# Upgrade of the ALICE Inner Tracking System

L. Musa - CERN

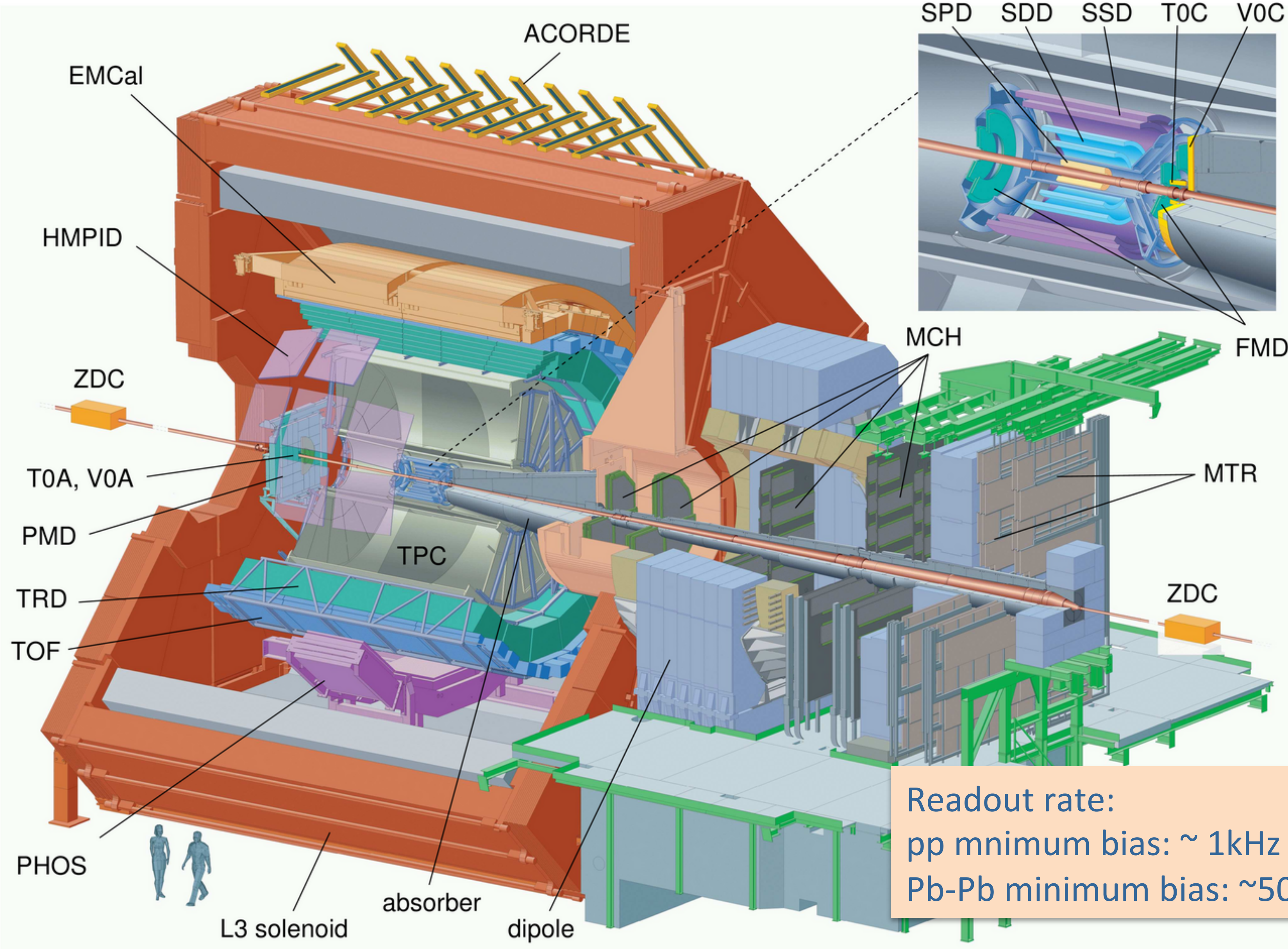
*CLIC Tracker Technology Meeting*
*CERN, 05 March, 2015*

# Upgrade of the ALICE Inner Tracking System

## OUTLINE

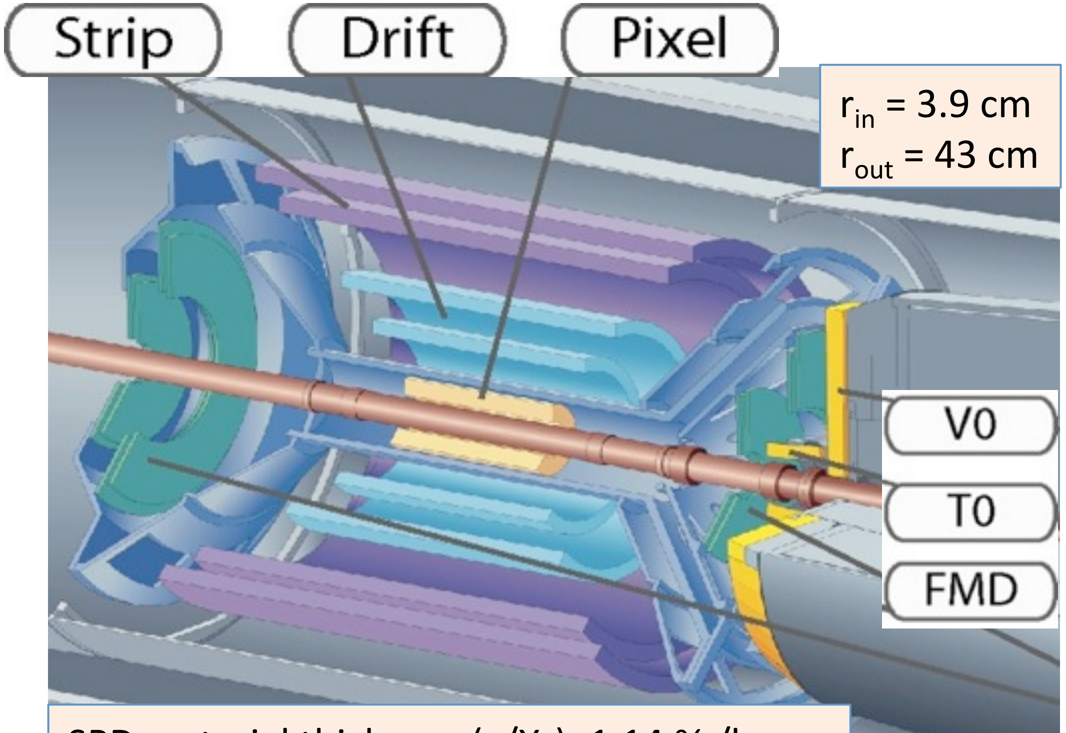
- ALICE current set-up
- Upgrade motivations and objectives
- ITS upgrade layout and main components
- Detector simulated performance: some examples

# The Current ALICE Detector

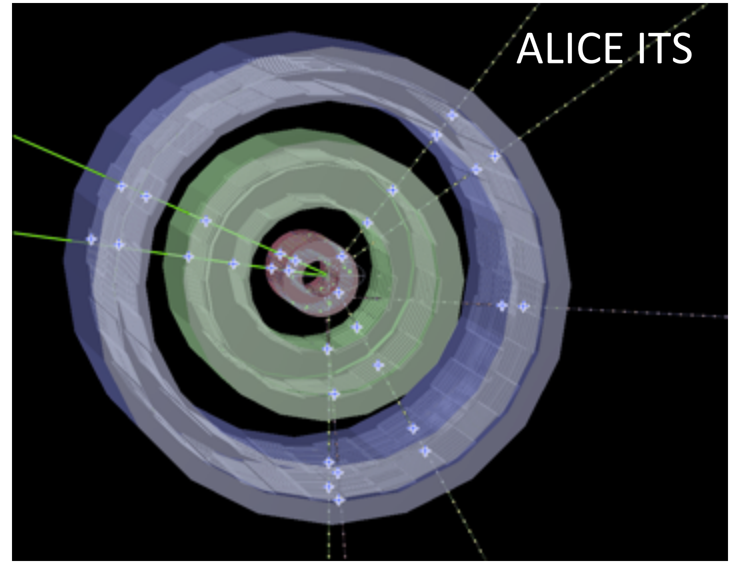


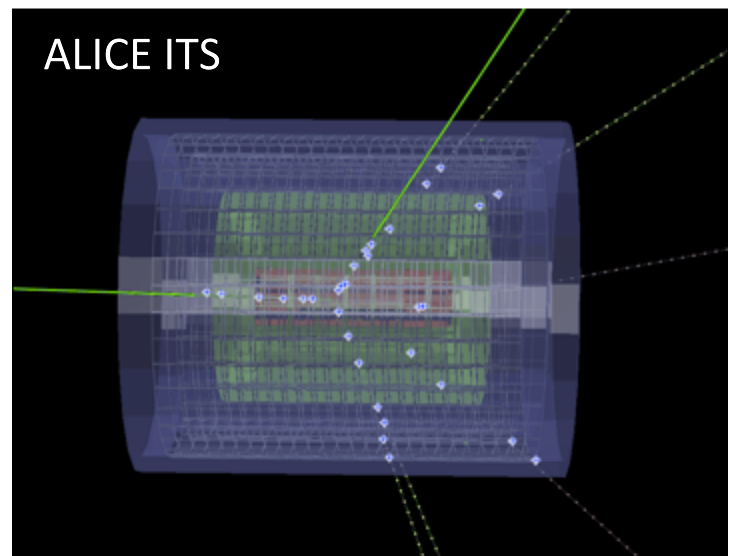

Readout rate:
pp mnimum bias: ~ 1kHz
Pb-Pb minimum bias: ~500 Hz

# The Current ALICE Inner Tracking System




SPD material thickness ($x/X_0$): 1.14 % /layer



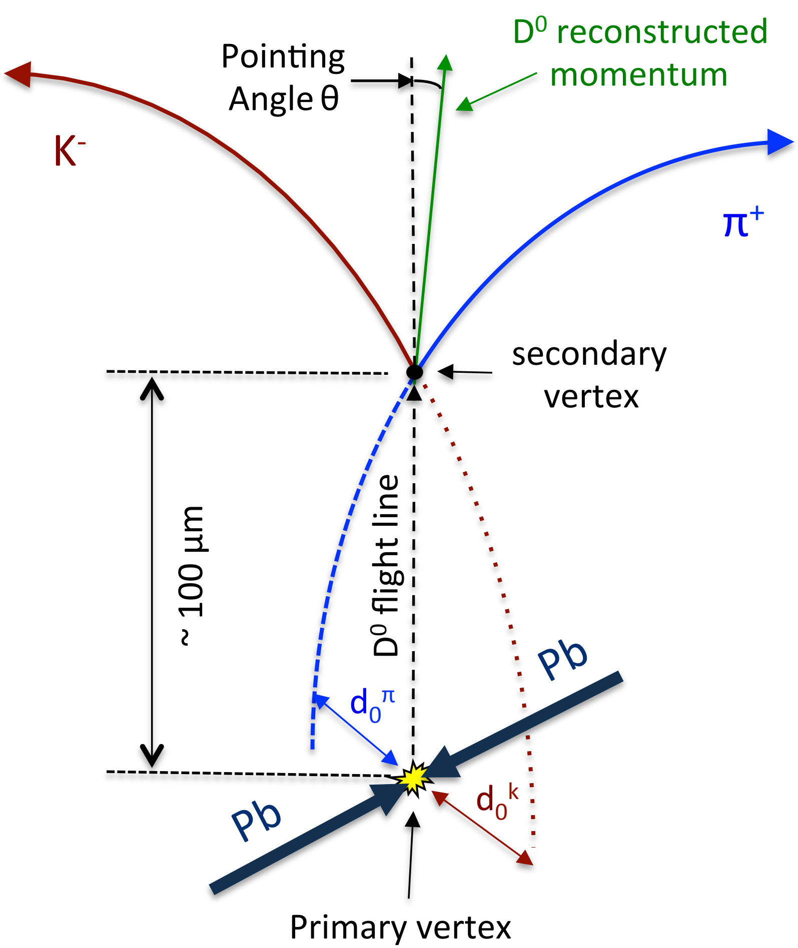




Current ITS

6 concentric barrels, 3 different technologies

- 2 layers of silicon pixel (SPD)
- 2 layers of silicon drift (SDD)
- 2 layers of silicon strips (SSD)

## Example: $D^0$ meson




Analysis based on decay topology and invariant mass technique

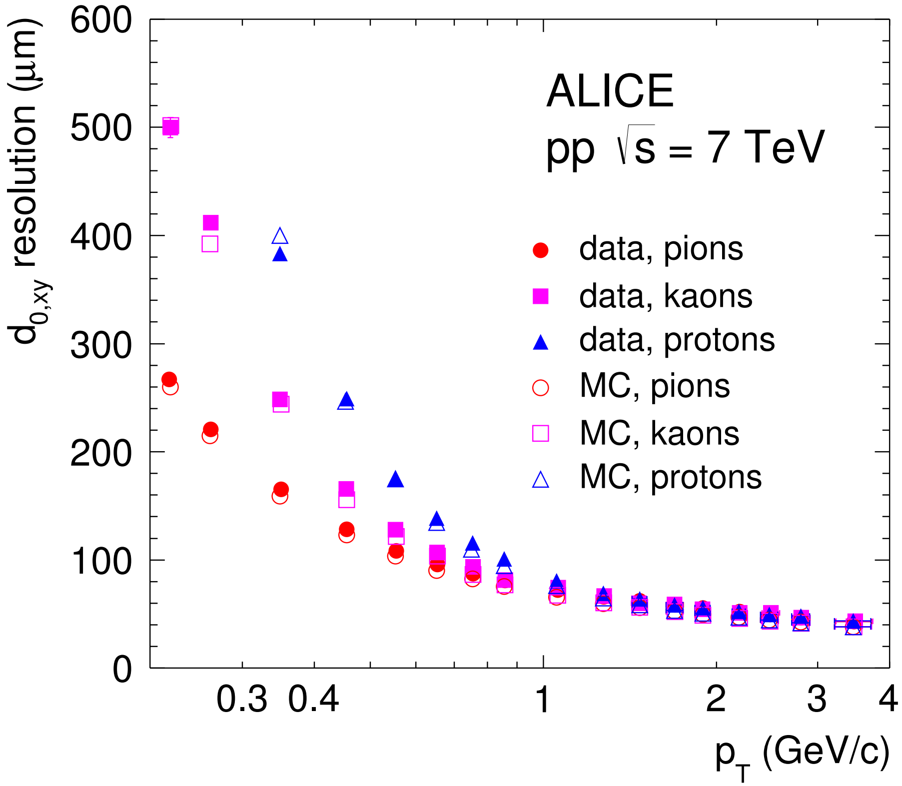
## Open charm

| 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 |
| $\Lambda_c^+$ | $p K^- \pi^+$ (5.0%) | 60 |

How precisely is $d_0$ measured with the current ITS detector?

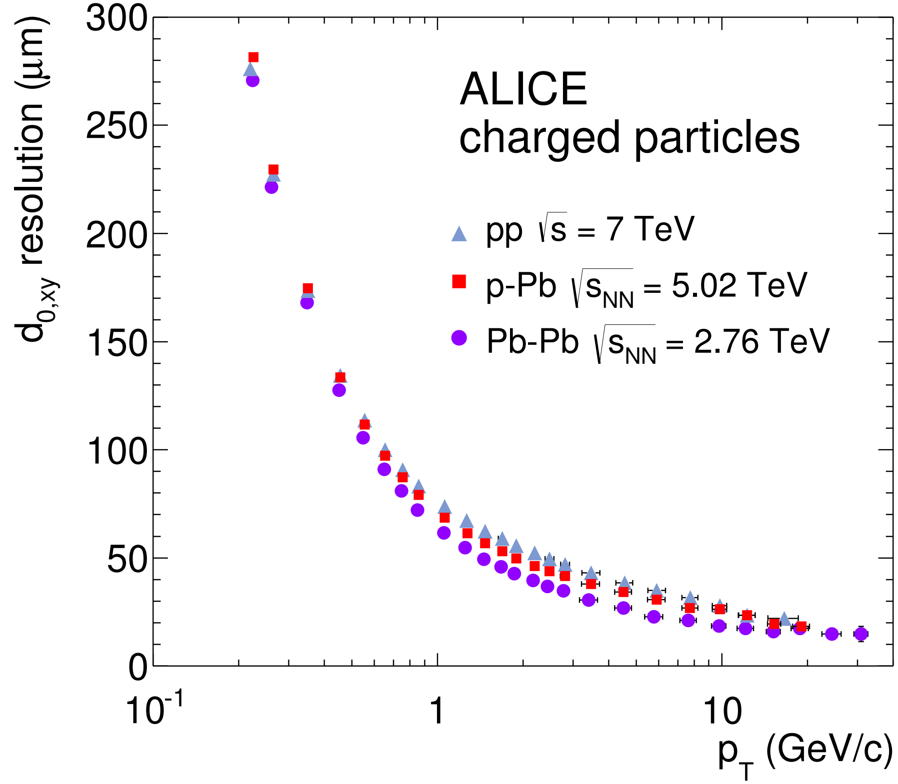
# ALICE ITS Upgrade – Impact parameter resolution

*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

# What determines the impact parameter resolution

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

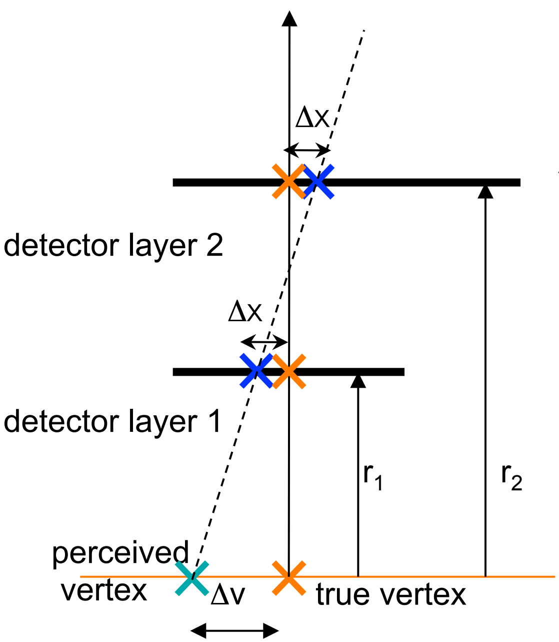
expectations for the ITS upgraded ➡ pointing resolution = $(5 \oplus 22\,\mathrm{GeV}/p\cdot c)\ \mu\mathrm{m}$

from detector position error

from coulomb scattering

first pixel layer

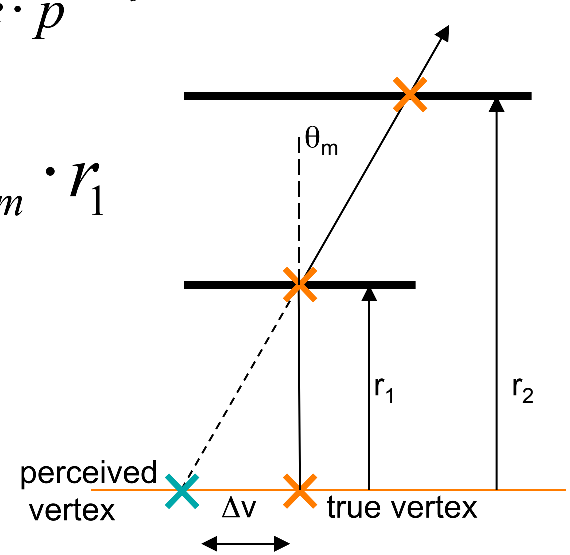
$$X_0 = 0.3\%$$




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

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

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



# Signal statistics and trigger rate

## Minimum bias Pb-Pb at 5.5 Tev

| Particle | Eff | $S/\mathrm{ev}$ | $S/B$ | $B'/\mathrm{ev}$ | trigger / event | $S/\mathrm{nb}^{-1}$ |
|---|---|---|---|---|---|---|
| $\mathrm{D}^0$ | 0.02 | $1.6 \cdot 10^{-3}$ | 0.03 | 0.21 | 0.11 | $1.3 \cdot 10^{7}$ |
| $\mathrm{D}_s^+$ | 0.01 | $4.6 \cdot 10^{-4}$ | *0.01* | 0.18 | 0.09 | $3.7 \cdot 10^{6}$ |
| $\Lambda_c$ | 0.01 | $1.4 \cdot 10^{-4}$ | $5 \cdot 10^{-5}$ | 11 | 0.5 | $1.1 \cdot 10^{6}$ |
| $\Lambda_c\ (p_t > 2\ Gev/c)$ | 0.01 | $0.8 \cdot 10^{-4}$ | 0.001 | 0.33 | 0.16 | $0.6 \cdot 10^{6}$ |
| $\mathrm{B} \to \mathrm{D}^0(\to \mathrm{K}^-\pi^+)$ | 0.02 | $0.8 \cdot 10^{-4}$ | 0.03 | $11 \cdot 10^{-3}$ | $5 \cdot 10^{-3}$ | $0.6 \cdot 10^{6}$ |
| $\mathrm{B} \to \mathrm{J}/\psi(\to \mathrm{e}^+\mathrm{e}^-)$ | 0.1 | $1.3 \cdot 10^{-5}$ | *0.01* | $5 \cdot 10^{-3}$ | $3 \cdot 10^{-3}$ | $1 \cdot 10^{5}$ |
| $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$ | *0.01* | $0.5 \cdot 10^{-7}$ | *0.01* | $2 \cdot 10^{-5}$ | $1 \cdot 10^{-5}$ | $4 \cdot 10^{-3}$ |
| $\mathrm{B}^+ \to \overline{\mathrm{D}}^0\pi^+$ | *0.01* | $1.9 \cdot 10^{-7}$ | *0.01* | $8 \cdot 10^{-5}$ | $4 \cdot 10^{-5}$ | $1.5 \cdot 10^{3}$ |
| $\mathrm{B}_s^0 \to \mathrm{J}/\psi\phi$ | *0.01* | $1.1 \cdot 10^{-8}$ | *0.01* | $4.4 \cdot 10^{-6}$ | $2 \cdot 10^{-6}$ | $9 \cdot 10^{1}$ |
| $\Lambda_b(\to \Lambda_c + \mathrm{e}^-)$ | *0.01* | $0.7 \cdot 10^{-6}$ | *0.01* | $2.8 \cdot 10^{-4}$ | $14 \cdot 10^{-5}$ | $5 \cdot 10^{3}$ |
| $\Lambda_b(\to \Lambda_c + \mathrm{h}^-)$ | *0.01* | $0.7 \cdot 10^{-5}$ | *0.01* | $2.8 \cdot 10^{-3}$ | $1.4 \cdot 10^{-3}$ | $5 \cdot 10^{4}$ |

