Ultrasonics for Cherenkov refractometry and leak hunting in silicon tracking detectors

G. Hallewell

Centre de Physique des Particules de Marseille

CNRS/IN2P3

G.H./Particle Physics Seminar, Cambridge University, April 14th 2015

Contents

- **How is ultrasonics used in gas analysis?**

 - **Simultaneous flowmetry & gas analysis in the same instrument**

- **Beginnings of use in particle physics for Cerenkov refractomery (Ring Imaging Cherenkov detectors) at SLAC (SLD CRID at the SLAC linear collider)**

- **Use in the context of evaporative cooling of the ATLAS inner silicon tracker (pixels, SCT IBL)**

- **Other uses and expanding the application in particle physics..?**

How is ultrasonics used in gas analysis?

- **Exploits the phenomenon whereby the sound velocity in a gas depends (to 1st order) on (molecuar weight)$^{-0.5}$**

$$c = \sqrt{\frac{\gamma R T}{M}}$$

where

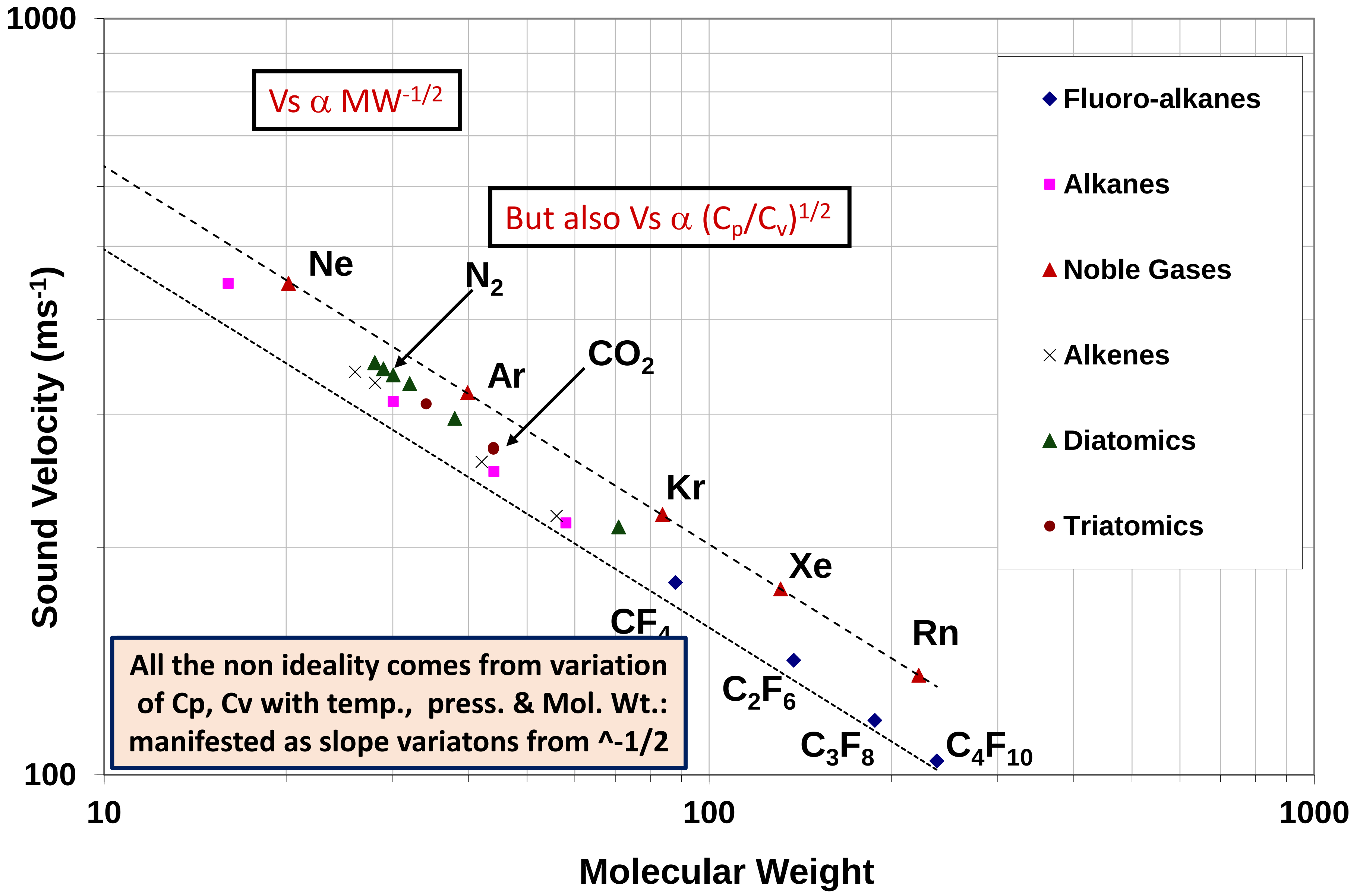
$$\gamma = \frac{Cp}{Cv}$$

- **Of course, life isn't quite as simple as this…**

  …(Cp & Cv also depend on the abs. temp. T & pressure)

  but - as the next slide shows - the relation is broadly true.

Sound Velocity vs MW (Gas ***Classes***) 295K, 1 Atm



Vs α $MW^{-1/2}$

But also Vs α $(C_p/C_v)^{1/2}$

All the non ideality comes from variation of Cp, Cv with temp., press. & Mol. Wt.: manifested as slope variatons from ^-1/2

Calculating sound velocity in binary mixes

- **When (one or both) gases are far from ideality more complex equations of state are needed:**

I.G.E. ➔

Van der Waals ➔

Benedict-Webb-Rubin ➔

PC-SAFT*

''Perturbative chain statistical associating fluid theory'' …
- basically a Monte Carlo using molecular chain structures etc…

- **Also need mixing rules for the two gases (can be worse problem:)**
- **A more pragmatic approach is to use an equation of state adapted to the two single gas components and to calculate their C_{vi} C_{pi} (the hard part) and then find c through:**
- ***NIST REFPOP v. 23 USEFUL FOR THIS ➔ ➔ ➔***

- **Sound velocity in a binary gas mixture of components i=1,2 of molecular weights m_1, m_2 & molar concentrations w_1, w_2 :**

$$c = \sqrt{\frac{\gamma RT}{M}}$$

- where

$$\gamma_m = \frac{C_{pm}}{C_{vm}} = \frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i}$$

- and the molar mass of the mixture is given by:

$$M = \sum_i w_i M_i$$

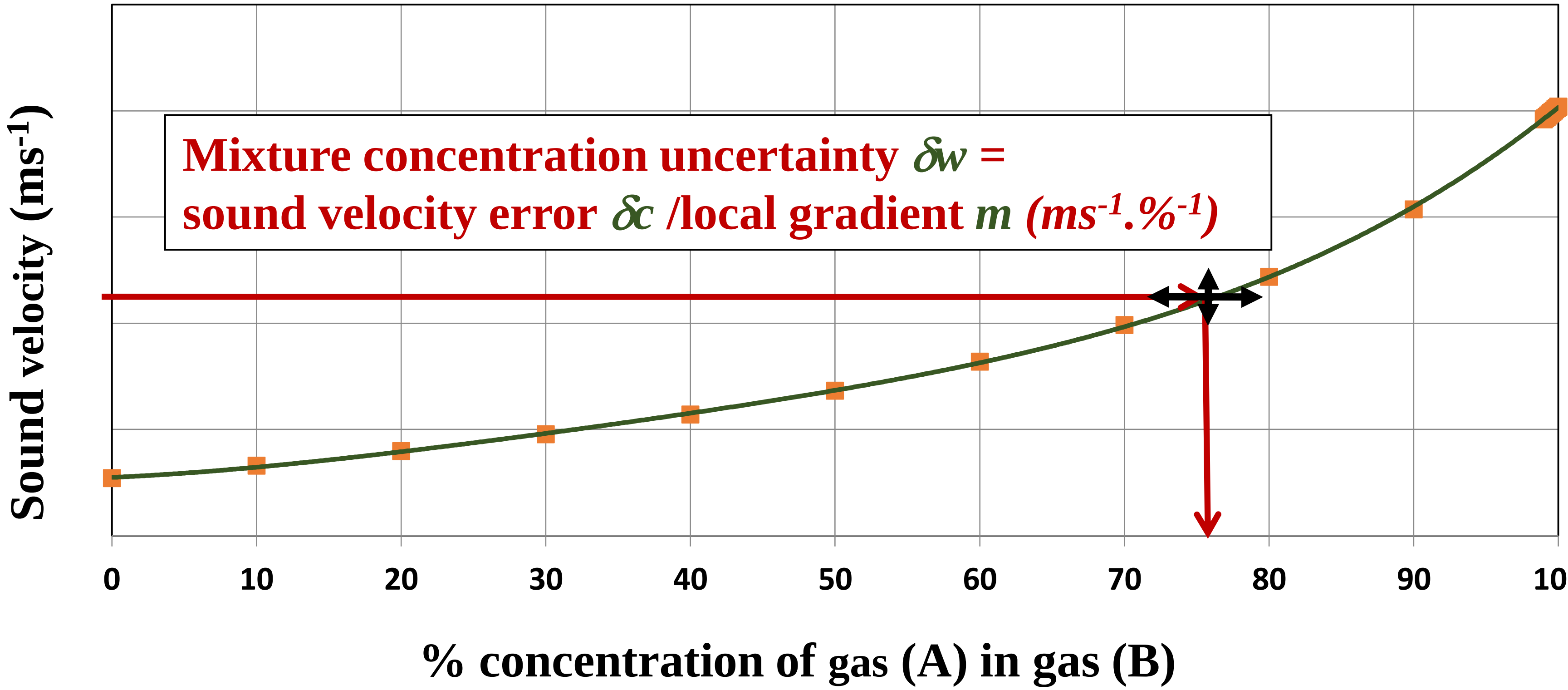
- so we end up with…

$$c = \sqrt{\frac{\frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i} RT}{\sum_i w_i M_i}}$$

Mixture calculating algorithm (1)

Continuous real-time measurement of transit time$_{\text{up, down}}$, T, P

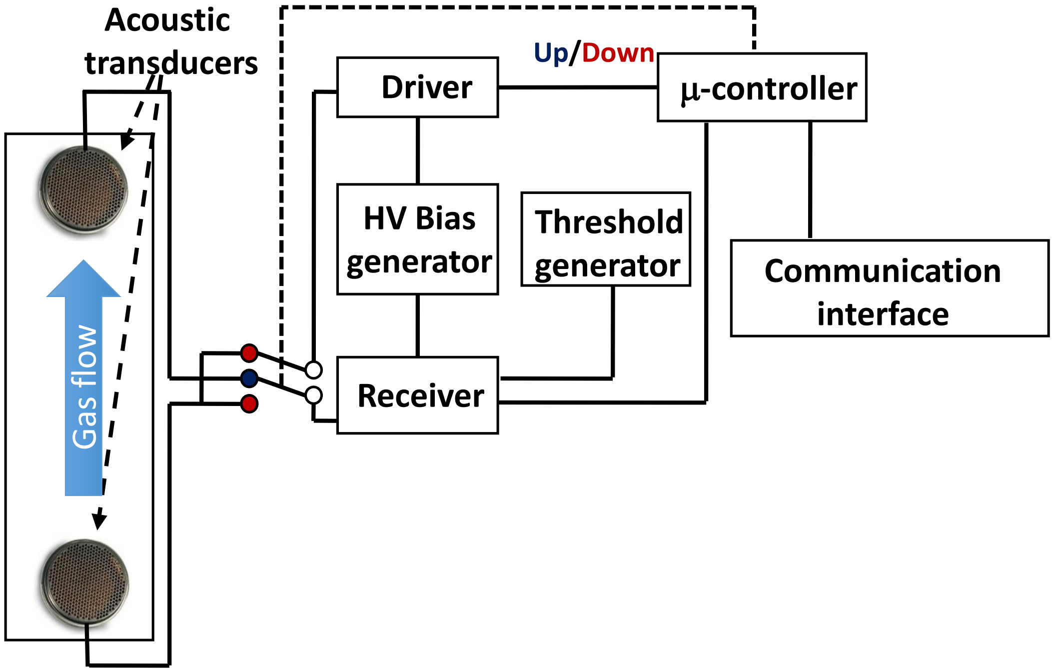
Pre-stored database of sound velocity *vs. molar* conc.
of gas A in gas B over a range of P, T;
(set up from prior measurements and/or theory)



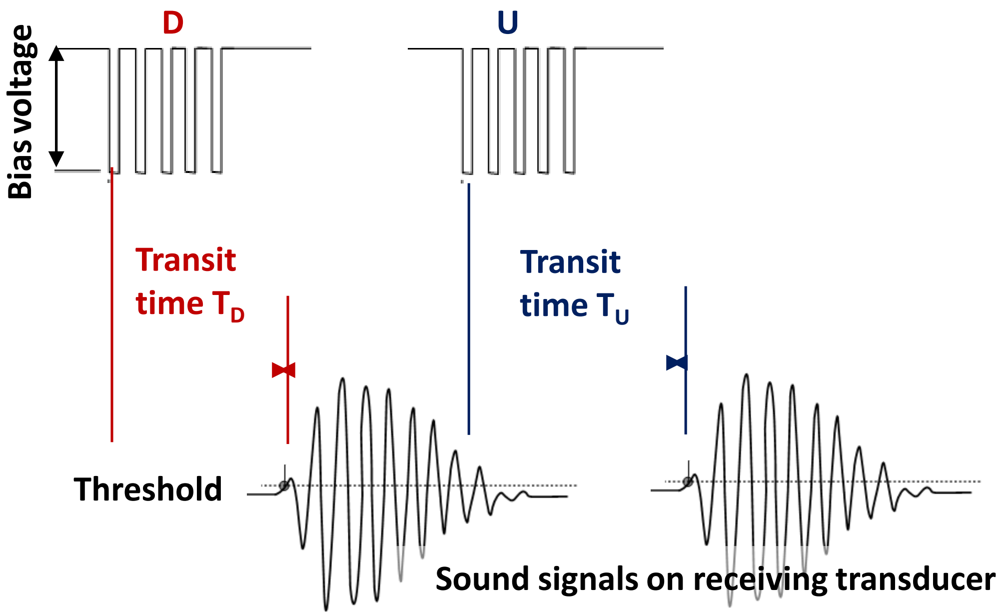
Mixture concentration uncertainty δw =
sound velocity error δc /local gradient m ($ms^{-1}.\%^{-1}$)

Electronics: principle of operation

Measurements in opposite directions relative to gas flow ➔ simultaneous gas analysis and flowmetry



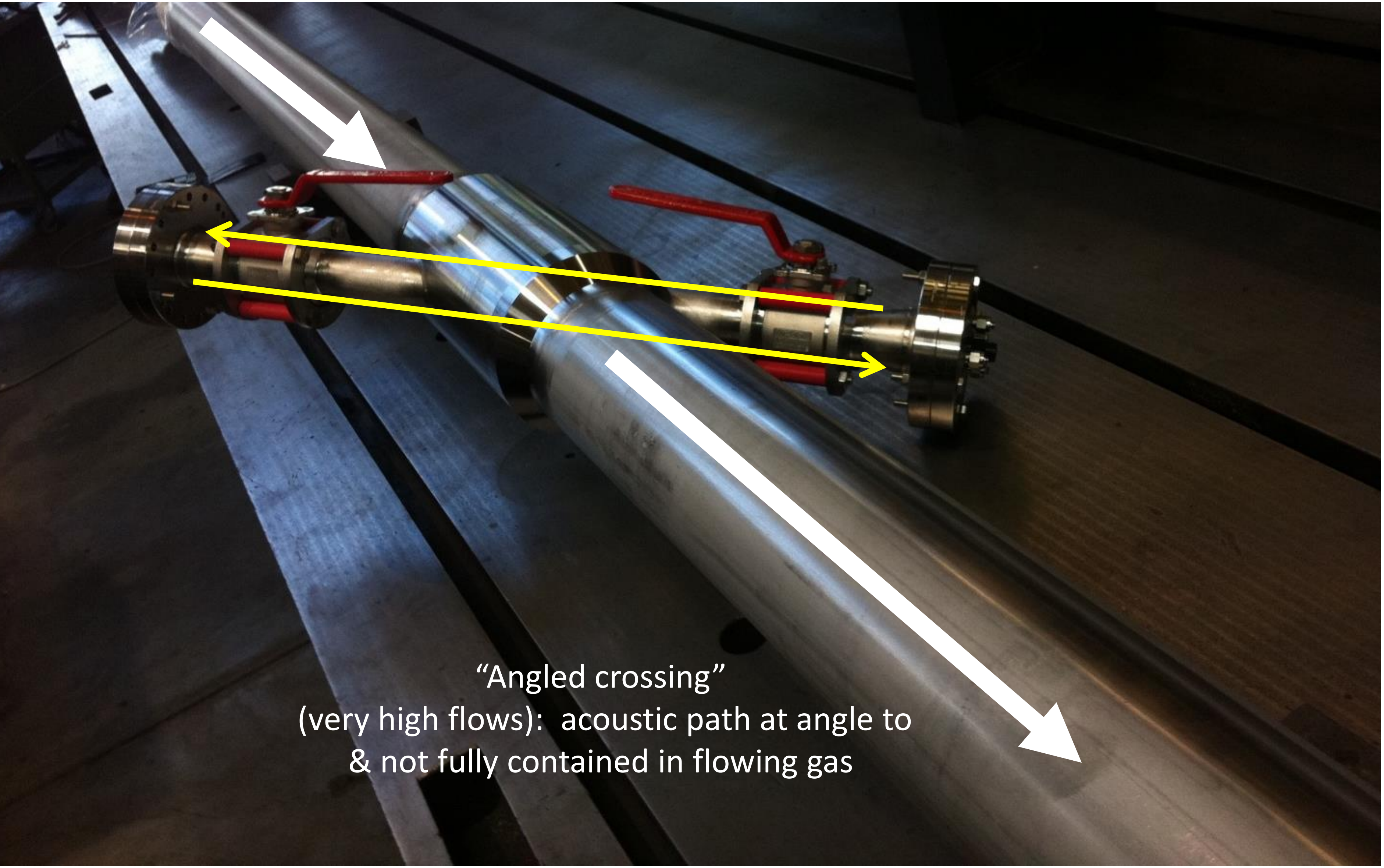
Transmitting transducer input signals



Sound signals on receiving transducer

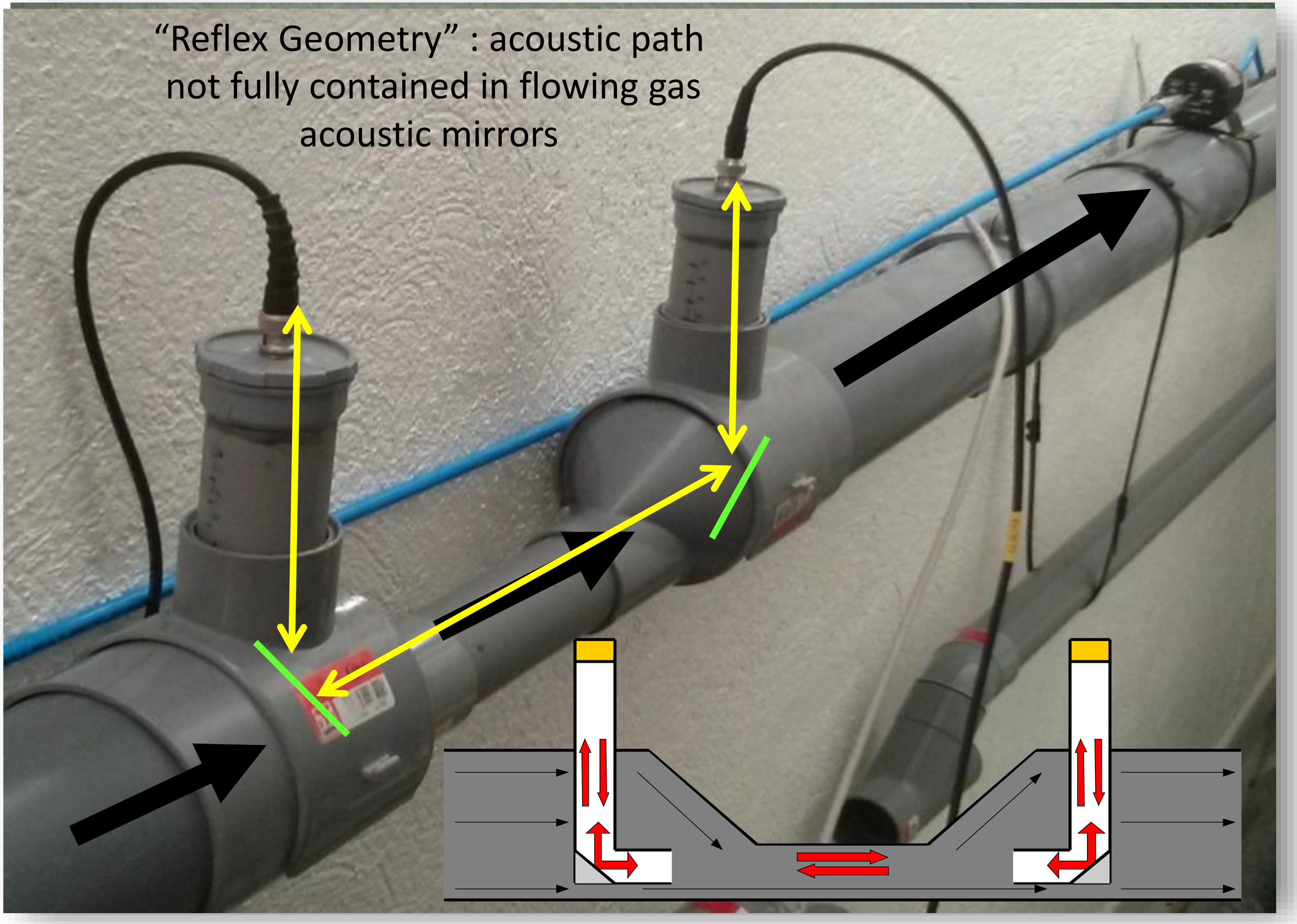
Above threshold received sound pulses stop fast (40MHz) transit time clock to find t_{up}, t_{down}

Examples of instrument geometries (1)



“Angled crossing”
(very high flows): acoustic path at angle to
& not fully contained in flowing gas

Examples of instrument geometries (2)

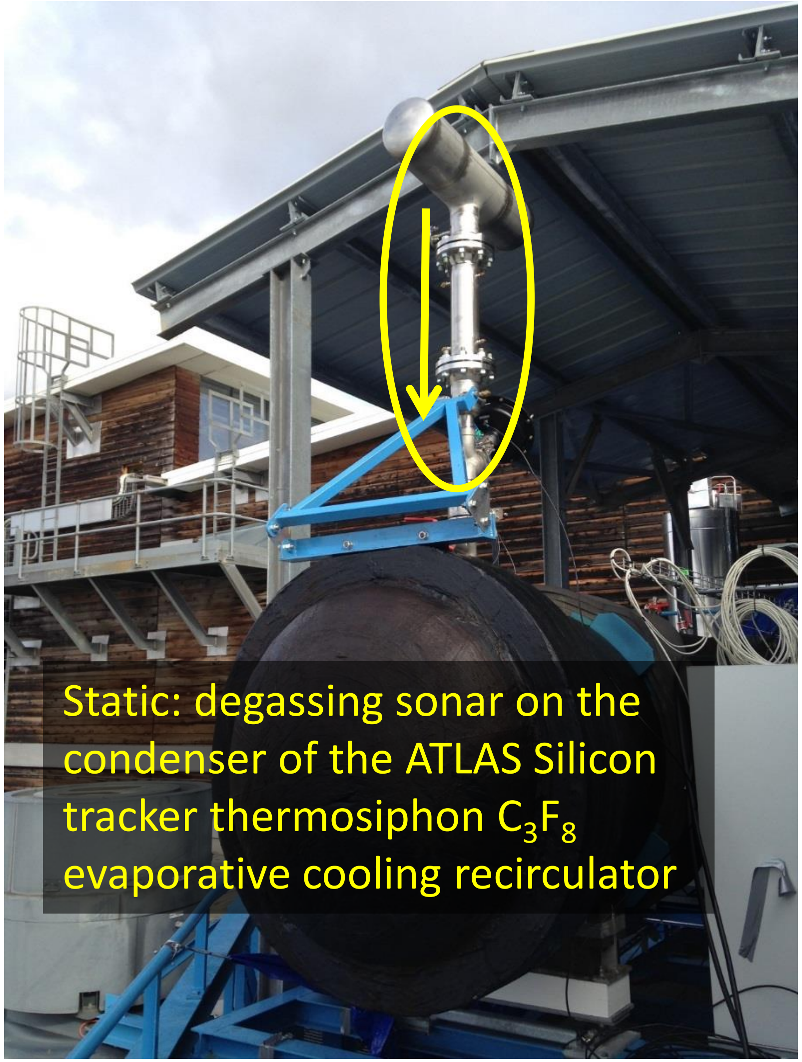


"Reflex Geometry" : acoustic path not fully contained in flowing gas

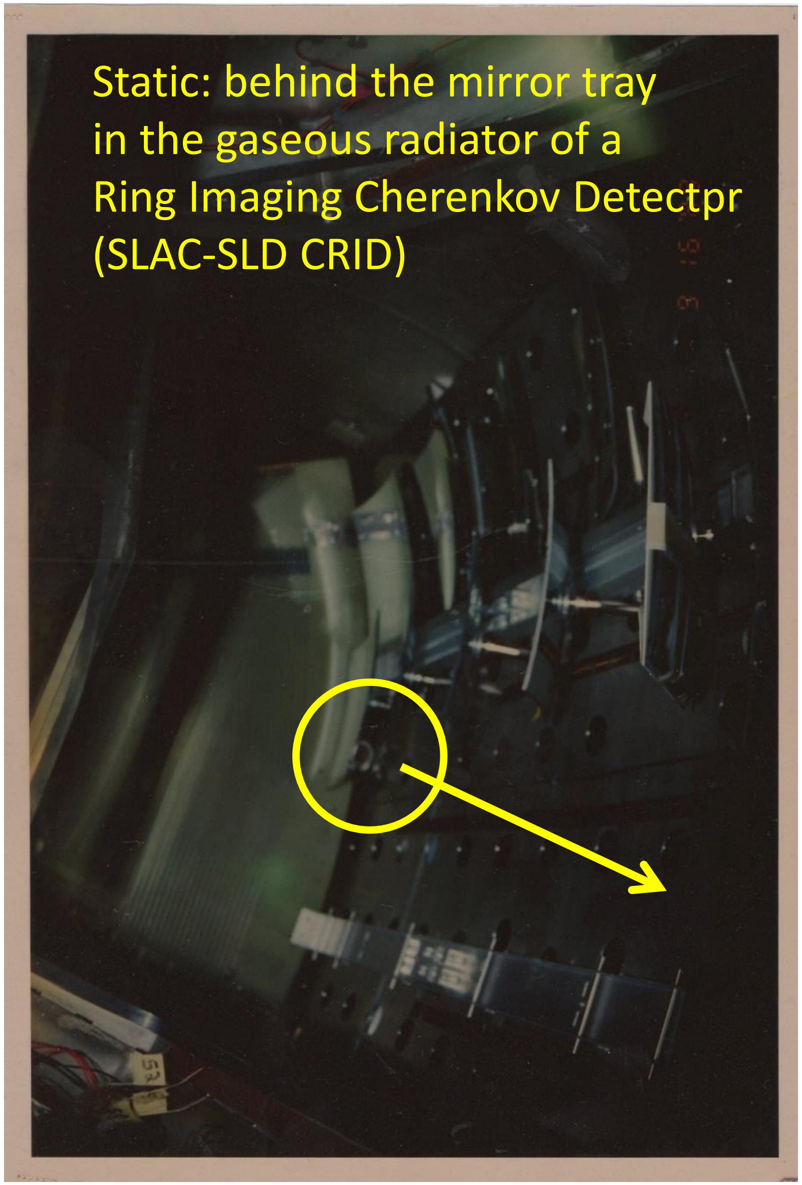
acoustic mirrors

G.H./Particle Physics Seminar, Cambridge University, April 14th 2015

Examples of instrument geometries (3)



Static: degassing sonar on the condenser of the ATLAS Silicon tracker thermosiphon C_3F_8 evaporative cooling recirculator

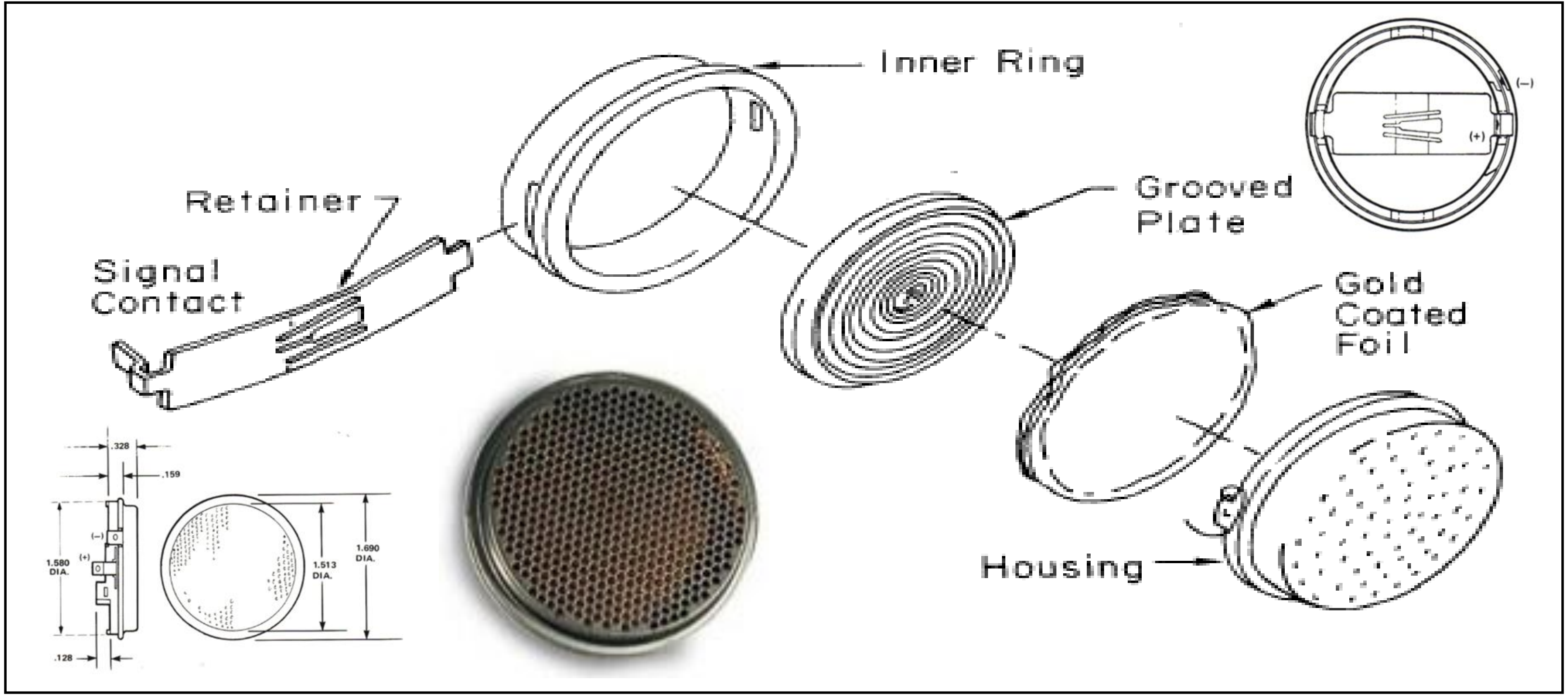


Static: behind the mirror tray in the gaseous radiator of a Ring Imaging Cherenkov Detectpr (SLAC-SLD CRID)

The ultrasonic transducer (d ~ 37mm)

Originally developed by Polaroid in the 1970's for autofocus cameras:

Now marketed by as Senscomp model 6000: http://www.senscomp.com/products/



- Capacitative operation at 50 kHz caracteristic frequency:
- HV (80➔350V) applied to grooved disc;
- gold coated side of mylar membrane at ground potential;
- much faster response time in gases than piezoelectric types
- high & low pressure operation possible: gas can access both sides of membrane

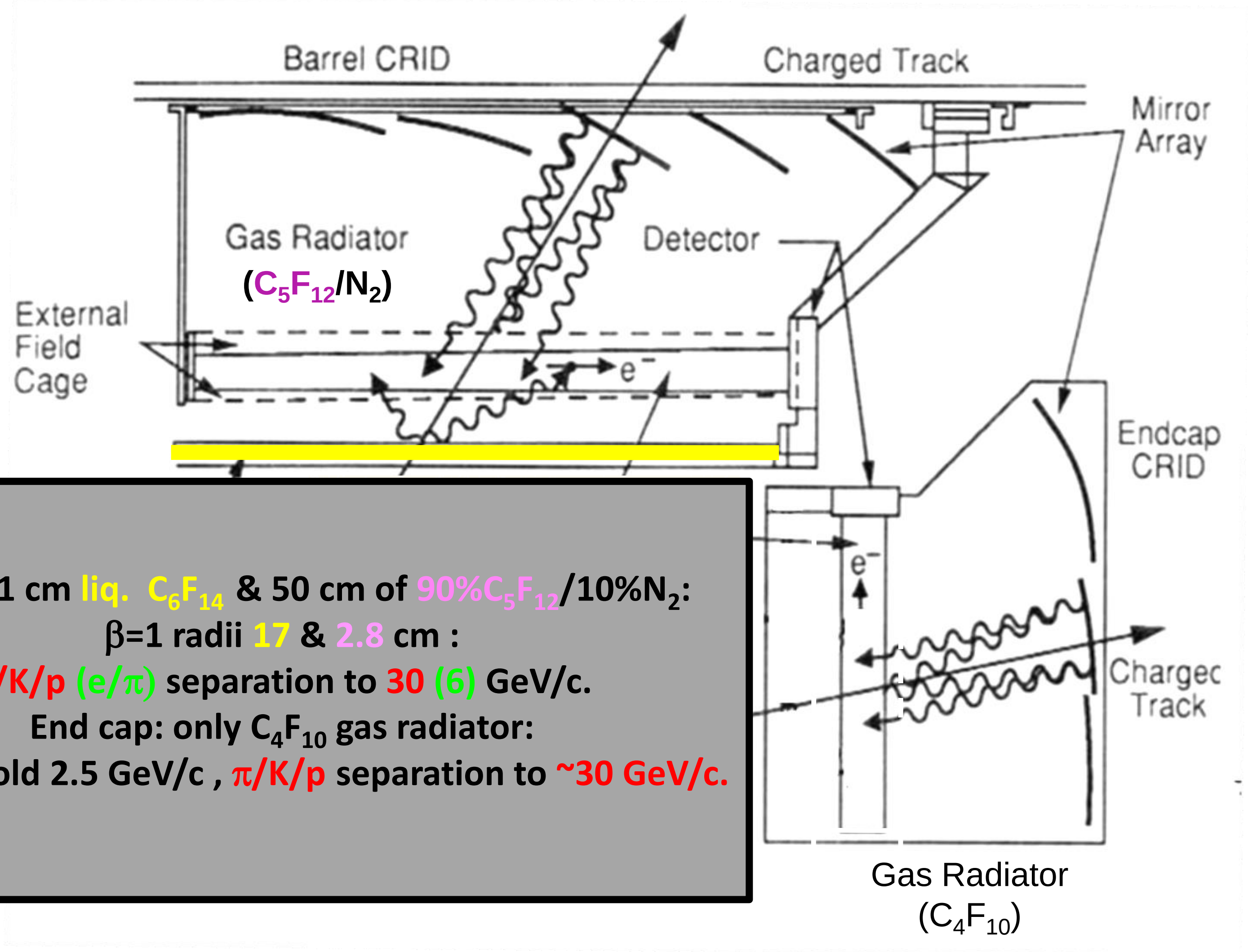
Beginnings in particle physics:

SLD experiment at SLAC

e+e- linear collider (1990s):
(Similar performance to DELPHI at LEP)

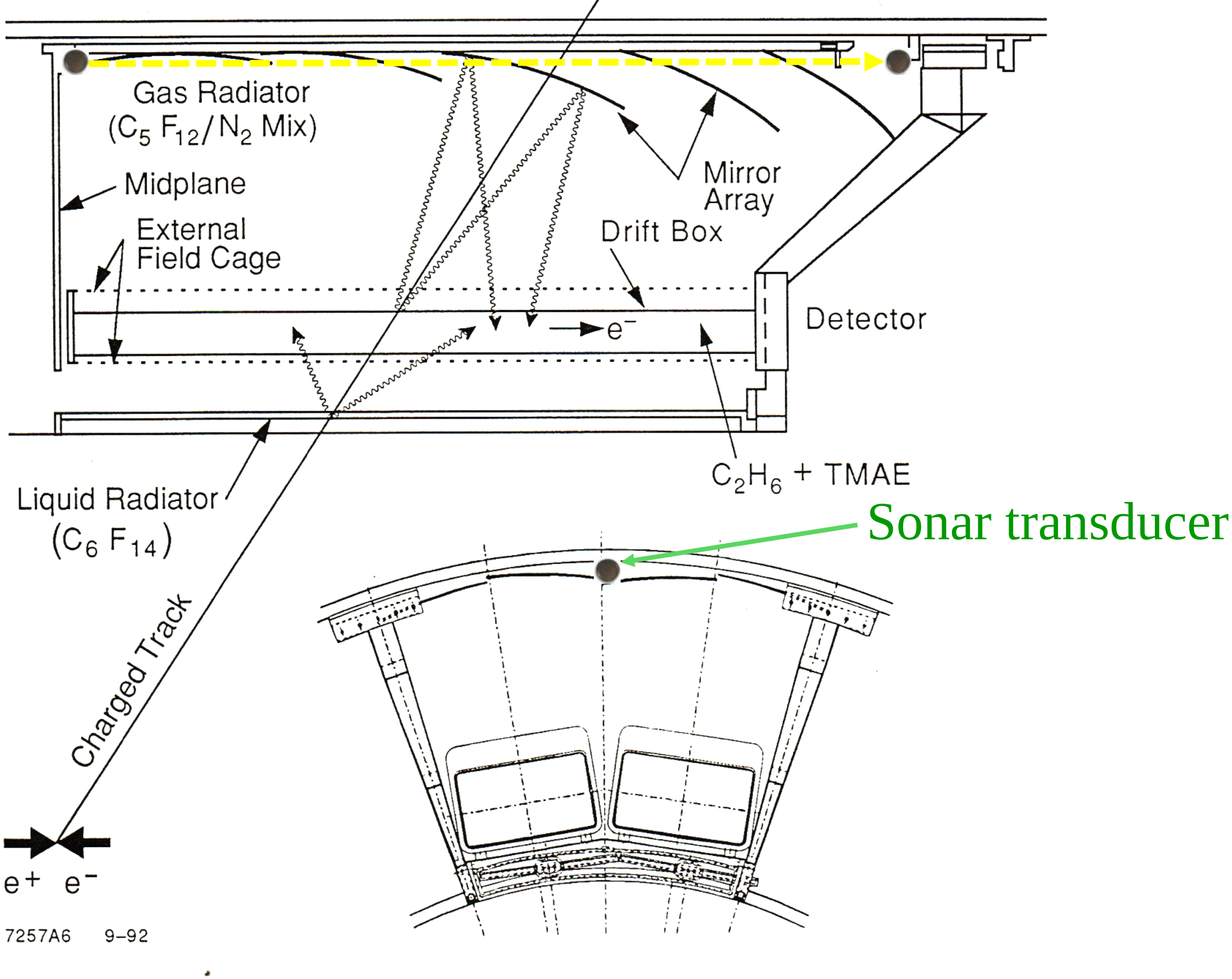
Ring Imaging Cherenkov detector (CRID)
divided into long drift barrel (> 1m):
(gas & liquid radiators) & shorter drift (~40cm) endcaps

SLD Barrel CRID C_5F_{12}/N_2 gas radiator + C_6F_{16liq}: endcap C_4F_{10} gas

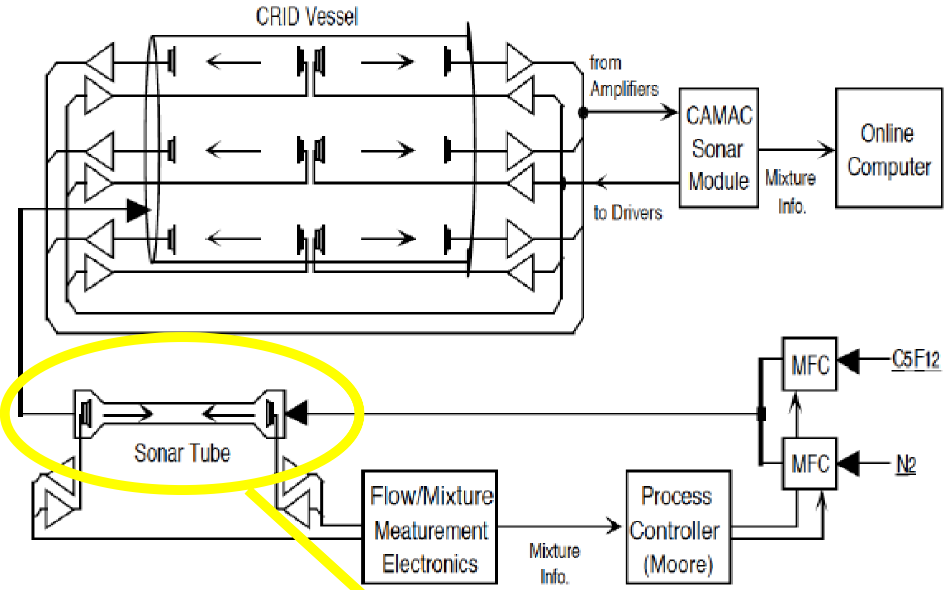


Barrel : 1 cm liq. C_6F_{14} & 50 cm of 90%C_5F_{12}/10%N_2:
β=1 radii 17 & 2.8 cm :
π/K/p (e/π) separation to 30 (6) GeV/c.
End cap: only C_4F_{10} gas radiator:
π threshold 2.5 GeV/c , π/K/p separation to ~30 GeV/c.

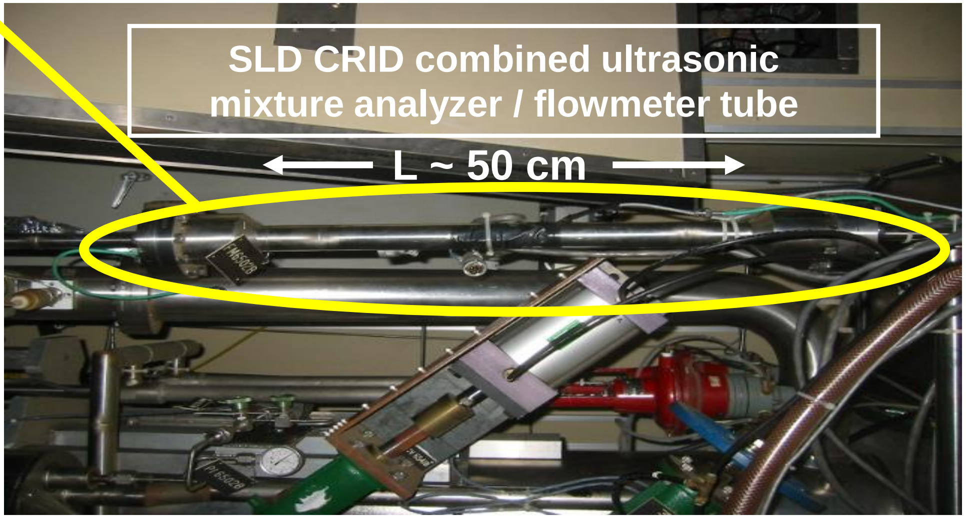
The utility of sonars in the SLD CRID gas radiator



CRID Sonar system

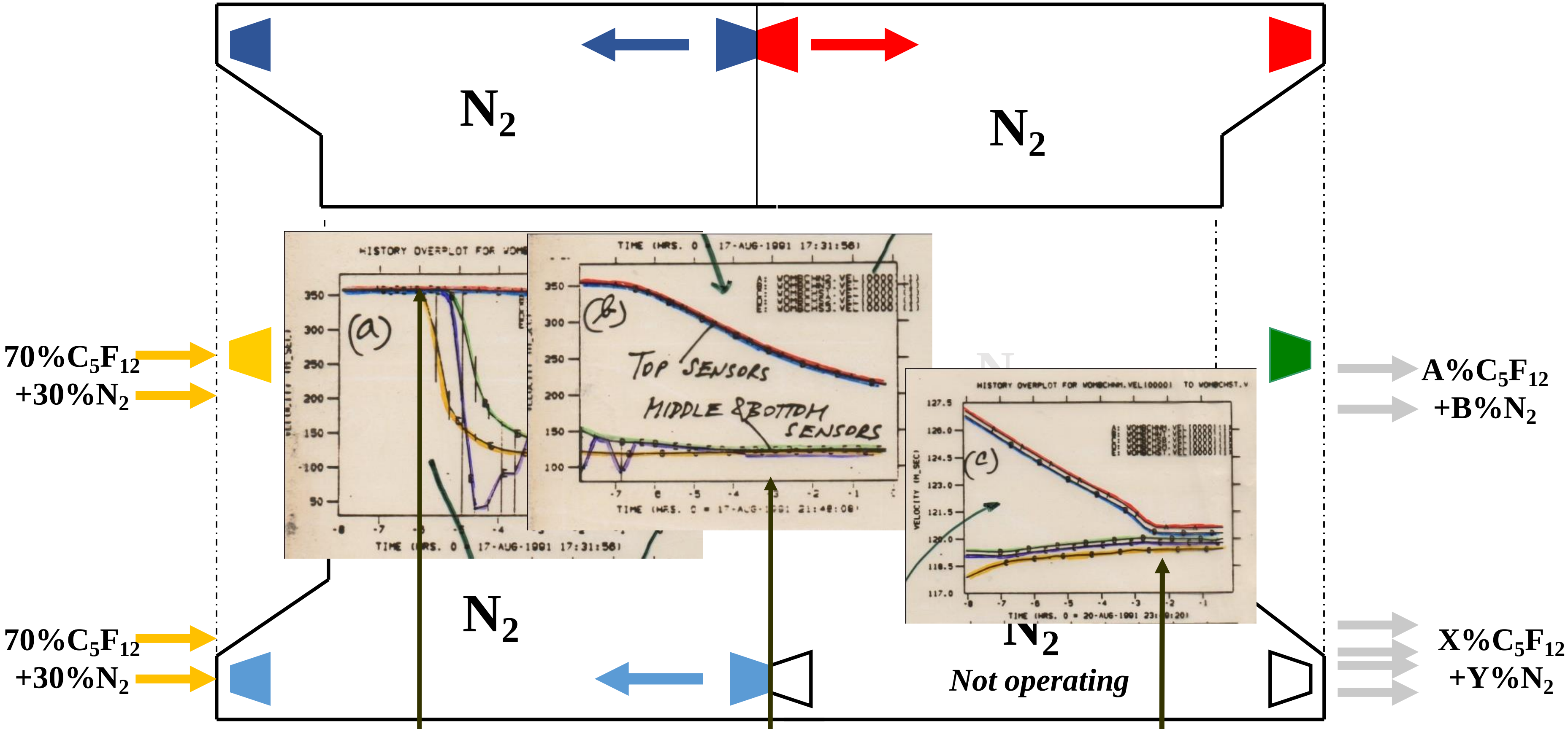


- The system was used to correct the variation in refraction index due to the N_2/C_5F_{12} mix instabilities, and other effects.
- The sonar system proved itself extremely valuable.


