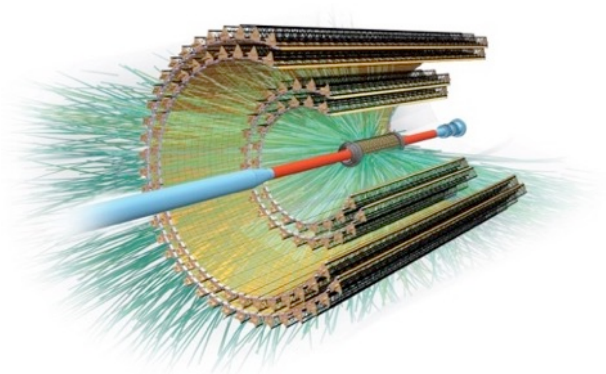
LXV International Conference on Nuclear Physics

«Nucleus 2015. New Horizons in Nuclear Physics, Nuclear Engineering, Femto- and Nanotechnologies»

June 29 – July 3, 2015, Saint-Petersburg

The new Inner Tracking System of the ALICE experiment: physics, design and performance



V. Manzari

INFN and CERN

on behalf of the ALICE Collaboration

Outline

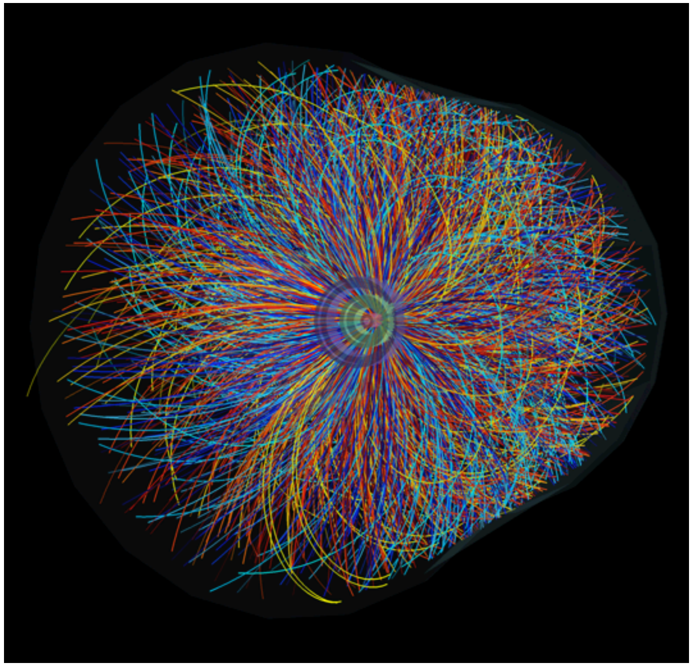
ALICE Today

ALICE Upgrade Strategy

Inner Tracking System Upgrade

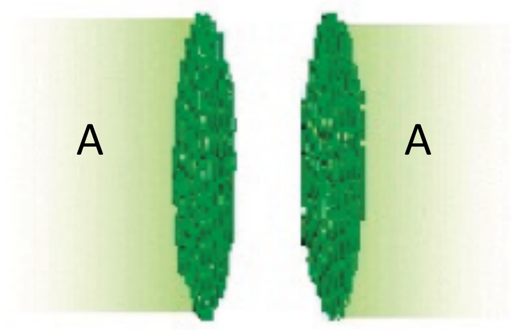
- Design Objectives
- Layout and Components
- Performance
- Timeline

Conclusions

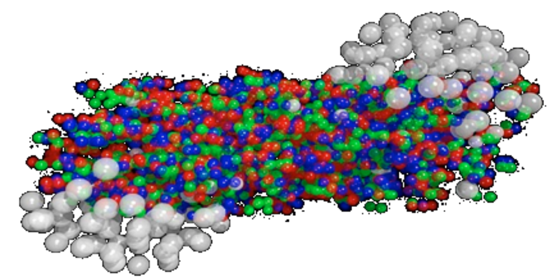


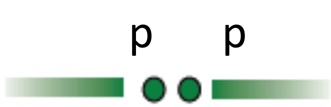
Study of QGP properties

ALICE is the CERN LHC experiment designed to study the physics of strongly interacting matter at extreme conditions of energy density (~15 GeV/fm^3) and temperature over a large volume (~ 1000 fm^3), and in particular the properties of the Quark Gluon Plasma (QGP), using



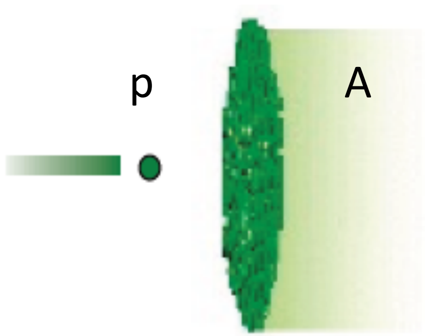
nucleus-nucleus collisions (A-A)





pp 'baseline', for the needed normalization

$$R_{AA}(,p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



proton-nucleus (p-A) to discriminate between **initial** state effects and **final** state effects

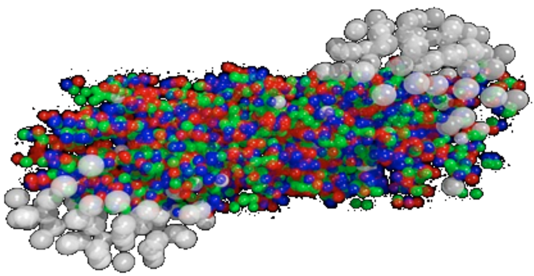
Cronin effect
modified PDF in nuclei

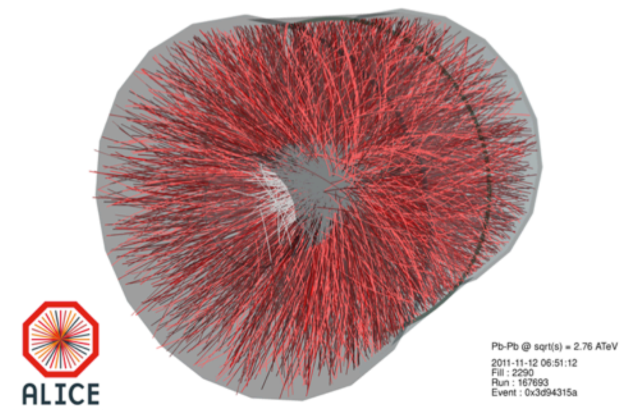
energy loss in the medium
hadronization mechanisms (fragmentation vs coalescence)

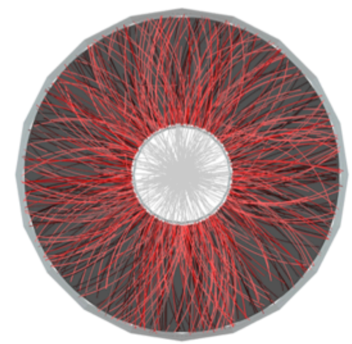
Study of QGP properties

Prior to LHC HI programme, nature of QGP – "a nearly perfect liquid" – emerged from experiments at CERN SPS and BNL RHIC

ALICE confirms basic picture: observation of hot hadronic matter at unprecedented values of temperatures, densities and volumes ….



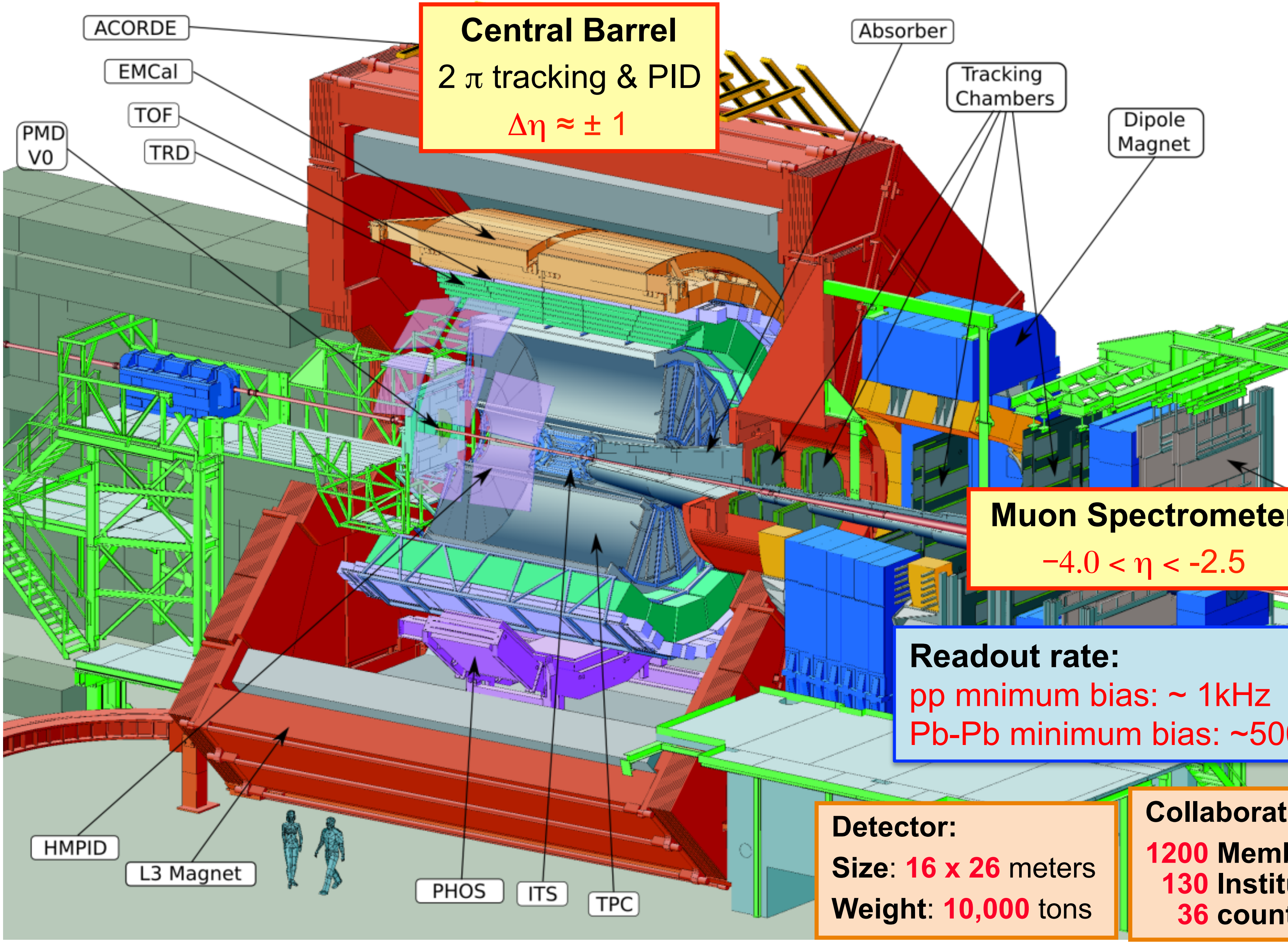




… and exceeding the precision and kinematic reach of all significant probes of the QGP measured in the past decades

➡ Excellent capabilities to measure high-energy nuclear collisions at LHC

The current ALICE Detector



Central Barrel
2 π tracking & PID
$\Delta\eta \approx \pm 1$

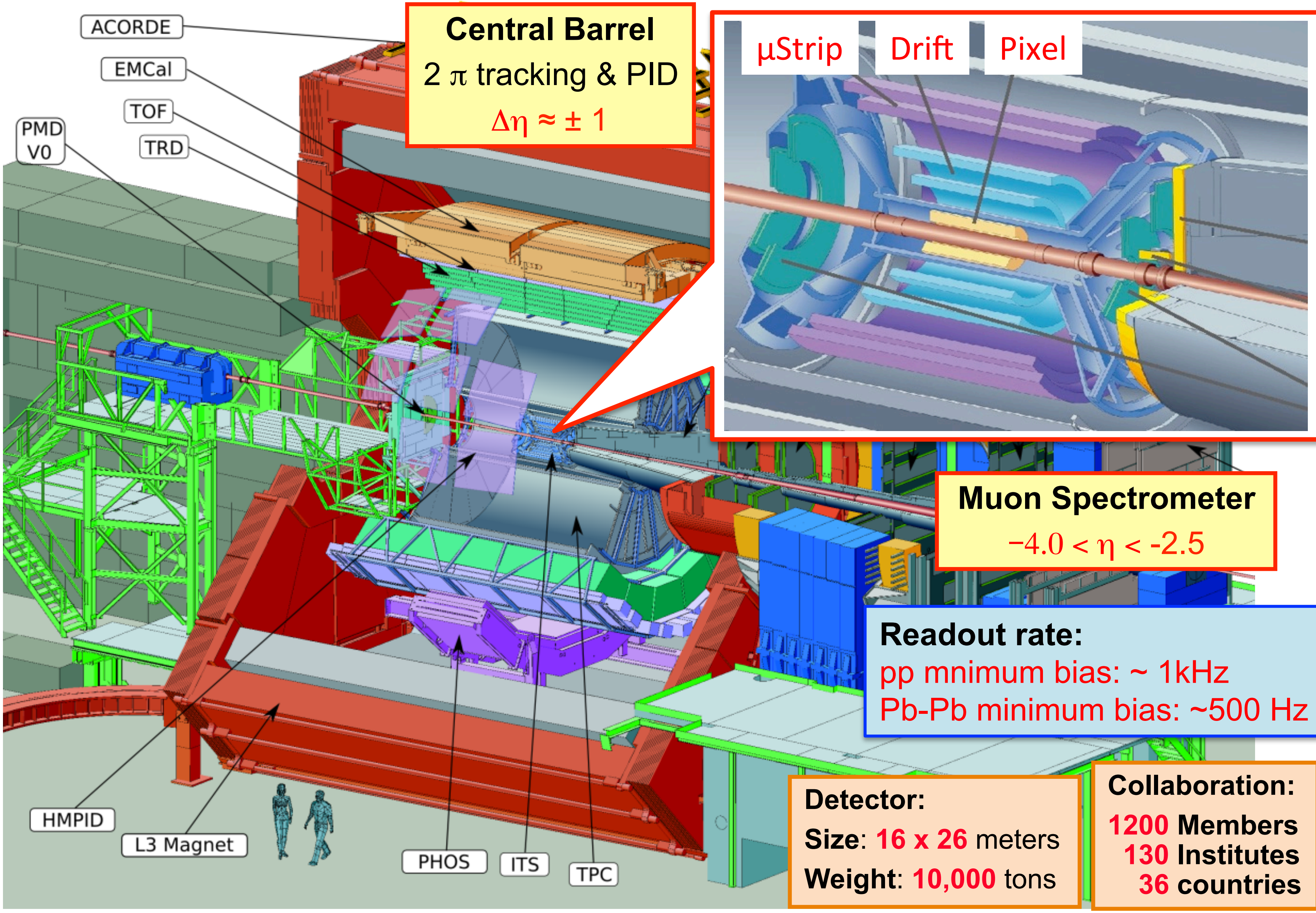
Muon Spectrometer
$-4.0 < \eta < -2.5$

Readout rate:
pp mnimum bias: ~ 1kHz
Pb-Pb minimum bias: ~500 Hz

Detector:
Size: **16 x 26** meters
Weight: **10,000** tons

Collaboration:
1200 Members
130 Institutes
36 countries

The current ALICE Detector



Central Barrel
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Δη ≈ ± 1

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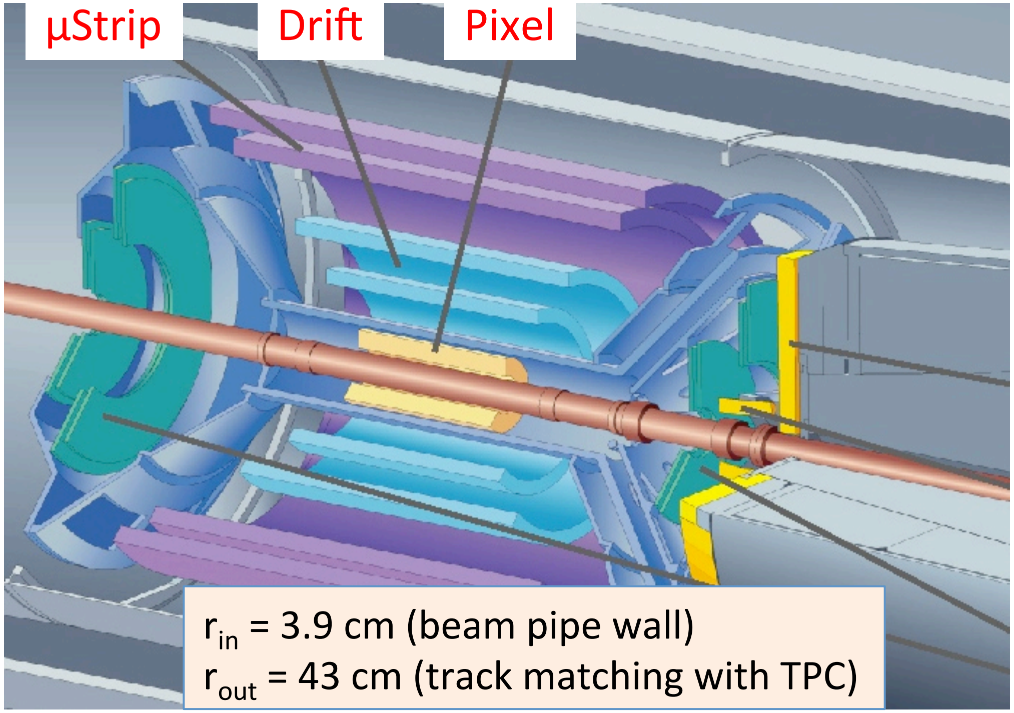
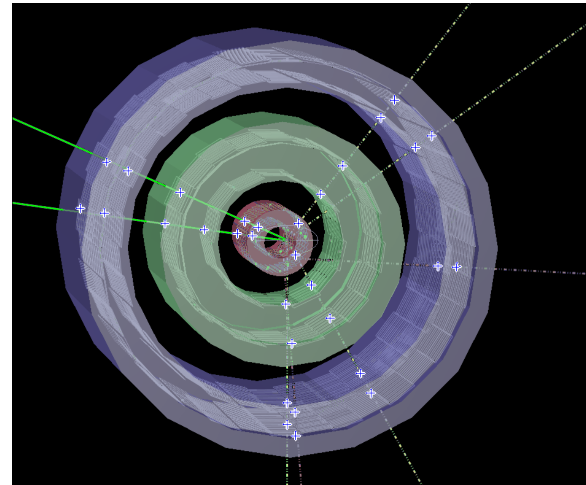
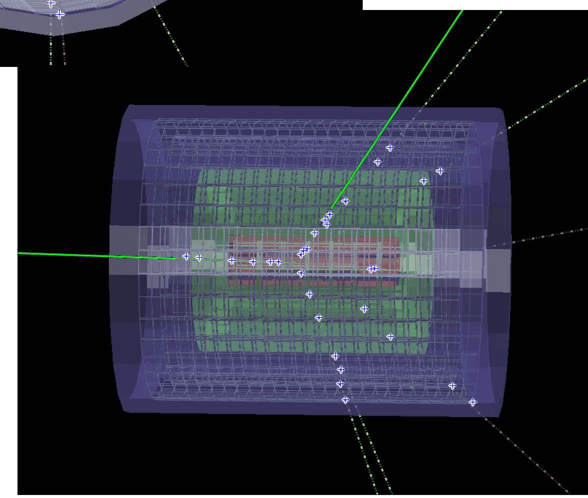
The current Inner Tracking System







6 concentric barrels of silicon detectors based on 3 different technologies

- 2 layers of Silicon Pixel (SPD), material X/X_0 1.14 % /layer → tracking and MB trigger
- 2 layers of Silicon Drift (SDD) → tracking and particle identification
- 2 layers of double-sided Silicon µStrips (SSD) → tracking and particle identification

ITS Tasks

Prompt Level-0 trigger capability with a maximum latency of < 800 ns (Pixel)

