Possibilities for cooling the SiPMs of the LHCb upgraded scintillating fibre tracker with blends of C_2F_6 /C_3F_8 saturated $C_nF_{(2n+2)}$ fluorocarbons

G. Hallewell

Centre de Physique des Particules de Marseille

G. Hallewell: LHCb Workshop on SiPM cooling for Fiber Tracker***, CERN Oct 17, 2013***

- FT will consist of 12 planes, arranged in 3 stations along the beam, spacing in pairs likely
- Each plane, 6 m (w) x 5 m (h) contains 12 x 53 cm wide modules, read out top & bottom

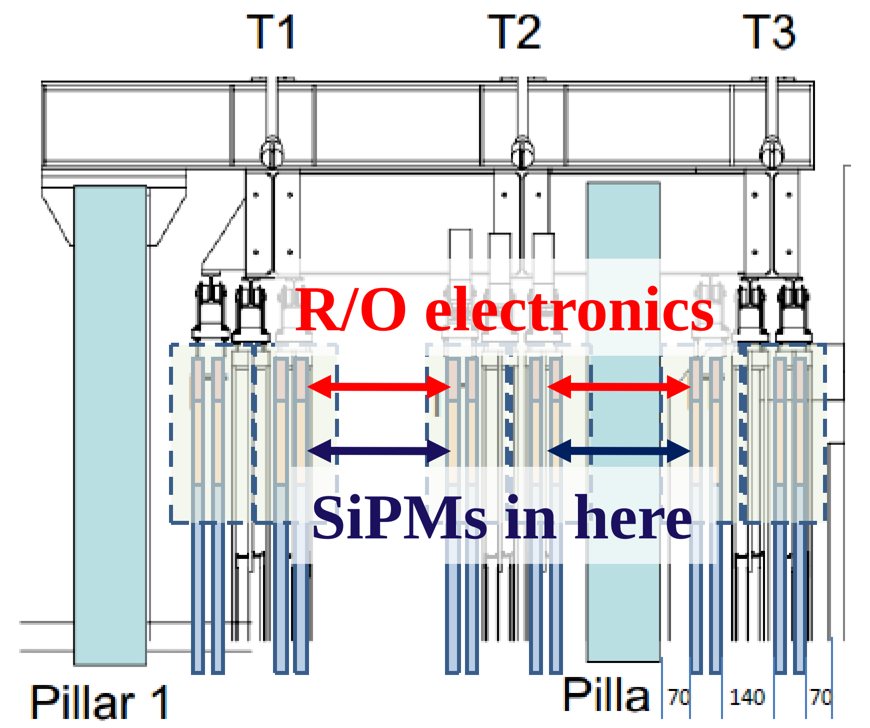
- SiPM arrays 53 cm long, each contain 16 x 33mm-long SiPMs, inside module “end-caps”.
- Each end-cap will have 10 W heat load (mainly parasitic: SiPMs dissipate mW. not including losses in incoming , outgoing connections: guess overall load 1.5-2 higher =20W

➔ total required cooling power 12 x 12 x 2 x (10-20)W ➔~ 3-6kW.

Each module to have own cooling structure inside,
➔ significant manifolding.

Limited space between planes
➔ big challenge
Approach with warm cooling
& flexible tubes preferred.

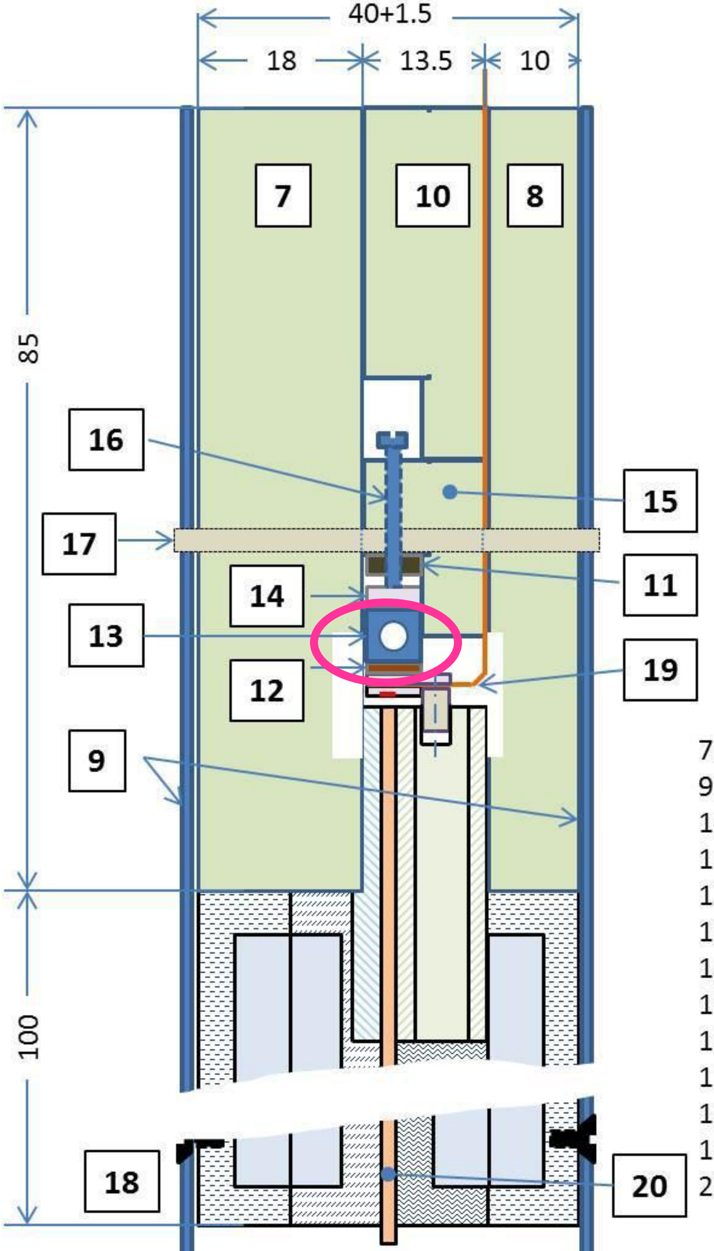
Lowest level cooling "branch"
will serve one side of 6 modules (series?),
➔48 branches, each dissipating
60➔120W.

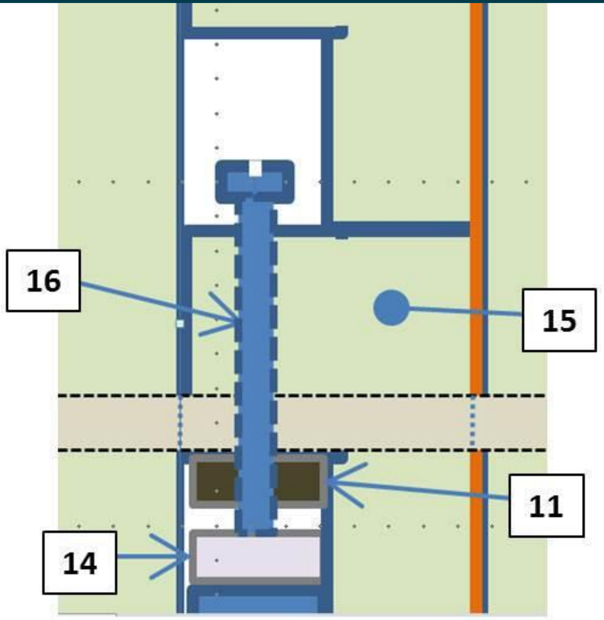


R/O electronics

SiPMs in here

Ideally, there should be “gas envelopes” flushed with dry gas around the end caps, like with all deep-cooled detectors. This would be a radical solution to a humidity condensation and the edge insulation problems. Real-life solutions should represent approximations to this approach.





The press bar (parts 11, 14-16)

7, 8 – composite side insulation plates (Rohacell+ 40 µm Alu foil)
9 – 2 mm Alu skins
10 – upper insulation plug (Rohacell + Alu foil)
11 – 2 mm threaded insert, with M2.5 holes (steel)
12 – thermal interface pad (silicon)
13 – cooling pipe (copper, 5x5 mm, OD 3 mm)
14 - cooling pipe cover (PC)
15 – pipe pressing bar (Rohacell + Alu foil)
16 – M2.5 steel pressing screws (x18)
17 – nylon M5 bolts
18 – steel M4 screws
19 – dummy flex PCB
20 – dummy fibre mat (1.5 mm rigid plexiglas sheet)

Cooling requirements: **Ref:** P.Gorbounov PH-LBO

Draft SiPM cooling system spec. for the FT for upgraded LHCb: V 1.1: update 23/9/13

- SiPM (*silicon die*) operation at -40°C → -50°C

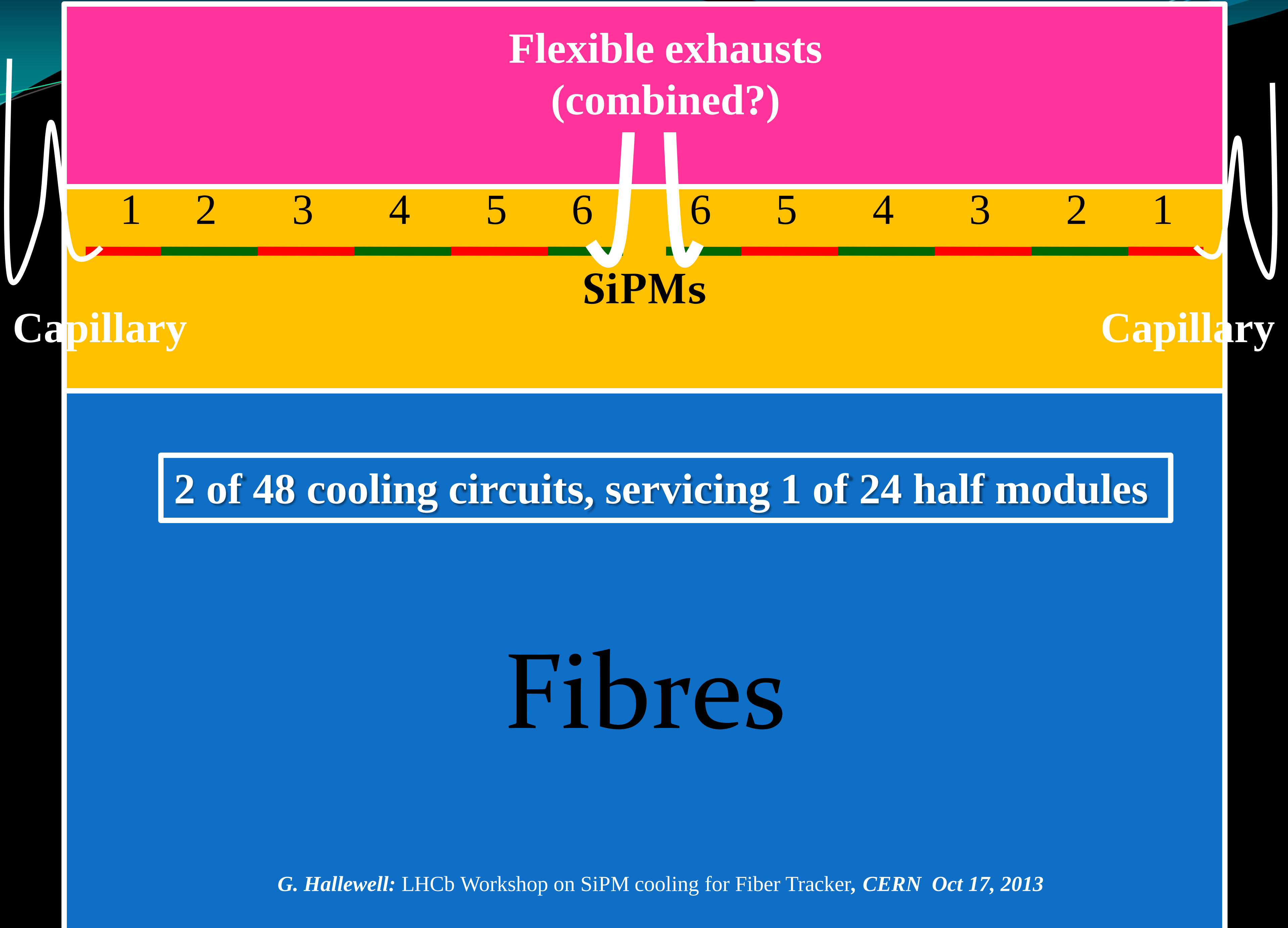
  (factor 2 drop in noise every 10 °C reduction)
- Power load (48 parallel circuits of 60-120W)→Total 3-6kW
- Temperature uniformity ≤ 1 °C over SiPM (length = 33mm)
- Temperature stability ≤ ±1 °C (timescale ~ 8 hrs)
- Fluid should be dielectric, low viscosity, non-flammable,

  non-toxic, radiation tolerant ($6{\cdot}10^{11}$ n(1 MeV)cm^{-2} & 50 Gy (ionizing);
- Cooling plant distant from detector (B field). No fans, pumps etc. in cooling distribution area (dome loaded regulators OK). Existing cooling plant in service cavern ~70 m from detector. LHCb pit depth = 110 m.

Local requirements: **Ref:** P.Gorbounov PH-LBO

Draft SiPM cooling system spec. for the FT for upgraded LHCb: V 1.1: update 23/9/13

- No condensation/frost in cold enclosure, or external surfaces.
  Gas tight enclosure flushed, dry gas (D.P. ≤-70°C)
- External module surface temp > D.P. in cavern (10-12°C).
- Modularity : Self-contained pre-assembled modules,
  no access to inner structures at the FT integration stage.
- Inlet & outlet structures on module side(s), not vertical
  (unless cooling connections flexible with no or thin insulation.)
- Clearance between FT planes ~40 mm (?).
  Limits insulation on in/out piping, favours warm external connections
- Coolant distribution : 48 branches (one per 6 end caps of every half-layer side (top/bottom)). Half-layers slide apart, distribution lines to each of 24 half-layers needs flexible section matching "caterpillar" cable trays.



2 of 48 cooling circuits, servicing 1 of 24 half modules

Some advantages of saturated $C_nF_{(2n+2)}$ fluorocarbons

- Dielectric, low visc., non-flamm., non-toxic, radiation resistant;
- Long experience of use at CERN as monophase (mainly C_6F_{14}) & evaporative (C_3F_8 , C_4F_{10}) coolant, and as Cherenkov radiators (C_2F_6, C_5F_{12}, C_6F_{14}, C_4F_{10}, CF_4);
- Evidence that increased C_2F_6 molar conc. in C_2F_6 /C_3F_8 blends reduces evaporation temperature in systems with pre-constrained input/exhaust services; →
- Blends rich in C_2F_6 offer possibility low temperature operation

  (close to or below -55°C: CO_2 snow point) with comparatively low pressure in on-detector cooling channels;
- Lower T_{CRIT}, P_{CRIT} than CO2
- The use of hybrid thermosiphon exploiting the 112 m deep LHCb pit can allow condenser cooling with a single stage secondary refrigeration plant.