SLD CRID combined ultrasonic mixture analyzer / flowmeter tube

L ~ 50 cm

SLD CRID Sonars : ➔ early (pre-run) hydrostatic discoveries Led to reheighting of input + exhaust tubes



Start: 11:32
17/08/1991

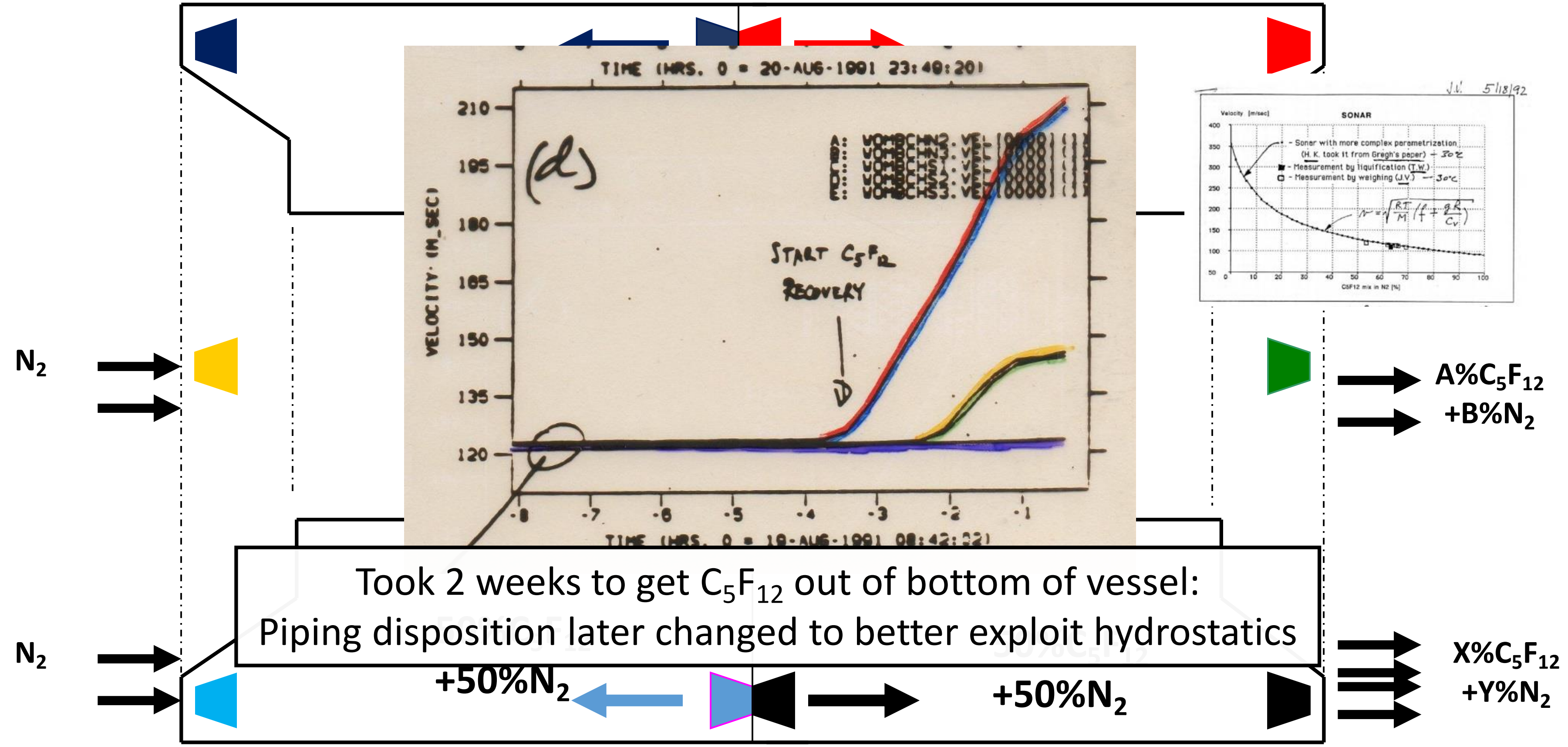
18:48
17/08/1991

21:00
20/08/1991

South Supply:
(4*1½" tubes @ 2 heights)

North Exhaust:
(6*1½" tubes @ 2 heights)

Sonars in the SLD CRID: ➔ hydrostatic discoveries!!

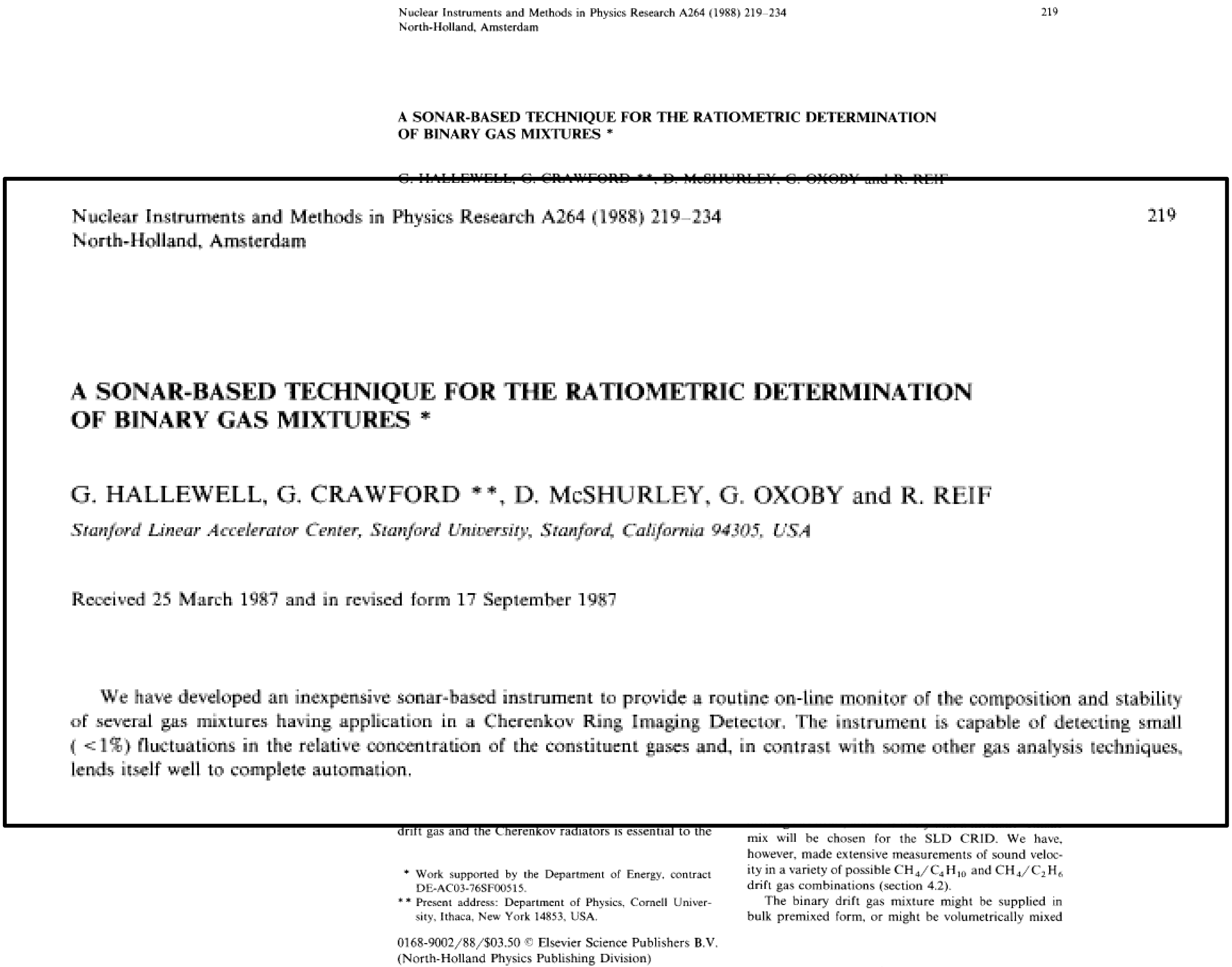


Took 2 weeks to get C_5F_{12} out of bottom of vessel:
Piping disposition later changed to better exploit hydrostatics

(2) Replacement of $50\%N_2+50\%C_5F_{12}$ by N_2

South Supply:
(4*1½” tubes @ 2 heights)

North Exhaust:
(6*1½” tubes @ 2 heights)



Nuclear Instruments and Methods in Physics Research A264 (1988) 219–234
North-Holland, Amsterdam

219

A SONAR-BASED TECHNIQUE FOR THE RATIOMETRIC DETERMINATION OF BINARY GAS MIXTURES *

Nuclear Instruments and Methods in Physics Research A264 (1988) 219–234
North-Holland, Amsterdam

A SONAR-BASED TECHNIQUE FOR THE RATIOMETRIC DETERMINATION OF BINARY GAS MIXTURES *

G. HALLEWELL, G. CRAWFORD **, D. McSHURLEY, G. OXOBY and R. REIF
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

Received 25 March 1987 and in revised form 17 September 1987

We have developed an inexpensive sonar-based instrument to provide a routine on-line monitor of the composition and stability of several gas mixtures having application in a Cherenkov Ring Imaging Detector. The instrument is capable of detecting small (<1%) fluctuations in the relative concentration of the constituent gases and, in contrast with some other gas analysis techniques, lends itself well to complete automation.

drift gas and the Cherenkov radiators is essential to the

mix will be chosen for the SLD CRID. We have, however, made extensive measurements of sound velocity in a variety of possible CH_4/C_4H_{10} and CH_4/C_2H_6 drift gas combinations (section 4.2).

The binary drift gas mixture might be supplied in bulk premixed form, or might be volumetrically mixed

---

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

** Present address: Department of Physics, Cornell University, Ithaca, New York 14853, USA.

0168-9002/88/$03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

Interesting… but what's the prize?

- **To get from measured speed of sound to the speed of light in the radiator – i.e. refractivity (n-1) ➔ thence γ threshold**

  that can be varying in real time,

  especially with a dynamically-mixed C_5F_{12}/N_2 blend

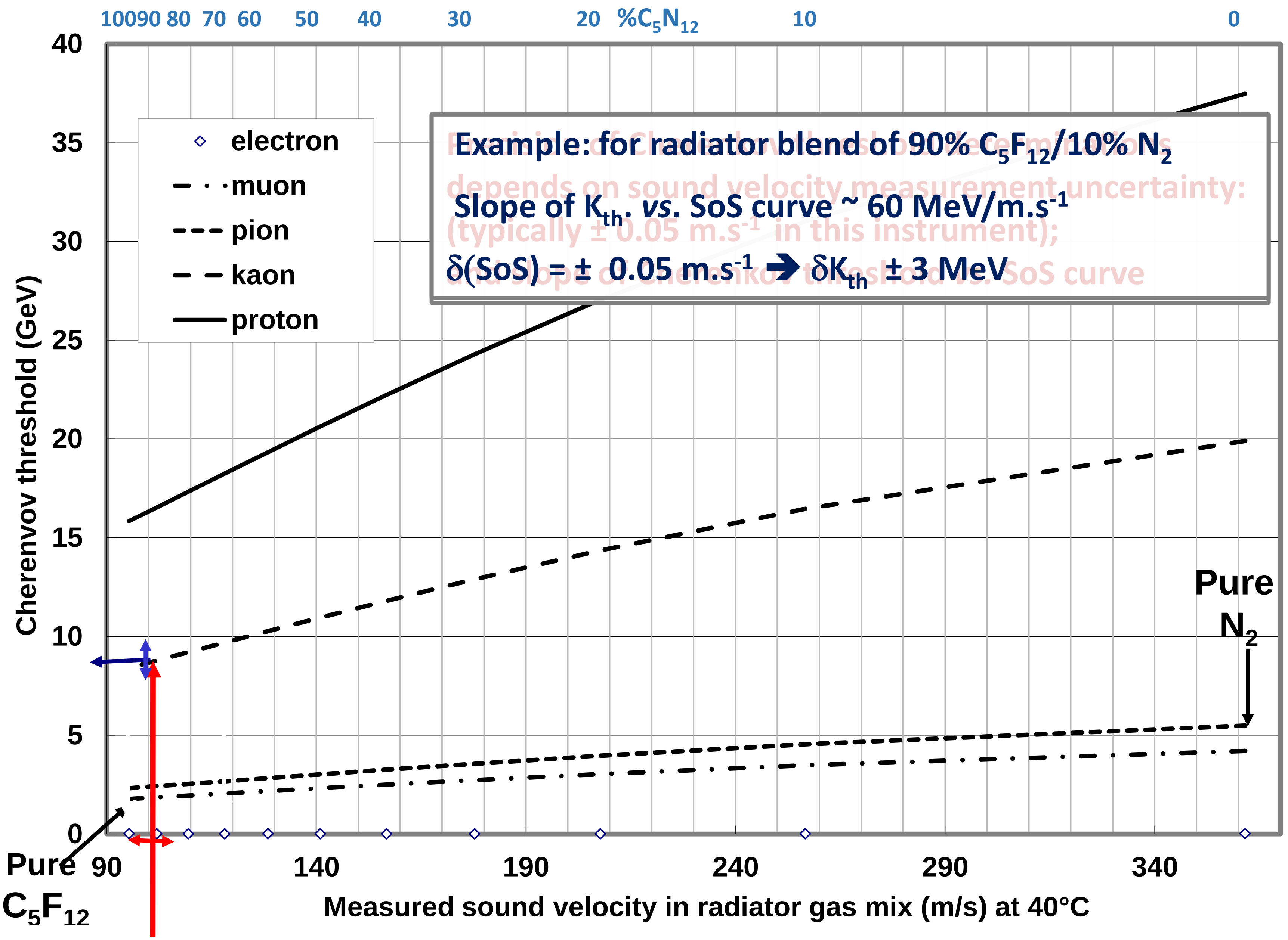
Via… Measured sound transit time over known distance at known T, P:

➔Mixture ratio (mole fractions M_{vap1}, M_{vap2}) from SOS/conc. look up table, based on measurements or theoretical predictions (in SLD, mainly calibration measurements…)

➔Refractivity related to mole fraction via Lorentz-Lorenz considerations:

$$(n-1)_{rad} = (n-1)_{vap1}*M_{vap1}+(n-1)_{vap2}*M_{vap2}$$

SLD barrel CRID: Cherenkov threshold in C_5F_{12}/N_2 *vs* measured sound velocity

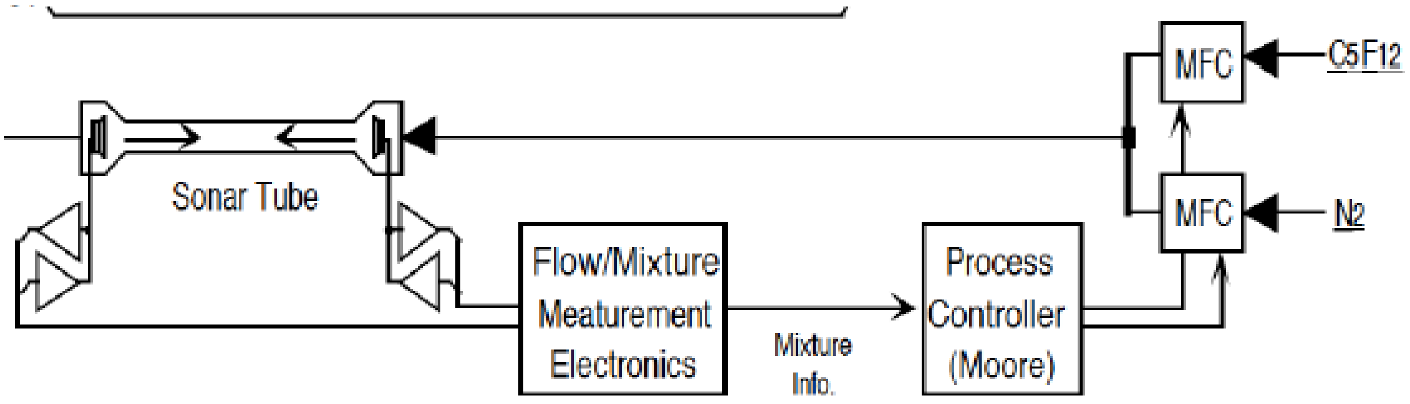


Example: for radiator blend of 90% C_5F_{12}/10% N_2

Slope of K_{th}. *vs.* SoS curve ~ 60 MeV/m.s^{-1}

δ(SoS) = ± 0.05 m.s^{-1} ➔ δK_{th} ± 3 MeV

SLD CRID β=1 Cherenkov radius comparison: measured radii *vs.* radii calculated from sonar–determined refractive index



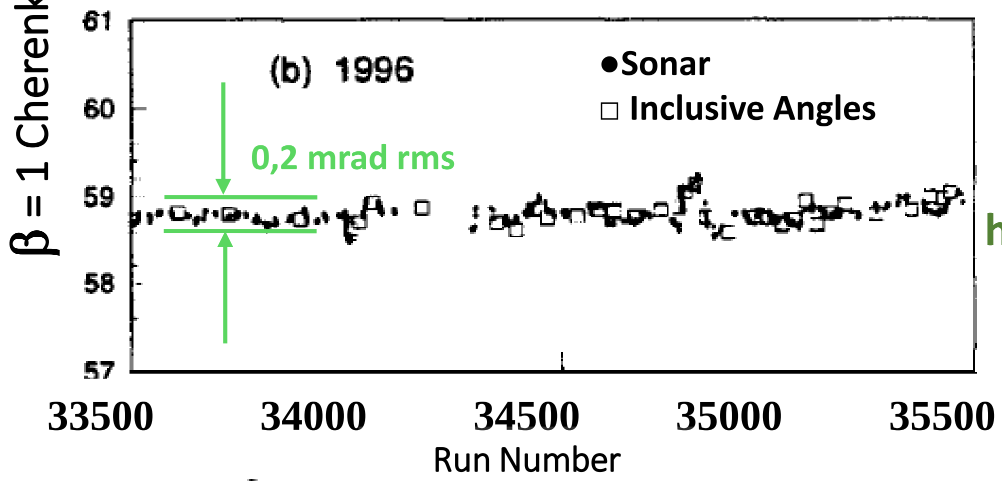
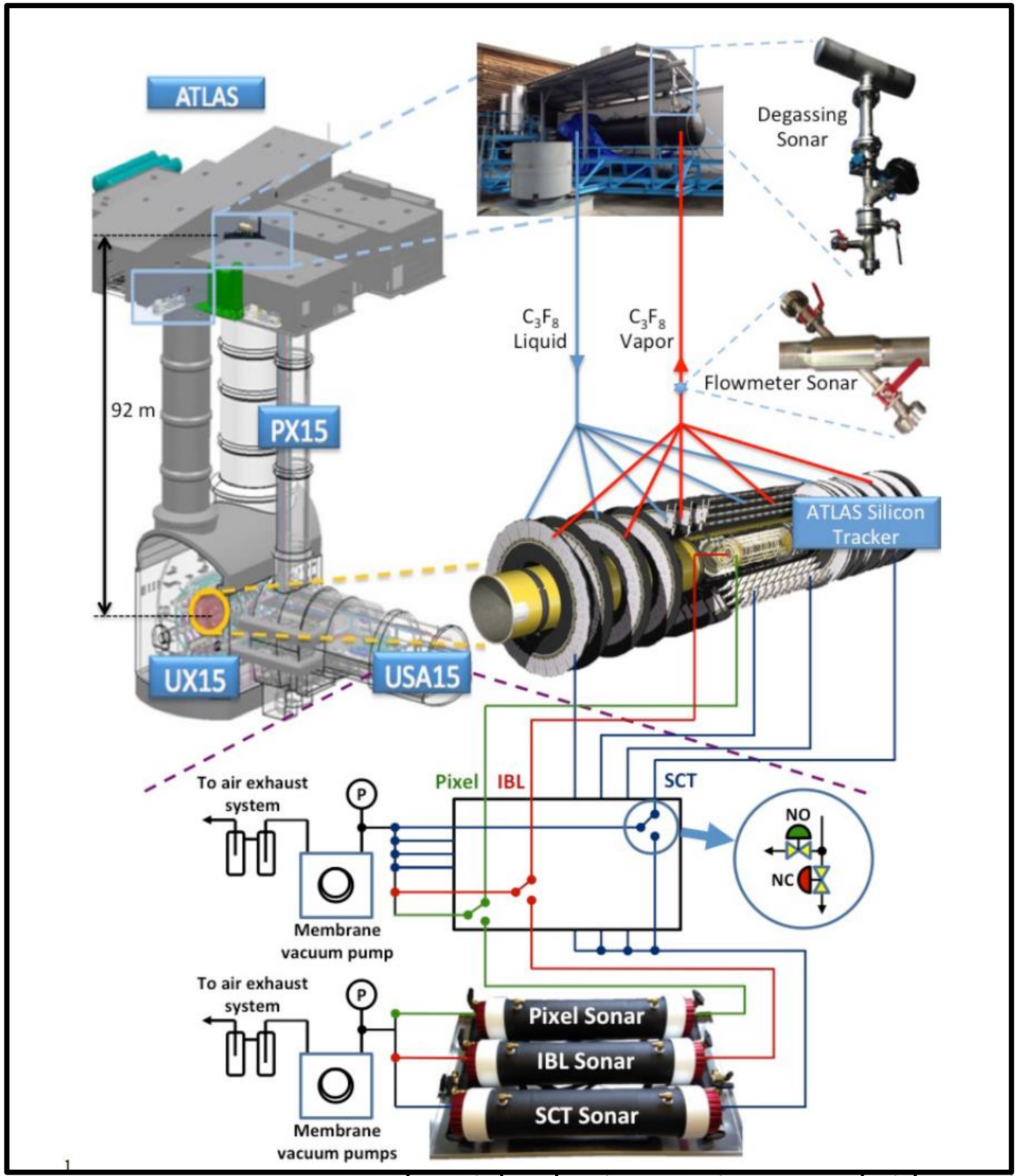


Fig.6 The β~1 Cherenkov angle measured from ring reconstruction (squares) compared to the value expected from the gas index measured by sound velocity in the CRID vessel and corrected for atmospheric pressure (dots).

Using the flowmeter analyzer in supply line to modify the blend by hardwired 4-20mA link to mass flow controllers

Note: before and after blend stabilization sonar interpreted β=1 radius agreed well with reconstructed radii!!

Use of sonar in the ATLAS experiment :



Almost all* the silicon tracker cooled by evaporation of C_3F_8 (octafluoro-propane: R218)

***SCT microstrip tracker + pixel detector**

Since late 2014: innermost IBL barrel pixel layer (“Insertable B Layer”) with CO_2

ATLAS IDE_Sonar Group (April 2015)

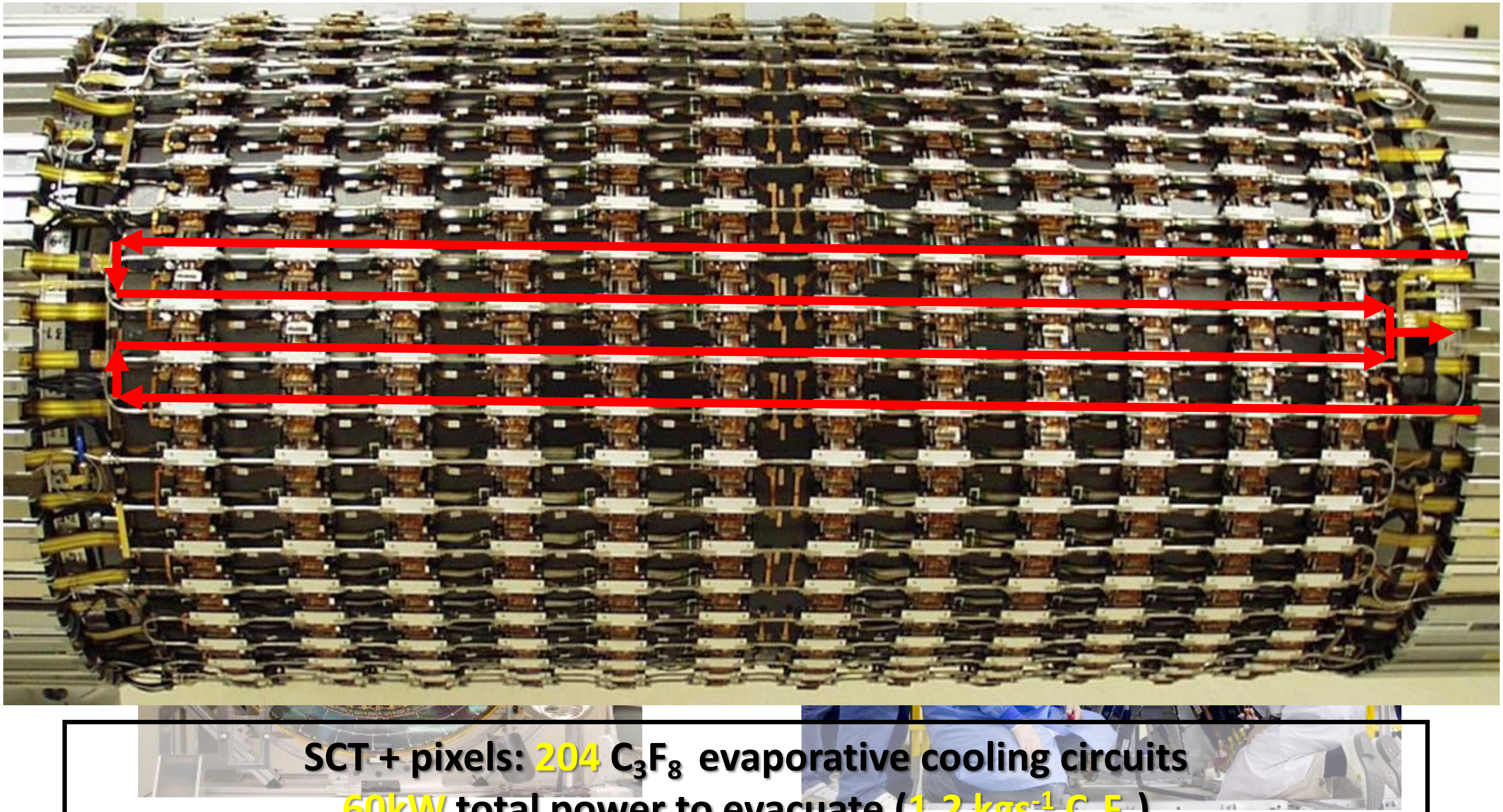
started 12/2009

M. Alhroob,[a] R. Bates,[b] M. Battistin,[c] S. Berry,[c] A. Bitadze,[b] P. Bonneau,[c] N. Bousson,[c] G. Boyd,[a] G. Bozza,[c] O. Crespo-Lopez,[c] C. Degeorge,[d] C. Deterre,[e] B. DiGirolamo,[c] M. Doubek,[f] G. Favre,[c] J. Godlewski,[b] G. Hallewell,[g] A. Hasib,[a] S. Katunin,[h,1] N. Langevin,[g] D. Lombard,[c] M. Mathieu,[g] S. McMahon,[i] K. Nagai,[j] A. O'Rourke,[e] B. Pearson,[a] D. Robinson,[k] C. Rossi,[l] A. Rozanov,[g] M. Strauss,[a] V. Vacek[f] and L. Zwalinski[c]

[a]Department of Physics and Astronomy, University of Oklahoma,
440 West Brooks Street, Norman, OK 73019, U.S.A.
[b]SUPA School of Physics and Astronomy, University of Glasgow, Glasgow, G62 7QB, U.K.
[c]CERN, 1211 Geneva 23, Switzerland
[d]Department of Physics, Indiana University, 727 East 3rd St., Bloomington, IN 47405, U.S.A.
[e]Deutsches Elektronen-Synchrotron, Notkestraße 85, D-22607 Hamburg, Germany
[f]Department of Applied Physics, Czech Technical University in Prague,
Technická 4, 166 07 Prague 6, Czech Republic
[g]Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS/IN2P3,
163 Avenue de Luminy, 13288 Marseille Cedex 09, France
[h]B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI), 188300 St. Petersburg, Russia
[i]Rutherford Appleton Laboratory - Science & Technology Facilities Council,
Harwell Science and Innovation Campus, Didcot OX11 0QX, U.K.
[j]Department of Physics, Oxford University, Oxford OX1 3RH, U.K.
[k]Department of Physics and Astronomy, Cavendish Laboratory, J.J. Thompson Avenue,
University of Cambridge, Cambridge, CB3 0HE, U.K.
[l]Academy of Sciences of the Czech Republic, 110 00 Prague, Czech Republic

ATLAS 'Semi-Conductor Tracker' (SCT)

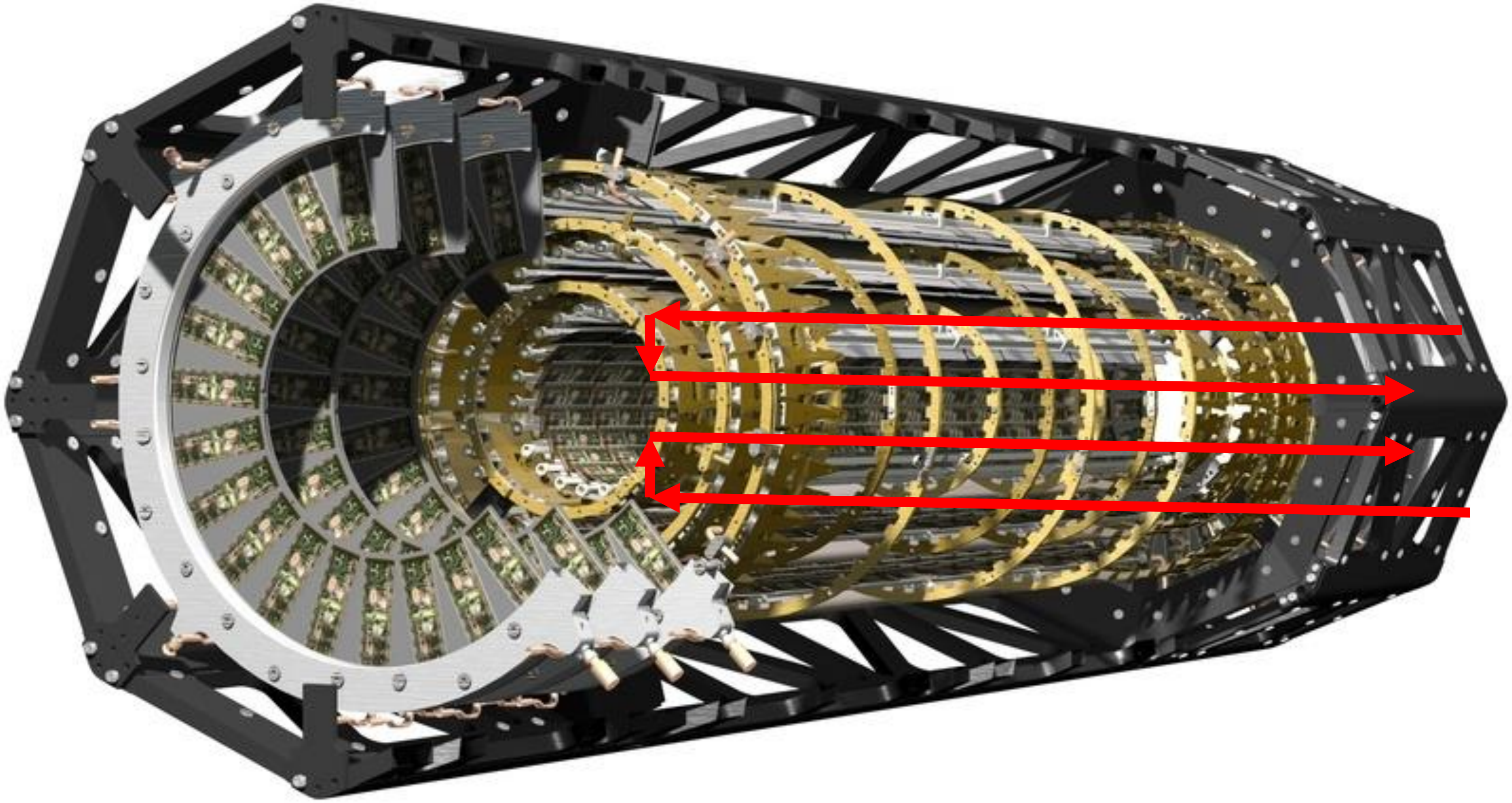
silicon microstrip tracker surrounding pixel detector



SCT + pixels: 204 C_3F_8 evaporative cooling circuits

60kW total power to evacuate (1.2 kgs^{-1} C_3F_8)

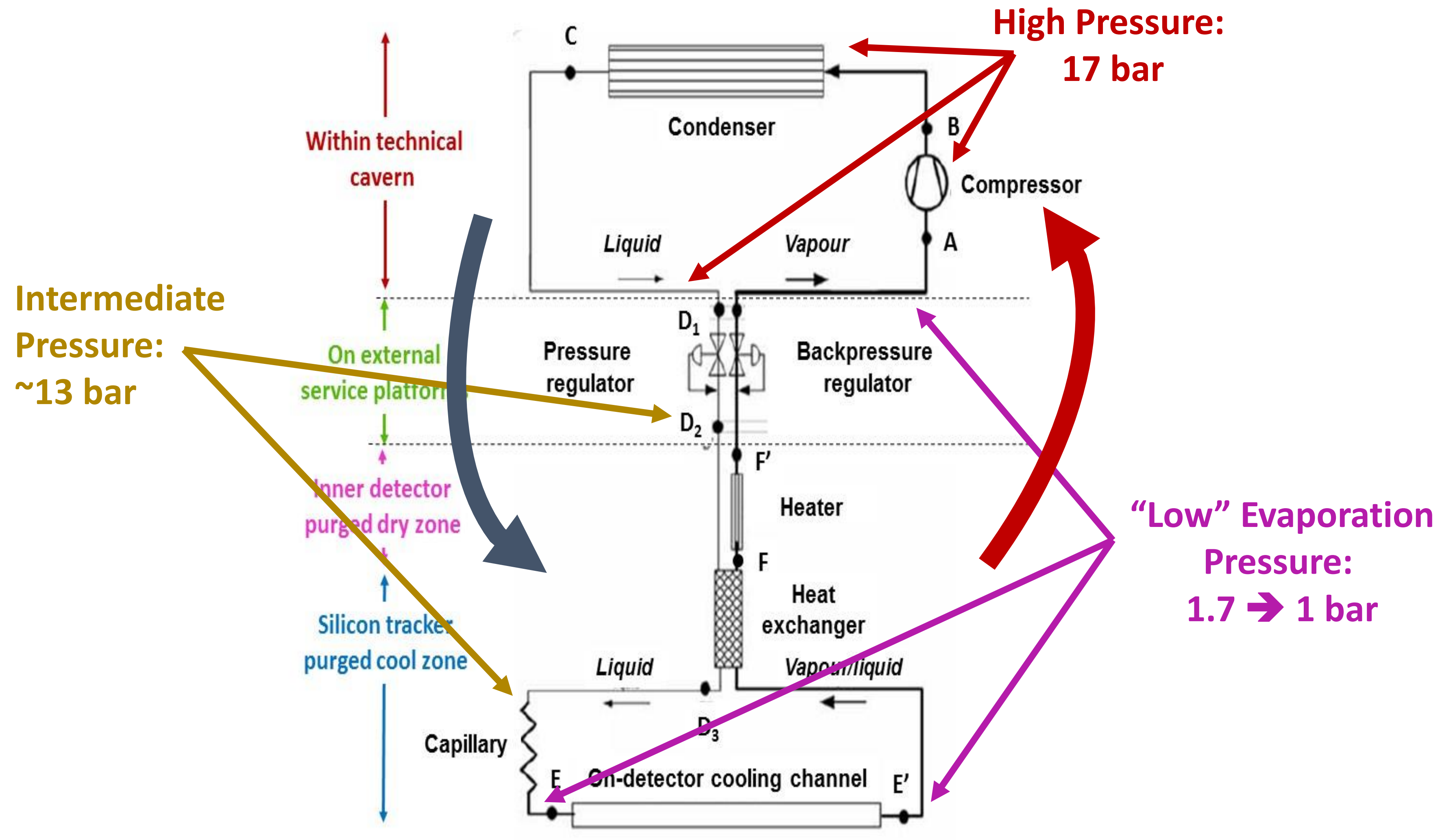
~50 Horizontal stave cooling channels (l ~ 1,60m)
18 “vertical” channels: disk sectors



ATLAS- Pixel Detector Structure

Principal Mechanical Components:

204 parallel C_3F_8 evaporative cooling channels in SCT & pixel detectors



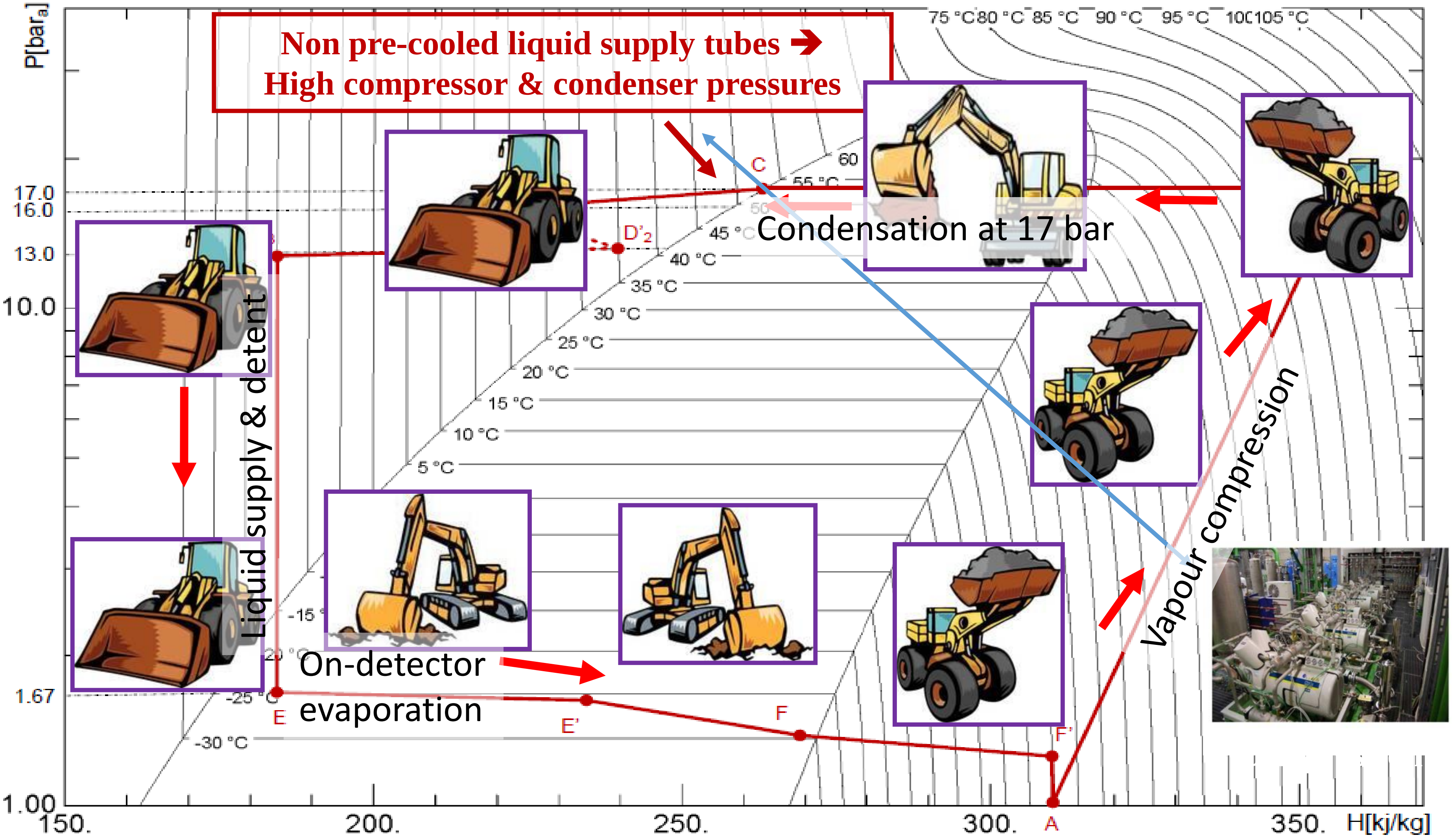
High Pressure:
17 bar

Intermediate Pressure:
~13 bar

"Low" Evaporation Pressure:
1.7 ➔ 1 bar

“As designed” Thermodynamic Cycle : evaporation of C_3F_8

Animation: JCB Digger = fluid; heat in vapour form = earth...



Non pre-cooled liquid supply tubes ➔
High compressor & condenser pressures

Condensation at 17 bar

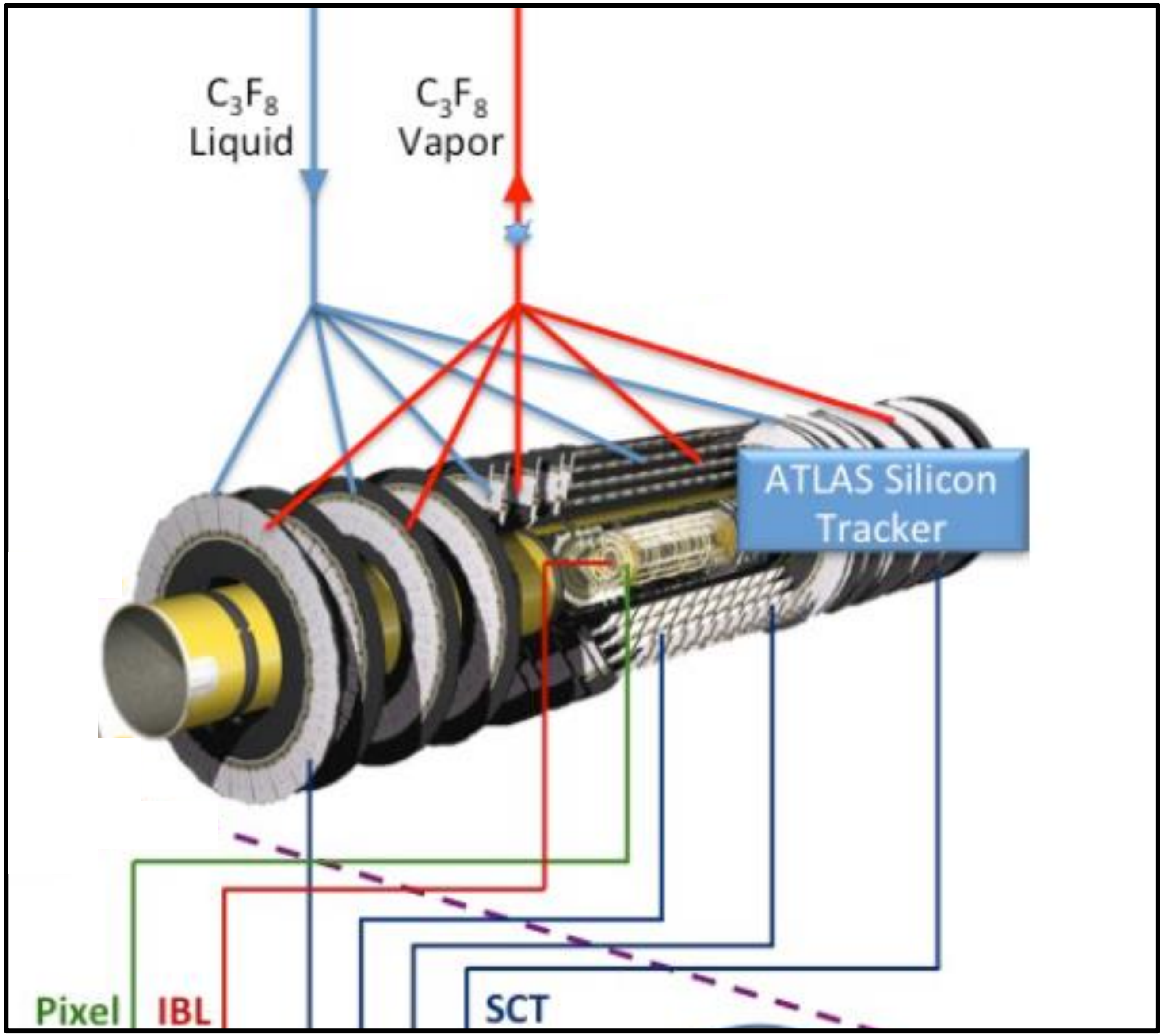
Liquid supply & detent

On-detector evaporation

Vapour compression

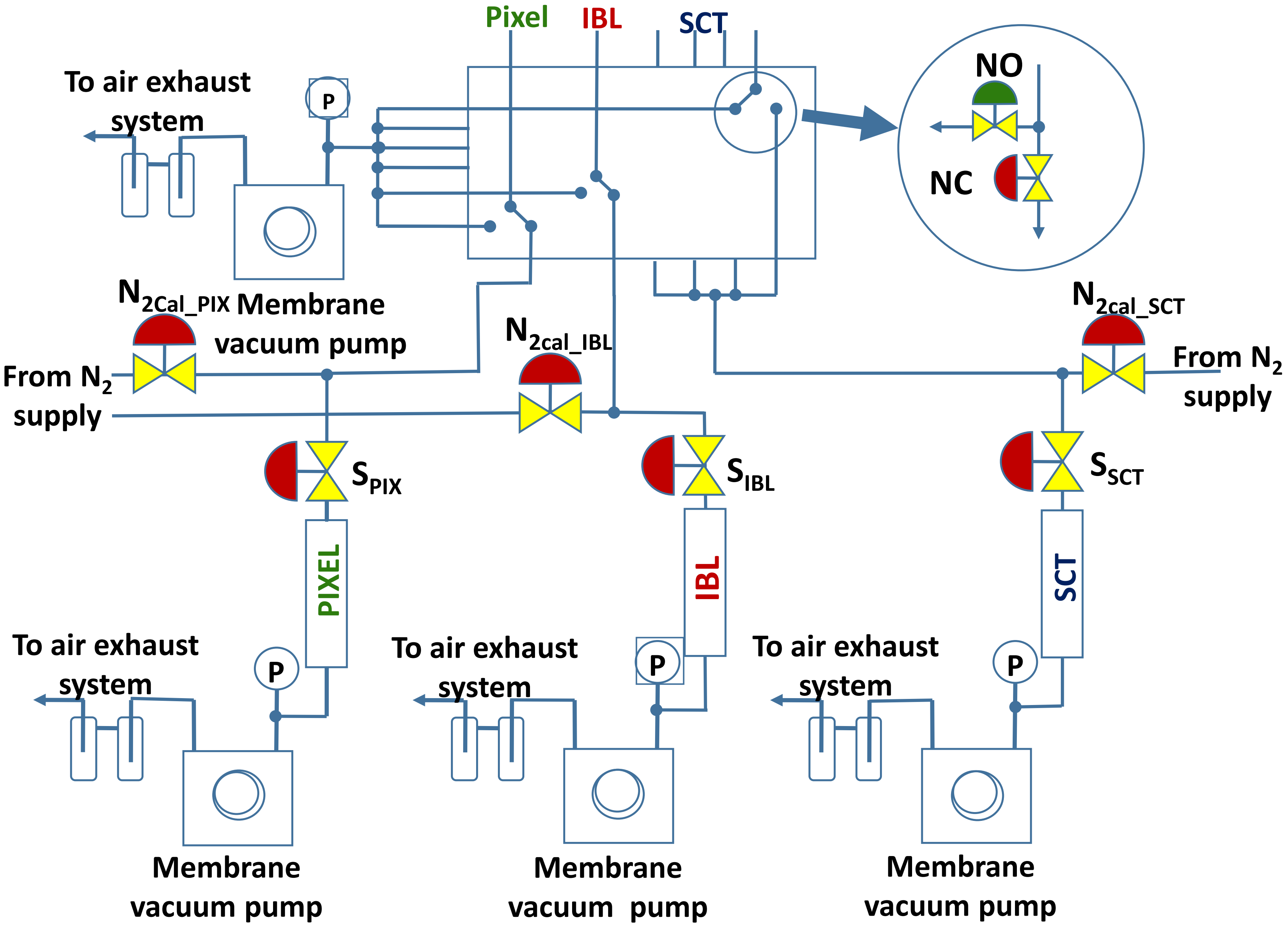
ATLAS SCT, Pixels & IBL in separate N_2-purged environmental volumes

ATLAS SCT, Pixels & IBL volumes continuously aspirated through 150m tubes into 3 sonar devices to monitor for coolant leaks



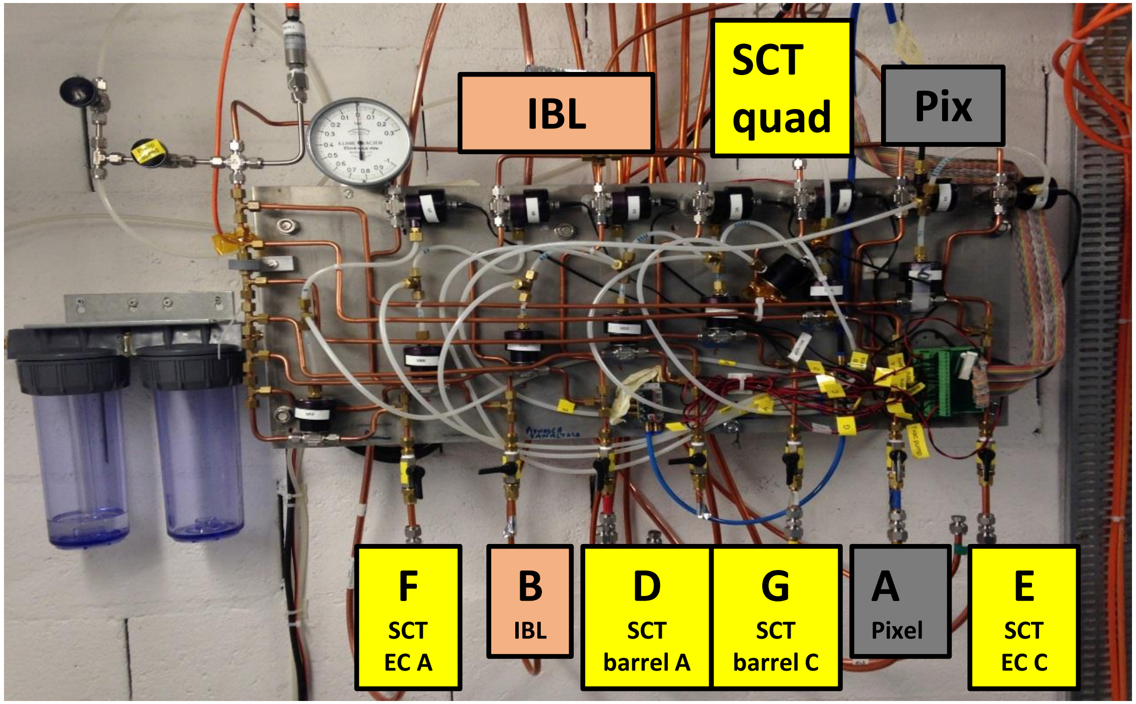
G.H./Particle Physics Seminar, Cambridge University, April 14th 2015