We assume a trigger efficiency $\varepsilon_{trigger} = 100\%$

B' = background in the broad invariant mass range (e.g. ± 12$\sigma$)

An IDEAL "charm trigger" would select almost all events

# ALICE Upgrade Strategy

High precision measurements of rare probes at low $p_{T,}$ which cannot be selected with a trigger, require a large sample of events recorded on tape

Target

- Pb-Pb recorded luminosity $\geq 10\ nb^{-1}$ ➡ $8 \times 10^{10}$ events
- pp (@5.5 Tev) recorded luminosity $\geq 6\ pb^{-1}$ ➡ $1.4 \times 10^{11}$ events

Gain a factor **100** in statistics over approved programme

... and significant improvement of vertexing and tracking capabilities

I. Upgrade the ALICE readout systems and online systems to

- read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6 \times 10^{27}\ cm^{-1}s^{-1}$), with a minimum bias trigger
- Perform online data reduction based on reconstruction of clusters and tracks (tracking used only to filter out clusters not associated to reconstructed tracks)

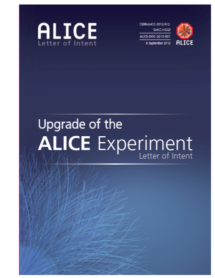
II. Improve vertexing and tracking at low $p_T$

# ALICE Upgrade Strategy, cont'd.

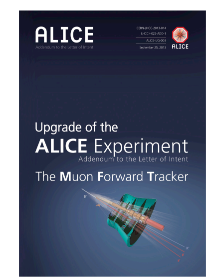
- The upgrade plans entails building
  - New, high-resolution, high-rate ITS
  - Upgrade of TPC with replacement of MWPCs with GEMs and new pipelined readout electronics
  - Upgrade of readout electronics of: TRD, TOF, PHOS and Muon Spectrometer
  - Upgrade of the forward trigger detectors and ZDC
 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

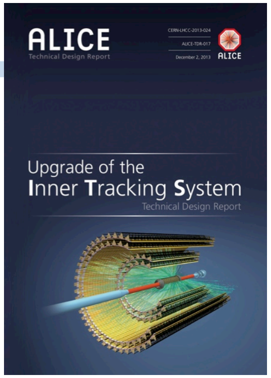



LoI
Sep 2012




Add. LoI
Sep 2013

# ITS upgrade design objectives



*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 ➡ 22mm
- Reduce $x/X_0$ /layer: ~1.14% ➡ ~ 0.3% (for inner layers)
- Reduce pixel size: currently 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 > 50 kHz and pp interactions at ~ several $10^5$ Hz (currently limited at 1kHz with full ITS and ~3kHz without silicon drift)

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

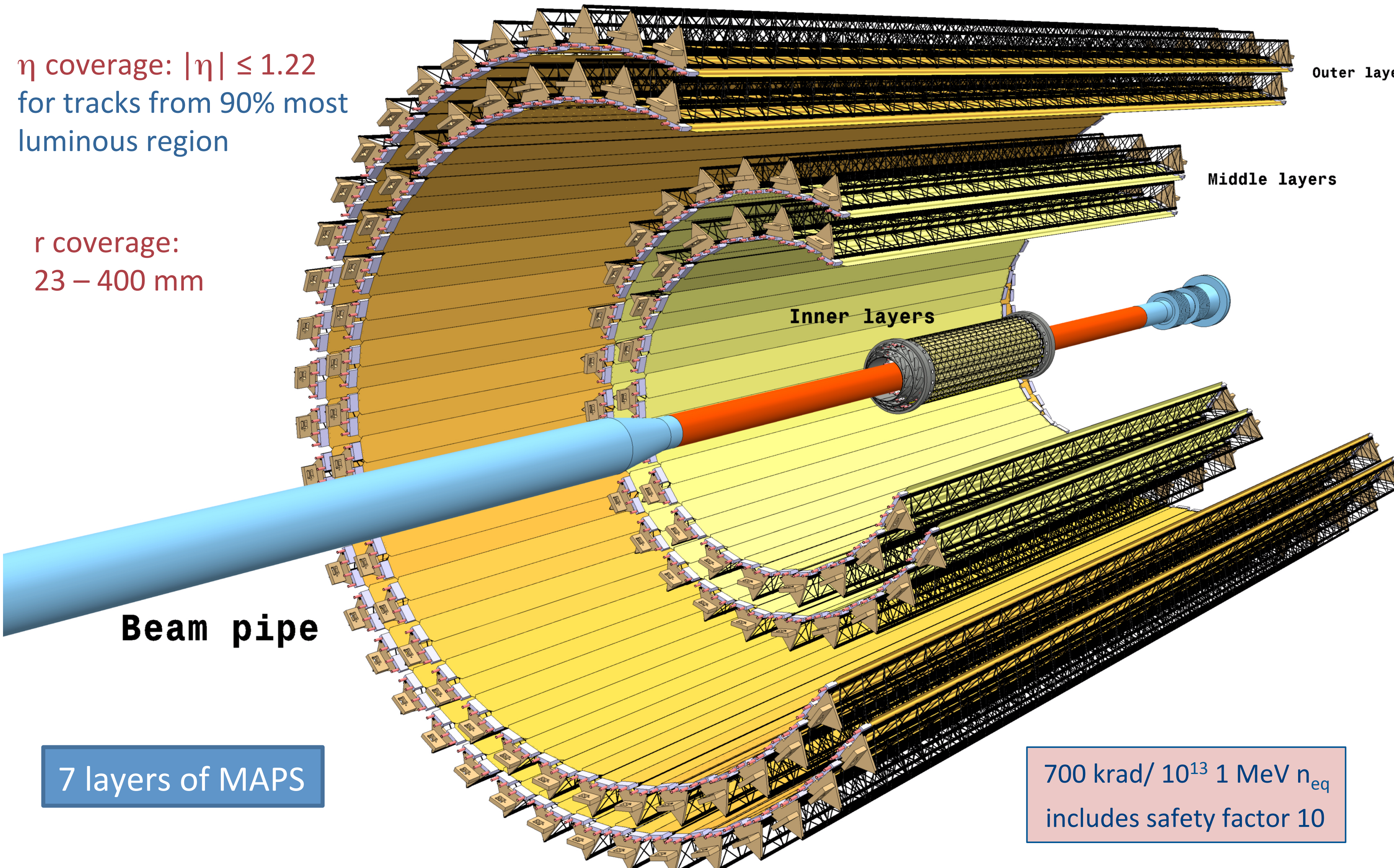
Install detector during LHCC LS2 (2018-19)

# New ITS Layout

12.5 G-pixel camera
(~10 $m^2$)

$\eta$ coverage: $|\eta| \leq 1.22$
for tracks from 90% most luminous region

r coverage:
23 – 400 mm

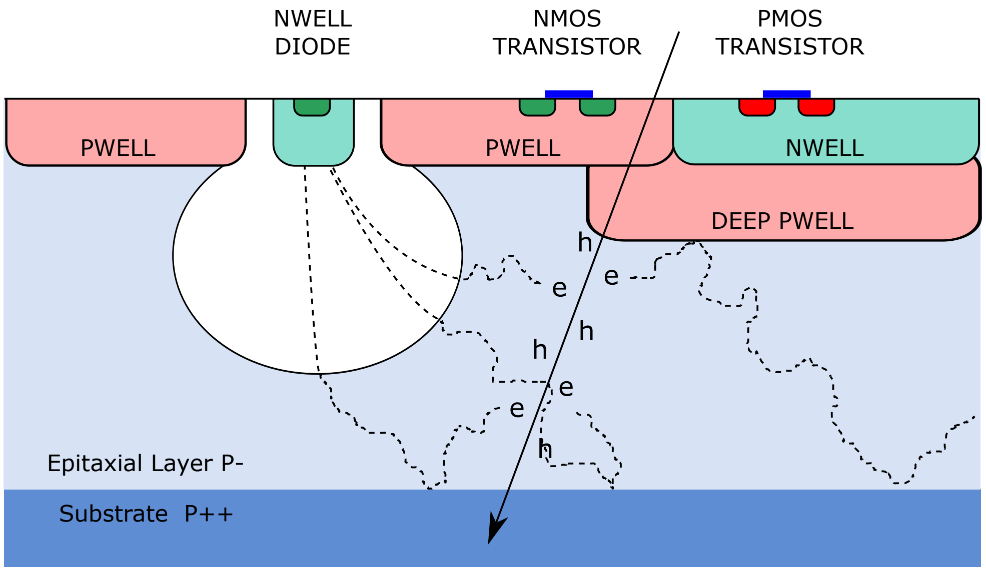



7 layers of MAPS

700 krad/ $10^{13}$ 1 MeV $n_{eq}$
includes safety factor 10

# ITS 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

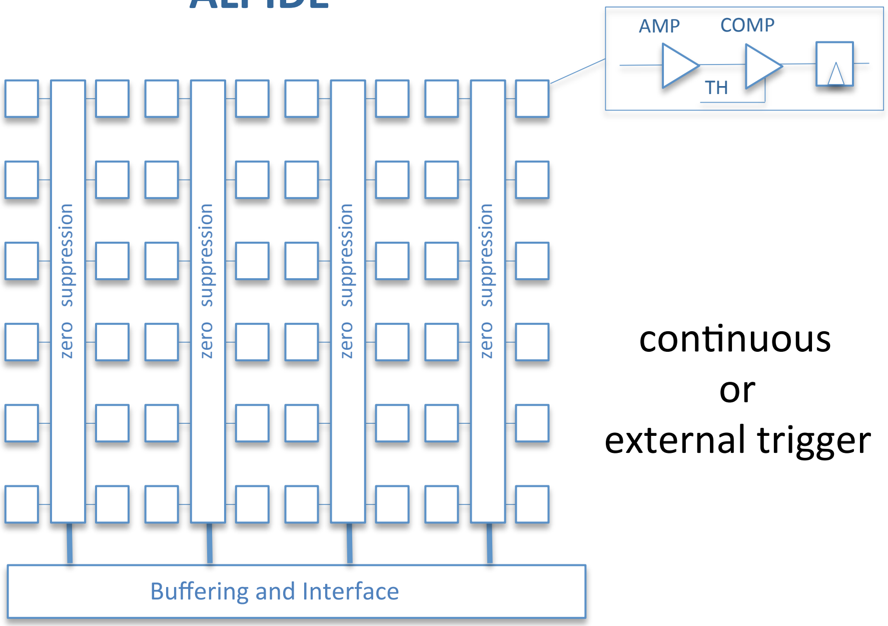
- Gate oxide 3nm

➔ 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

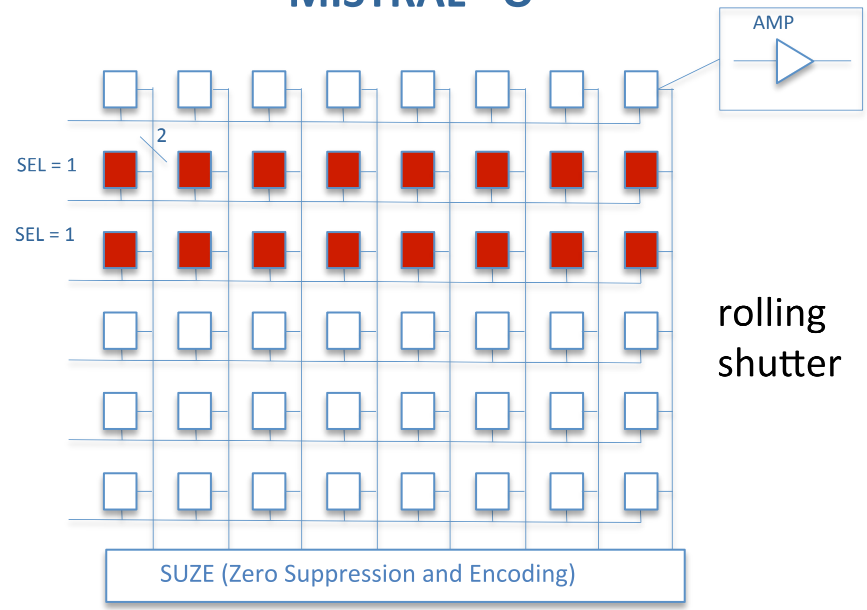
# ITS Pixel Chip – two architectures

## ALPIDE




continuous
or
external trigger

## MISTRAL - O




rolling
shutter

| | | | |
|---|---|---|---|
| Pixel pitch | 28μm x 28μm | Pixel pitch | 36μm x 64μm |
| Event time resolution | ~2μs | Event time resolution | ~20μs |
| Power consumption | 39mW/cm$^2$ | Power consumption(*) | 97mW/cm$^2$ |
| Dead area | 1.1 mm x 30mm | Dead area | 1.7 mm x 30mm |

ALPIDE and MISTRAL-O have same dimensions (15mm x 30mm), identical physical and electrical interfaces: position of interface pads, electrical signaling, protocol

(*) might further reduce to 73mW/cm$^2$

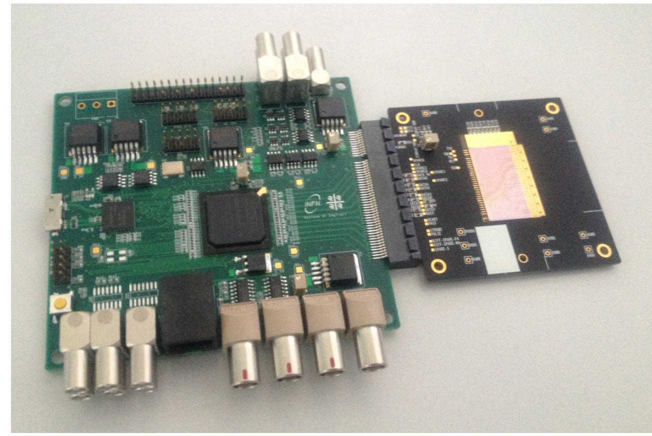
# pALPIDE-1 Characterization

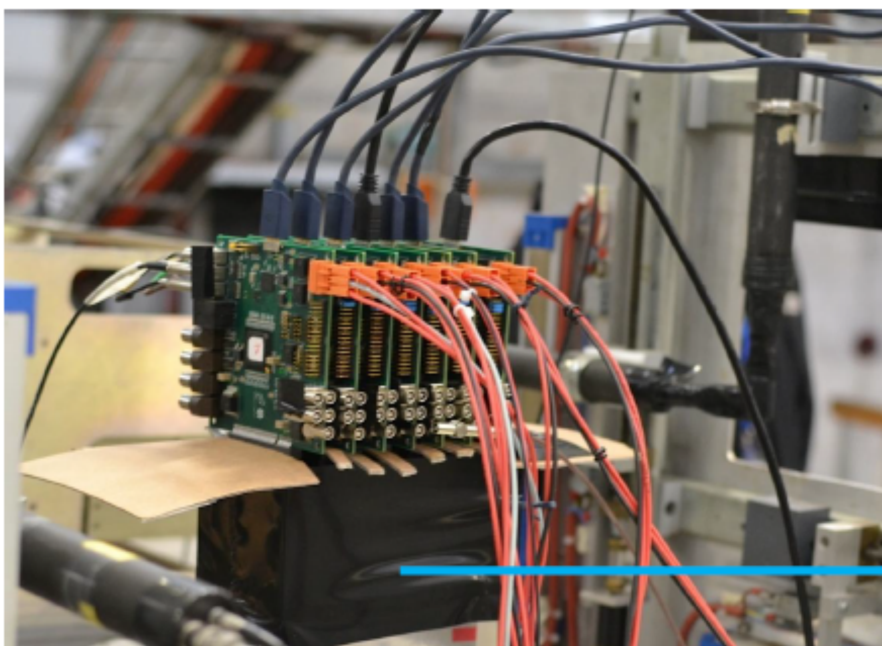
Intensive test beam campaign

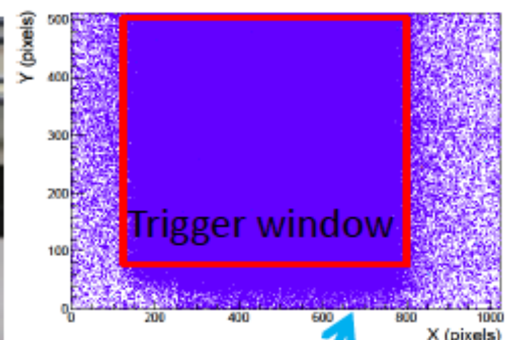
- PS: 5-7 Gev $\pi^-$
- SPS: 120 Gev $\pi^-$
- PAL (Korea): 60 MeV $e^-$
- BTF (Frascati): 450 MeV $e^-$
- DESY: 5.8 Gev $e^+$

Scan of main parameters ➔ ~ 200 settings

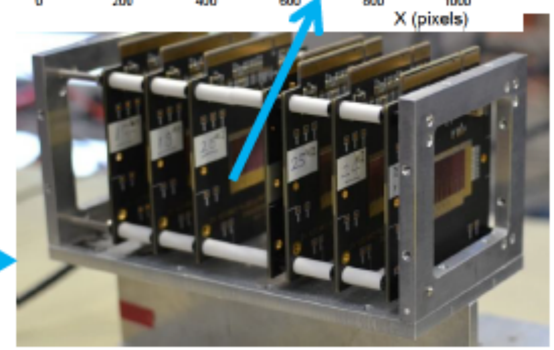
7-plane telescope based on pALPIDE-1 chip







