Cooling Solid State Detectors for inner tracking at very high luminosity

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Workshop on requirements for future detector technologies in view of FCC-hh
CERN, 3-4 February 2015

Cooling Solid State Detectors for Inner tracking at very high luminosity:

The starting challenges:

- ***Evacuation of (O ~ >> 200 kW) tracker heat dissipation, probably MW…***

  {deep sub-μ (65 nm - & maybe smaller) FEE, ➔ finer granularity & pixel density for higher Luminosity
  but should try to stay below 1 W.cm^{-2} on average}

- ***Maintain low Si substrate temperatures (probably ~ << -30 ^{0}C: technology & position dependent) for at least factor 2 safety margin against I_{leak} - induced thermal runaway after inner layer radiation dosed (O>~10^{16} n eq. cm^{-2}) equivalent to highest ʃL.dt***

  (10 yrs..? >> 3000 fb^{-1} (3-20 ab^{-1}…)

- ***Minimize dead %X/X0 of cooling & support services in $(0 \leq \eta \leq 2.5..?)$ bite of the tracker***

  Need to understand sharing of dissipation between FEE & its VLVDC supply cabling (~1.2VDC @ point of use),
  pulsed /serial powering: where these elements are determines their coolant type

➔ *Maybe in a position one day where more heat must be removed from power distribution services than FEE & Si substrates?*
See: P. Phillips (STFC-RAL: 2013 ECFA-LHC-HL-workshop: ***ATLAS and CMS long LVDC delivery only 40% efficient***
https://indico.cern.ch/event/252045/session/7/contribution/21/material/slides/

➔ ***Minimum mass flow in "on-detector" cooling channels ➔ phase change (rather than monophase) cooling:***

Cooling Solid State Detectors for Inner tracking at very high luminosity:

Some possible directions:

- *Radiation resistant phase-changing fluids*

  (+ non-conductive, non-toxic, non-flammable, non-O_3 depleting) :

  ➔ *Saturated ($C_nF_{(2n+2)}$) fluorocarbons and their blends, CO_2, N_2O? ..?*

- *Different coolant & working pressures in "On detector" **supports***

  &"Off detector" services?

  ➔ *Lower evaporating pressure fluids in "on-detector" elements,*

  particularly if Si micro-channels used here

Cooling Solid State Detectors for Inner tracking

4 technology threads…

(1) Gas flow convective cooling:

Heat transfer coefficient is low: suitable only for very low on-detector dissipation so probably not here…

Examples: Star RHIC, SLD vertex detector ➔

(2) Ducted monophase cooling:

***Water** and **fluorocarbons** used:*

(2.1) water must be used in "leakless" (= sub-atmospheric pressure) and at room temp to avoid toxic (or flammable) antifreeze additives Example: ALICE vertex detector upgrade ➔

(2.2) Saturated fluorocarbons: usually C_6F_{14} (like CMS today):

advantage of low viscosity and relatively low saturated vapor pressure:

can also be used in silicon, kapton μ-channel (pump is only pressure limitation) (see later)

(3) Ducted, Closed (conserved) evaporative cooling

Single Saturated Fluorocarbons and CO_2 in metal tubes, (N$_2$O also proposed but unlikely to be acceptable…)

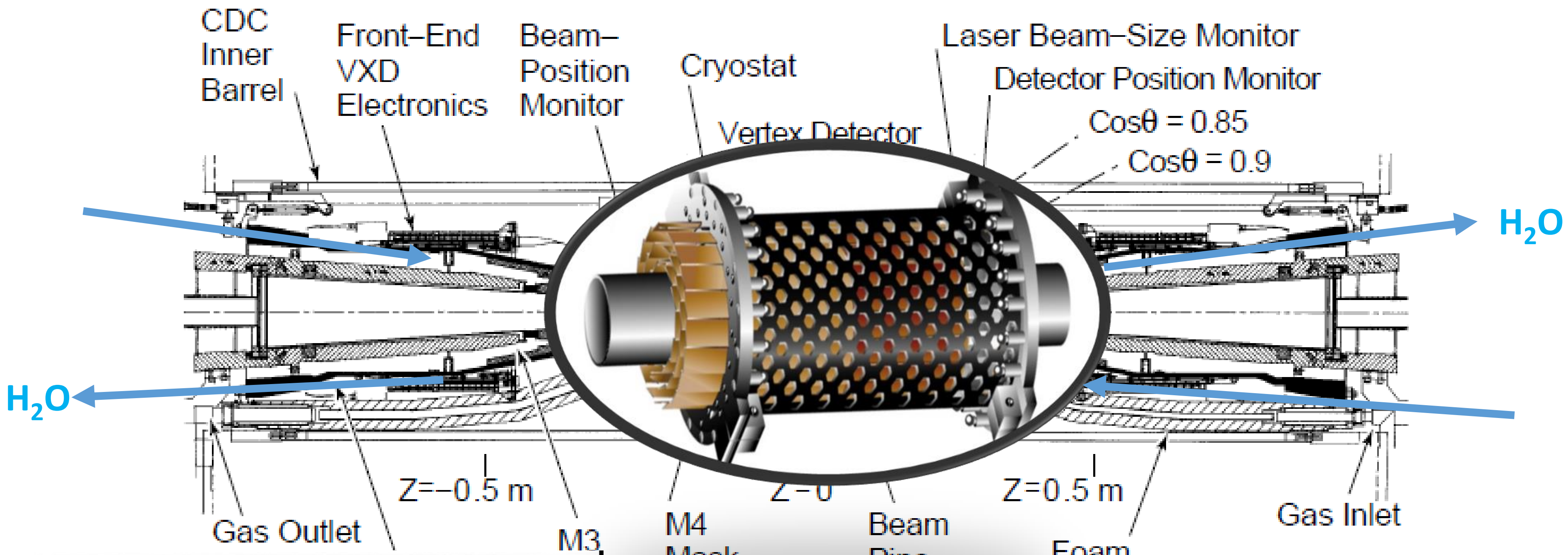
***fluorocarbon** blends with tunable thermodynamics possible silicon, kapton μ-channel* ➔

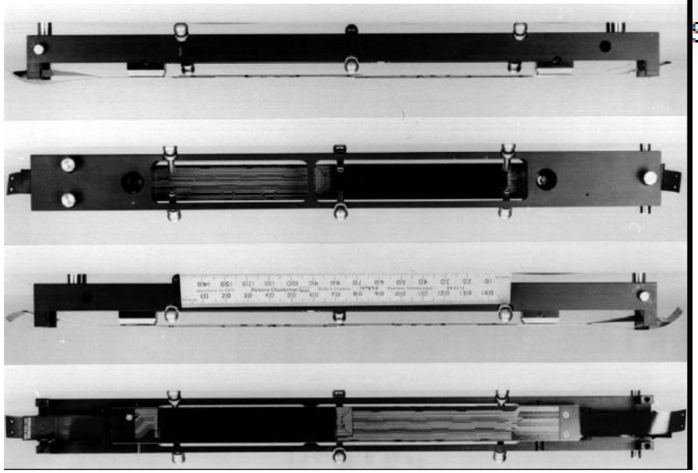
(4) Open evaporative cooling ({expensive} fluid conserved {cheap} not) :

*evaporant vents into tracker purged volume : - **<u>holy grail:</u> needs new technologies for evap. pressure control:***

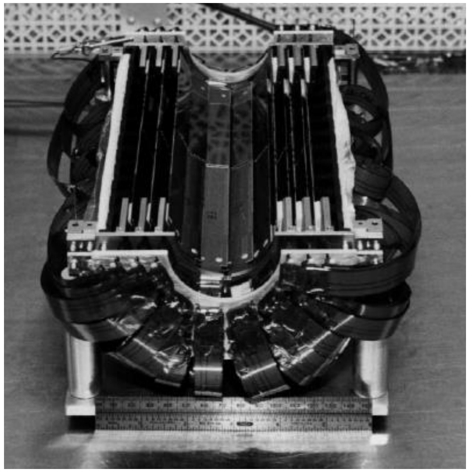
Example of gas cooled SLD VXD3 (SLAC, 1994➔) : low power (20W) 96 CCD chips in very small "can" cryostat: l, ϕ ~ 16 cm: cold N_2 gas (190K: ΔT ~10K) 0.4% X_0 per layer (inc. overlaps: Be support structure) :

HYBRID cooling concept with water cooling (35-40°C) of FEE, mounted outside can and acceptance

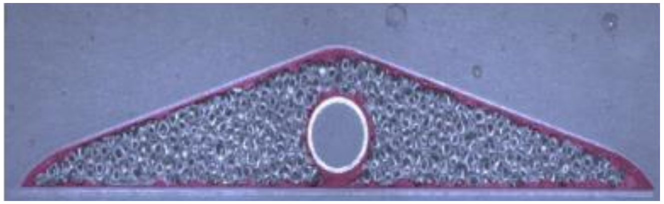


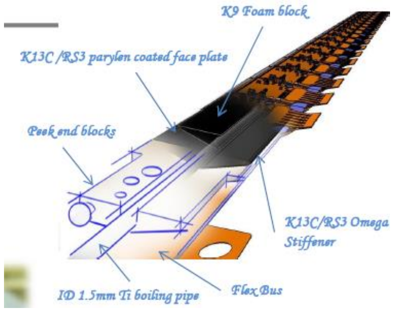


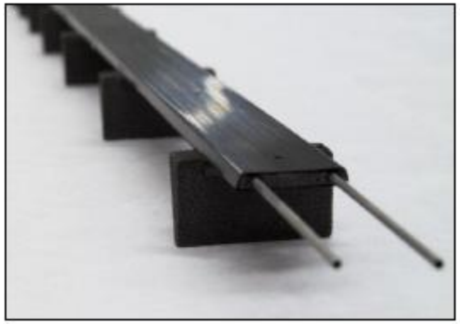
Gas cooled Si-microstrip ("football") tracker also proposed for ATLAS SITV (1996) Krakow: Gadomski, Turala et al…
(before pixel detector accepted in ATLAS)

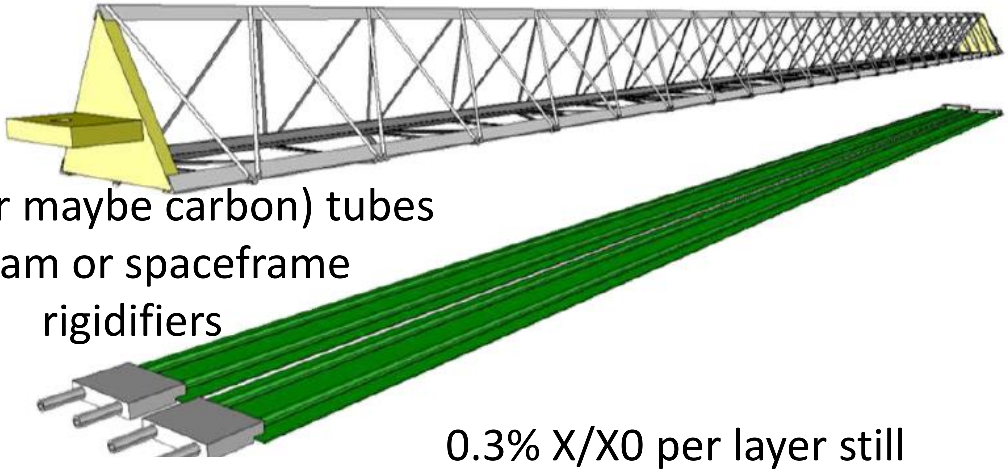


The modern ducted cooling family…





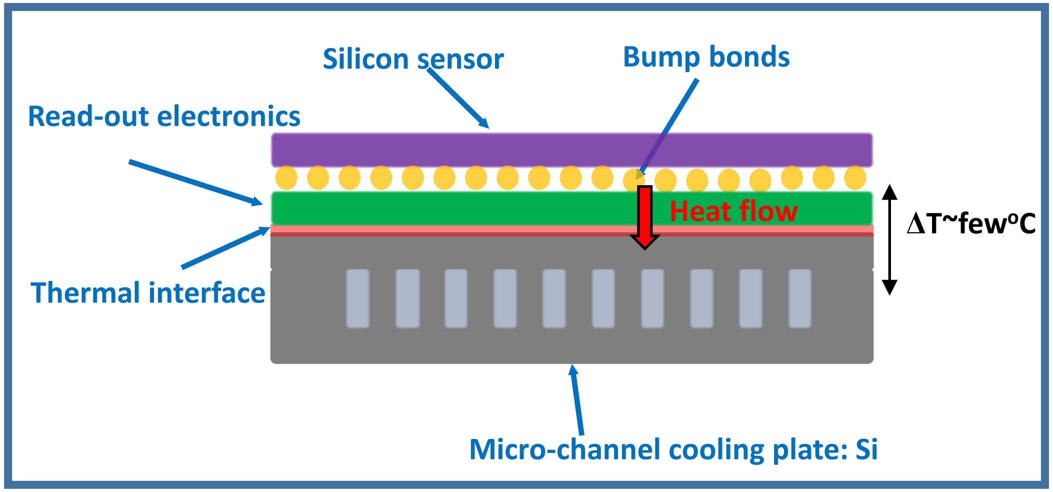




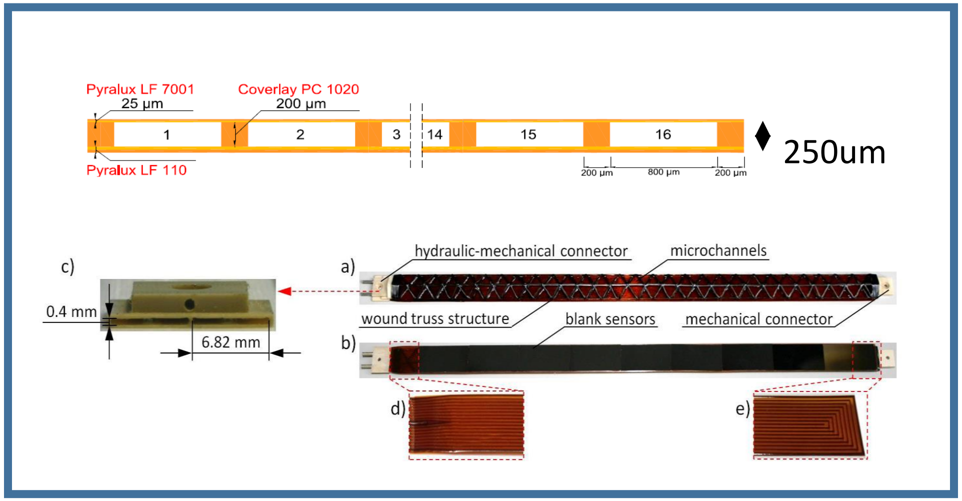
Metal (or maybe carbon) tubes in foam or spaceframe rigidifiers