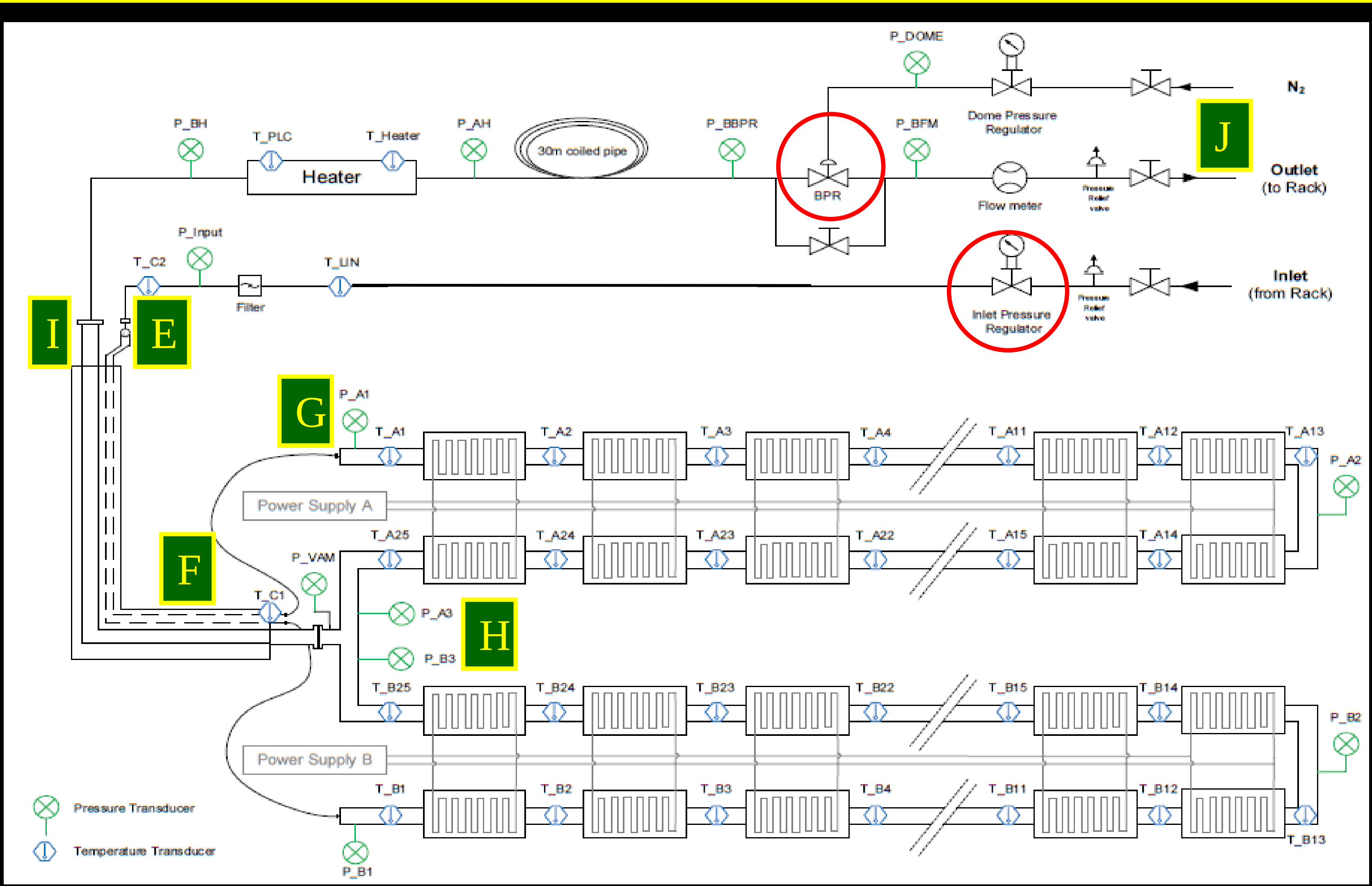
Studies of C_2F_6/C_3F_8 blends in a simulated SCT bi-stave structure

Evidence that increased C_2F_6 molar concentration in the blends reduces operating temperature in systems with pre-constrained input/exhaust services

(ATLAS inner tracker: as-installed through-detector uninsulated C_3F_8 liquid delivery/vapour return tubes)

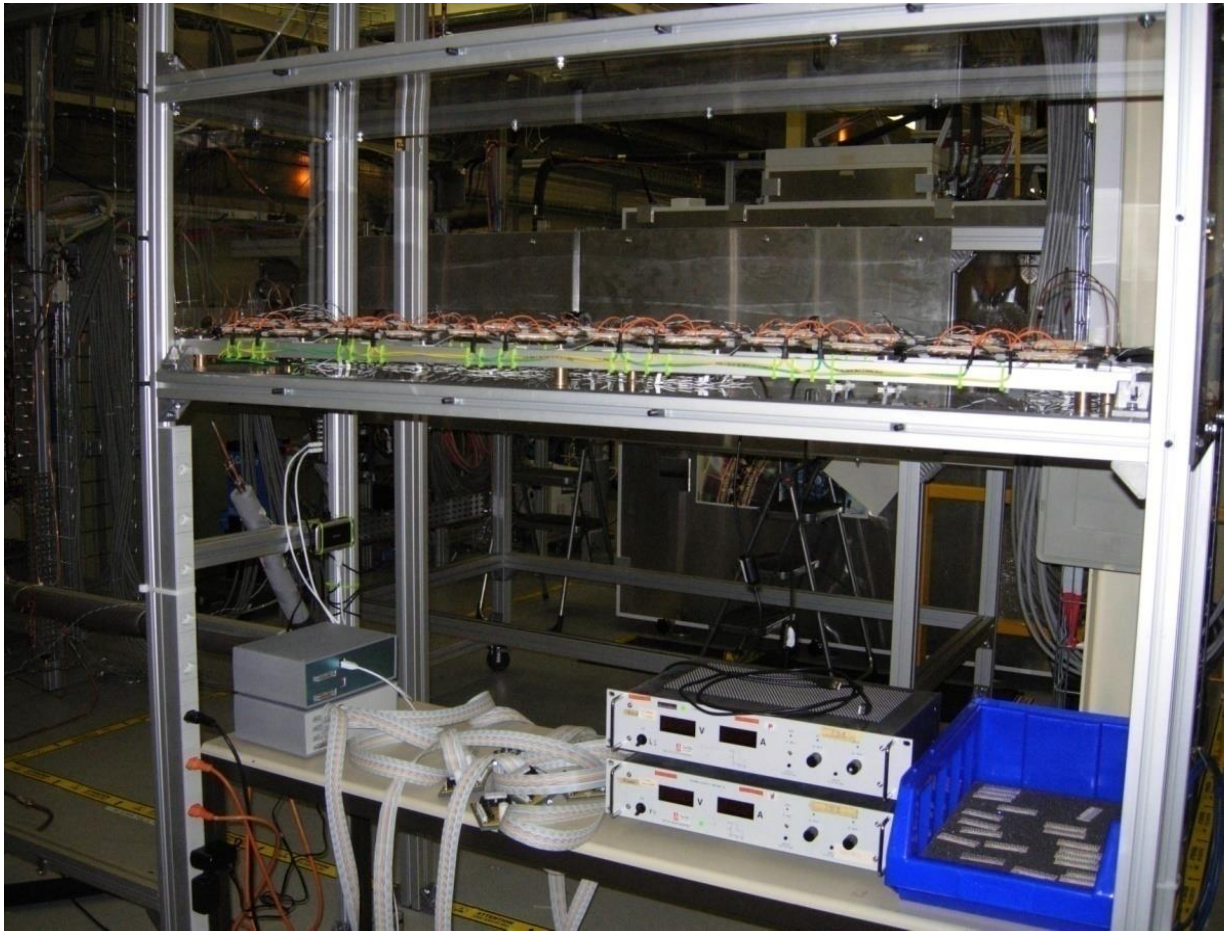
ATLAS SCT barrel bi-stave thermal model

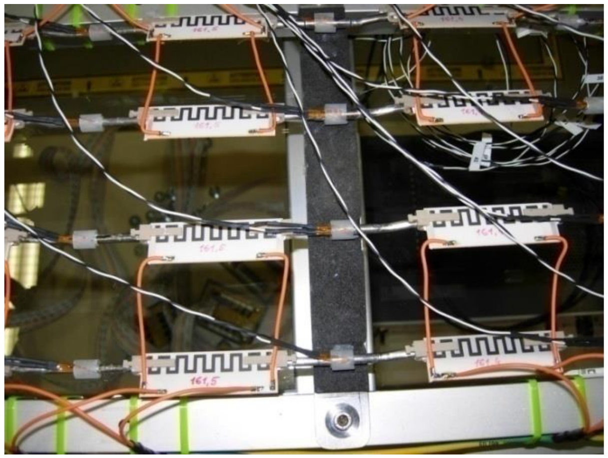
30 m uninsulated coolant tubes: local hex & exhaust heater,
48 modules: 2 capillaries, common exhaust



ATLAS SCT barrel bi-stave thermal model

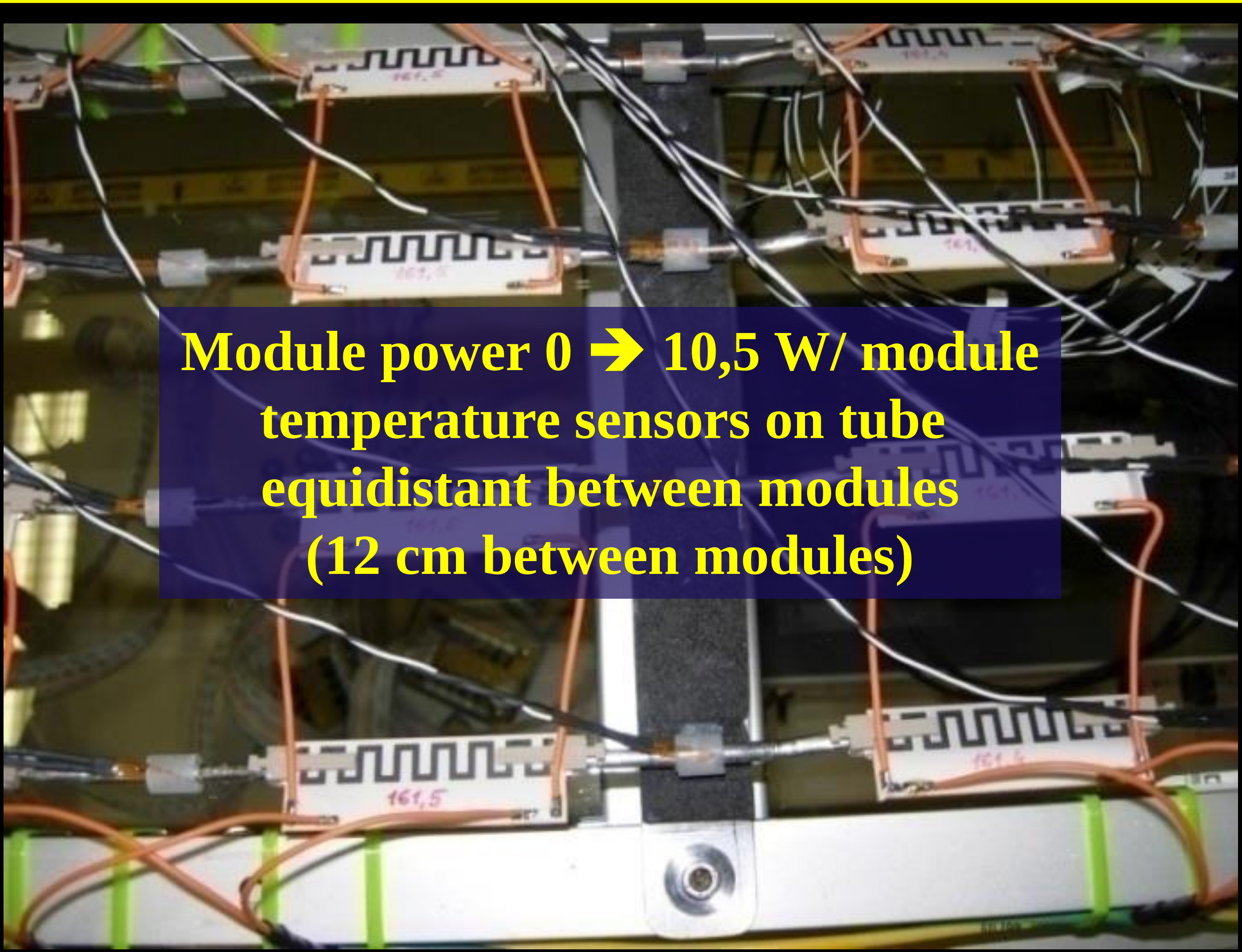
30 m uninsulated coolant tubes: local hex & exhaust heater,
48 modules: 2 capillaries, common exhaust