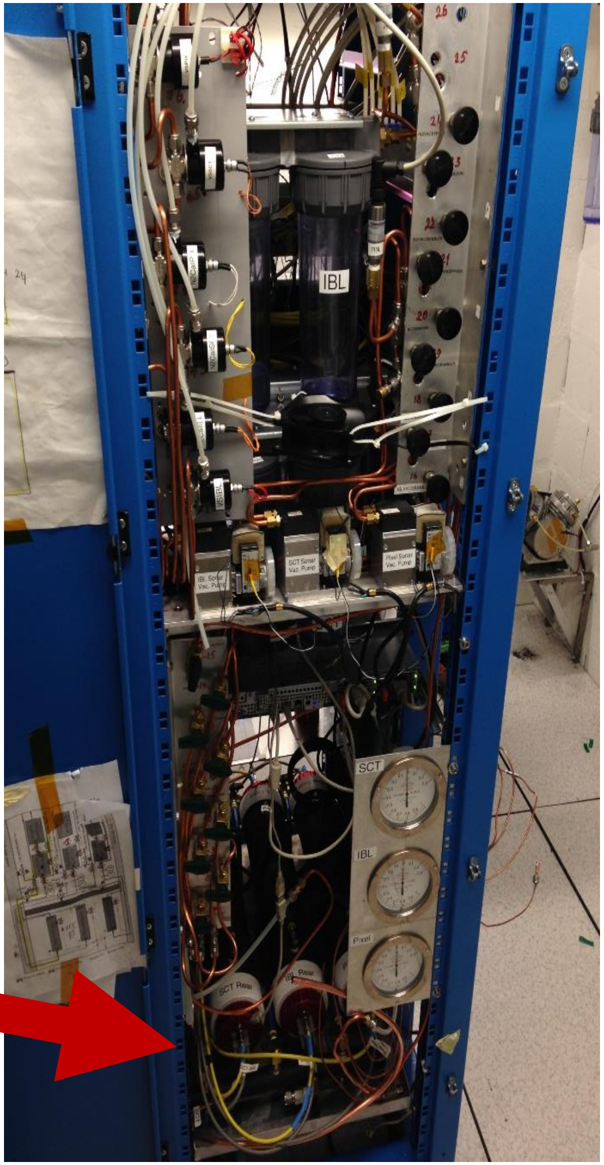
ATLAS SCT, Pixels & IBL environmental volume sampling system



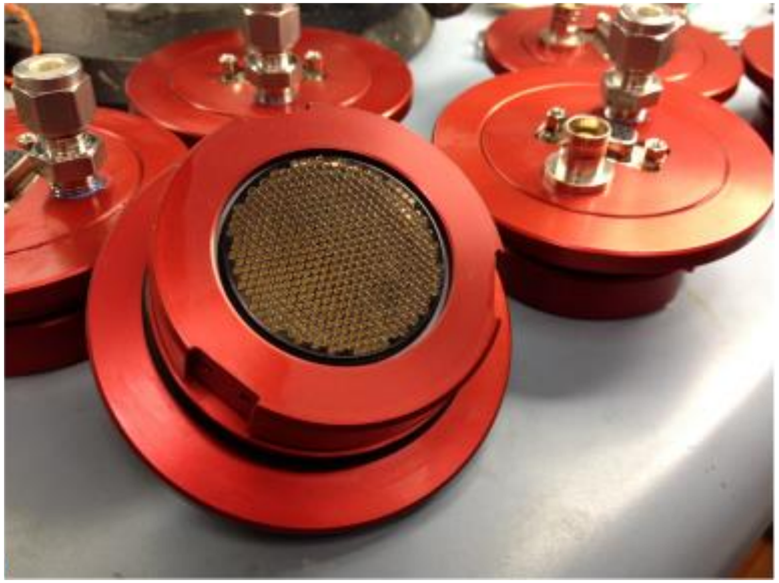
G.H./Particle Physics Seminar, Cambridge University, April 14th 2015

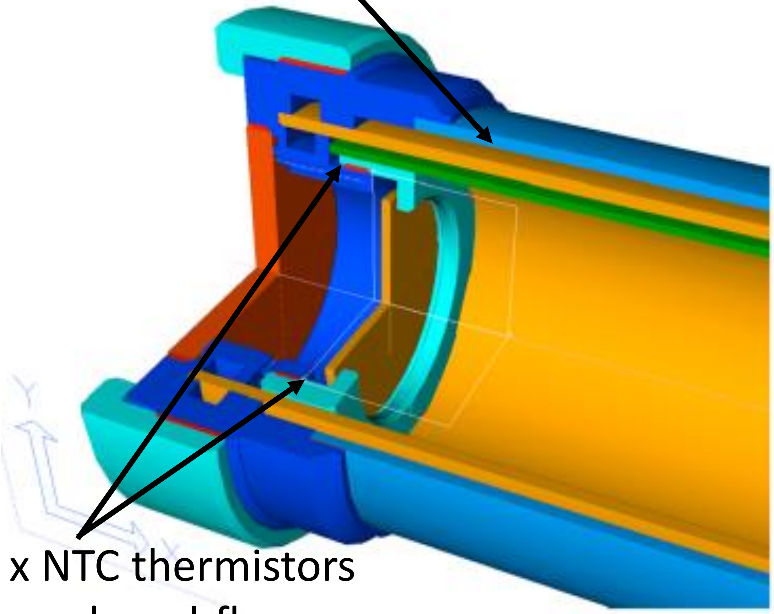
Implementation: Gas stream selection valves (wall & rack), + sonar tubes)





Sonar tubes built for ease of transducer replacement

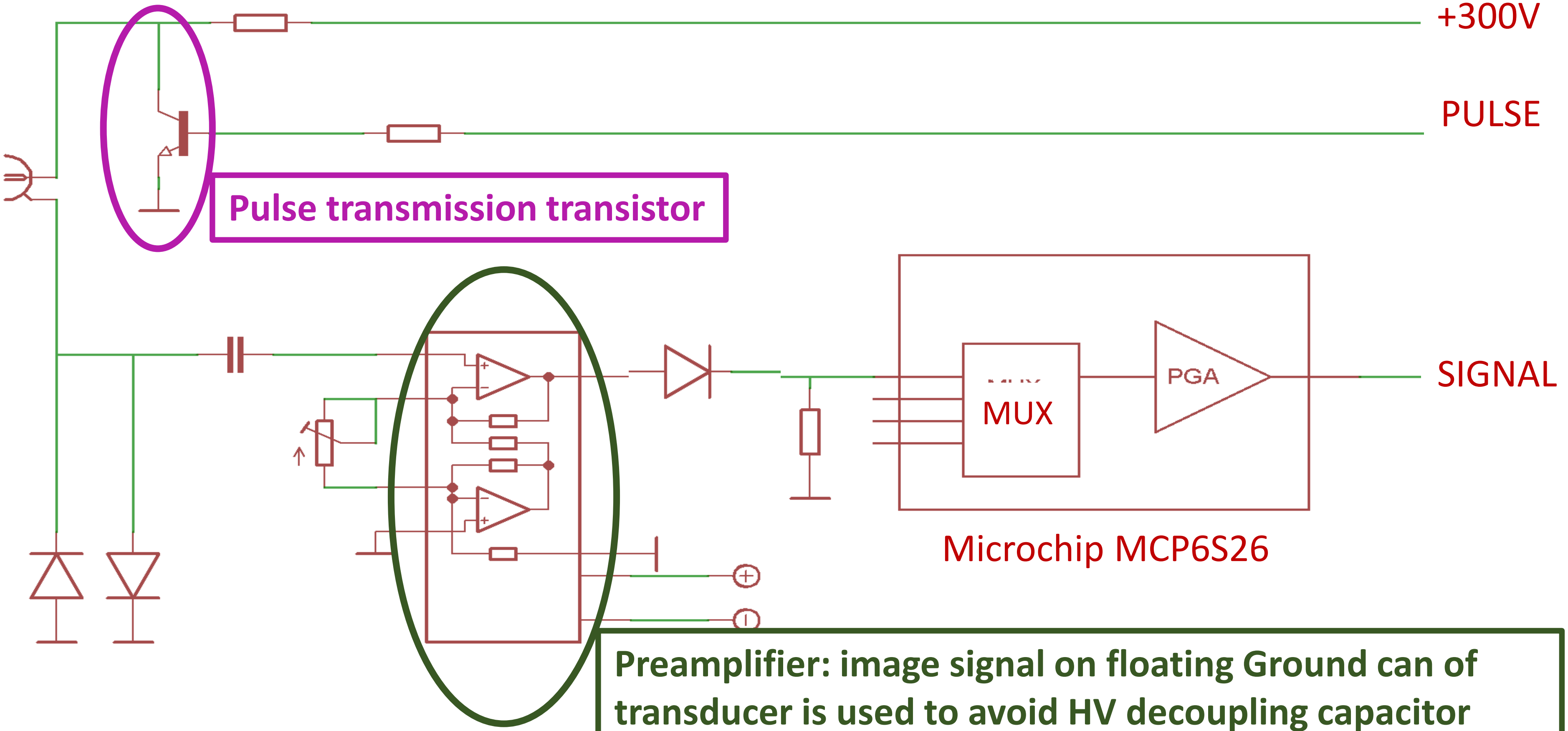




Concentric water jacket for optional temperature stabilization

2 x NTC thermistors in each end-flange

Recent front end electronics for biasing, pulse injection and received signal amplification

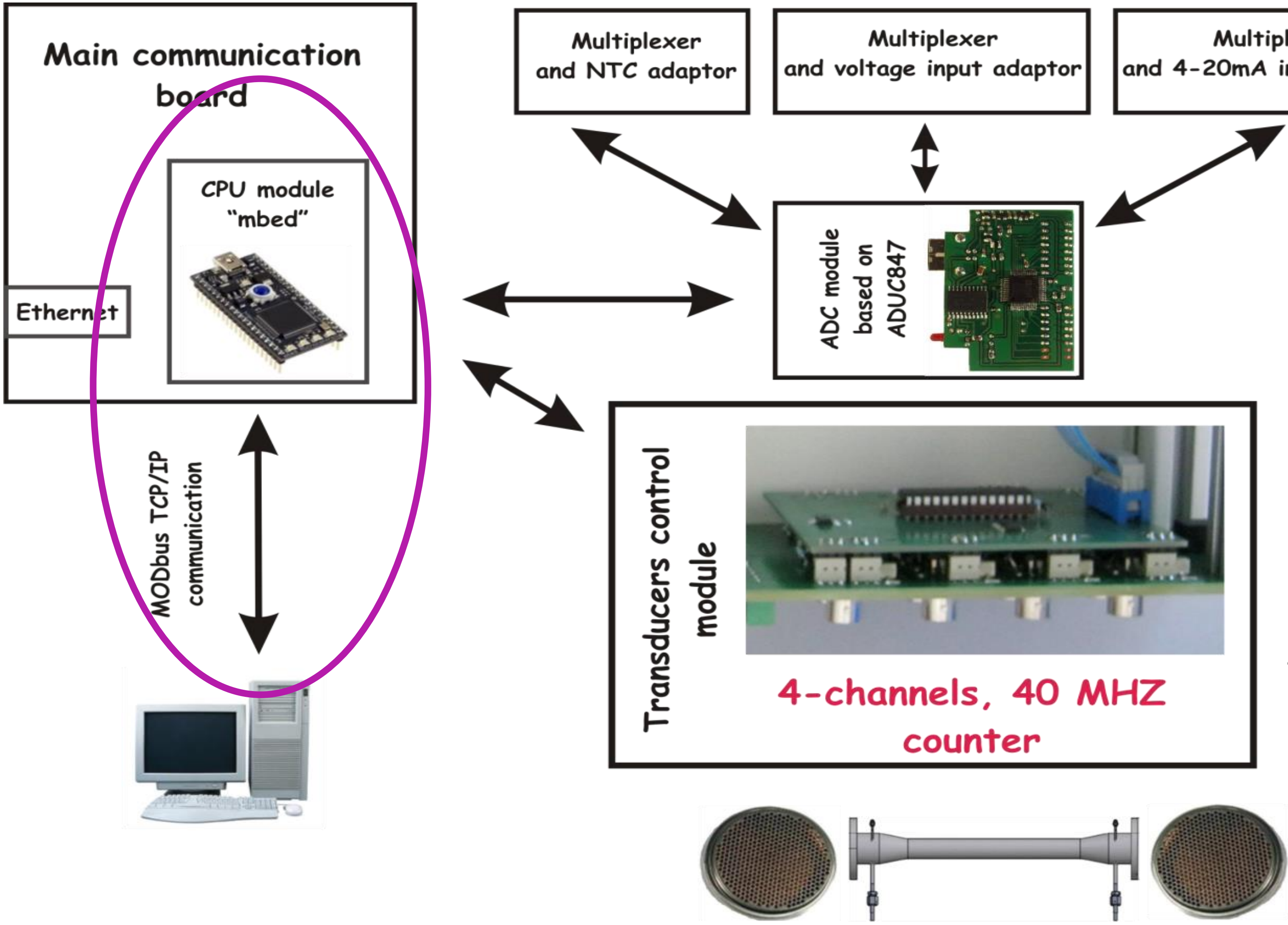


Pulse transmission transistor

Preamplifier: image signal on floating Ground can of transducer is used to avoid HV decoupling capacitor (allows echometry* over short distances without having to wait for capacitor charge/discharge to bias V)

**** Useful for flowmeter acoustic path calibration***

Electronics card oganisation and Modbus TCP/IP communication



Main communication board

CPU module “mbed”

Ethernet

MODbus TCP/IP communication

Multiplexer and NTC adaptor

Multiplexer and voltage input adaptor

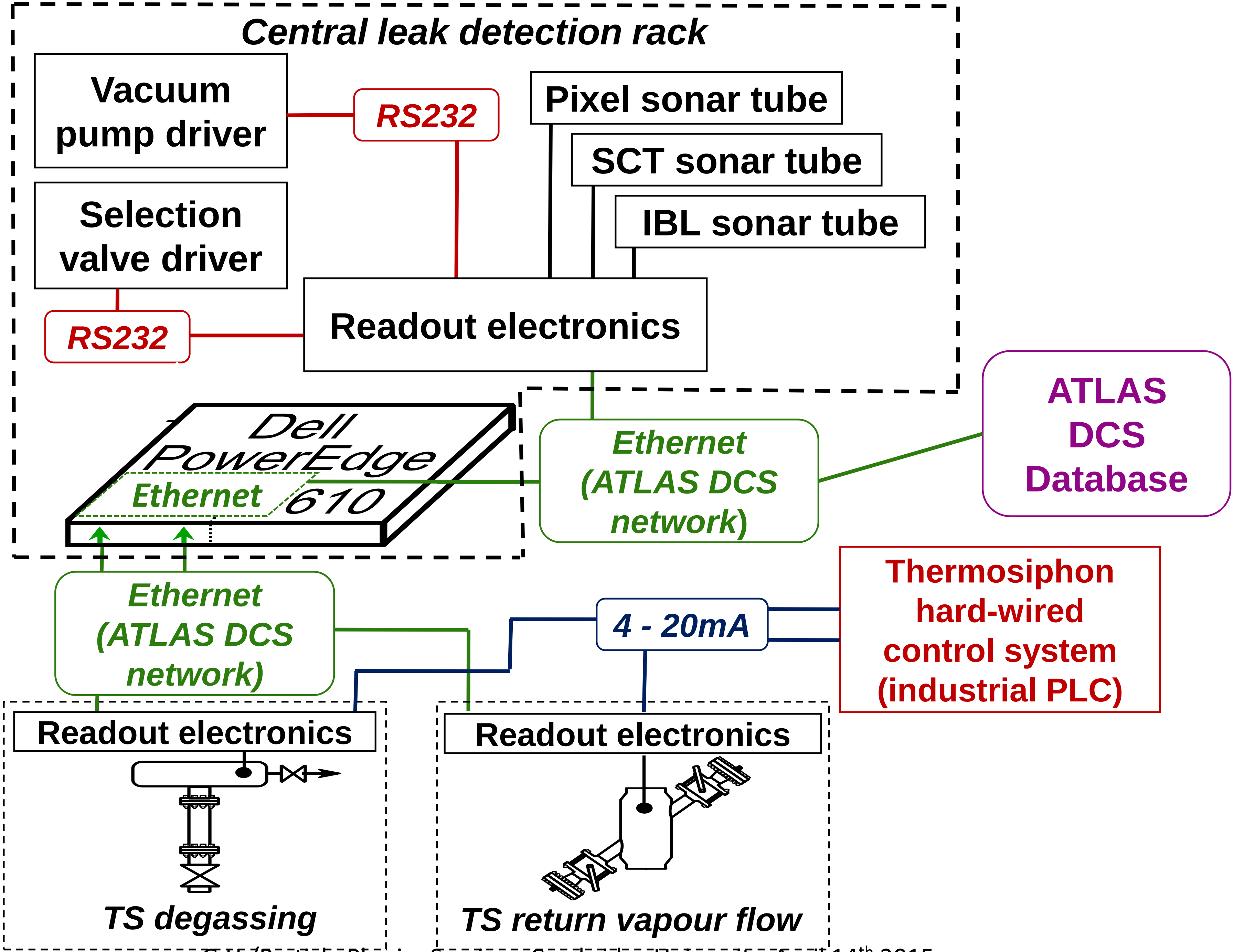
Multiplexer and 4-20mA input adaptor

ADC module based on ADUC847

Transducers control module

4-channels, 40 MHZ counter

Uses DSpiC μ-conroller



Central leak detection rack

Vacuum pump driver

RS232

Pixel sonar tube

SCT sonar tube

IBL sonar tube

Selection valve driver

RS232

Readout electronics

Dell PowerEdge 610

Ethernet

Ethernet (ATLAS DCS network)

ATLAS DCS Database

Thermosiphon hard-wired control system (industrial PLC)

4 - 20mA

Ethernet (ATLAS DCS network)

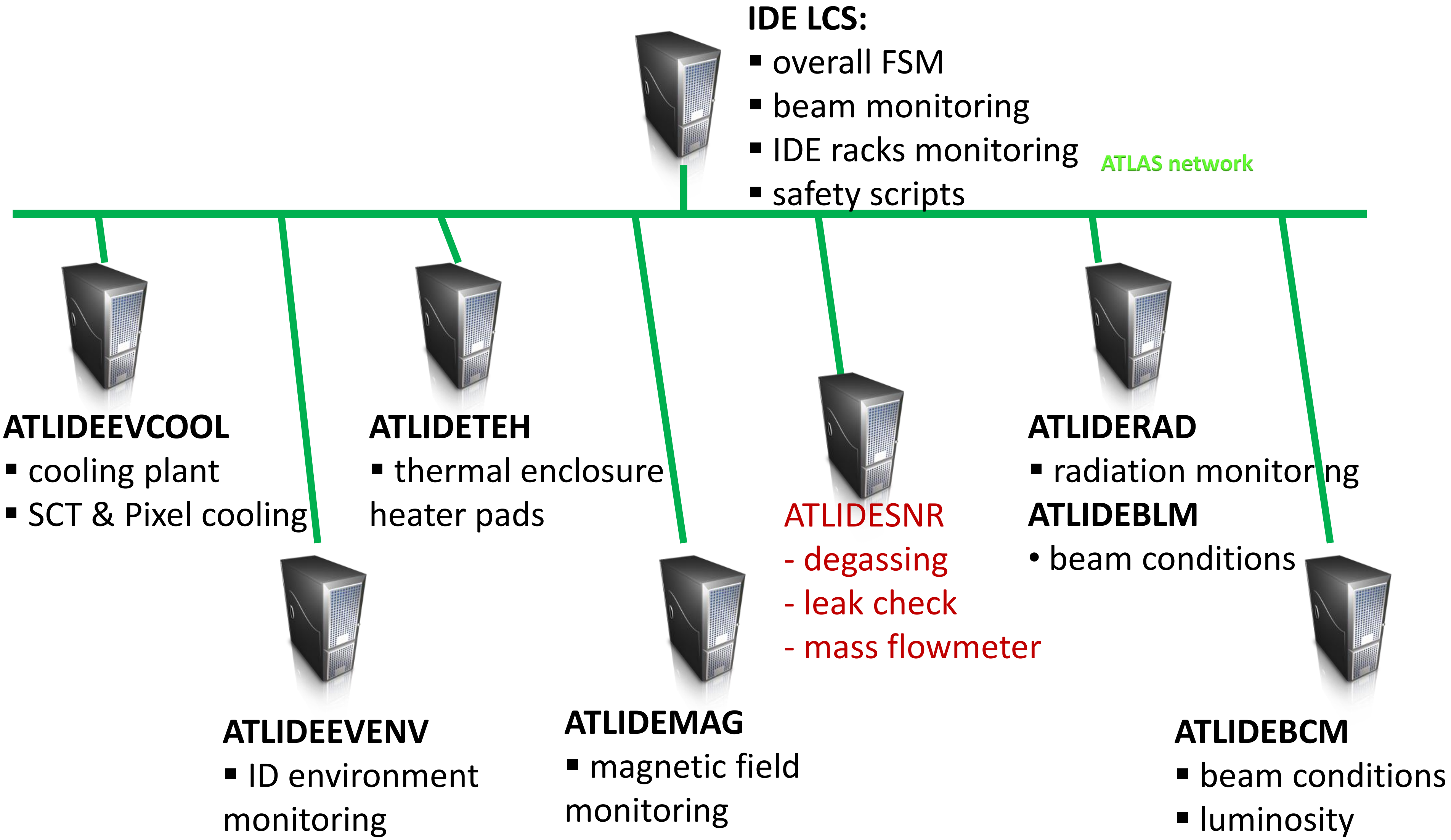
Readout electronics

TS degassing

Readout electronics

TS return vapour flow

Sonar in the ATLAS DCS framework



IDE LCS:
- overall FSM
- beam monitoring
- IDE racks monitoring
- safety scripts

ATLAS network

ATLIDEEVCOOL
- cooling plant
- SCT & Pixel cooling

ATLIDETEH
- thermal enclosure heater pads

ATLIDESNR
- degassing
- leak check
- mass flowmeter

ATLIDERAD
- radiation monitoring

ATLIDEBLM
- beam conditions

ATLIDEEVENV
- ID environment monitoring

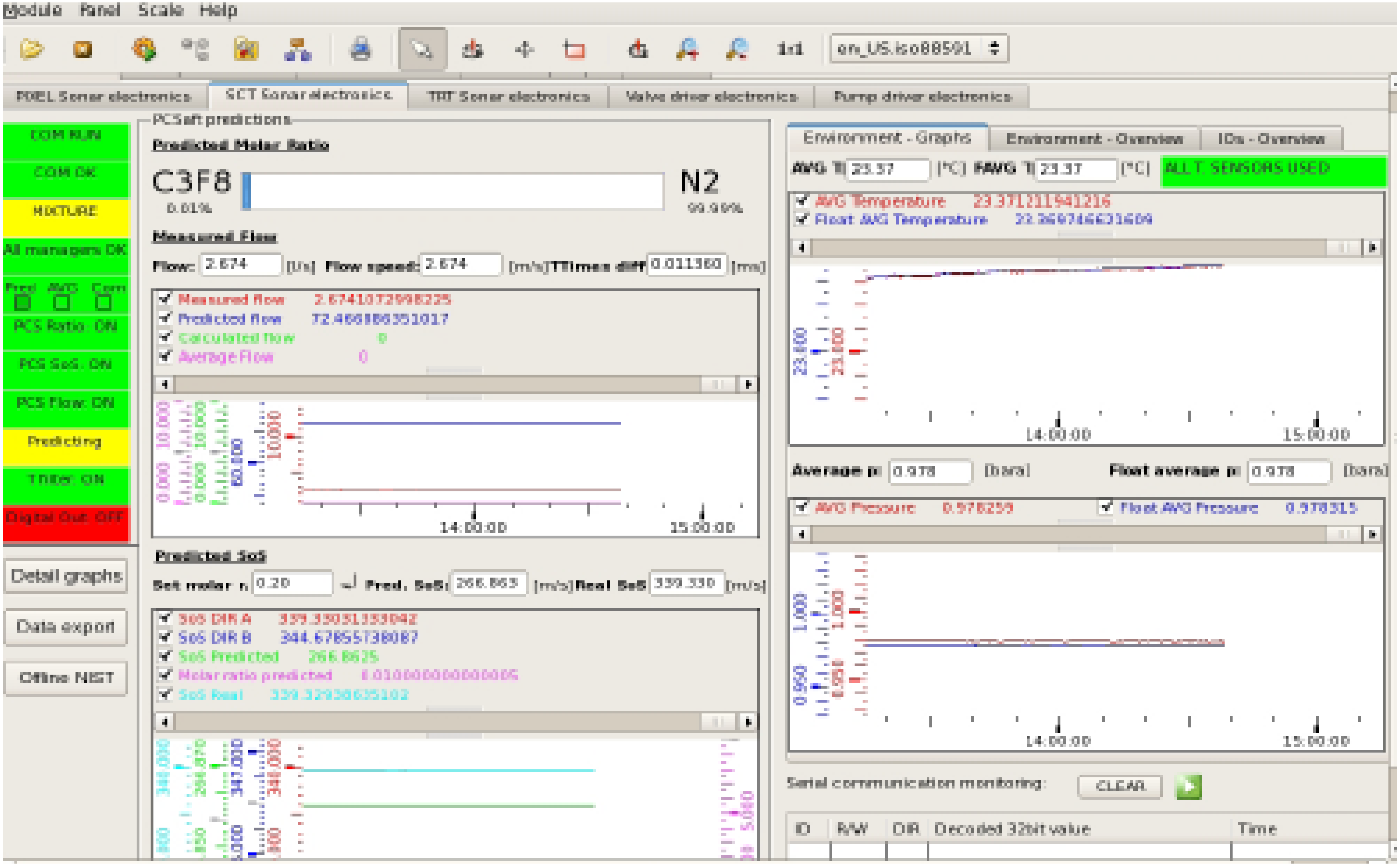
ATLIDEMAG
- magnetic field monitoring

ATLIDEBCM
- beam conditions
- luminosity

Example of GUI panel in Siemens Simatec WINcc on Linux

SCADA computer: Dell Poweredge R610 on ATLAS ATCN network

Sonar communication by MODBUS/TCP/IP over ethernet



C3F8 0.01%

N2 99.99%

Flow: 2.674 [l/s] Flow speed: 2.674 [m/s] TTimes diff 0.011360 [ms]

- ☑ Measured flow 2.6741072998225
- ☑ Predicted flow 72.466886351017
- ☑ Calculated flow 0
- ☑ Average Flow 0

Set molar r: 0.20 Pred. SoS: 266.863 [m/s] Real SoS 339.330 [m/s]

- ☑ SoS DIR A 339.33051333042
- ☑ SoS DIR B 344.67855738087
- ☑ SoS Predicted 266.8625
- ☑ Molar ratio predicted 0.01000000000000005
- ☑ SoS Real 339.32938635102

AVG T 23.37 [°C] FAVG T 23.37 [°C]

- ☑ AVG Temperature 23.371211941216
- ☑ Float AVG Temperature 23.369746631609

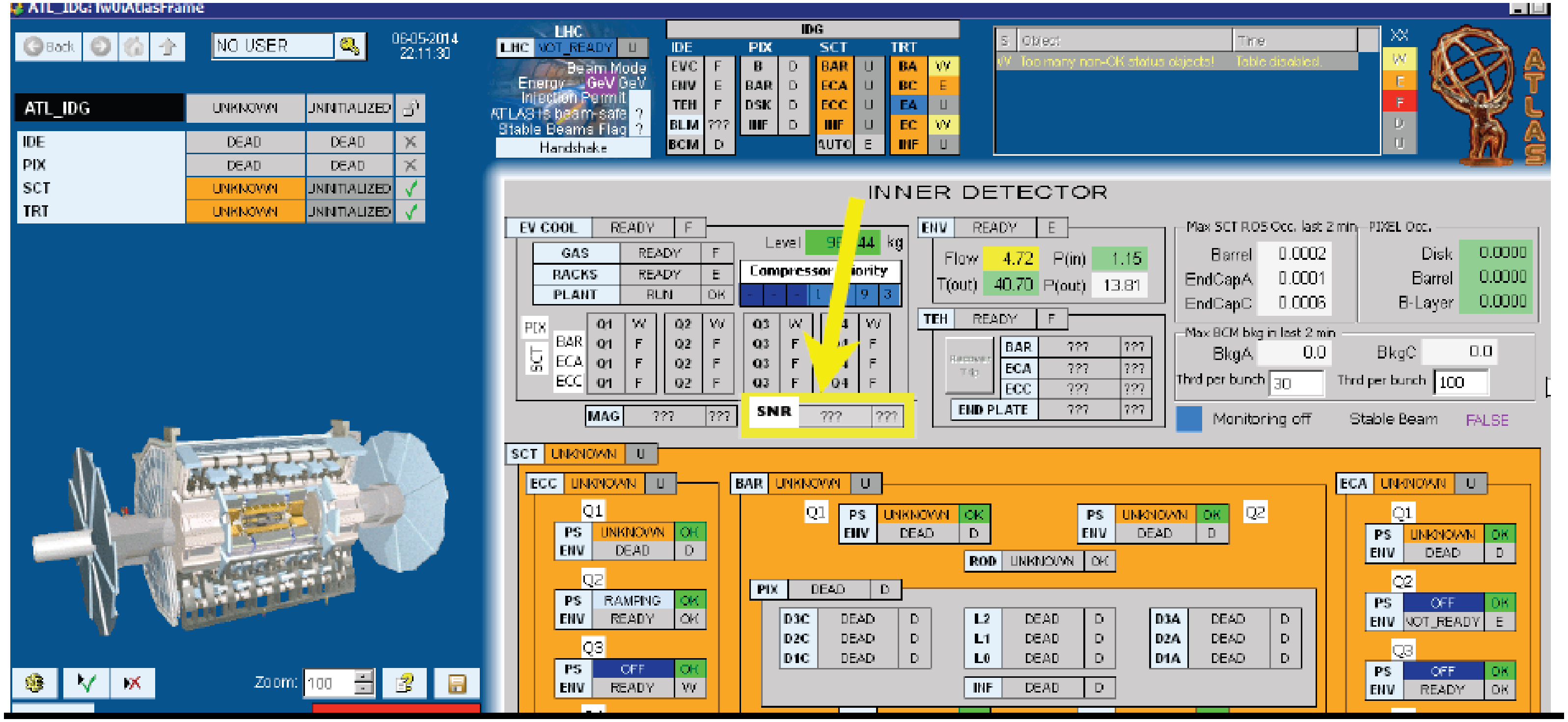
Average p 0.978 [bara] Float average p 0.978 [bara]

- ☑ AVG Pressure 0.978259
- ☑ Float AVG Pressure 0.978315

Future sonar integration into ATLAS alarm hierarchy

IDG Panel

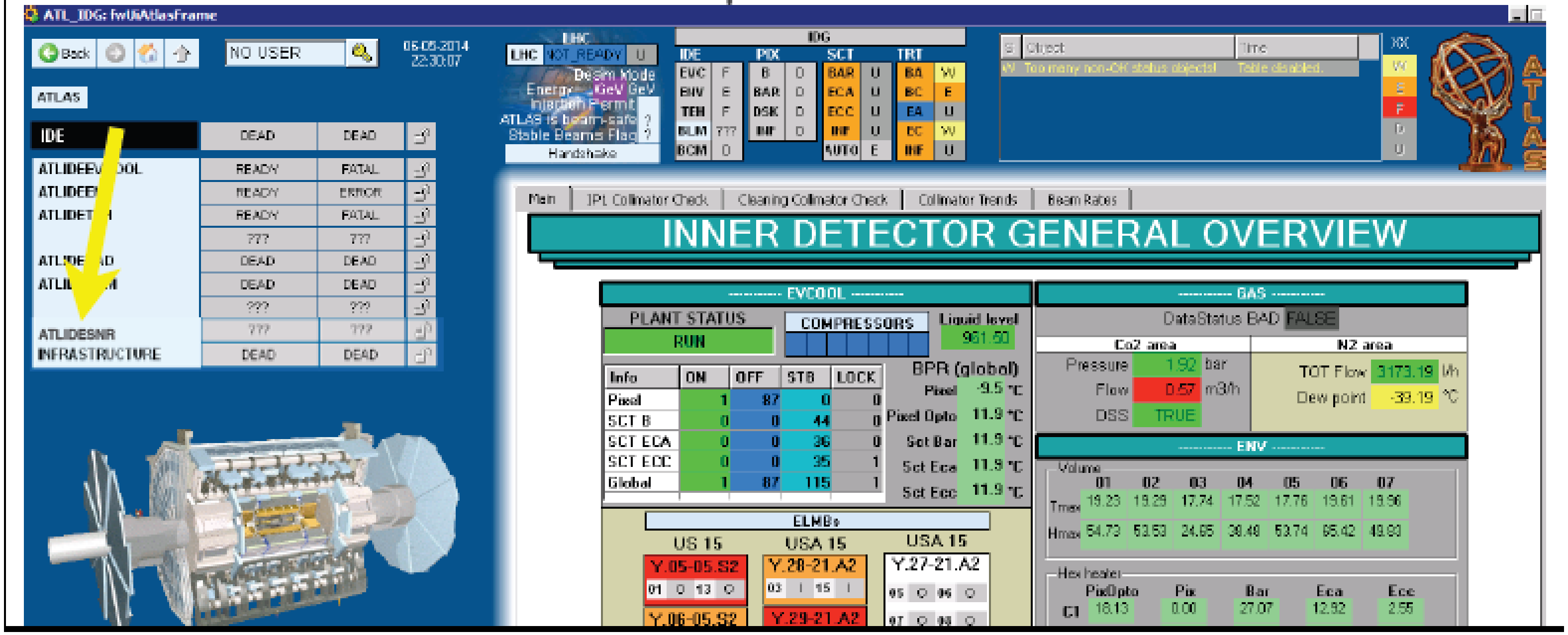
- IDG Panel is a brief summary of state and status of entire ID.
  - A "state & status" bar for IDESNR will be shown like IDEMAG



Future sonar integration into ATLAS alarm hierarchy

IDE Panel

- IDE Panel is a brief summary of IDE systems.
  - A "state & status" bar for IDESNR will be shown in FSM tree
  - More but simple summary (2, 3 lines) of SNR in the main panel



IDE	DEAD	DEAD
ATLIDEEV OOL	READY	FATAL
ATLIDEE	READY	ERROR
ATLIDET H	READY	FATAL
	???	???
ATLIDE D	DEAD	DEAD
ATLI M	DEAD	DEAD
	???	???
ATLIDESNR	???	???
INFRASTRUCTURE	DEAD	DEAD

IDG

IDE		PIX		SCT		TRT	
EVC	F	B	D	BAR	U	BA	W
ENV	E	BAR	D	ECA	U	BC	E
TEH	F	DSK	D	ECC	U	EA	U
BLM	???	INF	D	INF	U	EC	W
BCM	D			AUTO	E	INF	U

W Too many non-OK status objects! Table disabled.

INNER DETECTOR GENERAL OVERVIEW

EVCOOL

PLANT STATUS: RUN

COMPRESSORS

Liquid level: 961.50

Info	ON	OFF	STB	LOCK
Pixel	1	87	0	0
SCT B	0	0	44	0
SCT ECA	0	0	36	0
SCT ECC	0	0	35	1
Global	1	87	115	1

BPR (global)

Pixel	-9.5	°C
Pixel Opto	11.9	°C
Sct Bar	11.9	°C
Sct Eca	11.9	°C
Sct Ecc	11.9	°C

ELMBs

US 15	USA 15	USA 15
Y.05-05.S2 01 ○ 13 ○	Y.28-21.A2 03 I 15 I	Y.27-21.A2 05 ○ 06 ○
Y.06-05.S2	Y.29-21.A2	07 ○ 08 ○

GAS

DataStatus BAD FALSE

Co2 area

Pressure 1.92 bar
Flow 0.57 m3/h
DSS TRUE

N2 area

TOT Flow 3173.19 l/h
Dew point -39.19 °C

ENV

Volume

	01	02	03	04	05	06	07
Tmax	19.23	19.29	17.74	17.52	17.76	19.61	19.96
Hmax	54.73	53.53	24.65	39.49	53.74	65.42	49.93

Hex heater

	PixOpto	Pix	Bar	Eca	Ecc
C1	18.13	0.00	27.07	12.92	2.55

Results from the aspirating sonars

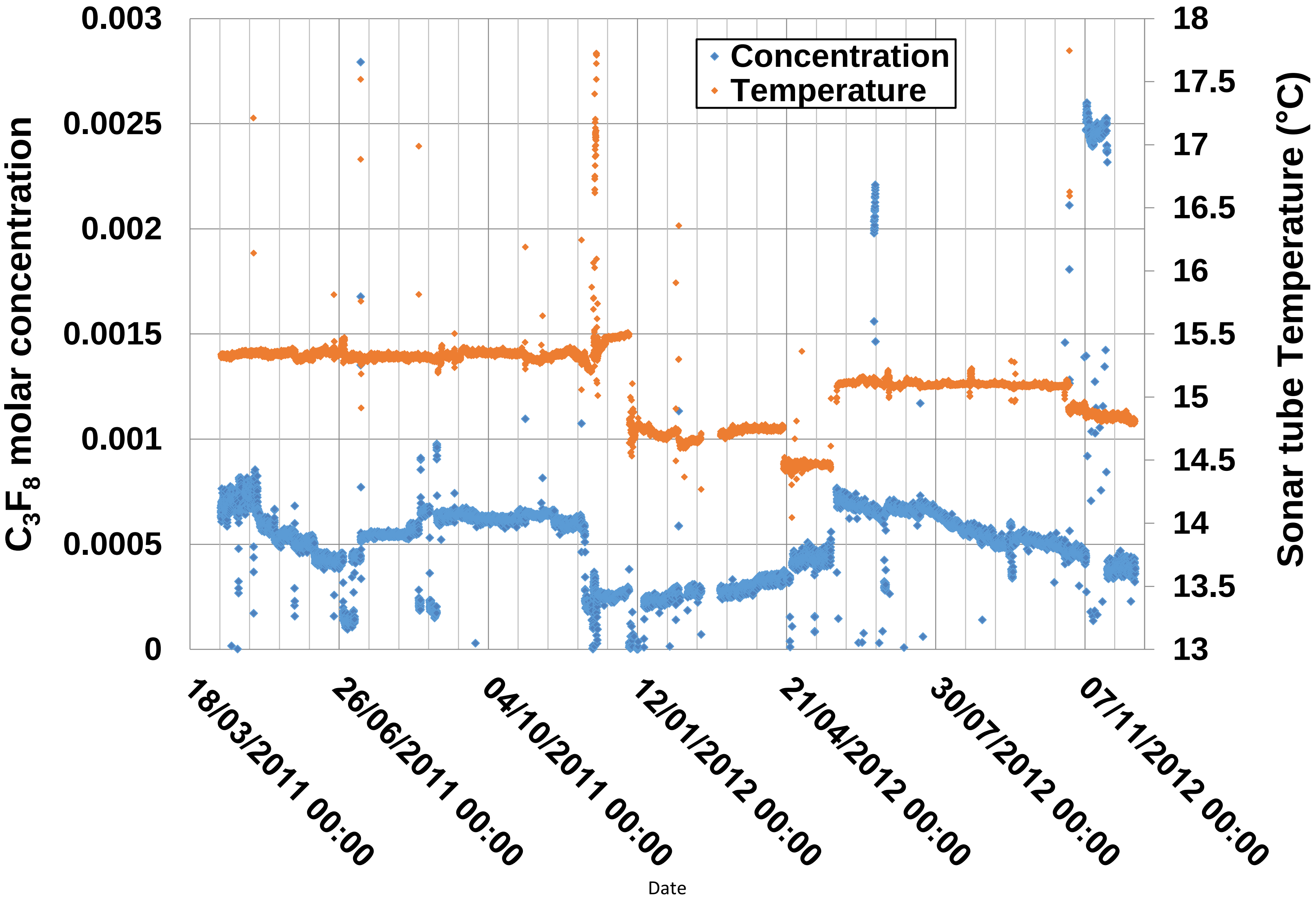
Long duration (18 month) study of the C3F8 leak rate to the pixel envelope (ended Feb 20 2013 - start of LHC shut down) →

Study leak rate during turn on + turn off of pixel detector to identify leaking channels →

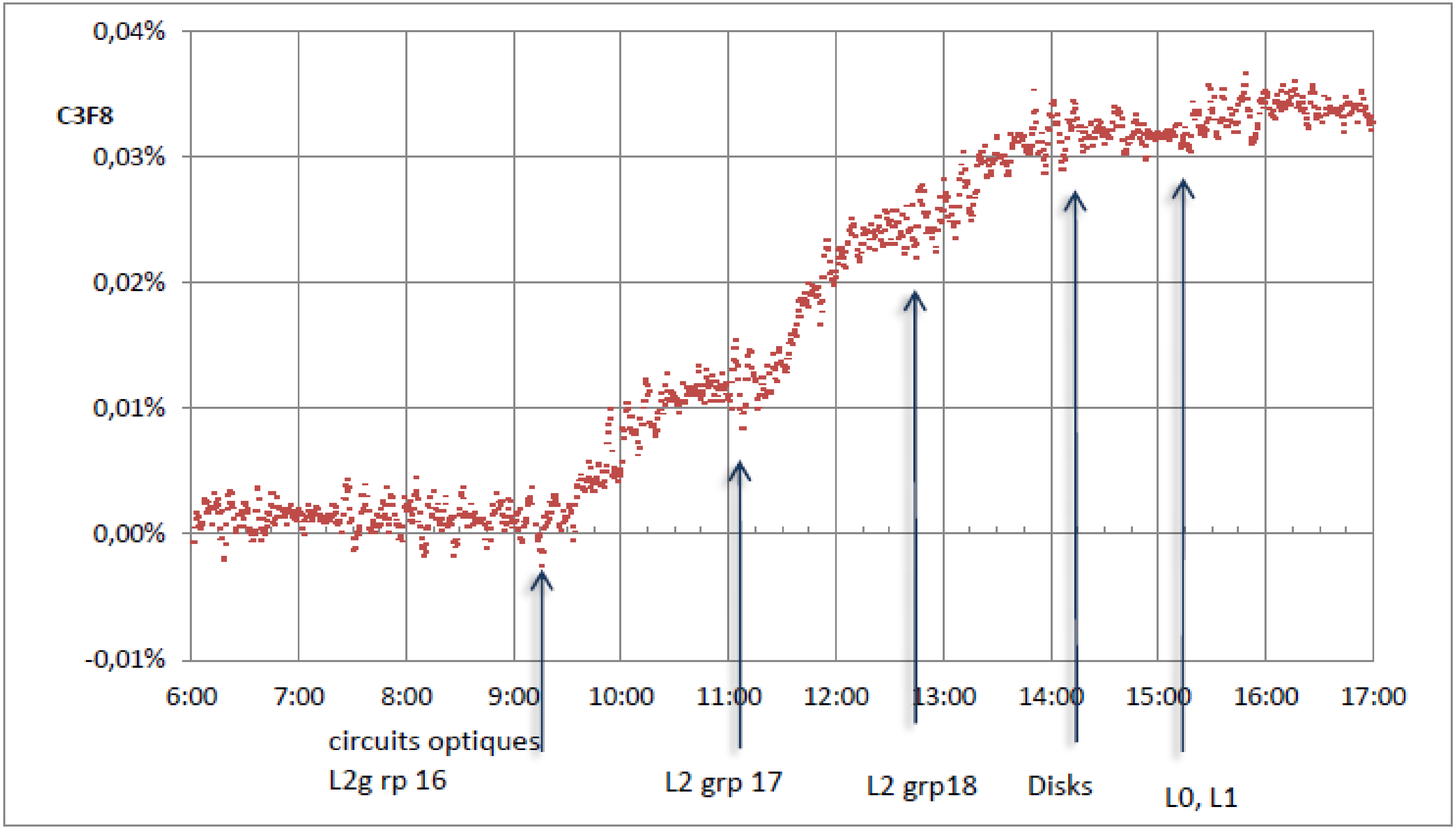
With 2nd sonar tube: 3 week analysis of SCT barrel C3F8 leak rate (ended Feb 20 2013 - start of LHC shut down) →

With new MODBUS electronics, new tube: data writing into ATLAS DCS database: SCT barrel and end-cap envelopes C3F8 content since LHC startup on April 5, 2015 →

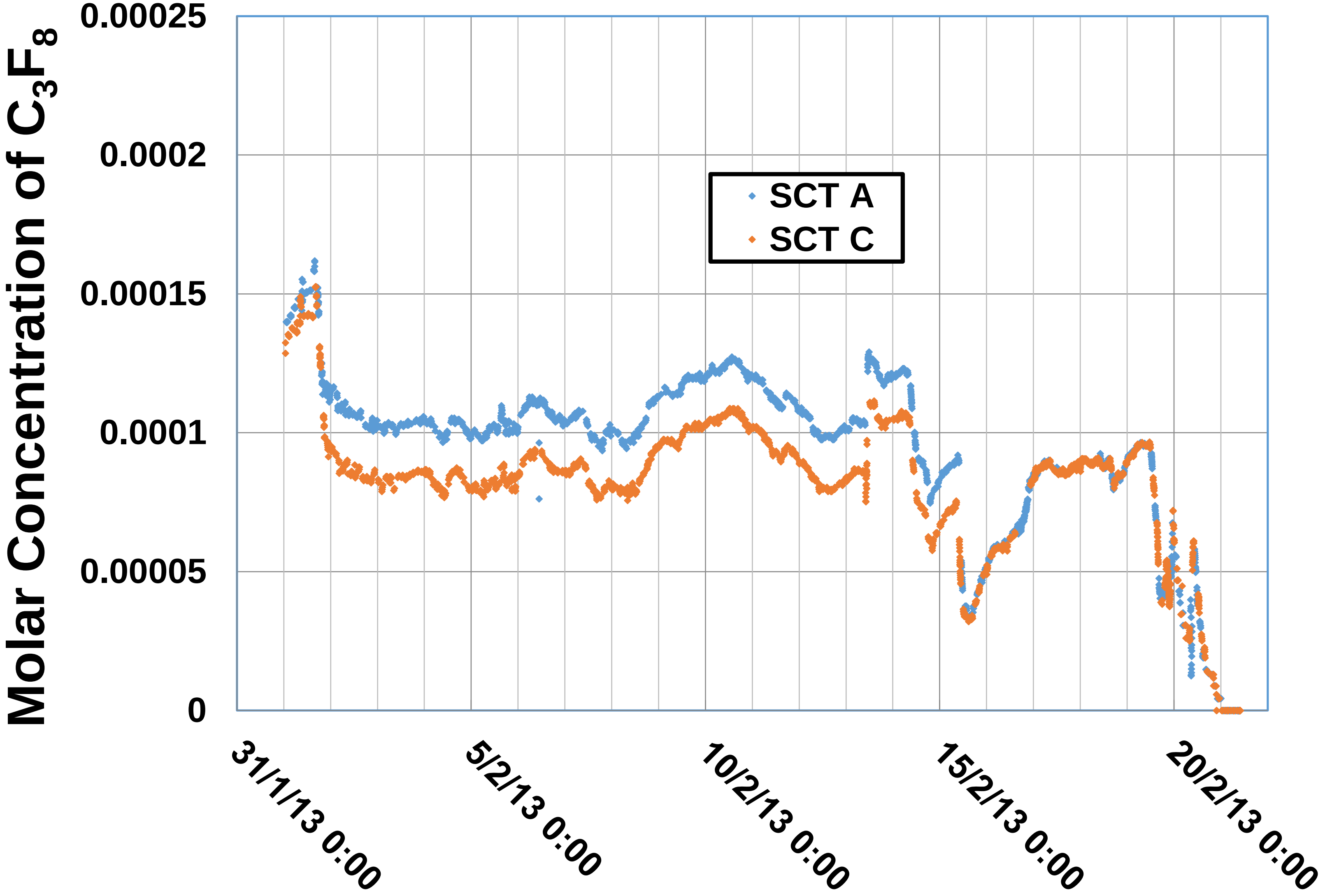
Long duration (18 month) study of C_3F_8 leak rate into Pixel detector envelope



