Belle II Pisa Group

A brief history and introduction

Francesco Forti

28/5/2025

Meeting with ALICE

INFN

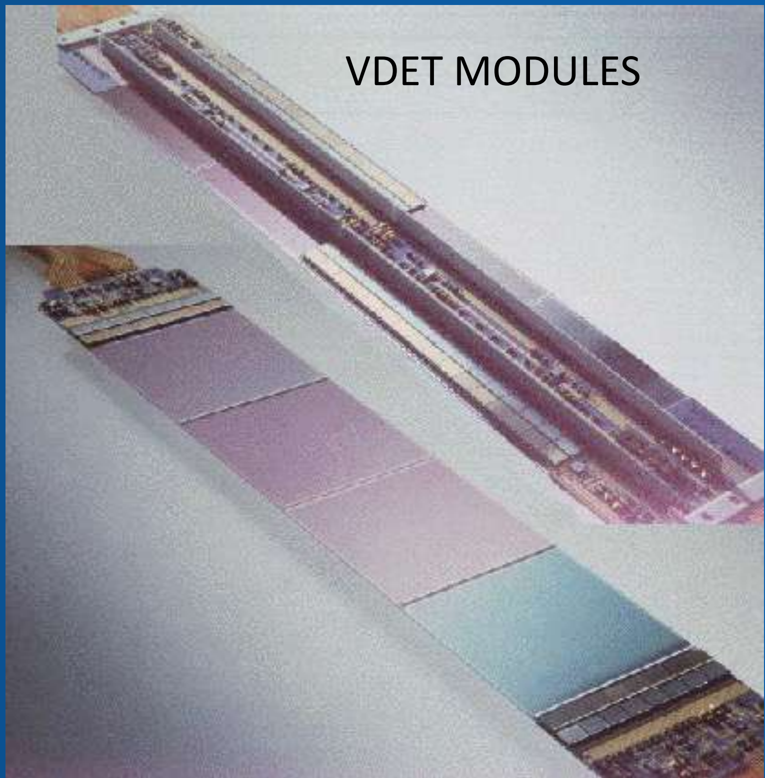
People (May 2025)

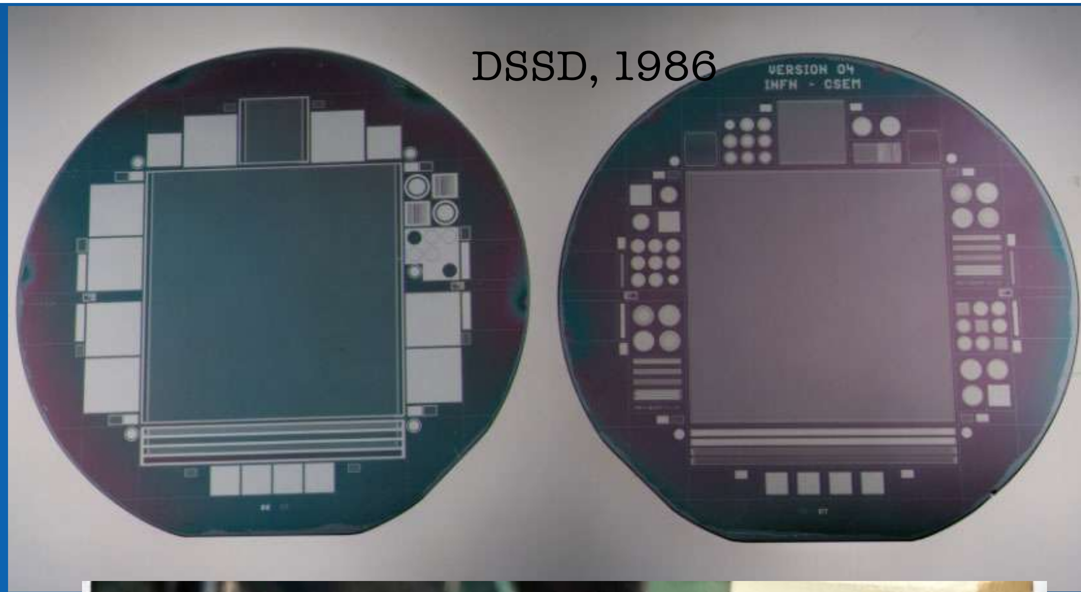
- Staff - Physics
  - Stefano Bettarini
  - Giulia Casarosa
  - Francesco Forti
  - Giuliana Rizzo
  - Giovanni Batignani (in Darkside)
  - Eugenio Paoloni (in Darkside)
- Staff – Engineers
  - Maurizio Massa (Mech)
  - Enrico Mazzoni (Comp)
  - Massimo Minuti (Elec)
  - Andrea Moggi (Mech)
- Postdoc
  - Luigi Corona
  - Alice Gabrielli
- Graduate Students
  - Ludovico Massaccesi
  - Foteini Trantou
- Master Students
  - Guglielmo Benfratello (Phys)
  - Alessandro Terranova (Phys)
  - Margherita Rovini (Eng)

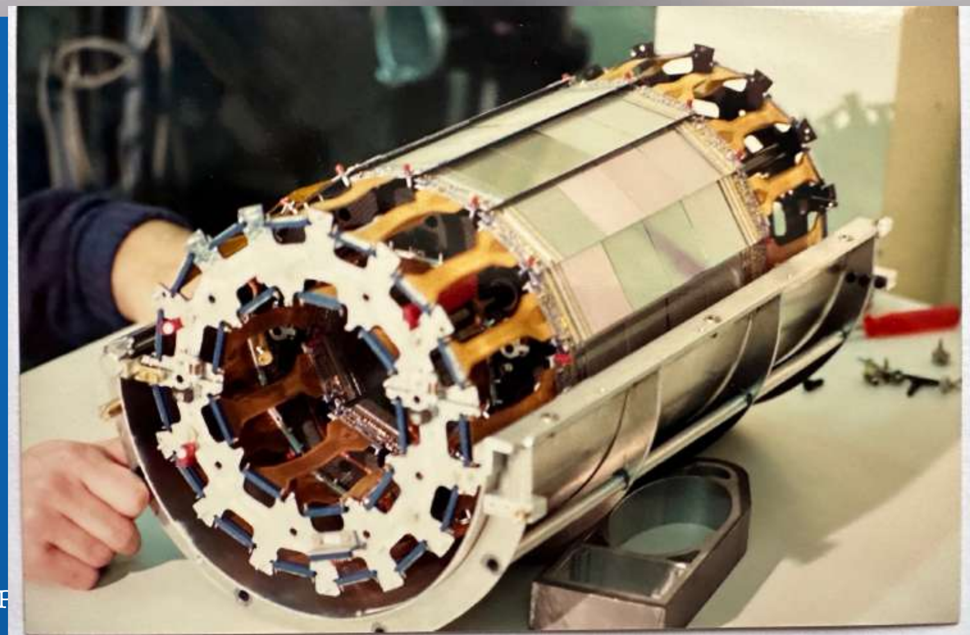
A brief history

- Long history of silicon sensors developments
- HEP Experiments
  - ALEPH @ LEP: 1985 - 2000
  - BABAR @ PEP-II: 1993 - present
  - SuperB Project: 2005 - 2012
  - Belle II @ SuperKEKB: 2013 - present
- R&D Projects
  - N PRIN projects (<2013)
  - CSN5 SLIM5 (2006), VIPIX (2008), PixFEL (2013)
  - AIDAInnova (2020), DRD3 (2025)