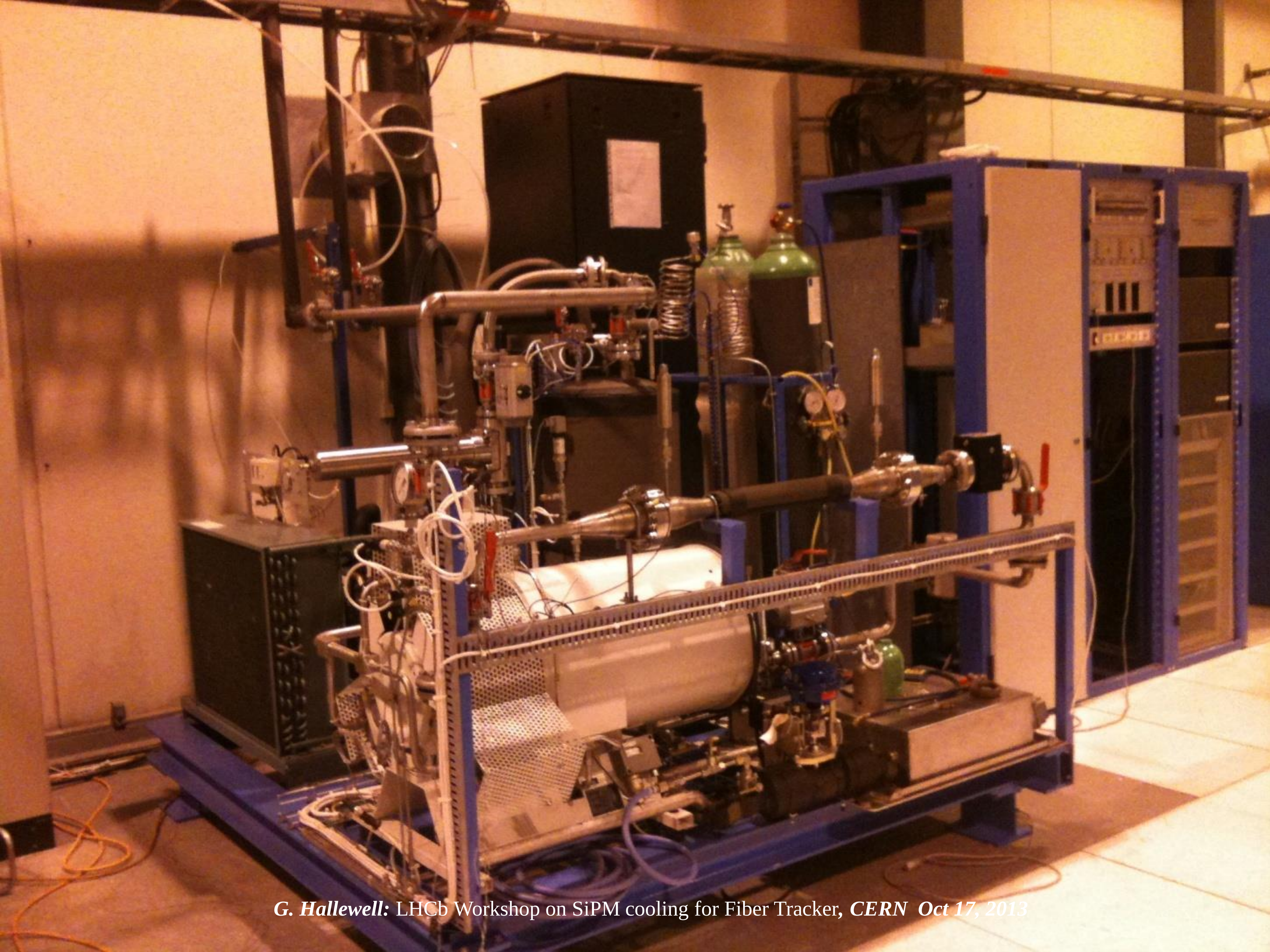


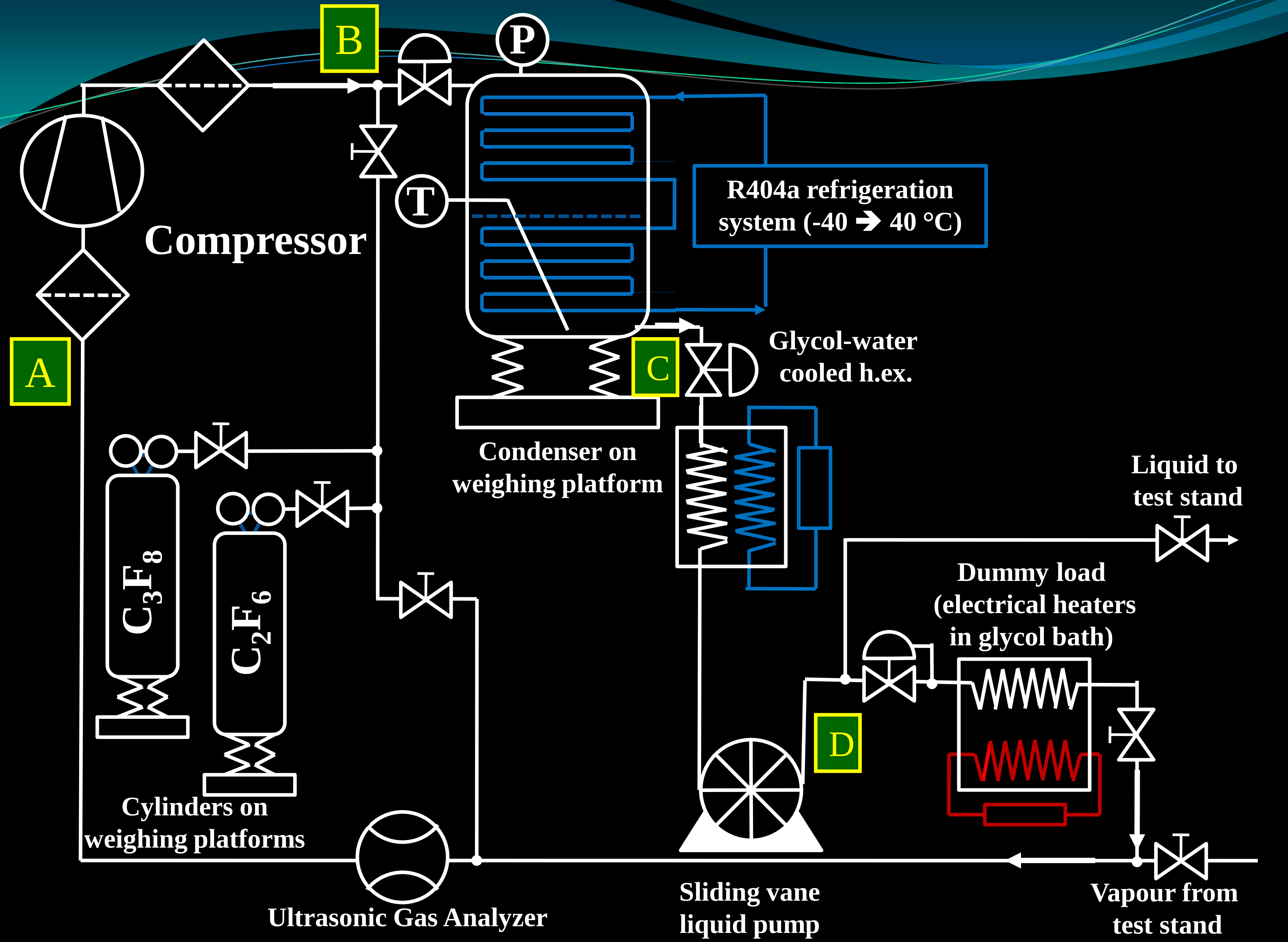
ATLAS SCT barrel bi-stave thermal model

30 m uninsulated coolant tubes: local hex & exhaust heater, 48 modules: 2 capillaries, common exhaust



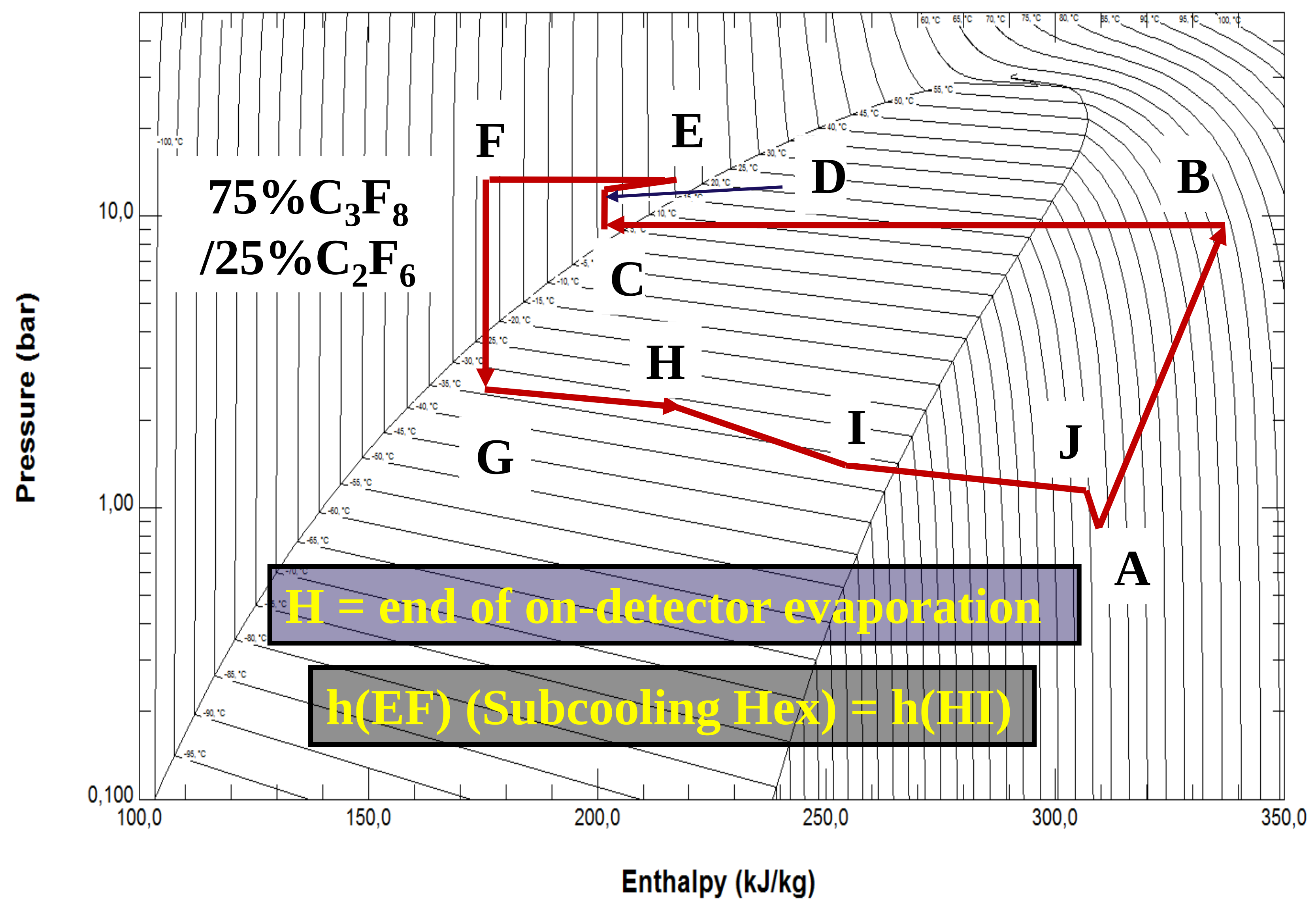
Module power 0 → 10,5 W/ module
temperature sensors on tube
equidistant between modules
(12 cm between modules)




B
P
A
T
Compressor
R404a refrigeration system (-40 ➔ 40 °C)
C
Glycol-water cooled h.ex.
C_3F_8
C_2F_6
Condenser on weighing platform
Liquid to test stand
Dummy load (electrical heaters in glycol bath)
D
Cylinders on weighing platforms
Ultrasonic Gas Analyzer
Sliding vane liquid pump
Vapour from test stand

Sliding vane liquid booster pump 3m below condenser, descending tube precooled with glycol

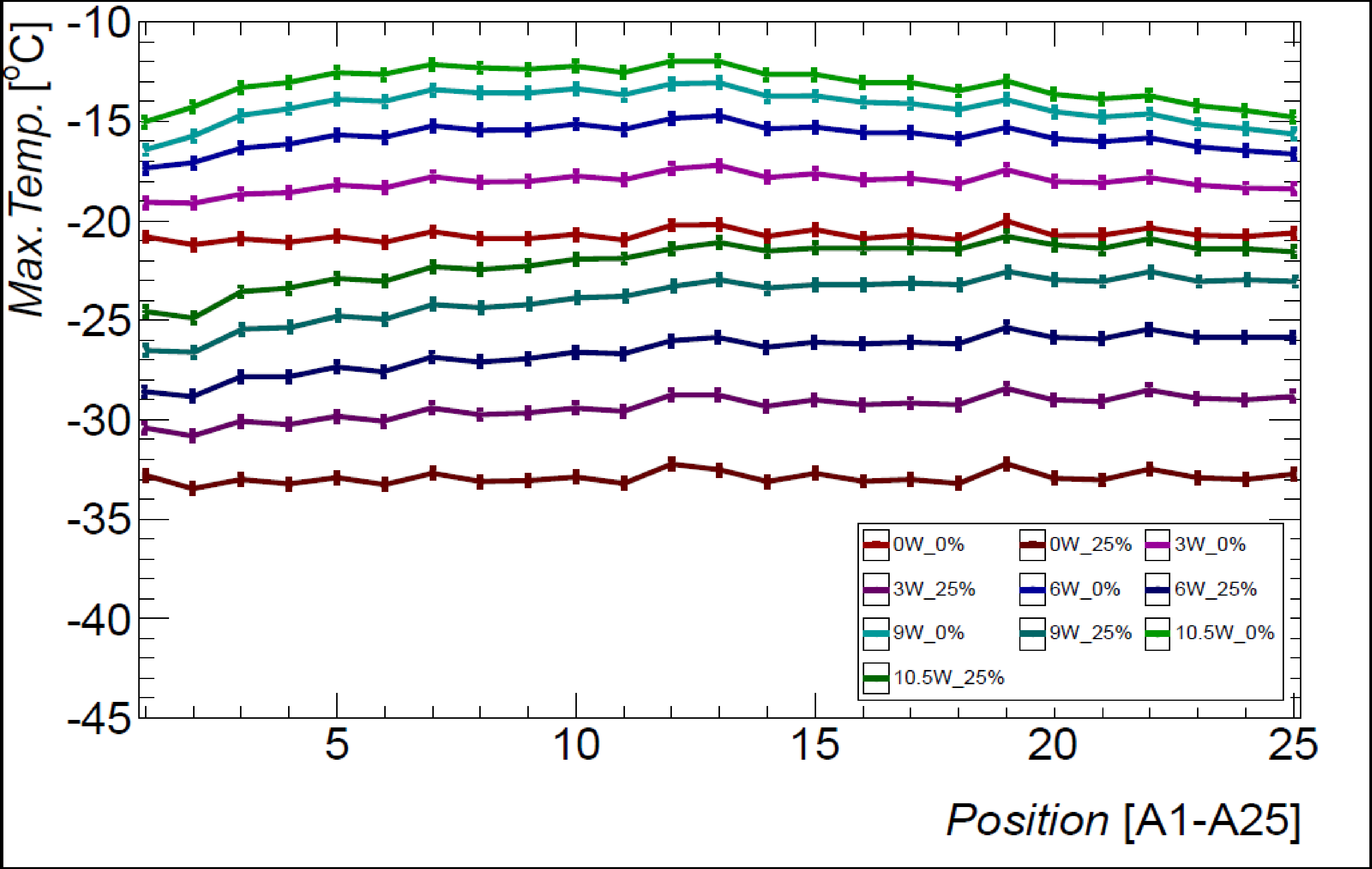
P-h diagram for 75%C_3F_8/25%C_2F_6
(liquid subcooling to -23ºC note: zeotropic temperature “glide”)