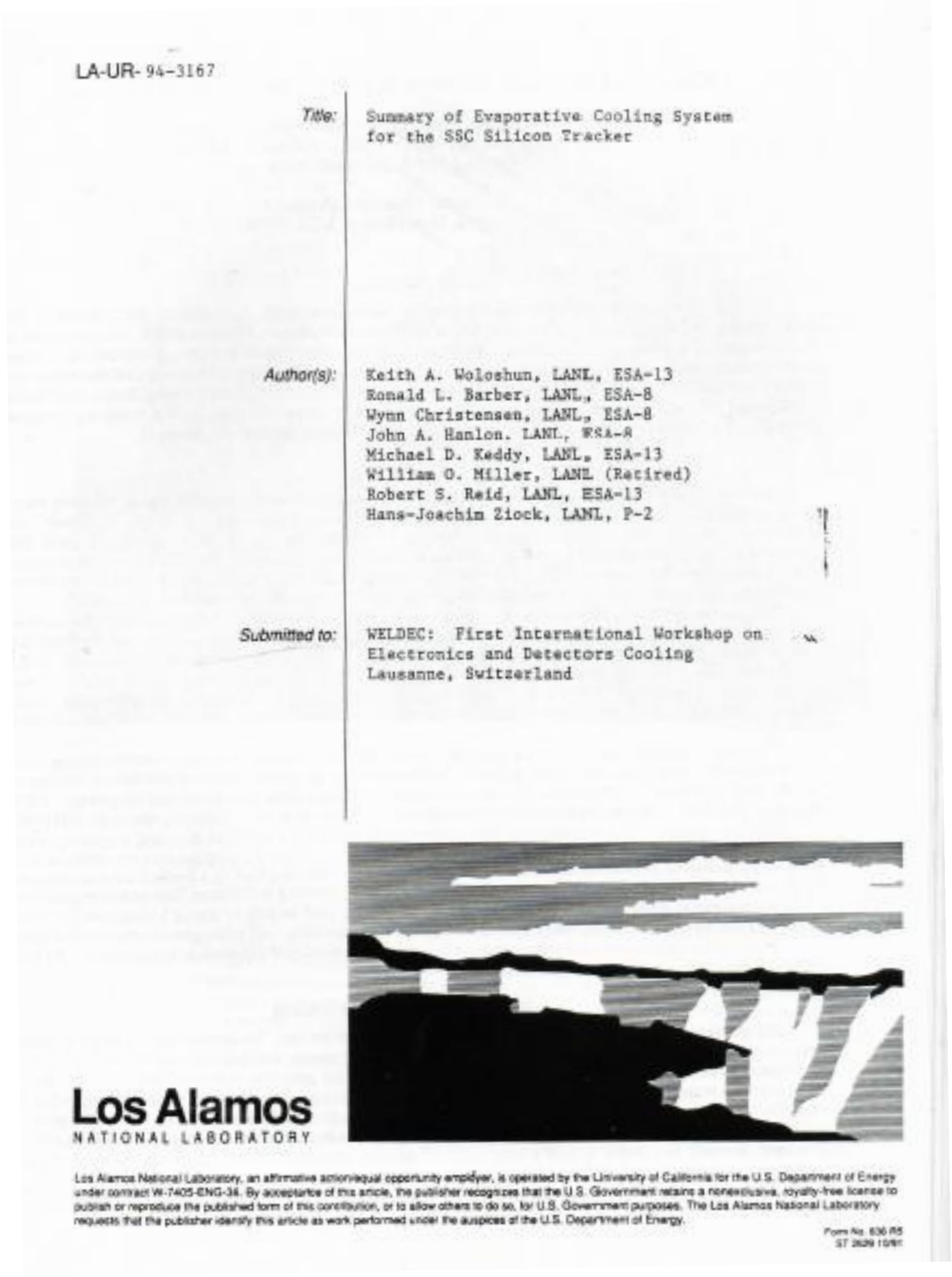
0.3% X/X0 per layer still a target

μ-channel in silicon substrate (eg. LHCb-VELO II, NA62 GTK)



μ-channel in polyimide sandwich structure (ALICE)





LA-UR- 94-3167

Title: Summary of Evaporative Cooling System
for the SSC Silicon Tracker

Author(s): Keith A. Woloshun, LANL, ESA-13
Ronald L. Barber, LANL, ESA-8
Wynn Christensen, LANL, ESA-8
John A. Hanlon, LANL, ESA-8
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William O. Miller, LANL (Retired)
Robert S. Reid, LANL, ESA-13
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Submitted to: WELDEC: First International Workshop on
Electronics and Detectors Cooling
Lausanne, Switzerland

Los Alamos
NATIONAL LABORATORY

Form No. 836 R5
ST 2629 10/91

But let's not forget…
an early abortive attempt
at the "Holy Grail"
(reported at Weldec 1994:
EPFL October 1994)

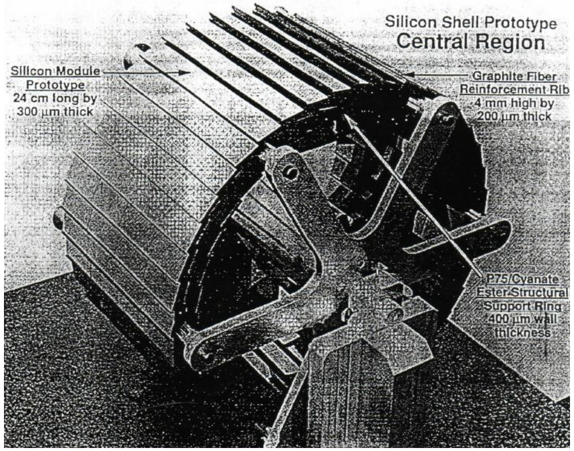
Los Alamos proposition for trackers for SSC
(Gem or SDC):
pixel detectors were not being seriously
considered for SSC
(except speculatively by a few people…)

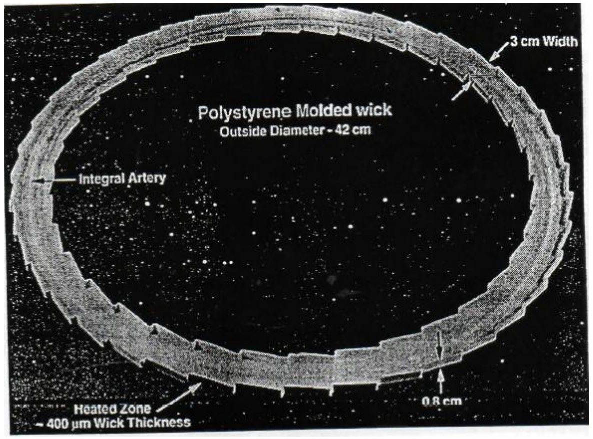
Early abortive attempt at the Holy Grail (reported at Weldec 1994: EPFL October 1994)

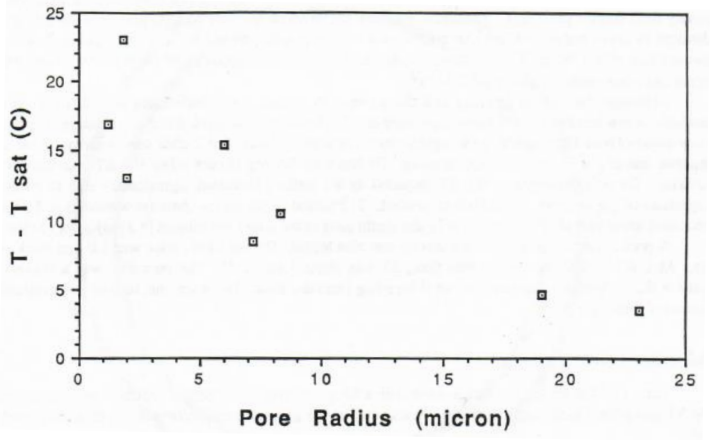
*Evaporation of **BUTANE $(C_4H_{10}!)$***: from wicks around FEE end rings of an ALEPH-style first generation Si μ-strip geometry VXD*

- ***The concept:***

Evaporant circulates by capillarity in (Polystyrene) wicks under FEE chips, then evaporates into detector "can" volume for recirculation







** <u>Believe it or not!</u> : presumably they hadn't heard about fluorocarbons already used in HEP as Cherenkov radiators : Omega & DELPHI (CERN), SLD CRID (SLAC)…*

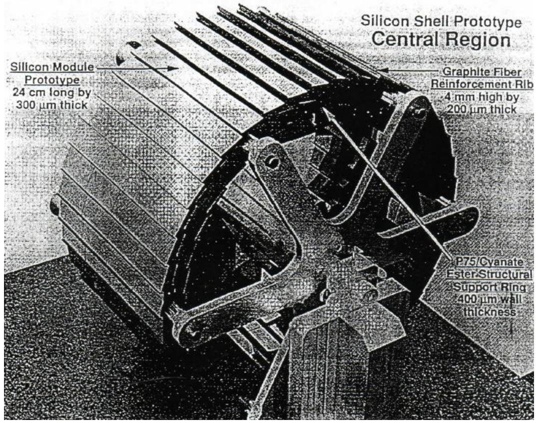
Early abortive attempt at the Holy Grail (reported at Weldec 1994: EPFL October 1994)

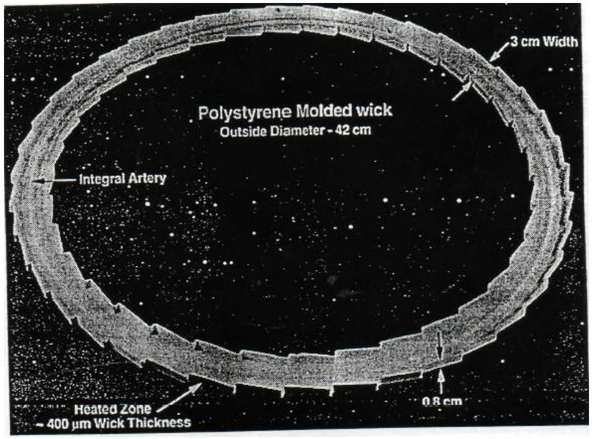
Evaporation of BUTANE (C_4H_{10}!): from polystyrene wicks*

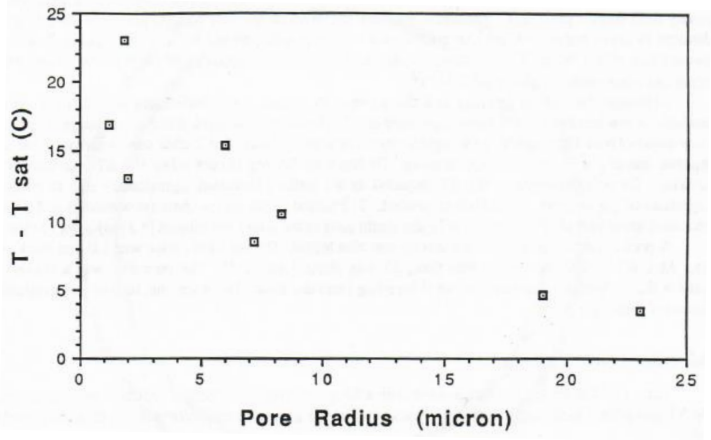
- *Concept abandoned (fortunately - with this coolant):*

hard to maintain flow: dryout in HP (equilibrium mode), flooding in positive feed pressure system:

porous graphite might have worked if pursued, but project abandoned





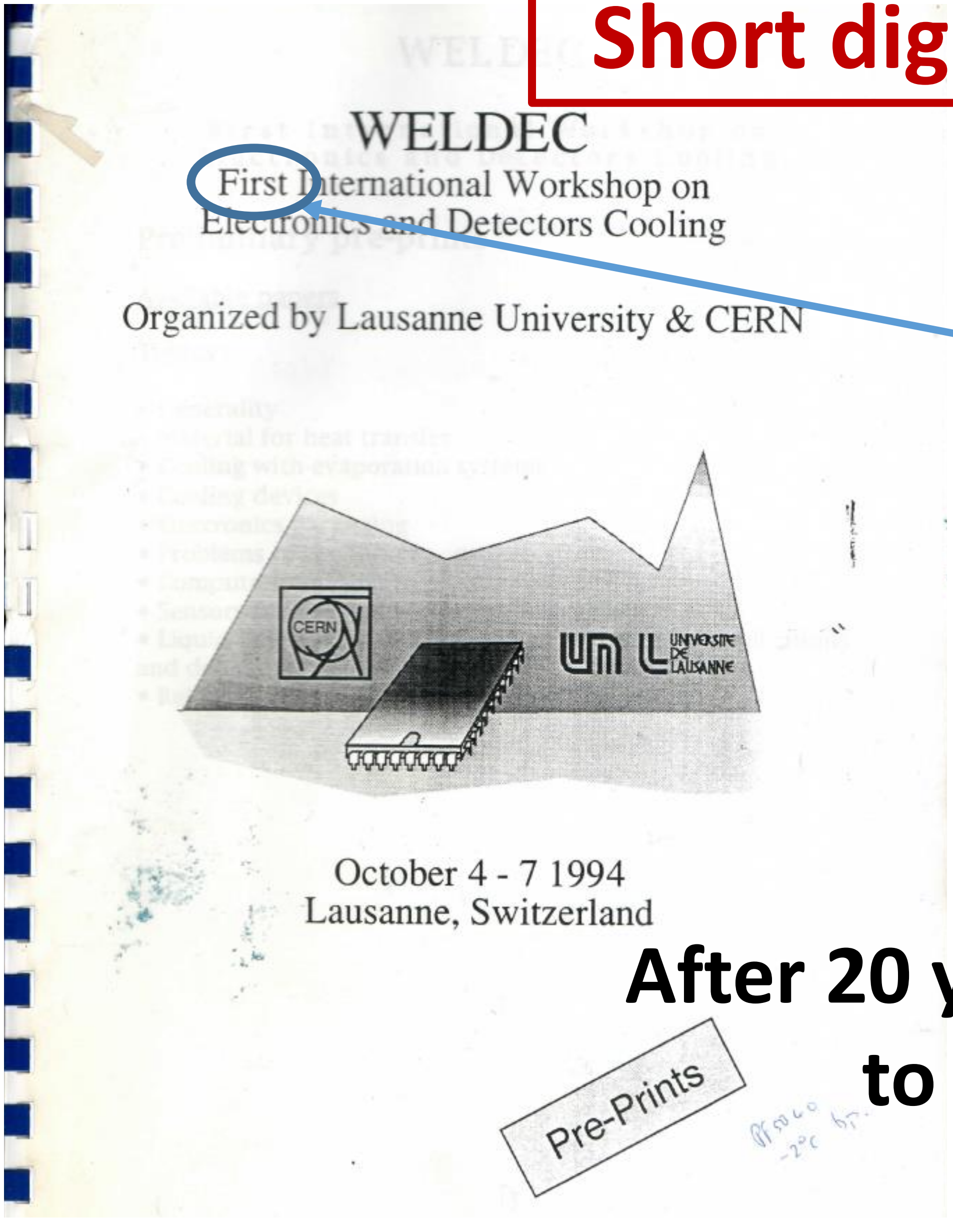


- *But materials science has evolved enormously (nanotubes, graphene…) in 20 years: can we revive concept with a non-flammable evaporant into atmospheric pressure "can" for recovery (or venting if cheap enough : CO_2?)*

➔ *support structure with tuned pore size for evaporation pressure (temperature) control?*

➔ *Positive pressure liquid feed with evaporation through pores to 1 bar_{abs} atmosphere..?*

Short digression…



WELDEC

First International Workshop on
Electronics and Detectors Cooling

Organized by Lausanne University & CERN

October 4 - 7 1994
Lausanne, Switzerland

Pre-Prints

[illegible] -2°C [illegible]

AND ONLY!!

