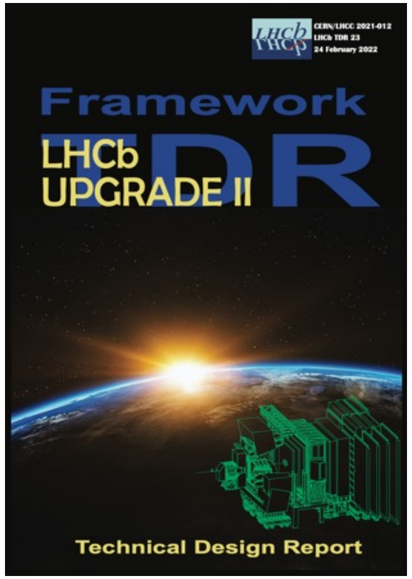
The University of Manchester

Environmental Issues in high energy physics detectors

Chris Parkes 27th November 2024

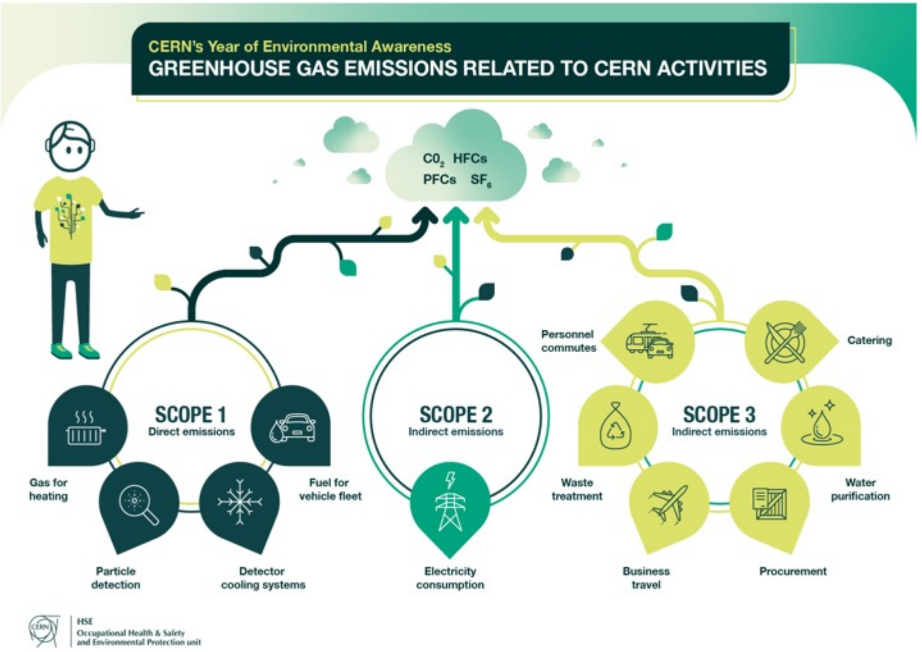
Main input from:
LHCb, DRD, Sustainable HEP,
ICHEP sustainability track,
CERN environment report



Definitions

R. Laxdal,Sustainability in HEP (accelerators, detectors, computing): ICHEP2024

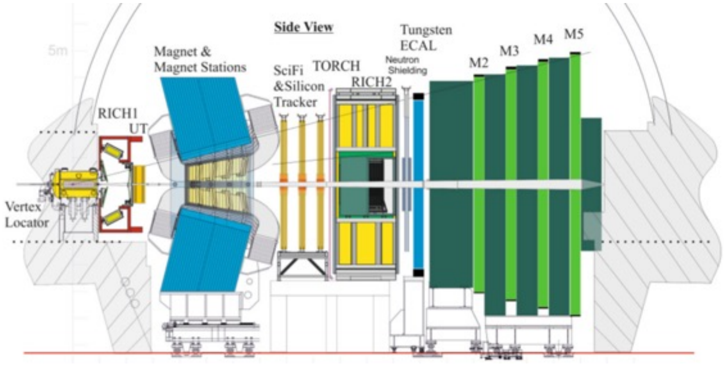
- **GWP_n = Global Warming potential**. A measure of how much energy the emissions of 1 kG of a gas will absorb over a given period of time, relative to the emissions of 1 kG of carbon dioxide (CO_2) relative to CO_2 after n years
- **Carbon footprint** - the amount of green house gases (GHGs), expressed as CO_2 equivalents, that are generated either directly or indirectly from a specific activity. Measured in kgCO2e (e=equivalent).
- **Scope 1**: Emissions from a source that an organization owns or controls directly, e.g. leaked gases from detector systems.
- **Scope 2**: Emissions associated with energy purchased and used by the organization, e.g. fossil fuels burned in power stations connected to the electrical grid
- **Scope 3**: Everything else. Emissions associated with the manufacture and disposal of products used by the organization, commuting, business travel.



LHCb Upgrade II Framework TDR CERN/LHCC 2021-012 LHCb TDR 23

Original	*Run 1 & 2: 2009-2018*
Upgrade I	*Run 3 & 4: 2022-2033*
Upgrade II	*Run 3 & 4: 2036-2041*

120-180M CHF core-cost
Major change to experiment



UKRI £50M FEC funding

- "The environmental impact of particle physics activities should continue to be carefully studied and minimised. A **detailed plan for the minimisation of environmental impact** and for the saving and re-use of energy should be part of the **approval process for any major project**. Alternatives to travel should be explored and encouraged." European Strategy for Particle Physics Update 2020.

- LHCb U. II for first time considered environmental issues
  - – Direct Emissions
  - – Power Consumption
  - – Travel

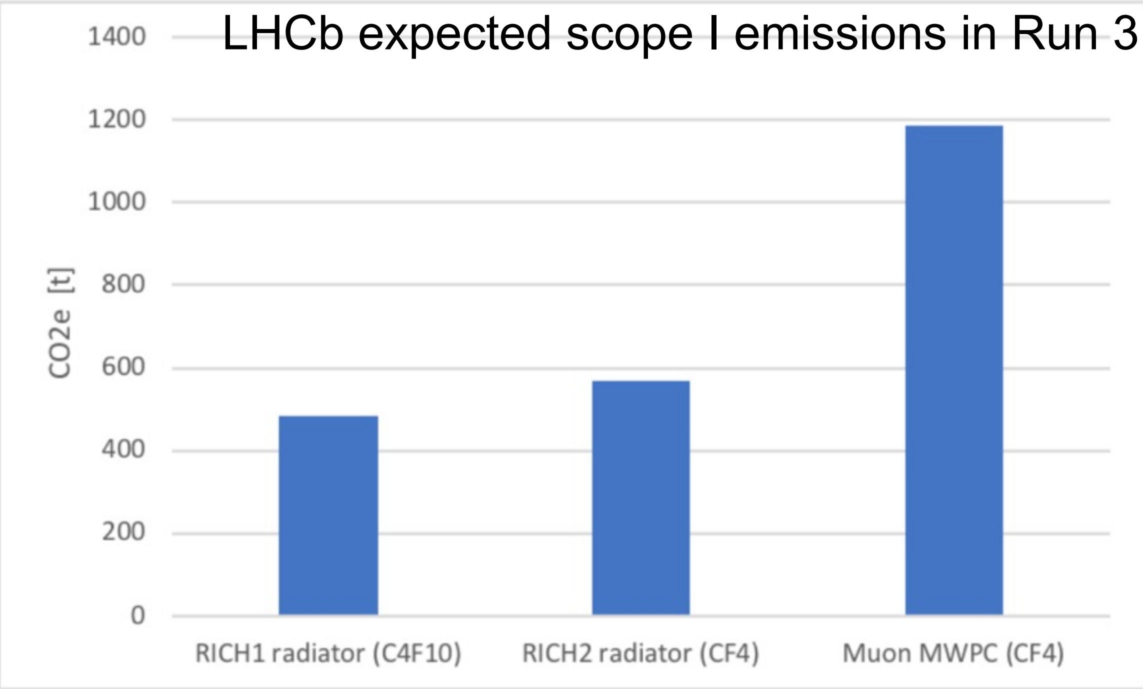
Next stages in approval:
Scoping document
Technical Design Reports of sub-systems

LHCb – Direct GHG Emissions (scope I) - Detection

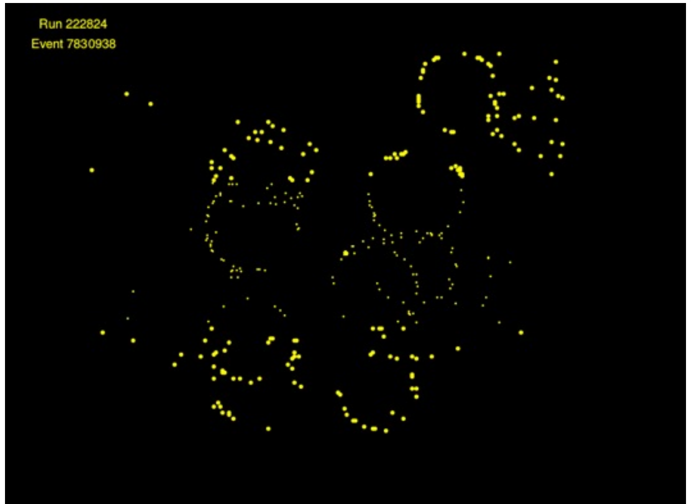
GWP_n = Global Warming potential relative to CO2 after n years

- **Detection systems**
- RICH – radiator gases, refractive index
  - RICH1 – C4F10: GWP_{100yr} 9200
  - RICH2 – CF4: GWP_{100yr} 6630
  - Upgrade I –
    - leak minimization
    - RICH2 test with CO2
      – Expect slight degradation in performance, system now ~leakless
- Muon systems
  - GEMs removed for Upgrade I
    - 40% reduction in emissions
  - MWPCs (default mixture Ar 40%/CO2 55%/CF4 5%)
  - μRWELL (default gas mixture Ar 45%/CO2 15%/CF4 40%) to be added for Upgrade II.

