4	158	23	3
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.9E+04	3.2E+05	1.1E+06	8.0E+06	1.1E+06	1.6E+07	5.4E+06	4.2E+06	8.3E+07
Detuning [kHz]	8.620	4.393	0.479	0.136	0.096	0.014	0.007	0.056	0.003
Pcav [kW]	912	205	379	91	379	46	79	163	8
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9936
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9876.13
cos phi	0.32	0.27	0.35	0.35	0.88	0.88	0.98	0.86	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

* heat loads from power coupler and HOM couplers not included

one RF system per beam

common RF system for both beams

Limiting parameters for RF

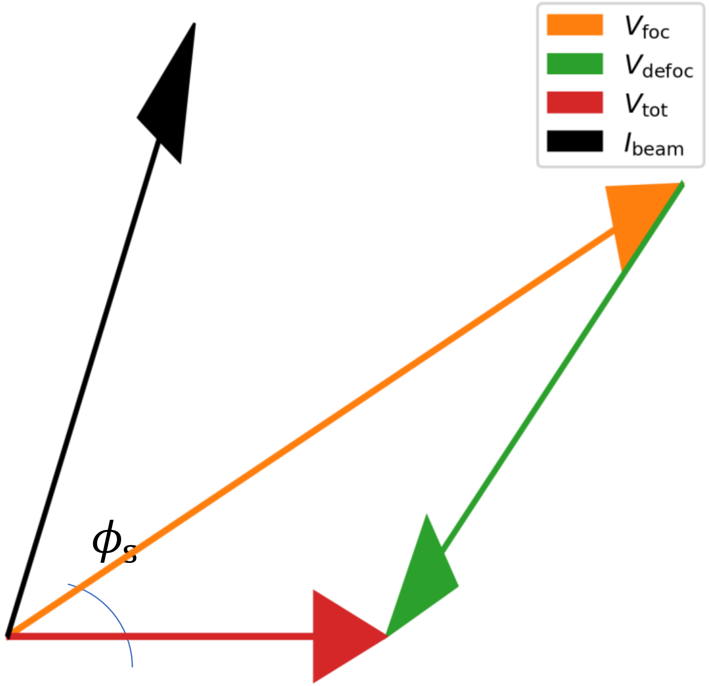
- **Cavity performances: 20 % margin added on Eacc and Q0 between vertical test and operation**
- **In total: 364 cryomodules, 1456 cavities, 25% with Nb/Cu technology, 75% with bulk niobium technology**

FCC-ee recent breakthrough

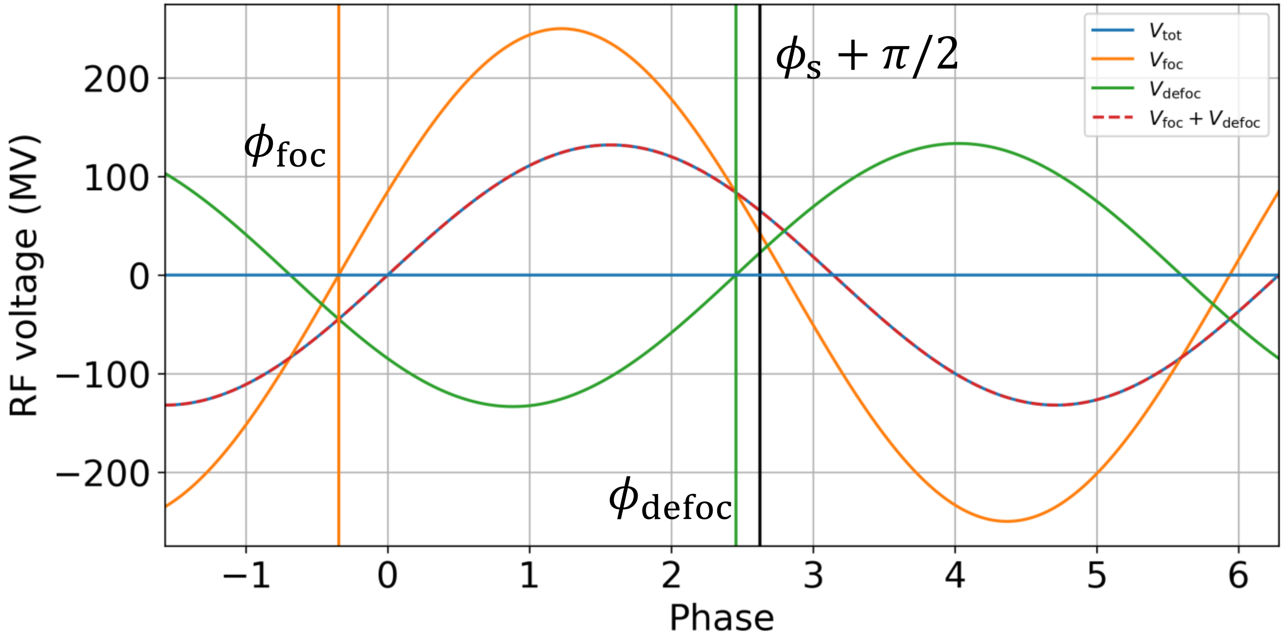
I. Karpov,
August ‘24

Reverse phase operation (RPO) mode allows increasing RF cavity voltage *(Y. Morita et al., SRF, 2009)*
- Experimentally verified with high beam loading in KEKB *(Y. Morita et al., IPAC, 2010)*
- Baseline solution for EIC ESR *(e.g., J. Guo et al., IPAC, 2022)*

Phasors



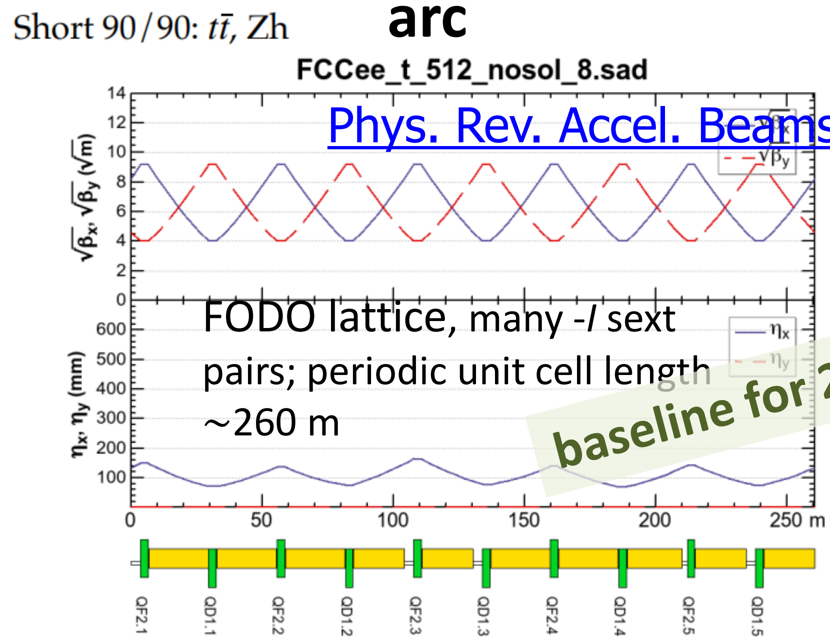
RF waves



We can use the same 2-cell SRF system for all collisions energies, Z, WW, and ZH, at constant cavity voltage and external coupling → faster installation, lower cost, much more flexible operation

FCC-ee collider optics development: 2 options

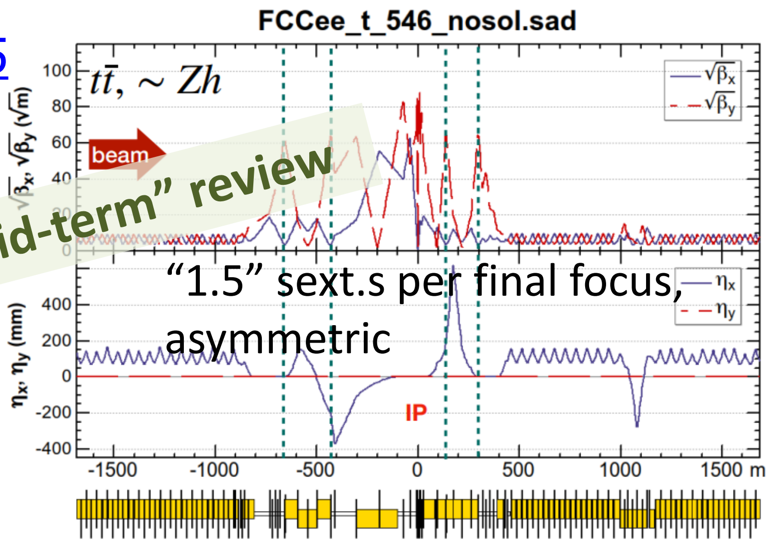
arc



[Phys. Rev. Accel. Beams **19**, 111005]

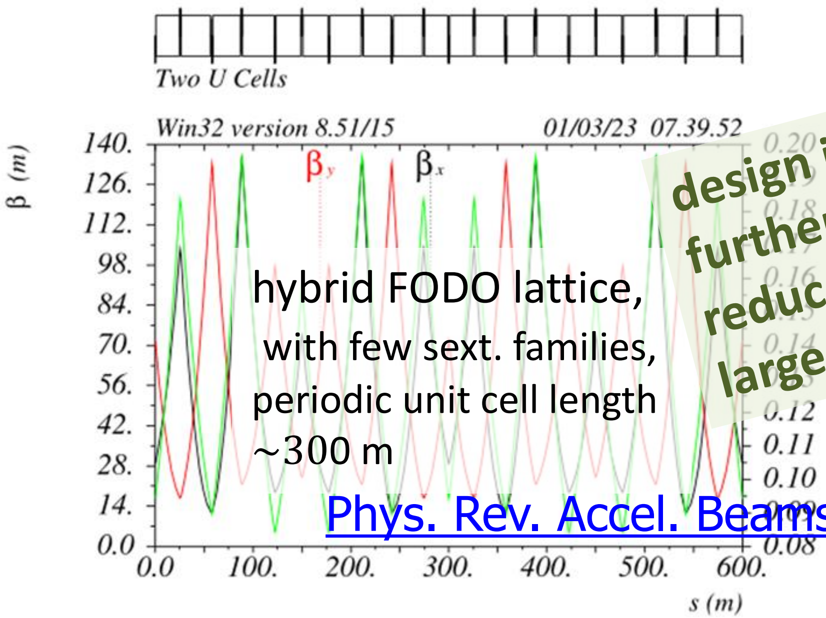
FODO lattice, many -*I* sext pairs; periodic unit cell length ~260 m

interaction region



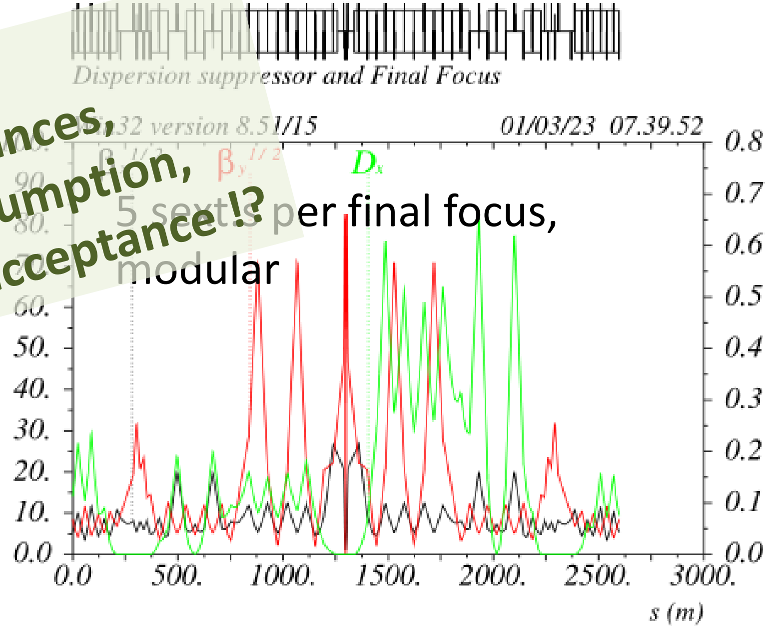
“1.5” sext.s per final focus, asymmetric

baseline for 2023 FCC “mid-term” review



hybrid FODO lattice, with few sext. families, periodic unit cell length ~300 m

[Phys. Rev. Accel. Beams **26**, 021601]



5 sext.s per final focus, modular

design in progress - further relaxed tolerances, reduced power consumption, larger momentum acceptance!?

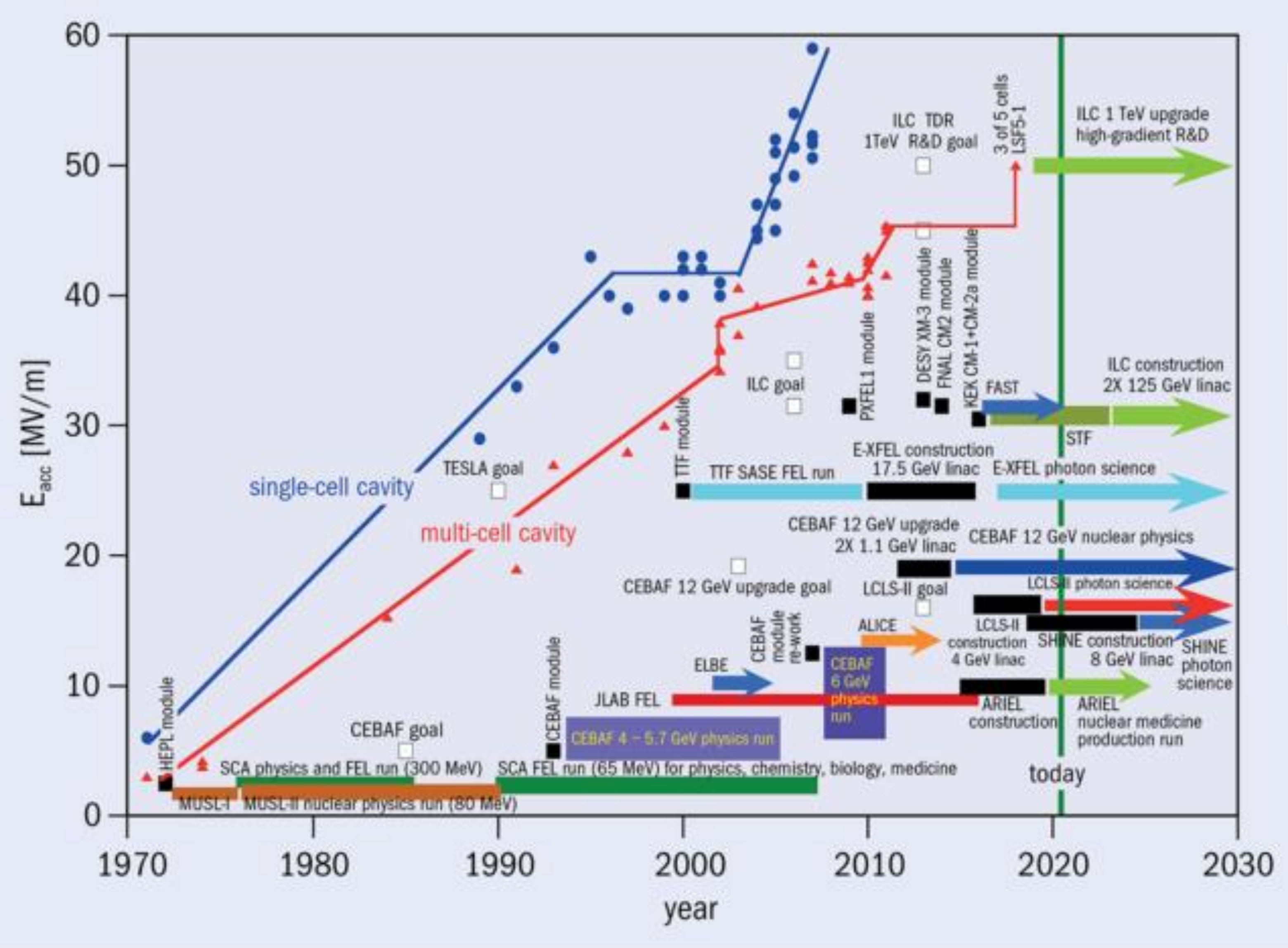
K. Oide, 2023 EPS
Rolf Wideroe award winner

P. Raimondi, 2017 EPS
Gersh Budker award winner

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

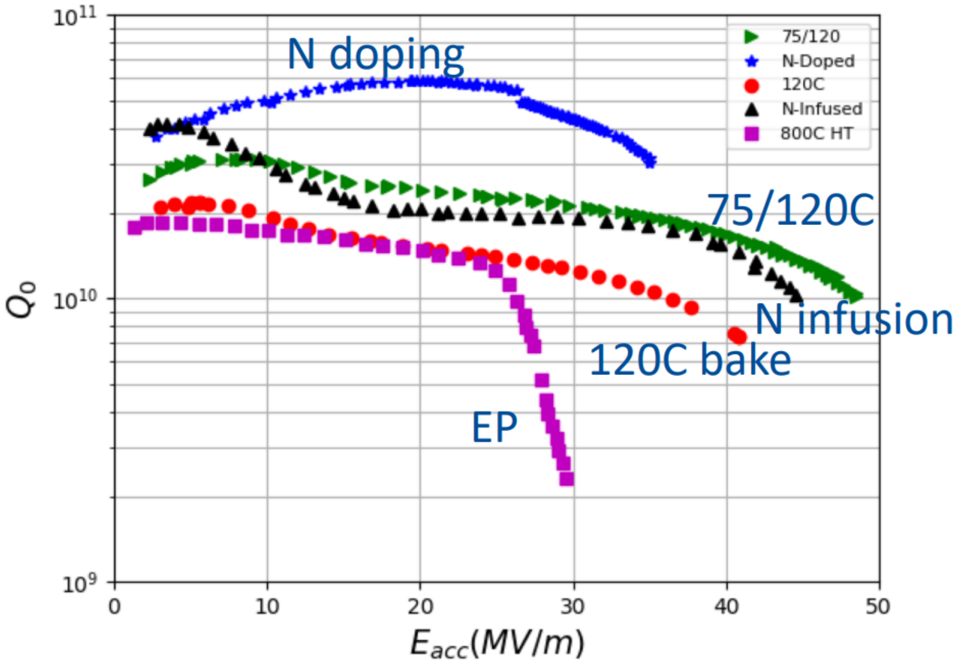
- High-field magnets
- SC Radiofrequency systems
- Efficient RF power sources
- e^+ production
- Gamma Factory
- Monochromatization
- Energy Recovery Linacs
- $\gamma\gamma$ colliders
- Muon Collider(s)
- Advanced Accelerator Concepts
- Sustainability

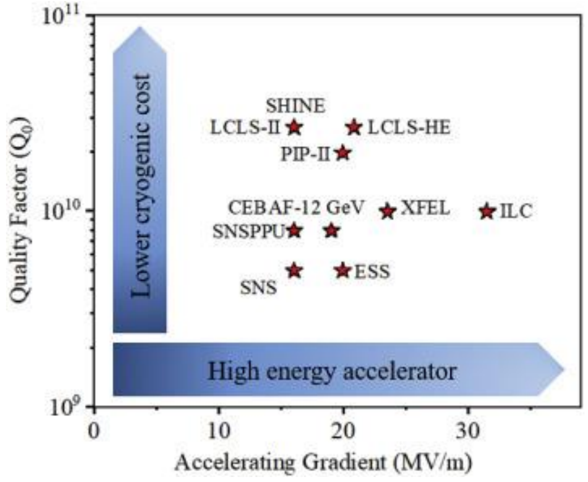
SC Radiofrequency Systems



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

Anna Grasselino

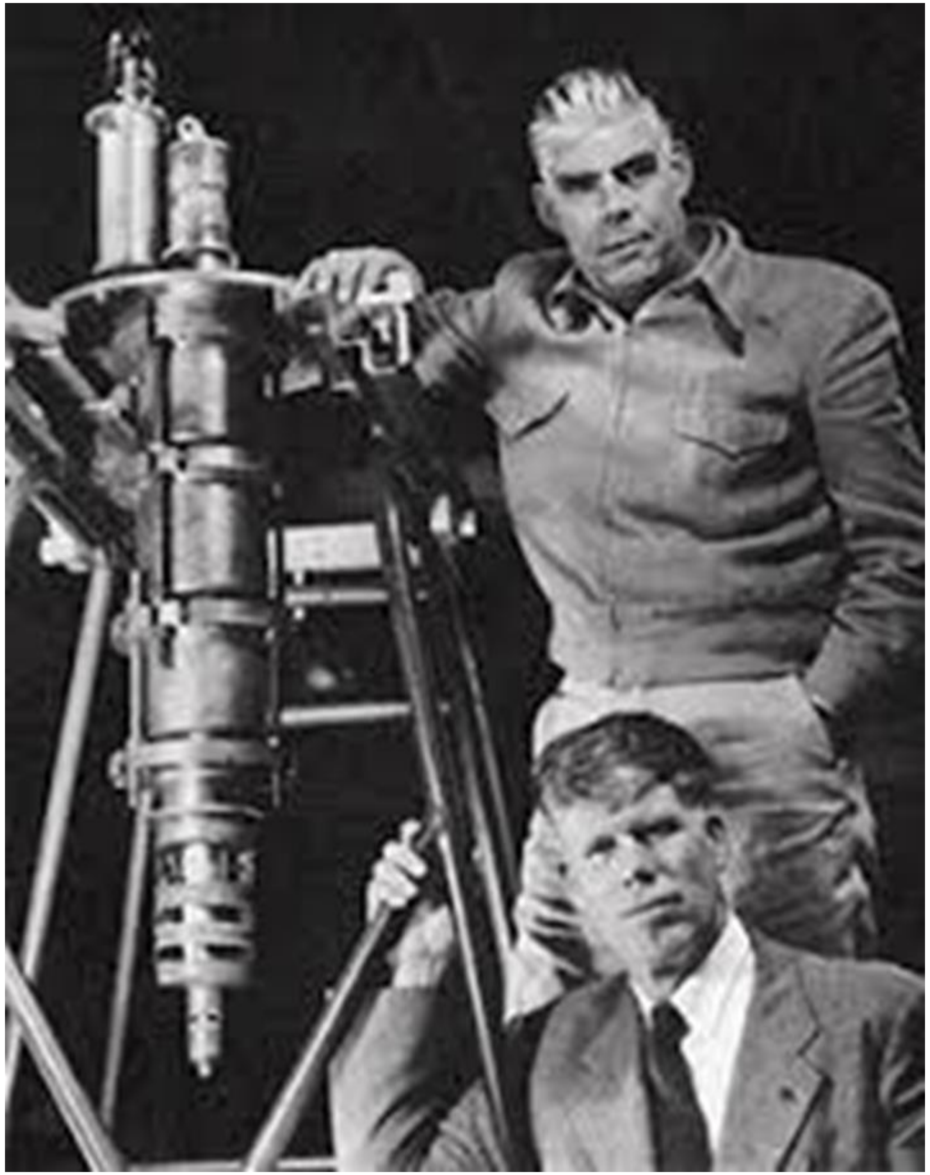




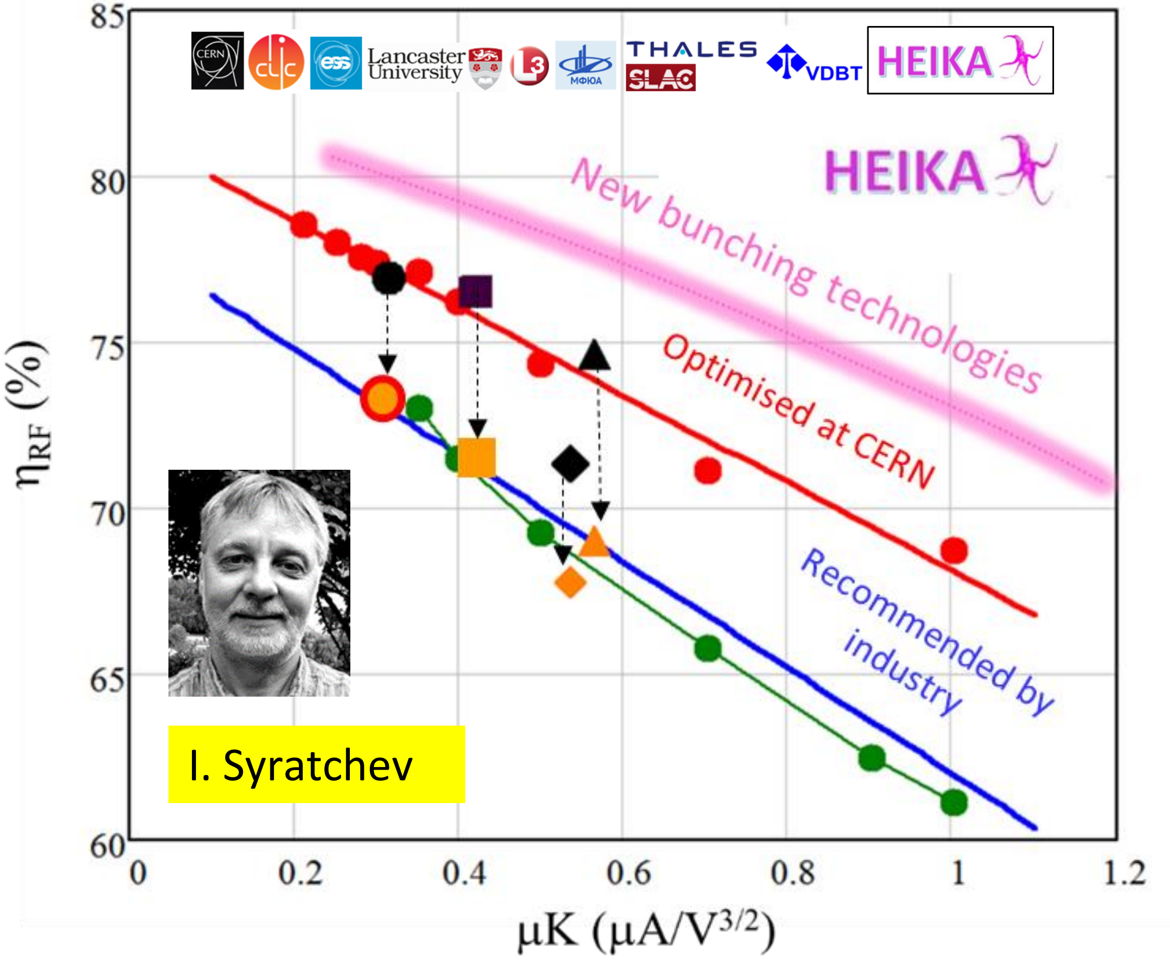
P. Dhakal

More Efficient RF Power Sources

1937: the Varian brothers of Palo Alto invent the klystron

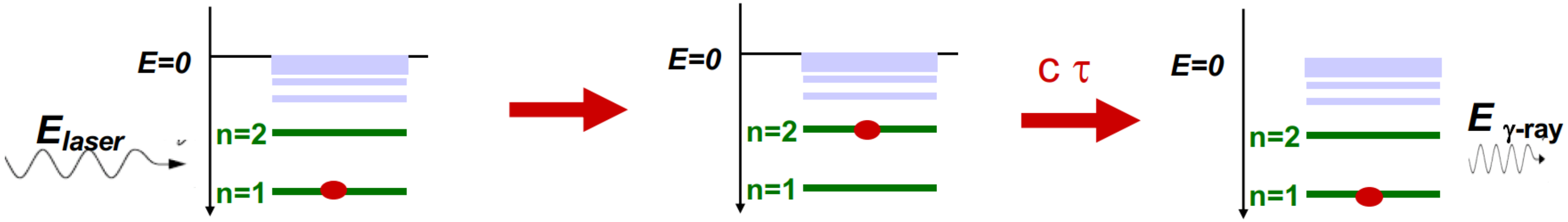


80 years later, another breakthrough in klystron technology



New bunching technologies

Gamma Factory concept



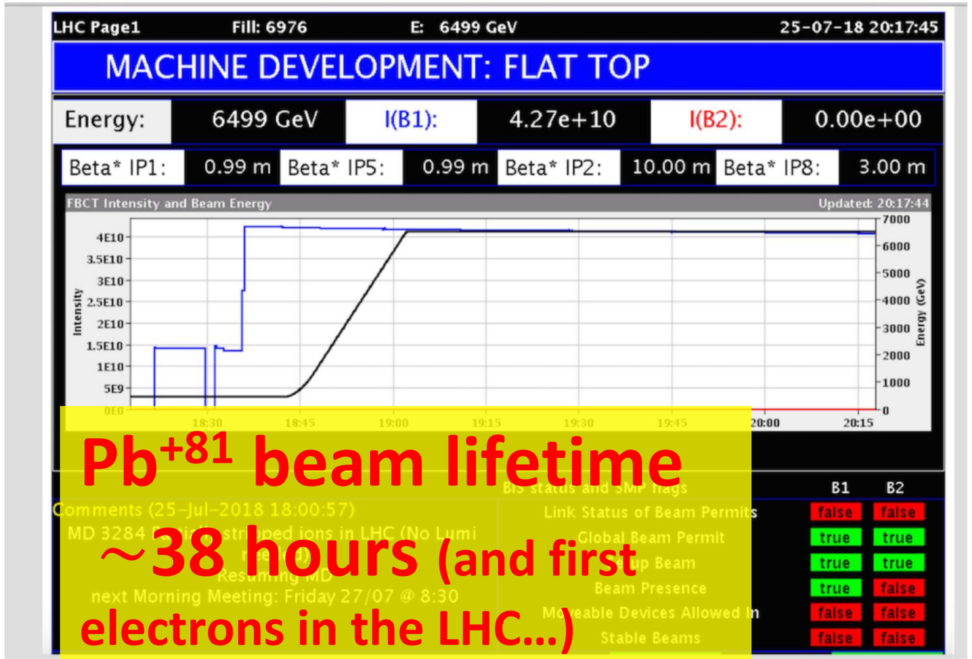
Witek Krasny

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



LHC Page1 Fill: 6976 E: 6499 GeV 25-07-18 20:17:45

MACHINE DEVELOPMENT: FLAT TOP

Energy:	6499 GeV	I(B1):	4.27e+10	I(B2):	0.00e+00

Beta* IP1:	0.99 m	Beta* IP5:	0.99 m	Beta* IP2:	10.00 m	Beta* IP8:	3.00 m

Comments (25-Jul-2018 18:00:57)
MD 3284 Partially stripped ions in LHC (No Lumi needed)
Resuming MD
next Morning Meeting: Friday 27/07 @ 8:30