After 20 years, maybe it's time to do this again…

Coolant choice for « on-detector* » heat extraction

(*meaning tubes in contact with the Si & within pseudorapidity bite of (at least) successive layers of the Si tracker itself)

Predicating the choice (in addition to all the fluid safety "non-"s..:

(1) Low enough Si temperature for sufficient safety factor against *positive feedback* effect of leakage current – induced thermal runaway in Si substrates for ∫L.dt = 3➔30 ab^{-1} (➔10^{17}neq cm^{-2})?

Need input on proposed sensor technology options,

- **FEA thermal models of Si sensor substrate with geometry of heat injection (uniform + FEE chip placements etc.),**
- **Si damage, annealing models etc;**
- **development of FCC luminosity profile, shut-downs, temperatures during shut downs etc…**

(2) %X/X0 of fluid, local structure (including tube/supports, close liquid delivery & exhaust (evaporative wins here: capillaries))

mass flow related to enthalpy, & how much of enthalpy is used in on detector cooling channels:

"Holy grail" venting evaporant into detector can wins even more…

Why evaporative cooling? - historical

1/10th → 1/20th massflow (Fluorcarbons) than monophase liquid

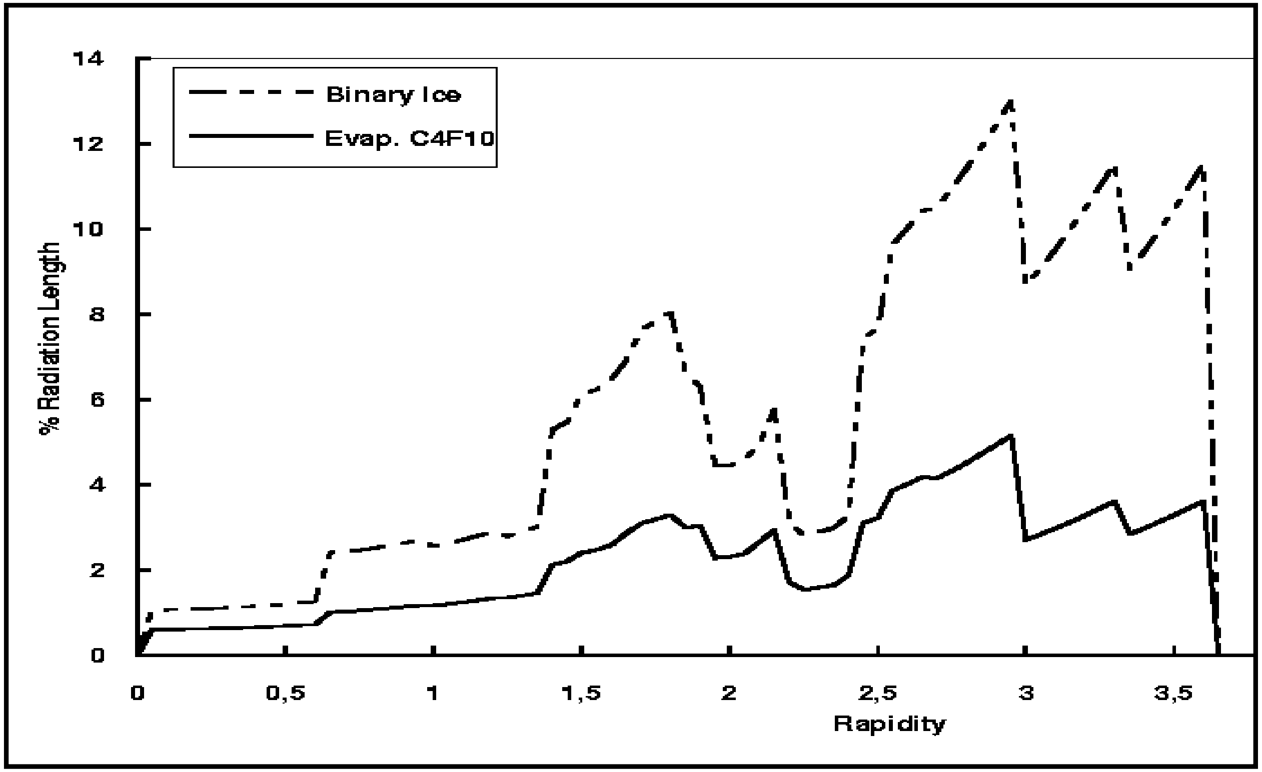
Latent heat of evaporation ➔ 1-2 gs^{-1}/100W heat to evacuate

c.f. 24 (12) gs^{-1} H_2O for DT_{H20} =1(2)°C (C_p =4184 $Jkg^{-1}K^{-1}$)

➔ (Smaller tube section + lower circulating fluid mass ➔ reduced $\%X/X_0$)

Cooling $\%X_0$ comparison for the ATLAS pixel detector

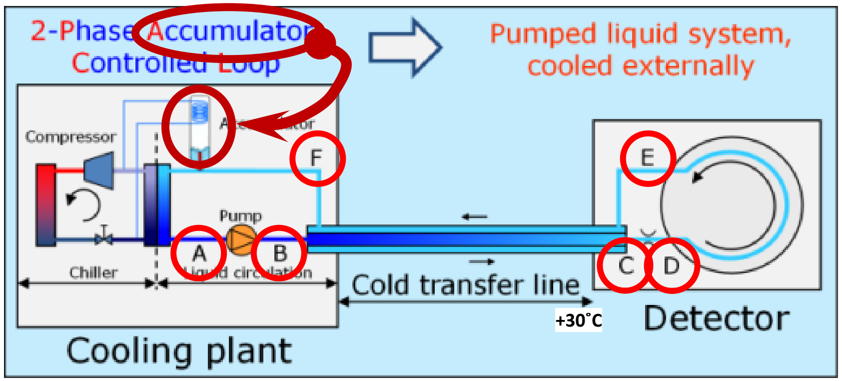
Cooling by evaporative FC compared to « binary ice »: (= water + methanol(!) + micro ice crystals)



from: ATLAS Collaboration, Pixel Detector Technical Design Report (1998), CERN-LHCC-98-13.

Trends in CO$_2$ evaporative cooling for Si trackers

The "2PACL" cycle



Developed at **NIKHEF** for AMS02 & **LHCb Velo**.

Cycle passively controlled through the pressure in the CO$_2$ "**accumulator**" vessel:

Cold transfer lines ideally require vacuum insulation

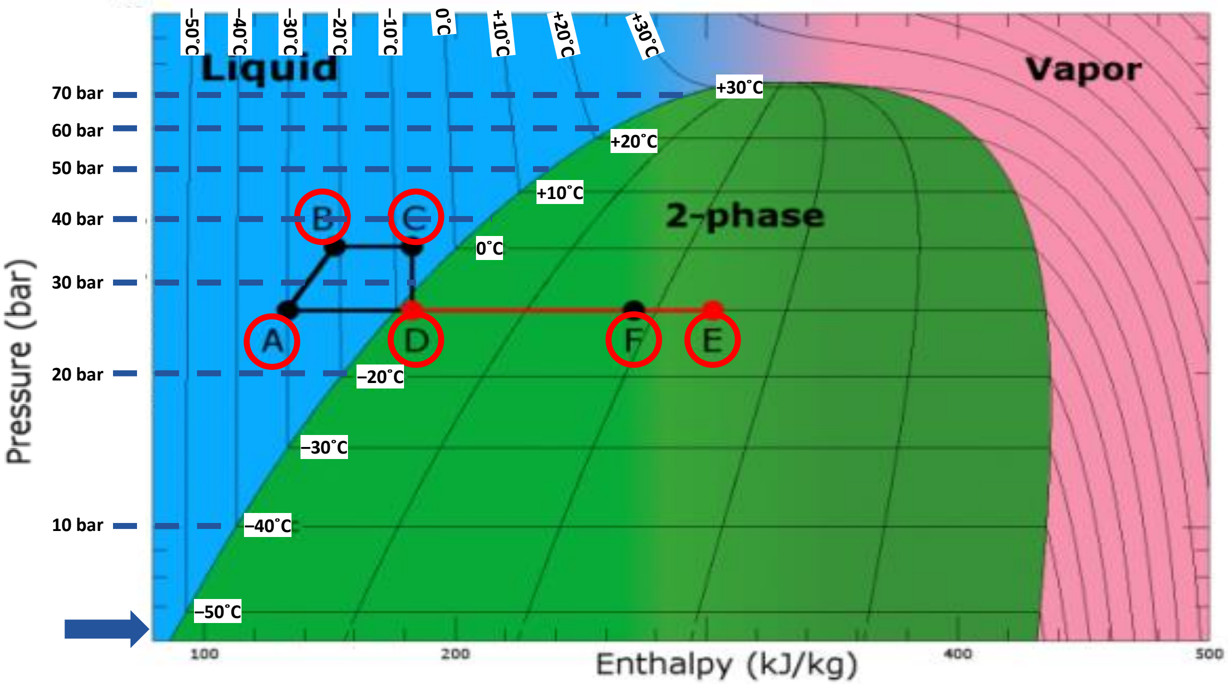
Liquid pump has "floating baseline", generating ~10 bar differential (depending on throttling element): baseline can be as high as 50 bar for cooling down from room temp.

Limiting temp. 55^{0}C (CO$_2$ t.p. (snow…))

Is this low enough for safety factor against Si thermal runaway at $\int L.dt = 3$➔$30\ \mathrm{ab}^{-1}$ (➔$10^{17}\mathrm{neq\ cm}^{-2}$)?

N$_2$O has similar "dome" thermodynamics, and would be compatible with this (standardizing) machinery but goes to lower temp.:

But would an oxidant ever be allowed in a secondary function like cooling?



Trends in CO_2 evaporative cooling for Si trackers

- **This thermodynamic cycle in use at AMS-02 (ISS), LHCb–VELO1, ATLAS IBL;**
- **Gained critical mass for acceptance in many future ducted systems at HL-LHC due to expectations of reduced %X/X_0 in small tubes (higher CO_2 enthalpy ➔ lower mass flows than FCs);**
  - **includes metallic tube LHC-HL upgrades (ATLAS, CMS)**
  - **even in (one) Si μ-channel application (LHCb-VELO II),**
  - **but not for polyimide μ-channel,**

- **Limiting temperature of ~-50C low enough for safety factor against Si thermal runaway at ∫L.dt = 3➔30 ab^{-1} (➔10^{17}neq cm^{-2})?**

- **CO_2 not so well adapted to full « pumps-free » gravity liquid-fed thermosiphon recirculation systems***

  (Combination of higher liquid supply pressure reqd. & lower liquid density than Fluoro-carbons)

  at least within max ~100m pit depth constraints of LHC (deeper at FCC)

  ****ATLAS thermosiphon system (to replace compressor driven system): Surface chiller commissioning Feb 2015: see back up slides…***

Saturated fluorocarbon ''Blengineering'' for Si trackers

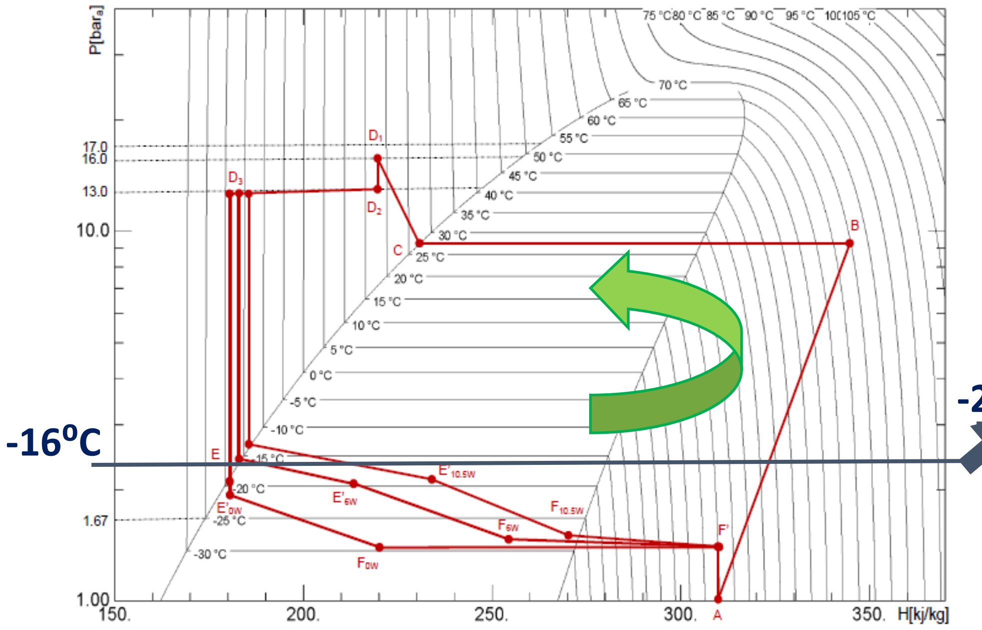
- Originally developed to solve an evaporation temperature limitation of the present ATLAS SCT within present servce constraints

- Can be attractive in fragile support & cooling structures like μ-channels due to lower evaporation pressures than CO_2

