Accelerator physics and technology challenges for the XXIst century

Frank Zimmermann, CERN

IN2P3 Scientific Council, 9 February 2021

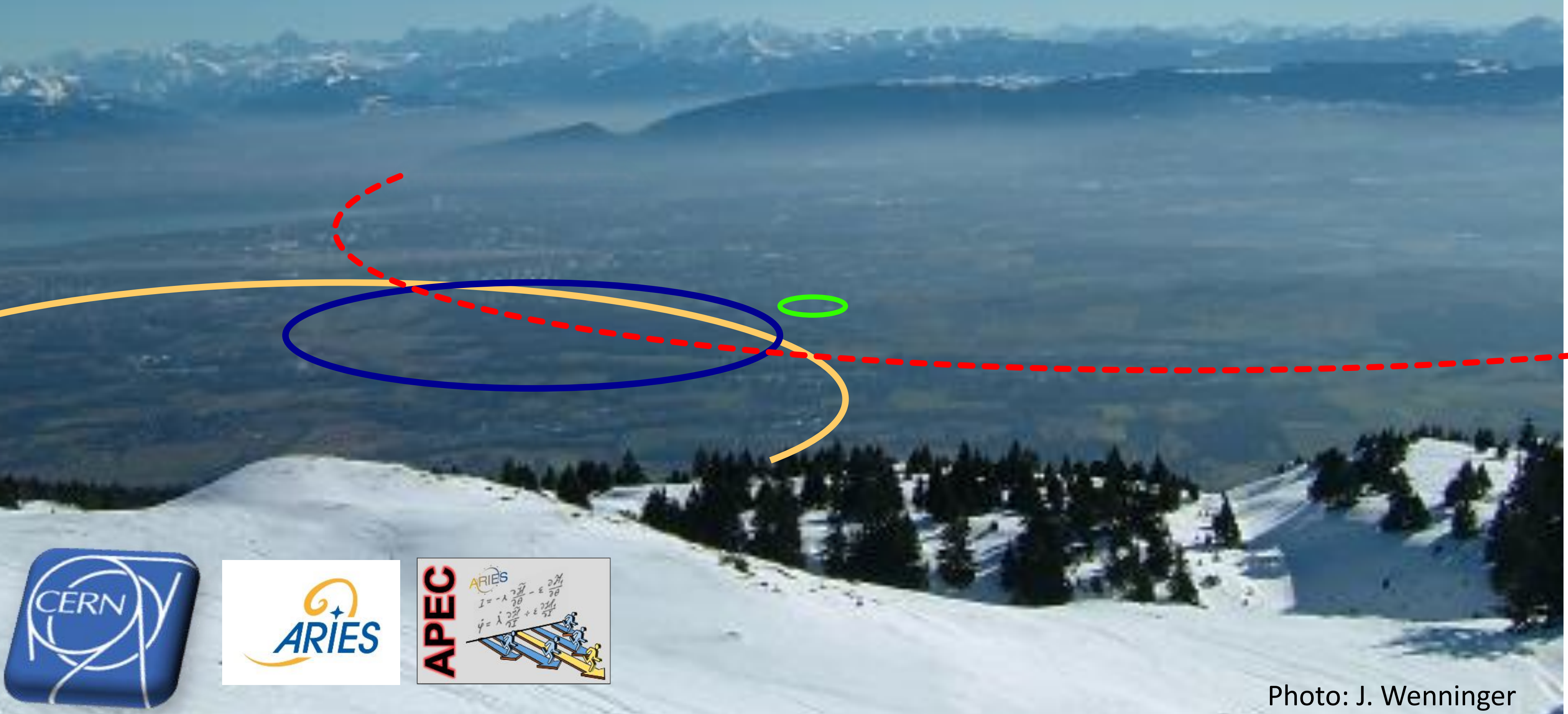
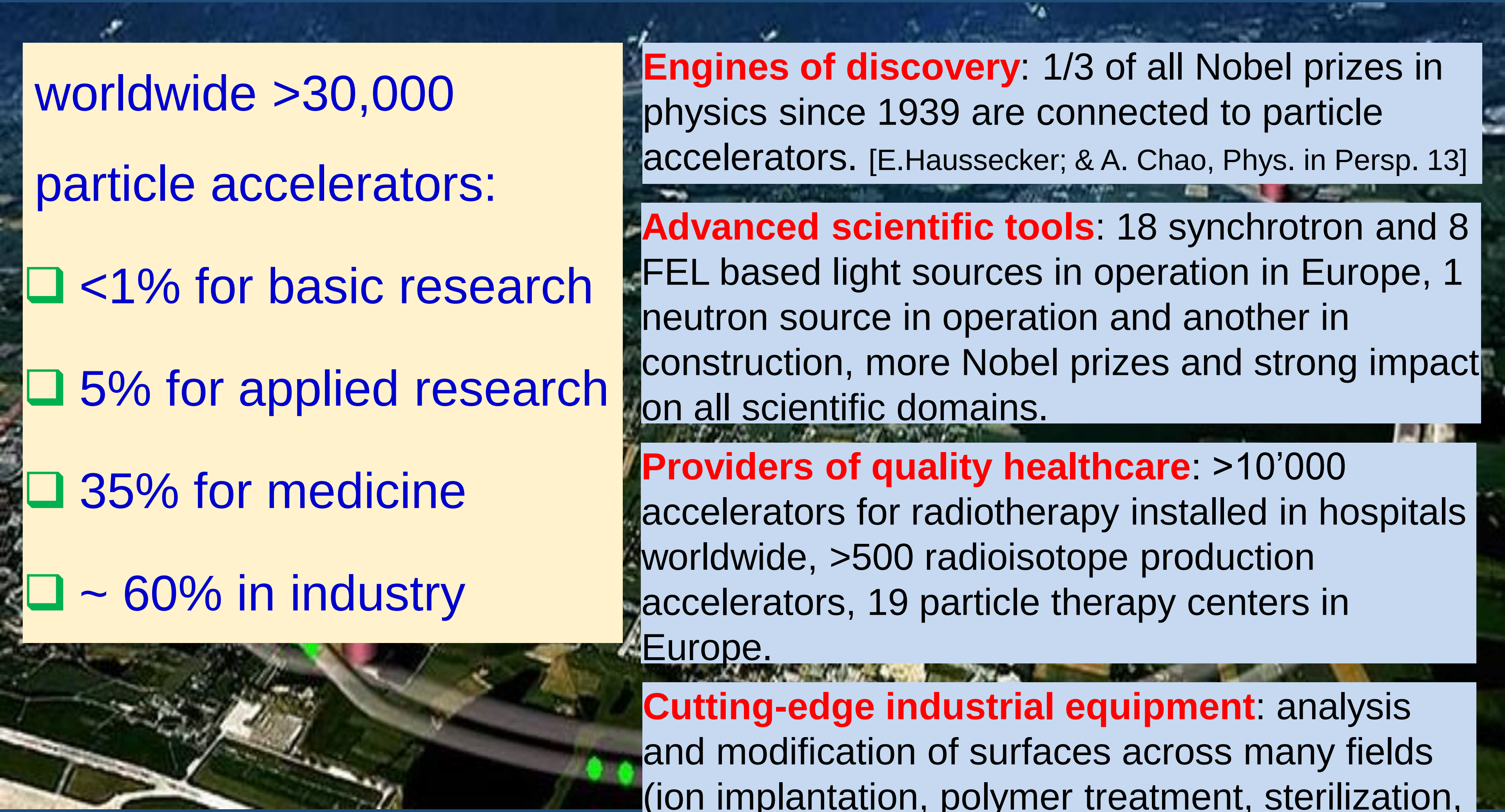


Photo: J. Wenninger

*Work supported by the **European Commission** under Capacities 7th Framework Programme, Grant Agreement 312453*

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]

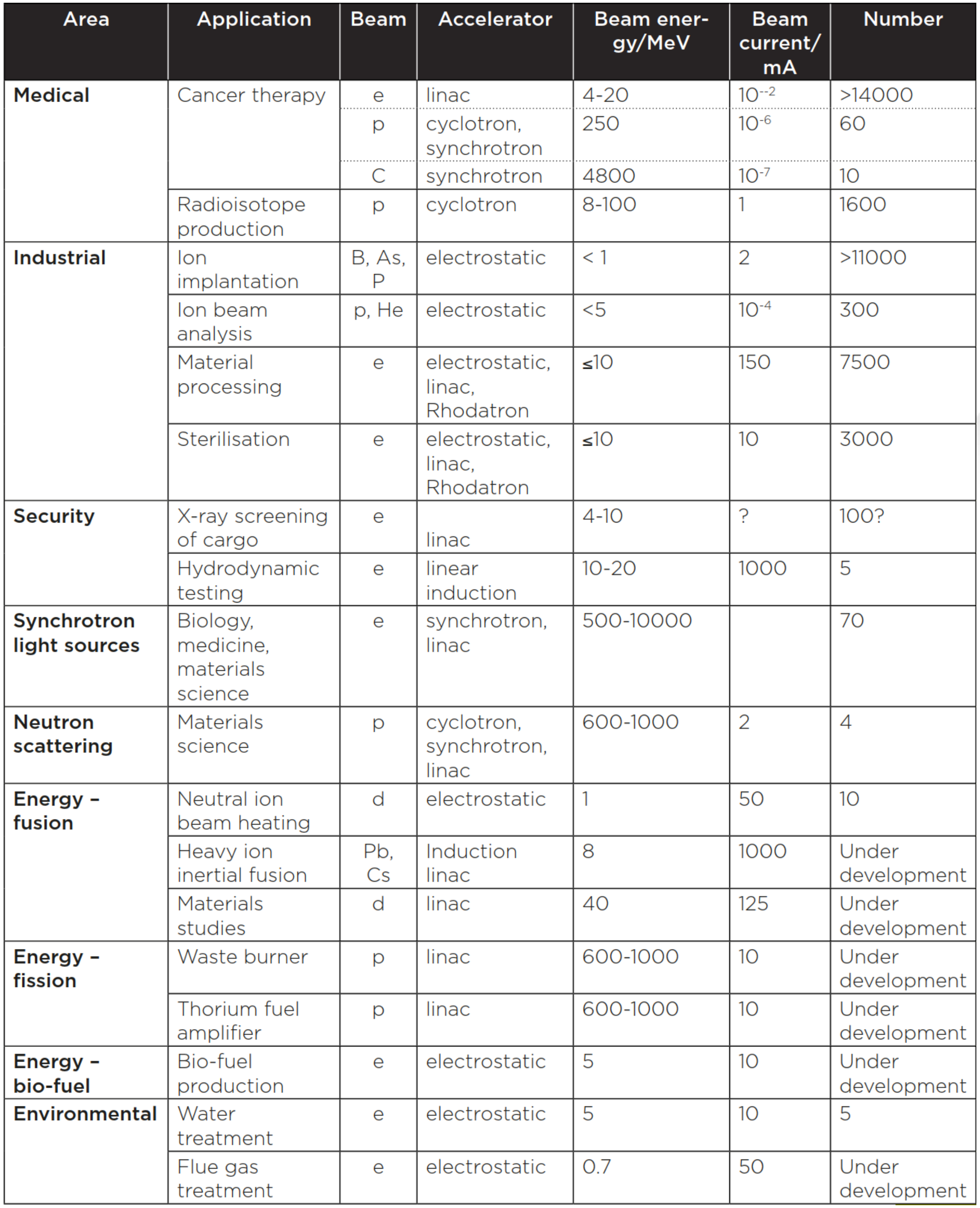
Advanced scientific tools: 18 synchrotron and 8 FEL based light sources in operation in Europe, 1 neutron source in operation and another in construction, more Nobel prizes and strong impact on all scientific domains.

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

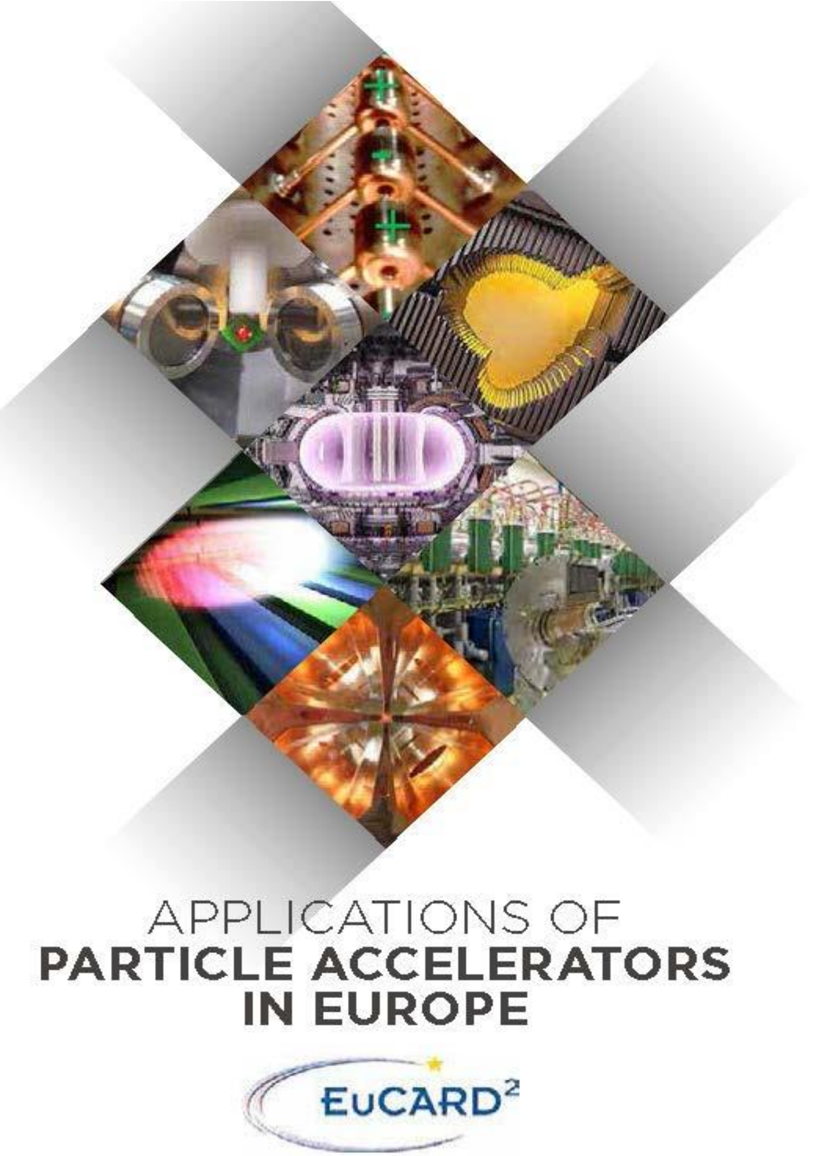
Cutting-edge industrial equipment: analysis and modification of surfaces across many fields (ion implantation, polymer treatment, sterilization, environment, etc.).

Applications of Particle Accelerators

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



APPLICATIONS OF
PARTICLE ACCELERATORS
IN EUROPE

EuCARD²

high energy particle accelerators

then ~1930

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

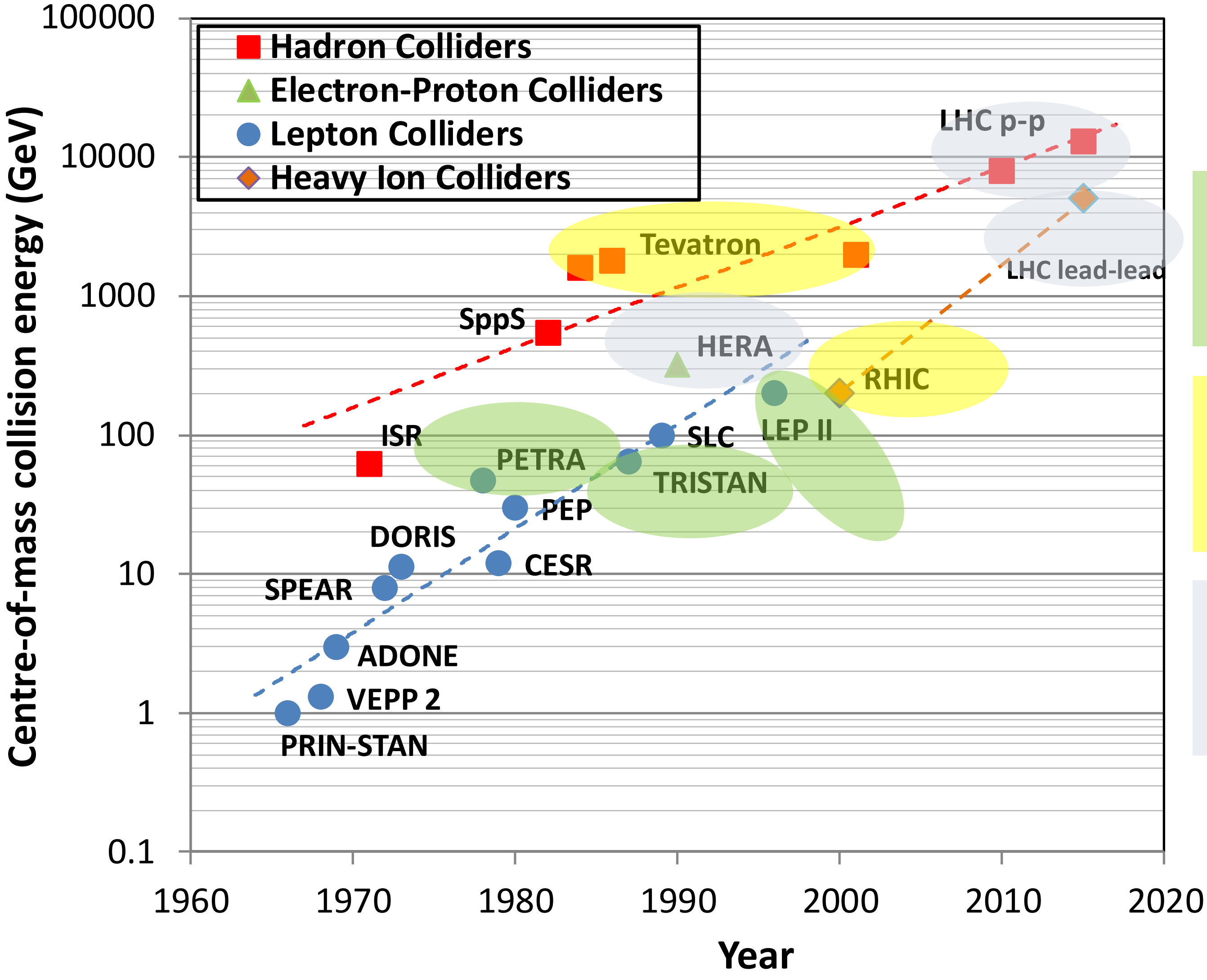
now

Large Hadron Collider
9 km diameter
7 TeV protons

G. Hoffstaetter

colliders constructed and operated

A. Ballarino



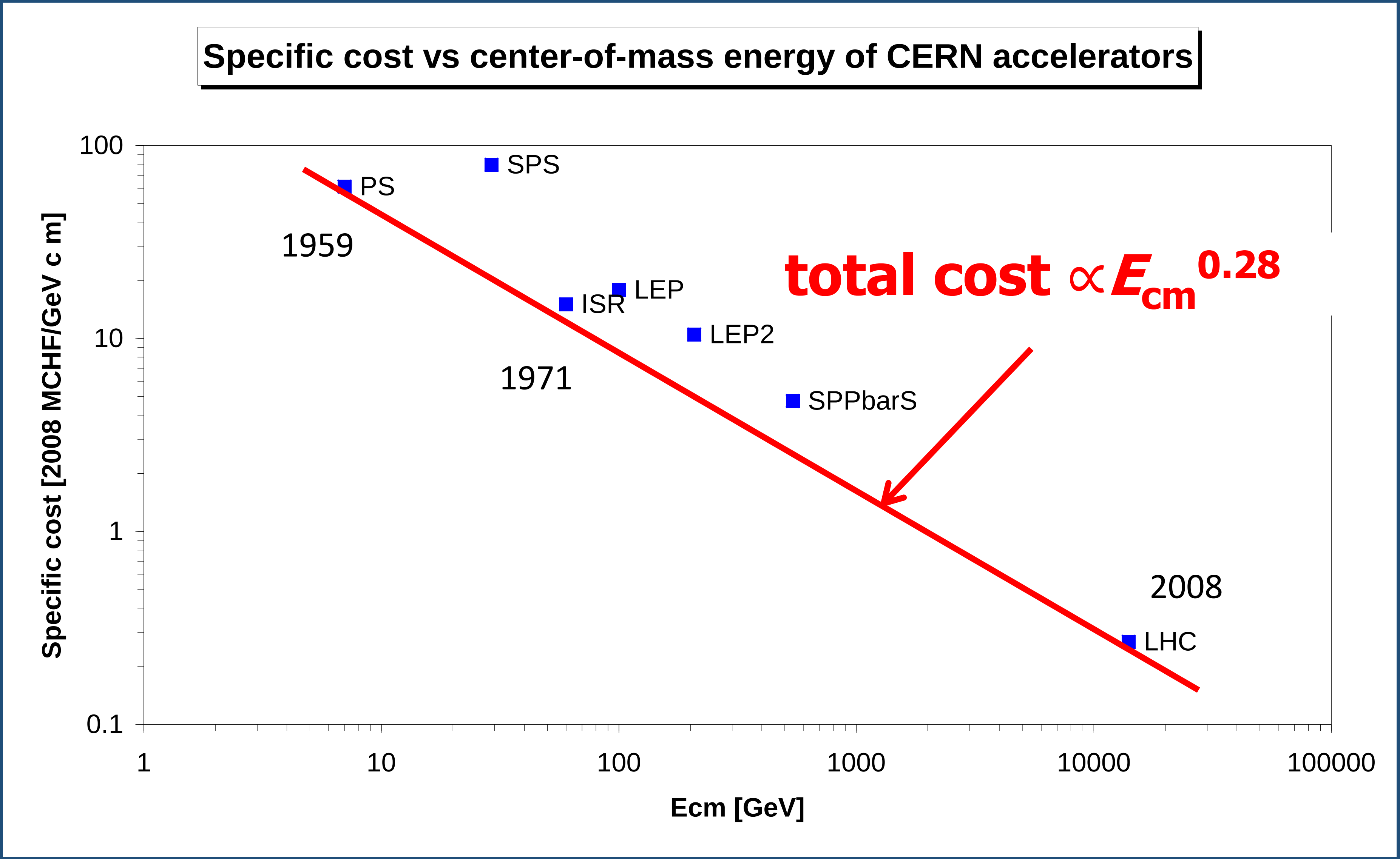
Colliders with superconducting RF system

Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF

advances by new technologies and new materials

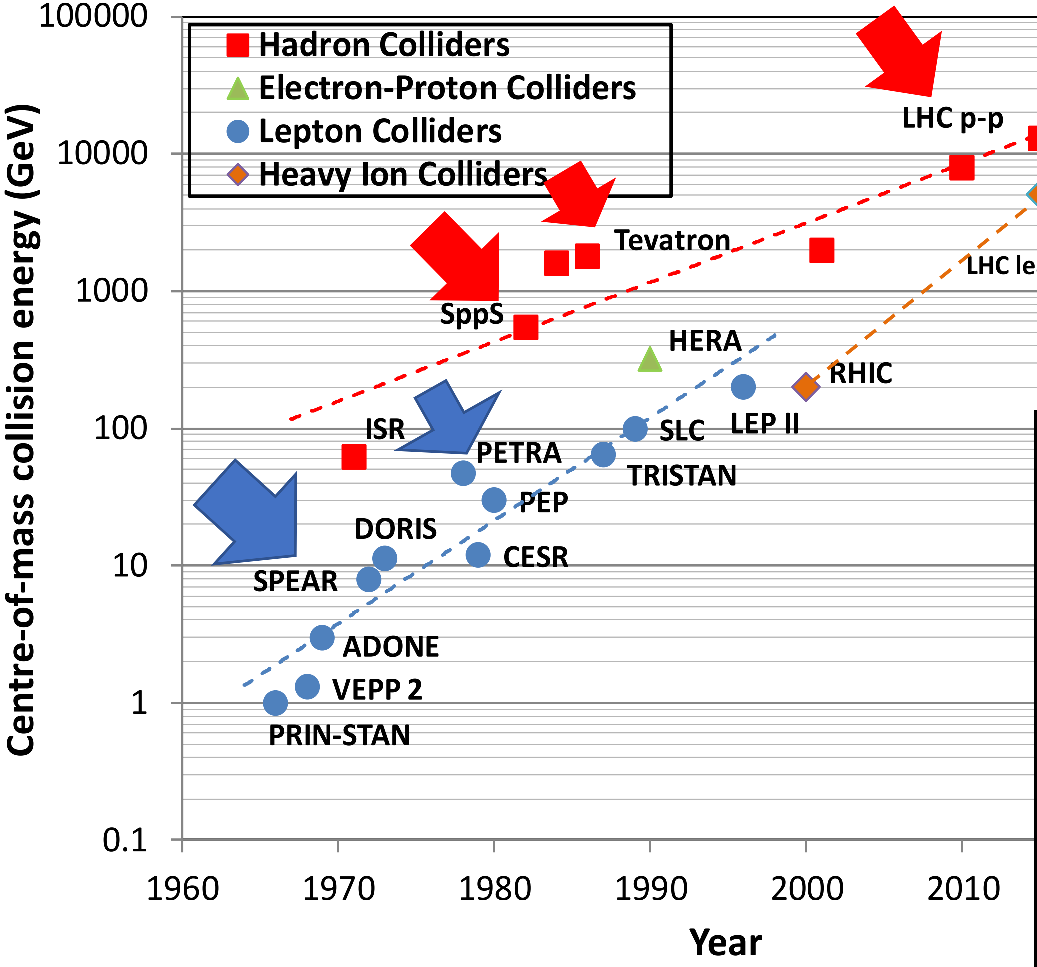
cost per energy greatly reduced



total cost $\propto E_{cm}^{0.28}$

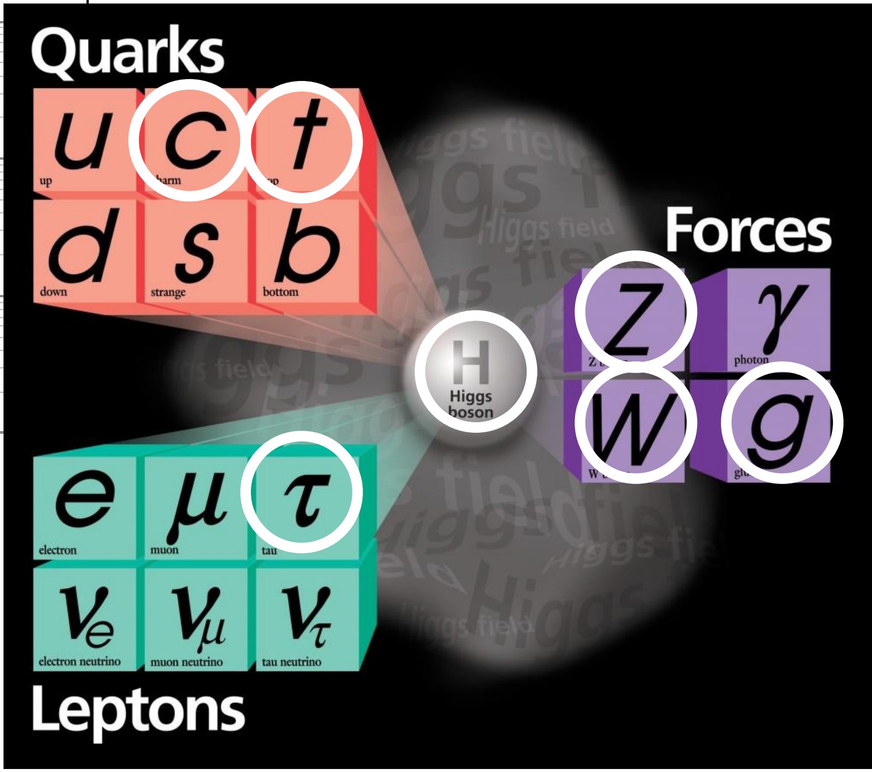
P. Lebrun, RFTech 2013

colliders and discoveries



Standard Model
Particles and forces

A. Ballarino

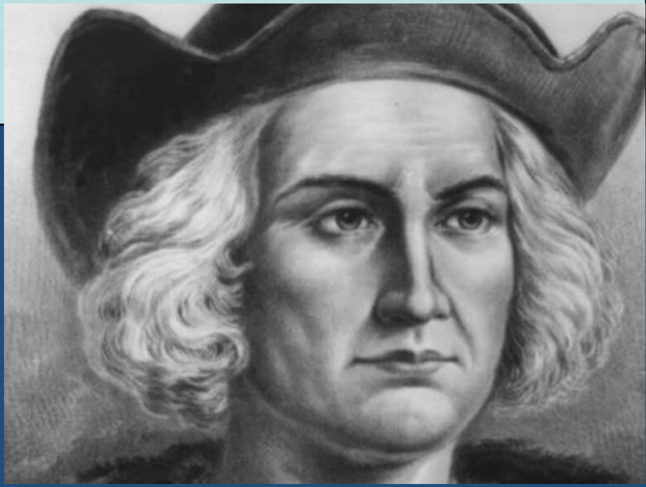


powerful instruments for discovery and precision measurement

No New Physics Beyond the Standard Model? Beware Historical Hubris

"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"

- Spanish Royal Commission, rejecting Christopher Columbus' proposal to sail west, < 1492

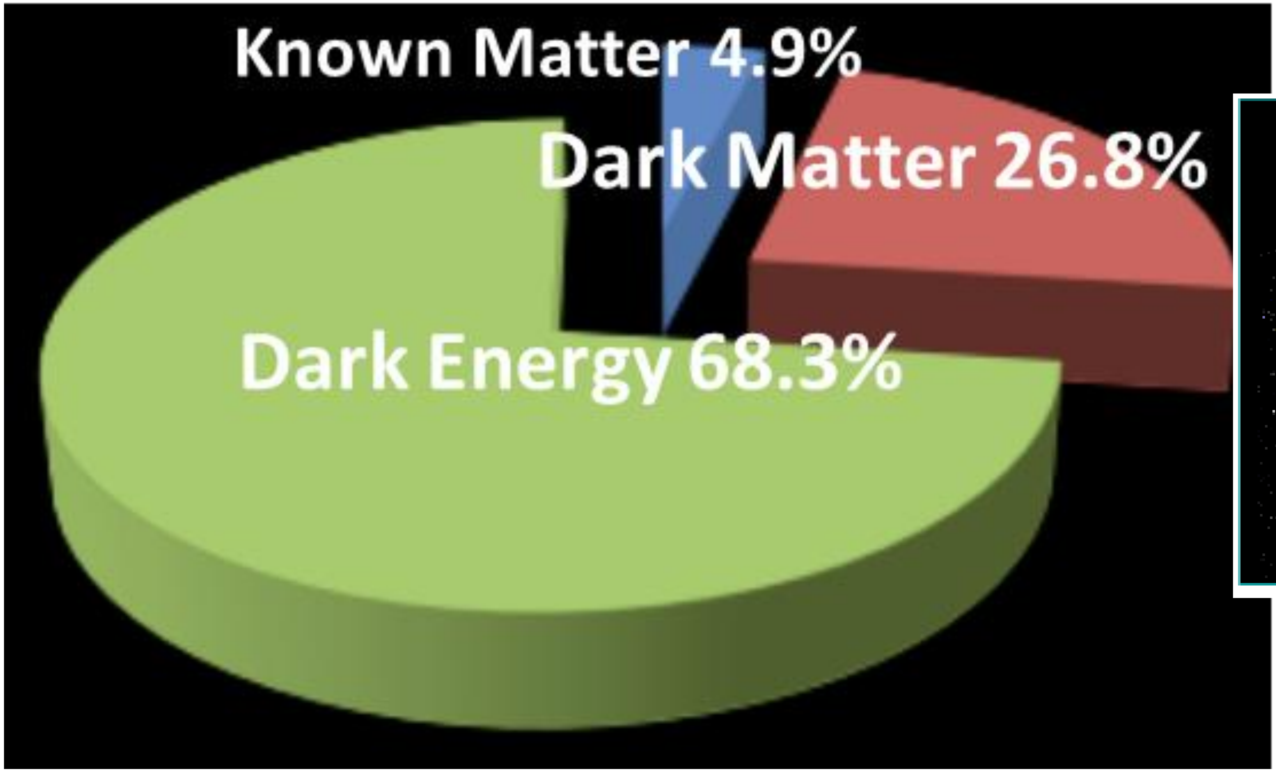


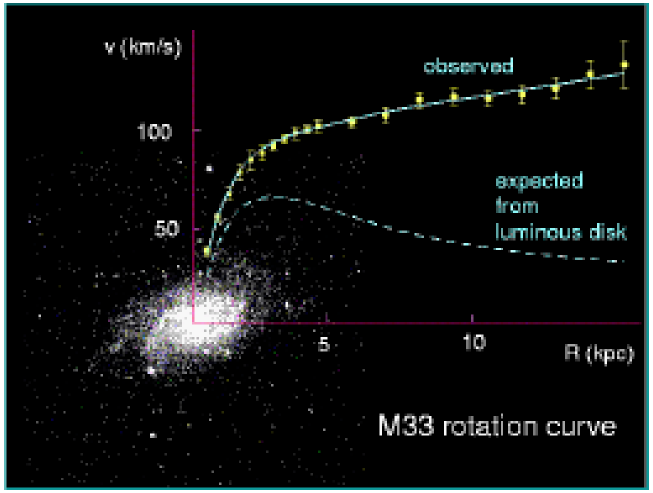
J. Ellis

still many open questions

standard model describes known matter = 5% of universe!

K. Borras





galaxy rotation curves,
1933 - Zwicky

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

- is there a theory of everything?

proposed locations of future energy frontier colliders

Geneva, Switzerland/France – FCC, CLIC

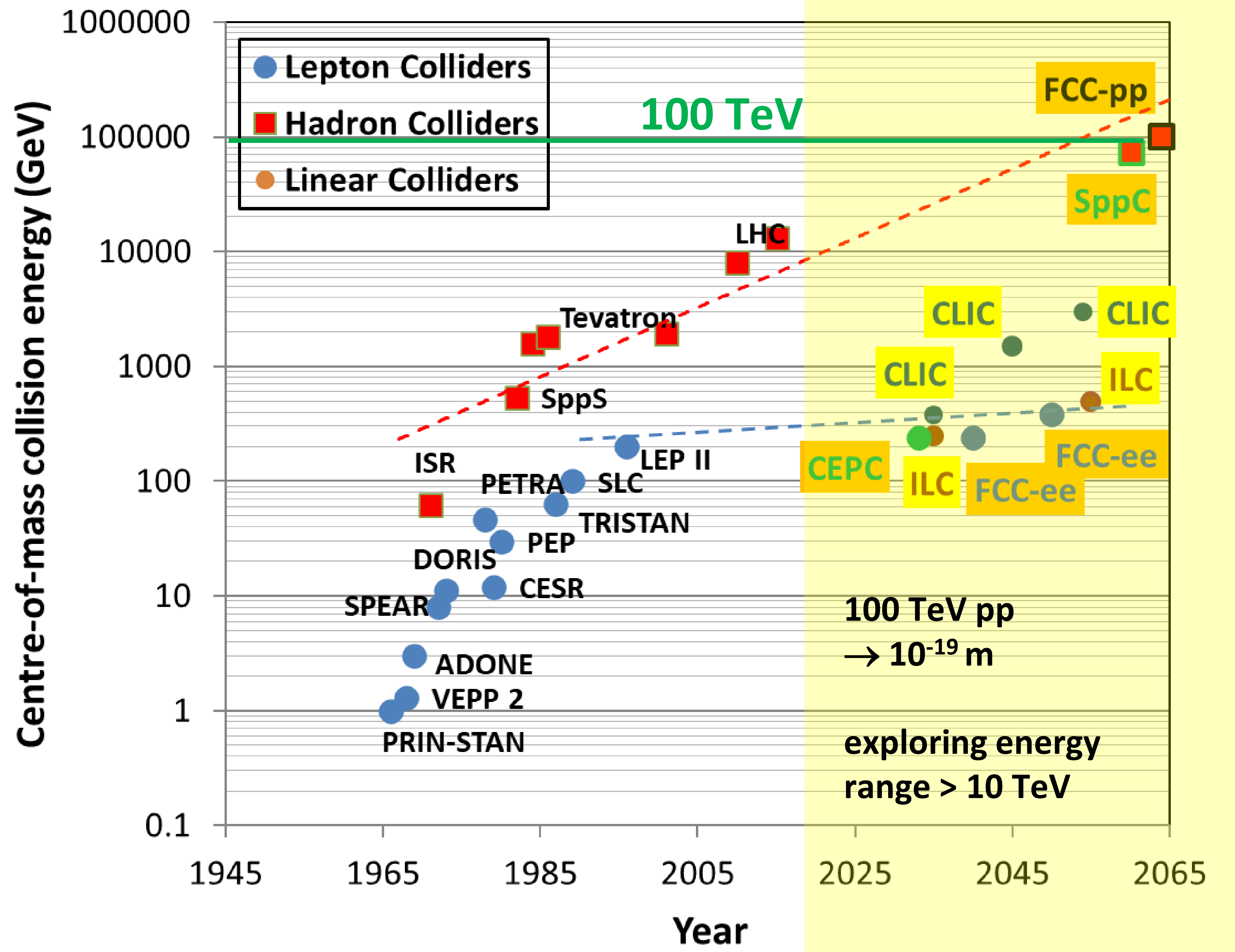
Kitakami Northeast Japan - ILC

Qinhuangdao China – CEPC, SppC

near proposed CEPC construction site and vinyards – bilingual beach resort (Chinese-Russian)

… Geneva beach (FCC) for comparison

proposed future highest energy particle accelerators



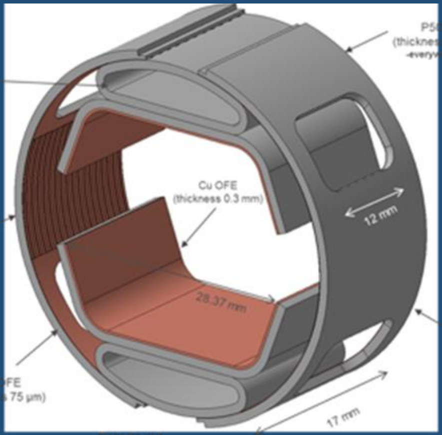
100 TeV pp
→ 10^{-19} m

exploring energy range > 10 TeV

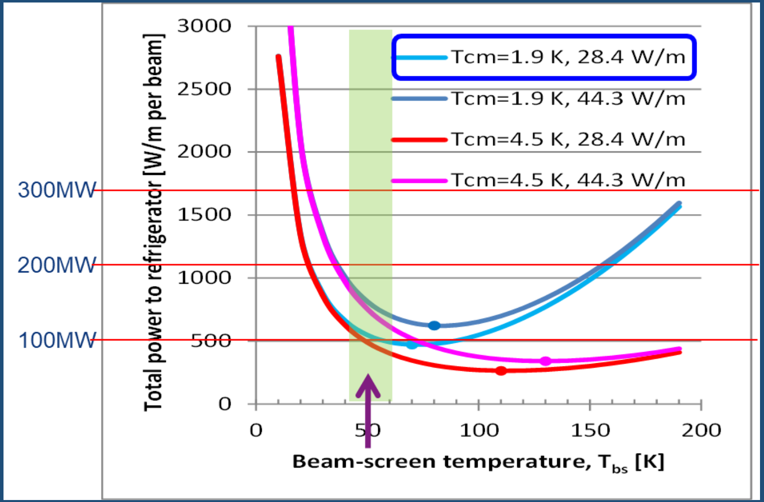
synchrotron radiation (SR), cryo & vacuum

FCC-ee ~100 MW at all beam energies (design constraint)

FCC-hh ~ 5 MW total SR power in arcs from proton beams, emitted inside the cold magnets →**strategy: SR absorption on "beam screen" (BS) at T >> 1.9 K**



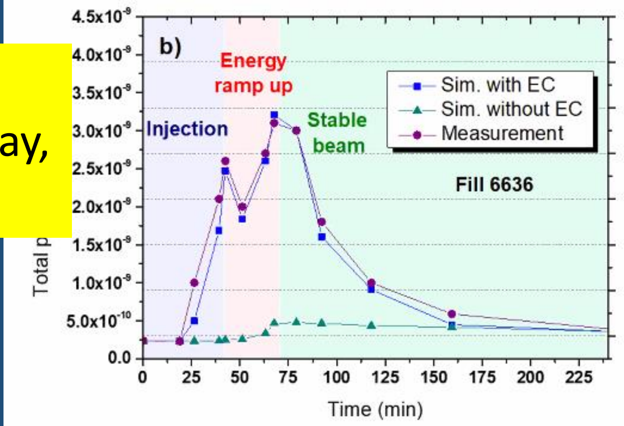
I. Bellafont,
F. Perez,
R. Kersevan
et al.



L. Tavian,
P. Lebrun

S. Bilgen,
G. Sattonay,
et al.

IJCLab
Irène Joliot-Curie

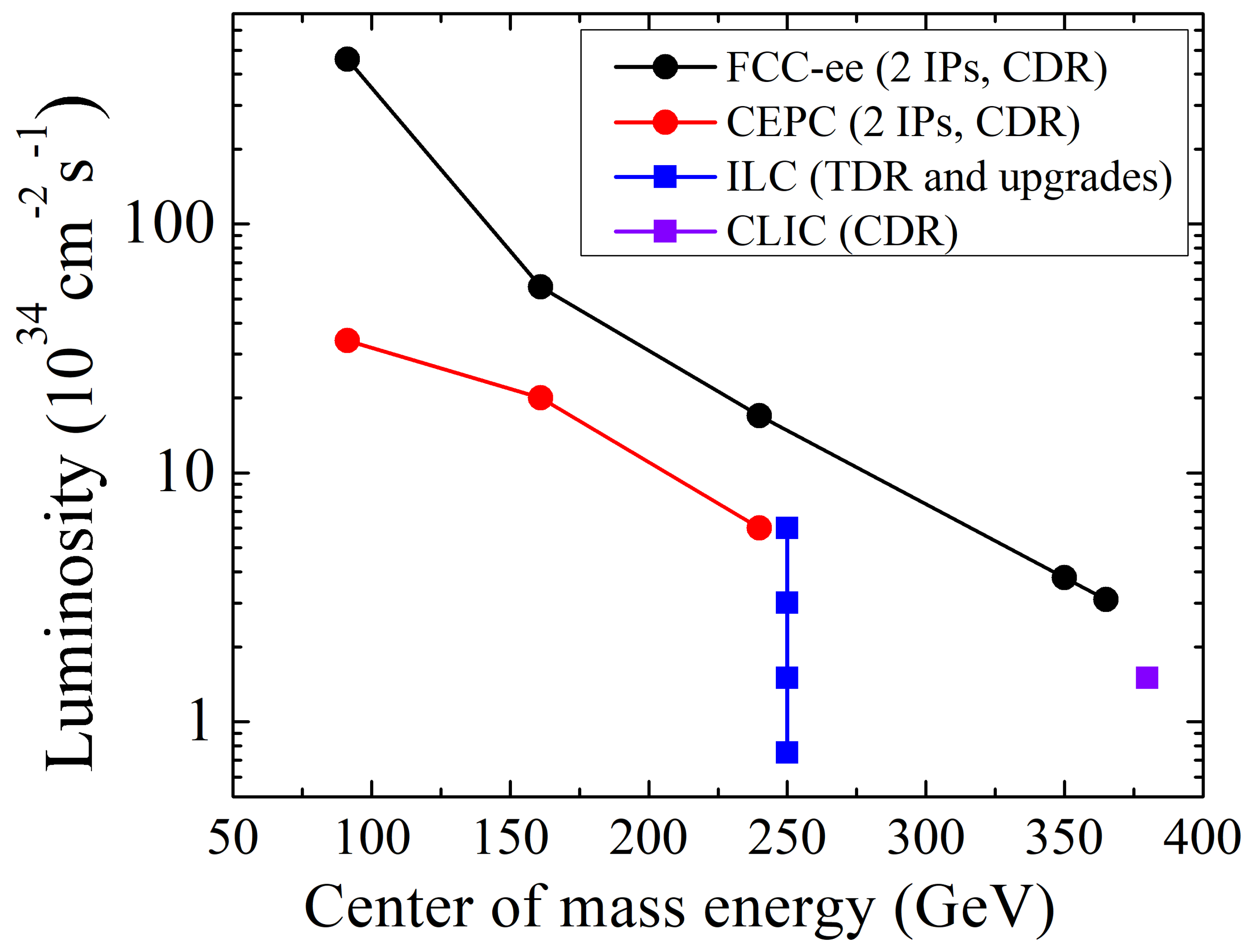


FCC-hh BS temperature choice through overall optimisation:

- cryoplant power consumption
- vacuum system performance
- impedance and beam stability

DYVACS simulations benchmarked at the LHC

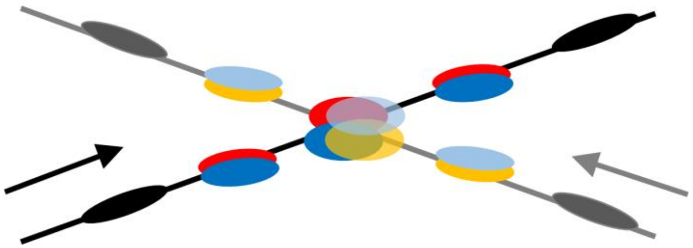
L vs *E* for Higgs & electroweak factories



V. Shiltsev, F. Zimmermann, RMP2021

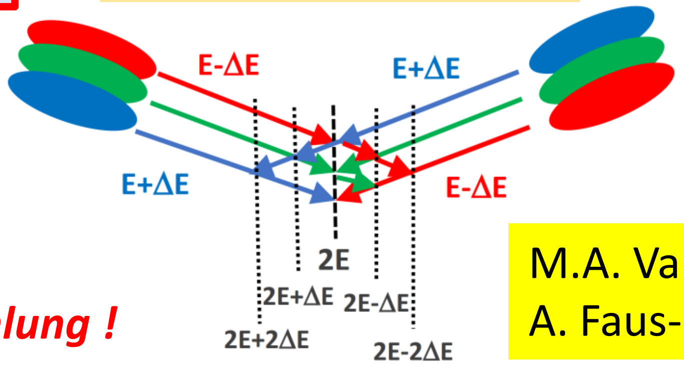
FCC-ee monochromatized direct Higgs production

w crab cavities



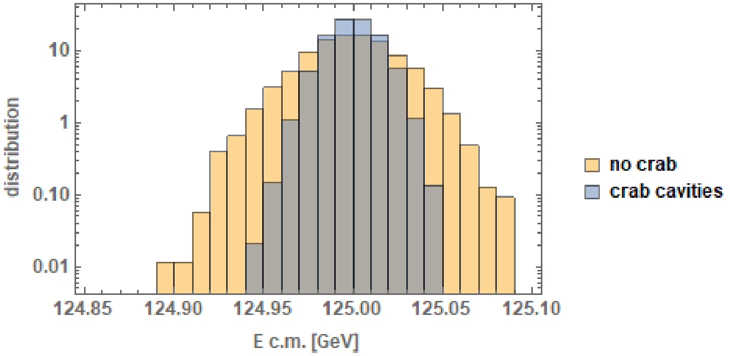
$D_x^* \neq 0$

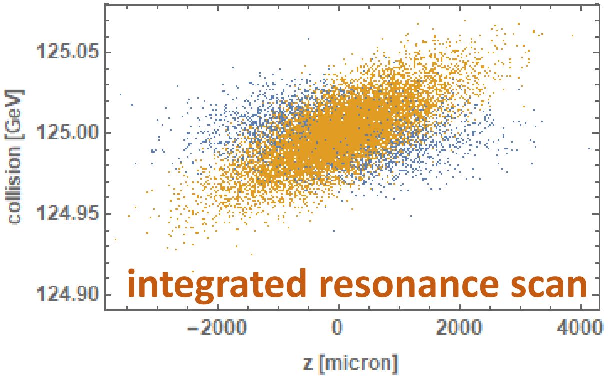
w/o crab cavities

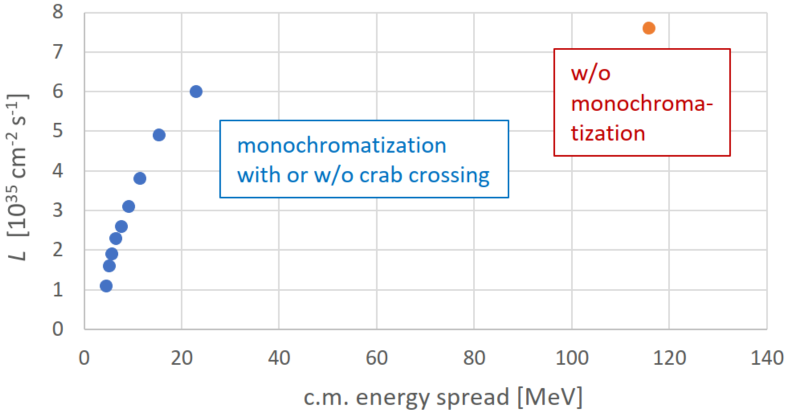


M.A. Valdivia Garcia,
A. Faus-Golfe, et al.

including beamstrahlung !





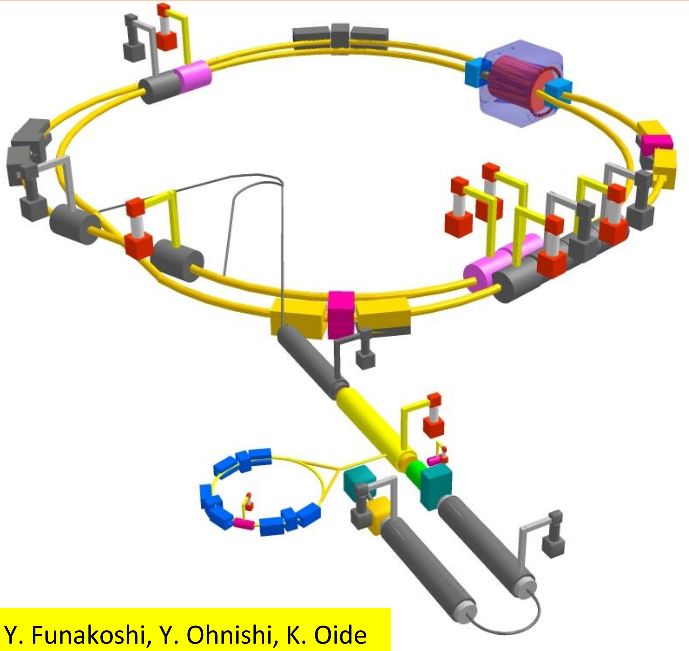


a few times higher Higgs production rate thanks to monochromatization

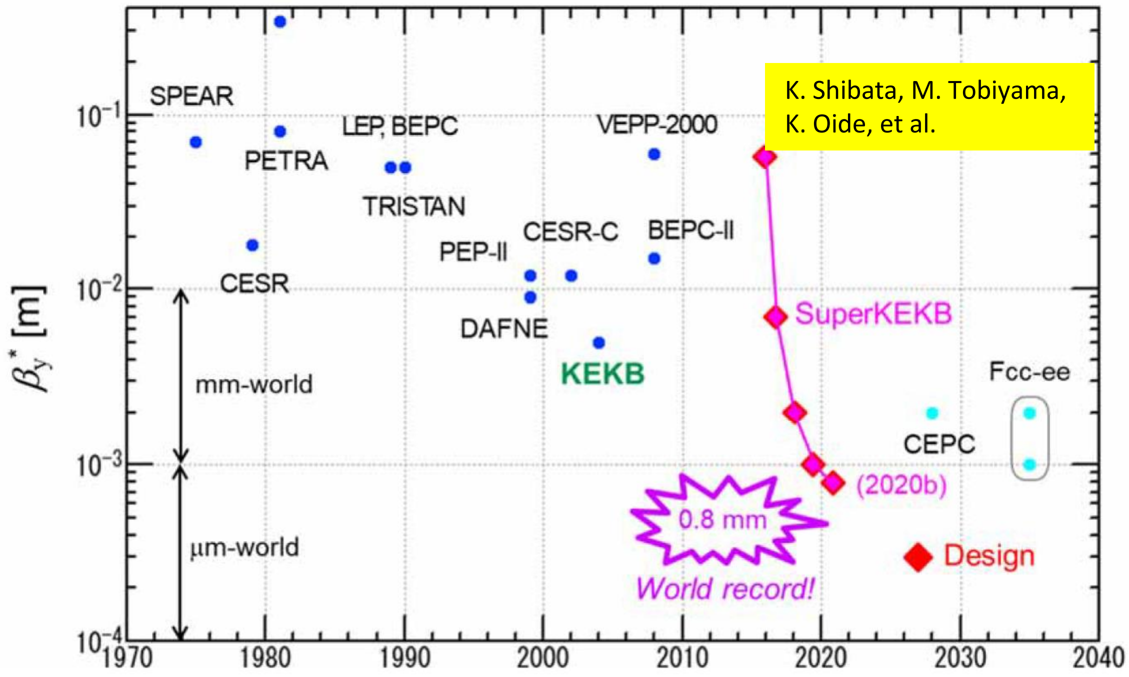
possibly the only available approach to measure the electron Yukawa coupling !

SuperKEKB – an FCC-ee demonstrator

Design: double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; $\beta_y^* \sim 0.3$ mm; nano-beam, large crossing angle collision scheme; beam lifetime ~5 minutes; top-up injection; ce^+ rate up to ~ 2.5 10^{12} /s



Y. Funakoshi, Y. Ohnishi, K. Oide



K. Shibata, M. Tobiyama, K. Oide, et al.

β_y^* = 0.8 mm achieved in both rings 2020 – using FCC-ee "virtual" crab-waist collision

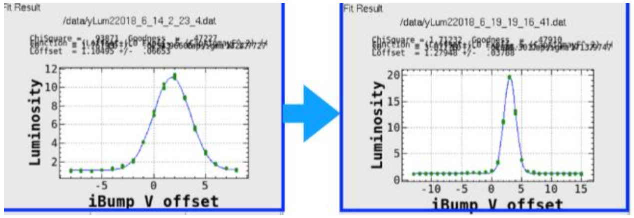
SuperKEKB polarization Upgrade ~2026, polarimete

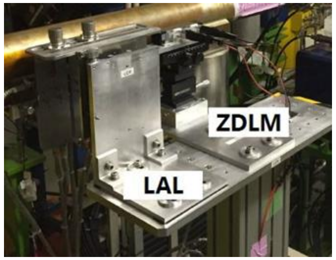
A Mertens, F. Zomer, et al.

M. Roney

P. Bambade et al.

fast luminosity monitor & IP tuning

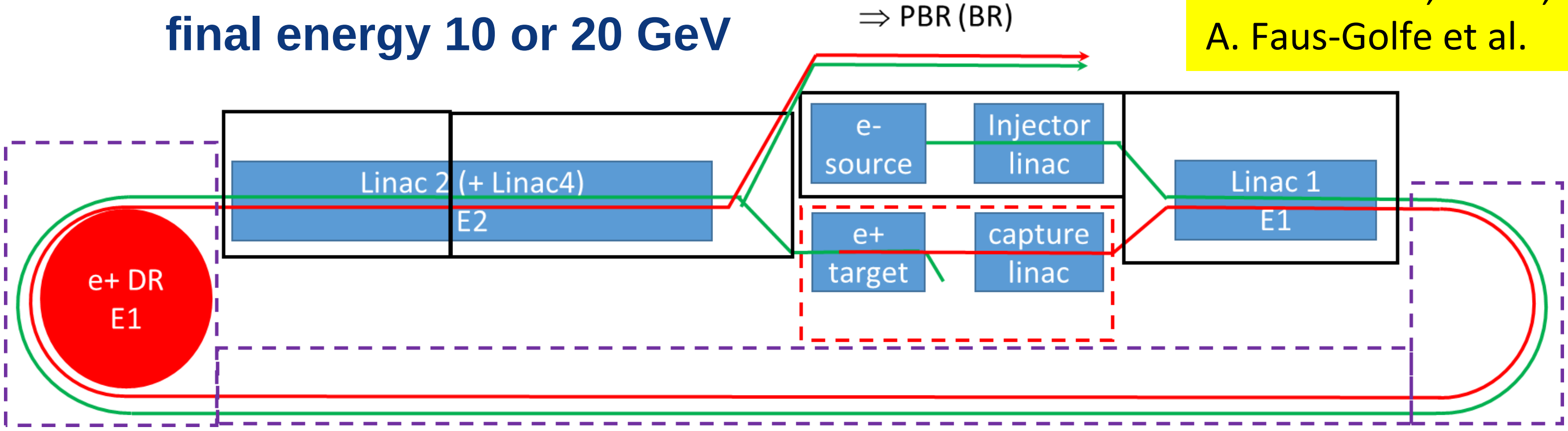




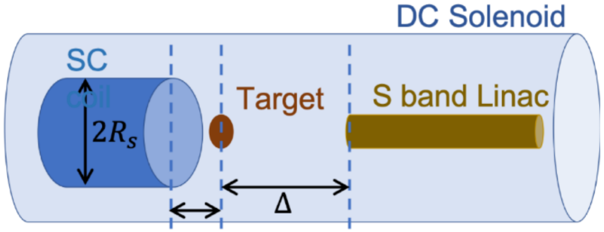
FCC-ee pre-injector complex

I. Chaikovska, B. Bai, A. Faus-Golfe et al.

final energy 10 or 20 GeV



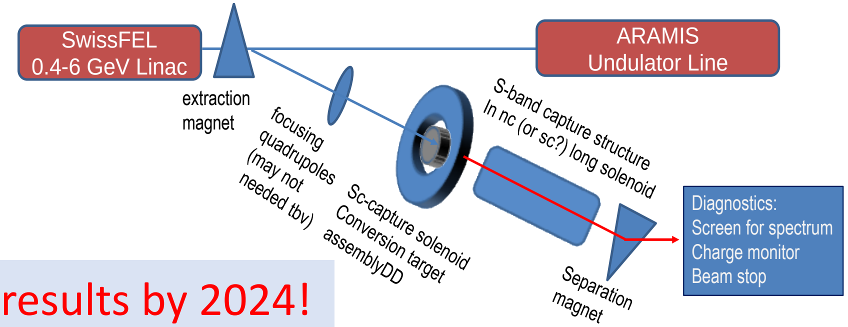
high-yield positron source target with SC solenoid or flux concentrator



SwissFEL 6 GeV C-band linac

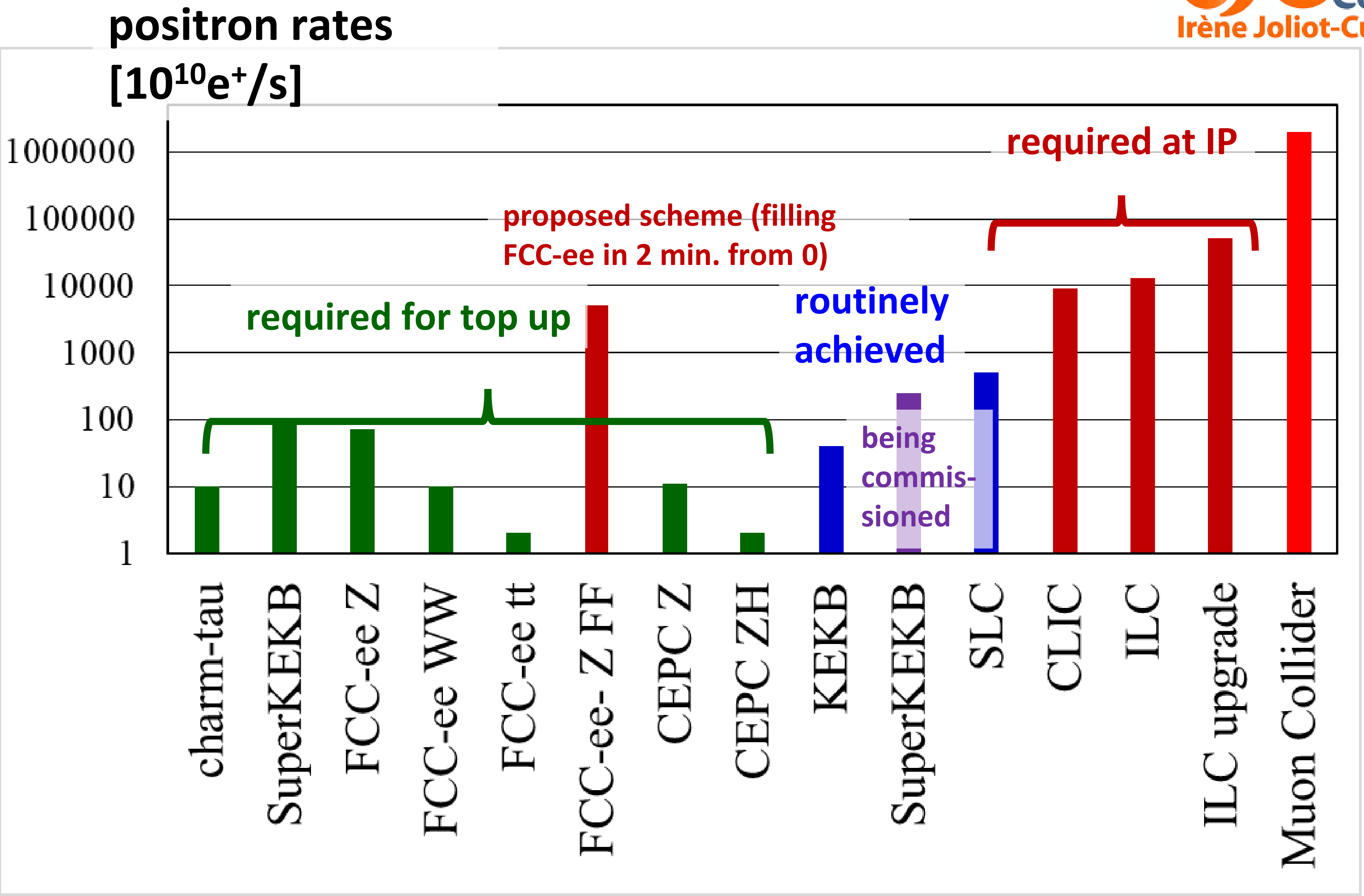
- Freq : 2.856 GHz
- 90 cells per structure
- Length: 3.254 m
- Distance between two TWs: 45 cm
- Gradient: 20 MV/m
- Aperture: 30 mm

FCC-ee demonstrator e^+ source at SwissFEL for e^-/e^+ conversion & capture efficiency



results by 2024!

e⁺ production for future colliders



trend: Machine Learning and Artificial Intelligence

Machine learning (IJClab, SLAC, PSI, CERN), **automated commissioning** (ANL), and **autonomous accelerators** (DESY):

I. Chaikovska,
V. Kubytsky,
H. Guler

- at IJClab: Artificial Intelligence (AI) based global optimization of e$^+$ injector complex including e$^-$ drive beam and final system acceptance

V. Sajaev

Automated commissioning is key to fast lattice commissioning for APS-U

MACHINE LEARNING for PARTICLE ACCELERATORS

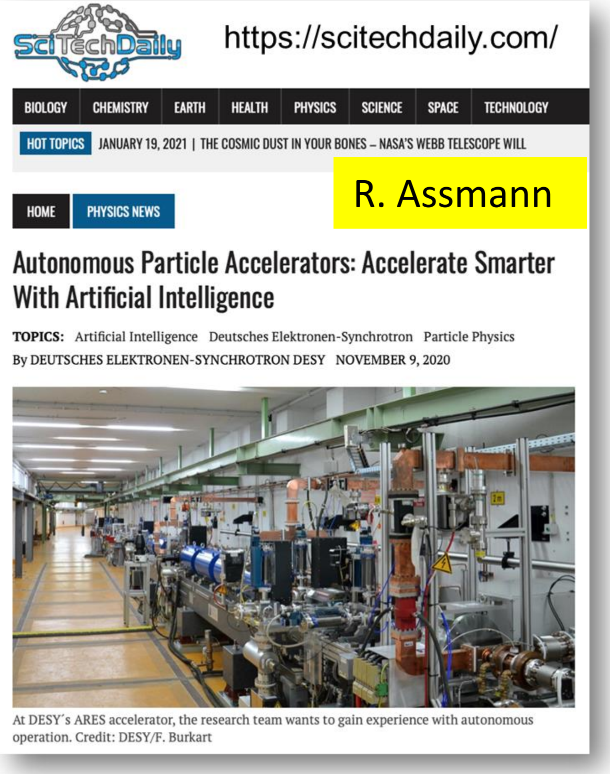
February 28 - March 2, 2018, SLAC National Accelerator Laboratory

D. Ratner

2nd ICFA Workshop on Machine Learning for Charged Particle Accelerators

26 February 2019 to 1 March 2019
Villigen PSI
Europe/Zurich timezone

A. Adelmann



https://scitechdaily.com/

JANUARY 19, 2021 | THE COSMIC DUST IN YOUR BONES – NASA'S WEBB TELESCOPE WILL

Autonomous Particle Accelerators: Accelerate Smarter With Artificial Intelligence

TOPICS: Artificial Intelligence Deutsches Elektronen-Synchrotron Particle Physics

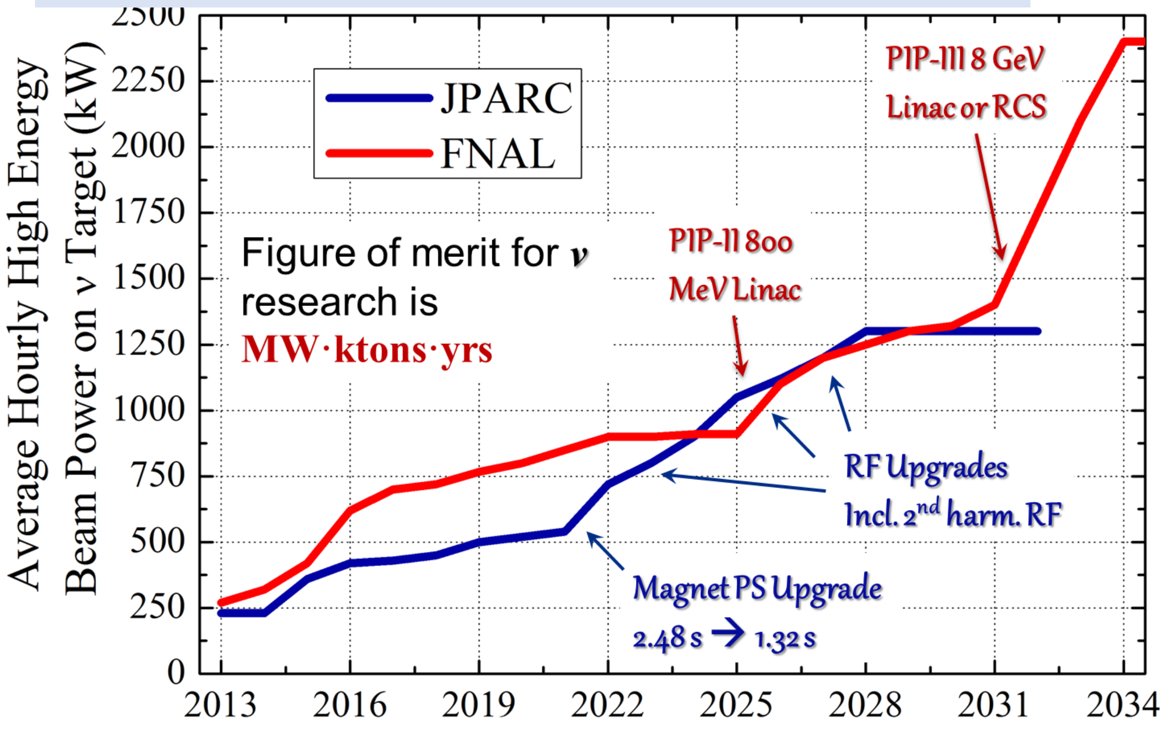
By DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY NOVEMBER 9, 2020