H = end of on-detector evaporation

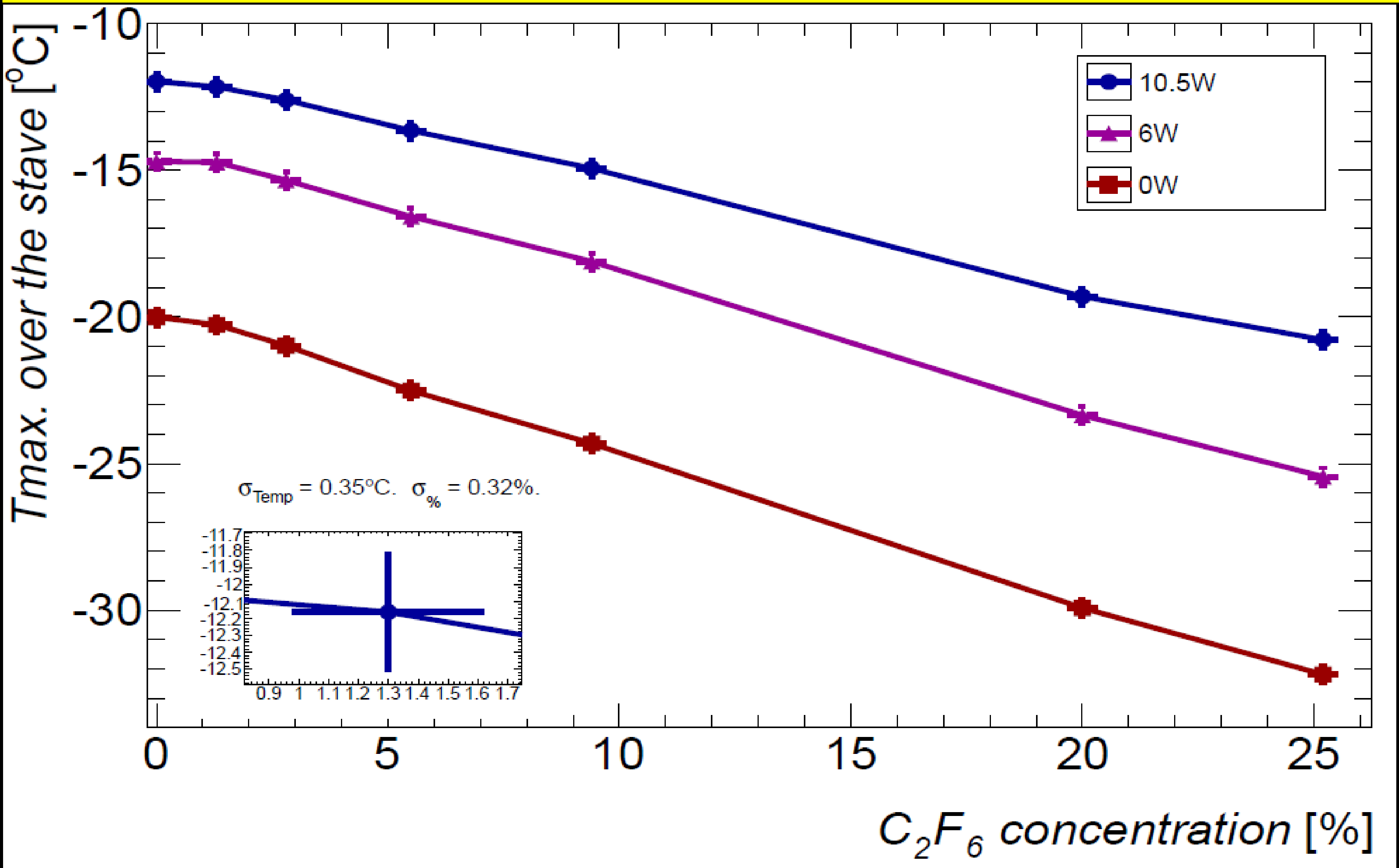
h(EF) (Subcooling Hex) = h(HI)

Dummy barrel SCT bi-stave: temp. profiles in pure C_3F_8 &75%C_3F_8/25%C_2F_6 (Back pressure (30 m downstream) at 1.2 bar_{abs})



Temperature gain (max. of 25 temperatures along 3.2m tube) *vs.* %C_2F_6 molar concentration in C_3F_8/C_2F_6 blend

(Back pressure (30 m downstream) at 1.2 bar_{abs})



Warm services outside the SiPM Tracker... Care needed!

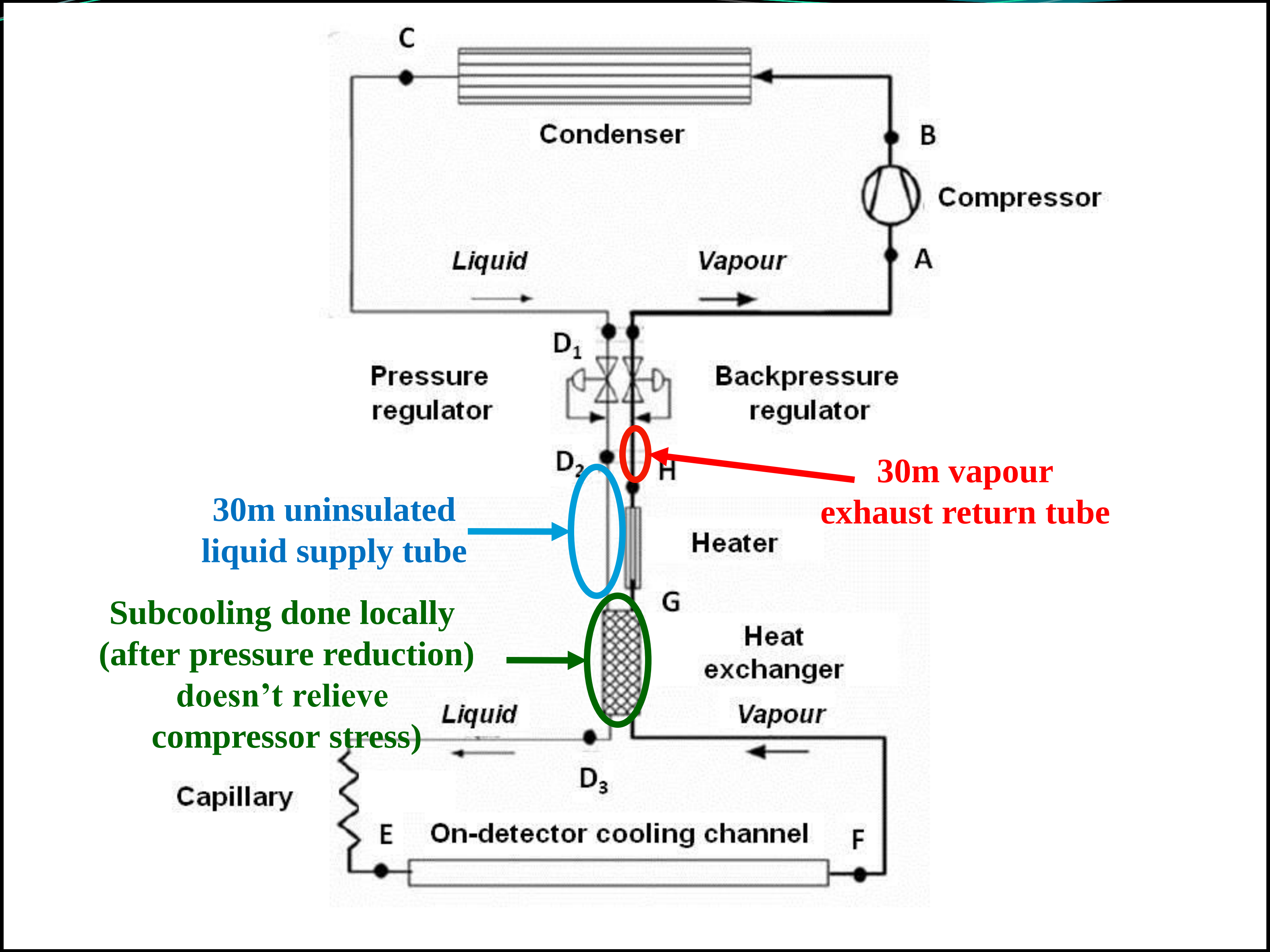
(ATLAS inner tracker suffers from as-installed through-detector uninsulated C_3F_8 liquid delivery/vapour return tubes and lack of dynamic flow control)

- ➔ **high compression ratio (x20) in 2 stage compressors**
- ➔ **compressor fragility and expensive ongoing maintenance**
- ➔ **thermosiphon replacement**
- ➔ **Constant mass flow overdrive**

(for 120% * worst case module dissipation)

requires powerful exhaust heaters (partially immersed) which have had serious reliability problems

The present ATLAS configuration



30m vapour exhaust return tube

30m uninsulated liquid supply tube

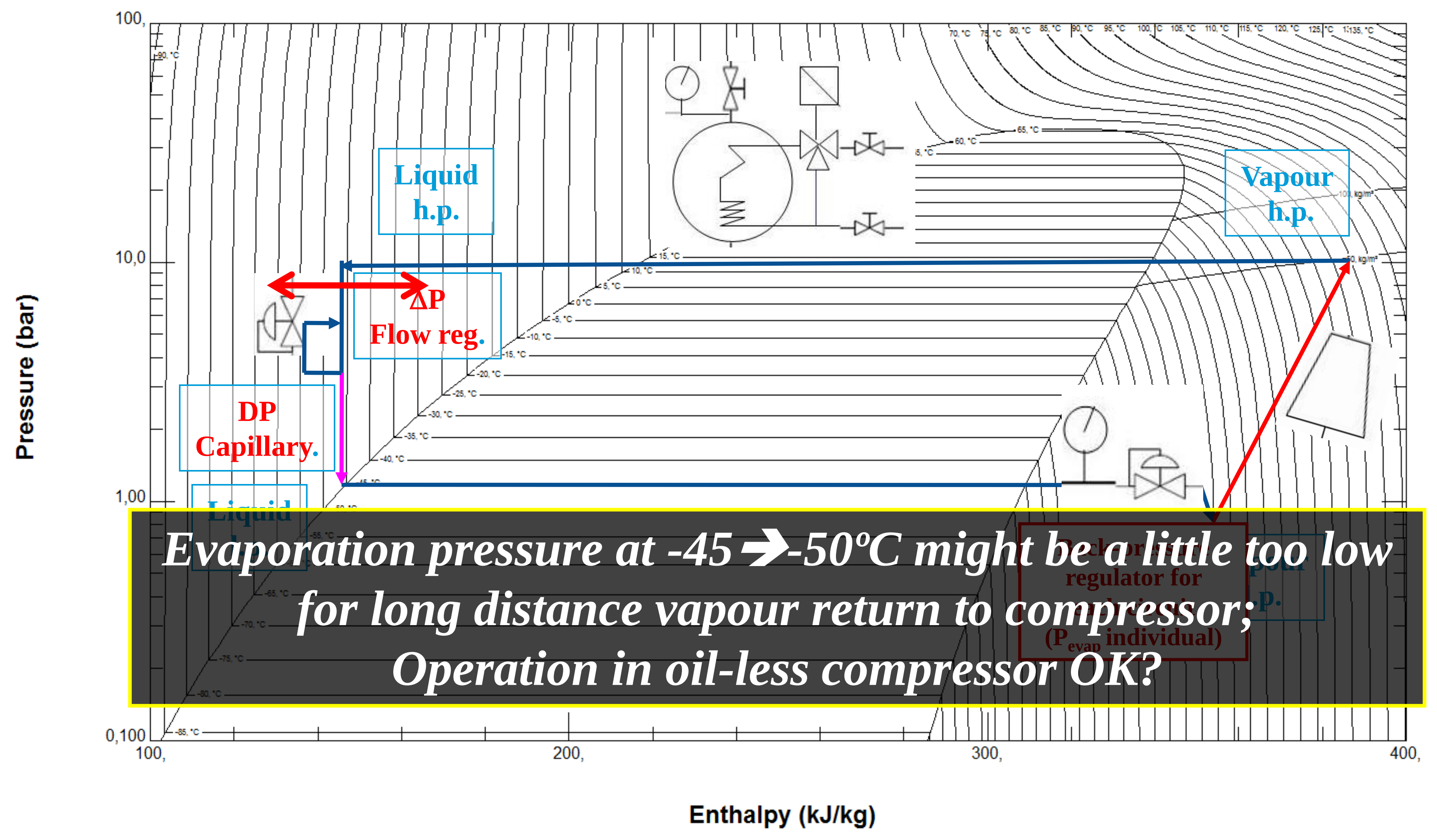
Subcooling done locally (after pressure reduction) doesn't relieve compressor stress)

Trying to keep warm services outside the SiPM tracker purged gas enclosure...

Dynamic flow control advatage

Advantage of flow regulation after full pre/sub cooling C_2F_5H (R125: pentafluoro-ethane) P-h diagram (following idea of Petr Gorbounov)

Is this fluid radiation-resistant enough (contains H, F, C)?? - Question for Sorin Ilie



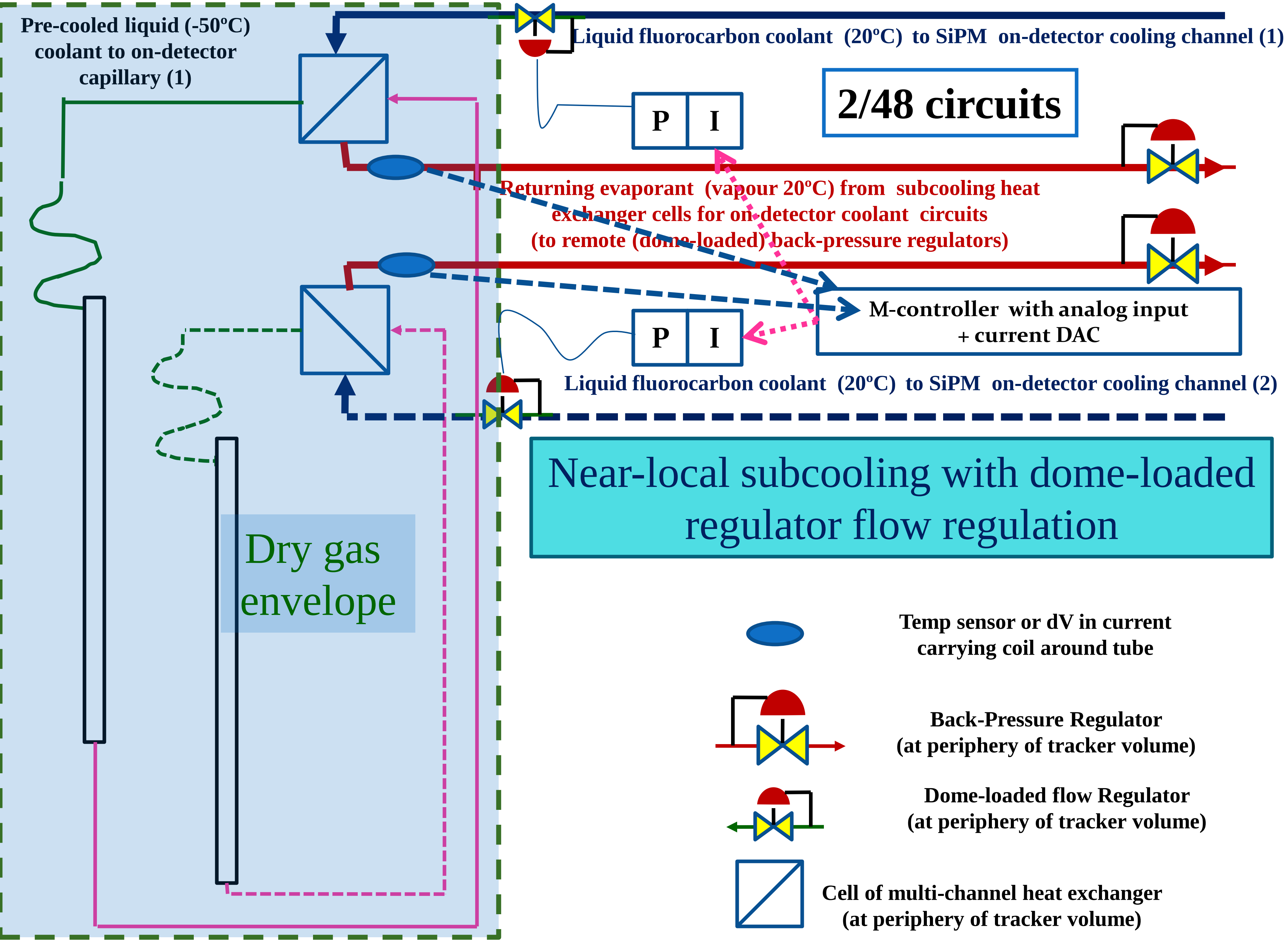
Evaporation pressure at -45 → -50ºC might be a little too low for long distance vapour return to compressor; Operation in oil-less compressor OK?