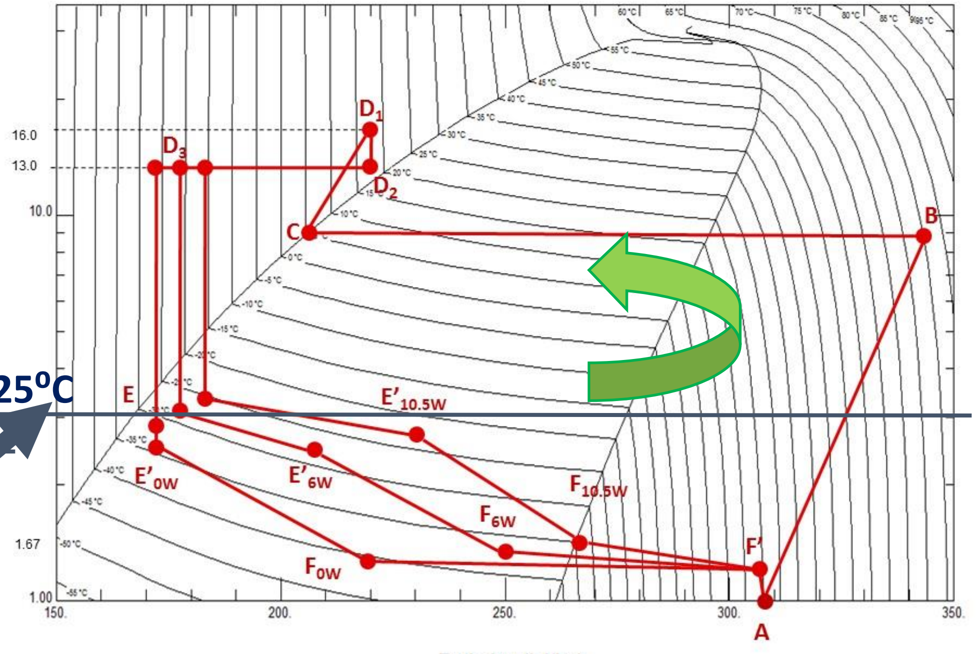
- Molar blends created by mass weighting and verified ultrasonically

Comparisons of thermodynamic cycles
(in same SCT structure: JINST_113P_1114)
in pure C_3F_8 (present coolant) & blend with 25% C_2F_6

P-h diagram pure C_3F_8



P-h diagram 75% C_3F_8/25% C_2F_6

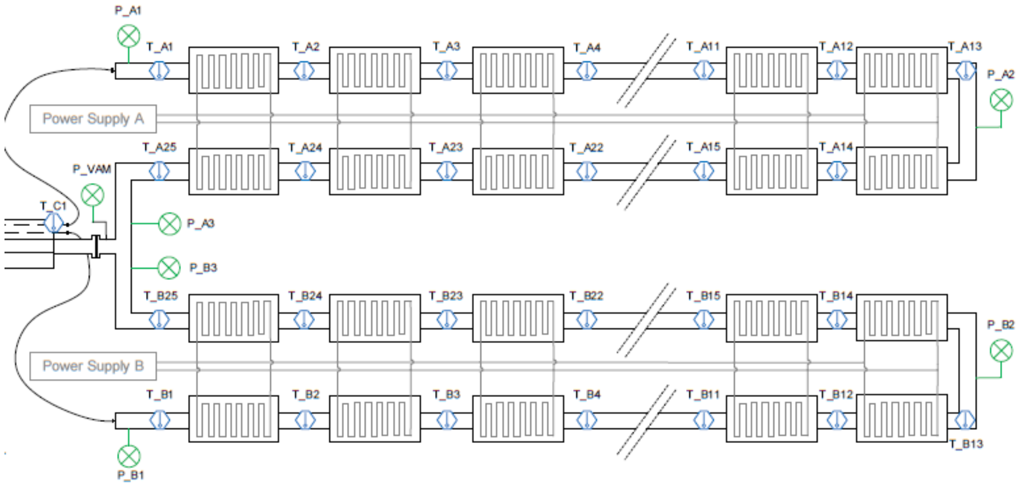


Reduction of 9°C in silicon module operating temperature would give SCT Si modules a factor 2 safety margin against leakage current induced thermal runaway *even after 700 fb^{-1}*

WITH SAME EXTERNAL (Liquid delivery & vapour exhaust) INACCESSIBLE SERVICES

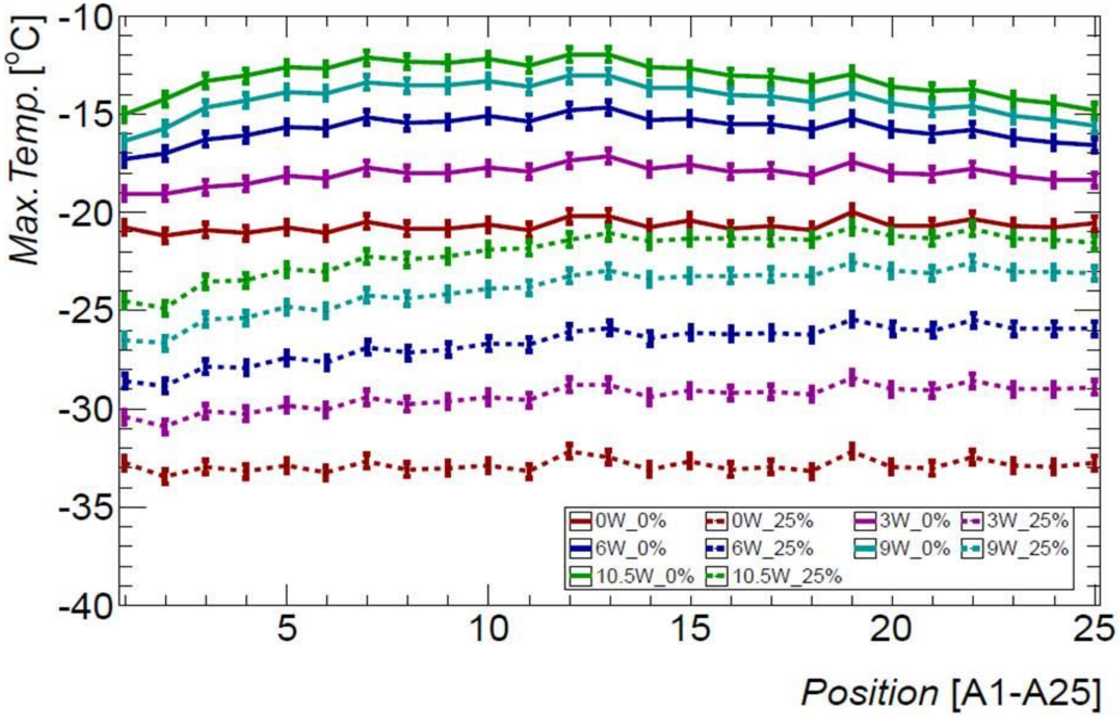
Workshop on requirements for future detector technologies in view of FCC-hh CERN, 3-4 Feb: 2015

Reduction of 9^{o}C in silicon module operating temperature in SCT Barrel bi-stave (48 modules: at 504 W (very) worst case power: greater reductons at lower power)

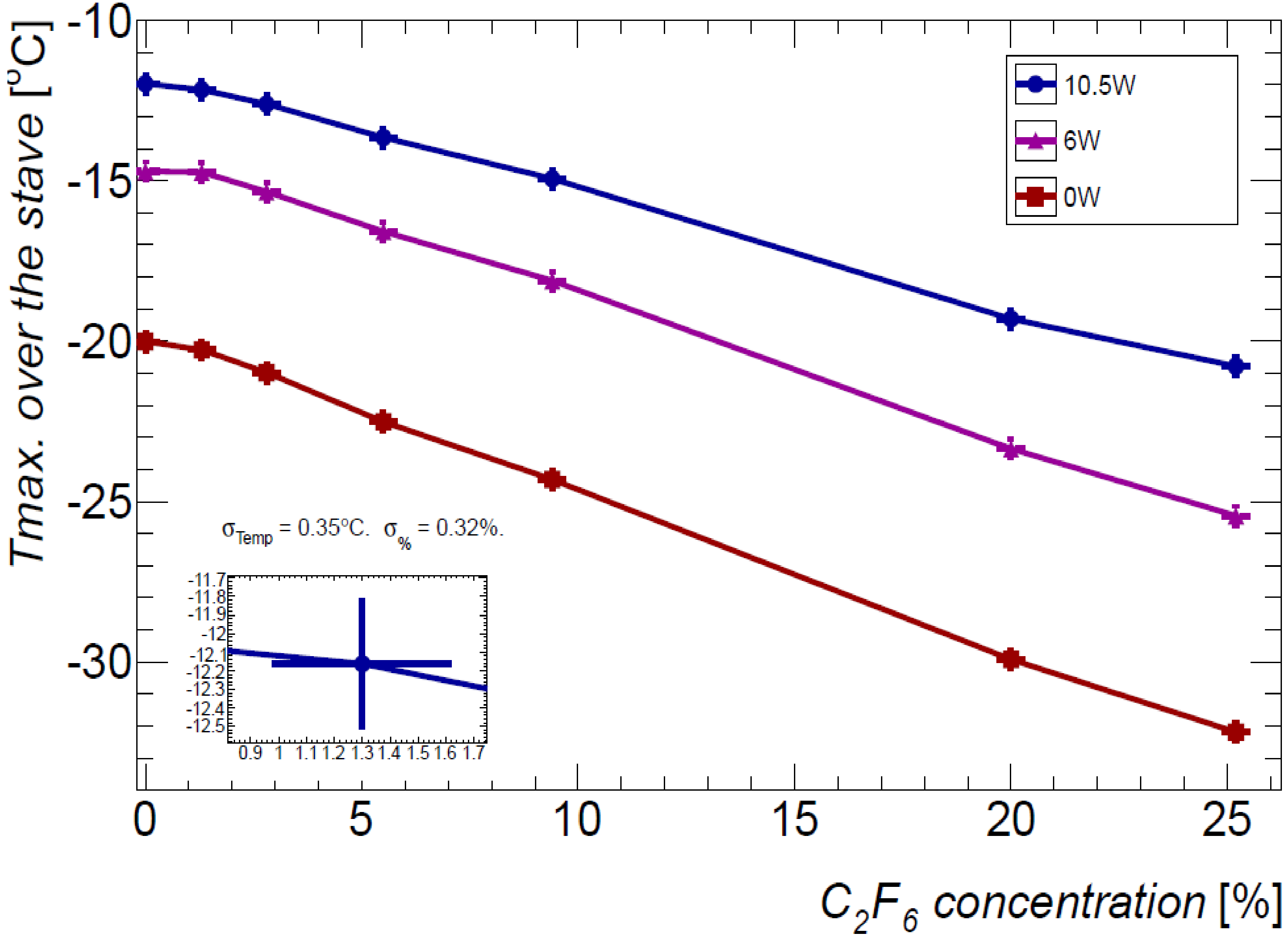


SCT Barrel bi-stave
(48 modules): 2 capillaries:
Common exhaust

Temperature profile tube
(24 modules stations)
with pure C_3F_8 vs module power
(solid lines)
with 25% C_2F_6 /C_3F_8 vs module power
(dashed lines)

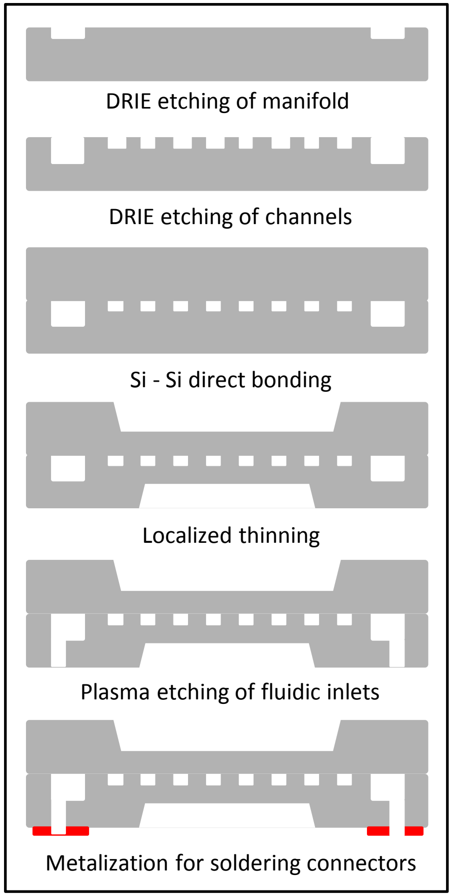


Evaporation temperature in SCT Barrel bi-stave *vs.* %C_2F_6 in molar blend with C_3F_8 (48 modules: at 504 W, 288W and zero power)



Microchannel cooling channels for Si trackers

Fabrication of Si μ-channels and the NA62 GTK (Giga-tracker)



DRIE etching of manifold

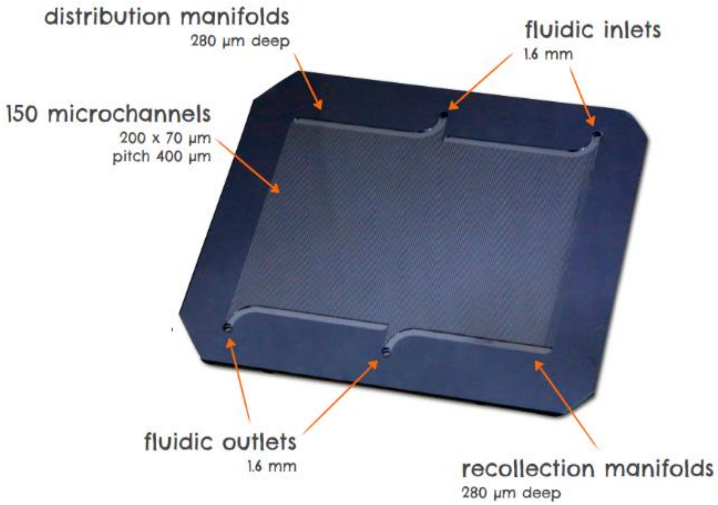
DRIE etching of channels

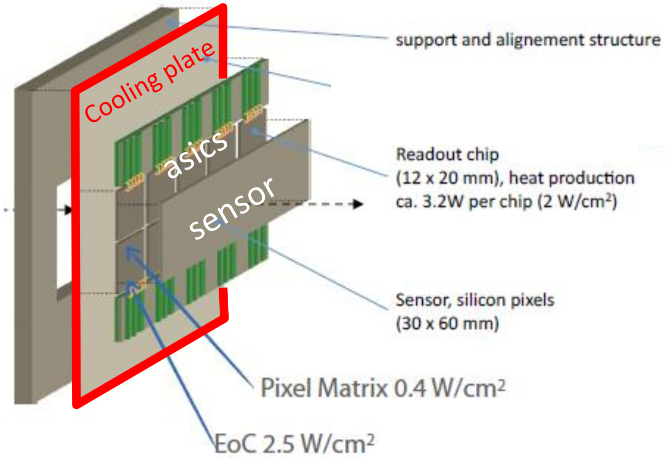
Si - Si direct bonding

Localized thinning

Plasma etching of fluidic inlets

Metalization for soldering connectors



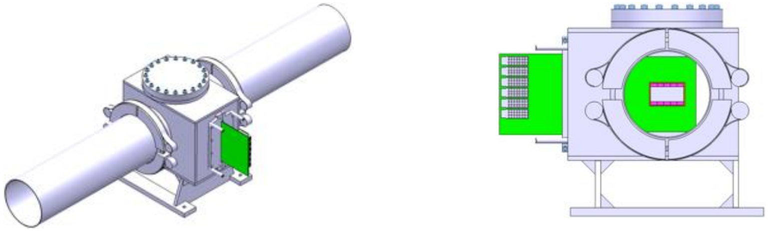


- $0.13\%\ X/X_0$
- $T_{sensor} < -20$ °C
- C_6F_{14} single phase
- 2.5 W/cm²
- Total power up to max 144 W
- In vacuum