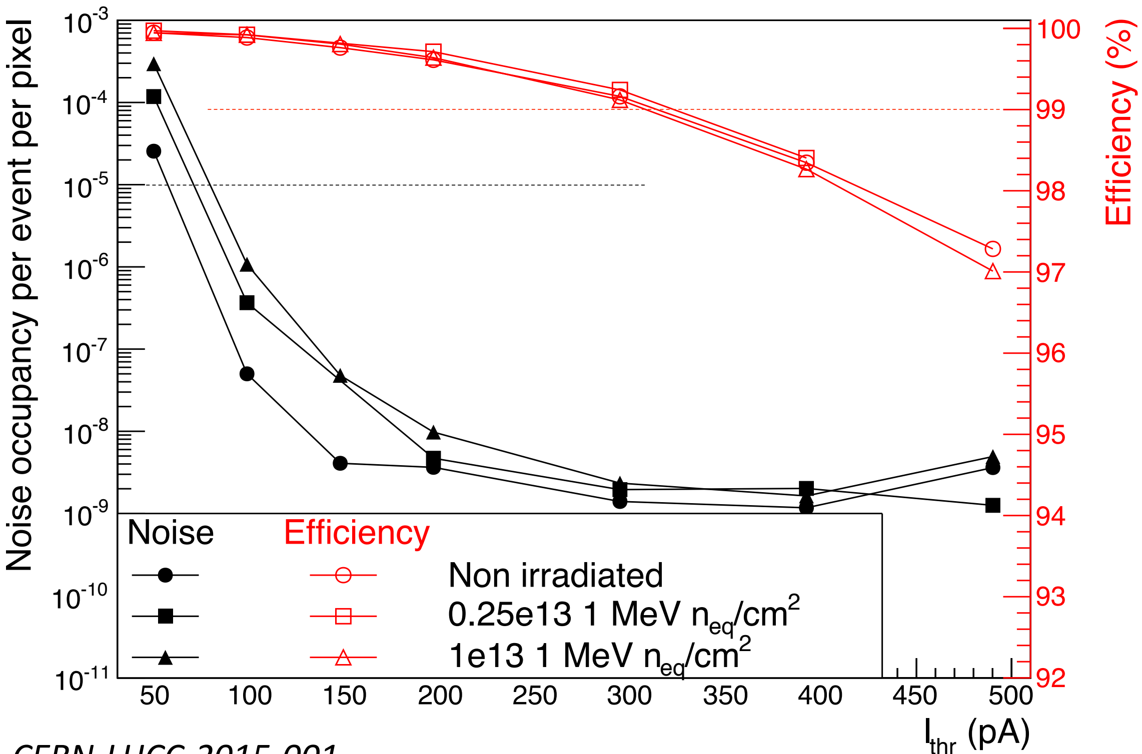

hit map



# pALPIDE-1 – PS test beam (Sep 2014)

ALICE

## Efficiency and fake hit rate




*MFT TDR, CERN-LHCC-2015-001*

50 pA ➔ ~80 e
500 pA ➔ ~180 e

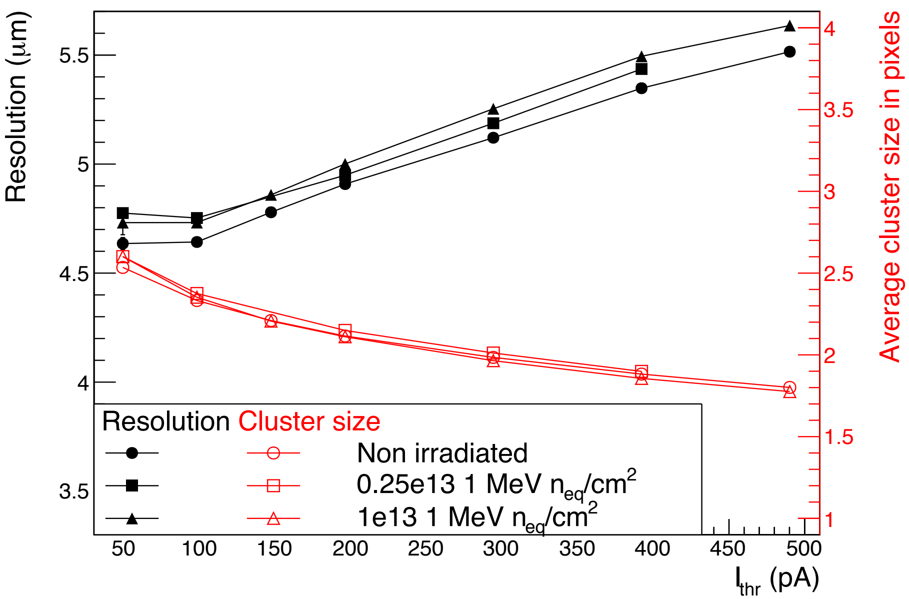
$\lambda_{fake} << 10^{-5}$ / event/pixel @ $\varepsilon_{det} > 99\%$ ➡ very large margin over design requirements

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

# pALPIDE-1 – PS test beam (Sep 2014)

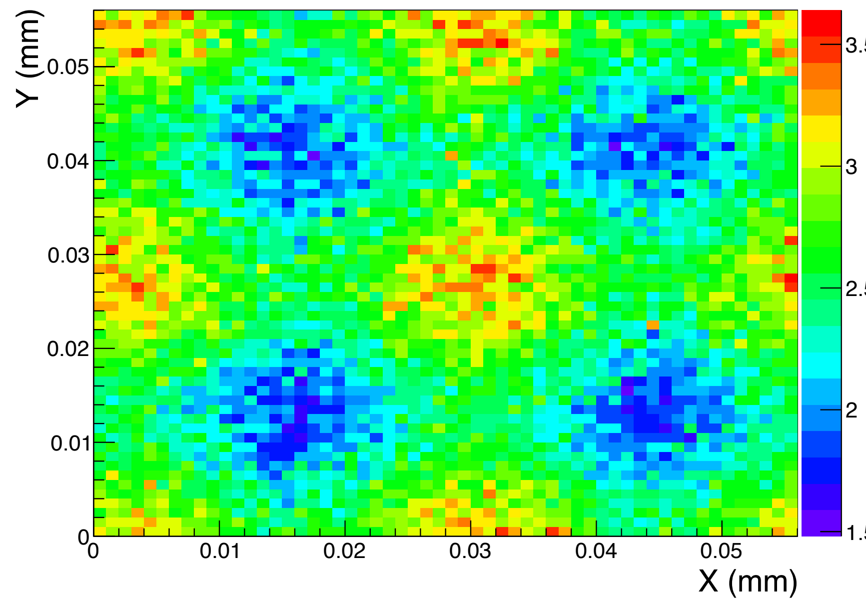


## Spatial resolution




*MFT TDR, CERN-LHCC-2015-001*

## Cluster size vs. position within pixel

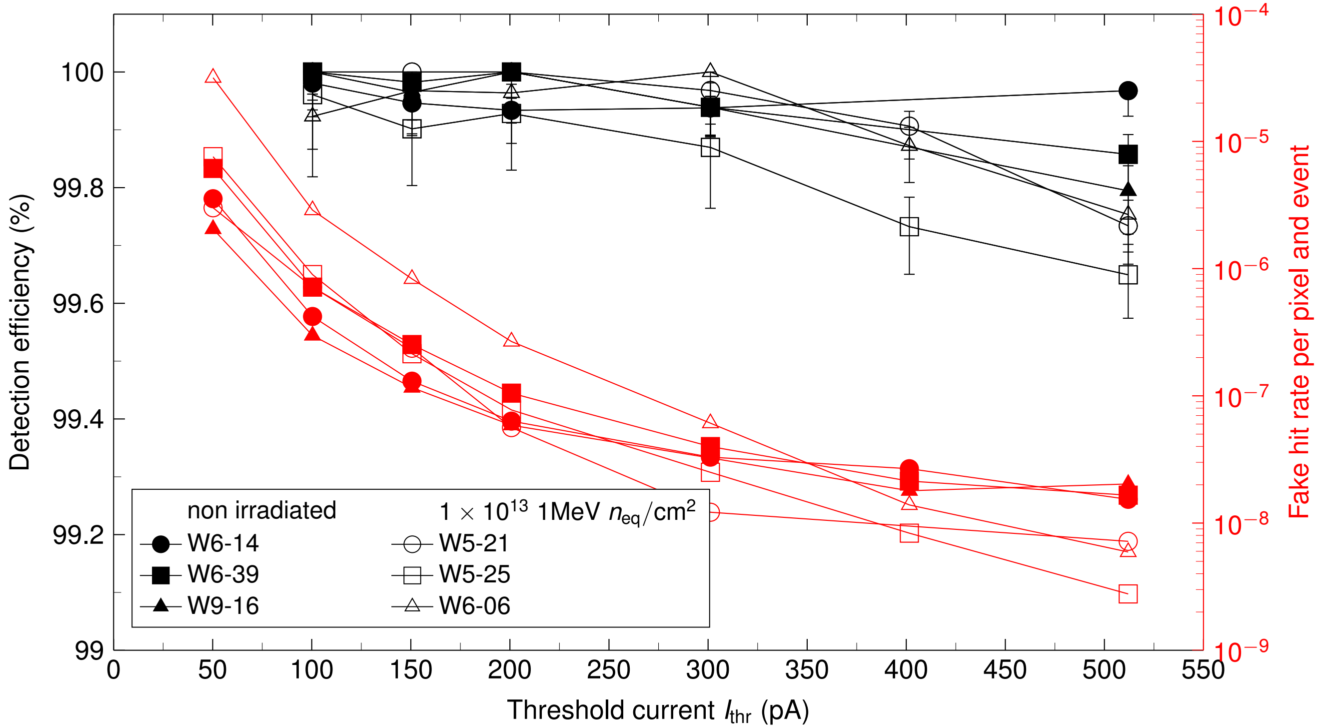



$\sigma_{det} < 5\ \mu m$ is achieved with sufficient margin of operation

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

# pALPIDE-1 – PS test beam (Dec 2014)

## Efficiency and fake hit rate



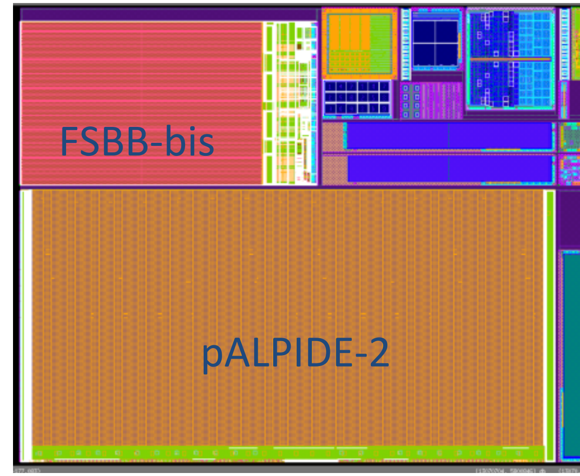

**Improved test-beam data analysis**

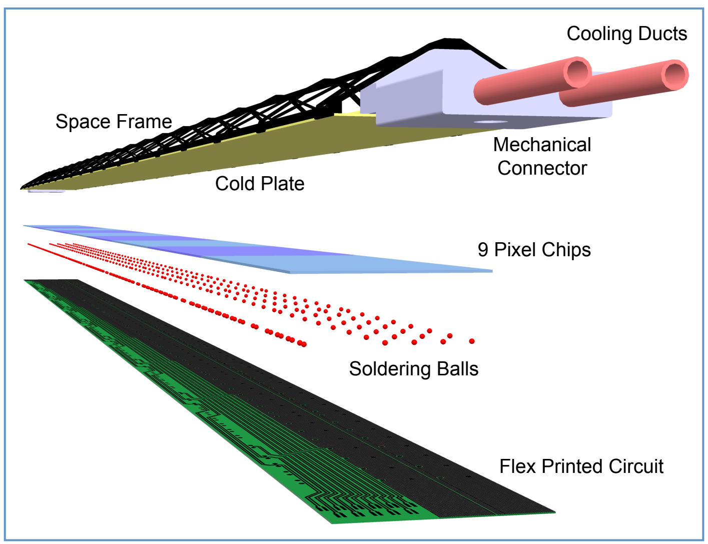
- Measurements at PS: 5 – 7 GeV $\pi^-$ December 2014
- Results refer to 50 µm thick chips: 3 non irradiated and 3 irradiated with neutrons

# ALPIDE finalization

## p-ALPIDE-2: 2nd full-scale prototype

- Optimization of some circuit blocks
- NO high-speed output link (1.2 Gbit/sec replaced by a 40Mb/s)
- Full Integration in IB and OB Module: main focus in 2015
- Delivery: mid March



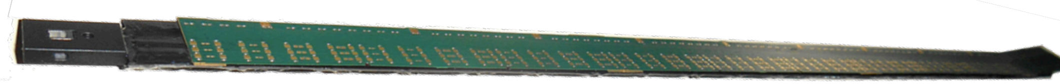




## p-ALPIDE-3: 3rd full-scale prototype

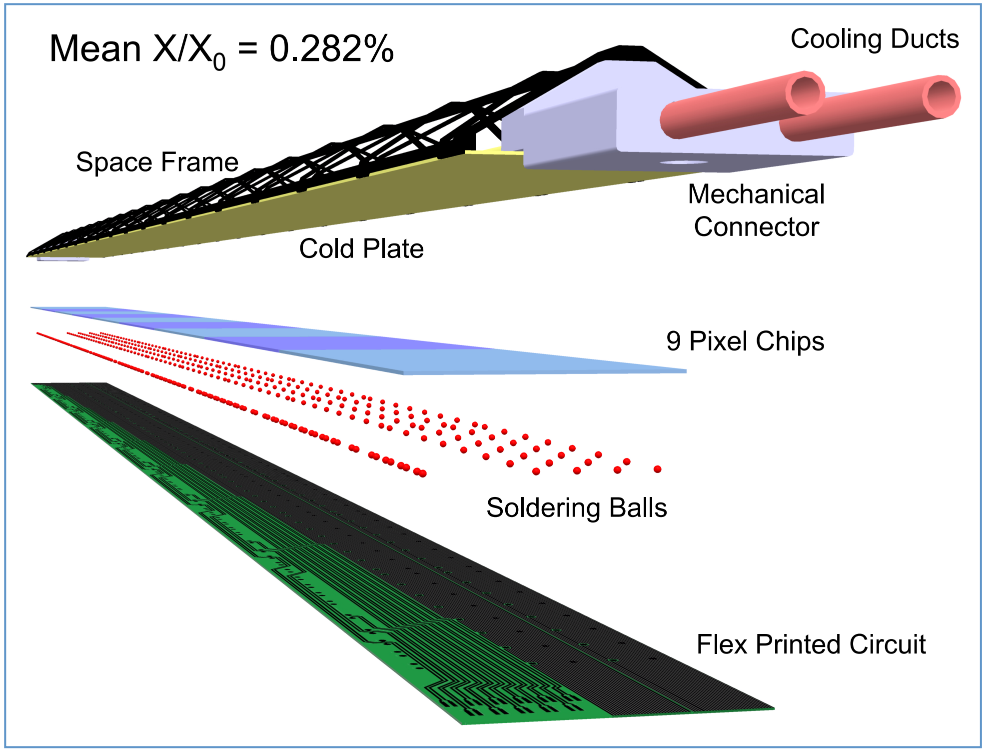
- Contains all final elements
- Submission: April '15 Delivery: July '15

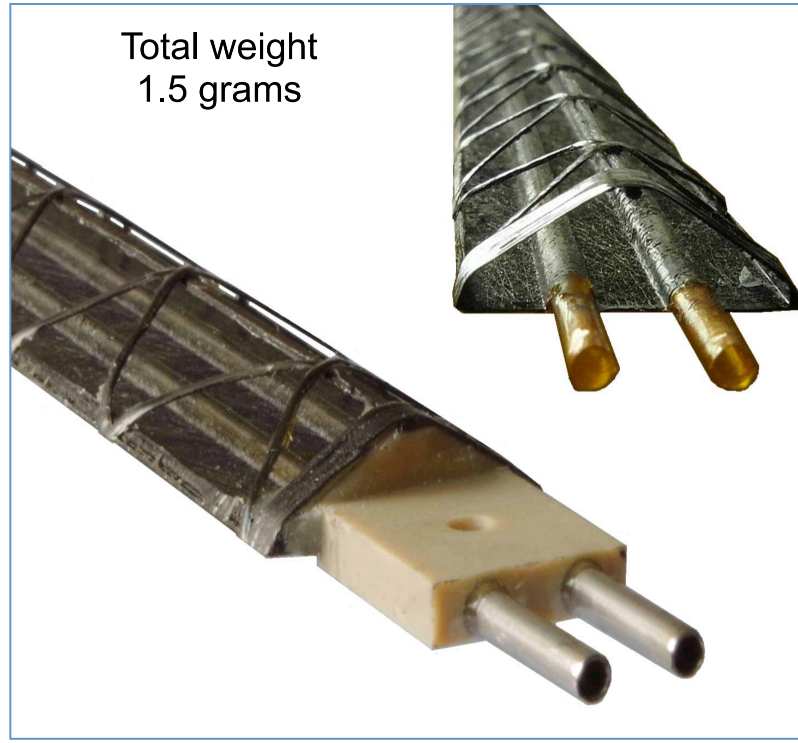
## p-ALPIDE-4: pre-series production

- Submission Dec '15



# New ITS Layout - Inner Barrel




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

Nr. of staves: 12, 16, 20

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

Power density: < 100 $mW/cm^2$

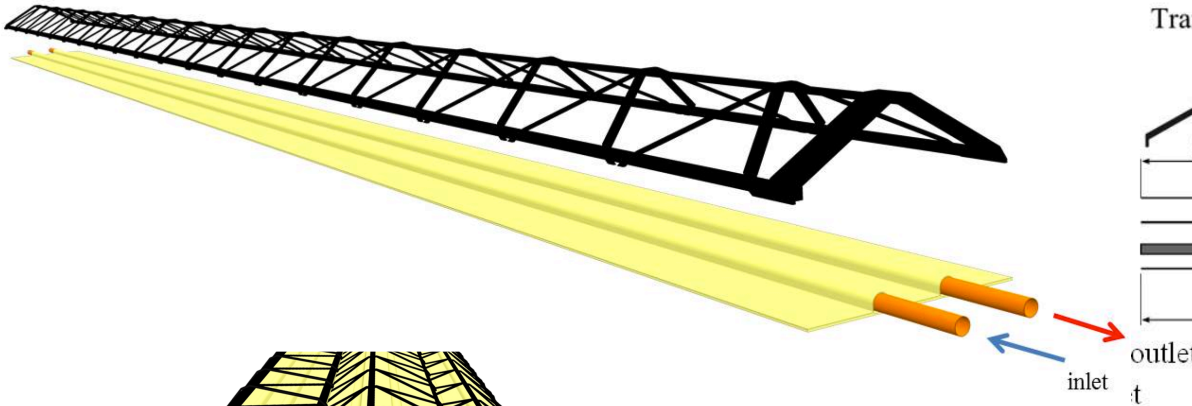
Length in z (mm): 270

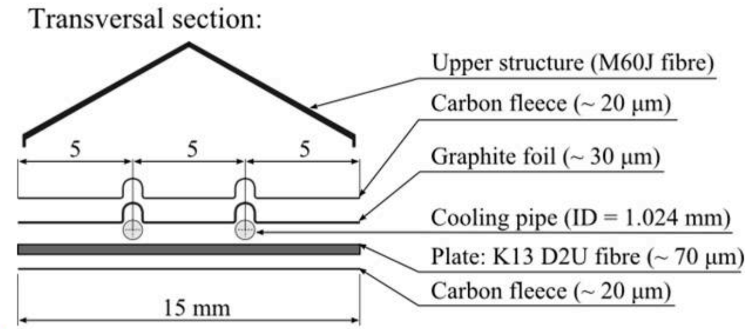
Nr. of chips/stave: 9

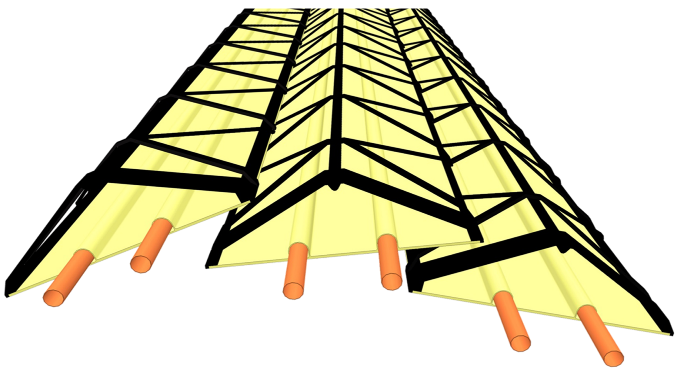
Material thickness: ~ 0.3% $X_0$

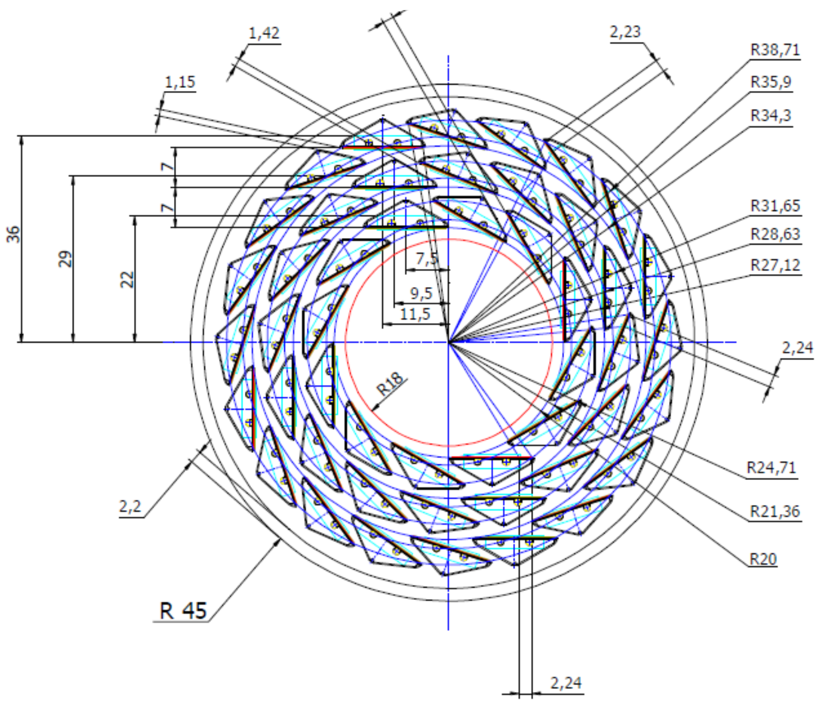
Throughput (@100kHz): < 80 $Mb/s \times cm^{-2}$

