Sustainability of Future Accelerator Facilities

Thomas Roser

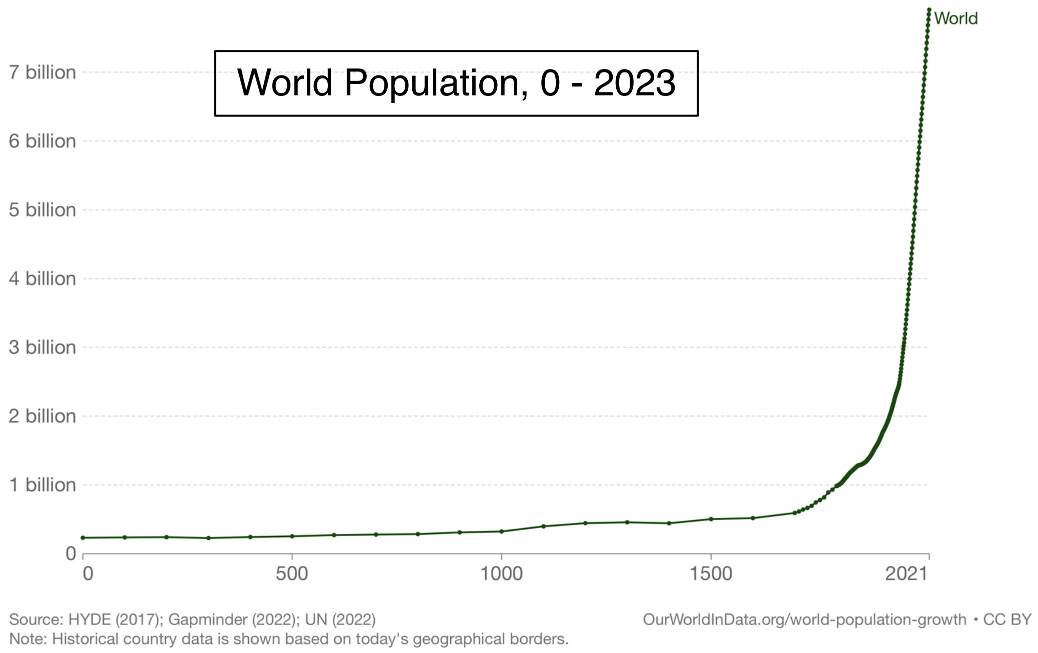
March 21, 2024

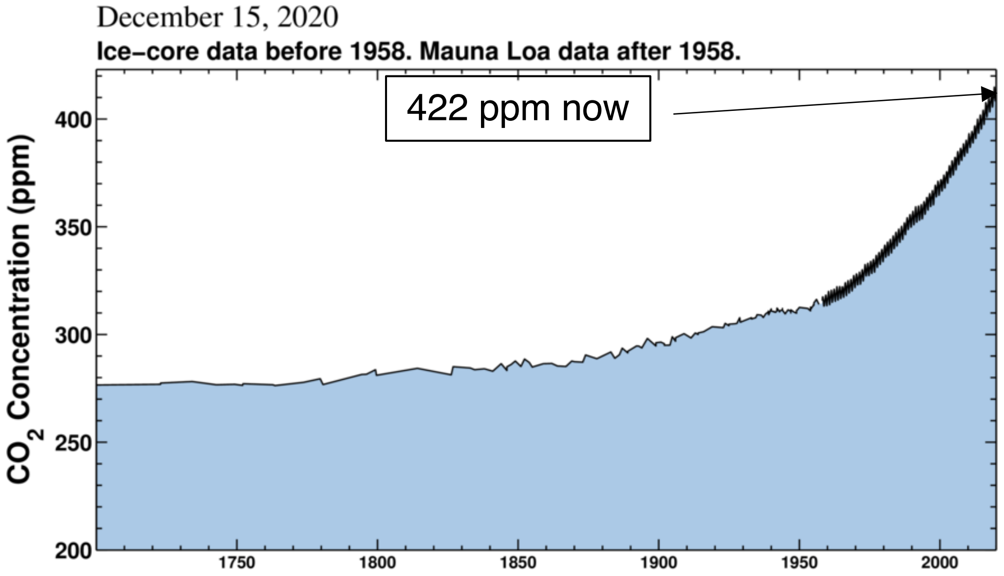
Thoughts on sustainability

- 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.