Nominal conditions:

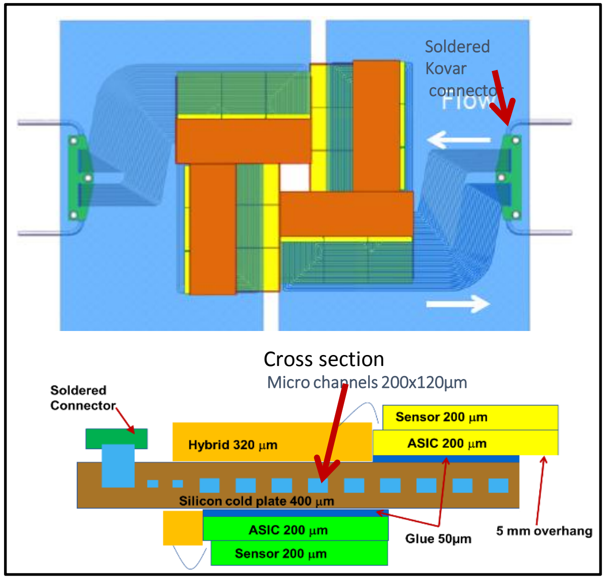
- 20 W on ASIC, 4 W on Pixel Matrix
- liquid flow: 8 g/s C_6F_{14} @ -21°C
- max ΔT_{sensor} = 1 °C,
- max ΔT_{chip} = 3 °C,
- max ΔT_{module} < 5 °C

Device size limited 4", 6" or 8" wafer



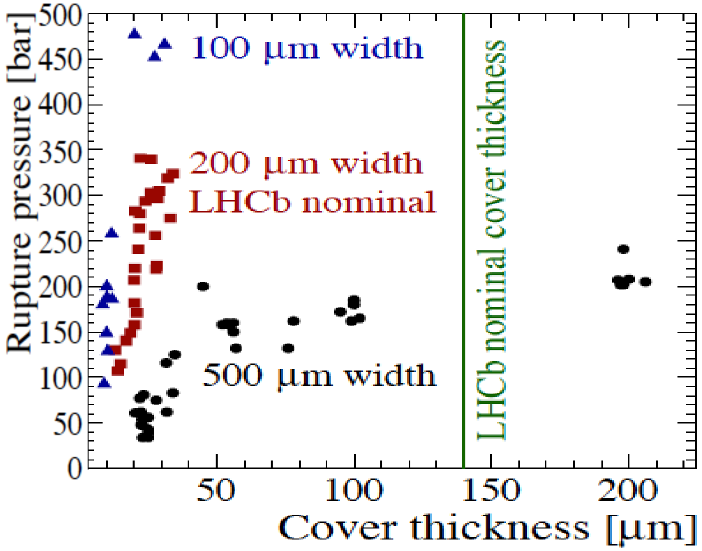
3 stations in the beam line

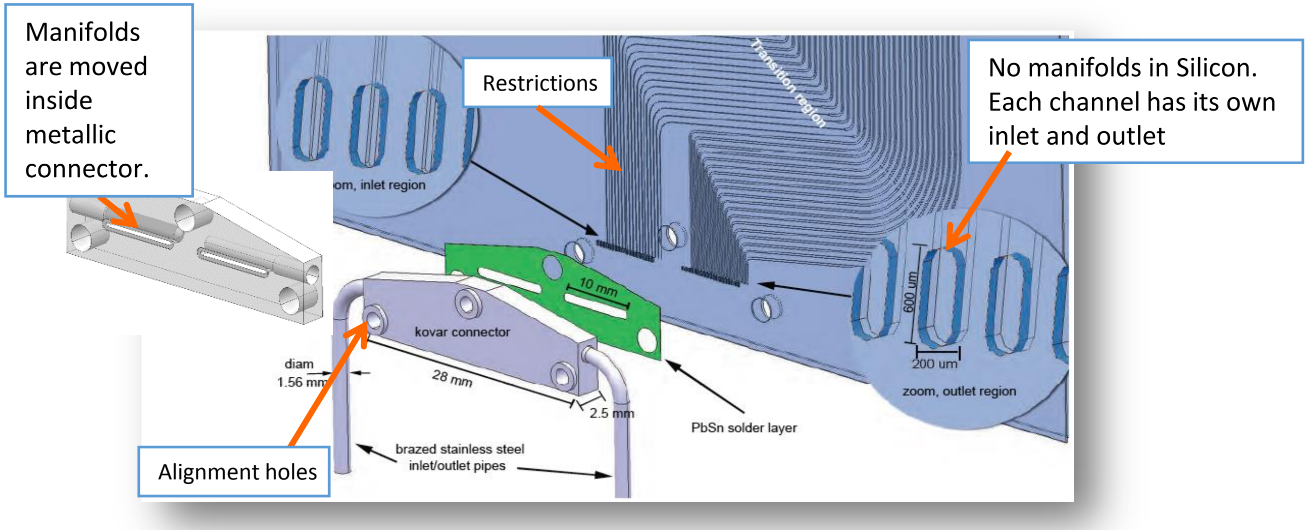
LHCb-VELO-II has successfullly demonstrated Roman Pot sized **Si μ-channels** with biphase CO_2, including manifolded fluid connectors



With an inlet fluid temperature of -30 °C, the detector can be held at a temperature below -20 °C with some margin.

ΔT ~7C relative to coolant for 6 dummy chips at 13 W total power





Manifolds are moved inside metallic connector.

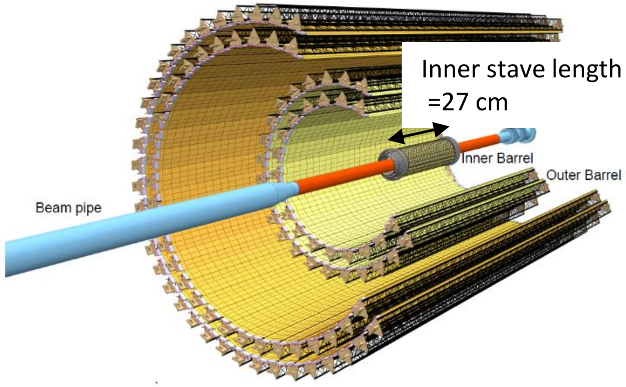
Restrictions

No manifolds in Silicon. Each channel has its own inlet and outlet

Alignment holes

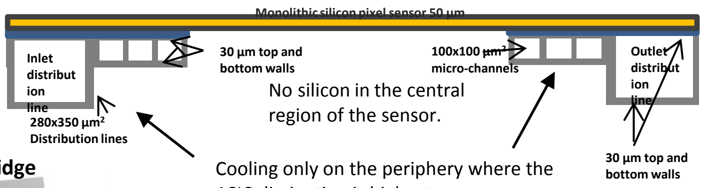
- **Pressure Specification 170 bar**
- **T_{sensor} < -20°C**
- **CO_2 two-phase**
- **1.8 W/cm^2**
- **Total power 1.9 kW (all pots)**
- **In vacuum**

But NA62 GTK and LHCb-VELO-II are small scale (few cm^2 devices): also need to think *linear*… example from ALICE ITS upgrade option



«Frame» design :

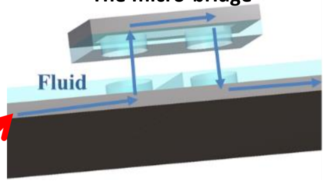
Cross-section view :



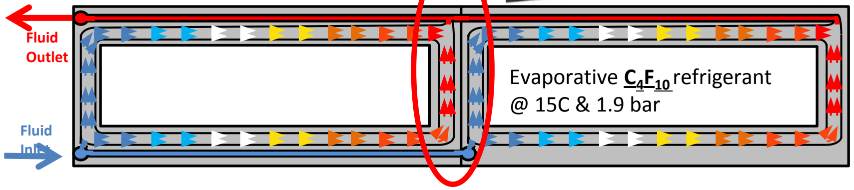
No silicon in the central region of the sensor.

Cooling only on the periphery where the ASIC dissipation is highest.

The micro-bridge



Total stave composed of 5 devices : interconnection using ˝micro-bridge˝.

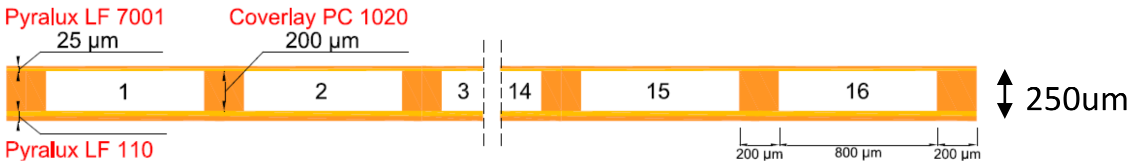


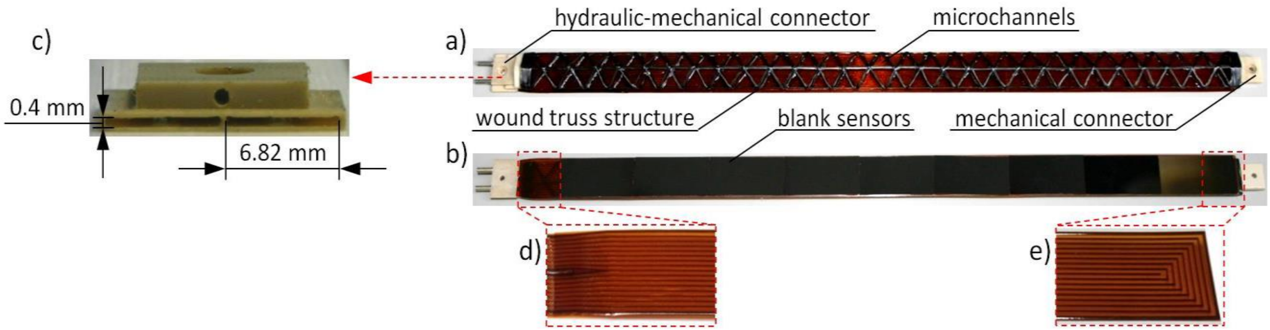
Evaporative C_4F_{10} refrigerant @ 15C & 1.9 bar

- Prototyped on 4” wafers
- produced on 6” wafers

Aim for 0.3% X/X0 per layer

Polyimide micro channel alternative.





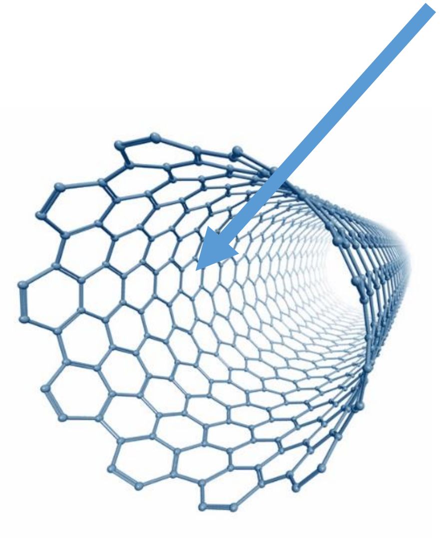
- **Proposal for ALICE ITS upgrade cooling.**
  - **water or C_6F_4 mono-phase cooling at ~ 30C.**
  - **Power requirement 0.5W/cm2**
  - **Coolant pressure ~10bar.**
  - **CERN & INFN development.**
  - **But maybe a good candidate for lower pressure FC “Blengineering”…**

And now… back to that Holy Grail thing…

Oh Brave Sir Knight, where may we find the path toward 0.3% X/X0 per layer?

Seely physics fellow; dont waste my time with zeese seely question: go an see zee nanoboys in zee forest! **??**!!

Could we (one) engineer porous structures based on Graphene/Carbon nanotubes that would allow evaporating coolant to exit uniformly along a stave?



This is not THE cooling tube but one of billions of randomly - oriented n-tubes (typical pore size O ~nm, length O~mm) consolidated to form a porous wick…

Build around metal rod mandrel, the dissolve it away?

Consolidaton by carbon vapour re-densification a la Carbon-Carbon?

Random n-tube orientation also redirects very high thermal planar conductivity (~ 3500 W/m.K) in transverse direction

Can exit impedance (**and hence back pressure = here evap. pressure**) **for a given coolant liquid injection pressure be statistically engineered from the number of stacked layers the liquid must evaporate through?**

NIAIVELY…

Backpressure (evap pressure) α {Supply pressure$*$ No of stacked layers} **/**

{ f(molecular diam. Van der Waals**)*(**pore conductance* # pores communicating with detector can)**}**

So … maybe some new directions to investigate (not only conventional tubes)

- **Fluorocarbon "*blengineering*" has been demonstrated with C_3F_8/C_2F_6 (recently) and with C_3F_8/C_4F_{10} (2000-1) : other blends possible to tune thermodynamics to the FCC silicon tracker application.**
- **Such blends might be better adapted to fragile μ-channel structures, particularly polyimide based and in-tube based structures if temps lower than ~-50°C needed**
- **CO_2 advantage of cheapness and no future possible proscription**

  (Greenhouse potential = 1 (FCs in range 5000-10000 by mass)
- **CO_2 ideal candidate in « Holy Grail » evaporate-to-can implementation, with new advanced porous structures**

Yes.. but should we be thinking to organize a graphene cooling structure funded research program like AIDA/H2020 for μ-channels?