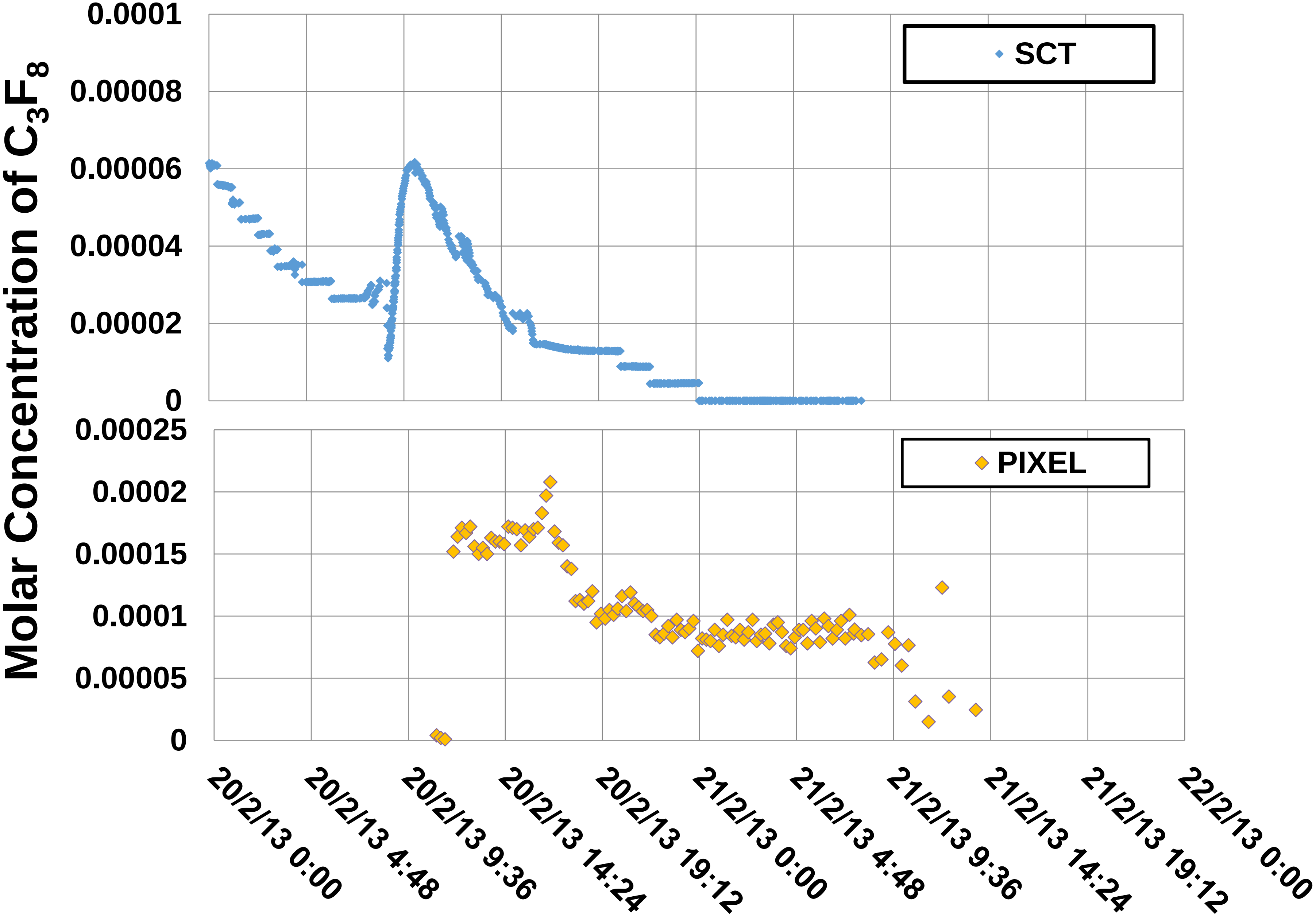
Correlation of leaks with particular cooling circuits in the pixel detector during detector cooling startup (January 2012)



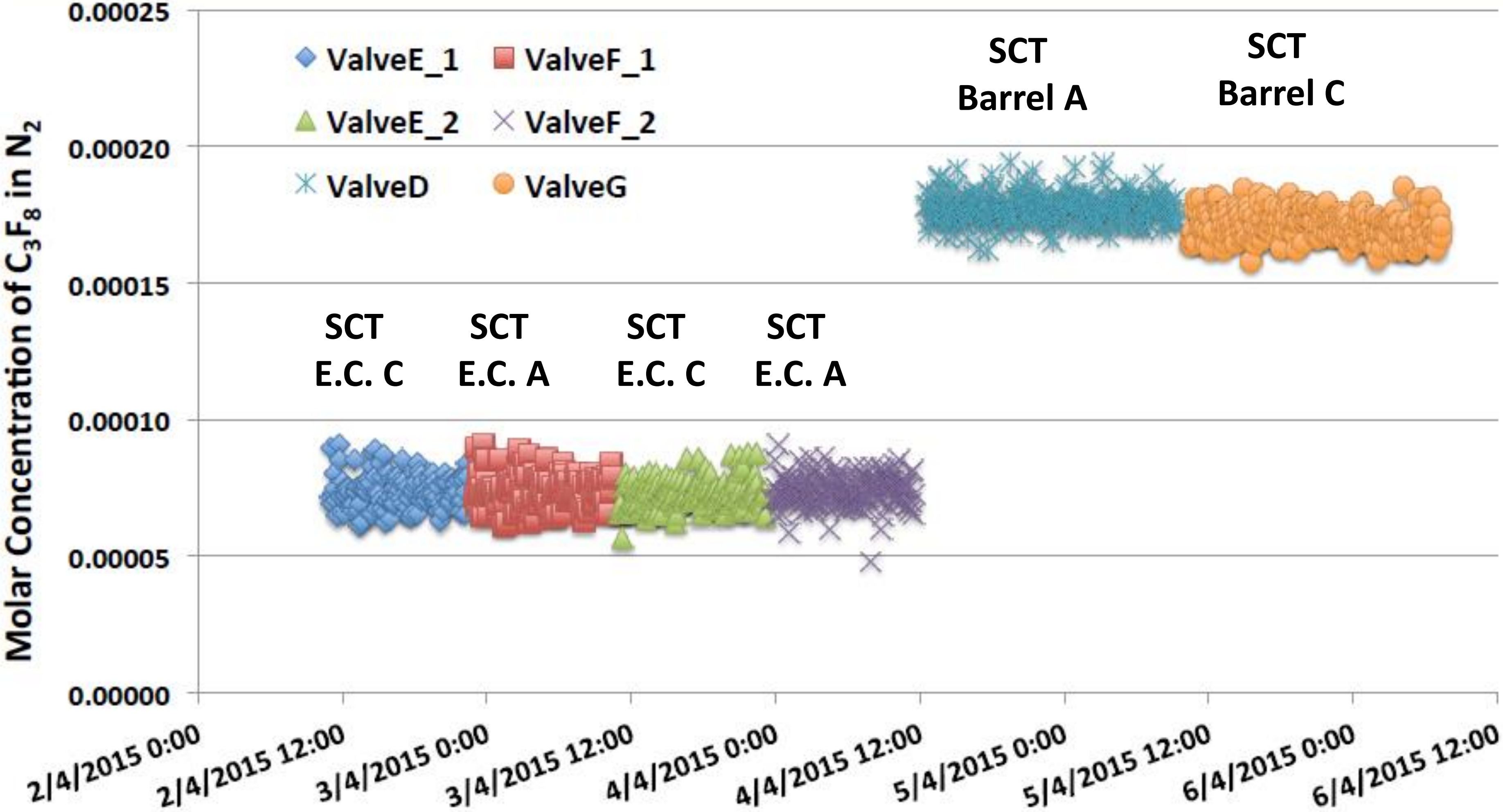
3- week study of C_3F_8 leak rate into A & C sides of Barrel SCT envelope



C_3F_8 leak rate into pixel & SCT barrel envelopes during shutdown (20/2/2013)



SCT Data



*Uses interpolated curve parameters corresponding to each data point temperature individually, staying with 0.98 bar

*Valves E & F are SCT endcaps while valves D & G are SCT barrel regions

C_3F_8 / N_2 SoS *vs*. molar conc. look up tables

- **Powerful software packages available,**
  including NIST-REFPROP
  (Modified Benedict-Webb-Rubin equation of state),
  but doesn't have mixing rules for saturated ($C_nF_{(2n+2)}$) fluorocarbons with N_2, so can't calculate thermophyiscal properties (inc. C_p, C_v, speed of sound etc.) for these mixtures;

- **PC-SAFT can calculate thermophyiscal properties Cp, Cv, speed of sound, but is slow;**

- **More pragmatic approach: calculate C_p, C_v independently for the two components over a range of T, P using NIST-REFPROP, then combine to get SoS via:**

$$c = \sqrt{\frac{\frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i} RT}{\sum_i w_i M_i}}$$

CAN BE DONE ON-LINE IN WINCC!!

Source data for C_3F_8/N_2 Analysis C_p, C_v in the two components

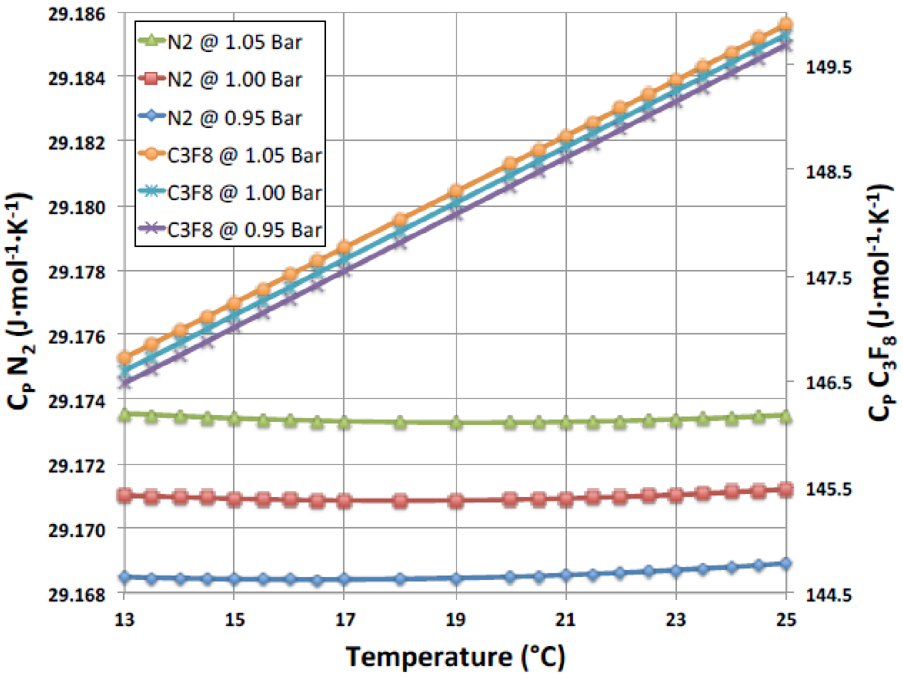


Fig. 6. Molar specific heat at constant pressure vs. temperature for N_2 (left ertical axis) and C_3F_8 (right vertical axis) at a range of pressures.

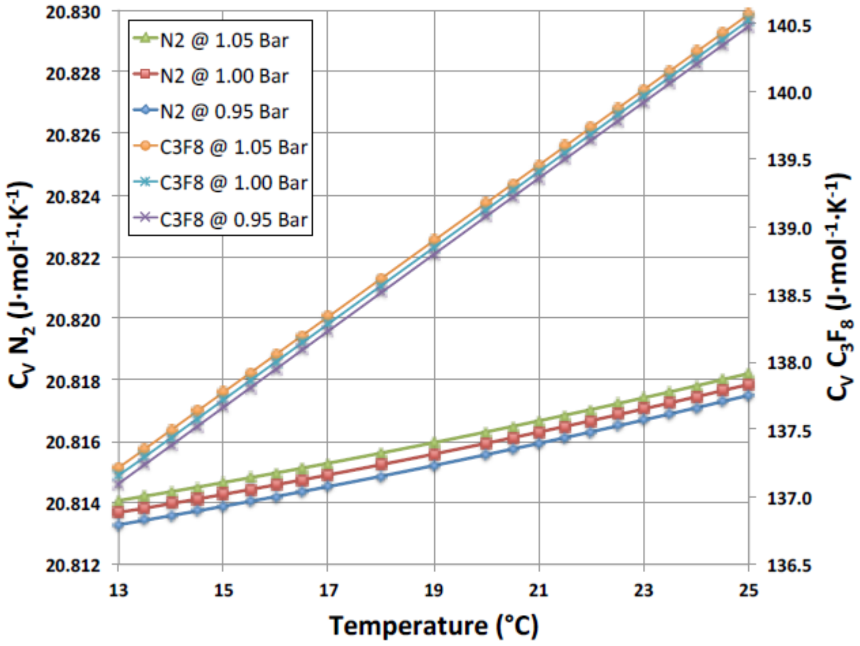
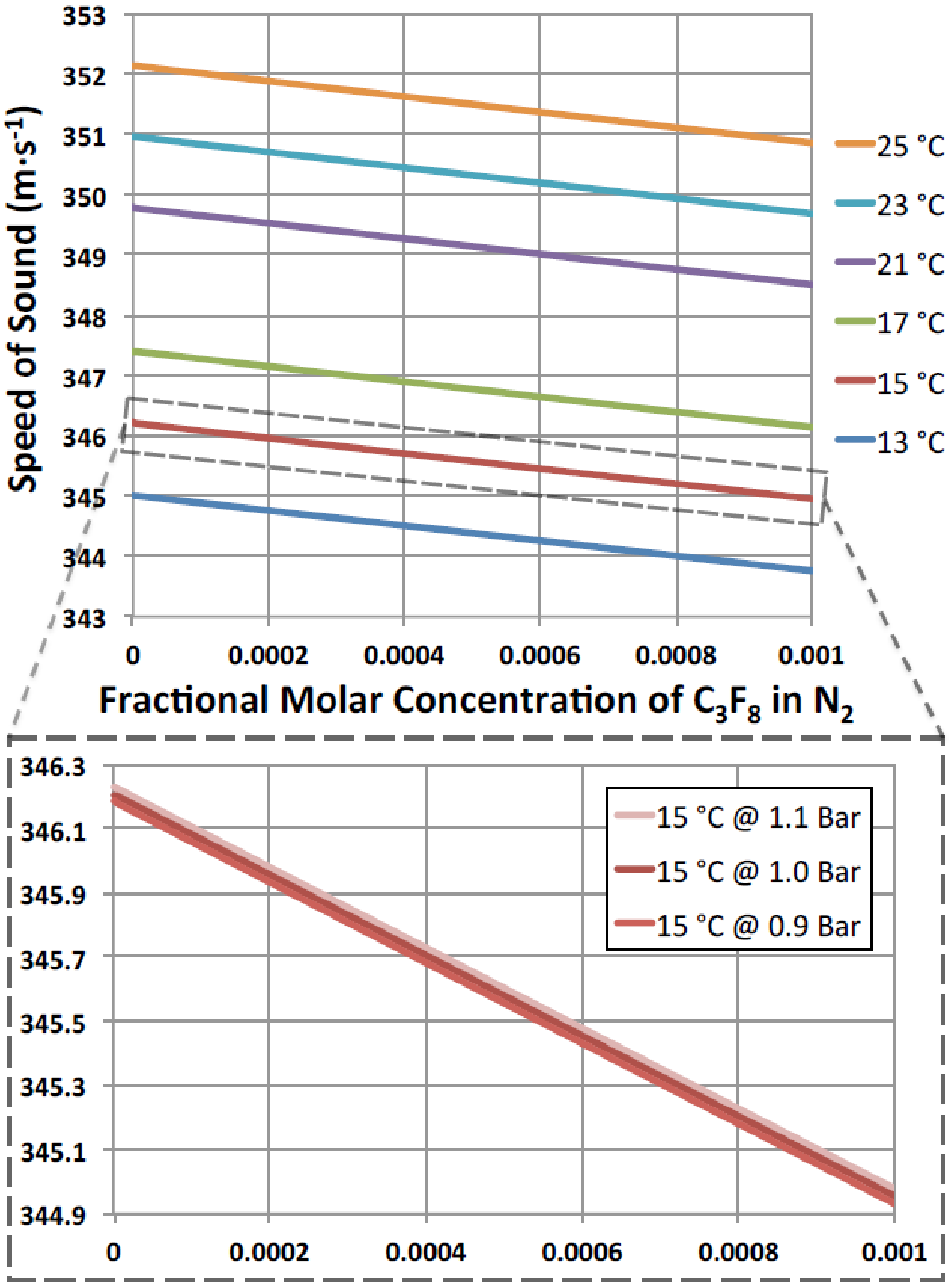


Fig. 7. Molar specific heat at constant volume vs. temperature for N_2 (left ertical axis) and C_3F_8 (right vertical axis) at a range of pressures.

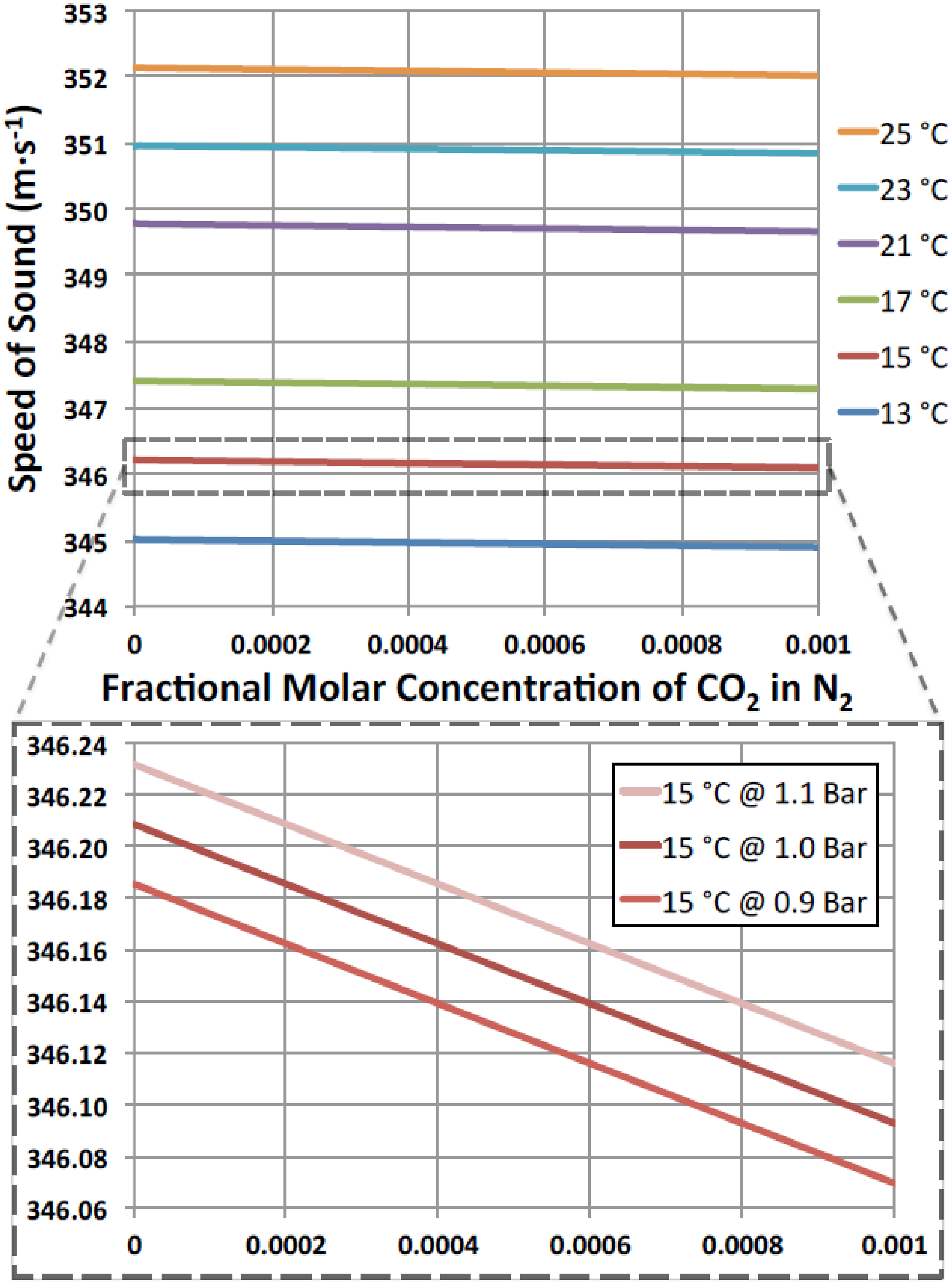
Sound velocity calculaton for C_3F_8/N_2 mixtures from C_p, C_v in the two components:

Pressure dependence is negligible as aspirating sonars operate near atmospheric pressure



Sound velocity calculaton for CO_2/N_2 mixtures from C_p, C_v in the two components:

Pressure dependence is negligible as aspirating sonars operate near atmospheric pressure



1

Precision of C_3F_8/N_2 & CO_2/N_2 look up tables

Precision of mixture determination δf, depends on precision measurement of sound velocity, δc, & molecular weight difference between the two components.

Contributions to the present overall δc = ± 0.025 m.s^{-1} :

- ± 0.1 °C Temperature precision in tube (***equiv. ± 0.022 m.s^{-1}***);
- ± 1 mbar Pressure precision in the tube (***equiv. ± 0.003 m.s^{-1}***);
- ± 0.1 mm transducer inter-foil measurement uncertainty (***equiv. ±0.011 m.s^{-1}***);
- ± 25 ns electronic transit time uncertainty (***equiv. ± 0.0005 m.s^{-1}***).

Mixture precision, δf, at any conc. of the 2 components given by:

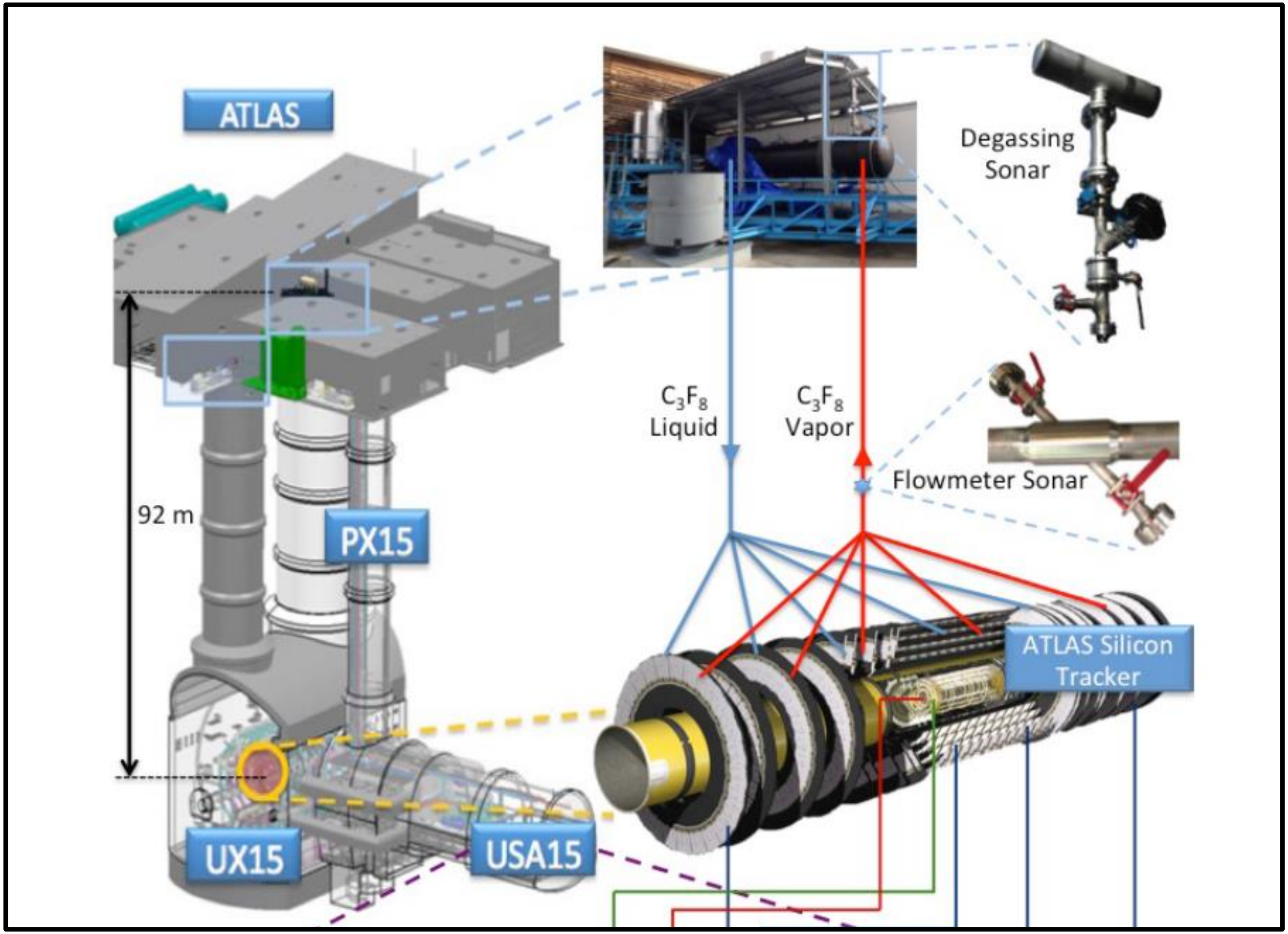
$$\delta f = \delta c / m$$

where m (m.s^{-1}.[%C_3F_8]$^{-1}$) is local slope of SoS/conc. curve.

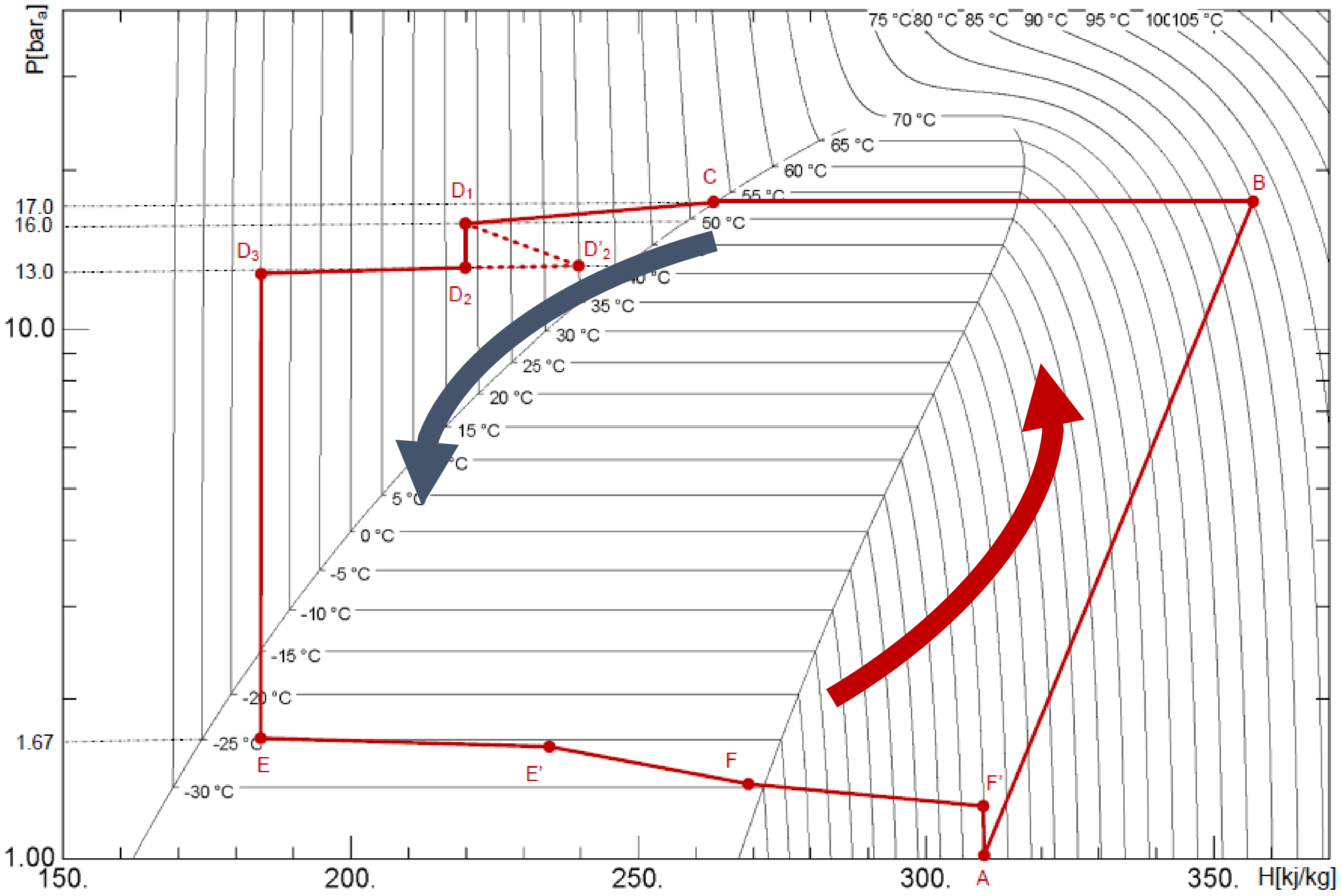
C_3F_8 (0-0.1%) /N_2: m = -12.55 m.s^{-1}.[%C_3F_8]$^{-1}$ δf = ± 2. 10^{-5}

CO_2 (0-0.1%) /N_2: m = -1.12m.s^{-1}.[%C_3F_8]$^{-1}$ δf = ± 0.02%

The thermosiphon and other sonars



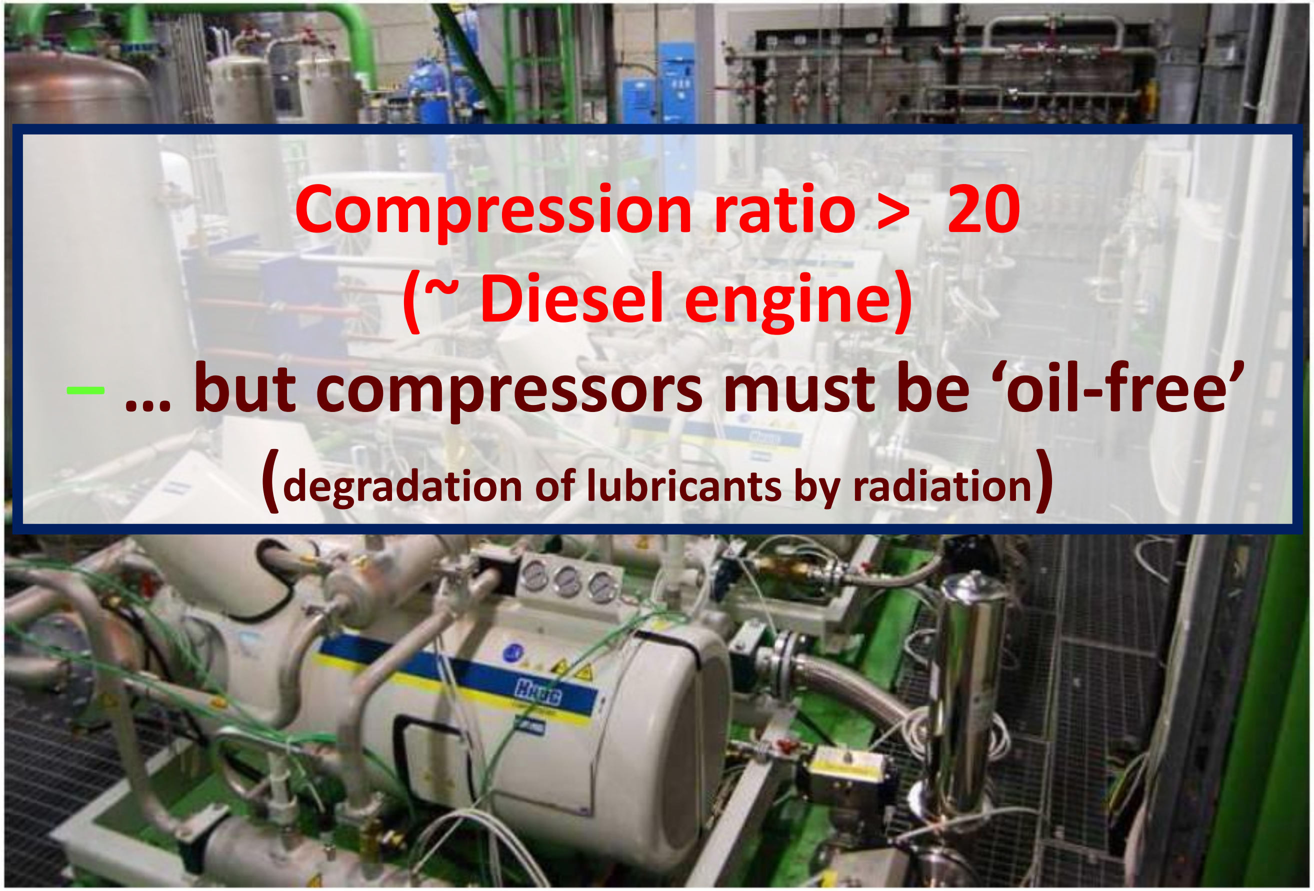
Reminder: "As designed" C_3F_8 compressor circulation system.



Consequence of C_3F_8 liquid tubing without insulation :

very high compressor output pressure

➔ frequent breakdowns + heavy, expensive maintenence



Compression ratio > 20

(~ Diesel engine)

– … but compressors must be ‘oil-free’

(degradation of lubricants by radiation)

Solution: a system with no moving parts in the primary cooling loop (apart from the circulating fluid…)

Boundary condition:

Use existing (inaccessible, unchangeable, invariant….)
on-detector and through-magnet liquid delivery and vapour exhaust tubing

Implications:

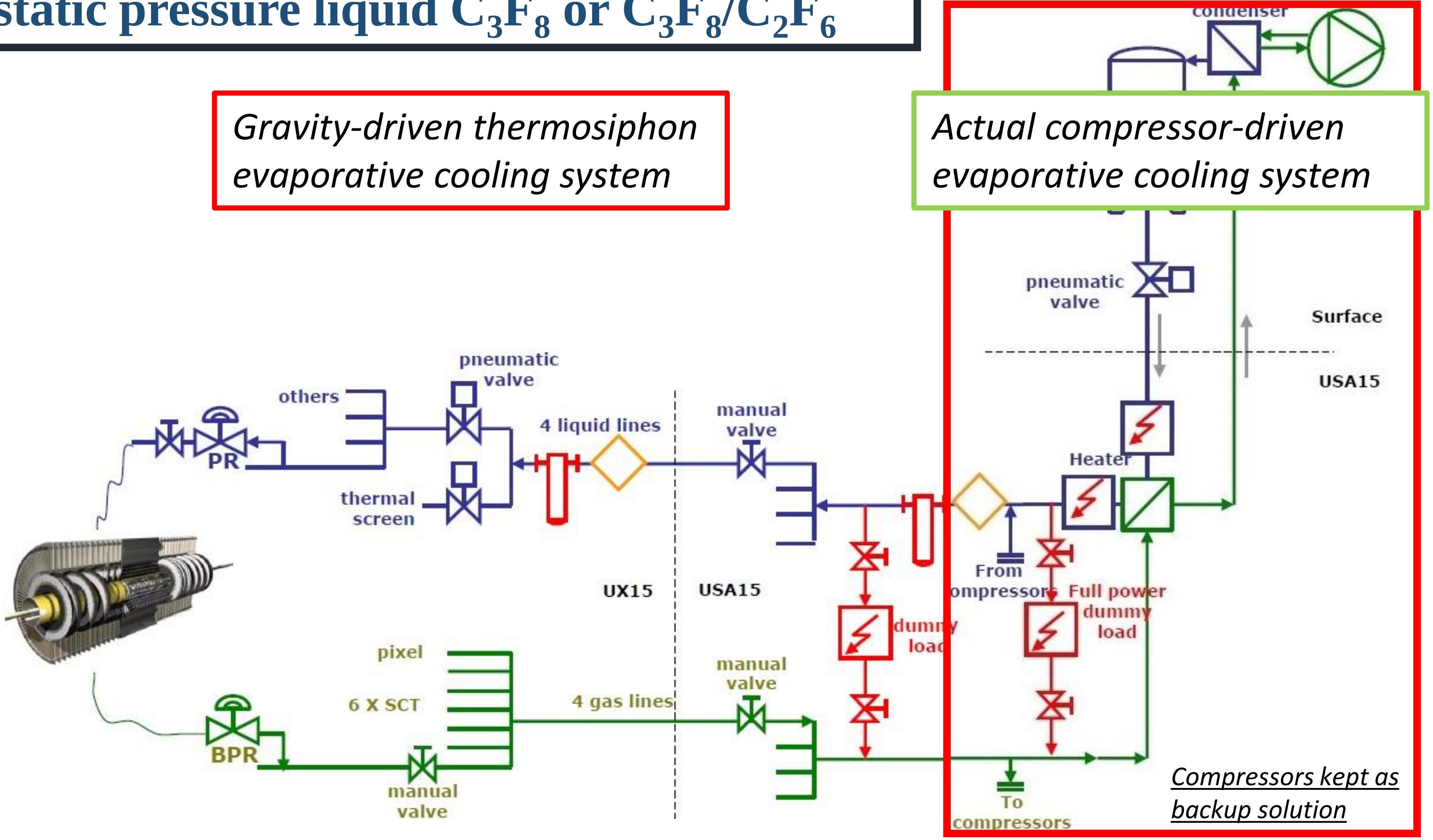
Get the liquid supply pressure required to drive through the capillaries another way (other than compressors) ➔ Gravity over 92 m pit depth…("dive drive")

But… have to send the vapour back upstairs to a condenser, which has to be Lowest pressure part of the system (potential air collector)

❖92m pit depth at ATLAS ➔ > 13 bar (ρgh) hydrostatic pressure liquid C_3F_8 or C_3F_8/C_2F_6

Gravity-driven thermosiphon evaporative cooling system

Actual compressor-driven evaporative cooling system



Compressors kept as backup solution

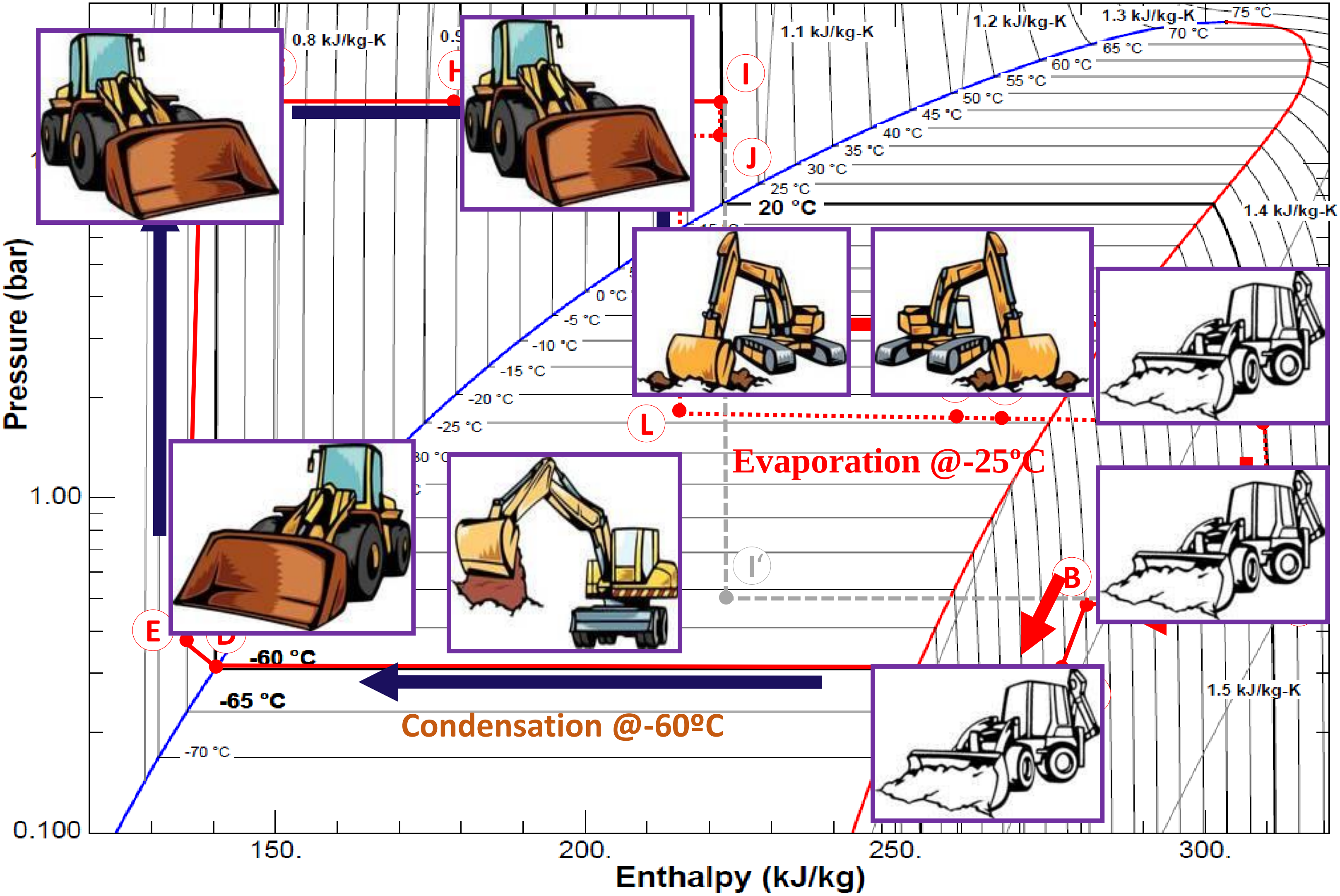
INTERNAL PART

EXTERNAL PART

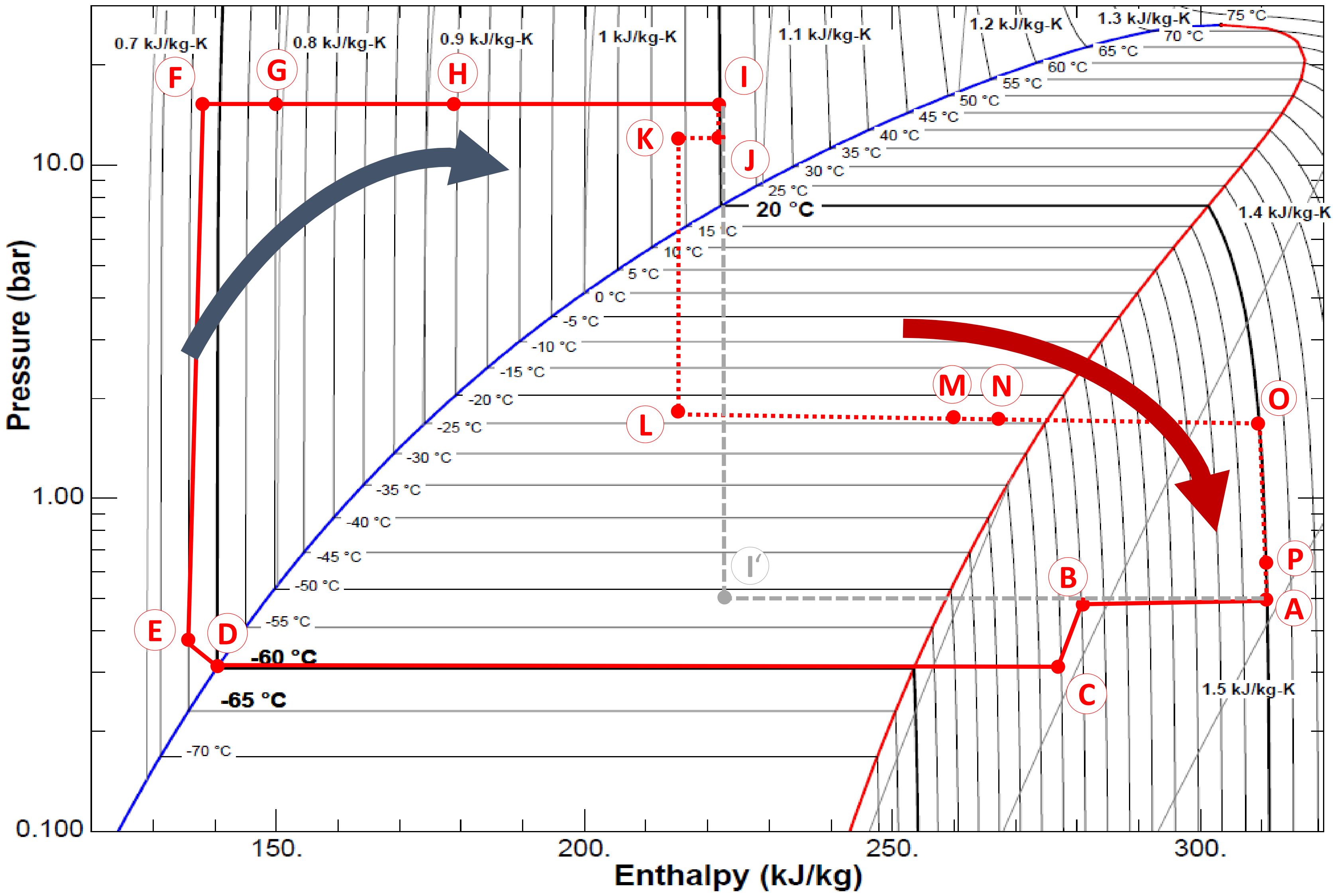
❖ But ρgh from 92m of C_3F_8 ou C_3F_8/C_2F_6 vapour is only ~70mbar …

Thermodynamic cycle of the thermosiphon with C_3F_8

Animation: JCB Digger = fluid; heat in vapour form = earth...



Thermosiphon: Reversal on Pressure-Enthaply Diagram!