Candidate compressor (Haug, oil-less, Pin ~ 1 bar, Pout ~ 9 bar) to be returned to CERN from Oxford in November 2013

(ex. C_3F_8 phase 2 6kW demonstrator (Vacek, Hallewell: 2000) & SCT C_3F_8 evaporative cooling commissioning (Viehhauser))

Flow control elements can be ‘dome loaded’ regulators with analog compressed air signals converted in I/P or V/P converters from DAC voltages/currents

Near-local subcooling with dome-loaded regulator flow regulation



2/48 circuits

Pre-cooled liquid (-50°C) coolant to on-detector capillary (1)

Liquid fluorocarbon coolant (20°C) to SiPM on-detector cooling channel (1)

Returning evaporant (vapour 20°C) from subcooling heat exchanger cells for on-detector coolant circuits (to remote (dome-loaded) back-pressure regulators)

M-controller with analog input + current DAC

Liquid fluorocarbon coolant (20°C) to SiPM on-detector cooling channel (2)

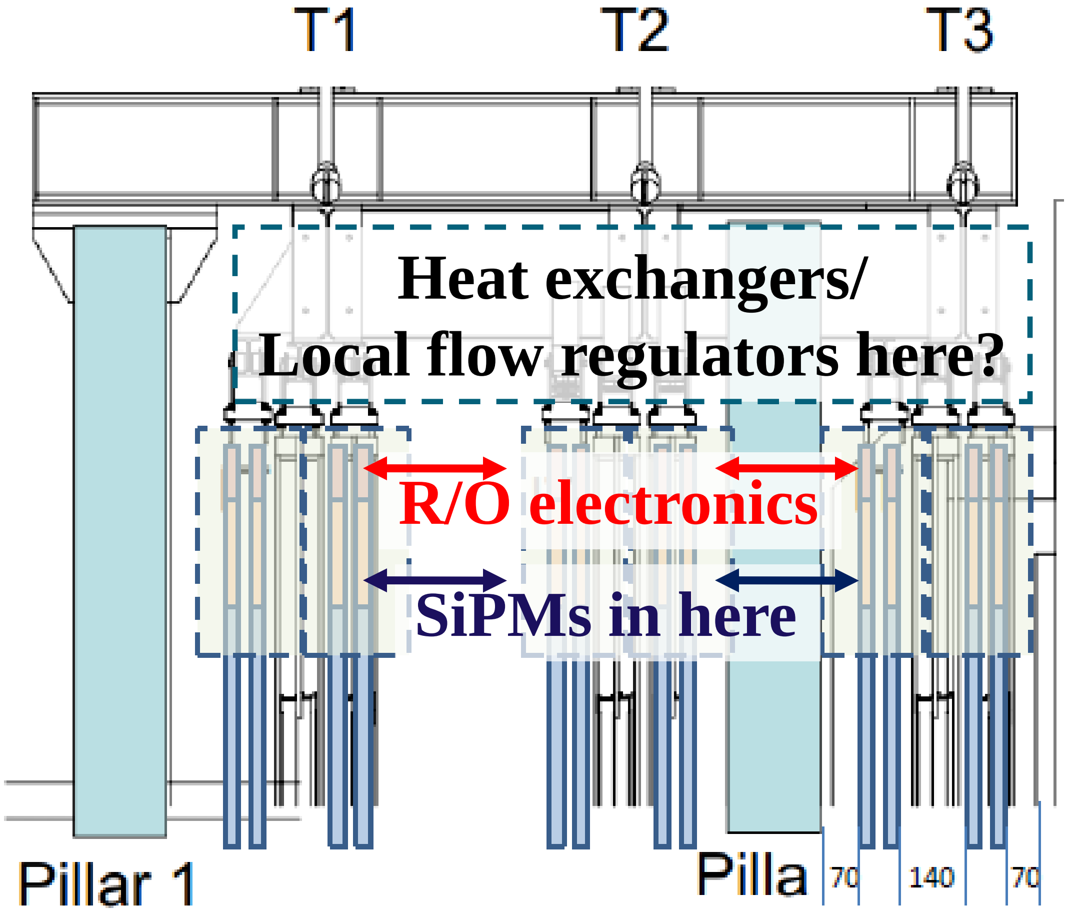
Dry gas envelope

Temp sensor or dV in current carrying coil around tube

Back-Pressure Regulator (at periphery of tracker volume)

Dome-loaded flow Regulator (at periphery of tracker volume)

Cell of multi-channel heat exchanger (at periphery of tracker volume)



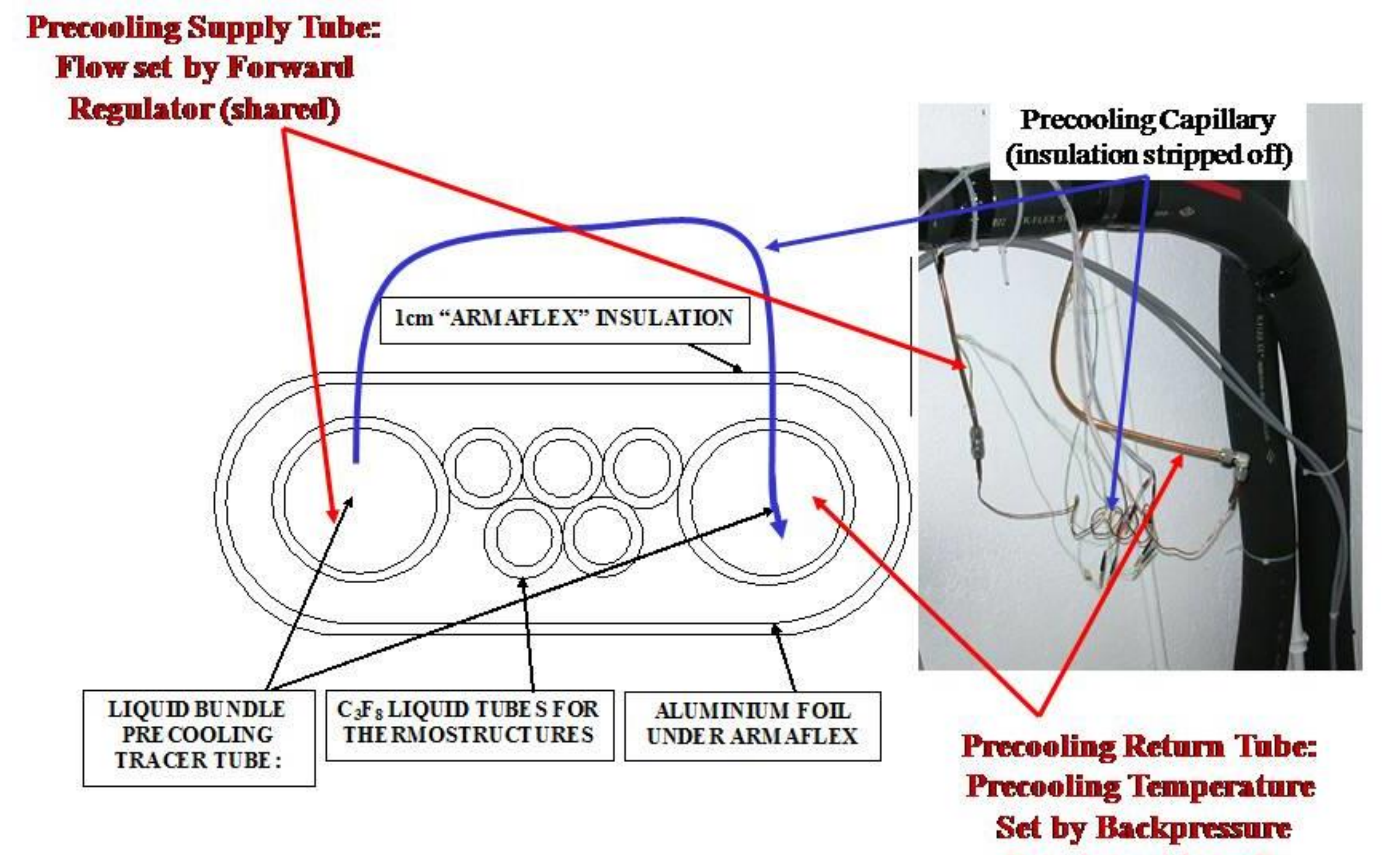
**Heat exchangers/
Local flow regulators here?**

R/O electronics

SiPMs in here

Ideally, there should be "gas envelopes" flushed with dry gas around the end caps, like with all deep-cooled detectors. This would be a radical solution to a humidity condensation and the edge insulation problems. Real-life solutions should represent <u>approximations</u> to this approach.

First stage precooling can be distributed along tube, if insulation is allowed



Precooling Supply Tube: Flow set by Forward Regulator (shared)

Precooling Capillary (insulation stripped off)

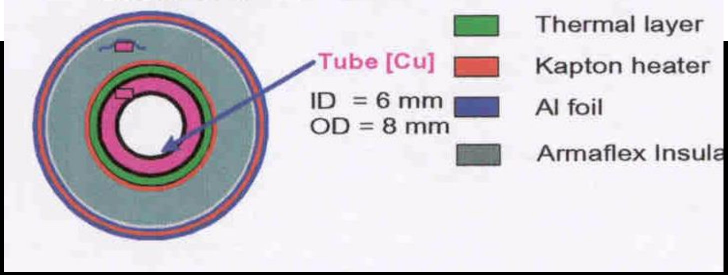
1cm “ARMAFLEX” INSULATION

LIQUID BUNDLE PRECOOLING TRACER TUBE :

C_3F_8 LIQUID TUBES FOR THERMOSTRUCTURES

ALUMINIUM FOIL UNDER ARMAFLEX

Precooling Return Tube: Precooling Temperature Set by Backpressure Regulator (shared)



Tube [Cu]

ID = 6 mm

OD = 8 mm

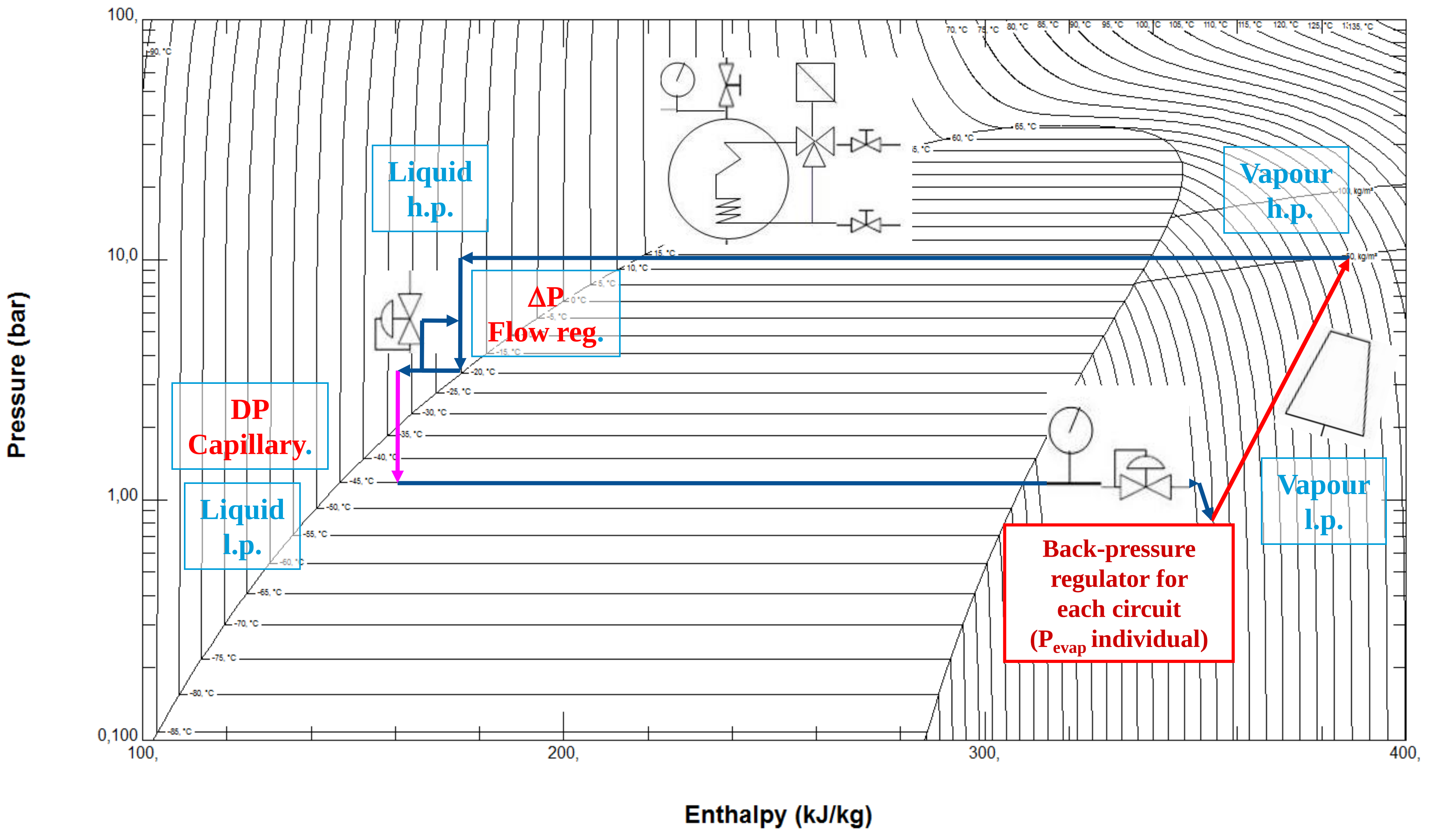
🟩 Thermal layer

🟥 Kapton heater

🟦 Al foil

⬛ Armaflex Insula

Flow regulation after partial pre/sub cooling is more responsive "plus nerveux" and may be necessary if there is no space for local flow regulator on detector