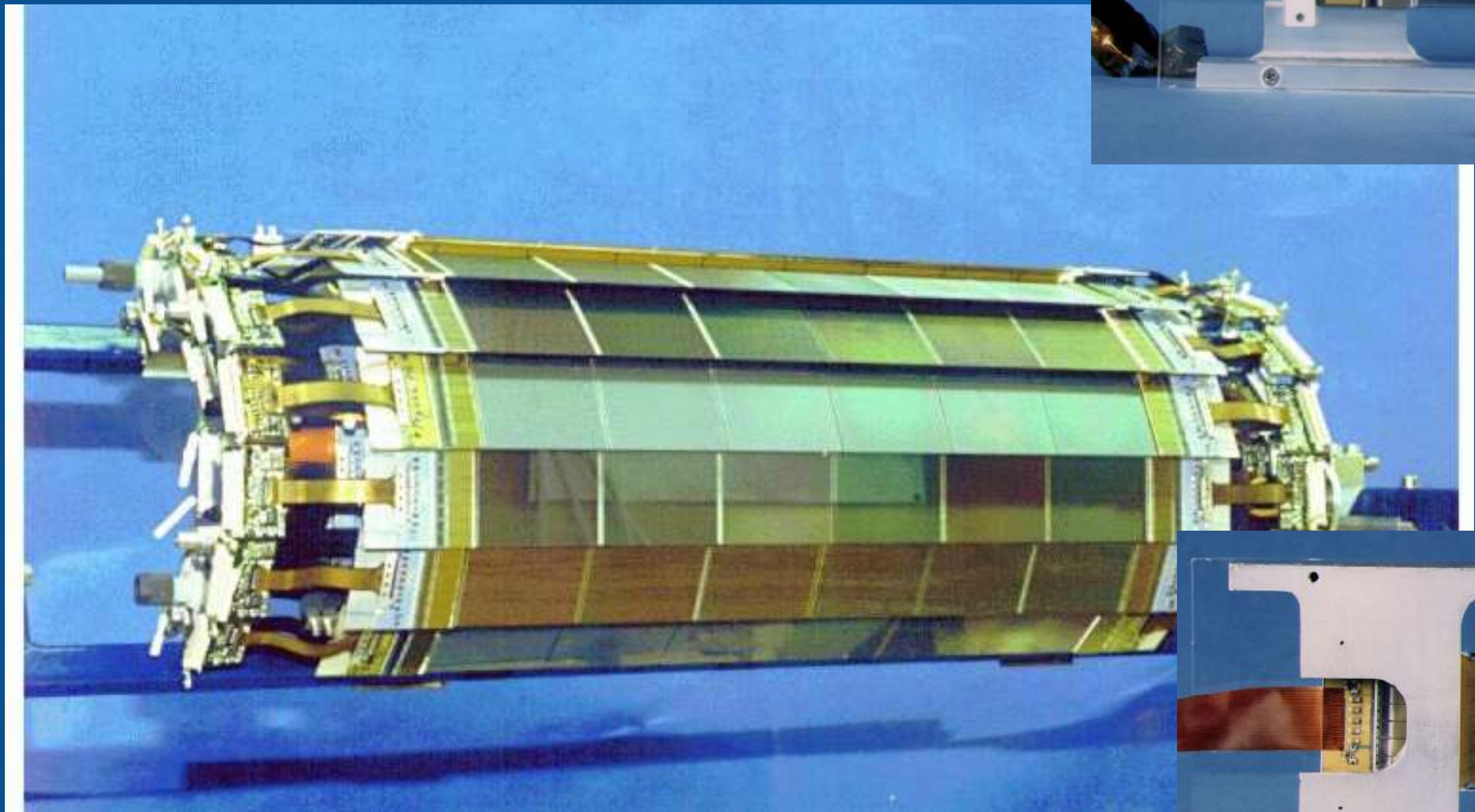
ALEPH VDET, 1991

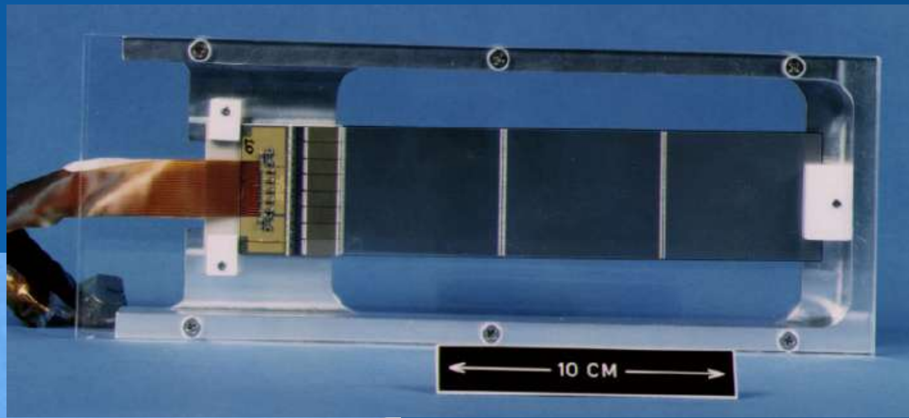






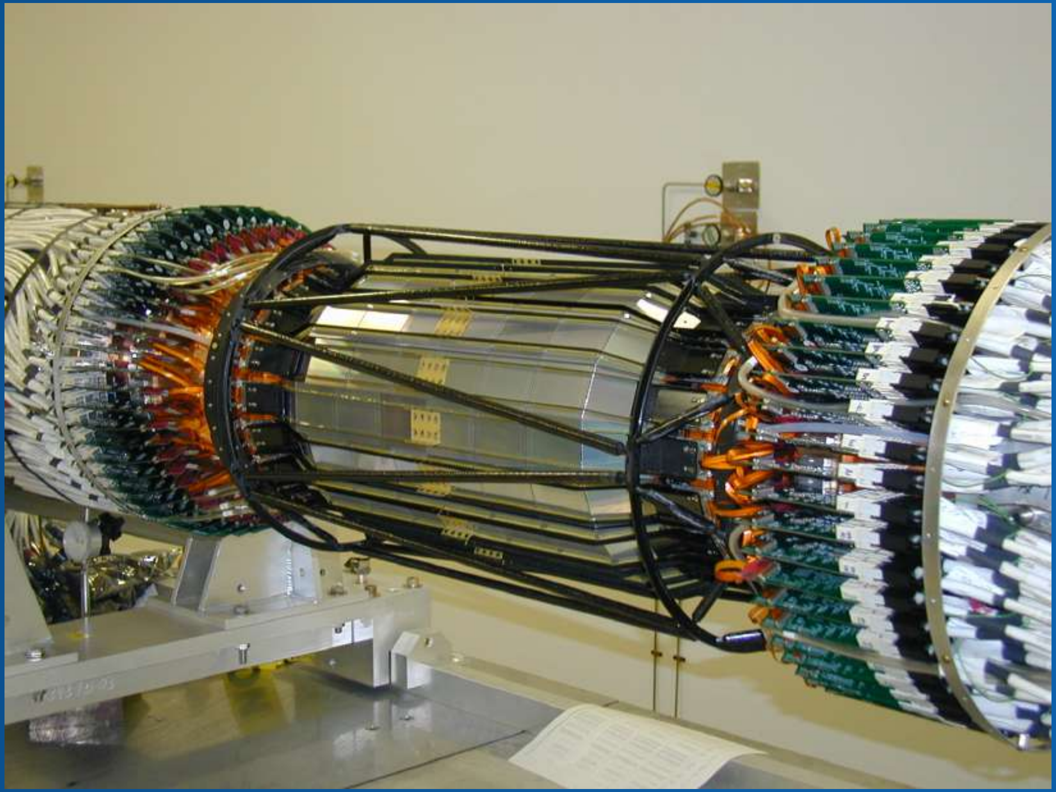
ALEPH
VDET200, 1995

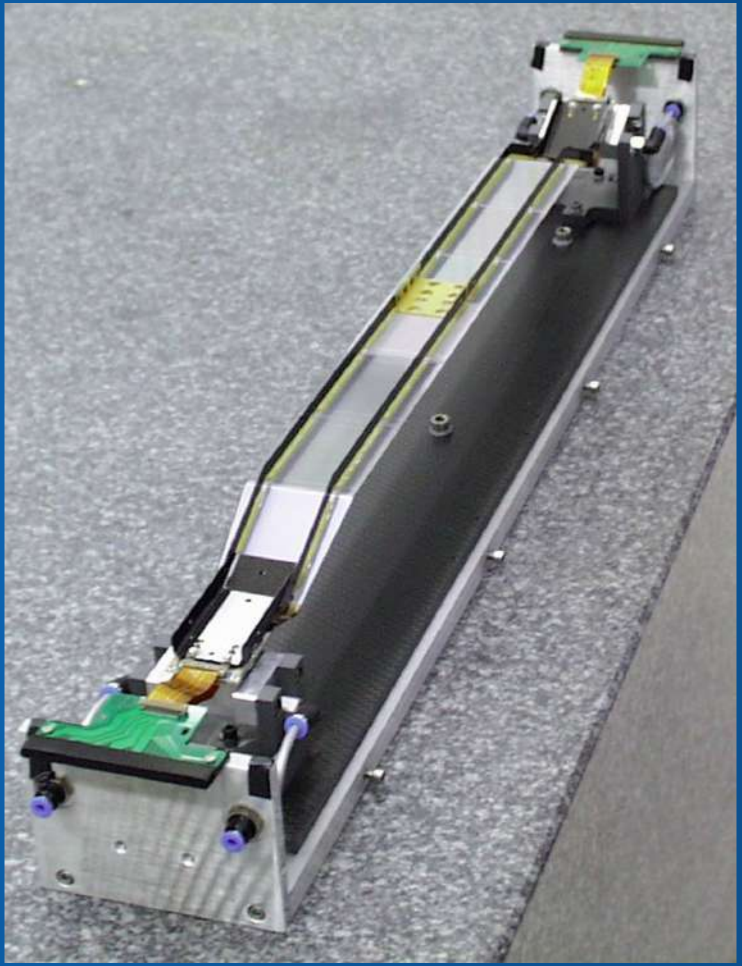




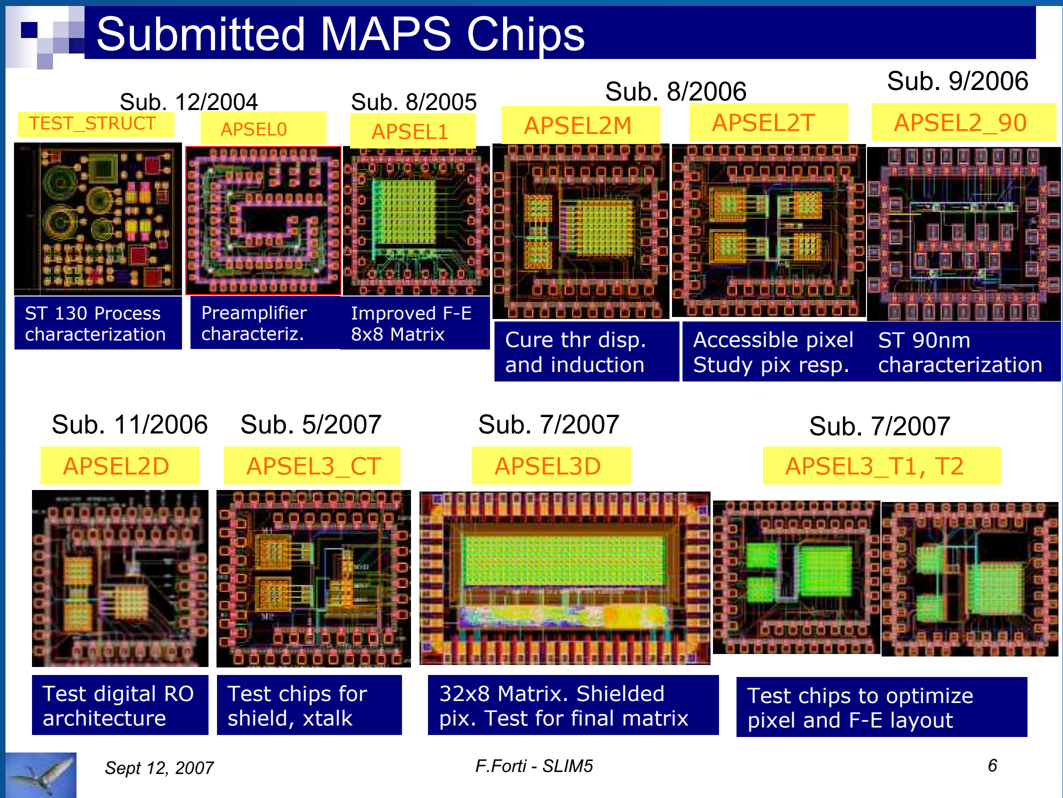
Babar SVT, 1999

- Lampshade





CMOS MAPS R&D for the SuperB Project



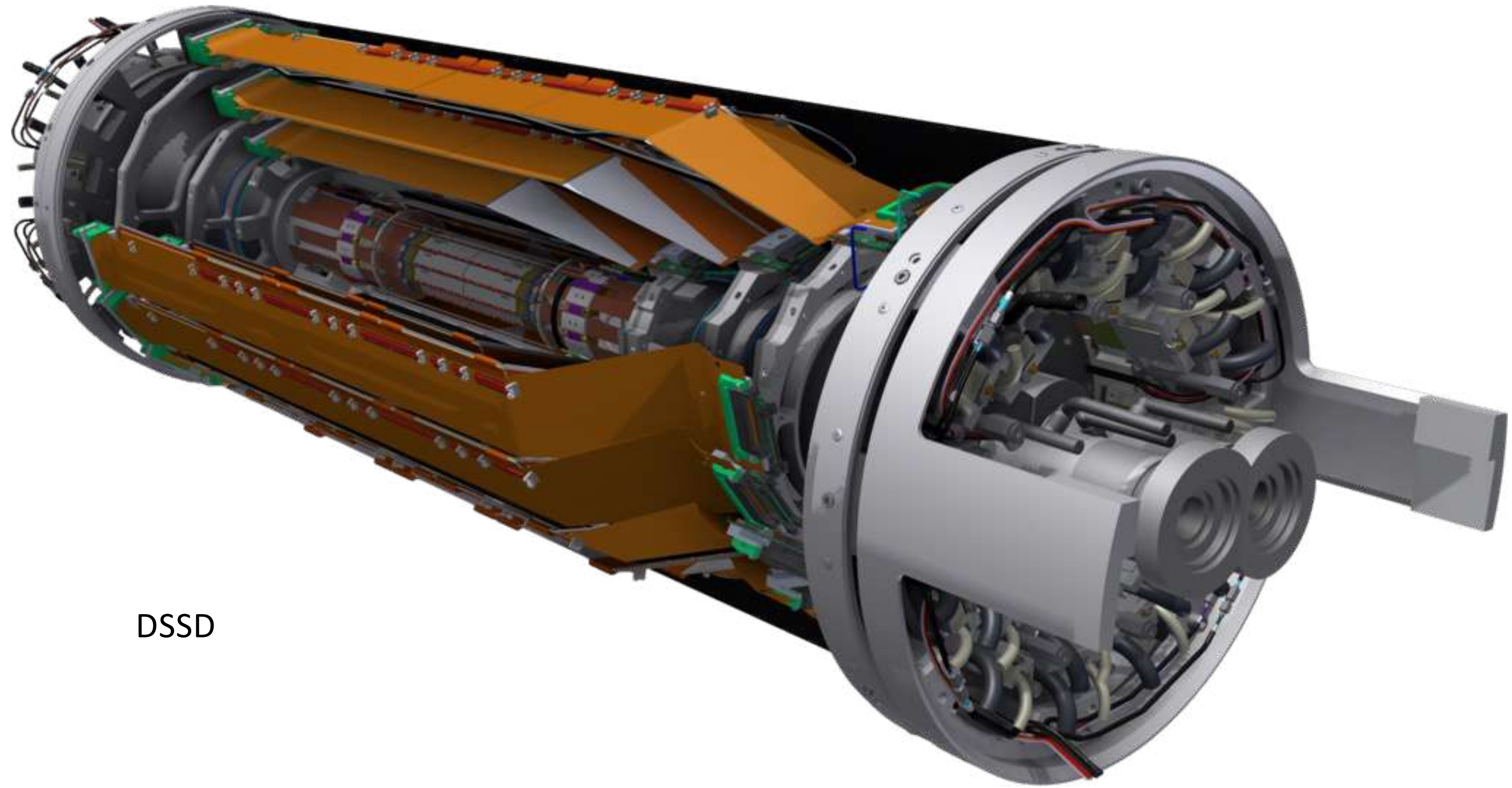
SLIM5 Collaboration

APSEL4D sub 11/2007- rec 3/2008

32x128 4k pixel matrix for beam test

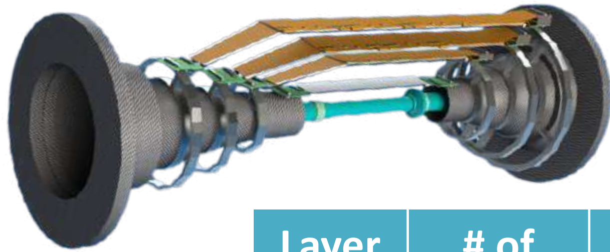