Some acknowledgements (not a complete list):

ECFA High Luminosity LHC Experiments Workshop – 2014

Talks by

E. Anderssen, https://indico.cern.ch/event/315626/session/7/contribution/50/material/slides/

J. Buytaert https://indico.cern.ch/event/315626/session/7/contribution/48/material/slides/

C. Gargiulo, https://indico.cern.ch/event/315626/session/7/contribution/49/material/slides/

P. Petanga, https://indico.cern.ch/event/315626/session/7/contribution/14/material/slides/

ECFA High Luminosity LHC Experiments Workshop – 2013

Talk by P. Phillips: https://indico.cern.ch/event/252045/session/7/contribution/21/material/slides/

On fluorocarbon blends:

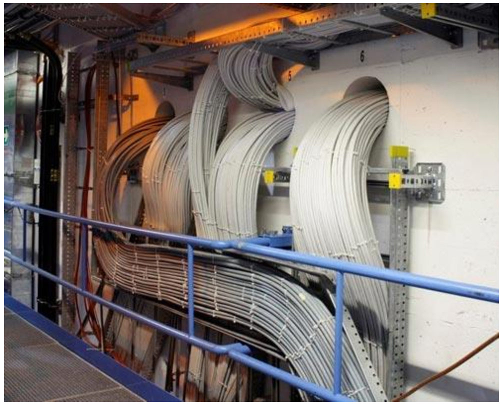
A. Bitadze, Ph.D. thesis (2013): University of Glasgow Department of Physics and Astronomy

"The cooling capabilities of C_2F_6/C_3F_8 saturated fluorocarbon blends for the ATLAS silicon tracker"
R. Bates, M. Battistin, S. Berry, A. Bitadze, P. Bonneau, N. Bousson, G. Boyd, J. Botelho-Direito, O. Crespo-Lopez,
B. DiGirolamo, M. Doubek, D. Giugni, G. Hallewell, D. Lombard, S. Katunin, S. McMahon, K. Nagai,
D. Robinson, C. Rossi, A. Rozanov, V. Vacek and L. Zwalinski: JINST_113P_1114 (2015)

Back-up slides

Example: ATLAS SCT (Silicon Strips); 2013

(from ECFA-LHC-HL-workshop, Oct 2013)

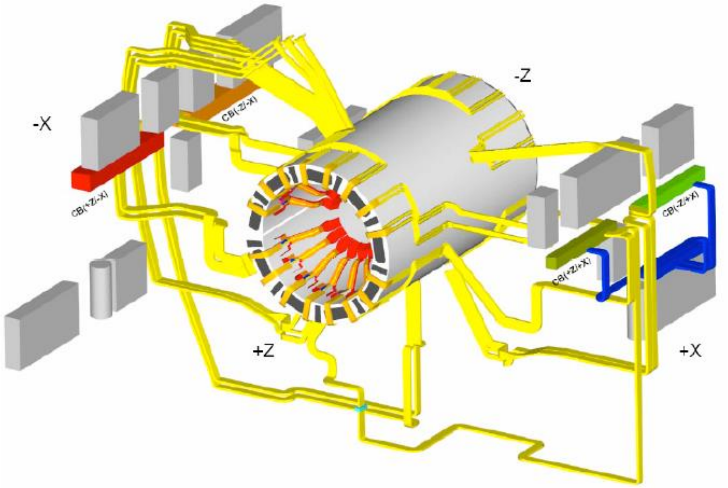


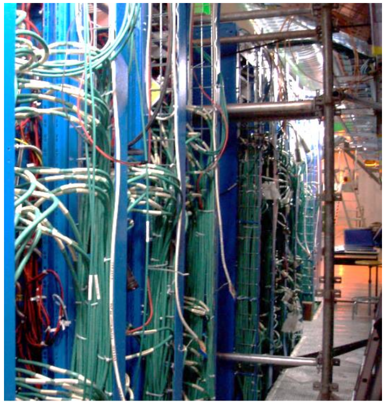
- 4088 Detector Modules
- **Independent Powering**
  - 4088 cable chains
  - 22 PS racks *in service caverns*
  - 4 crates / rack
  - (up to) 48 LV and 48 HV channels / crate
- Longest cable run
  - ~130m copper cable (3 gauges)
  - ~2m copper/kapton (endcap) or aluminium/kapton (barrel) power tapes
  - Voltage limiter in line to block spikes due to sudden drops in load
- Typical overall efficiency ~40%

https://indico.cern.ch/event/252045/session/7/contribution/21/material/slides/

Example: CMS Silicon Strip Tracker (2013)

(from ECFA-LHC-HL-workshop, Oct 2013)





- 15000 Detector Modules
- **Parallel Powering**
  - 1944 “detector power groups”
  - 29 racks in **main cavern**
  - (up to) 6 crates per rack
  - CAEN EASY system for “hostile environments”
    - Magnetic field tolerant
    - Radiation tolerant
- Typical cable run
  - 40m copper + 6m aluminium
- Typical overall efficiency ~40%

https://indico.cern.ch/event/252045/session/7/contribution/21/material/slides/

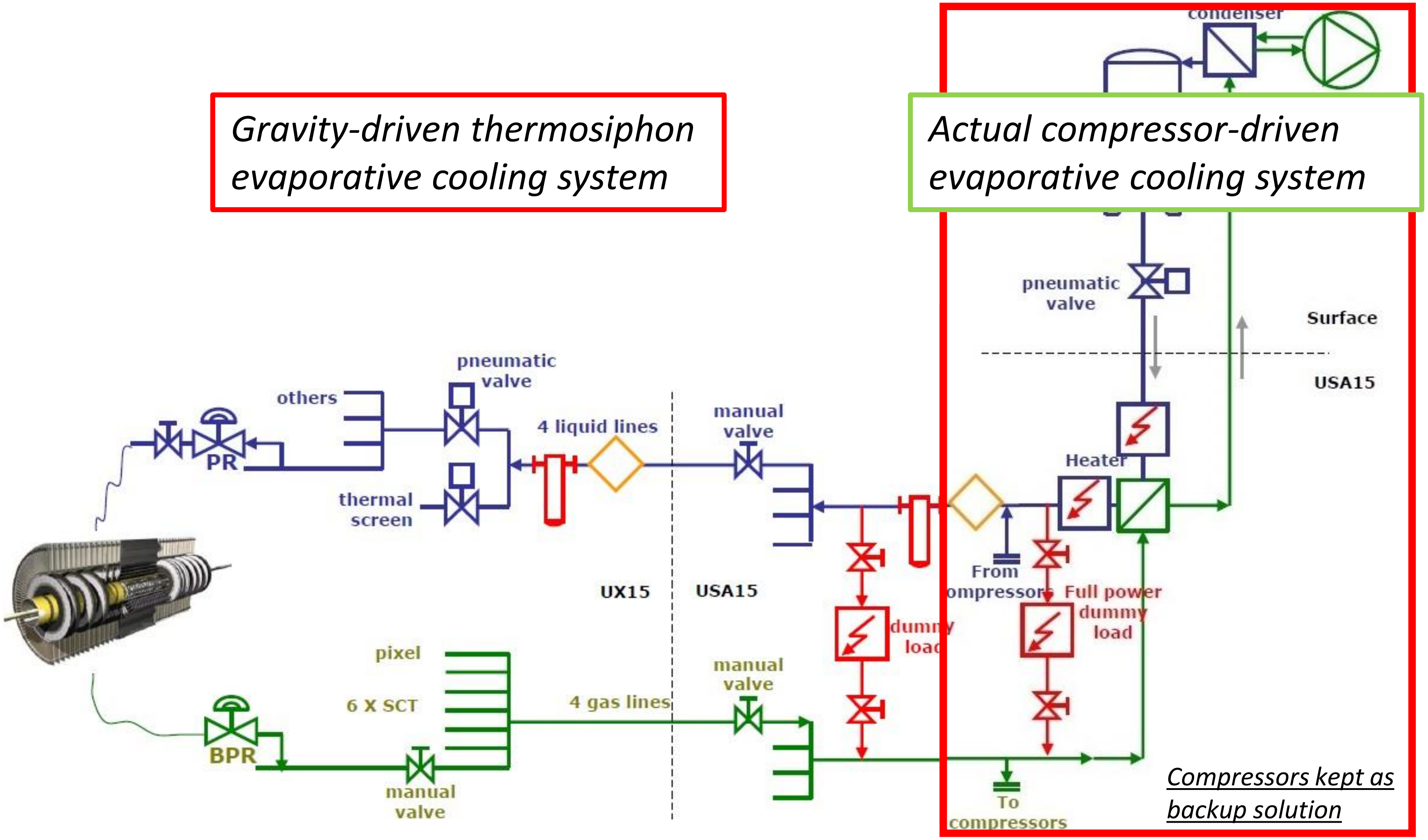
References to microchannel cooling from J. Buytaert

https://indico.cern.ch/event/315626/session/7/contribution/48/material/slides/

- “Development of interconnected silicon micro-evaporators for the on-detector electronics cooling of the future ITS detector in the ALICE experiment at LHC”. A. Francescon et al. 4th Micro and nano flows conference, UCL,London,7-10 September.
- “Silicon Micro-Fluidic cooling for NA62 GTK Pixel detectors”. G. Romagnoli et al., MNE2014 Conference, Lausanne, Switzerland, 23 September 2014.
- “Evaporative CO2 micro channel cooling for the LHCb VELO pixel upgrade”. O. Augusto et al., PIXEL2014, Niagara Falls, Canada, 1-5 September 2014.
- “An innovative polyimide micro channels cooling system for the pixel sensor of the upgraded ALICE inner tracker”. G. Fiorenza et al., 5th IEEE International Workshop on Advances in Sensors and Interfaces (IWASI), 2013, p. 81-85, 10.1109/IWASI.2013.6576065.

Gravity-driven thermosiphon evaporative cooling system

Actual compressor-driven evaporative cooling system



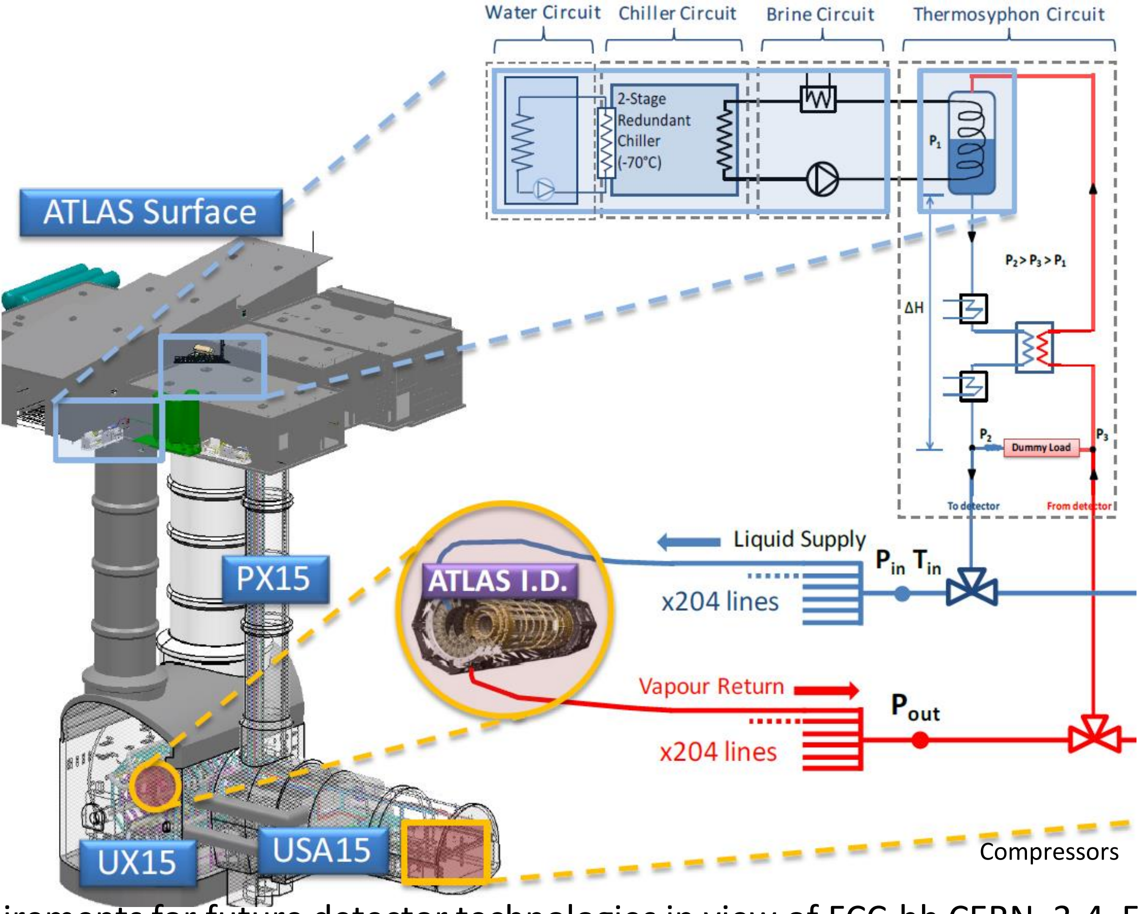
Compressors kept as backup solution

INTERNAL PART

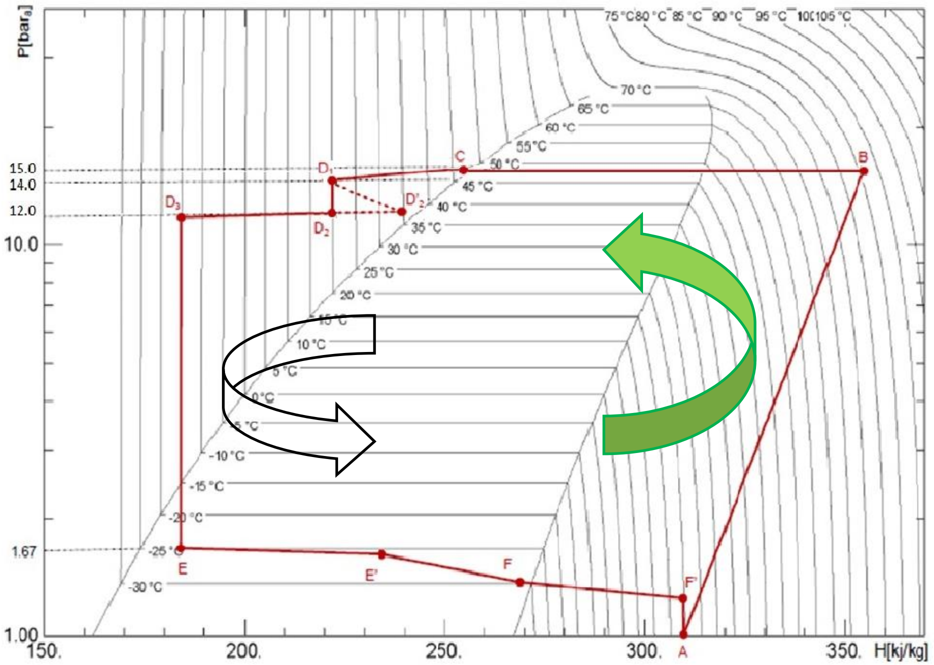
EXTERNAL PART

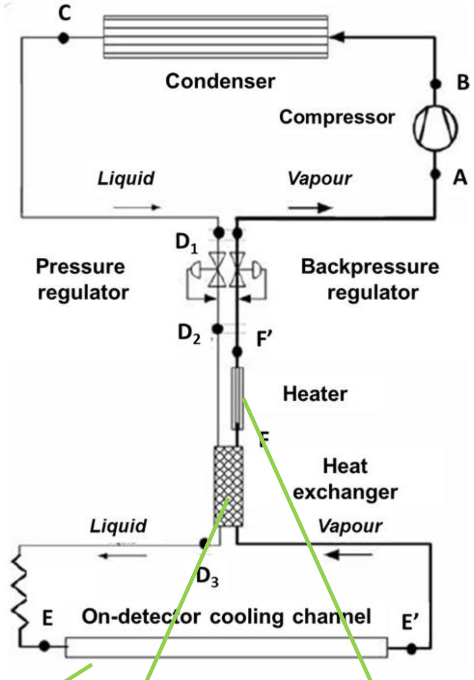
The full scale thermosiphon

The ATLAS thermosiphon evaporative cooling circulator takes advantage of the peculiarities of LHC experiments.
The great height difference (92 m) between the underground cavern housing the experiment and the surface allows natural circulation of the coolant with no active components (pumps or compressors) in the primary loop.



