Accelerator Sustainability at Snowmass and ICFA Sustainability Panel

Thomas Roser

June 6, 2024

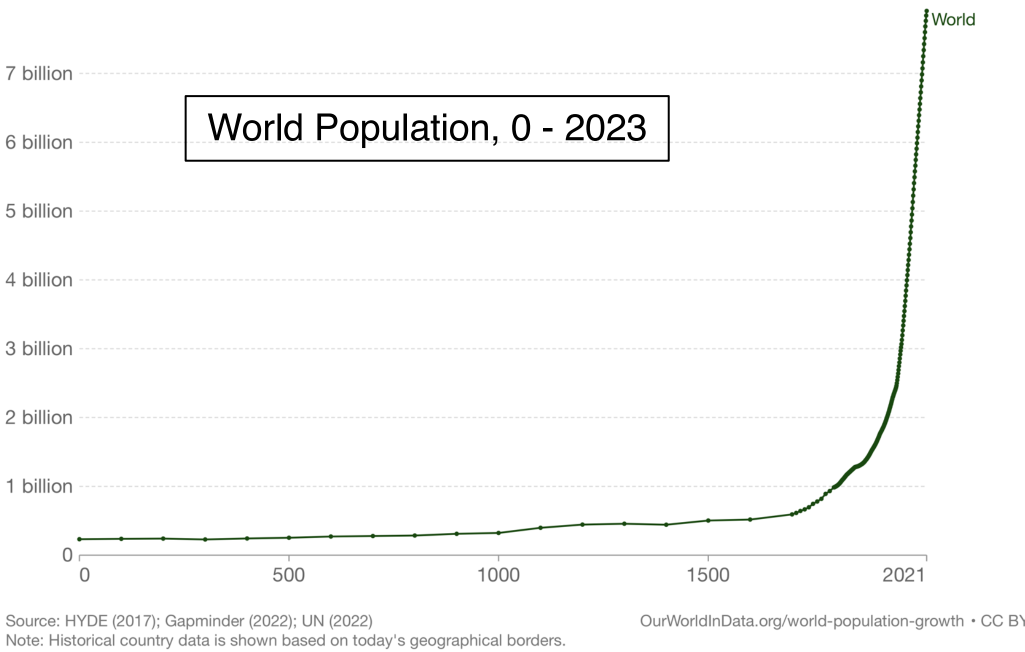
Thoughts on sustainability – importance of reduced energy consumption

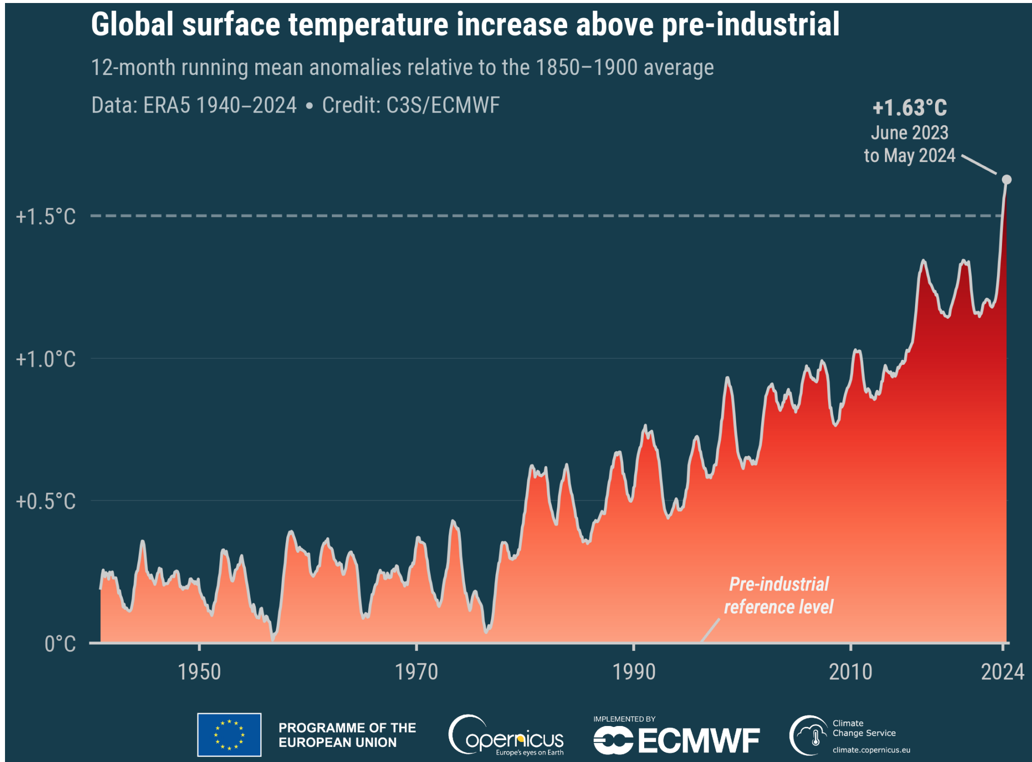
- Human life on earth as we know it is endangered by the unsustainable exploitation of many natural resources.