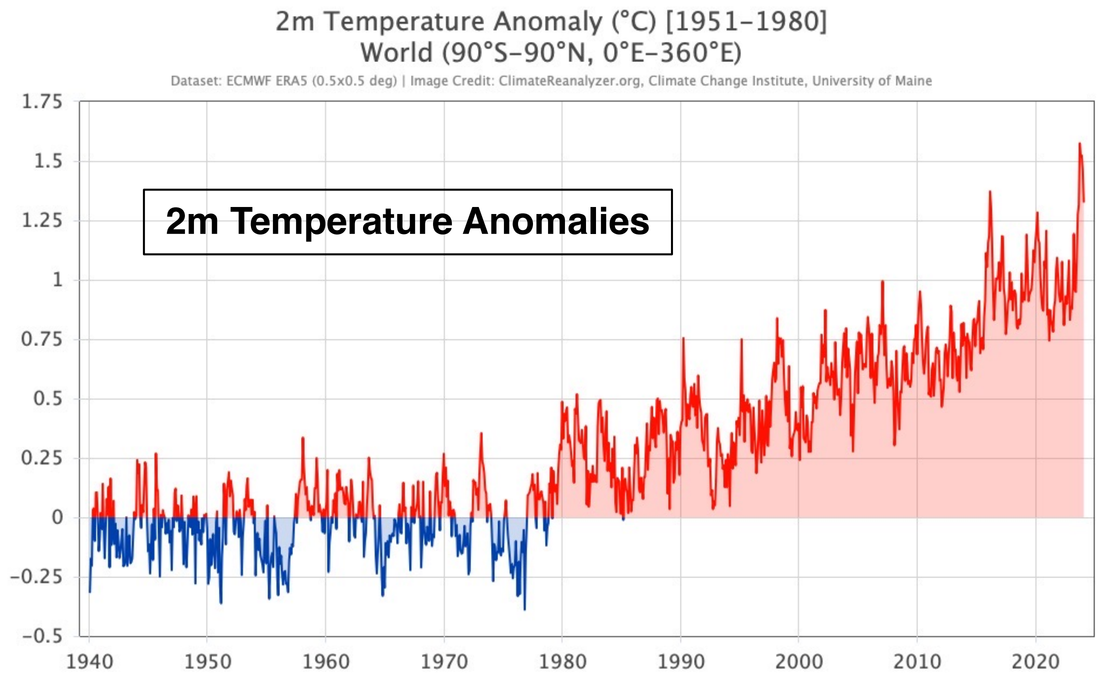
- The most urgent issue but not the only one: CO_2 from burning fossil fuels accumulates in the atmosphere.