  R&D on gas mixtures to reduce CF4

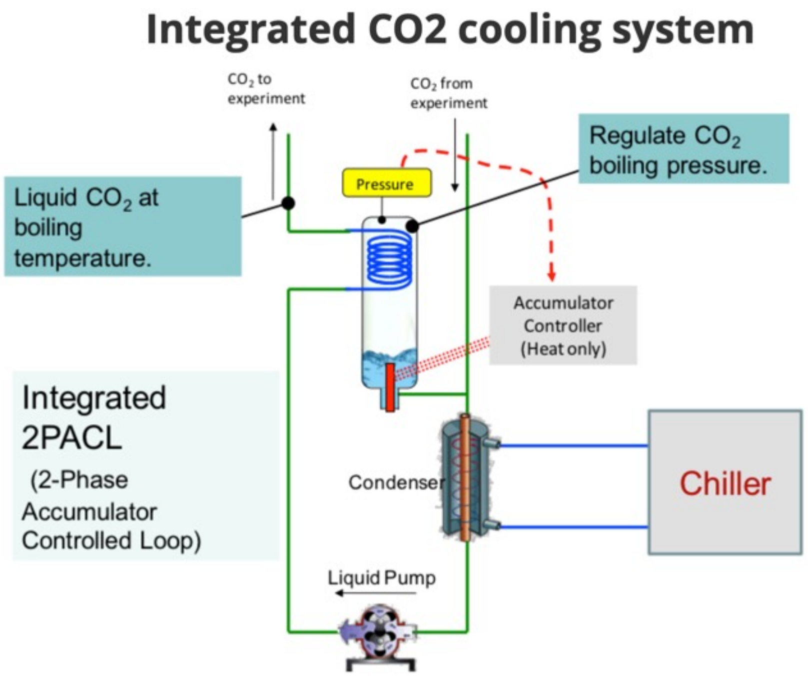


RICH2 rings
With CO2
Pilot beam test
2021



LHCb – Direct Emissions – Cooling Systems

- LHCb Run 1&2:
  - Pioneered bi-phase CO_2 cooling for VELO (widespread adoption at LHC)
  - C_6F_{14} gas GWP 7910 used in RICH/Silicon Tracker
- LHCb Run 3:
  - CO_2 for silicon tracker & VELO
  - Partial replacement others with NOVEC liquids
- **CO2 cooling systems**
  - A solution for larger detector systems.
  - + low GWP, radiation tolerant
  - Complex technology
- **Liquid Coolants**
  - Complex situation, discussed on following pages



What Green House Gases (GHGs) are used at CERN ?

G. Rigoletti, Overview of CERN strategies for the reduction of greenhouse gas emissions from particle detectors :Sustainability session ICHEP2024

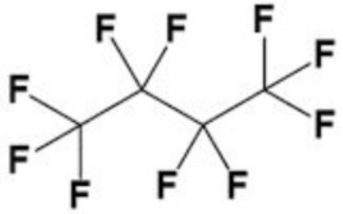
Greenhouse gases

The strength of a GHG is defined by its Global Warming Potential **GWP** ($GWP_{CO2} = 1$)

GHGs are often required in gaseous detectors

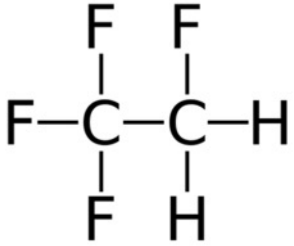
Fluorinated gases account for the **biggest emissions** at CERN

Most of F- gases were used before their environmental impact was understood



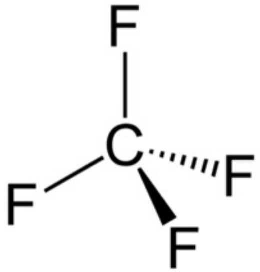
C4F10 (GWP = 8860)

Used in **RICH** for optical properties



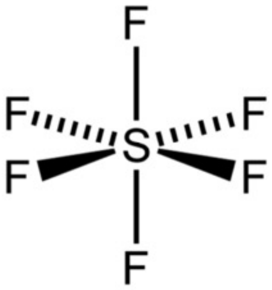
C2H2F4/R-134a (GWP = 1430)

Used in **RPCs** for primary ionization and charge multiplication



CF4 (GWP = 7390)

Used in **RICHs** (optical properties), **Wire** chambers (anti-polymerization) and **MPGDs** (time resolution)



SF6 (GWP = 22800)

Used mainly in **RPCs** as electron quencher

“Green” fluorocarbons ?

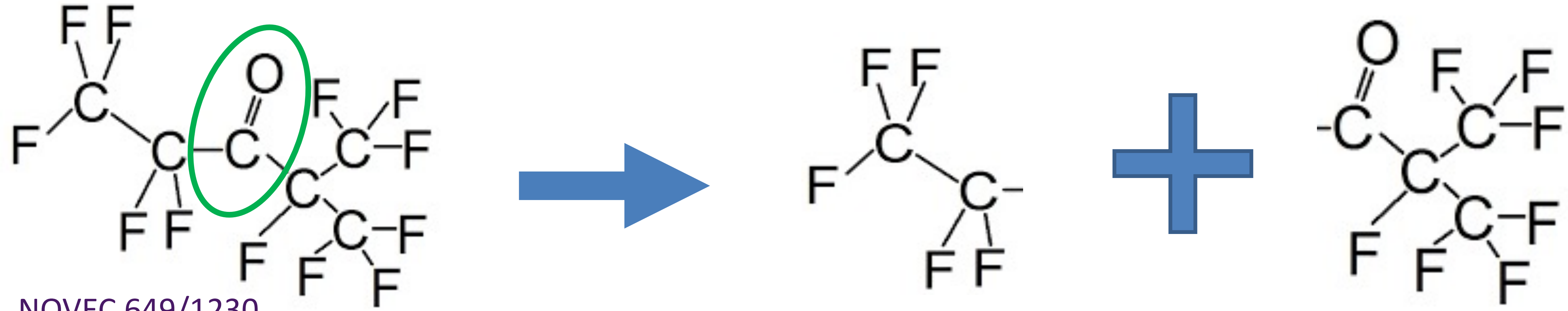
(for RICH radiators as well as cooling)

G. D. Hallewell, Green FCs for Cherenkov detectors and Si tracker cooling: Sustainability session ICHEP2024
B. Mandelli, Strategies to reduce GHG emissions from particle detectors: DRD Collaboration meeting, June 2024

ODP Ozone Depletion Potential → GHG Greenhouse gases → “ECO” gases → Natural gases

ODP Ozone Depletion Potential	GHG Greenhouse gases	“ECO” gases	Natural gases
Remove ~30 yrs ago	High GWP	3M NOVEC	Remove PFAS

Saturated Fluorocarbons high GWP e.g. CF4: GWP_{100yr} 6630
Fluorokeytones (such as NOVEC) can have low GWP