Main driving force
Join Belle II after cancellation of SuperB

Belle II Silicon Vertex Detector

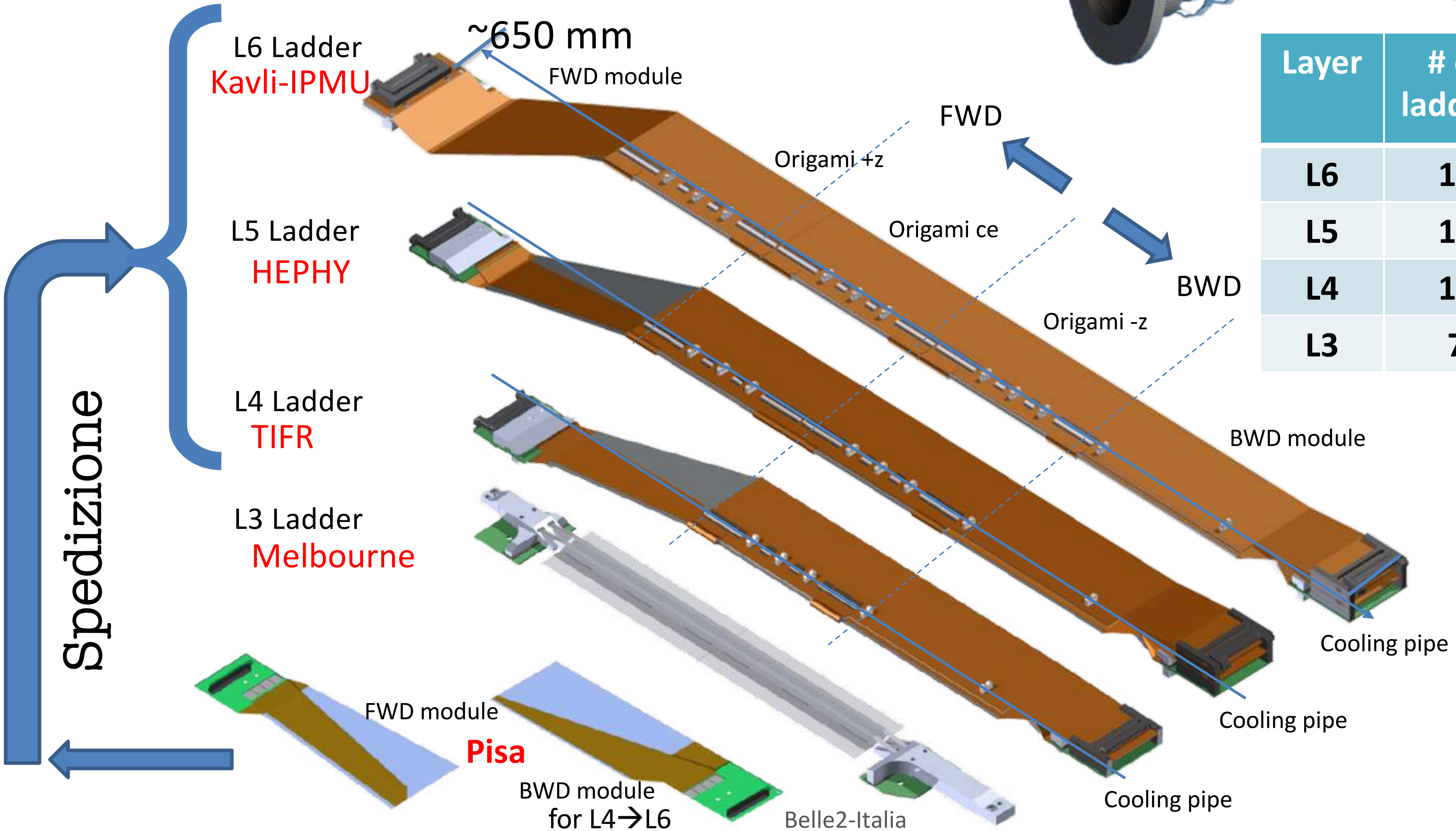


DSSD

The SVD ladder design



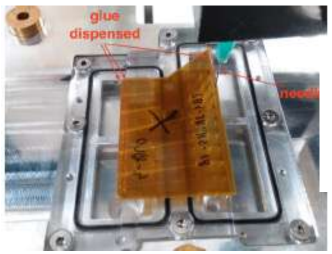
Layer	# of ladders	Radius (mm)
L6	16	140
L5	12	115
L4	10	80
L3	7	39



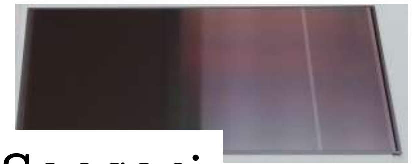
Produzione dei FW/BW subassemblies

- Realizzata interamente nei Laboratori Alte Tecnologie
- Necessità di attrezzature di precisione
    - Progettate e realizzate (in parte) in sezione