Improve primary vertex reconstruction, momentum and impact parameter resolution

Standalone tracking and PID of low p_T particles

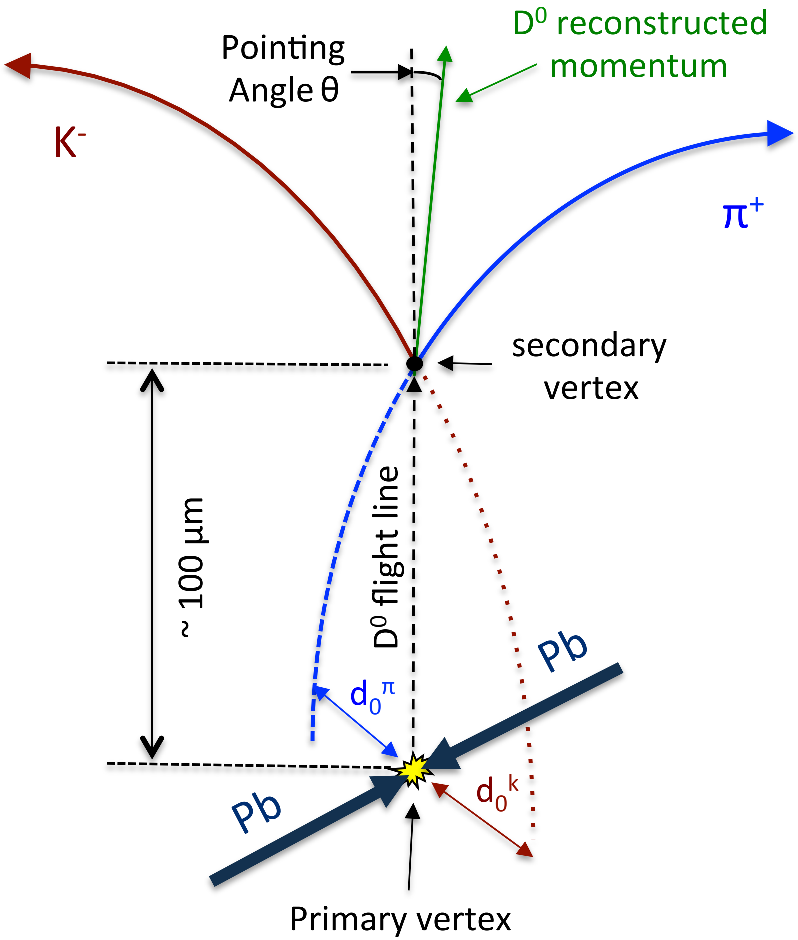
Reconstruction of secondary vertices from c and b decays with high resolution

Measurement of charged particles pseudo-rapidity distribution

Event pile-up rejection

ITS Upgrade – Secondary Vertex Determination

Example: D^0 meson



Open charm

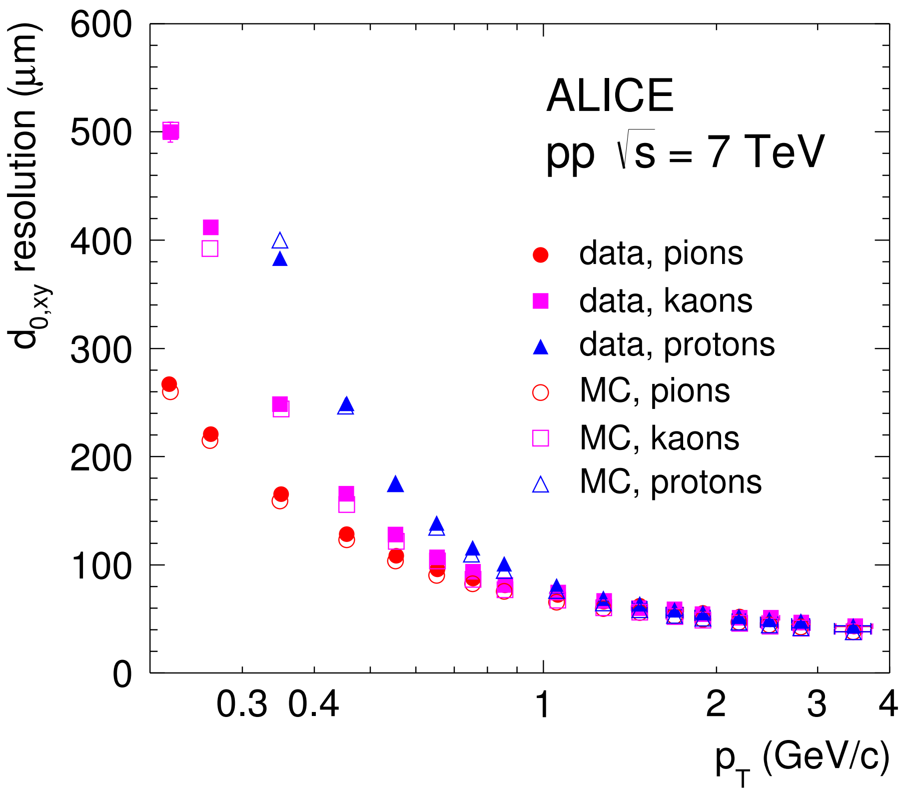
Particle	Decay Channel	cτ (μm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p K^- \pi^+$ (5.0%)	60

Analysis based on decay topology and invariant mass technique

How precisely is d_0 measured with the current ITS detector?

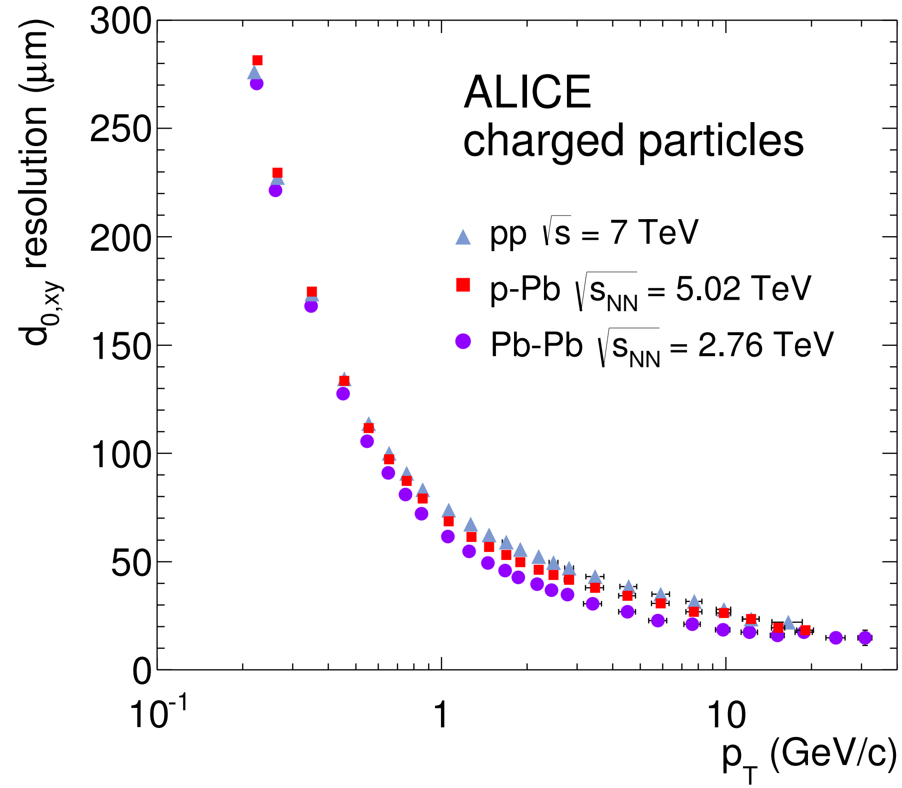
Current ITS – Impact Parameter Resolution

Very good MC description



ALICE, Int. J. Mod. Phys. A29 (2014) 1430044

Very weak dependence on the colliding system



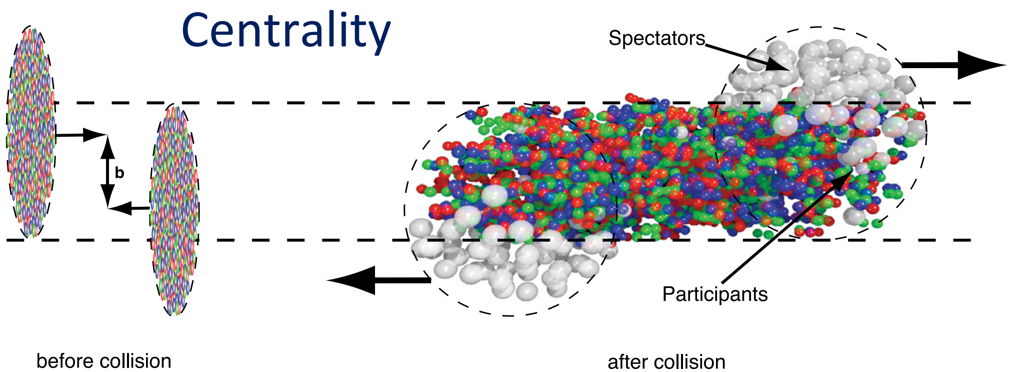
ALICE, Int. J. Mod. Phys. A29 (2014) 1430044

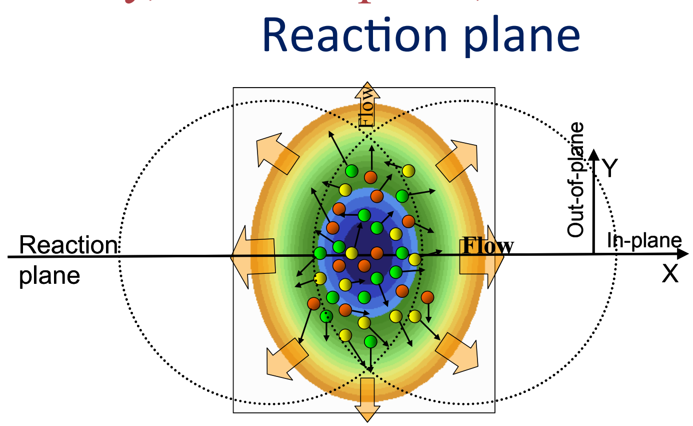
~70 μm at p_T = 1 GeV/c

ALICE Upgrade: Detailed Characterization of QGP

Progress on the characterization of QGP properties

- precision measurements of rare probes
- over a large kinematic range: from high to very low transverse momenta
- as function of multi-differential observables: centrality, reaction plane, …





Upgrade physics plans focus on physics observables where ALICE detector unique features are essential

PID, **low material thickness, precise vertexing and tracking down to low p_t**

Example:

precision measurements of spectra, correlations and flow of heavy flavour hadrons and quarkonia at low transverse momenta (not possible to trigger!)

ALICE Upgrade Strategy

➢ The ALICE Upgrade Physics Programme requires

statistics (luminosity)

Target for Run3+4: Pb-Pb recorded luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} evts

precision measurements

I. Upgrade detectors, readout systems and online systems

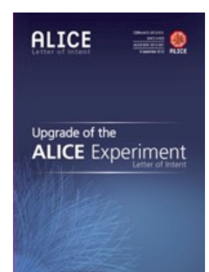
- read out all Pb-Pb interactions at a maximum rate of **50kHz** (i.e. $L = 6 \times 10^{27}\ cm^{-2}s^{-1}$), with a minimum bias trigger (at present 500Hz)

➡Gain a factor **100** in statistics wrt originally approved programme (Run1+2)

II. Significant improvement of vertexing and tracking capabilities at low p_T

New Inner tracking System

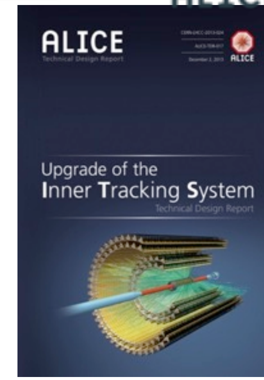
It targets LHC 2nd Long Shutdown (2019/20)



ALICE Upgrade LoI
September 2012

Addendum
September 2013

ITS Upgrade Design Features



CERN-LHCC-2013-24

J. Phys. G (41) 087002

1. Improve impact parameter resolution by a factor of ~3
- Get closer to IP (position of first layer): 39mm ➡ 23mm
- Reduce x/X_0 /layer: ~1.14% ➡ ~ 0.3% (for inner layers)
- Reduce pixel size: 50μm x 425μm ➡ O(30μm x 30μm)

2. Improve tracking efficiency and p_T resolution at low p_T
- Increase granularity:
  - 6 layers ➡ 7 layers
  - silicon drift and strips ➡ pixels

3. Fast readout
- readout Pb-Pb interactions at > 100 kHz and pp interactions at ~ several 10^5 Hz (currently limited at 1kHz with full ITS)

4. Fast insertion/removal for yearly maintenance
- possibility to replace non functioning detector modules during yearly shutdown

Memorandum of Understanding

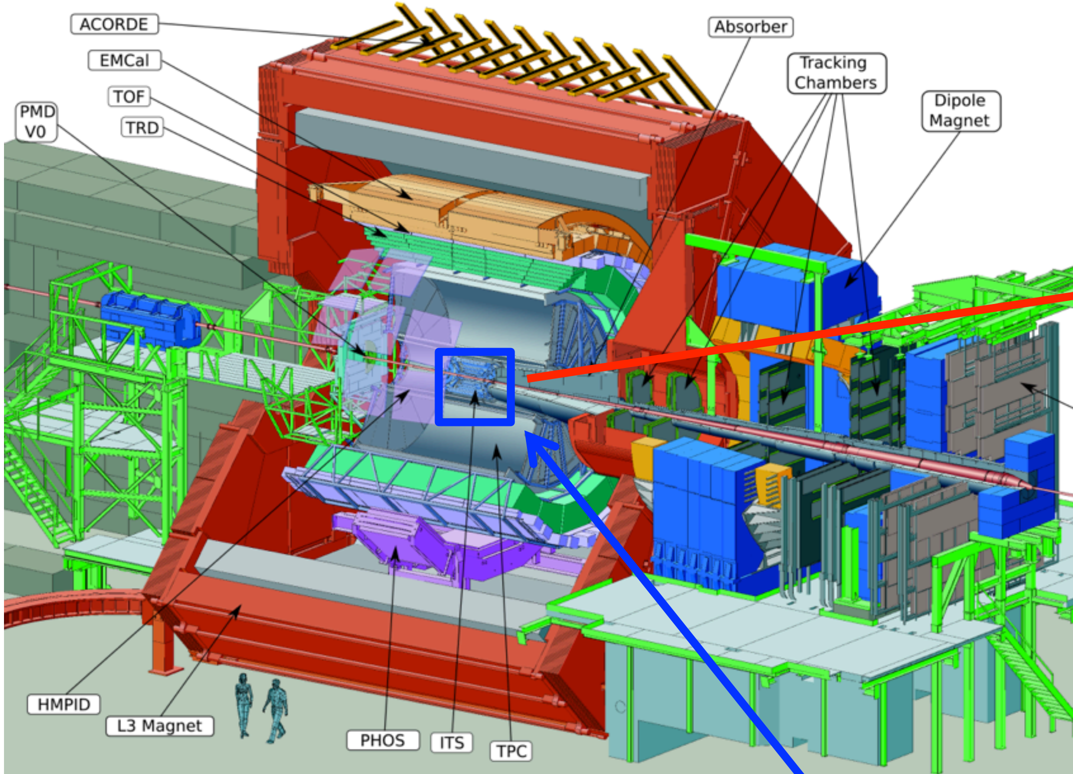
Project approval process completed

- Conceptual Design Report — Dec 2012
- Technical Design Report — Dec 2013
- Upgrade Cost Group Review — Mar 2014
- **Research Board Approval — Mar 2014**

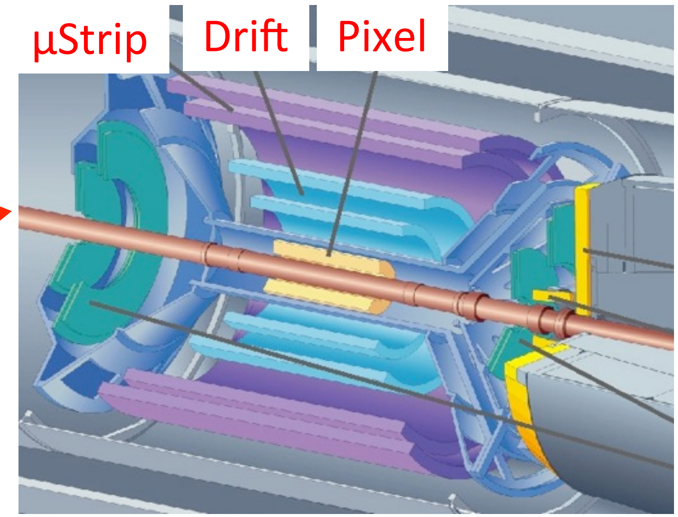
Responsibilities & Funding (ITS Upgrade MoU)