- Maybe most importantly, over the last 250 years the availability of essentially unlimited amounts of fossil energy has resulted in rapid population growth and unsustainable use of many natural resources.

- The most urgent issue but certainly not the only one: CO_2 from burning fossil fuels accumulates in the atmosphere. CO_2 in the atmosphere is the primary determinant of the earth's average surface temperature.

- The future accelerator projects will overlap in time with increasingly more extreme weather events around the world and urgent demands to cut CO_2 emissions.





How can we reduce CO_2 emissions?

- Human-caused CO_2 emissions are mainly the product of three factors:

1. Number of people x
2. Energy consumption per person x
3. CO_2 emission per energy produced.

- Present actions have no noticeable effect! Actions on each of the three factors are urgently needed:
  - (1) **Slowing population growth (mainly cultural change):** A historically successful approach is reducing poverty and supporting women rights and education worldwide.
  - (2) **Reduce energy consumption per person by increasing energy efficiency for all activities (cultural change and technological innovation):** Increasing energy efficiency is very feasible and can be implemented quickly. Interesting approach: "2000W Society" in Switzerland: Numerical goal for primary power consumption of 2.0kW per person (Now: US: 9.0kW, Europe: 4.4kW, China: 3.6kW, India: 0.8kW, World: 2.4kW, required food for humans: ~ 100W)
  - (3) **Switch to carbon-neutral energy sources on a large scale. (technological innovation):** The low-density (solar and wind) require much more hardware, resources and energy investment per energy produced than the high-density energy sources (fossil, nuclear) Needs full lifecycle analyses.
    Today, only nuclear energy has the demonstrated scalability to completely replace fossil fuels.

What can the Accelerator Community do?

- Sustainability regarding CO2 emissions mainly consists of reducing energy consumption AND transition to carbon-neutral energy sources. This approach needs to be applied to all accelerator projects.

- We need to focus on the development of energy efficient accelerator technologies with the same priority as achieving higher performance. Every new facility should be as energy efficient as possible, even if it means that it is delayed to do the necessary R&D.

- Like the 2000W Society idea, a numerical goal or budget for the energy consumption of accelerator-based user facilities could be a useful concept. For example, a goal for the energy consumption per user could be defined (5kW per user?).

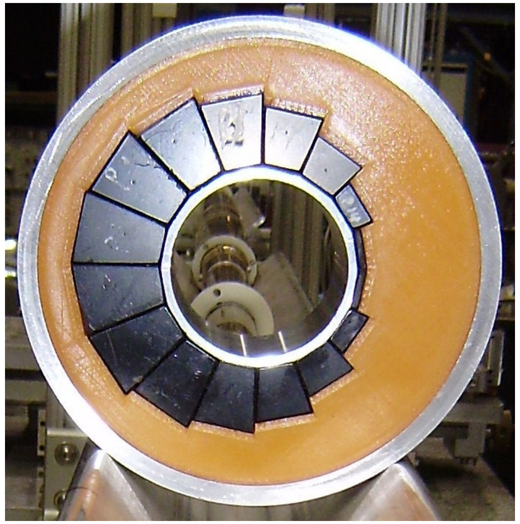
Areas of R&D to reduce energy consumption