At DESY's ARES accelerator, the research team wants to gain experience with autonomous operation. Credit: DESY/F. Burkart

R. Assmann

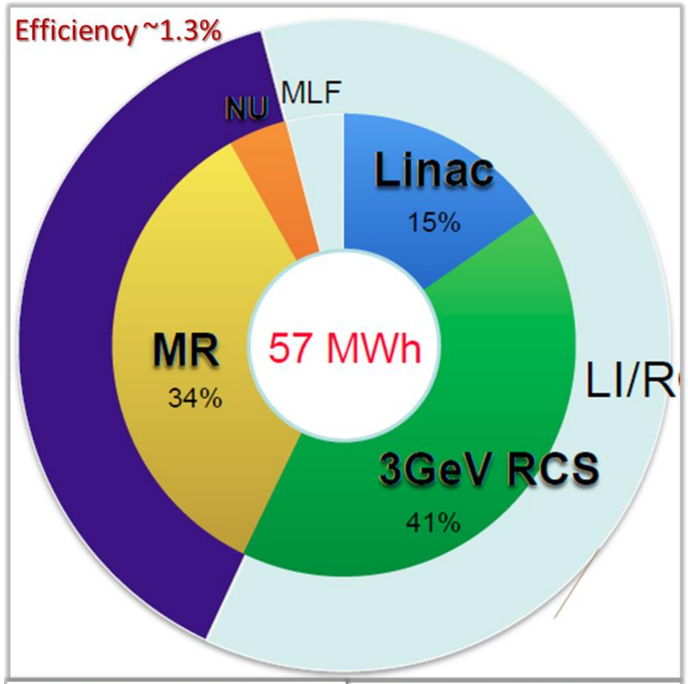
super-beam facilities & upgrades

Fermilab & J-PARC Power Upgrades



power efficiency challenge

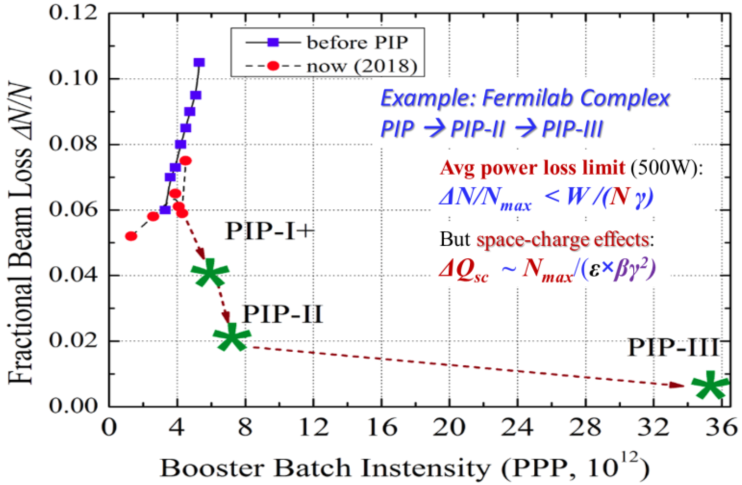
J-PARC : 0.5 MW beams vs ~40 MW site power



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

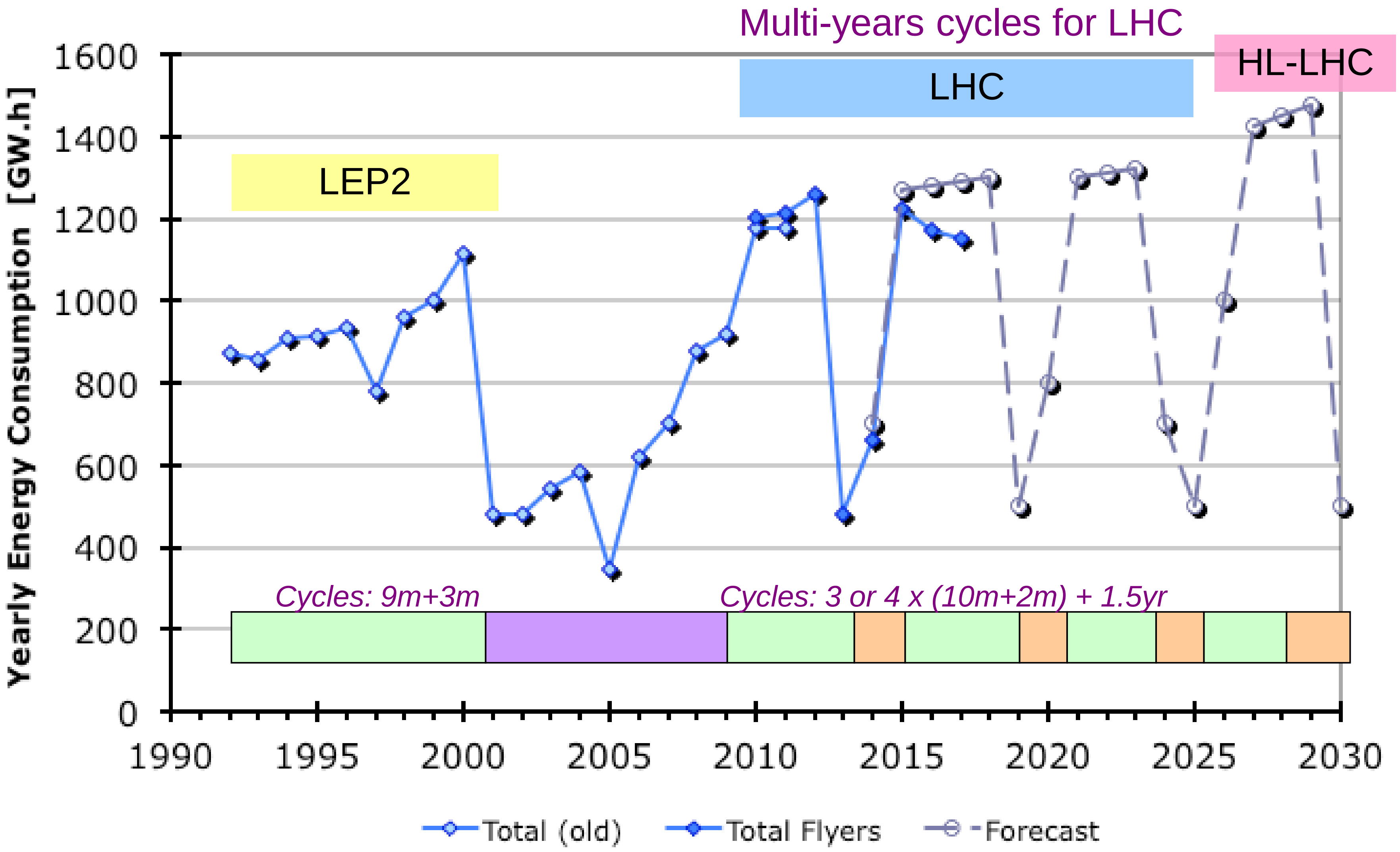
- RCS Magnets: 9.6 MWh per hour
- RCS RF: 7 MWh per hour

protons per pulse challenge



V. Shiltsev

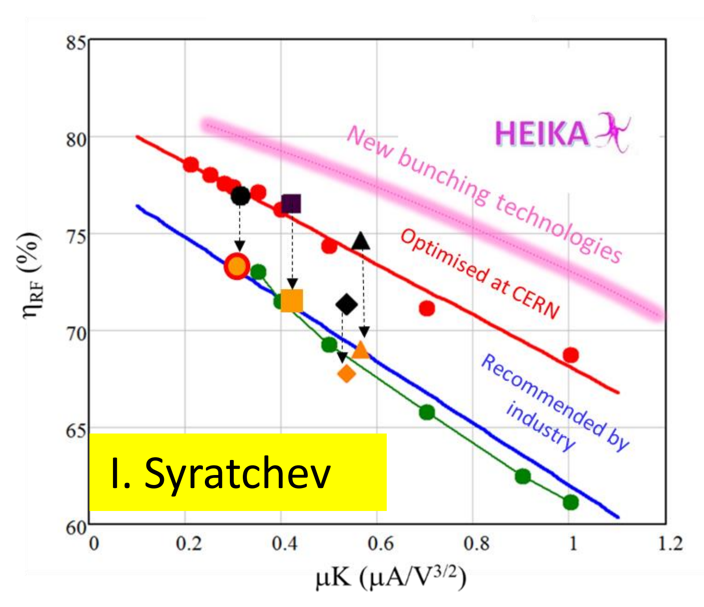
energy consumption – example CERN



V. Mertens

“green” energy efficient technologies

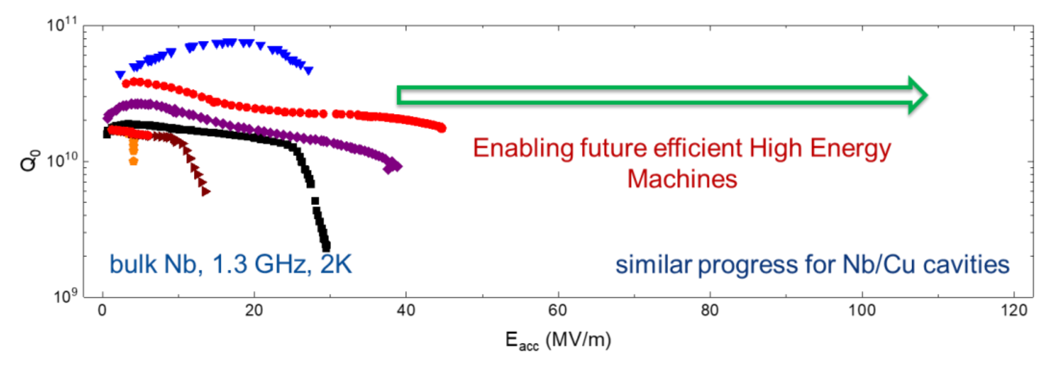
more efficient RF power sources



I. Syratchev

more efficient SC cavities

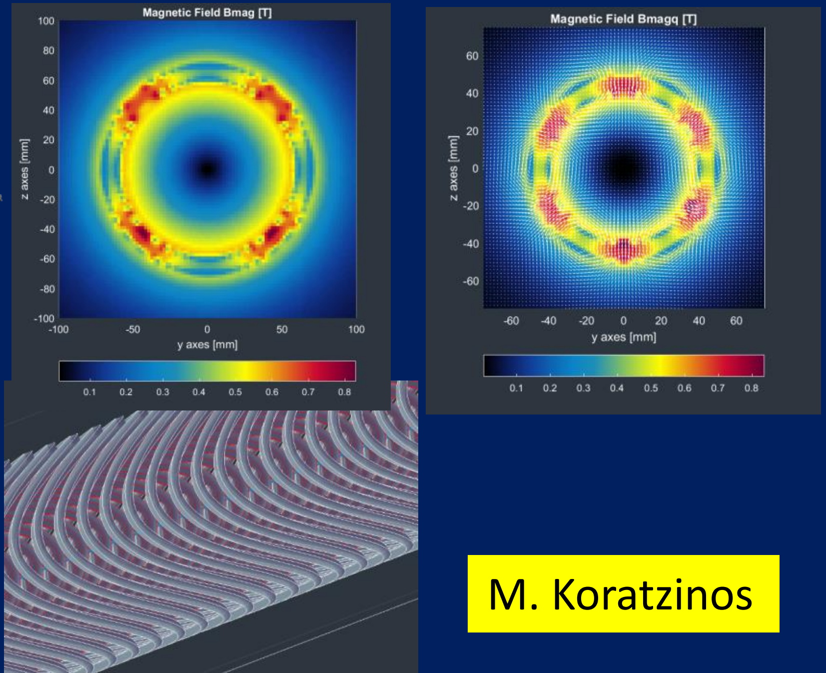
A. Grasselino



Enabling future efficient High Energy Machines

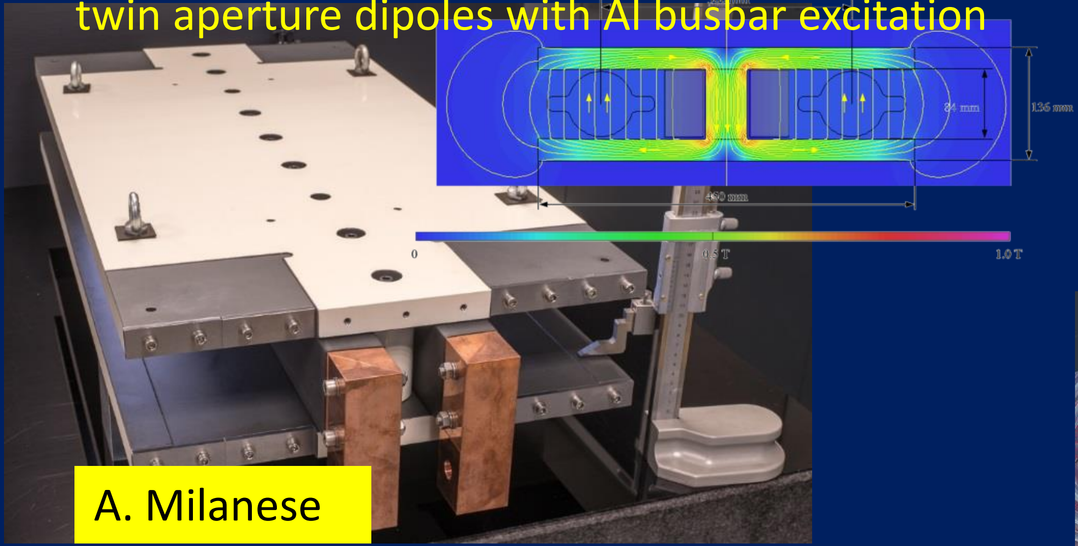
similar progress for Nb/Cu cavities

CCT HTS quadrupoles & sextupoles



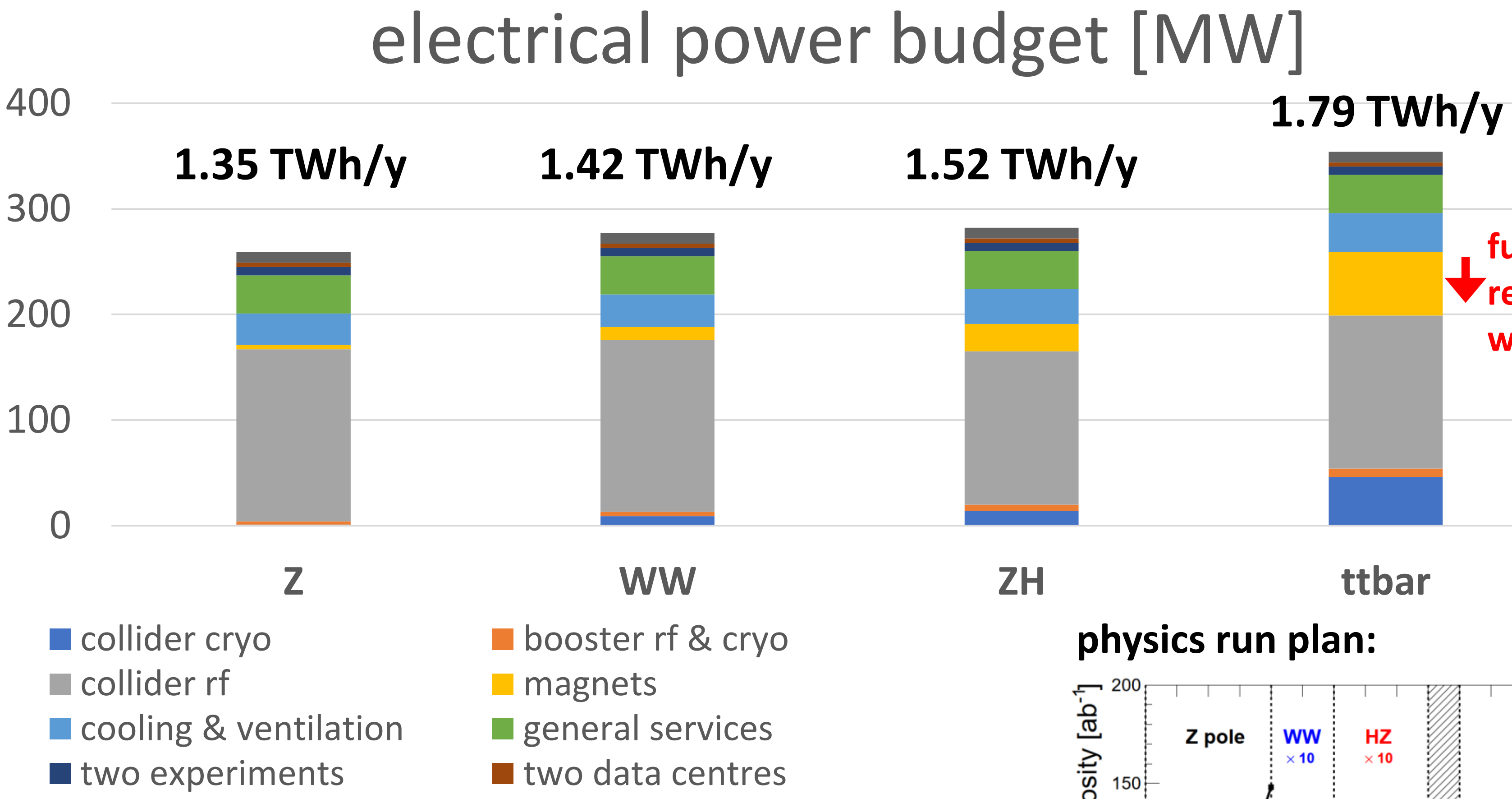
M. Koratzinos

twin aperture dipoles with Al busbar excitation



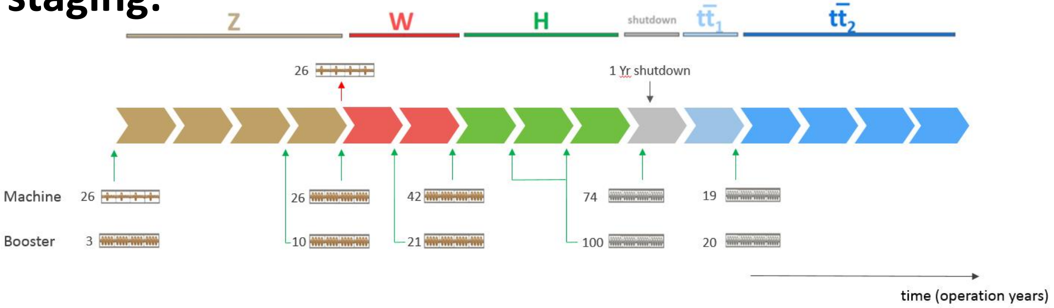
A. Milanese

FCC-ee electrical power requirements

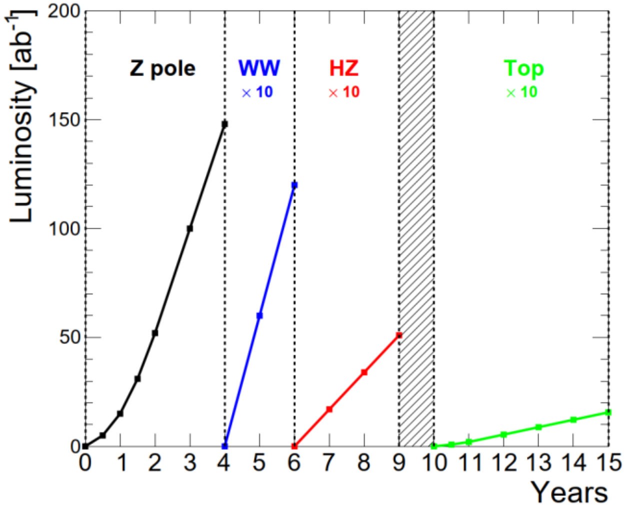


further reduction with HTS ?