- **Signed — Apr 2015**

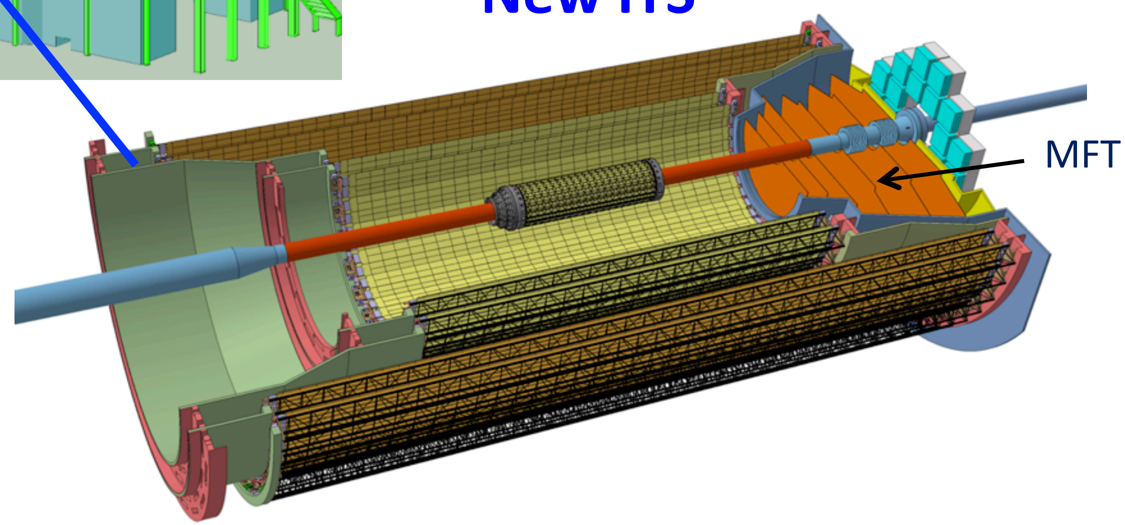
ALICE New ITS



Current ITS



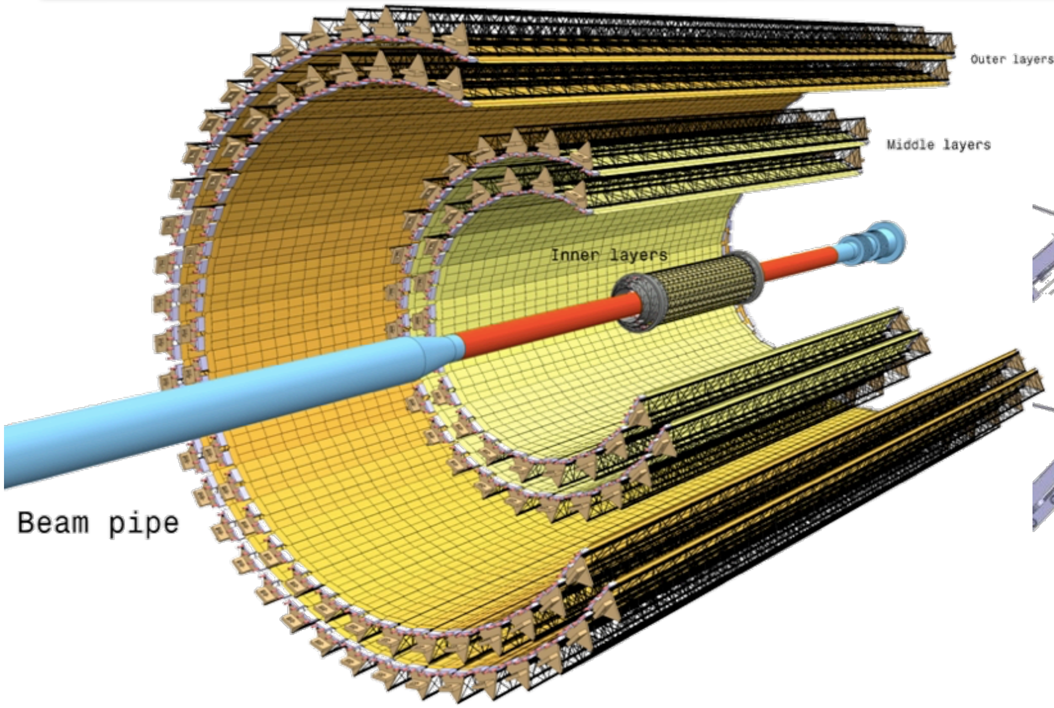
New ITS

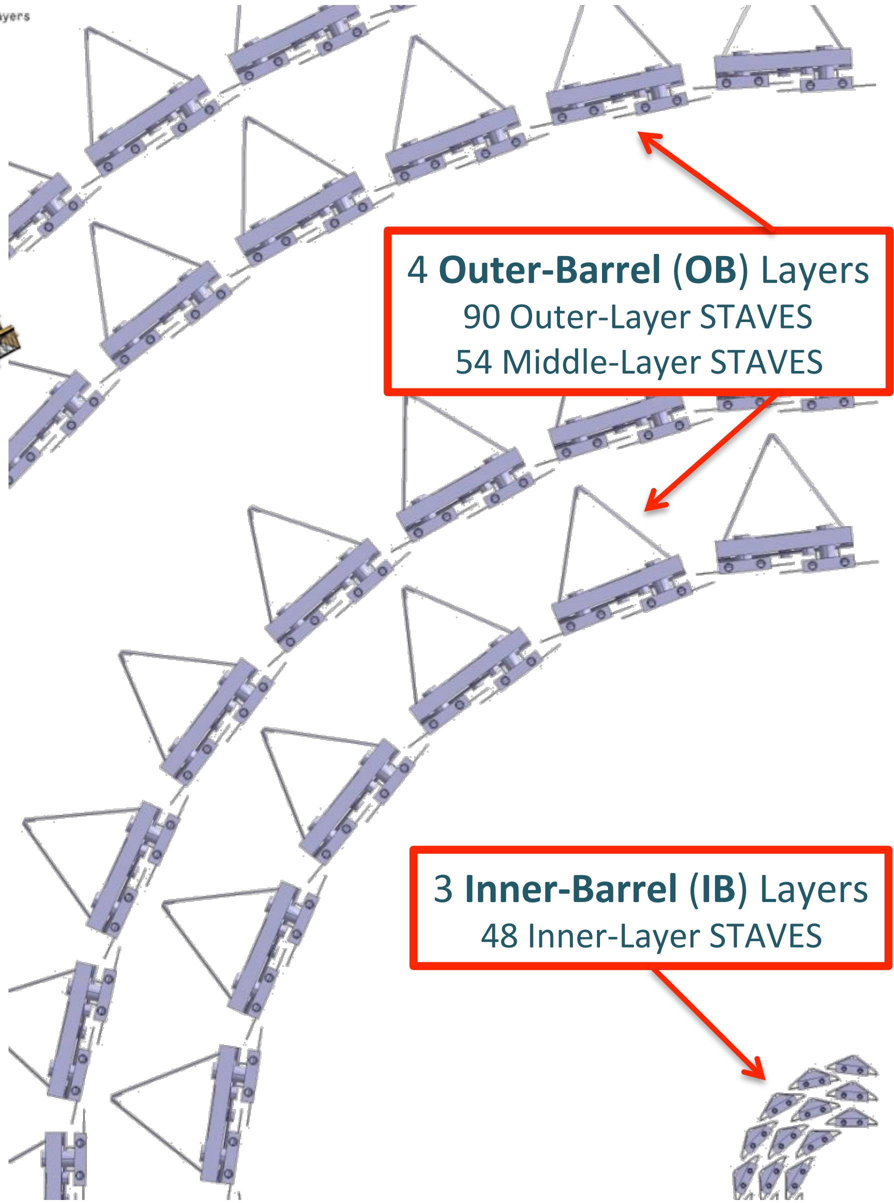


ITS Upgrade Objectives

- Increase readout rate: > x 50
- Increase vertexing and tracking accuracy

The New ITS





7 layers of Monolithic Active Pixel Sensors

12.5 G-pixel (~10 m^2)

r coverage: 22 – 400 mm

η coverage: $|\eta| \leq 1.22$

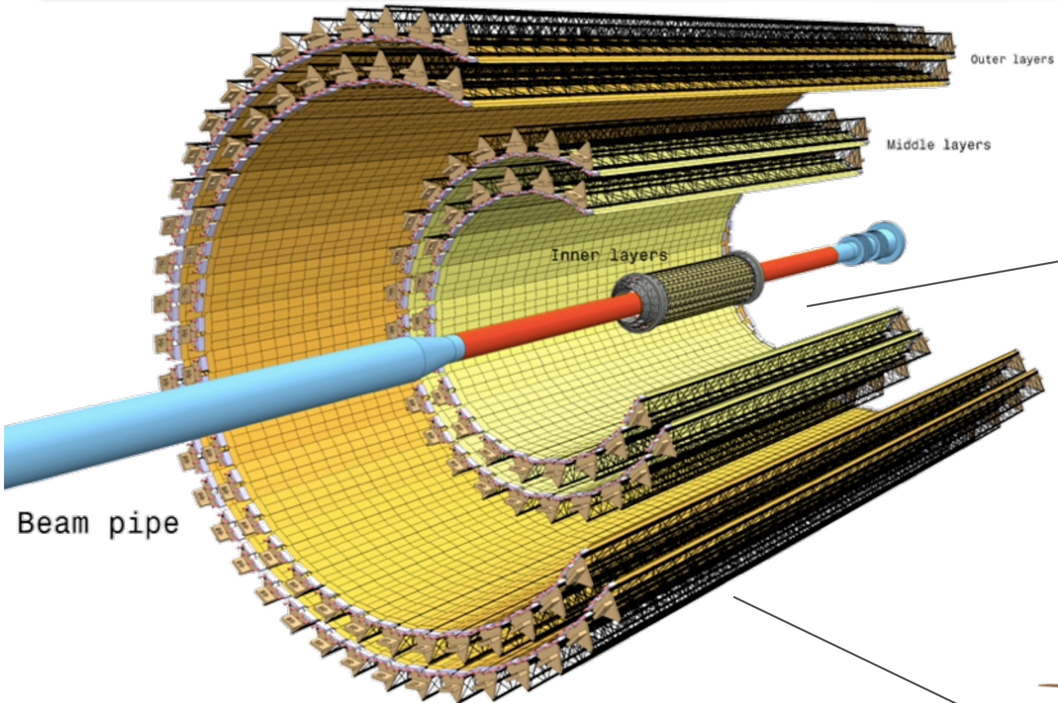
for tracks from 90% most luminous region

Material budget/layer: ~0.3% X_0 IB, ~1% X_0 OB

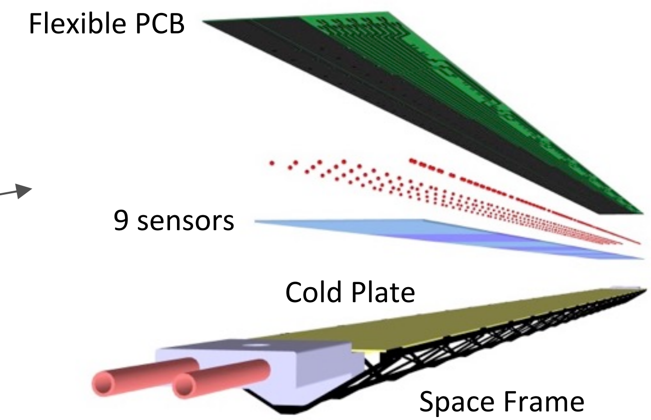
Radiation load: 700 krad/ 1×10^{13} 1 MeV n_{eq}

includes safety factor 10

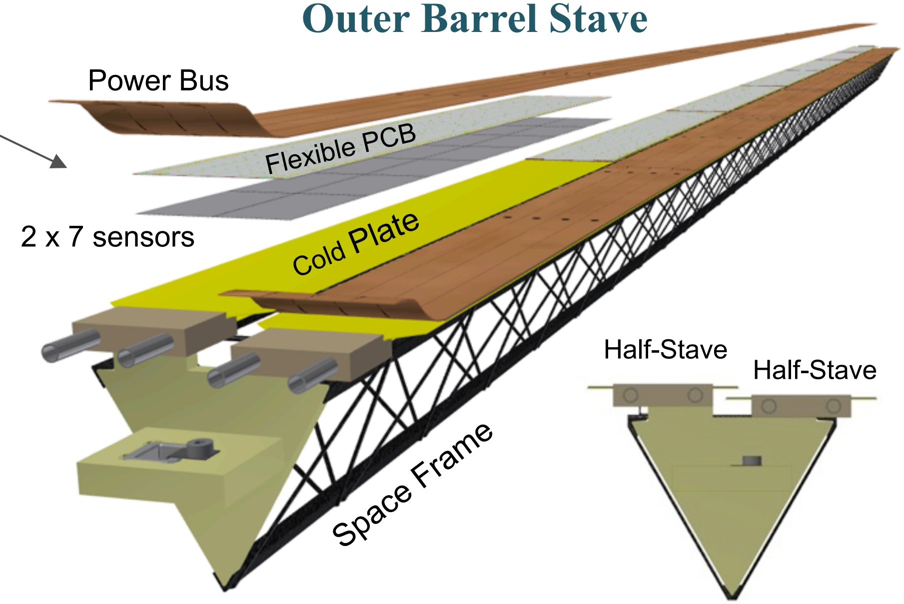
New ITS Staves



Inner Barrel Stave



Outer Barrel Stave



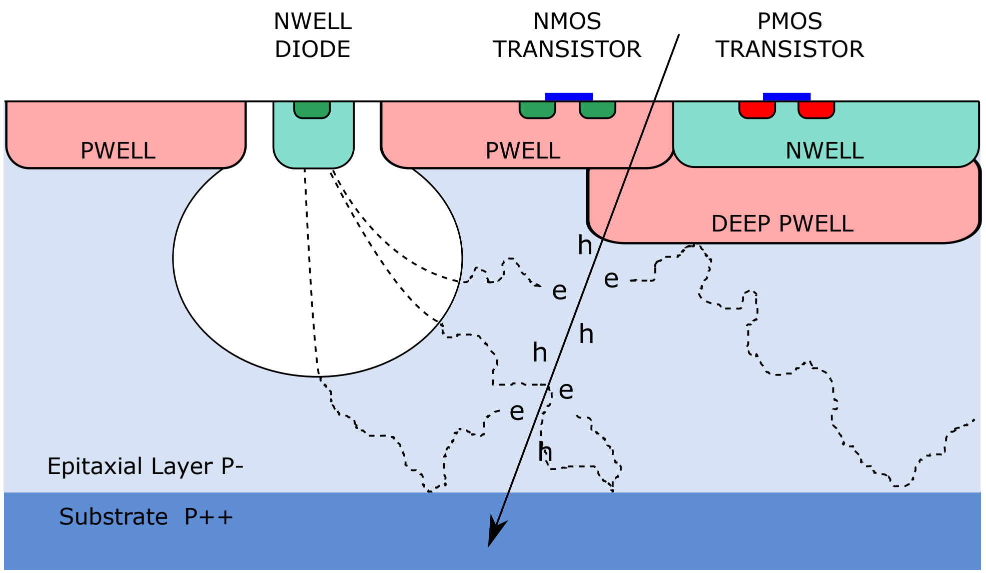
Layers are azimuthally segmented in **Staves**

Inner Layers	L = 290mm
Middle Layers	L = 900mm
Outer Layers	L = 1500mm

Staves have independent mechanics, power, cooling and readout

Pixel Chip – Technology choice

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



Tower Jazz 0.18 μm CMOS

- feature size 180 nm
- metal layers 6

➔ Suited for high-density, low-power

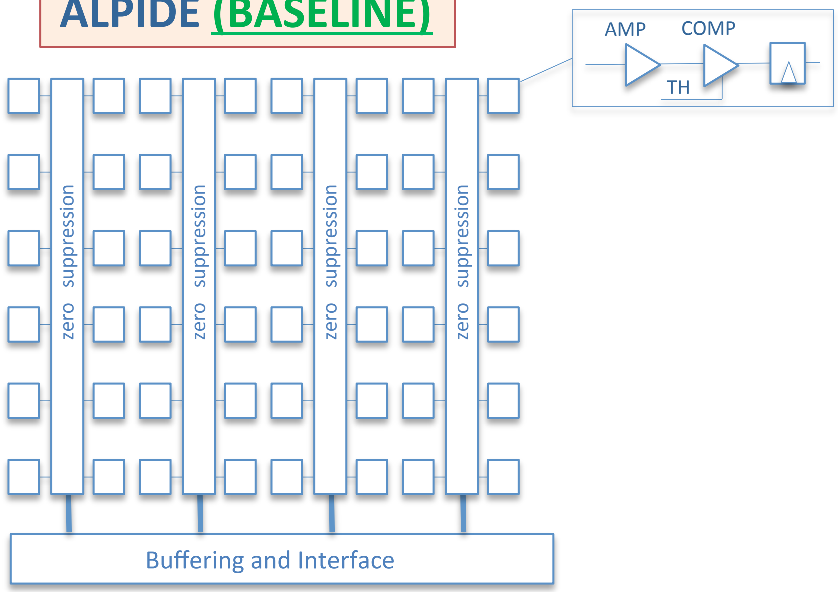
- Gate oxide 3nm

➔ Circuit rad-tolerant

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (20μm - 40μm thick) on p-type substrate
- Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate can be used to increase depletion zone around NWELL collection diode
- Quadruple well process: deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area

Pixel Chip

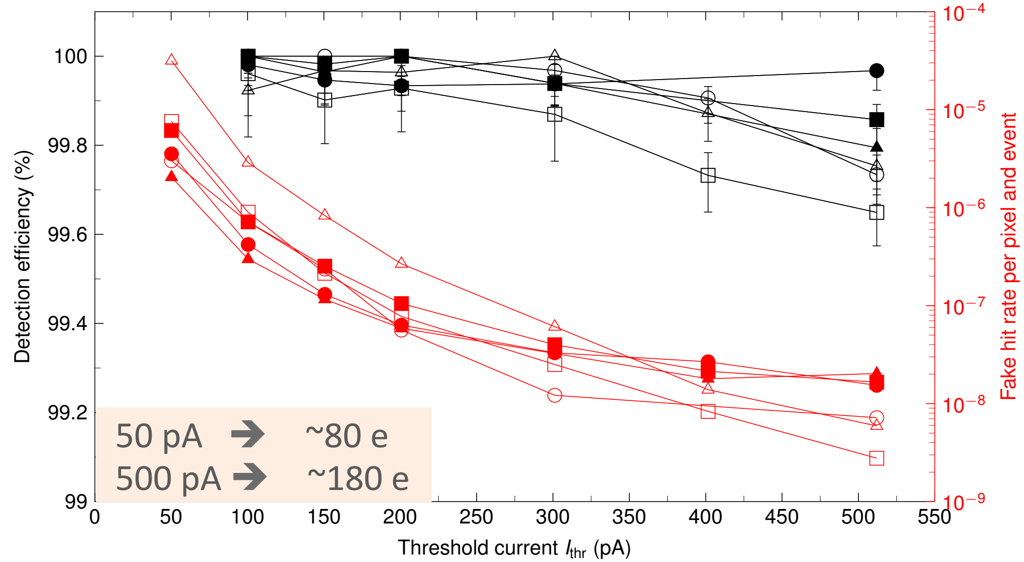
ALPIDE (BASELINE)



Dimensions	15 mm x 30 mm
Pixel pitch	28 μm x 28 μm
Event time resolution	<2 μs
Power consumption	39 mW/cm^2
Dead area	1.1 mm x 30mm
Continuous or external trigger	

Efficiency and fake hit rate

- Measurements at CERN PS: 5 – 7 GeV π^- Dec '14
- 50 μm thick chips: 3 non irradiated and 3 irradiated with neutrons at 10^{13} 1MeV n_{eq} / cm^2



$\lambda_{fake} << 10^{-5}$ / event/pixel @ $\varepsilon_{det} > 99\%$ ➡

➡ large margin over design requirements

for more details see Poster of V.I. Zherebchevsky et al.

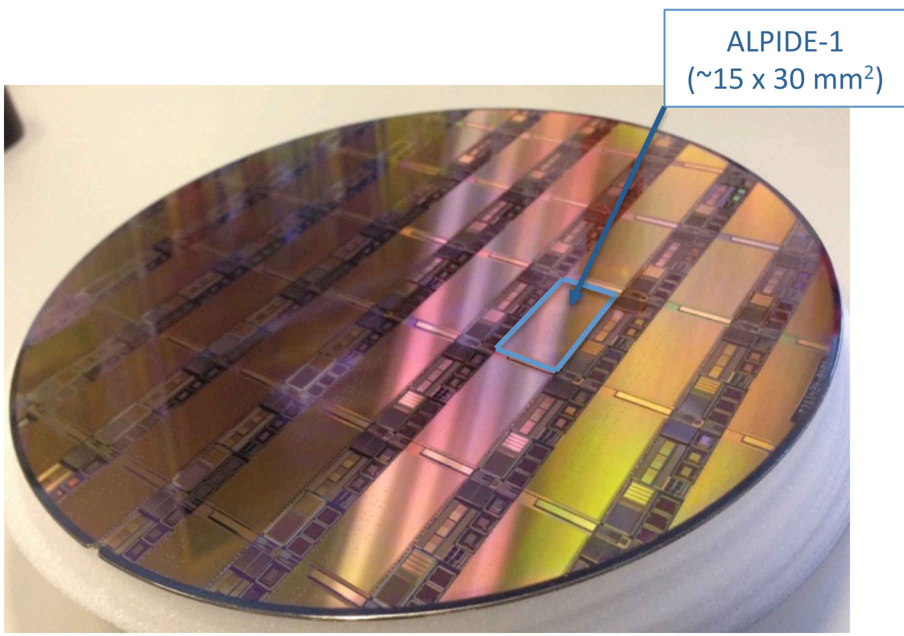
Back-up architecture **MISTRAL-O**:

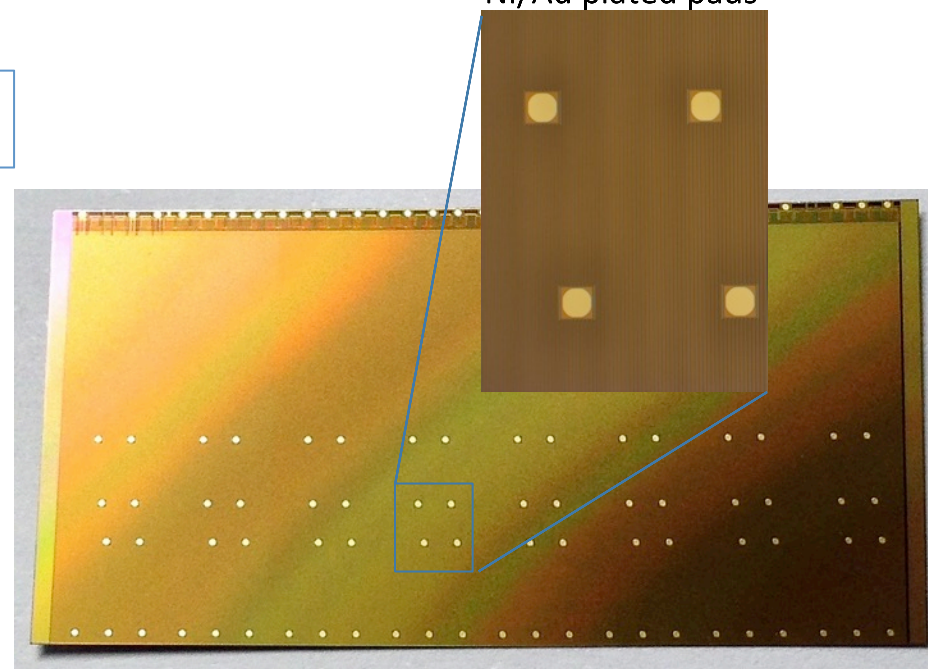
conservative double-row rolling shutter readout

identical dimensions, physical and electrical interfaces

Interconnection of pixel chip to Flex PCB (FPC)

- Solder Contact Pads are distributed over the matrix (custom designed)
- Wafer post-processing:
  - chip Al pads need to be covered with Ni-Au (wet-able surface) in order to solder the chip on the Flexible Printed Circuit (FPC)
  - plating is done using electroless Ni-Au plating, prior to thinning and dicing