Ibrido

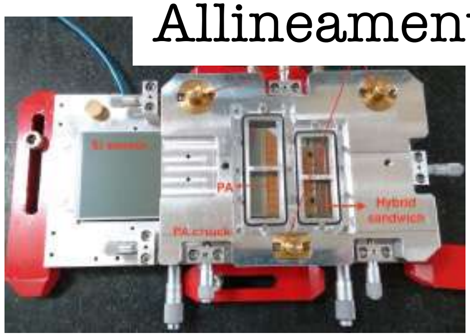


Sensori

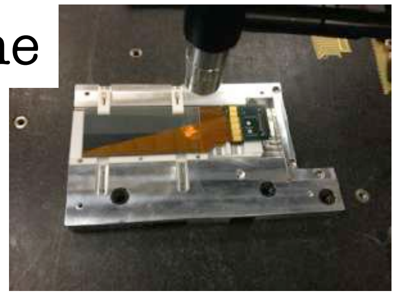


Pitch Adapters

Allineamento e incollaggio

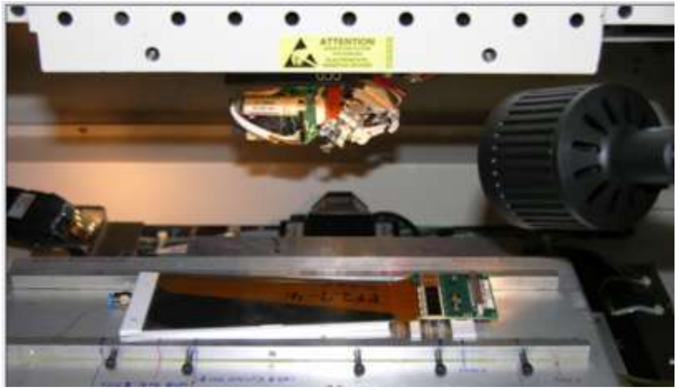


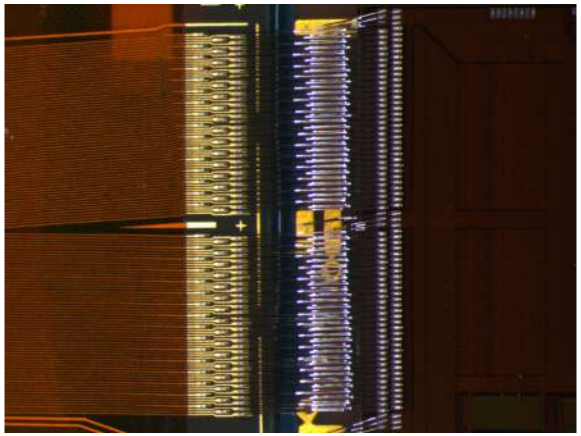
Ispezione

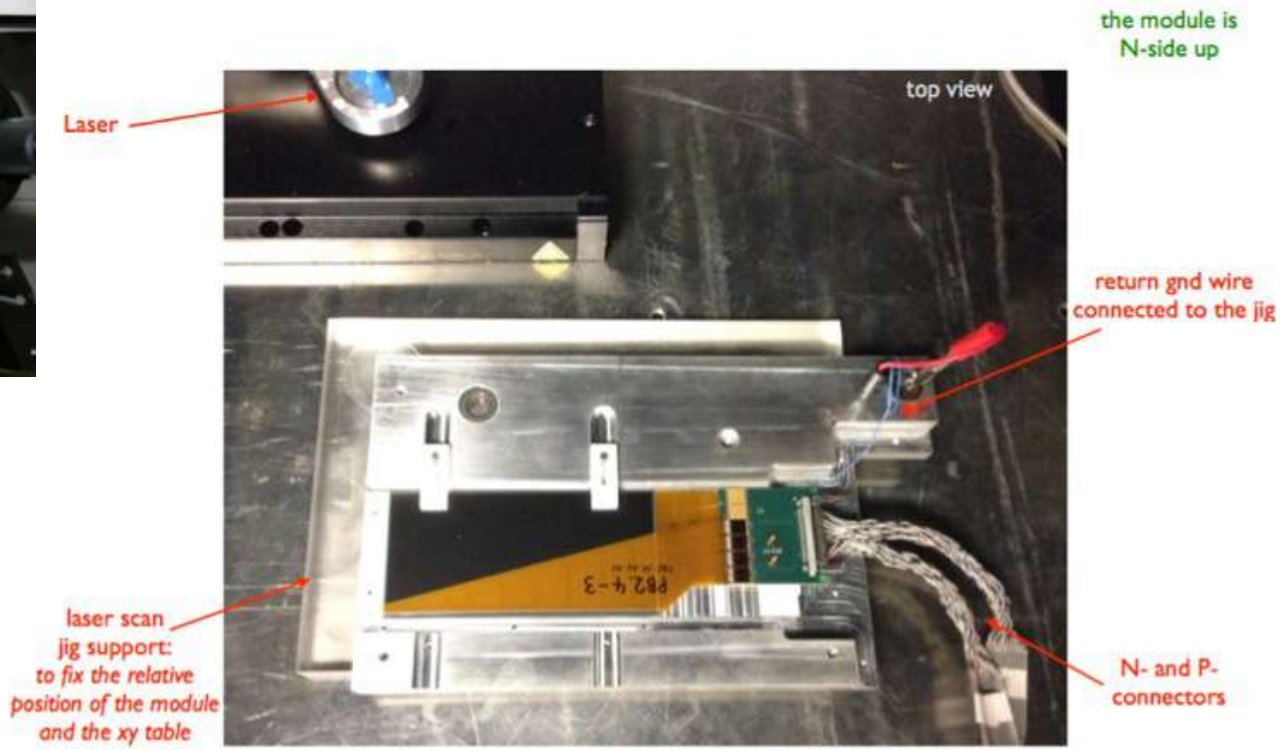


Produzione dei FW/BW subassemblies

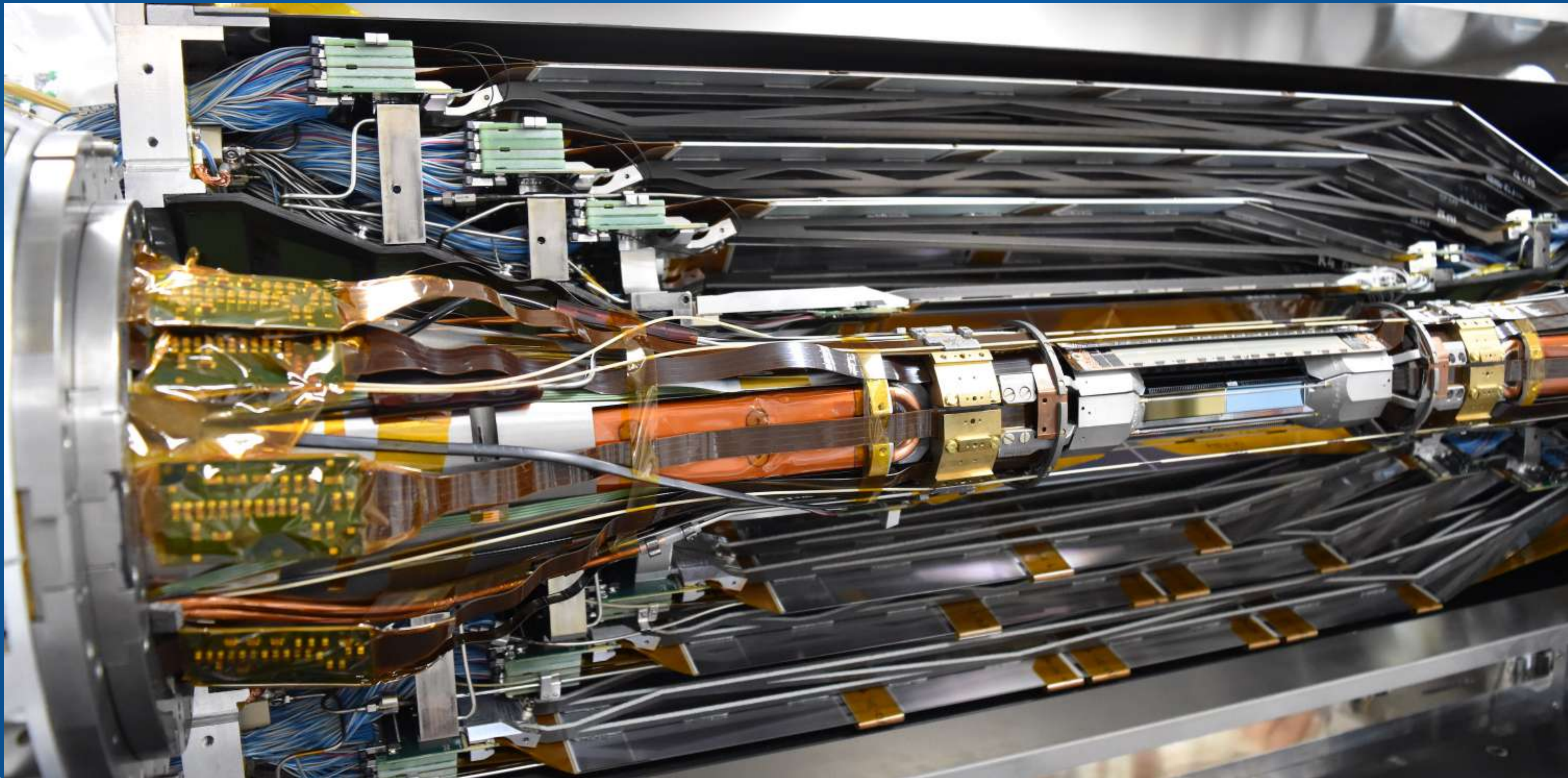
- Microsaldatura, test elettrico, laser scan