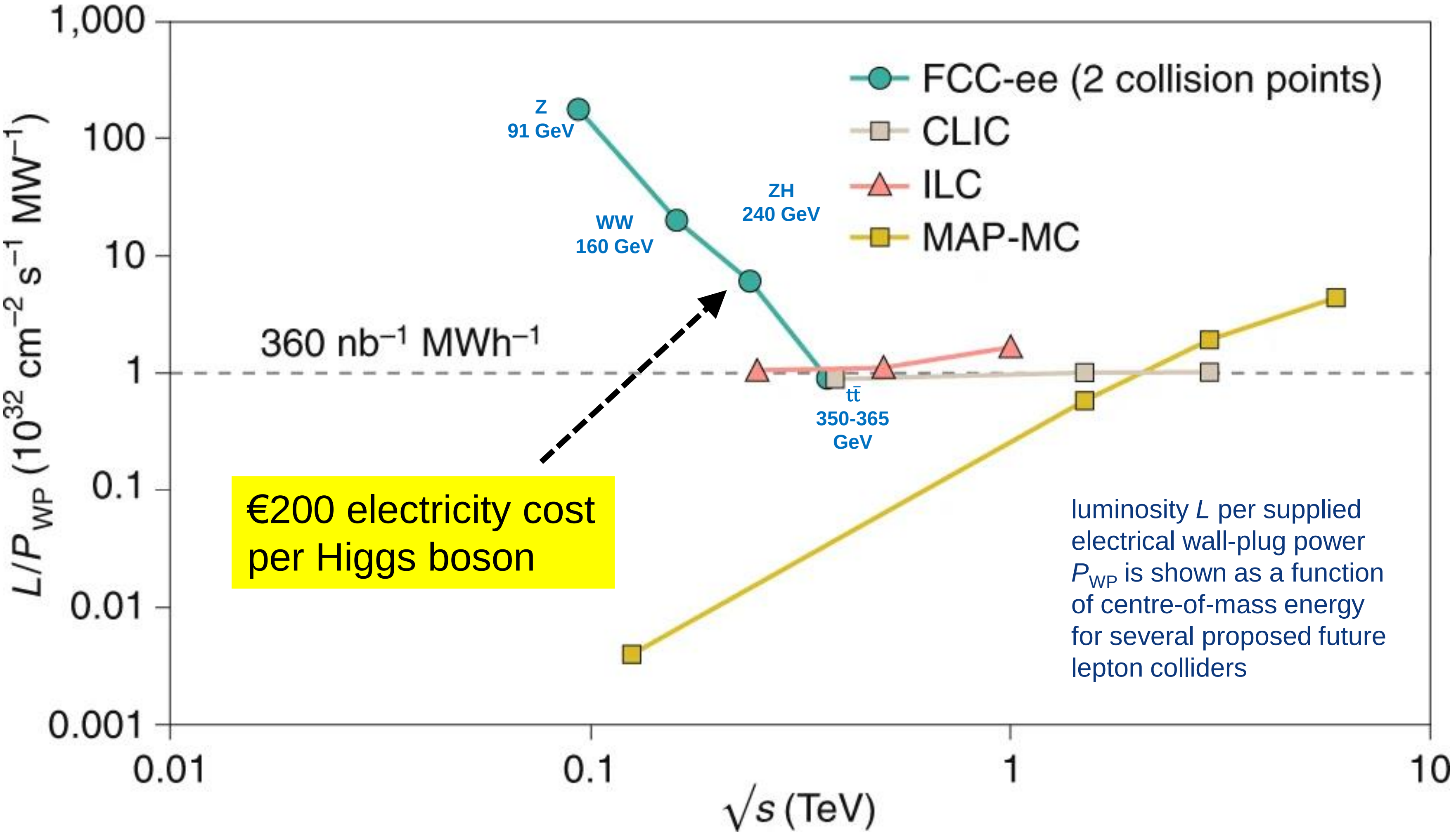
RF staging:



physics run plan:



FCC-ee: efficient Higgs/electroweak factory



€200 electricity cost per Higgs boson

luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders

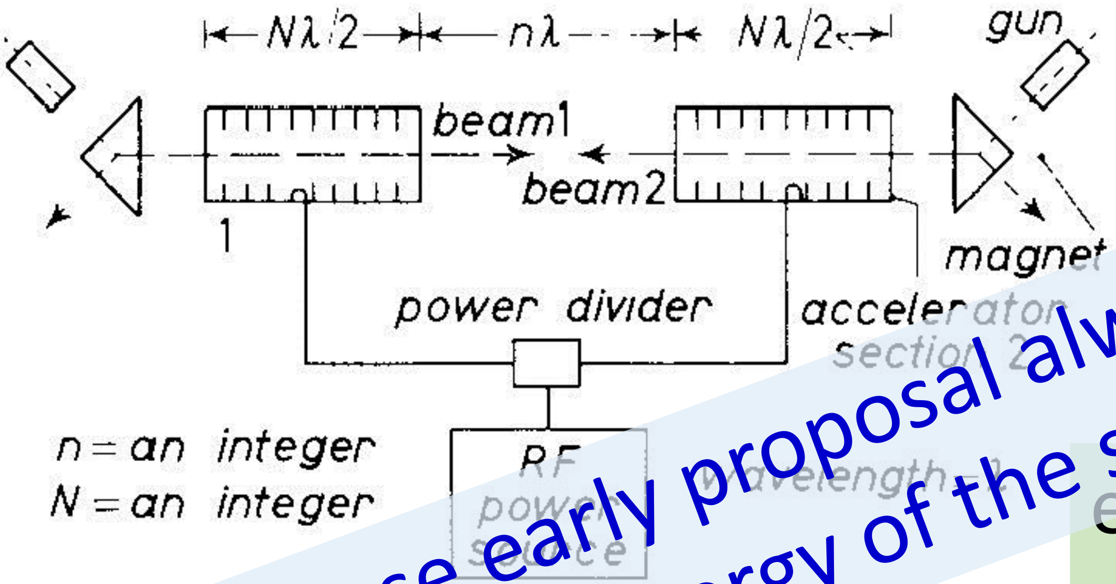
FCC-ee is greenest collider from Z to $t\bar{t}$

M. Benedikt, A. Blondel, P. Janot, et al., **Nat. Phys. 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

future cw LC's with energy recovery ?

1-6 GeV c.m.

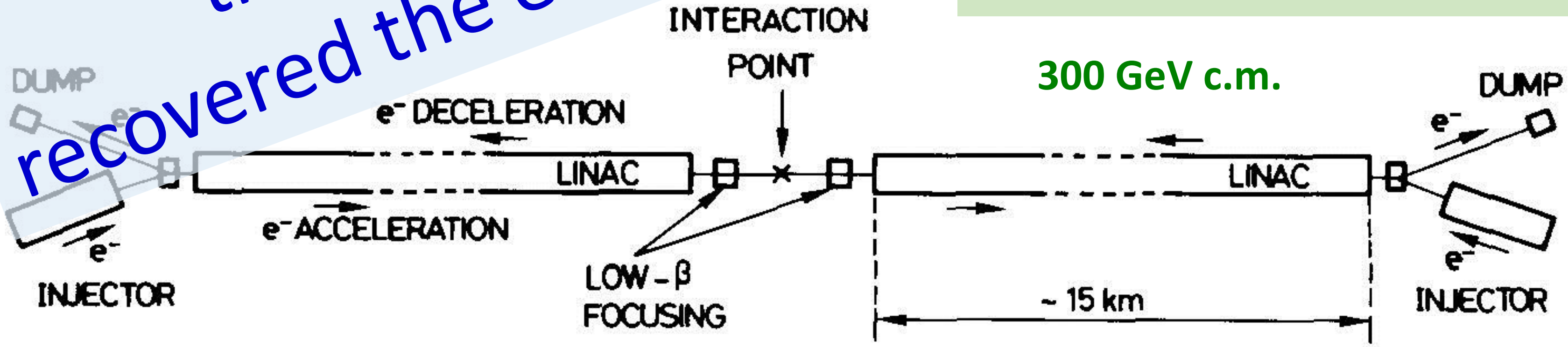
Maury Tigner, "*A Possible Apparatus for Clashing-Beam Experiments*", Nuovo Cimento 37, 1228 (**1965**)



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

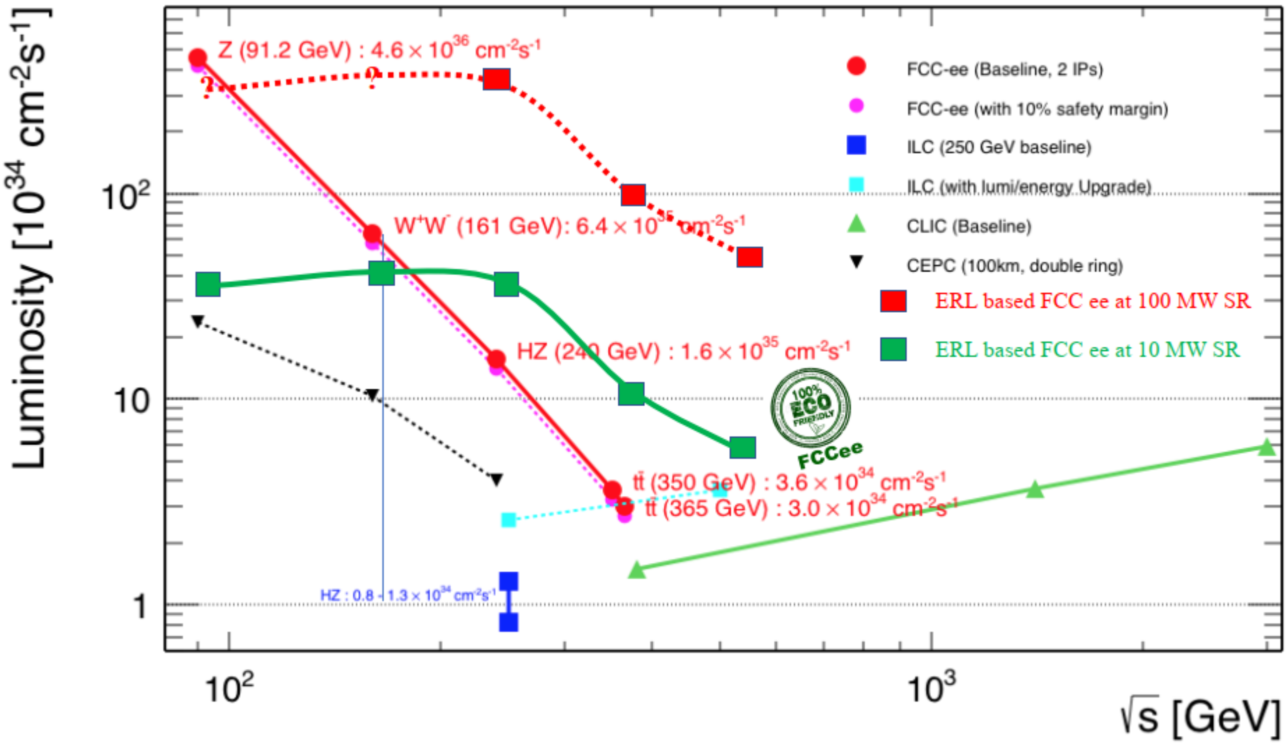
early linear-collider proposals

300 GeV c.m.



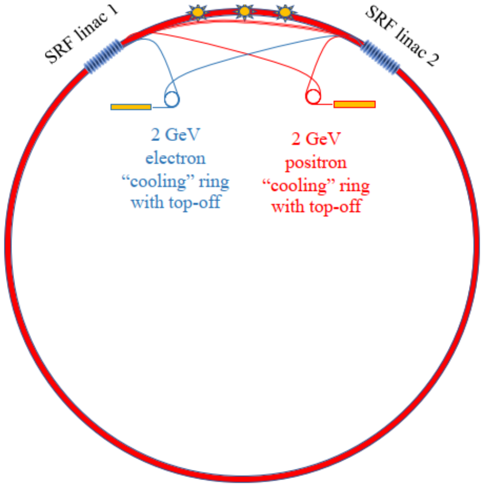
Ugo Amaldi, "*A possible scheme to obtain e-e- and e+e- collisions at energies of hundreds of GeV*", Physics Letters B61, 313 (**1976**)

FCC-ee ERL option: boosting luminosity & energy

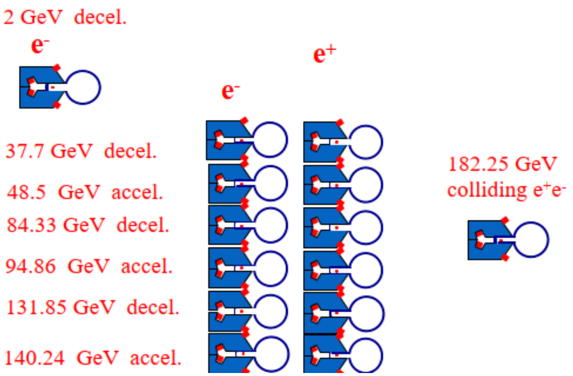


V. Litvinenko,
T. Roser,
M. Chamizo

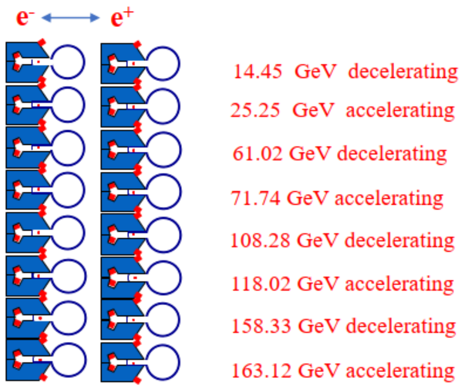
"High-energy high-luminosity e$^+$e$^-$ collider using energy-recovery linacs," Physics Letters B Vol 804, 135394 (2020)



IRs side arcs (after linac 2)

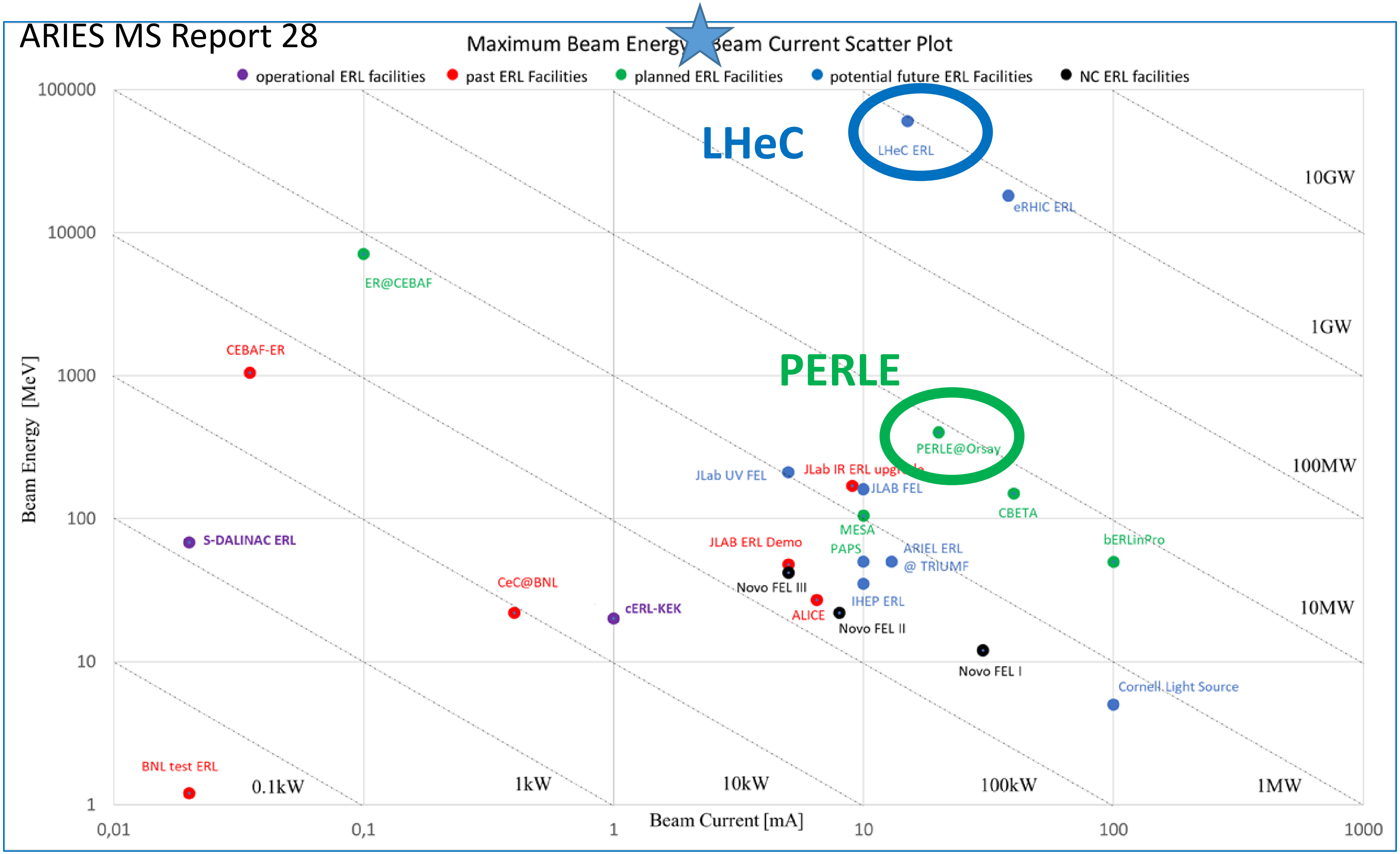


Main portion (5/6) of the ring arcs



ERL landscape

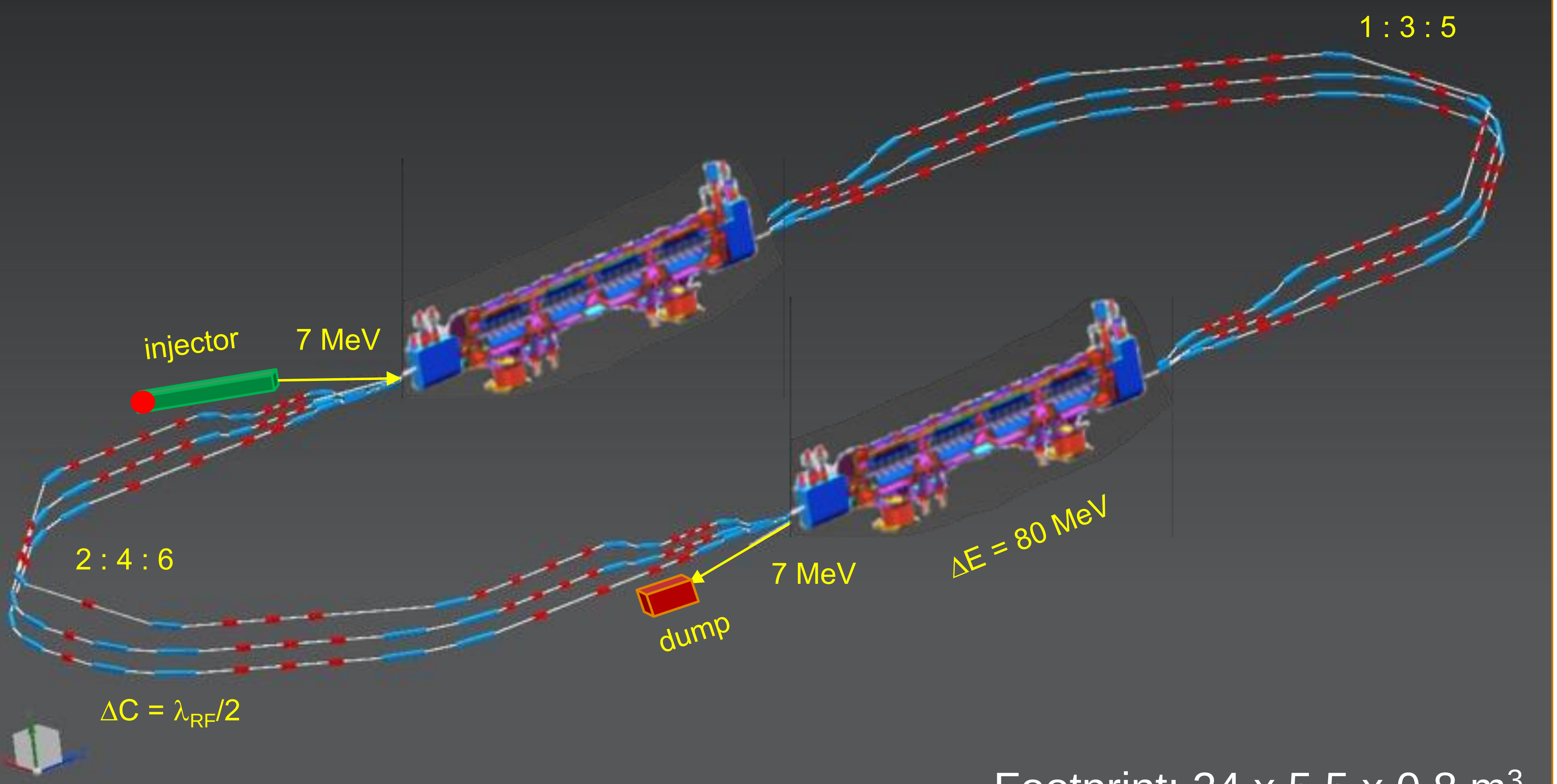
FCC-ee-ERL



F. Hug

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

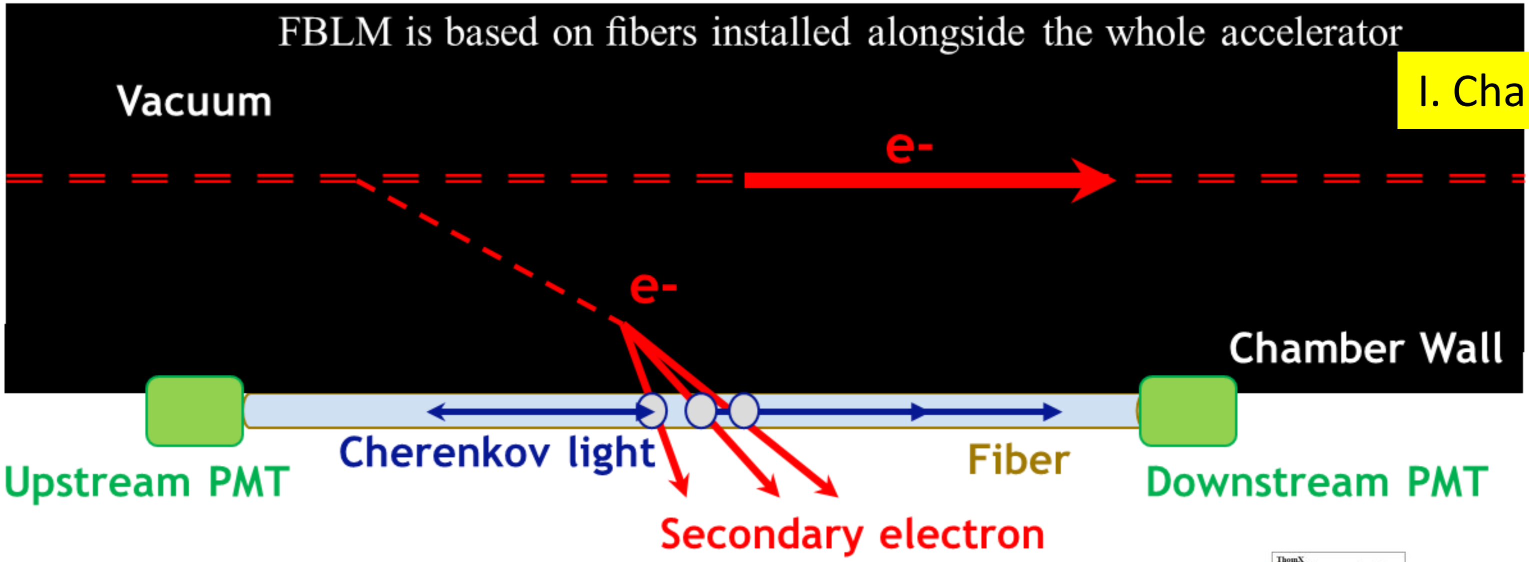
the ERL beam loss challenge

PERLE: beam loss control at 10^{-6} level

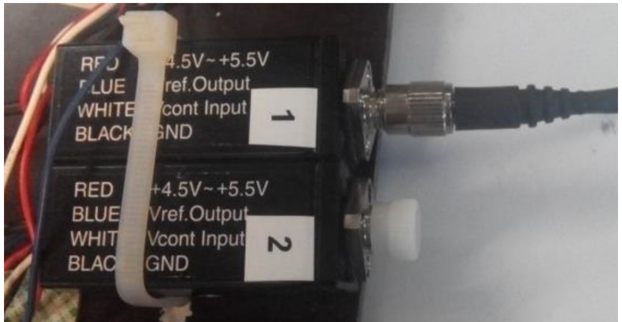
Higher-energy/higher-power machines: even tighter tolerances !