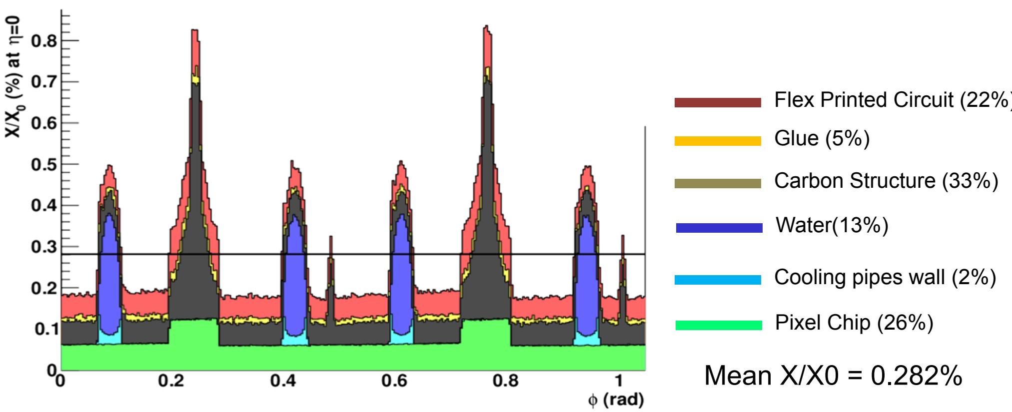
# Inner Barrel – Geometry and material budget



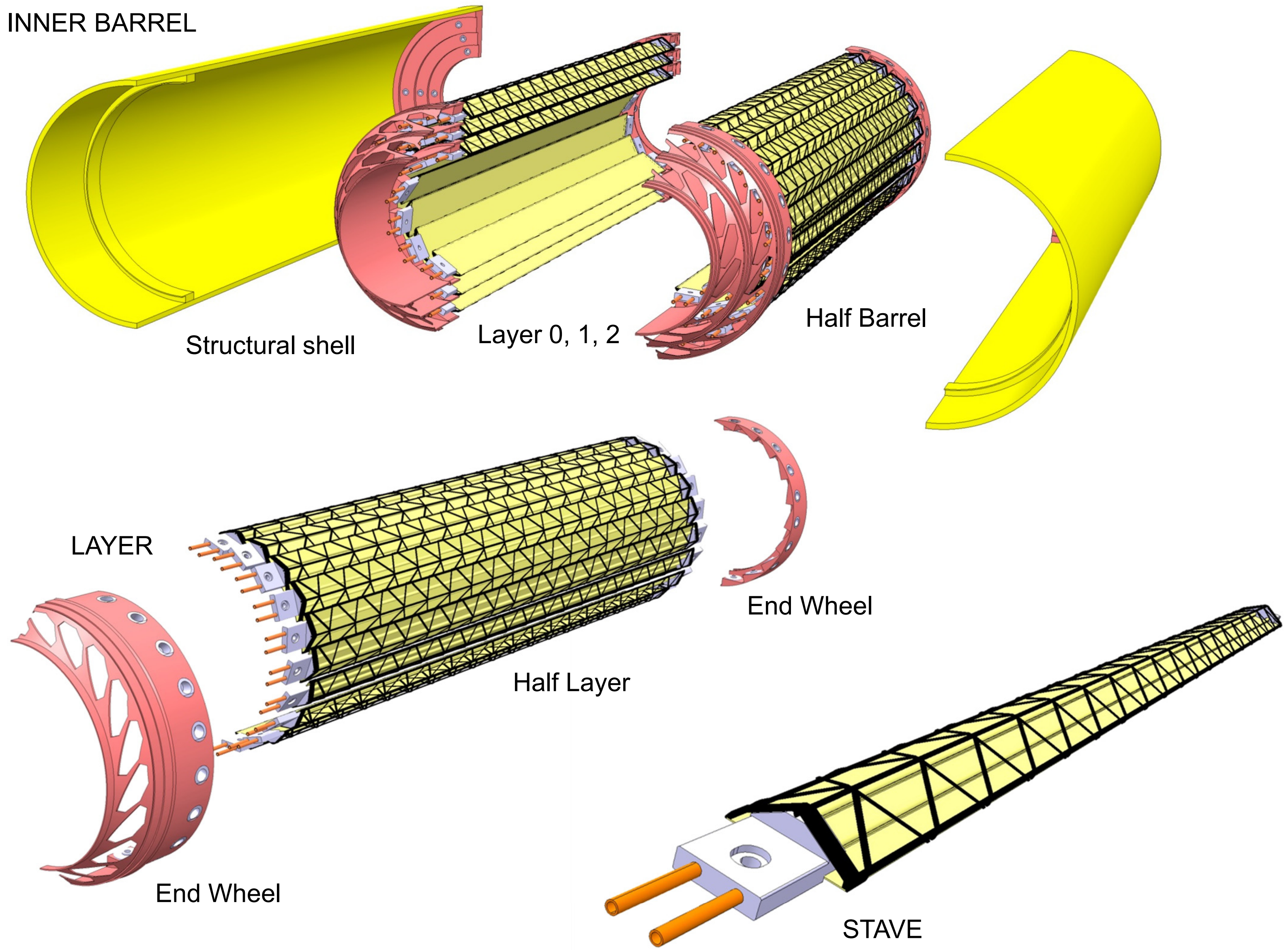





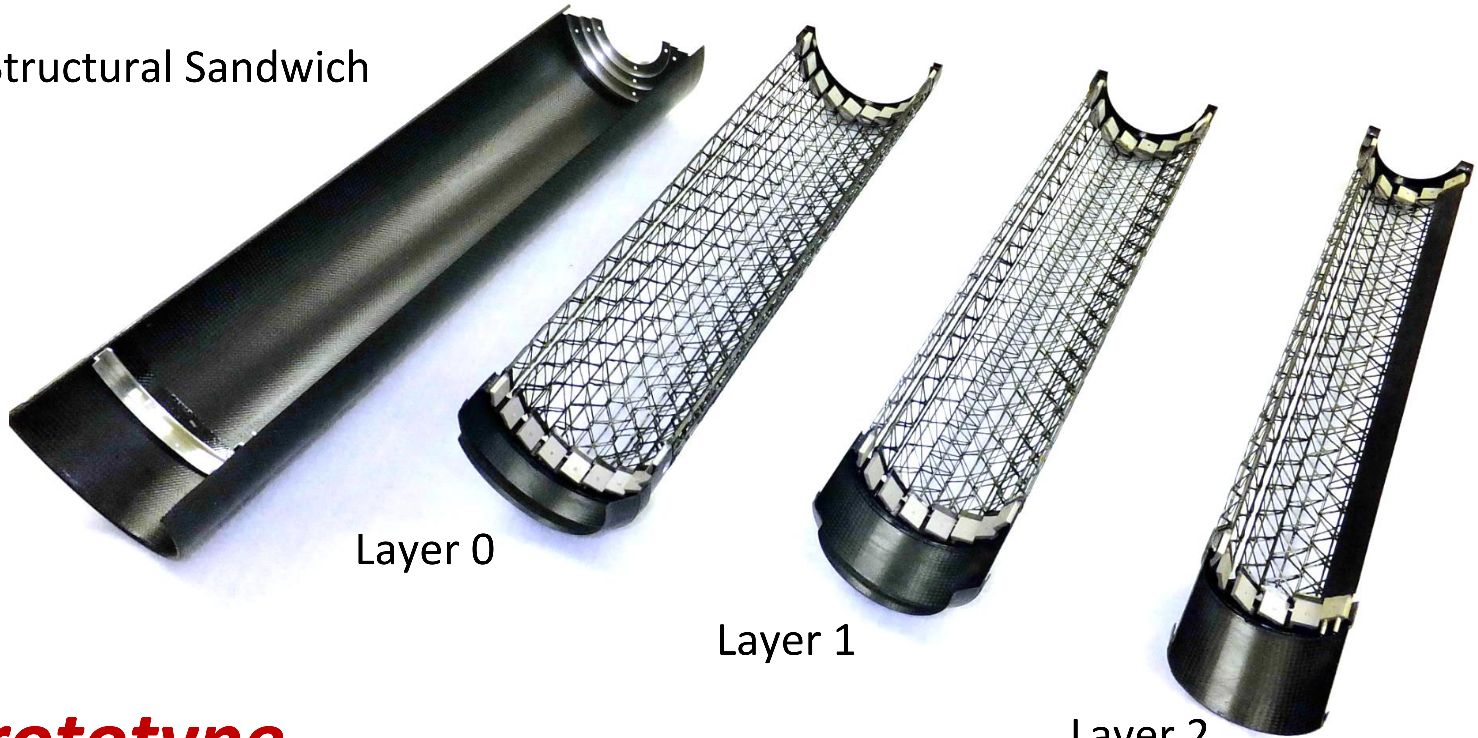




Mean X/X0 = 0.282%

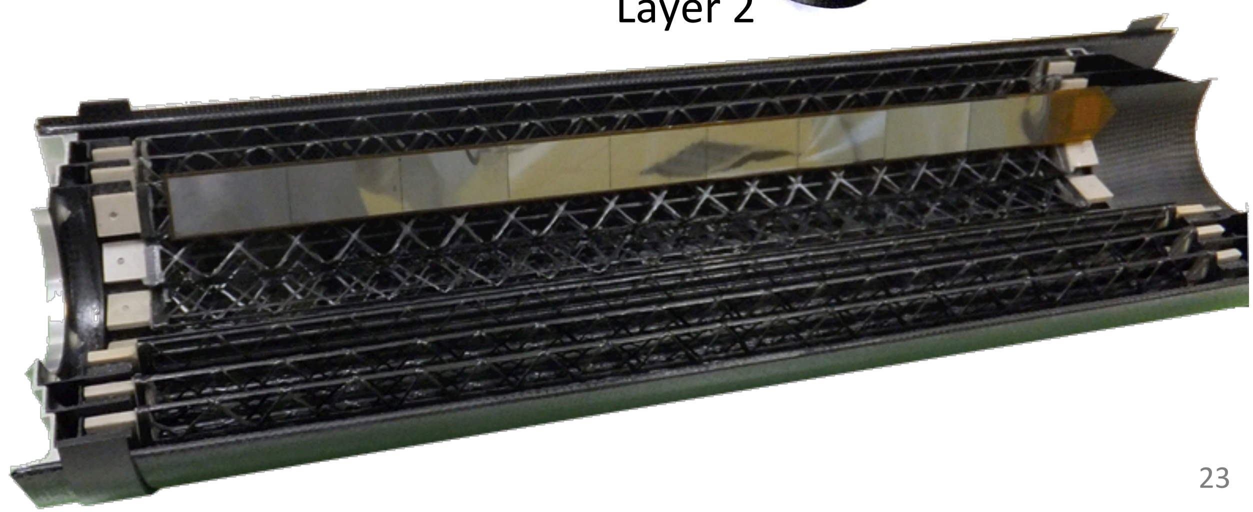
# Inner Barrel



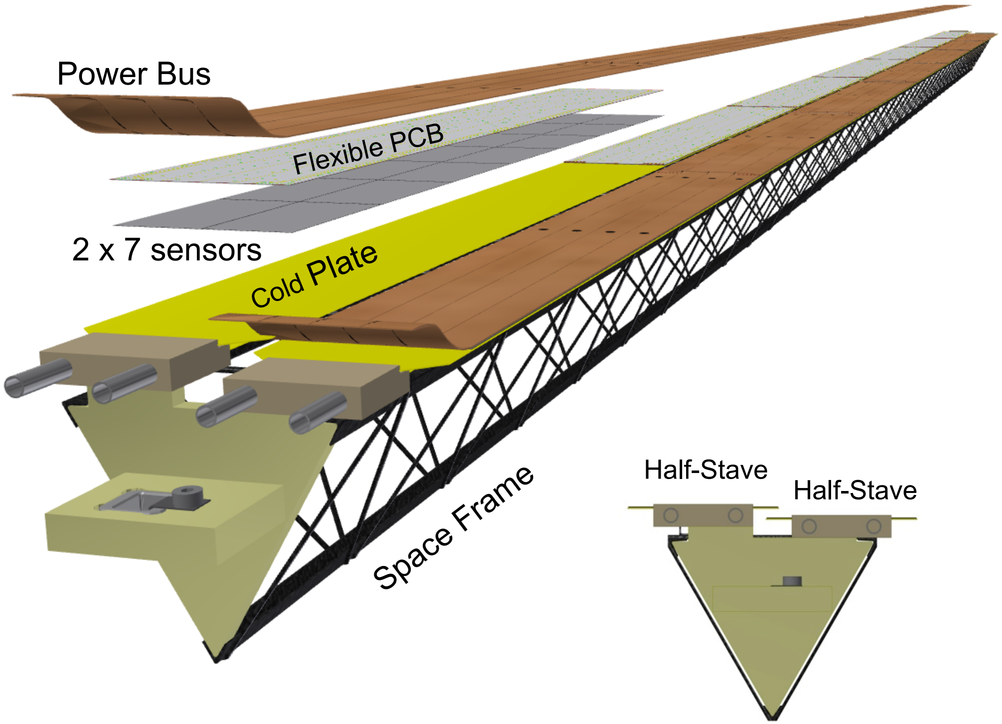
# Inner Barrel – full-scale prototype

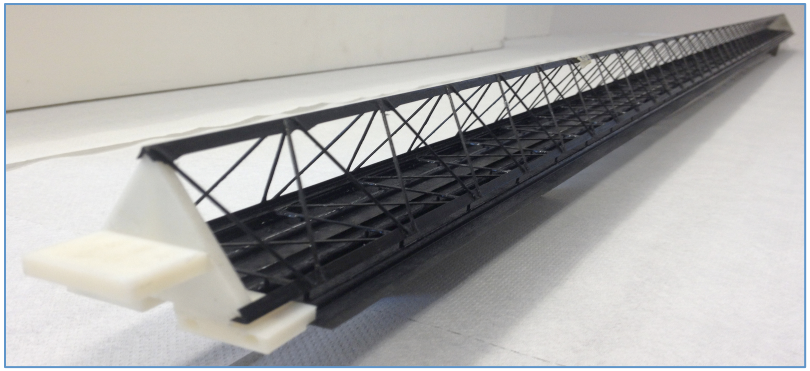



***Prototype***



# Outer Barrel




## Outer Barrel (OB)

<radius> (mm): 194, 247, 353, 405

Nr. staves: 22, 28, 40, 46

Nr. Chips/layer: (ML), (OL)

Power density < 100 mW / cm$^2$

Length (mm): 843 (ML), 1475 (OL)

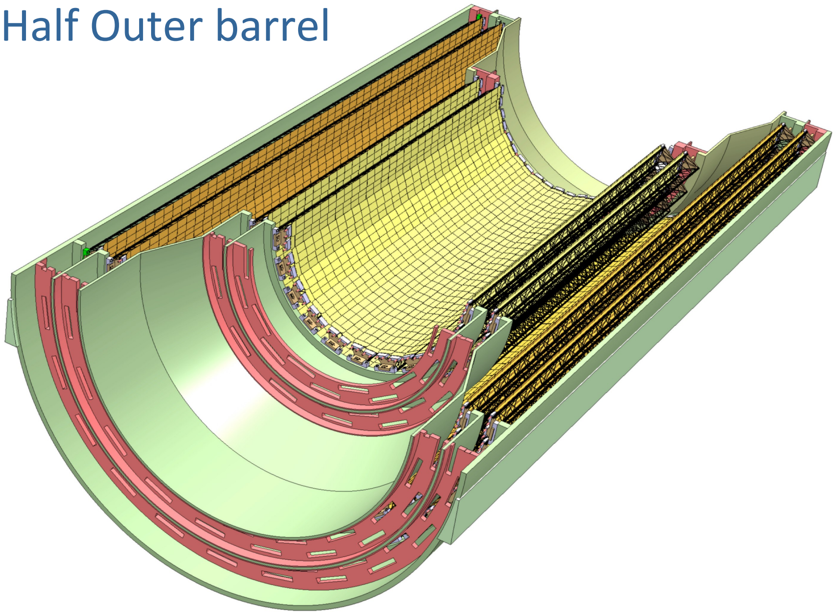
Nr. modules/stave: 4 (ML), 7 (OL)

Material thickness: ~ 1% $X_0$

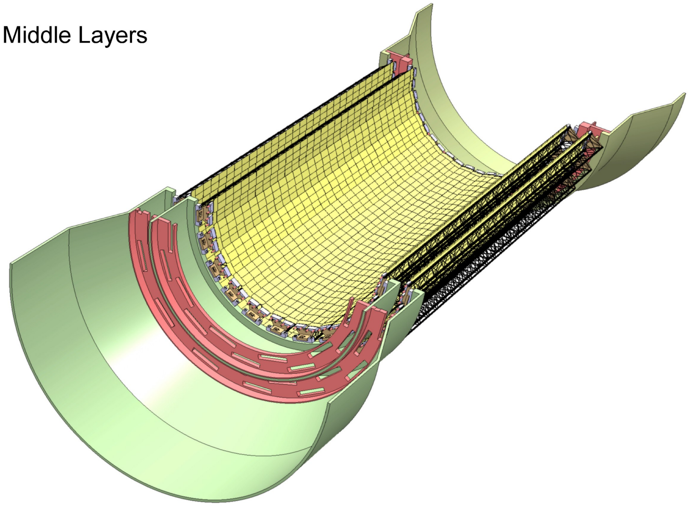
Throughput (@100kHz): < 3Mb/s × cm$^{-2}$