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

Pb^{+81} beam lifetime ~38 hours (and first electrons in the LHC…)

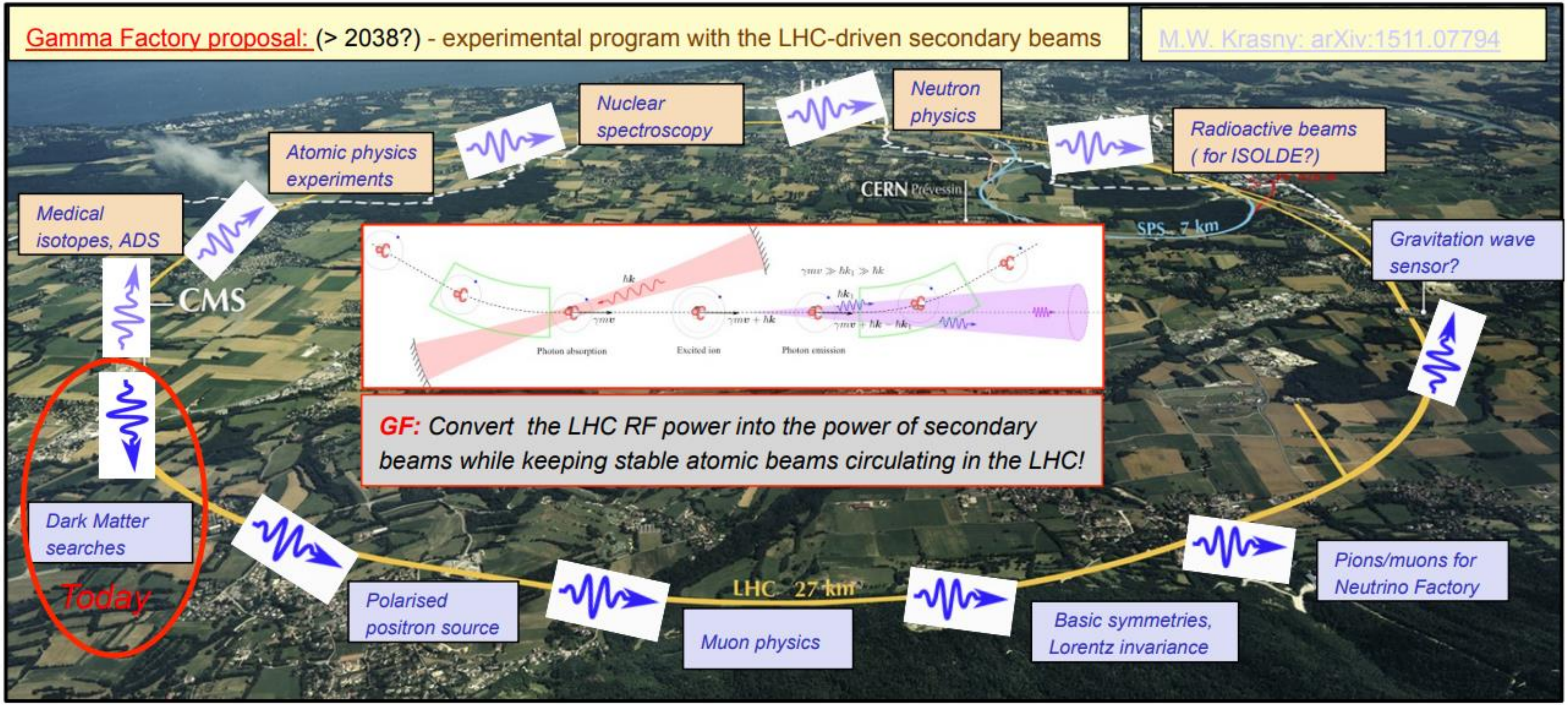
proposed applications:

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



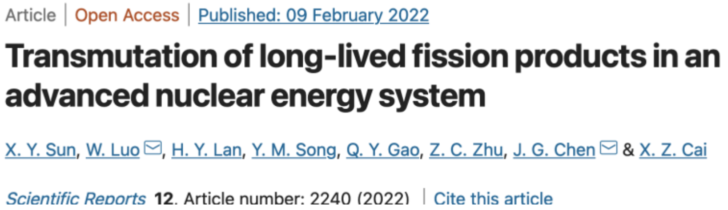
Gamma Factory proposal: (> 2038?) - experimental program with the LHC-driven secondary beams

M.W. Krasny: arXiv:1511.07794

GF: Convert the LHC RF power into the power of secondary beams while keeping stable atomic beams circulating in the LHC!

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

Gamma Factory driving subcritical nuclear reactor?

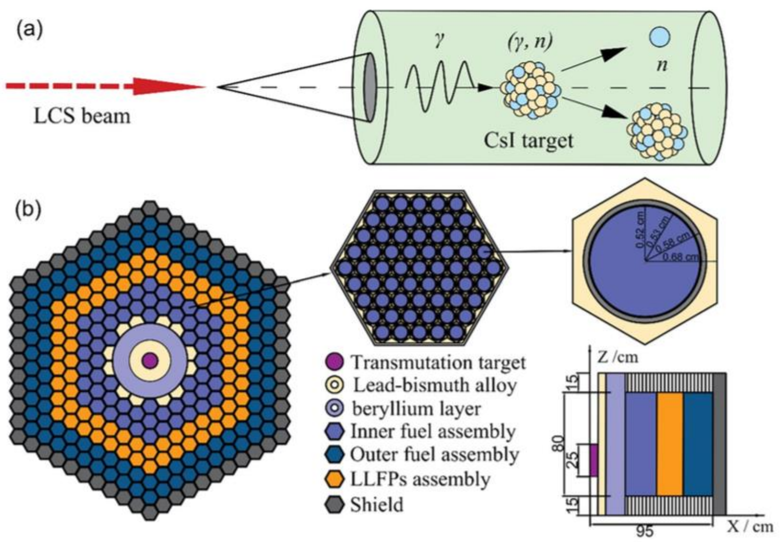


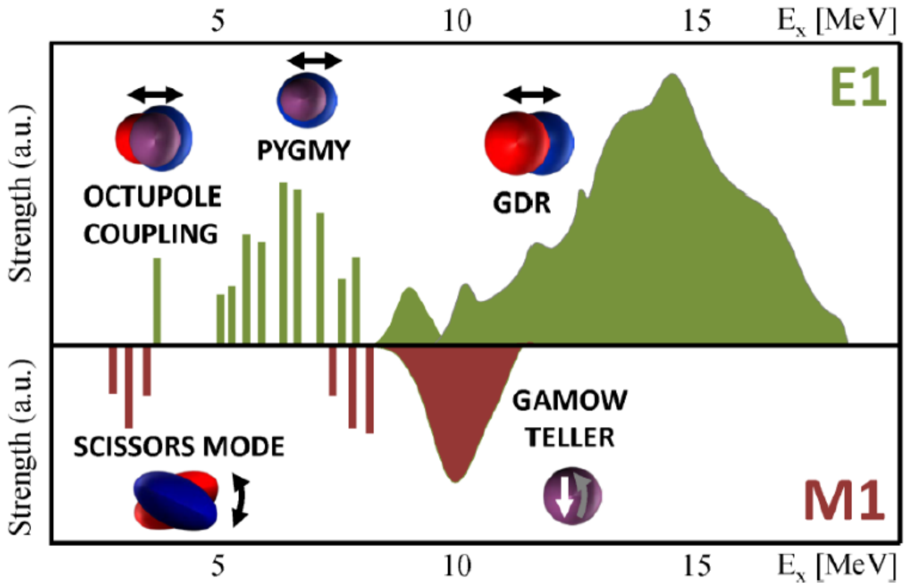
Article | Open Access | Published: 09 February 2022

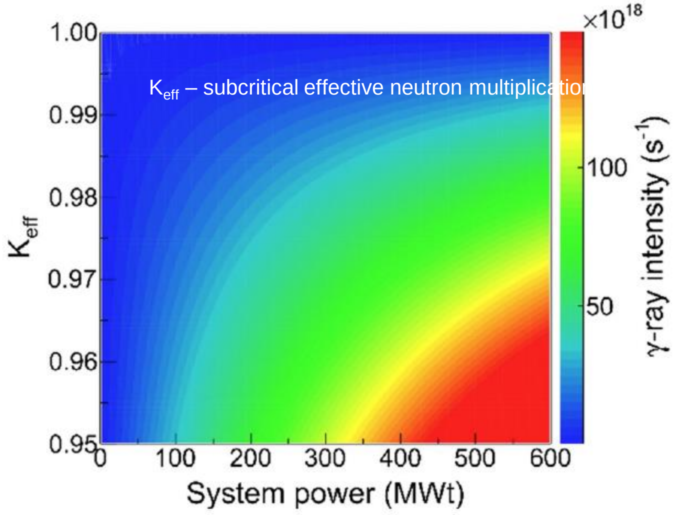
Transmutation of long-lived fission products in an advanced nuclear energy system

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



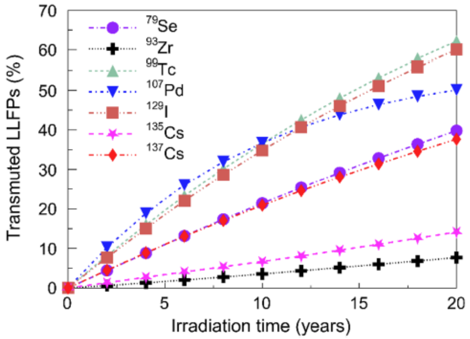




Required photon-beam energy:
5-20 MeV -- He(H)- like Ca or Kr beams + commercial ~ 1 μm lasers

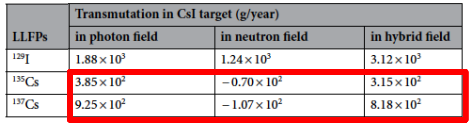
Required beam intensity:
O(10 MW) power

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

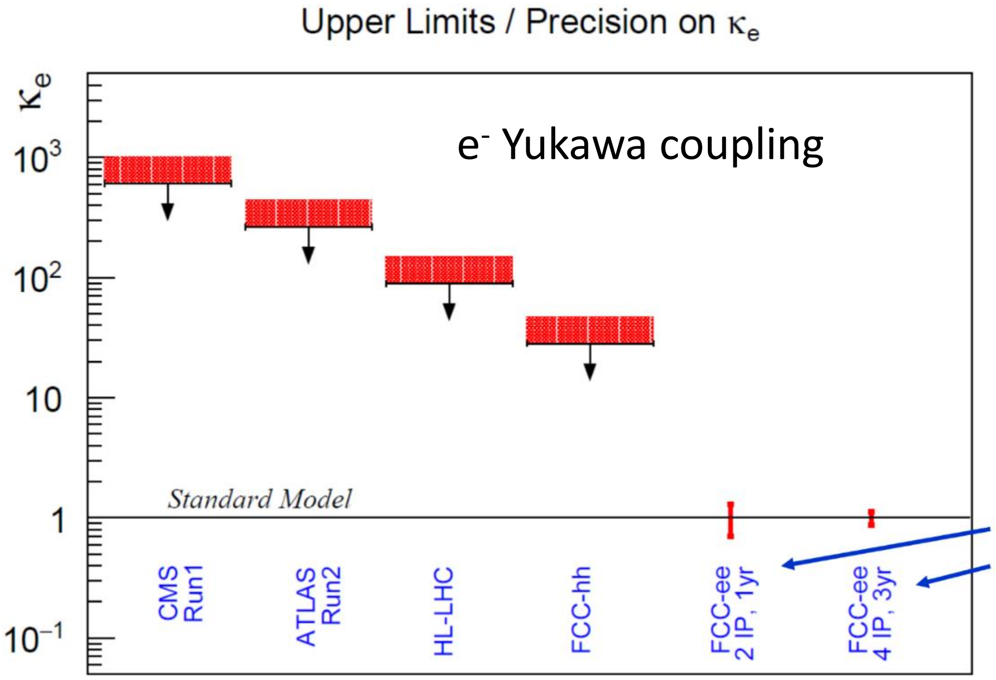
Efficiency = 1.3 %

Photon beam CERN-GF

Efficiency ~ 20 %

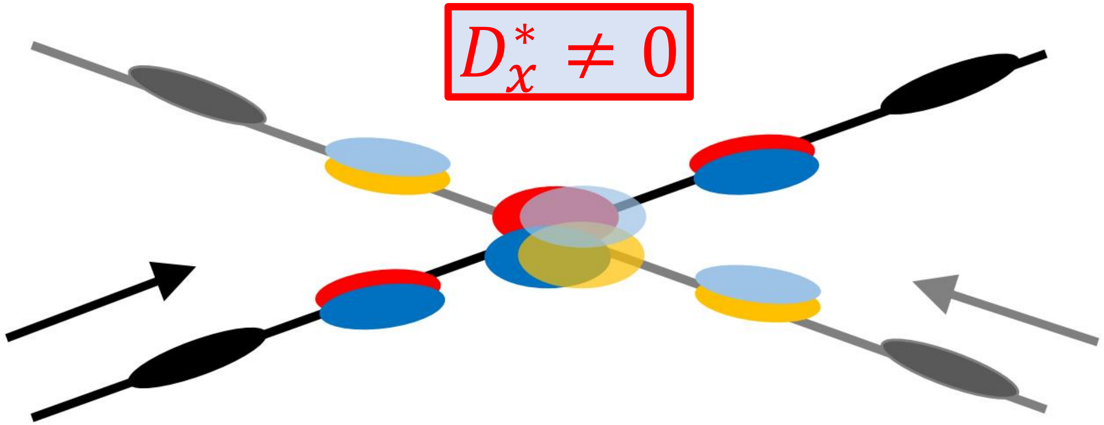
plus targeting specific isotopes and transitions

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



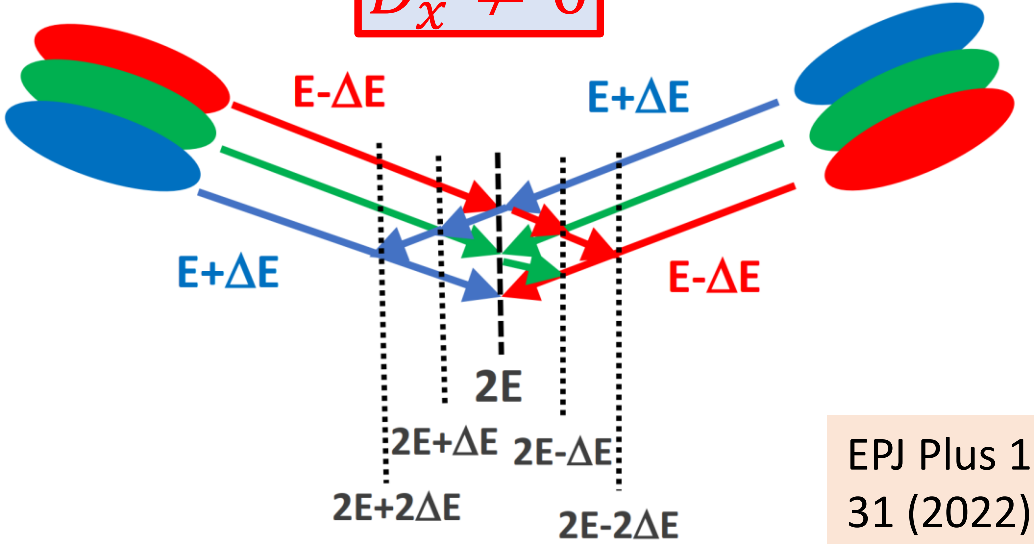
nonvanishing IP dispersion

w crab cavities

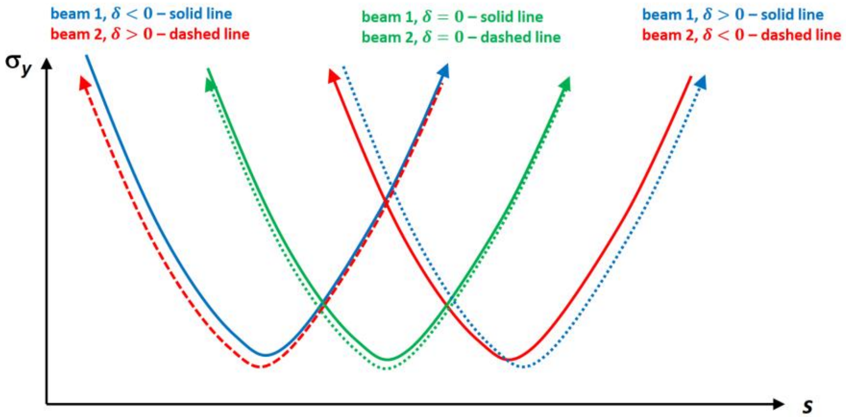


w/o crab cavities

$D_x^* \neq 0$



chromatic waist shift



Pantaleo
Raimondi

EPJ Plus 137,
31 (2022)

Energy Recovery Linac - Principle

V. Litvinenko, T. Roser, M. Chamizo

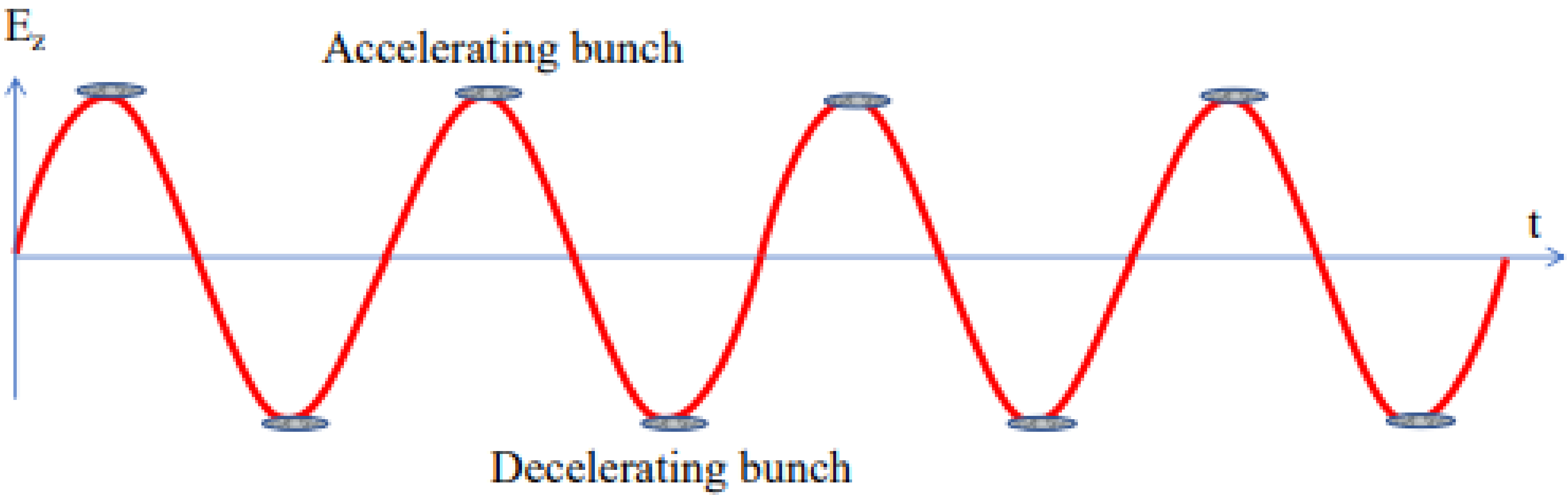
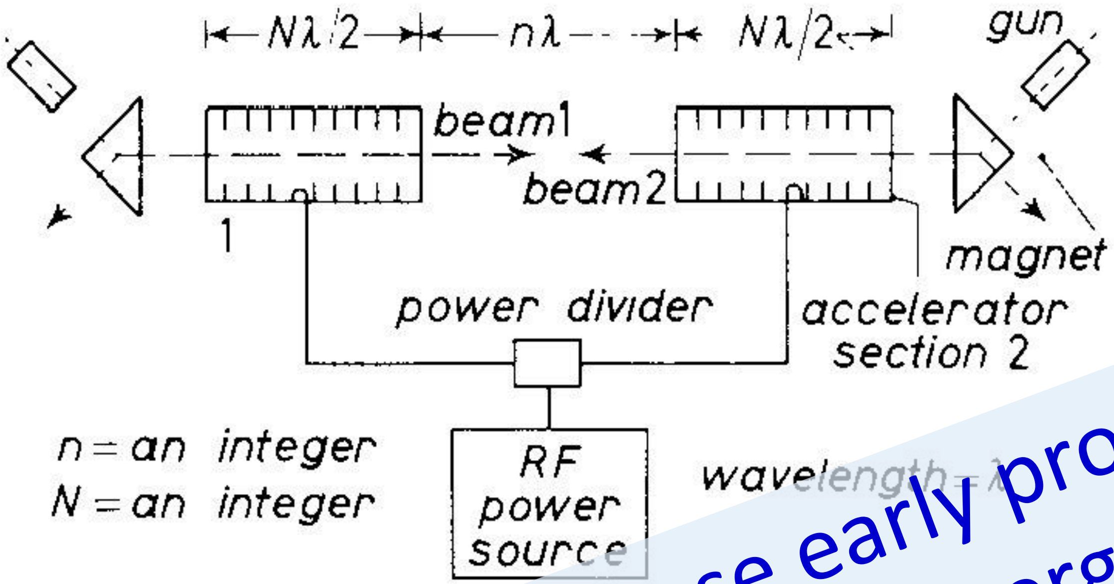


Illustration of ERL principle (intentionally simplified): accelerating bunches take energy from SRF linac, while decelerating bunches return energy back.

Energy Recovery Linacs - Historical Proposals 1960s & 70s

early linear-collider proposals



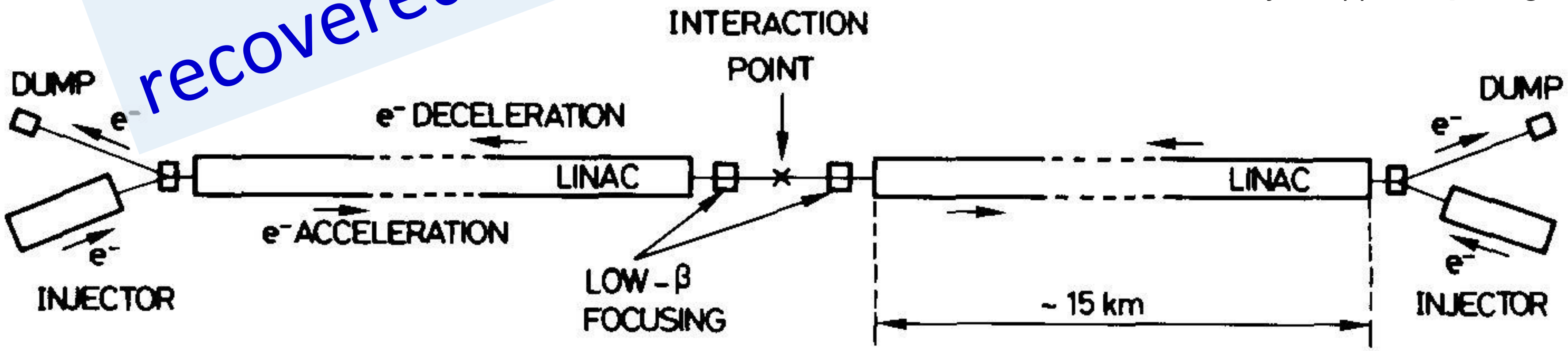
1-6 GeV c.m.

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!

w/o ER: "*Although in principle it may be possible to produce and handle this large power the sheer brutishness of the scheme robs it of all appeal.*" [M. Tigner]

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



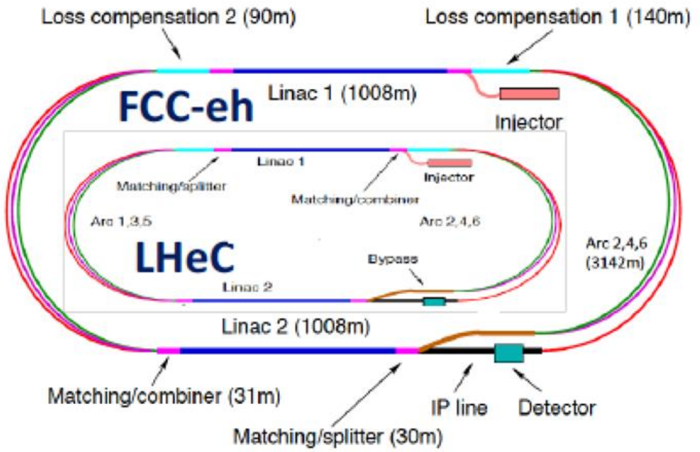
300 GeV c.m.