NOVEC 649/1230
C6F12O GWP ~ 1

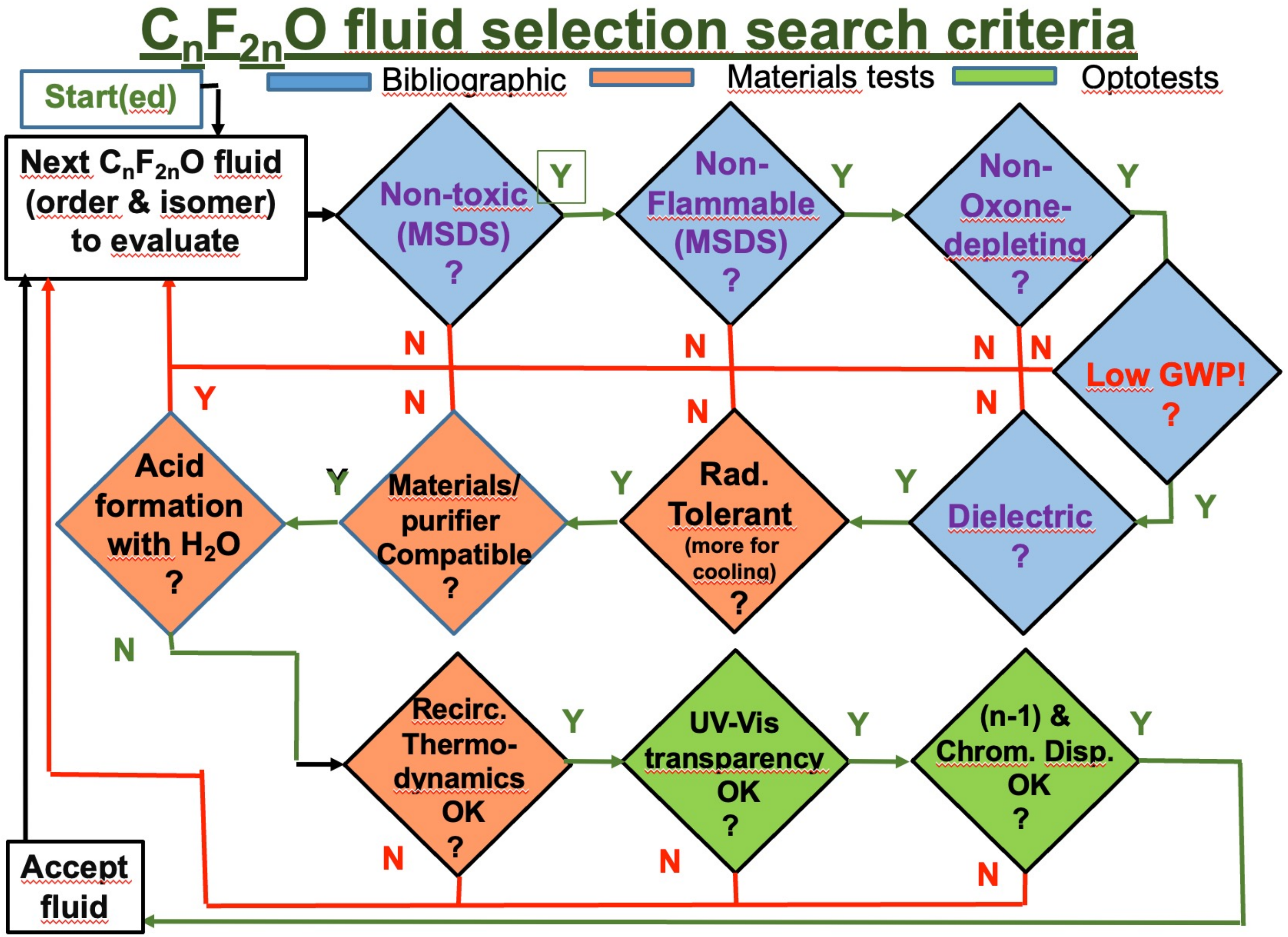
Scission by UV photons of λ ~300 nm in upper atmosphere
Gives Low GWP

Some Fluorokeytones are toxic

"Green" fluorocarbons ?

(for RICH radiators as well as cooling)

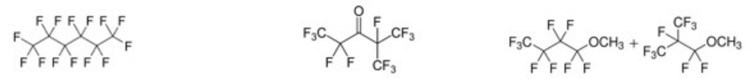
G. D. Hallewell, Green FCs for Cherenkov detectors and Si tracker cooling: Sustainability session ICHEP2024



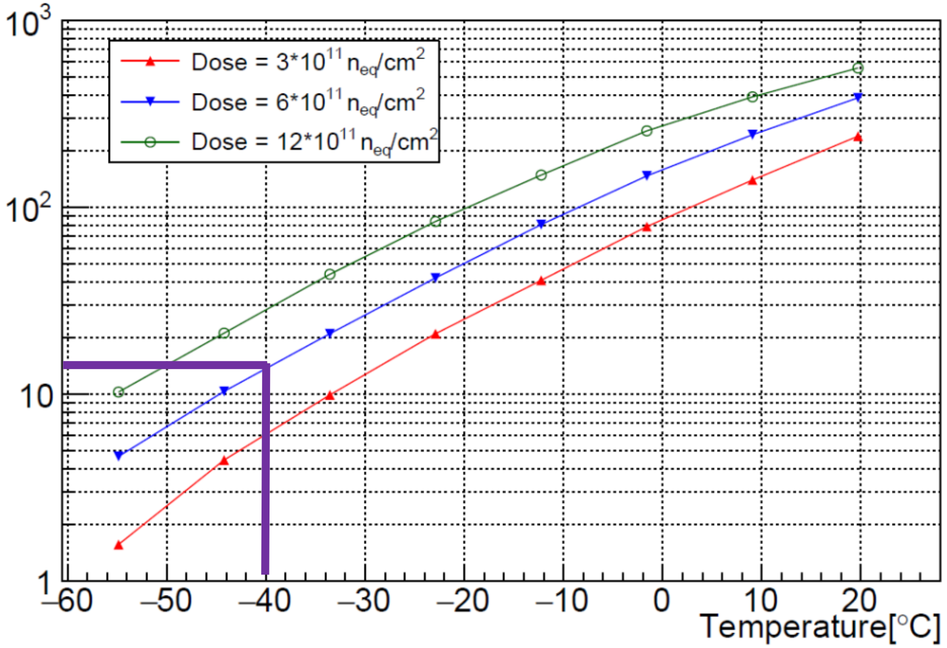
- Large number of requirements

Cooling Fluids – LHCb case study – SciFi Run 3

S. Jakobsen, Environmentally friendly fluids for detector cooling in LHCb: Sustainability session ICHEP2024



	Perfluorohexane (C_6F_{14})	NOVEC 649	NOVEC 7100
Freeze point [°C]	-86	-108	-135
Boiling point [°C]	57	49	61
Density [kg/l]	1.69	1.6	1.56
Flammability Range in Air	None	None	None
Volume Resistivity [Ohm·cm]	10^{16}	10^{12}	10^{8}
Global Warming Potential (GWP 100-year ITH)	9300	1	320



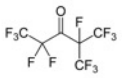
- SciFi SiPMs operated at -40C to limit dark count rate
- Cooling designed for Novec 649
- Liquid circulation pumps broke after short time

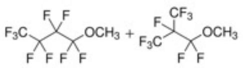
Water reacts with NOVEC 649 to form acid strong enough to corrode even stainless steel.

- Currently operating C6F10
- Moving to NOVEC7100

Cooling Fluids – LHCb case study – RICH Run 3

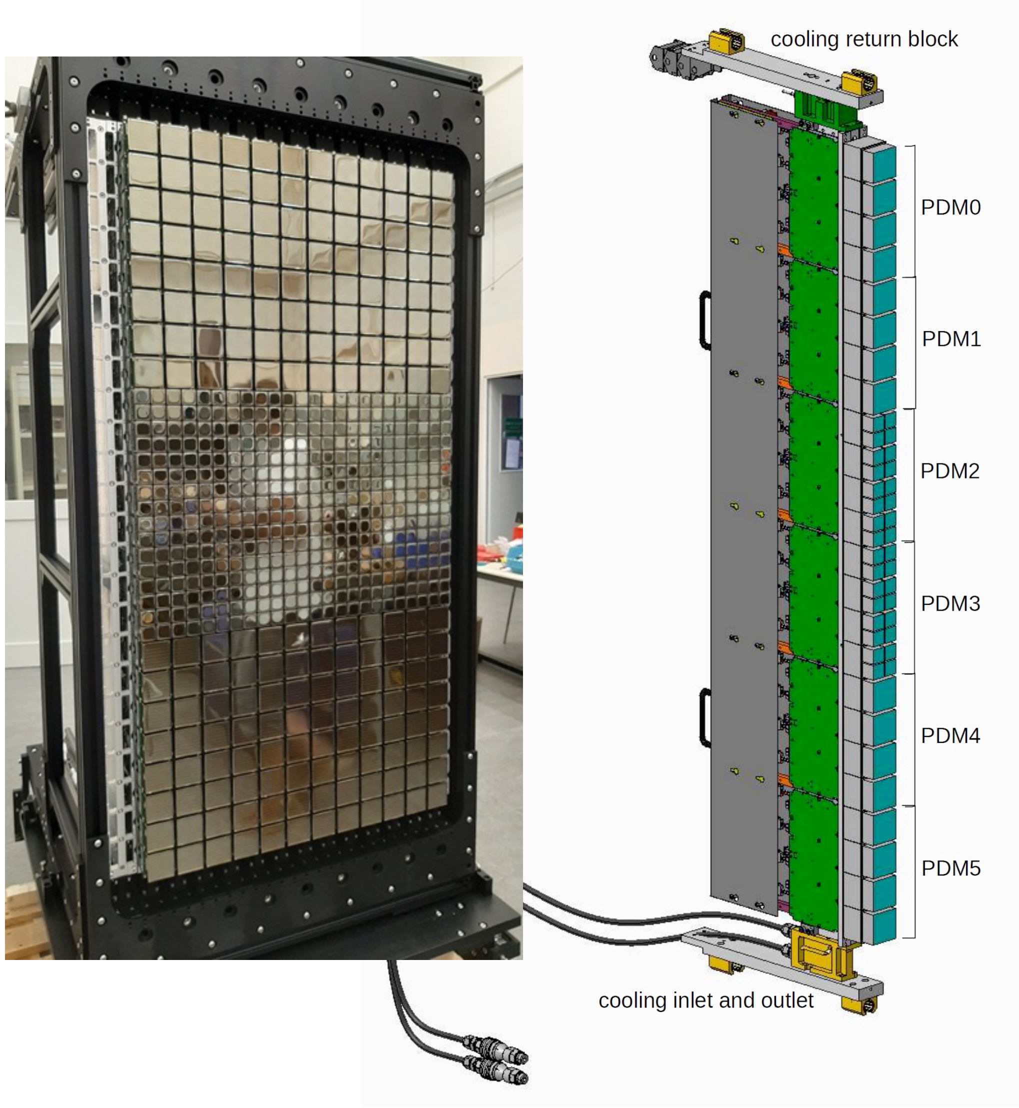
S. Jakobsen, Environmentally friendly fluids for detector cooling in LHCb: Sustainability session ICHEP2024





