Overview of Accelerator R&D
including sustainability challenges &
R&D towards solutions

Frank Zimmermann
Lepton Photon Conference 2022
14 January 2022, 11h30 Geneva time
outline

• brief historical perspective
• five key challenges for accelerator R&D including sustainability aspects
• ESPPU 2020: FCCFS including sustainability aspects
• ESPPPU 2020: LDG R&D roadmap 2021 including sustainability aspects
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
colliders constructed and operated

Centre-of-mass collision energy (GeV) vs. Year

- **Hadron Colliders**
- **Electron-Proton Colliders**
- **Lepton Colliders**
- **Heavy Ion Colliders**

**Colliders with**
- superconducting RF system
- superconducting arc magnet system
- superconducting magnets & RF

advances by new technologies and new materials
next-generation high energy colliders under study

- Linear $e^+e^-$ colliders (CLIC, ILC)
  $E_{CM}$ up to $\sim 3$ TeV

- Circular $e^+e^-$ colliders (CEPC, FCC-ee)
  $E_{CM}$ up to $\sim 400$ GeV
  limited by $e^\pm$ synchrotron radiation
  $\Delta E/\text{turn} \propto \gamma^4 \rho$
  $\rightarrow$ precision measurements

- Circular p-p colliders (SppC, FCC-hh)
  $E_{CM}$ up to $\sim 100$ TeV
  energy (momentum) limited by $p = eB\rho$
  $\rightarrow$ direct discoveries, energy frontier

next-next(-next) generation:
ERL based colliders?
muon colliders?
plasma-based colliders?
key challenges for accelerator R&D

1. synchrotron radiation
2. bending magnetic field
3. accelerating gradient
4. (rare) particle production – e^+ and \( \mu \)
5. cost and sustainability
Challenge #1: Synchrotron radiation (SR)

circular colliders

- Energy loss per particle per turn: \( U_0 = \frac{e^2 \gamma^4}{3 \varepsilon_0 \rho} \)
- SR power: \( P_{SR} = \frac{I_{beam}}{e} U_0 \)

Electromagnetic radiation

For electrons and positrons:
- \( P_{SR} = 23 \) MW for LEP (former e+e- collider in the LHC tunnel),
- 100 MW for FCC-ee (imposed as design constraint),

For protons:
- \( P_{SR} = 0.01 \) MW for LHC,
- 5 MW for FCC-hh – this requires >100 MW cryoplant power
SR in the arcs: possible solutions (challenge #1)

mitigations:

- **large bending radius** $\rho$
  - large circular collider $\rightarrow$ next slide

- **linear collider**
  - ”almost” no arcs, but beamstrahlung $\rightarrow$ next next slides

- **muon collider**
  - $\mu \sim 200$ heavier than $e^\pm \rightarrow \sim 10^9$ x less radiation at same energy and radius, but $\mu$’s decay $\rightarrow$ later

- **shaping beam vacuum chamber or the beam itself**
  - tiny vacuum chamber in large ring, $\lambda_{sh} \approx 2\sqrt{d^3/\rho}$ with $d$: pipe diameter
  - beam shaping to suppress radiation; a DC beam does not radiate!
    - explored in EU projects ARIES & I.FAST $\rightarrow$ not part of ESPPU 20
SR $\rightarrow$ size of circular e$^+$e$^-$ colliders (challenge #1)

365 GeV c.m. $\leftrightarrow$ 
$\sim 100$ km cost-optimized circumference

Serendipitously, 90-100 km is exactly the size required for a 100 TeV hadron collider and optimum tunnel size in the Lake Geneva basin!

Data points from

SR → linear collider beam delivery (challenge #1)

linear colliders

SR in bending magnets of the beam-delivery system

SR in final quadrupole magnet ("Oide effect") limits collision spot size

Other footprints of CLIC 3-TeV and 500-GeV beam delivery systems (G. Zamudio, R. Tomas, 2011, CLIC-Note-882)


Historical footprints of CLIC 3-TeV and 500-GeV beam delivery systems (M. Aleksa et al., 2003, CLIC-Note-551)

SR in bending magnets caused a factor ~2 loss in luminosity in 2003 CLIC BDS design at 3 TeV; similarly for the SLC at 91 GeV c.m. (!)