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

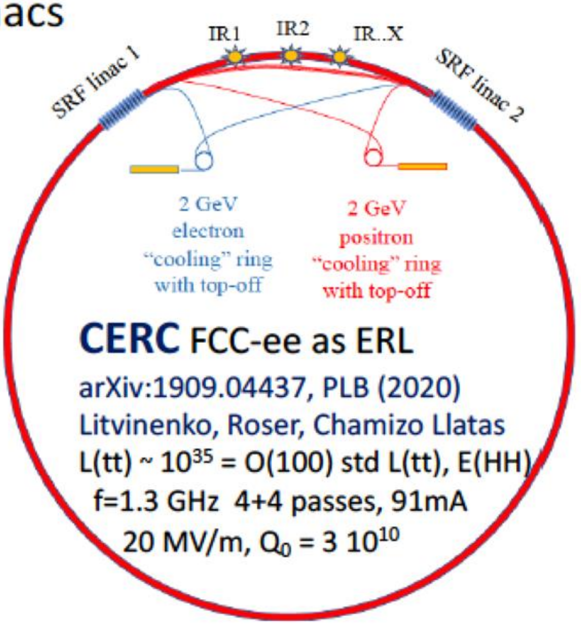


$\sqrt{s_{ep}}$ = 1-4 TeV

L(HERA) x 1000
(ERL and LHC)

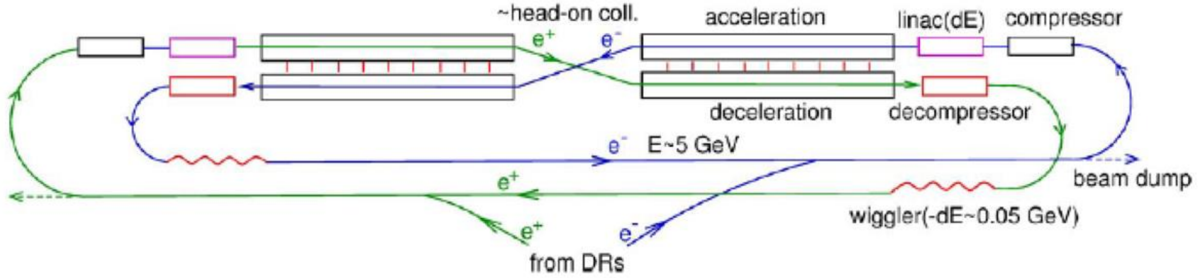
1206.2913, JPhysG
2007.14491, JPhysG

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

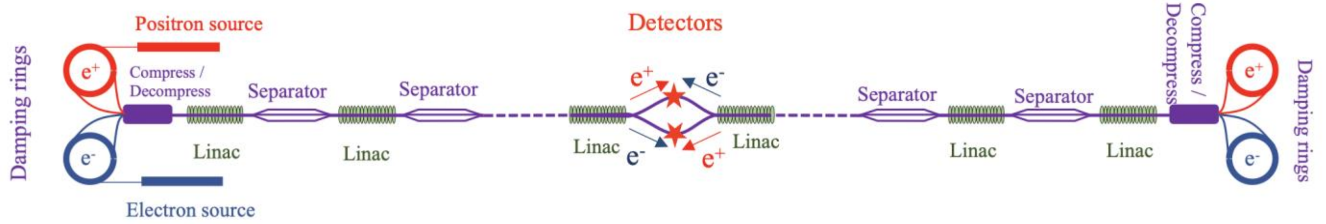


CERC FCC-ee as ERL
arXiv:1909.04437, PLB (2020)
Litvinenko, Roser, Chamizo Llatas
L(tt) ~ 10^{35} = O(100) std L(tt), E(HH)
f=1.3 GHz 4+4 passes, 91mA
20 MV/m, $Q_0 = 3\ 10^{10}$

LHeC ERL was first proposed by Swapan Chattopadhyay

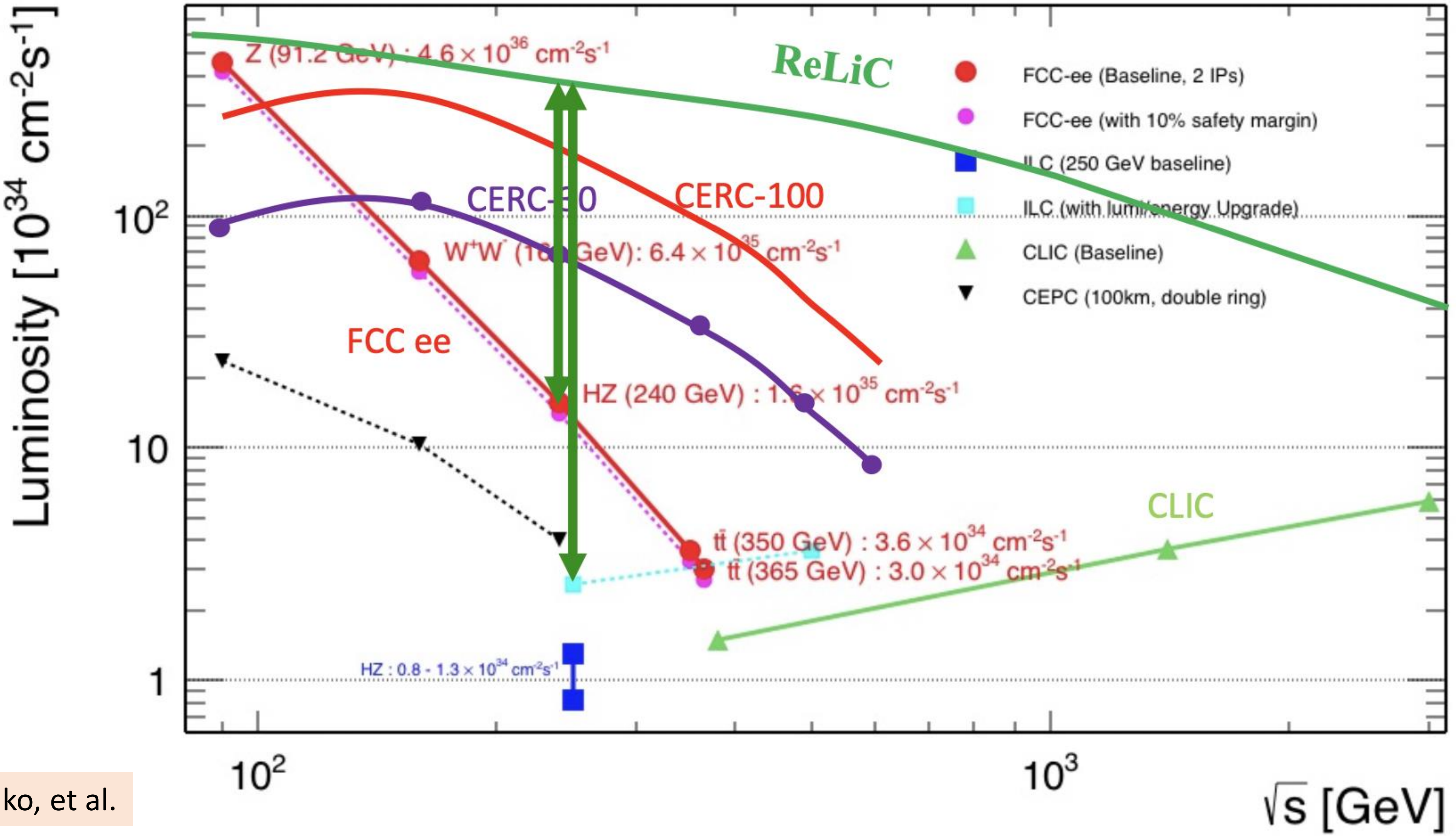


ERLC ILC as ERL
V. Telnov at LCWS → arXiv:2105.11015
L(ERLC) ~ 10^{36} = O(100) std L(ILC)
This yields O(10^7) HZ events in 3 years.
1+1 passes.
650 MHz coll rate, 20 MV/m, Q~10^{11}



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.

comparison of ERL collider proposals then and now

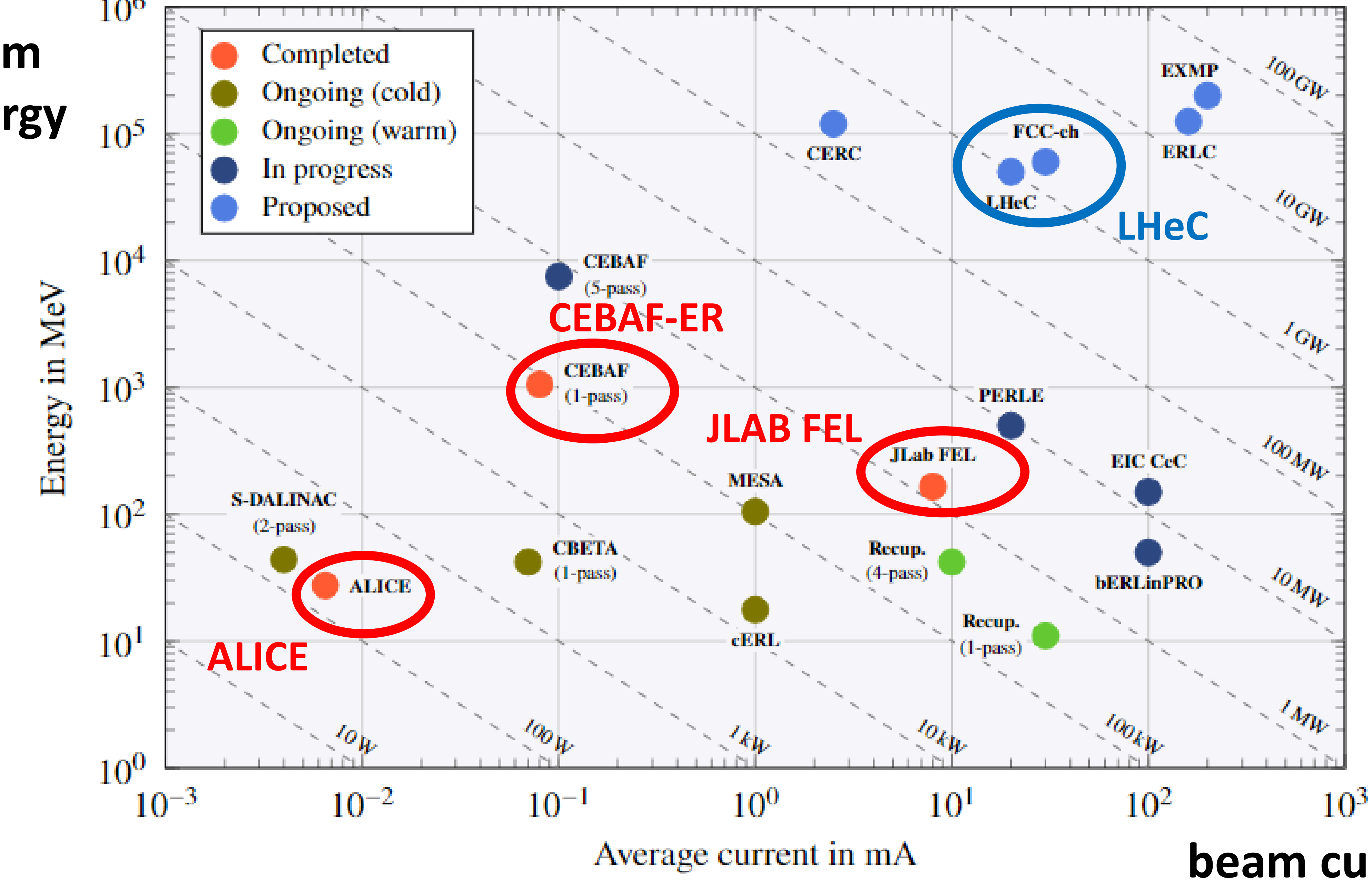
	Tigner 1965	**Amaldi 1976**	**Gerke – Steffen 1979**	**Litvinenko-Roser-Chamizo 2019**		**Telnov 2021**	
c.m. energy [GeV]	1-6	300	200	240	600	250	500
average beam current [mA]	120	10	0.3	2.5	0.16	100	100
vertical rms IP beam size [nm]	40,000 (round)	2,000 (round)	900 (round)	6	5	6.1	7.4
luminosity [10^{34} cm^{-2}s^{-1}]	0.0003	0.01	0.004	73	8	90	64

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

LDG ERL report

ERL landscape

beam energy



LHeC

CEBAF-ER

JLAB FEL

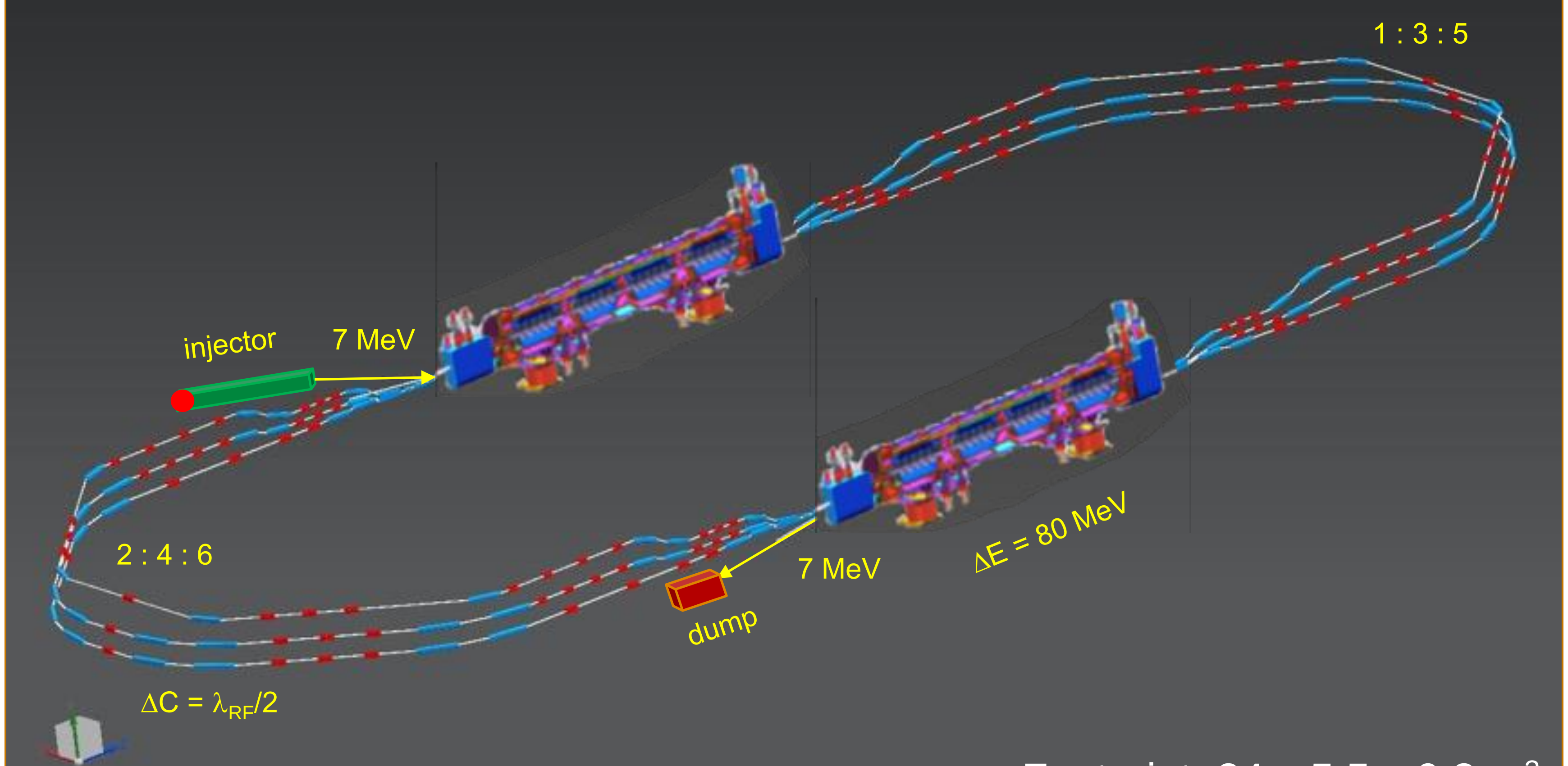
ALICE

beam current

PERLE

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

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

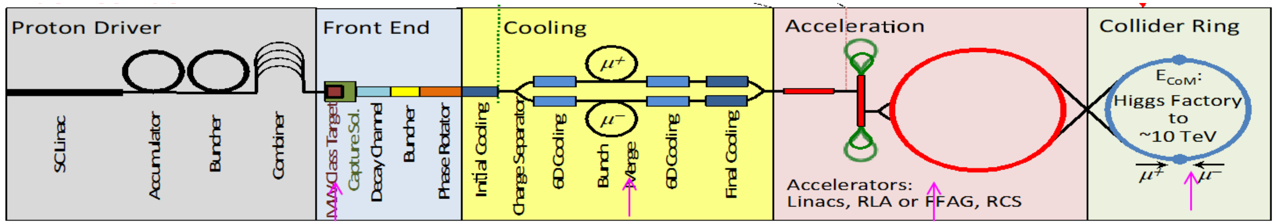
arXiv:1705.08783

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

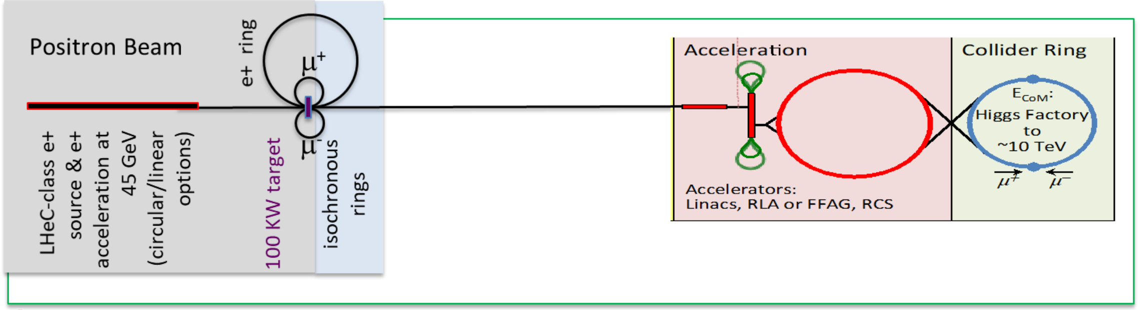
~10^{13}-10^{14} μ / sec tertiary particle $p \to \pi \to \mu$:

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**

needs large 45 GeV e⁺ ring like FCC-ee, possible upgrade path to **FCC-μμ**

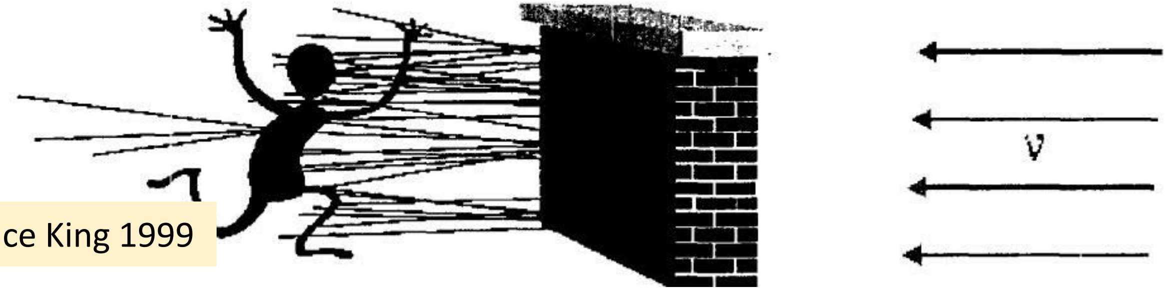
μ's decay within a few 100 - 1000 turns:

→ rapid acceleration

(perhaps plasma?)

→ ν radiation hazard

(limits maximum μ energy)



Bruce King 1999

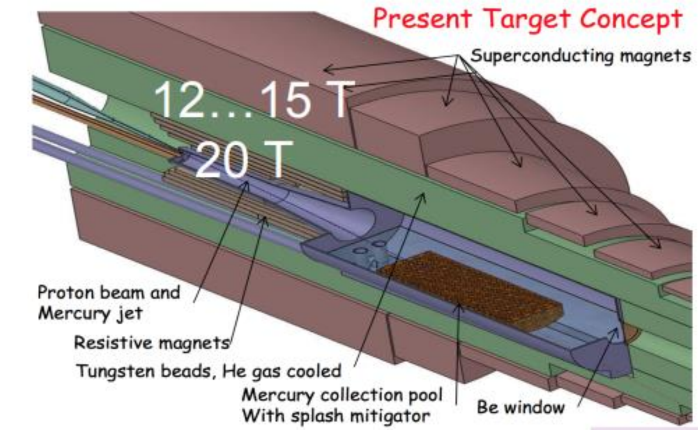
$\sigma_\nu \propto E$, **flux** $\propto E^2$ (Lorentz boost)

solution beyond 10 TeV unclear

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.

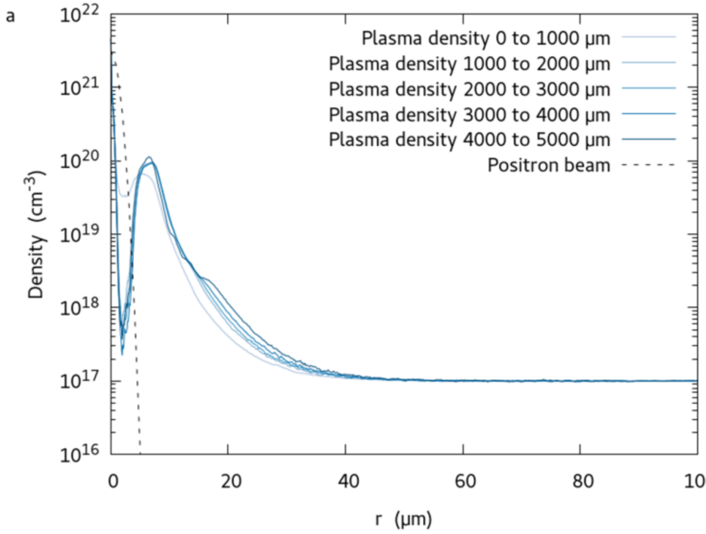
Shock in target: Simulations of graphite target indicate 2 MW could be acceptable

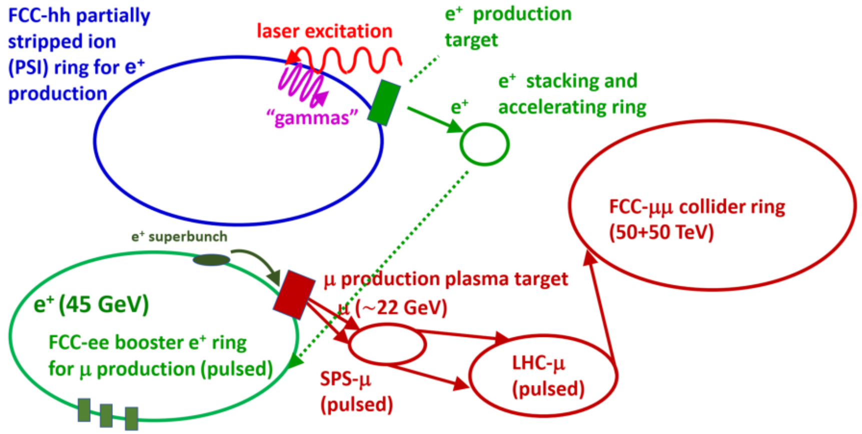
STFC will also study alternatives

Rui Franqueira Ximenes et al.

Operation at 2000 °C to maximise stress resistance

plasma target for e^+ driven μ collider



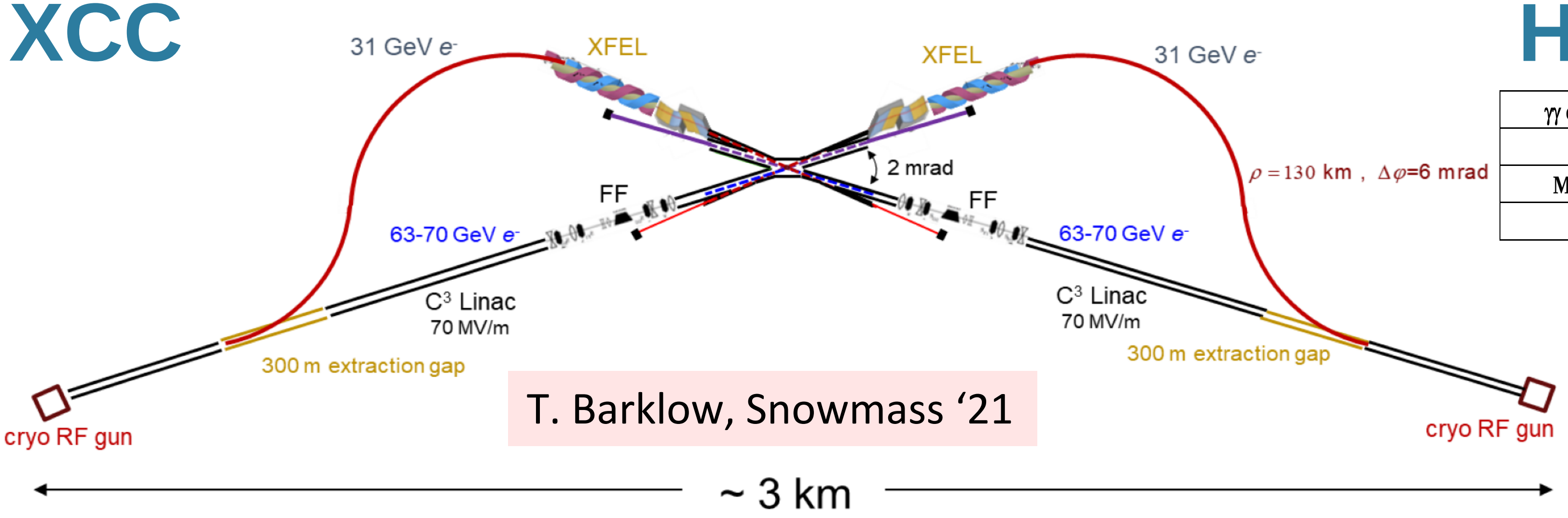


D. Schulte, IPAC'22

J. Farmer et al., IPAC'22

$\gamma\gamma$ colliders

XCC



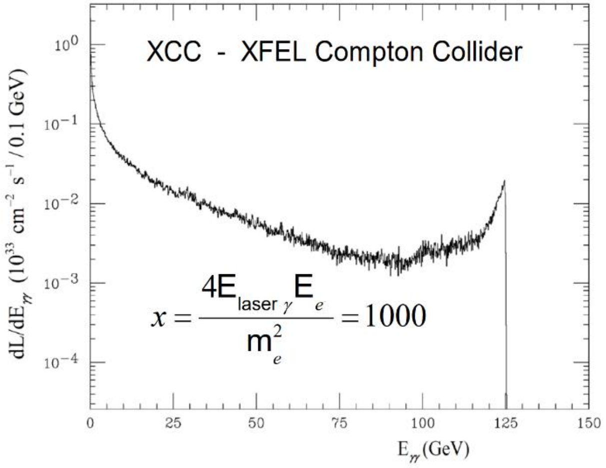
T. Barklow, Snowmass '21

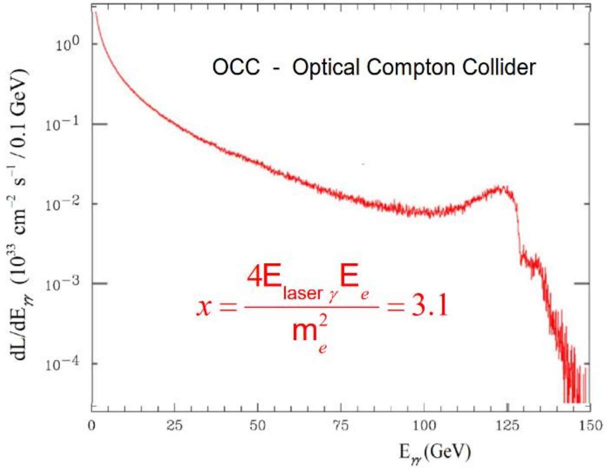
HE - HL $\gamma\gamma$ Collider

$\gamma\gamma$ 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
$\mathcal{L}_{\text{geometric}}$	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		