	Perfluorohexane (C_6F_{14})	NOVEC 649	NOVEC 7100
Freeze point [°C]	-86	-108	-135
Boiling point [°C]	57	49	61
Density [kg/l]	1.69	1.6	1.56
Flammability Range in Air	None	None	None
Volume Resistivity [Ohm·cm]	10^{16}	10^{12}	10^{8}
Global Warming Potential (GWP 100-year ITH)	9300	1	320

- RICH MaPMTs cooled to 16C, remove heat from electronics
- Operated with Novec 649
  - Avoid water, NOVEC nonconductive in case of leaks
- O ring leak after 3 months
  - NoVEC or production problem ?
- Undecided if stay with NOVEC649 or move to 7100



LHCb - Validating NOVEC 7100

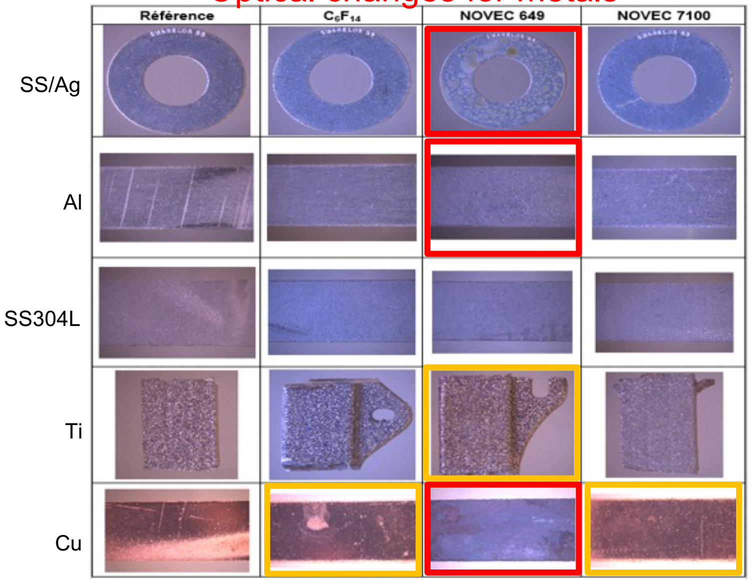
S. Jakobsen, Environmentally friendly fluids for detector cooling in LHCb: Sustainability session ICHEP2024

- Test metals, PEEK, polymers…
  - NOVEC 649 problematic
  - NOVEC 7100 OK
- Year long test performed
  - NOVEC 7100 OK
- **Moving to NOVEC 7100**
  - Factor 30 GWP better than C_6F_{10}

Encourage CO_2 in LHCb for Upgrade II

LHCb Mighty Tracker cmos pixels in Manchester – were designing for NOVEC now moving to CO_2

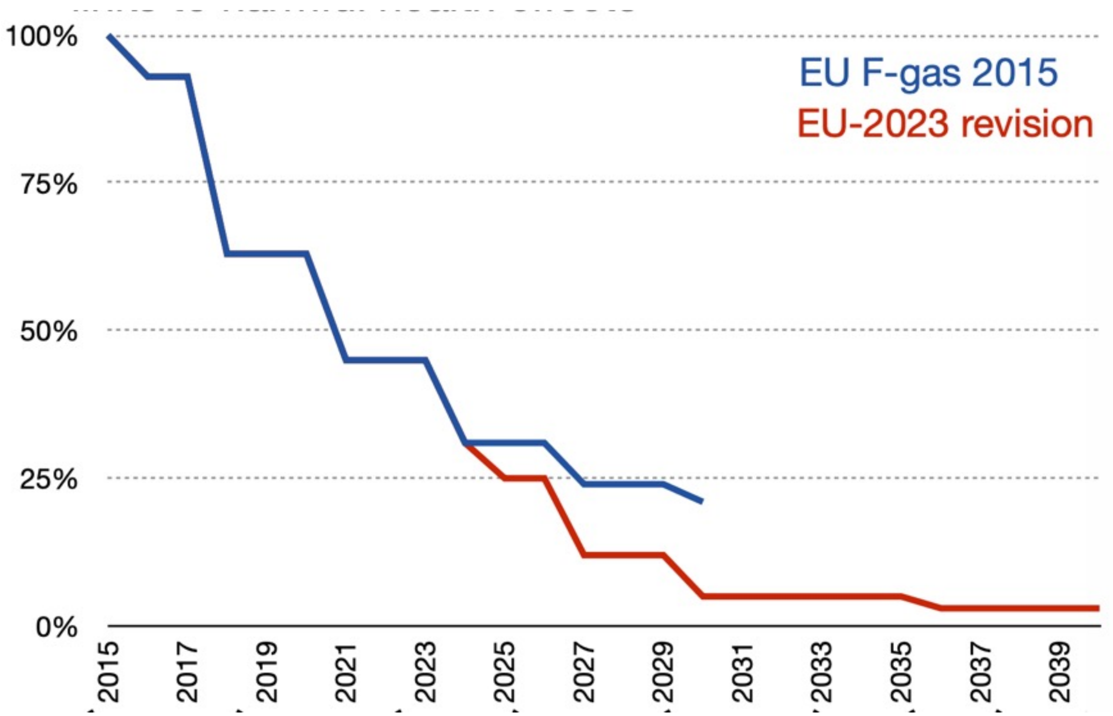
Optical changes for metals



New F-gas regulation

B. Mandelli, Strategies to reduce GHG emissions from particle detectors: DRD Collaboration meeting, June 2024

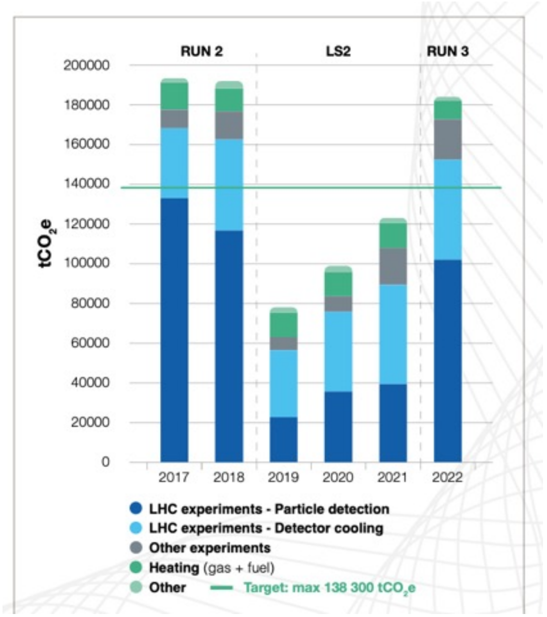
- European Chemical Agency proposal 2023
- Elimination of hydroflourocarbons by 2050
- Future availability determined by manufacturers & legal restrictions
- 3M withdrawing NOVEC as PFAS
- Alternative manufacturers
- Demand is driven by electronics industry demands