→ efficient collimation strategies

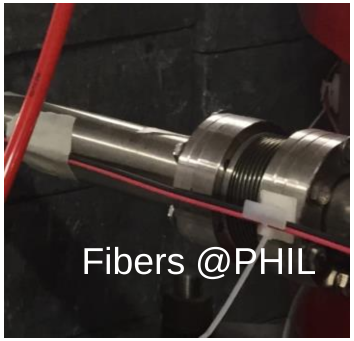
→ adequate beam-loss diagnostics – great expertise available

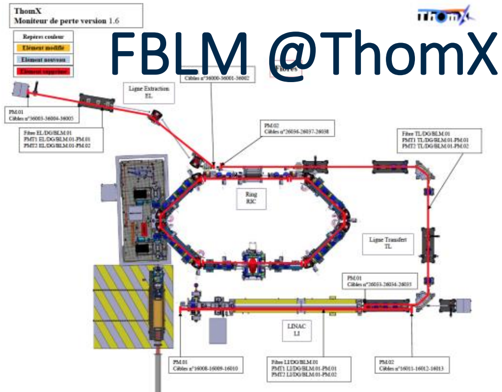


I. Chaikovska



Compact PMT for diagnostics at PHIL



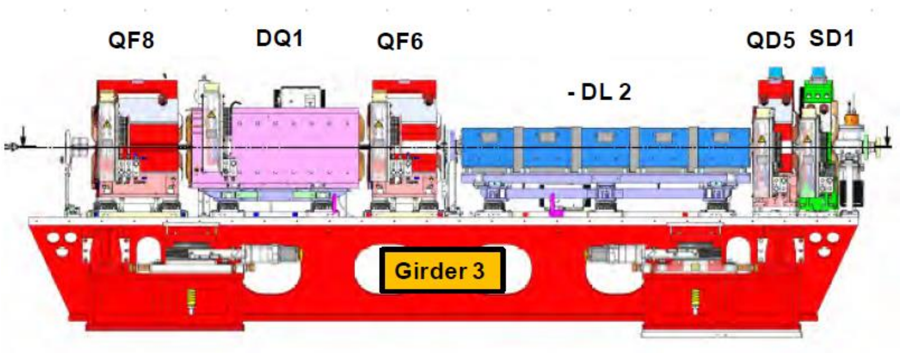


the 100 km alignment challenge

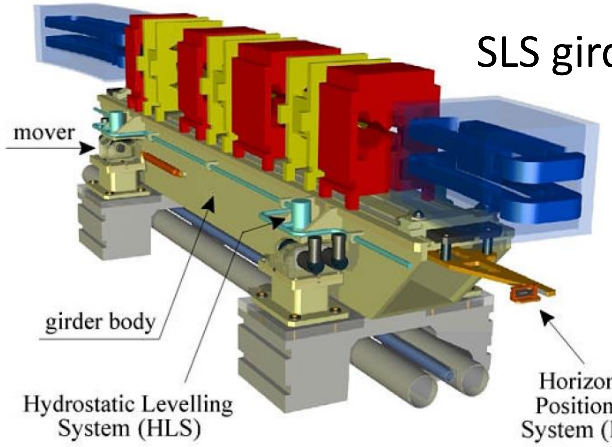
"*Even if we were able to use standard alignment methods and had four weeks to carry out a smoothing of the two accelerators, we would need more than 200 survey teams*" !?

[note: LEP aligned all ~800 quadrupoles every winter shutdown]

approach: pre-alignment of BPM/quad/sext assembly on girder



ESRF-EPS girder layout



SLS girder assembly

testing FCC-ee positioning strategy at ATF3 ?

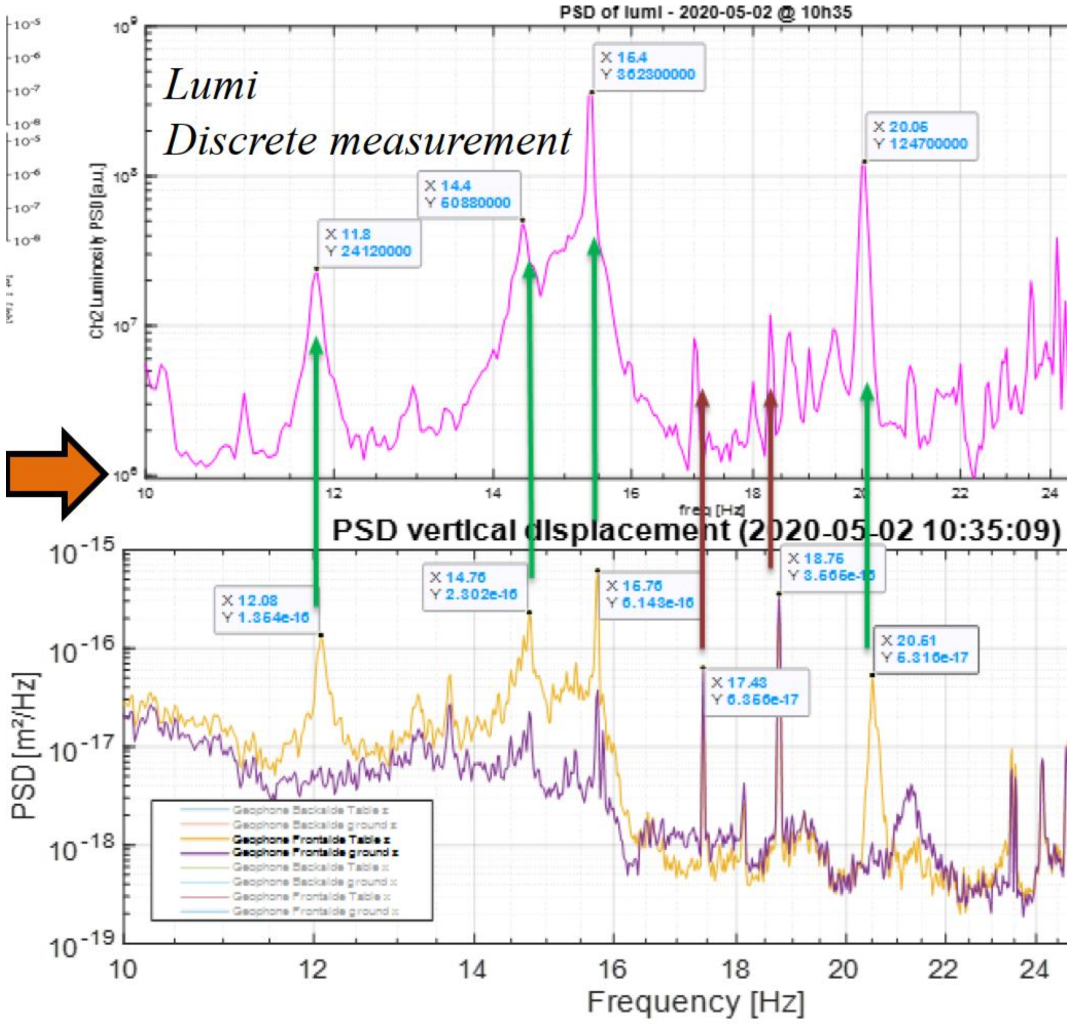
G. Balik

parameter	achieved alignment [µm/µrad, rms]		tolerances FCC-ee [µm/µrad, rms]
	PETRA III	SPring-8	FCC-ee
quad on girder *x,y*	22,22	19, 14	50, 50
sext n girder *x,y*	22,22	19, 14	50, 50
girder *x,y,s*	100	89, 61, <500	150,150,500

T. Charles

vibration mitigation: from SuperKEKB to FCC-ee

Correlation between spectral density of cryostat vibration & SuperKEKB luminosity

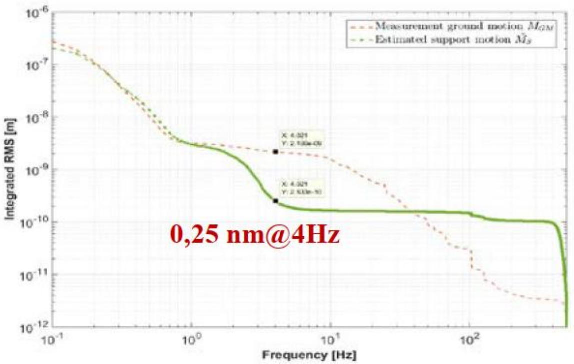


L. Brunetti

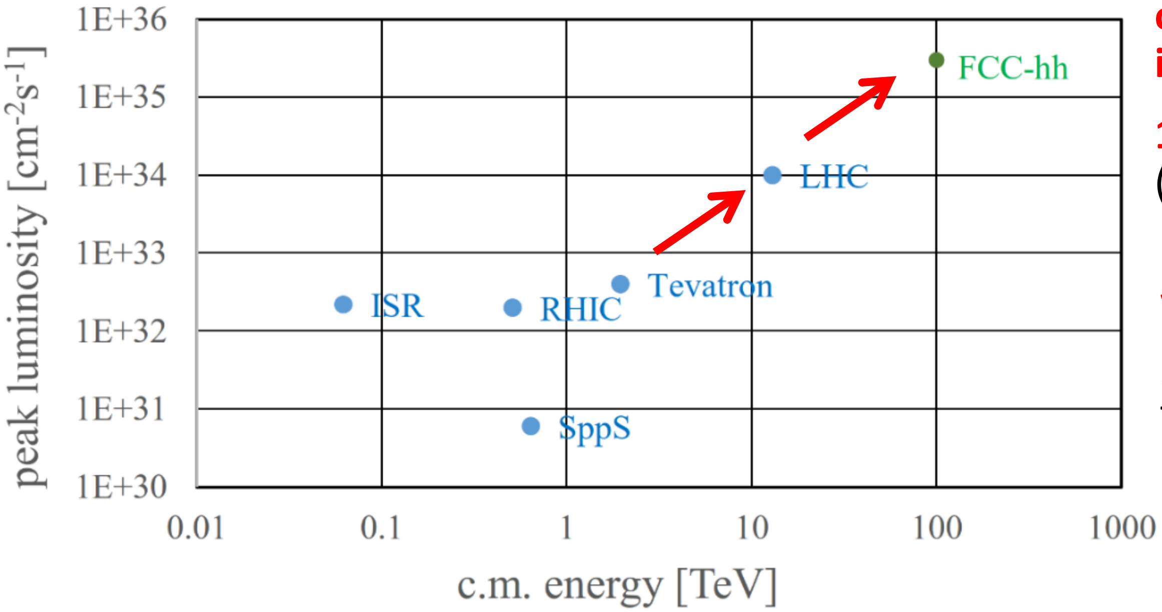
mitigation measures:

stiff support
& coherence

active stabilization



FCC-hh: performance



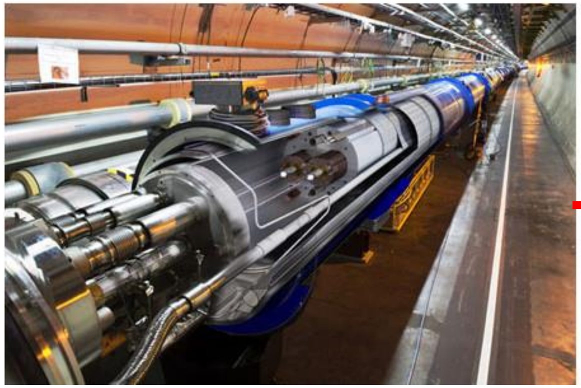
order of magnitude performance increase in **energy & luminosity**

100 TeV cm collision energy (vs 14 TeV for LHC)

20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

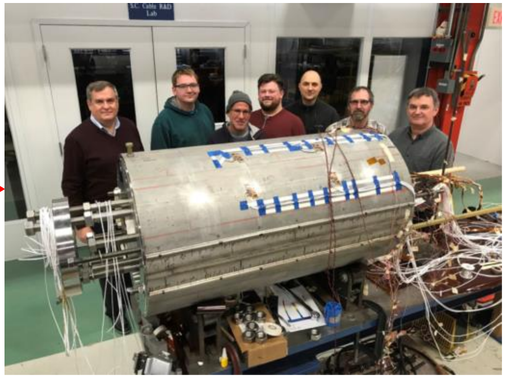
similar performance increase as from Tevatron to LHC

key technology: high-field magnets



from
LHC technology
8.3 T NbTi

via
HL-LHC technology
11 T Nb_3Sn

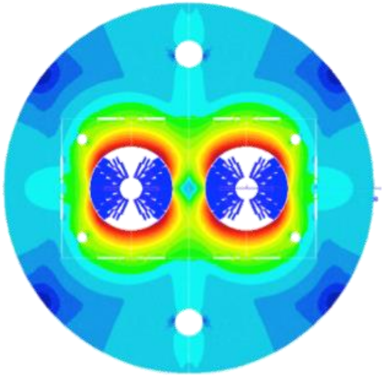


FNAL
demonstrator
14.5 T Nb_3Sn

16 T dipole design activities and options

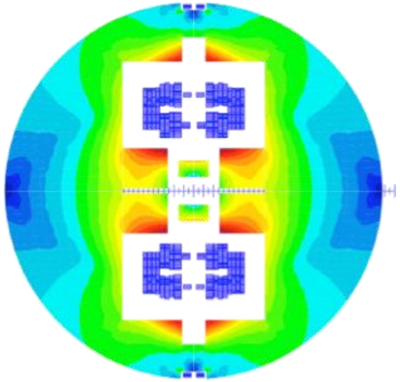
H2020
EuroCirCol
A key to New Physics

Cos-theta



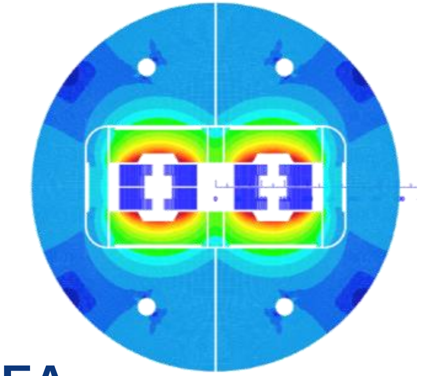
INFN

Common coils



CIEMAT

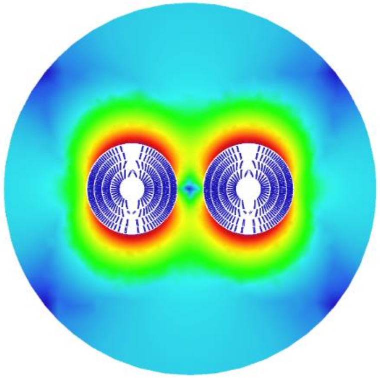
Blocks



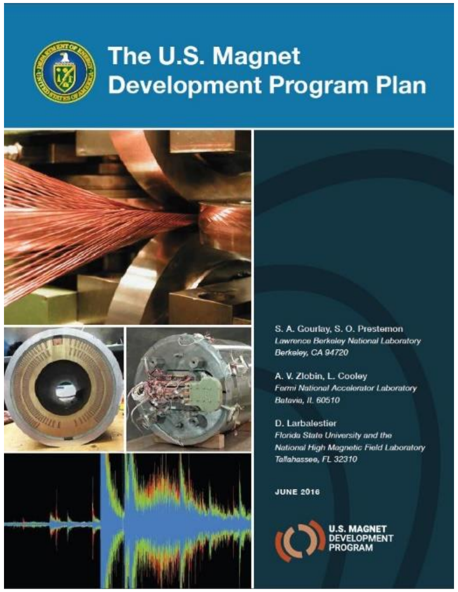
CEA

Swiss contribution

Canted Cos-theta



PSI



The U.S. Magnet Development Program Plan

S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

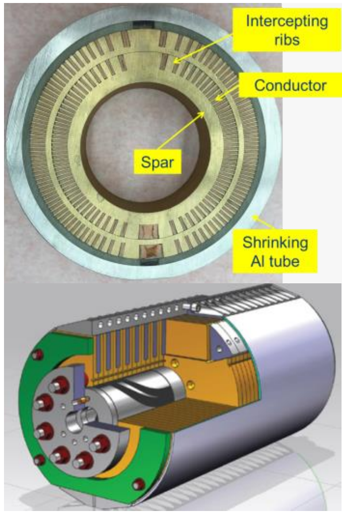
A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

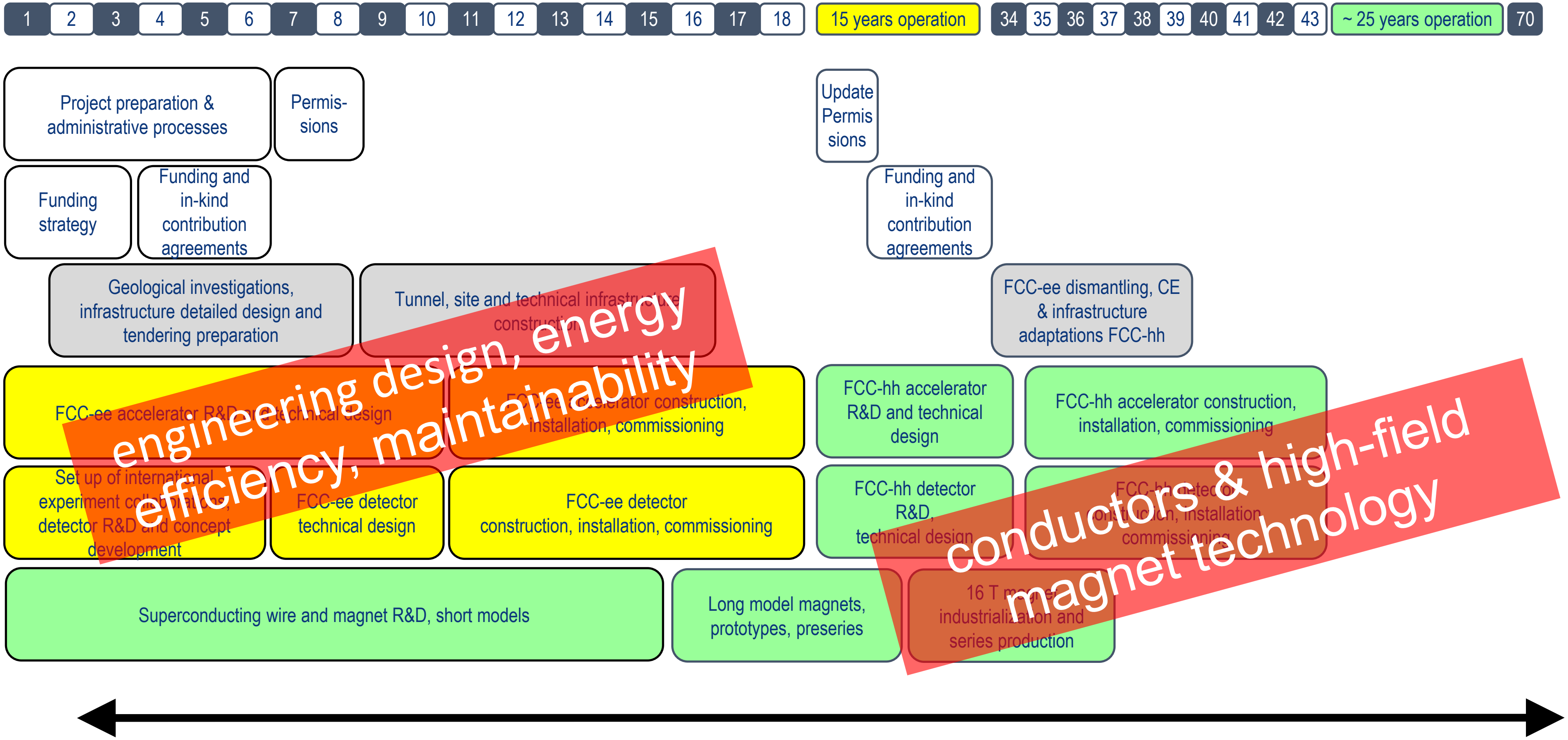
LBNL



FNAL

Short model magnets (1.5 m lengths) will be built until ~2025

FCC integrated project technical schedule



engineering design, energy efficiency, maintainability

conductors & high-field magnet technology

for comparison:

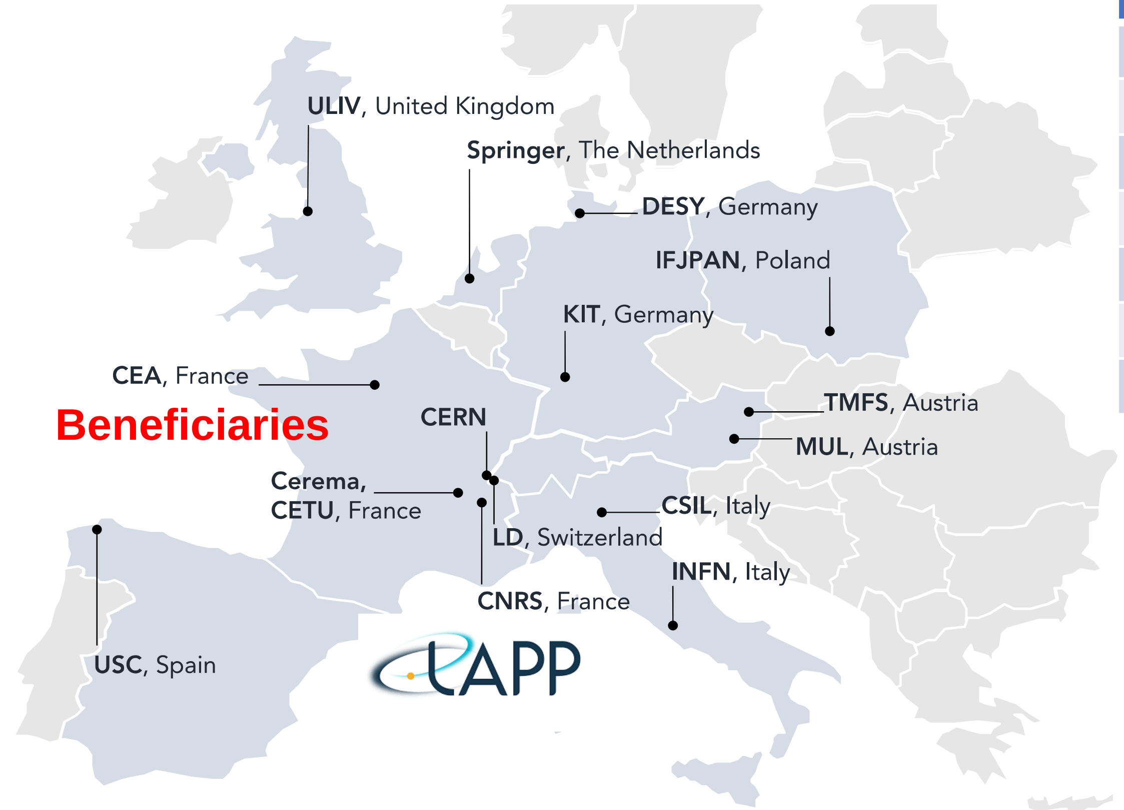
>60 years

LEP proposed 1976, approved 1981; LHC proposed 1983, appr. 1994; LHC/HL-LHC till ~2040

