IFD 2014
INFN Workshop on Future Detectors for HL-LHC

Vertexing & Tracking Detectors

Local mechanical supports and cooling systems

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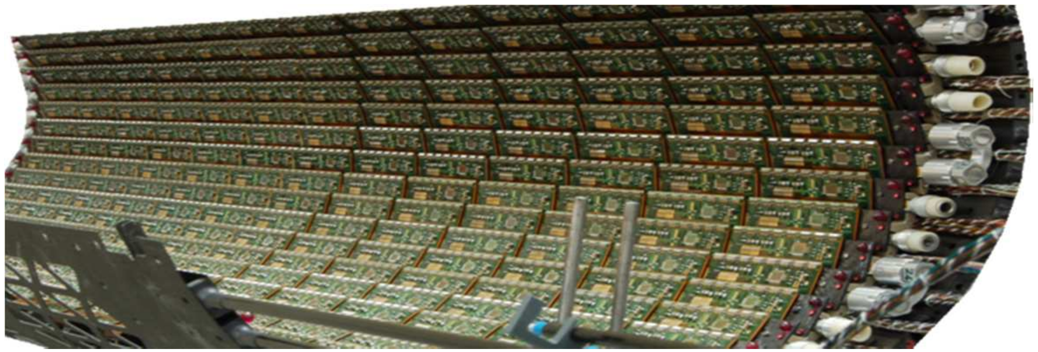
SUMMARY:

- STAVE DESIGN
- EVAPORATIVE PROCESS
- DETECTORS COOLING PLANT
- CERN TRACKERS UPGRADE OVERVIEW (FROM THE POINT OF VIEW OF THE COOLED SUPPORTS)
- R&D WORK IN PROGRESS

TRACKERS LOCAL SUPPORTS: THE CHALLENGE

USUAL STAVE REQUIREMENTS:

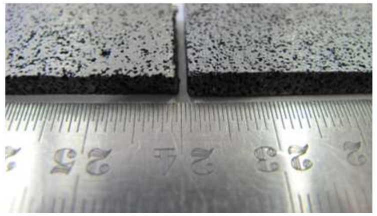
- TAKE IN PLACE WITH PRECISION THE TRACKER SENSORS
- THERMAL MANAGEMENT: EXTRACT THE DISSIPATED POWER (>1 W/cm^2)
- SUB-ZERO WORKING TEMPERATURES (WHEN IN HARD RAD. ENVIRONMENT)
- HOMOGENEOUS AND CONSTANT OPERATING TEMPERATURES
- ROBUST SYSTEM - AFFORDABLE - MAINTENANCE FREE
- LOW MATERIAL BUGET - GOOD X_0 – MINIMUM MASS SYSTEM
- STRUCTURAL STIFFNESS - NO VIBRATIONS
- LOW DEFORMATION – LOW C.T.E. MATERIALS – LOW MISMATCH (AMB. TO -40 °C)
- ELECTRIC AND FLUID CONNECTIVITY
- CORROSION COMPATIBILITY (COOLANT)
- PERFECT INTEGRATION SCHEME – ONE-STAVE-REMOVAL WHEN POSSIBLE



TECHNOLOGICAL OPTIONS MOSTLY PURSUED

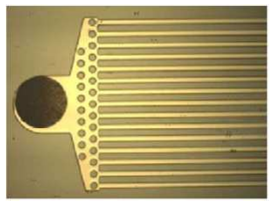
- «SUPPORT + COOLING SYSTEM» INTEGRATION

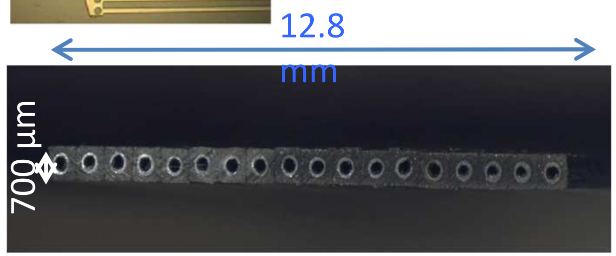
- CFRP CARBON FIBERS ULTRA-LIGHT SUPPORT STRUCTURES (HIGH RIGIDITY AND STRENGHT, LOW DENSITY, VERY LONG RAD. LENGTH, LOW %X0)
- CARBON FOAM MATERIALS (HIGH THERMAL CONDUCTIVITY, LOW DENSITY)
- EVAPORATIVE COOLING
- SMALL PIPES (Φ1-2 mm), EMBEDDED IN THE SUPPORT
- IMPROVED GLUE THERMAL CONDUCTIVITY (ADDITIVES EPOXY + BN, THIN LAYERS 50 μm)
- FLEX-BUS INTEGRATED IN THE STAVE



SOME EXPERIMENT ALREADY EXPLOITING MICRO-CHANNELING:

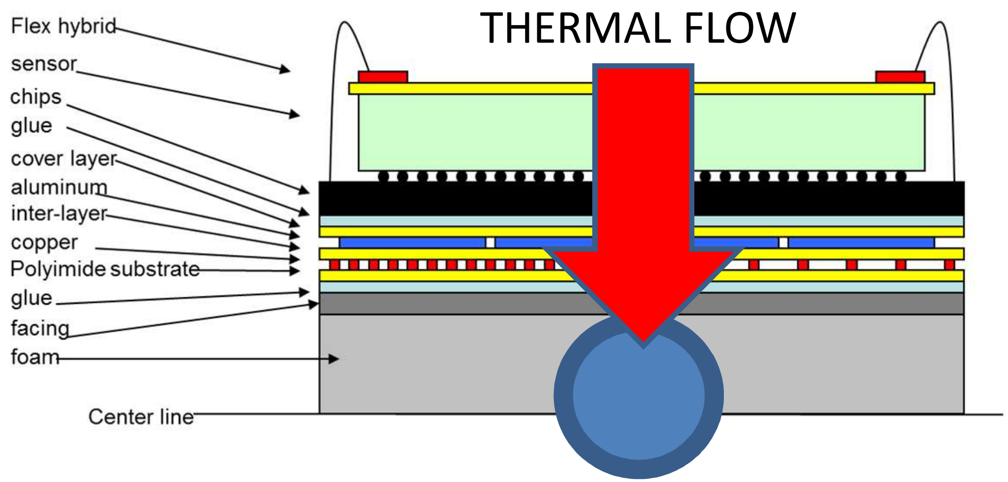
- SILICON MICRO-CHANNEL
- CARBON MICRO-CANNELS



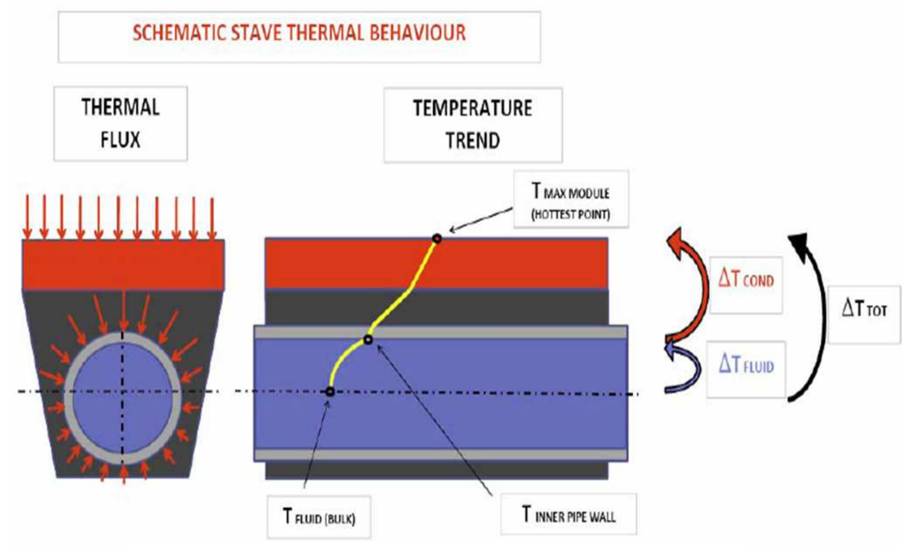


STAVE DESIGN GOAL

- MANAGE THE THERMAL LOADS
- EXPLOITING THE BEST MATERIALS THERMAL CONDUCTION
- THERMAL CONVECTION TOWARDS THE FLUID
- PHASE CHANGE WHEN USING THE EVAPORATING COOLANT