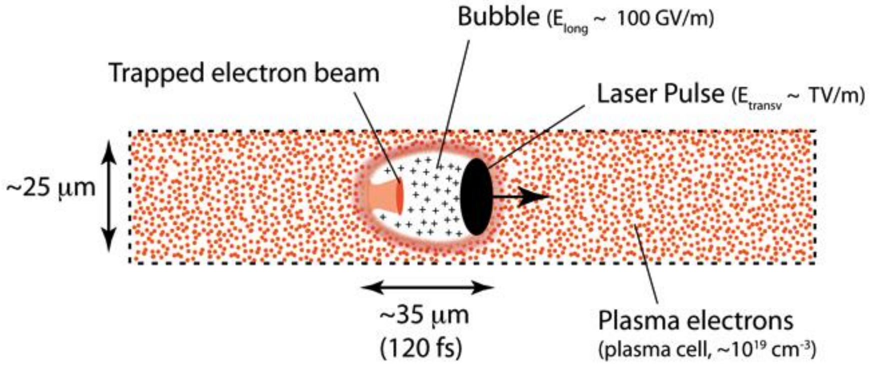




Machine	E_{e^-} (GeV)	N_{e^-} (nC)	Polarization	N_{H}/yr	$N_{\text{Hadronic}}/N_{\text{H}}$	$N_{\text{minbias/BX}}$
XCC	62.8	1.0	90% e^-	34,000	170	9.5
OCC	86.5	1.0	90% e^-	30,000	540	50
ILC	125	3.2	-80% e^- +30% e^+	42,000	140	1.3
ILC	125	3.2	+80% e^- -30% e^+	28,000	60	1.3

Advanced Accelerators: Plasma

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

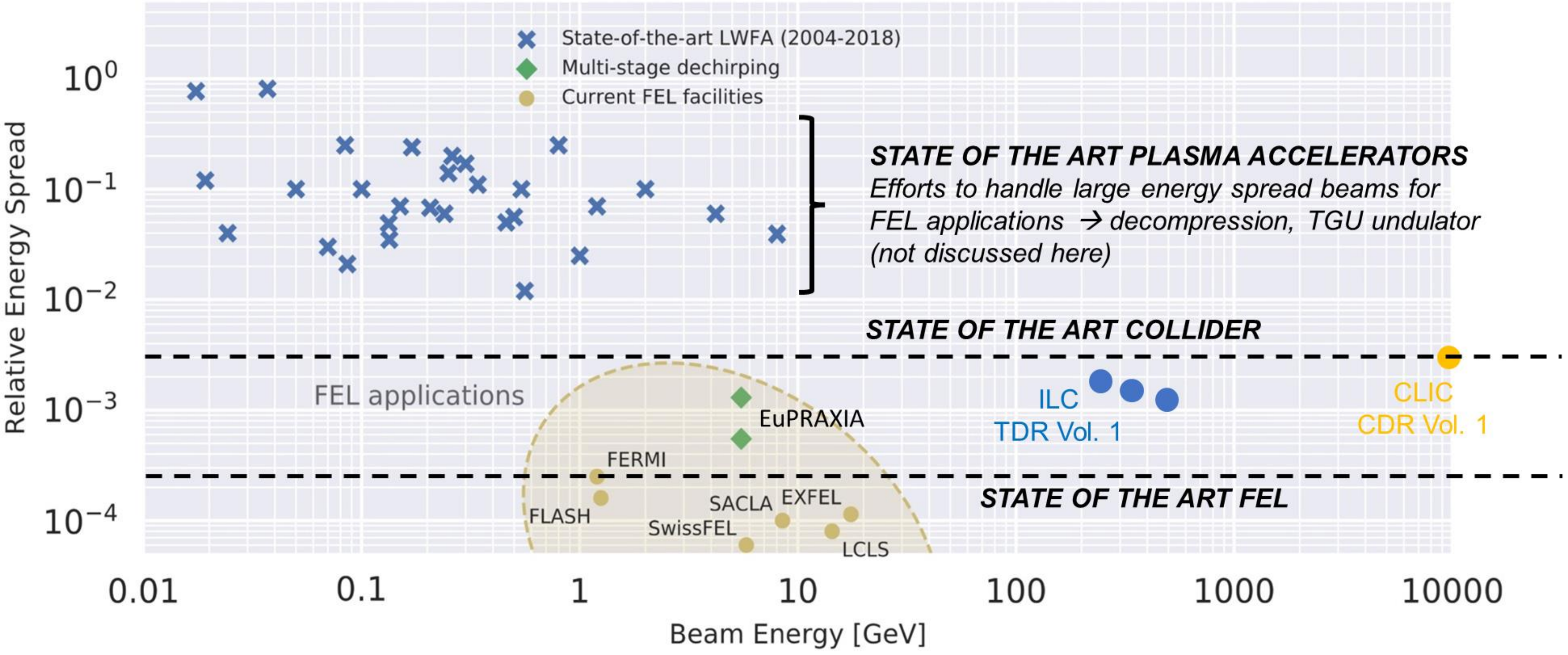


R. Assmann

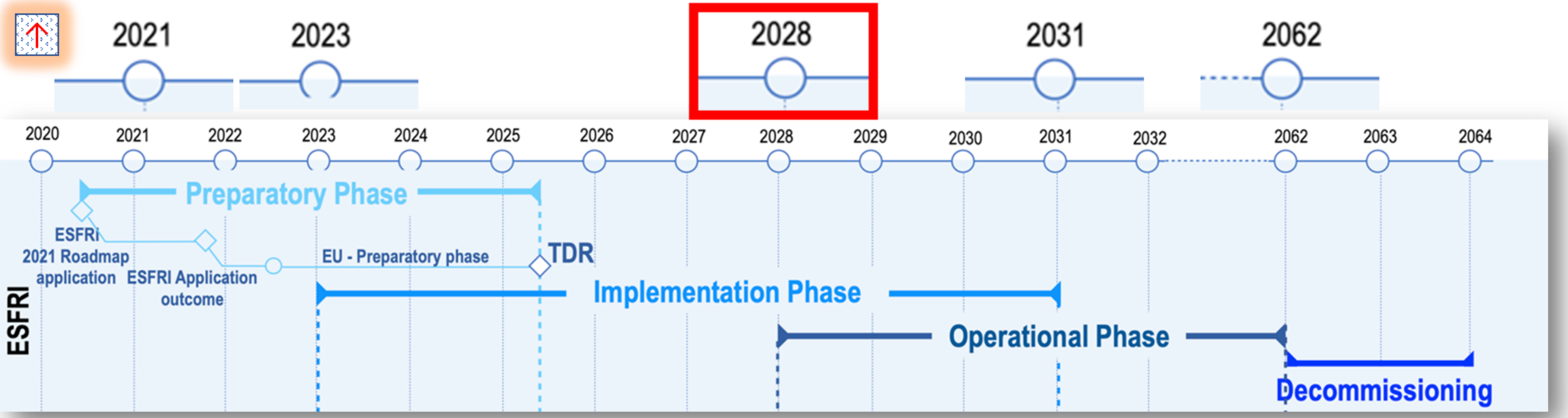
R. Assmann, E. Gschwendtner, R. Ischebeck, LDG Draft

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.

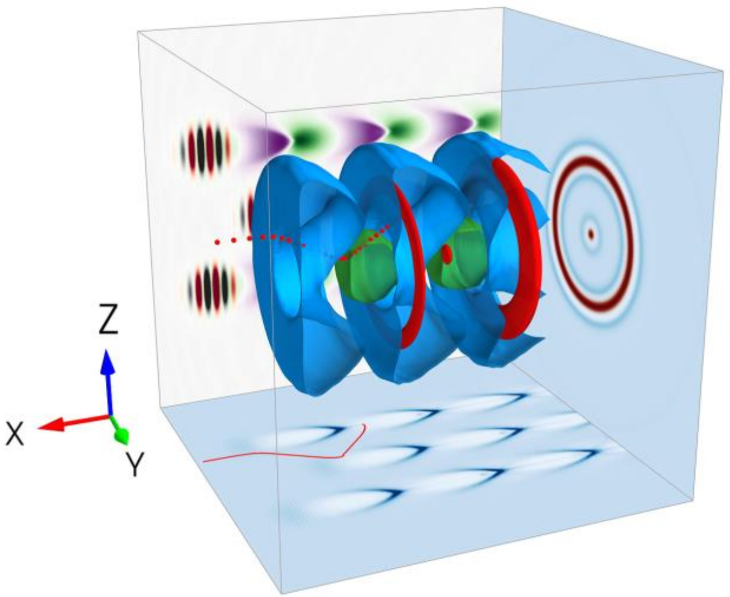
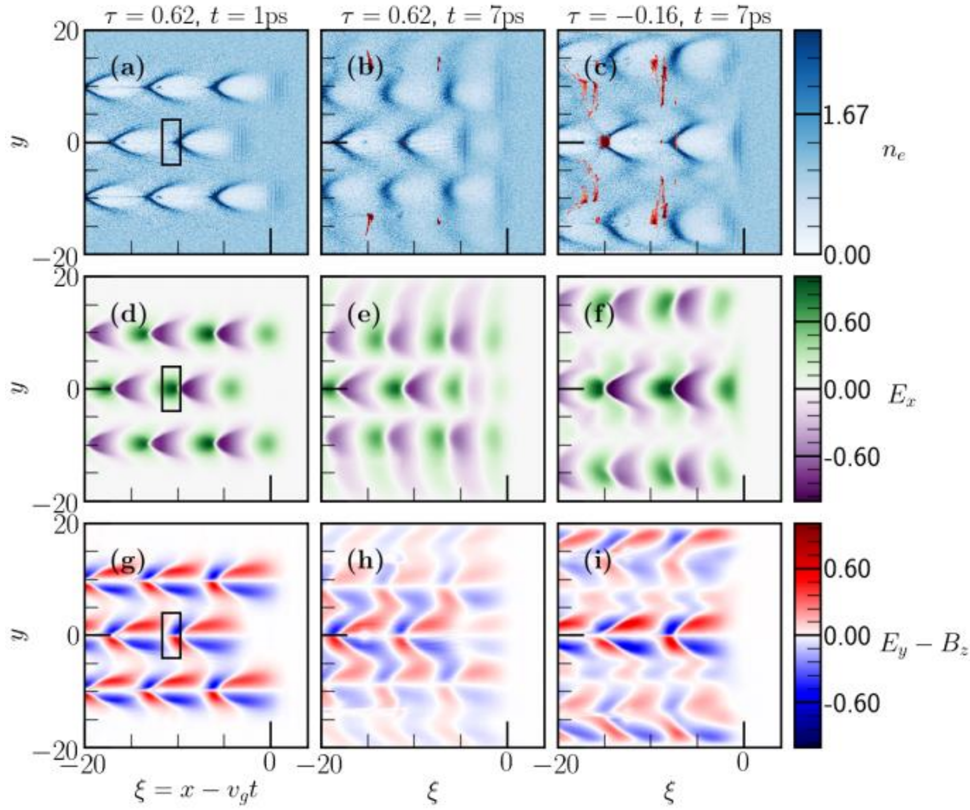


FIG. 1. The concept of the positron ballistic injection scheme. The blue and green colors are contour surfaces of electron densities of donut and center bubbles, respectively. The red color represents injected positrons. The x–y and x–z planes are transverse slices of the density distribution and the 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)

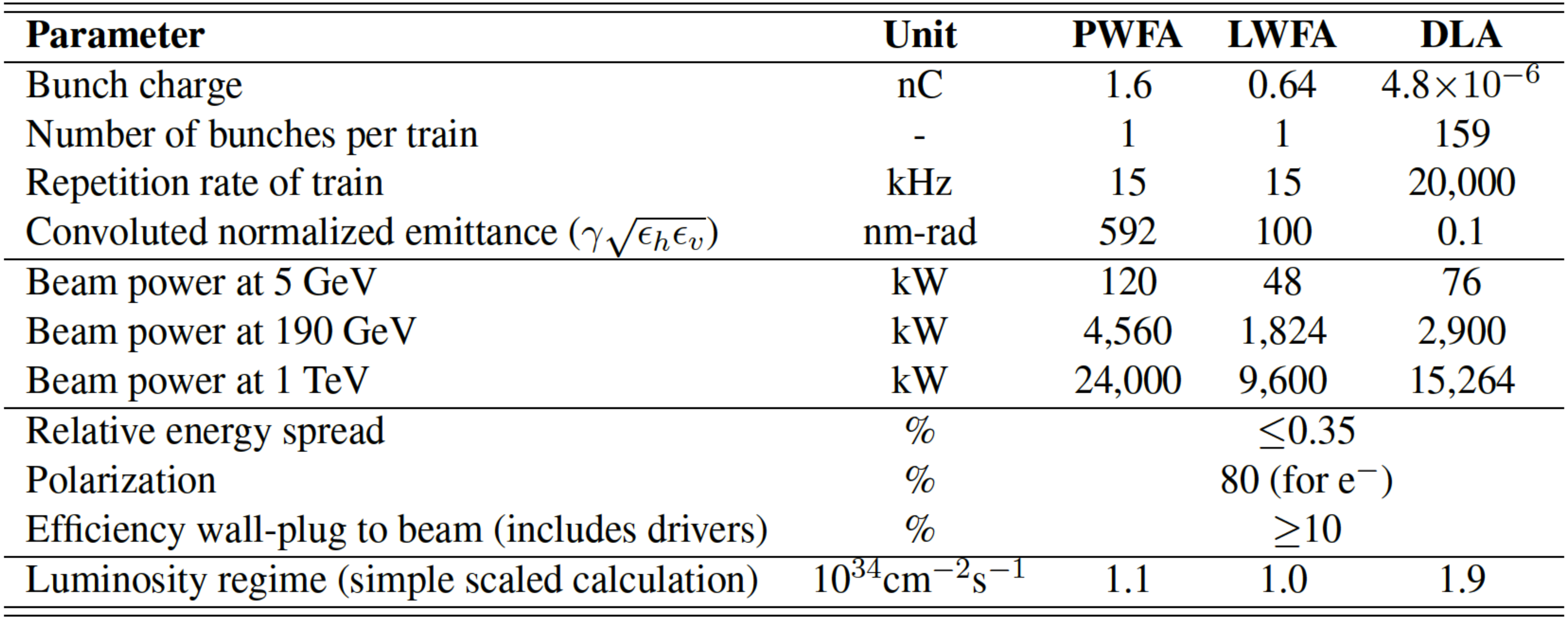
New injection and acceleration scheme of positrons in the laser-plasma bubble regime

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

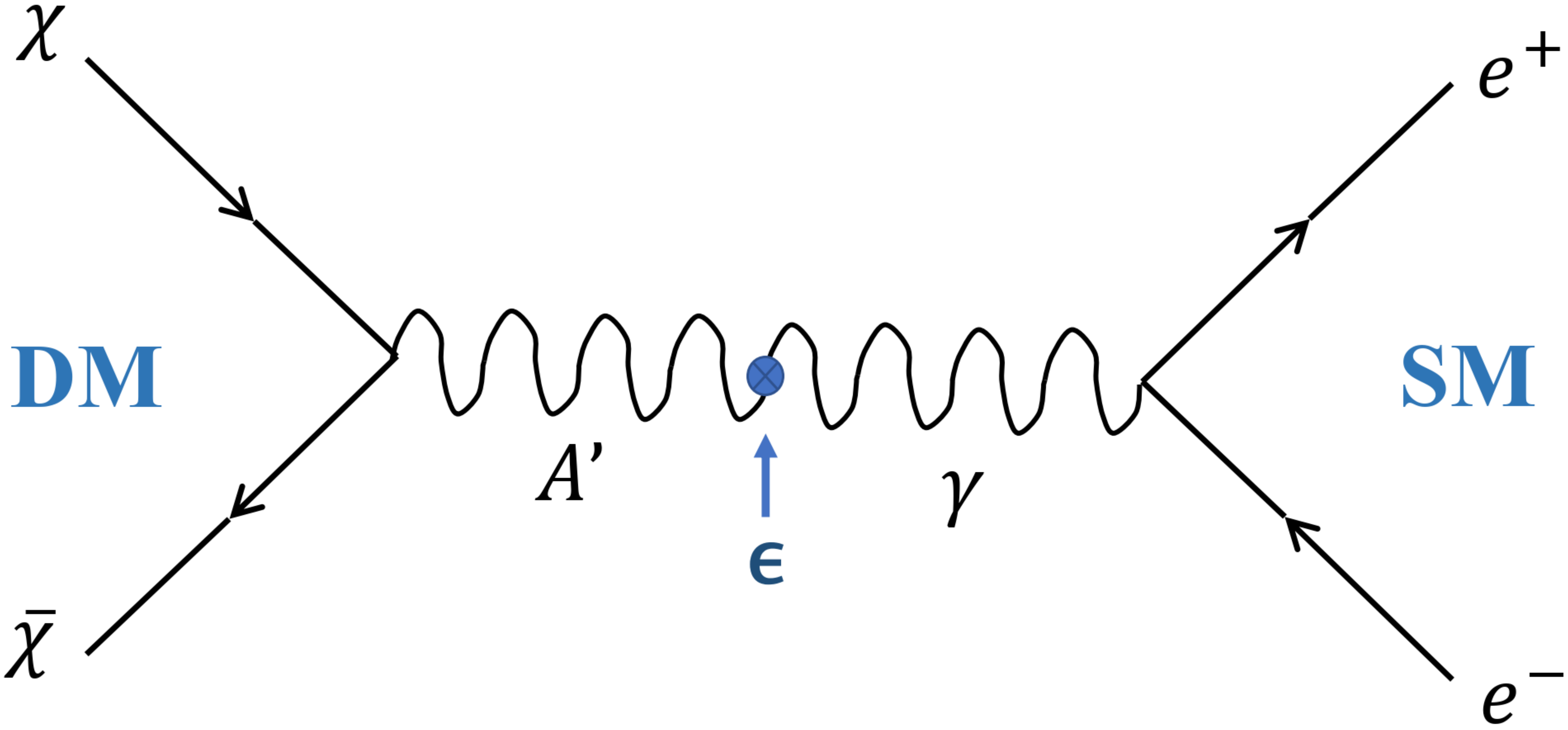
Advanced Accelerator Types

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]

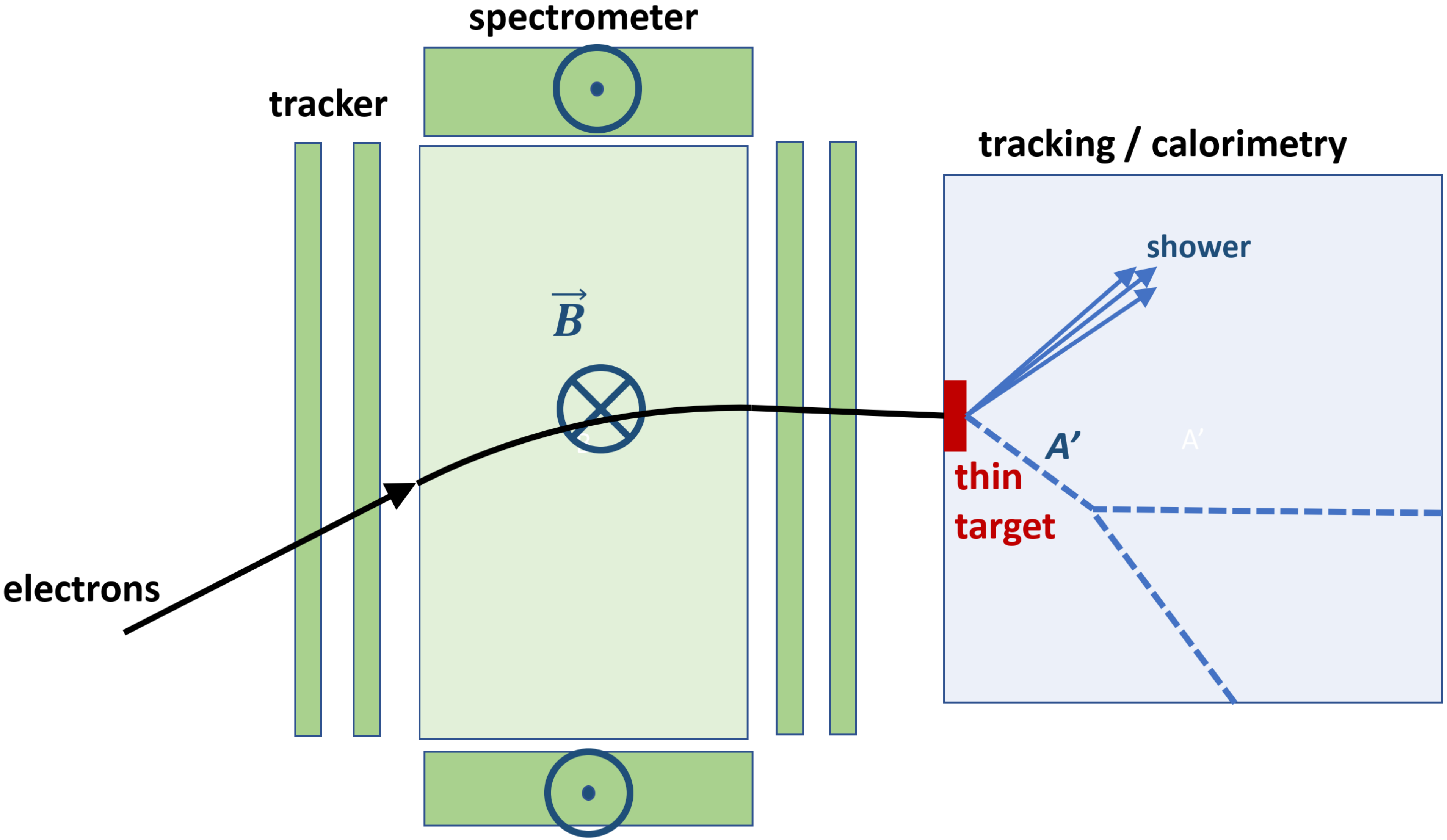


Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 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

Accelerators for Indirect Dark Sector Searches



Feynman diagram for **coupling of Standard Model particles & photons to** corresponding **Dark Sector objects A' and χ**, with coupling strength ϵ.



reference experiments:

- **NA64 experiment** at CERN [4]
- proposed **LDMX** based on the LCLS-II linac at SLAC [3] – goal: 1.6× 10^{15} 8-GeV electrons on target over 4 years

Concept of indirect DM search by missing momentum with spectrometer and trackers upstream and calorimeter downstream of a thin target, based on Refs. [1–3]. A' indicates a particle carrying missing energy.

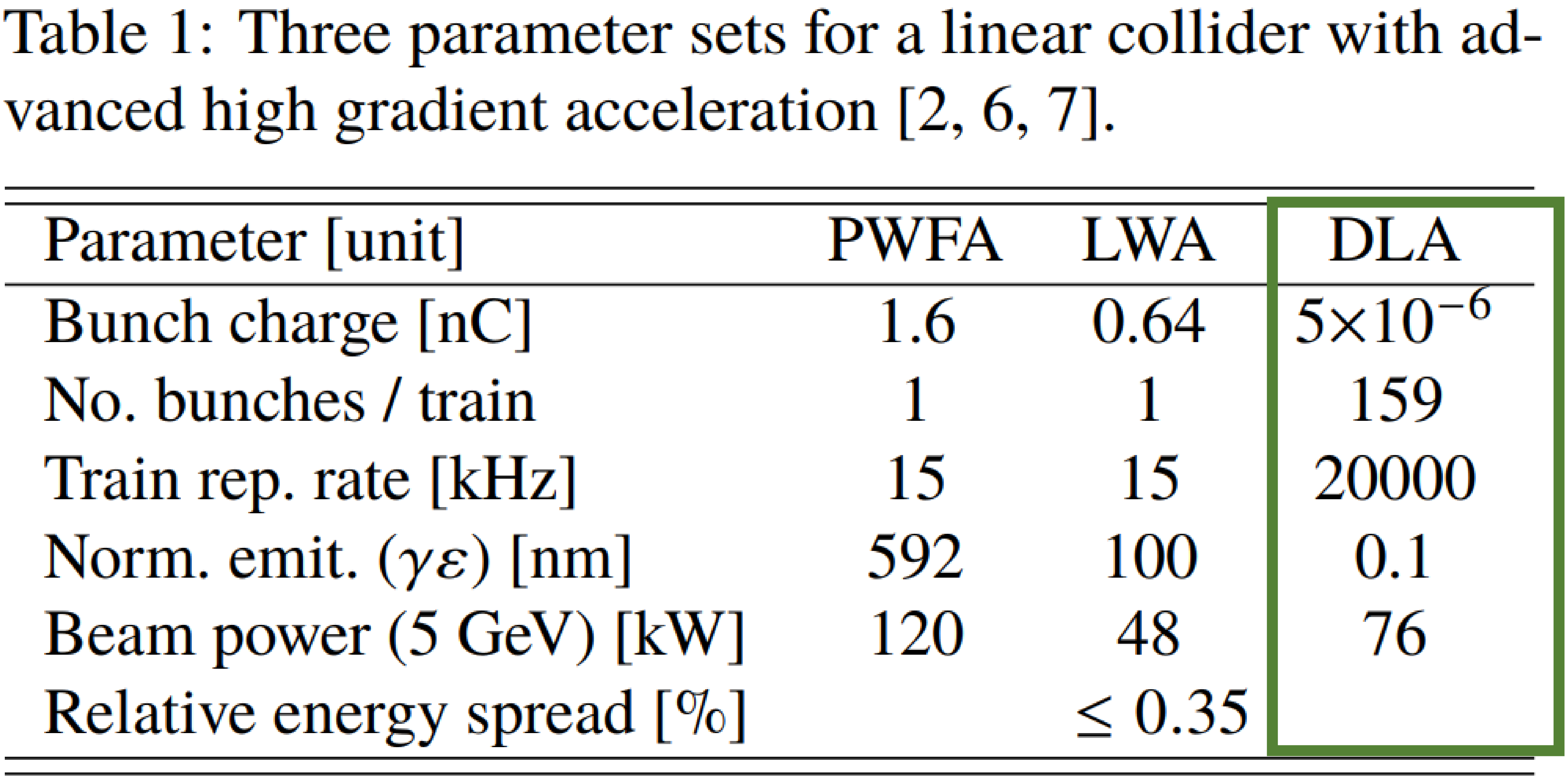


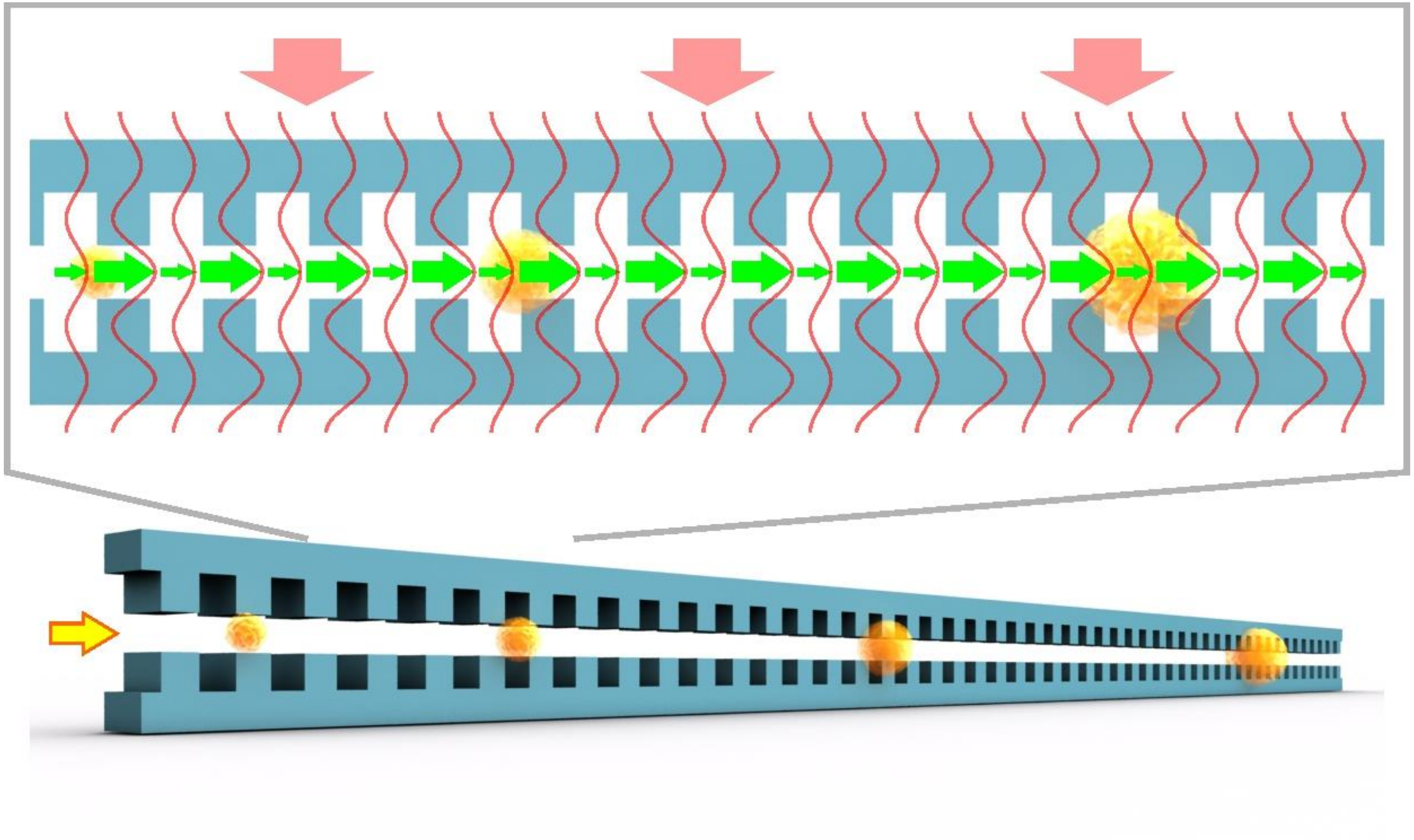
Table 1: Three parameter sets for a linear collider with advanced high gradient acceleration [2, 6, 7].