Thermosiphon: Surface installations at ATLAS Point 1

Condenser on platform :
H =15m + (77 m pit)

Cold Plant -70°C

Thermosiphon: main components

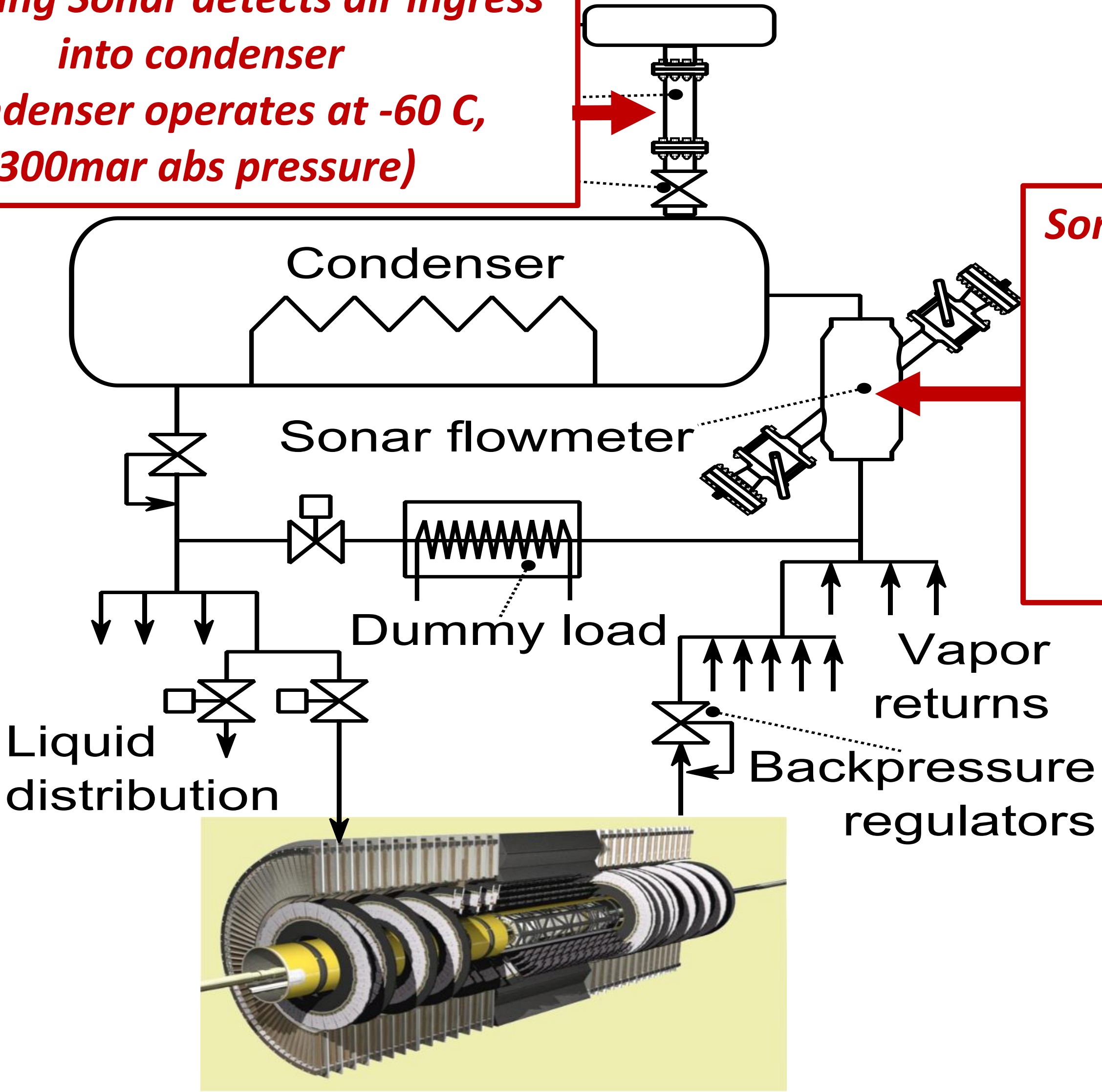
TS Condenser: 15m above ground level

Brine and Chiller circuit: Ground level

Connection to existing system: 90m underground

Water circuit: 90m underground

The Thermosiphon sonars

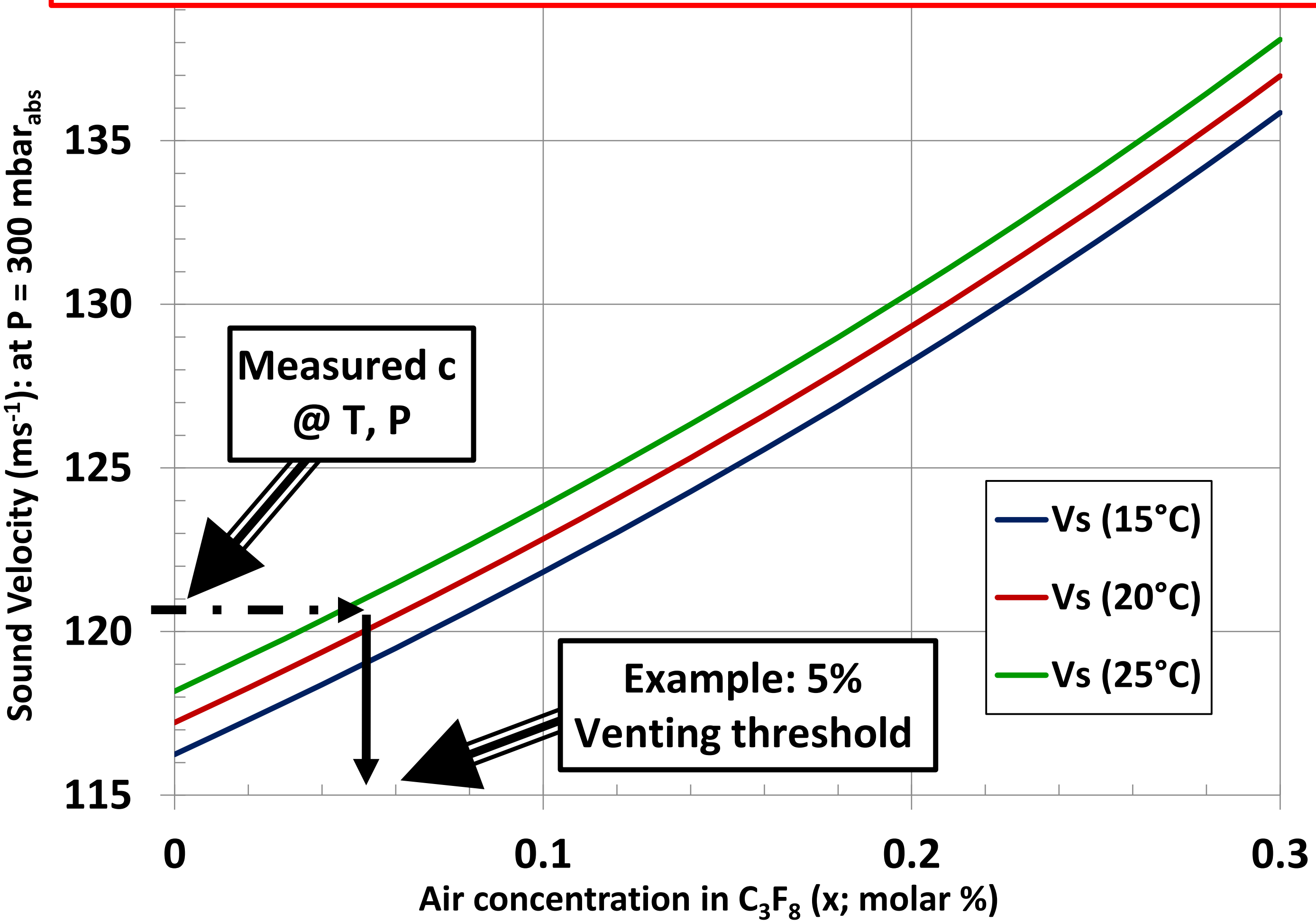


Degassing Sonar detects air ingress into condenser
(Condenser operates at -60 C, 300mar abs pressure)

Sonar flowmeter measures return vapour flow
(1.2 kg/s: 0.4 m^3/s)
to condenser
Can also measure
C_2F_6/C_3F_8
blends to ±0.3%

Thermosiphon Condenser Degassing sonar

Degassing sonar: doesn't need to make high precision C_3F_8/air measurements (~ 1% probably OK… though can do much better)

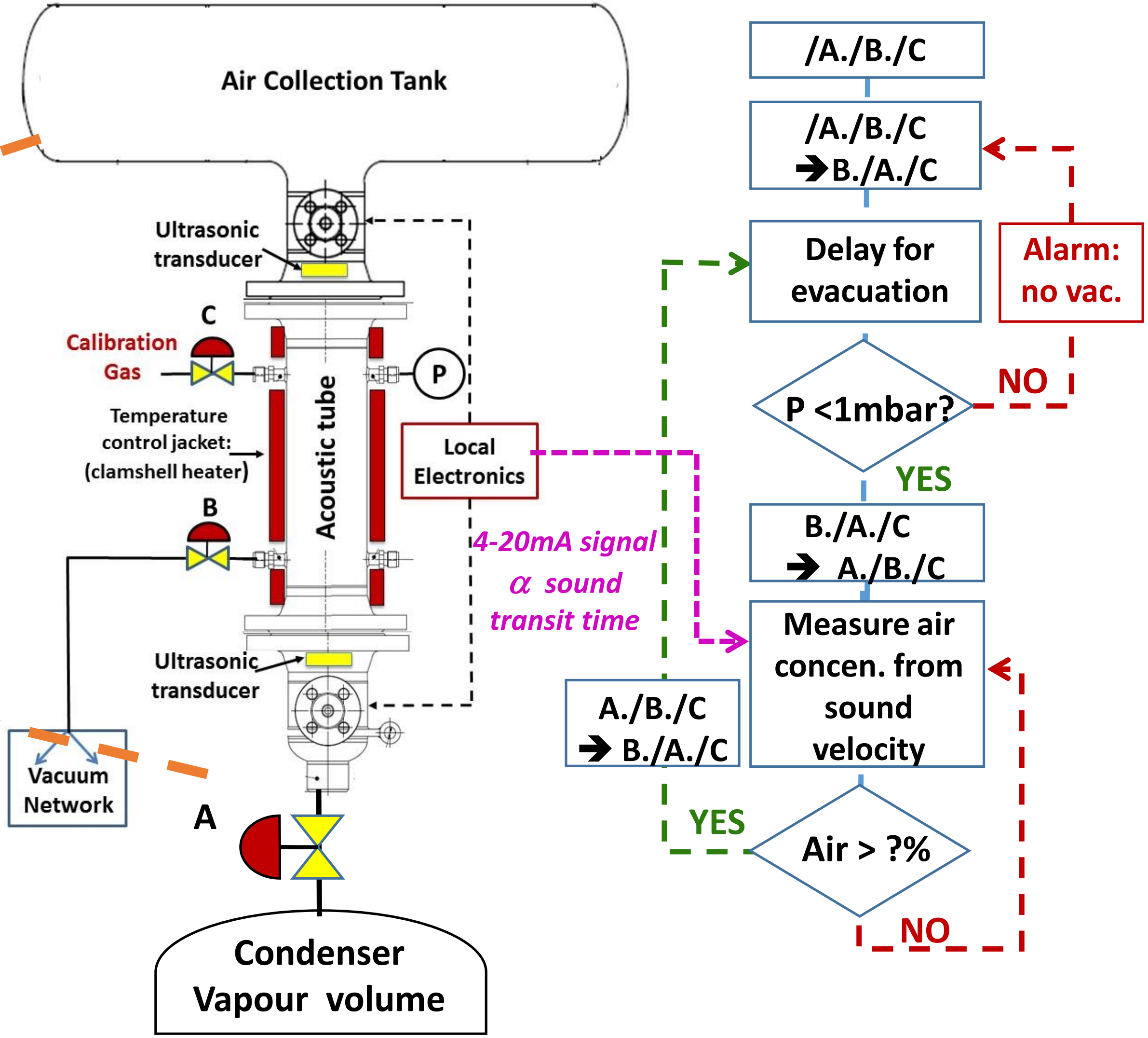


Measured c @ T, P

Example: 5% Venting threshold

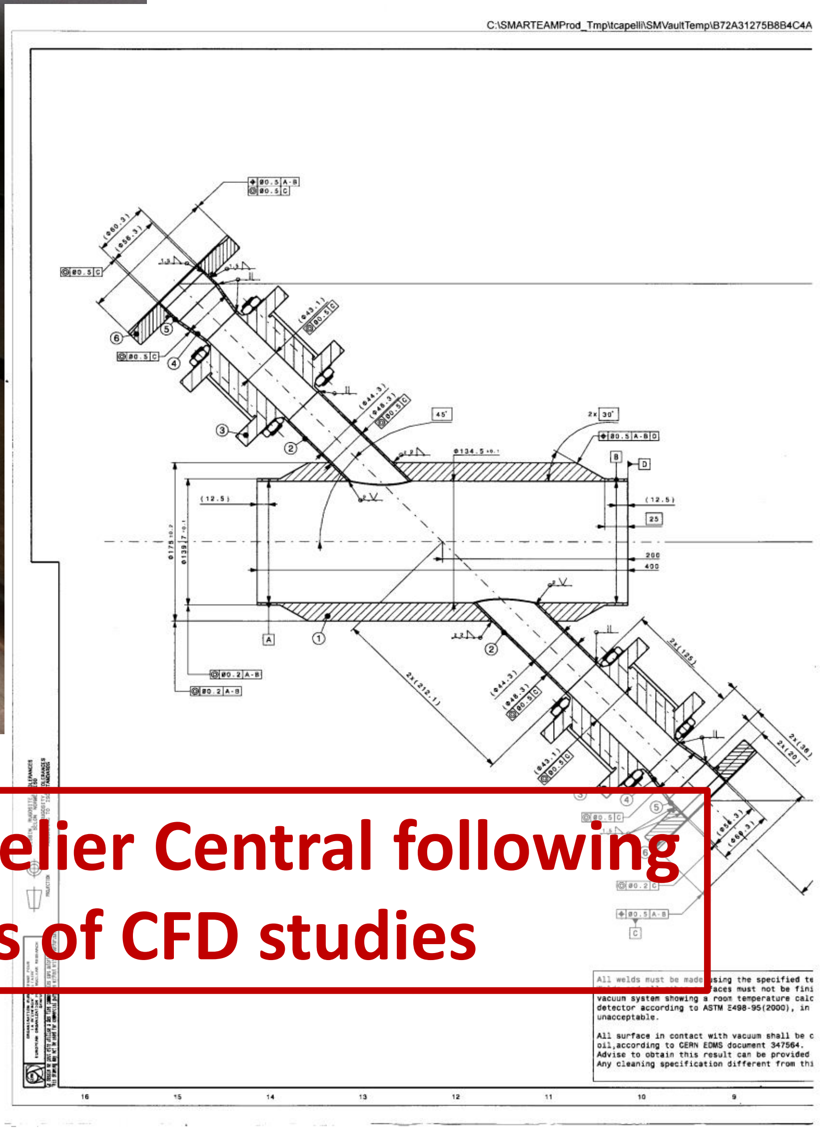
Degassing sonar: collects air in upper reservoir: when sound velocity indicates air conc. > few %, isolated from condenser & vents air to vacuum

(forms part of thermosiphon hard-wired control system: CERN UNICOS)



Thermosiphon High flow vapour flowmeter

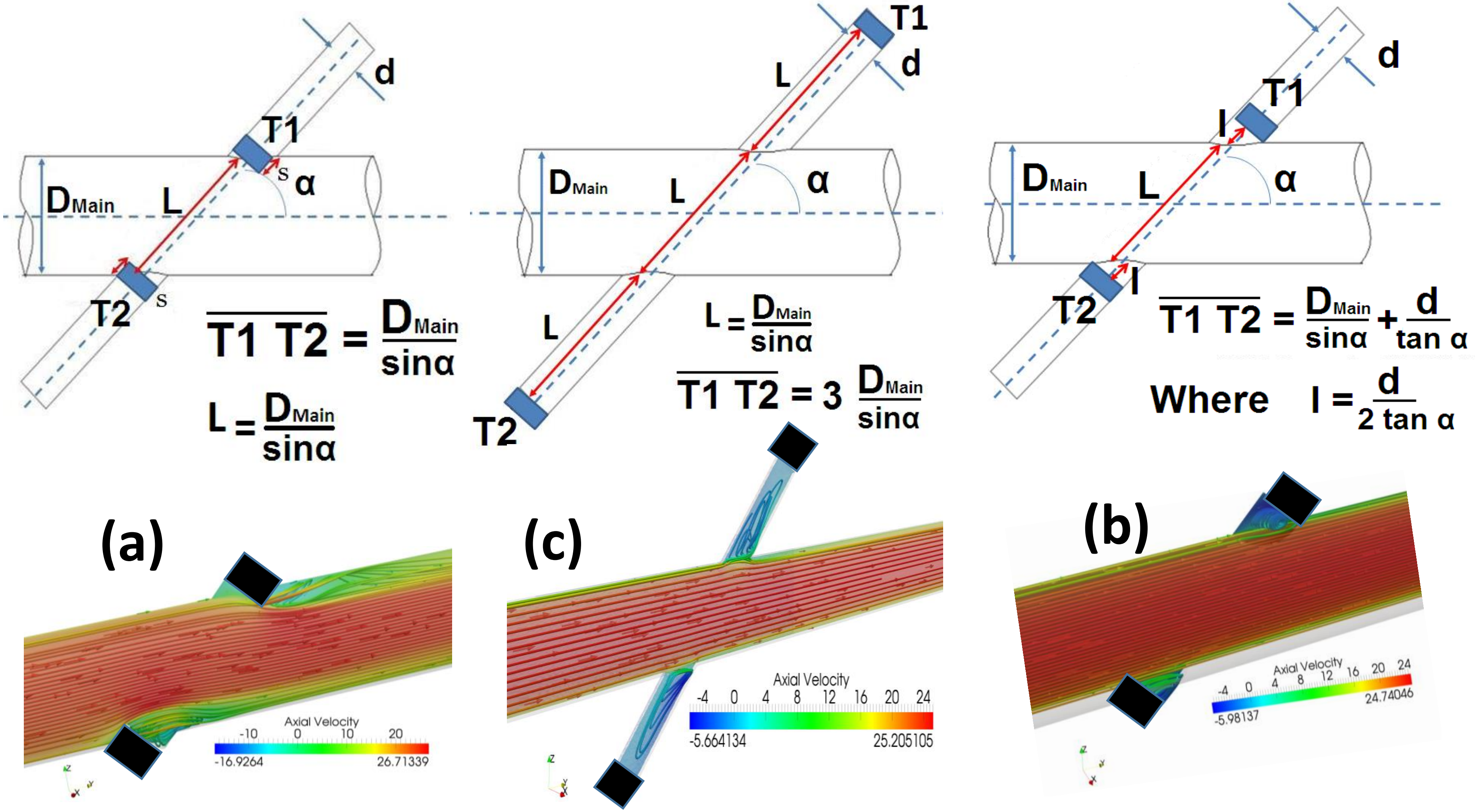
Thermosiphon High flow vapour flowmeter



Fabricated in CERN Atelier Central following Extensive series of CFD studies

CFD simulations made with OpenFoam® (Gennaro Bozza)

C_3F_8 flows to 1.2 kgs^{-1}: (0.4 m^3s^{-1}, 22 m^{-1} : Mach 0.2); 45^o crossing angle adopted



$$\overline{T1\ T2} = \frac{D_{Main}}{\sin\alpha}$$

$$L = \frac{D_{Main}}{\sin\alpha}$$

$$L = \frac{D_{Main}}{\sin\alpha}$$

$$\overline{T1\ T2} = 3\,\frac{D_{Main}}{\sin\alpha}$$

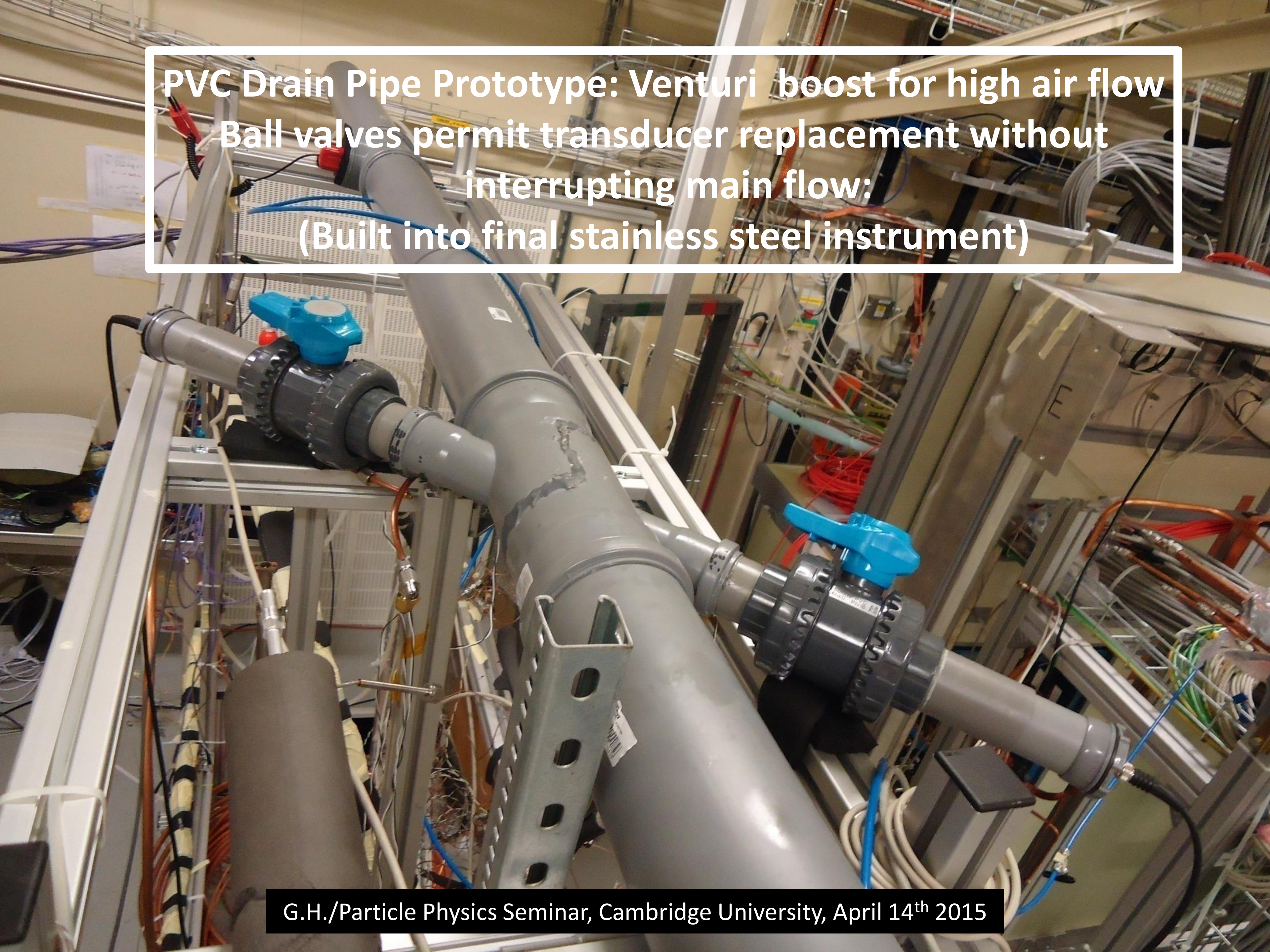
$$\overline{T1\ T2} = \frac{D_{Main}}{\sin\alpha} + \frac{d}{\tan\alpha}$$

Where $l = \frac{d}{2\tan\alpha}$

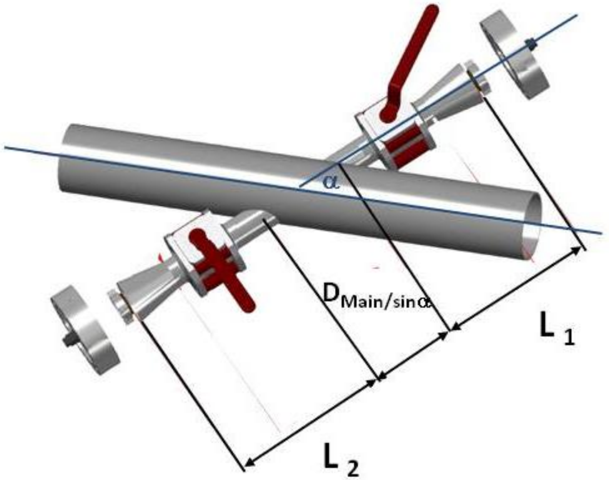
Turbulence study in impinging & non-impinging transducer placements

Create minimal turbulence in main flow & only closed turbines in side tubes

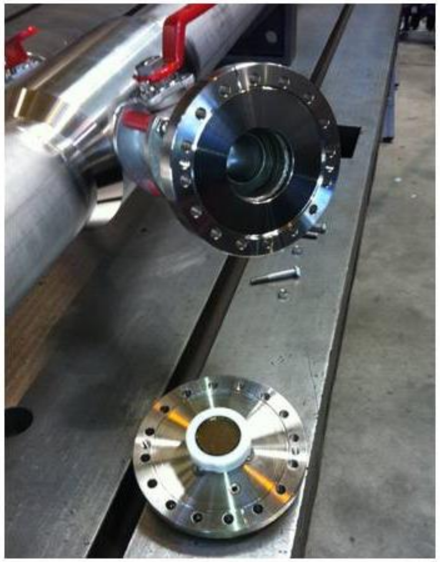
PVC Drain Pipe Prototype: Venturi boost for high air flow
Ball valves permit transducer replacement without interrupting main flow:
(Built into final stainless steel instrument)

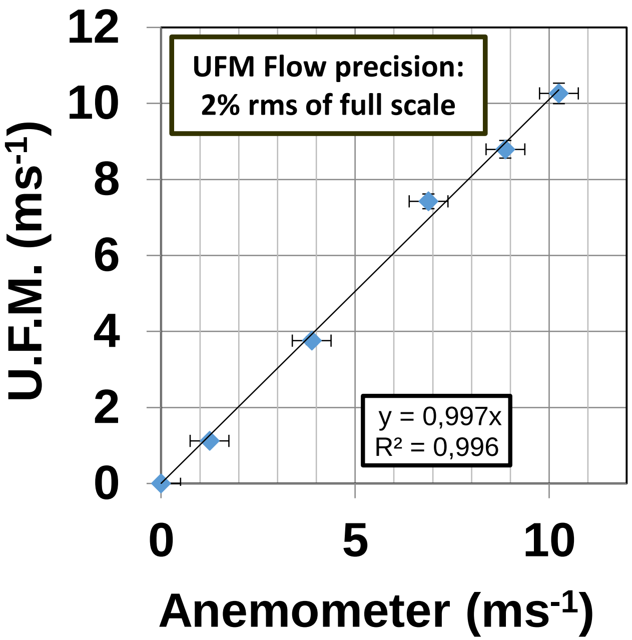


Developed completely new algebra (not used in any industrial flowmeter) relating flow to measurable T_{up}, T_{down}, & lengths of static gas in the acoustic path



$L' = L_1 + L_2$ $\quad$ $L = L' + D_{Main} / \sin\alpha$





$$t_{\mathrm{down}} = \frac{L'}{c} + \frac{D_{\mathrm{Main}}}{\sin\alpha\,(c + v\cos\alpha)}, \qquad t_{\mathrm{up}} = \frac{L'}{c} + \frac{D_{\mathrm{Main}}}{\sin\alpha\,(c - v\cos\alpha)} \tag{3.9}$$

The sound velocity, c, is the physical root derived from the relations of eq. (3.9) in terms of measurables L, D_{Main}, α, t_{up} and t_{down}:

$$c = \frac{(t_{\mathrm{up}} + t_{\mathrm{down}})\left(2L' + \frac{D_{\mathrm{Main}}}{\sin\alpha}\right) \pm \sqrt{(t_{\mathrm{up}} + t_{\mathrm{down}})^2\left(2L' + \frac{D_{\mathrm{Main}}}{\sin\alpha}\right)^2 - \left(16L' t_{\mathrm{up}} t_{\mathrm{down}}\left(L' + \frac{D_{\mathrm{Main}}}{\sin\alpha}\right)\right)}}{4 t_{\mathrm{up}} t_{\mathrm{down}}}$$

allowing the gas flow velocity, v, to be calculated as

$$v = \frac{c\left(c t_{\mathrm{up}} - \frac{D_{\mathrm{Main}}}{\sin\alpha} - L'\right)}{\cos\alpha\,(c t_{\mathrm{up}} - L')} \qquad v = \frac{c\left(\frac{D_{\mathrm{Main}}}{\sin\alpha} + L' - c t_{\mathrm{down}}\right)}{\cos\alpha\,(c t_{\mathrm{down}} - L')}$$

So why is this new (arcane?) algebra important?

(Sound velocity applies over the whole acoustic path, but transit time differences in opposite directions only apply over the part of the path with flowing gas.)

Because it is NOT used in industrial flowmeters and (worse) not used in medical anesthesia flowmeters like this one (Gill Spirocell):

When the anesthesia mix changes, errors due to uncorrected sound velocity in the static zones of the acoustic path correspondingly increase:

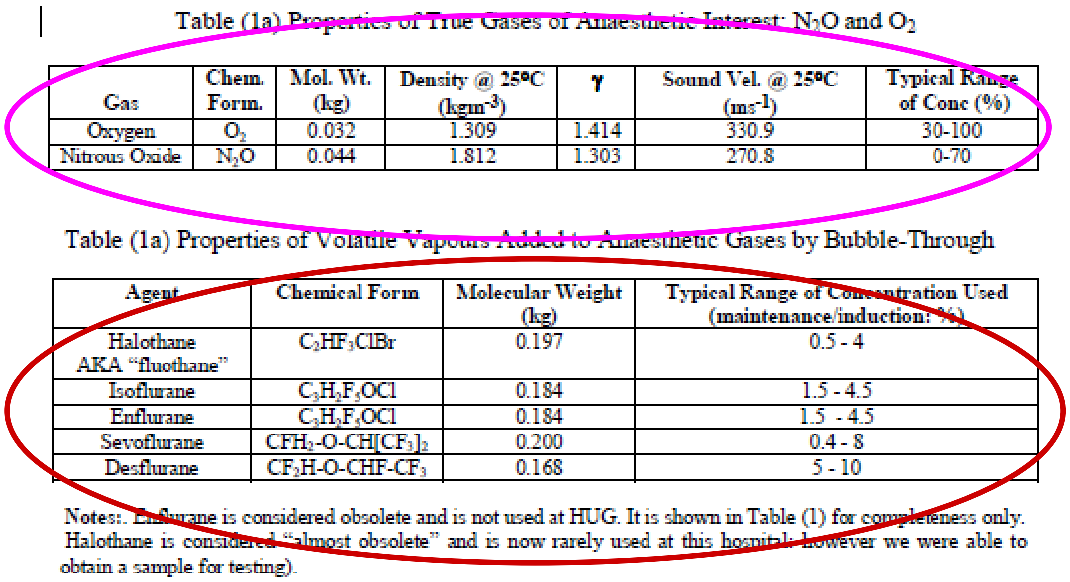


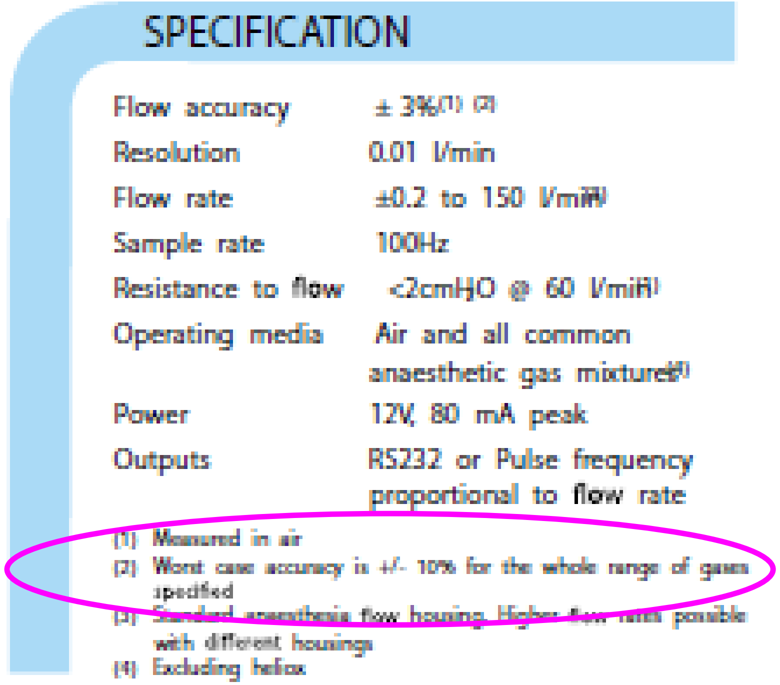
Table (1a) Properties of True Gases of Anaesthetic Interest: N_2O and O_2

Gas	Chem. Form.	Mol. Wt. (kg)	Density @ 25°C (kgm^{-3})	γ	Sound Vel. @ 25°C (ms^{-1})	Typical Range of Conc (%)
Oxygen	O_2	0.032	1.309	1.414	330.9	30-100
Nitrous Oxide	N_2O	0.044	1.812	1.303	270.8	0-70

Table (1a) Properties of Volatile Vapours Added to Anaesthetic Gases by Bubble-Through

Agent	Chemical Form	Molecular Weight (kg)	Typical Range of Concentration Used (maintenance/induction: %)
Halothane AKA "fluothane"	C_2HF_3ClBr	0.197	0.5 - 4
Isoflurane	$C_3H_2F_5OCl$	0.184	1.5 - 4.5
Enflurane	$C_3H_2F_5OCl$	0.184	1.5 - 4.5
Sevoflurane	CFH_2-O-$CH[CF_3]_2$	0.200	0.4 - 8
Desflurane	CF_2H-O-CHF-CF_3	0.168	5 - 10

Notes:. Enflurane is considered obsolete and is not used at HUG. It is shown in Table (1) for completeness only. Halothane is considered "almost obsolete" and is now rarely used at this hospital; however we were able to obtain a sample for testing).

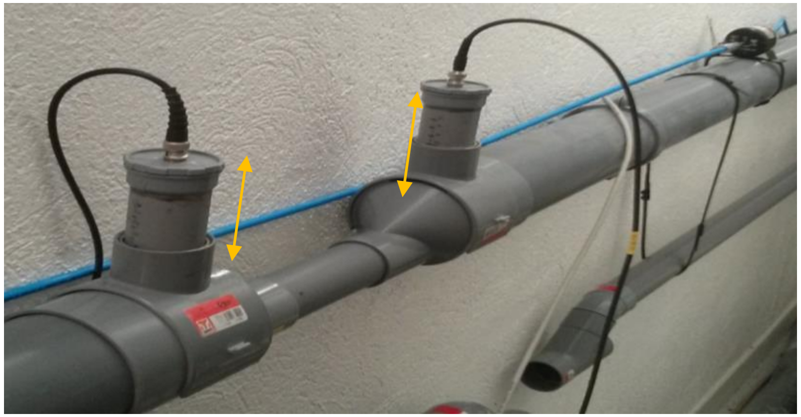


SPECIFICATION

Flow accuracy	± 3%[1] [2]
Resolution	0.01 l/min
Flow rate	±0.2 to 150 l/min[3]
Sample rate	100Hz
Resistance to flow	<2cmH_2O @ 60 l/min[3]
Operating media	Air and all common anaesthetic gas mixtures[4]
Power	12V, 80 mA peak
Outputs	RS232 or Pulse frequency proportional to flow rate

(1) Measured in air
(2) Worst case accuracy is +/- 10% for the whole range of gases specified
(3) Standard anaesthesia flow housing. Higher flow rates possible with different housings
(4) Excluding heliox

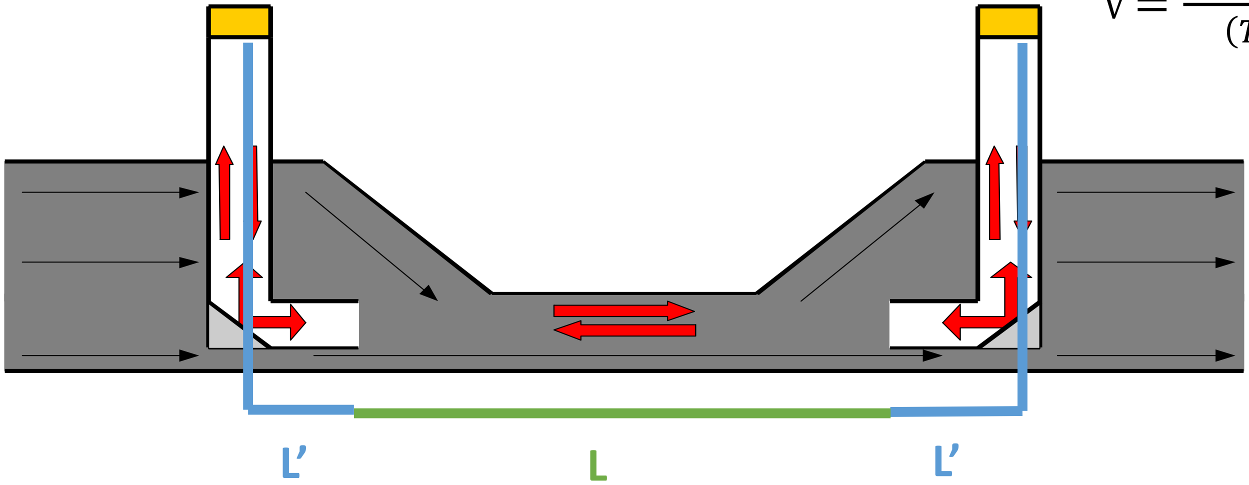
Related algebra for non-angled (π - or reflex FM geometry)

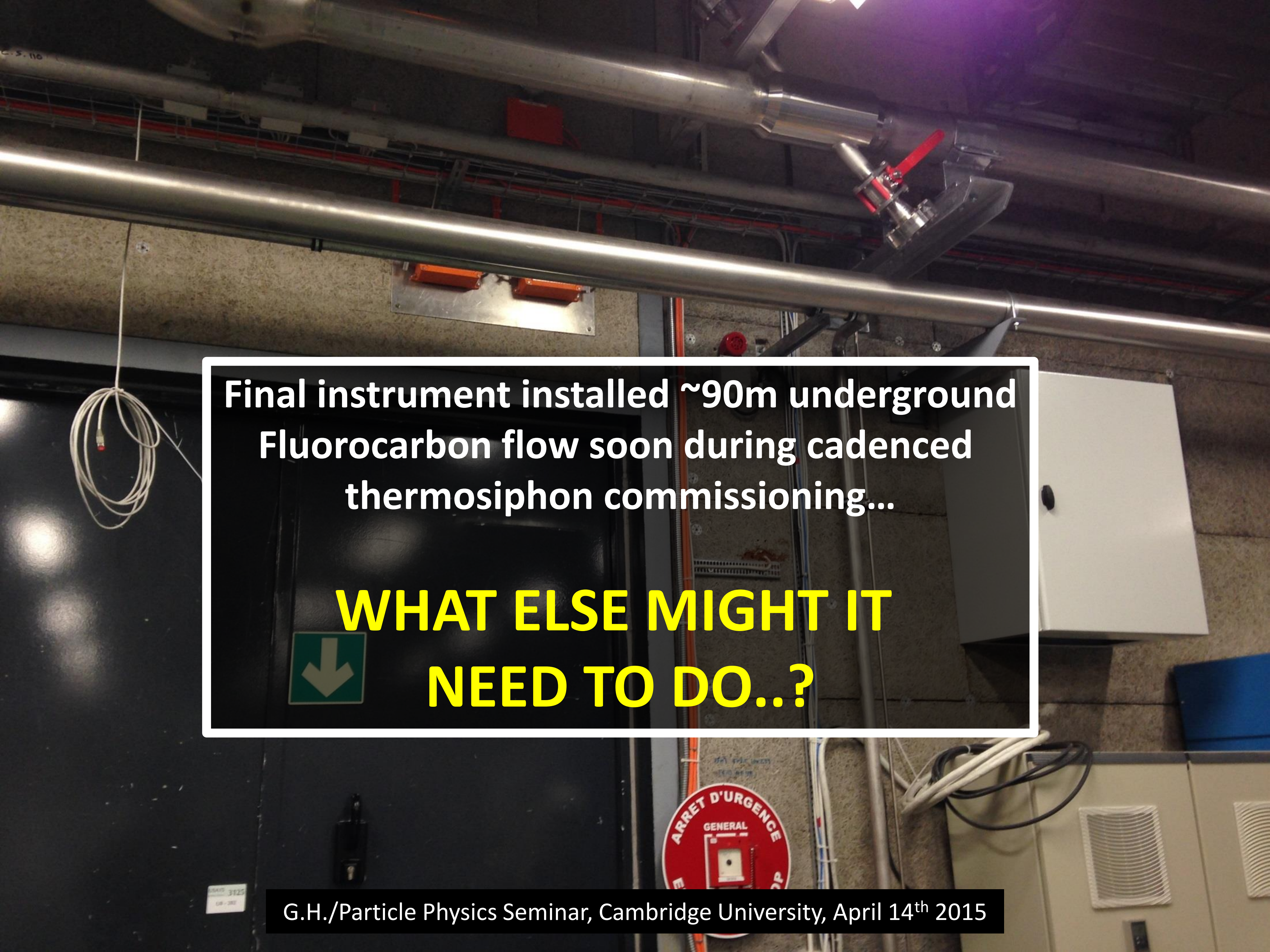


$$c = \frac{(Tu+Td)(2L'+L) \pm \sqrt{(Tu+Td)^2 - 16 \times Td \times Tu \times L'(L+L')}}{4\,Td \times Tu}$$

$$V = \frac{c * (Tu \times c \quad - L \quad - L')}{(Tu \times c - L')}$$

$$\mathrm{V} = \frac{c*(L+L'-Td \times c)}{(Td \times c - L')}$$





Final instrument installed ~90m underground
Fluorocarbon flow soon during cadenced
thermosiphon commissioning…

WHAT ELSE MIGHT IT NEED TO DO..?

Another known problem with the present evaporative cooling system tubing

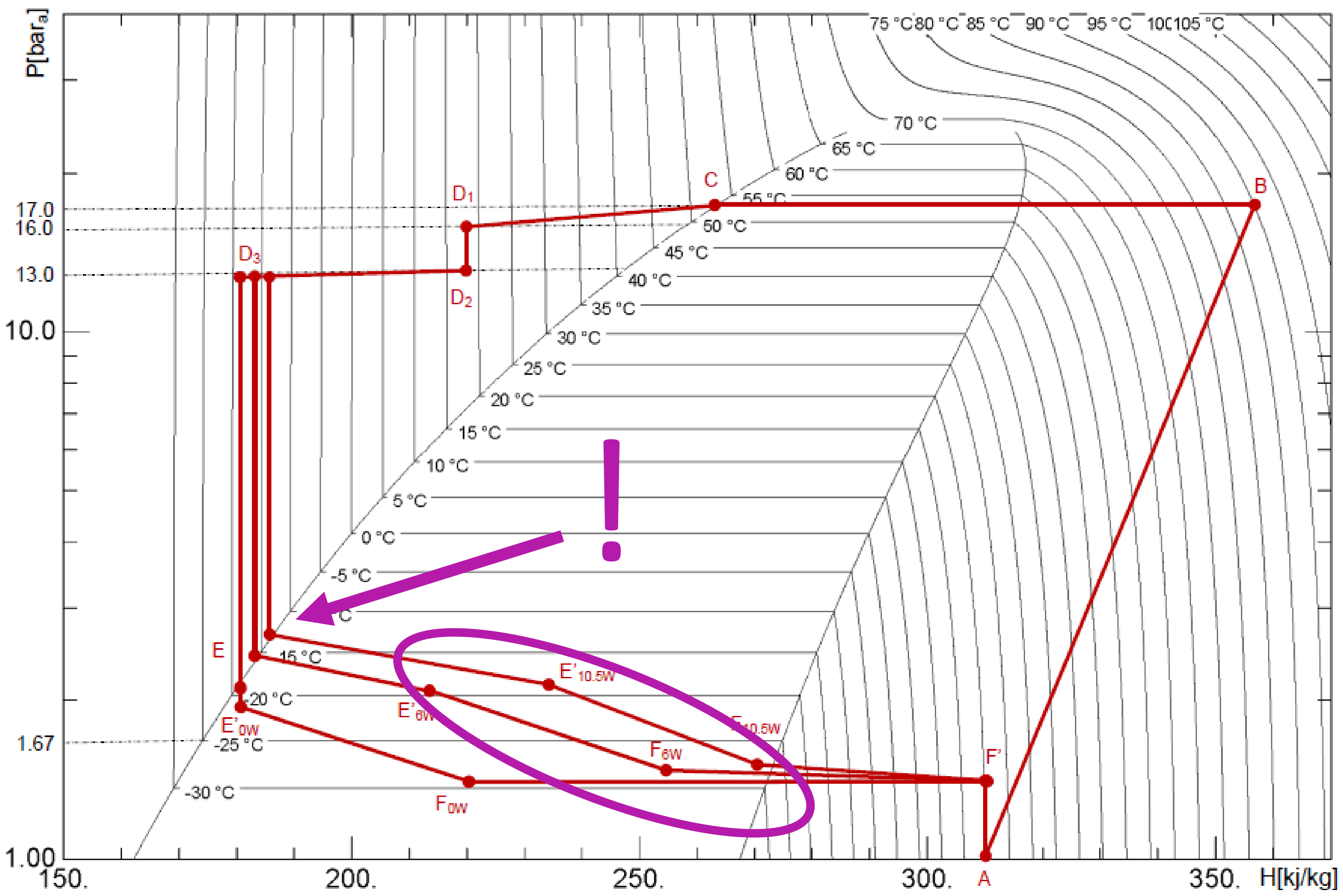
- **Excessive pressure drop in exhaust tubing of SCT barrel bi-staves (in heat exchangers following bi-staves) ➔**

- *doesn't allow sufficiently cold Si module temperatures with C_3F_8 for operation at ∫LdT of 1000 fb^{-1}(or 629 fb^{-1}) foreseen in TDR (more recent)* estimates…*

Need factor 2 against leakage current - induced thermal runaway when SCT modules may be dissipating 10.5W:

After 629 fb^{-1} this requires -15^{o} C evaporation temperature in tubes for Silicon module temperature ~ 0^{o} C

Excessive pressure drop in exhaust tubing of SCT barrrel bi-staves doesn’t allow evaporation temperatures of -15°C with pure C_3F_8 for module operation at 0°C

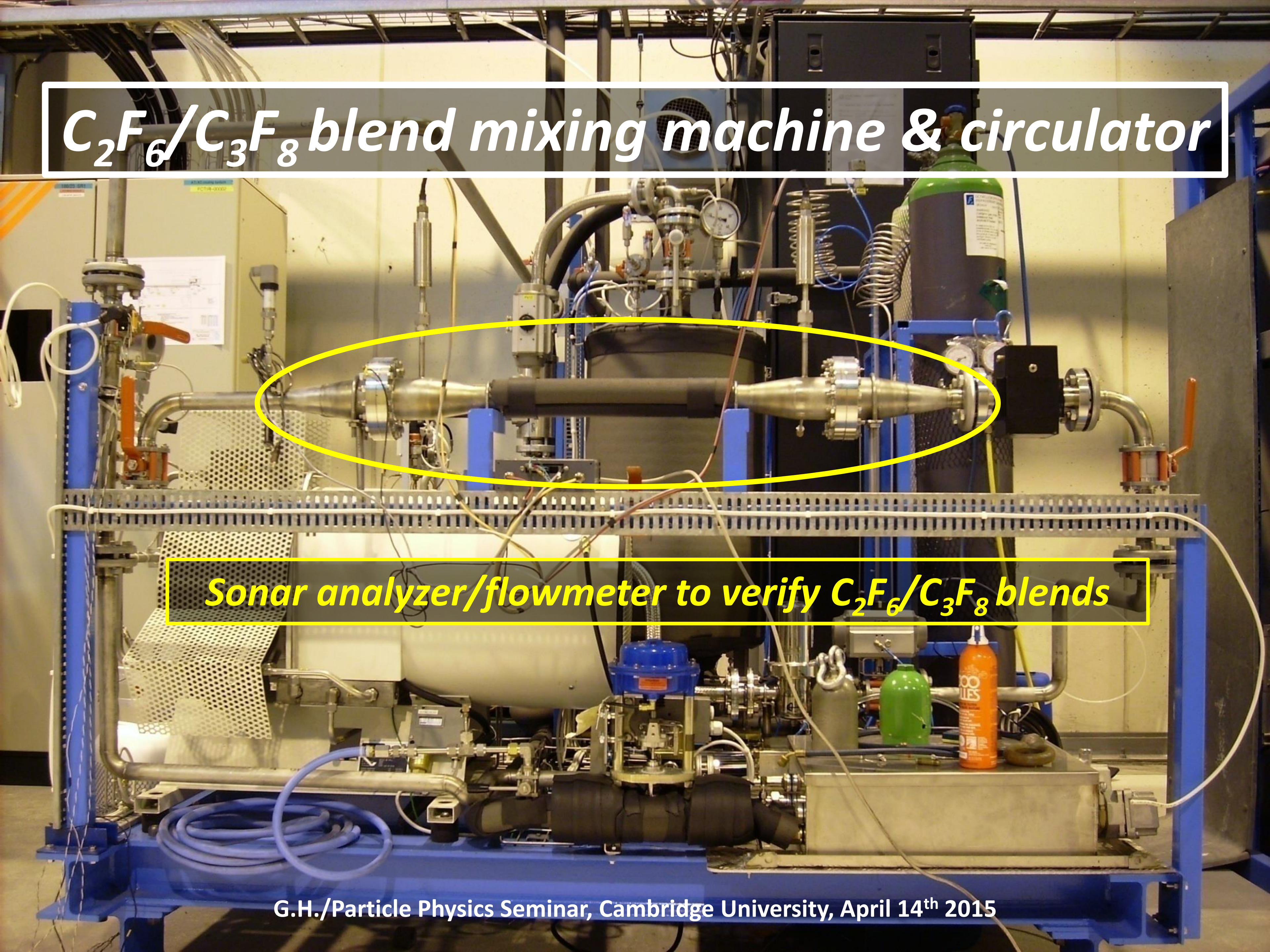


Again: How to do this without changing the unchangeable exhaust tubing..?