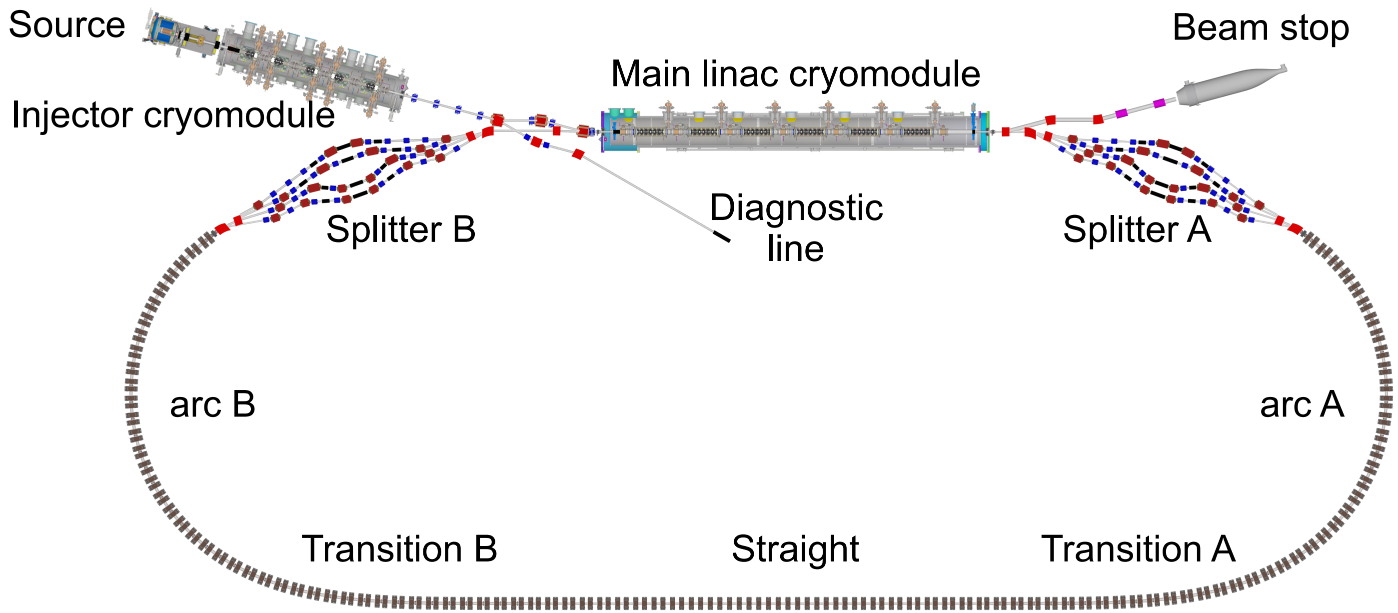
- Accelerator facilities need to produce high energy conditions. This means that energy efficiency often requires some form of recovery of the lost energy.

  - More efficient power converters to DC and RF (incremental)
  - Pulsed systems with energy recovery
  - More efficient He refrigerators (presently 3 – 4 times worse than Carnot efficiency!)
  - Recovery of process heat using heat pump technology
  - Use of energy efficient components (Superconducting technology, permanent magnets, HTS, …)
  - Compact accelerators using fewer resources for construction (Muon collider, Wakefield Accelerators (?), …)
  - Energy efficient accelerator concepts (Storage rings, Energy Recovery Accelerators, …)

CBETA – the first test accelerator dedicated to energy efficiency R&D

- CBETA successfully demonstrated energy efficient technologies (funded by NYSERDA, BNL-Cornell Collaboration): compact 4-turn ERL with SRF and high quality permanent Halbach magnets
- Possible applications for ERLs with reduced energy consumption: high power light sources, high luminosity, high energy colliders.
- The high quality permanent Halbach magnets are iron-free and have high gradient. They are ideal for Fixed Field Alternating gradient beam lines and low emittance synchrotrons light sources. They of course eliminate the need for power supplies, power cables and water cooling.