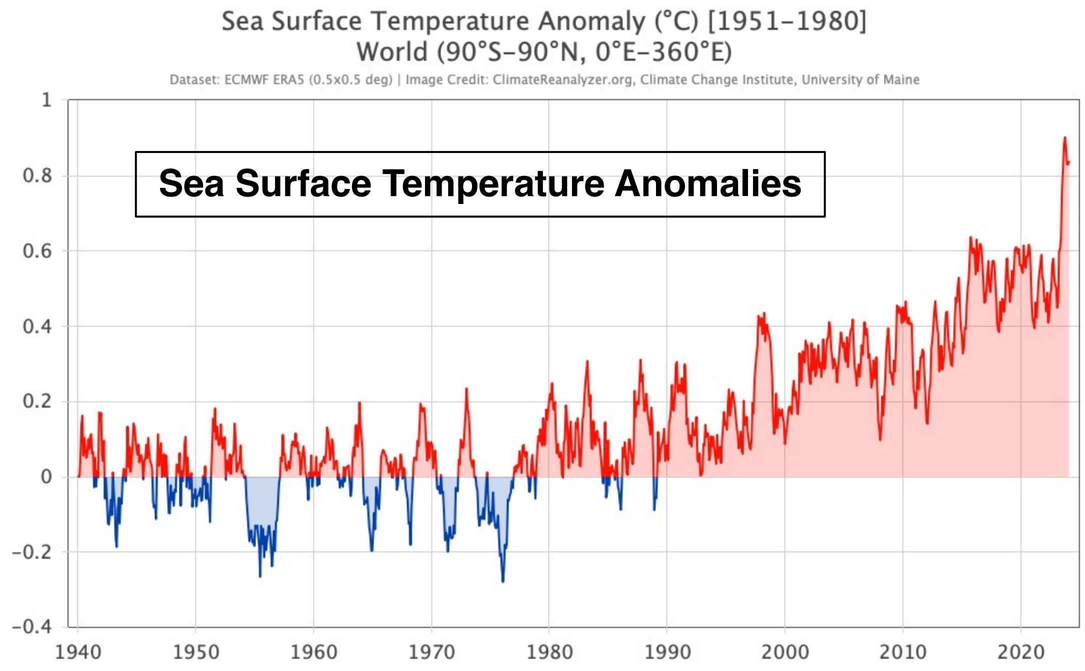




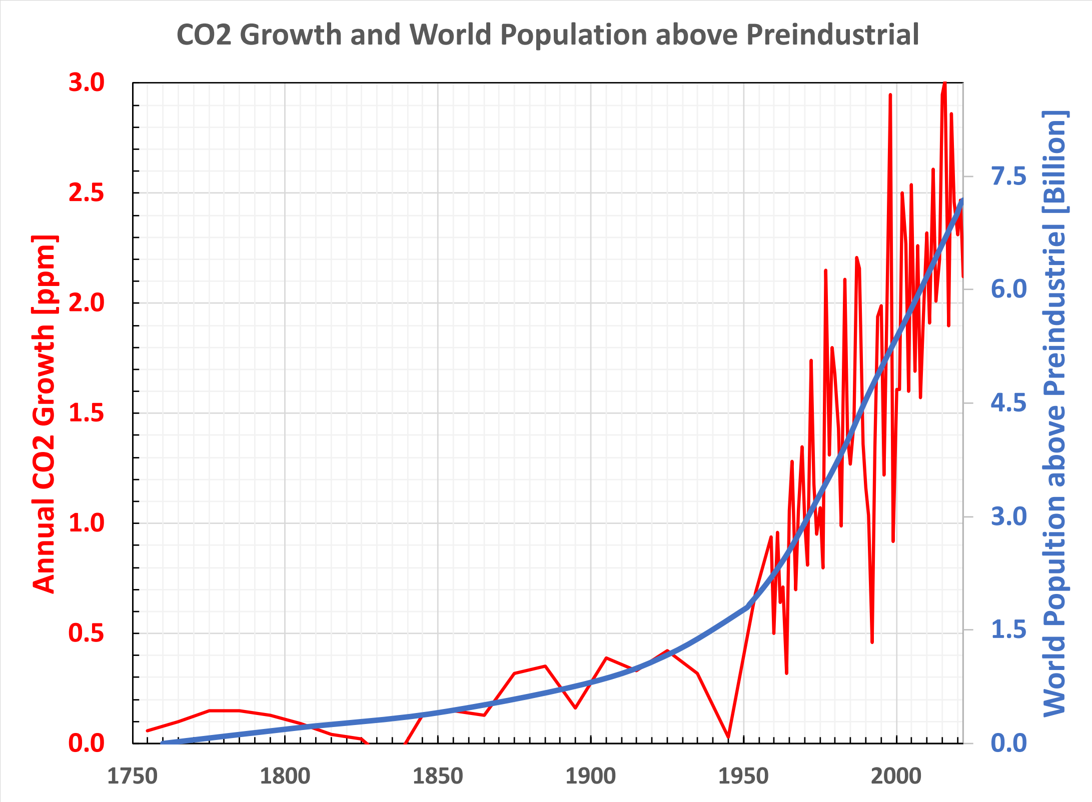
Thoughts on sustainability (cont'd)

- CO_2 in the atmosphere is the primary determinant of the earth's average surface temperature.
- Today's CO_2 concentration of 422 ppm last existed about 15 million years ago. Energy balance was in equilibrium with much higher temperature and no ice sheet in Greenland. The sea level was at least 7 m higher, and the area of Norfolk was under water.
- More and more climate scientists are calling this a "climate emergency". The world needs to stop extracting and burning fossil fuels as soon as possible.
- 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.





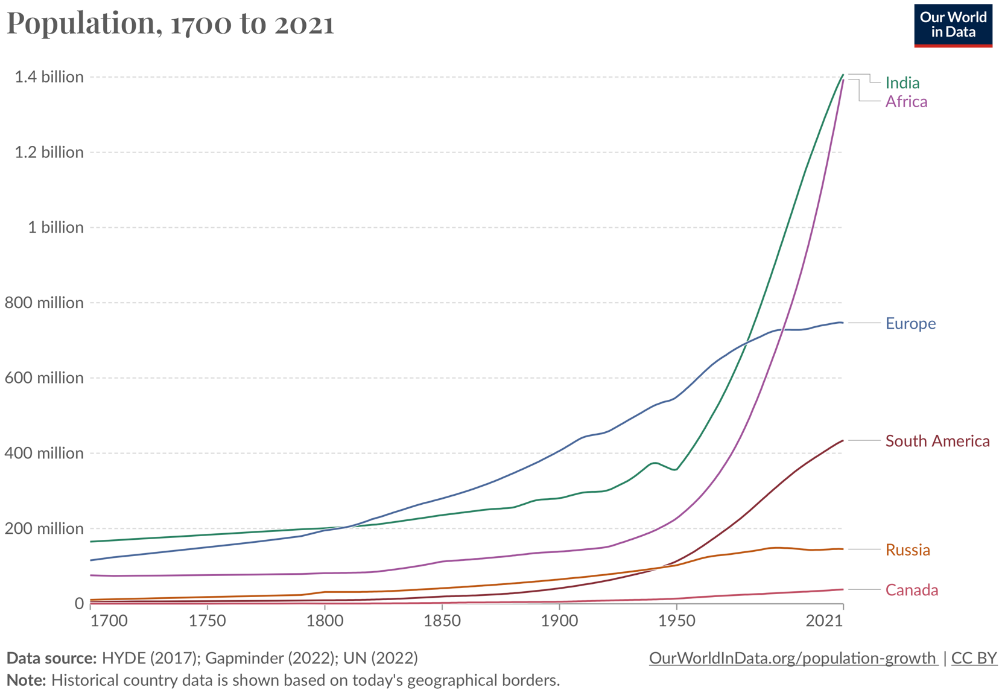
How can we reduce CO_2 emissions?