… Take a thermodynamic sidestep blending C_3F_8 with the more volatile C_2F_6

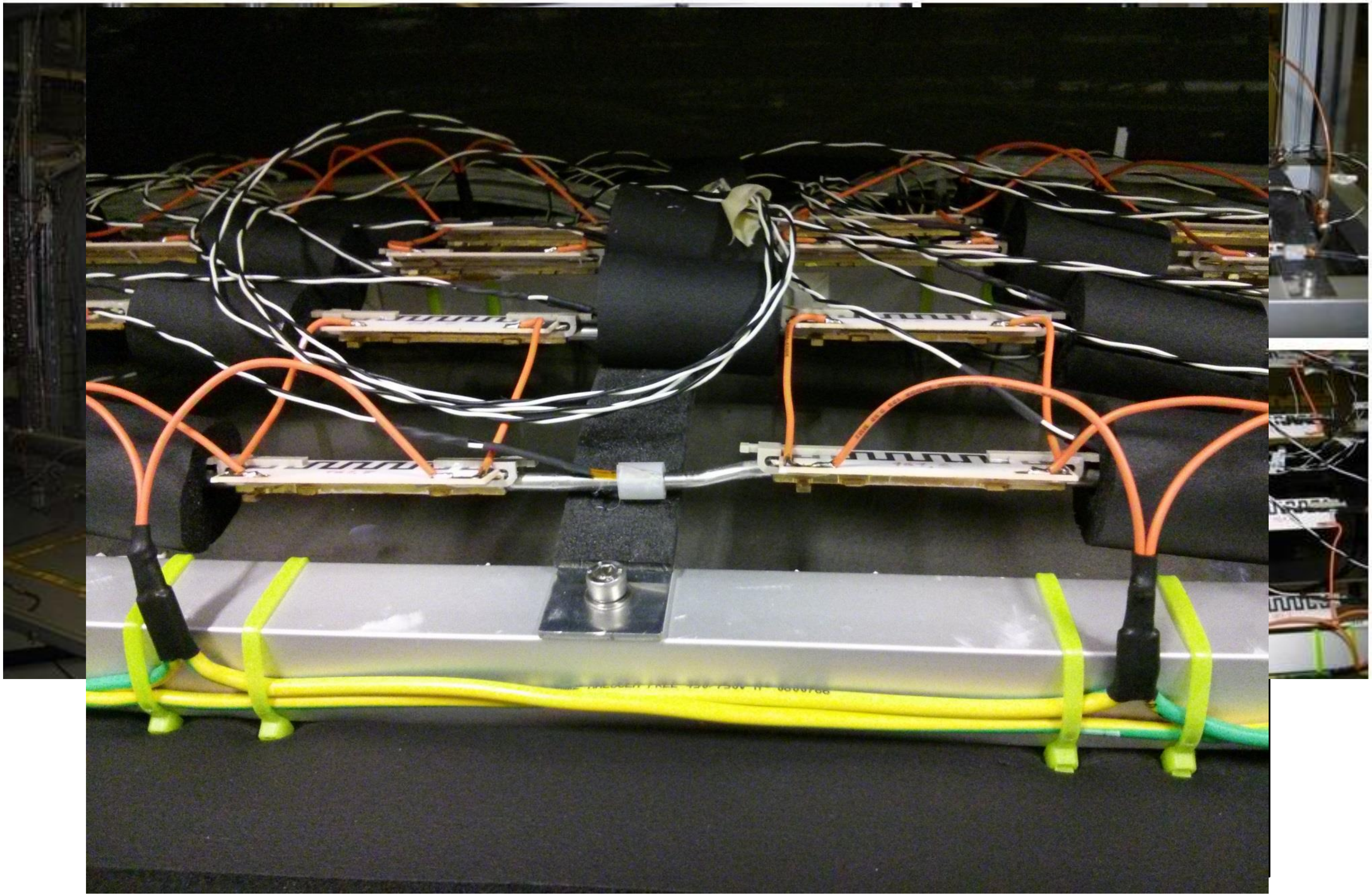
But… first build a machine to create and circulate C_2F_6/C_3F_8 blends and an instrument to verify them…

C_2F_6/C_3F_8 blend mixing machine & circulator

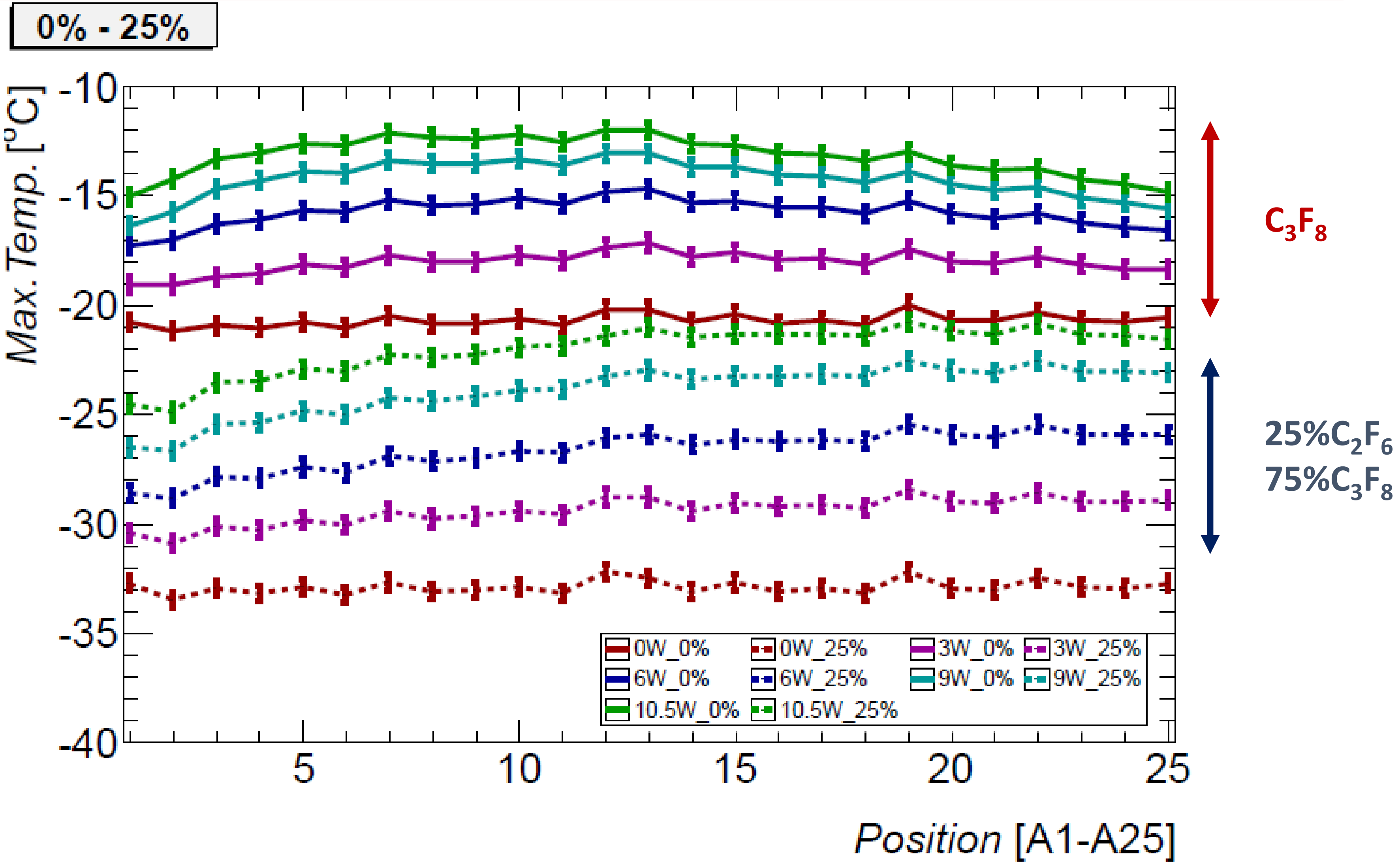


Sonar analyzer/flowmeter to verify C_2F_6/C_3F_8 blends

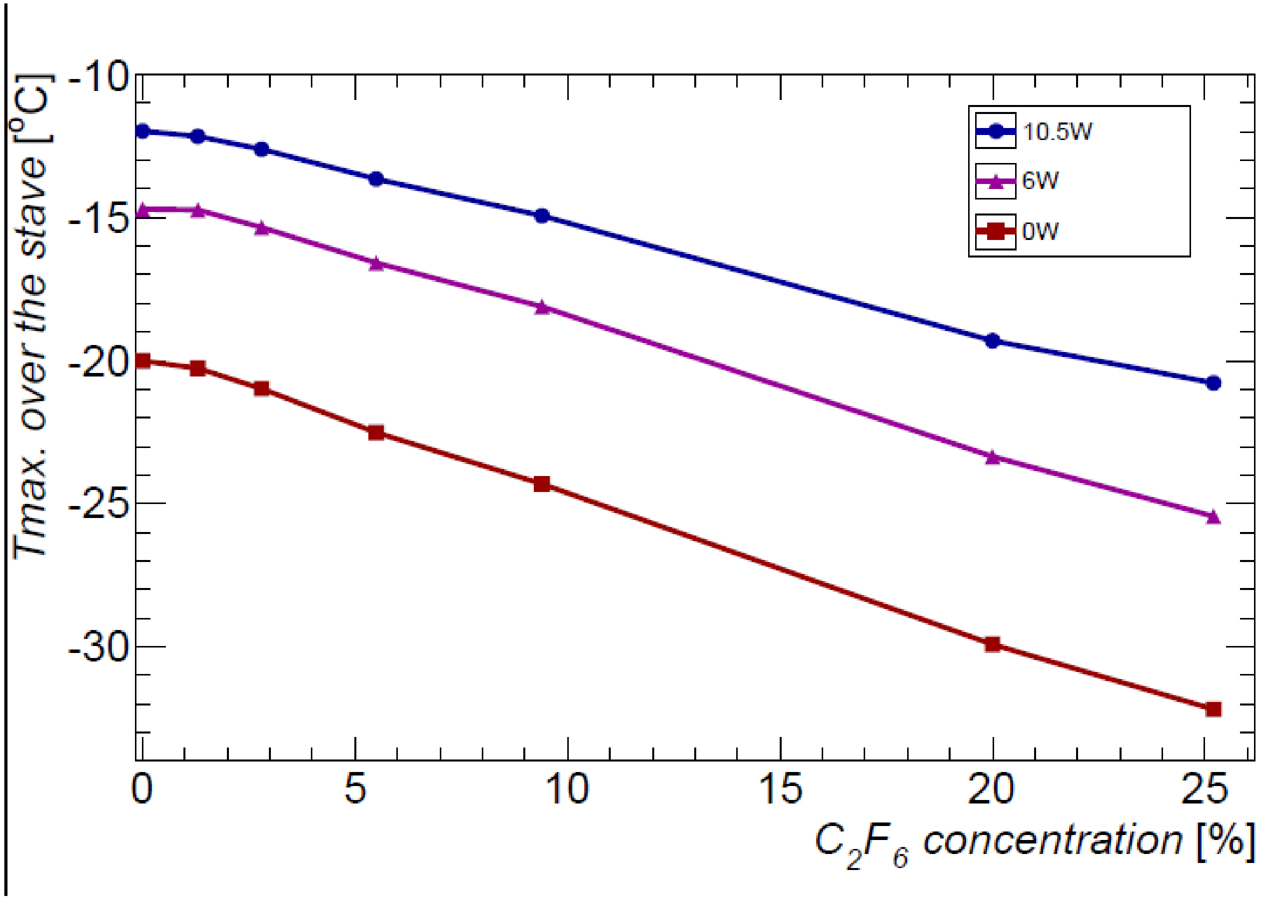
Thermal studies with C_3F_8 and C_3F_8/C_2F_6 made in a thermal model of an SCT bi-stave



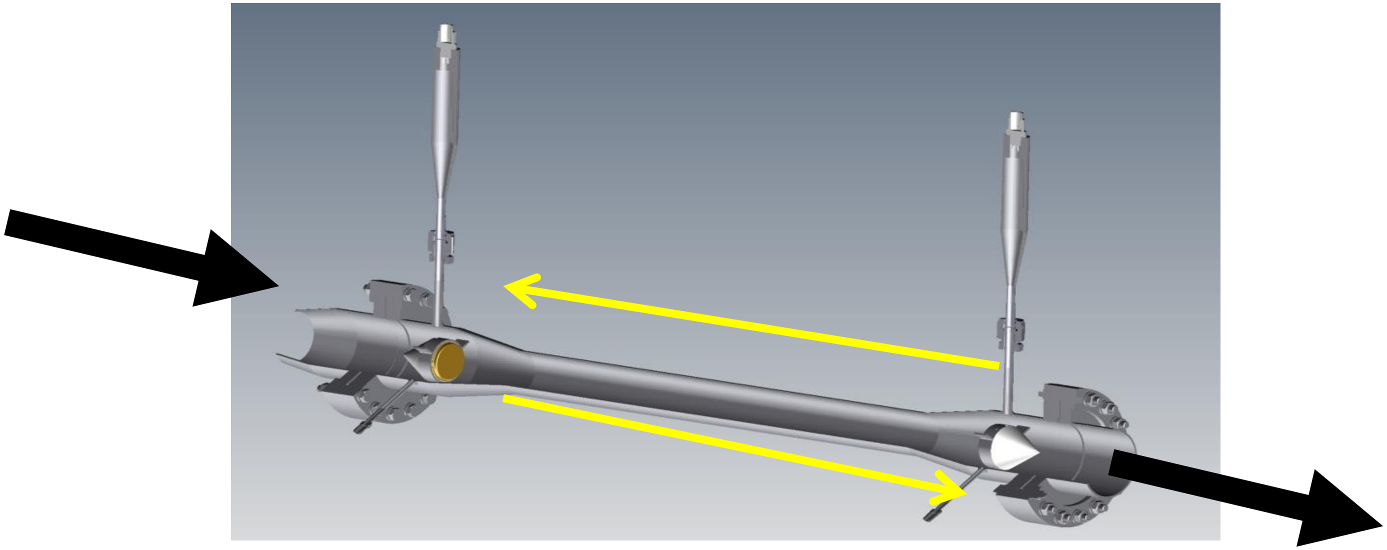
Temperature profile along tubes of one parallel half of simulated SCT bistave: pure C_3F_8 and 25%C_2F_6/75%C_3F_8 for different power/module (48 modules total)

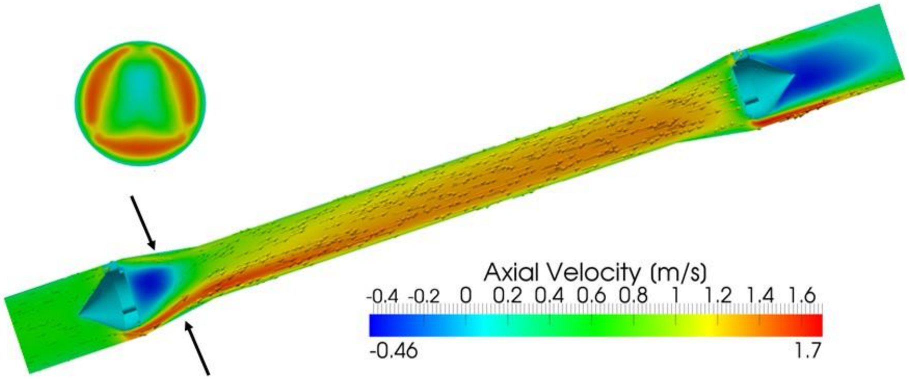


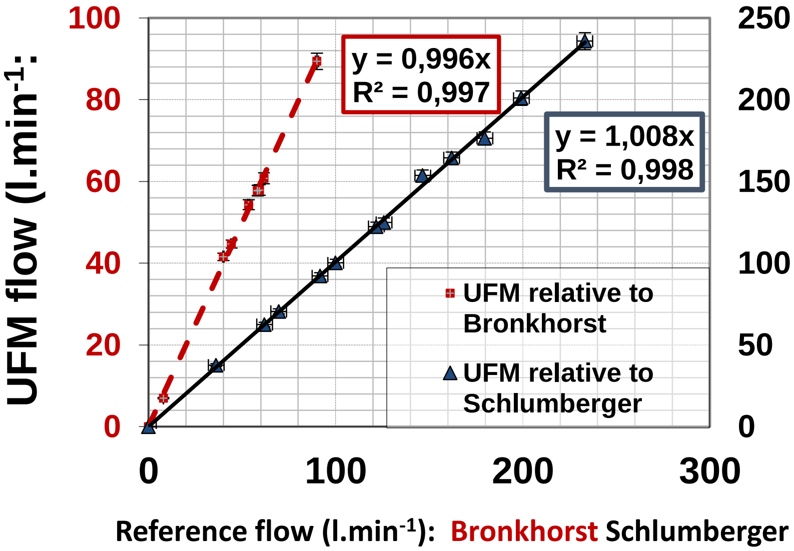
Reduction in evaporation pressure with molar concentration of added C_2F_6



(Deceptively) simple “Pinched Axial” implementation combining analysis & flowmetry

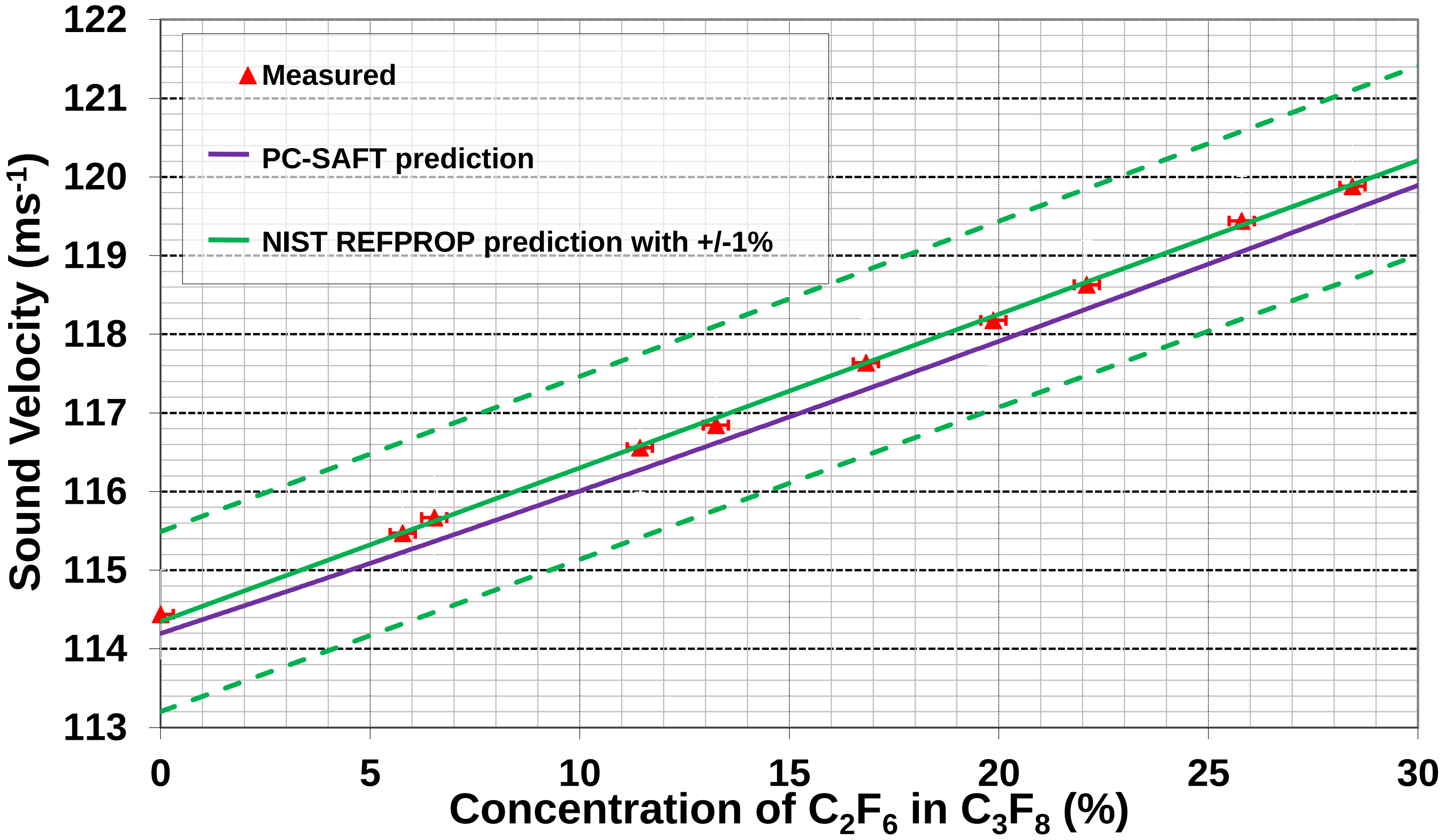






As in any UFM, absolute normalisation depends on good knowledge of flow patterns from CFD

Pinched Axial instrument combining analysis & flowmetry



$\delta c = 0.05 ms^{-1}$ ➔ C_2F_6 (0-25%) / C_2F_6 : $m = 0.18\ m.s^{-1}.[\%C_3F_8]^{-1}$ $\delta f = \pm 3.10^{-3}$

The blends conclusion

- C_2F_6/C_3F_8blends with up to 25% C_2F_6 can be used in existing ATLAS tubing…

- They will allow the SCT to be operated far beyond the present interated luminosity estimate of 350 fb^{-1} (i.e. to at least 620 fb^{-1}) should the high luminosity upgrade (2023..?) be postponed…

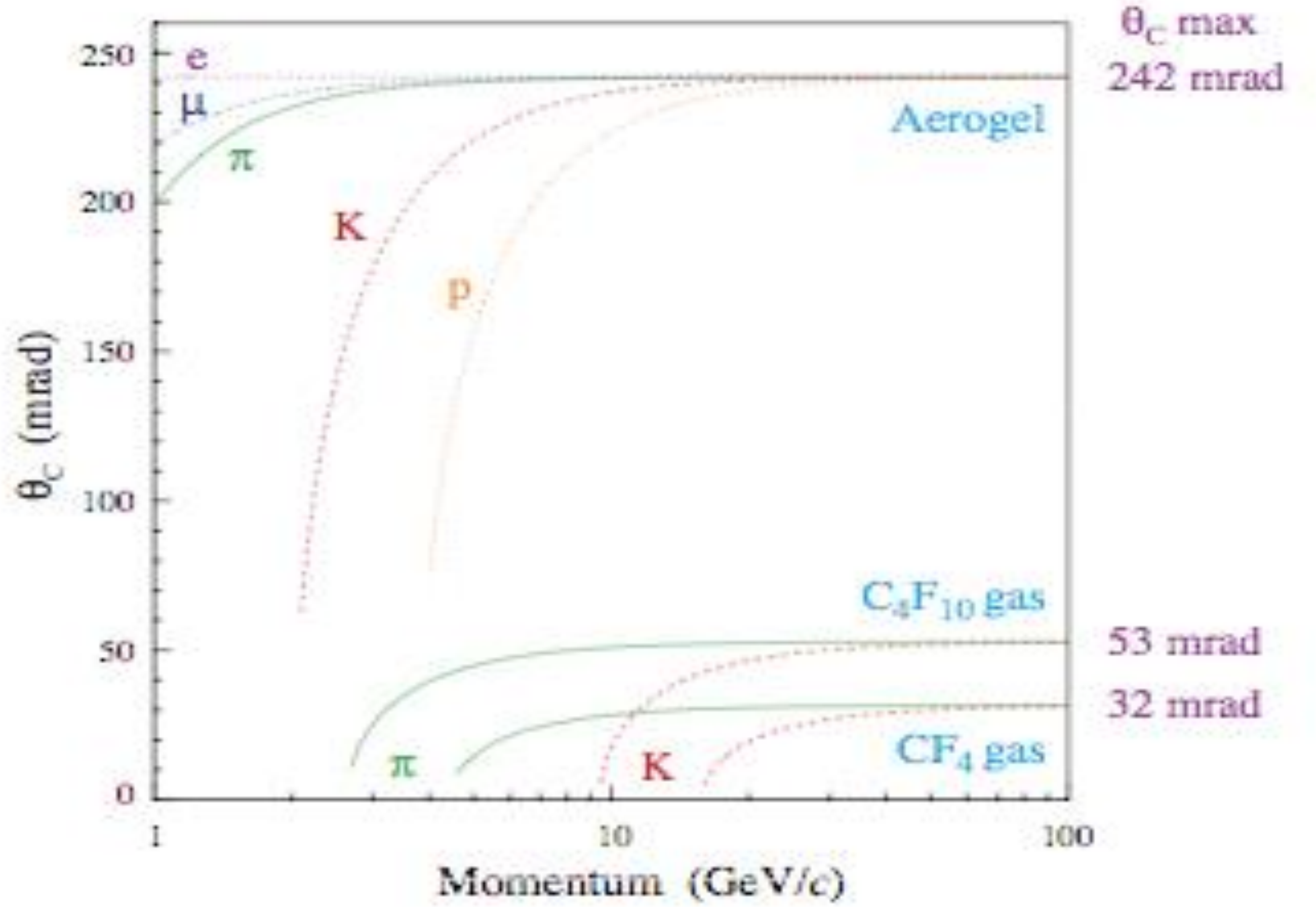
- Sonar instruments allow on line monitoring of the blend to < 0.3% and correction of it. The angled flowmeter will do this in the context of thermospihon operation.

Use of sonars in other RICH detectors

- Beginnings of Cerenkov refractomery in SLD CRID
- Used – but not extensively - in the DELPHI and COMPASS RICH detectors
- As we have seen: well adaped to use in circulation piping and RICH radiator volumes

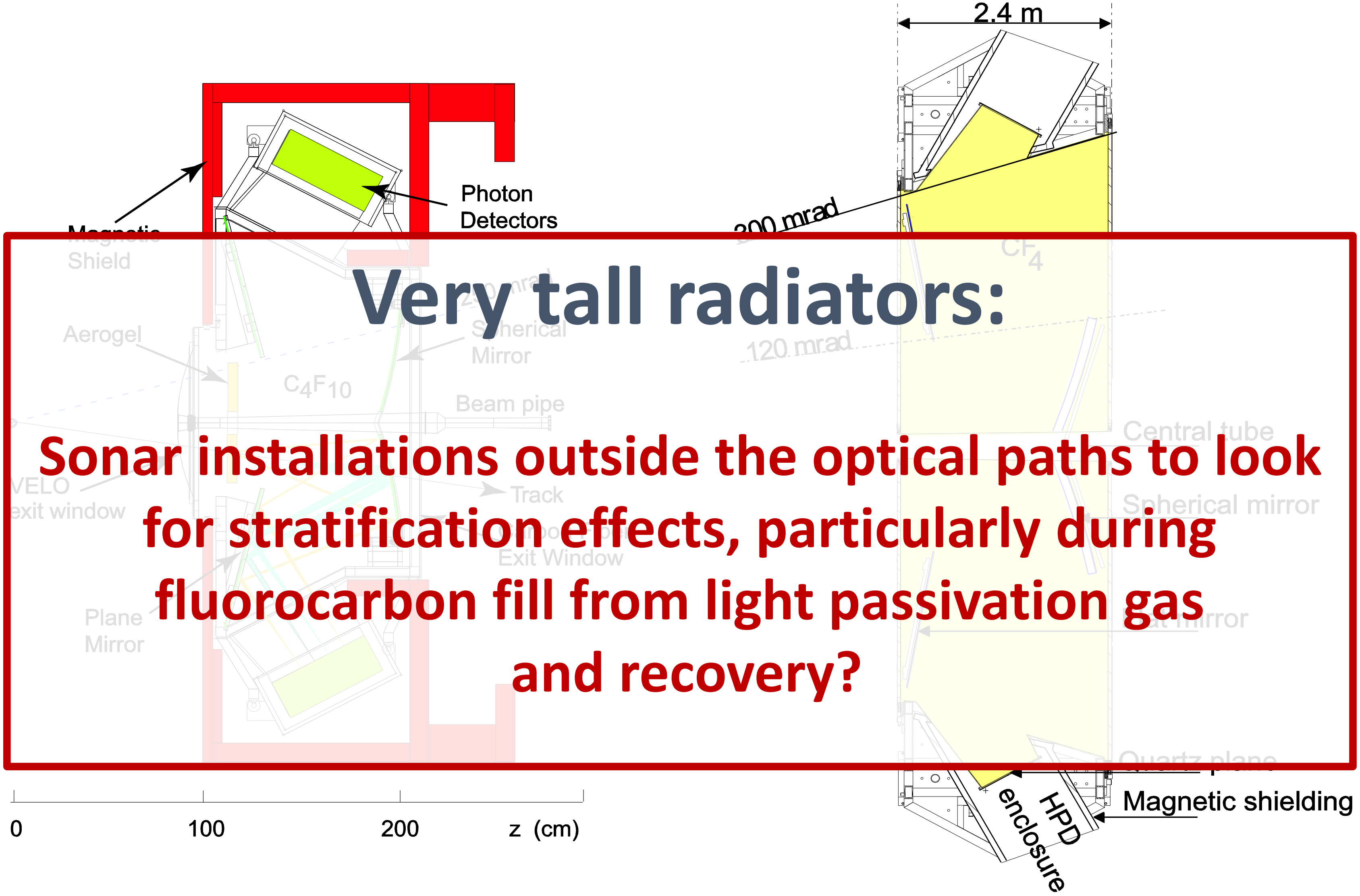
(worth considering for LHCb RICH upgrades…?)

The LHCb Detector



n

Before Upgrades: LHCb RICH 1 and RICH 2 detectors at CERN
RICH 1: C_4F_{10} & aerogel radiators; RICH 2: CF_4 radiator.



Very tall radiators:

Sonar installations outside the optical paths to look for stratification effects, particularly during fluorocarbon fill from light passivation gas and recovery?

LHCb RICH 1 and RICH 2 C_4F_{10} CF_4 recirculators.

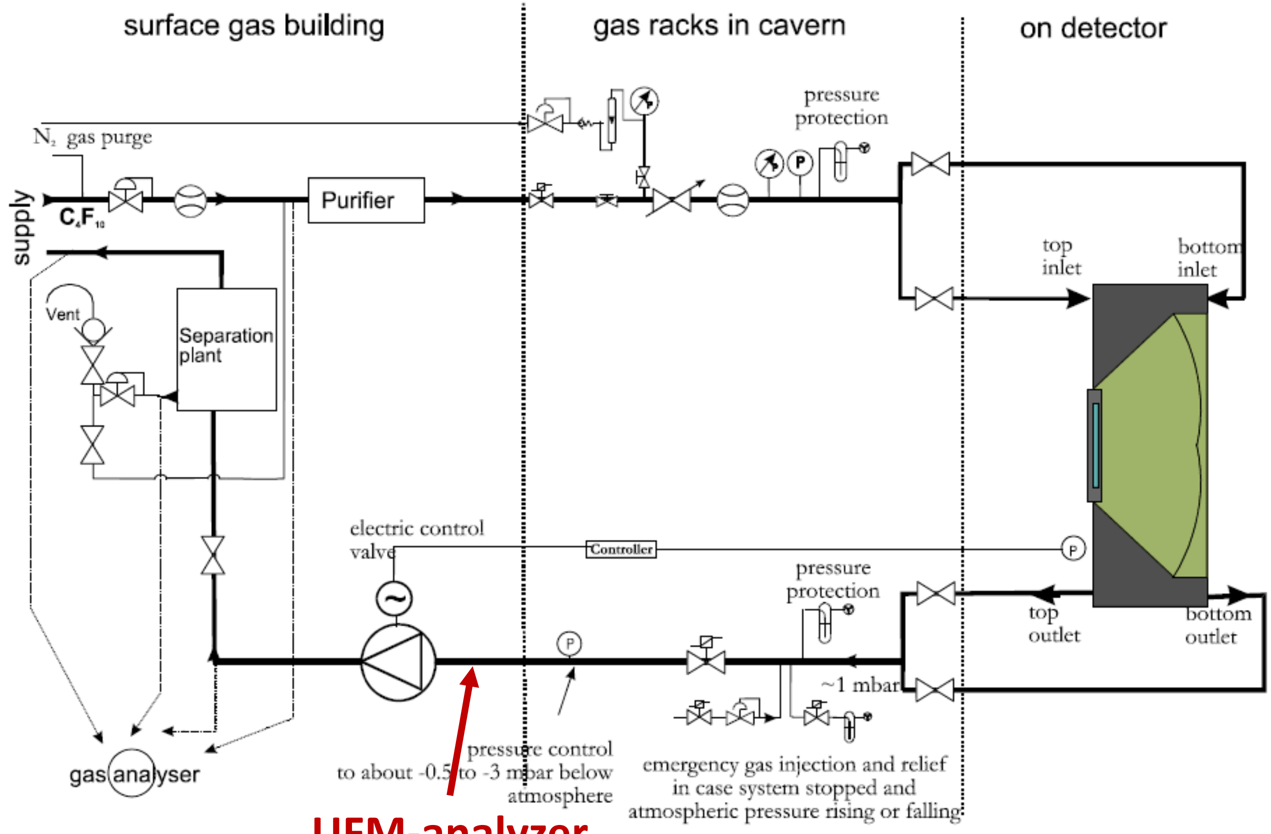


Figure 1: **RICH 1 gas distribution system**

UFM-analyzer here..?

RICH1: C_4F_{10} circulating @ 0.4m^3/hr

LHCb RICH 1 and RICH 2 C_4F_{10} CF_4 recirculators.

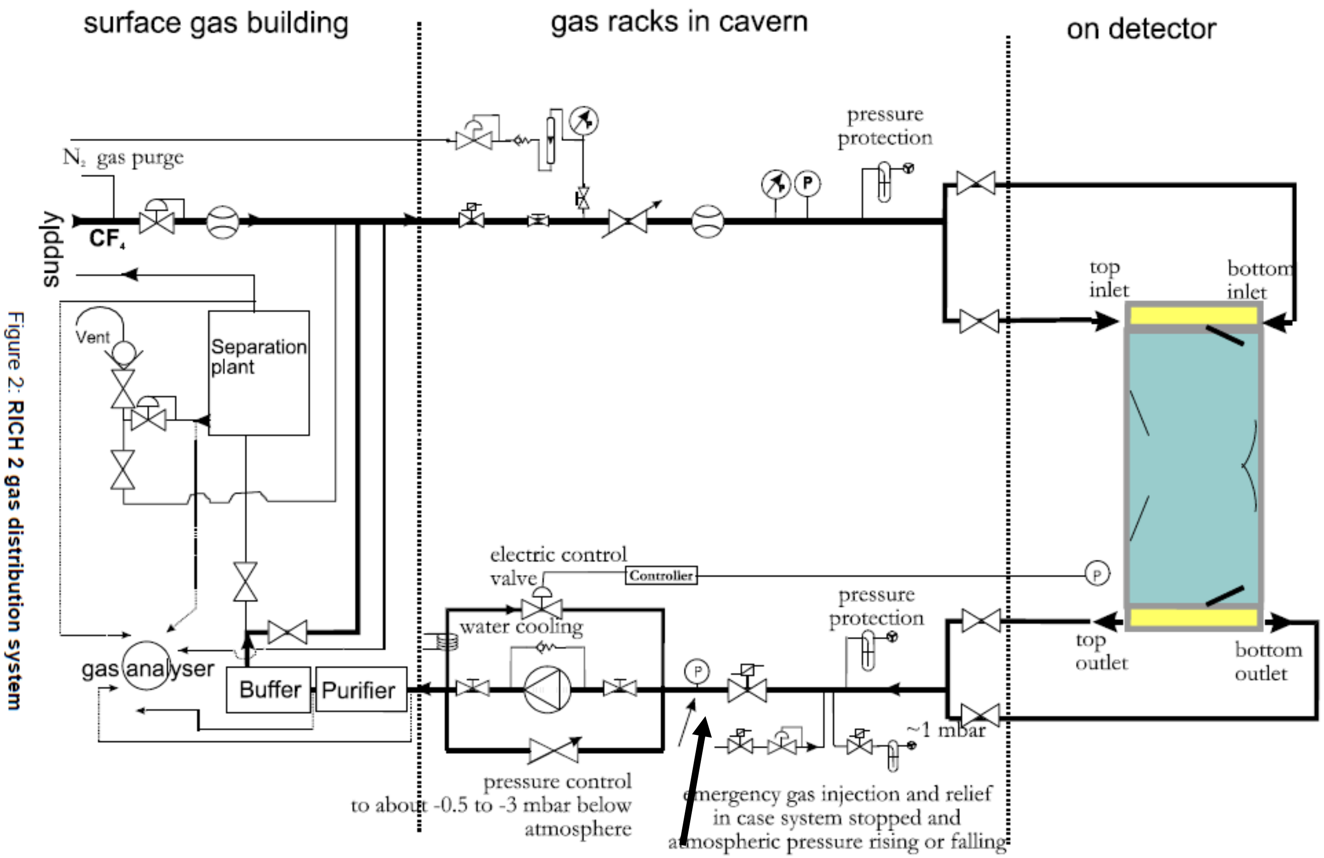


Figure 2: **RICH 2 gas distribution system**

UFM-analyzer here..?

RICH2: CF_4 circulating @ 10m^3/hr.

Example: new medical application: Xenon-based anaesthesia

Simultaneous Real-Time binary gas analysis & flowmetry in the same instrument

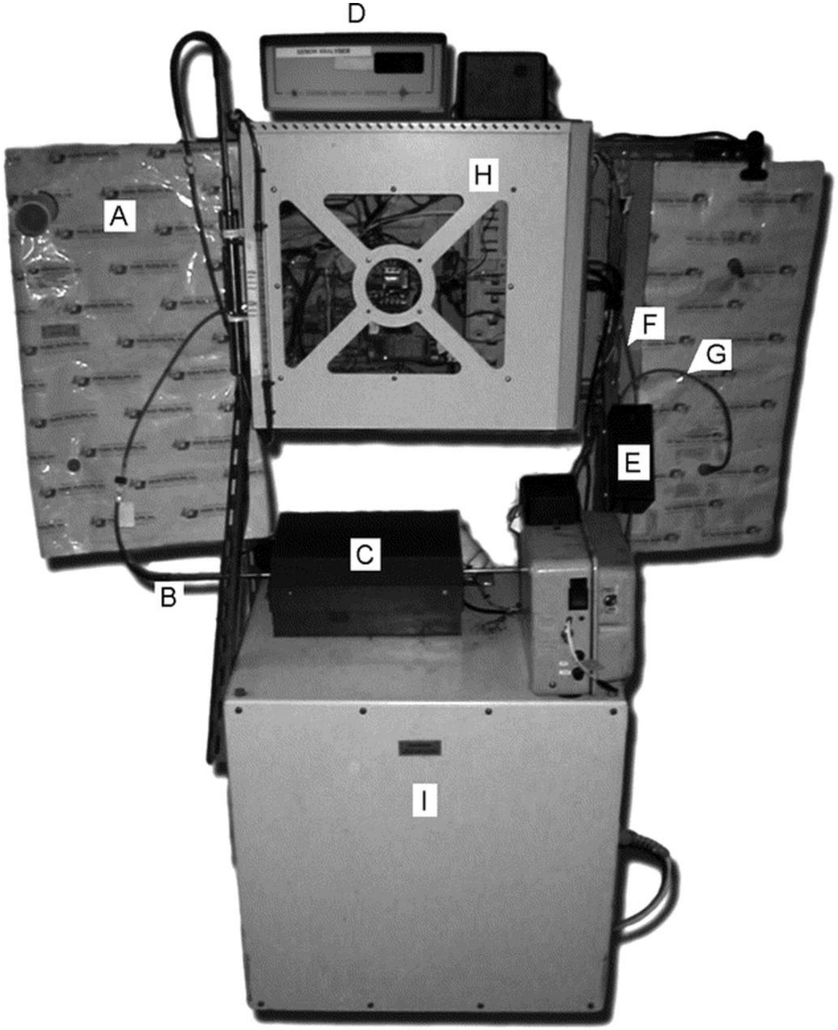
- ***Particlarly well suited to measurements of a heavy additive in a light carrier***

Mixtures of Xenon (MW 131.7) /$O_{2\,:}$ (MW 32):

➔ Need to recover very expensive Xe after surgery (price ~1 CHF/litre at 1 bar), recover by condensing patient exhalations (« degassing the patient »)

Research on Xe delivery/recovery at Swansea (Dingley et al),

Figure 2. Freeze cycle: Gas to be processed is contained in bag (A).

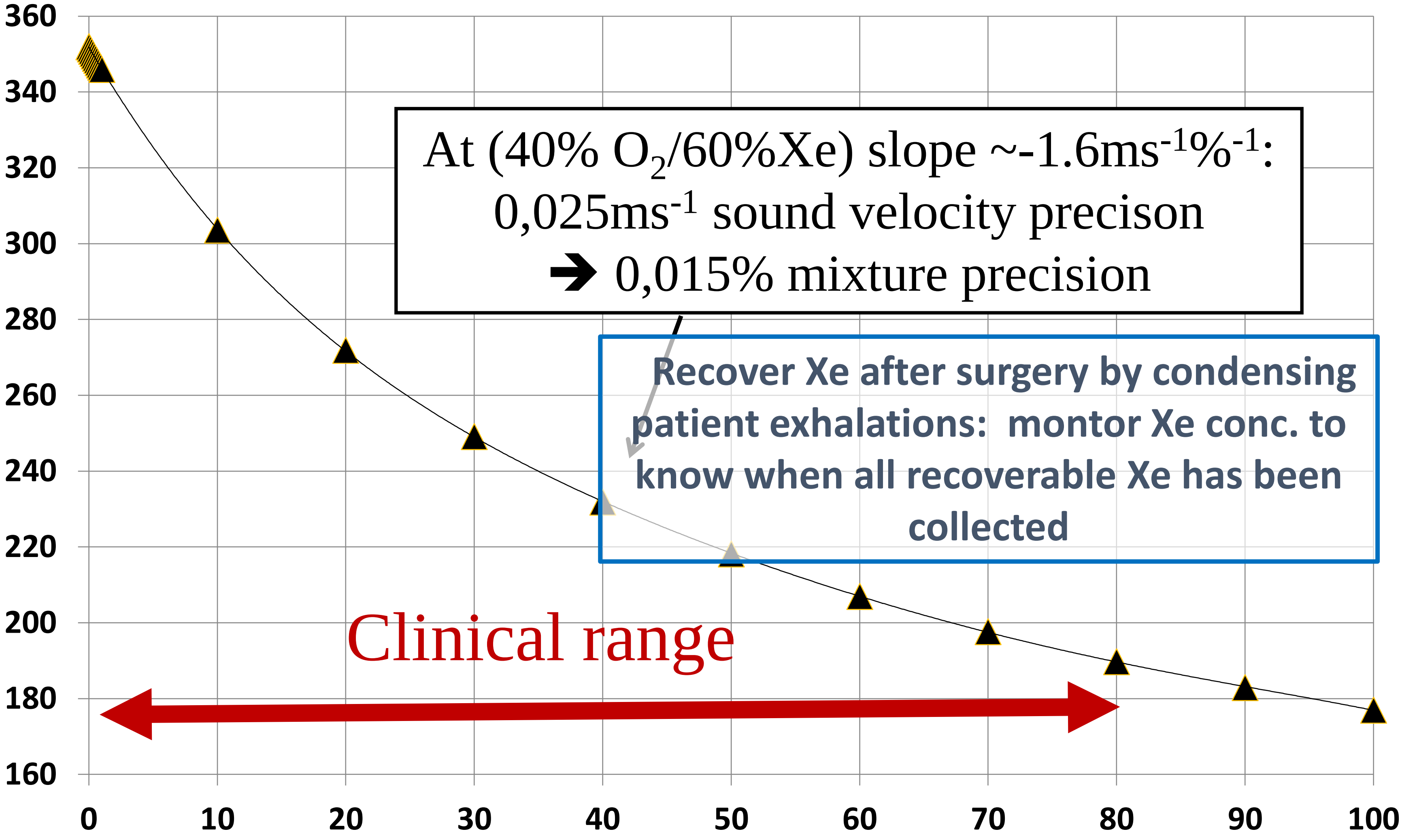


Dingley J , Mason R S Anesth Analg 2007;105:1312-1318

ANESTHESIA & ANALGESIA

©2007 by Lippincott Williams & Wilkins

Sonar for O_2/Xe ratio measurement


Sound Velocity (m/s) vs % Xe in O_2 @24.5 C

At (40% O_2/60%Xe) slope ~$-1.6ms^{-1}\%^{-1}$:
$0{,}025ms^{-1}$ sound velocity precison
➔ 0,015% mixture precision

Recover Xe after surgery by condensing patient exhalations: montor Xe conc. to know when all recoverable Xe has been collected

Clinical range

CONCLUSION

Simultaneous Real-Time binary gas analysis & flowmetry in the same instrument

- *Resolution in blends C_2F_6 /C_3F_8 (δMW = 50) ~ 0.3%;*
- *Precision for C_3F_8 leak measurement into N_2 (δMW = 160) O ~ 10^{-5};*
- *Precision for CO_2 leak measurement into N_2 (δMW = 16) O ~ 10^{-4};*
- *Auto-vent triggering for air leaks into C_3F_8 condenser ~ sub - percent (tbd);*

- ***Particlarly well suited to measurements of a heavy additive in a light carrier***

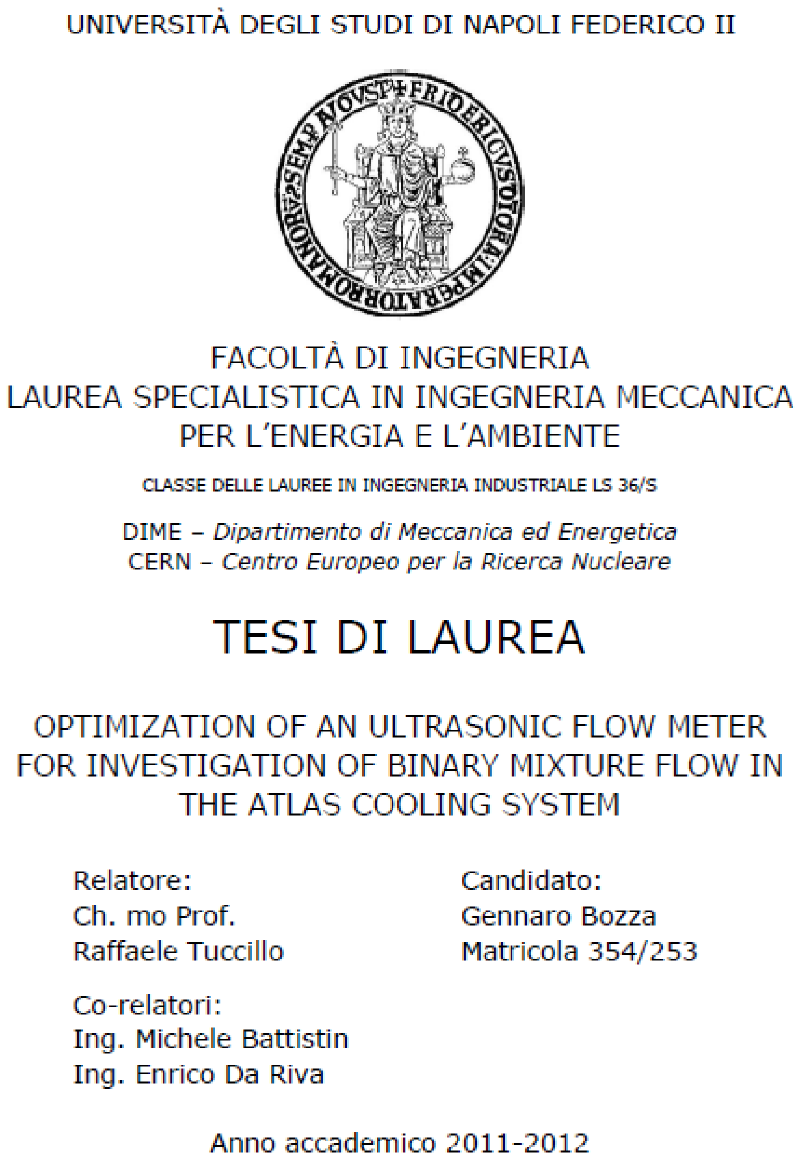
- *Flow measurement precision ~ 2% full scale in "pinched axial"*
  (flow ➔ 250 $l.min^{-1}$) – 3 examples built
  ~ 1.9% full scale in version with 45° acoustics for high flow ($\geq$ $15ms^{-1}$)

Sonar instruments commissioned into the ATLAS Detector Control system (DCS): use ATLAS DCS DB

Back up slides

Some sonar publications and theses

Theses, reports related to sonar



UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

FACOLTÀ DI INGEGNERIA
LAUREA SPECIALISTICA IN INGEGNERIA MECCANICA PER L'ENERGIA E L'AMBIENTE

CLASSE DELLE LAUREE IN INGEGNERIA INDUSTRIALE LS 36/S

DIME – *Dipartimento di Meccanica ed Energetica*
CERN – *Centro Europeo per la Ricerca Nucleare*

TESI DI LAUREA

OPTIMIZATION OF AN ULTRASONIC FLOW METER FOR INVESTIGATION OF BINARY MIXTURE FLOW IN THE ATLAS COOLING SYSTEM

Relatore:	Candidato:
Ch. mo Prof.	Gennaro Bozza
Raffaele Tuccillo	Matricola 354/253

Co-relatori:
Ing. Michele Battistin
Ing. Enrico Da Riva

Anno accademico 2011-2012

CERN

IUT Annecy

MISE EN ŒUVRE D'UN DÉBITMÈTRE ET D'UN ANALYSEUR DE MÉLANGES GAZEUX

STAGE DE FIN D'ÉTUDES

Responsable du stage : DI GIROLAMO Beniamino
Tuteurs au centre de recherche : HALLEWELL Gregory & DJAMA Farès
Tuteur IUT : LE DANTEC Ronan