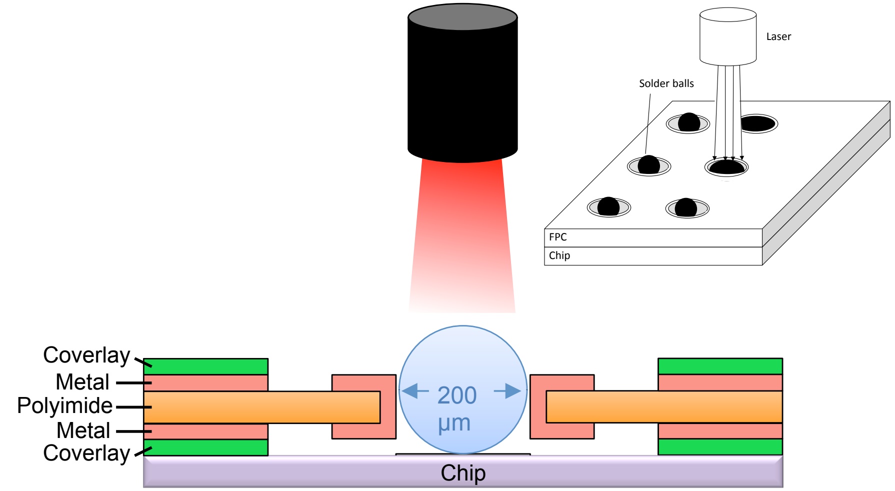


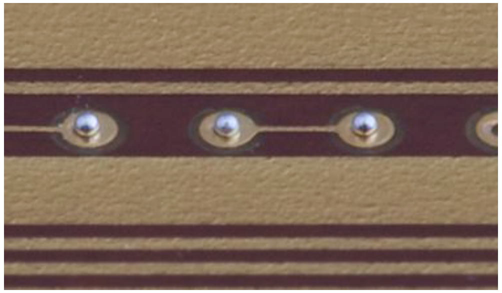


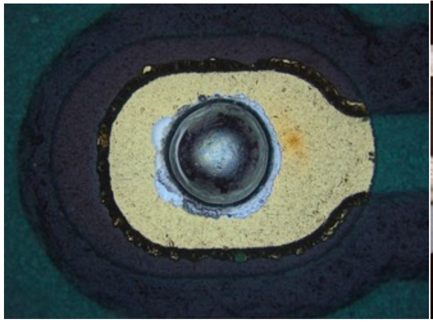
Interconnection of pixel chip to Flex PCB (FPC)

Laser Soldering

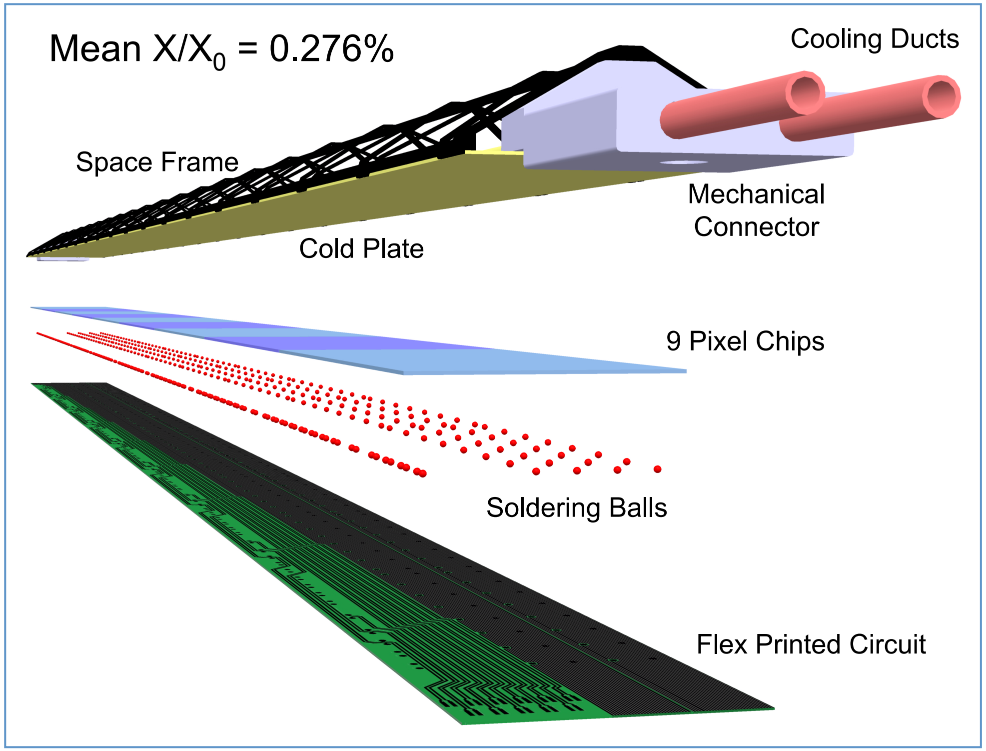
- Flux-less soldering of 200 µm diameter Sn/Ag(96.5/3.5) balls (227 °C melting T) in vacuum ($\leq 10^{-1}$ mbar)
- IR diode laser, 976 nm, 25 W, 50 mm focal length, 250 mm beam spot size
- Laser power modulated by pyrometer, programmable T profile ensures precise limitation of heating
- Soldering mask (in Macor® or Rubalit ®) used to press FPC on chip and guide soldering balls inside FPC vias
- Solder provides electrical and mechanical connection → no glue

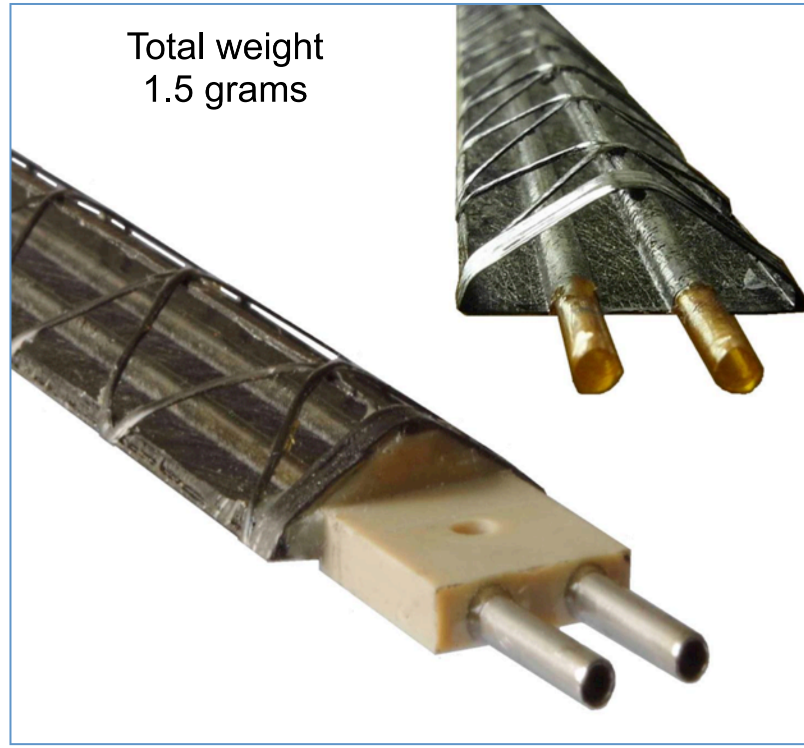






Inner Barrel Stave





<Radius> (mm): 23, 31, 39

Nr. of staves: 12, 16, 20

Nr. of chips/layer: 108, 144, 180

Power density: < 100 mW/cm^2

Length in z (mm): 290

Nr. of chips/stave: 9

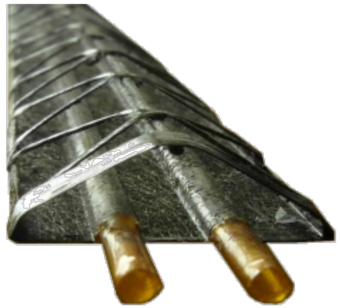
Material thickness: ~ 0.3% X_0

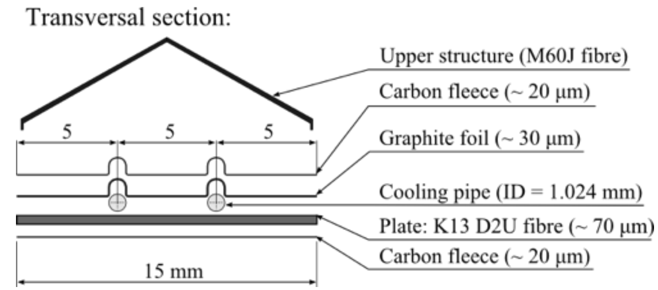
Throughput (@100kHz): < 80 Mb/s × cm^{-2}

Inner Barrel Stave

- ✓ New innovative stave design developed for the ALICE ITS Upgrade
- ✓ Thermal characterization of the inner barrel stave at **St Petersburg University**