# Outer Barrel Support Structure and Assembly

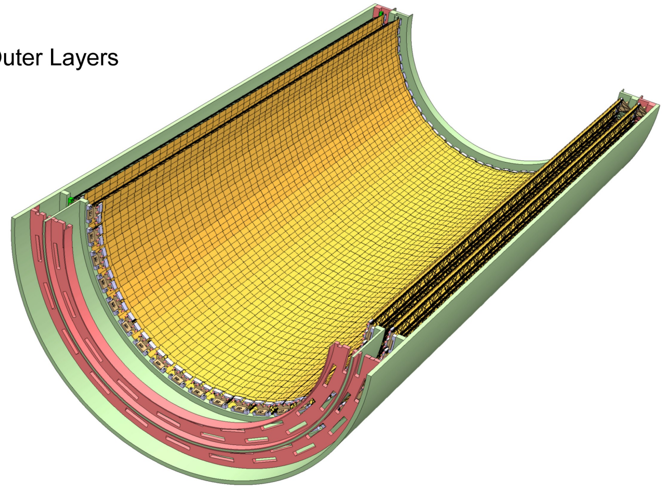
Assembly
Half Outer barrel



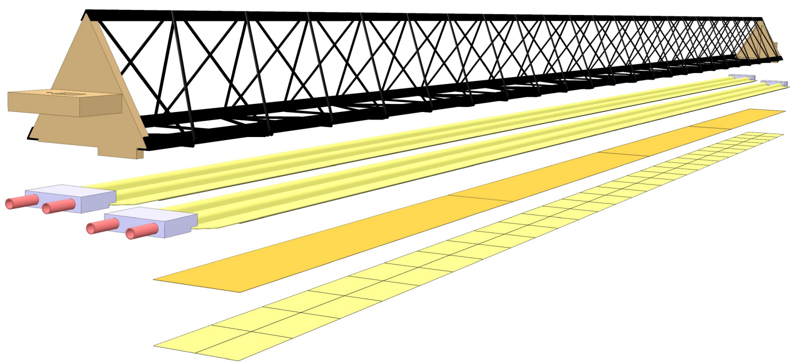
Middle Layers



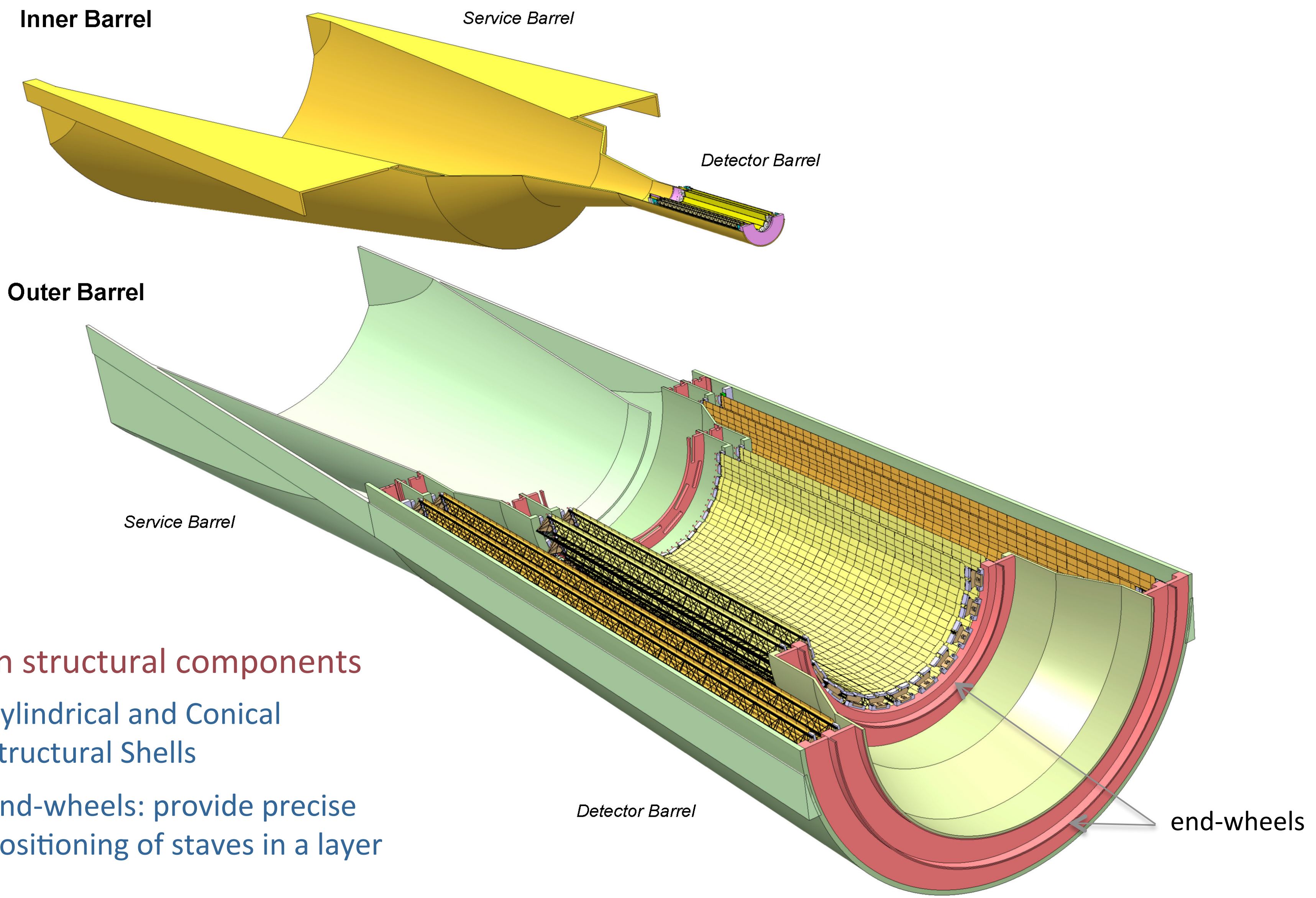
Outer Layers



**Stave**



# Detector Assembly

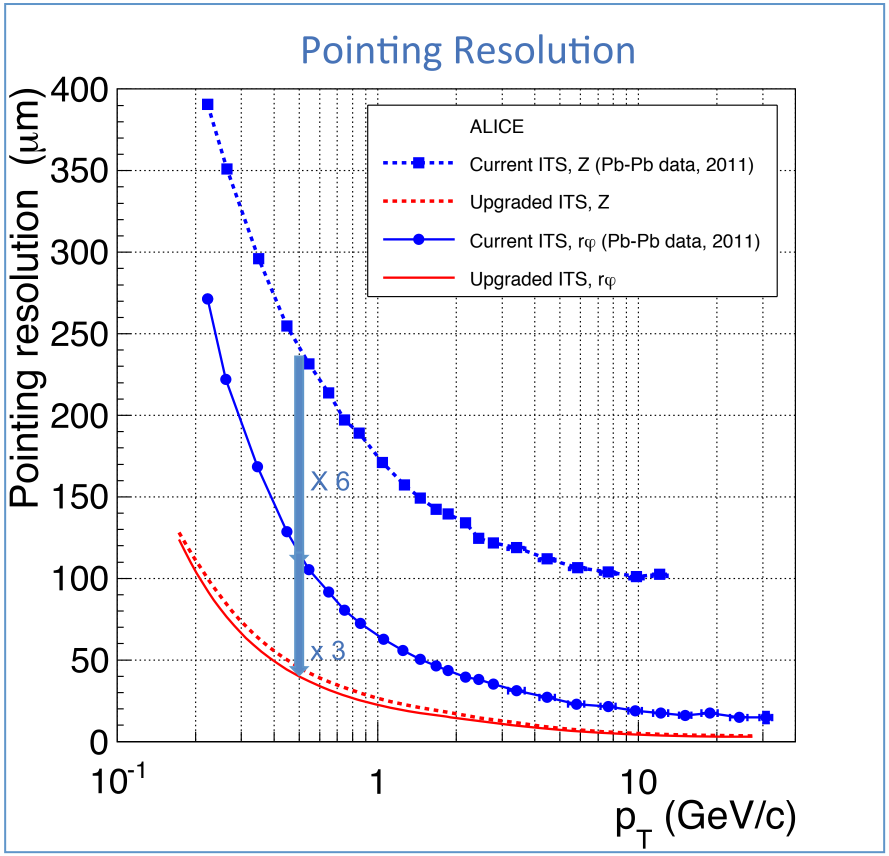



Main structural components

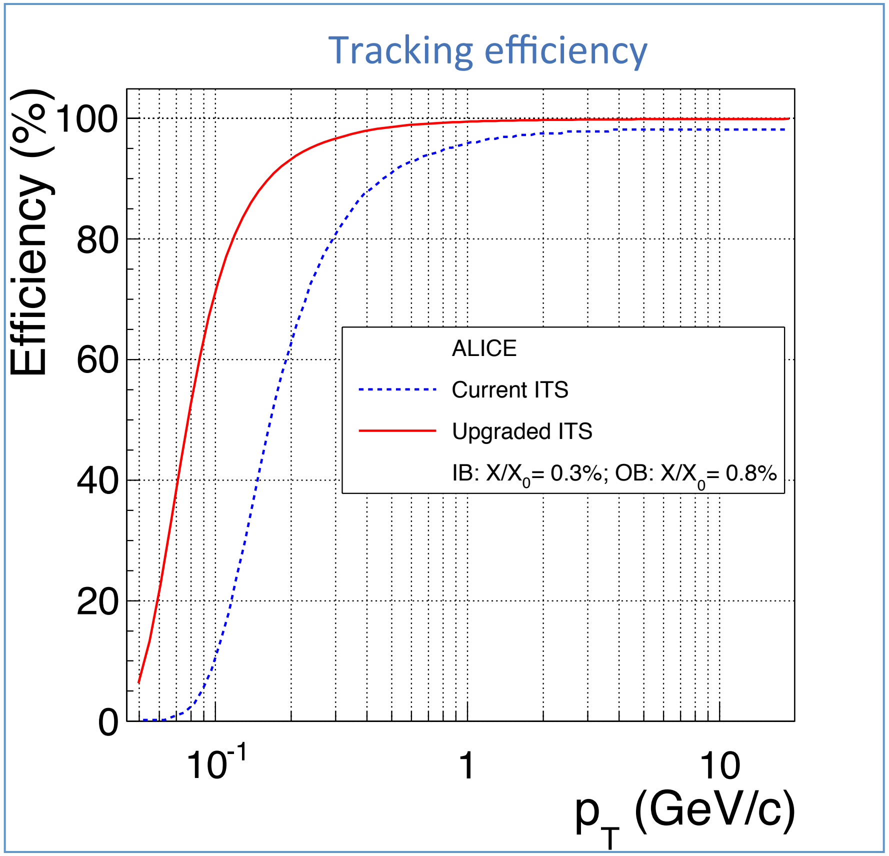
- Cylindrical and Conical Structural Shells
- End-wheels: provide precise positioning of staves in a layer

# Performance of new ITS (MC simulations)

## Impact parameter resolution



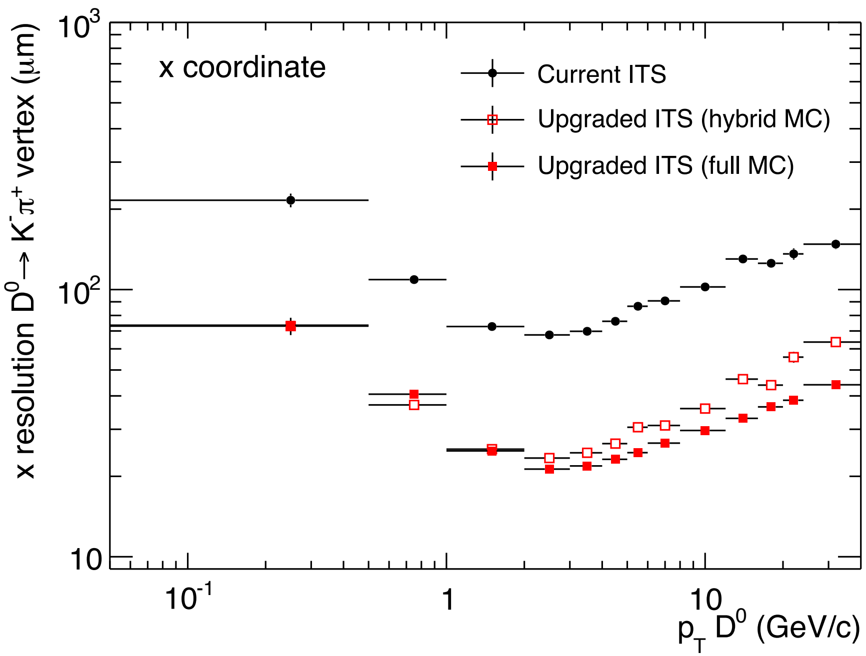

## Tracking efficiency (ITS standalone)

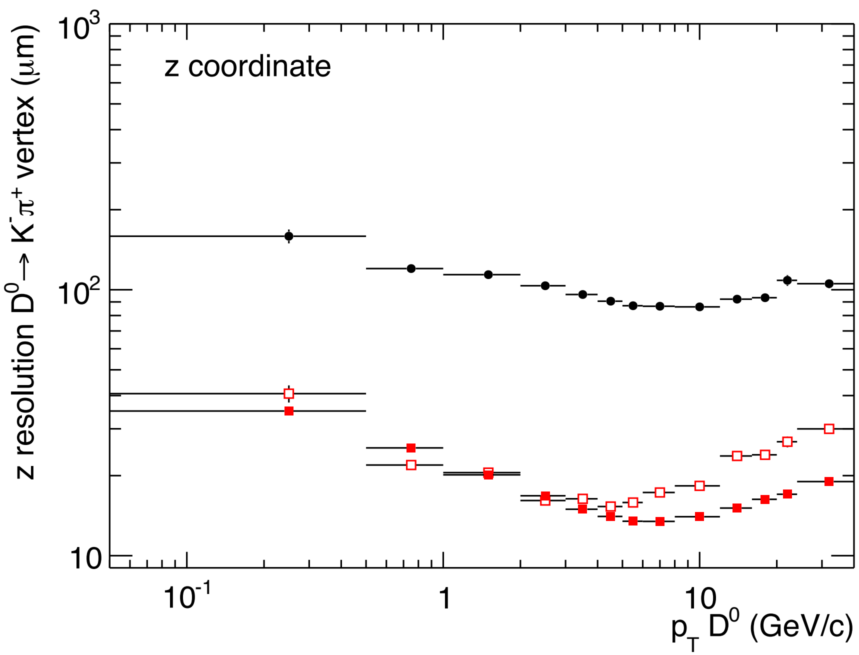



~40 μm at $p_T$ = 500 MeV/c

# Performance of new ITS (MC simulation)

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

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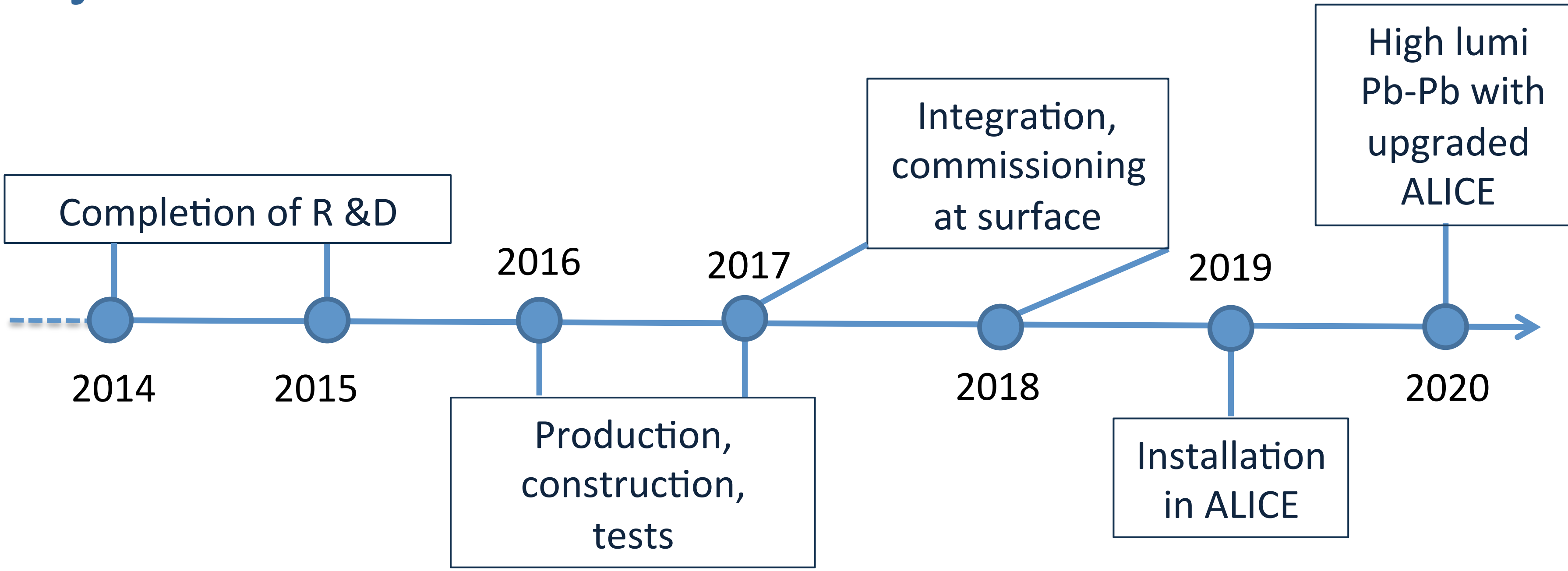
# Project Timeline and Collaboration



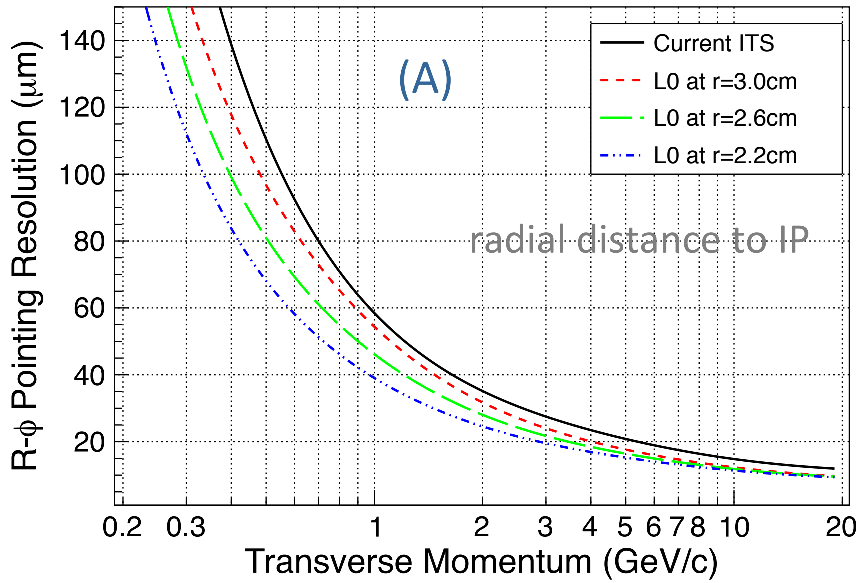

ALICE ITS Collaboration

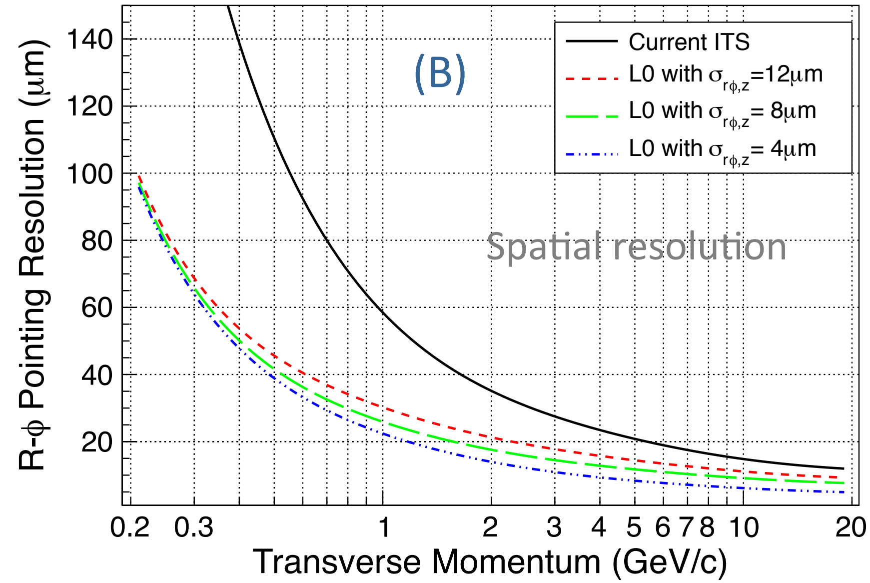
CERN, China (Wuhan), Check Republic (Prague), France (Grenoble, Strasbourg), Italy (Aless., Bari, Cagliari, Catania, Frascati, Padova, Roma, Trieste, Torino), Indonesia (LIPI), Korea (Pusan, Inha, Yonsei), Netherlands (Nikhef, Utrecht), Pakistan (CIIT-Islamabad), Russia (St. Petersburg), Slovakia (Kosice),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