Evaporative fluorocarbon cooling system presently cools the Pixel and SCT detectors.
→ System based on compression-condensation cycle:
similar to standard industrial direct expansion cooling plant





Temperature set for each circuit with a **Back-Pressure Regulator** (BPR) in the exhaust vapour return tube.

Flow can be slightly modified, setting pressure of inlet liquid with a **Pressure Regulator** (PR)

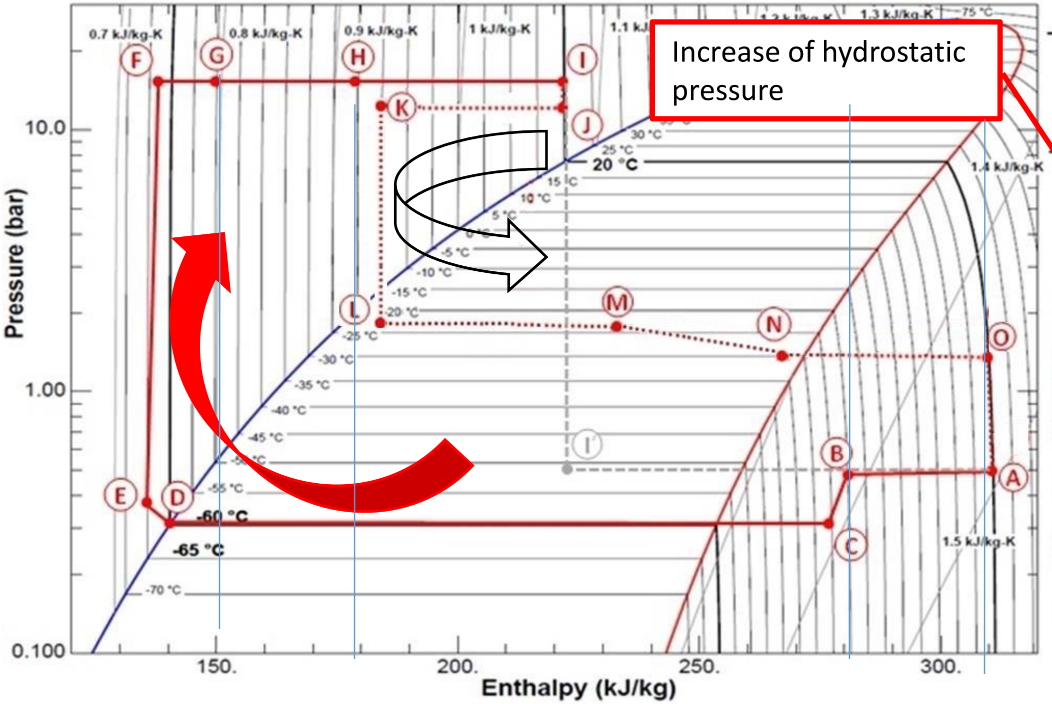
Target evaporation temperature @ on-detector cooling pipes **-25°C** (**saturation pressure** of **1.67 bar$_{abs}$** with C_3F_8 coolant)

Electrical heater: evaporates and raises above the cavern dew point residual liquid - avoid condensation on ext. surface of return pipes.

Controlled by PLC system - feedback from temperature sensors placed on external surface of heaters and on downstream tubes

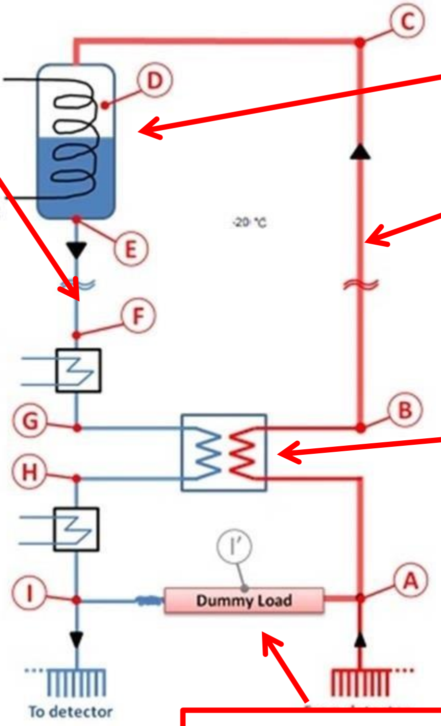
Recuperative heat exchanger to increase overall efficiency and maximize phase-change enthalpy

The full scale thermosiphon



Increase of hydrostatic pressure

Thermodynamic cycle of the thermosiphon



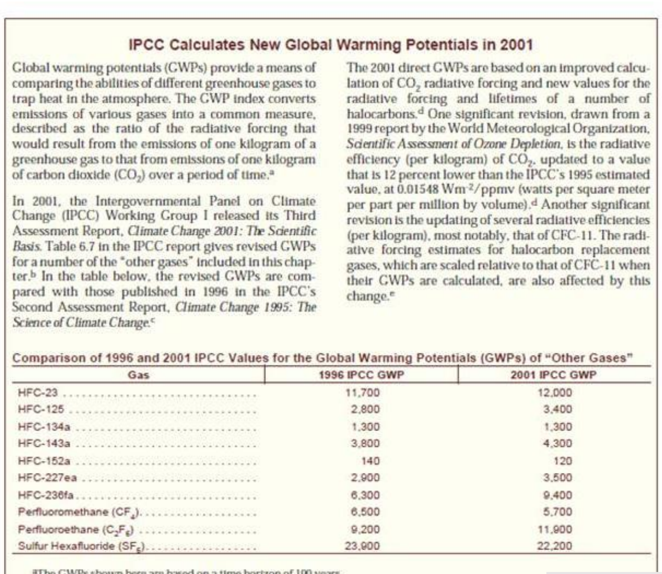
condenser and subcooling.
storage when system is stopped.

pressure drop along vapour return line (vapour column weight and frictional pressure drop)

counter flow heat exchanger

I-A: by-pass to rapidly ramp down at start-up. Stable performance even when SCT and Pixel trackers are off (minimum thermal load).

Fluorocarbon usage and green house potential



IPCC Calculates New Global Warming Potentials in 2001

Global warming potentials (GWPs) provide a means of comparing the abilities of different greenhouse gases to trap heat in the atmosphere. The GWP index converts emissions of various gases into a common measure, described as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from emissions of one kilogram of carbon dioxide (CO_2) over a period of time.[a]

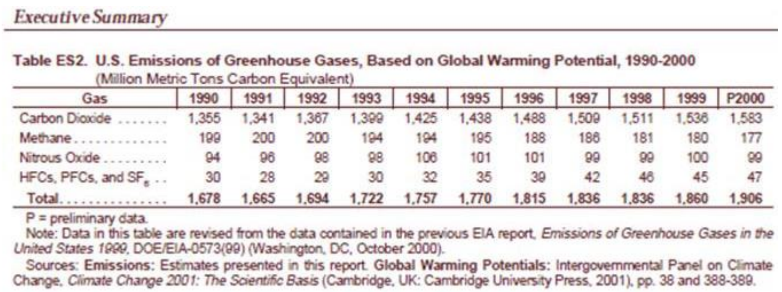
In 2001, the Intergovernmental Panel on Climate Change (IPCC) Working Group I released its Third Assessment Report, *Climate Change 2001: The Scientific Basis*. Table 6.7 in the IPCC report gives revised GWPs for a number of the "other gases" included in this chapter.[b] In the table below, the revised GWPs are compared with those published in 1996 in the IPCC's Second Assessment Report, *Climate Change 1995: The Science of Climate Change*.[c]

The 2001 direct GWPs are based on an improved calculation of CO_2 radiative forcing and new values for the radiative forcing and lifetimes of a number of halocarbons.[d] One significant revision, drawn from a 1999 report by the World Meteorological Organization, *Scientific Assessment of Ozone Depletion*, is the radiative efficiency (per kilogram) of CO_2, updated to a value that is 12 percent lower than the IPCC's 1995 estimated value, at 0.01548 $Wm^{-2}/ppmv$ (watts per square meter per part per million by volume).[d] Another significant revision is the updating of several radiative efficiencies (per kilogram), most notably, that of CFC-11. The radiative forcing estimates for halocarbon replacement gases, which are scaled relative to that of CFC-11 when their GWPs are calculated, are also affected by this change.[e]

Comparison of 1996 and 2001 IPCC Values for the Global Warming Potentials (GWPs) of "Other Gases"

Gas	1996 IPCC GWP	2001 IPCC GWP
HFC-23	11,700	12,000
HFC-125	2,800	3,400
HFC-134a	1,300	1,300
HFC-143a	3,800	4,300
HFC-152a	140	120
HFC-227ea	2,900	3,500
HFC-236fa	6,300	9,400
Perfluoromethane (CF_4)	6,500	5,700
Perfluoroethane (C_2F_6)	9,200	11,900
Sulfur Hexafluoride (SF_6)	23,900	22,200

[a] The GWPs shown here are based on a time horizon of 100 years.
[b] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: C
Press, 2001), pp. 388-389.
[c] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge
versity Press, 1996), p. 121.
[d] *Climate Change 2001*, p. 386.
[e] *Climate Change 2001*, p. 387.



Executive Summary

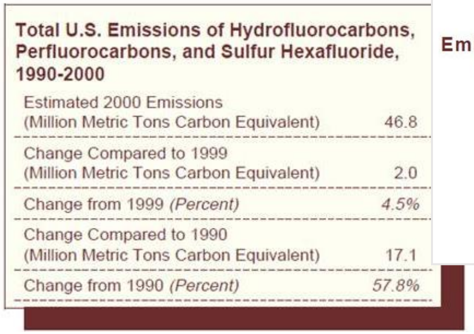
Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-2000
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Carbon Dioxide	1,355	1,341	1,367	1,399	1,425	1,438	1,488	1,509	1,511	1,536	1,583
Methane	199	200	200	194	194	195	188	186	181	180	177
Nitrous Oxide	94	96	98	98	106	101	101	99	99	100	99
HFCs, PFCs, and SF_6	30	28	29	30	32	35	39	42	46	45	47
Total	**1,678**	**1,665**	**1,694**	**1,722**	**1,757**	**1,770**	**1,815**	**1,836**	**1,836**	**1,860**	**1,906**

P = preliminary data.

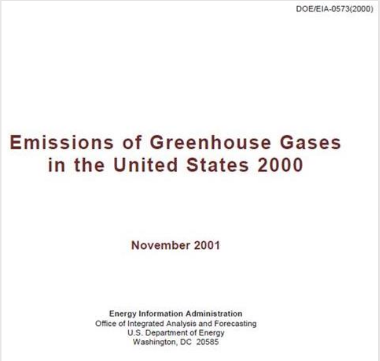
Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1999*, DOE/EIA-0573(99) (Washington, DC, October 2000).

Sources: **Emissions:** Estimates presented in this report. **Global Warming Potentials:** Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 38 and 388-389.



Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-2000

Estimated 2000 Emissions (Million Metric Tons Carbon Equivalent)	46.8
Change Compared to 1999 (Million Metric Tons Carbon Equivalent)	2.0
Change from 1999 *(Percent)*	*4.5%*
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	17.1
Change from 1990 *(Percent)*	*57.8%*



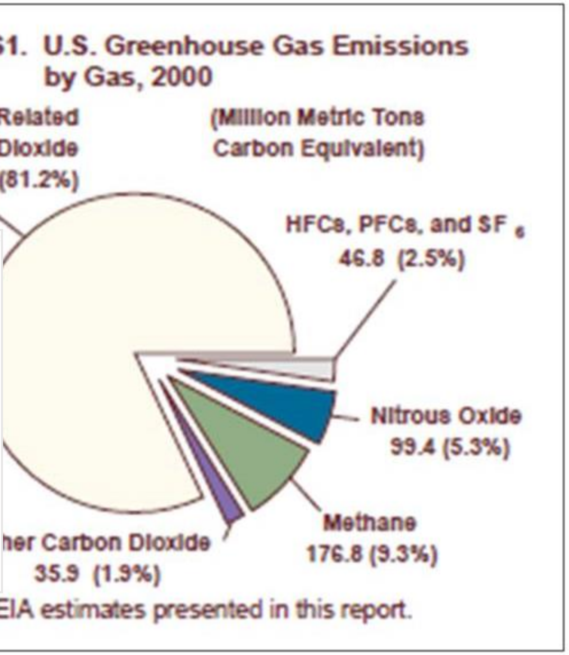
DOE/EIA-0573(2000)