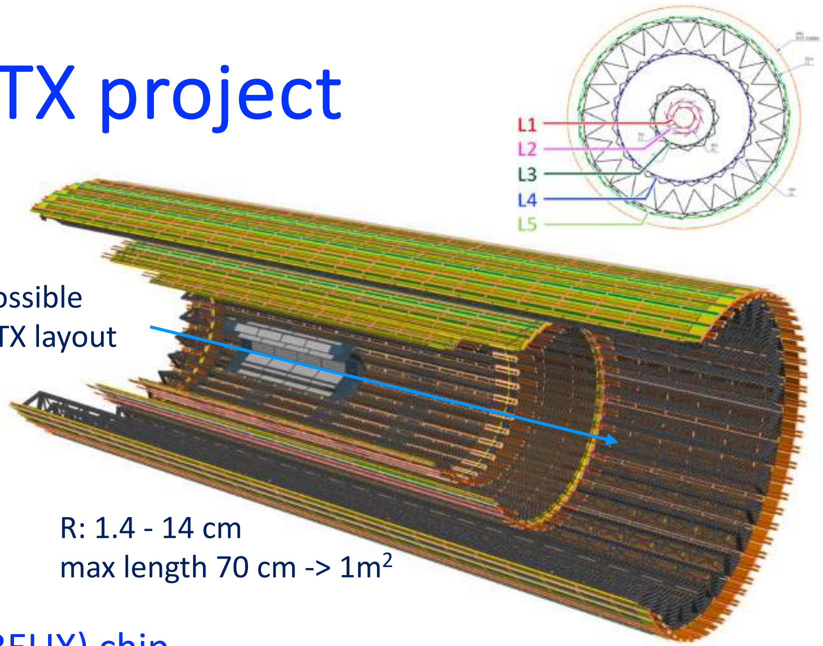




Belle II, 2019



Vertex detector upgrade: the VTX project



❑ Concept = 5 straight layers with DMAPS pixel sensors

- Higher space-time granularity & lower material budget
  - Reduce occupancy to improve tracking in high background
  - Better tracking & vertex resolution at low momentum
- Lighter services & “easy” geometry
  - adaptable to potential changes of Interaction Region

❑ Technical choices

- Identical pixel sensor on all layers: **O**ptimized **BEL**le II p**IX**el (OBELIX) chip
  - Thin DMAPS sensor, derived from TJ-Monopix2, with 33 um pitch & 50-100 ns timestamping
  - Operated at room temperature, power consumption 120-200 mW/cm^2 (hit rate 1- 120 MHz/cm^2)
- **iVTX**: innermost 2 layers, all-silicon, self-supported (PXD-inspired), air cooled (0.2 % X0)
- **oVTX**: 3 outer layers, Carbon fiber frame (ALICE-ITS2 inspired), water cooled (0.3 - 0.8% X0)
- Total material budget reduced to 2.4% X0

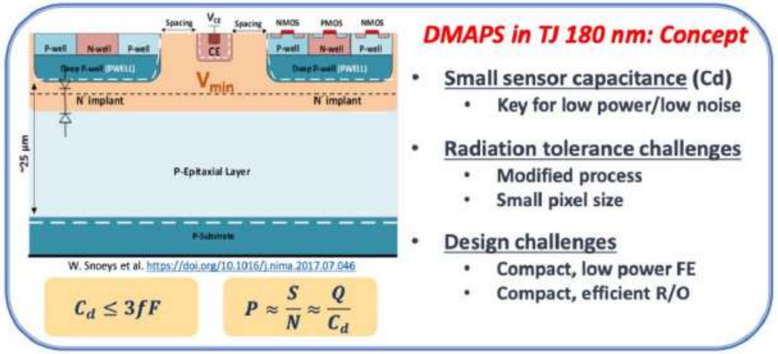
	L1	L2	L3	L4	L5	Unit
Radius (mm)	14.1	22.1	39.1	89.5	140	mm
# Ladders	6	10	17	40	31	
# Sensors	4	4	7	16	2x24	per ladder
Expected hit rate*	19.6	7.5	5.1	1.2	0.7	MHz/cm2

**Large uncertainty on BG extrapolation/possible changes in IR region*

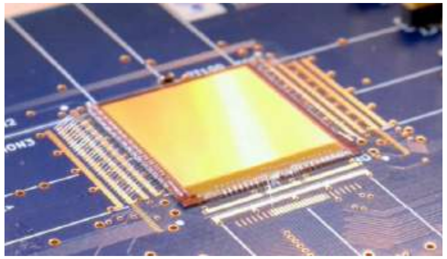
TJ-Monopix2

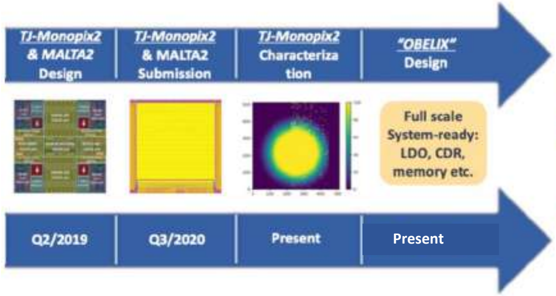
❑ TJ-Monopix2 as forerunner of OBELIX

- Developed for ATLAS (ITK outer layers), TJ 180 nm (same as ALPIDE) but modified process to improve rad hardness & faster redout → core features matching Belle II needs
  - 33x33 µm2 pitch, 25 ns integration, large matrix 2x2 cm2
  - 7 bit ToT information, 3 bit in-pixel threshold tuning
  - Column drain readout capable to handle >> 120 MHz/cm2 -> triggerless in TJMP2
  - Various sensing volume thickness (epi-30 um, CZ-bulk)
  - F. Huegging Poster on “Recent results on DMAPS Monopix sensors”
    # 299 in Solid State Poster session
- OBELIX design based on the TJMP2 matrix with new digital periphery with trigger logic for Belle II + optional features to allow Track Trigger capability & additional finer timestamping for outer layer hits, low rate.
- Detailed characterization of TJ-Monopix2 to validate key performance crucial for OBELIX design



TJ-Monopix2: Proof-of-principle for Belle II VTX – OBELIX





VTX - WG3: Characterization and test system

WG3: Characterization and test system
G. Rizzo

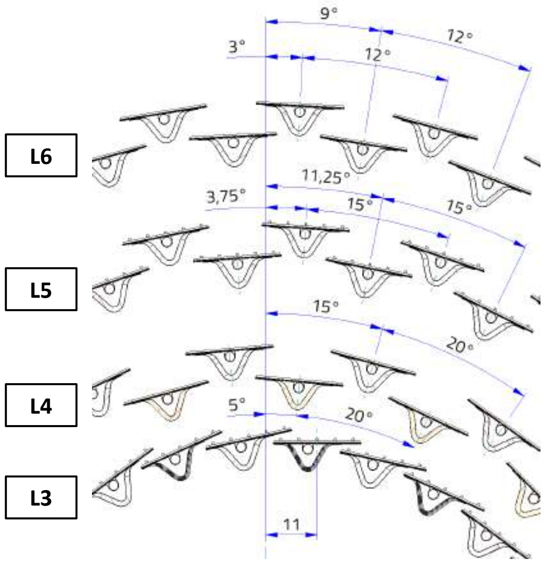
- Irradiations
- Lab tests
- Beam Tests

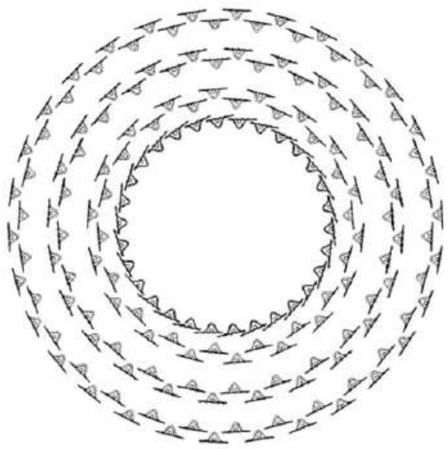
WG3 main focus/activities in last 12 months

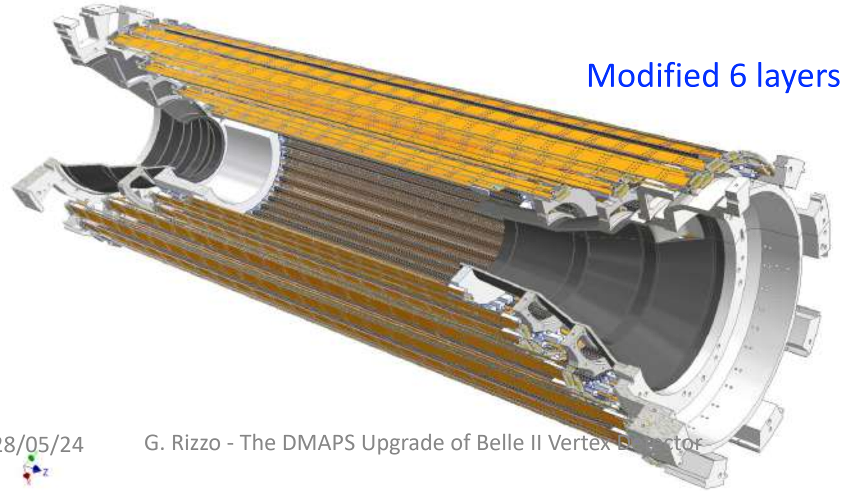
1. TJ-Monopix2 detailed tests as input for OBELIX design
   - Comparison simulation/measurement on TJMP2 → tune simulation to improve matching
   - Improved TDAC THR tuning power implemented in OBELIX: confirmation with TJMP2 tests
   - BCID cross talk measurements: critical for OBELIX submission
2. Characterization of TJ-Monopix2 irradiated chips
   - Testbeams: DESY- July 2024, KEK - Dec 2024 : irradiated chips TID @100Mrad, p and e- irrad NIEL @ 5×10^{14} neq/cm^2
   - Detailed lab tests on NIEL irradiated samples adding Temperature control
   - Preparation for April 2025 DESY Testbeam
     - Prepared more NIEL irradiated chips with different fluences (1- 5×10^{14} neq/cm^2),
     - Temperature control setup (T_NTC ~ 10-40C), DAQ improvements, TB data analysis tuning
3. Definition of OBELIX temperature specs (lab+beam tests + thermal simulation)
4. Effort yet to start: preparation for OBELIX-1 testing , HW, SW, teams ....
   - 6 months after submission need to be ready for first functional tests on OBELIX-1