Parameter [unit]	PWFA	LWA	DLA
Bunch charge [nC]	1.6	0.64	5×10^{-6}
No. bunches / train	1	1	159
Train rep. rate [kHz]	15	15	20000
Norm. emit. ($\gamma\varepsilon$) [nm]	592	100	0.1
Beam power (5 GeV) [kW]	120	48	76
Relative energy spread [%]		≤ 0.35	

from European LDG roadmap & Assmann, 2022

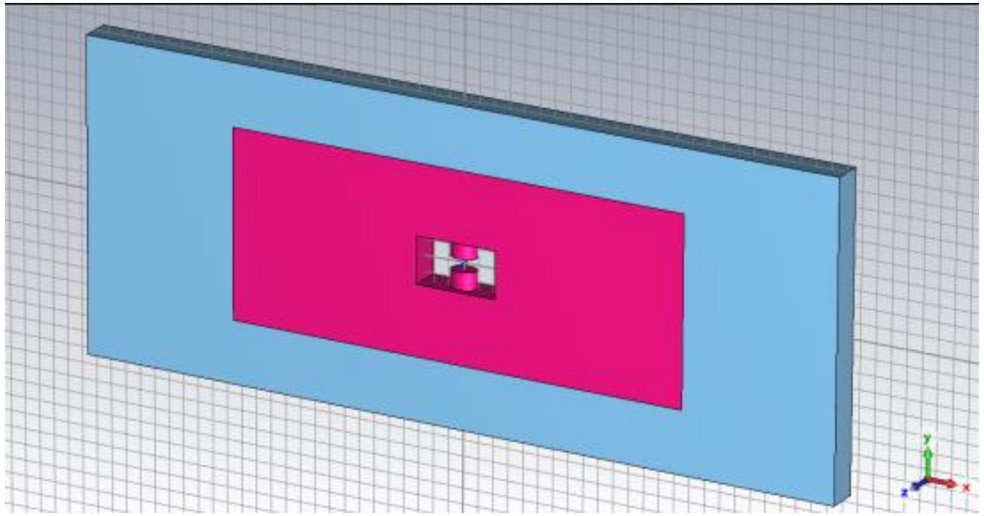
perfect match with indirect searches for dark sector !

Principle of Dielectric Laser Acceleration (DLA)

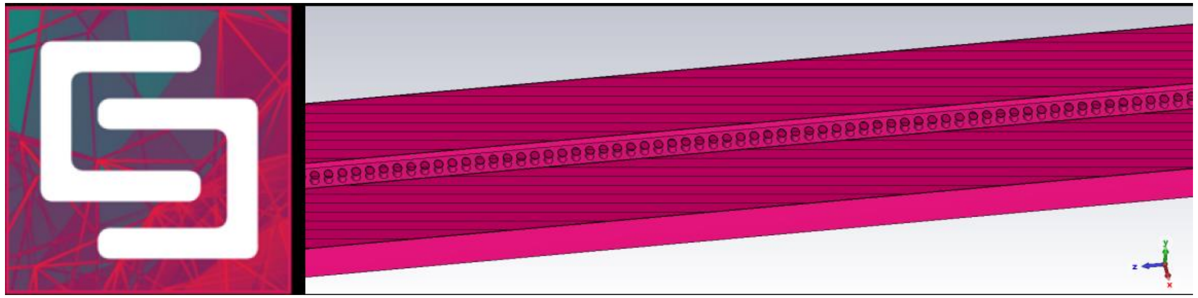


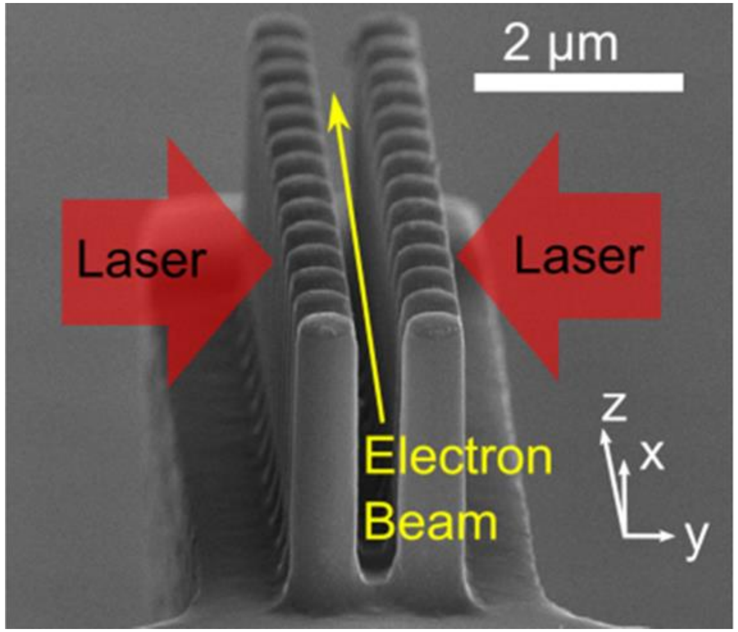
The DLA structure is illuminated by laser light from the top. Green arrows indicate the positive force of the laser's electric field that can accelerate electrons.

Example DLA structures

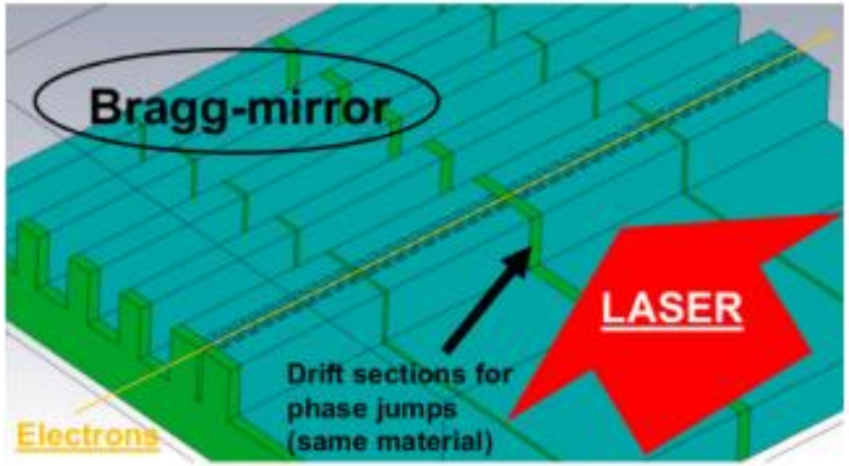


R. Dadashi (2022/23)



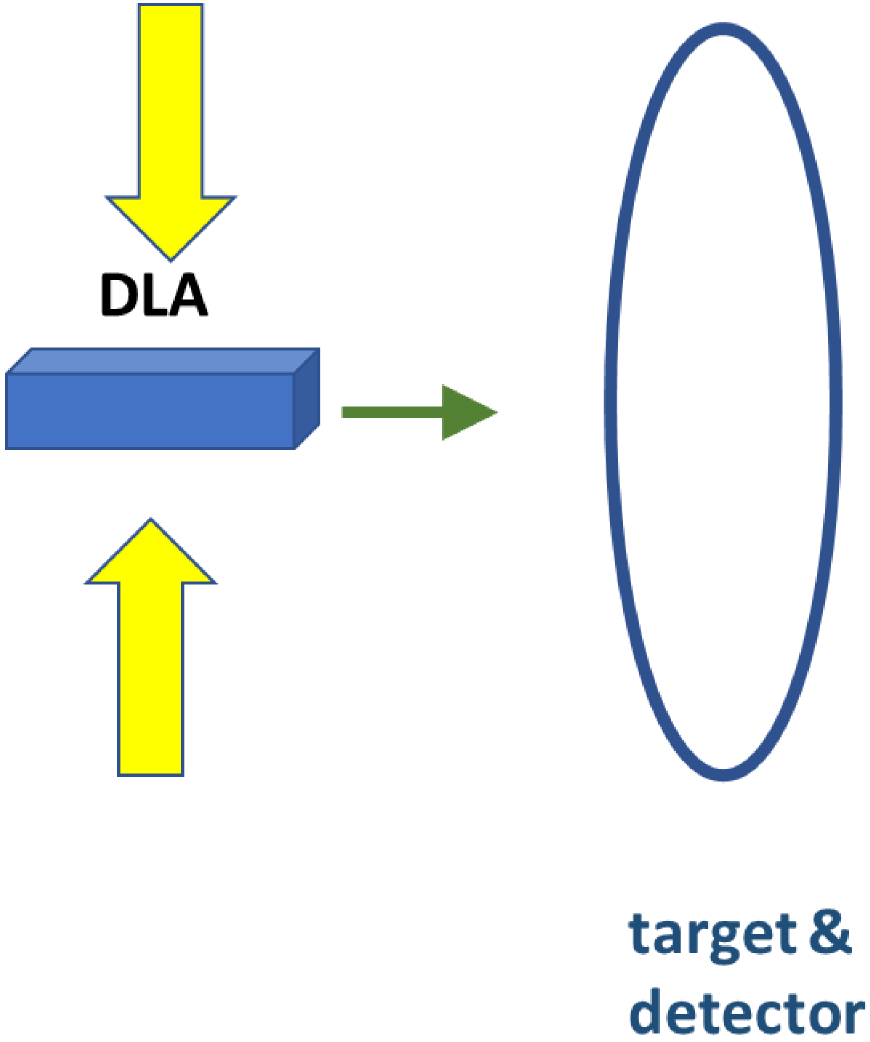


K.J. Leedle et al.,
Opt. Lett. 43,
2181-2184 (2018)



U. Niedermayer et al., Phys Rev Accel. Beams 20, 111302 (2017)

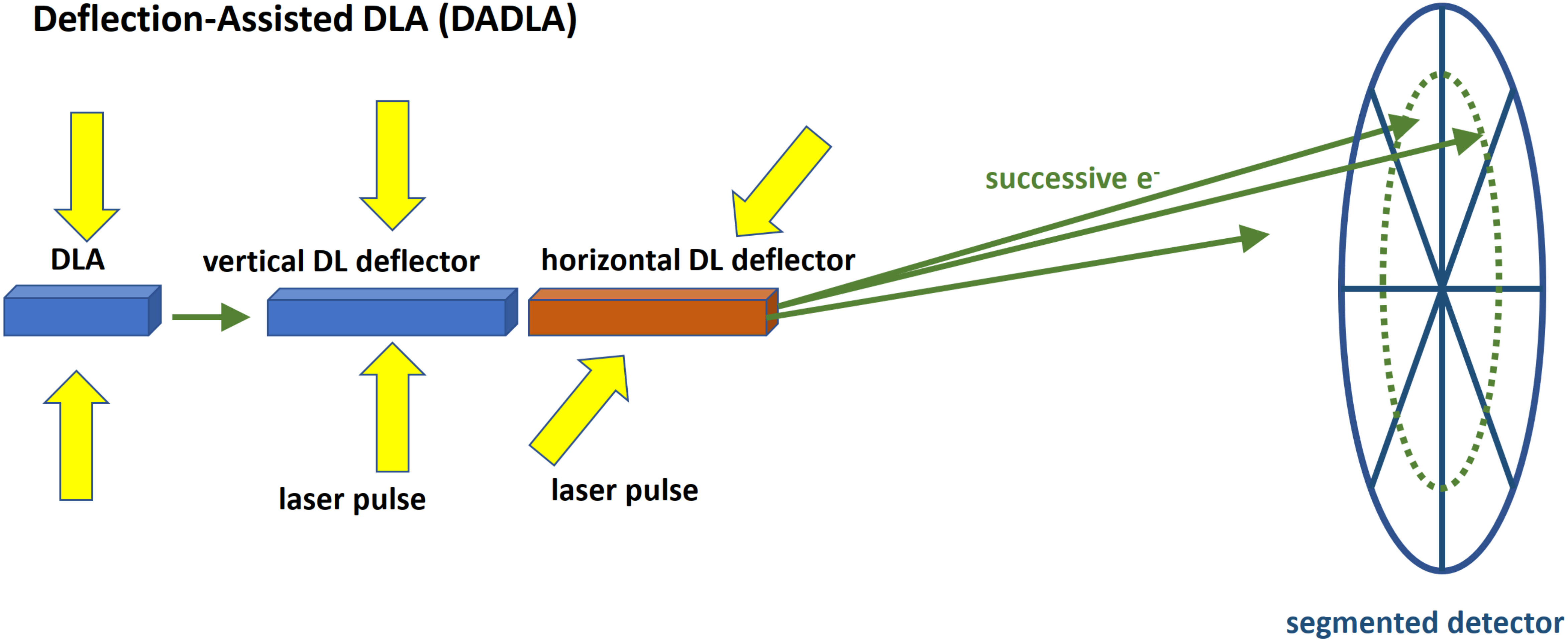
Minimum DLA (MDLA)



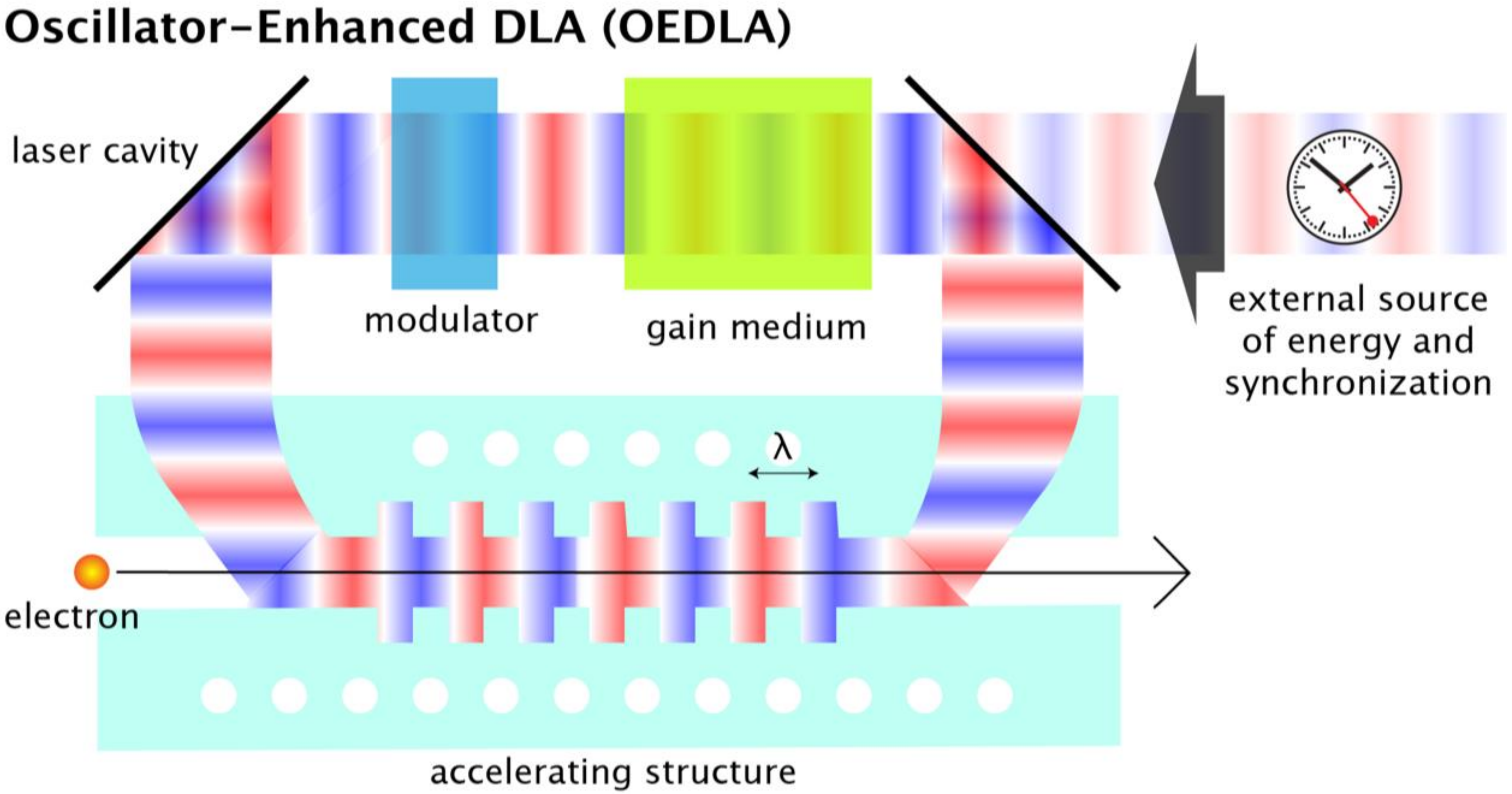
DLA

target & detector

Deflection-Assisted DLA (DADLA)



A pair of **orthogonal dielectric laser deflectors** installed at the exit of the DLA (DADLA setup) is sending each electron in a train of ~160 onto **separate segments of the detector,** thereby overcoming the time resolution limit and allowing bunch spacing of <10 ps within a train



DLA structure as part of a laser oscillator (OEDLA); e$^-$ pass rightwards through the structure; laser pulse circulates at 100 GHz (path ~3 mm).

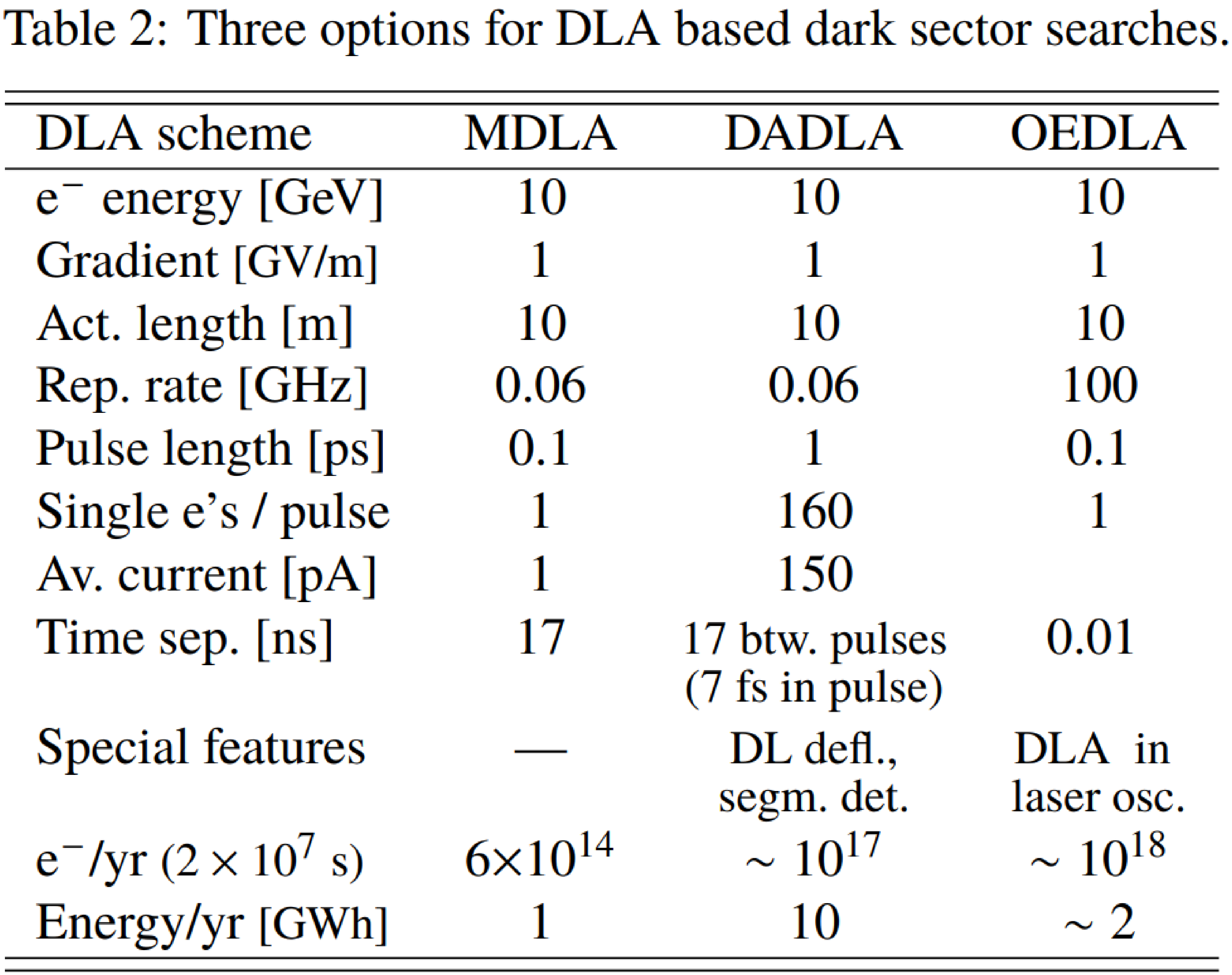
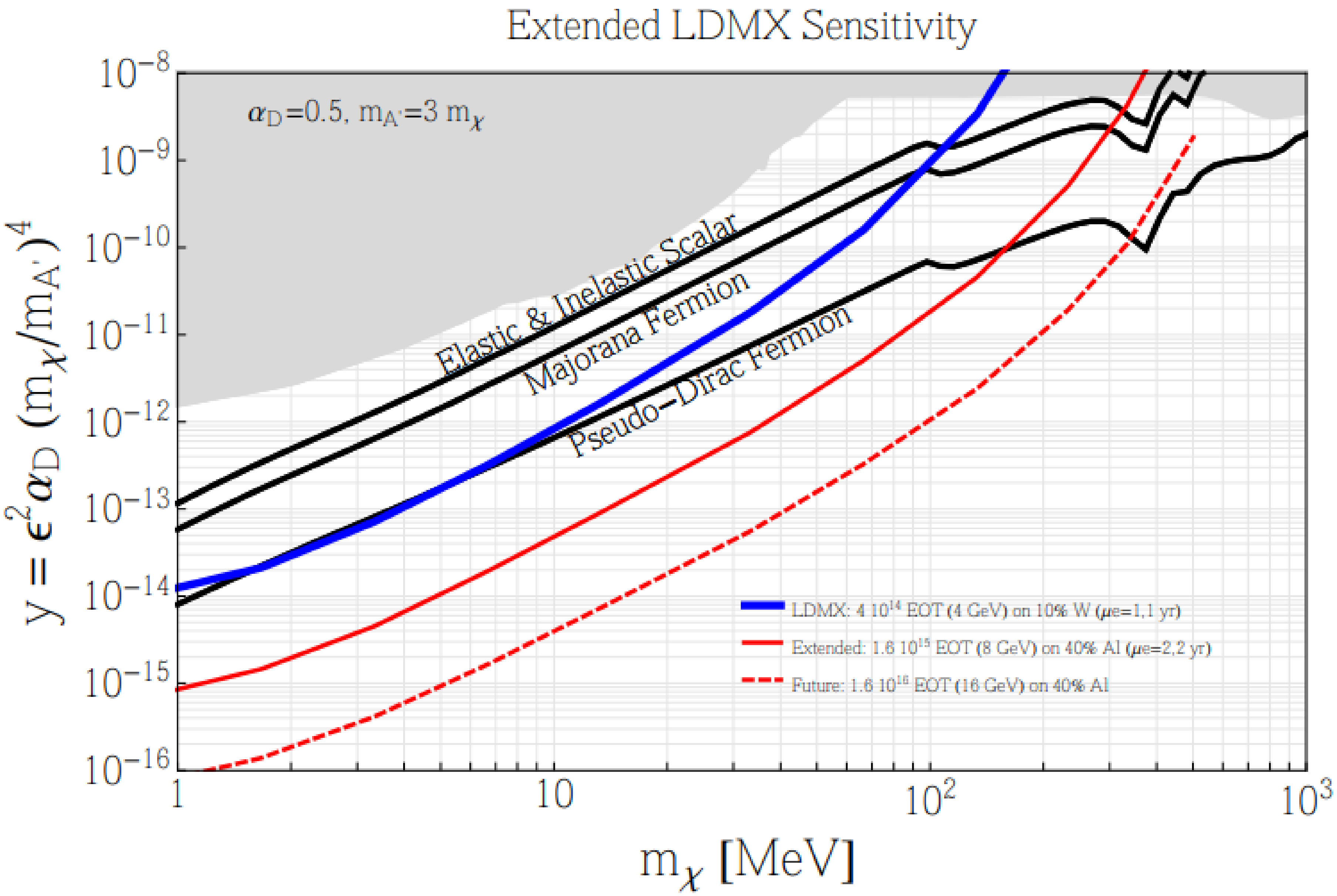


Table 2: Three options for DLA based dark sector searches.