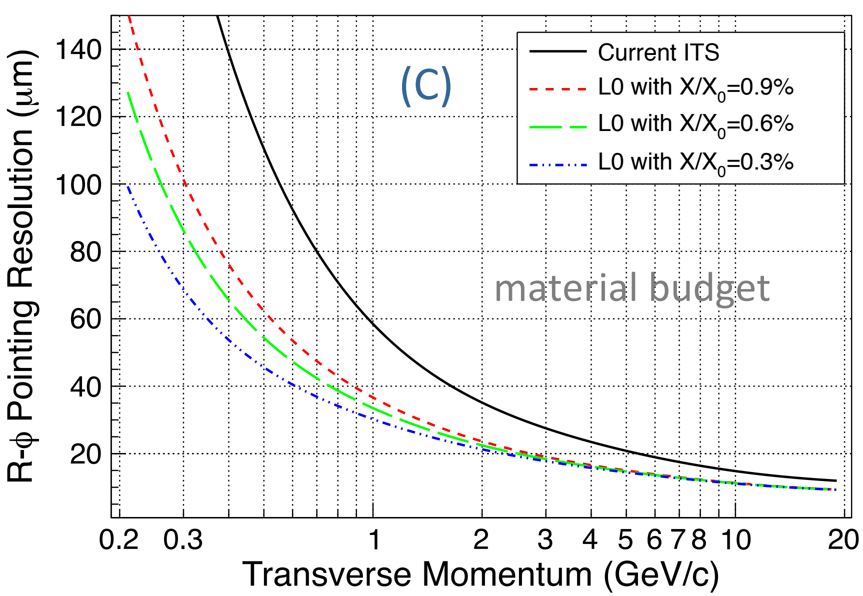
Institute = participated in current ITS

# SPARES

# Impact parameter studies (ALICE ITS Upgrade)



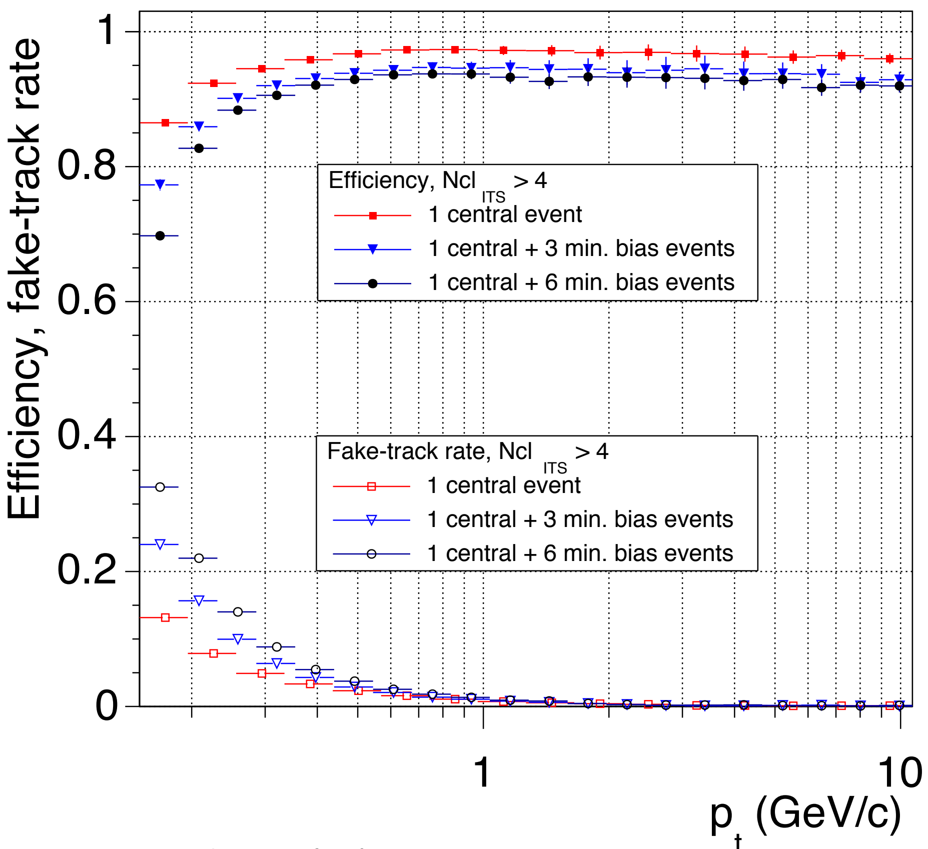




- Current ALICE ITS
  - radial position of first layer: 39mm
  - $x/X_0$: 1.14% per layer
  - spatial resolution (r-phi): 12 μm
- A) current ITS + L0: x/X0 = 0.3%, res.=4μm;
- B) current ITS + L0: r = 22mm, $x/X_0$ = 0.3%;
- C) current ITS + L0: r = 22mm, $x/X_0$ = 0.3%;

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

# Performance of new ITS (MC simulations)

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

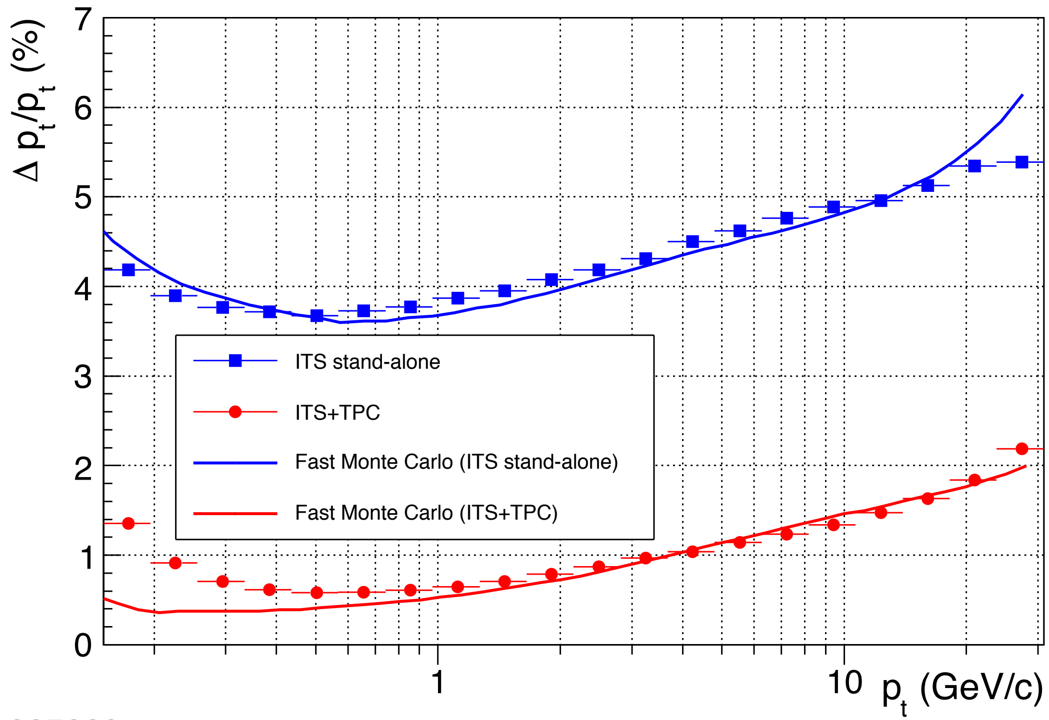
For 30 μs integration time (worst case design):

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

# Performance of new ITS (MC simulations)

ALICE

## MOMENTUM RESOLUTION

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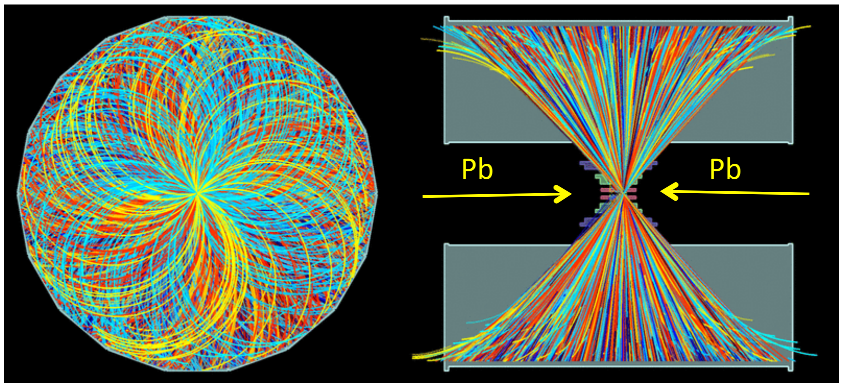
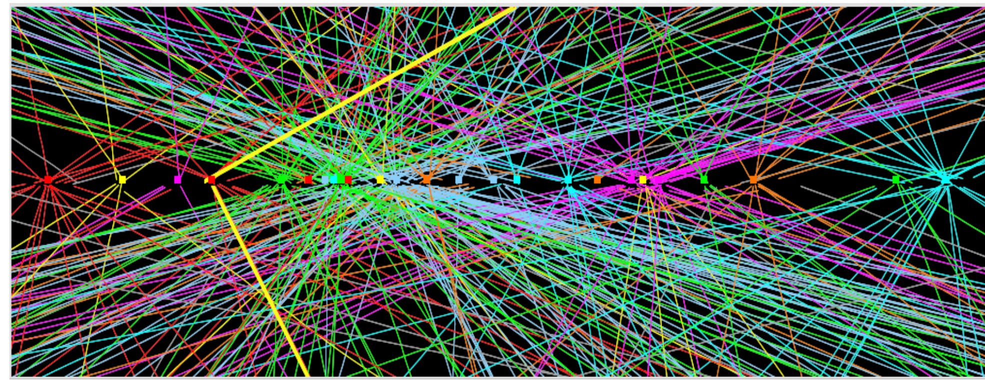
Transverse momentum resolution as function of $p_T$ for primary charged pions for the upgraded ITS and current ITS. The results are shown for ITS standalone and ITS-TPC combined tracking.

# Why use Silicon Pixels 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)

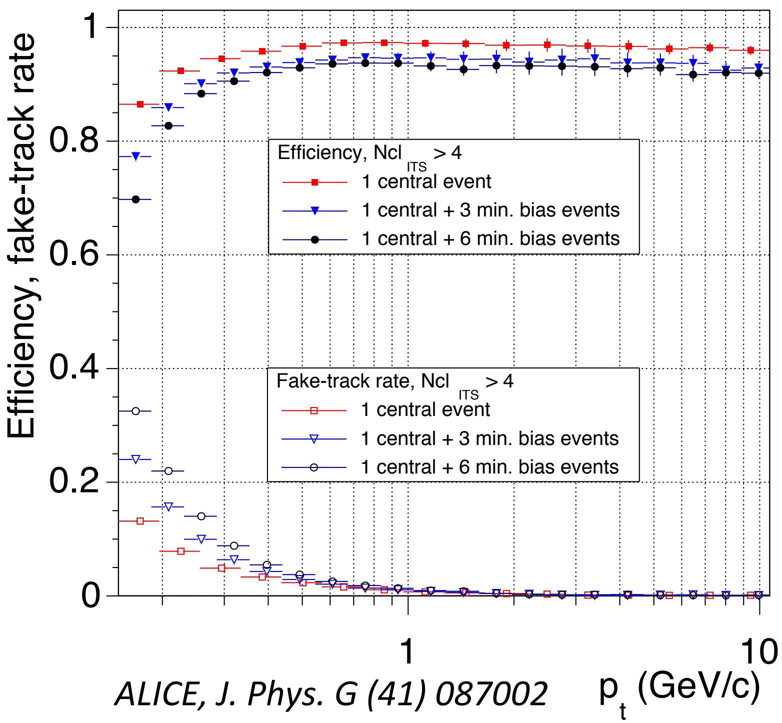


**LHC pp collisions**: a candidate Z boson event in the dimuon decay with 25 reconstructed vertices. (ATLAS, April 2012)

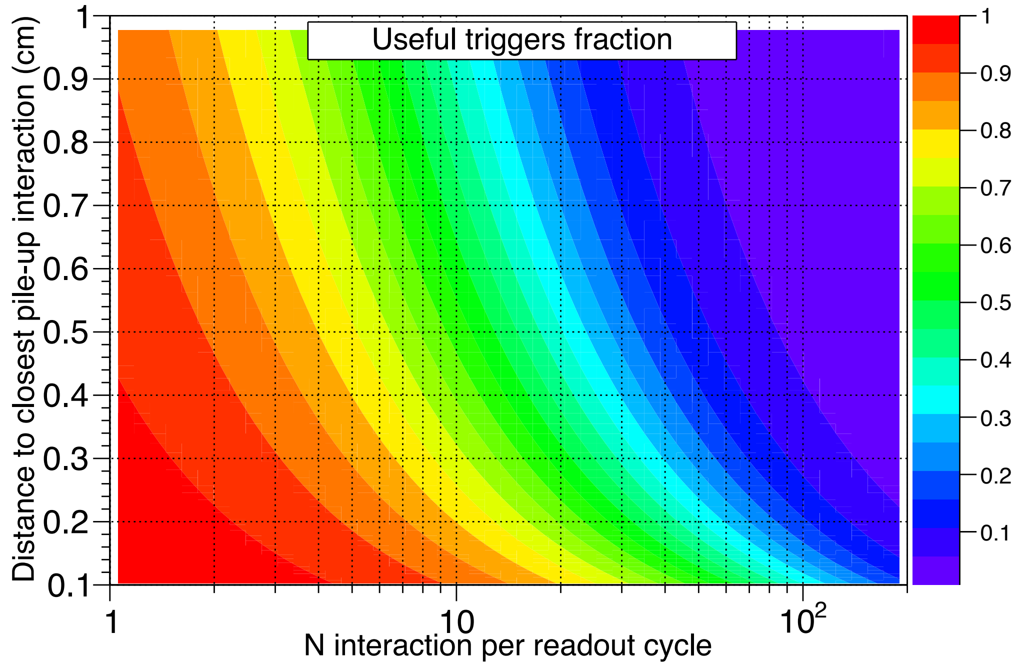
- Position resolution down to few microns
- Unambiguous hit information in high track density region
- High resolution for determination primary and secondary vertex
- Fast readout
- High level of radiation hardness

# How integration time and pile-up affect performance

## ALICE ITS Upgrade



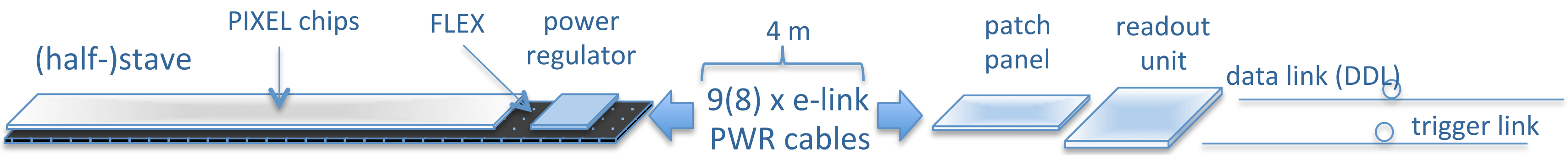

*ALICE, J. Phys. G (41) 087002*



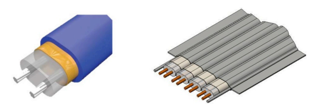

At 50 kHz Pb-Pb interaction rate
<pile-up> @ 20 μs integration time: 1 central + 1 minimum bias

At 200 kHz pp interaction rate
<pile-up> @ 20 μs integration time: 5 interaction

# Readout – general scheme and data throughput



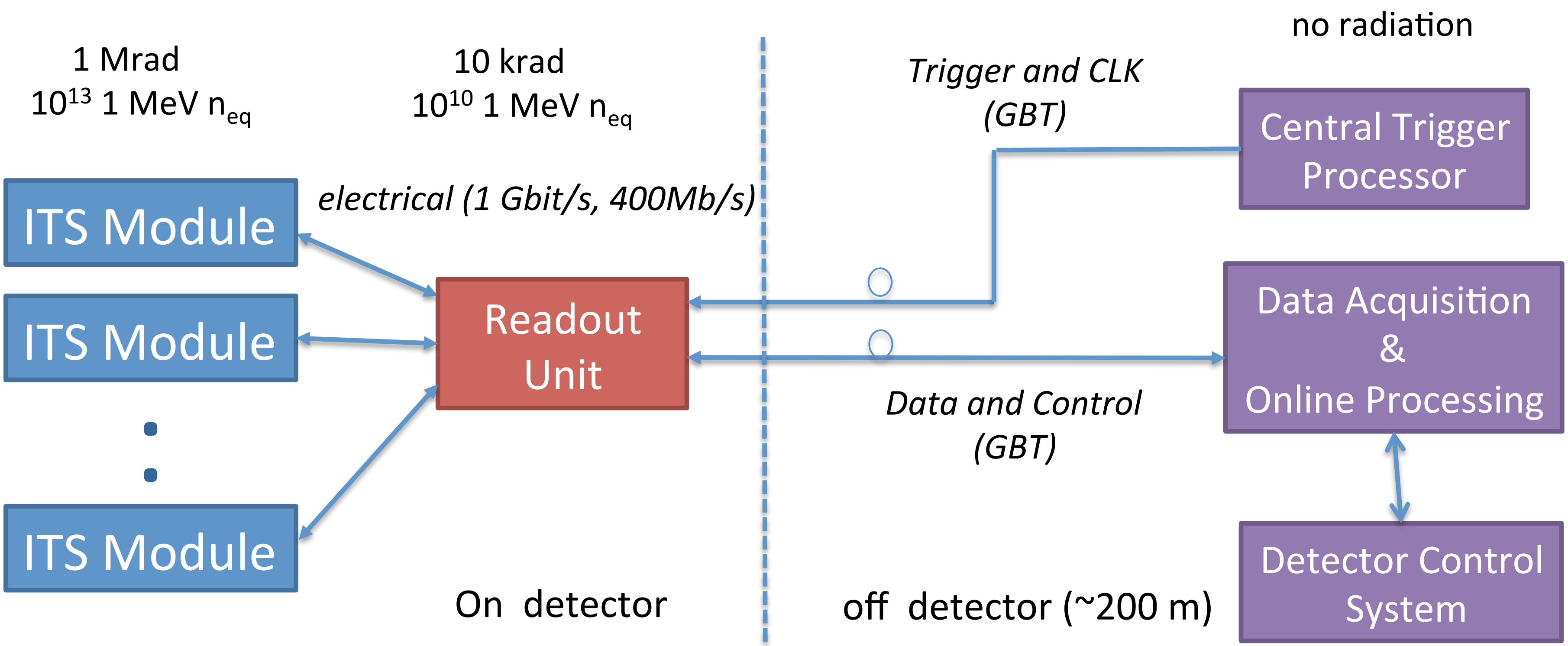

Schematic representation of the readout path



SAMTEC twinax "Firefly"