TYPICAL STAVE SECTION



THERMAL GRADIENTS

REQUIREMENT WITH HIGHLY IRRADIATED SENSORS

TO AVOID THERMAL RUNAWAY

=> OPERATIVE TEMP.ERATURE < - 5 °C

CHARACTERISTICS OF THE EVAPORATIVE PROCESS

- NEAR ISO-THERMAL => SMALL ΔT ALONG THE STAVE (LOW TEMP.GRADIENTS)
- EFFICIENT: high heat transfer coefficient (W/m^2K)
- ALLOWS SMALL TUBES: low material; easy bending; low forces due to CTE mismatch
- COOLANT => BOILING AT – 20 °C / - 40 °C inside the channel

DETECTOR COOLING FLUIDS

(RAD HARD, DIELECTRIC)

FLUOROCARBONS

C_2F_6 → MOST LIKELY CANDIDATES FOR LOW-TEMPERATURE OPERATION

C_3F_8

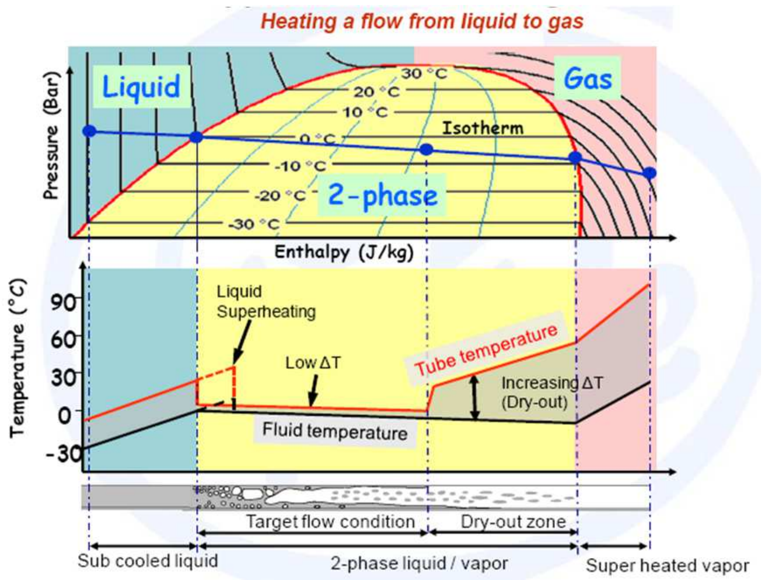
C_4F_{10}

C_6F_{14} => USED IN SINGLE PHASE FLOWS ONLY (NEED TO BE UNDER VACUUM FOR TEMPERATURES LOWER THAN 56 °C)

PURE OR BLENDED TO OBTAIN SPECS.

CARBON DIOXIDE CO_2 => HIGH LATENTHEAT, LOW PRESSURE DROP, more environmentally friendly and less expensive

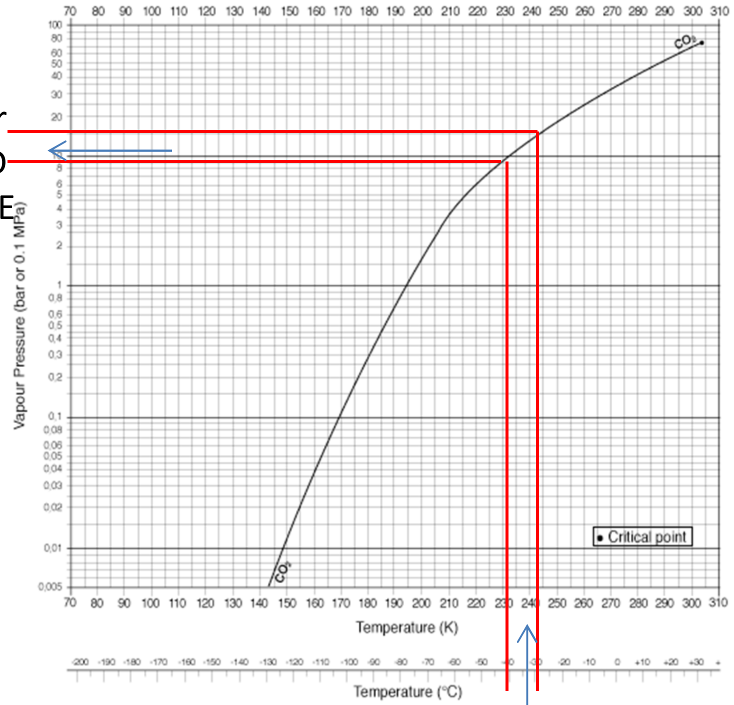
THERMODYNAMICS OF THE EVAPORATIVE PROCESS