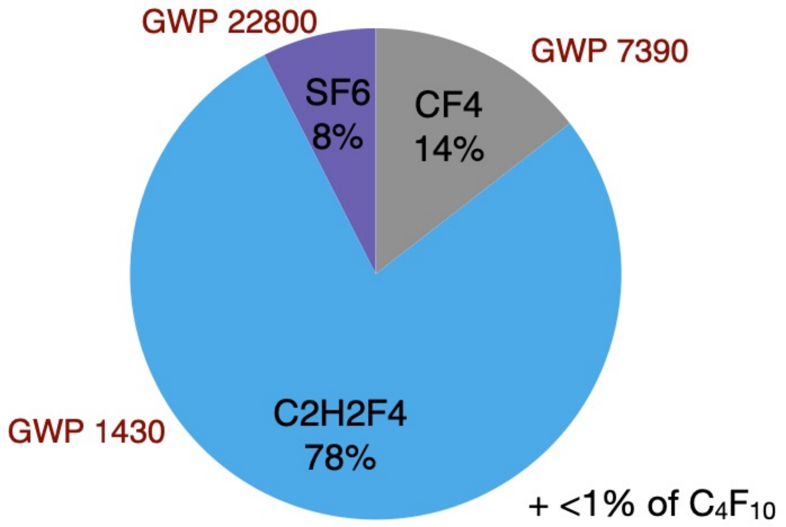


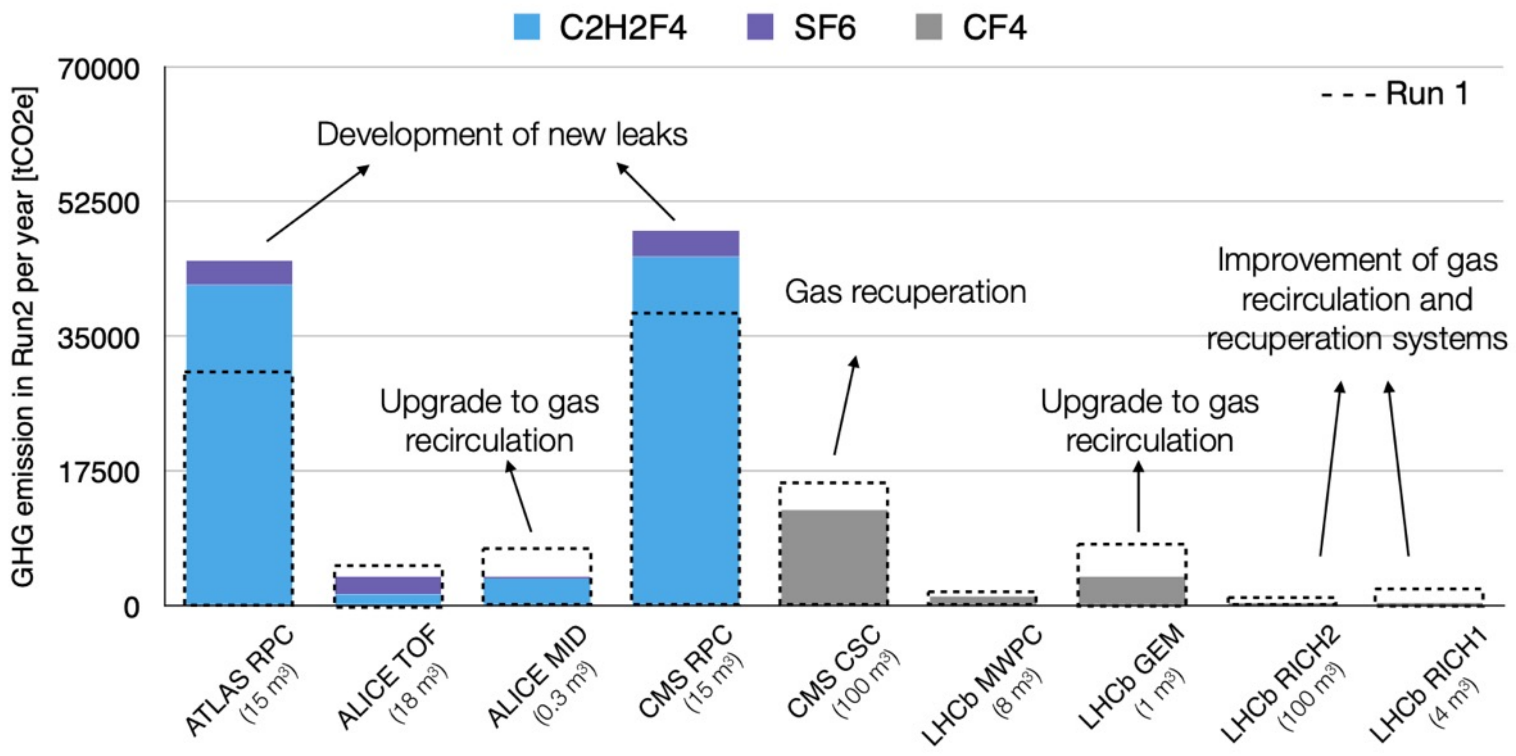
- Likely exemption in short term for low temp cooling since no monophase alternative but we have longterm projects

CERN Scope 1 Emissions

B. Mandelli, Strategies to reduce GHG emissions from particle detectors: DRD Collaboration meeting, June 2024
CERN Environment Report 2021-2022





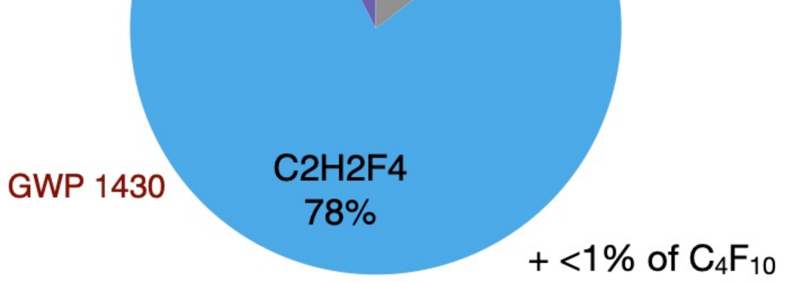


- 90% CERN emissions from LHC
- 78% from fluorinated gases
- ATLAS & CMS RPCs dominate

CERN Scope 1 Emissions

B. Mandelli, Strategies to reduce GHG emissions from particle detectors: DRD Collaboration meeting, June 2024
CERN Environment Report 2021-2022

100,000 tCO2e /annum =
fully occupied A340 London → New York per day



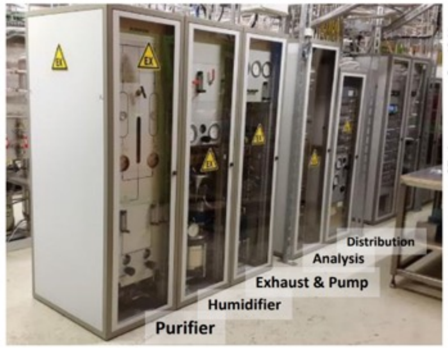
- 90% CERN emissions from LHC
- 78% from fluorinated gases
- ATLAS & CMS RPCs dominate

GHG gas reduction strategies

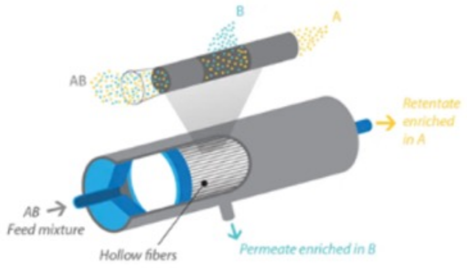
B. Mandelli, Strategies to reduce GHG emissions from particle detectors: DRD Collaboration meeting, June 2024

- Gas Recirculation
  – purify & resupply – since start of LHC.
  – Typically large systems, developing smaller for labs
- Gas Recuperation
  – Remove impurities, more complex

ALICE MID gas system

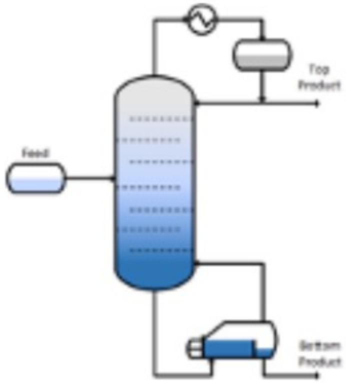


Membrane separation



Pressure and thermal swing adsorption

Distillation



Gas recuperation systems for GHGs at CERN:

CF_4: CMS Cathode Strip Chambers and LHCb RICH2
- Both systems operational

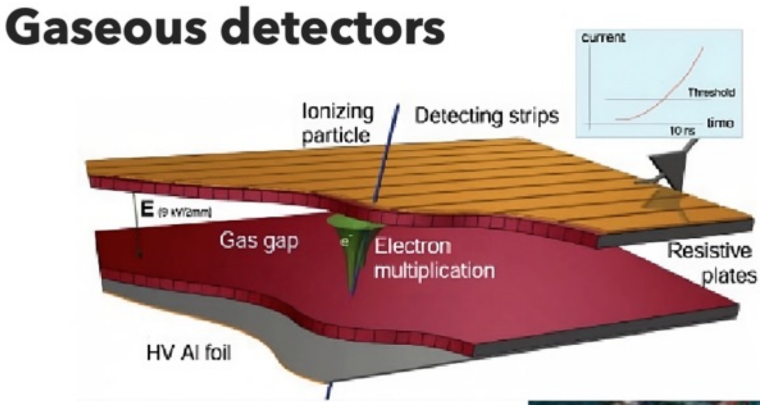
$C_2H_2F_4$ and **SF_6**: Resistive Plate Chambers (RPC)
- First system will be operational in ~1month

C_4F_{10}: LHCb RICH1
- Old system operational new under design

- **Alternative gases**

Alternative Gases –RPCs etc..