S. Brooks, G. Mahler, J. Cintorino, J. Tuozzolo, and R. Michnoff
Phys. Rev. Accel. Beams **23**, 112401 (2020) - Published 30 November 2020

ICFA Panel on Sustainable Accelerators and Colliders

- **Panel members:**
  - **Europe:** Mike Seidel (PSI, Switzerland), Jerome Schwindling (CEA/IRFU, France), Ruggero Ricci (LNF, Italy), Peter McIntosh (STFC, UK), Roberto Losito (CERN, Switzerland), Maxim Titov (CEA), Denise Völcker (DESY)
  - **Asia:** Takayuki Saeki (KEK, Japan), Yuhui Li (IHEP, China), Hiroki Okuno (Riken, Japan), Jui-Che Huang (NSRRC, Taiwan), Eugene Levichev (BINP, Russia)
  - **America:** John Byrd (ANL, USA), Soren Prestemon (LBNL, USA), Thomas Roser (BNL, USA), Andrew Hutton (JLAB, USA), Robert Laxdal (TRIUMF, Canada), Mary Convery (FNAL, USA), Emilio Nanni (SLAC, USA)
- **Mandate:**
  - Assess and promote developments on energy efficient and sustainable accelerator concepts, technologies, and strategies for operation
  - Assess and promote the use of accelerators for the development of Carbon-neutral energy sources.
  - Formulate recommendations on R&D and support ICFA with networking across the laboratories and with communications.
- Many laboratories are expanding their use of Carbon-neutral energy sources. Whereas this is a highly welcome development it does not replace or obviate the need for increased energy efficiency and reduced energy consumption, which is the focus of this panel.

Recent Activities of ICFA Sustainability Panel

- Members of the panel biannually prepare and update summary slides of the energy efficiency efforts and plans at their labs. These summaries are very helpful to exchange information between labs and might foster a friendly competition of who can do the most.
- The panel is collaborating with the European LDG Working Group on "Sustainability Assessment of Accelerators" to develop guidelines for uniform lifecycle analyses of energy and carbon footprints of future accelerator projects.
- The panel chair is a member of the IOC of the 7th WS on Energy for Sustainable Science at Research Infrastructures (ESSRI), to be held in Madrid on September 25-27, 2024. ESSRI is the premier European WS on energy efficiency at accelerator laboratories. Long term, this workshop could either be expanded to be held more internationally or similar workshop series could be established outside Europe.
- A large part of the carbon footprint of our community comes from attending meetings and conferences. One possibility is to limit in-person attendance to participants that can reach the site without needing a plane ride and offer equivalent participation for remote attendees from overseas. It will require a concerted effort to develop tools and organizations that can make such hybrid meetings successful. The panel is promoting such efforts.

Lifecycle analyses

- All projects and efforts need to be analyzed in terms of total lifecycle energy consumption (energy footprint) and CO2 emissions (carbon footprint). This is especially important for energy production projects!
- All future accelerator proposals also need to be analyzed for total lifecycle energy and carbon footprints. Such analyses should play an important role, maybe defining role, in selecting the next project.
- Some large collider proposals (FCC, ILC, CLIC, CCC) have already prepared such lifecycle analyses. They cover or should cover construction of infrastructure, accelerators, and detectors, operation and appropriate decommissioning. (Recent report: M. Breidenbach et al., PRX Energy 2, 047001)
- The European Laboratory Director Group (LDG) recently established the Sustainability Working Group to take a leading role in organizing such analyses of all major proposals by identifying the main parameters to be used such as total operating time of the facility, CO2 emission and energy consumed per ton of concrete, steel, and aluminum used, CO2 emission per GWh used (~ 400 tCO_2/GWh for natural gas, ~ 40 tCO_2/GWh for solar energy), level of decommissioning required, …

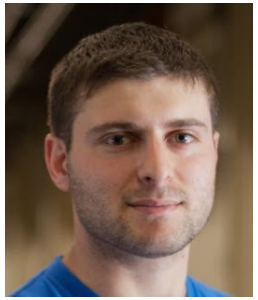
Snowmass 2021 Accelerator Frontier Collider Implementation Task Force

- The Collider Implementation Task Force (ITF) was charged with the evaluation and **fair and impartial comparison** of future collider proposals, including R&D needs, schedule, cost (using the same accounting rules), and **environmental impact and sustainability**.
- The full report is published in Journal of Instrumentation (TR et al, 2023 JINST **18** P05018).