Condensation risk if vapour exhaust tube temperatures are below the local dew point(s)

Control by Proportional, Integral & Derivative *firmware* in microcontroller;

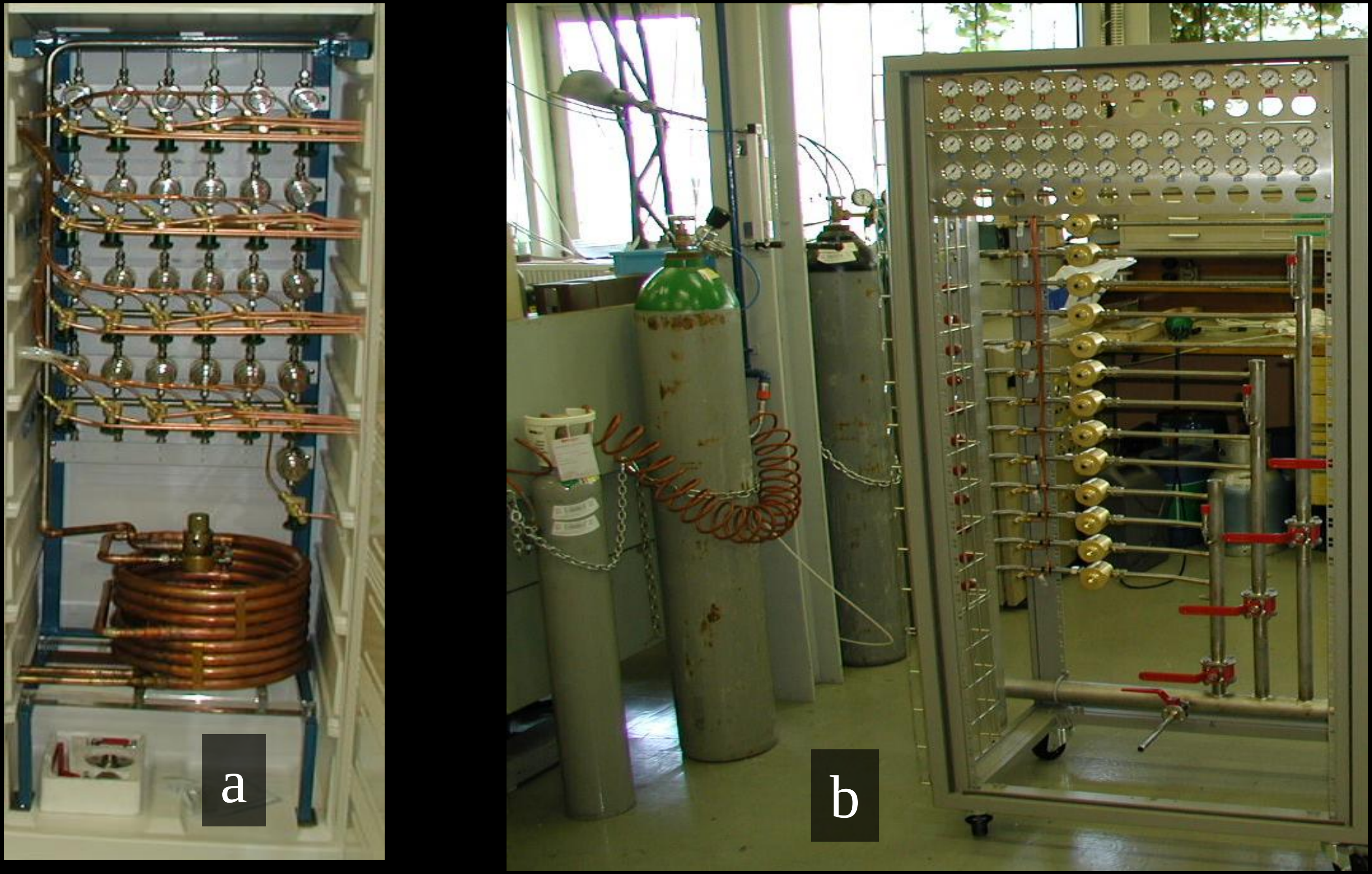
$$p(t) = K_c[e(t) + (1/\tau_I) \int_0^t e(t^*)dt^* + t_D(de/dt)]$$

Object: maintain temperature downstream of heat exchanger few ºC above external dew point

- Temperature sensors or current coils ➔ microcontroller analog inputs;
- Microcontroller DAC outputs (0-10VDC, 4-20mA) ➔ E/P, I/P converter
- E/P, I/P generates proportional air pressure to dome of flow regulator (varying coolant mass flow)

Note: Evaporation temperature -40 ➔-50ºC settable by dome pressure applied to backpressure regulator in exhaust line (not dynamically varied)

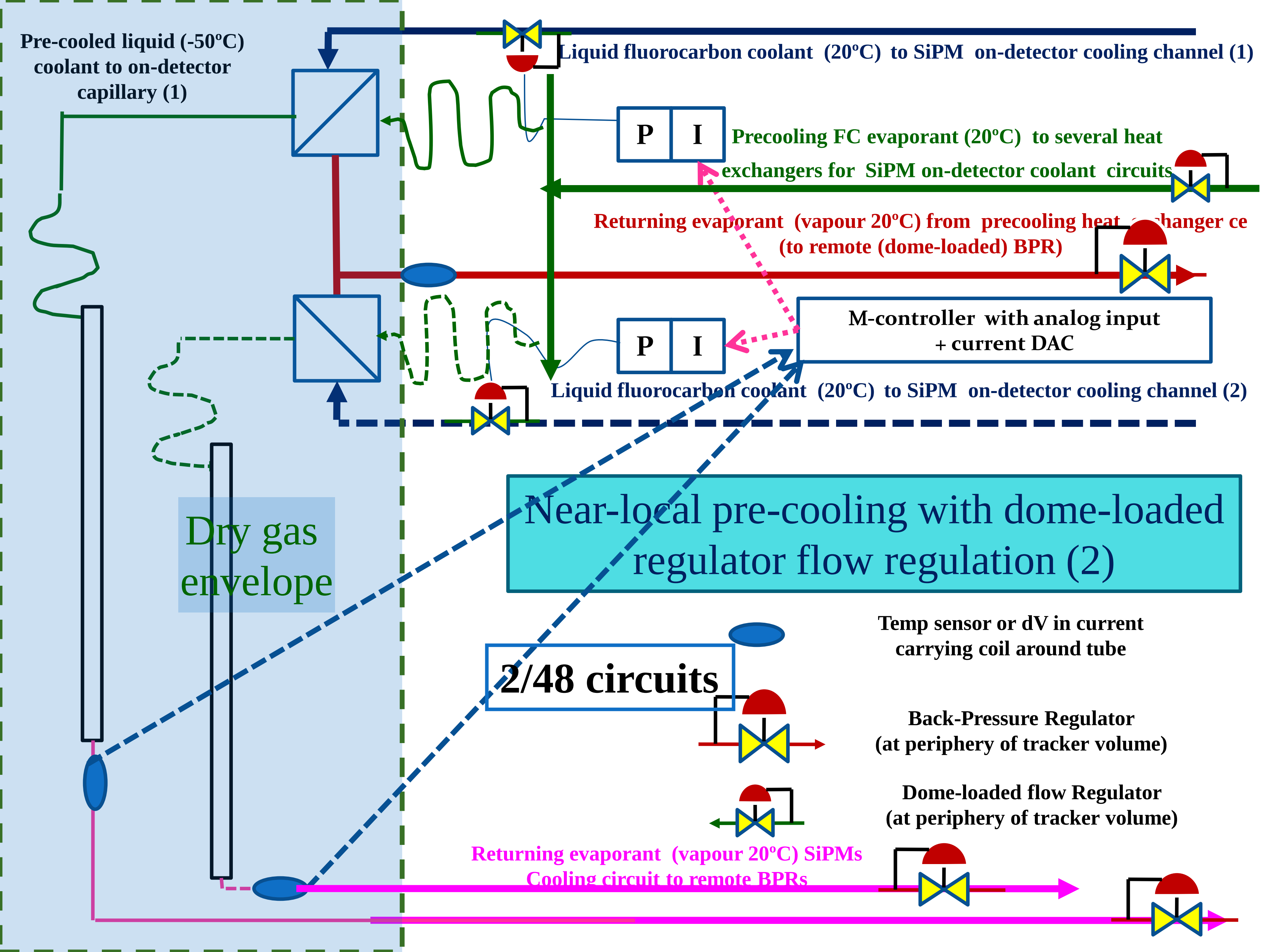
Dome loaded flow (pressure) regulators (a) and backpressure regulators (b)



Many heat exchanger combinations possible:

example without circuit-specific sub-cooling
or dynamic flow control
➔ Cascaded local heat exchangers
with 20ºC intermediate cooling liquid (C_6F_{14}?)
might be possible

Near-local pre-cooling with dome-loaded regulator flow regulation (2)



Pre-cooled liquid (-50°C) coolant to on-detector capillary (1)

Liquid fluorocarbon coolant (20°C) to SiPM on-detector cooling channel (1)

Precooling FC evaporant (20°C) to several heat exchangers for SiPM on-detector coolant circuits

Returning evaporant (vapour 20°C) from precooling heat exchanger ce (to remote (dome-loaded) BPR)

M-controller with analog input + current DAC

Liquid fluorocarbon coolant (20°C) to SiPM on-detector cooling channel (2)

Dry gas envelope

2/48 circuits

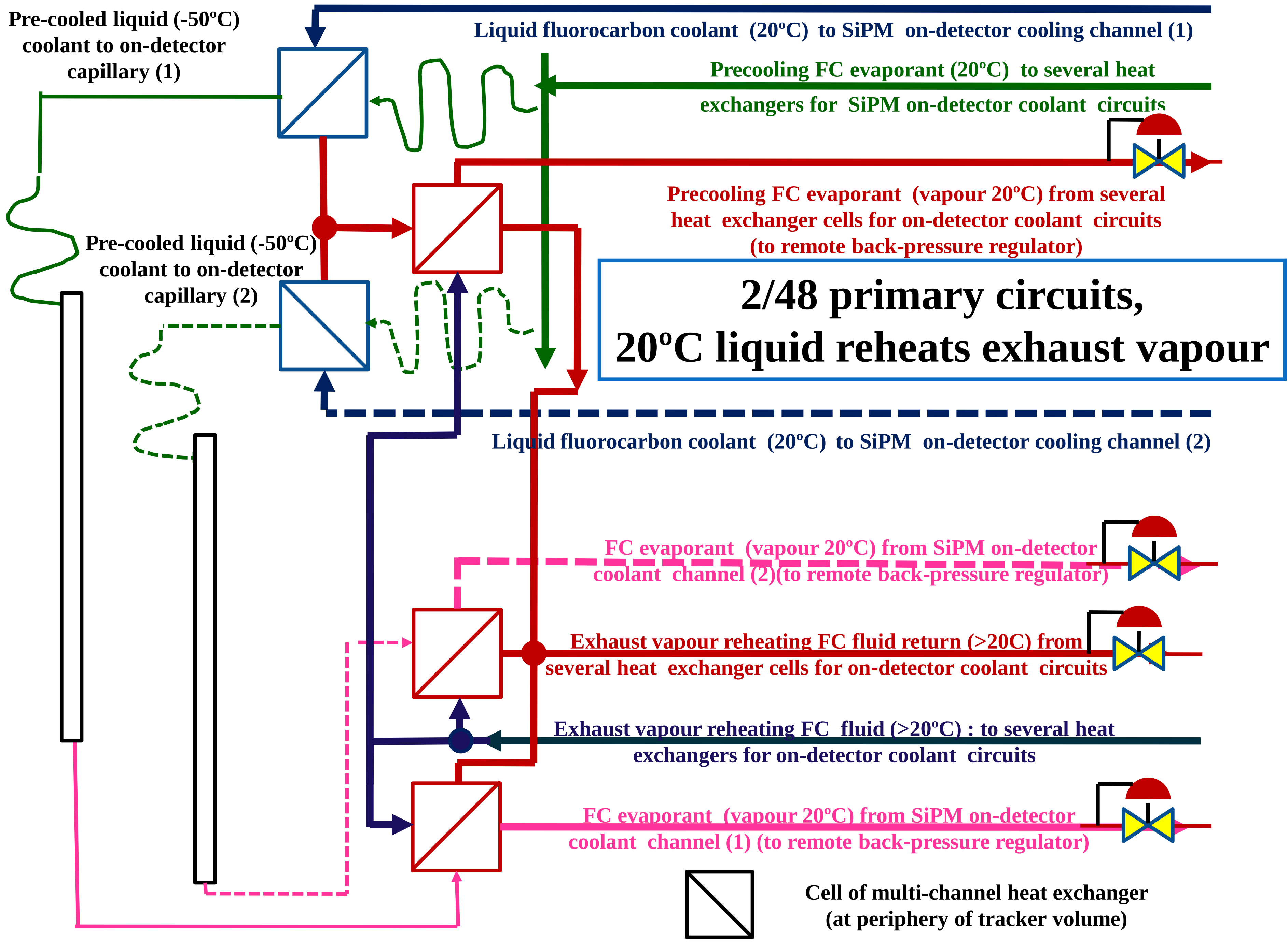
Temp sensor or dV in current carrying coil around tube

Back-Pressure Regulator (at periphery of tracker volume)

Dome-loaded flow Regulator (at periphery of tracker volume)

Returning evaporant (vapour 20°C) SiPMs Cooling circuit to remote BPRs

2/48 primary circuits, 20°C liquid reheats exhaust vapour



Pre-cooled liquid (-50°C) coolant to on-detector capillary (1)

Liquid fluorocarbon coolant (20°C) to SiPM on-detector cooling channel (1)

Precooling FC evaporant (20°C) to several heat exchangers for SiPM on-detector coolant circuits