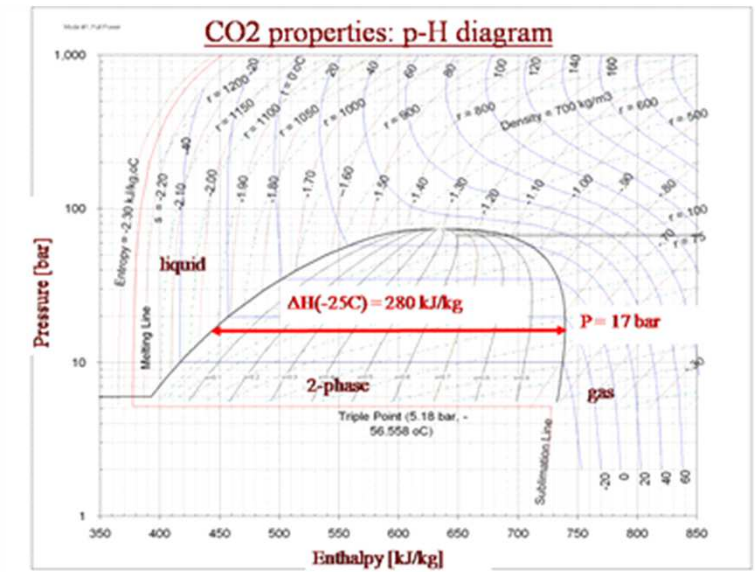
TEMPERATURE GRADIENTS

THE PURE CO2 SATURATION CURVE CORRELATES TEMPERATURE AND PRESSURE INSIDE THE EVAPORATION CHANNEL

=> 10 TO 20 bar COOLING FLUID OPER. PRESSURE



COOLING FLUID OPER. TEMP. - 20 / - 30 °C

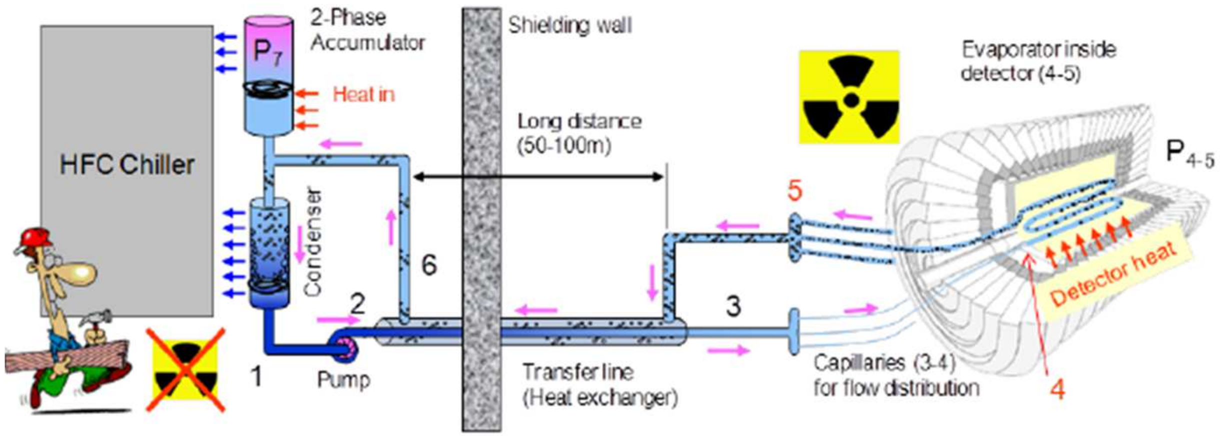


LATENT HEAT OF VAPORIZATION FOR CO2 IN THE RANGE OF INTEREST

DELTA H liq.=> vap. = 280 kJ/kg

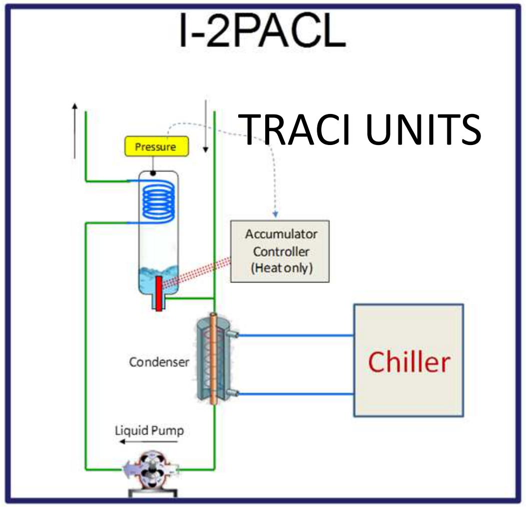
CERN EXPERIMENTS COOLING PLANT

2 PACL = 2-Phase Accumulator Controlled Loop

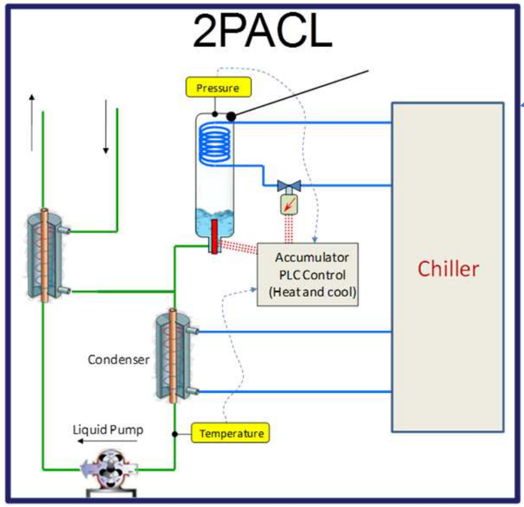


USES ONLY PASSIVE SYSTEMS IN THEUNACESSIBLE AREA

CERN EXPERIMENT DETECTOR COOLING CIRCUIT SKETCH



NEW INTEGRATED SYSTEM
patented: CERN & NIKHEF



Used at CERN for:

- LHCb Velo
- Atlas Pixel IBL
- CMS Pixel upgrade
- LHCb UT upgrade
- LHCb Velo microchannel upgrade

DETECTOR COOLING PLANT

- THE DETECTOR IS A PRESSURE SYSTEM
- CO_2 DESIGN PRESSURE ~ 100 bar (Safety Factor above the Critical Point pressure)
- Pipe material baseline: Stainless Steel or Titanium ~ 0.1 mm wall thickness

NOTES:

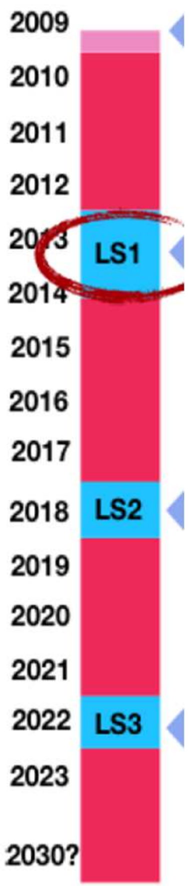
- OPERATIVE CONDITION LESS DEMANDING THAN <u>TRANSIENTS => DESIGN</u>
- THERMO-HYDRAULIC INSTABILITIES
- THE PROCESS IS DRIVEN BY MANIFOLDING AND CONNECTION DESIGN
- PRESSURE DROP AT THE INLET OF THE BOILING CHANNELS ALWAYS BENEFICIAL FOR STABILITY => CAPILLARY PIPES / FLOW RESTRICTIONS IN SILICON MICROCHANNELS

Design Parameters	Requirement
Max Operating Pressure	100 bar_a
Max Testing Pressure	150 bar_a
Minimum temperature	-40 °C
Max Temperature	+40 °C
Max ΔT to be considered for structural analysis	-60 °C
Integrated design radioactive dose	$5*10^{+6}$ Gy ($5*10^{+8}$ Rads)
Maximum leak rate per joint	10^{-7} atm.cc/s of He
Joint diameter range	3 ÷ 5 mm

Table 1 Specs and general parameters of the joint

TYPICAL DESIGN SPECIFICATION FOR A PIPE JOINT

UPGRADE OF THE CERN TRACKERS: TIMESCALE OVERVIEW



EXPERIMENT TRACKER	ACTUAL 2009-2012	long shutdown 2013/2014	Shutdown 2017/2018	long shutdown 2017/2018 => PHASE-II
ATLAS	PIXEL Evaporative fluorocarbon system	+ IBL PIXEL CO2 1.5 kW < BEAMPIPE DIAM		NEW TRACKER ALL SILICON CO2 > 200 kW
CMS	PIXEL Mono-phase fluorocarbon system		+ PIXEL REPLACEMENT CO2 15 kW < BEAMPIPE DIAM	NEW TRACKER ALL SILICON CO2
LHCb	VELO FIRST 2PACL AT CERN CO2 1.5 KW GOOD EXPERIENCE!		VELO FIRST SILICON MICRO-CHANNEL CO2 4 KW UT TRIGGER (STRIPS) CO2 4 KW	
ALICE	ULTRALIGHT SUPPORTS			=> VERY ULTRALIGHT ENHANCED COOLING < BEAMPIPE DIAM
NA-62 GTK	SILICON	MICRO-CHANNEL	CO2	

COMMON CONSIDERATIONS

in some cases:
PHASE-I UPGRADES
=> produce detectors that can operate successfully throughout PHASE-II

in other cases:
PHASE-I UPGRADES
⇒ provide an infrastructure that can facilitate the additional modifications necessary for PHASE-II

R&D for PHASE-II
=> builds on the design of the PHASE-I UPGRADES

demands of PHASE-II
=> may require the COMPLETE REPLACEMENT of some detectors

R&D for PHASE-II and PHASE-I UPGRADES
take place over the same 5 year period 2011-2016
=> .. competion for human and financial resources ..

OVERVIEW OF THE TRACKER UPGRADES: SOME CLUES FROM THE LOCAL SUPPORT AND COOLING POINT OF VIEW

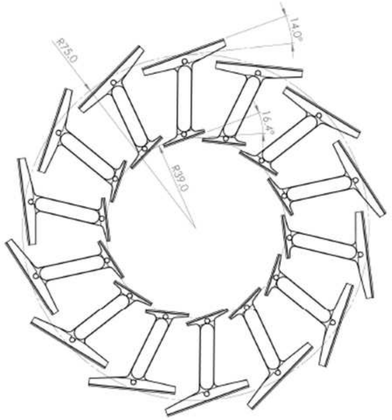
ATLAS PIXEL System

I-BEAM SOLUTION

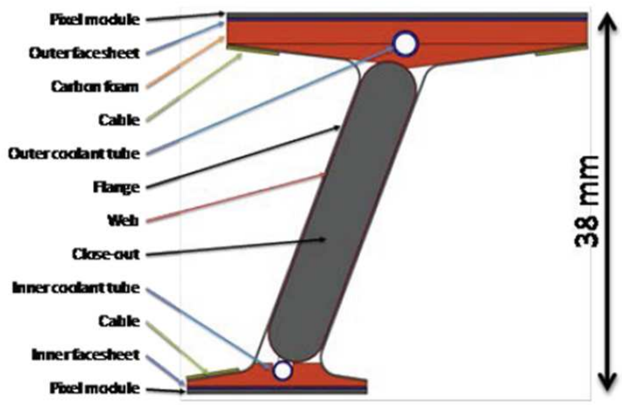
baseline for the innermost two layers

different module sizes in the two layers
not need an external support structure
bare stave contribution to the material budget is only 0.43 % X0 per layer (normal)

inherent stiffness
end-supported
allows fast replacement
can be mounted as "clam shells" for **extraction without breaking the LHC vacuum**.



layout of I-beams for two inner pixel layers



I-beam concept prototype

with CO_2 cooling

ATLAS PIXEL system
ALPINE ALTERNATIVE SOLUTION

new design NO BARREL & DIS
=> USE OF STAVES WITH SENSORS FACING THE I.P.