oVTX

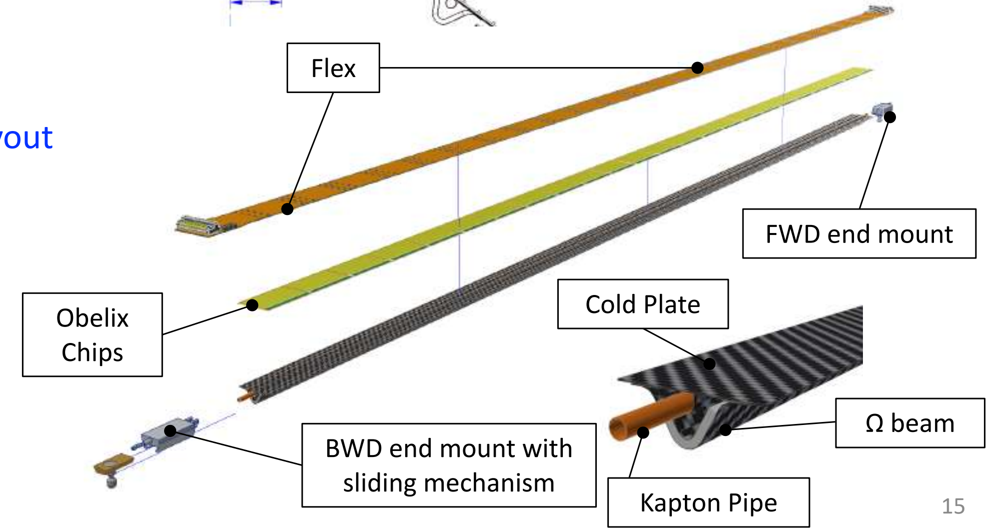
- Ladder structure (ALICE ITS2-inspired):
  - CF support structure (Ω beam), cold-plate with pipes (2 or 1 pipe) with liquid cooling
  - Chip and Flex circuit for power & signal
- Prototypes:
  - Mechanical & thermal characterization done for the longer ladder ~70 cm (outermost layer)
- Mechanical design already advanced
  - now also exploring a 6 layers option



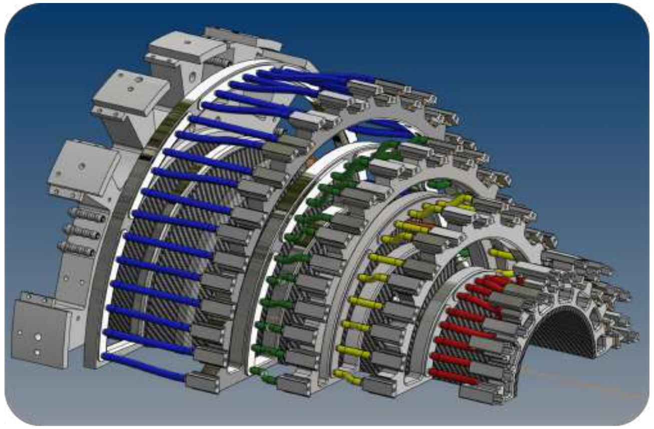




Modified 6 layers layout



Hydraulic services – BWD side

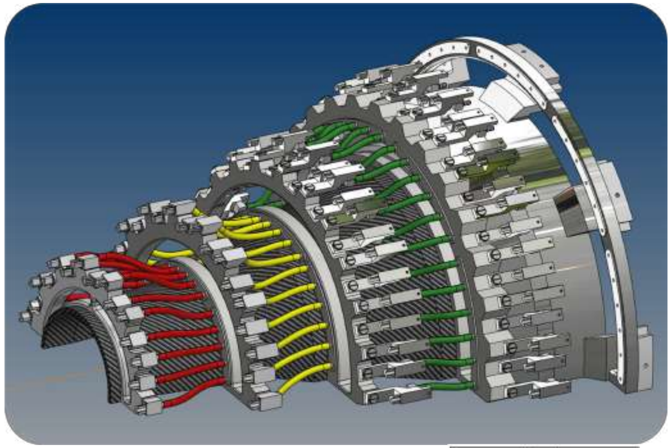


Legenda:
L6 - ladders to manifolds
L5 - ladders to manifolds
L4 - ladders to manifolds
L3 - ladders to manifolds

- *All the manifolds (except for Layer 6) are integrated into the end rings.*
- *The pipes are grouped into manifolds in sets of 5 for Layer 3, and in sets of 6 for the other layers.*
- *The configuration follows the scheme: Layer "N" with manifold on the Layer "N +1" end ring.*
- *The manifold for the Layer 6 ladders is a standalone component that is glued onto the top of the BWD cone.*
- *This task concerns only the hydraulic aspect; however, the end rings are hollow to allow space for cables routing.*

Hydraulic services – FWD side

- *The scheme on the FWD side is the same as the one on the BWD side.*
- *The grouping of pipes on the BWD side is also applied on the FWD side.*
- *The available space for routing is smaller, so we need close and continuous interaction with WP5 to determine the size and number of cables.*
- *The layer 6 manifold has not been defined yet. There is an issue regarding its positioning.*
- ***Is it possible to move the FWD end flange?***

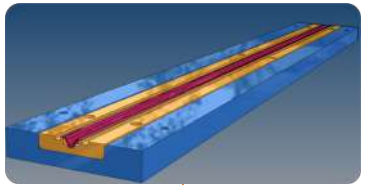


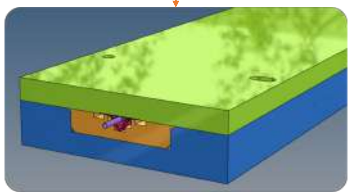
To complete the hydraulic setup, we must implement the pipes connecting the manifolds to the end flange ("patch panels"?) and we must define the position of the L6 FWD manifold.

Legenda:
~~L6 - ladders to manifolds~~
L5 - ladders to manifolds
L4 - ladders to manifolds
L3 - ladders to manifolds

L6 ladder: 1-pipe cooling plate to Omega gluing mask

Design





After attaching the cold plate, two resin 3D-printed end pieces will be glued to both ends of the ladder

Manufacturing

PTFE mold to avoid gluing issues on removing the final ladder

Dry test, no glue applied yet

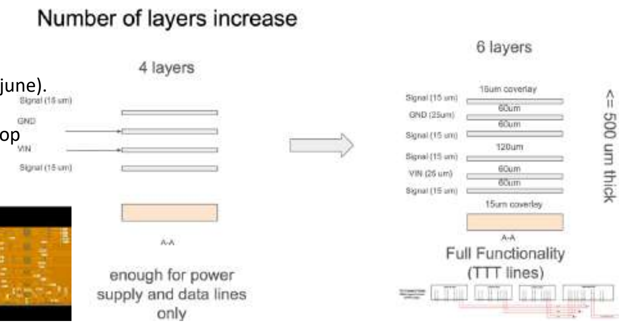
Objective: *mech. characterization with a bending test with 20 gm concentrated, comparison with CAD and previous test results.*

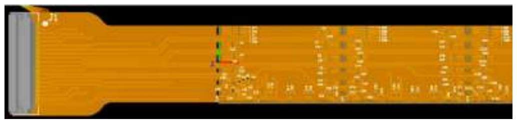
The new cold plate uses 120-um thick unidirectional K13D2U.

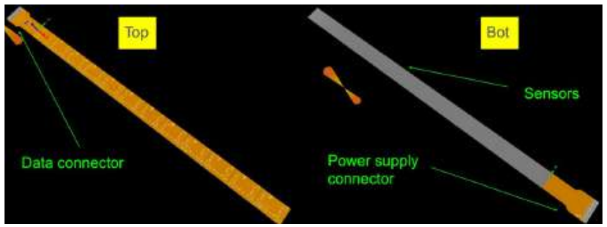
Belle-II VTX Upgrade oVTX Flex

Completed the first version of the FLEX design.
To be "adapted" to the Obelix GDS file, with the final dimensions and pad floorplan (ready @end of june).

To be submitted for production at the CERN workshop after closing the chip design (August 2025).