Beam delivery tunnel should be compatible w. future beam energies

Gaussian beam profile

Final quadrupole lens

\( \gamma \)
challenge #1: synchrotron radiation - cont’d

linear colliders

synchrotron radiation in the strong field of the opposing beam (=“beamstrahlung”) degrades the luminosity spectrum


CLIC at 380 GeV: 60% of total luminosity within 1% of target energy

CLIC at 3 TeV: only 33% of total luminosity within 1% of target energy

e⁺e⁻ collisions in linear colliders lose their distinct energy precision

D. Schulte

Record fields attained with dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature.
challenge #3: accelerating gradient

Gradient growth Superconducting RF linac accelerating gradient achievements and applications since 1970. CERN Courier 2020

RF Accelerators
> 30,000 operational – many serve for Health
30 million Volt per meter
RF: 90 years of success story for society

Plasma Accelerators
first user facility to be realized
100,000 million Volt per meter

Added value
new RI’s due to compactness and cost-efficiency bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

Typical RF Based Accelerator Facility to 5 GeV

400 m

EuPRAXIA Plasma Accelerator Facility to 5 GeV

Shrinking the Size of the Accelerator Facility

60° m

*realistic design including all required infrastructure for powering, shielding,
challenge #4: particle production – $e^+$, $\mu$

- **Positron Rates**
  - $10^{10} e^+$/s
  - Required for top up
  - Routinely achieved
  - Required at IP

- **Muon Rates**
  - $10^{16} e^+$/s
  - Required for $\mu$ collider

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### Positron Rates

- **SuperKEKB**
- **FCC-ee Z**
- **FCC-ee WW**
- **FCC-ee tt**
- **CEPC ZH**
- **CEPC Z**
- **KEKB**
- **SLC**
- **CLIC**
- **ILC**
- **ILC upgrade**
- **Muon Collider**
- **Lemma scheme**

- **Existing**
- **Required for collider**

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### Muon Rates

- **ISIS**
- **J-PARC**
- **PSI**
- **LEMA**
- **MAP**

- $\sim x100$
- $x10,000$
- $> x100,000$

- $\times 1000$
failure of SLC e\(^+\) target after 5 years of operation (challenge #4)

SLC target analysis at LANL: Failed SLC positron target was cut into pieces and metallographic studies were carried out to examine level of deterioration of material properties due to radiation exposure.

Radiation damage, work hardening, or temperature cycling?

David Schultz
Snowmass, July 10, 2001
Beam tests at SwissFEL from 2024 onwards

Main goal
Test HTS solenoid as Adiabatic Matching Device & confirm predicted $e^+$ yield ($\sim 5 e^+ / e^-$ after capture)

Main parameters
• $Q_{\text{drive}} = 200$ pC (vs. 5 nC for FCC-ee)
• Rep. rate = 1 Hz (vs. 100-200 Hz for FCC-ee)
• variable SwissFEL beam energy 0.4-6 GeV
resonant scattering of laser photons off partially stripped heavy-ion beam in LHC (or FCC): high-stability laser-light-frequency converter

proposed applications:
- Intense source of $e^+$ ($10^{16}$-$10^{17}$/s), $\mu$ ($10^{11}$-$10^{12}$/s), $\pi$, etc. – sufficient for LEMMA type $\mu$ collider
- Doppler laser cooling of high-energy beams
- HL-LHC with laser-cooled isocalar ion beams

Gamma Factory could provide $e^+$ rate required for LEMMA $\mu$ collider
challenge #5: cost / sustainability

Specific cost vs center-of-mass energy of CERN accelerators

- PS
- SPS
- ISR
- LEP
- LEP2
- SPPbarS
- LHC

Specific cost [2008 MCHF/GeV cm]

Ecm [GeV]

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

P. Lebrun, RFTech 2013

new concepts and new technologies

cost per collision energy greatly reduced
ESPP Update 2020 “High-priority future initiatives”

• An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

• “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.”