H2020 DS FCC Innovation Study 2020-24

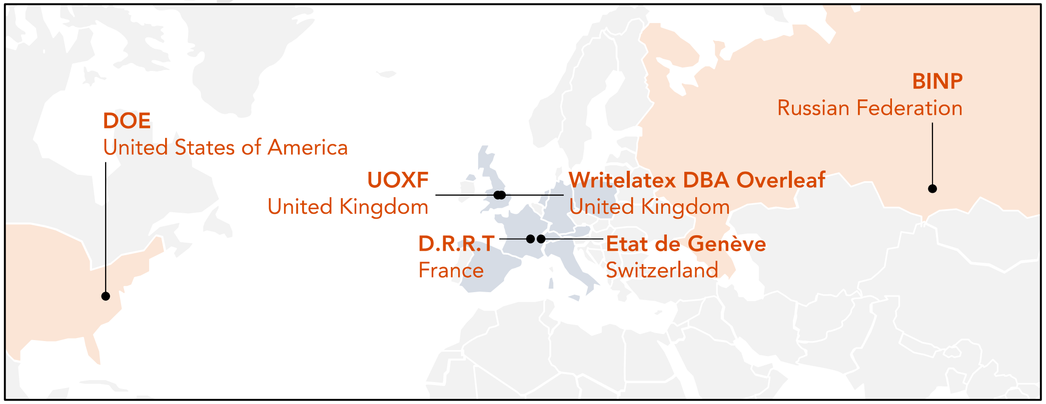
Topic	INFRADEV-01-2019-2020
Grant Agreement	FCCIS 951754
Duration	48 months
From-to	2 Nov 2020 – 1 Nov 2024
Project cost	7 435 865 €
EU contribution	2 999 850 €
Beneficiaries	16
Partners	6

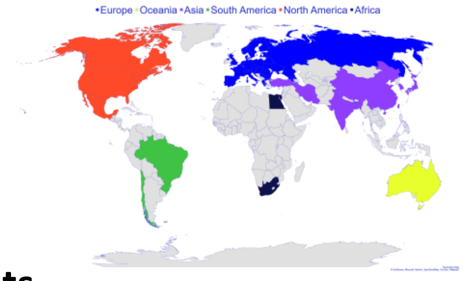
Beneficiaries



J. Gutleber,
M. Benedikt

Partners

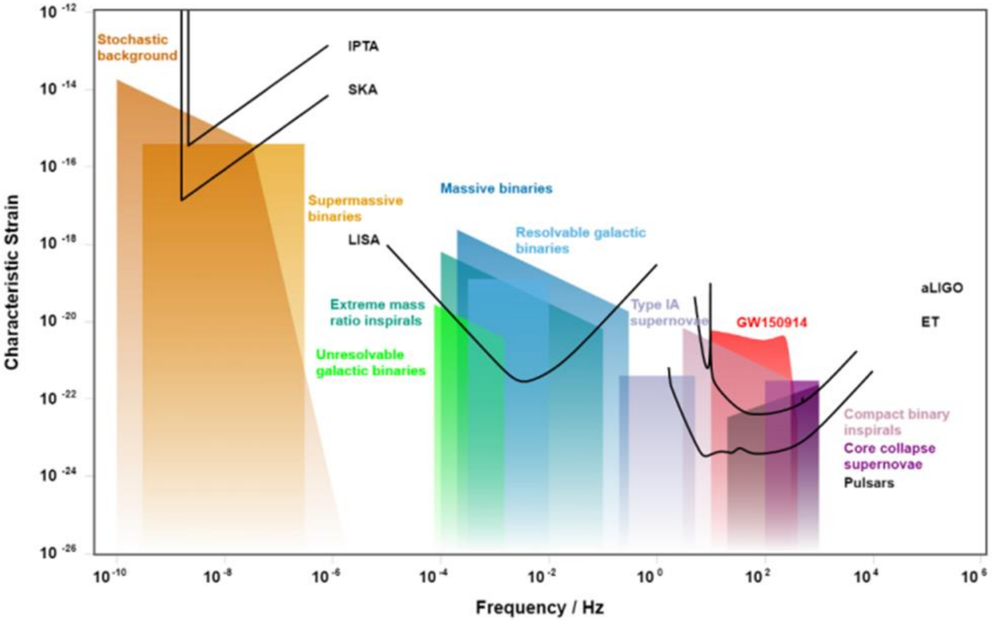




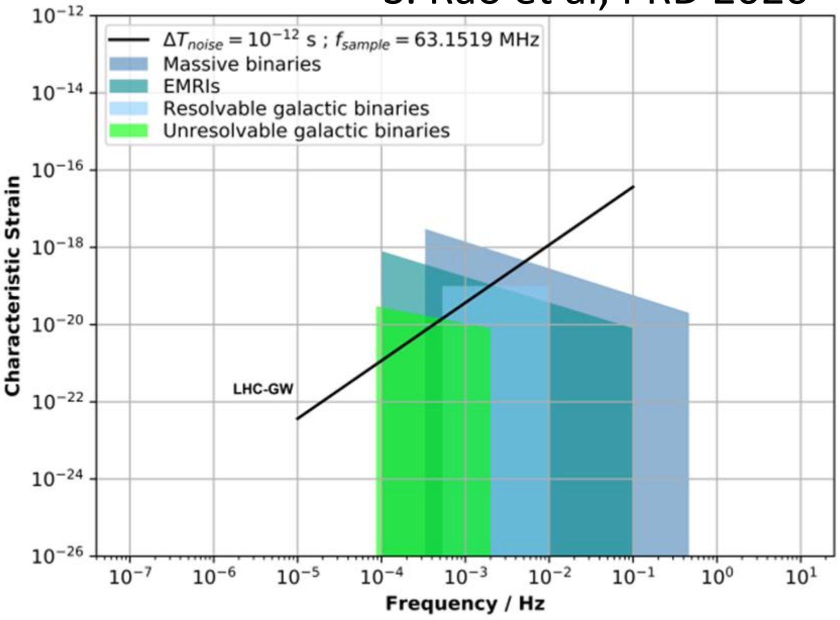
FCCIS kickoff
& physics WS,
Nov'20:
910 participants

trend: accelerators & gravity

can a storage ring like LHC or FCC detect or generate gravitational waves?



S. Rao et al, PRD 2020



slide from R. Assmann, HKIAS HEP 2021

SRGW2021 - ARIES WP6 Workshop: Storage Rings and Gravitational Waves

2 February 2021 to 31 March 2021

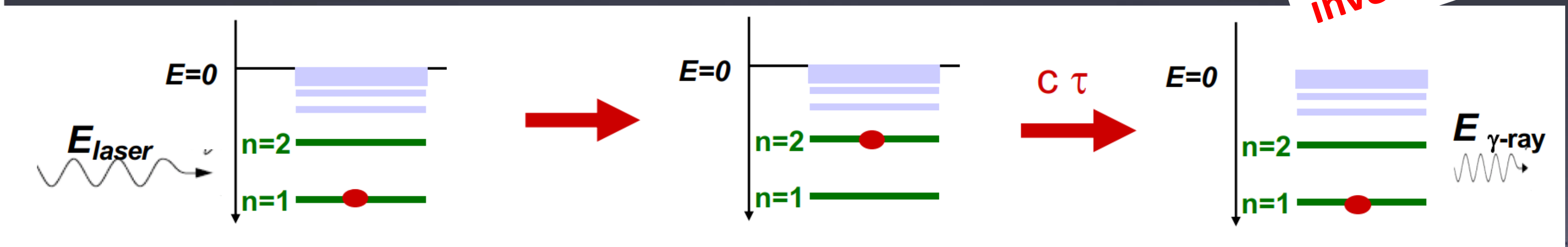
Europe/Zurich timezone

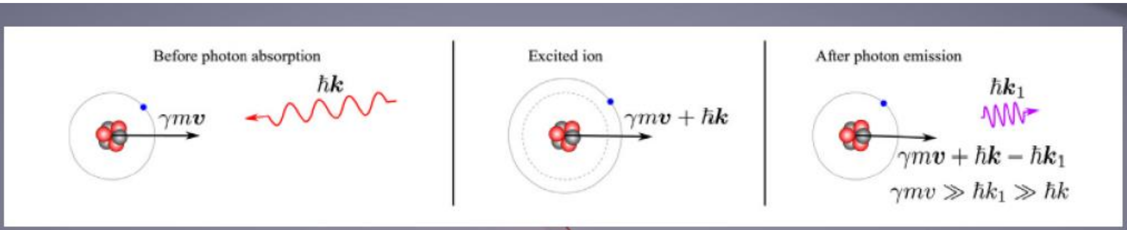
https://indico.cern.ch/event/982987/

W. Krasny

trend: Gamma Factory

invented in Paris





partially stripped heavy-ion beam in LHC (or FCC):
high-stability laser-light-frequency converter

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

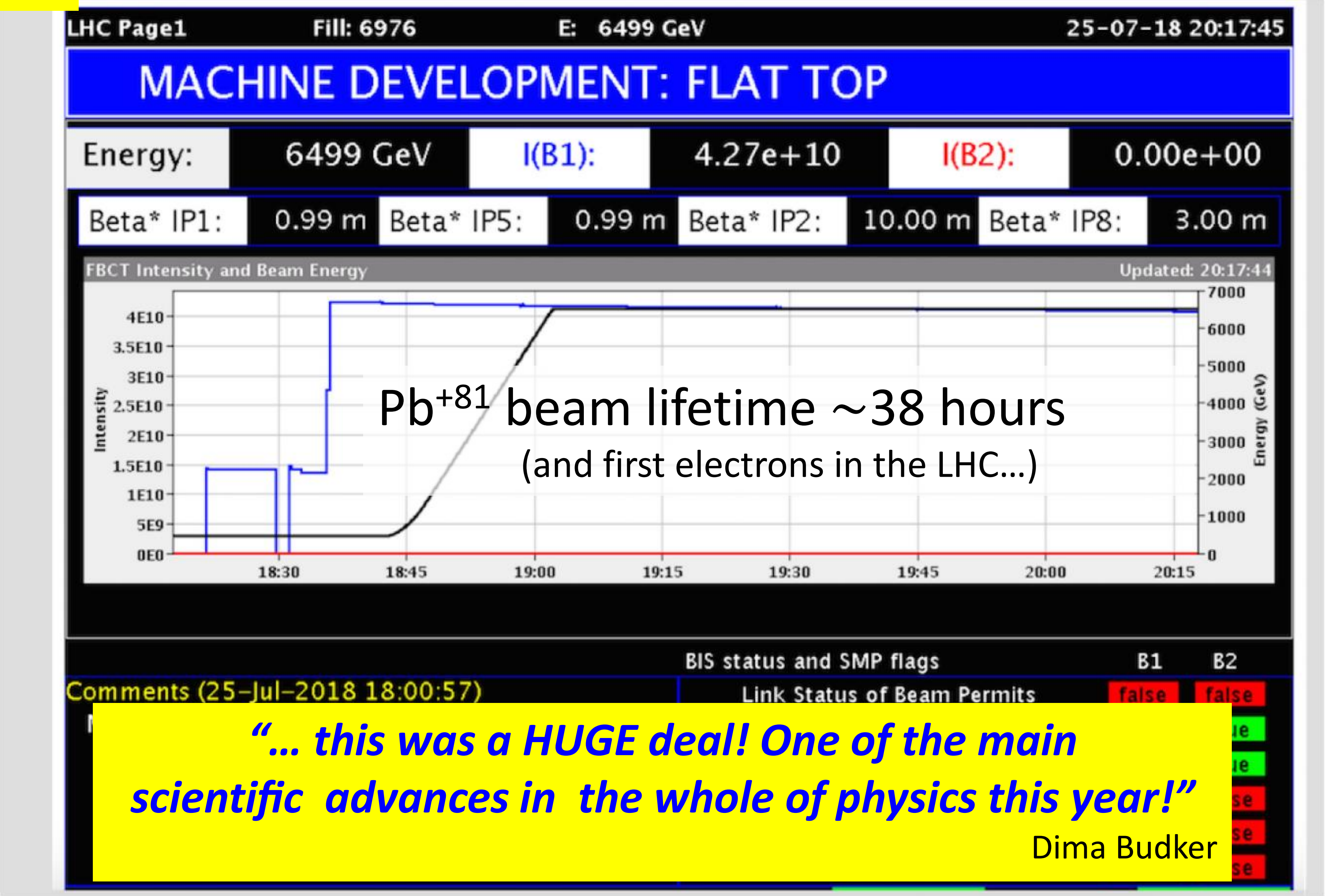
Novel technology: Resonant scattering of laser photons on ultra-relativistic atomic beam

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

γ factory proof-of-principle experiment in the LHC

W. Krasny



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)

BIS status and SMP flags B1 B2

Link Status of Beam Permits false false

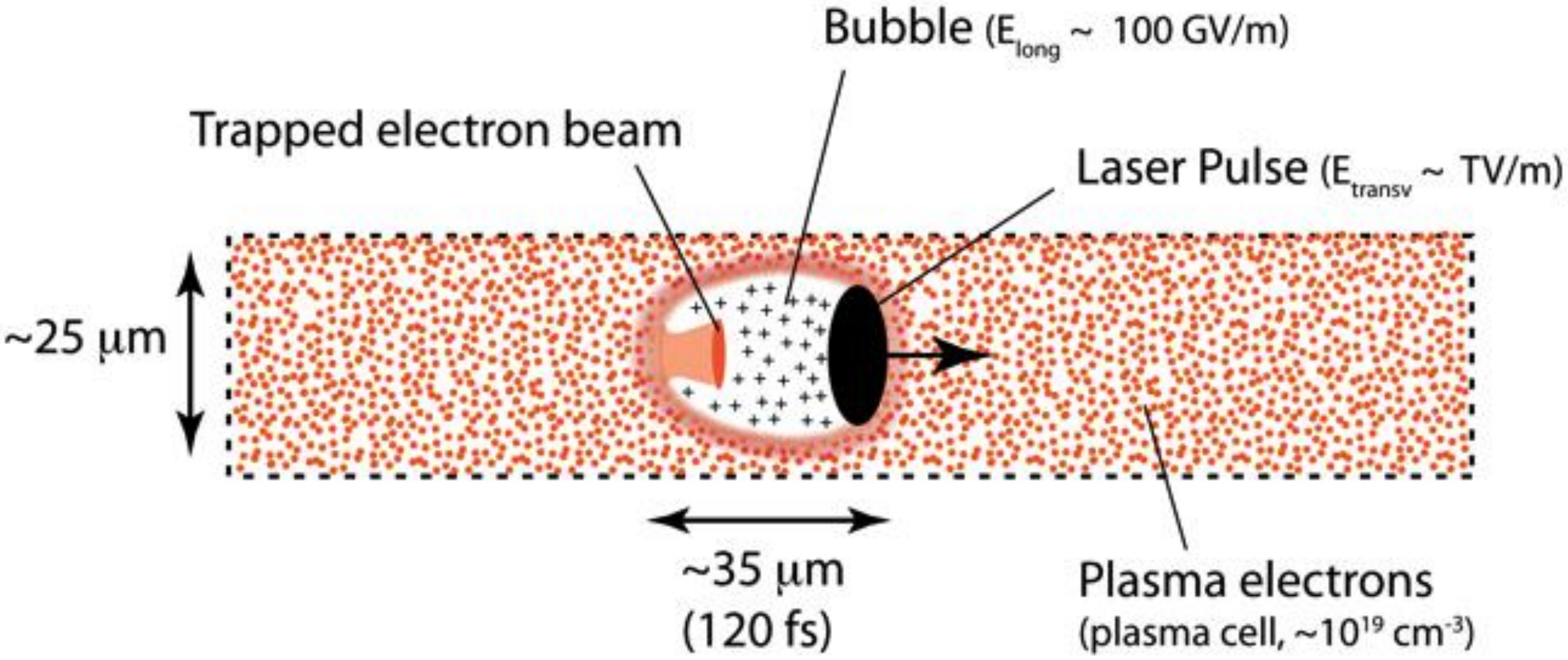
Pb^{+81} beam lifetime ~38 hours

(and first electrons in the LHC…)

> ***"… this was a HUGE deal! One of the main scientific advances in the whole of physics this year!"***
>
> Dima Budker

trend: laser-plasma acceleration

This accelerator fits into a human hair



R. Assmann

EuPRAXIA: A European Strategy for Accelerator Innovation

intermediate step between PoP & production facility – make one acceleration unit!

PRESENT EXPERIMENTS

Demonstrating
100 GV/m routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon

→ beam quality?

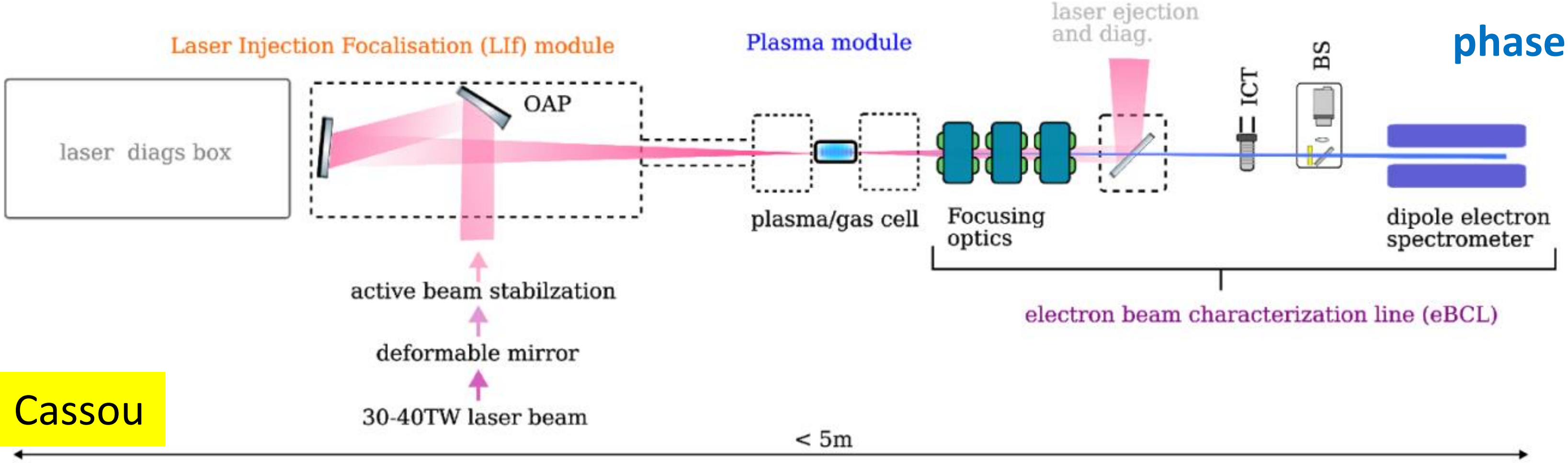
→ energy efficiency?