Carbon layers
and polyimide tubes





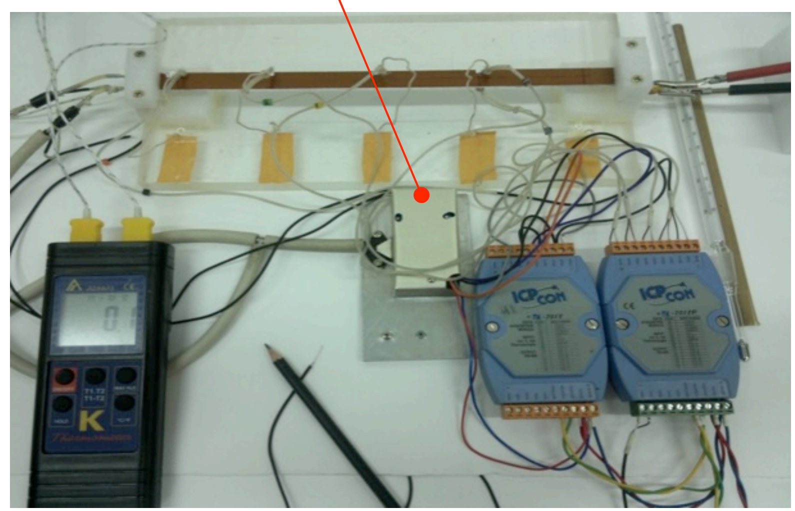
15°C IN

16.5°C OUT

0.15 W cm^{-2}, 3.0 L h^{-1}

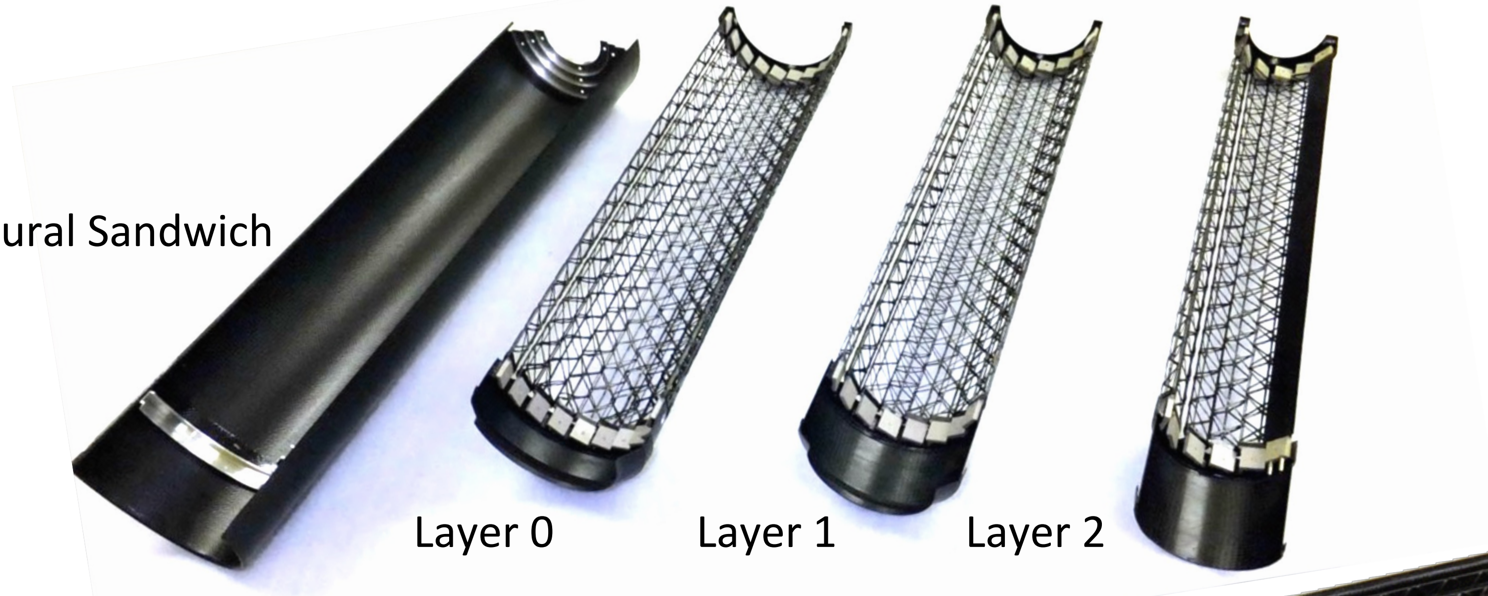
Water cooling leakless system

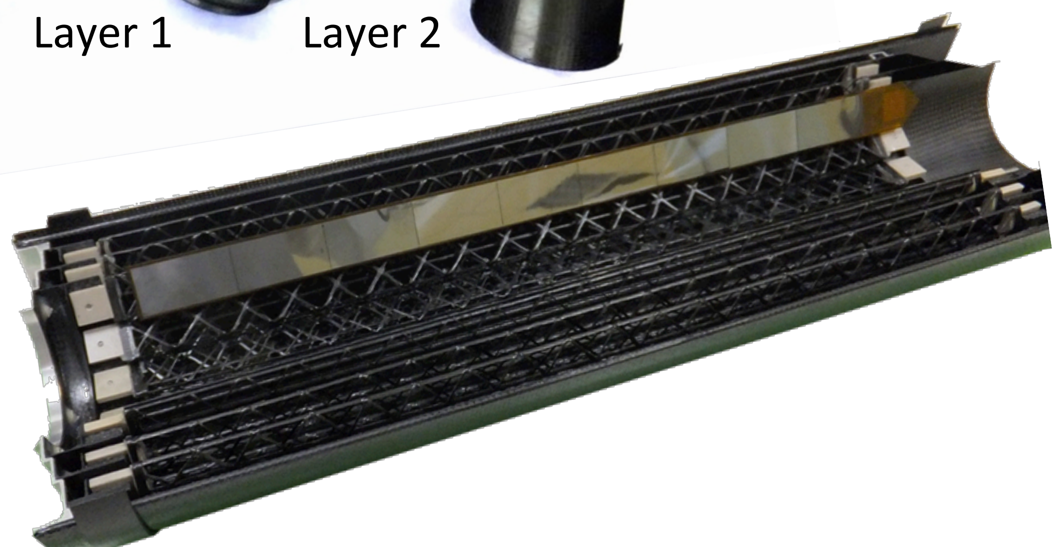
Temperature non-uniformity < 5°C



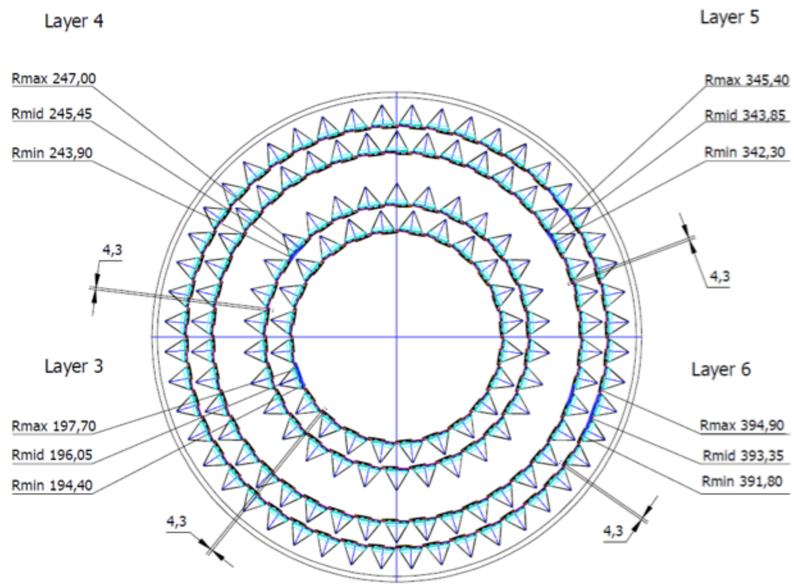
Inner Barrel – Full-scale Prototype

Cold Plate & Spaceframe carbon structure ~ 290mm, 1.5gr

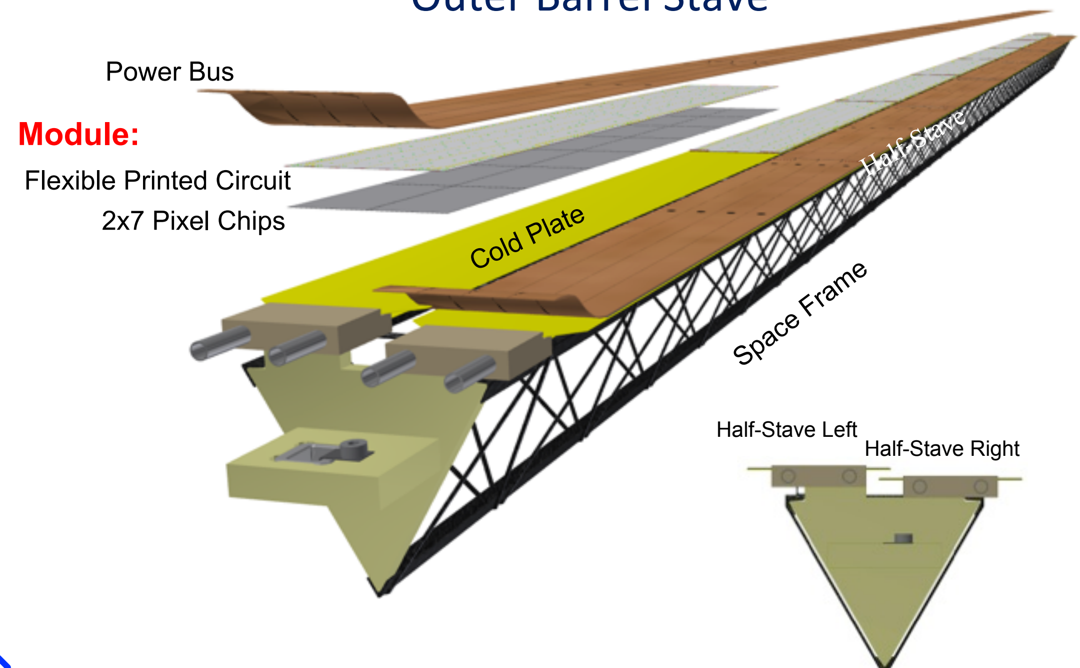




Outer Barrel Stave



Outer Barrel Stave

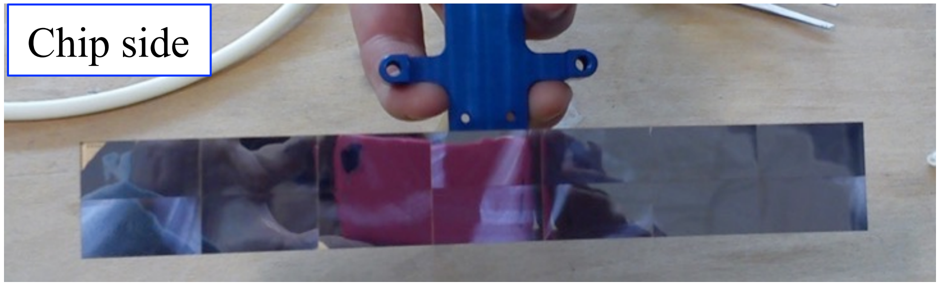


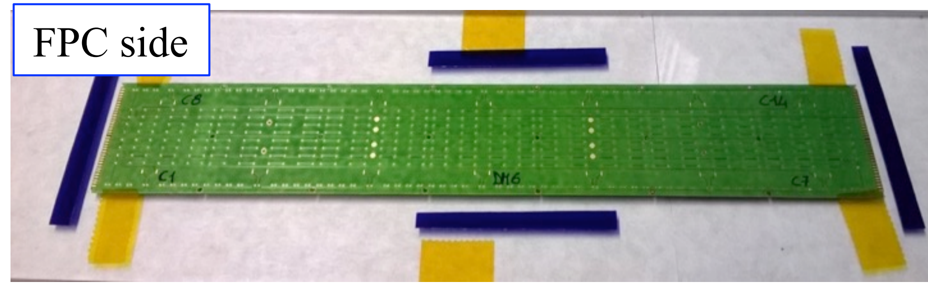
Outer Barrel (OB): 2 ML + 2 OL

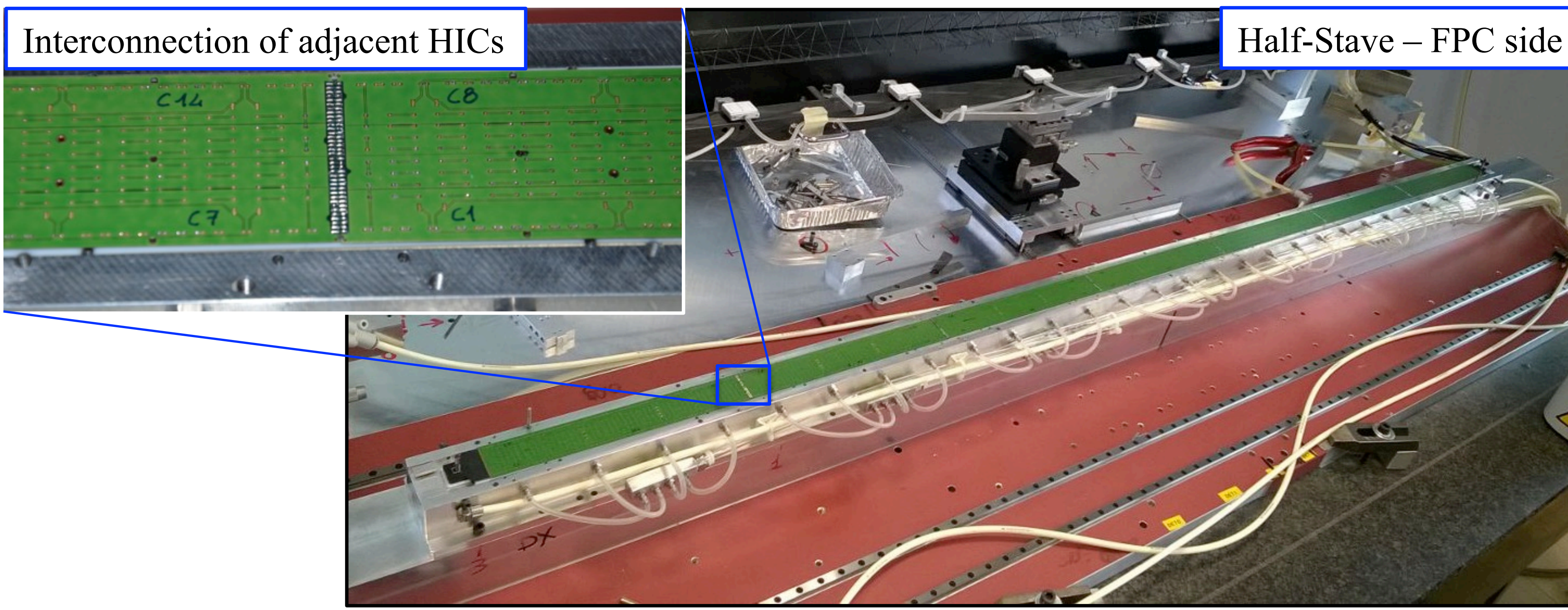
Radial position (mm): 196, 245, 344, 393
Length in z (mm): 843, 1475
Nr. of staves: 24, 30, 42, 48
Nr. of half-staves/stave: 2
Nr. of modules/half-stave: 4 (ML), 7 (OL)
Nr. of chips/module: 14
Nr. of chips/layer: 2688, 3360, 8232, 9408
Material thickness: ~ 1% X_0 per layer

Module to Module and Power Bus connections

Outer Barrel – Full-Scale Module and Stave Prototypes





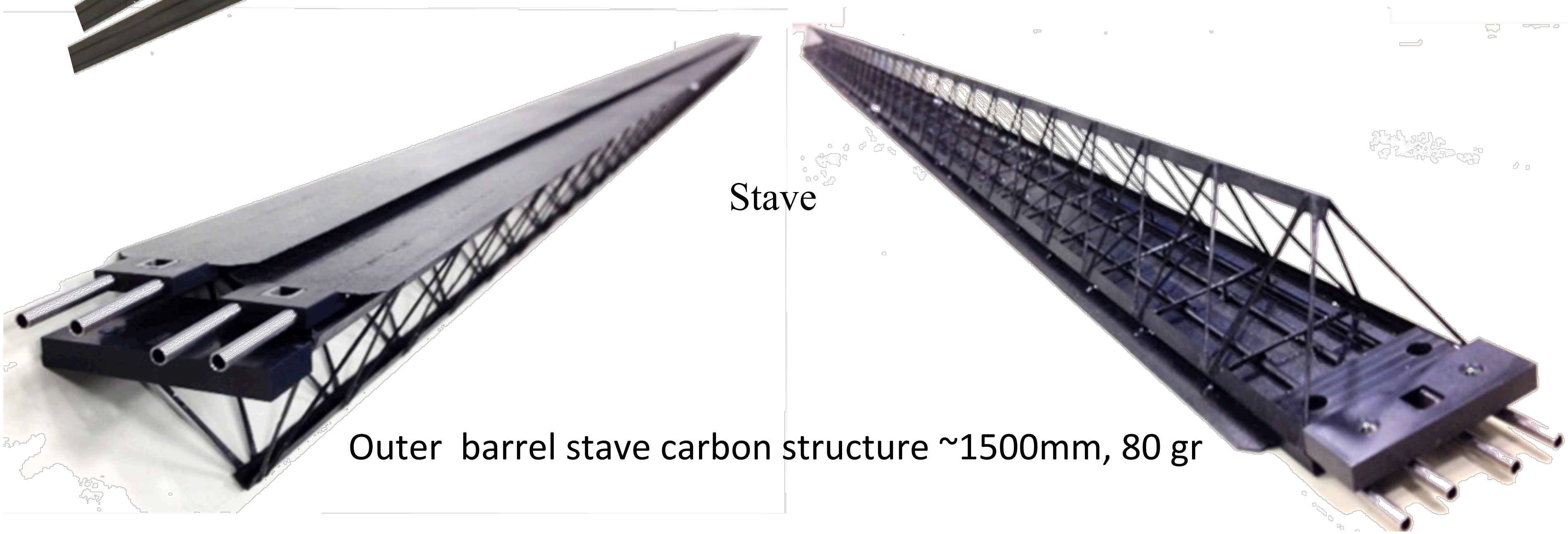


Outer Barrel Stave – Full-scale Prototype

Cold Plates

Spaceframe

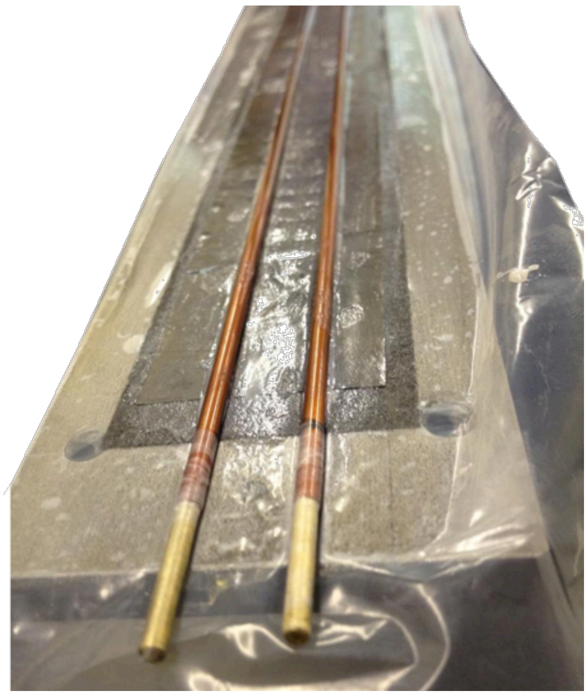
Stave



Outer barrel stave carbon structure ~1500mm, 80 gr

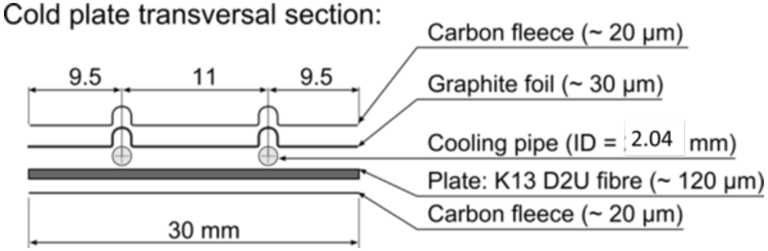
Outer Barrel – Cold Plate

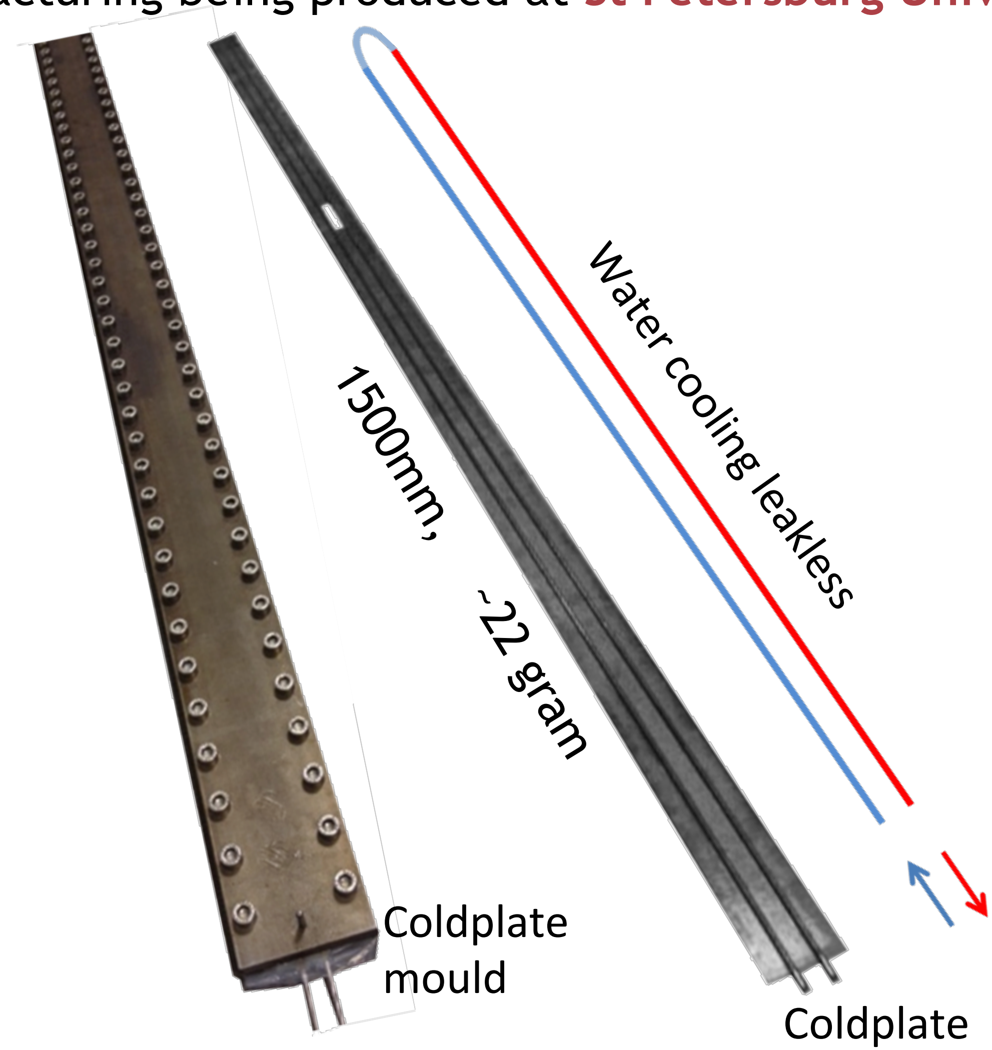
- ✓ New innovative cold plate design developed for the ALICE ITS Upgrade
- ✓ A new mould for cold plate manufacturing being produced at **St Petersburg Univ.**



Carbon layers and polyimide tubes

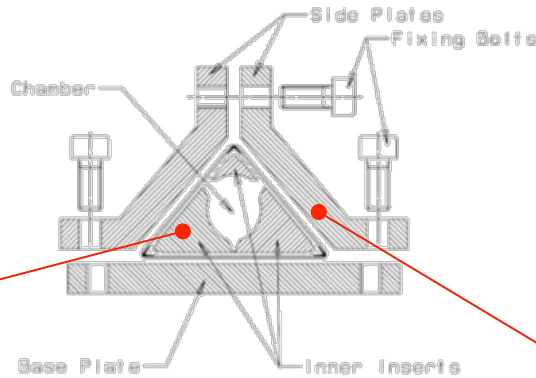
Cold plate transversal section:

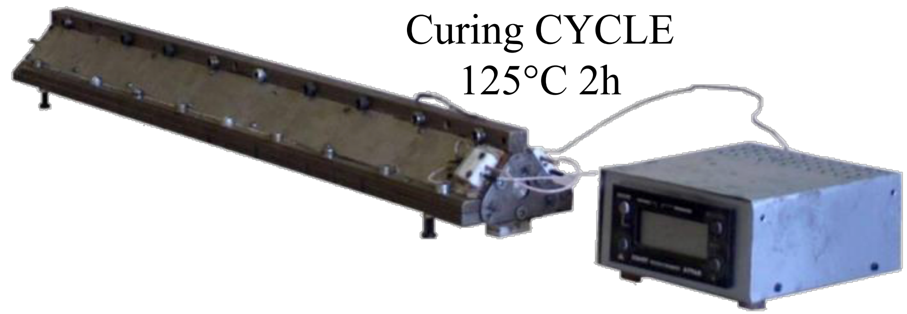




Outer Barrel – Spaceframe

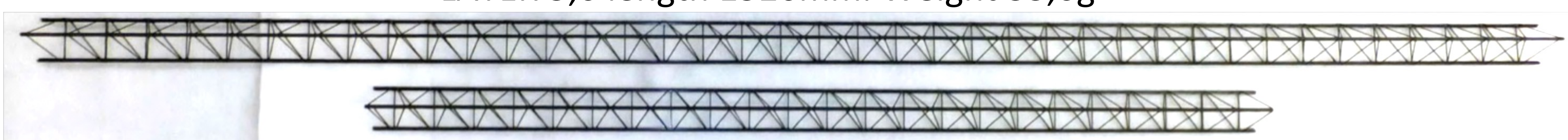
- ✓ A 1.5m spaceframe is required for the ALICE ITS Upgrade
- ✓ A new mould to manufacture such spaceframe produced at **St Petersburg Univ.**





Curing CYCLE
125°C 2h

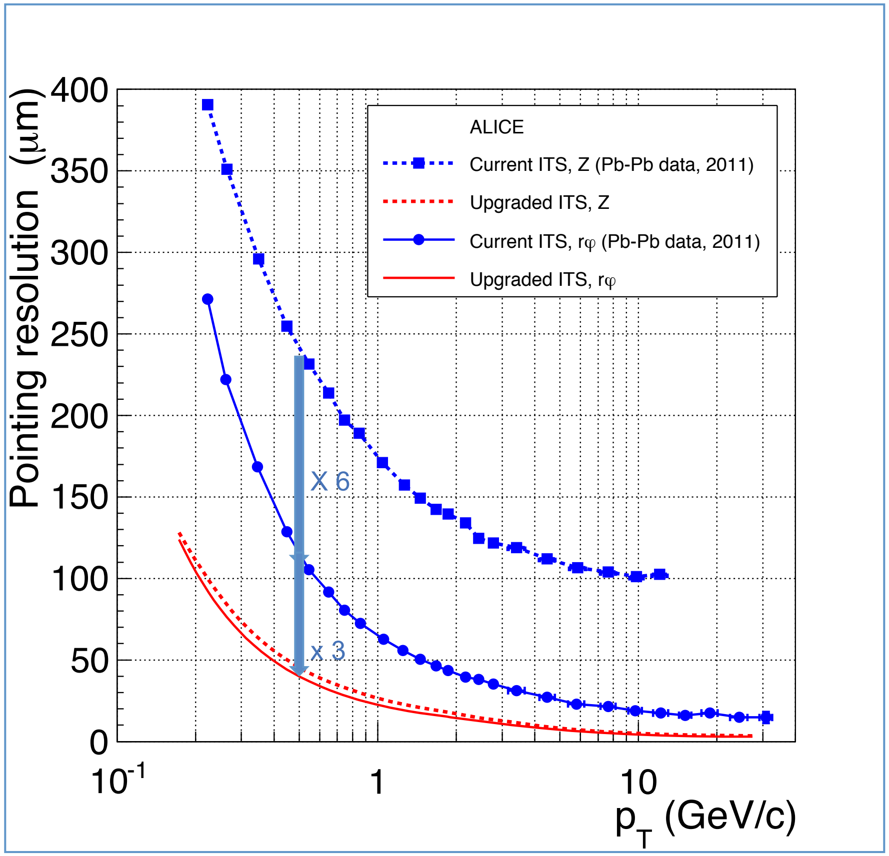
LAYER 5,6 length 1526mm. Weight 33,6g



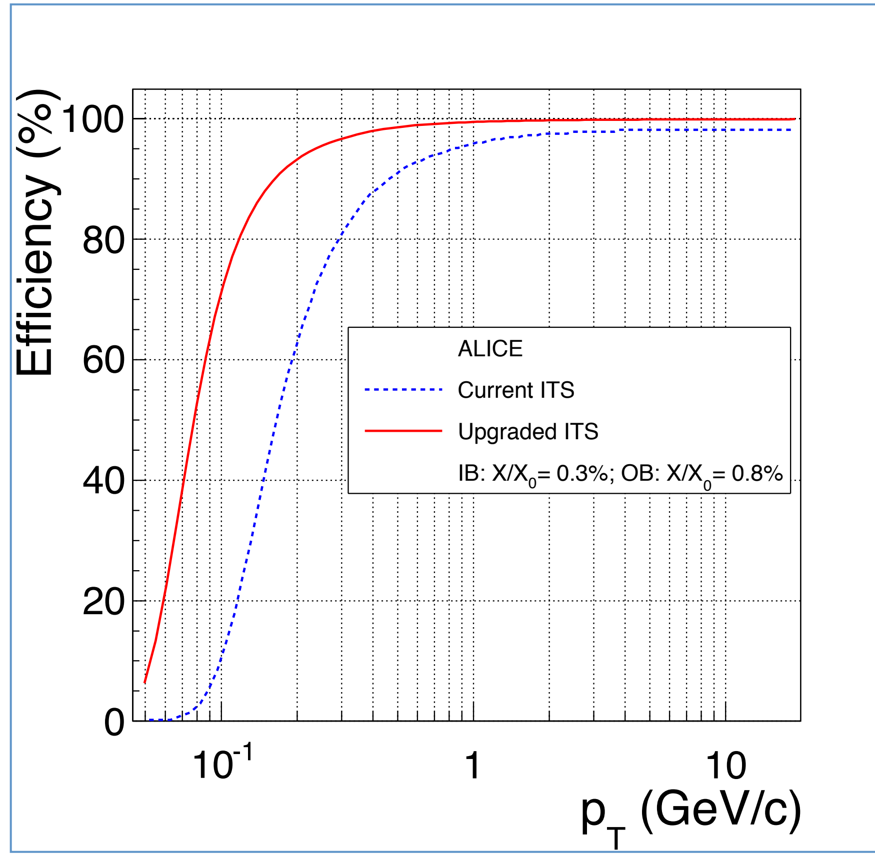
LAYER3,4 length 900mm. Weight 18g

Performance of new ITS

Impact parameter resolution



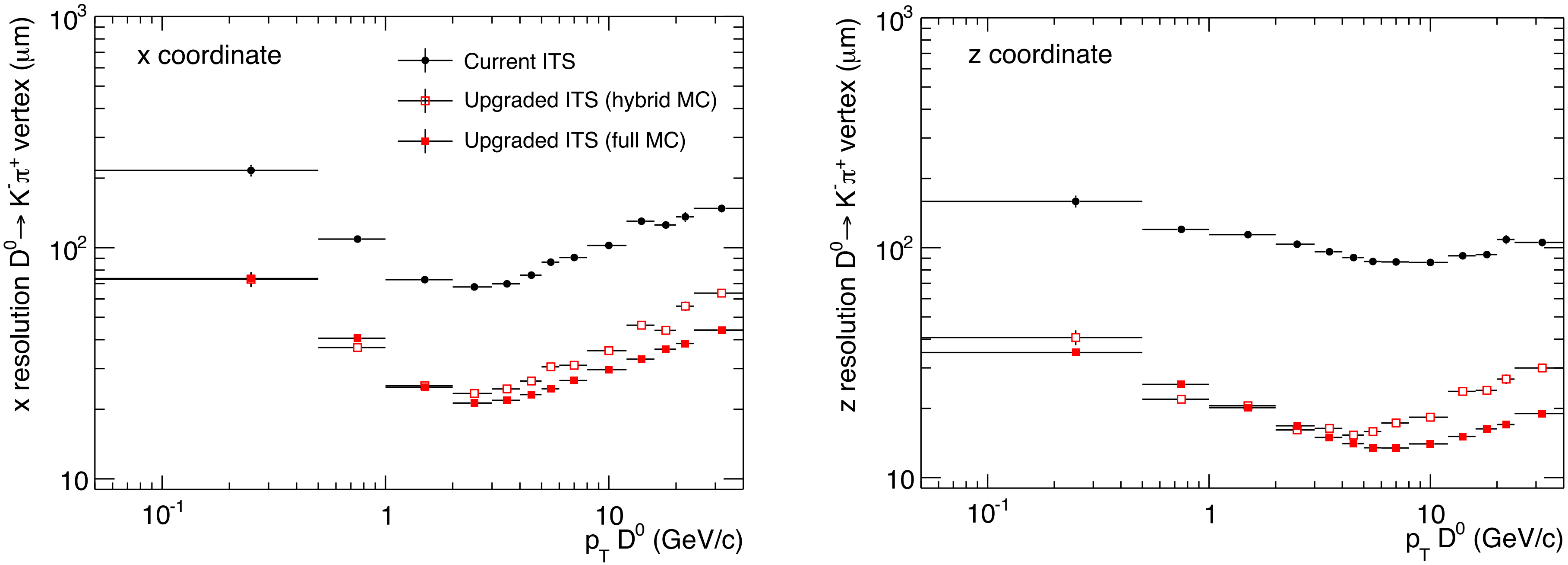
Tracking efficiency (ITS standalone)