→ launch of Future Circular Collider Feasibility Study in summer 2021
The Future Circular Collider integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- stage 1: FCC-ee (Z, W, H, \(t\bar{t}\)) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- complementary physics
- common civil engineering and technical infrastructures
- building on and reusing CERN’s existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC
independent R&D in China → “same” solution

comprehensive long-term program maximizing physics opportunities

- stage 1: CEPC (Z, W, H, optionally $t\bar{t}$?) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: SPPC (~75 TeV) as natural continuation at energy frontier
- complementary physics
- common civil engineering and technical infrastructures, green field construction
SuperKEKB – “FCC-ee demonstrator”

Double ring $e^+e^-$ collider $B$-factory at $7(e^-) & 4(e^+)$ GeV; design luminosity $\sim 8 \times 10^{35}$ cm$^{-2}$s$^{-1}$; design $\beta_y^* \sim 0.3$ mm; beam lifetime $\sim 5$ min; top-up inj.; $\sim 2.5 \times 10^{12}$ e$^+$/s; under commissioning

$\beta_y^* = 0.8$ mm achieved in both rings – using the FCC-ee-style “virtual” crab-waist collision scheme

new world record $L = 3.81 \times 10^{34}$ cm$^{-2}$s$^{-1}$ on 23 December ‘21
Overview of Accelerator R&D

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Lepton-Photon Conference 2022

FCC integrated project technical schedule

1. Feasibility Study
2. Project preparation & administrative processes
3. Geographical investigations, infrastructure detailed design and tendering preparation
4. Funding strategy
5. Funding and in-kind contribution agreements
6. Long model magnets, prototypes, preseries
7. Superconducting wire and magnet R&D, short models
8. FCC-ee accelerator R&D and technical design
9. FCC-ee detector technical design
10. Tunnel, site and technical infrastructure construction
11. FCC-ee detector construction, installation, commissioning
12. Set up of international experiment collaborations, detector R&D and concept development
13. FCC-ee accelerator construction, installation, commissioning
14. FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
15. FCC-ee detector R&D, technical design
16. FCC-ee detector construction, installation, commissioning
17. Set up of international experiment collaborations, detector R&D and concept development
18. FCC-ee R&D and technical design
19. Update Permissions
20. Funding and in-kind contribution agreements

~ 15 years operation
7 – 10 years
~ 25 years operation

~2040/2045: start of FCC-ee

~2065/2070: start of FCC-hh

Engineering design, energy efficiency, maintainability, conductors & high-field magnet technology

M. Benedikt
Main development goal is wire performance increase:
• $J_c (16T, 4.2K) > 1500 \text{ A/mm}^2 \rightarrow 50\% \text{ increase wrt HL-LHC wire}$
• Reduction of coil & magnet cross-section

After 1-2 years development, **prototype Nb$_3$Sn wires from several new industrial FCC partners already achieve HL-LHC $J_c$ performance**

**FCC conductor development collaboration:**
• Bochvar Institute (production at TVEL), Russia
• Bruker, Germany, Luvata Pori, Finland
• KEK (Jastec and Furukawa), Japan
• KAT, Korea, Columbus, Italy
• University of Geneva, Switzerland
• Technical University of Vienna, Austria
• SPIN, Italy, University of Freiberg, Germany

2019/20 results from US, meeting FCC $J_c$ specs:
• Florida State University: high-$J_c$ Nb$_3$Sn via Hf addition
• Hyper Tech /Ohio SU/FNAL: high-$J_c$ Nb$_3$Sn via artificial pinning centres based on Zr oxide.
16 T dipole design activities and options

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

16 T dipole design activities and options

Cos-theta

Common coils

Swiss contribution

Canted Cos-theta

Blocks

INFIN

Common coils

CIEMAT

PSI

LBNL

FNAL

INFN

CEA

H2020

EuroCirCol

A key to New Physics

Swiss contribution

Canted Cos-theta

INFIN

CEA
US – MDP: 14.5 T magnet tested at FNAL

- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T
CERN Nb$_3$Sn progress: FRESCA2 & eRMC