D. Ramos Lopez, Performance and ageing studies on Eco-Friendly Resistive Plate Chamber detectors : Sustainability session ICHEP2024
L. Quaglia, Green transition of Resistive Plate Chamber detectors for HEP applications : Sustainability session ICHEP2024



Efficient, good time response
Modest resolution, **cover large area cheaply**
Muon detector systems

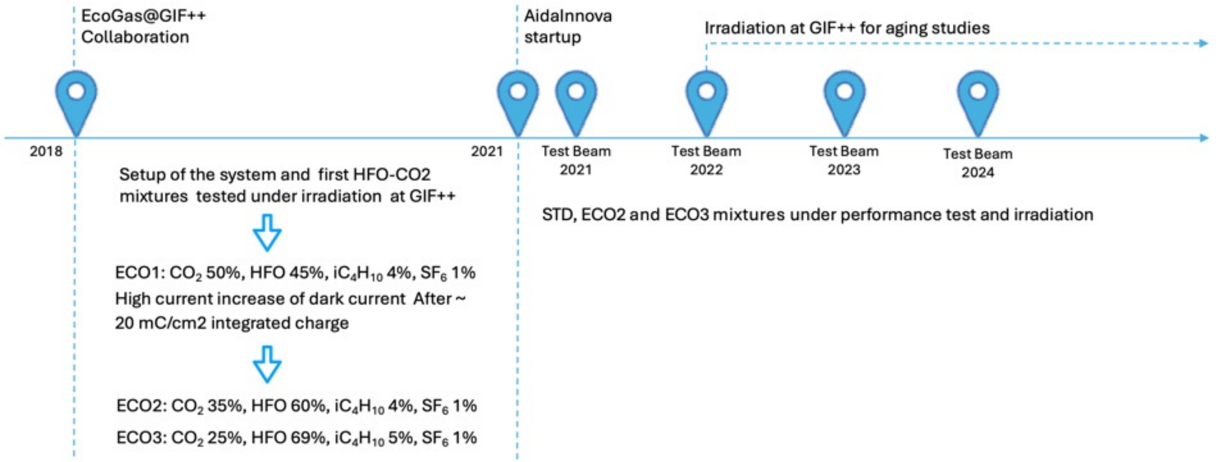
Gas Properties

1) High density of primary ion-electron pairs

2) Relevant quenching properties
→ Ability of capturing recombination photons without further ionization

3) Enough electron affinity to capture free electrons, reducing the spatial size of the discharge

ECO-Gas @ GIF++ Collaboration
24 Institutes (none UK)
Efficiency
Streamer probability
Aging with irradiation

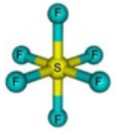


- Very difficult to find eco-friendly gas mixtures for current LHC gaseous detectors
- Need to understand detector lifetime with new eco-friendly gases

ATLAS Muon RPCs

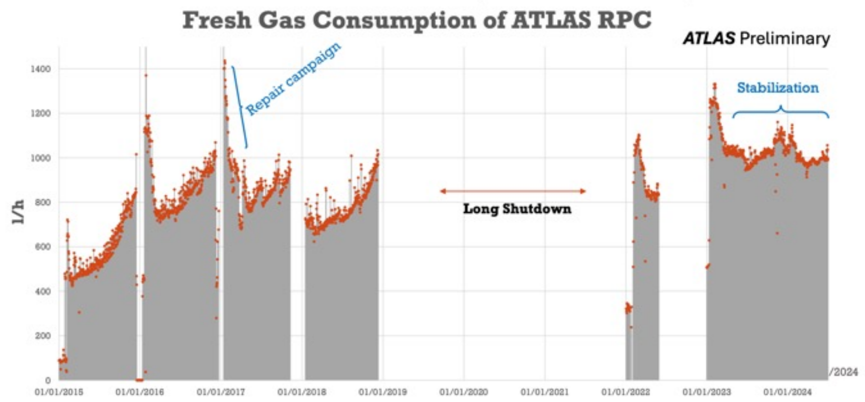
Sinem Simsek, Mitigation of the ATLAS RPC environmental impact: Sustainability session ICHEP2024

- Significant leaks 1000l/hr



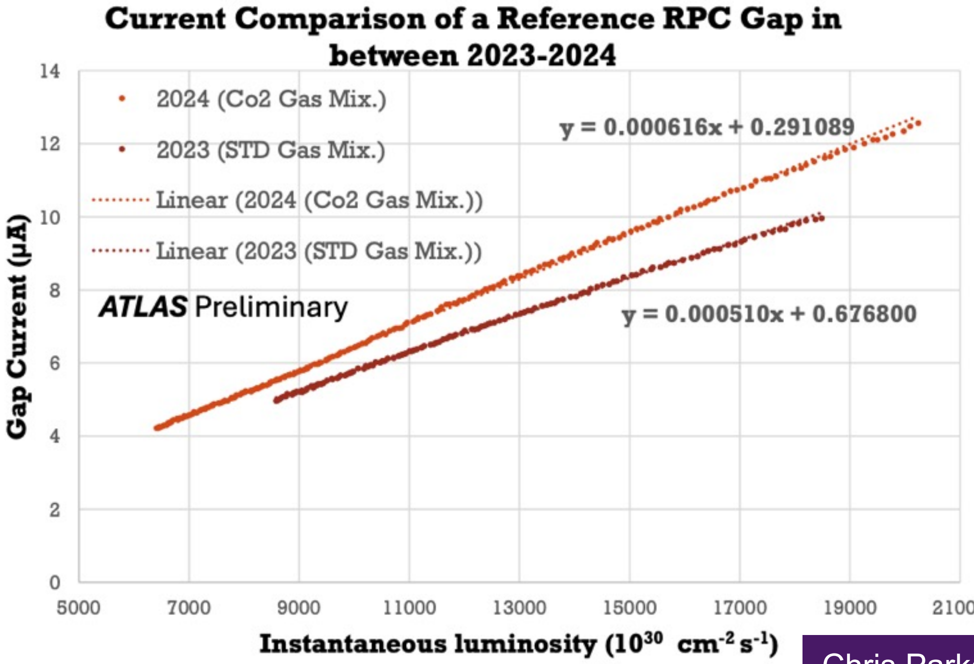
The RPC (Atlas case) standard mix is 94.7 % [R134A] 5 % [C4H10] 0.3% SF6

- R134A has high electron density (high primary ionization) and is electronegative to control the avalanche growth;
- C4H10 absorbs photons provoking the degradation of fluorinated gases which byproducts may damage the chamber
- SF6 an electronegative component that helps to prevent the transition to streamer.



Non-return valves
Glueing & polyurethane foam at leaks

- RPC Gas mixture has been changed to include 30% CO_2 from August 2023
- Good Performance & aging test results
- GWP of mixture 661-> 569, 14% reduction
- Aim for 36% reduction in future



Current / Future RPC projects

Aashaq Shah, Eco-friendly gas mixtures for gaseous detectors at CERN and beyond : Sustainable HEP 2024
The Road Ahead for CODEX-b, Snowmass whitepaper 2022
The SHiP experiment at the proposed CERN SPS Beam Dump Facility 2022

- ATLAS & CMS Upgrade II: 4000 m^2 & 3000 m^2
  - Aim produce new detectors with leak tight construction

Large scale **future projects** proposals for **RPCs**
with UK involvement for long lived particle searches

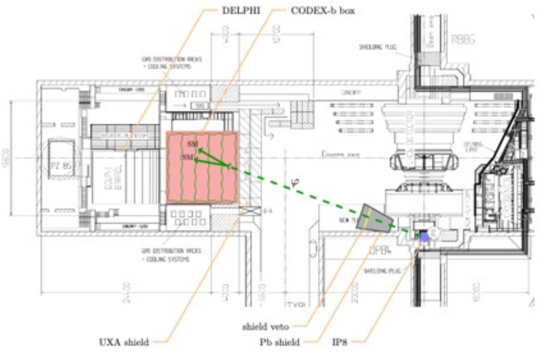
LHCC: New projects will not be approved unless they have minimal environmental impact

ANUBIS – AN Underground Belayed In-Shaft search experiment
Instrument ceiling of ATLAS cavern & service shafts ~ 1000 m^2 detector
Plan to utilize ATLAS Phase II RPC Design
R&D work on gases in Cambridge

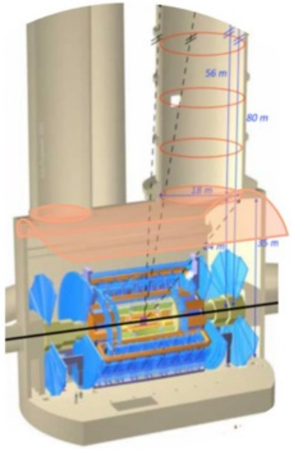
CODEXb - COmpact Detector for EXotics at LHCb
Instrument in LHCb Service Cavern ~ 1600 m^2 detector
ATLAS Phase II design, Birmingham involved