Reinhard Brinkmann (DESY)


Sarah Cousineau (ORNL)


Dmitri Denisov (BNL)


Spencer Gessner (SLAC)


Steve Gourlay (LBNL)


Philippe Lebrun (CERN)


Meenakshi Narain (Brown U., deceased)


Katsunobu Oide (KEK)


Tor Raubenheimer (SLAC)


Thomas Roser (BNL, Chair)


John Seeman (SLAC)


Vladimir Shiltsev (FNAL)

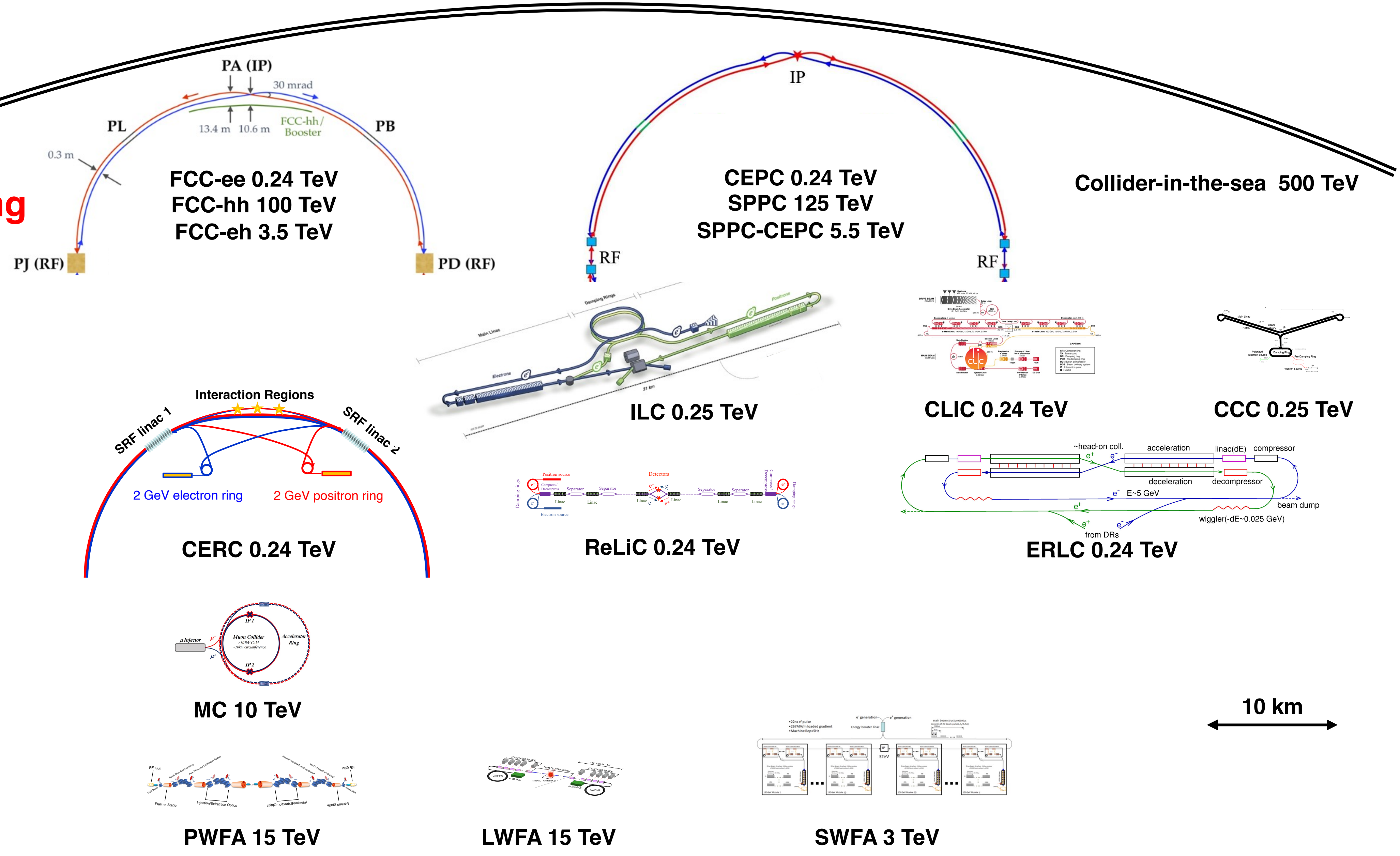

Jim Strait (FNAL)


Marlene Turner (LBNL)


LianTao Wang (U. Chicago)