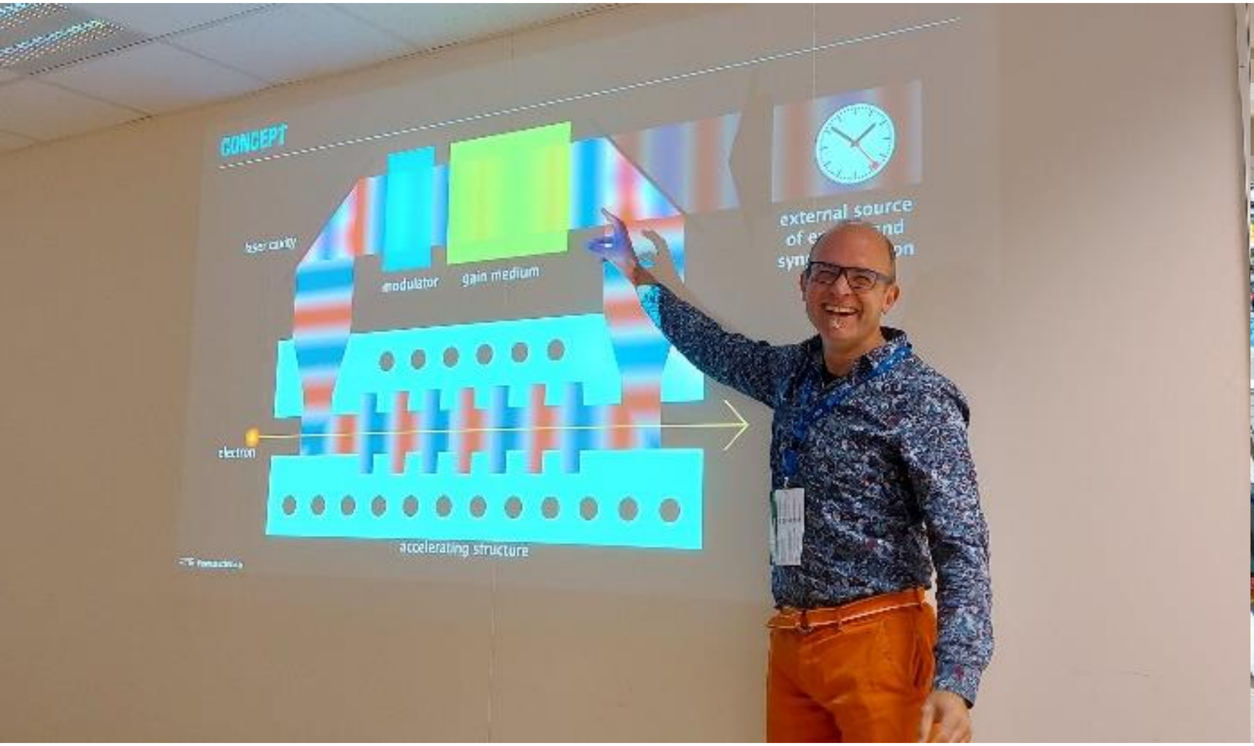
DLA scheme	MDLA	DADLA	OEDLA
e^- energy [GeV]	10	10	10
Gradient [GV/m]	1	1	1
Act. length [m]	10	10	10
Rep. rate [GHz]	0.06	0.06	100
Pulse length [ps]	0.1	1	0.1
Single e's / pulse	1	160	1
Av. current [pA]	1	150	
Time sep. [ns]	17	17 btw. pulses (7 fs in pulse)	0.01
Special features	—	DL defl., segm. det.	DLA in laser osc.
e^-/yr (2×10^7 s)	6×10^{14}	$\sim 10^{17}$	$\sim 10^{18}$
Energy/yr [GWh]	1	10	~ 2

LDMX:
4×10^{14} e^-/yr



The interaction strength between dark matter and Standard Model matter versus the possible mass of the dark matter particles. The black lines show the interaction strength compatible with the dark matter abundance in the universe, and for the types of dark matter particles that are not excluded from the analysis of the Cosmic Microwave Background. The grey area shows the already excluded region. The colored lines show the reach of LDMX. The plot is taken from T. Akesson et al., Dark Sector Physics with a Primary Electron Beam Facility at CERN, tech. rep., ***CERN-SPSC-2018-023****, 2018, URL: http://cds.cern.ch/record/2640784*

Two snapshots from iFAST WP5.2 topical dark-sector accelerator meeting at CERN, 31 October 2022

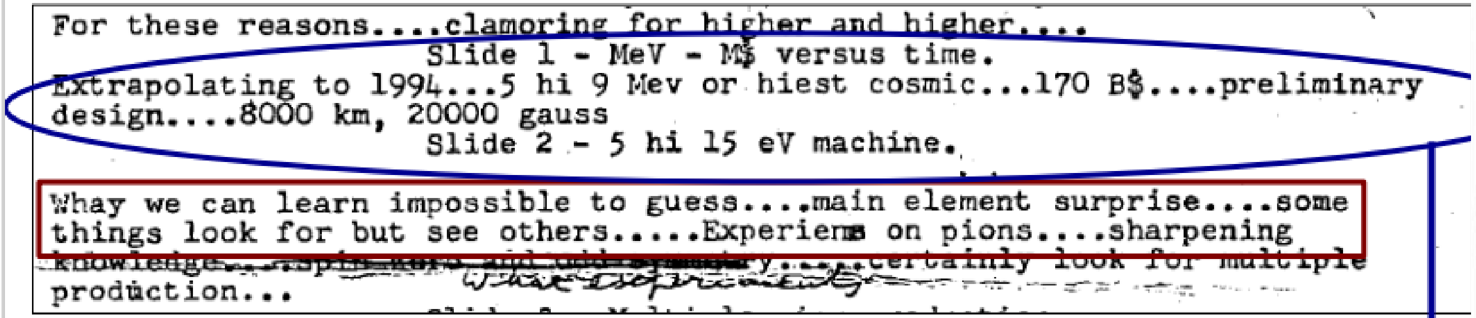


Rasmus Ischebeck

Raziyeh Dadashi, Rasmus Ischebeck, Jeremy Jacobsson, Richard Jacobsson, Massimiliano Ferro-Luzzi, Witek Krasny, Frank Zimmermann

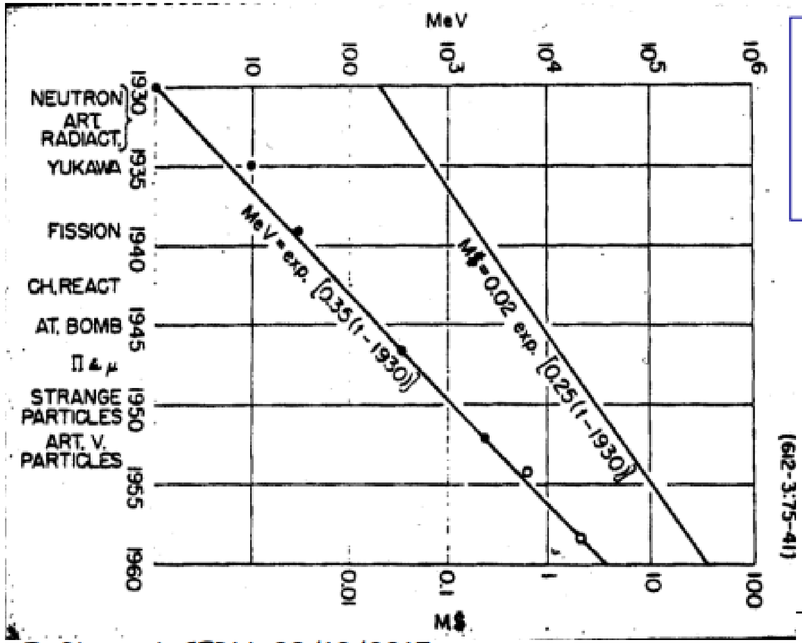
Enrico Fermi's space-based world machine

From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ?"
given to the American Physical Society, NY, Jan. 29th 1954

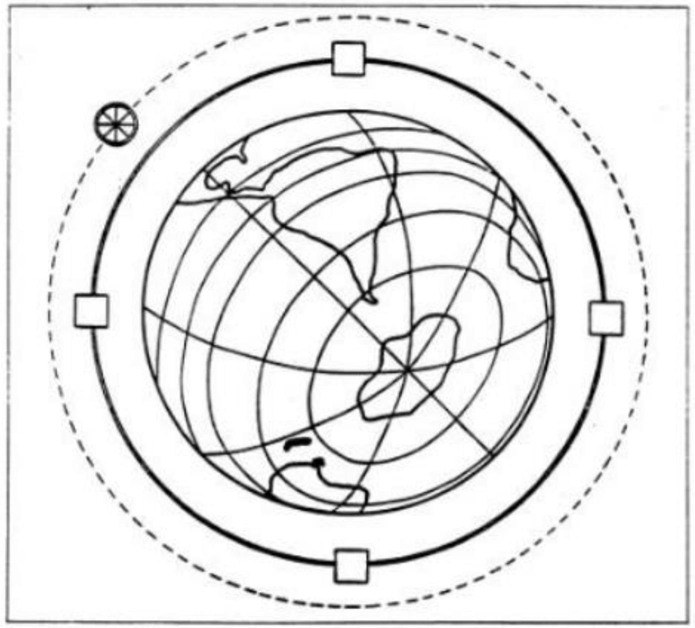


For these reasons....clamoring for higher and higher....
Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss
Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening knowledge....~~spin zero and odd symmetry~~.....certainly look for multiple production...
~~What experiments~~



Fermi's extrapolation to year 1994:
E_{beam} ~ 5×10^3 TeV, 2T magnets → R=8000 km
Note: fixed target accelerator → $\sqrt{s}$ ~ 3 TeV
Cost : 170 B$



From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

Rivkin

F. Gianotti, CERN, 29/10/2015

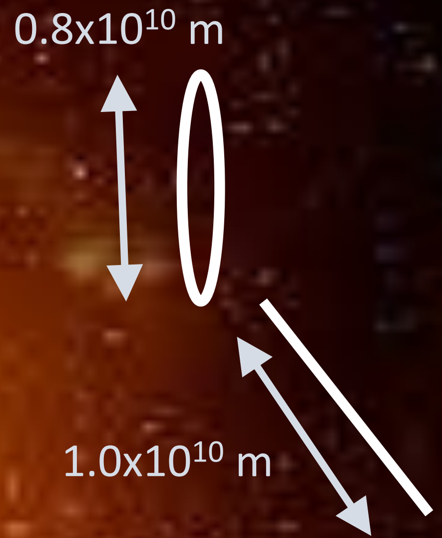
ultimate limit on electromagnetic acceleration

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

Planck scale: 10^{28} eV

“not an inconceivable task for an advanced technological society”

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

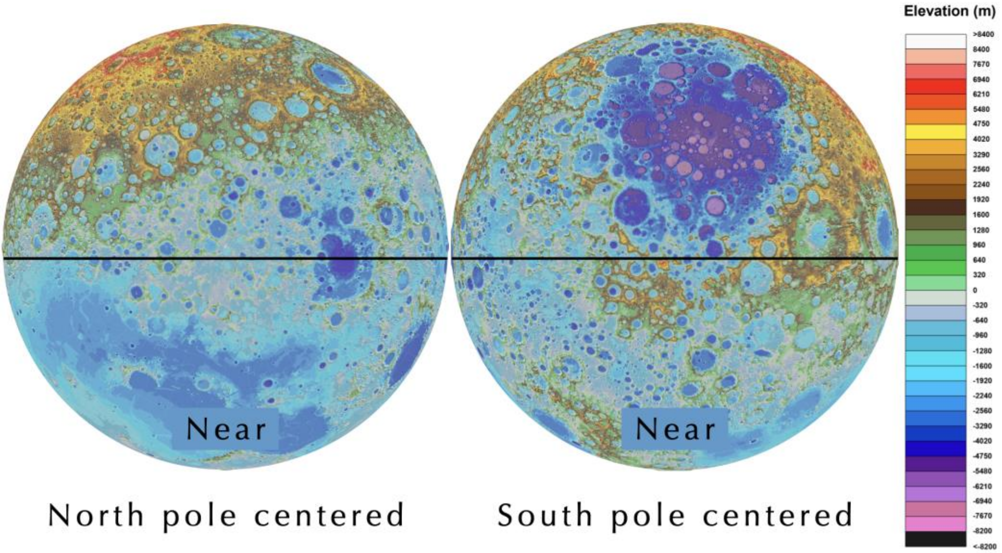


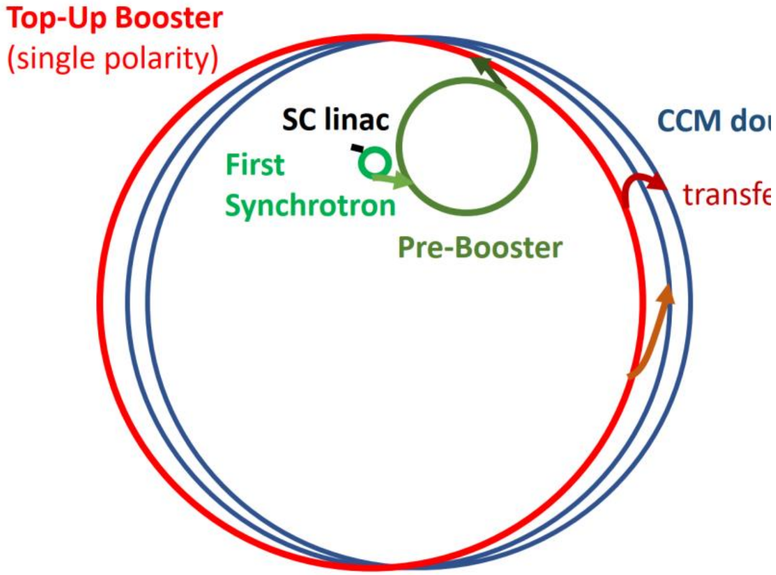
circular & linear Planck-scale colliders

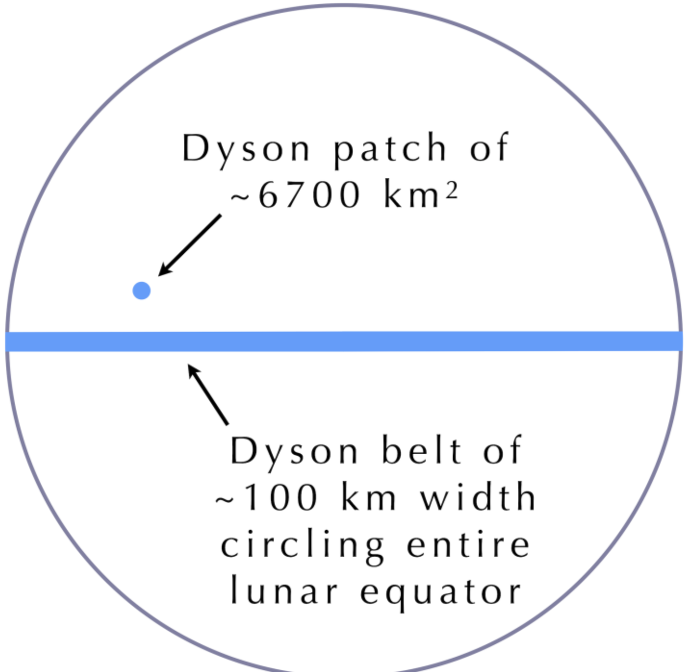
~1/10th for distance earth-sun

stepping stone towards Planck scale collider ?!

Very large hadron collider on the Moon (CCM), $C\sim11$ Mm, $E_{c.m.}\sim14$ 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.



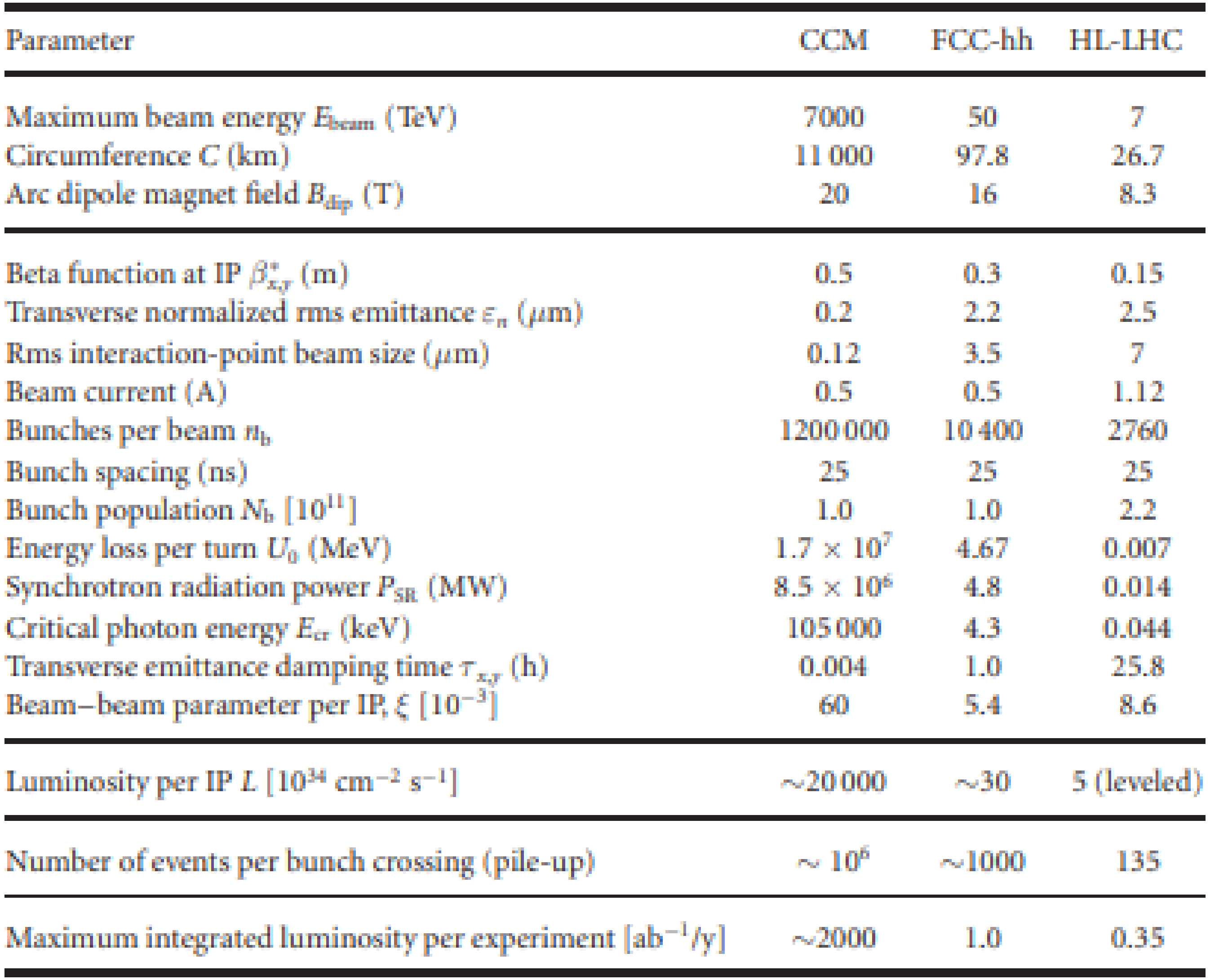




J. Beacham, F. Zimmermann, 2022 *New J. Phys.*, https://doi.org/10.1088/1367-2

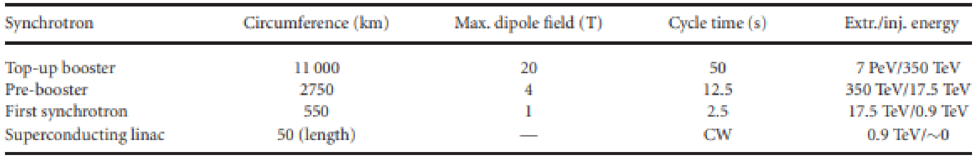
tentative CCM parameters & layout

Table 1. Tentative proton–proton parameters for CCM, compared with FCC-hh and HL-LHC [48].



Parameter	CCM	FCC-hh	HL-LHC
Maximum beam energy E_{beam} (TeV)	7000	50	7
Circumference C (km)	11 000	97.8	26.7
Arc dipole magnet field B_{dip} (T)	20	16	8.3
Beta function at IP $\beta^*_{x,y}$ (m)	0.5	0.3	0.15
Transverse normalized rms emittance ε_n (μm)	0.2	2.2	2.5
Rms interaction-point beam size (μm)	0.12	3.5	7
Beam current (A)	0.5	0.5	1.12
Bunches per beam n_b	1200 000	10 400	2760
Bunch spacing (ns)	25	25	25
Bunch population N_b [10^{11}]	1.0	1.0	2.2
Energy loss per turn U_0 (MeV)	1.7×10^7	4.67	0.007
Synchrotron radiation power P_{SR} (MW)	8.5×10^6	4.8	0.014
Critical photon energy E_{cr} (keV)	105 000	4.3	0.044
Transverse emittance damping time $\tau_{x,y}$ (h)	0.004	1.0	25.8
Beam–beam parameter per IP, ξ [10^{-3}]	60	5.4	8.6
Luminosity per IP L [10^{34} cm^{-2} s^{-1}]	$\sim$20 000	$\sim$30	5 (leveled)
Number of events per bunch crossing (pile-up)	$\sim 10^6$	$\sim$1000	135
Maximum integrated luminosity per experiment [ab^{-1}/y]	$\sim$2000	1.0	0.35

Table 2. Parameters for a possible CCM injector chain.



Synchrotron	Circumference (km)	Max. dipole field (T)	Cycle time (s)	Extr./inj. energy
Top-up booster	11 000	20	50	7 PeV/350 TeV
Pre-booster	2750	4	12.5	350 TeV/17.5 TeV
First synchrotron	550	1	2.5	17.5 TeV/0.9 TeV
Superconducting linac	50 (length)	—	CW	0.9 TeV/$\sim$0

J. Beacham, F. Zimmermann, 2022 *New J. Phys.*, https://doi.org/10.1088/1367-2630

a timely consideration ?!

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

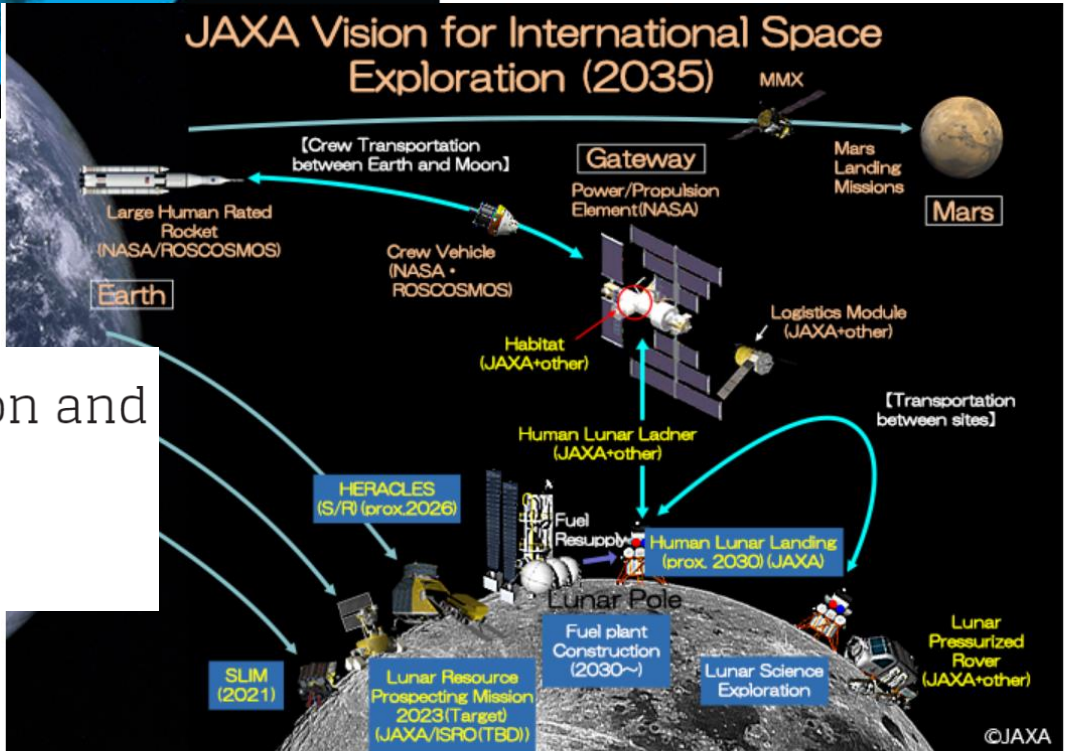
Jan 4, 2022 ... Everyone's going to the moon—a new space race · Our podcast on the science and technology making the news. Also this week: how to avoid conflict ...