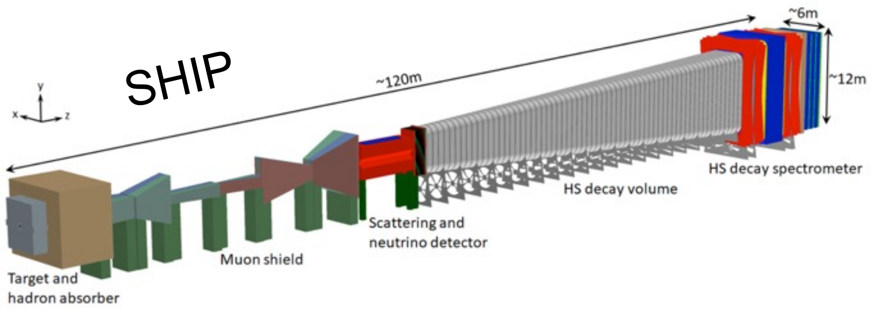
SHIP – Search for Hidden Particles
CERN approved project in 2024
~ 288 m^2 muon detector Scintillator or RPC + straw tracker
Several UK institutes involved

CODEXb



ANUBIS





DRD Collaborations – started Jan. 2024

https://drd.hep.ac.uk/

- Detector R&D Collaborations
  - DRD1: R&D on alternative gas mixtures
  - DRD4: D4.1.3 - Design of eco-friendly fluorocarbon gas system

Roadmap

Implementation

CERN/SPC/1190
CERN/3679

3

Annex 1

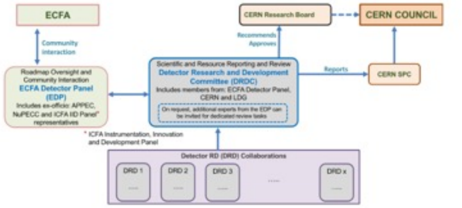
Proposed Implementation Plan for the 2021 ECFA Detector Research and Development Roadmap

For each of the technology areas considered, the 2021 ECFA Detector Research and Development Roadmap[1] (hereinafter referred to as the Roadmap) has identified major detector R&D themes (DRDTs) where longer-term research must be carried out, in most cases directed towards experiments at large future facilities with earlier experiments as important "stepping stones". A major guideline was to define the requirements and milestones such that detector R&D would not be the limiting factor in establishing the next large research projects envisaged on timescales extending well beyond the High-Luminosity LHC programme.

In addition, community themes have been developed, some of which are reflected in the general strategic recommendations (GSRs) that must also be addressed in the coming years.

1. Establishment of DRD Collaborations at CERN

It is proposed that the long-term R&D efforts be organised into newly established Detector R&D (**DRD**) collaborations, as illustrated below, following the model of the well-known and very successful RD collaborations established in the early 1990s to address the huge challenges posed by the construction of the LHC detectors.



Proposed organisational structure for implementation of the Roadmap (the arrows indicate the reporting lines)

- In the detector area, larger DRD collaborations should be considered. The proposal is that such collaborations be established to address each of the six detector technology areas identified in the Roadmap. This would guarantee a critical mass of institutes, expertise and effort, thereby avoiding too much fragmentation. It would also keep the administrative support and reviewing requirements to a manageable level. For the cross-cutting areas of electronics and integration, one or two further DRD collaborations should be anticipated; they should pick up on specific themes, but not necessarily be mapped directly onto the TF topic areas.
- In addition, the community themes identified in the area of training must be addressed. However, for these, alternative implementation steps are needed, as discussed later in this document.

[1] http://cds.cern.ch/record/2784893/files/

STFC considering sustainability policy, SOI options

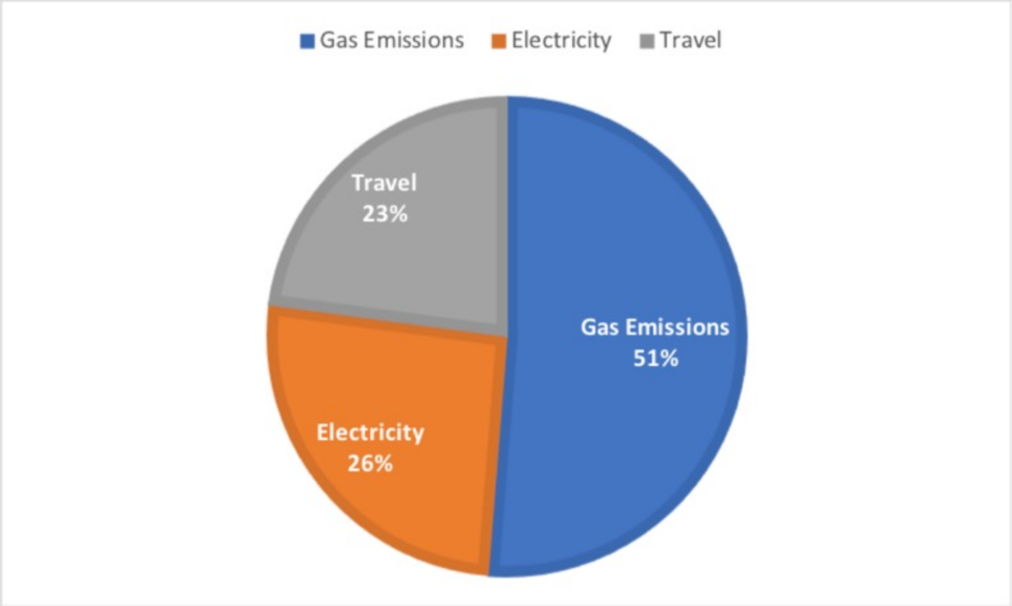
DRD-UK:

- low-GWP gases for detectors
- Low-GWP and non-PFAS liquid coolants
- Computing farm power consumption

LHCb – Indirect – Power Consumption

- 88% carbon free French electricity
- In longer term expect increased renewables use and thus not focus of detector sustainability plan
- Warm magnet – 4.6MW in operation
  - 84% of peak power in Run 2
  - Heat-recovery plant recently implemented
    - Hot water for heating 8000 homes in new area of adjacent town of Ferney Voltaire
- Computing
  - Increased demand 0.5MW Run 2 →1.5 MW Run 3
  - New computing farm – efficient cooling (see next slide)
    - But not in heat recovery plant due to practicalities
  - Operation modes, software rewrites
    - All good for HEP but beware “bounce back”, impact on sustainability may be low
    - Savings get ploughed back into more event generation / computing power

LHCb expected emissions in Run 3
Total 4400t CO2e / annum



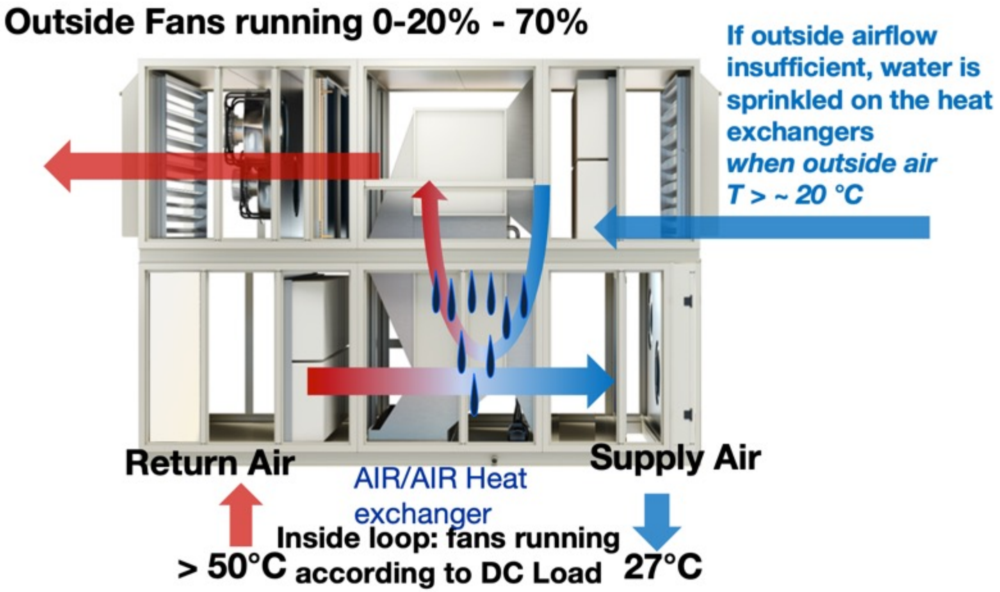
Data Centre Cooling – LHCb Case Study – Trigger Run 3