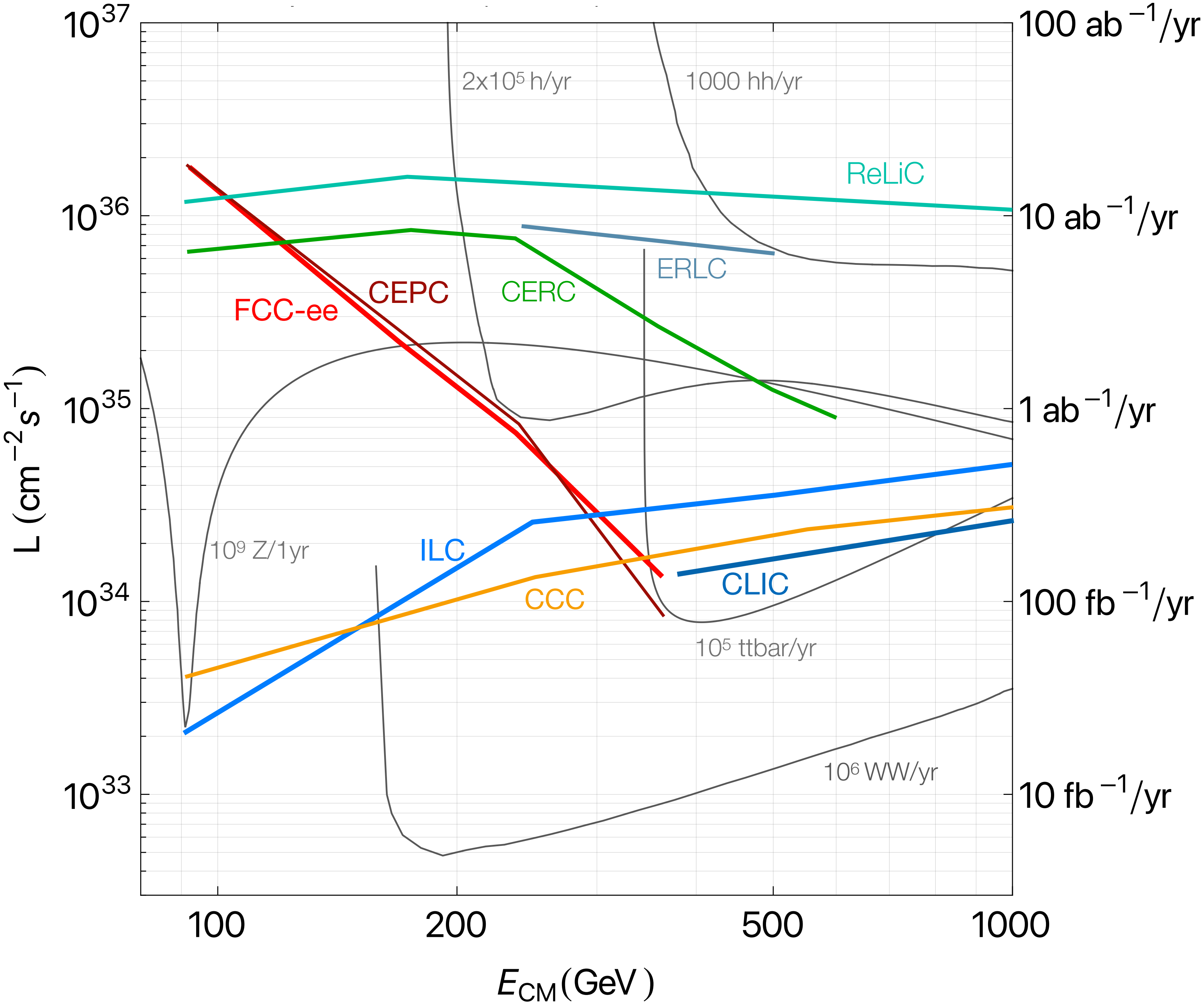
Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, …

- Storage ring colliders
- Linear colliders
- ERL colliders
- Muon collider
- Wakefield colliders



Higgs factory summary plot

- Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents.
- The right axis shows integrated luminosity for one Snowmass year (10^7 s).
- Also shown are lines corresponding to the required luminosity for yearly production rates of important processes.



