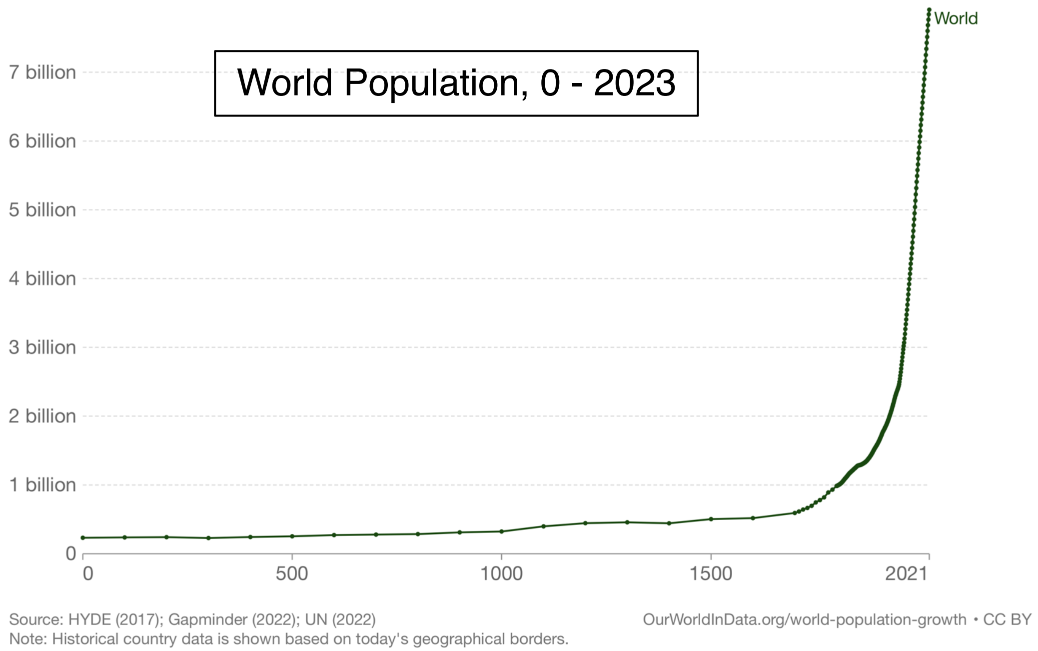
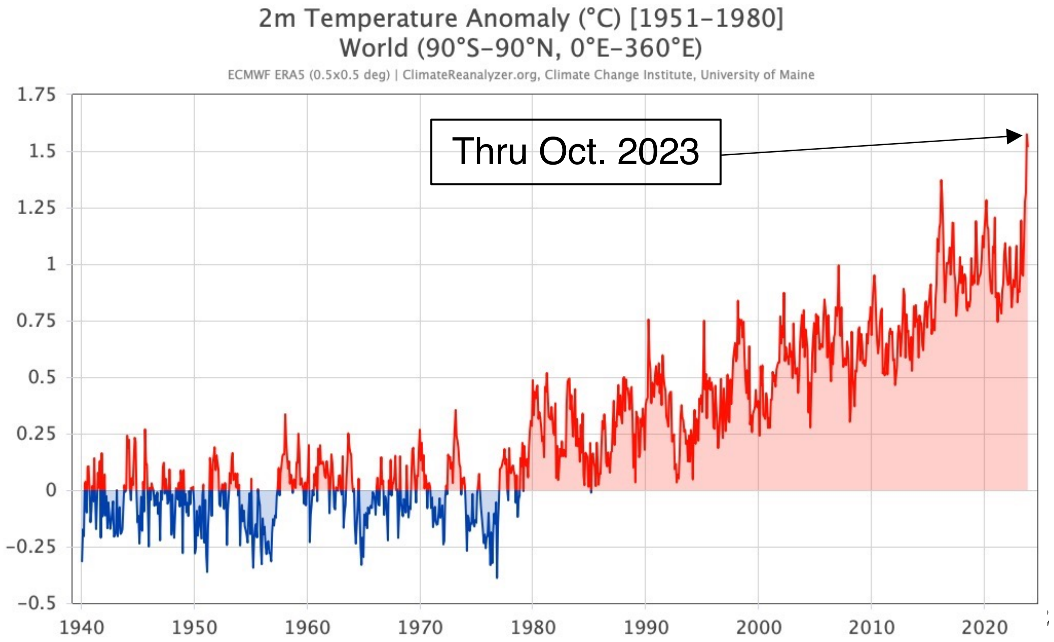
# Sustainability of HEP

Thomas Roser
Chair, ICFA Panel on Sustainable Accelerators and Colliders
November 29, 2023

# Thoughts on sustainability

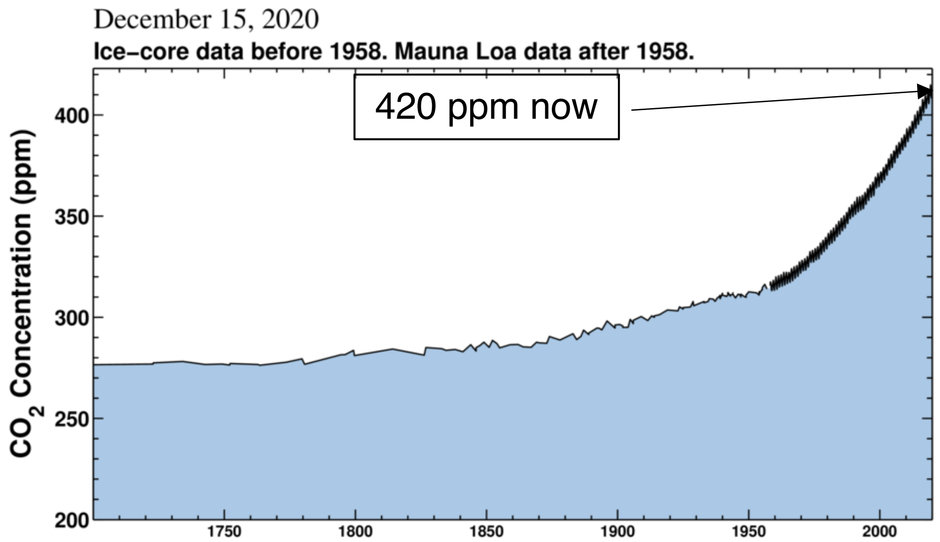
- Human life on earth as we know it is endangered by the unsustainable exploitation of many natural resources.
- Maybe most importantly, over the last 250 years the availability of essentially unlimited amounts of fossil energy has resulted in rapid population growth and unsustainable use of many natural resources.
- The most urgent issue but not the only one: $CO_2$ from burning fossil fuels accumulates in the atmosphere and leads to increased global temperatures and extreme weather events.
- 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 large high energy collider projects will overlap in time with increasingly more extreme weather events around the world and urgent demands to cut $CO_2$ emissions.