Precooling FC evaporant (vapour 20°C) from several heat exchanger cells for on-detector coolant circuits (to remote back-pressure regulator)

Pre-cooled liquid (-50°C) coolant to on-detector capillary (2)

Liquid fluorocarbon coolant (20°C) to SiPM on-detector cooling channel (2)

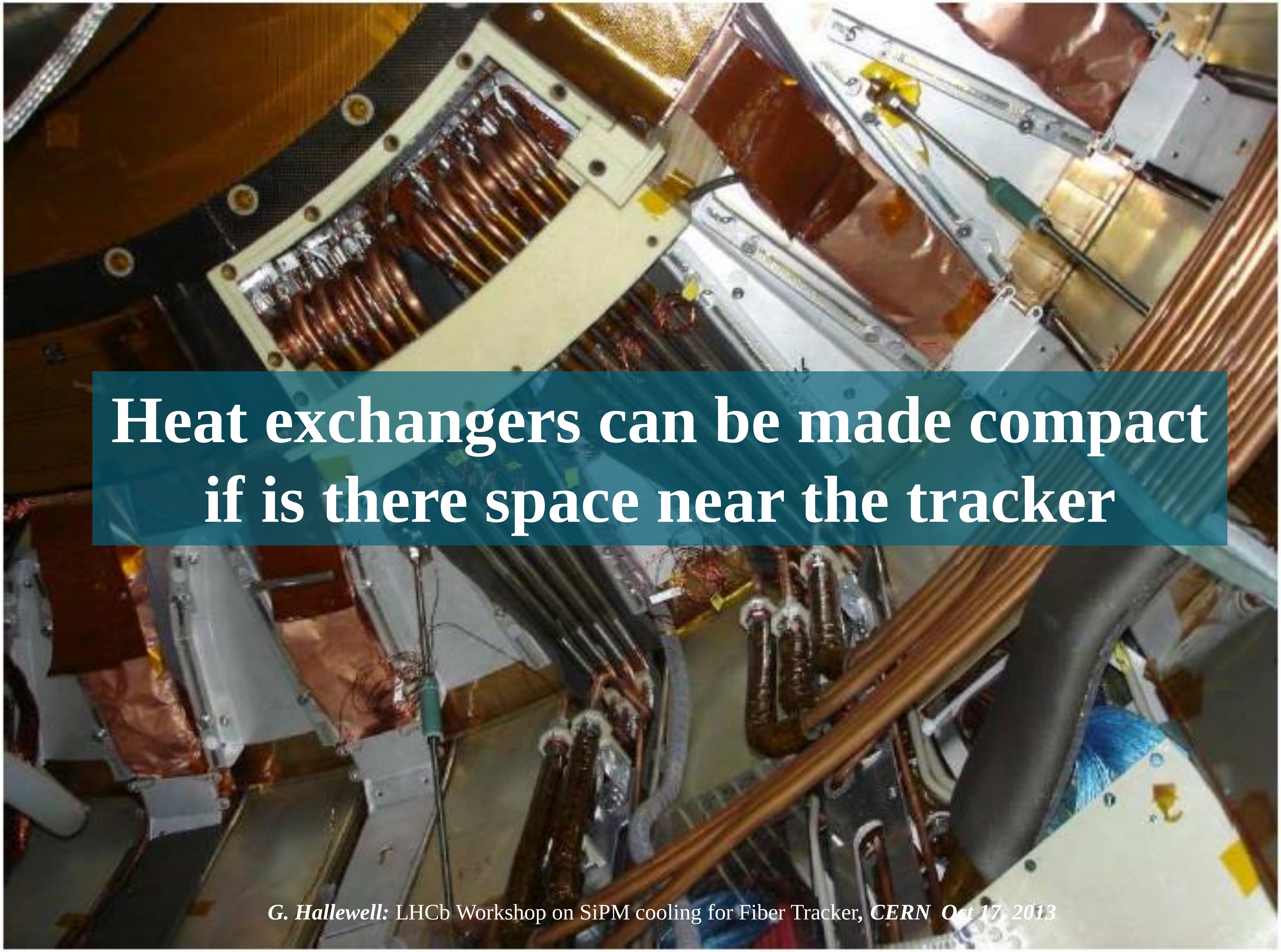
FC evaporant (vapour 20°C) from SiPM on-detector coolant channel (2)(to remote back-pressure regulator)

Exhaust vapour reheating FC fluid return (>20C) from several heat exchanger cells for on-detector coolant circuits

Exhaust vapour reheating FC fluid (>20°C) : to several heat exchangers for on-detector coolant circuits

FC evaporant (vapour 20°C) from SiPM on-detector coolant channel (1) (to remote back-pressure regulator)

Cell of multi-channel heat exchanger (at periphery of tracker volume)

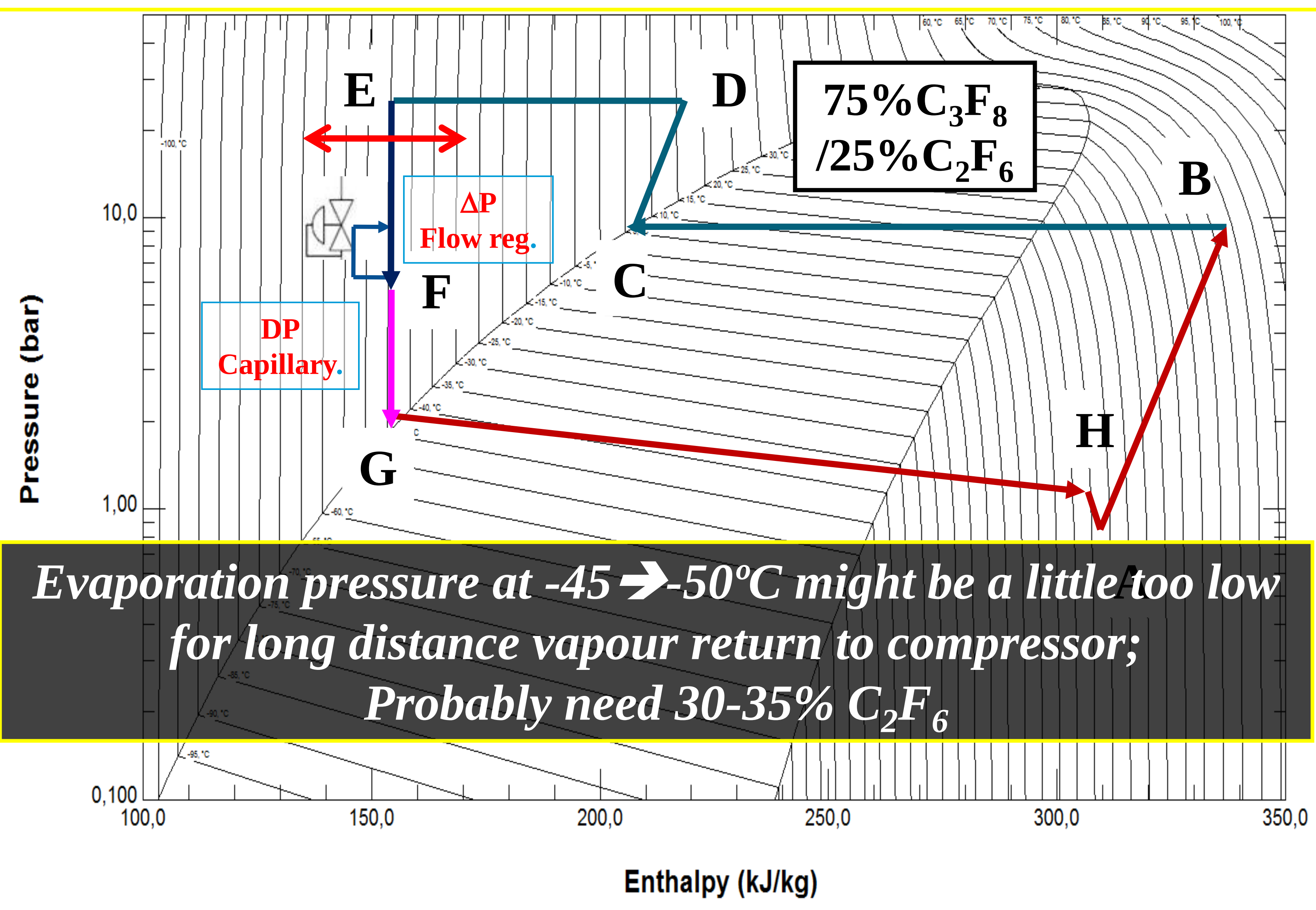


Heat exchangers can be made compact if is there space near the tracker

G. Hallewell: LHCb Workshop on SiPM cooling for Fiber Tracker, ***CERN Oct 17, 2013***

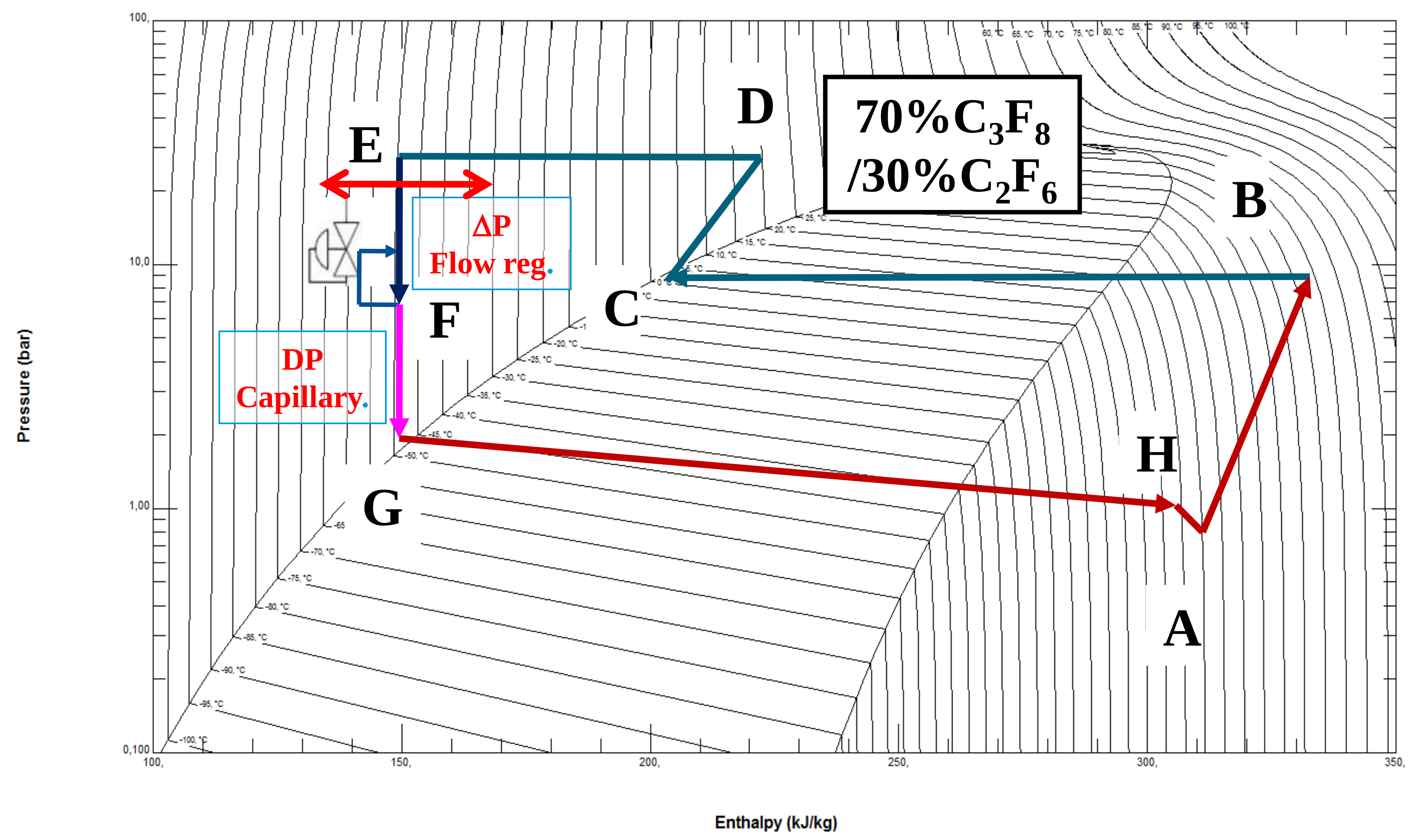
Achieving the low required SiPM temperature with blends, (an a reasonably comfortable condenser temperature)

P-h diagram: 75%C_3F_8/25%C_2F_6 in hybrid thermosiphon: 9 bar condensation at 5-10 °C (local liquid subcooling to -45°C: zeotropic temperature “glide” partially cancelled by dynamic pressure drop)

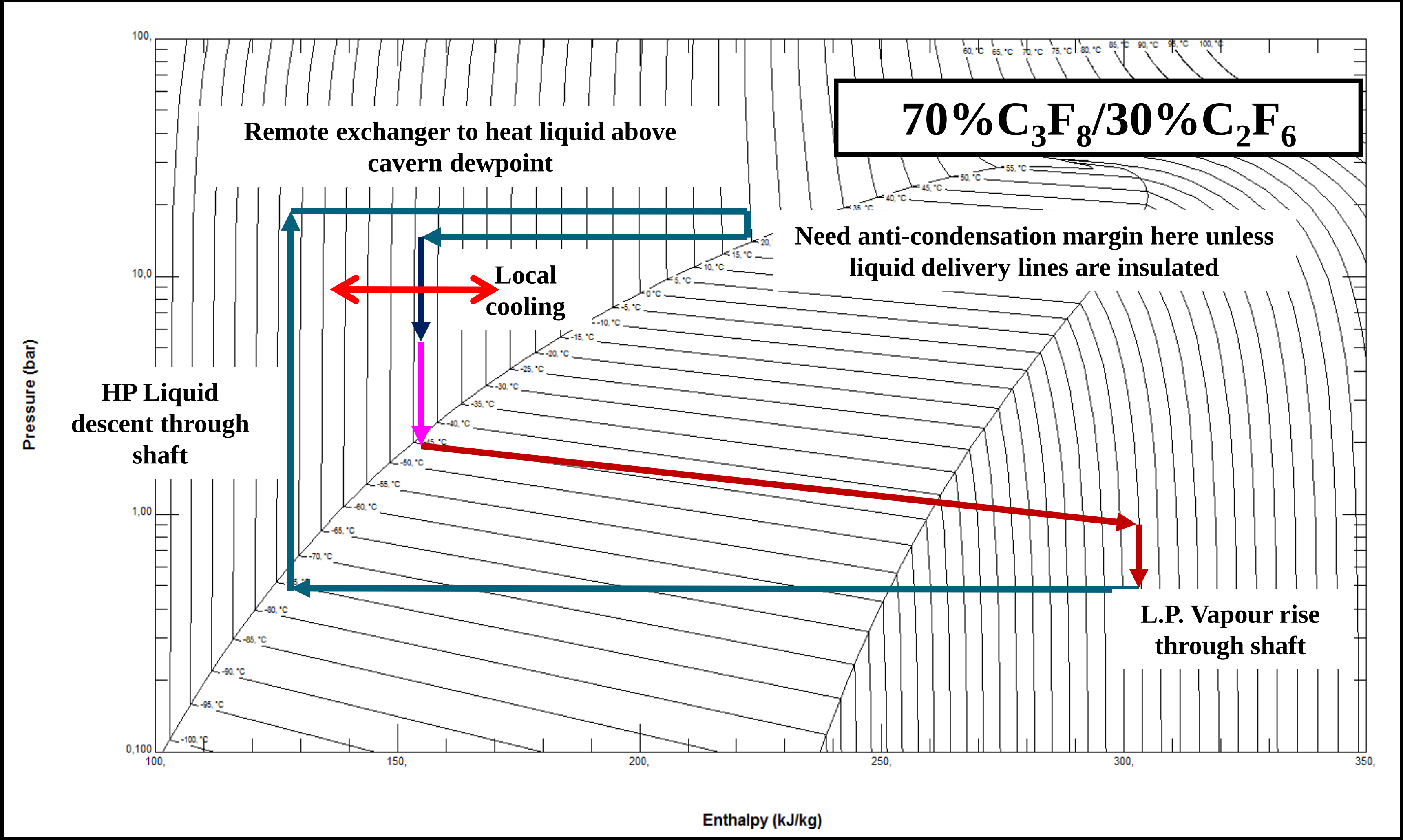


Evaporation pressure at -45 ➔-50°C might be a little too low for long distance vapour return to compressor;
Probably need 30-35% C_2F_6