~40 μm at p_T = 500 MeV/c

Performance of new ITS

$D^0 \rightarrow K^-p^+$ secondary vertex position resolution



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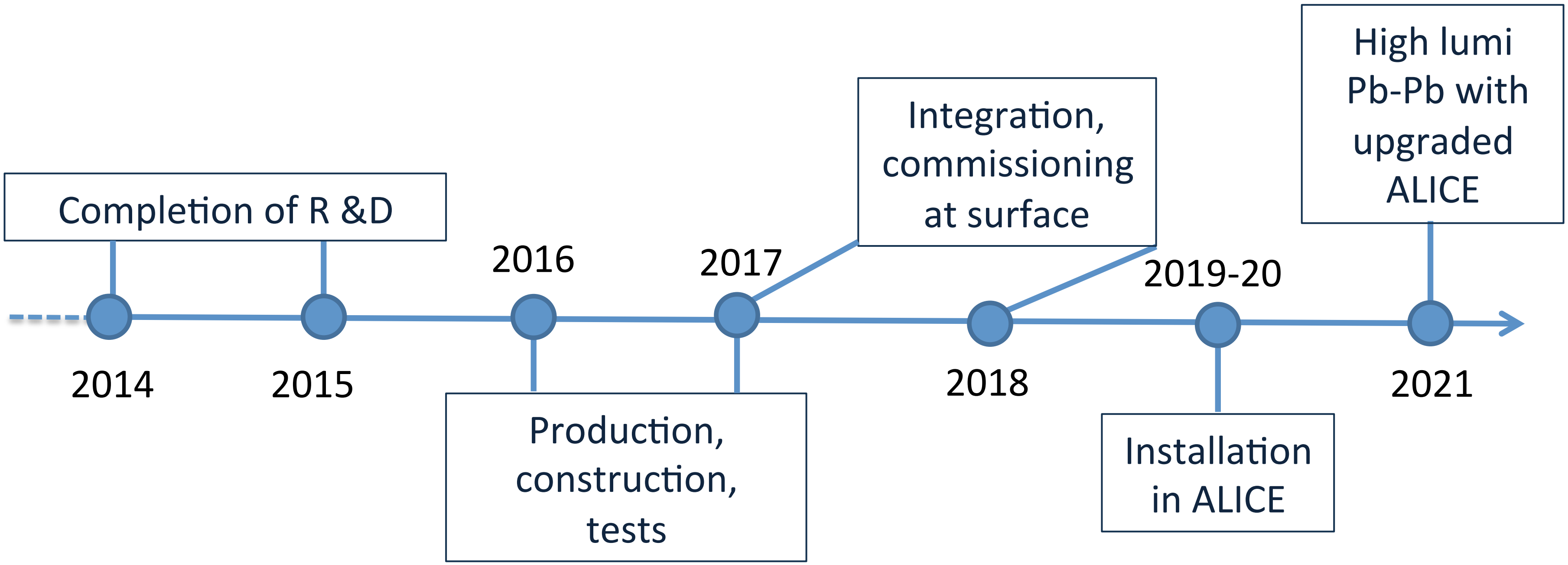
Project Timeline



Conclusions

ALICE has excellent capabilities to measure high-energy nuclear collisions at LHC

The ALICE Upgrade will allow a detailed characterization of the QGP

The new ITS will enhance the ALICE capabilities to measure heavy-flavour hadrons and quarkonia

The ITS Upgrade project has been fully approved and is well on-track for the installation during LS2 (2019-2020)

ALICE ITS Collaboration

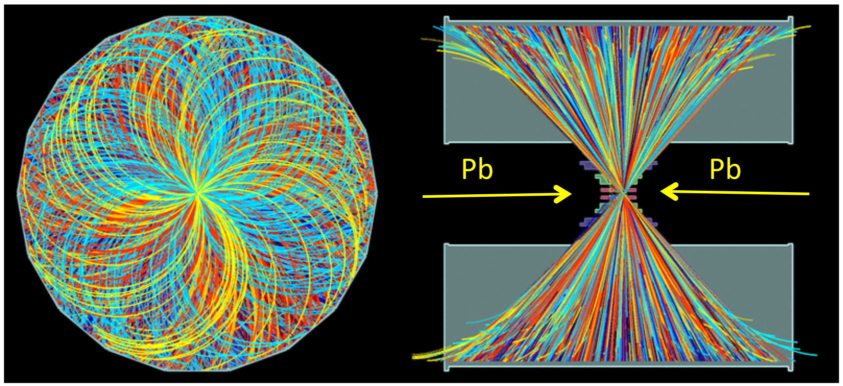
CERN, China (Wuhan), Check Republic (Prague), France (Grenoble, Strasbourg),
Italy (Aless., Bari, Cagliari, Catania, Frascati, Padova, Roma, Trieste, Torino),
Indonesia (LIPI), Korea (Pusan, Inha, Yonsei), Netherlands (Nikhef, Utrecht),
Pakistan (CIIT-Islamabad), **Russia (St. Petersburg)**, Slovakia (Kosice),
Thailand (Suranaree, SLRI, TMEC), UK (Daresbury, Liverpool, RAL), Ukraine (Kharkov),
USA (Austin, Berkeley)

Institute = participating in current ITS

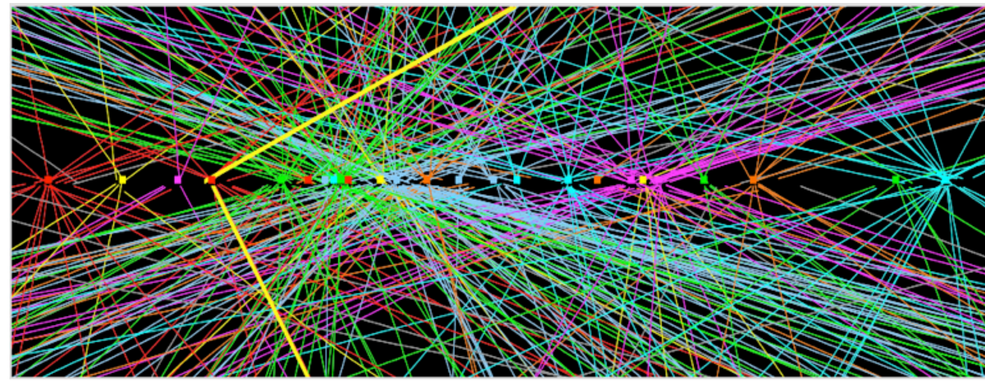

Thank you !

Why Silicon Pixel Detector in HEP Experiments

Silicon Pixel Detectors are high granularity detectors, which provide unambiguous and precise hit information in a harsh environment close to the interaction point



LHC Pb-Pb collision (ALICE, Sep 2011)



LHC pp collisions: a candidate Z boson event in the dimuon decay with 25 reconstructed vertices. (ATLAS, April 2012)

- Position resolution down to few microns
- Unambiguous hit information in high track density region
- High resolution for determination primary and secondary vertex
- Fast readout
- High level of radiation hardness

What determines the Impact Parameter Resolution

Vertex projection from two points: a simplified approach (telescope equation)

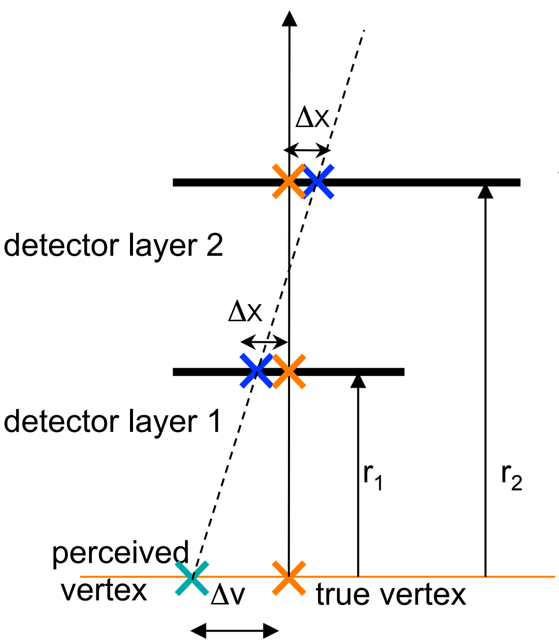
expectations for the ITS upgraded ➡ pointing resolution = (5 ⊕ 22GeV/p·c) μm

from detector position error

from coulomb scattering

first pixel layer

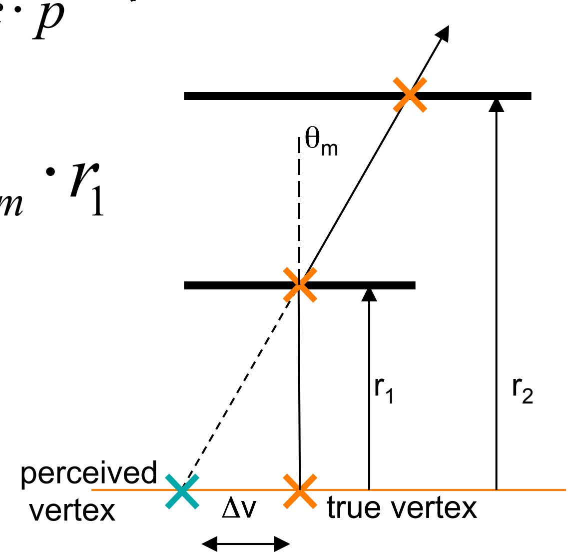
$$X_0 = 0.3\%$$



$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

$$\theta_m = \frac{13.6Mev}{\beta \cdot c \cdot p} \cdot \sqrt{X_0}$$

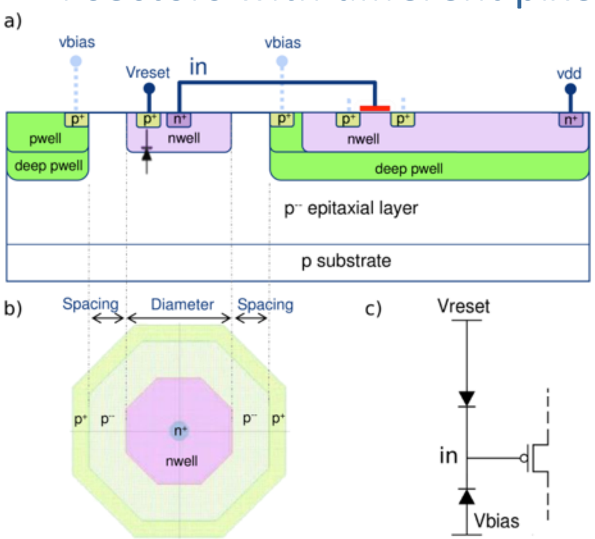
$$\Delta v = \theta_m \cdot r_1$$



pALPIDE-1 – Main Design Features

ALPIDE Full Scale prototype

- Dimensions: 30mm x 15 mm
- Pixel Matrix: 1024 cols x 512 rows
- Pixel pitch: 28μm x 28μm
- Peaking time (defines time res): <2μs
- Pulse length: 10-20μs
- In-pixel discriminator + 1 register
- Power consumption: < 40mW/cm^2
- 4 sectors with different pixels



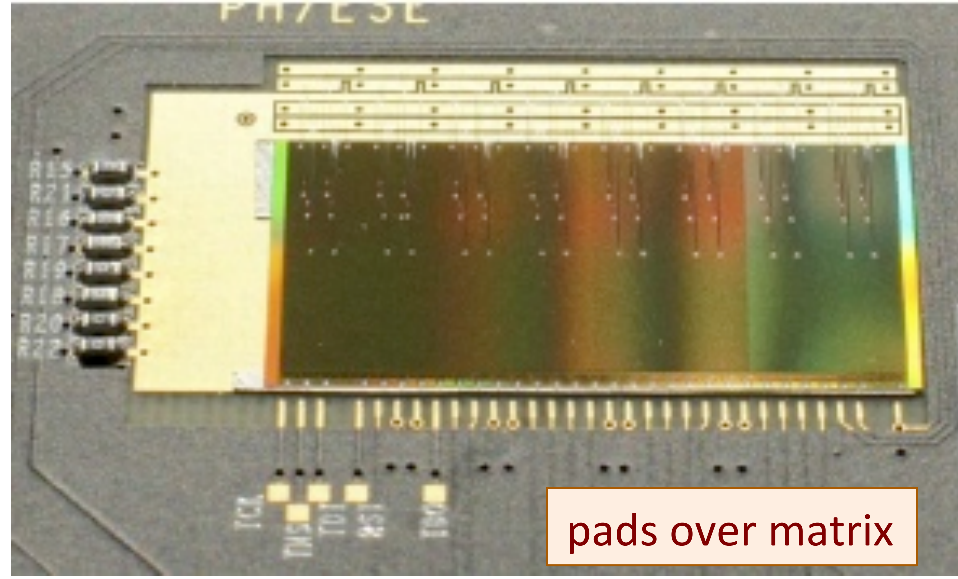


Figure: picture of pALPIDE-1

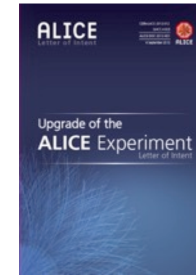
Sector	nwell diameter	spacing	pwell opening	reset
0	2μm	1μm	4μm	PMOS
1	2μm	2μm	6μm	PMOS
2	2μm	2μm	6μm	Diode
3	2μm	4μm	10μm	PMOS

ALICE Upgrade Strategy

- The upgrade plans entails building
  - New, high-resolution, high-rate ITS
  - Upgrade of TPC with replacement of MWPCs with GEMs and new pipelined readout electronics
  - Upgrade of readout electronics of: TRD, TOF, PHOS and Muon Spectrometer
  - Upgrade of the forward trigger detectors and ZDC
  - Upgrade of the online systems (DAQ & HLT)
  - Upgrade of the offline reconstruction framework

  O2

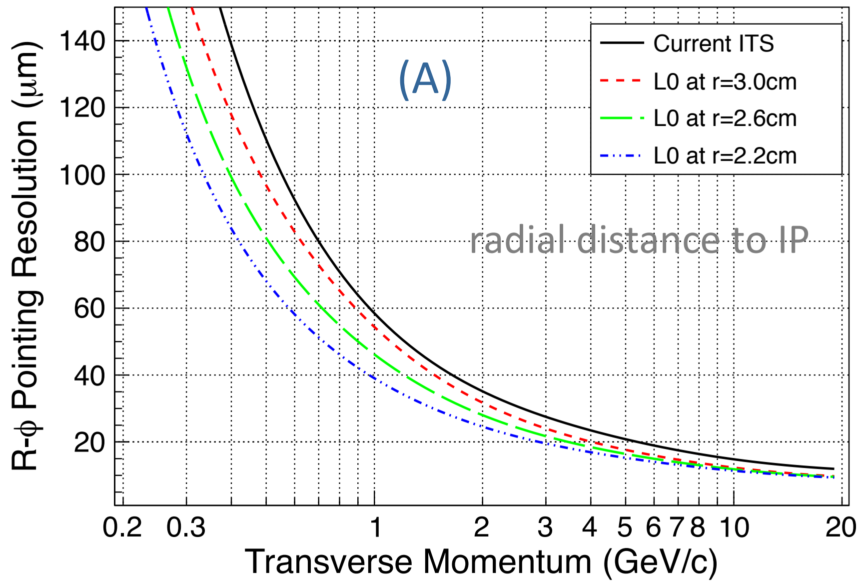
  - New 5-plane silicon telescope in front of the hadron absorber covering the acceptance of the muon Spectrometer
- It targets 2018/19 (LHC 2nd Long Shutdown)