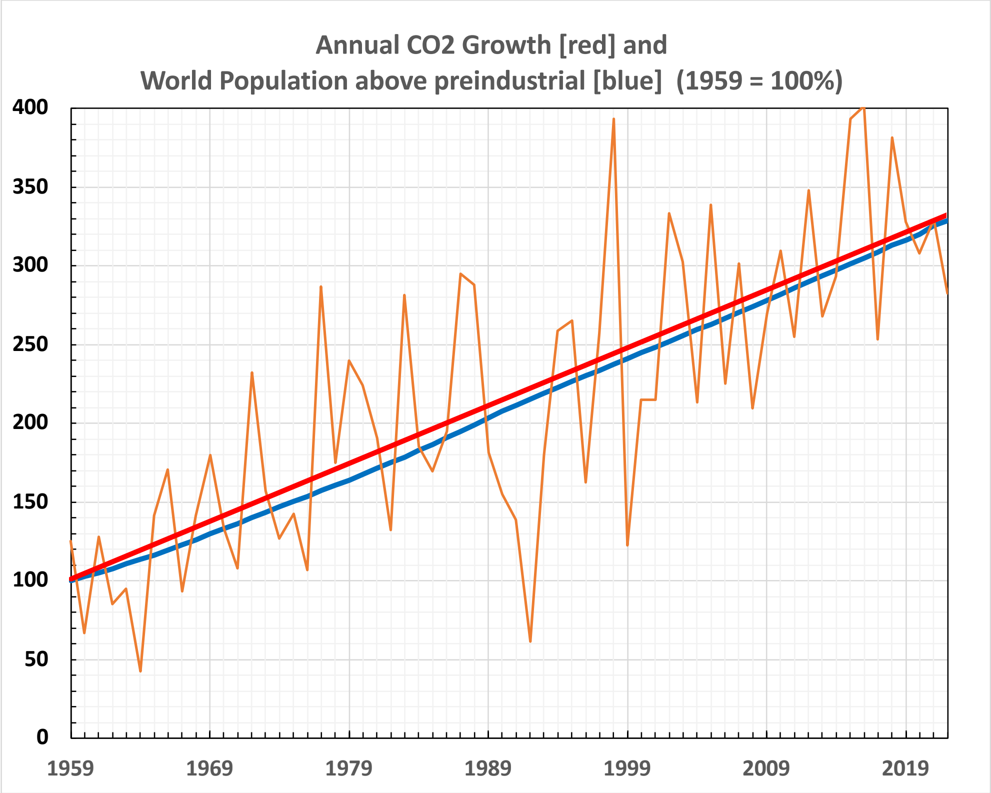


# How can we reduce $CO_2$ emissions?

- 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.
- It is important to start doing something. Actions on each of these factors are urgently needed:
  1. Slowing population growth (mainly cultural change, has started)
  2. Reduce energy consumption per person by increasing energy efficiency for all activities (cultural change and technological innovation)
  3. Switch to carbon-neutral energy sources on a large scale. (technological innovation)
- Note: increased energy efficiency AND carbon-neutral energy sources are both required. Transitioning to carbon-neutral energy sources alone would be much too late and also would further increase the use of natural resources unsustainably whereas increased energy efficiency can be achieved on a shorter time scale.



# What can the Accelerator Community do?

- **For population growth**: It Is slowing. A historically successful approach is supporting women rights and education worldwide.
- **For energy efficiency**: we need to focus on the development of energy efficient accelerator technologies with the same or 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 energy recovery.
  - More efficient power converters to DC and RF (incremental)
  - More efficient refrigerators (limited by Carnot)
  - Recovery of process heat using heat pump technology
  - Energy efficient components (Superconducting technology, permanent magnets, HTS, …)
  - Compact accelerators with high accelerating gradient (Wakefield Accelerators, …)
  - Energy efficient accelerator concepts (Storage rings, Energy Recovery Accelerators, …)
  - …
- **For Carbon-neutral energy source**: Besides hydropower, biomass (wood), and geothermal, all of which cannot be expanded significantly, nuclear power is the only proven carbon-neutral energy source that is scalable. The main obstacle is the treatment of the radioactive “waste”. **Accelerator Driven Systems** (accelerator driven sub-critical reactors) 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!

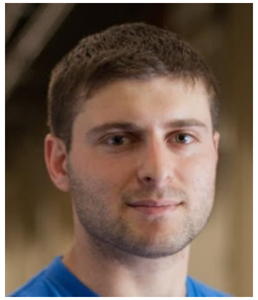
# Snowmass 2021 Accelerator Frontier Collider Implementation Task Force

- 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)

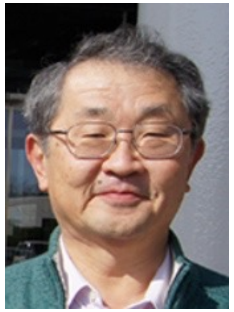

Dmitri Denisov (BNL)


Spencer Gessner (SLAC)


Steve Gourlay (LBNL)


Philippe Lebrui (CERN)


Meenakshi Narain (Brown U., deceased)


Katsunobu Oide (KEK)


Tor Raubenheimer (SLAC)


Thomas Roser (BNL, Chair)


John Seeman (SLAC)


Vladimir Shiltsev (FNAL)

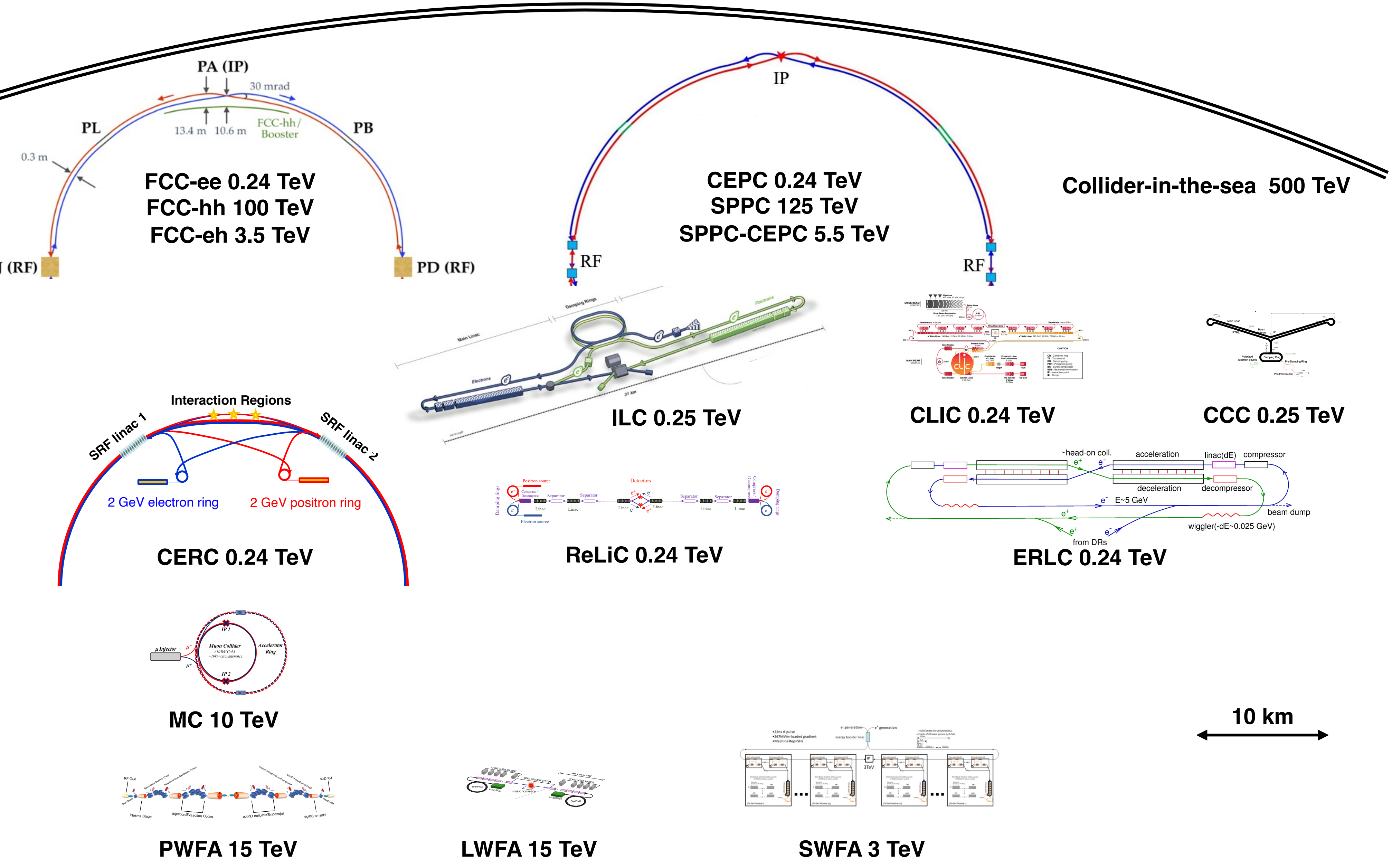

Jim Strait (FNAL)


Marlene Turner (LBNL)


LianTao Wang (U. Chicago)