Block dipoles

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

RMC/eRMC (2-decks, no aperture), 16.5 T
September 2021

toroidal model coil

important synergies with magnet development for fusion projects
Constraints

- Jura limestone
- Vuache limestone and faults
- Known water reservoirs and protected nature in CH (legal + technical reasons)
- Water protection zones, landscape protection zones, altitudes
- Densely urbanized and emerging areas
- Densely populated
- High altitudes
- Likely major opposition: local urbanistic planning for traffic calming & nature protection
- Strict landscape protection and re-naturalization areas
- Protected forest
- Terrain difficult to access and water reservoirs
- Densely urbanized and agriculture/nature
- Densely urbanized and emerging areas (some spots possible)
- High mountains (900 m) north of Fillière river valley
- Water protection and natural zones without developed access
- Clustered residential areas and farm areas
- Discouraged due to likely oppositions

Ongoing work – FCC placements studies (i) J. Gutleber, V. Mertens
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CERN Prevessin
SPS BA4
LHC Pt8 area

Challex area south of D884
Permit north of D884, east of water bearing layer zone.
Permit entering swiss territory connected by access tunnel Vulbens south of water Protection zone until A40
Dingy north up to A40, except water protection zones Minzier area outside forests, which are inaccessible on mountains
North-east of Choisy

Meyrin site

Target areas

GE public plot in Bellevue
GE public plot in Pallanterie
GE public plot in Présinge
Selected plots south of Cranves-Salves
Selected plots south of Bonne
West of A40 at Arve
Some plots in Contamine sur Arve
Some plots in Arenthon
North of Roche-s.-Foron, industrial area and Étaux
700 m altitude line at Roche-s.-Foron railroad
One 3 ha unprotected location at D2 in Fillière valley
North of Ollières, few selected locations

Charvonnex, Villy
Between A41, railroad and route d’Annecy
South of A410
North & south of A410 at selected places to be analysed individually

Ongoing work – FCC placements studies (ii)
J. Gutleber, V. Mertens
new “lowest risk” placement/optics allows 4 exp’s

perfect symmetry and
perfect 4-fold superperiodicity

beam optics for ¼ ring

C = 91 km

8 surface sites
Due to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

This is the number of Z bosons collected by each experiment during the entire LEP programme!

Capital cost per luminosity dramatically decreased compared with LEP!

Highest lumi/power of all proposals

Electricity cost ~200 CHF per Higgs boson

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Multi-years cycles for LHC

- LEP2
- LHC
- HL-LHC
- FCC-ee

V. Mertens

energy consumption – example CERN today

- Yearly Energy Consumption [GW.h]
- Cycles: 9m+3m
- Cycles: 3 or 4 x (10m+2m) + 1.5yr
- Average annual consumption
"green" energy efficient technologies

more efficient SC cavities

more efficient RF power sources

twin aperture dipoles for FCC-ee

CCT HTS quadrupoles & sextupoles for FCC-ee

A. Grasselino

I. Syratchev

A. Milanese

M. Koratzinos
5 expert panels:
- High-field magnets
- High-gradient acceleration
- RF structures
- Muon beams
- Energy recovery linacs

European LDG Accelerator R&D Roadmap 2021

D. Newbold
High-Field Magnets – Challenge Force Management

Luca Bottura et al., LDG draft report

horizontal forces per quadrant in dipole accelerator magnets (built and tested or design studies)
High-Field Magnets - R&D Program Goals

Development of robust and cost-efficient processes

- LHC
- Robust Nb$_3$Sn
- HL-LHC QXF
- Logical step for a next phase (2027-2034)
- Ultimate Nb$_3$Sn
- HL-LHC 11T
- D20 Fresca2 MDPCT1
- HTS

Exploration of new concepts and technologies

Luca Bottura
High-Gradient Acceleration (Plasma/Laser)

This accelerator fits into a human hair

Trapped electron beam

Bubble ($E_{\text{long}} \sim 100 \text{ GV/m}$)

Laser Pulse ($E_{\text{transv}} \sim \text{TV/m}$)

$\sim 25 \mu m$

$\sim 35 \mu m$

(120 fs)

Plasma electrons
(plasma cell, $\sim 10^{19} \text{ cm}^{-3}$)

R. Assmann
“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 $E_z$. 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).