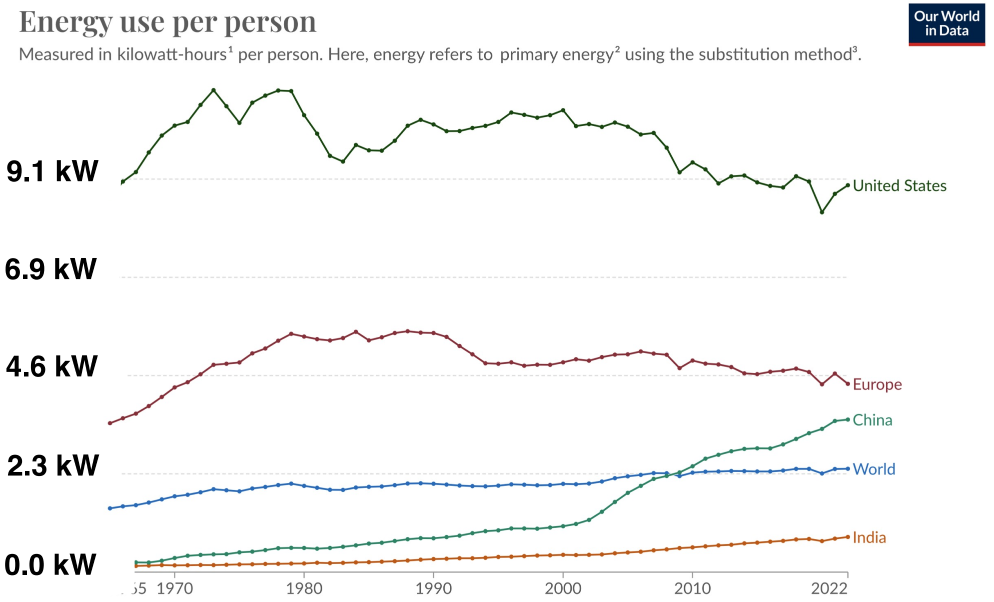


- Human-caused CO_2 emissions are mainly the product of three factors:
  1. Number of people x
  2. Energy consumption per person x
  3. CO_2 emission per energy produced.
- Since CO_2 stays in the atmosphere for centuries the annual increase of CO_2 in the atmosphere is proportional to annual CO_2 emissions. Maybe unsurprisingly it is also proportional to world population.
- CO_2 emission information is not reliable. Many countries just guess or simply lie. Instead, one can measure CO_2 concentration in the atmosphere directly. CO_2 is quickly distributed around the two hemispheres.
- There are significant fluctuations that prevent the detection of annual changes of the world CO_2 emissions. Could this be improved?
- Since fossil fuels have no C14 measuring C14 deficiency in the atmosphere gives a direct and fast measure of CO_2 from fossil fuel burning. Important accelerator application: improved and miniaturized mass spectrometers for local determination of C14 concentrations.

What should be done?

- Present actions have no noticeable effect! Actions on each of these 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. Reduced population in northern countries could allow for migration from countries too hot to support human life.
  - (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: ~ 100W)





What should be done? (cont'd)

- Actions are urgently needed:
  - (3) **Switch to carbon-neutral energy sources on a large scale. (technological innovation):** Energy sources principally come in two forms: collecting energy (solar, wind, …) with low energy density and liberating stored energy (fossil fuels, nuclear, hydro, fusion, …) with high energy density. The low-density solar and wind energies require much more hardware, resources and energy investment per energy produced than the high-density energy sources, which needs to be accounted for based on a full life cycle analysis.
    Today, only nuclear energy has the demonstrated scalability to completely replace fossil fuels.
- **Sustainability regarding energy and CO2 emissions mainly consists of reducing energy consumption AND transition to carbon-neutral energy sources. This needs to be applied to accelerator projects as well.**
- **Like the 2000W Society idea a numerical goal for the energy consumption of accelerator labs could be useful. For example, a goal for the energy consumption per user could be defined (5kW per user?)**

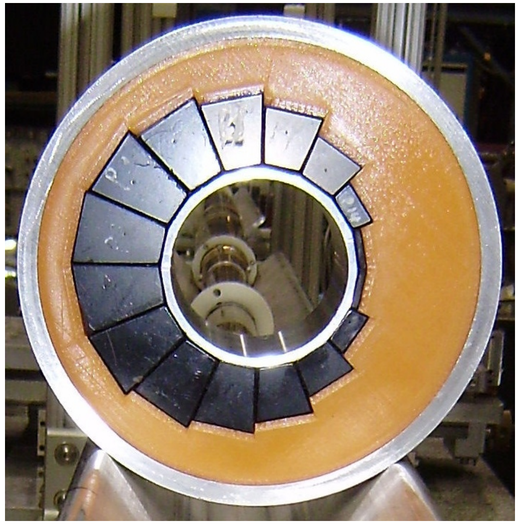
What can the Accelerator Community do? Efficiency