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

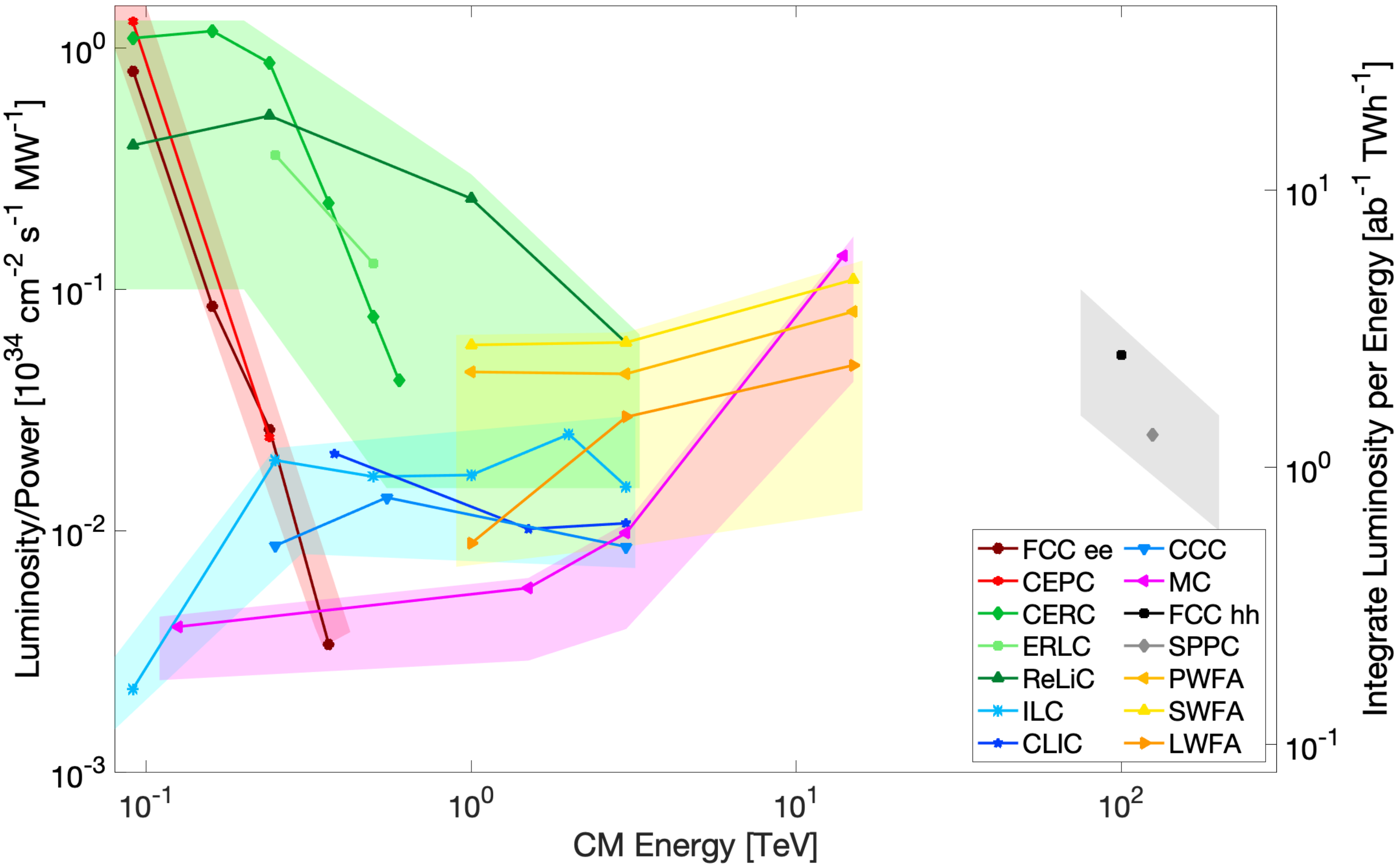
- Storage ring colliders
- Linear colliders
- ERL colliders
- Muon collider
- Wakefield colliders



# Higgs factory summary 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



# Lifecycle analyses

- All new projects and efforts needs 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 high energy collider 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 high energy collider project.
- Some 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)
- ICFA could 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, …
- Note that I propose here to not include total integrated luminosity in the parameter list. This is because utilization of such a large and expensive research facility would require operation for a minimum number of years (20?) independent of achieved peak luminosity.

# ICFA Panel on Sustainable Accelerators and Colliders

- **Panel members:**
  - **Europe:** Mike Seidel (PSI, Switzerland), Andreas Hoppe (DESY, Germany), Jerome Schwindling (CEA/IRFU, France), Ruggero Ricci (LNF, Italy), Peter McIntosh (STFC, UK), Roberto Losito (CERN, Switzerland)
  - **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), Vladimir Shiltsev (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.

# ICFA Panel on Sustainable Accelerators and Colliders

- **Recent activities:**
  - Members of the panel have prepared summary slides of the energy efficiency efforts and plans at their labs and update them periodically. They are attached to this presentation file.
  - The panel chair was invited, as a representative of the ICFA Sustainability Panel, to join the IOC of the 7$^{th}$ 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 HEP community. Future HEP facilities 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 should be completed for all future collider proposals.

- 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 on equal terms with the in-person attendees.

# Energy efficiency efforts and plans at accelerator labs

# CERN for SDG 7: Affordable and clean Energy

- **CERN is managing its energy use responsibly since at least 10 years, well before the establishment of the UN SDGs.**
- **Recently issued an Energy* policy with three pillars:**

- **LESS** : Reduce consumption (consolidation & operation)
- **BETTER** :
  - **Precise Forecasting & Measurement**
  - **Raising awareness**
- **RECOVER** : Waste energy

**Energy is not only electricity…*

# CERN’s Action Plan (in the frame of ISO 50001 certification)

| | Energy saved |
|---|---|
| Cooling and ventilation consolidation projects | 6 GWh/year |
| 75 consolidation projects for buildings | 10 GWh/year |
| Science Gateway | 200+ MWh/year |
| Optimisation of Cryo operations mode | 25 GWh/year |
| ***Heat recovery projects*** | |
| Meyrin and Prévessin | 30+GWh/year |
| Ferney-Voltaire | 20 GWh/year (for the neighbors) |

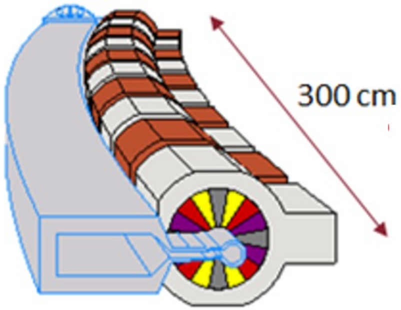
# Responsible Procurement at CERN

- CERN's Directorate adopted in July '23 a new policy on responsible procurement
- The policy objective is to limit Scope 3 emissions from procured material and services.
- Implementation will take time, as one needs to balance with readiness of the market.

- Our action will be based on ISO 20400:2017

# Energy efficiency efforts and plans at BNL

- NSLS II: upgrade plans include replacing large parts of the ring with “complex bends” using permanent Halbach or hybrid magnets. Power consumption could be up to 80% lower.



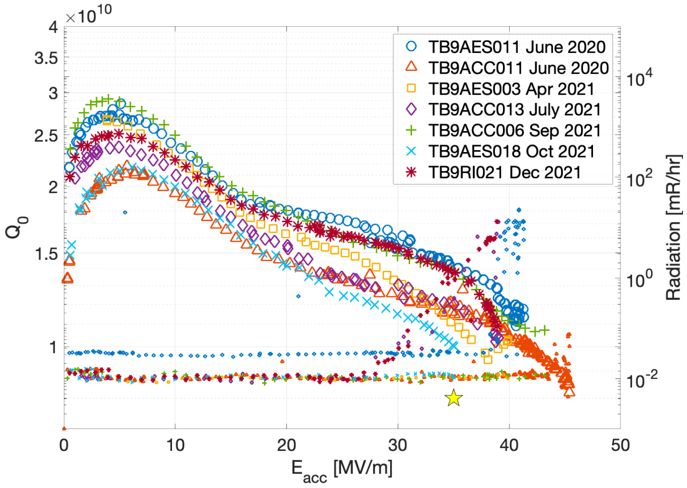

- RHIC (mature facility): many upgrades to improve efficiency (variable speed cooling systems, etc., also careful maintenance to increase equipment lifetime); efficiency upgrade of helium refrigerator