The Economist

CNRS News

Artemis: To the Moon and beyond

08.26.2022



NASA Reveals Future Plans for Colonization of the Moon

APRIL 5, 2020

275 SHARES Facebook Twitter Pinterest LinkedIn Reddit WhatsApp

techeblog.com

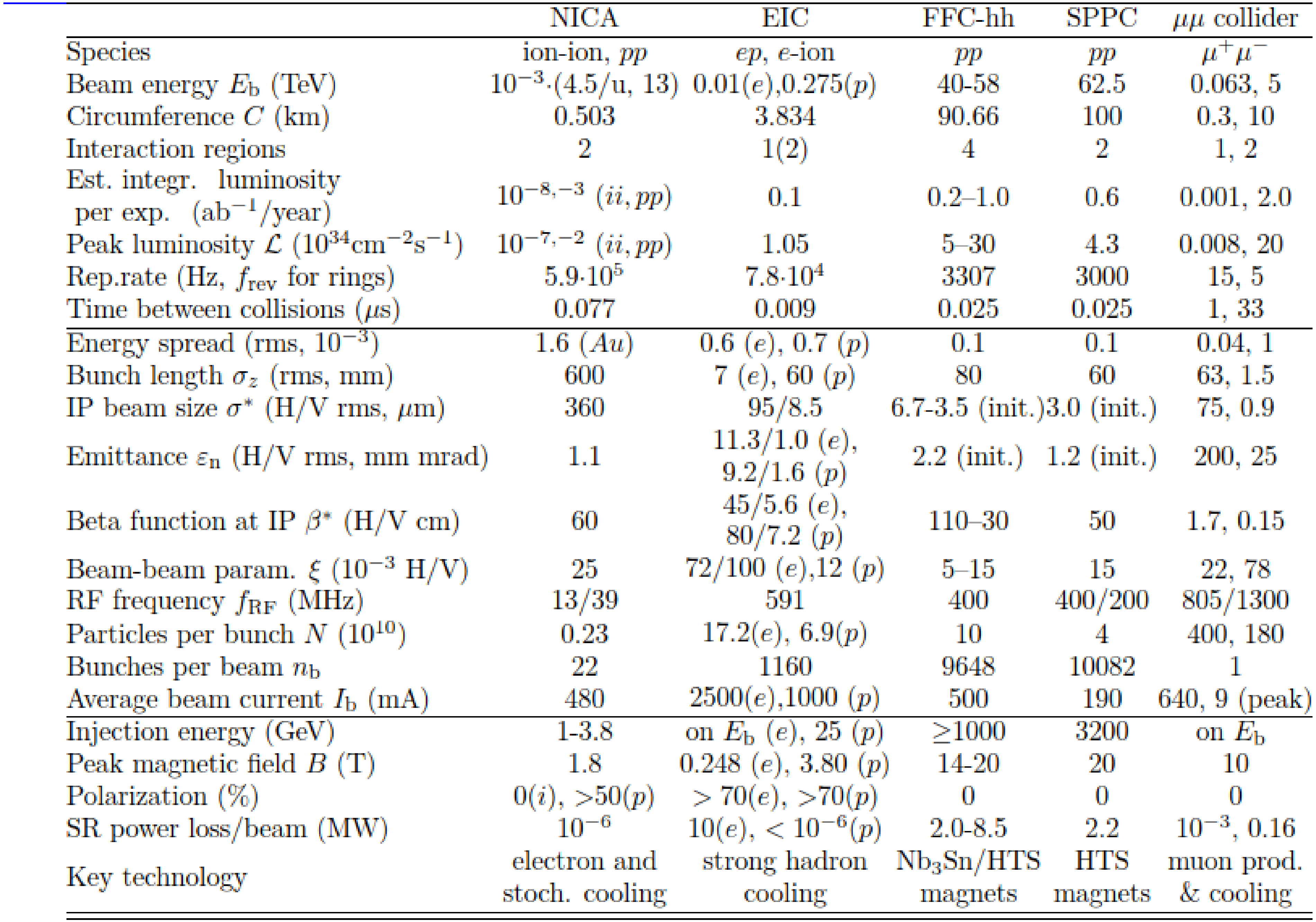
Isro plans to explore dark side of the Moon with Japan, venture towards Venus

India Today Web Desk

New Delhi, UPDATED: Nov 7, 2022 11:05 IST *back to the next generation*

design parameters of future hadronic & muon colliders

from Particle Data Group
Draft update July 2023

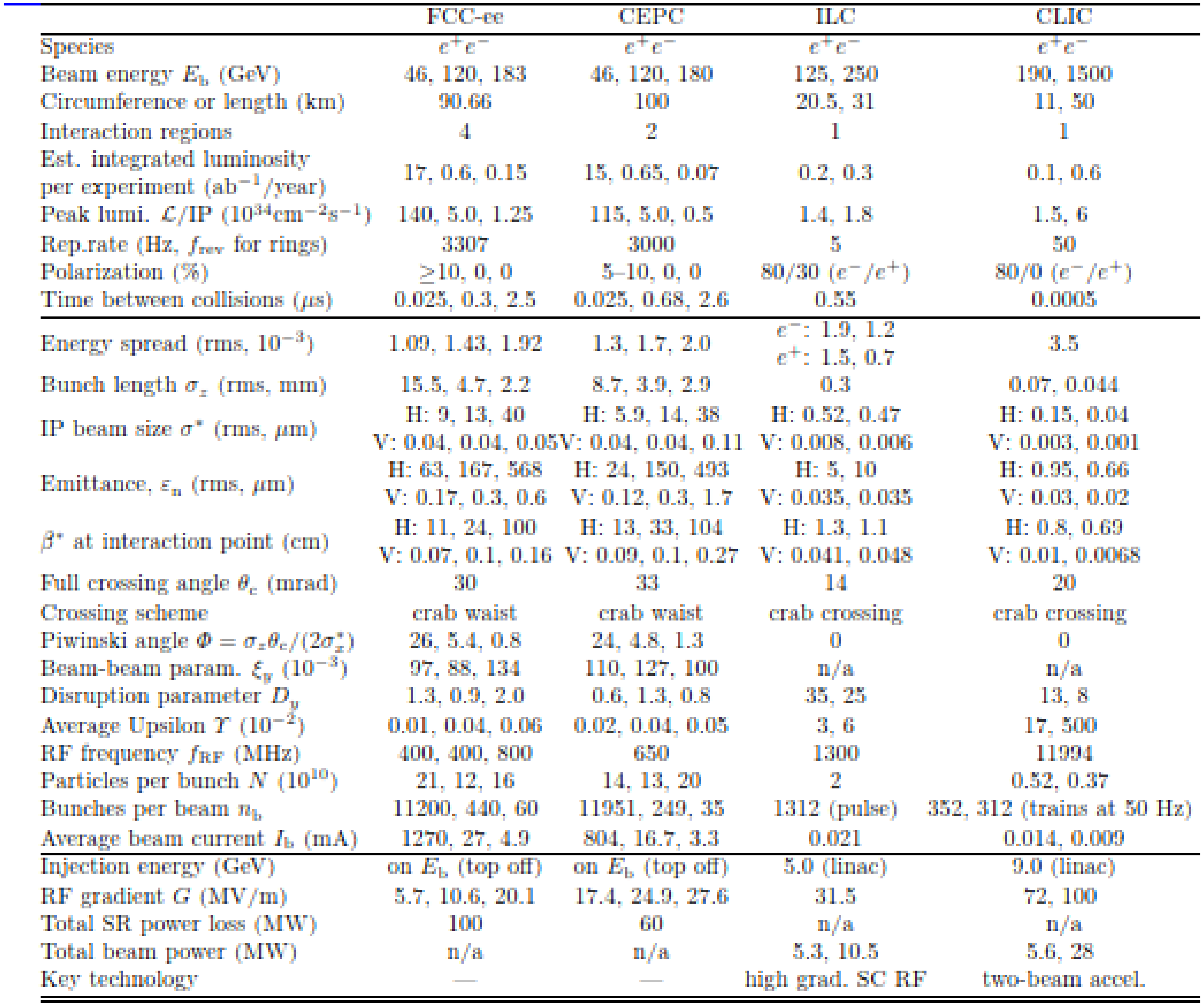


	NICA	EIC	FFC-hh	SPPC	$\mu\mu$ collider
Species	ion-ion, pp	ep, e-ion	pp	pp	$\mu^+\mu^-$
Beam energy E_b (TeV)	$10^{-3}\cdot(4.5/\text{u}, 13)$	$0.01(e)$,$0.275(p)$	40-58	62.5	0.063, 5
Circumference C (km)	0.503	3.834	90.66	100	0.3, 10
Interaction regions	2	1(2)	4	2	1, 2
Est. integr. luminosity per exp. (ab^{-1}/year)	$10^{-8,-3}$ (ii, pp)	0.1	0.2–1.0	0.6	0.001, 2.0
Peak luminosity $\mathcal{L}$ ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	$10^{-7,-2}$ (ii, pp)	1.05	5–30	4.3	0.008, 20
Rep.rate (Hz, f_{rev} for rings)	$5.9\cdot10^5$	$7.8\cdot10^4$	3307	3000	15, 5
Time between collisions (μs)	0.077	0.009	0.025	0.025	1, 33
Energy spread (rms, 10^{-3})	1.6 (Au)	0.6 (e), 0.7 (p)	0.1	0.1	0.04, 1
Bunch length σ_z (rms, mm)	600	7 (e), 60 (p)	80	60	63, 1.5
IP beam size σ^* (H/V rms, μm)	360	95/8.5	6.7-3.5 (init.)	3.0 (init.)	75, 0.9
Emittance ε_n (H/V rms, mm mrad)	1.1	11.3/1.0 (e), 9.2/1.6 (p)	2.2 (init.)	1.2 (init.)	200, 25
Beta function at IP β^* (H/V cm)	60	45/5.6 (e), 80/7.2 (p)	110–30	50	1.7, 0.15
Beam-beam param. ξ (10^{-3} H/V)	25	72/100 (e),12 (p)	5–15	15	22, 78
RF frequency f_{RF} (MHz)	13/39	591	400	400/200	805/1300
Particles per bunch N (10^{10})	0.23	17.2(e), 6.9(p)	10	4	400, 180
Bunches per beam n_b	22	1160	9648	10082	1
Average beam current I_b (mA)	480	2500(e),1000 (p)	500	190	640, 9 (peak)
Injection energy (GeV)	1-3.8	on E_b (e), 25 (p)	$\geq$1000	3200	on E_b
Peak magnetic field B (T)	1.8	0.248 (e), 3.80 (p)	14-20	20	10
Polarization (%)	0(i), >50(p)	> 70(e), >70(p)	0	0	0
SR power loss/beam (MW)	10^{-6}	10(e), < 10^{-6}(p)	2.0-8.5	2.2	10^{-3}, 0.16
Key technology	electron and stoch. cooling	strong hadron cooling	Nb_3Sn/HTS magnets	HTS magnets	muon prod. & cooling

V. Shiltsev,
F. Zimmermann

design parameters
of future e^+e^- colliders

from Particle Data Group
Draft update July 2023



	FCC-ee	CEPC	ILC	CLIC
Species	e^+e^-	e^+e^-	e^+e^-	e^+e^-
Beam energy E_b (GeV)	46, 120, 183	46, 120, 180	125, 250	190, 1500
Circumference or length (km)	90.66	100	20.5, 31	11, 50
Interaction regions	4	2	1	1
Est. integrated luminosity per experiment (ab^{-1}/year)	17, 0.6, 0.15	15, 0.65, 0.07	0.2, 0.3	0.1, 0.6
Peak lumi. $\mathcal{L}$/IP ($10^{34}cm^{-2}s^{-1}$)	140, 5.0, 1.25	115, 5.0, 0.5	1.4, 1.8	1.5, 6
Rep.rate (Hz, f_{rev} for rings)	3307	3000	5	50
Polarization (%)	≥10, 0, 0	5–10, 0, 0	80/30 (e^-/e^+)	80/0 (e^-/e^+)
Time between collisions (μs)	0.025, 0.3, 2.5	0.025, 0.68, 2.6	0.55	0.0005
Energy spread (rms, 10^{-3})	1.09, 1.43, 1.92	1.3, 1.7, 2.0	e^-: 1.9, 1.2 e^+: 1.5, 0.7	3.5
Bunch length σ_z (rms, mm)	15.5, 4.7, 2.2	8.7, 3.9, 2.9	0.3	0.07, 0.044
IP beam size σ^* (rms, μm)	H: 9, 13, 40 V: 0.04, 0.04, 0.05	H: 5.9, 14, 38 V: 0.04, 0.04, 0.11	H: 0.52, 0.47 V: 0.008, 0.006	H: 0.15, 0.04 V: 0.003, 0.001
Emittance, ε_n (rms, μm)	H: 63, 167, 568 V: 0.17, 0.3, 0.6	H: 24, 150, 493 V: 0.12, 0.3, 1.7	H: 5, 10 V: 0.035, 0.035	H: 0.95, 0.66 V: 0.03, 0.02
β^* at interaction point (cm)	H: 11, 24, 100 V: 0.07, 0.1, 0.16	H: 13, 33, 104 V: 0.09, 0.1, 0.27	H: 1.3, 1.1 V: 0.041, 0.048	H: 0.8, 0.69 V: 0.01, 0.0068
Full crossing angle θ_c (mrad)	30	33	14	20
Crossing scheme	crab waist	crab waist	crab crossing	crab crossing
Piwinski angle $\Phi = \sigma_z\theta_c/(2\sigma_x^*)$	26, 5.4, 0.8	24, 4.8, 1.3	0	0
Beam-beam param. ξ_y (10^{-3})	97, 88, 134	110, 127, 100	n/a	n/a
Disruption parameter D_y	1.3, 0.9, 2.0	0.6, 1.3, 0.8	35, 25	13, 8
Average Upsilon Υ (10^{-2})	0.01, 0.04, 0.06	0.02, 0.04, 0.05	3, 6	17, 500
RF frequency f_{RF} (MHz)	400, 400, 800	650	1300	11994
Particles per bunch N (10^{10})	21, 12, 16	14, 13, 20	2	0.52, 0.37
Bunches per beam n_b	11200, 440, 60	11951, 249, 35	1312 (pulse)	352, 312 (trains at 50 Hz)
Average beam current I_b (mA)	1270, 27, 4.9	804, 16.7, 3.3	0.021	0.014, 0.009
Injection energy (GeV)	on E_b (top off)	on E_b (top off)	5.0 (linac)	9.0 (linac)
RF gradient G (MV/m)	5.7, 10.6, 20.1	17.4, 24.9, 27.6	31.5	72, 100
Total SR power loss (MW)	100	60	n/a	n/a
Total beam power (MW)	n/a	n/a	5.3, 10.5	5.6, 28
Key technology	—	—	high grad. SC RF	two-beam accel.

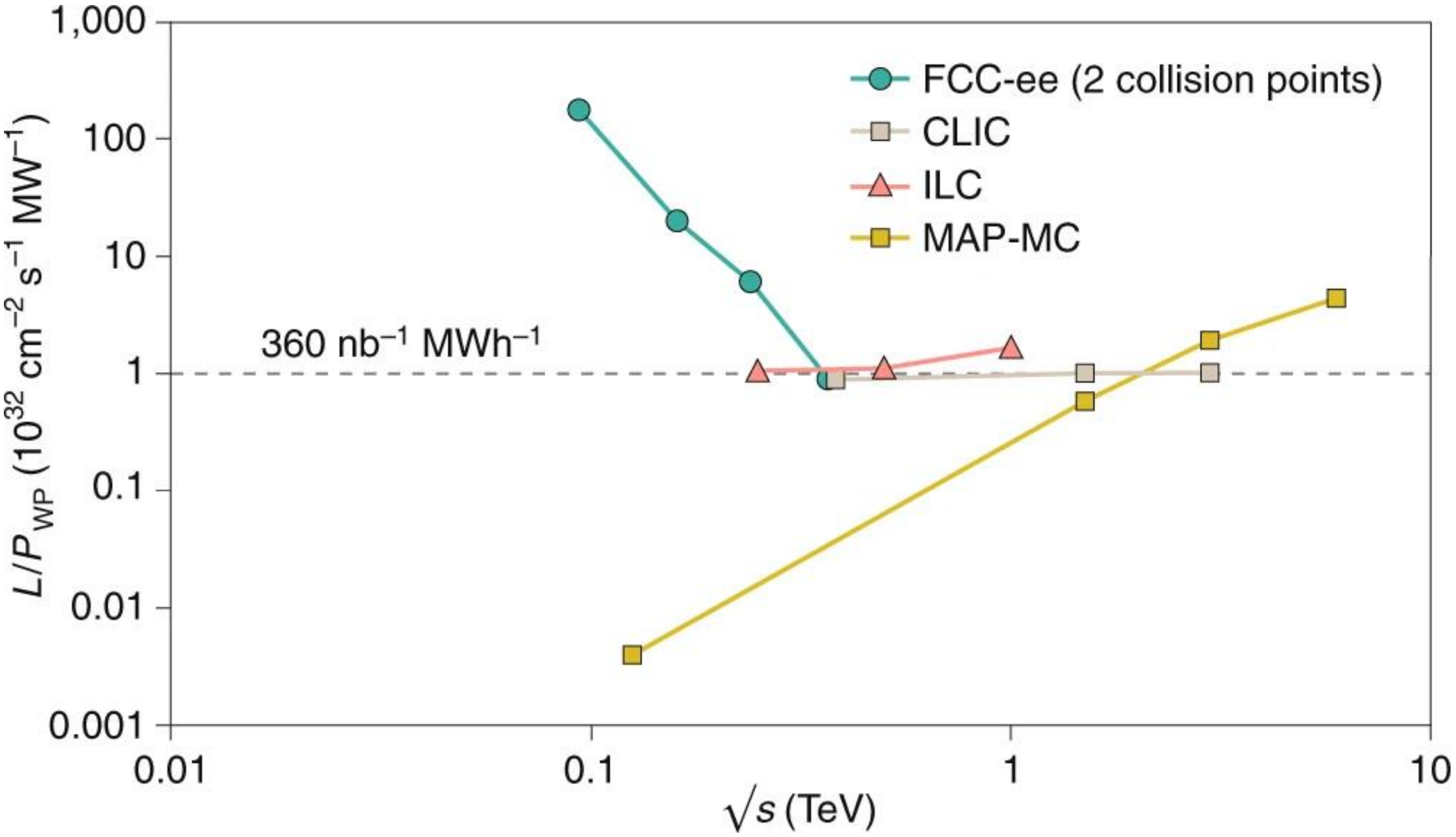
V. Shiltsev,
F. Zimmermann

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

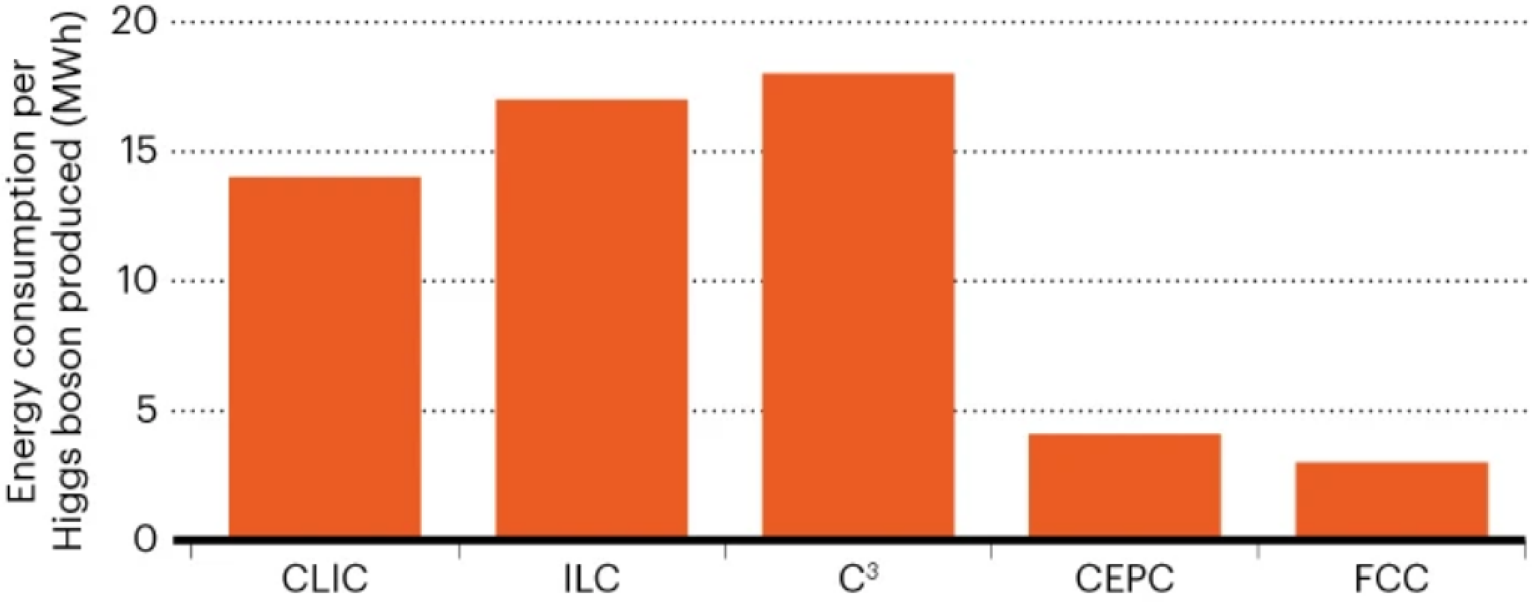
*CEPC missing

Energy efficiency: Higgs factories

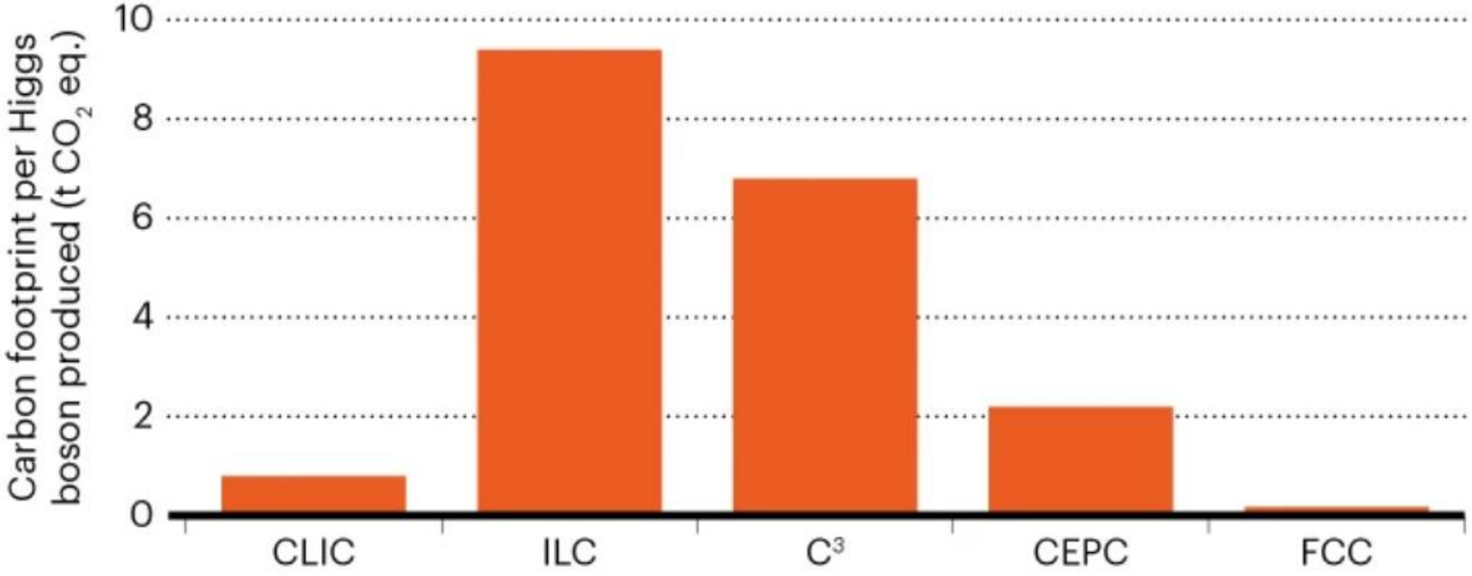


Total luminosity per electrical power. (Nature Physics vol. 16, 402, 2020)

Energy Consumption & Carbon Footprint per Higgs



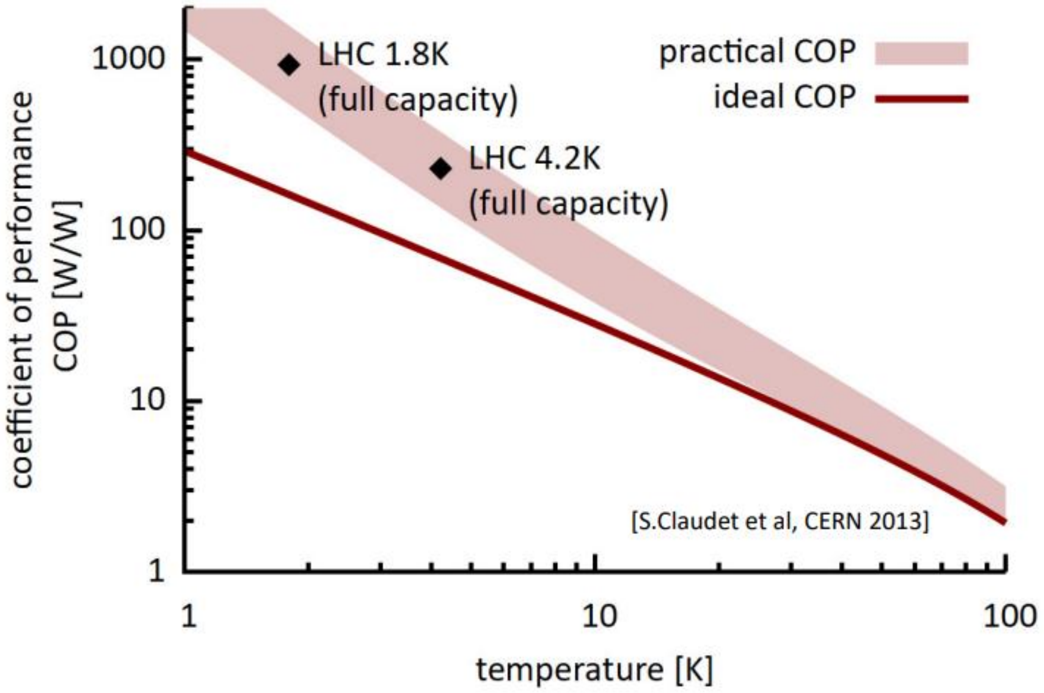
P. Janot and A. Blondel, *The carbon footprint of proposed e^+e^- Higgs factories*, arXiv 2208.10466 (2022); *The European Physical Journal Plus* **volume 137**, Article number: 1122 (2022) https://link.springer.com/content/pdf/10.1140/epjp/s13360-022-03319-w.pdf also see https://www.nature.com/articles/d41586-022-03551-5



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

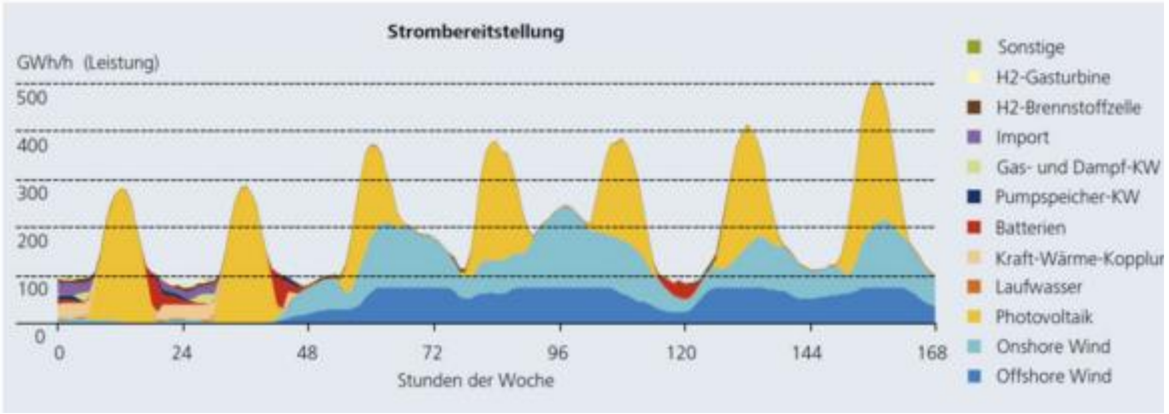


[S.Claudet et al, CERN 2013]

still far from ideal Carnot efficiency

Future: fluctuating energy sources

Simulation for Germany 2050



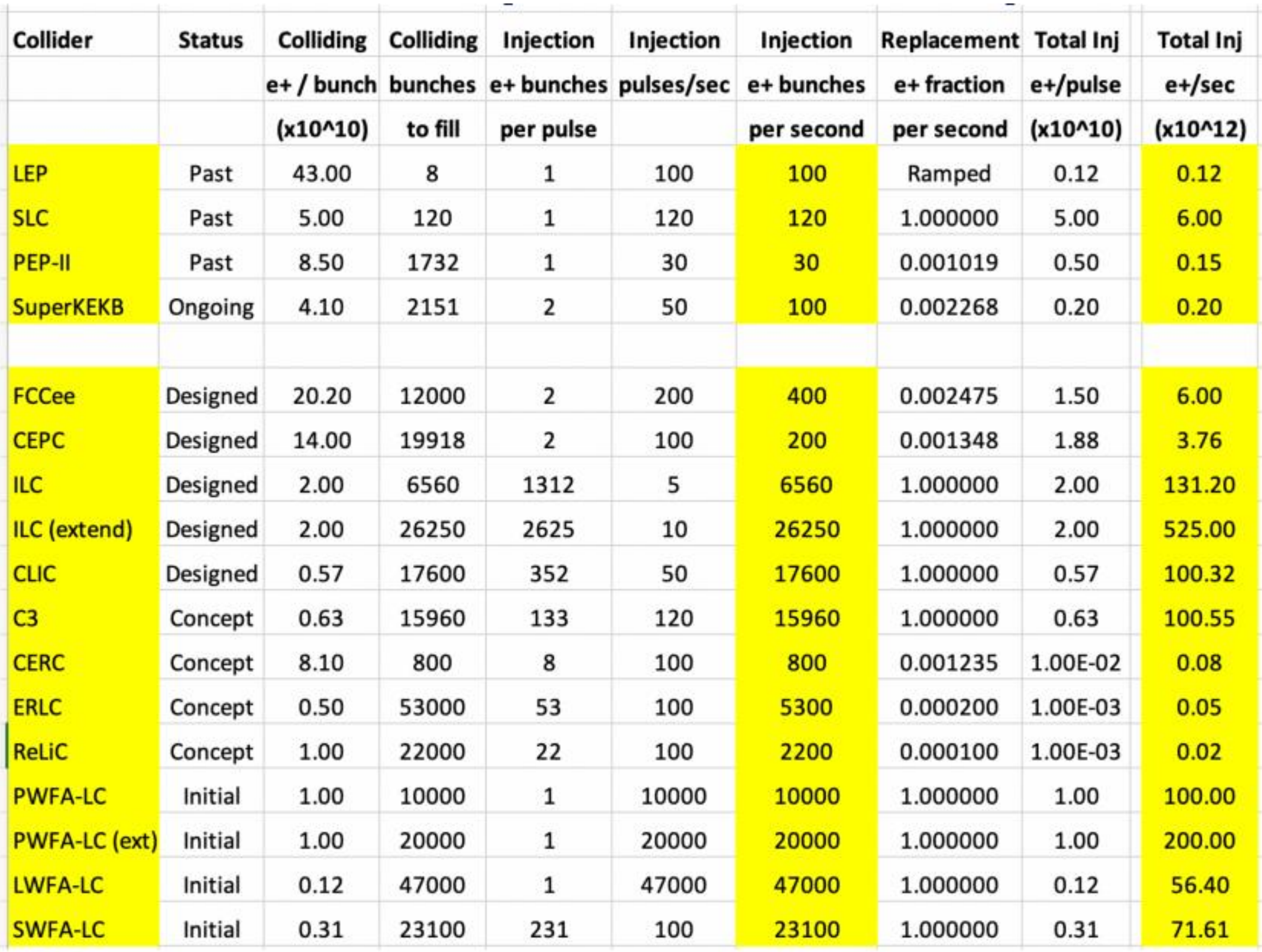
full collider operation at times of high grid production