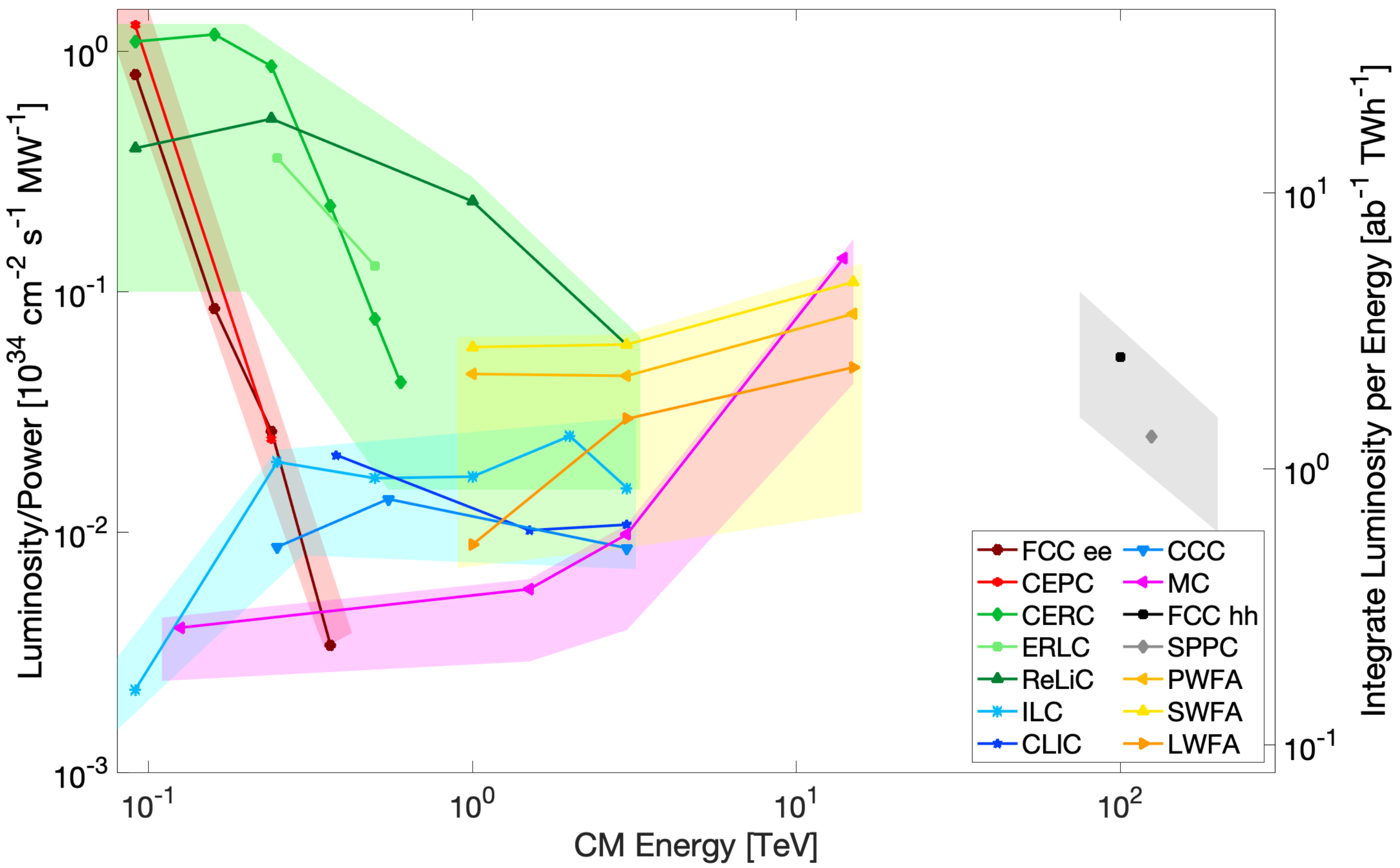
Higgs factory summary table

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Colliders with high parton CM energy (10 – 15 TeV) summary table

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

Peak luminosity per power consumption



Summary

- The worldwide “Climate Emergency” requires everybody to take urgent action, including the accelerator community. Future accelerator projects will need to minimize resource use, especially energy consumption and CO2 emissions throughout their lifecycle from construction, operation, to decommissioning.

- Comparative lifecycle analyses of total energy consumption and CO2 emissions (energy and carbon footprint) should be completed for all future accelerator projects.

- R&D of increased efficiency and new more efficient concepts to reduce energy consumption and CO2 emissions should be prioritized at least as high as performance and cost reduction R&D.

- Air travel in our community should be minimized as much as possible. Remote meetings are already very common, but to make further progress will likely require new and creative approaches that treat remote participants and the in-person attendees on equal terms.