Stagiaire : BERTHOUD Jonathan

MPh
Mesures Physiques

2 avril – 20 juin 2012

Theses, reports related to sonar: (cont.)

cnrs

Centre de Physique des Particules de Marseille

CPPM

IN2P3

Institut National de Physique Nucléaire et de Physique des Particules

Etude d'un débitmètre/analyseur de gaz par ultrasons

Tuteur au centre de recherche : Gregory HALLEWELL

Tuteur IUT : Jean-Claude VAILLES

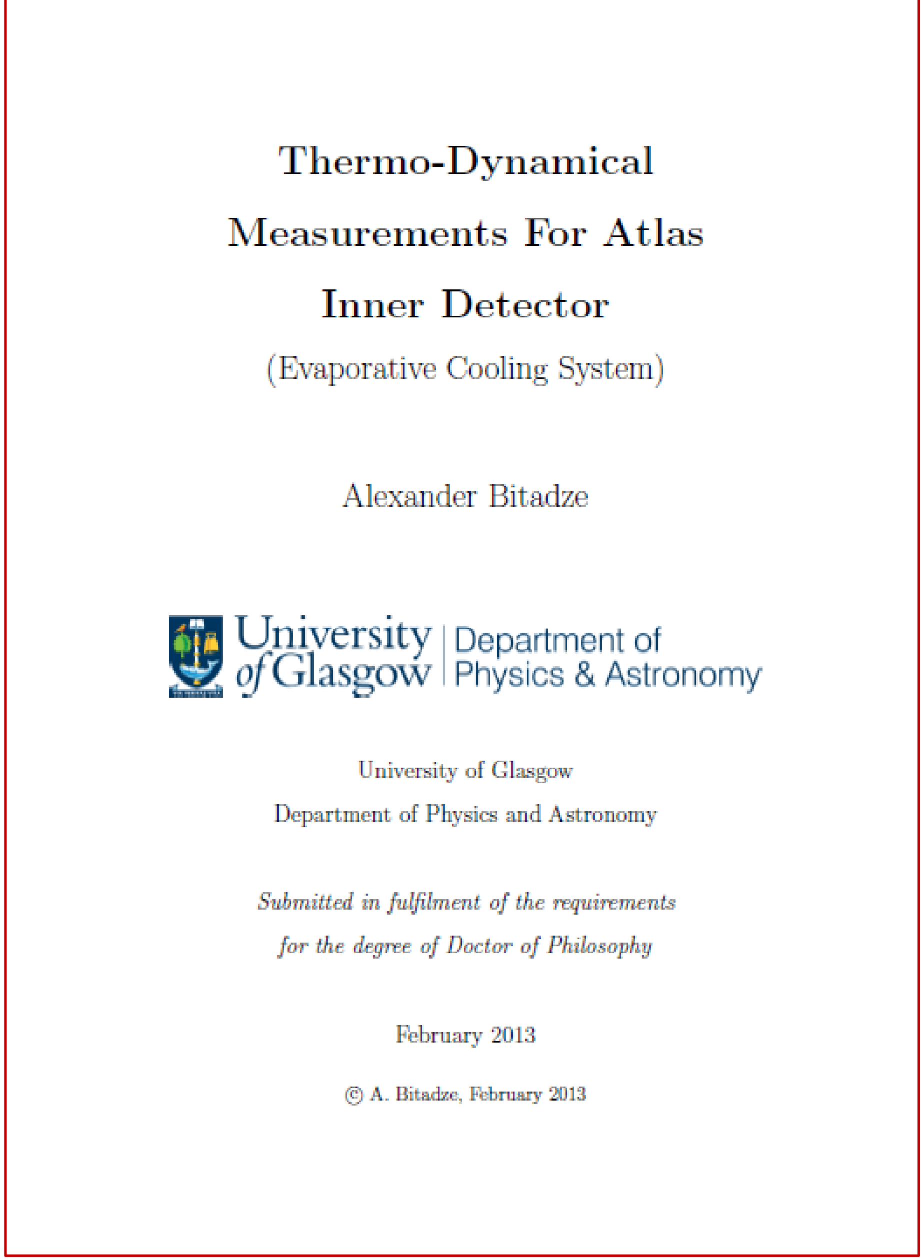
Stagiaire : Nicolas LANGEVIN

8 Avril – 21 Juin 2013

Aix*Marseille université

Institut Universitaire de Technologie de Marseille
Aix-Marseille Université

Mesures Physiques



Thermo-Dynamical Measurements For Atlas Inner Detector

(Evaporative Cooling System)

Alexander Bitadze

University of Glasgow | Department of Physics & Astronomy

University of Glasgow

Department of Physics and Astronomy

Submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy

February 2013

© A. Bitadze, February 2013

Major Publications related to sonar (1)

Jinst
Published by IOP Publishing for Sissa Medialab
Received: *October 18, 2012*
Revised: *December 12, 2012*
Accepted: *January 13, 2013*
Published: *February 12, 2013*

A combined ultrasonic flow meter and binary vapour mixture analyzer for the ATLAS silicon tracker

R. Bates,[a] M. Battistin,[b] S. Berry,[b] J. Berthoud,[b] A. Bitadze,[a] P. Bonneau,[b]
J. Botelho-Direito,[b] N. Bousson,[c] G. Boyd,[d] G. Bozza,[b] E. Da Riva,[b] C. Degeorge,[e]
C. Deterre,[f] B. DiGirolamo,[b] M. Doubek,[g] D. Giugni,[h] J. Godlewski,[b] G. Hallewell,[c,1]
S. Katunin,[i] D. Lombard,[b] M. Mathieu,[c] S. McMahon,[j] K. Nagai,[k]
E. Perez-Rodriguez,[b] C. Rossi,[l] A. Rozanov,[c] V. Vacek,[f] M. Vitek[f] and L. Zwalinski[b]

[a] *SUPA School of Physics and Astronomy, University of Glasgow,*
Glasgow, G62 7QB, United Kingdom
[b] *CERN,*
1211 Geneva 23, Switzerland
[c] *Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS/IN2P3,*
163 Avenue de Luminy, 13288 Marseille Cedex 09, France
[d] *The Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma,*
440 West Brooks Street, Norman, OK 73019, United States of America
[e] *Indiana University, Department of Physics, 727 East Third St.,*
Bloomington, IN 47405-7105, United States of America
[f] *Deutsches Elektronen-Synchrotron, Notkestraße 85, D-22607*
Hamburg, Germany
[g] *Czech Technical University in Prague, Department of Applied Physics,*
Technická 4, 166 07 Prague 6, Czech Republic
[h] *INFN Milano and Università di Milano, Dipartimento di Fisica,*
Via Celoria 16, 20133 Milano, Italy
[i] *B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI),*
188300 St. Petersburg, Russia
[j] *Rutherford Appleton Laboratory - Science & Technology Facilities Council,*
Harwell Science and Innovations Campus, Didcot OX11 0QX, United Kingdom
[k] *Graduate School of Pure and Applied Sciences, University of Tsukuba,*
1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan
[l] *Department of Mechanical Engineering - Thermal Energy and Air Conditioning Division,*
Università degli Studi di Genova Via All'Opera Pia 15a - 16145 Genova, Italy

E-mail: gregh@cppm.in2p3.fr

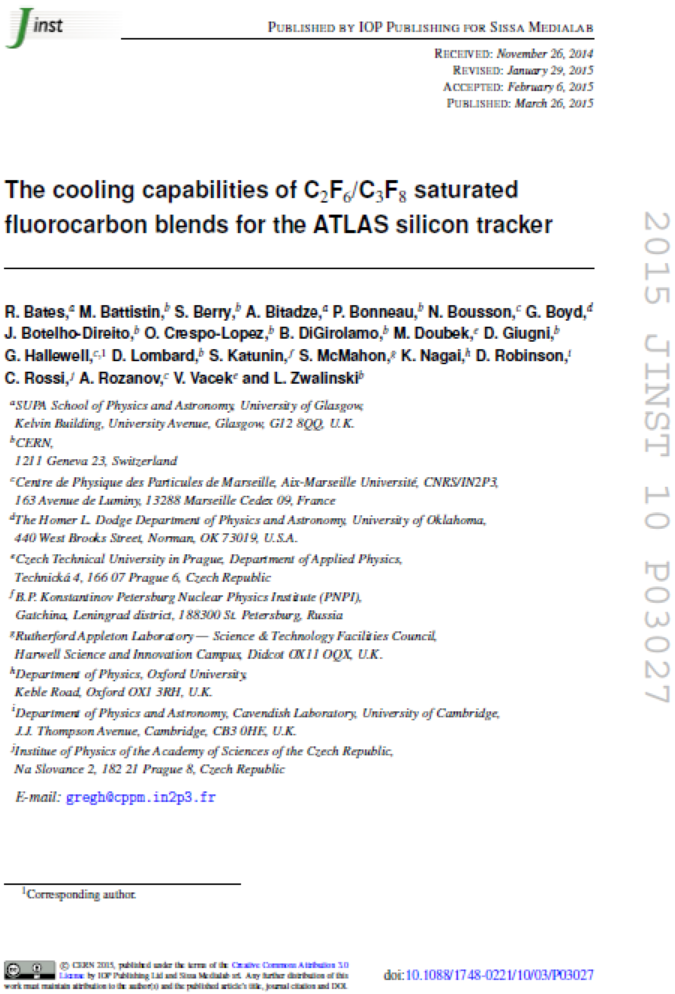
---

[1] Corresponding author.

© CERN 2013, published under the terms of the Creative Commons Attribution 3.0 License by IOP Publishing Ltd and Sissa Medialab srl. Any further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation and DOI.

doi: 10.1088/1748-0221/8/02/P02006

2013 JINST 8 P02006



Jinst
Published by IOP Publishing for Sissa Medialab
Received: *November 26, 2014*
Revised: *January 29, 2015*
Accepted: *February 6, 2015*
Published: *March 26, 2015*

The cooling capabilities of C_2F_6/C_3F_8 saturated fluorocarbon blends for the ATLAS silicon tracker

R. Bates,[a] M. Battistin,[b] S. Berry,[b] A. Bitadze,[a] P. Bonneau,[b] N. Bousson,[c] G. Boyd,[d]
J. Botelho-Direito,[b] O. Crespo-Lopez,[b] B. DiGirolamo,[b] M. Doubek,[e] D. Giugni,[b]
G. Hallewell,[c,1] D. Lombard,[b] S. Katunin,[f] S. McMahon,[g] K. Nagai,[h] D. Robinson,[i]
C. Rossi,[j] A. Rozanov,[c] V. Vacek[e] and L. Zwalinski[b]

[a] *SUPA School of Physics and Astronomy, University of Glasgow,*
Kelvin Building, University Avenue, Glasgow, G12 8QQ, U.K.
[b] *CERN,*
1211 Geneva 23, Switzerland
[c] *Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS/IN2P3,*
163 Avenue de Luminy, 13288 Marseille Cedex 09, France
[d] *The Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma,*
440 West Brooks Street, Norman, OK 73019, U.S.A.
[e] *Czech Technical University in Prague, Department of Applied Physics,*
Technická 4, 166 07 Prague 6, Czech Republic
[f] *B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI),*
Gatchina, Leningrad district, 188300 St. Petersburg, Russia
[g] *Rutherford Appleton Laboratory — Science & Technology Facilities Council,*
Harwell Science and Innovation Campus, Didcot OX11 0QX, U.K.
[h] *Department of Physics, Oxford University,*
Keble Road, Oxford OX1 3RH, U.K.
[i] *Department of Physics and Astronomy, Cavendish Laboratory, University of Cambridge,*
J.J. Thompson Avenue, Cambridge, CB3 0HE, U.K.
[j] *Institue of Physics of the Academy of Sciences of the Czech Republic,*
Na Slovance 2, 182 21 Prague 8, Czech Republic

E-mail: gregh@cppm.in2p3.fr

---

[1] Corresponding author.

© CERN 2015, published under the terms of the Creative Commons Attribution 3.0 License by IOP Publishing Ltd and Sissa Medialab srl. Any further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation and DOI.

doi: 10.1088/1748-0221/10/03/P03027

2015 JINST 10 P03027

Major Publications related to sonar (2)

Sensors **2014**, *14*, 11260-11276; doi:10.3390/s140611260

OPEN ACCESS

sensors

ISSN 1424-8220

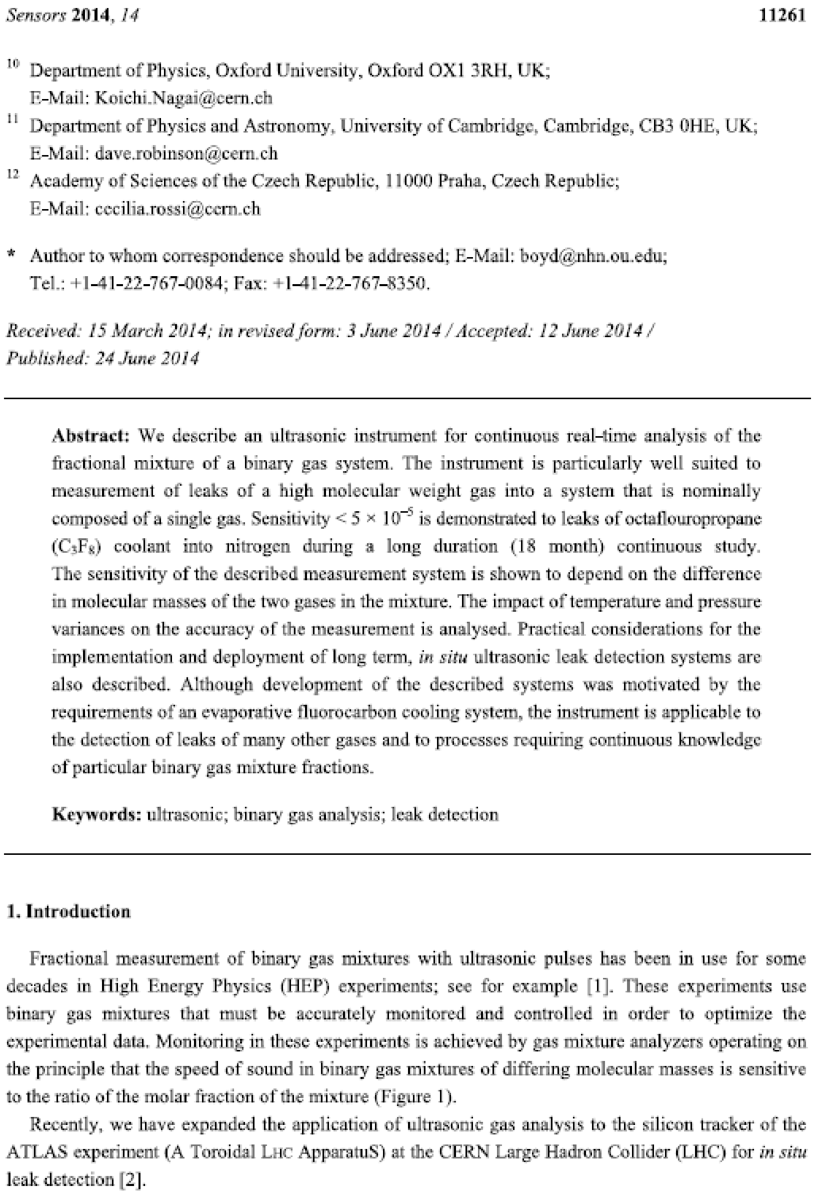
www.mdpi.com/journal/sensors

Article

Implementation of Ultrasonic Sensing for High Resolution Measurement of Binary Gas Mixture Fractions

Richard Bates [1], Michele Battistin [2], Stephane Berry [2], Alexander Bitadze [1], Pierre Bonneau [2], Nicolas Bousson [3], George Boyd [4,*], Gennaro Bozza [2], Olivier Crespo-Lopez [2], Enrico Da Riva [2], Cyril Degeorge [5], Cecile Deterre [6], Beniamino DiGirolamo [2], Martin Doubek [7], Gilles Favre [2], Jan Godlewski [2], Gregory Hallewell [3], Ahmed Hasib [4], Sergey Katunin [8], Nicolas Langevin [3], Didier Lombard [2], Michel Mathieu [3], Stephen McMahon [9], Koichi Nagai [10], Benjamin Pearson [4], David Robinson [11], Cecilia Rossi [12], Alexandre Rozanov [3], Michael Strauss [4], Michal Vitek [7], Vaclav Vacek [7] and Lukasz Zwalinski [2]

[1] SUPA School of Physics and Astronomy, University of Glasgow, G627QB, UK;
E-Mails: richard.bates@glasgow.ac.uk (R.B.); Alexander.Bitadze@cern.ch (A.B.)
[2] CERN, 1211 Geneva 23, Switzerland; E-Mails: Michele.Battistin@cern.ch (M.B.);
Stephane.Berry@cern.ch (S.B.); Pierre.Bonneau@cern.ch (P.B.); gennaro.bozza@cern.ch (G.B.);
Olivier.Crespo-Lopez@cern.ch (O.C.-L.); enrico.da.riva@cern.ch (E.D.R.);
Beniamino.Di.Girolamo@cern.ch (B.D.); Gilles.Favre@cern.ch (G.F.); Jan.Godlewski@cern.ch (J.G.);
Didier.Lombard@cern.ch (D.L.); lukasz.zwalinski@cern.ch (L.Z.)
[3] Centre de Physique des Particules de Marseille, 163 Avenue de Luminy, 13288 Marseille, France;
E-Mails: nicolas.bousson@cern.ch (N.B.); gregh@cppm.in2p3.fr (G.H.);
nicolas.langevin.nl@gmail.com (N.L.); mathieu@cppm.in2p3.fr (M.M.);
mathieu@cppm.in2p3.fr (A.R.)
[4] Department of Physics & Astronomy, University of Oklahoma, Norman, OK 73019, USA;
E-Mails: a.hasib@cern.ch (A.H.); benpearson@ou.edu (B.P.); strauss@nhn.ou.edu (M.S.)
[5] Department of Physics, Indiana University, Bloomington, IN 47405 7015, USA;
E-Mail: Cyril.Degeorge@cern.ch
[6] Deutsches Elektronen-Synchrotron , Notkestraße 85, D-22607 Hamburg, Germany;
E-Mail: cecile.deterre@desy.de
[7] Czech Technical University, Technická 4, 16607, Praha Czech Republic;
E-Mails: Martin.Doubek@cern.ch (M.D.); miguel.vitek@gmail.com (M.V.);
Vaclav.Vacek@cern.ch (V.V.)
[8] B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI), Orlova Roscha, RU-188300, Russia; E-Mail: Sergey.Katunin@cern.ch
[9] STFC Rutherford Appelton Laboratory—Harwell Oxford, Didcot, OX11 OQX, UK;
E-Mail: steve.mcmahon@stfc.ac.uk



[10] Department of Physics, Oxford University, Oxford OX1 3RH, UK;
E-Mail: Koichi.Nagai@cern.ch
[11] Department of Physics and Astronomy, University of Cambridge, Cambridge, CB3 0HE, UK;
E-Mail: dave.robinson@cern.ch
[12] Academy of Sciences of the Czech Republic, 11000 Praha, Czech Republic;
E-Mail: cecilia.rossi@cern.ch

* Author to whom correspondence should be addressed; E-Mail: boyd@nhn.ou.edu;
Tel.: +1-41-22-767-0084; Fax: +1-41-22-767-8350.

Received: 15 March 2014; in revised form: 3 June 2014 / Accepted: 12 June 2014 / Published: 24 June 2014

Abstract: We describe an ultrasonic instrument for continuous real-time analysis of the fractional mixture of a binary gas system. The instrument is particularly well suited to measurement of leaks of a high molecular weight gas into a system that is nominally composed of a single gas. Sensitivity $< 5 \times 10^{-5}$ is demonstrated to leaks of octaflouropropane (C_3F_8) coolant into nitrogen during a long duration (18 month) continuous study. The sensitivity of the described measurement system is shown to depend on the difference in molecular masses of the two gases in the mixture. The impact of temperature and pressure variances on the accuracy of the measurement is analysed. Practical considerations for the implementation and deployment of long term, *in situ* ultrasonic leak detection systems are also described. Although development of the described systems was motivated by the requirements of an evaporative fluorocarbon cooling system, the instrument is applicable to the detection of leaks of many other gases and to processes requiring continuous knowledge of particular binary gas mixture fractions.

Keywords: ultrasonic; binary gas analysis; leak detection

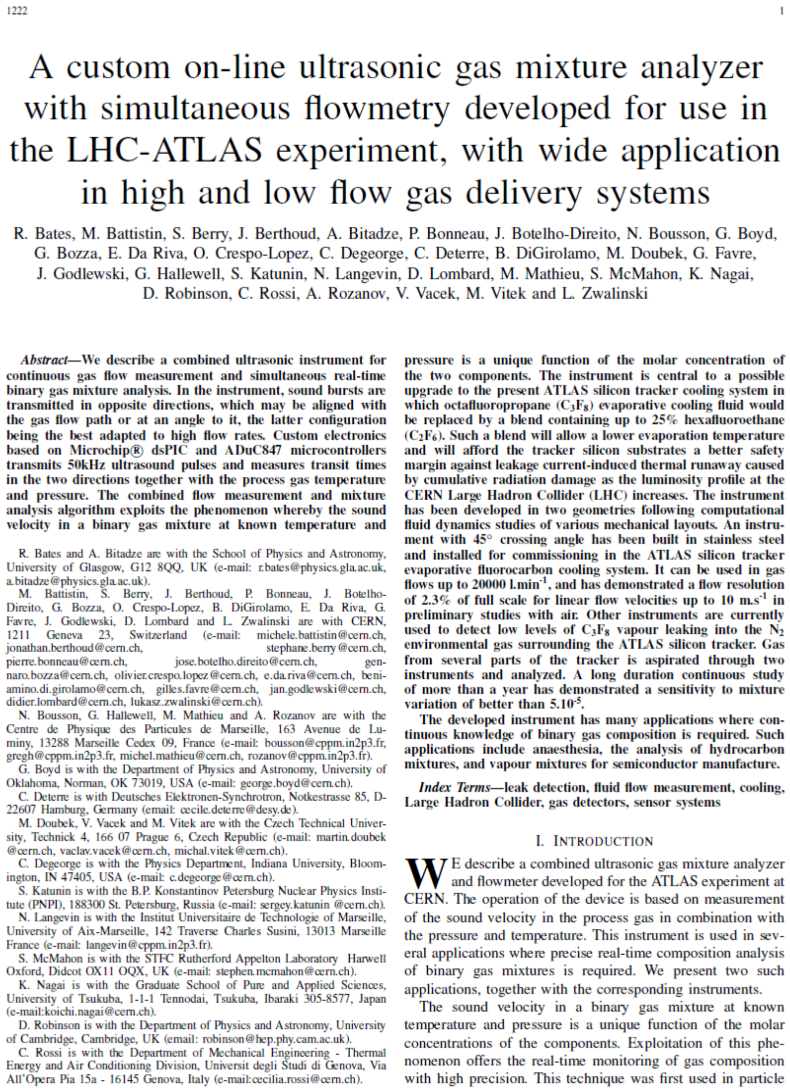
1. Introduction

Fractional measurement of binary gas mixtures with ultrasonic pulses has been in use for some decades in High Energy Physics (HEP) experiments; see for example [1]. These experiments use binary gas mixtures that must be accurately monitored and controlled in order to optimize the experimental data. Monitoring in these experiments is achieved by gas mixture analyzers operating on the principle that the speed of sound in binary gas mixtures of differing molecular masses is sensitive to the ratio of the molar fraction of the mixture (Figure 1).

Recently, we have expanded the application of ultrasonic gas analysis to the silicon tracker of the ATLAS experiment (A Toroidal LHC ApparatuS) at the CERN Large Hadron Collider (LHC) for *in situ* leak detection [2].

Some conference Publications related to sonar

ANIMMA 2013 June 2013 (IEEE TNS)



A custom on-line ultrasonic gas mixture analyzer with simultaneous flowmetry developed for use in the LHC-ATLAS experiment, with wide application in high and low flow gas delivery systems

R. Bates, M. Battistin, S. Berry, J. Berthoud, A. Bitadze, P. Bonneau, J. Botelho-Direito, N. Bousson, G. Boyd, G. Bozza, E. Da Riva, O. Crespo-Lopez, C. Degeorge, C. Deterre, B. DiGirolamo, M. Doubek, G. Favre, J. Godlewski, G. Hallewell, S. Katunin, N. Langevin, D. Lombard, M. Mathieu, S. McMahon, K. Nagai, D. Robinson, C. Rossi, A. Rozanov, V. Vacek, M. Vitek and L. Zwalinski

***Abstract*—We describe a combined ultrasonic instrument for continuous gas flow measurement and simultaneous real-time binary gas mixture analysis. In the instrument, sound bursts are transmitted in opposite directions, which may be aligned with the gas flow path or at an angle to it, the latter configuration being the best adapted to high flow rates. Custom electronics based on Microchip® dsPIC and ADuC847 microcontrollers transmits 50kHz ultrasound pulses and measures transit times in the two directions together with the process gas temperature and pressure. The combined flow measurement and mixture analysis algorithm exploits the phenomenon whereby the sound velocity in a binary gas mixture at known temperature and pressure is a unique function of the molar concentration of the two components. The instrument is central to a possible upgrade to the present ATLAS silicon tracker cooling system in which octafluoropropane (C_3F_8) evaporative cooling fluid would be replaced by a blend containing up to 25% hexafluoroethane (C_2F_6). Such a blend will allow a lower evaporation temperature and will afford the tracker silicon substrates a better safety margin against leakage current-induced thermal runaway caused by cumulative radiation damage as the luminosity profile at the CERN Large Hadron Collider (LHC) increases. The instrument has been developed in two geometries following computational fluid dynamics studies of various mechanical layouts. An instrument with 45° crossing angle has been built in stainless steel and installed for commissioning in the ATLAS silicon tracker evaporative fluorocarbon cooling system. It can be used in gas flows up to 20000 l.min^{-1}, and has demonstrated a flow resolution of 2.3% of full scale for linear flow velocities up to 10 m.s^{-1} in preliminary studies with air. Other instruments are currently used to detect low levels of C_3F_8 vapour leaking into the N_2 environmental gas surrounding the ATLAS silicon tracker. Gas from several parts of the tracker is aspirated through two instruments and analyzed. A long duration continuous study of more than a year has demonstrated a sensitivity to mixture variation of better than 5.10^{-5}.**

The developed instrument has many applications where continuous knowledge of binary gas composition is required. Such applications include anaesthesia, the analysis of hydrocarbon mixtures, and vapour mixtures for semiconductor manufacture.

***Index Terms*—leak detection, fluid flow measurement, cooling, Large Hadron Collider, gas detectors, sensor systems**

I. INTRODUCTION

WE describe a combined ultrasonic gas mixture analyzer and flowmeter developed for the ATLAS experiment at CERN. The operation of the device is based on measurement of the sound velocity in the process gas in combination with the pressure and temperature. This instrument is used in several applications where precise real-time composition analysis of binary gas mixtures is required. We present two such applications, together with the corresponding instruments.

The sound velocity in a binary gas mixture at known temperature and pressure is a unique function of the molar concentrations of the components. Exploitation of this phenomenon offers the real-time monitoring of gas composition with high precision. This technique was first used in particle

---

R. Bates and A. Bitadze are with the School of Physics and Astronomy, University of Glasgow, G12 8QQ, UK (e-mail: r.bates@physics.gla.ac.uk, a.bitadze@physics.gla.ac.uk).

M. Battistin, S. Berry, J. Berthoud, P. Bonneau, J. Botelho-Direito, G. Bozza, O. Crespo-Lopez, B. DiGirolamo, E. Da Riva, G. Favre, J. Godlewski, D. Lombard and L. Zwalinski are with CERN, 1211 Geneva 23, Switzerland (e-mail: michele.battistin@cern.ch, jonathan.berthoud@cern.ch, stephane.berry@cern.ch, pierre.bonneau@cern.ch, jose.botelho.direito@cern.ch, gennaro.bozza@cern.ch, olivier.crespo.lopez@cern.ch, e.da.riva@cern.ch, beniamino.di.girolamo@cern.ch, gilles.favre@cern.ch, jan.godlewski@cern.ch, didier.lombard@cern.ch, lukasz.zwalinski@cern.ch).

N. Bousson, G. Hallewell, M. Mathieu and A. Rozanov are with the Centre de Physique des Particules de Marseille, 163 Avenue de Luminy, 13288 Marseille Cedex 09, France (e-mail: bousson@cppm.in2p3.fr, gregh@cppm.in2p3.fr, michel.mathieu@cern.ch, rozanov@cppm.in2p3.fr).

G. Boyd is with the Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA (e-mail: george.boyd@cern.ch).

C. Deterre is with Deutsches Elektronen-Synchrotron, Notkestrasse 85, D-22607 Hamburg, Germany (email: cecile.deterre@desy.de).

M. Doubek, V. Vacek and M. Vitek are with the Czech Technical University, Technick 4, 166 07 Prague 6, Czech Republic (e-mail: martin.doubek @cern.ch, vaclav.vacek@cern.ch, michal.vitek@cern.ch).

C. Degeorge is with the Physics Department, Indiana University, Bloomington, IN 47405, USA (e-mail: c.degeorge@cern.ch).

S. Katunin is with the B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI), 188300 St. Petersburg, Russia (e-mail: sergey.katunin @cern.ch).

N. Langevin is with the Institut Universitaire de Technologie of Marseille, University of Aix-Marseille, 142 Traverse Charles Susini, 13013 Marseille France (e-mail: langevin@cppm.in2p3.fr).

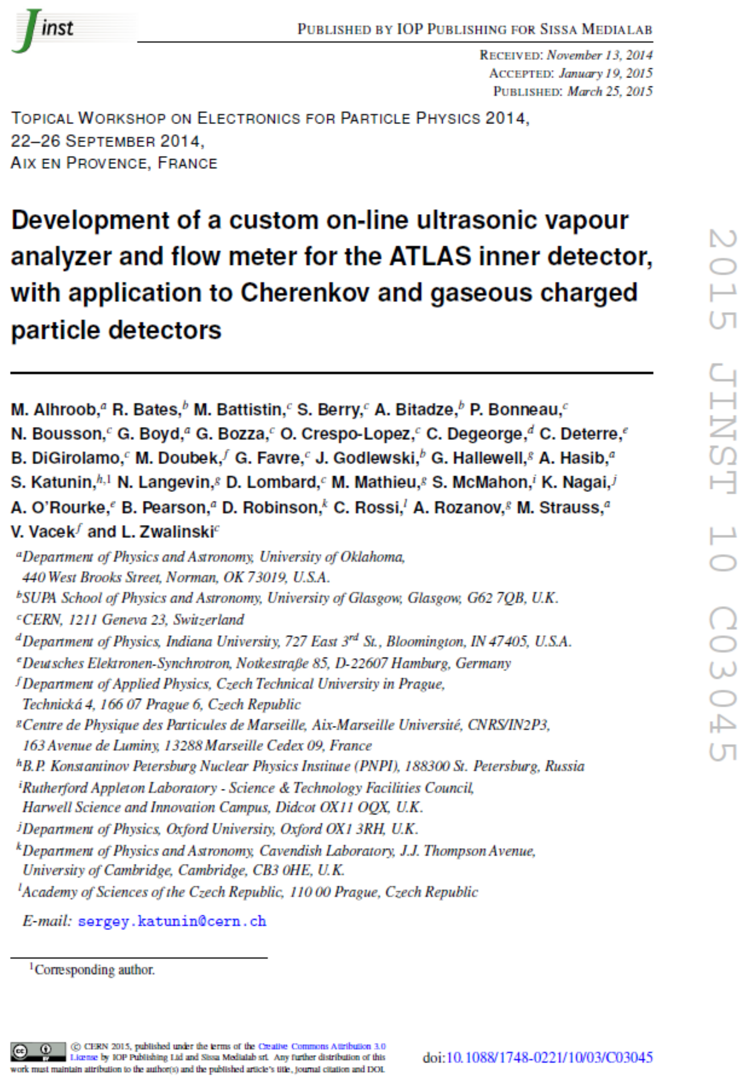
S. McMahon is with the STFC Rutherford Appelton Laboratory Harwell Oxford, Didcot OX11 OQX, UK (e-mail: stephen.mcmahon@cern.ch).

K. Nagai is with the Graduate School of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan (e-mail:koichi.nagai@cern.ch).

D. Robinson is with the Department of Physics and Astronomy, University of Cambridge, Cambridge, UK (email: robinson@hep.phy.cam.ac.uk).

C. Rossi is with the Department of Mechanical Engineering - Thermal Energy and Air Conditioning Division, Universit degli Studi di Genova, Via All'Opera Pia 15a - 16145 Genova, Italy (e-mail:cecilia.rossi@cern.ch).

Topical Workshop on Electronics for Particle Physics (TWEPP2014): Sept 2014 (JINST)



*J*inst PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *November 13, 2014*
ACCEPTED: *January 19, 2015*
PUBLISHED: *March 25, 2015*

TOPICAL WORKSHOP ON ELECTRONICS FOR PARTICLE PHYSICS 2014,
22–26 SEPTEMBER 2014,
AIX EN PROVENCE, FRANCE

Development of a custom on-line ultrasonic vapour analyzer and flow meter for the ATLAS inner detector, with application to Cherenkov and gaseous charged particle detectors

M. Alhroob,[a] R. Bates,[b] M. Battistin,[c] S. Berry,[c] A. Bitadze,[b] P. Bonneau,[c] N. Bousson,[c] G. Boyd,[a] G. Bozza,[c] O. Crespo-Lopez,[c] C. Degeorge,[d] C. Deterre,[e] B. DiGirolamo,[c] M. Doubek,[f] G. Favre,[c] J. Godlewski,[b] G. Hallewell,[g] A. Hasib,[a] S. Katunin,[h,1] N. Langevin,[g] D. Lombard,[c] M. Mathieu,[g] S. McMahon,[i] K. Nagai,[j] A. O'Rourke,[e] B. Pearson,[a] D. Robinson,[k] C. Rossi,[l] A. Rozanov,[g] M. Strauss,[a] V. Vacek[f] and L. Zwalinski[c]

[a] *Department of Physics and Astronomy, University of Oklahoma,*
440 West Brooks Street, Norman, OK 73019, U.S.A.
[b] *SUPA School of Physics and Astronomy, University of Glasgow, Glasgow, G62 7QB, U.K.*
[c] *CERN, 1211 Geneva 23, Switzerland*
[d] *Department of Physics, Indiana University, 727 East 3rd St., Bloomington, IN 47405, U.S.A.*
[e] *Deutsches Elektronen-Synchrotron, Notkestraße 85, D-22607 Hamburg, Germany*
[f] *Department of Applied Physics, Czech Technical University in Prague,*
Technická 4, 166 07 Prague 6, Czech Republic
[g] *Centre de Physique des Particules de Marseille, Aix-Marseille Université, CNRS/IN2P3,*
163 Avenue de Luminy, 13288 Marseille Cedex 09, France
[h] *B.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI), 188300 St. Petersburg, Russia*
[i] *Rutherford Appleton Laboratory - Science & Technology Facilities Council,*
Harwell Science and Innovation Campus, Didcot OX11 OQX, U.K.
[j] *Department of Physics, Oxford University, Oxford OX1 3RH, U.K.*
[k] *Department of Physics and Astronomy, Cavendish Laboratory, J.J. Thompson Avenue,*
University of Cambridge, Cambridge, CB3 0HE, U.K.
[l] *Academy of Sciences of the Czech Republic, 110 00 Prague, Czech Republic*

E-mail: sergey.katunin@cern.ch

---

[1] Corresponding author.

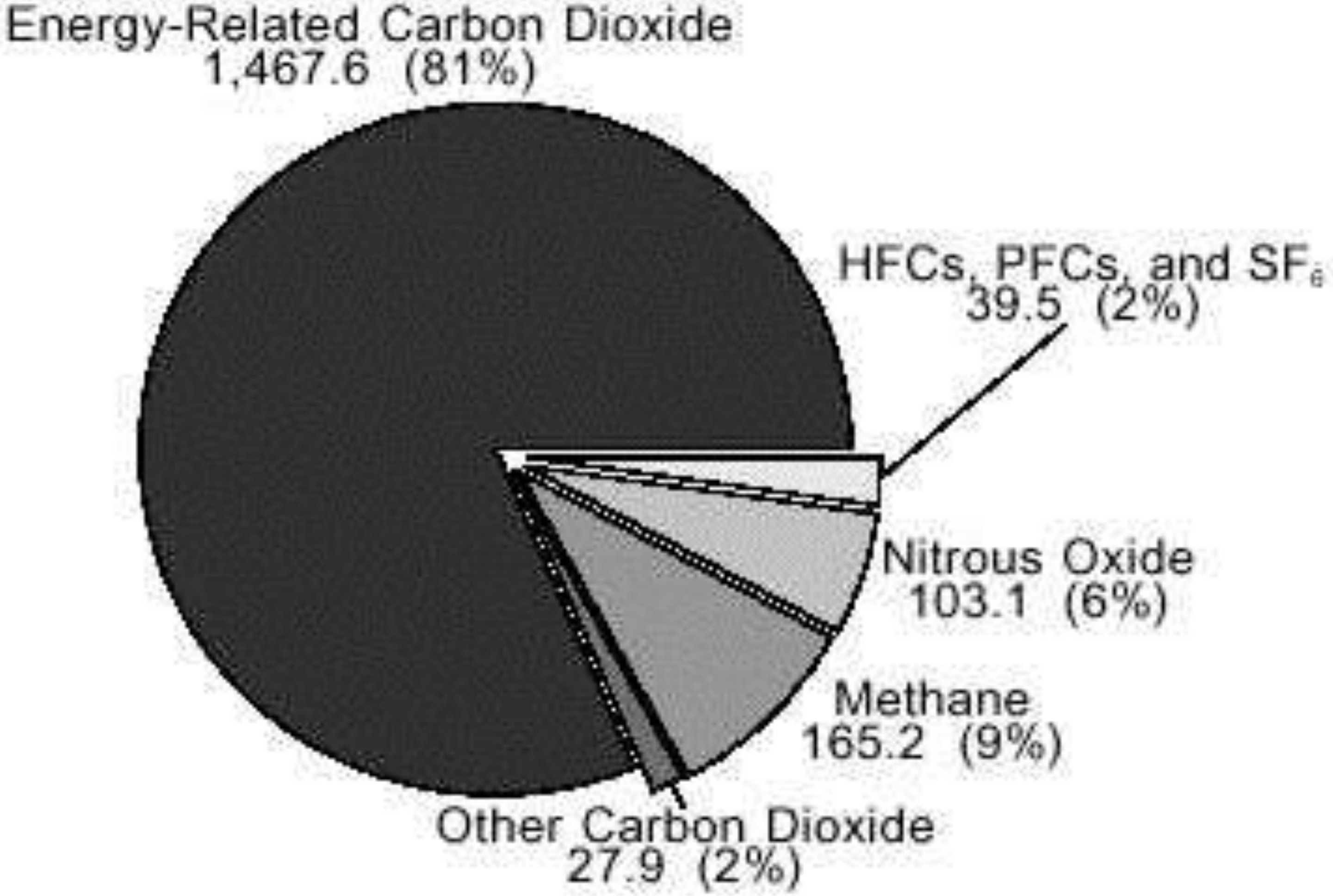
© CERN 2015, published under the terms of the Creative Commons Attribution 3.0 License by IOP Publishing Ltd and Sissa Medialab srl. Any further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation and DOI.

doi:10.1088/1748-0221/10/03/C03045

2015 JINST 10 C03045

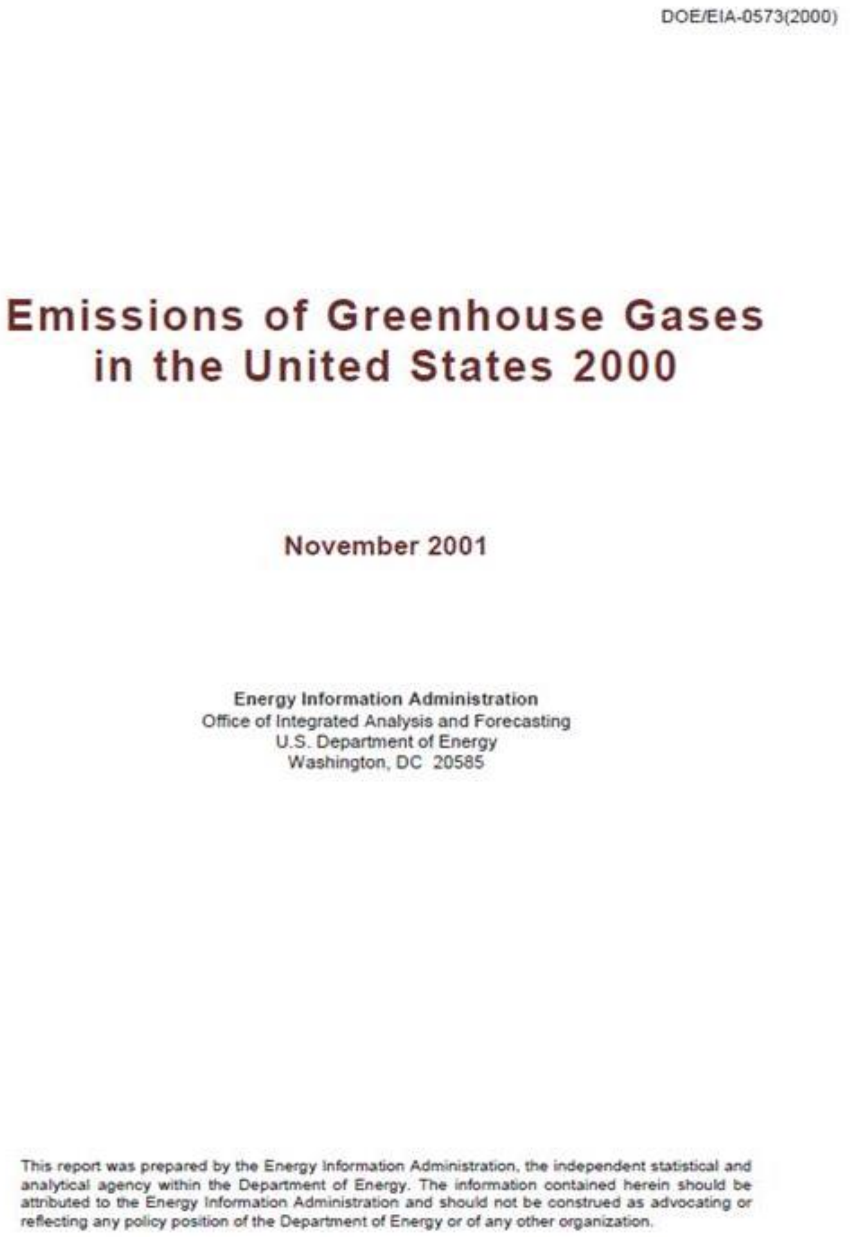
Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 1998

Million Metric Tons Carbon Equivalent



2000: US PFC emissions 8.8 Mtons C equivalent

Source: EIA estimates documented in this report.



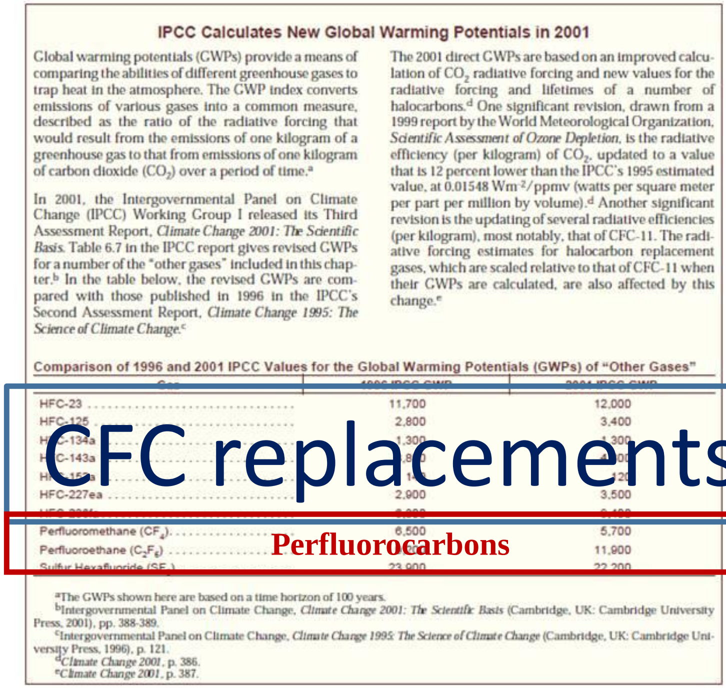
DOE/EIA-0573(2000)

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

This report was prepared by the Energy Information Administration, the independent statistical and analytical agency within the Department of Energy. The information contained herein should be attributed to the Energy Information Administration and should not be construed as advocating or reflecting any policy position of the Department of Energy or of any other organization.



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	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
HFC-227ea	2,900	3,500
[illegible]	[illegible]	[illegible]
Perfluoromethane (CF_4)	6,500	5,700
Perfluoroethane (C_2F_6)	[illegible]	11,900
Sulfur Hexafluoride (SF_6)	23,900	22,200

CFC replacements

Perfluorocarbons

---

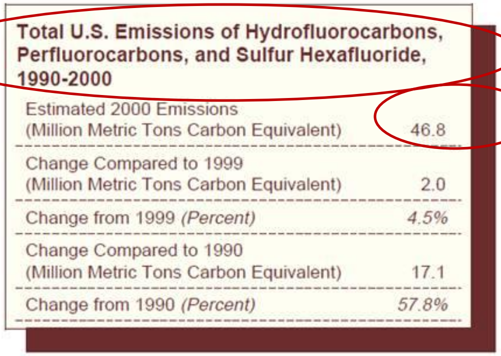
[a] The GWPs shown here are based on a time horizon of 100 years.

[b] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), pp. 388-389.

[c] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

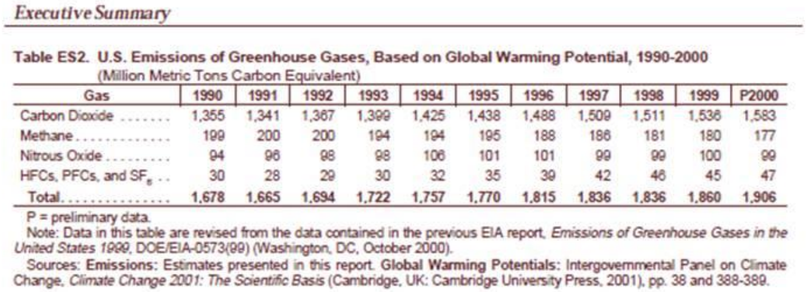
[d] *Climate Change 2001*, p. 386.

[e] *Climate Change 2001*, p. 387.



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%*



Executive Summary

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

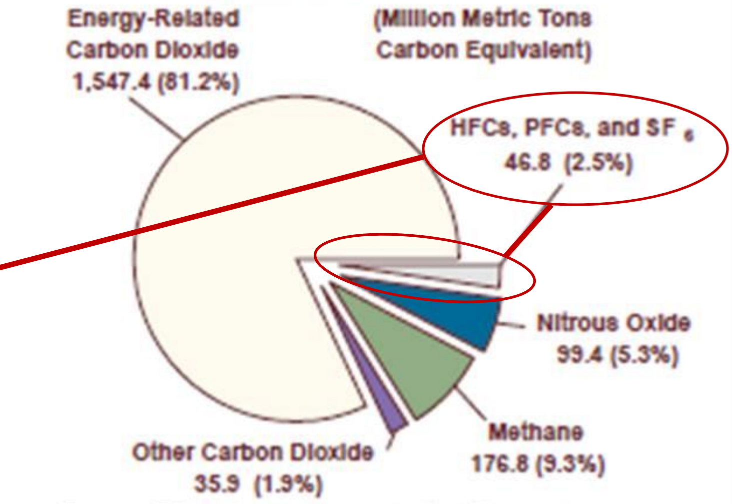
Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	P2000
Carbon Dioxide	1,355	1,341	1,367	1,399	1,425	1,438	1,488	1,509	1,511	1,536	1,583
Methane	199	200	200	194	194	195	188	186	181	180	177
Nitrous Oxide	94	96	98	98	106	101	101	99	99	100	99
HFCs, PFCs, and SF_6	30	28	29	30	32	35	39	42	46	45	47
Total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

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



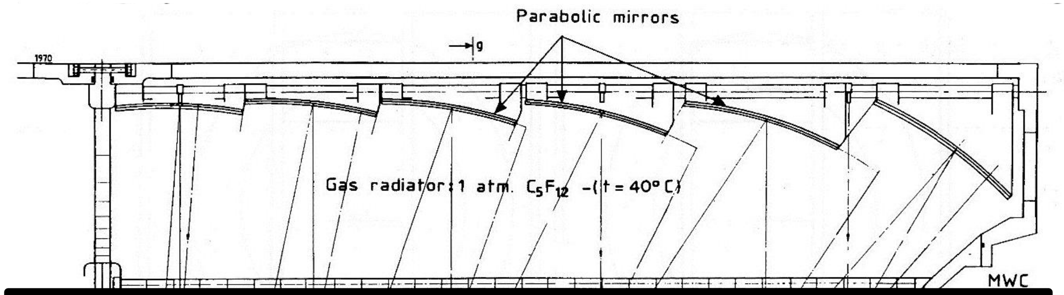
Source: EIA estimates presented in this report.