- EIC: RHIC/EIC Helium refrigerator efficiency upgrade; use of Energy Recovery Linac for high intensity electron beam for proton beam electron cooling; efficient reuse of process heat using heat pumps

# Sustainable Accelerators R&D at Fermilab

- High $Q_0$ SRF cavities:
  - > 1e10 for current projects (ILC, LCLS-II, etc)
  - > 3e10 for future projects (FCCee, Muon Collider, etc)
  - And high gradient > 45 GV/m
- HTS high field magnets:
  - High field solenoids >30 T, inserts (with NHMFL)
  - Economical 0.1T HTS dipoles for FCCee
  - Up to 50 T solenoids for muon colliders (in plan)
- HTS fast cycling magnets:
  - For RCS and muon colliders
  - ReBCO ~1m magnet 300 T/s (record)
  - Plans for 1000-3000 T/s prototypes

V.Shiltsev and S.Posen



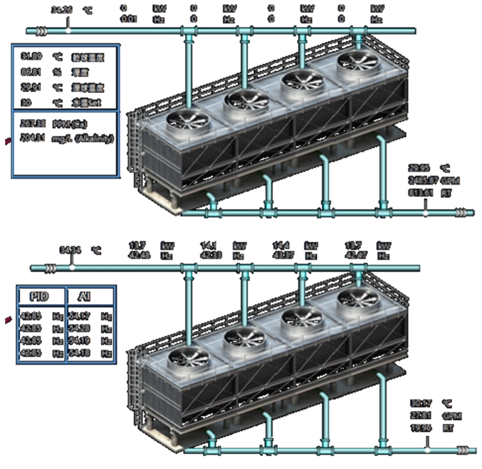

# Energy Saving at NSRRC

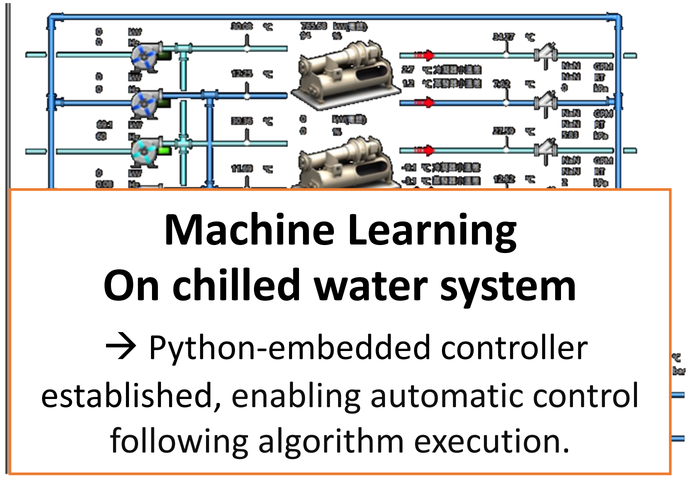
Reduce annual power consumption by ~ 5 %, from 72.7 GW·h in 2019 to 69.1 GW·h in 2022, despite the increasing beam current (400 mA --> 500mA) and 7 % of beam time.

- Starting machine learning to improve the energy efficiency of the chilled water system, which constitutes up to 22% of our annual energy consumption.
- Renovating our existing buildings (~ 30 yrs) to attain green building certification.
- Improve the energy efficiency of solid-state RF power chips
- Planning the permanent magnets (PMs) for transfer line at TPS , and permanent dipole magnets at TPS-II Project.

NSRRC, Taiwan

國家同步輻射研究中心
*National Synchrotron Radiation Research Center*





**Machine Learning**
**On chilled water system**

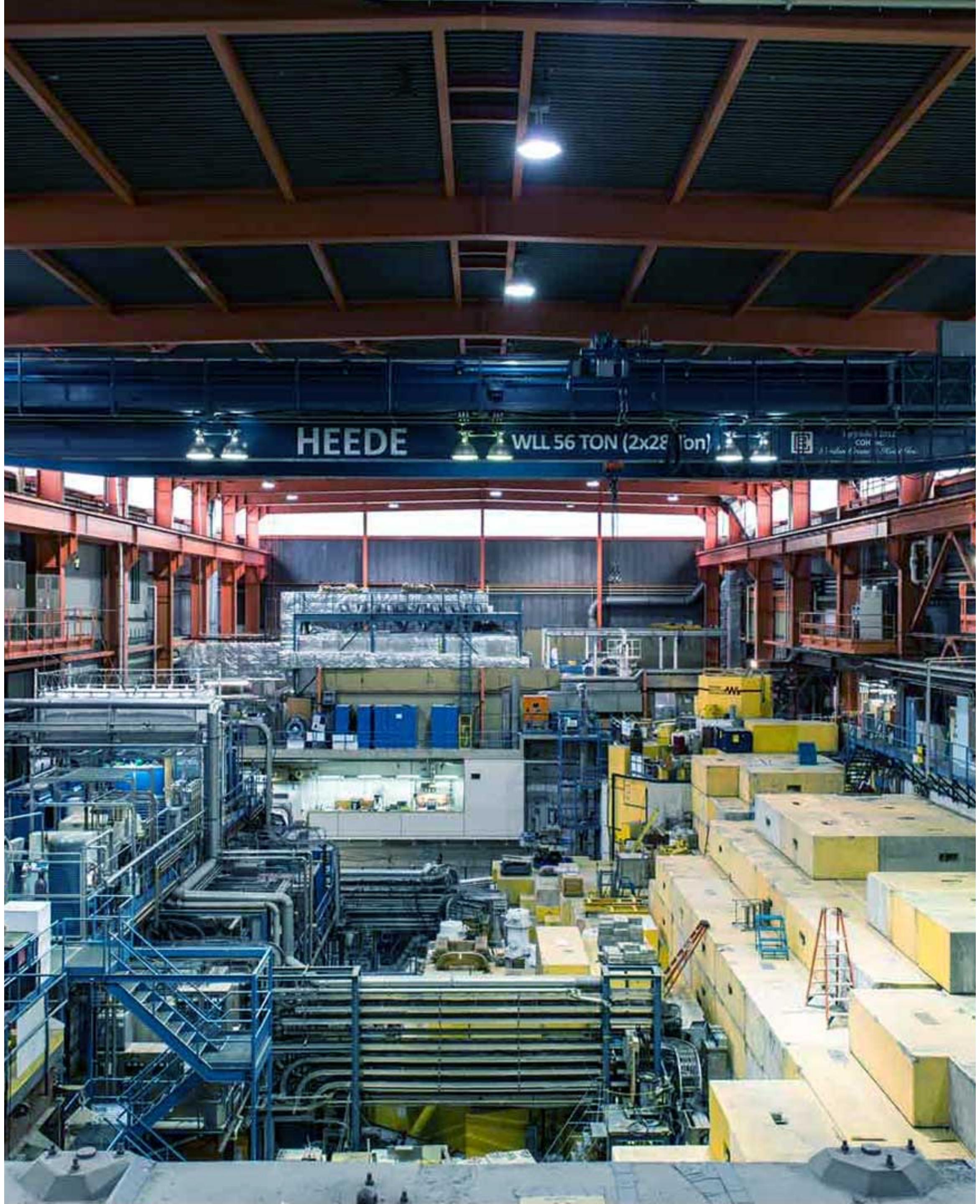
→ Python-embedded controller established, enabling automatic control following algorithm execution.