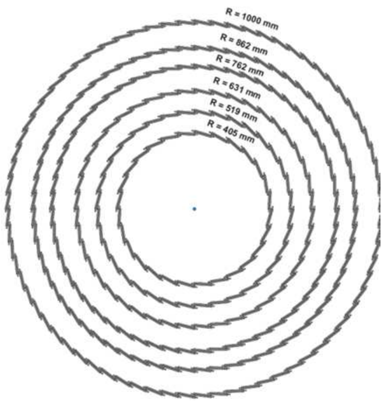
Prototype of an alpine stave

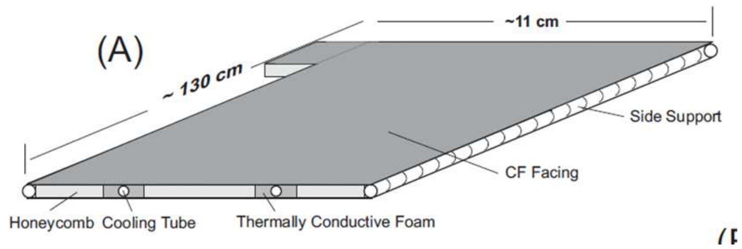
with CO2 cooling

ATLAS STRIP system

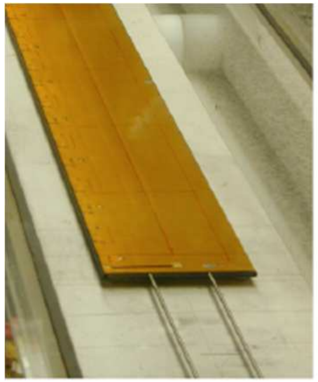
Extensive use of Sandwich technology

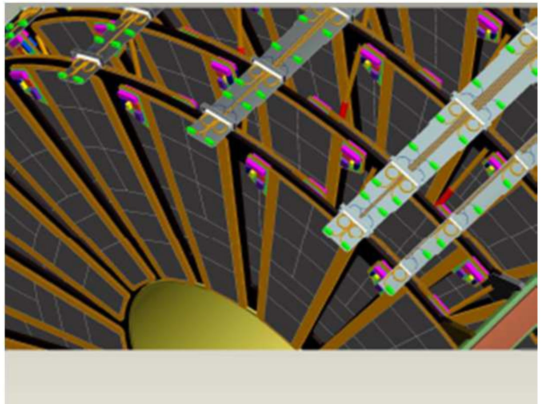
- carbon fibre facings
- core honeycomb/carbon foam
- embedded cooling pipe(s)

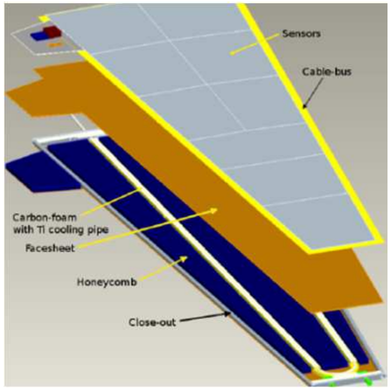


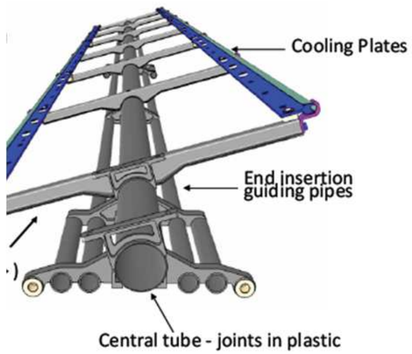


TYPICAL BARREL **STAVE**









TYPICAL DISK **PETAL**

with CO_2 cooling

COOLING SYSTEM
FOR ATLAS PHASE-II

ITK

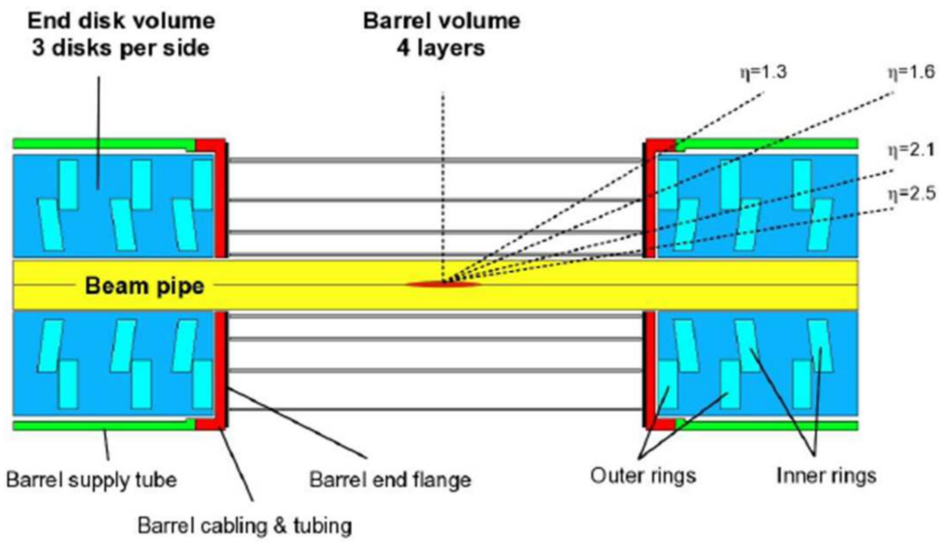
coolant temperature of - 35 °C

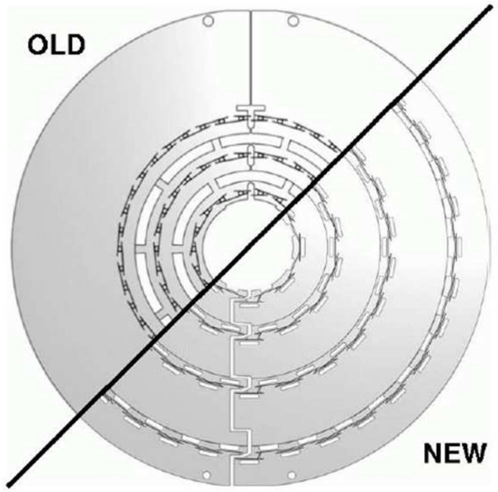
ESTIMATED POWER TO BE EXTRACTED
180 kW nominal
240 kW with safety-factors

large development needed
⇒ scale up an IBL-like design to about 20 Kw
⇒ and then install 10 or so identical copies

back-up option of using fluorocarbon cooling
⇒ will require a mixture of C_2F_6 / C_3F_8
⇒ to achieve the required temperatures