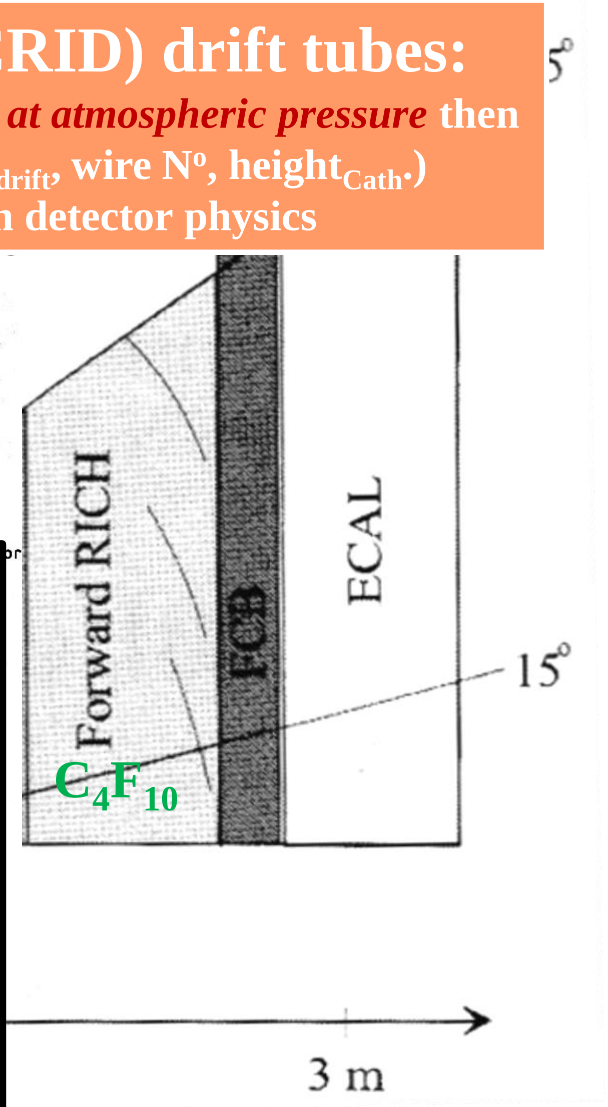
DELPHI RICH detector barrel $C_5F_{12\ vap}$ + C_6F_{14liq} radiators:
end-cap $C_4F_{10\ vap}$+ C_6F_{14liq} radiators:

DELPHI (SLD)Barrel RICH (CRID) drift tubes:

Drift single Cherenkov electrons up to 1.6m in gas *at atmospheric pressure* then spatially reconstruct them in 3-D to $1mm^3$ (T_{drift}, wire Nº, $height_{Cath}$.)

➔ still the greatest Q.C. achievement in detector physics





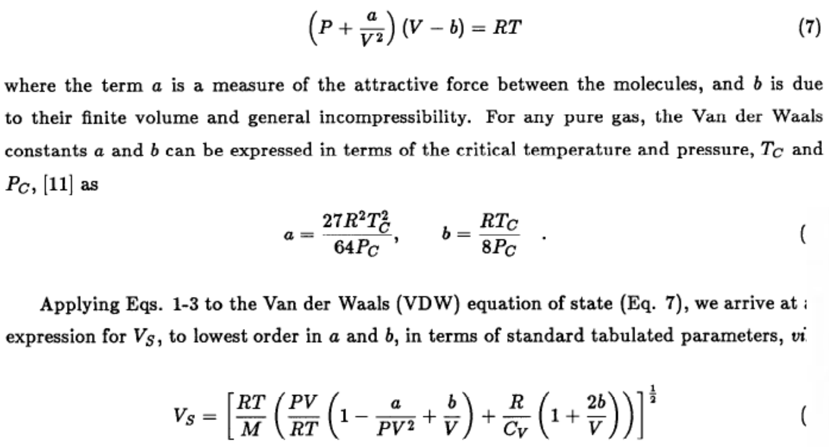
Barrel : liq. C_6F_{14} & C_5F_{12} gas radiator:
π/K/p (e/π) separation to 30 (6) GeV/c.

End cap: liq. C_6F_{14} & C_4F_{10} gas radiator:
Similar performance to barrel

Flutec PP1, Flutec PP50, 3M PF-5040

For most gases and certainly mixtures we need more realistic equations of state

Simplest 'realistic' is the Van der Waals EOS:



$$\left(P + \frac{a}{V^2}\right)(V - b) = RT \qquad (7)$$

where the term a is a measure of the attractive force between the molecules, and b is due to their finite volume and general incompressibility. For any pure gas, the Van der Waals constants a and b can be expressed in terms of the critical temperature and pressure, T_C and P_C, [11] as

$$a = \frac{27R^2T_C^2}{64P_C}, \qquad b = \frac{RT_C}{8P_C} \quad .$$

Applying Eqs. 1-3 to the Van der Waals (VDW) equation of state (Eq. 7), we arrive at expression for V_S, to lowest order in a and b, in terms of standard tabulated parameters, vi

$$V_S = \left[\frac{RT}{M}\left(\frac{PV}{RT}\left(1 - \frac{a}{PV^2} + \frac{b}{V}\right) + \frac{R}{C_V}\left(1 + \frac{2b}{V}\right)\right)\right]^{\frac{1}{2}}$$

Problem: hard to find VDW coefficients for fluorocarbons in 1980s- approximate with those of hydrocarbons of similar n-structures…

Other 'Empirical' EOS, e.g. Benedict-Webb-Rubin use 'reduced parameters' to calculate compressibility (Z=PV/T) etc.
and can be combined with 'mixing rules'.

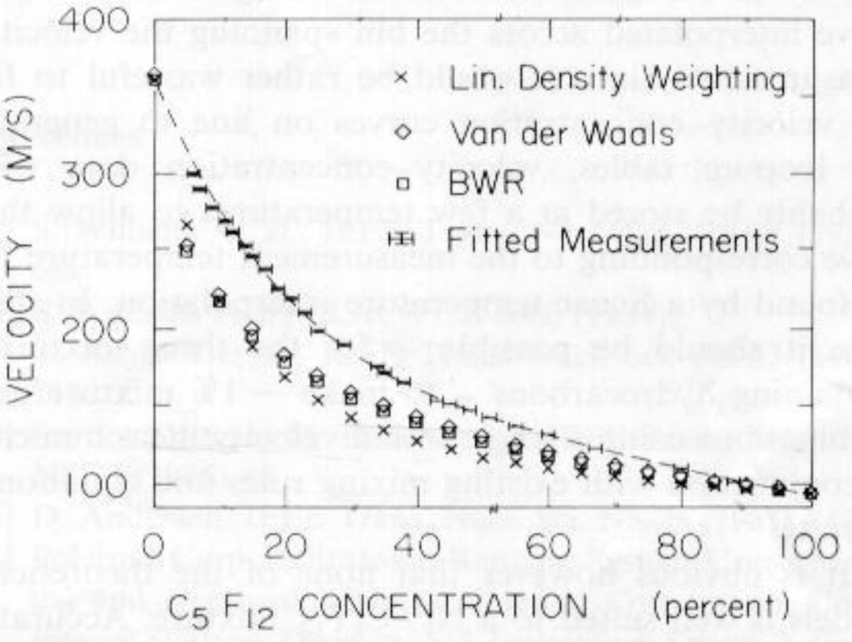


Fig. 16. Variation of sound velocity with concentration of C_5F_{12} in N_2 at 41 °C: comparison between fitted measurements and predictions.

Speed of sound is a valuable tool in EOS verification:

EOS have developed significantly since 1990s: and new thermodynamic parameters have been extensively added to NIST databases for saturated fluorocarbons: R218 (C_3F_8), R116 (C_2F_6) or R610 (C_4F_{10})

(Vaclav Vacek et al Czech Technical University, Prague for ATLAS collaboration)

most recently the new PC SAFT EOS

("Perturbed Chain Statistical Associating Fluid Theory")

PC-SAFT equation of state adopts a hard-sphere chain fluid as a reference fluid. The EOS, contains a reference hard-chain EOS and a perturbation

$$\frac{A}{NkT} = \frac{A^{hc}}{NkT} + \frac{A^{pert}}{NkT} \qquad Z = Z^{hc} + Z^{pert}$$

***Z**=Pv/(RT) is the compressibility factor,*
***P** is the pressure,*
***v** is the molar volume,*
***R** denotes the gas constant,*
***T** is the absolute temperature,*
***A** is the Helmholtz free energy,*
***N** is the total number of molecules,*
***k** is the Boltzmann constant,*

*and superscripts **hc**, and **pert** denote the hard-sphere chain reference equation of state, and the perturbation contribution, respectively*

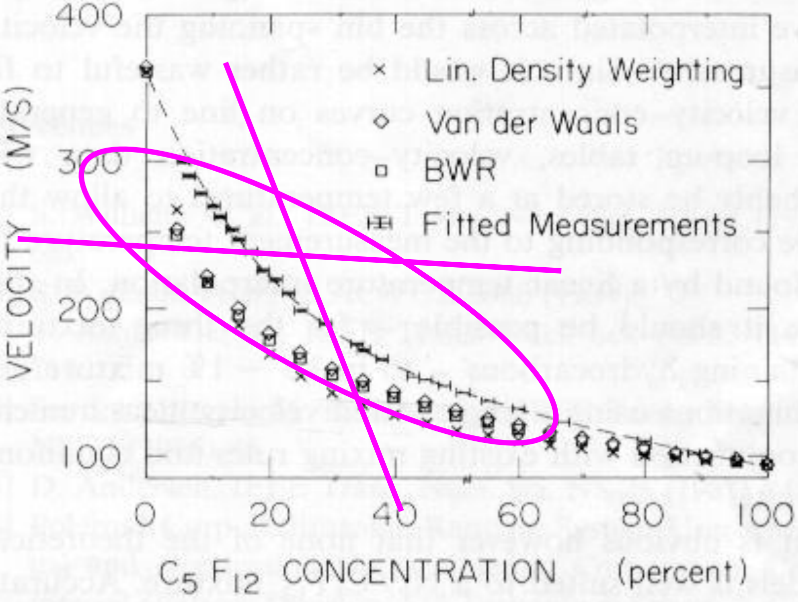


Fig. 16. Variation of sound velocity with concentration of C_5F_{12} in N_2 at 41°C: comparison between fitted measurements and predictions.

Valorisation (3)

Ultrasonic Time-of-Flight Method for On-Line Quantitation of in Situ Generated Arsine

Jorge L. Valdes* and Gardy Cadet
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

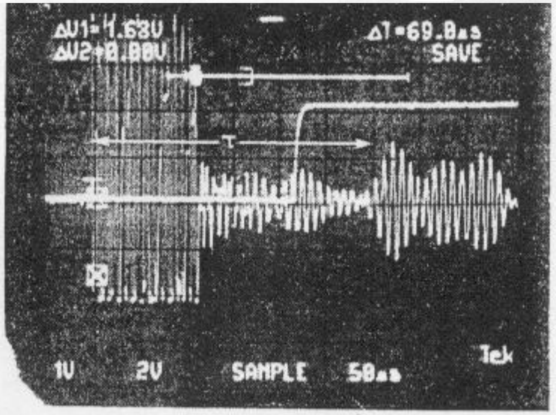


Figure 5. Acoustic spectrum for a binary mixture consisting of 0.019 mole fraction arsine in hydrogen.

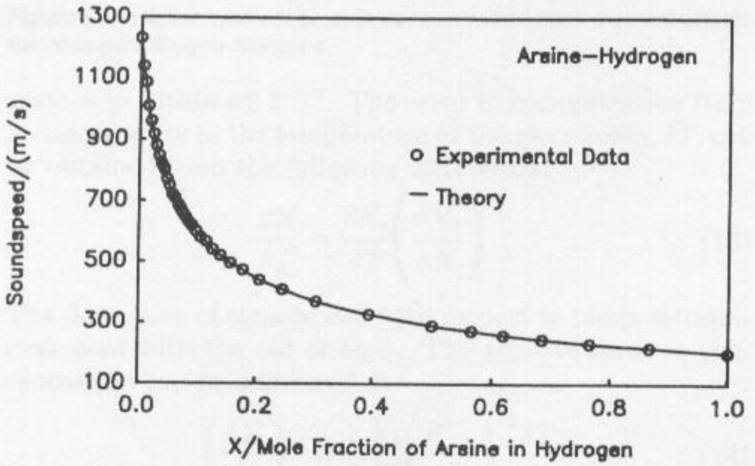


Figure 6. Comparison of experimental (O) and theoretical (—) soundspeed vs mole fraction of arsine for the arsine/hydrogen system.

A Simplified Formula for the Analysis of Binary Gas Containing a Low Concentration of a Heavy Vapor in a Lighter Carrier

Greg D. Hallewell[1] and Lawrence C. Lynnworth[2]

entre de Physique des Particules de Marseille
Université d'Aix-Marseille II
163 Avenue de Luminy
13288 Marseille, France

[2]Panametrics, Inc.
221 Crescent Street
Waltham, MA 02154-3497
USA

TABLE 2

TMI Concen. in H_2	c_{mix} (ms^{-1} @ 20°C) [Eq. 3]	c_{mix} (ms^{-1} @ 20°C) [Eq. 4a,c]	$\Delta c_{mix}/c_{mix}$ [Eq.4a,c] (%)	Toluene Concen. in Air	c_{mix} (ms^{-1} @ 20°C) [Eq. 3]	c_{mix} (ms^{-1} @20°C) [Eq. 4a, c]	$\Delta c_{mix}/c_{mix}$ [Eq. 4a,c] (%)
0	1302.95	1302.95	0	0.0059	340.06	340.71	0.19
0.0001	1297.78	1297.83	0.00	0.0060	340.00	340.67	0.20
0.0002	1292.62	1292.76	0.01	0.0061	339.95	340.63	0.20
0.0003	1287.46	1287.75	0.03	0.0062	339.89	340.58	0.20
0.0004	1282.29	1282.80	0.04	0.0063	339.84	340.54	0.21
0.0005	1277.13	1277.90	0.06	0.0064	339.78	340.50	0.21
0.0006	1271.96	1273.06	0.09	0.0065	339.73	340.45	0.21
0.0007	1266.80	1268.27	0.12	0.0066	339.68	340.41	0.21
0.0008	1261.64	1263.54	0.15	0.0067	339.62	340.37	0.22
0.0009	1256.46	1258.85	0.19	0.0068	339.57	340.32	0.22
0.0010	1251.30	1254.22	0.234	0.0069	339.51	340.28	0.23
0.0011	1246.14	1249.64	0.28	0.0070	339.46	340.24	0.23
0.0012	1240.97	1245.10	0.30	0.0071	339.40	340.20	0.24
				0.0072	339.35	340.16	0.24

simplified formula (Eq. 3a), and the equation of V & C, which they used to accurately compute sound velocity in mixtures of a heavy additive gas (arsine) in a light carrier (H_2) for an MOCVD application.

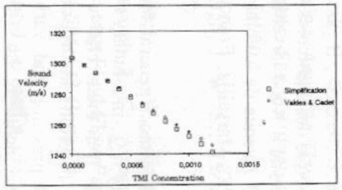


Fig 1a. Sound velocity calculated with the proposed simplification and the V & C equation as a function of (0-0.12%) tri-methyl-indium concentration in hydrogen.

Tri-Methyl-Indium/H_2

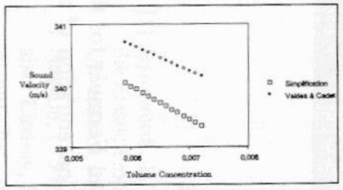


Fig 1b. Sound velocity calculated with the proposed formula and with the V & C equation as a function of (0.59-0.72%) toluene concentration in dry air.

Toluene-Air

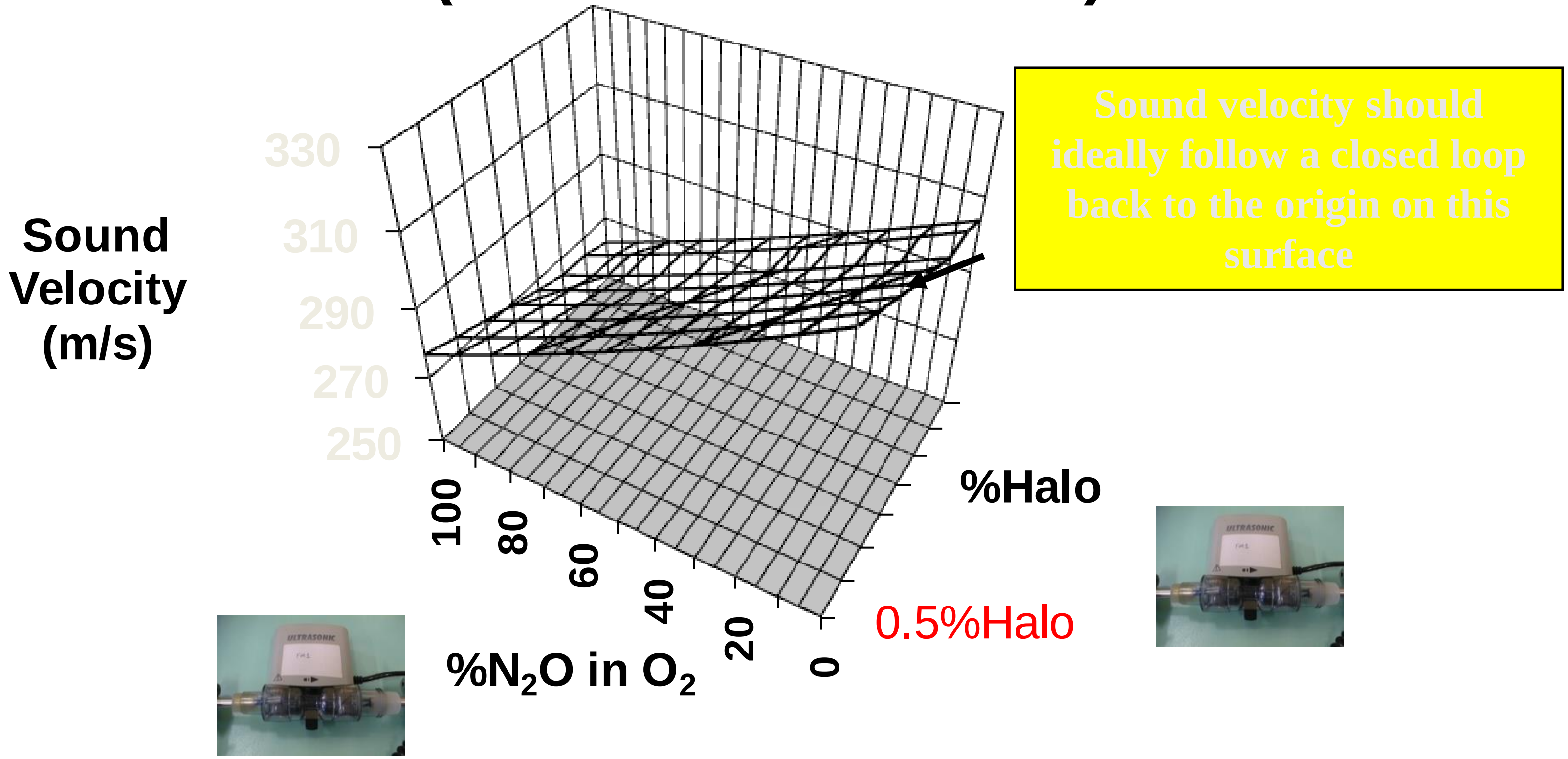
The dependence of sound velocity [calculated with Eq. 3a and with the V & C equation] upon the

1994 ULTRASONICS SYMPOSIUM – 1313

"With your consent we can experiment further still"
Centre Hospitalier Universitaire de Genève, aout 2000)

Exemple: variation de vitesse de son dans mélange 3-composants (2 cellules sonar) en anesthésie – étude fait a l'hôpital Cantonal de Genève (CHUG) (2000).

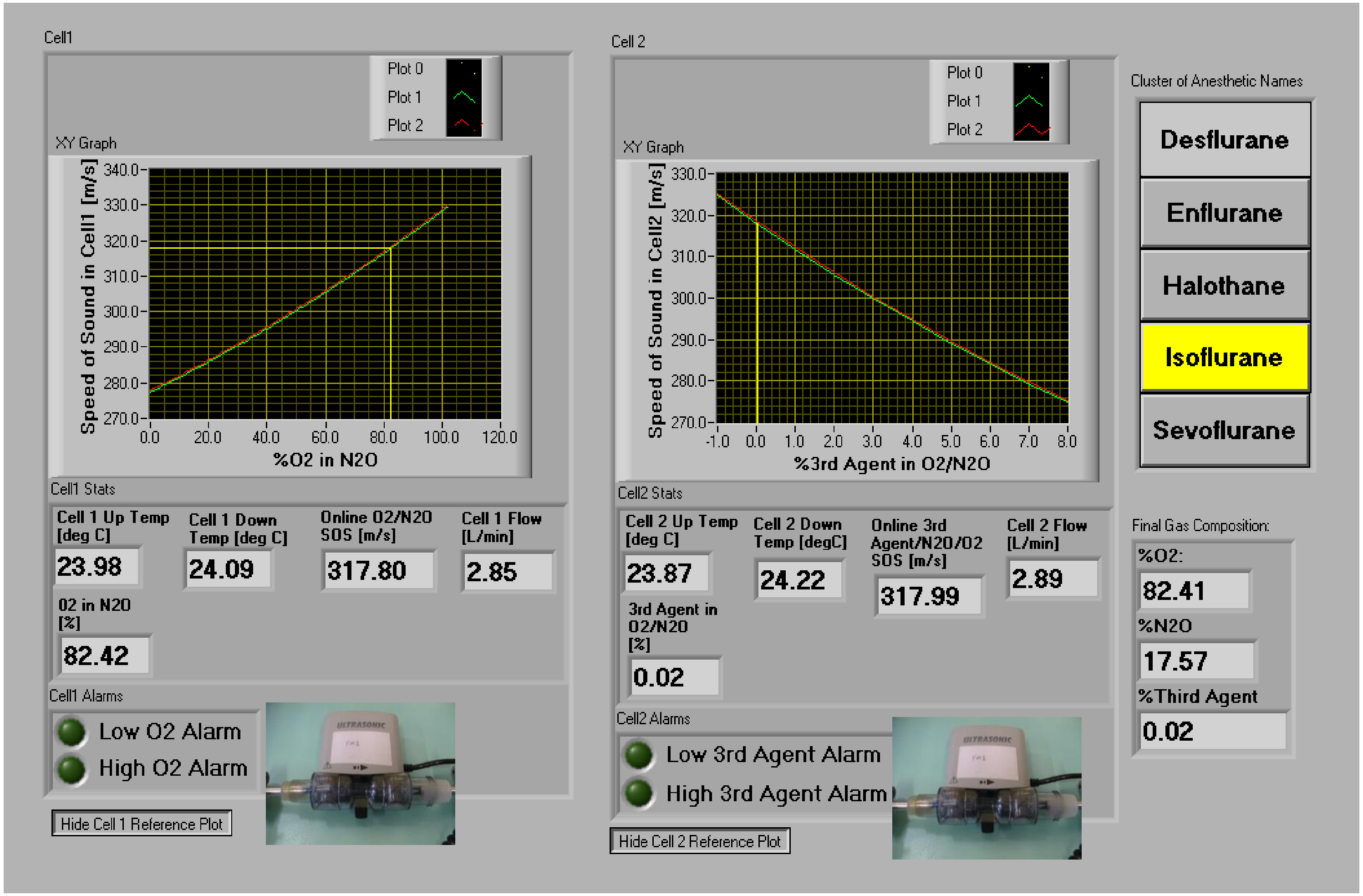
Sound velocity *vs.* %N_2O in O_2,
(% Halothane variable)



Sound velocity should ideally follow a closed loop back to the origin on this surface

LabView front panel ofprospective instrument performing complete 3-component anesthetic gas analysis via velocity of sound

(Scott Lindsay; U. Melbourne)

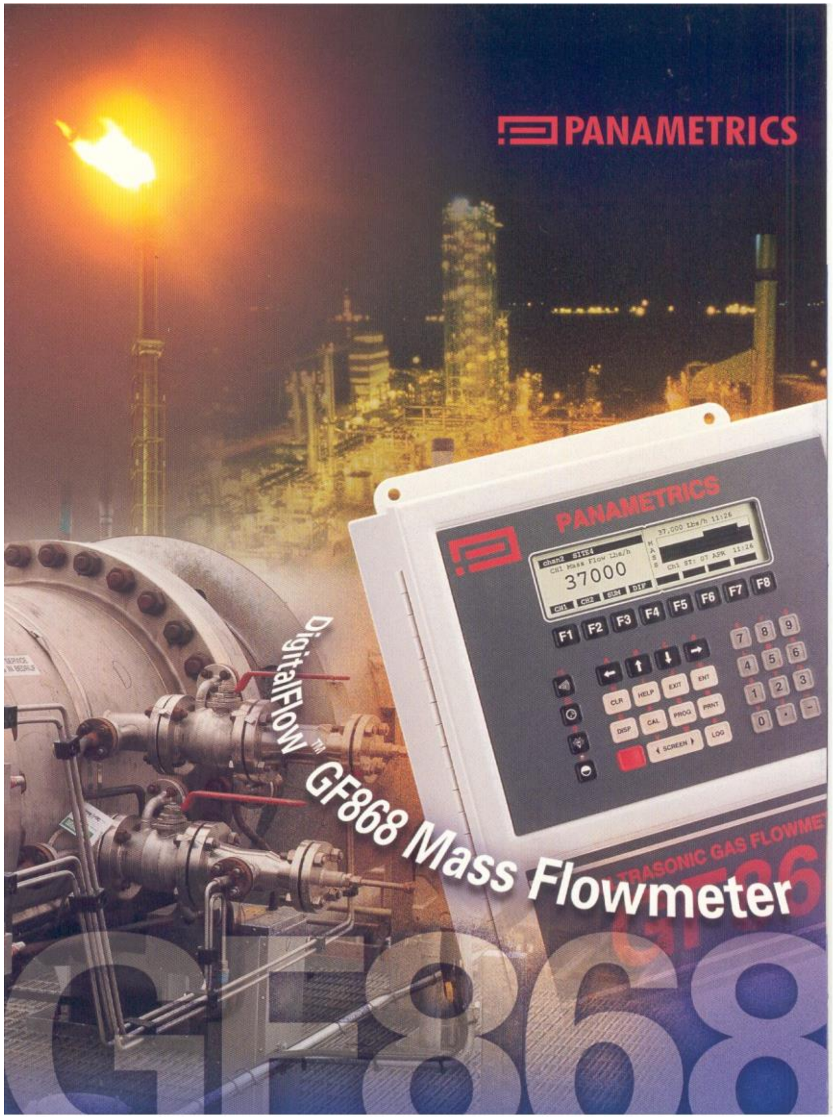


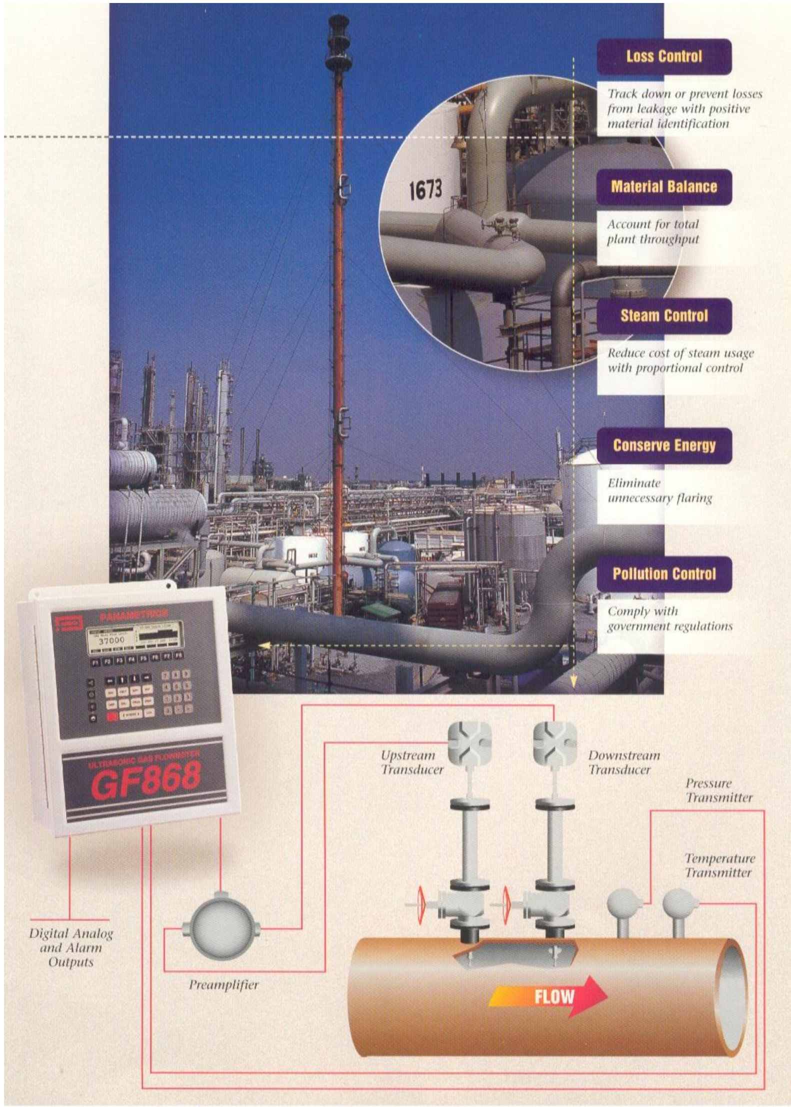
Cell 1 Up Temp [deg C]: 23.98
Cell 1 Down Temp [deg C]: 24.09
Online O2/N2O SOS [m/s]: 317.80
Cell 1 Flow [L/min]: 2.85
O2 in N2O [%]: 82.42

Cell 2 Up Temp [deg C]: 23.87
Cell 2 Down Temp [degC]: 24.22
Online 3rd Agent/N2O/O2 SOS [m/s]: 317.99
Cell 2 Flow [L/min]: 2.89
3rd Agent in O2/N2O [%]: 0.02

Final Gas Composition:
%O2: 82.41
%N2O: 17.57
%Third Agent: 0.02

Combined UFM, Molecular weight analyzer for hydrocarbons up to MW =58 (iso C_4F_{10})




Loss Control

Track down or prevent losses from leakage with positive material identification

Material Balance

Account for total plant throughput

Steam Control

Reduce cost of steam usage with proportional control

Conserve Energy

Eliminate unnecessary flaring

Pollution Control

Comply with government regulations

Investigate the adaptation of an oxygen flowmeter (neonates) as a combined flowmeter analyzer for anaesthetic gas mixtures

Interim Report on a Sonar Gas Analyser for Anaesthesia
Based on the "Spirocell" Ultrasonic Flowmeter:
Results of Tests at Hôpital Cantonal de Genève, Aug 6-10

Greg Halle

We report on tests ma
Universitaire de Gen
agreement of Professo
808 anaesthesia gas d
of oxygen, nitrous oxi

Transit time measuren
the three flowmeters
calibrated NTC (negat
Nitrous Oxide and Ox
Data were taken with
equipment was lent
software.

Results from analysis
the third anaesthetic a
can make an approac
agreement to add a mi

Table (

Gas	Chem Form
Oxygen	O_2
Nitrous Oxide	N_2O

Table (1a)

Agent
Halothar AKA "fluot
Isofluran
Enfluran
Sevoflura
Desflura

Notes:. Enflu
Halothane is
obtain a sampl

Extensive look up tables compiled of sound velocity at measured temp vs. % Halo/Iso/En/Des/

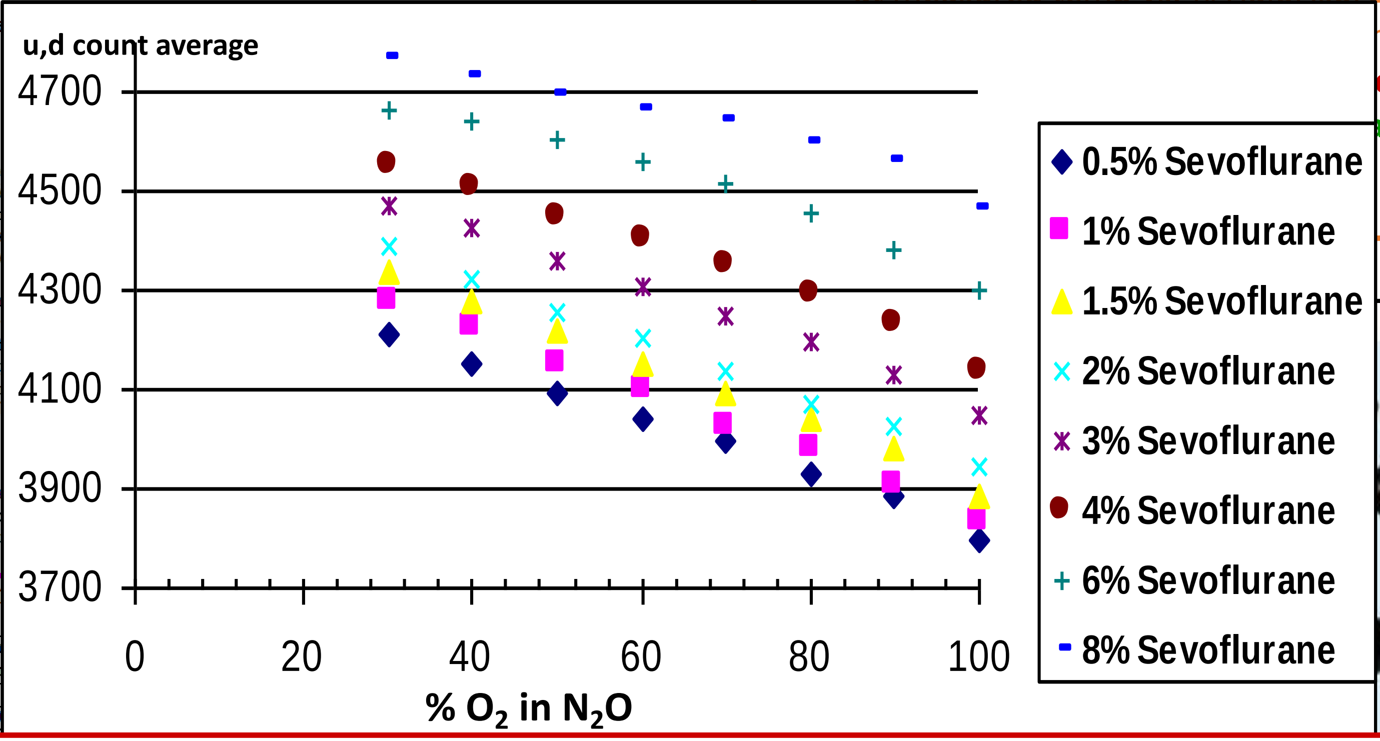
maries

c gas cart

alyzer:

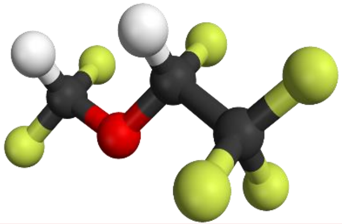
1%

1%

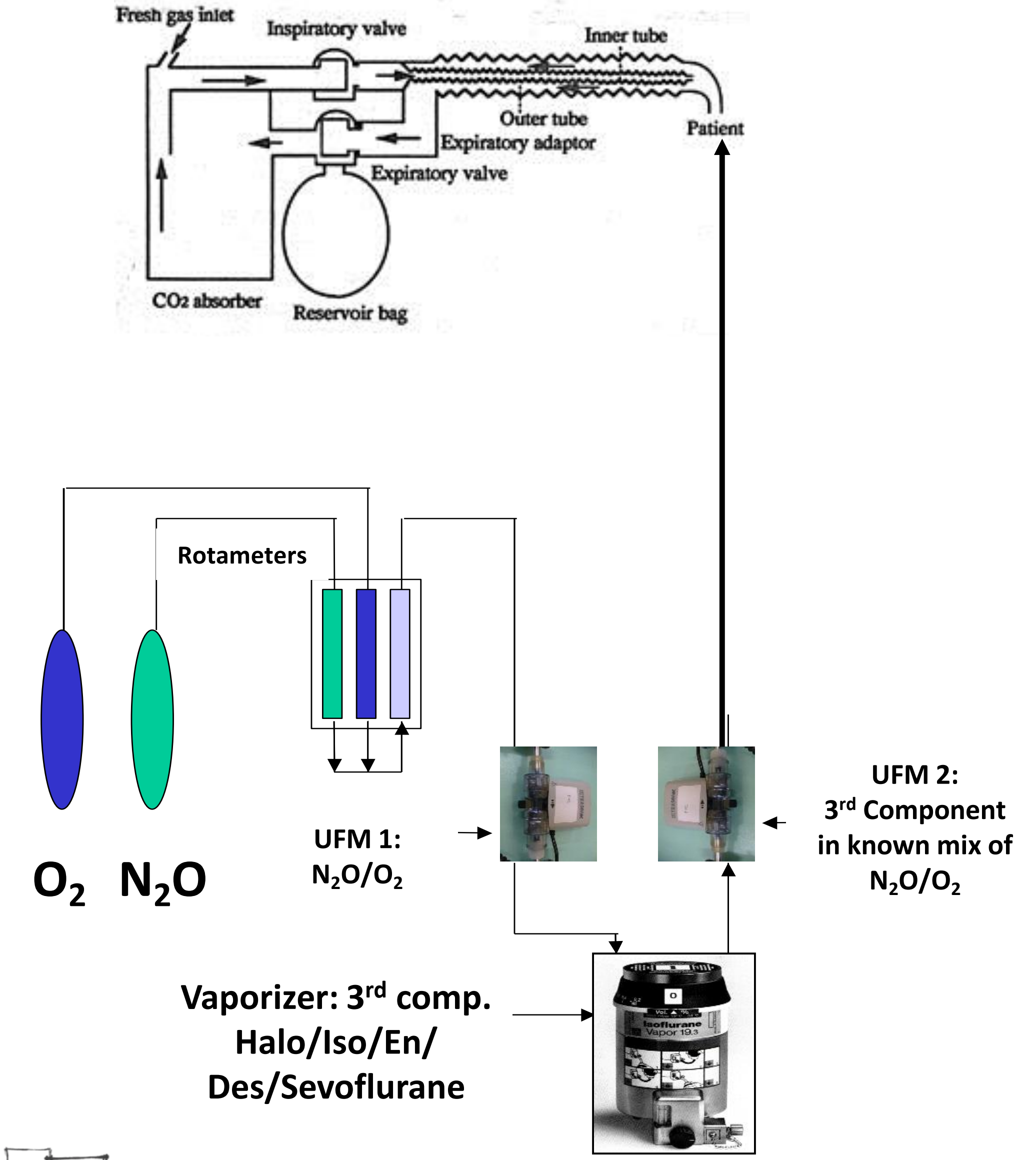


A familiar story, a heavy additive in a light carrier

Desflurane: CF2-H-O-CHF-CF3:
M.W. =168



Implementation & calibration



Rotameters

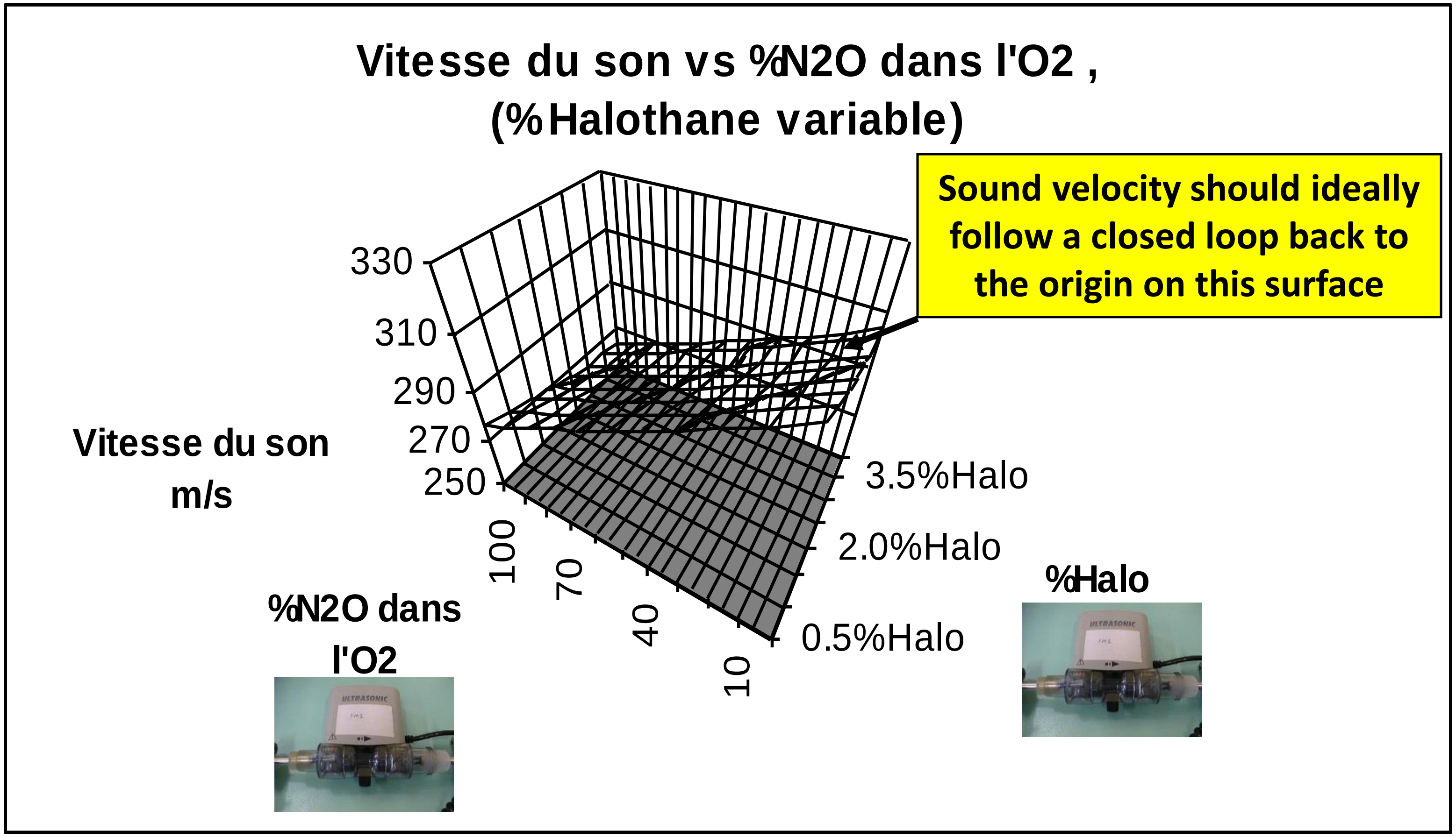
O_2 N_2O

UFM 1:
N_2O/O_2

UFM 2:
3rd Component
in known mix of
N_2O/O_2

Vaporizer: 3rd comp.
Halo/Iso/En/
Des/Sevoflurane

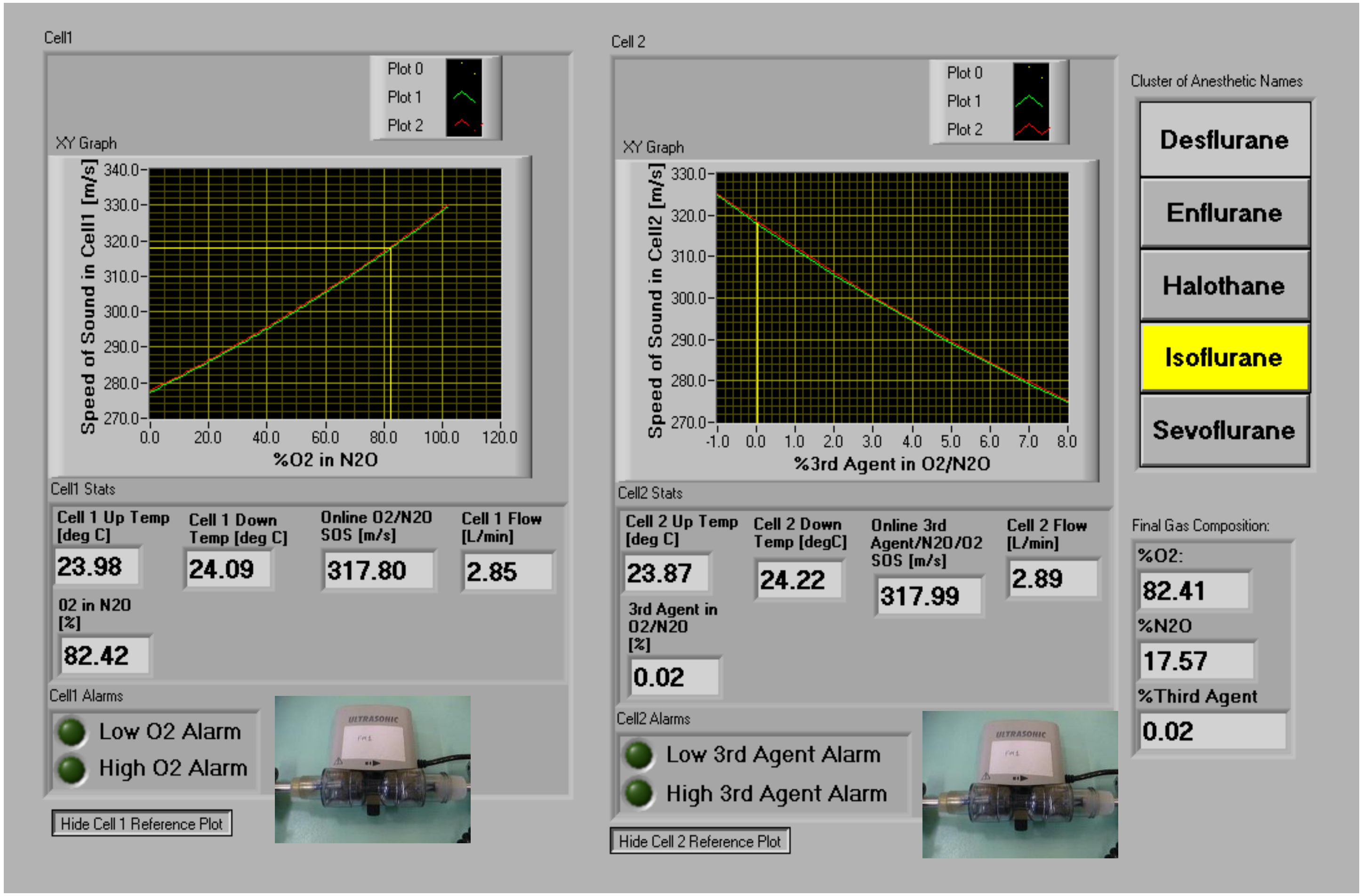
Example of sound velocity envelope in a 3-component anesthetic gas combination



Sound velocity should ideally follow a closed loop back to the origin on this surface

LabView front panel for a prospective instrument performing complete 3-component anesthetic gas analysis via velocity of sound

(Scott Lindsay; U. Melbourne)



Cell1 Stats

Cell 1 Up Temp [deg C] 23.98

Cell 1 Down Temp [deg C] 24.09

Online O2/N2O SOS [m/s] 317.80

Cell 1 Flow [L/min] 2.85

O2 in N2O [%] 82.42

Cell2 Stats

Cell 2 Up Temp [deg C] 23.87

Cell 2 Down Temp [degC] 24.22

Online 3rd Agent/N2O/O2 SOS [m/s] 317.99

Cell 2 Flow [L/min] 2.89

3rd Agent in O2/N2O [%] 0.02

Final Gas Composition:

%O2: 82.41

%N2O 17.57

%Third Agent 0.02

Familiar story, a heavy additive in a light carrier…

Ambiguity spoiler: CO_2 & N_2O have same MW (44) &similar C_p/C_v (1.316/1.303)

Present anesthetic delivery carts use two technologies for gas analysis:
IR absorption for N_2O &
volatile agent, electrochemical for O_2
Could a single technology
(speed of sound analysis)
replace the two?

Xenon long known for its good anesthetic properties – replacing N_2O in some applications, but expense (>10 CHF/litre @ NTP) requires closed recirc. systems
(Note: Halo/Iso/En/Des/Sevoflurane recovery also now common due to their high greenhouse potentials)
Xe does not have the MW & γ ambiguity with CO_2…

A role for PC-SAFT in predicting anesthetic mixture properties?