P-h diagram: 70%C_3F_8/30%C_2F_6 in hybrid thermosiphon: 9 bar condensation at 0 °C (local liquid subcooling to -45°C: zeotropic temperature "glide" partially cancelled by dynamic pressure drop)



True (compressorless) thermosiphon requires very low condensation pressure (would probably need to use cold N_2 gas heat exchange from LN_2 boil-off)



$70\%C_3F_8/30\%C_2F_6$

Remote exchanger to heat liquid above cavern dewpoint

Need anti-condensation margin here unless liquid delivery lines are insulated

Local cooling

HP Liquid descent through shaft

L.P. Vapour rise through shaft

General Impressions

C_3F_8/C_2F_6 blends might be adaptable to SiPM cooling (30-35% C_2F_6 if services are to remain uninsulated)

Although low radiation level might allow HFCs (C_2F_5H ➔ $C_2F_4H_2$?)

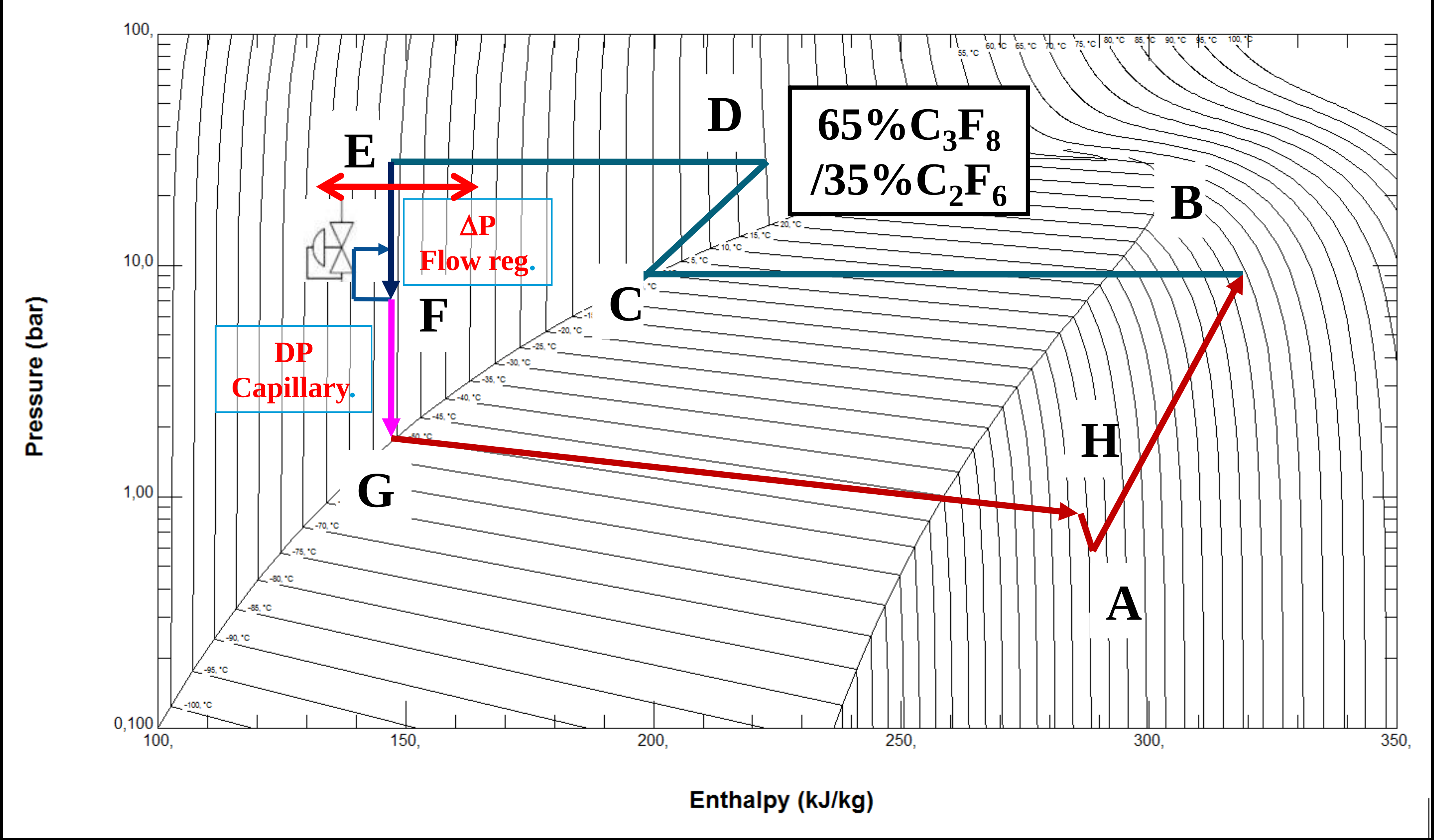
- **True thermosiphon requires very cold condenser (<-70C)**
- **Single stage compressor available:**
  might meet needs alone or in hybrid thermosiphon

Large cost saving in re-use of plant.

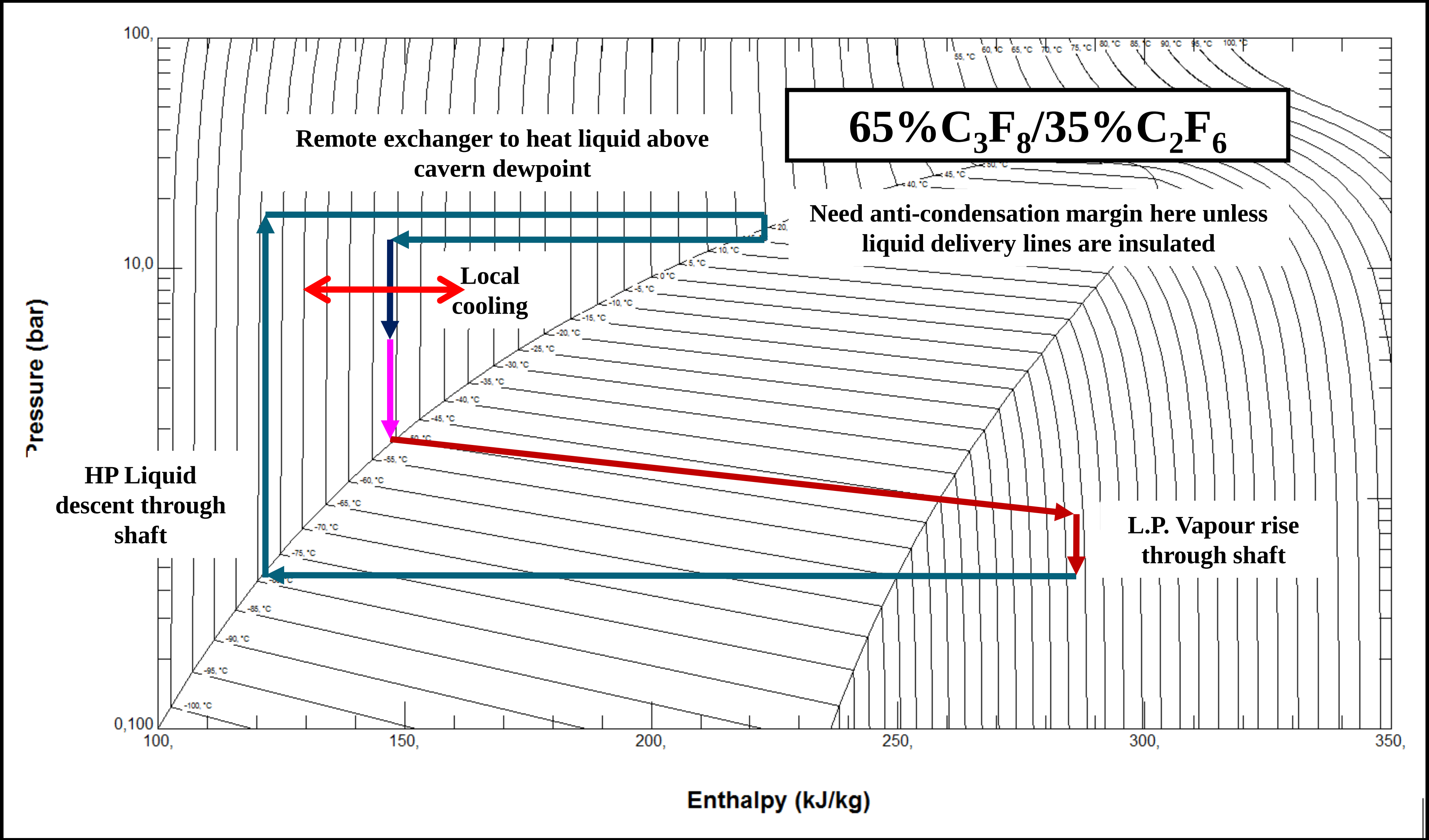
➔ Use of local heat exchangers with dynamic flow control could meet requirement of uninsulated liquid supply &vapour returns; otherwise would need active insulation on liquid supply tubes and maybe on exhaust (length minimized through dynamic flow control)

Back-up slides

P-h diagram: 65%C_3F_8/35%C_2F_6 in hybrid thermosiphon: 9 bar condensation at 0 ºC (local liquid subcooling to -45ºC): zeotropic temperature "glide"partly cancelled by dynamic pressure drop)



True (compressorless) thermosiphon requires very low condensation pressure (would probably need to use cold N_2 gas heat exchange from LN_2 boil-off)



$65\%C_3F_8/35\%C_2F_6$

Remote exchanger to heat liquid above cavern dewpoint

Need anti-condensation margin here unless liquid delivery lines are insulated

Local cooling

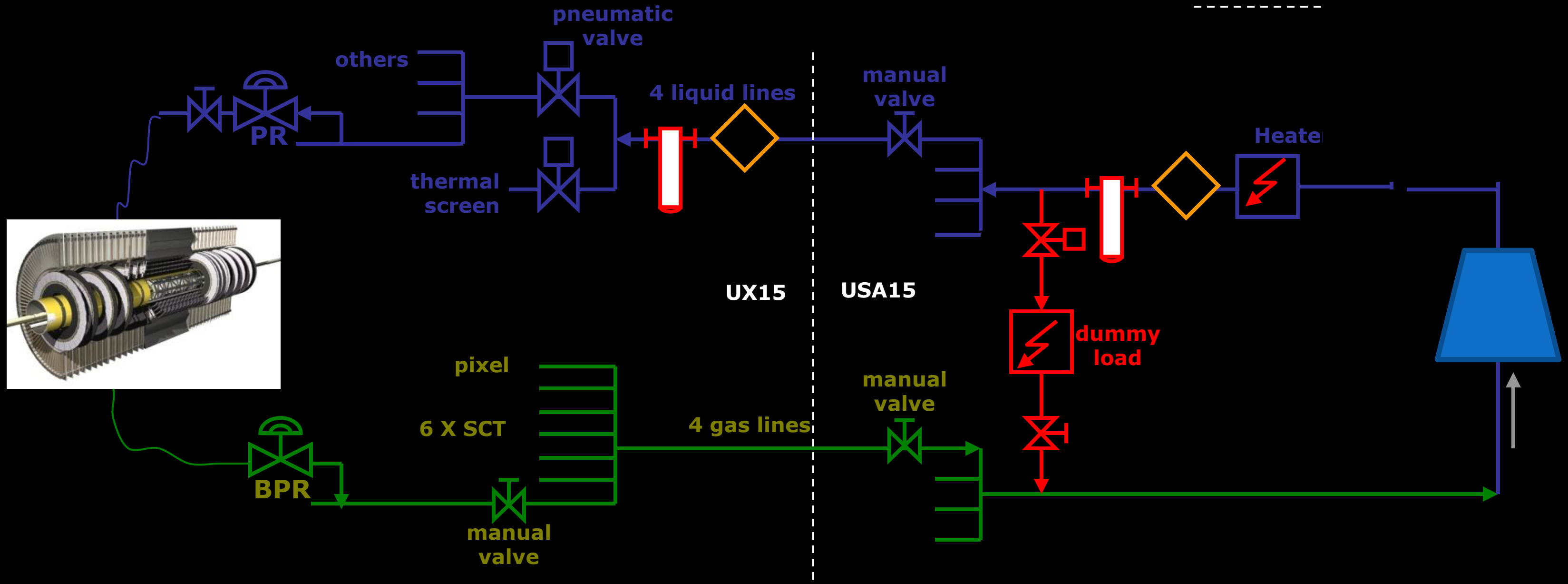
HP Liquid descent through shaft

L.P. Vapour rise through shaft

‘Thermosiphon’ to eliminate unreliable compressors completely from the primary fluorocarbon cooling loop

❖ 92m height of ATLAS pit generates ~13 bar hydrostatic (ρgh) pressure in C_3F_8 or C_3F_8/C_2F_6 liquid

❖ But... ρgh of 92m height of rising C_3F_8 or C_3F_8/C_2F_6 vapour adds only ~70mbar



ATLAS Thermosiphon condenser cooling plant (for 60kW at -60°C)

ATLAS Thermosiphon condenser (for 60kW at -60°C)