TRIUMF



# Energy efficiency efforts and plans at TRIUMF

- The 500MeV cyclotron is now 50 years old and ISAC is 25 years old - refurbishing efforts are being done on both systems to improve electrical efficiency with partial financial incentive from the local power utility – they help fund a portion of a portion of an FTE to think energy efficiency
  - New higher efficiency power supplies for magnets
  - All new purchases for upgrades are reviewed for power efficiency
- TRIUMF site – exploring the use of heat pumps for future operation together with the local university community
- Sustainability is a new platform of TRIUMF focus for our next FYP starting in 2025
  - Lead institute to discuss ADS for Canada



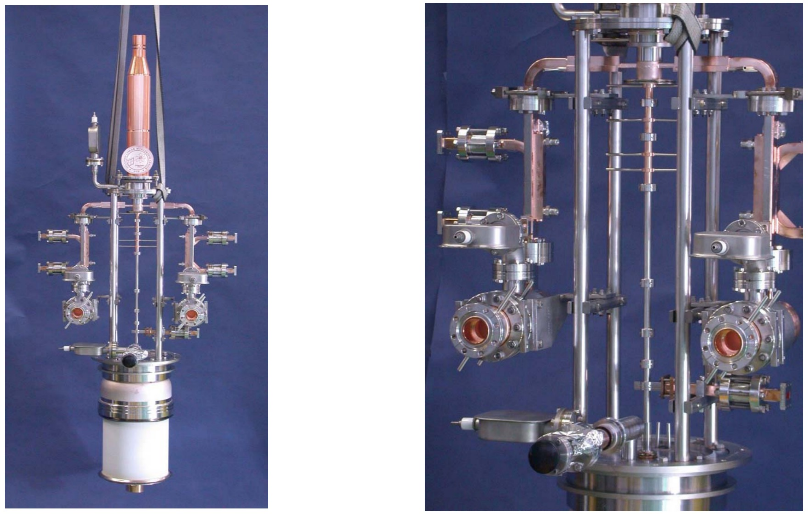

Discovery, accelerated

# RF Source Efficiency is a Limiting Factor for Sustainability of Facilities

- For pulsed systems solenoid often uses the most average power
  - Restarting production of PPM 75 MW klystrons
- Incorporating higher efficiency bunching mechanisms in new designs (BAC/COM) developed under HEIKA
- Energy recovery for rf sources – Green RF
- Goal to reach 65-80% electrical efficiency

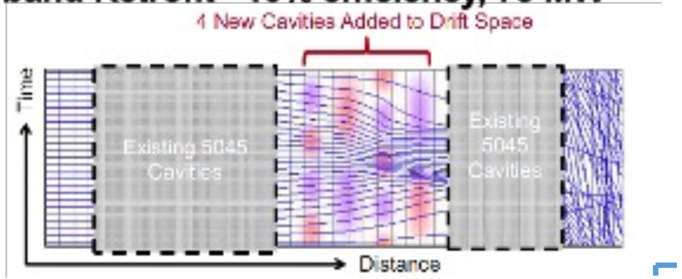
**PPM High Power Klystron**

75XP-3



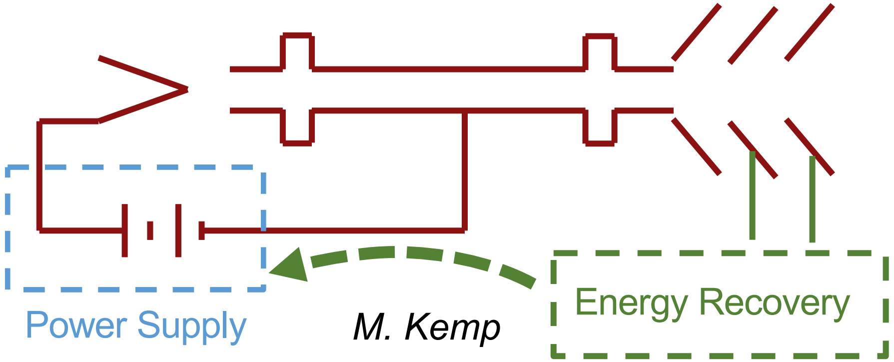
https://indico.cern.ch/event/39372/contributions/1829827/attachments/787979/1080133/AVlieks-X-Band_Klystron_Development_at_SLAC-final.pdf