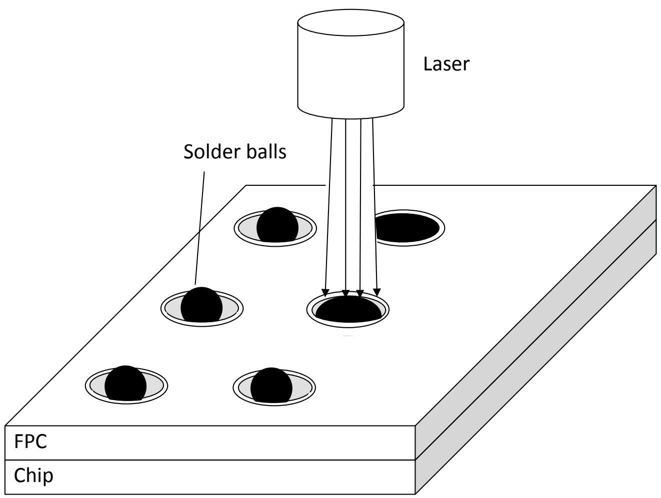
Data throughput 324 Gbit/s
1008 electrical links

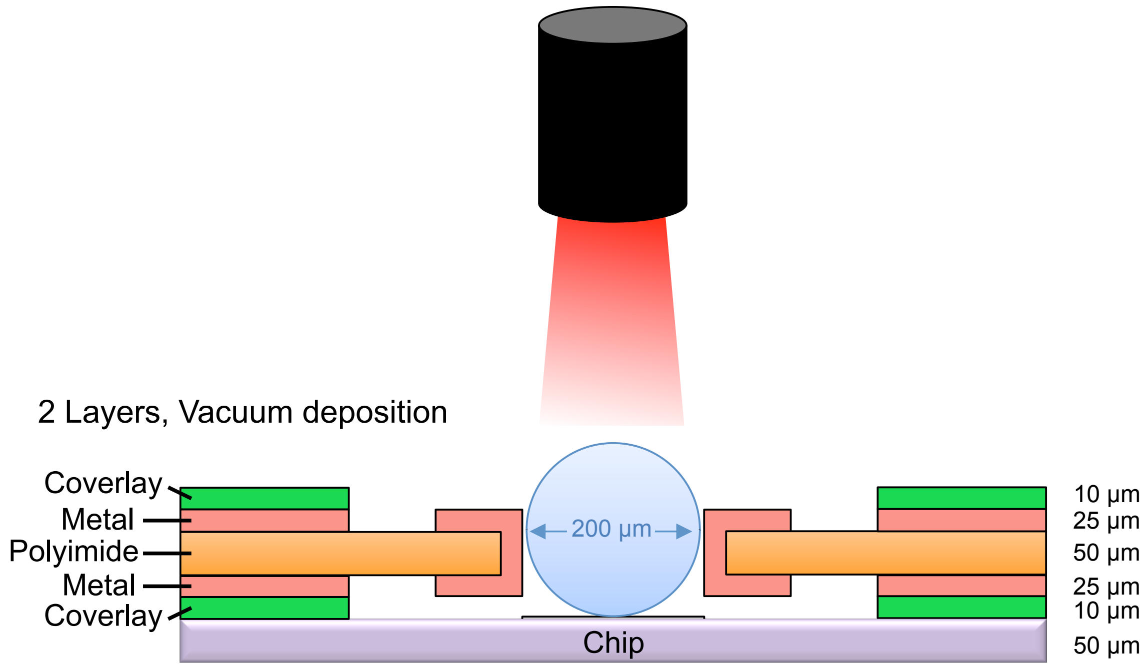
(184 DAQ optical links + n Trigger links )

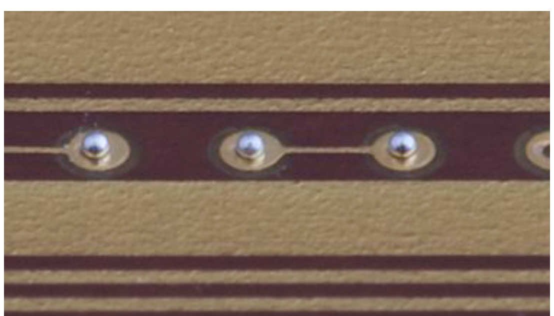


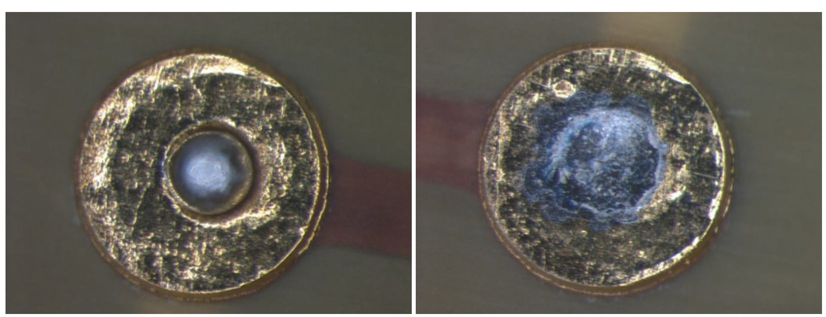
# Chip Assembly – laser soldering

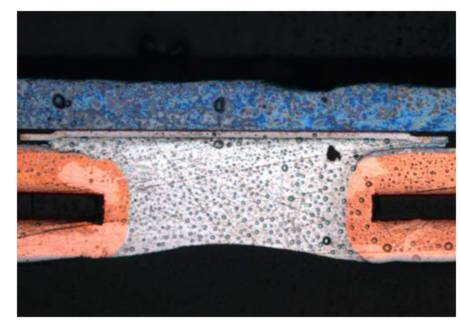
Interconnection of Pixel chip on flexible printed circuit
Laser soldering (baseline)



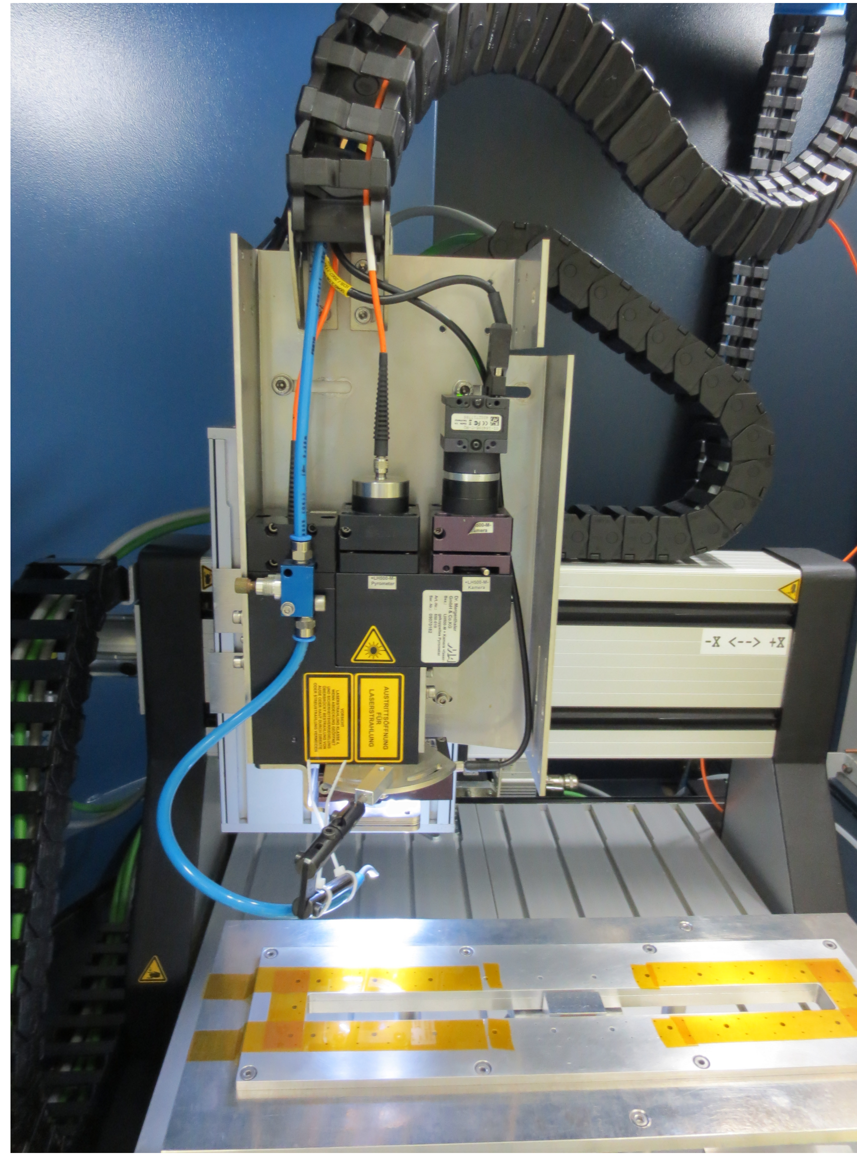







# Chip Assembly – laser soldering

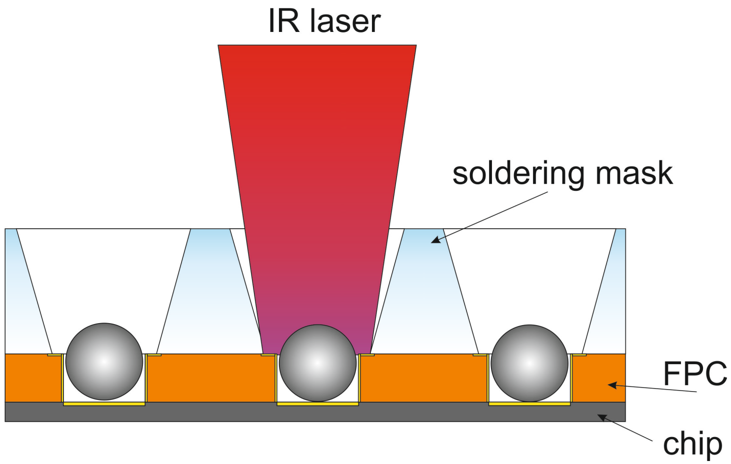
Laser soldering machine (Dr. Mergenthaler GMBH) put in service at the CERN ITS Lab (Sep 2013)

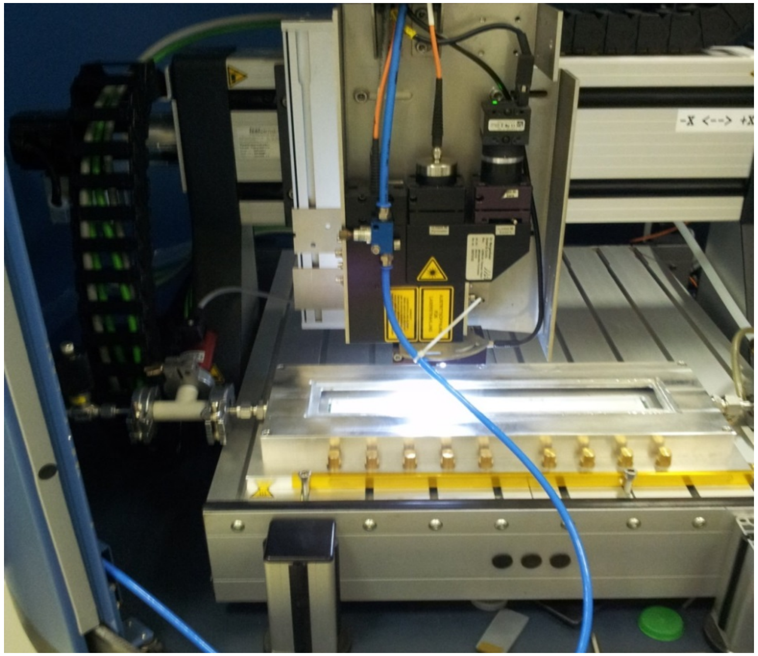


# Laser Soldering

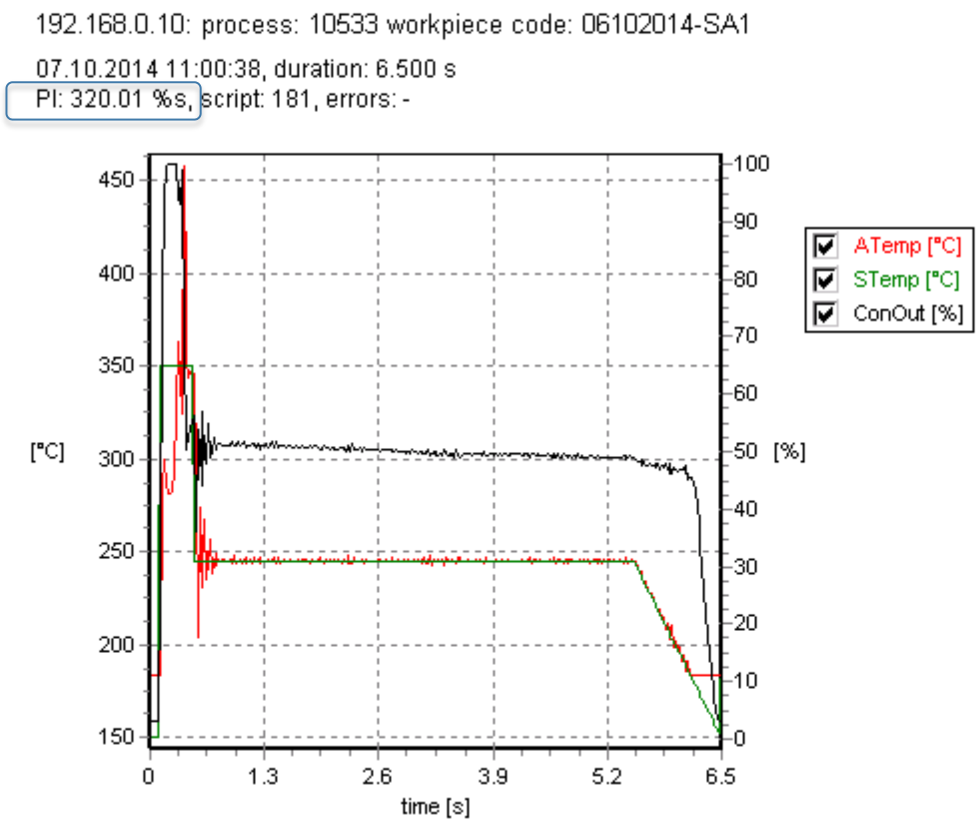
## Selective laser soldering

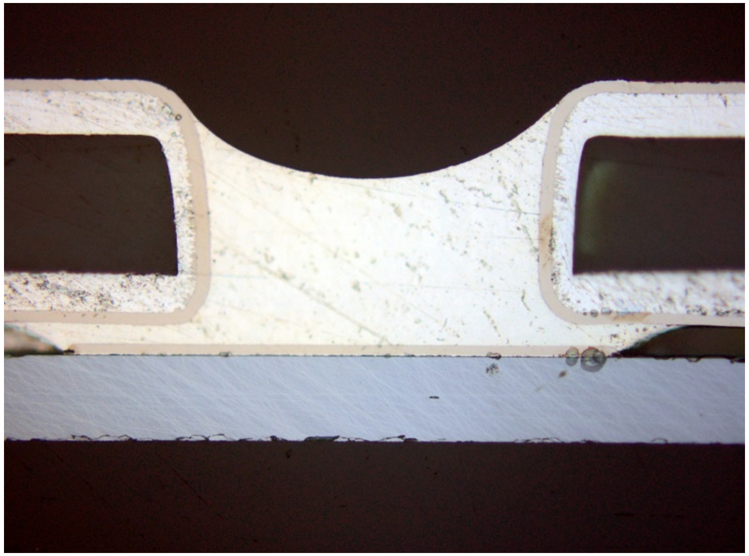
- Interconnection between FPC and chip by flux-less laser soldering of 200 μm diameter Sn/Ag(96.5/3.5) balls (227 °C melting T) in vacuum ( ≤$10^{-1}$ mbar)
- IR diode laser, 976 nm, 25 W, 50 mm focal length, 250 μm beam spot size
- Laser power modulated by pyrometer, programmable T profile ensures precise limitation of heating
- Soldering mask (in Macor® or Rubalit ®) used to push FPC on chip and guide soldering balls inside FPC vias

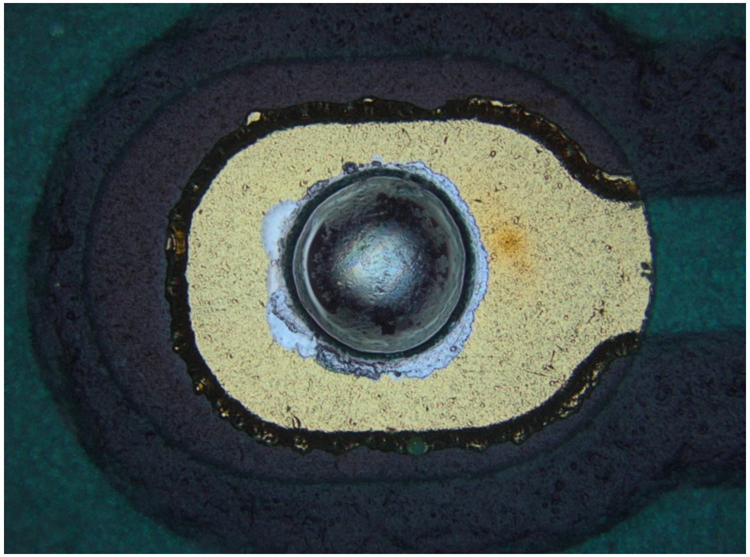


## Good soldering





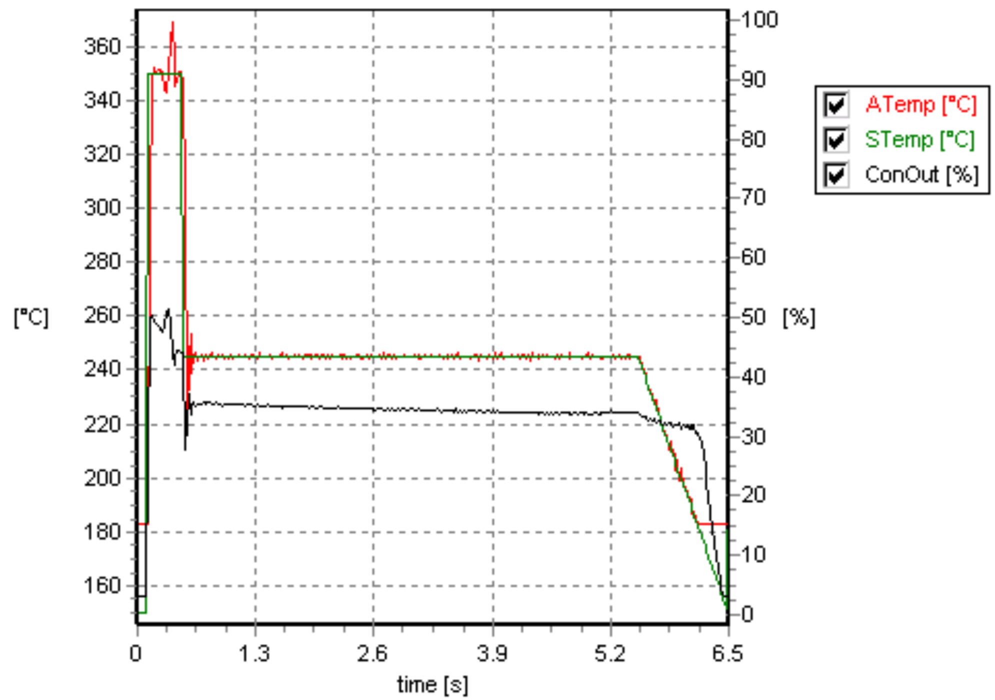
# Laser Soldering

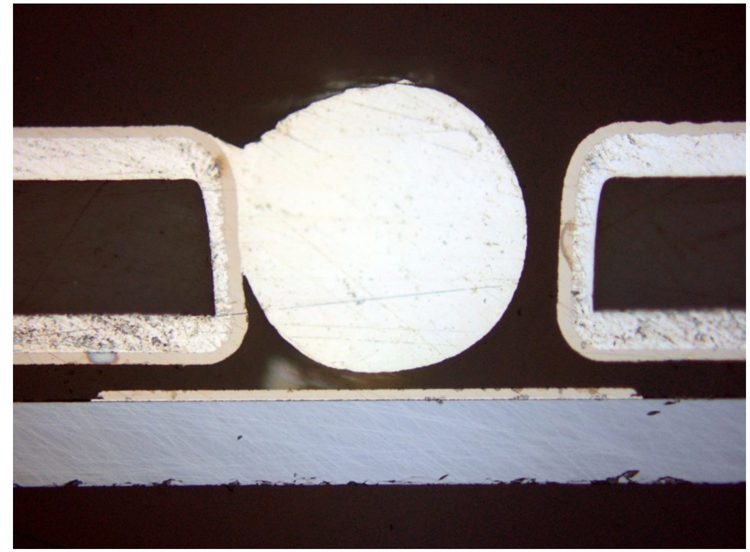
## Bad soldering

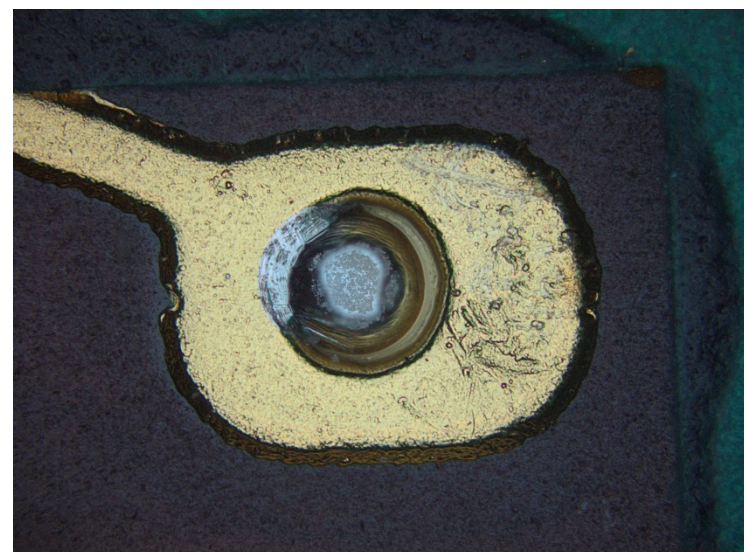
192.168.0.10: process: 10532 workpiece code: 06102014-SA1