Emissions of Greenhouse Gases in the United States 2000

November 2001

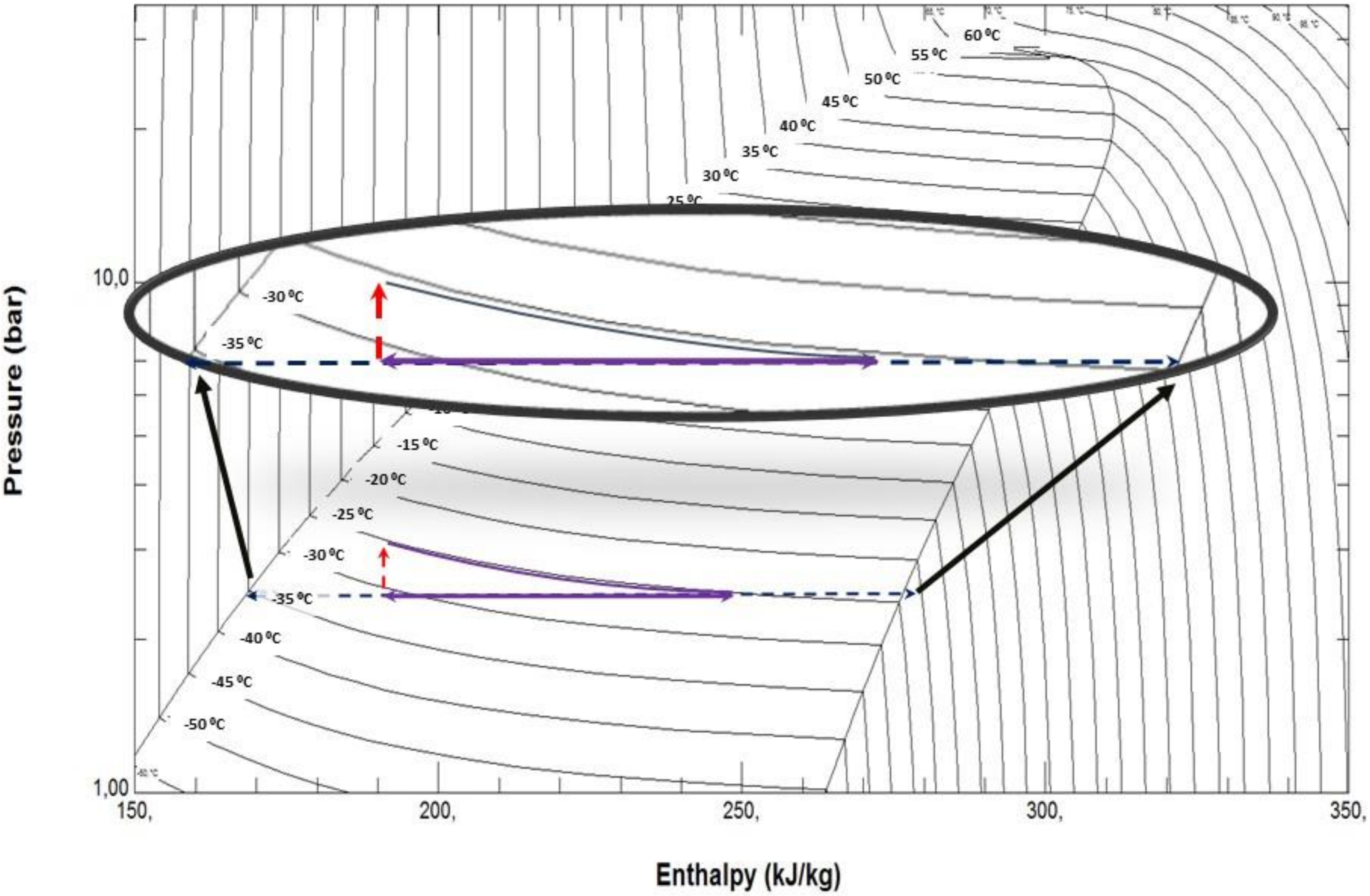
Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, DC 20585

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 2000



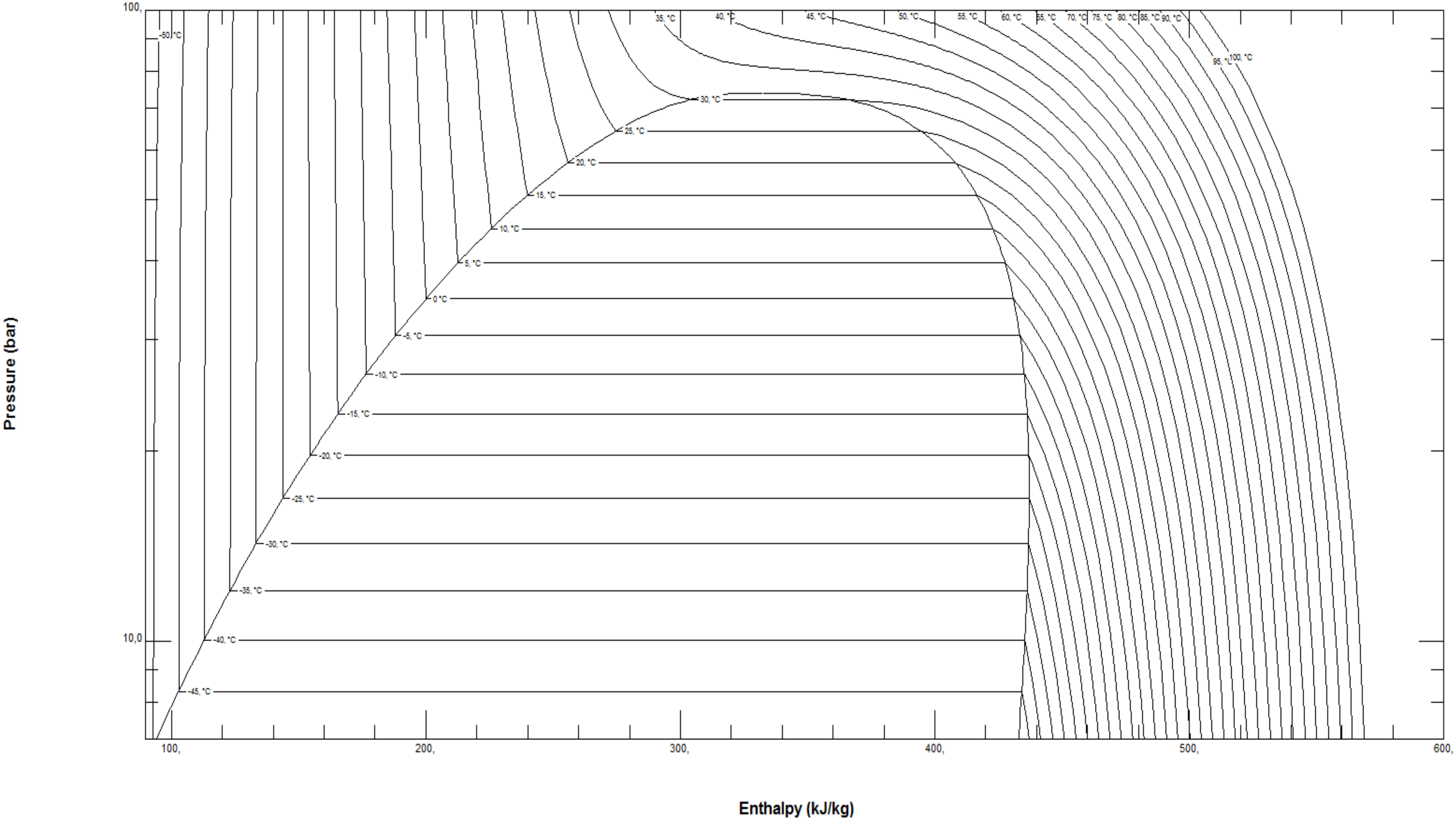
Source: EIA estimates presented in this report.

Exploitable zeotropic temperature « glide" in C2F6/C3F8 blends : here 25%/85%

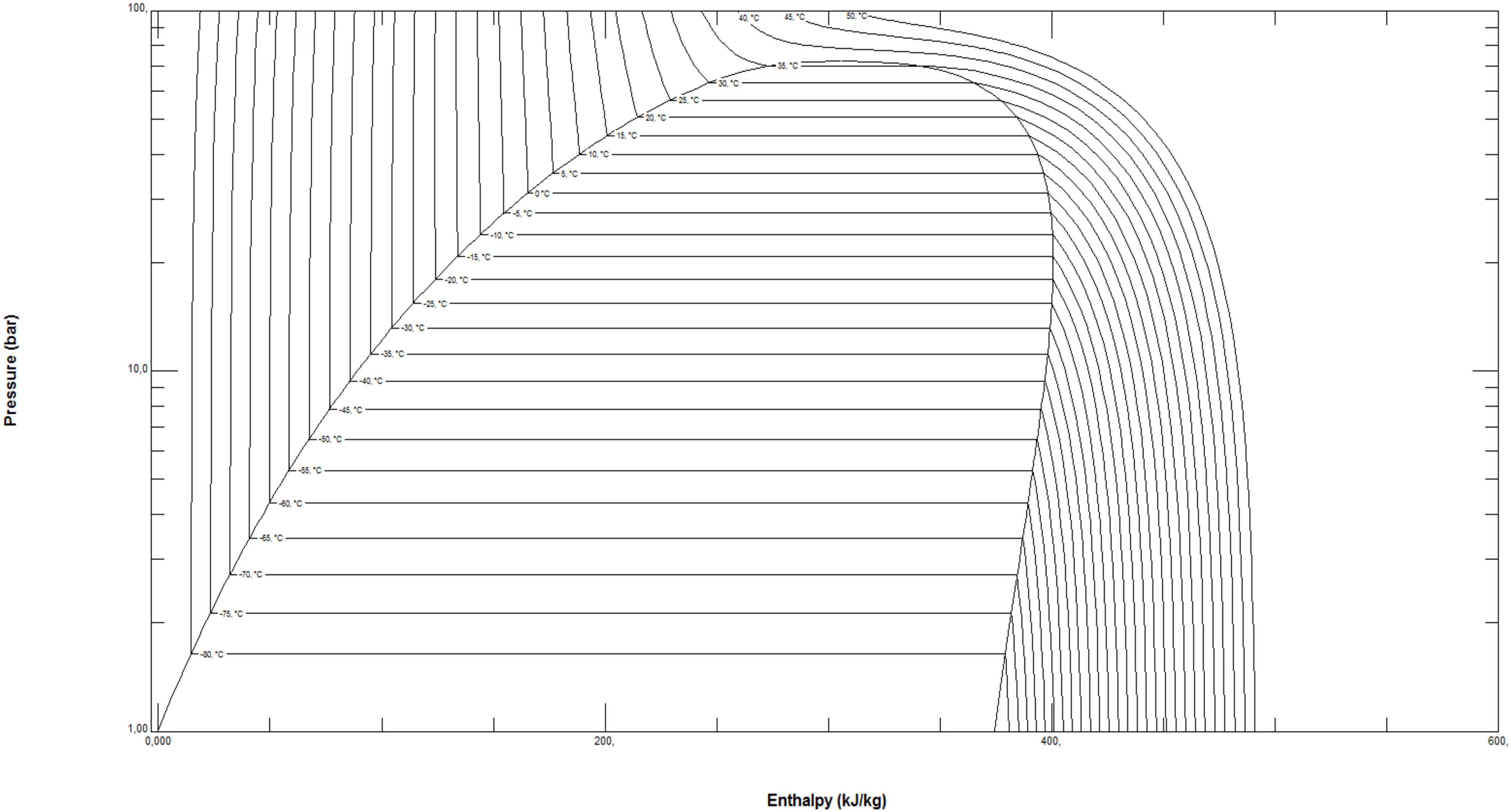


Workshop on requirements for future detector technologies in view of FCC-hh CERN, 3-4 Feb: 2015

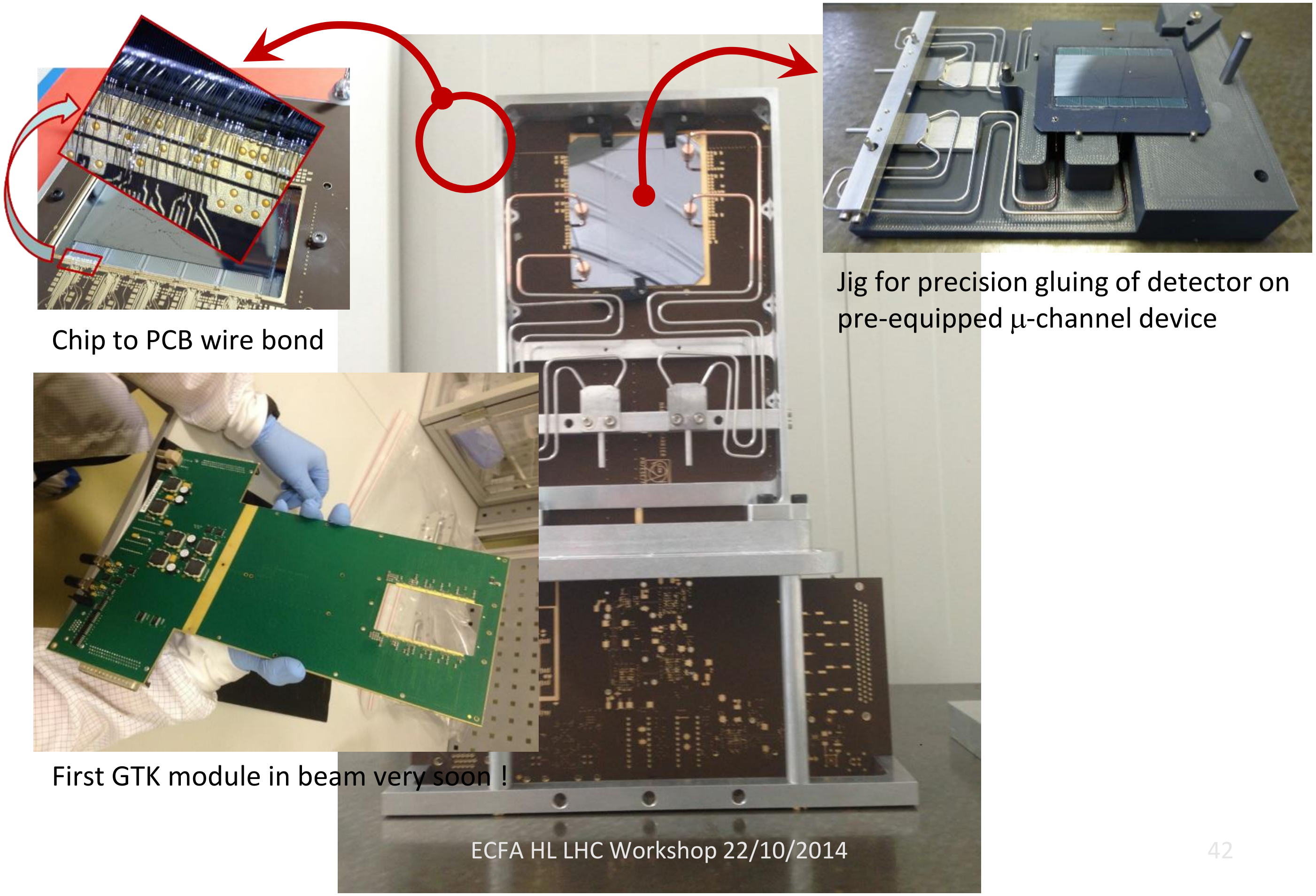
CO_2 pressure – enthalpy diagram



N_2O pressure – enthalpy diagram



NA62 GTK: assembly of detector module



Chip to PCB wire bond

Jig for precision gluing of detector on pre-equipped μ-channel device

First GTK module in beam very soon !