Material Budget:

Aluminum VDD Bus 0.03 % X0 (0.96 fill fraction)
Aluminum GND Bus 0.03 % X0 (0.96 fill fraction)
Aluminum local rails 0.001 % X0 (0.02 fill fraction)
Aluminum LocalData Bus 0.004 % X0 (0.14 fill fraction)
Aluminum GlobalData Bus 0.001 % X0 (0.04 fill fraction)
Total Current(I0)=7.6A
Polyimide FPC Substrate Budget 0.14 % X0 (1.00 fill fractio
Total Budget 0.2 % X0 (Capacitors and Sensors not include

Detector Expertise and Responsibilities

- Sensors
  - Long experience and expertise on various kinds of sensors
  - No chip designers
  - Sensor design, test and qualification, in lab and on beam
- Modules and mechanics
  - Experience with mechanical design and integration
  - Thermal analysis, including measurements
  - Flex design, test and qualification
- Fabrication and assembly
  - Precision component assembly and metrology
  - Wirebonding
  - Module testing and qualification, including thermal cycling
  - More in the presentation on facilities
- Detector commissioning and operation

Additional information

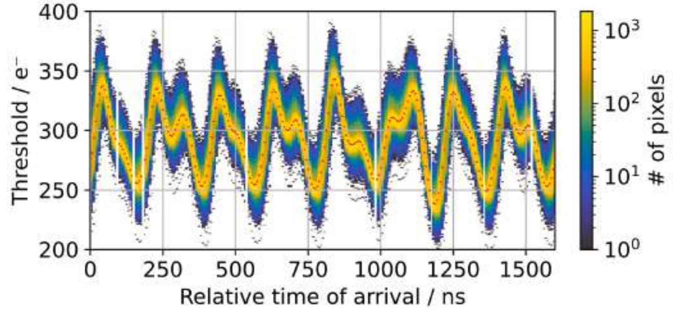
1. TJ-Monopix2 lab tests → input for OBELIX design

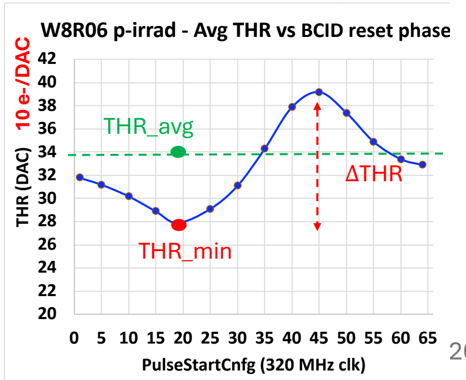
- Comparison simulation/measurement on TJMP2 → tune simulation to improve matching with data
  - Summary shown @ OBELIX designer meeting, April 2024
- Improved TDAC THR tuning power implemented in OBELIX: confirmation with TJMP2 tests
  - Summary in slides 13-14
- BCID cross talk measurements:
  - understand mechanism & identify possible countermeasures for OBELIX
    - NIMA1064 (2024) 169381, tests in Bonn, some mitigation options (HEPHY)
  - quantify effects on operation & define lab test procedure to minimize impact
    - summary slides (Pisa)
  - In operation with particles, random arrival time, BCID cross talk causes a random THR variation, that spans the full range → change in THR and increase the effective noise → could prevent operation at low THR (<300 e-), crucial after NIEL irradiation.

1. **THR_avg** = THR_min +ΔTHR/2
2. **noise_effective** = $\sqrt{\text{thermal noise}^2 + \Delta THR/2^2}$

- ΔTHR from BCID cross talk: in TJMP2 ~ 100e- already >> thermal noise (<10 e-) and effect scales with number pixels → will be larger (x1.6) in OBELIX ~ 160 e-
- BCID cross talk origin not fully understood, but good hints now, some modifications in OBELIX are proposed to mitigate the effects.

BCID cross talk: changes the threshold depending on the phase w.r.t the hit



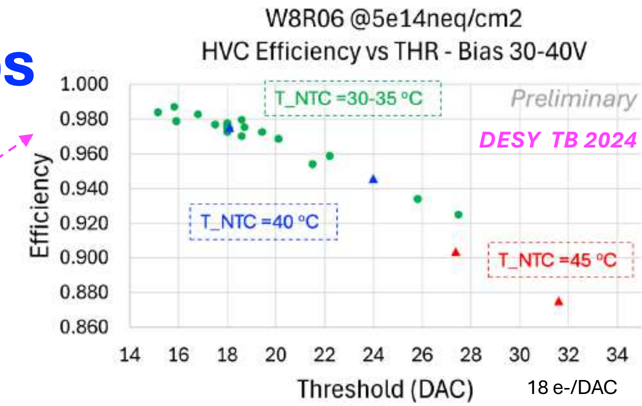


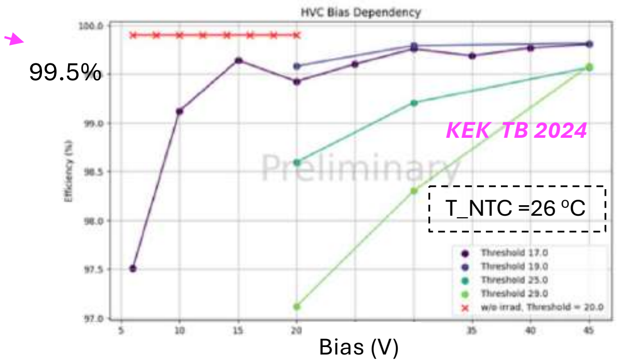
2. - Characterization of TJ-Monopix2 irradiated chips

- DESY Testbeam - July 2024:
  - perfomance deterioration @ high temperature (higher THR → lower efficiency) with p-irrad NIEL=5x10^{14} neq/cm2, OK with TID 100 Mrad → summary slides (202501220)
- KEK Testbeam - Dec 2024:
  - Better results with e- irradiated @ 90 MeV NIEL @ 5x10^{14} neq/cm^2 related to lower operating temp → preliminary results (20241216)

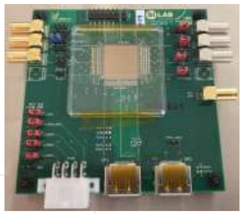
DESY TB:
- HVC: max efficiency ~ 98.5%
- DCC: effi > 99% but 3% pixels masked

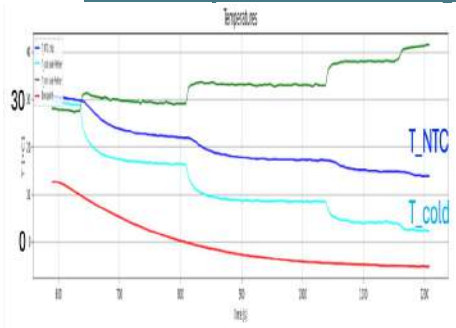
KEK TB:
- reached efficiency > 99%

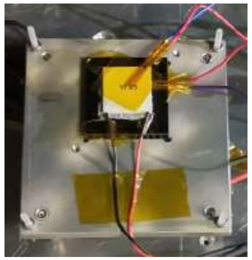


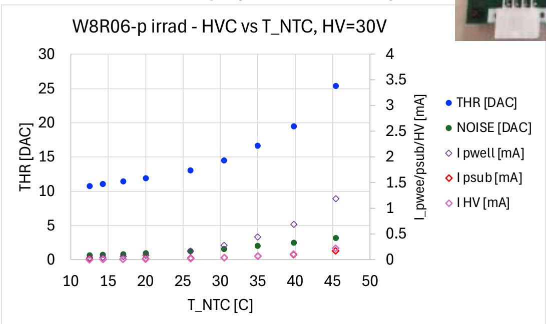


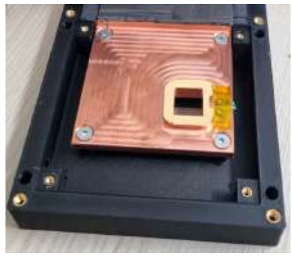
- Lab test on NIEL irradiated sample with temperature control
  - Prepared a lab cooling setup with peltier cell to operate with T_NTC = 14-45 °C
  - Performance evolution with temperature: THR, Noise, BCID cross talk effects
  - Summary of effects of high Temperature on NIEL irradiated chip (20241202)

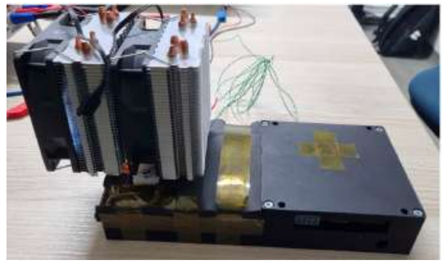












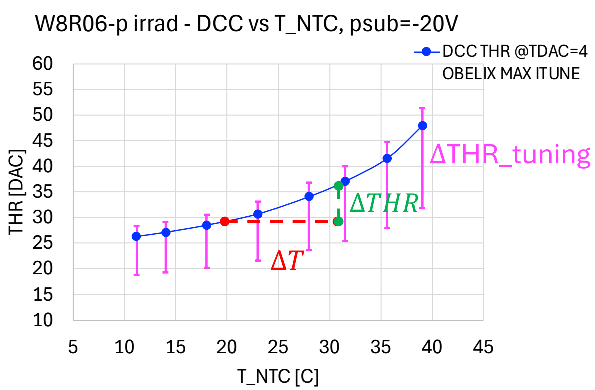
- Preparation for April 2025 DESY Testbeam with temperature control:
  - 4 irradiated chips: 2 new chips NIEL @ 1- 2.5 x10^{14} neq/cm2 (Strasbourg/Pisa post irrad tests with Temp ongoing) + 2 chips NIEL @ 5 x10^{14} neq/cm2 (e- , p irradiated)

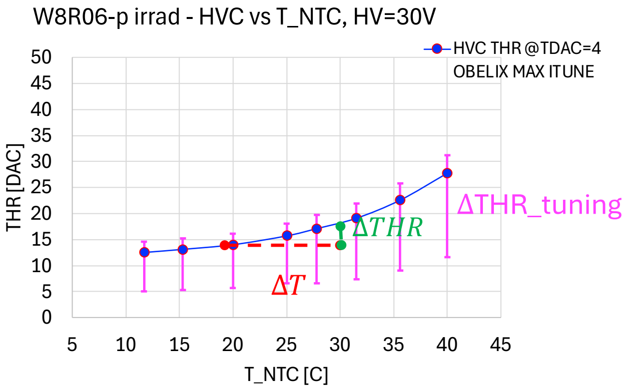
- HW & cooling system with peltier cell (T_NTC ~ 0-40C), DAQ preparation, TB data analysis tuning

3. Definition of OBELIX temperature specs & cooling needs

- Summary slides on OBELIX temperature specs (20250120)
- With present data with NIEL @5x10^{14} neq/cm2:
  - Performance ~ OK with T_NTC_max ~ 30-35°C → T_chip_max ~ 40-45°C
  - We should exclude iVTX cooling options w/o water: Tchip_max ~ 60 °C → not affordable
- iVTX thermal simulation with 1 water cooling pipe: $T_{max} = 36°C,\ \Delta T = 11°C$ → T_NTC_max = $26°C,\ \Delta T = 11°C$
- Threshold and Noise levels seems OK for operation @ T_NTC ~ 25°C (for both DCC and HVC)