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

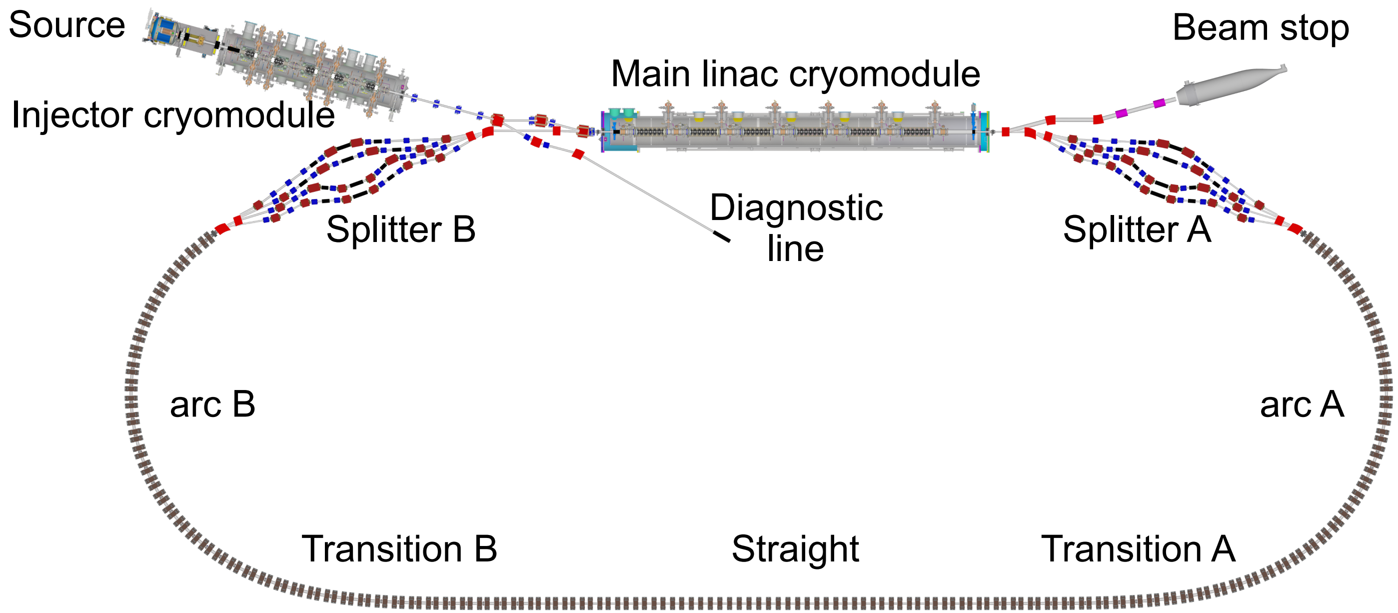
- More efficient power converters to DC and RF (incremental)
- More efficient He refrigerators (presently 3 – 4 times worse than Carnot!)
- Recovery of process heat using heat pump technology
- Use of energy efficient components (Superconducting technology, permanent magnets, HTS, …)
- Compact accelerators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

CBETA – the first test accelerator testing energy efficiency

- CBETA successfully demonstrated energy efficient technologies (NY State funded, 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



What can the Accelerator Community do? Carbon-neutral energy

- **Accelerator driven sub-critical reactors:** Nuclear power is the only carbon-neutral energy source that has been proven to be scalable. The main obstacle is the treatment of the radioactive “waste”. Accelerator driven sub-critical reactors (Accelerator Driven Systems) can transmute this waste and also generate more energy. The accelerator must be highly reliable and very energy efficient. The accelerator community can do this!

- **Heavy ion inertial fusion:** The inertial fusion experiments at NIF have demonstrated the concept: more energy was released than the energy of the laser beams used to compress the fuel pellet. However, the energy efficiency of producing the laser beams is very low. Heavy ion beams used compress the pellets can be produced much higher energy efficiency. Fusion energy might well not be ready for many decades, but R&D of possible approaches need to be done now.