N. Neufeld, Sustainable computing solutions: a case-study of the LHCb data-centre: Sustainability session ICHEP2024

Core metric = Power Usage Efficiency

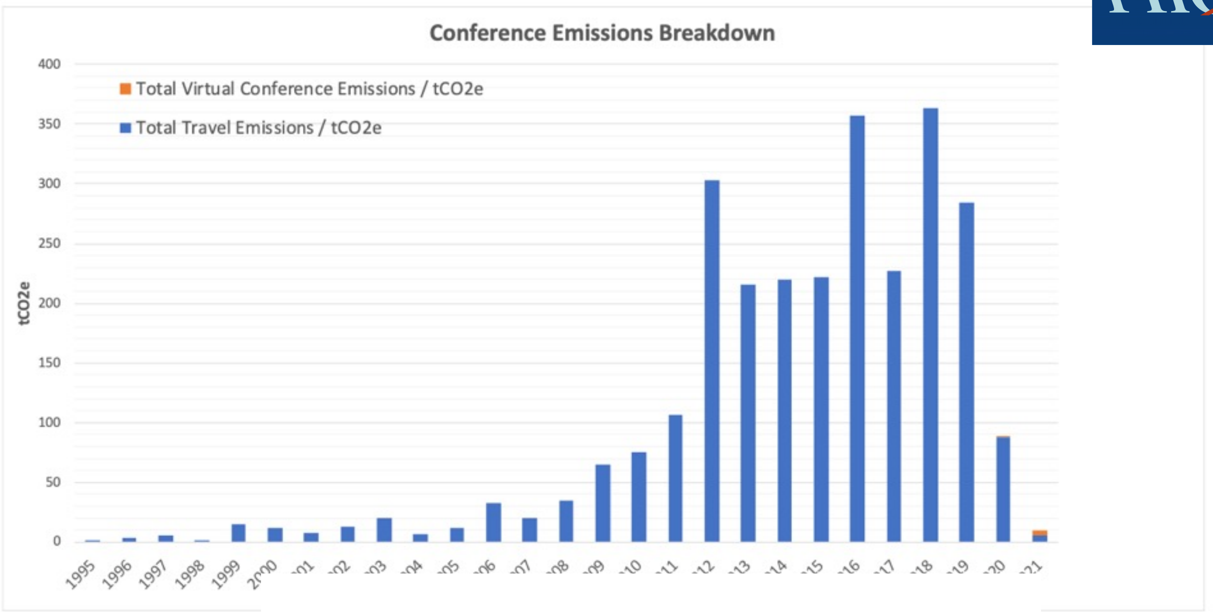
PUE = $\frac{\text{Total } power\ consumed\ by\ the\ data-centre}{\text{Total } power\ consumed\ by\ IT\ equipment}$

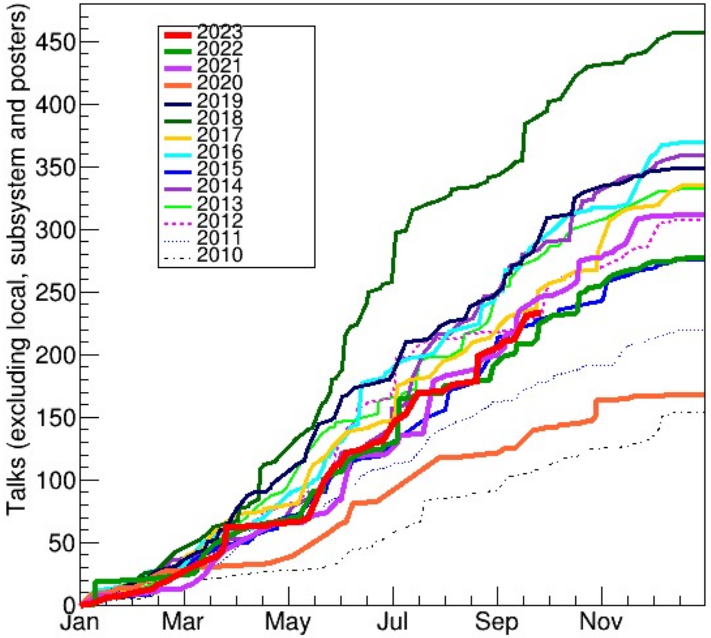
- Main heat dissipating unit are compute servers pushing hot air out at the rear of a metallic enclosure
- 1.4MW DAQ+Trigger
- **indirect free air-cooling**
- Achieve a PUE < 1.1
- Future: direct liquid cooling ?



LHCb - Travel

- Tension with:
  - international cooperation
  - career development of ECRs
  - Prestige & finances of conference hosting institutions / cities
- Estimated for LHCb weeks & conferences only
  - LHCb week outside Europe – indication of compensation as less people attend.
- Discussions in pandemic period of not returning to same model
  - Conferences seem to have gone back to like before
  - (Experiment travel maybe less ?)



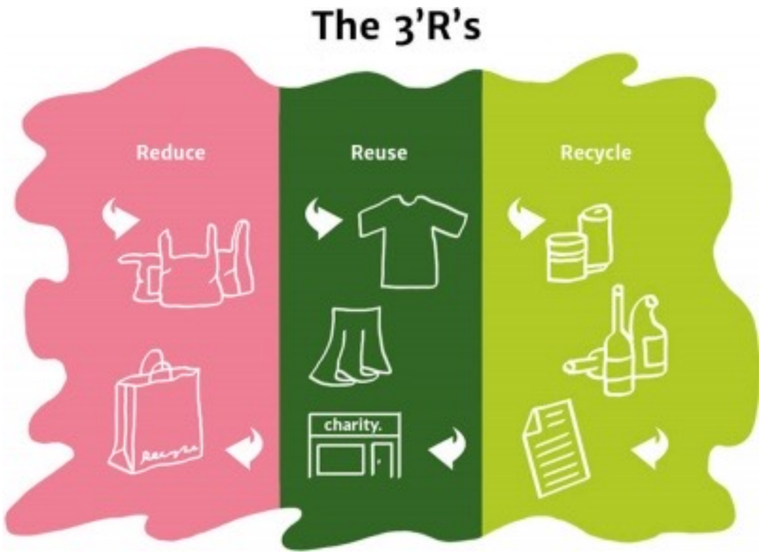


LHCb embedded emissions (scope 3)

- Not estimated
- Proposal to estimate for Subsystem TDRs
- Potential method
  - Obtain materials from simulation description
  - Use life cycle analysis database to estimate impact

Thanks to Hannah Wakeling for advice

- **Reuse**
  - LHCb Run1 &2 Outer tracker donated to GSI Darmstadt FAIR Panda
  - More of this ! Anecdotally, Nuclear physics better than HEP



Radiation Protection & Safety

- Assess radiation impact on installation, maintenance & decommissioning
- Measurements & simulations for workplace radiation limits
- Radioactive waste minimization
  - Installed temporary building for LS2 for storage
- Modify and Reuse
  - Rails of outer tracker modified for SciFi (360kg of material)

LEAF - Laboratory Efficiency Assessment Framework

Sustainability not only for large scale facilities

CATEGORY	Bronze	Silver	Gold
Waste	Provide recycling bins in the lab	Single-use plastic waste has been reduced (guidance provided)	Recycling rates have been increased, or overall waste produced has been decreased
People	Samples owned by departing staff are cleared or tracked	The lab has engaged other labs on LEAF and sustainability	One action to reduce travel has been implemented
Sample & Chemical Management	Labels are legible, and there's a common labeling system in place	Procedures are in place in case cold storage equipment breaks down	At least 80% of all samples and/or chemicals are clearly catalogued
Equipment	Equipment is turned off when not in use	There is a system in place for communal equipment booking	Excess equipment is repaired, sold, and/or donated
Ventilation	There is a clear reporting system for building issues	Fume cupboard sashes are kept closed when not in use	Solvent vapours are condensed and disposed and not released into the atmosphere

- Laboratory standard to improve the sustainability and efficiency of laboratories

LEAF
The Laboratory Efficiency Assessment Framework

Summary & Actions

Adapted from
R. Laxdal, Sustainability in HEP (accelerators, detectors, computing): ICHEP2024

- Large HEP detectors have a significant carbon footprint from green house gases from detectors, consumption of electrical energy for magnets and data centres, procurements, travel and waste.

Proposed actions include:

- Perform **lifecycle analyses** of total energy and carbon footprint for all future large detector projects
- Support **R&D to reduce carbon emissions** with a priority as high as performance and cost reduction R&D.
- Advocate **remote or hybrid meetings** to reduce air travel in our community
- Reward **industrial partners** who exemplify best practise in sustainability
- Consider **carbon cost** in addition to capital cost in procurement decisions

First Dog on the Moon

Sources & Credits

LHCb Upgrade II Framework Technical Design Report

HEPCAP+ report

CERN environmental report

ICHEP '24 sustainability stream

Sustainable HEP 2024

Individuals:

Olaf Behrendt, Roberta Cardinale, Gloria Corti, Silvia Gambetta, Greg Hallewell, Sune Jakobsen, Robert Laxdal, Dayron Ramos Lopez, Beatrice Mandelli, Niko Neufeld, Jonas Rademacker, Gianluca Rigoletti, Angela Romano, Heinrich Schindler, Aashaq Shah, Sinem Simsek, Luca Quaglia, Hannah Wakeling

First Dog on the Moon

backup

- ~1tCo2e London->New York return journey / passenger
- 100,000 tCo2e/annum = 200,000 passenger journeys
- 555 passengers/ A340 plane in 3 class setup
- Emissions equiv. to 360 planes/yr
- 1 full plane per day
- CERN 2022 emissions 180,000 tCO2e