**SLAC BAC Prototype**
**S-band Retrofit +10% efficiency, 73 MW**




*J. Neilson*

**Energy Recovery**

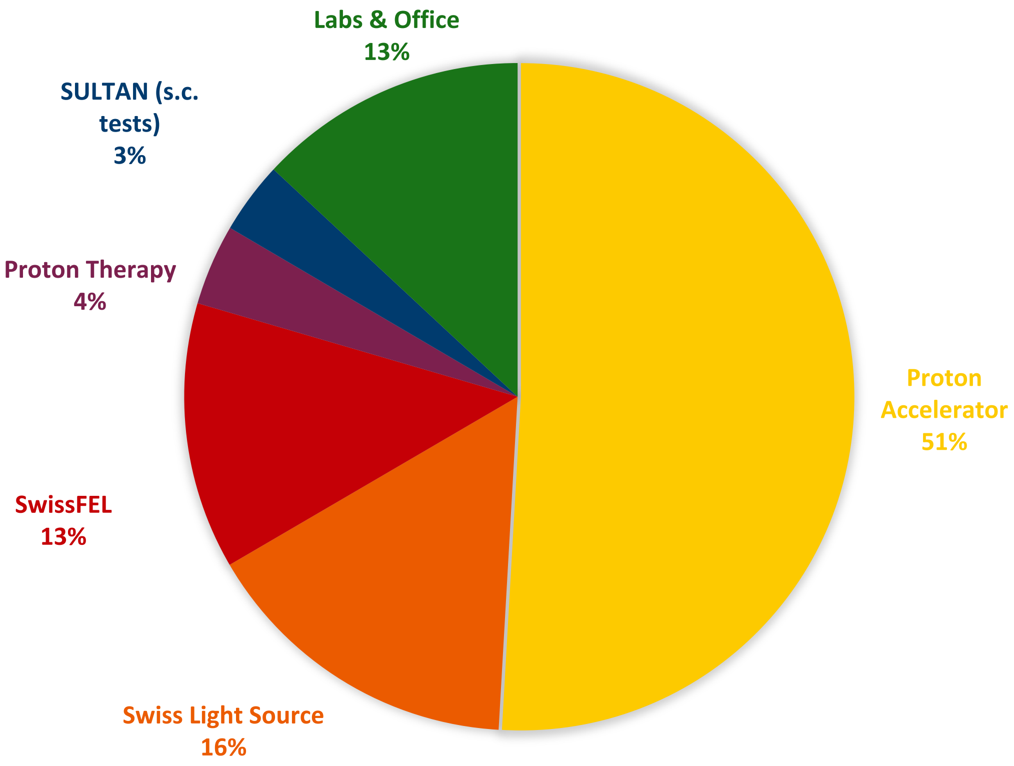



*M. Kemp*

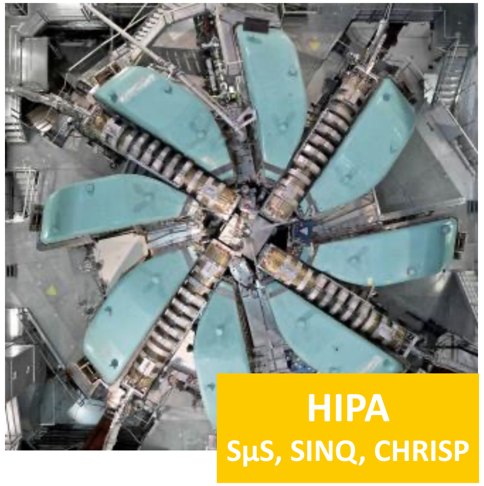
Depressed Collector on VKS-8262

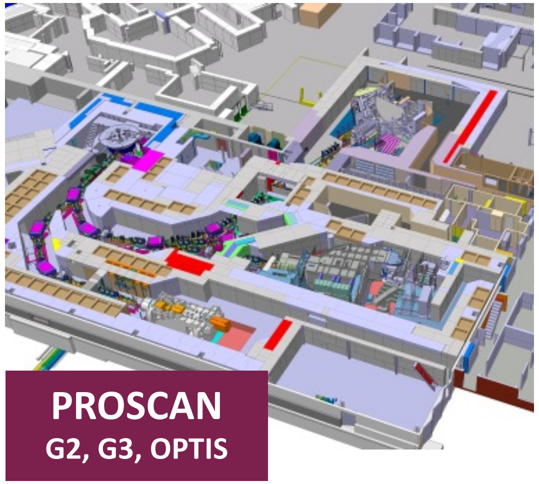
“Inverse” Marx power recovery module

# PSI Energy Consumption

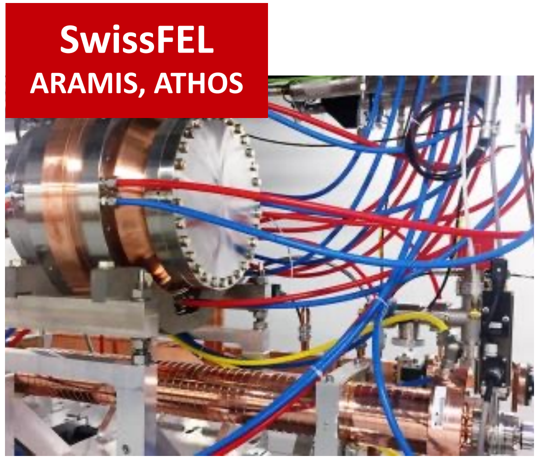



**Total PSI: 139 GWh/y (2022)**

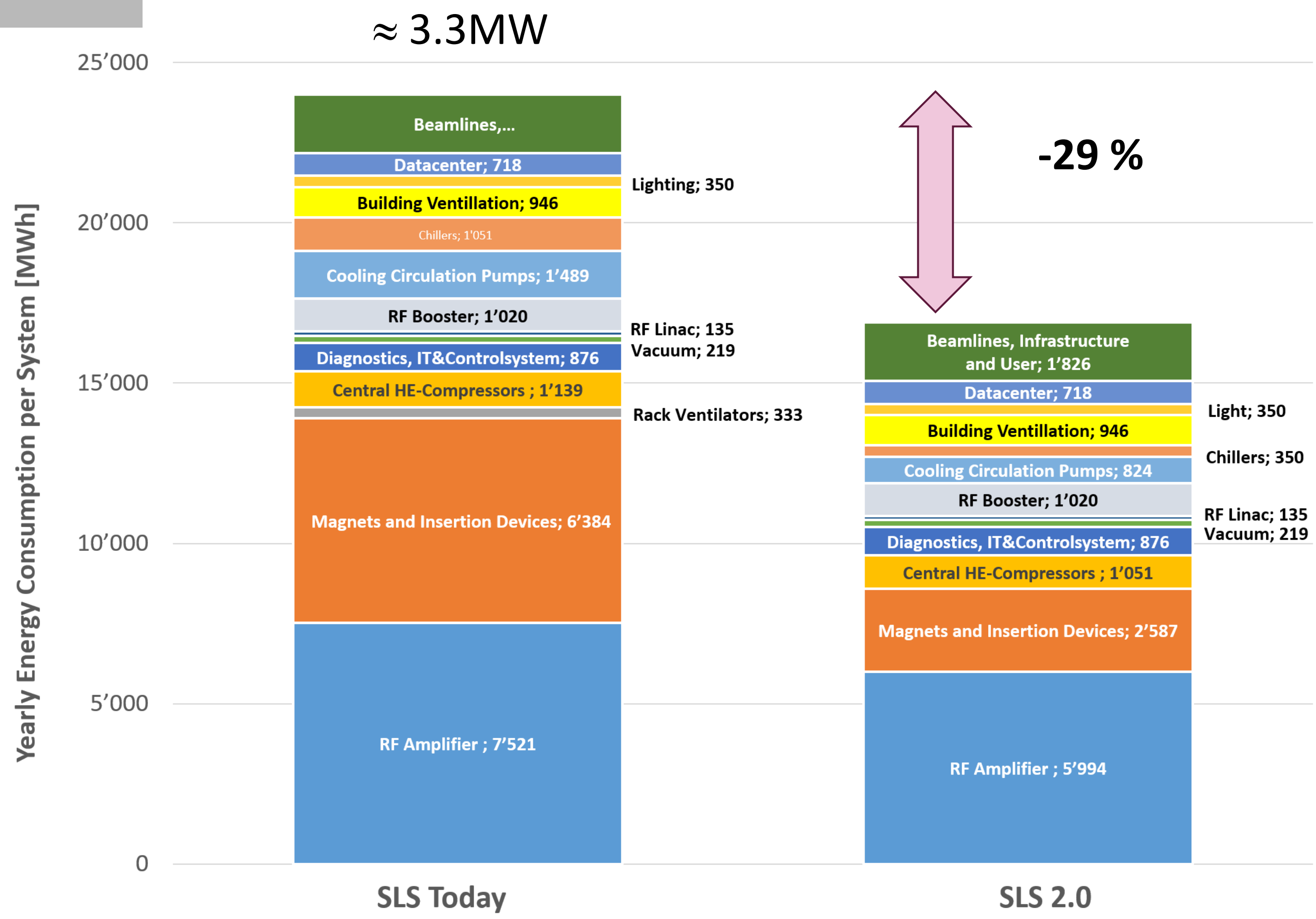






# Swiss Light Source SLS and its Upgrade @ PSI




[courtesy M.Jörg, PSI]

**Brilliance x 35 for users**
**Less electricity consumption**

Key savings:

Electromagnets → Permanent magnets
Klystrons → Solid state amplifiers (63%)
standard pumps → modern pumps for cooling