- Expected gradient across chip ΔT ~10 °C , gives a gradient in threshold ΔTHR
- THR tuning power implemented in OBELIX (measured in TJMP2) can compensate this effect: $\Delta THR < \Delta THR\_tuning$





- Based on TB 2024 data with T_NTC ~ 25°C achievable THR and efficiency should be OK → need confirmation with TB 2025, but "hot pixels" from BCID cross talk could be an issue
- Effect will larger in OBELIX → mitigation need to be implemented

4. Preparation for OBELIX-1 testing

Very preliminary still to be discussed

- **Effort yet to start: HW, FW, SW, teams ...need to be ready to start tests ~ 6 months after submission. Autumn/end of 2025 (?)**
- Use similar DAQ setup as for TJMP2: BDAQ53 board + custom PCB
  - Design/production of OBELIX-1 PCB & prepare for bondings (hope easier than now)
  - Firmware specific for OBELIX needs to be developed?
  - Control SW for data taking in part adaptable (hope!) from TJMP2 scripts + new

Crucial contribution from Bonn, developers of TJMP2 DAQ

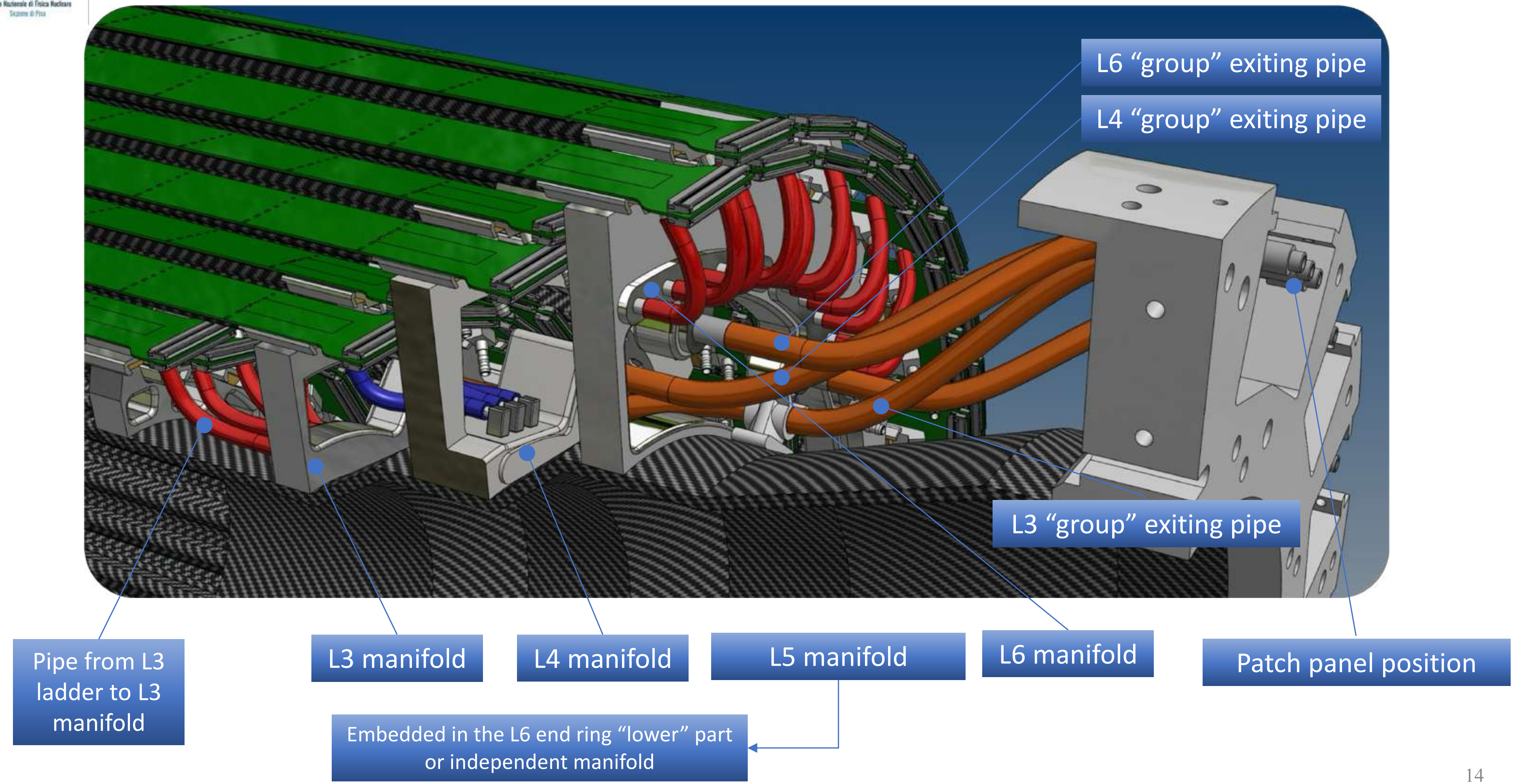
- Need to prepare different sets of tests:

1. "standard" tests to measure THR, noise, THR dispersion, BCID coupling in OBELIX in a similar way as we do in TJMP2 (triggerless mode operation)

   → possible with modifications of the TJMP2 testing scripts (?)
2. "new" tests to verify OBELIX new features → need clear indications from designers
   1. triggered operation
   2. TTT Track Trigger Transmission
   3. PTD Peripheral Time-to-Digital converter
   4. ...

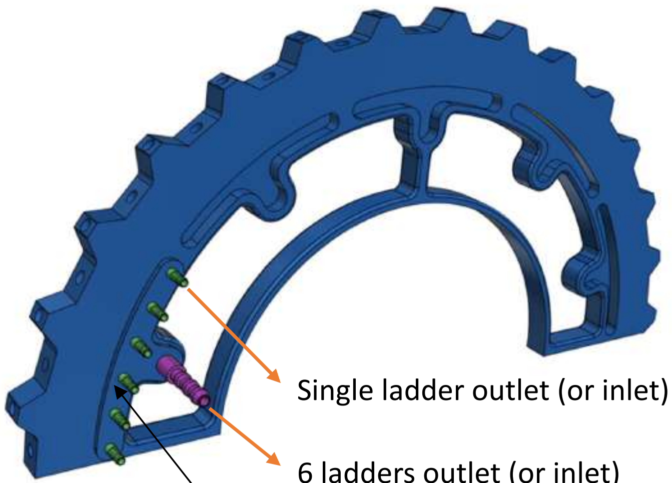
- Plan first OBELIX testbeam asap after "standard" test: Spring 2026?
- In 2026: irradiation campaigns, test robustness against huge spikes of radiation (SBL!) ...

Services - Embedded manifolds – BWD Side



Services - Embedded manifolds – BWD Side

L6 SS ring

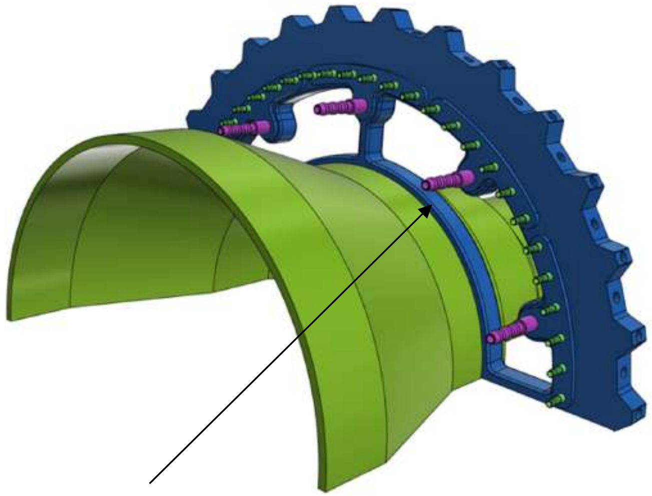


Single ladder outlet (or inlet)

6 ladders outlet (or inlet)

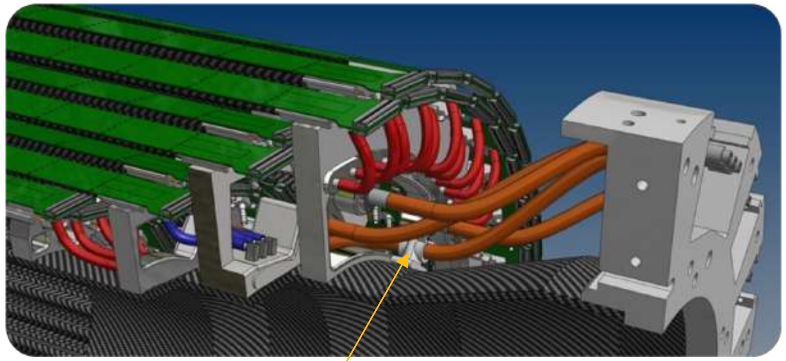
Welded cap and fittings

L6 SS ring + BWD Half Cone



Ring glued on top of the cone

BWD Side hydraulic services preliminary study



Pipe's clamp (example)

- Each ladder has a dedicated pipe running from the forward side to the backward side (or BWD to FWD)
- The pipes are grouped into manifolds, and then, for each group, only one pipe exits (or enters)
- The estimated mass flow/ladder (l/min): 0.11 (*See oVTX mech note for details*)

Tubing: Festo pipes – PUN-H
Services safety requirements: Comply with Fire safety Instruction / Radiation tolerant / Halogen free

Tubing

Designation	Polyurethane (PU) PUN-H ★ PUN-H-DUO
Operating medium[1]	Compressed air, vacuum, water
Temperature [°C]	−35 ... +60
Temperature-dependent operating pressure [MPa]	−0.095 ... +1
Resistant to chemicals	+
Food-safe[2]	+++
Resistant to hydrolysis	++
Fire-tested	UL 94 HB
Halogen-free	+++
Flexible	+++
Special feature	Wide choice of variants