CMS Upgrade



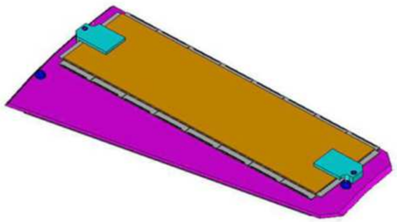


With CO2 cooling
15 kW
will replace the current single phase C_6F_{14}

<u>A fullscale system has been built in the CERN CryoLab</u>

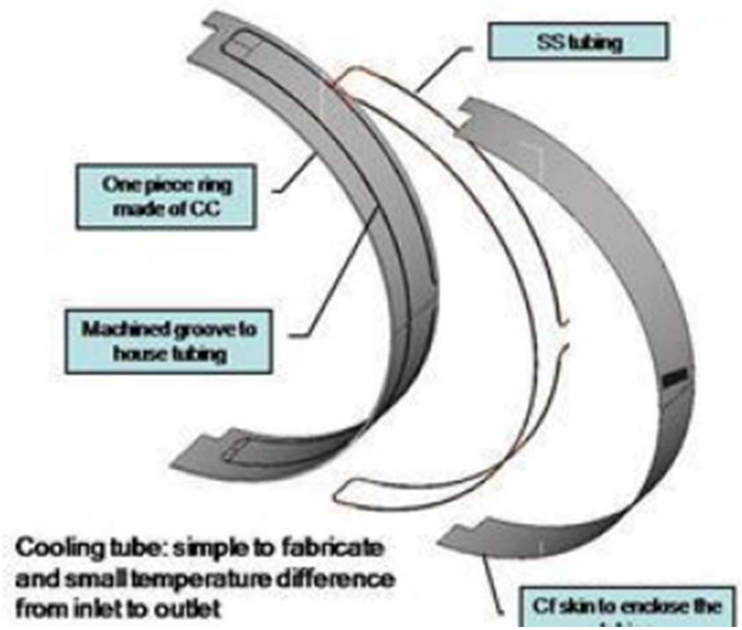
CMS Pixel System Upgrade

Prototype of the mechanical structure
for the innermost layer
mechanical stability of the ladder
is given by the cooling tubes



- Solid TPG*(0.68 mm thick)
- encapsulated with carbon-fiber facings (0.06 mm thick)

Edge Cooling Concept:
- carbon fiber skins
- carbon-carbon ring
- cooling tube captured inside



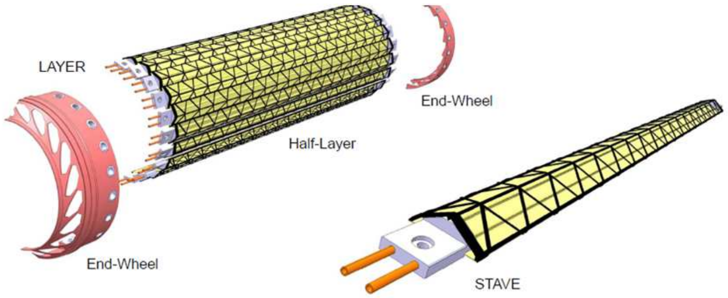
TPG =thermo-pyrolitic graphite
Thermal conductivity
Can reach 1500/1500/20 W/mK

ALICE Upgrade

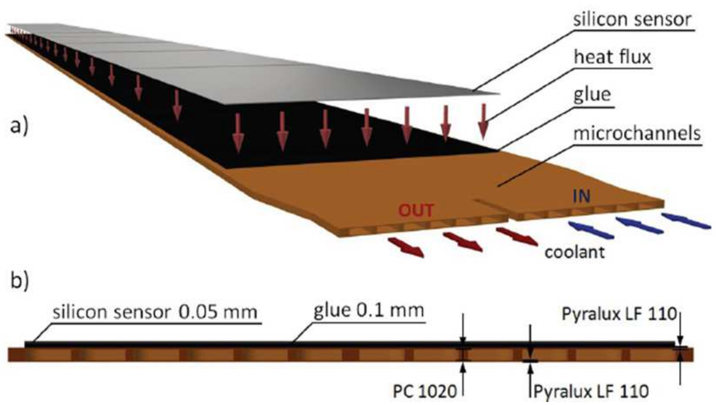
NEW ITS DETECTOR:

- MATERIAL BUDGET => VERY STRINGENT REQUIREMENTS => **ULTRALIGHT**
- THE DETECTOR WILL BE OPERATED AROUND **ROOM TEMPERATURE (+ 30 °C)**

- COOLING SYSTEM 15 KW
- **water flow** leakless (below atmospheric pressure)
- for the Inner Layers alternative coolants sconsidered C_4F_{10}



(a) ITS Inner Barrel design.



Microchannel cooling systems array fabricated either in:

- polyimide substrate
- silicon substrate

ALICE Upgrade

minimization of the material budget
Silicon microchannel cooling

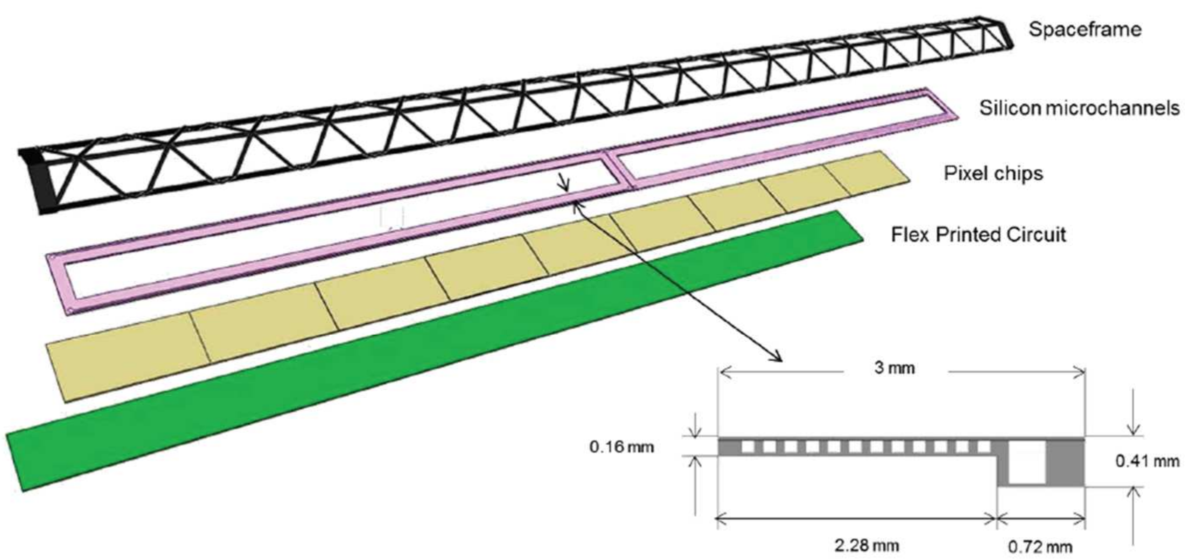


Figure B.8: Concept of the integration of the silicon micro-channel frames into the ITS IL stave.