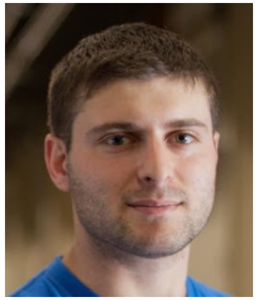
Snowmass 2021 Accelerator Frontier Collider Implementation Task Force

- 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)

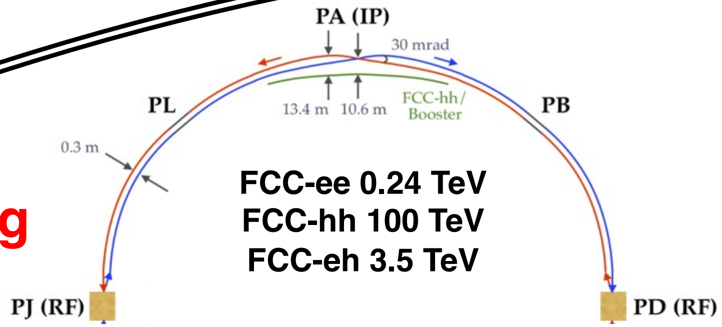

Jim Strait (FNAL)


Marlene Turner (LBNL)

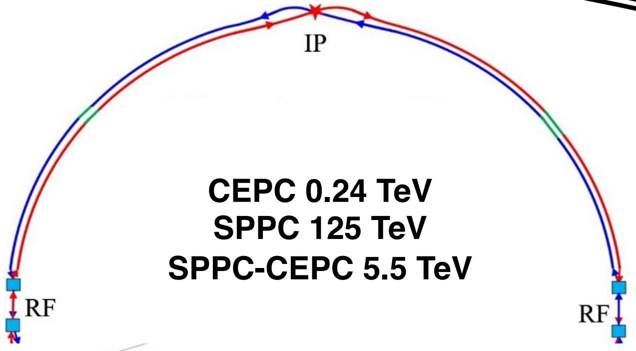

LianTao Wang (U. Chicago)

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

Collider-in-the-sea 500 TeV

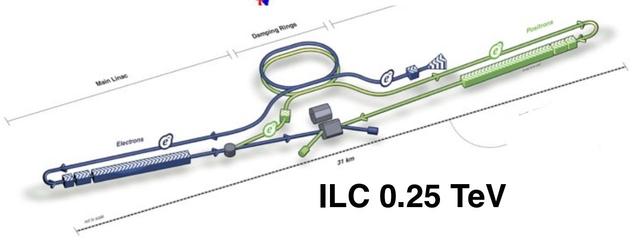


FCC-ee 0.24 TeV
FCC-hh 100 TeV
FCC-eh 3.5 TeV

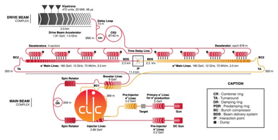


CEPC 0.24 TeV
SPPC 125 TeV
SPPC-CEPC 5.5 TeV

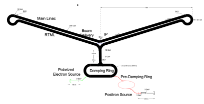
- **Storage ring colliders**
- **Linear colliders**