R. Assmann

PALLAS : A cornerstone of EuPRAXIA

2020-22 2022-24 2024-26

parameters	phase 1	phase 2	phase 3	unit
energy	150	200	200	MeV
charge	15-30	30	30	pC
repetition rate	10	10	10	Hz
energy spread	10%	<5%	<5%	-
emittance	1	<1	<1	mm.mrad
stability	5%	3%	1%	-
reproducibility	5%	3%	3%	-



phase 1

K. Cassou

summary & outlook

particle colliders: glorious history & exciting future
heeding lessons learnt at LEP, SLC, KEK, PEP-II, LHC, S-KEKB

challenge: making future colliders truly green !

trends:
more powerful e^+ sources, energy recovery
nanobeam handling – stabilisation, positioning, tuning
polarization control at 0.1% level, monochromatization
machine learning, AI – automated design & operation
probing gravity ?
bringing advanced acceleration schemes to maturity

- **next steps for FCC** : **concrete local/regional implementation scenario** in collaboration **with host states, machine optimization, physics studies and technology R&D**, performed **via global collaboration** and supported by **EC H2020 Design Study, to prove feasibility by 2025/26**

…surely great times ahead!

spare slides

FCC-ee CDR baseline parameters

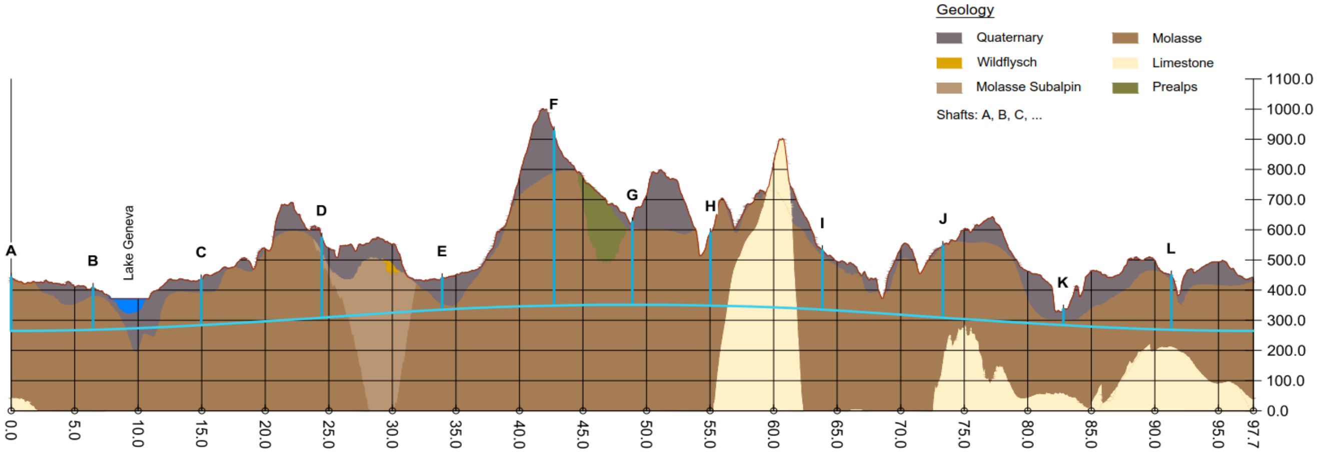
parameter	FCC-ee				LEP2
energy/beam [GeV]	**45.6**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**230**	**28**	**8.5**	**1.6**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
synchrotron power [MW]	100				22
RF voltage [GV]	0.1	0.75	2.0	4.0+6.9	3.5
rms bunch length (SR,+BS) [mm]	3.5, 12	3.0,6.0	3.2, 5.3	2.0, 2.5	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.27, 1	0.84, 1.7	0.63, 1.3	1.5, 2.9	22, 250
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime [min]	68	59	**12**	**12**	434

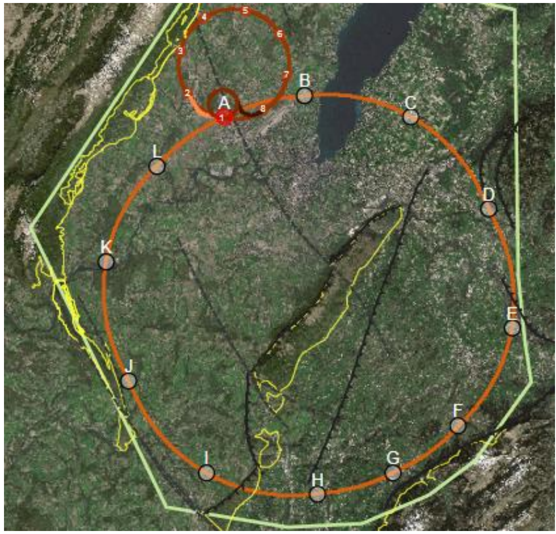
FCC-ee & CEPC: 2 separate rings

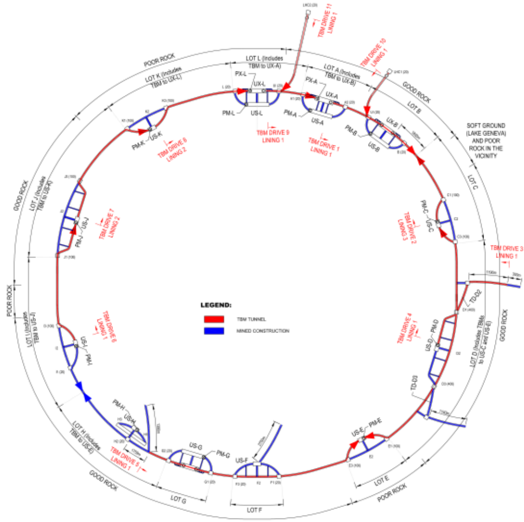
FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

FCC implementation - footprint baseline



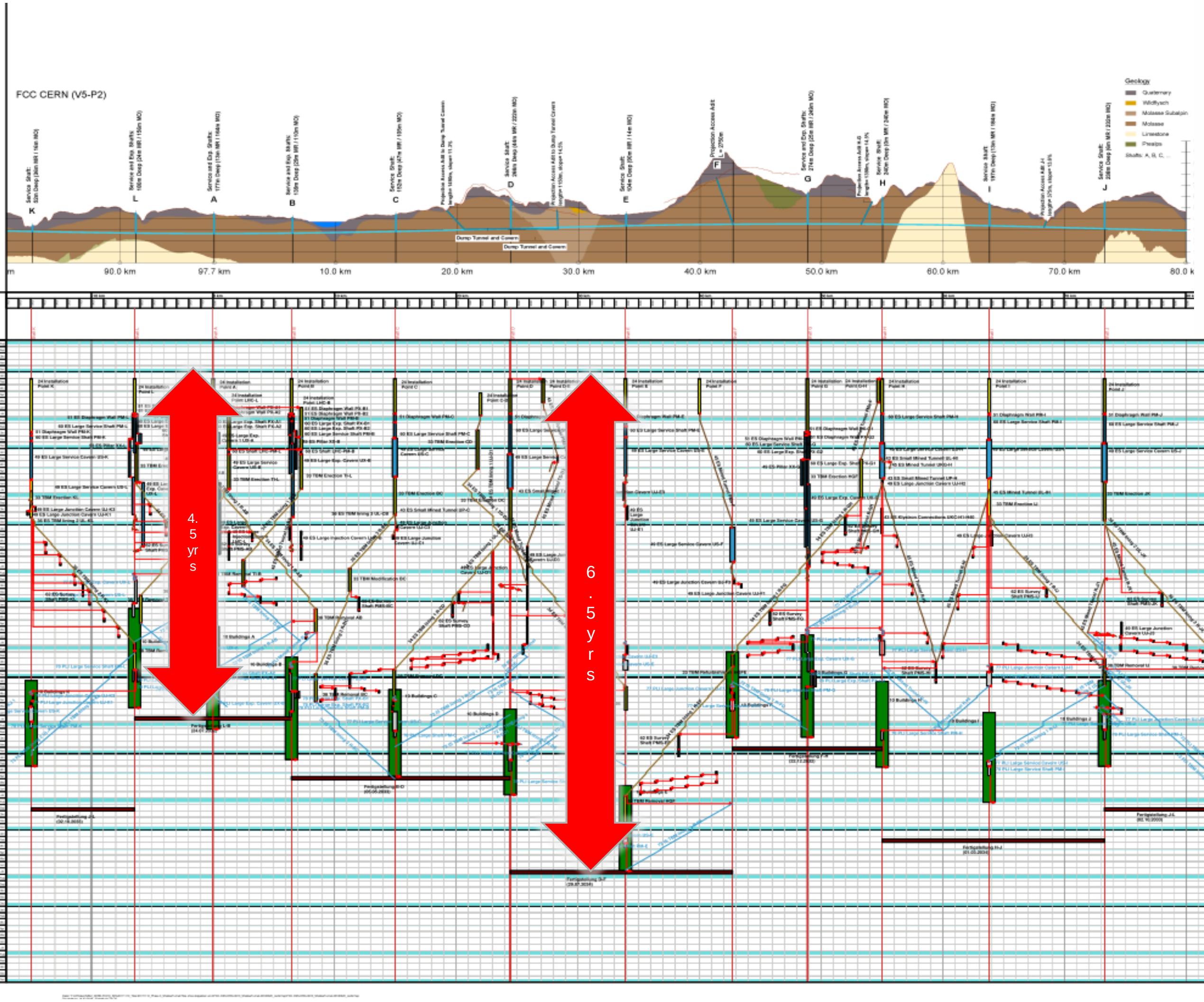


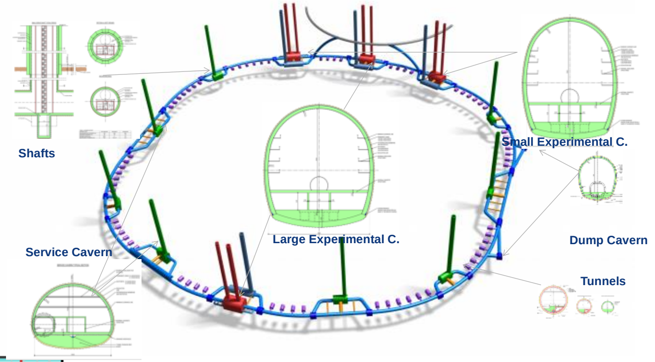


present baseline position based on:

- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)
- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

civil engineering studies





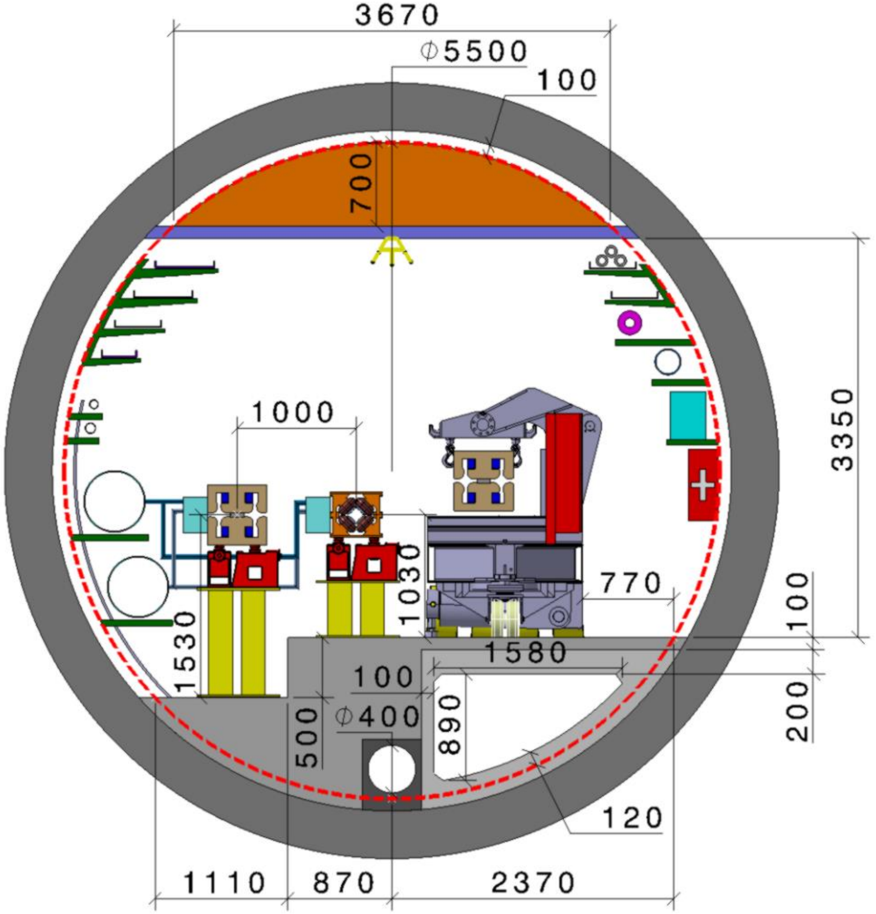
total construction duration 7 years

first sectors ready after 4.5 years

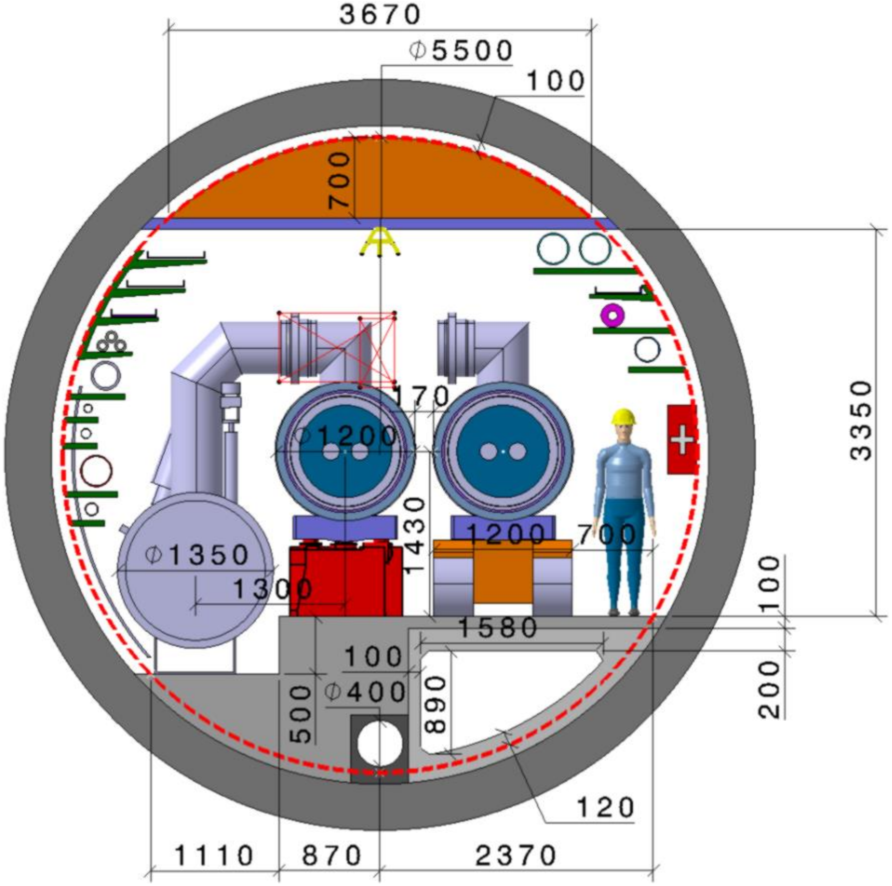
FCC-tunnel integration in the arcs

5.5 m inner diameter

FCC-ee



FCC-hh



FCC CDR and Study Documentation

>1350 contributors from > 350 institutes, a truly global effort

- **FCC-Conceptual Design Reports (completed in 2018):**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

  EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

2020 Update of the European Strategy for Particle Physics

Core sentence "order of the further FCC study":

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC feasibility study: main challenges

Financial feasibility

cost of tunnel: ~5.5 BCHF; FCC-ee: ~5-6 BCHF; FCC-hh: ~17 BCHF (if after FCC-ee)

→ cannot be funded only from CERN's (constant) budget + "one-off" contributions from non-Member States → need new mechanisms (global project funding model; EC? private?)

1st priority of feasibility study: find ~ 5 BCHF for the tunnel from outside CERN's budget

Technical and administrative feasibility of tunnel

❑ highly-populated area; two countries with different legislative frameworks
❑ land expropriation and reclassification
❑ high-risk zones
❑ environmental aspects

1st priority of feasibility study: no show-stopper for ~100 km tunnel in Geneva region

Technologies of machine and experiments

❑ huge challenges, but under control of our scientific community
❑ pressing environmental aspects: energy, cooling, gases, etc.

1st priority of feasibility study: magnets; minimise environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support

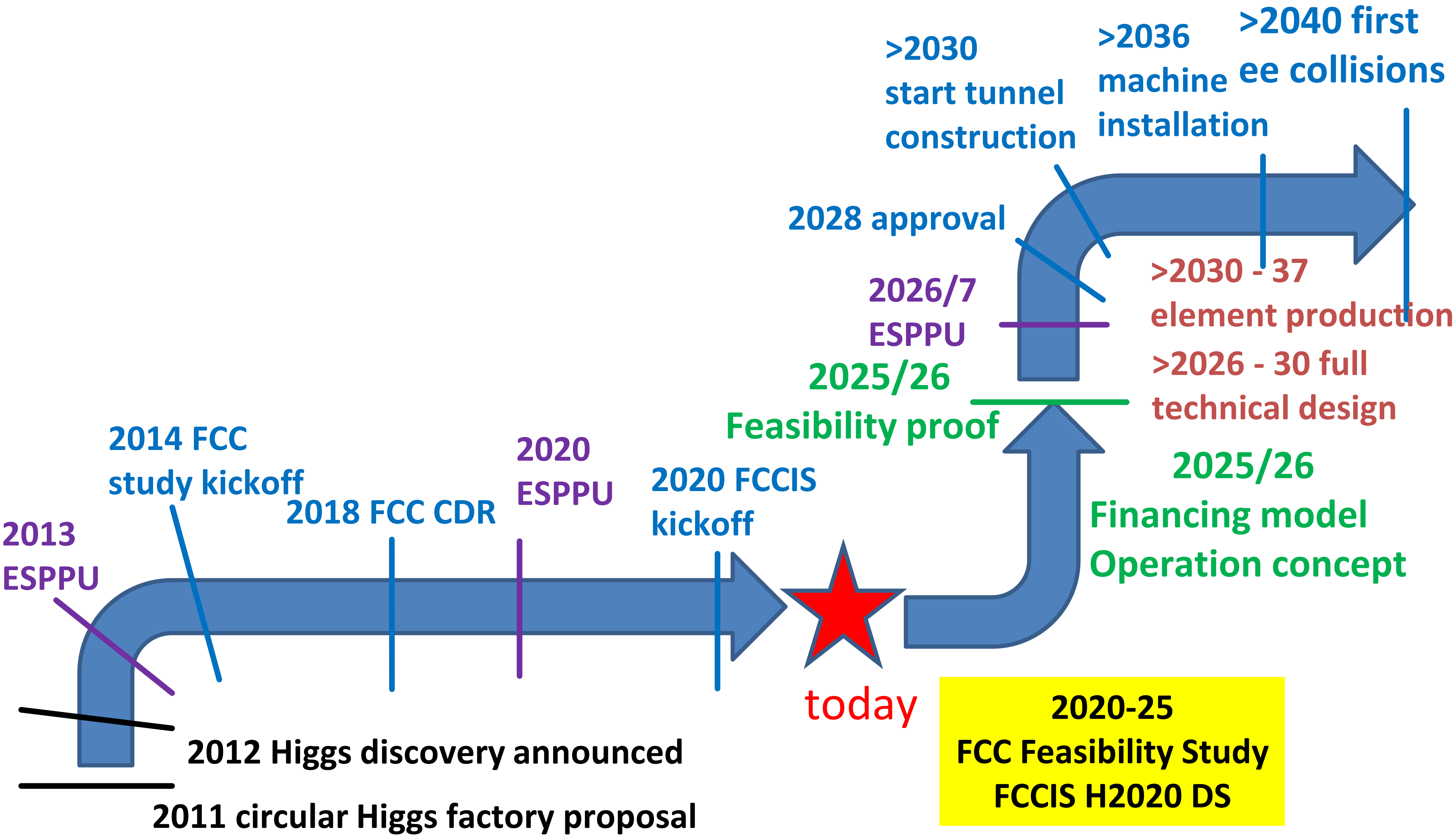
→ requires "political work" and communication campaign for "consensus building" with governments and other authorities, scientists from other fields, industry, general public, etc.

→ **can FCC be a facility also for other disciplines** (nuclear science, photon science, etc.)**?**

→ creative and proactive ideas for technology transfer from FCC to society

Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

FCC Roadmap towards Stage 1



2011 circular Higgs factory proposal

2012 Higgs discovery announced

2013 ESPPU

2014 FCC study kickoff

2018 FCC CDR

2020 ESPPU

2020 FCCIS kickoff

today

2020-25
FCC Feasibility Study
FCCIS H2020 DS

2025/26
Financing model
Operation concept

2025/26
Feasibility proof

>2026 - 30 full technical design

2026/7
ESPPU

2028 approval

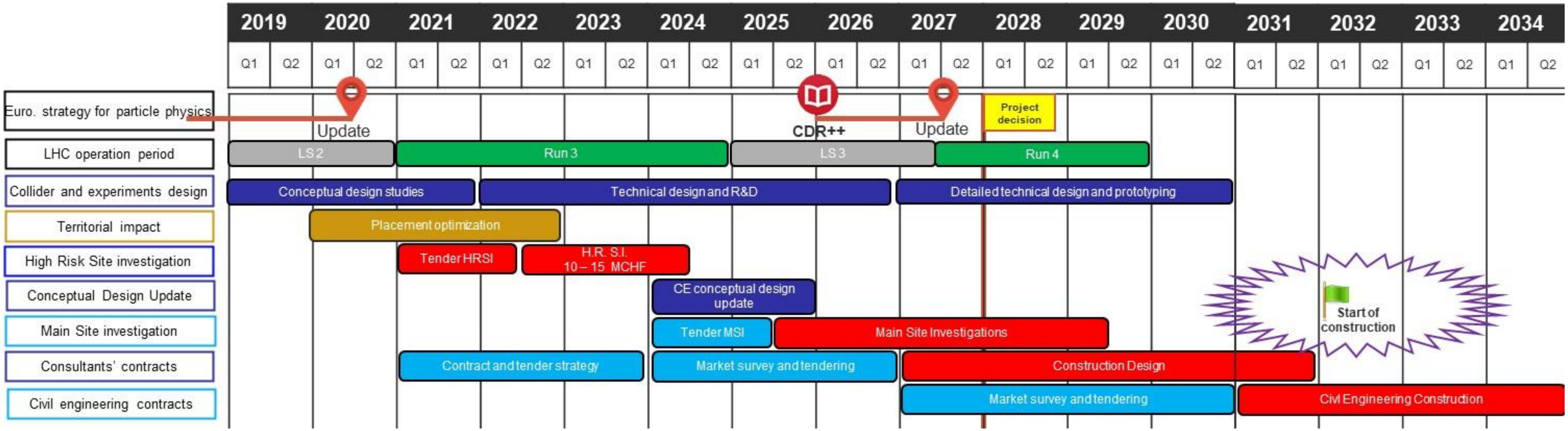
>2030 - 37
element production

>2030
start tunnel construction

>2036
machine installation

>2040 first ee collisions

CE preparatory activities 2020 - 2030



- **technical schedule of main processes leading to start of construction begin 2030ies**
- **for proof of principle feasibility: high risk area site investigations, 2022 – 2024**
- **followed by update of civil engineering conceptual design and CE cost estimate 2025**

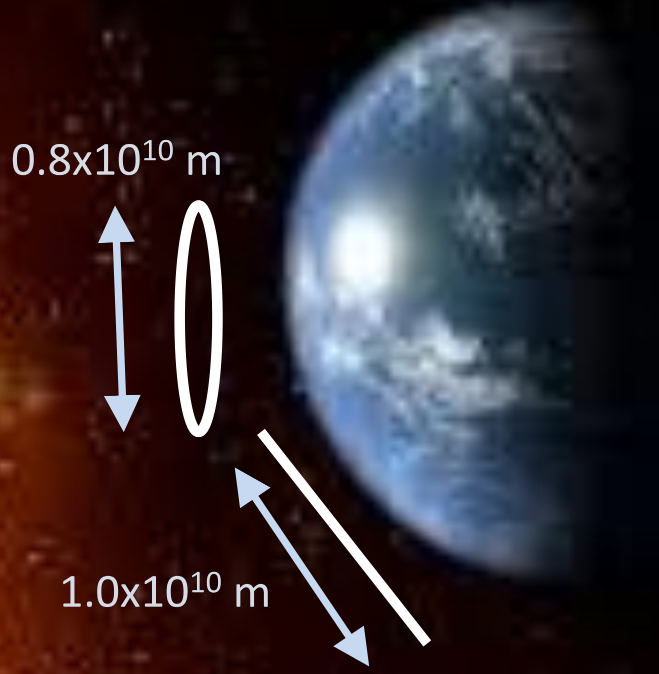
ultimate limit on electromagnetic acceleration

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