LHCb Upgrade

- **<u>VELO UPGRADE</u>**

=> SILICON MICRO-CHANNEL

with CO2 cooling

- **<u>UT UPGRADE</u>**

DESIGN OPTIONS UNDER STUDY

with CO2 cooling

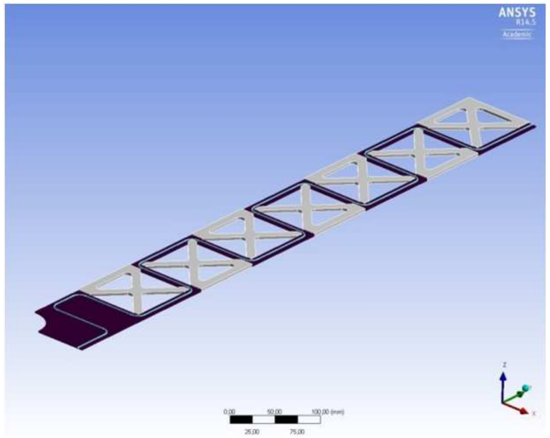
FOR THE NEW VELO AND UT DETECTORS

4000 W @ – 30 °C EACH

PLANNED DEVELOPMENT AND ONSTRUCTION OF A COMMON PLANT

SNAKE PIPE DESIGN

MORE THERMALLY EFFICIENT



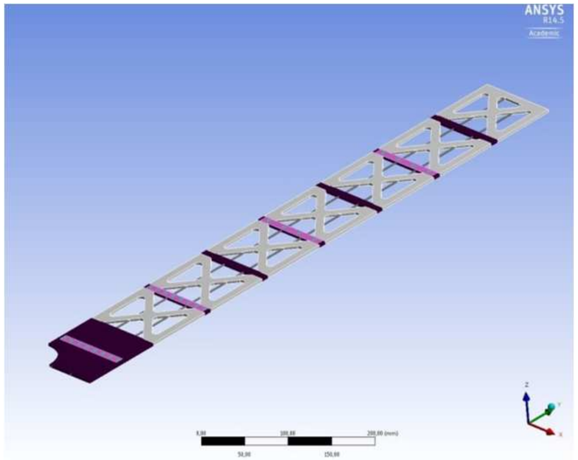
BENDED PIPE, PARALLEL CHANNELS

=> FLOW DISTRIBUTION ISSUES

TRACI COOLING SYSTEM TEST PLANNED

STRAIGHT PIPES DESIGN

NEEDING DOUBLE PIPE AND TPG INSERTS

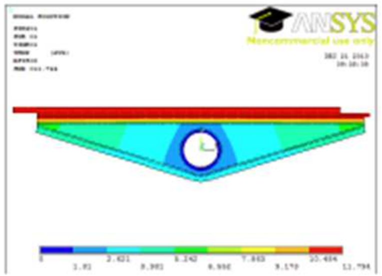


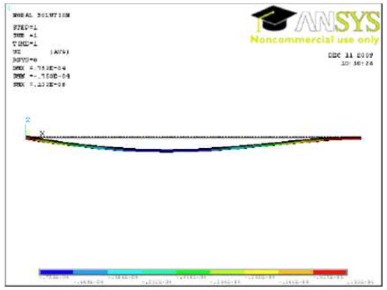
REQUIRED KNOW-HOW AND INNOVATIVE MATERIALS

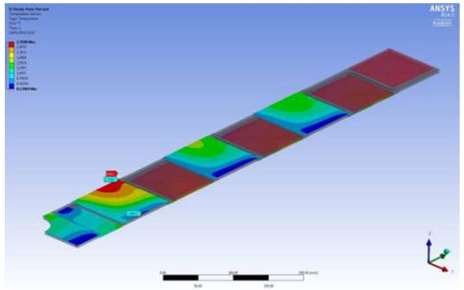
DESIGN:

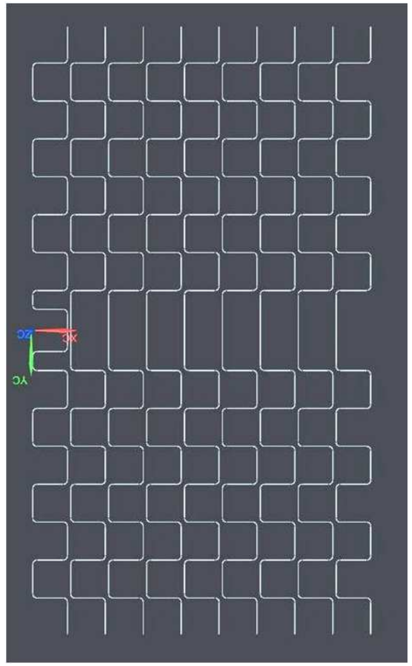
FINITE ELEMENT ANALYSIS

- THERMAL AND THERMO-MECHANICAL SIMULATIONS
- NEED CHARACTERIZATION TO HAVE REALISTIC MATERIAL PROPERTIES IN THE MODELS
- EXPERIENCE IN MESHING TECHNIQUES FOR VERY MULTY-THIN LAYERED OBJECTS (GLUE LAYERS)
- ANISOTROPIC MATERIALS, LAYERED CFRP MATERIALS





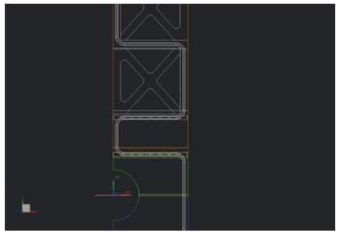




THERMOHYDRAULIC CALCULATION
FOR THE COOLING CIRCUIT

- CoBRA (CO2 BRANCH CALCULATOR)
- SPECIAL ATTENTION TO INSTABILITIES

IN 2-PHASE EVAPORATING SYSTEMS



REQUIRED KNOW-HOW AND INNOVATIVE MATERIALS

PROTOTYPE & DETECTOR REALIZATION:

CO_2 PIPING MATERIALS (MDP = 100 bar)
- TITANIUM: low CTE, high rad length, high strenght / pipe acquisition not easy
- STAINLESS STEEL
- ALUMINUM: used in the actual detector, not considered for upgrades

CARBON BASED MATERIALS
- CFRP
- CARBON FOAMS

GLUING IMPROVEMENTS
- TECHNOLOGY TO OBTAIN CALIBRATED GLUE LAYERS
- SUFFICIENT FOR STRUCTURAL AND THERMAL CONTACT
- NOT MORE THAN REQUIRED (MINIMIZING MATERIALS)

Cooling

R&D steps

- characterizing heat transfer in small channel through laboratory measurements
- deriving guidelines for detector cooling optimization
- developing numerical models that correctly describe the flows and heat transfers

- design and engineering of the system
- analysis of system aspects such as manifolding
- novel challenges due to the much larger scale of the system

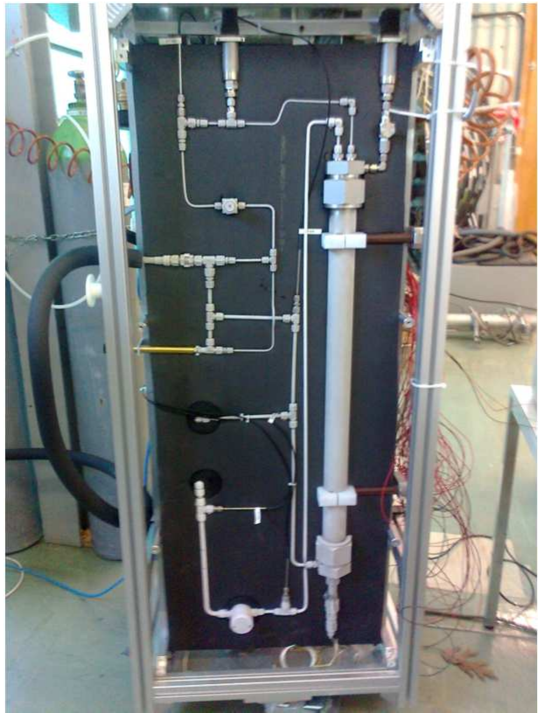
R&D IN PROGRESS

Development of a portable CO_2 laboratory cooling unit called Traci

TRACI=Transportable Refrigeration Apparatus for Co2 Investigation.

TRACI: **T**ransportable **R**efrigeration **A**pparatus for **C**o2 **I**nvestigations

- Collaboration between CERN and NIKHEF
- Small and simple to operate
- ~100 W @ - 35 °C



Development in AIDA framework together with interested partners

Nikhef & CERN lead development

Co-funding from clients

Collaboration with Sheffield, Oxford, Liverpool and Milano

AIDA funds => TRACI SYSTEM

FIRST UNIT will be identified as “the” final AIDA deliverable for WP 9.3.

AIDA-2

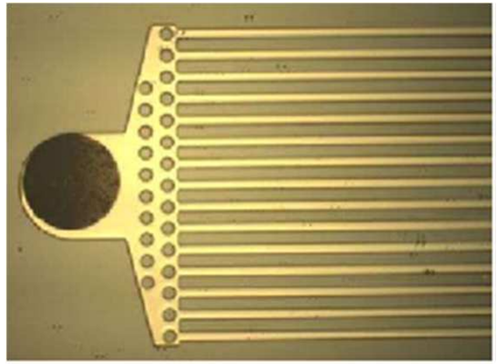
WILL CONTINUE THE COOLING ACTIVITIES IN PROGRESS..