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


Z.Y. Xu
Key elements:

(1) **SRF**: higher Q of bulk Nb, field emission, SC films, SRF couplers (FPC and HOM), substrate fabrication & engineering;

(2) **NCRF**: manufacturing, RF in strong magnetic field;

(3) **High RF power and LLRF**: klystrons & solid-state, FE-FRT, mm-wave & gyro, Al

(4) **Facilities & infrastructures**
$\sim 1.6 \times 10^9$ x less SR than $e^+e^-$, no beamstrahlung problem

two production schemes proposed


- $\sim 10^{13} - 10^{14}$ $\mu$ / sec tertiary particle $p \rightarrow \pi \rightarrow \mu$
- fast cooling ($\tau = 2 \mu$s) by $10^6$ (6D)
- fast acceleration mitigating $\mu$ decay
- background from $\mu$ decay

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

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

$\mu$'s decay within a few 100 - 1000 turns:

$\rightarrow$ rapid acceleration
  (perhaps plasma?)

$\rightarrow$ $\nu$ radiation hazard (limits maximum $\mu$ energy)

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

solution beyond 10 TeV unclear

Bruce King 1999
post FCC-ee option: feeding 14 TeV $\mu$ collider

14 TeV $\mu$ collider LHC-$\mu\mu$ with FCC-ee $\mu^{\pm}$ production

$e^{+}$ (45 GeV)

FCC-ee $e^{+}$ ring for $\mu$ production

$\mu$ production target

$\mu$ ($\sim$20 GeV)

SPS-$\mu\mu$

(fast ramping from 20 to 450 GeV)

$\mu^{+}\mu^{-}$ (7+7 TeV)

LHC-$\mu\mu$ (pulsed)

P. Raimondi, M. Antonelli, M. Boscolo.
M. Boscolo et al., PRAB 23, 051001 (2020)

after FCC-hh: FCC-\(\mu\mu\), a 100 TeV \(\mu\) collider?

FCC-hh PSI ring for \(\mu\) production

FCC-\(\mu\mu\) (50+50 TeV)

FCC-ee \(e^+\) ring for \(\mu\) production

\(e^+\) (45 GeV)

LHC-\(\mu\mu\) (pulsed)

Laser excitation

\(e^+\) production target

\(\mu\) production target

\(\mu\) (~20 GeV)

\(e^+\) stacking and accelerating ring


PSI: partially stripped ion (“Gamma Factory”)

Energy Recovery Linacs (ERLs) – Landscape

V. Litvinenko, T. Roser, M. Chamizo

test Facility PERLE at IJClab (high current, multi-turn) would complement MESA, CBETA, bERLinPRO and EIC cooler

M. Klein
Possible Future Colliders based on ERLs

Energy Frontier Collider Applications of Energy Recovery Linacs

FCC-eh

LHeC

Linac 1 (1008m)

Linac 2 (1008m)

Matching/combiner (31m)

Matching/splitter (30m)

Arc 1,2,5

Arc 2,4,6 (842m)

Dipole

Injector

Loss compensation 1 (140m)

Loss compensation 2 (90m)

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

L(HERA) x 1000 (ERL and LHC)

f = 802 MHz

3+3 passes: 20 MV, 180

20 MV/m, $Q_0 = 3 \times 10^{10}$

CERC as ERL

ERLC as ERL

V. Telnov at LCWS \rightarrow arXiv:2105.11015

L(ERLC) \sim 10^{36} = O(100) std l(lc)

This yields $O(10^7)$ Hz events in 3 years.

1+1 passes, $l = 160m$

f = 750 MHz, 20 MV/m, $Q_0 > 10^{10}$

being analysed by expert sub panel

cost, power & feasibility of ERLC & CERC

A. Hutton, M. Klein
reappraisal of historical ERL proposals


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

300 GeV c.m.
## Comparison of ERL Collider Proposals Then and Now

<table>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [GeV]</td>
<td>1-6</td>
<td>300</td>
<td>200</td>
<td>240</td>
<td>250</td>
</tr>
<tr>
<td>average beam current [mA]</td>
<td>120</td>
<td>10</td>
<td>0.3</td>
<td>2.5</td>
<td>100</td>
</tr>
<tr>
<td>vertical rms IP beam size [nm]</td>
<td>40,000 (round)</td>
<td>2,000 (round)</td>
<td>900 (round)</td>
<td>6</td>
<td>6.1</td>
</tr>
<tr>
<td>luminosity ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</td>
<td>0.0003</td>
<td>0.01</td>
<td>0.004</td>
<td>73</td>
<td>90</td>
</tr>
</tbody>
</table>

Main differences: flat instead of round beams, much smaller (vertical) beam sizes, higher beam current → ~10,000x higher luminosity
Fermilab & J-PARC Power Upgrades

protons per pulse challenge

V. Shiltsev
expected inputs for ESPP Update 2026/27

- FCC Feasibility Study Report
- LDG Accelerator Roadmap R&D results
- other new developments and proposals
thank you!