reduced operation or standby modes with fast L recovery otherwise

varying #bunches in circular colliders

M. Seidel

Future e^+e^- Collider Positron Requirements

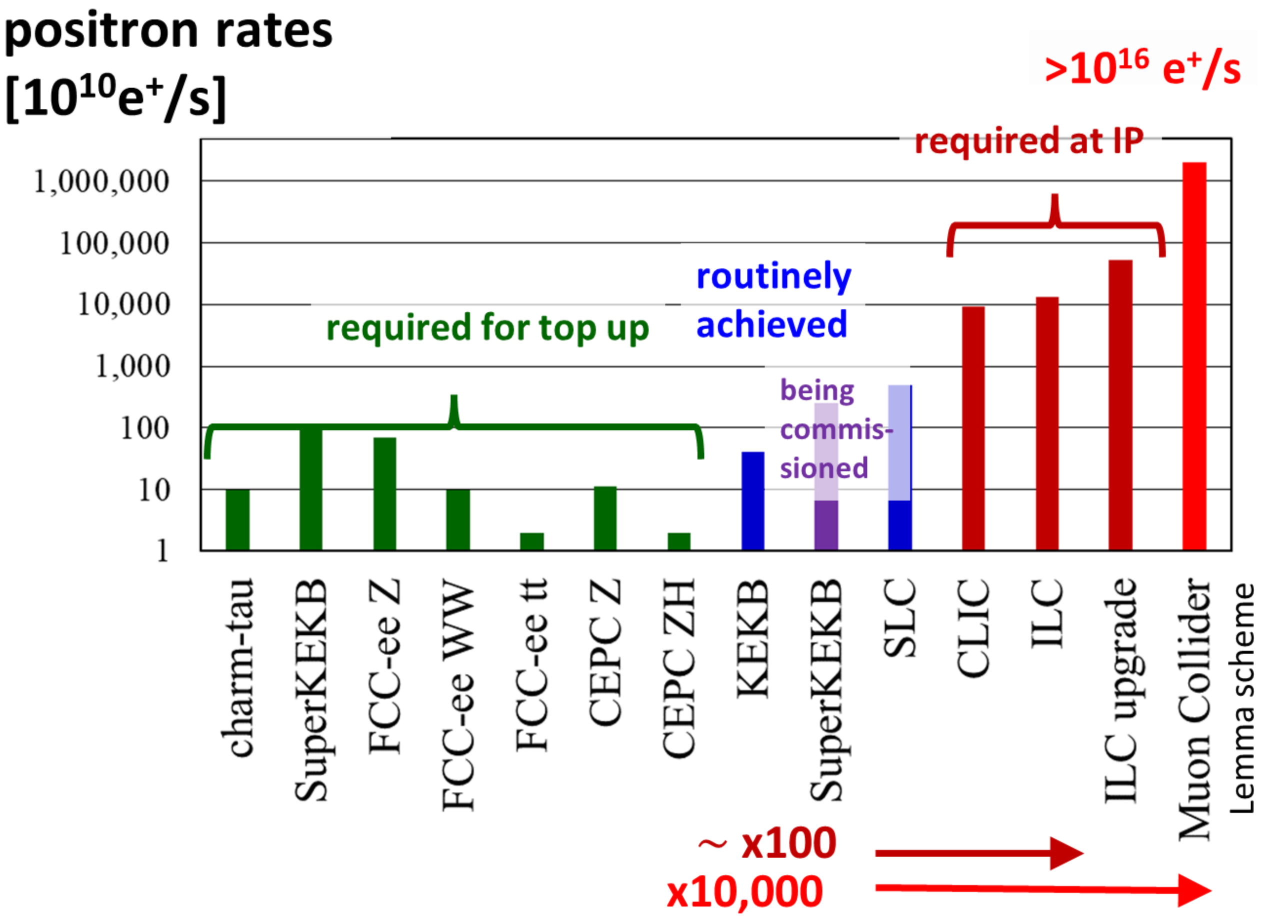


Collider	Status	Colliding e+ / bunch (x10^10)	Colliding bunches to fill	Injection e+ bunches per pulse	Injection pulses/sec	Injection e+ bunches per second	Replacement e+ fraction per second	Total Inj e+/pulse (x10^10)	Total Inj e+/sec (x10^12)
LEP	Past	43.00	8	1	100	100	Ramped	0.12	0.12
SLC	Past	5.00	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

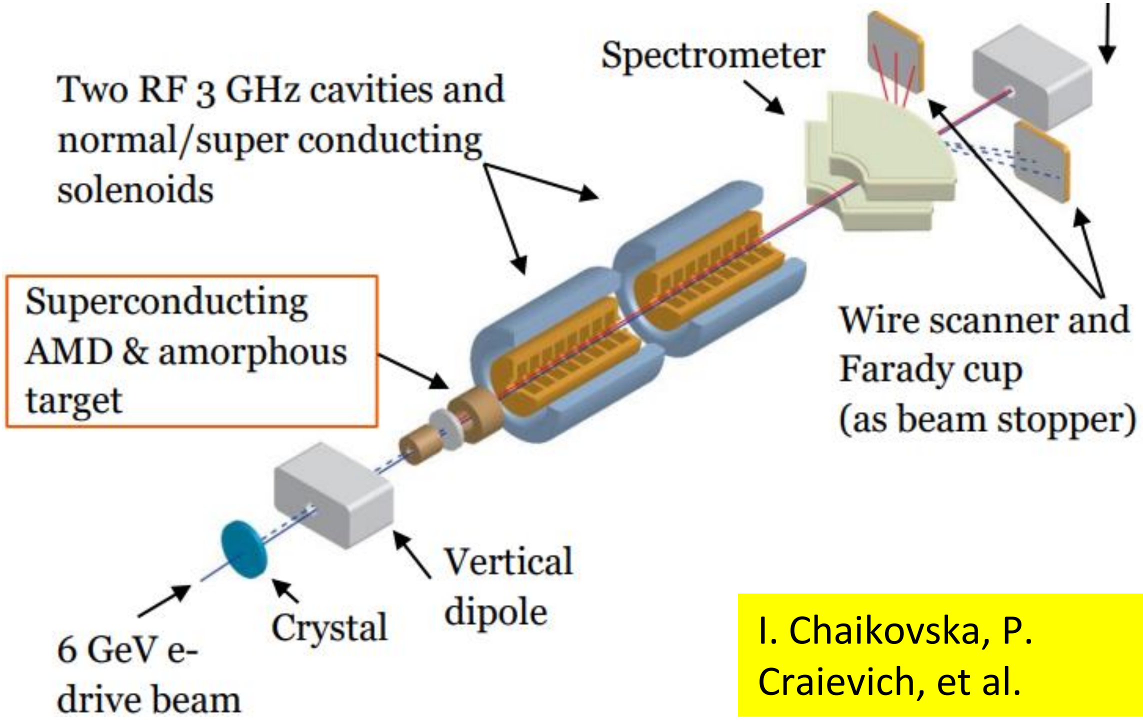
?

Positron Production

Challenging demands



Innovative high-yield source



I. Chaikovska, P. Craievich, et al.

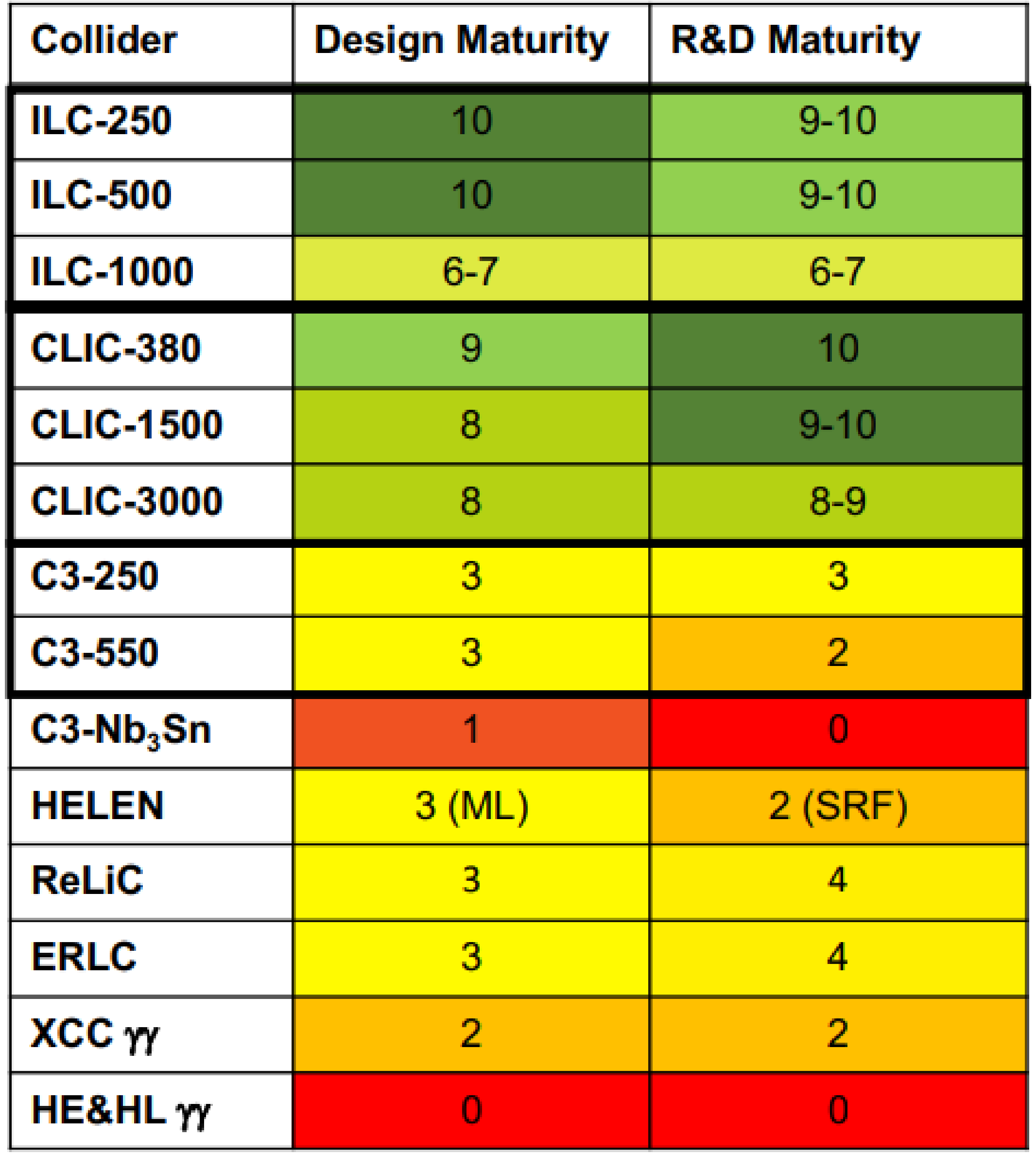
P³: PSI e⁺ production experiment with HTS solenoid at SwissFEL

planned for 2024/25

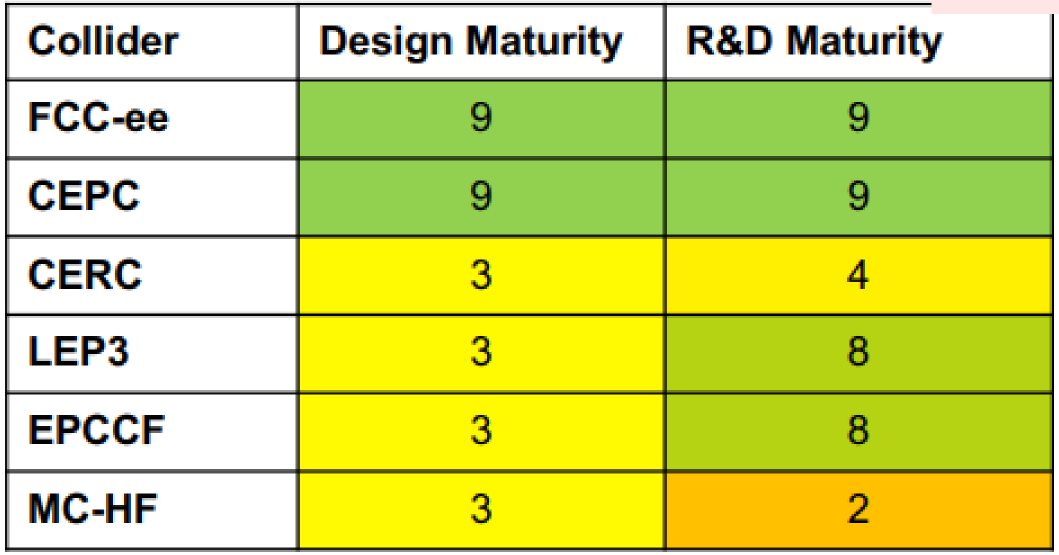
Snowmass’21 (2022) – maturity ranking

arXiv:2209.05827

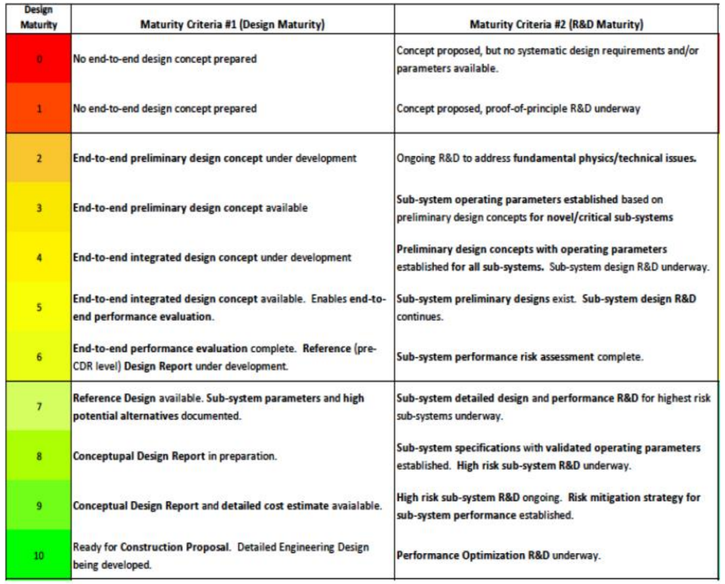
A. Faus-Golfe et al.



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 $\gamma\gamma$	2	2
HE&HL $\gamma\gamma$	0	0

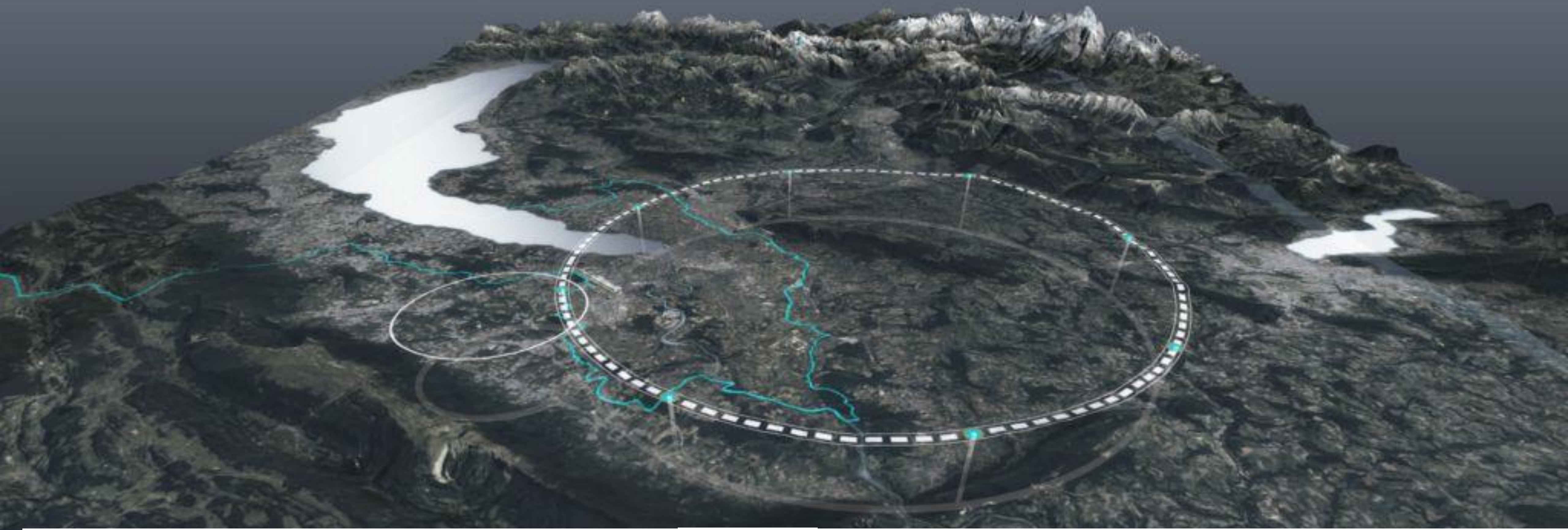


Collider	Design Maturity	R&D Maturity
FCC-ee	9	9
CEPC	9	9
CERC	3	4
LEP3	3	8
EPCCF	3	8
MC-HF	3	2



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	Conceptupal 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.

FCC Feasibility Study 2021-2025



Swiss Accelerator Research and Technology

http://cern.ch/fcc

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **iFAST**, grant agreement 101004730, **FCCIS**, grant agreement 951754; **E-JADE,** contract no. 645479; **EAJADE**, contract number 101086276; and by the Swiss **CHART** program*

European Commission

Horizon 2020
European Union funding
for Research & Innovation

photo: J. Wenninger

Regional implementation activities

Meetings with municipalities concerned in France (31) and Switzerland (10)

PA – Ferney Voltaire (FR) – experiment site

PB – Présinge/Choulex (CH) – technical site

PD – Nangy (FR) – experiment site

PF – Roche sur Foron/Etaux (FR) – technical site

PG – Charvonnex/Groisy (FR) – experiment site

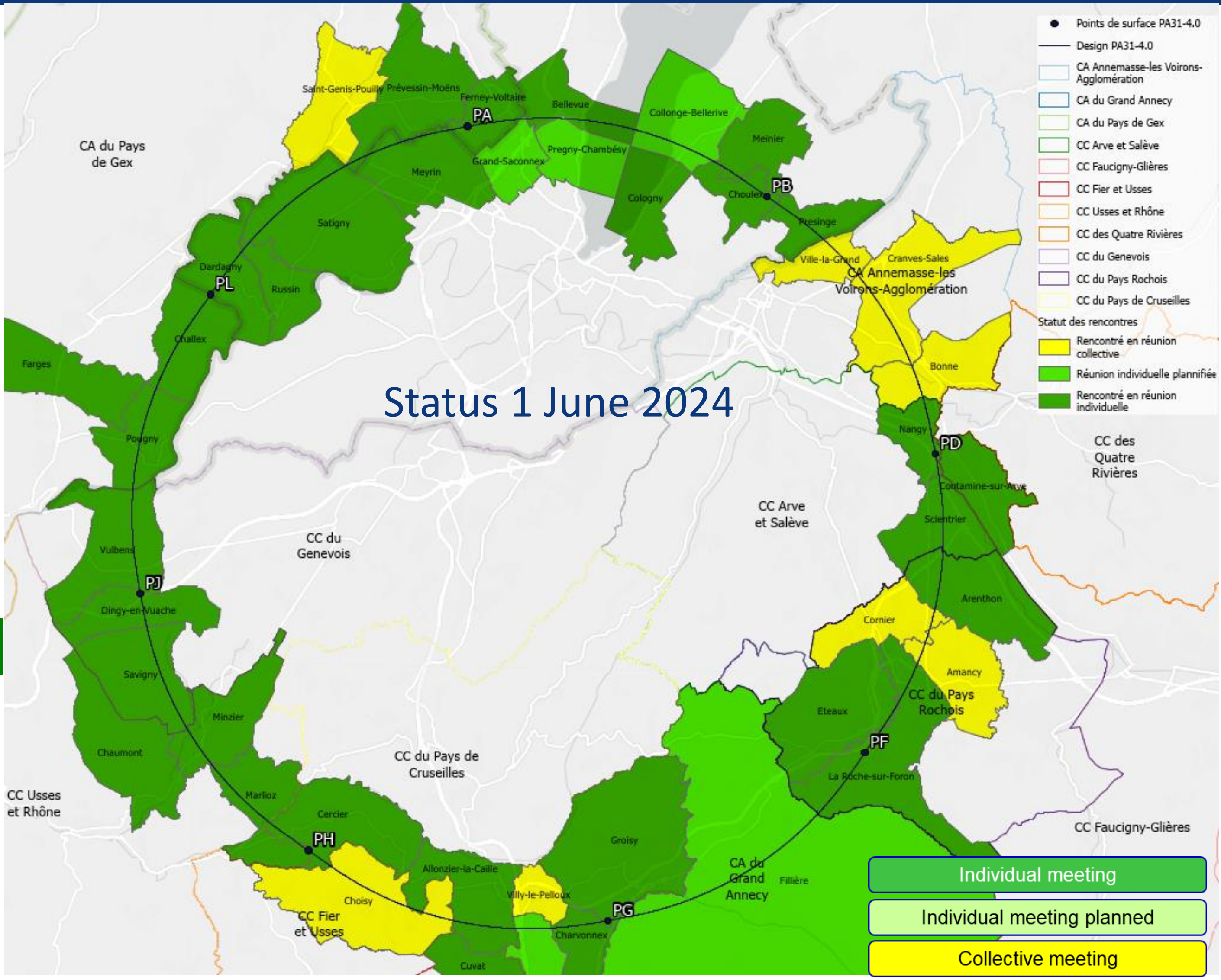
PH – Cercier (FR) – technical site

PJ – Vulbens/Dingy en Vuache (FR) experiment site

PL – Challex (FR) – technical site

Detailed work with municipalities and host states

- identify land plots for surface sites
- understand specific aspects for design
- identify opportunities (waste heat, tec.)
- reserve land plots until project decision



Status 1 June 2024

🟩 Individual meeting

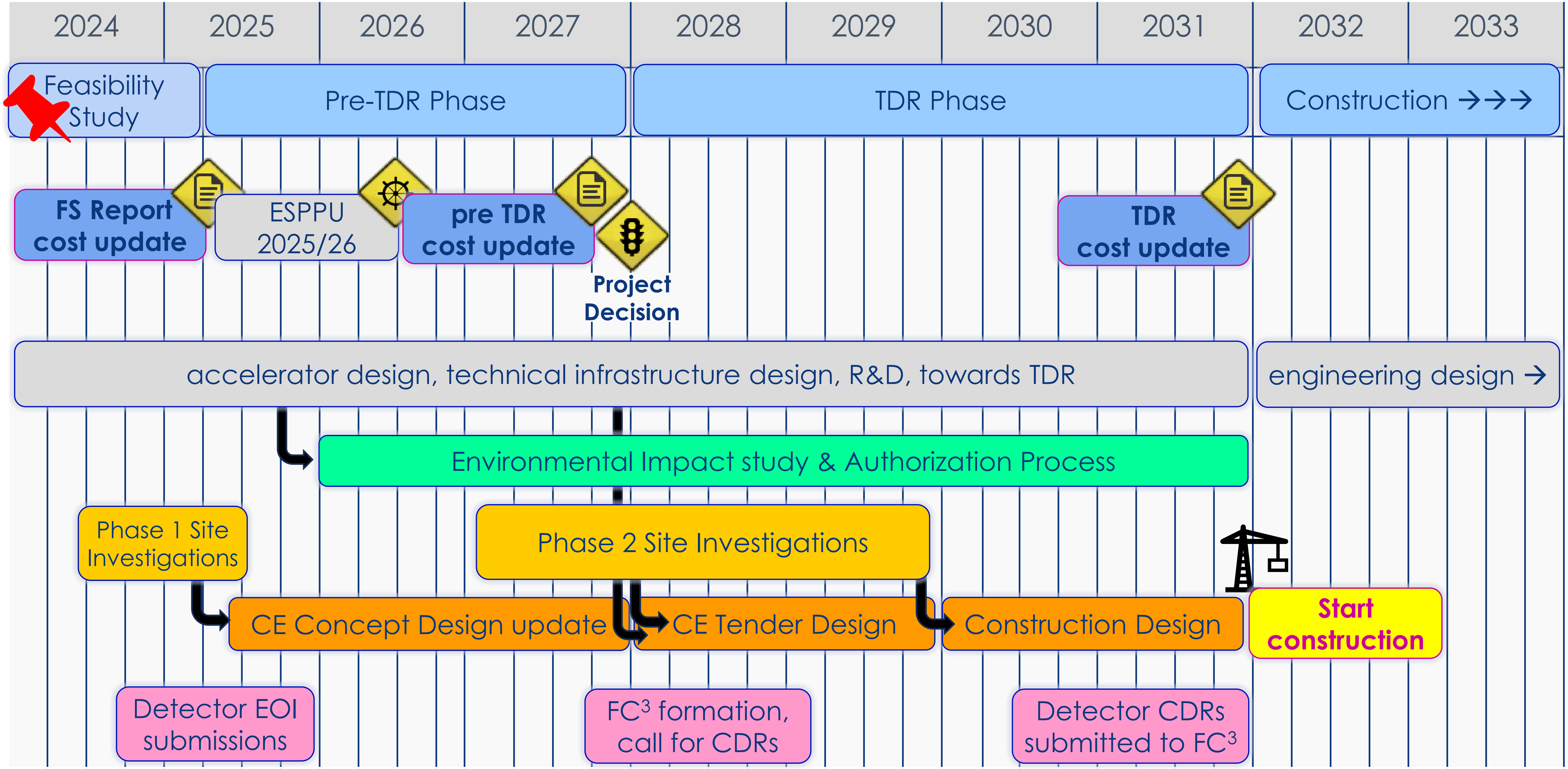
🟩 Individual meeting planned

🟨 Collective meeting

The support of the host states is greatly appreciated and essential for the study progress!

FUTURE
CIRCULAR
COLLIDER

Expected time line till start of construction



2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

Feasibility Study

Pre-TDR Phase

TDR Phase

Construction →→→

FS Report cost update

ESPPU 2025/26

pre TDR cost update

Project Decision

TDR cost update

accelerator design, technical infrastructure design, R&D, towards TDR

engineering design →

Environmental Impact study & Authorization Process

Phase 1 Site Investigations

Phase 2 Site Investigations

CE Concept Design update

CE Tender Design

Construction Design

Start construction

Detector EOI submissions

FC^3 formation, call for CDRs

Detector CDRs submitted to FC^3

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 the future
- Advanced DLAs for indirect dark sector searches ?
- Sustainability has become important design criterion
- Several promising paths forward – circular and/or linear
- FCC-ee is CERN's "plan A" and a wonderful one

"A circle is a round straight line with a hole in the middle"- Mark Twain

surely great times ahead !

thank you !