R&D
FULL SILICON STAVE

SILICON PACKAGE INCLUDING:

- ELECTRONICS
- STRUCTURAL SUPPORT / SELF SUPPORTING SYSTEM
- COOLING CHANNELS

- VELO LHCb
- ALICE ITS
- NA62 GTK
- … ATLAS & CMS FOR PHASE-II



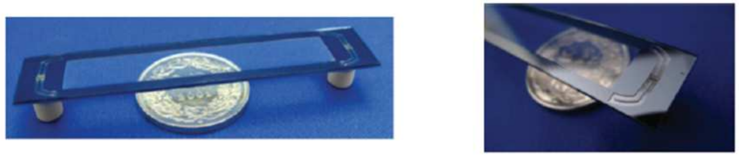
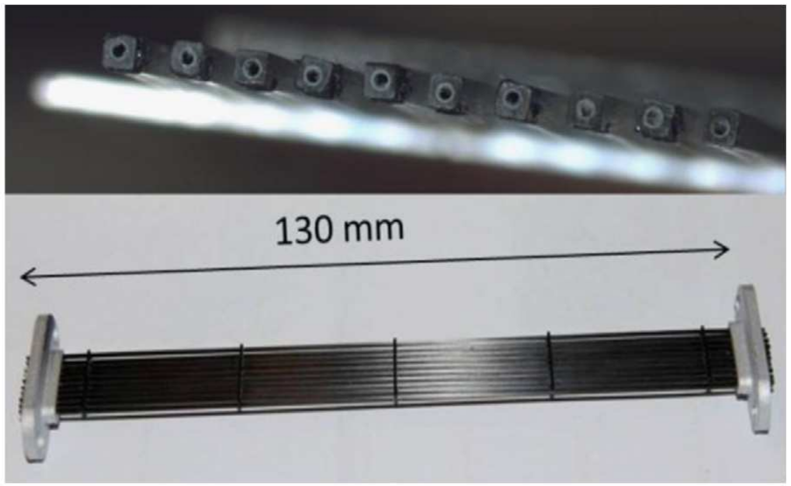


Figure B.4: The silicon frame with embedded microchannels (left) and a particular of the inlet manifold (right).

CARBON MICRO CHANNEL COOLING

=> See details in the 2 last slides from Filippo Bosi (INFN PISA)

- ADDITIVE TECHNOLOGY
- PEEK PIPE INTO CFRP



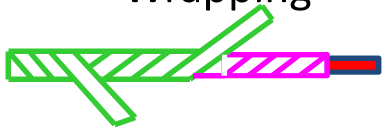
SupeB SVT LAYER-0 PROTOTYPE

R&D

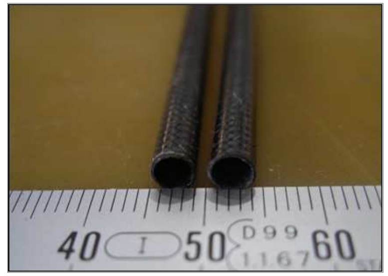
The Homogeneous Stave

ALL CARBON STAVE

Wrapping



Braids



USING A CARBON-FIBER COOLING PIPE

COMPLIANT FOR FOR A CO_2 PRESSURE SYSTEM
considered as an option for ATLAS IBL
.. and HL-LHC upgrade structures?

- VERY GOOD RAD LENGTH
- ALMOST ZERO CTE
- PRESSURE SYSTEM WITH MDP 100 BAR

⇒ THICKNESS OF MATERIAL

- **LOW TRANSVERSAL THERMAL CONDUCTIVITY**
  => NEED R&D TO IMPROVE

- DEDICATED CONNECTIONS DEVELOPED

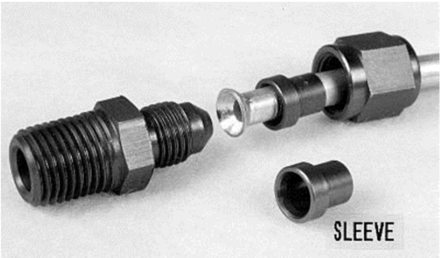
several pipes have been produced that meet the specs and, at the moment, two are the validated techniques

full homogeneous stave

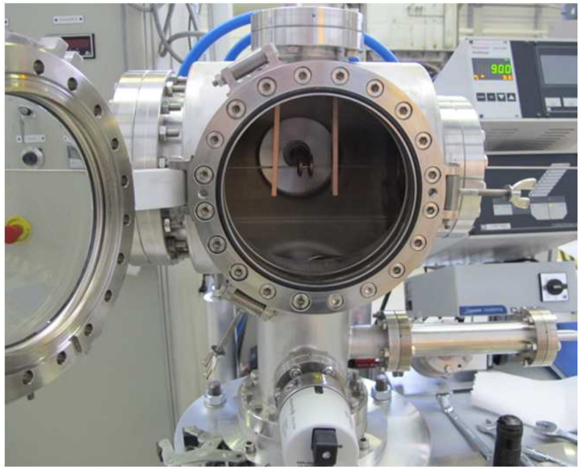
Institutes and collaborators (2008)

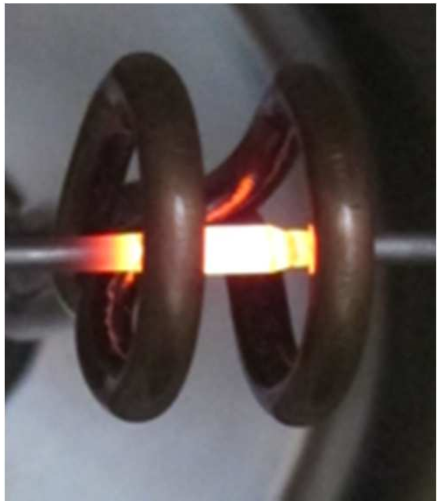
- *IVW : Institut für Verbundwerkstoffe GmbH Kaiserslautern*
- *IFB :Institut für Flugzeugbau Universitat Stuttgart*
- *Wuppertal University*
- *INFN Milano*
- *CPPM Marseille*
- *LAPP Annecy*
- *BERCELLA Carbon Fiber (Parma IT)*

R&D
JOINING TECHNIQUES

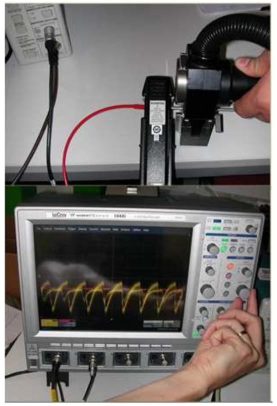


Swaging



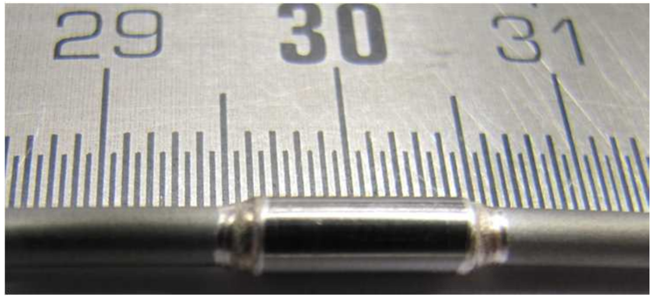


IBL Brazing activity



Orbital welding
Not for small 1.5 mm pipe

- Brazing work fine on a lot of material (Stainless steel, Ceramics, Titanium …)
- compatible with modules on local supports during operation
- permit mixture of materials
- helpful for electrical breaks for example



COLLABORATION WITH INDUSTRIES

Peculiarity of the present systems:
"Small"detector => Small quantity of material required
$\Rightarrow$ Not very attractive business for industry
$\Rightarrow$ always needed:

- custom design and prototype qualification
- custom production of detector components
- => expensive (small scale) material acquisition and external works

COLLABORATION BETWEEN INSTITUTES

DESIDERABLE COLLABORATION INSIDE INFN
TO JOIN EFFORTS IN COMMON R&D

SOFTWARE SIMULATION CODES:
ALREADY DONE (NATIONAL CONTRACT) FOR:

- CAD SYSTEMS
- FEM ANSYS
- ESACOMP
- NOW NEED CoBRA code (CO2 BRANCH CALCULATOR)

PROTOTYPE TESTING R&D RESULTS & INDICATIONS

- SHARING OF TECHNOLOGIES DEVELOPMENT AND LABORATORY INFRASTRUCTURES

Thank you

for your attention

BACK-UP

SLIDES

COURTESY OF FILIPPO BOSI (INFN PISA)