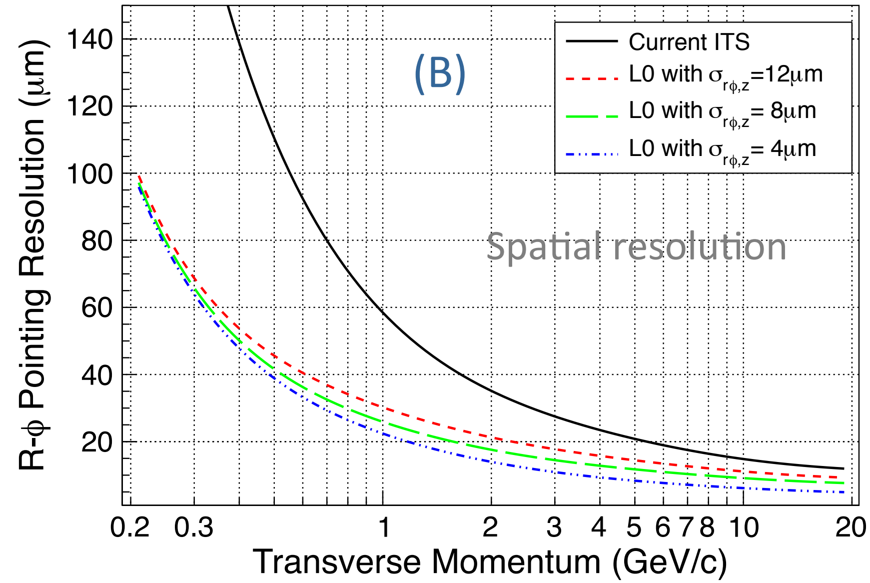


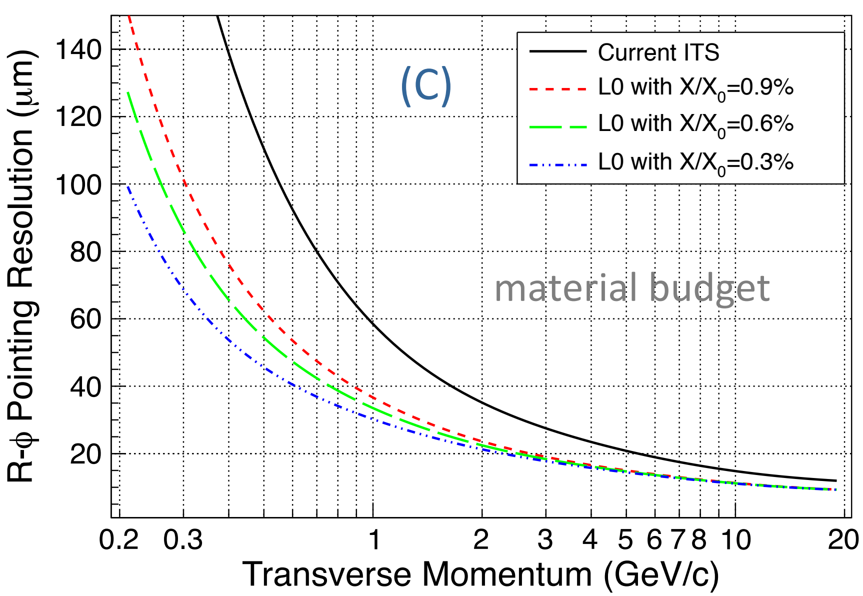
LoI
Sep 2012

Add. LoI
Sep 2013

ITS Upgrade: Impact Parameter studies





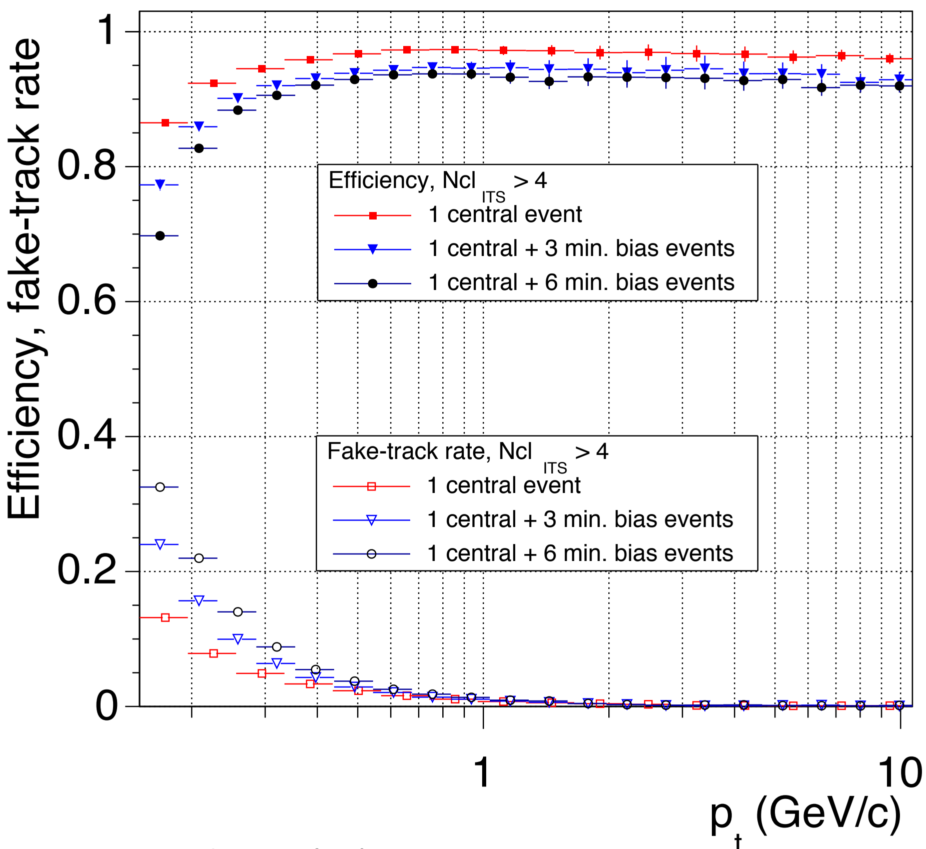


- Current ALICE ITS
  - radial position of first layer: 39mm
  - x/X_0: 1.14% per layer
  - spatial resolution (r-phi): 12 μm
- A) current ITS + L0: x/X0 = 0.3%, res.=4μm;
- B) current ITS + L0: r = 22mm, x/X_0 = 0.3%;
- C) current ITS + L0: r = 22mm, x/X_0 = 0.3%;

ALICE ITS Upgrade CDR, CERN-LHCC-2012-12

Performance of ITS Upgrade

Matching efficiency between the tracks reconstructed in the upgraded ITS and TPC for different values of event pile-up



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The average event pile-up depends on the interaction rate and detector integration time

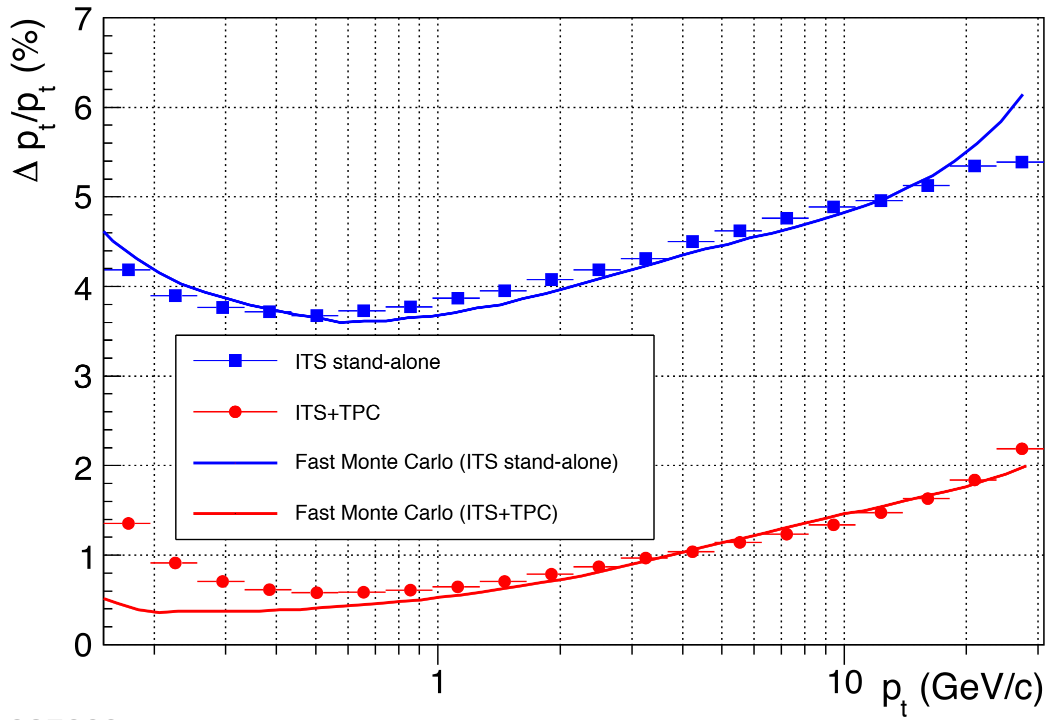
interaction rate 50 kHz
integration time: 4 – 30 μs

For 30 μs integration time (worst case design):

<pile-up> = 1 central + 1.5 min. bias

Performance of ITS Upgrade

MOMENTUM RESOLUTION



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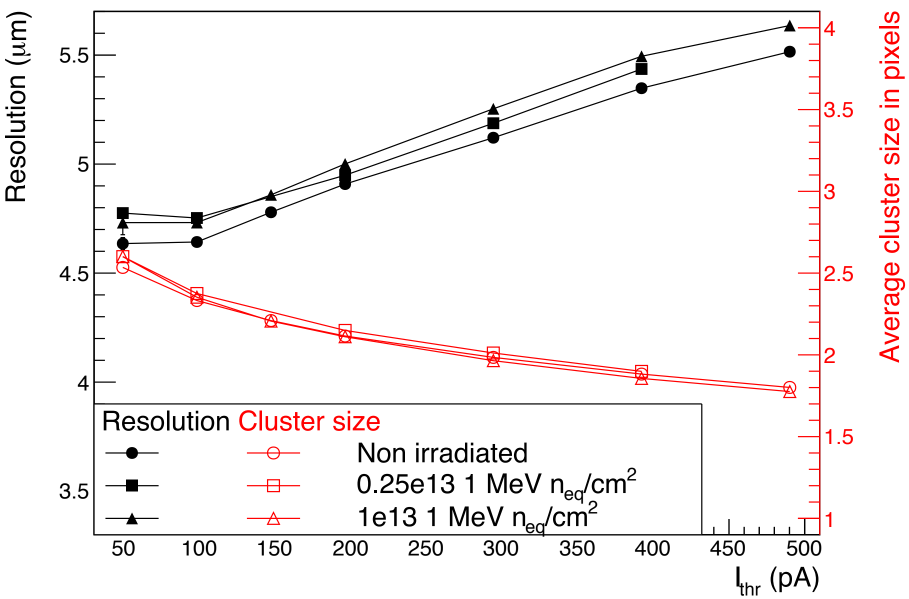
Transverse momentum resolution as function of p_T for primary charged pions for the upgraded ITS and current ITS. The results are shown for ITS standalone and ITS-TPC combined tracking.

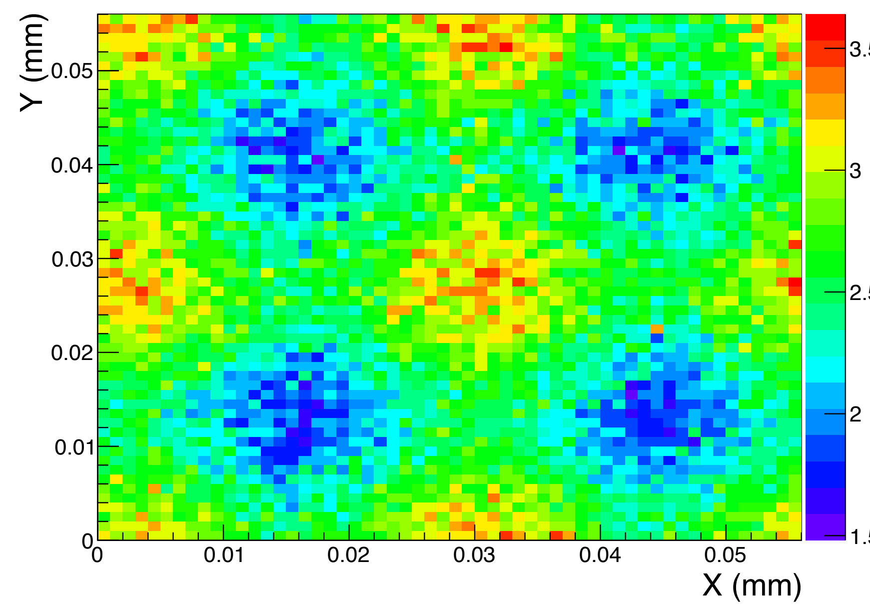
pALPIDE-1 – Test Beam results at PS (9/14)

ALICE

Spatial resolution



Cluster size vs. position within pixel



$\sigma_{det} <$ 5 μm is achieved with sufficient margin of operation

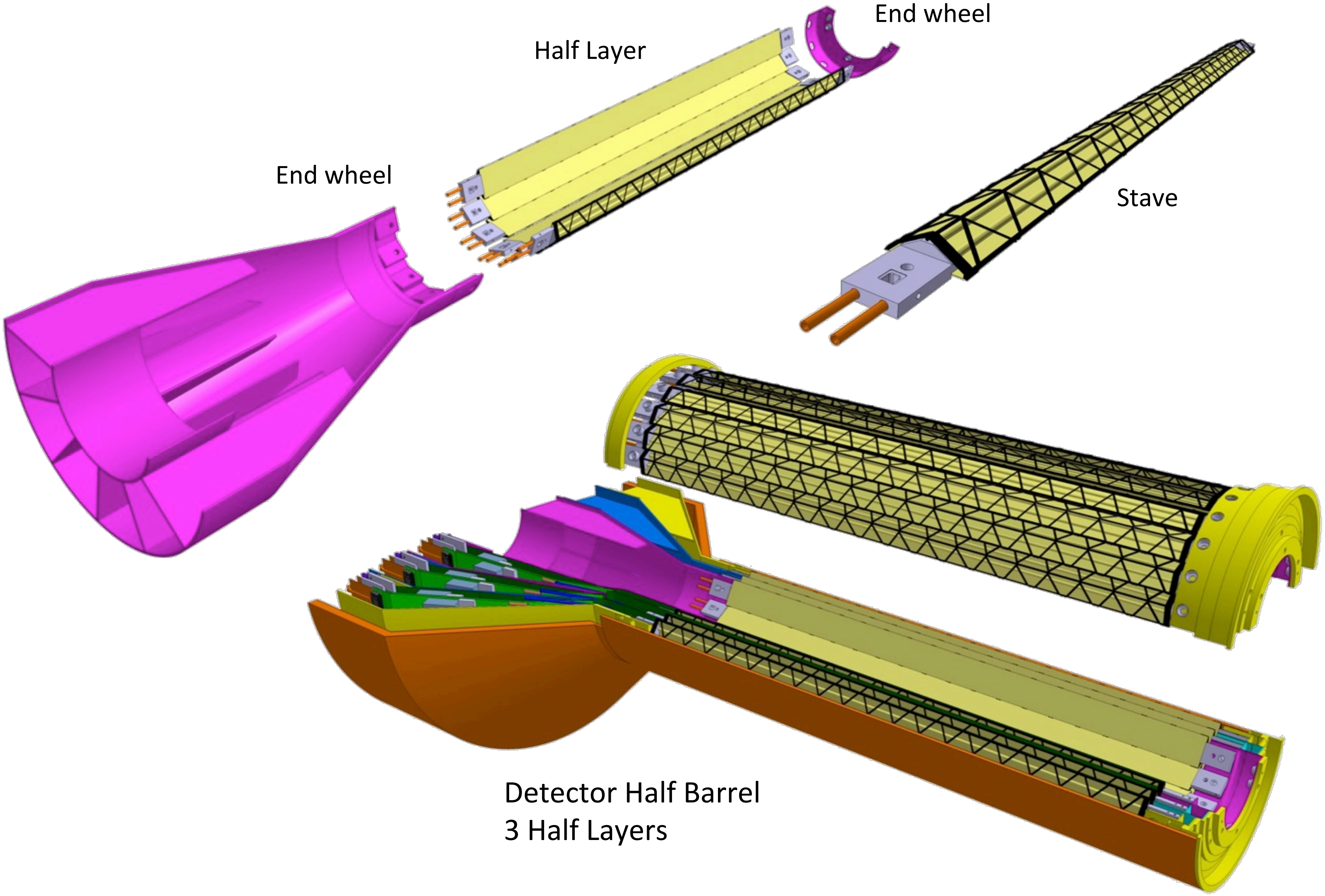
- Measurements at PS: 5 – 7 GeV π^- September 2014
- Results refer to 50 μm thick chips: non irradiated and irradiated with neutrons 0.25 x 10^{13} and 10^{13} 1MeV n_{eq} / cm^2

Pixel Chip Requirements

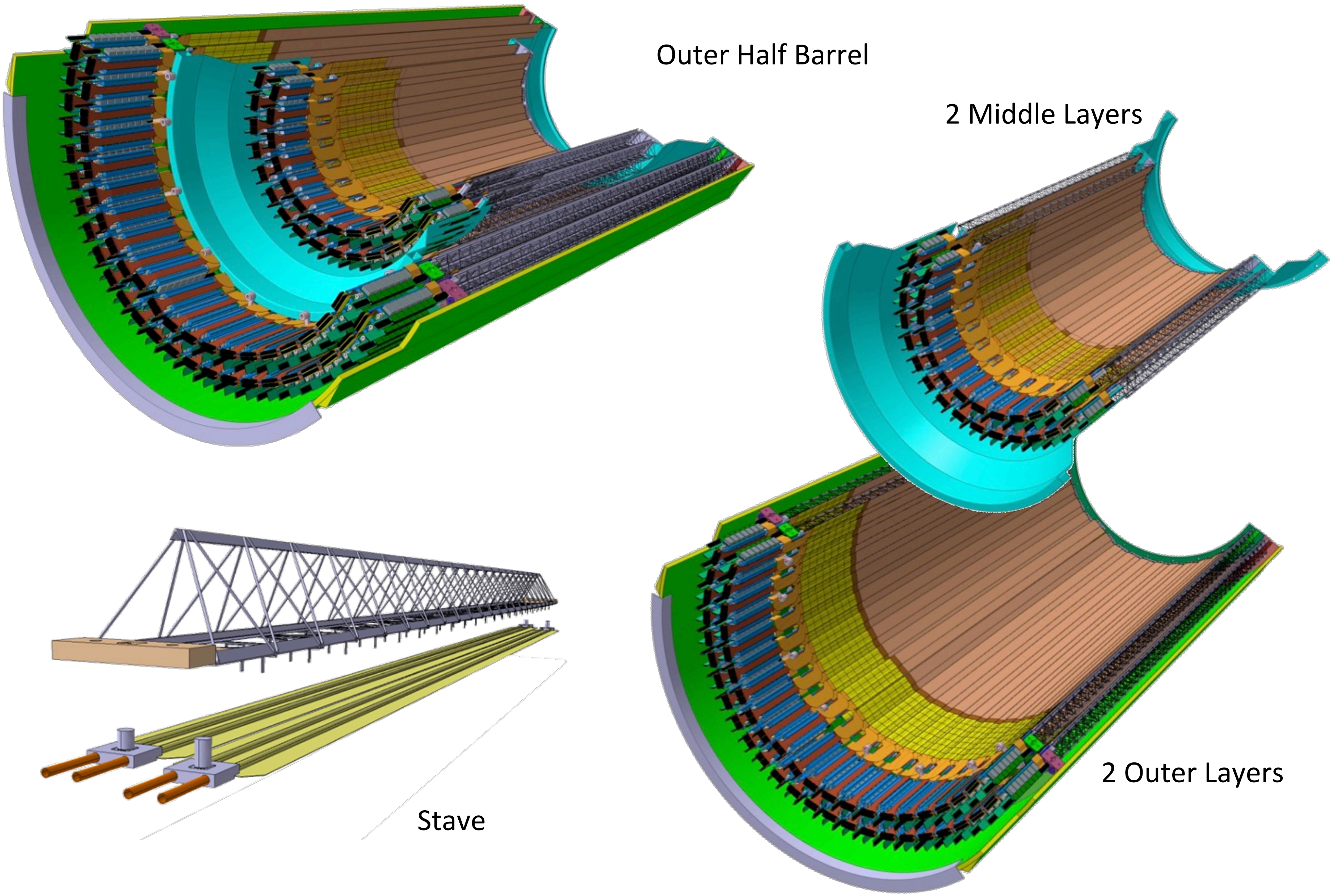
Parameter	Inner Barrel	Outer Barrel
Silicon thickness	50 μm	
Spatial resolution	5 μm	10 μm
chip dimensions	15 mm x 30 mm	
Power density	< 300 mW/cm^2	< 100 mW/cm^2
Event time resolution	< 30 μs	
Detection efficiency	> 99%	
Fake hit rate	< 10^{-5} per readout frame	
TID radiation hardness (*)	2700 krad	100 krad
NIEL radiation hardness (*)	1.7×10^{13} 1MeV n_{eq}/cm^2	10^{12} 1MeV n_{eq} / cm^2

(*) 10 x radiation load integrated over approved programme (~ 6 years of operation)