ILC 0.25 TeV

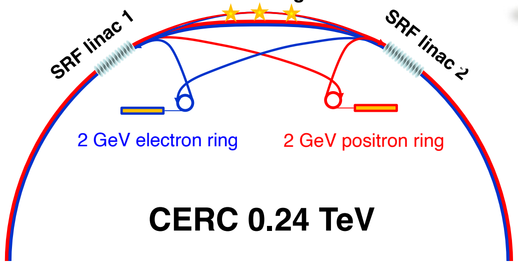


CLIC 0.24 TeV

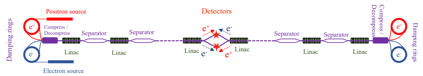


CCC 0.25 TeV

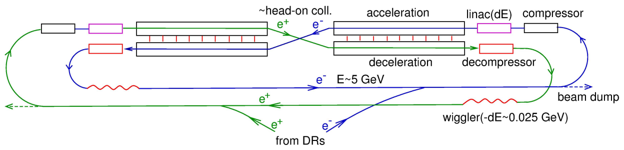
- **ERL colliders**



CERC 0.24 TeV

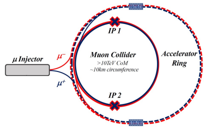


ReLiC 0.24 TeV



ERLC 0.24 TeV

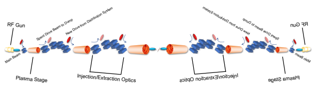
- **Muon collider**



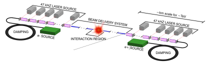
MC 10 TeV

10 km

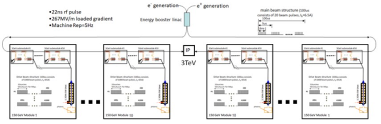
- **Wakefield colliders**



PWFA 15 TeV



LWFA 15 TeV

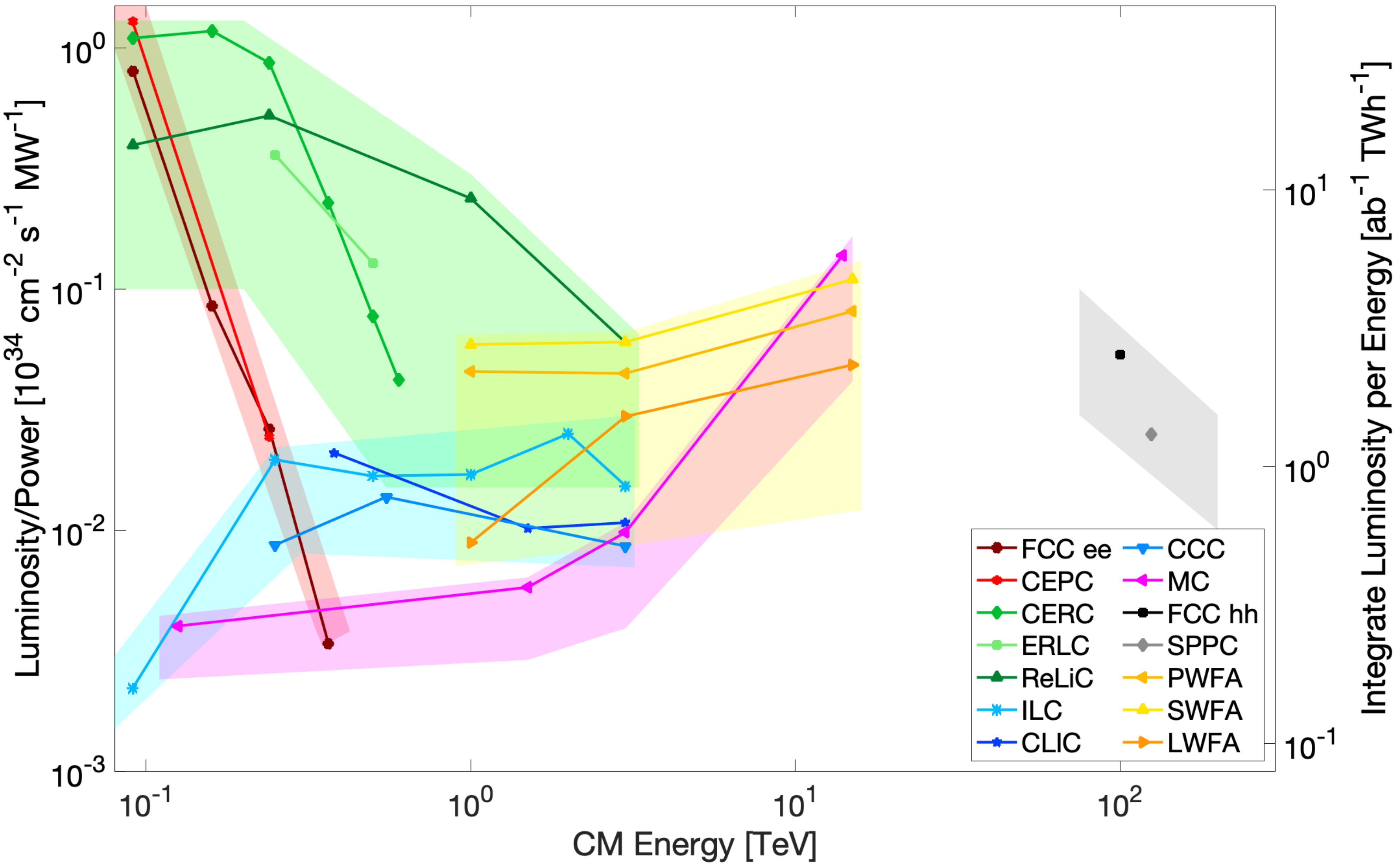


SWFA 3 TeV

Higgs factory summary table

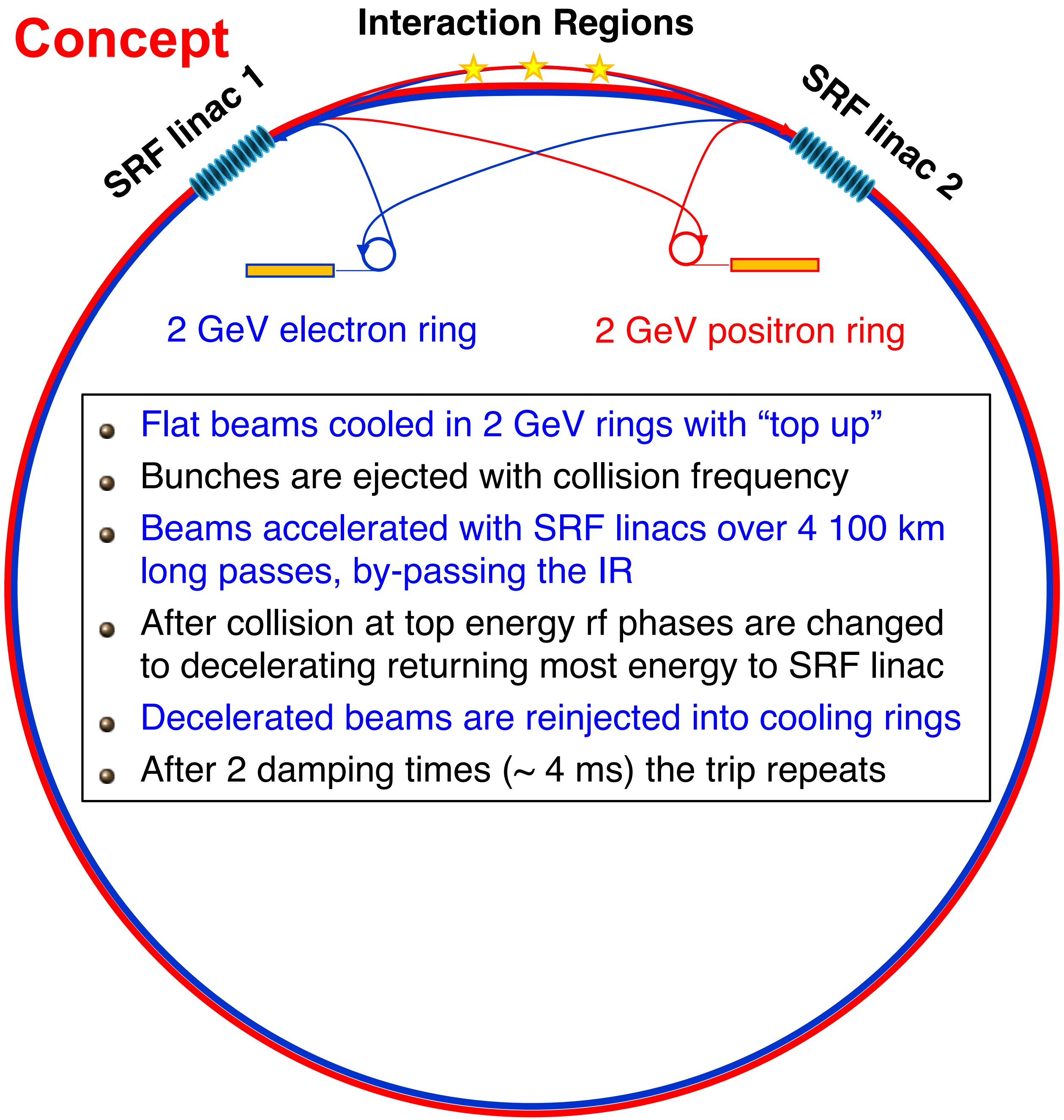
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} $cm^{-2}s^{-1}$]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	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

Peak luminosity per power consumption



Circular Energy Recovery Collider Concept

- New collider concept using existing accelerator technologies
- Combines advantages of existing collider concepts:
  - Storage ring collider: Recycling of beam energy and particles
  - Linear collider: efficient collisions (collisions per beam particles) using a large disruption parameter
- R&D: energy efficient CW SRF



- Flat beams cooled in 2 GeV rings with "top up"
- Bunches are ejected with collision frequency
- Beams accelerated with SRF linacs over 4 100 km long passes, by-passing the IR
- After collision at top energy rf phases are changed to decelerating returning most energy to SRF linac
- Decelerated beams are reinjected into cooling rings
- After 2 damping times (~ 4 ms) the trip repeats

"High-energy high-luminosity e^+e^- collider using energy-recovery linacs"
V.N. Litvinenko, T. Roser, M. Chamizo-Llatas
Physics Letters B 804 (2020) 13594

Lifecycle analyses