CMS PIXEL TRACKER FASE 2: proposal R&D presentata alla CSN1 febbraio 2014

Le linee R&D proposte per il Tracker: Micro Channel Cooling

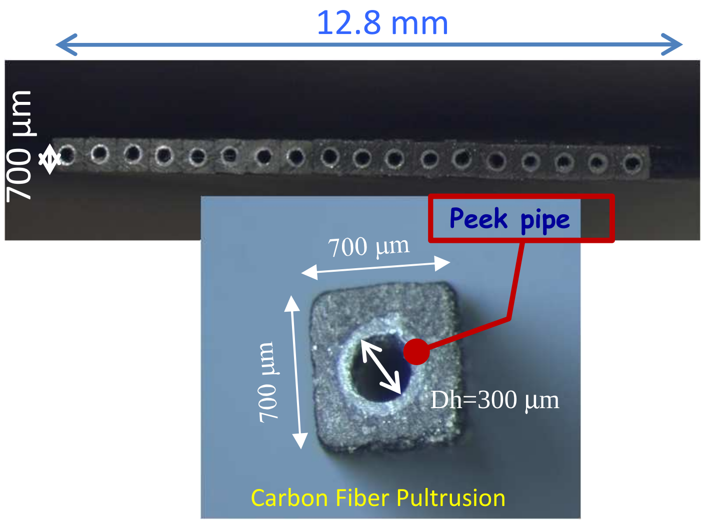
I rivelatori a pixel per Fase-2 necessitano di un raffreddamento efficace:

- potenza dissipata dall'elettronica di front end con elevata densità di interconnessione ($\geq$1 W/cm^2);
- danneggiamento da radiazione che implica condizioni di lavoro dei sensori a bassa temperatura (-20° C);
- Localizzazione in rivelatori vicini al punto di interazione :
  - Material budget minimizzato
  - Distribuzione uniforme della potenza di raffreddamento con ponti termici tali da garantire temperatura costante del sensore;
  - Sistema robusto e "maintenance-free" (zona sperimentale inaccessibile)

- Micro-channel Cooling + CO_2 a transizione di fase: soluzione promettente per il tracciatore di Fase-2.
  - Metodo ed apparato sperimentale già parzialmente sviluppati a Pisa (per scambio termico monofase liquido con punto di lavoro a 30° e 2W/cm^2 di dissipazione) per avere un cooling efficiente e con bassa quantità di materiale in zona attiva .

Micro tubi Compositi

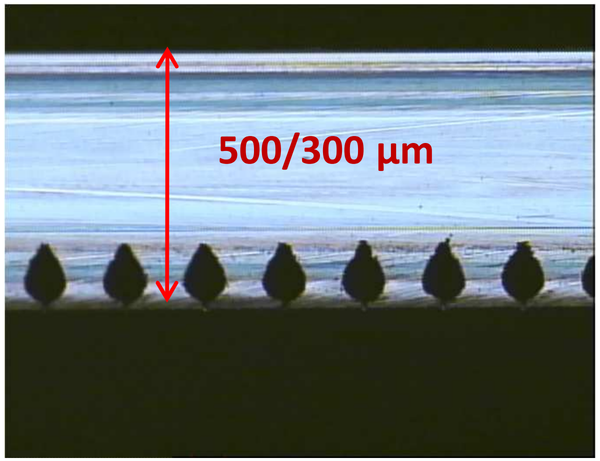
- Carbon Fiber Reinforced Plastic

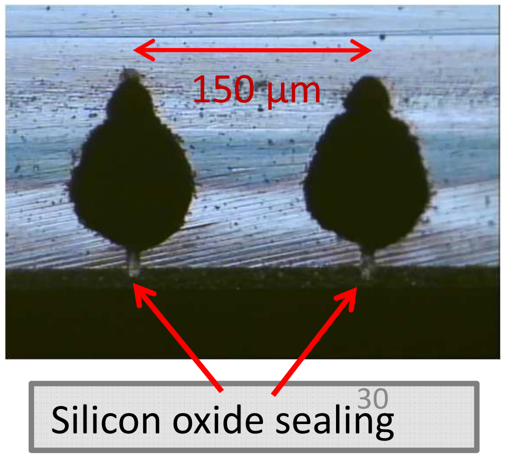


Eventuale sviluppo con FBK di micro-canali in Silicio

Tecnologia DRIE (Deep Reactive Ion Etching) , le stesse usate per i pixel 3D

Silicon buried channels for pixel detector cooling : M.Boscardin et al., Nucl.Instrum.Meth. A718 (2013) 297-298



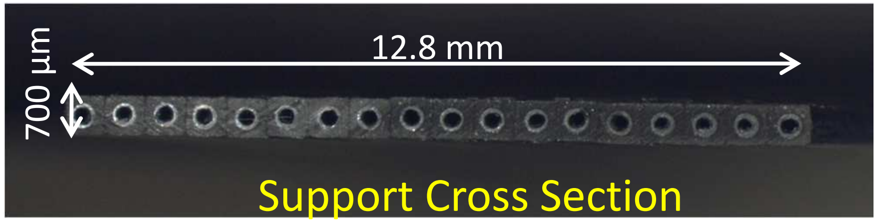


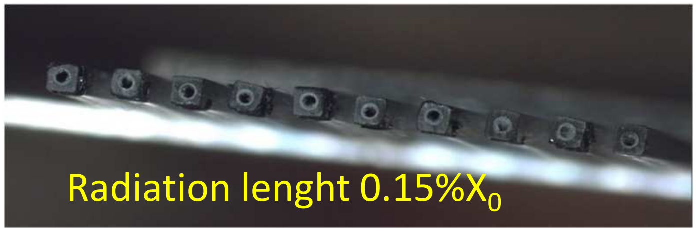
COURTESY OF FILIPPO BOSI (INFN PISA)

Programma di lavoro Micro Channel Cooling

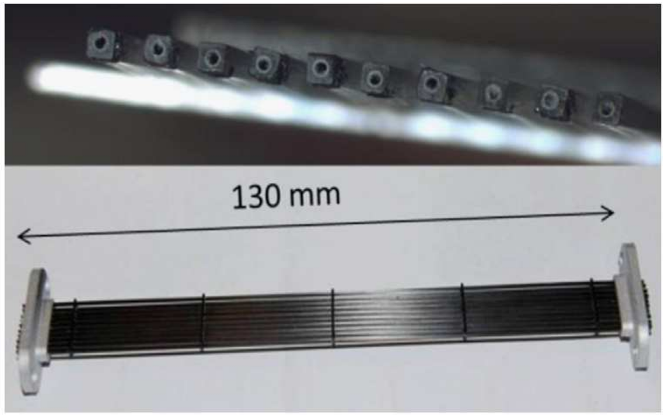
- Progettazione e produzione di sistema a CO_2 evaporativo per la verifica della fattibilita' di cooling a microchannel su supporti a microtubi costruiti in CFRP.
  - Soluzione conservativa per questo R&D
  - Focalizzazione a design specifici per un rivelatore plausibile per il vertex detector di CMS
- Ottimizzazione/minimizzazione delle dimensioni dei micro-tubi a partire da valori sperimentati: sezione $\leq$ 700 x 700 μm^2 e diametro idraulico $\leq$ 300 µm.
- Riduzione del material budget: $\leq$ 0.15% X_0 - ottimizzazione in funzione della temperatura di lavoro.

Light prototype support using micro-channel technology as high efficiency system for silicon pixel detector cooling :
Nucl.Instrum.Meth. A650 (2011) 213-217





Progettazione e produzione di un layout sperimentale per prototipi di supporto con lunghezza dei canali ottimizzata per un rivelatore di vertice (30-60 cm) con connessioni idrauliche idonee (alto ΔP e miniaturizzazione)



Outlook

The upgrade of the Tracker for the high-luminosity operation of the LHC is a formidable challenge. A substantial amount of R&D is already ongoing, and all major aspects are receiving attention. Some of the developments, in particular those addressing the most advanced technologies, may soon be confronted with the lack of financial resources. Together with the R&D on the components, design, modelling and simulation studies (for tracking and trigger) are the key for an optimal choice of detector concept. The progress in the next two years will be crucial for the project, as it will lead to the choice of the detector concept to be designed and built.