...surely great times ahead!
spare slides

SuperKEKB

FCC-hh SR handling
### KEKB, SuperKEKB ’21, SuperKEKB design

<table>
<thead>
<tr>
<th>parameter</th>
<th>KEKB w Belle</th>
<th>SuperKEKB 2021 w Belle II</th>
<th>SuperKEKB Design</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>LER</td>
<td>HER</td>
<td>LER</td>
</tr>
<tr>
<td>E [GeV]</td>
<td>3.5</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>(\beta_x^*) (mm)</td>
<td>1200</td>
<td>1200</td>
<td>0.30</td>
</tr>
<tr>
<td>(\beta_y^*) (mm)</td>
<td>5.9</td>
<td>5.9</td>
<td>0.27</td>
</tr>
<tr>
<td>(\varepsilon_x) (nm)</td>
<td>18</td>
<td>18</td>
<td>4.6</td>
</tr>
<tr>
<td>(\varepsilon_y) (pm)</td>
<td>150</td>
<td>150</td>
<td>12.9</td>
</tr>
<tr>
<td>I (mA)</td>
<td>1640</td>
<td>1190</td>
<td>3600</td>
</tr>
<tr>
<td>(n_b)</td>
<td>1584</td>
<td>1174</td>
<td>2500</td>
</tr>
<tr>
<td>(I_b) (mA)</td>
<td>1.04</td>
<td>0.75</td>
<td>1.44</td>
</tr>
<tr>
<td>(\xi_y^*)</td>
<td>0.046</td>
<td>0.030</td>
<td>0.069</td>
</tr>
<tr>
<td>(L_{sp}) ((10^{30}\text{cm}^{-2}\cdot\text{s}^{-1}))</td>
<td>67.6</td>
<td>67.6</td>
<td>67.6</td>
</tr>
<tr>
<td>L ((10^{34}\text{cm}^{-2}\cdot\text{s}^{-1}))</td>
<td>3.12</td>
<td>3.12</td>
<td>80</td>
</tr>
</tbody>
</table>

KEKB, SuperKEKB '21, SuperKEKB design

50% more luminosity than KEKB with half the beam currents → greatly 6x improved "efficiency" – concepts validated –, but still long way to go
FCC-ee demonstrator

- FCC-ee type “virtual crab waist” collisions (K. Oide, Phys. Rev. Accel. Beams 19, 111005) work well at S-KEKB
- smallest $\beta_y^*$ considered for FCC-ee: 1 mm and 0.8 mm
- $e^+$ prod. rate similar to FCC-ee’s – feasibility shown; top-up injection w. <10 min beam lifetime

SuperKEKB challenges

- design luminosity optimistic: ~2x higher than simulated for ideal case w/o impedance & w/o errors
- bunch currents and esp. beam currents lower than design: LER TMCI threshold (impedance model!); bunch lengthening (imp. model) sudden beam losses in the LER (noise?); poor injection efficiency (emittance growth in HER transfer line - CSR?!); beam-beam blow up; collimation & machine protection (aperture bottlenecks near experiment); collision stability; lack of beam diagnostics; aging equipment (inherited from TRISTAN); aging accelerator experts (many working far beyond retirement age)
- vertical emittances 4-10x too large, even at low current & w/o collision
- $\beta_y^*$ still 3-4 times larger than design: detector background, limited IR aperture & large emittance of inj. beam

New International Task Force was formed two months ago to address these challenges
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Lepton-Photon Conference 2022

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 $T \gg 1.9$ K

FCC-hh BS temperature choice through overall optimisation:
• cryoplant power consumption
• vacuum system performance
• impedance and beam stability

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