- All new projects and efforts need to be analyzed in terms of total lifecycle energy consumption 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 consumption and CO2 emissions. Such analyses should play an important 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 Lab Director Group 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, …

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)
  - **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, and assess and promote the use of accelerators for the development of Carbon-neutral energy sources. The panel will formulate recommendations on R&D and support ICFA with networking across the laboratories and with communications. The membership will ensure a broad regional participation and coverage of accelerator technologies and concepts, relevant in the context of energy consumption and production.
- 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 have prepared summary slides of the energy efficiency efforts and plans at their labs and update them periodically.

- The panel chair was invited, as a representative of the ICFA Sustainability Panel, to join 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.

- Such workshops, as well as all other meetings where feasible, should be held in a sustainable manner. One possibility is to limit in-person attendance to participants that can reach the site without needing a plane ride and offer <u>equivalent</u> participation for remote attendees from overseas. It will require a concerted effort to develop tools and organizations that can make such hybrid meetings successful.

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 CO_2 emissions throughout their lifecycle from construction, operation, to decommissioning.

- Comparative lifecycle analyses of total energy consumption and CO_2 emissions should be completed for all future accelerator projects.

- R&D of increased efficiency and new more efficient concepts to reduce energy consumption and CO_2 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 on equal terms with the in-person attendees.