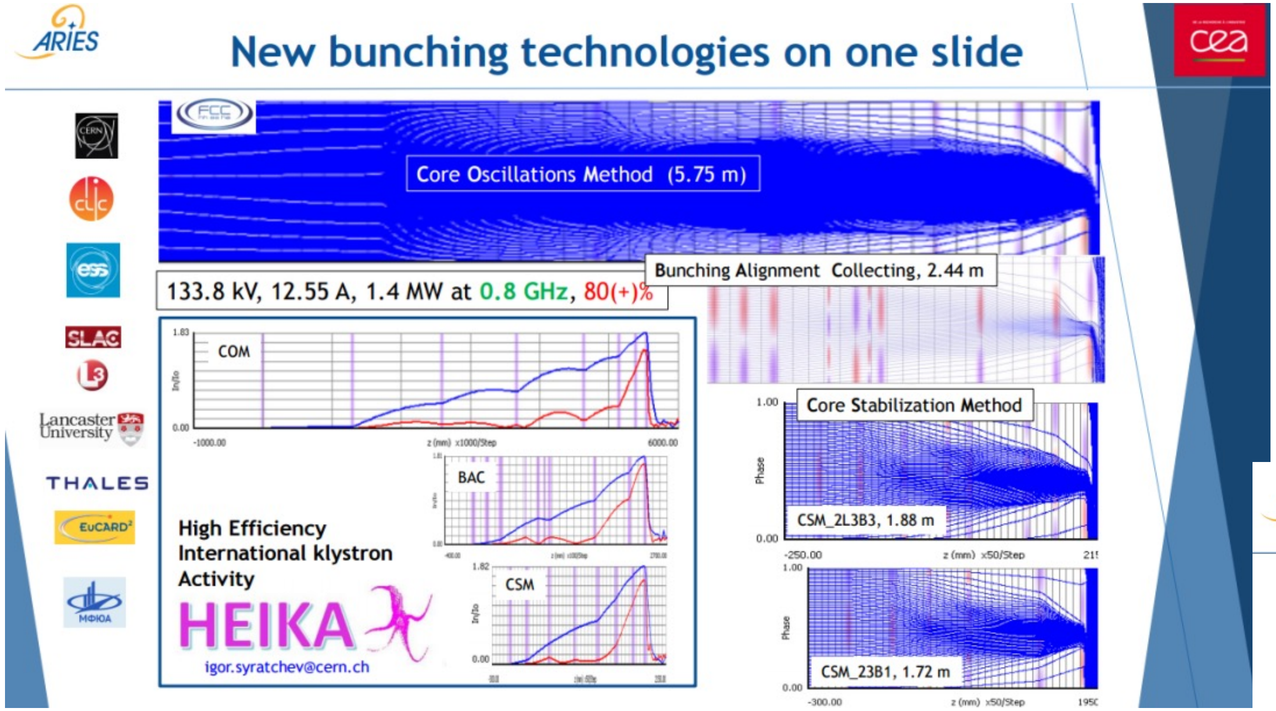
**SLS2.0: Grid to user X-rays**

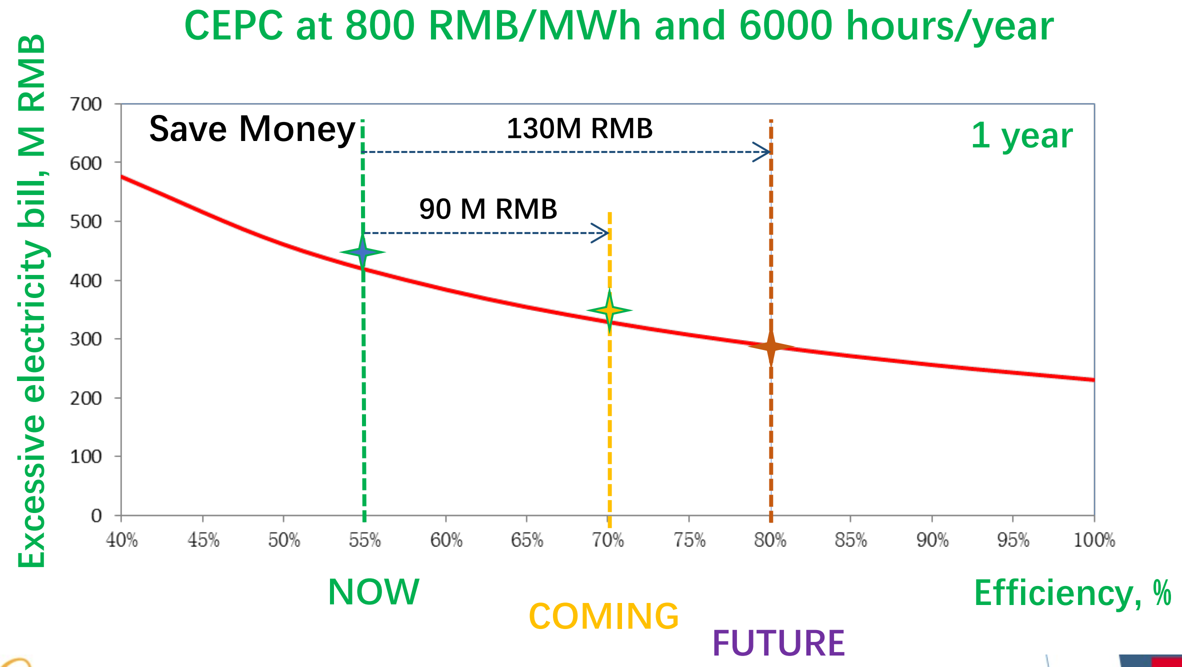
$P_{tot}$ = 2.4 MW
$P_{RF}$ = 0.82MW
$P_{\gamma}$ (undulators) = 91 kW

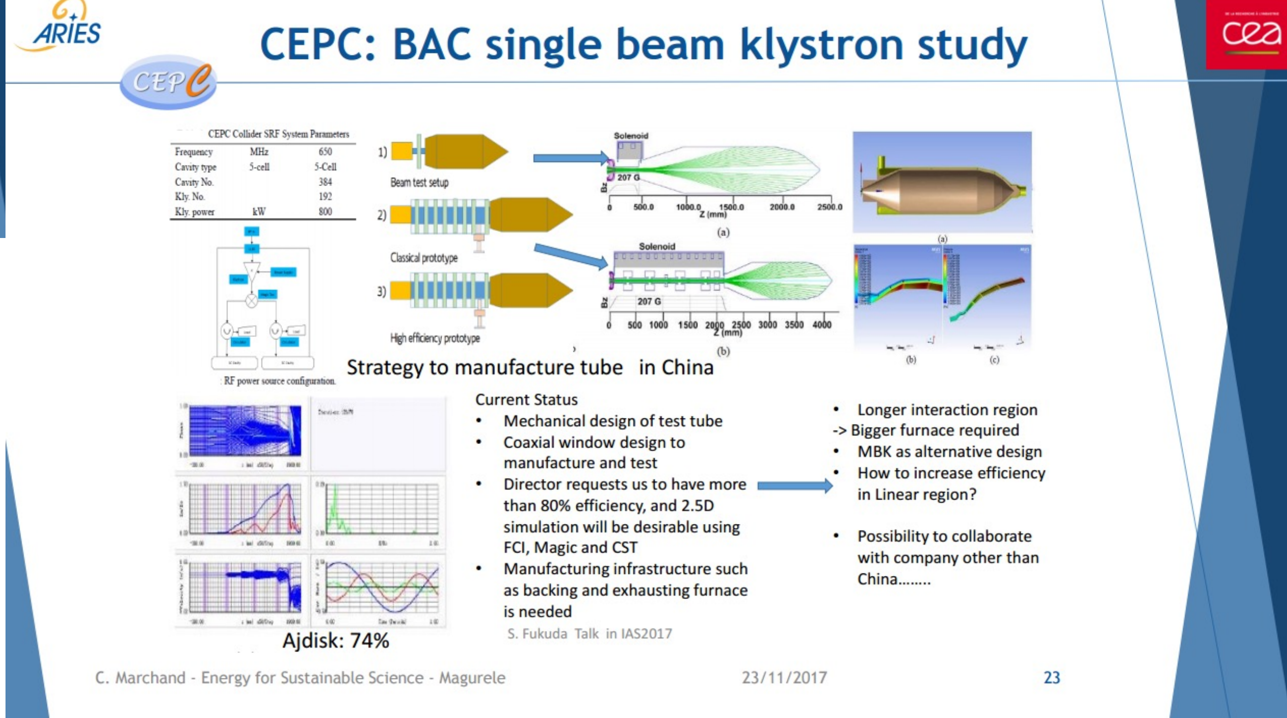
**planned photovoltaics on roof**
energy: 0.9 GWh / year = 5 % of SLS consumption