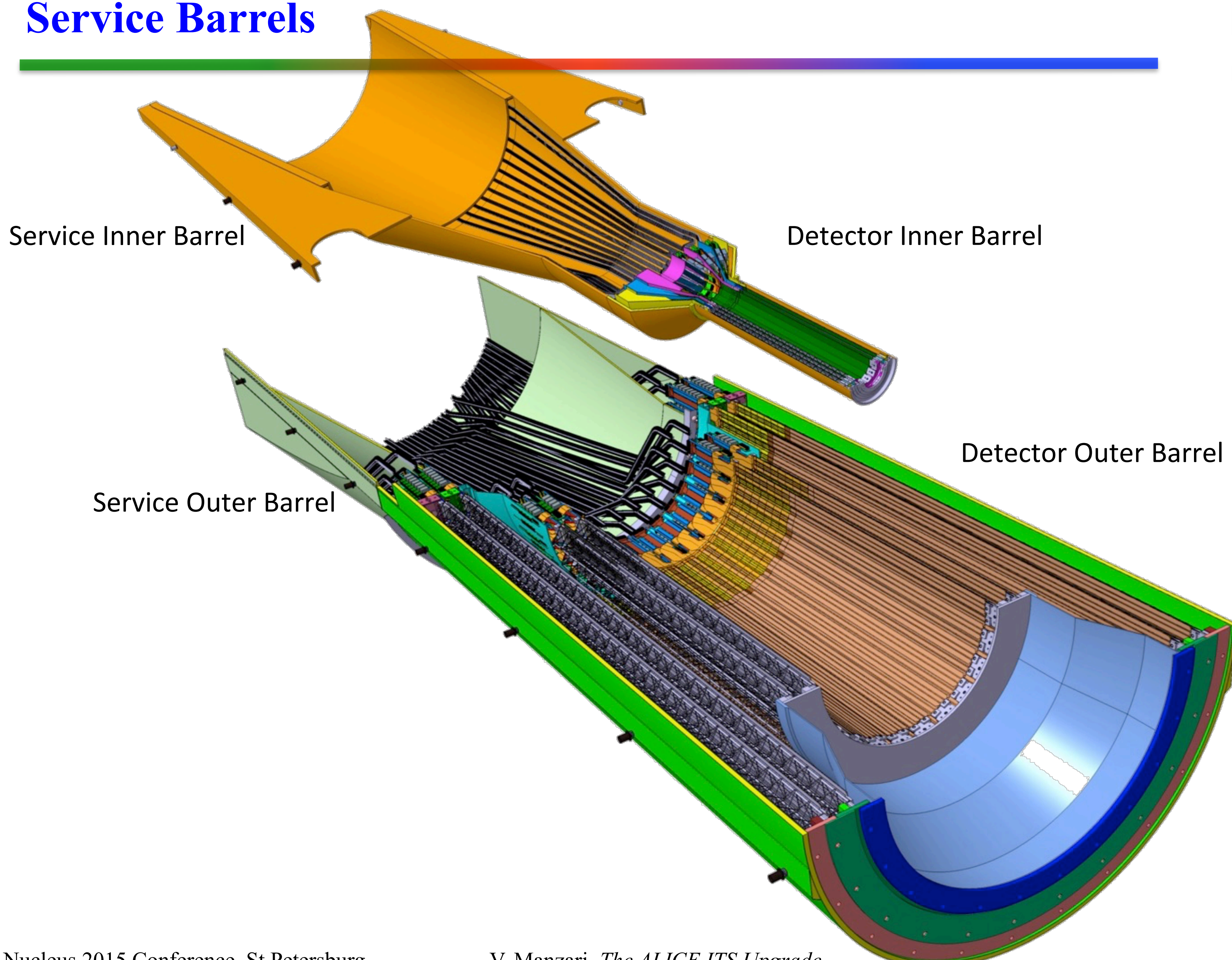
Inner Barrel



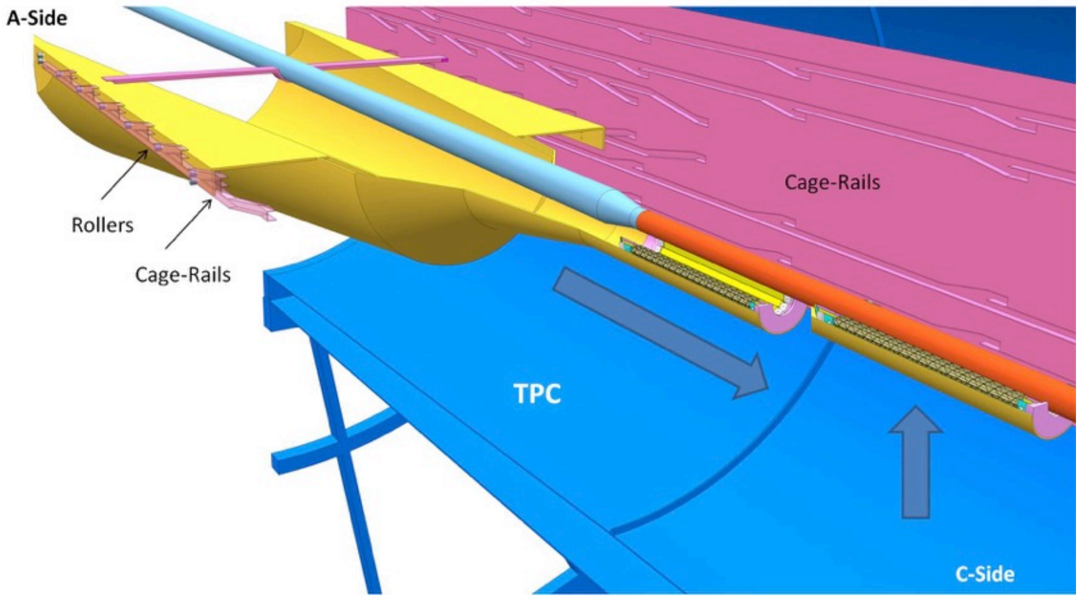
Outer Barrel

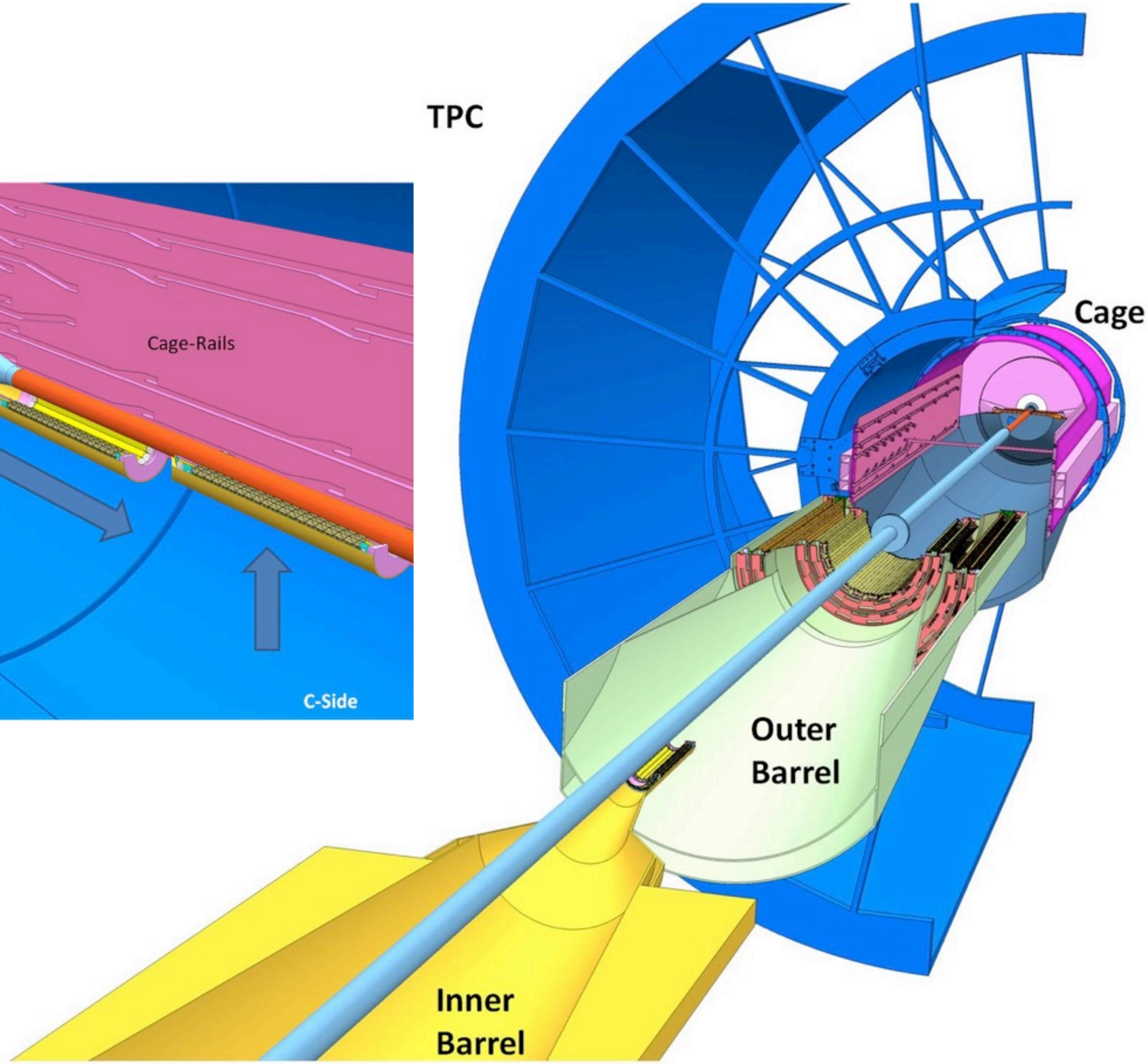


Service Barrels



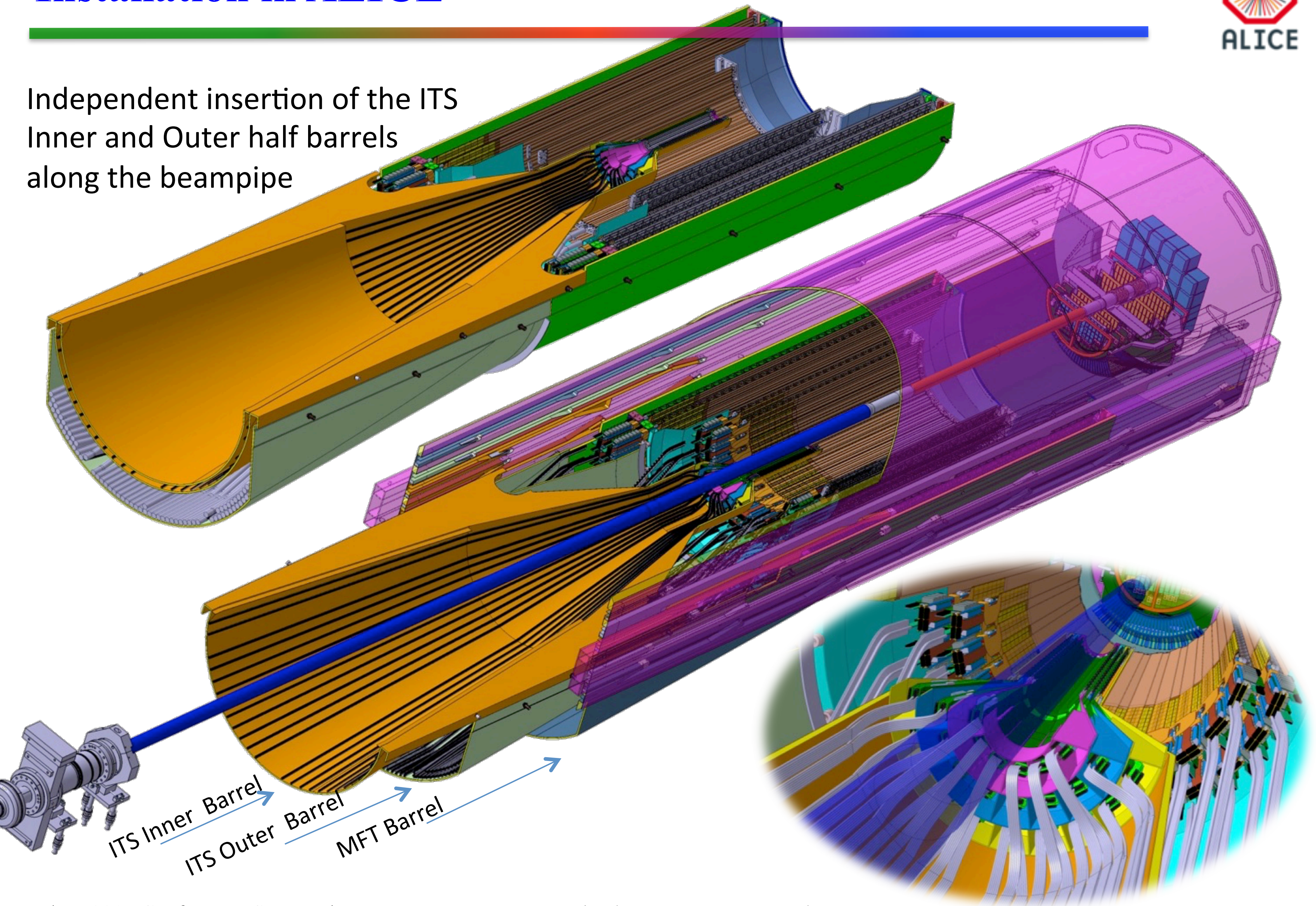
Installation in ALICE



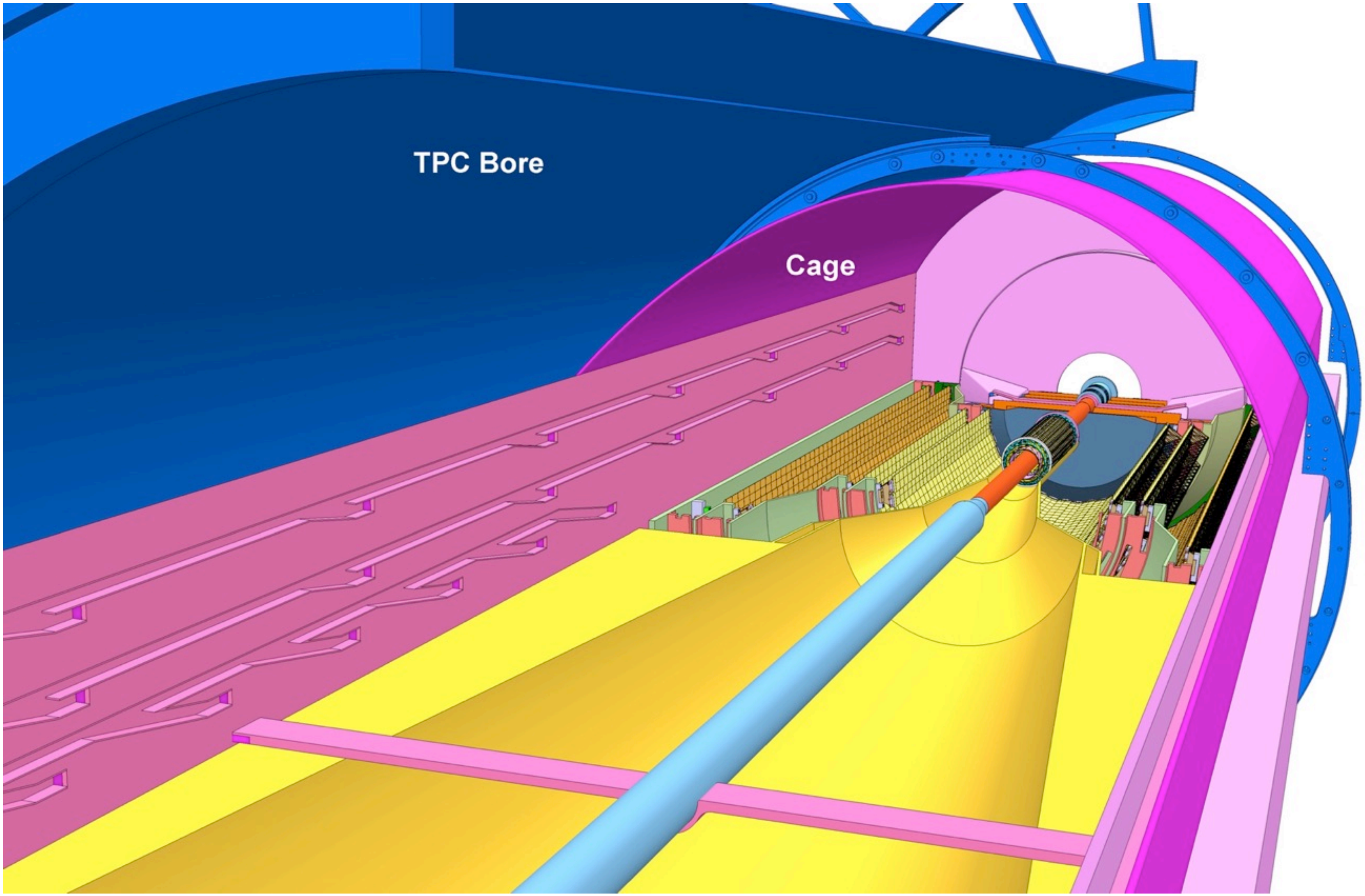


Installation in ALICE

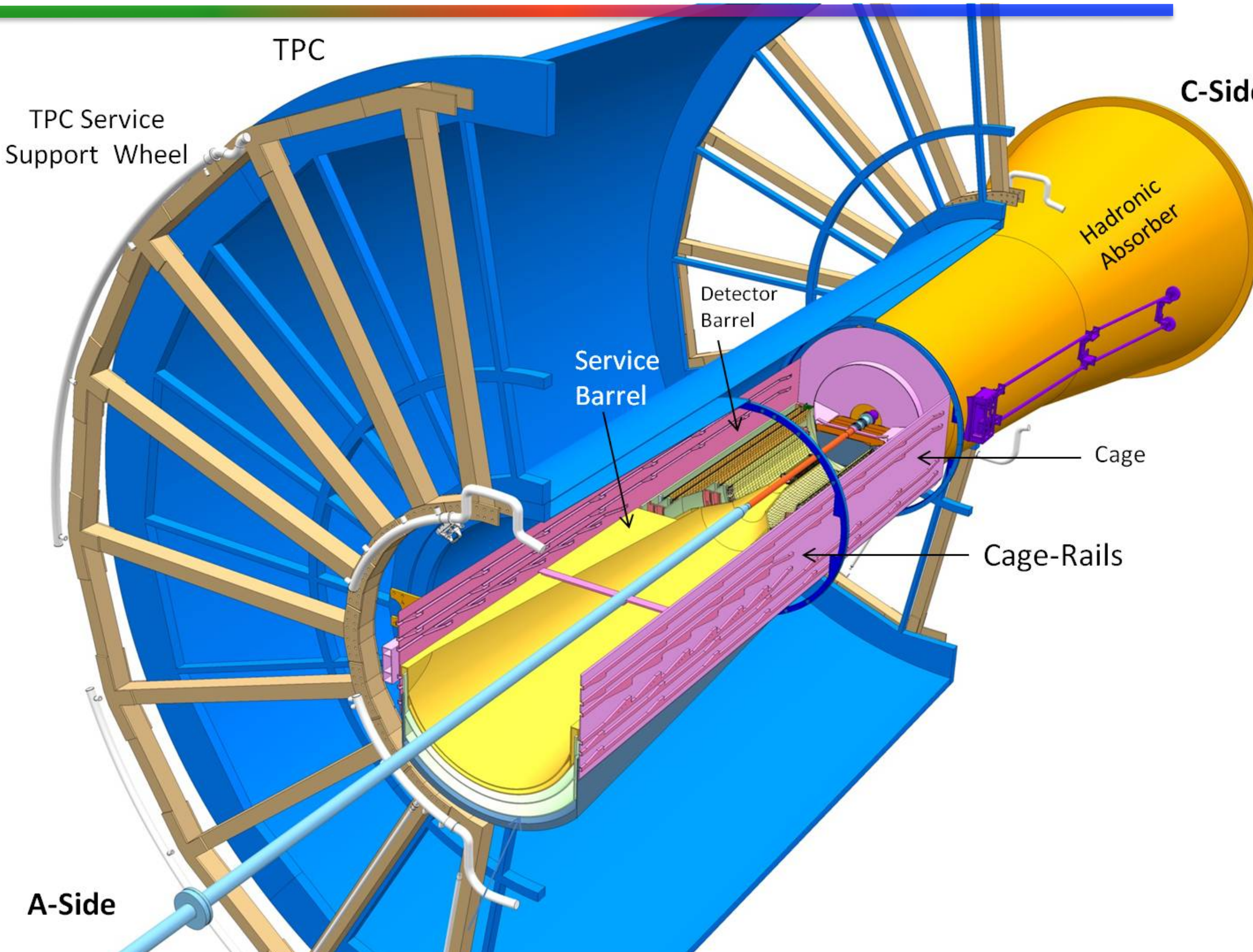
Independent insertion of the ITS Inner and Outer half barrels along the beampipe



Integration in ALICE



Integration in ALICE



ALICE Approved Programme

RUN1 (2010 - 2013)

Year	System	Energy sqrt(s_{NN})	Integrated lumin
2010	Pb-Pb	2.76 TeV	~ 0.01 nb^{-1}
2011	Pb-Pb	2.76 TeV	~ 0.1 nb^{-1}
2013	p-Pb	5.02 TeV	~ 30 nb^{-1}

RUN2 (2015 - 2018)

- **1nb^{-1}** for Pb-Pb collisions, with improved detectors and double energy