# High efficiency klystron for CEPC

- 70% already reached, 80% still need to develop

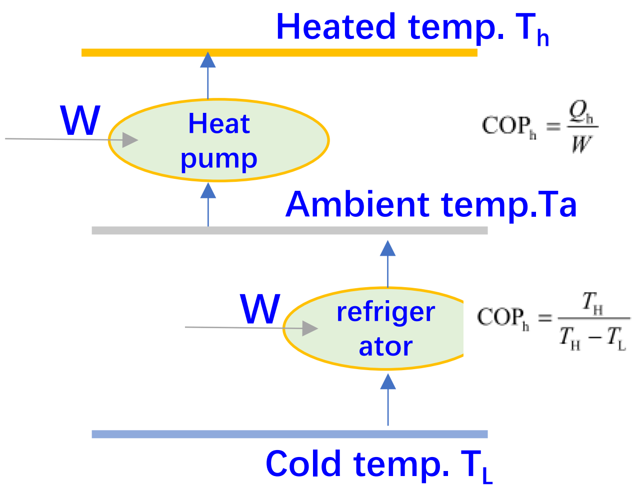


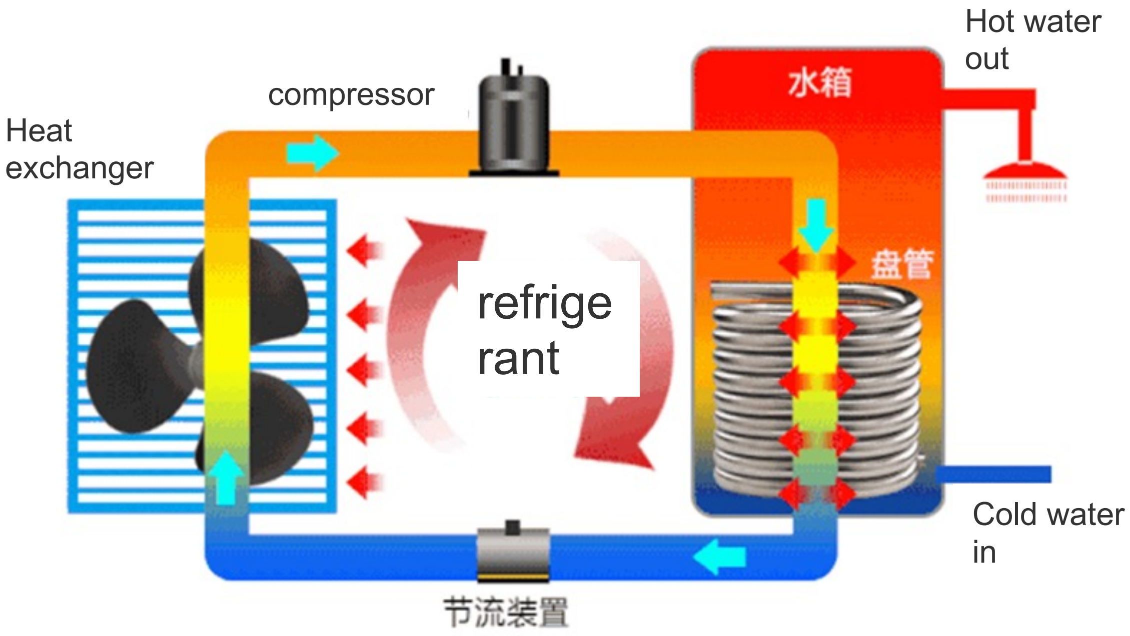



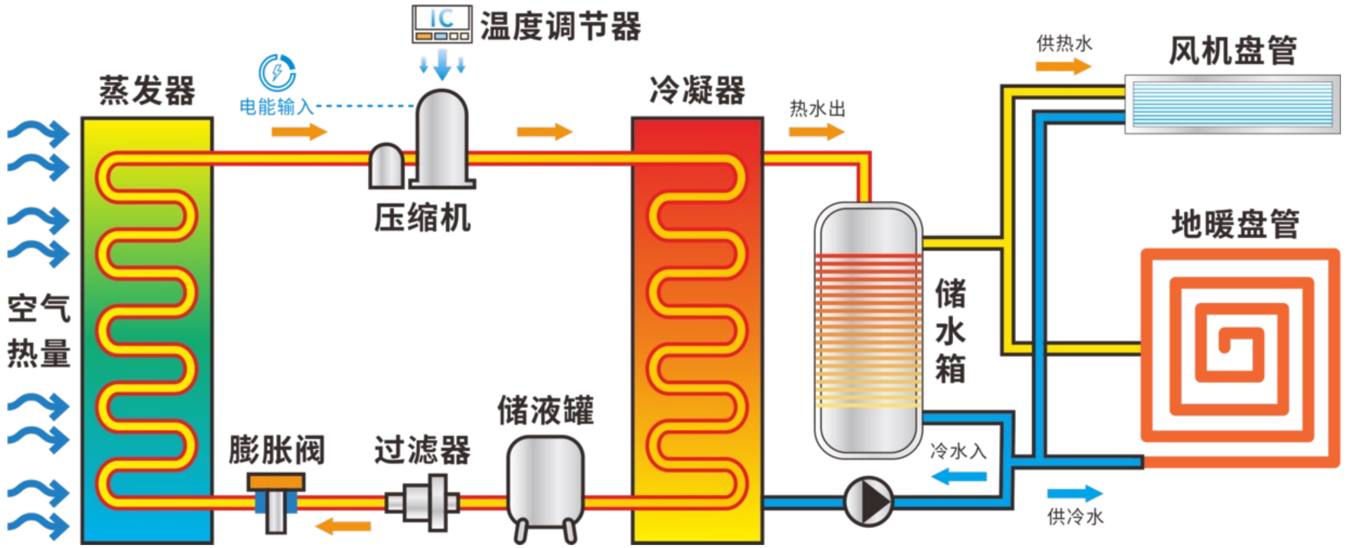
# Waste energy reuse plan @ CEPC

- We plan to use heat pump to reuse the waste energy.
- Heat naturally flows from high temperature to low temperature, but not in the opposite direction. A heat pump can reverse the flow of heat from lower temperatures to higher temperatures with minimal added energy.




Heat pump schematic diagram



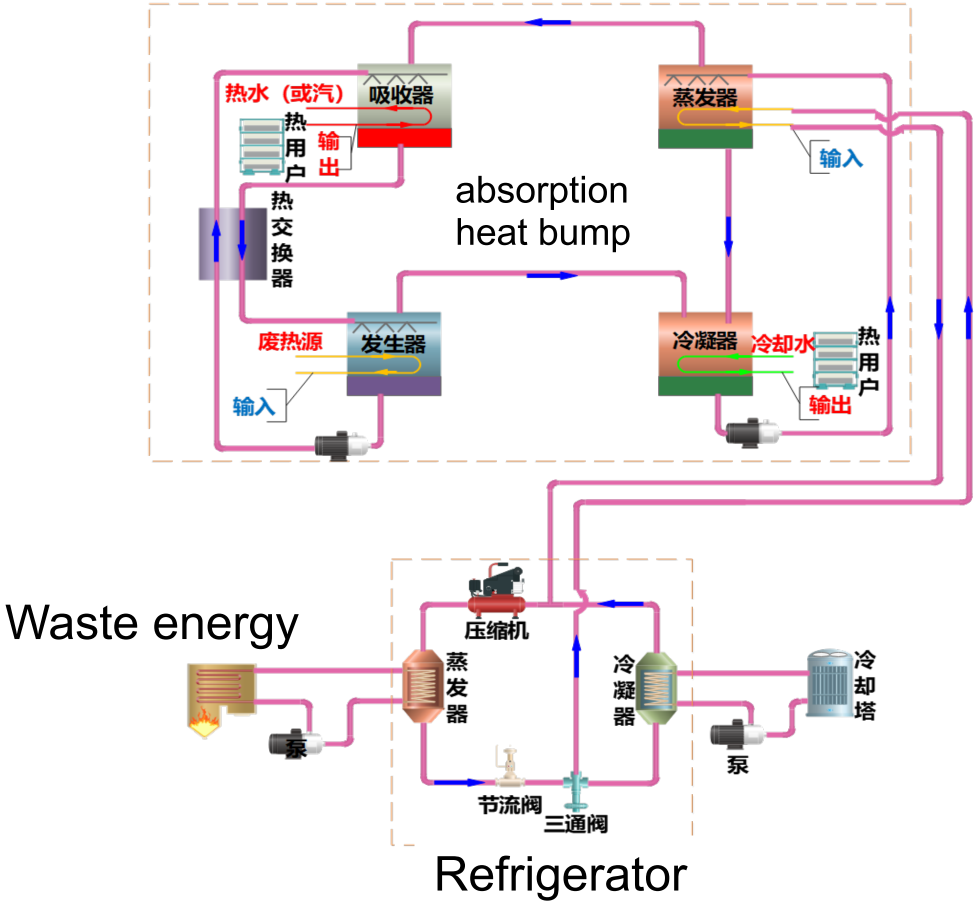

Working principle of air energy heat pump

# Waste energy reuse plan @ CEPC

cold-warm switchable heat bump

Refrigerator + absorption heat bump

- We plan to reuse the waste energy by “cold-warm switchable heat bump”
- In winter, it generates hot water at 80 ℃ for civil heating purposes. In summer, it is switched to generate cold water at 10 ℃ for air conditioning.




- It is possible to reuse waste energy of 282 MW, which corresponds to 2.92million-GJ per year (assuming an annual heating period of 2,880 hours).

# Energy Efficient Efforts at Daresbury Laboratory

- **SRF Thin Films:**
  - Extensive R&D programme underway with Horizon Europe IFAST programme.
  - Aim to demonstrate high-Tc SRF cavity performance ($E_{acc}$ and $Q_o$) capability.
  - Technology solutions to be developed for future UK-XFEL and ISIS-II facilities.

- **ZEPTO Permanent Magnets:**
  - Tuneable quadrupole and dipole prototypes developed for CLIC.
  - Quadrupole prototype developed and installed on Diamond synchrotron.
  - Technology solutions to be developed for CLARA and future UK-XFEL.

- **High Efficiency Klystrons:**
  - Strong collaboration with CERN to optimise designs for higher efficiency.
  - First prototype demonstrated by Canon – 8 MW, X-Band at 53.5% efficiency, compared to ~40% typical.
  - Technology solutions being developed for HL-LHC and FCC

- **Fast Reactive Tuners:**
  - Strong collaboration also with CERN, to develop viable technology to more optimally match RF power to SRF cavity.
  - Factor of >10x RF power reduction potentially feasible.
  - Recent Horizon Europe innovative Sustainable Accelerator Systems (iSAS) proposal submitted, is a mechanism for integrated capability demonstration.

UKRI Science and Technology Facilities Council