07.10.2014 10:59:08, duration: 6.500 s

PI: 217.28 %s, script: 181, errors: -

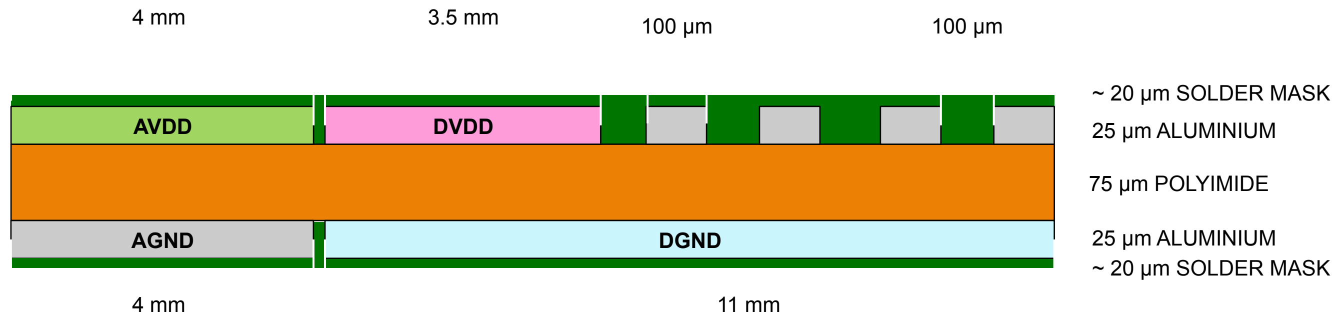


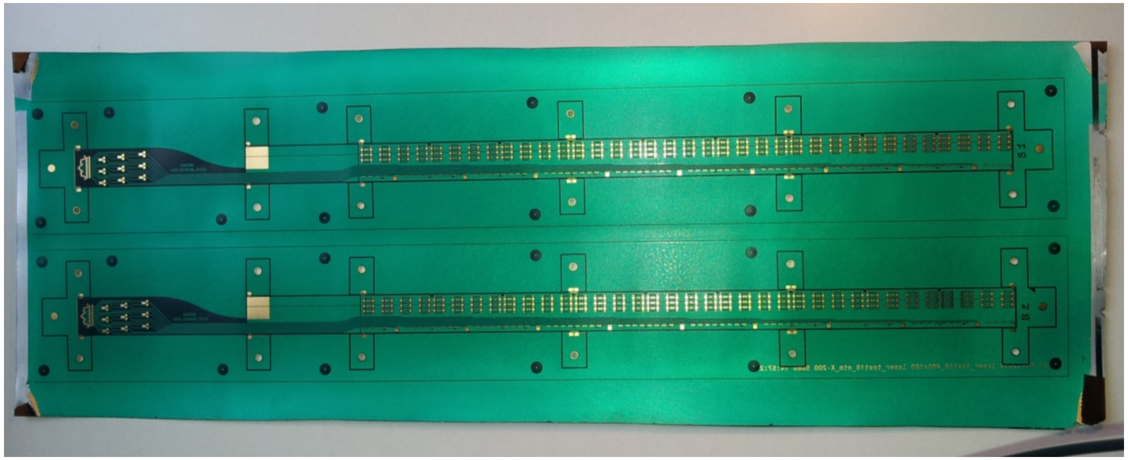


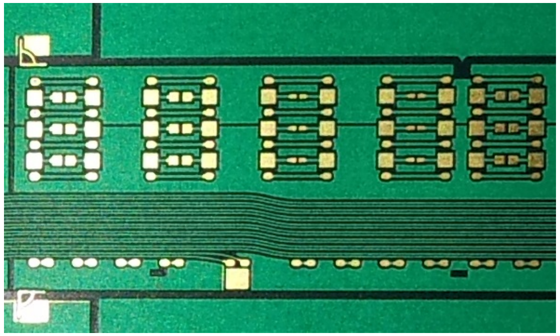
# FPC main characteristics

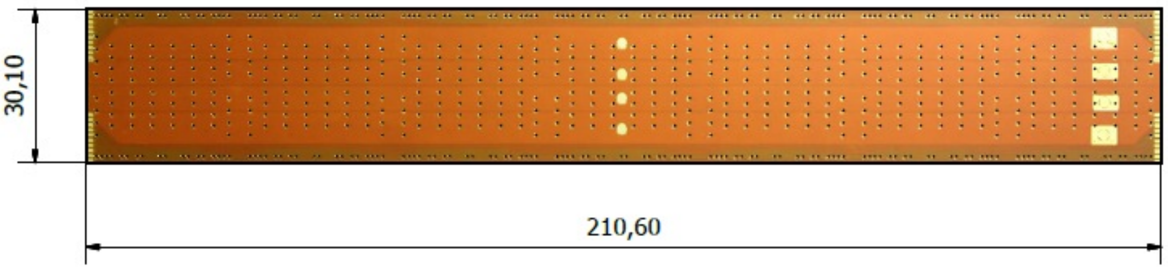
## Flexible Printed Circuit




- 2 layouts:
  - IB: 1x9 chips, Al
  - OB: 2x7 chips, Cu
- Metallised vias of 220 mm diameter
- Two openings of 1x1 and 1x0.4 mm$^2$, respectively, to “see” chip targets





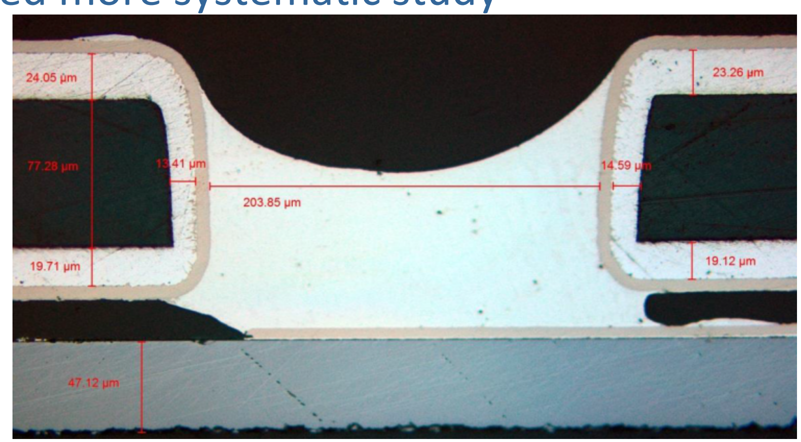


# Key aspects of HIC assembly

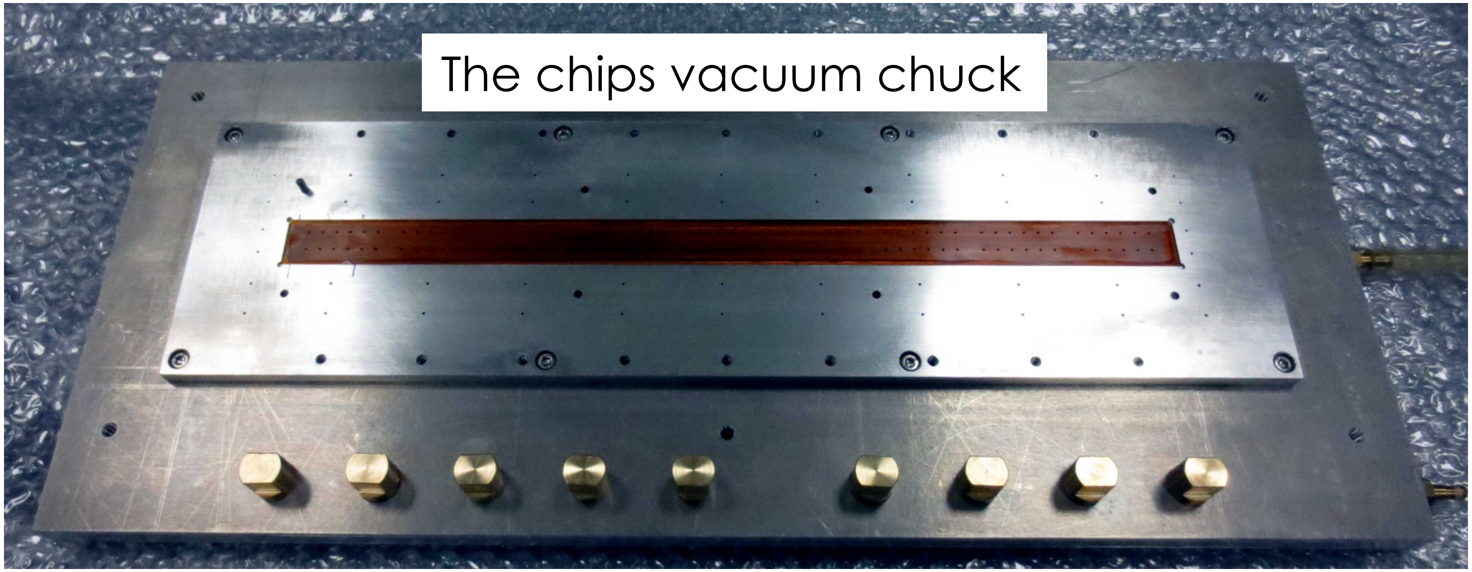


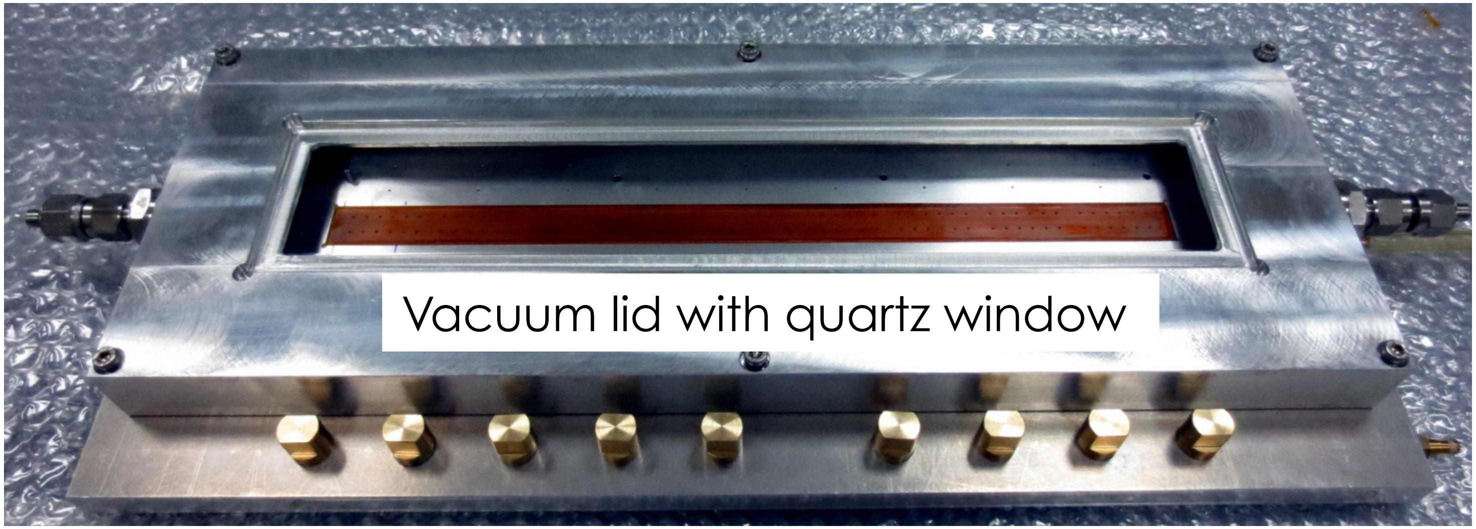
- The amount of HICs and the time available require a distributed production over many sites
- Usage of same procedure and system is necessary to ensure homogenous production
- To simplify/shorten the assembly procedure, chips are placed in nominal positions and FPC is overlapped using nominal pinholes
- Depending on FPC hole position accuracy, possibility of mismatch, i.e. hole is not fully contained in a pad

- A few soldering tests with misaligned (up to 20 mm) pads have been performed: not conclusive, need more systematic study

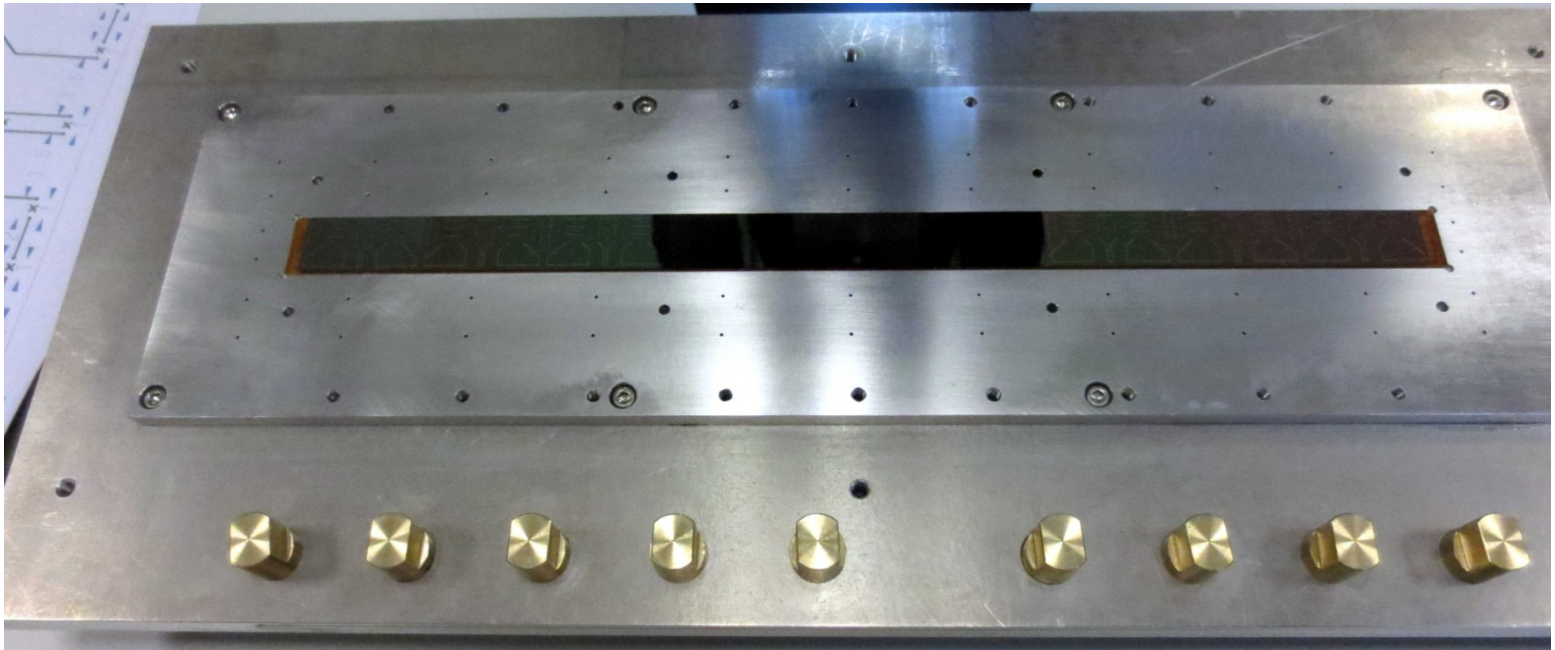


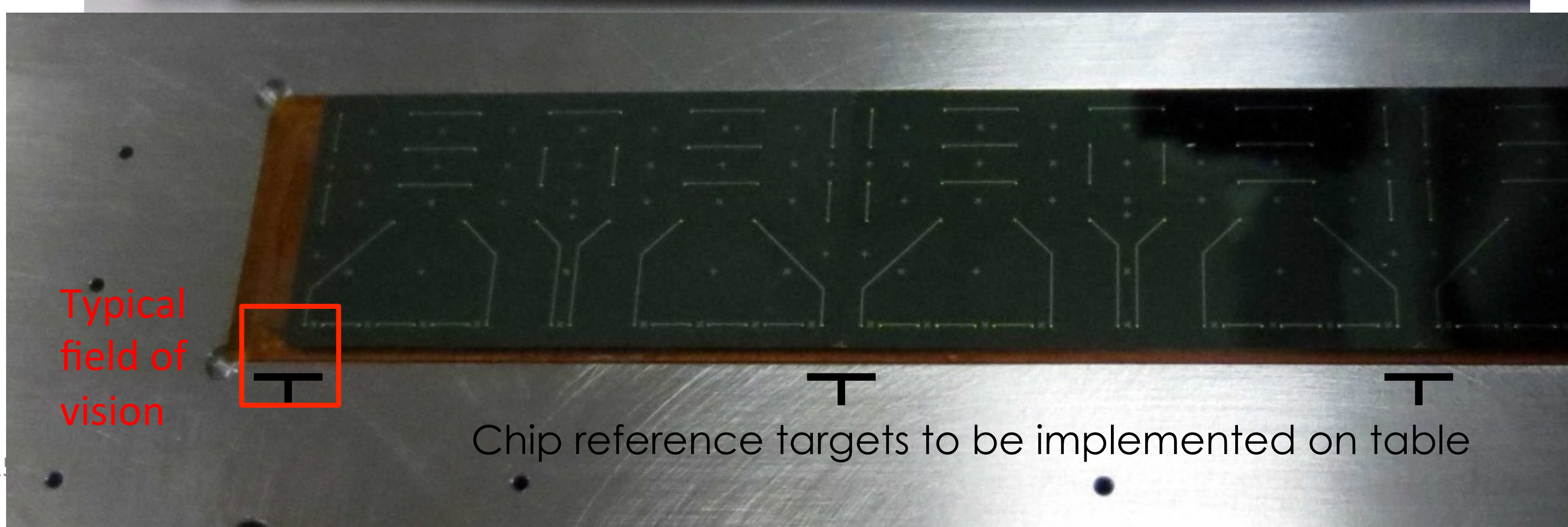
# HIC assembly - the IB work table



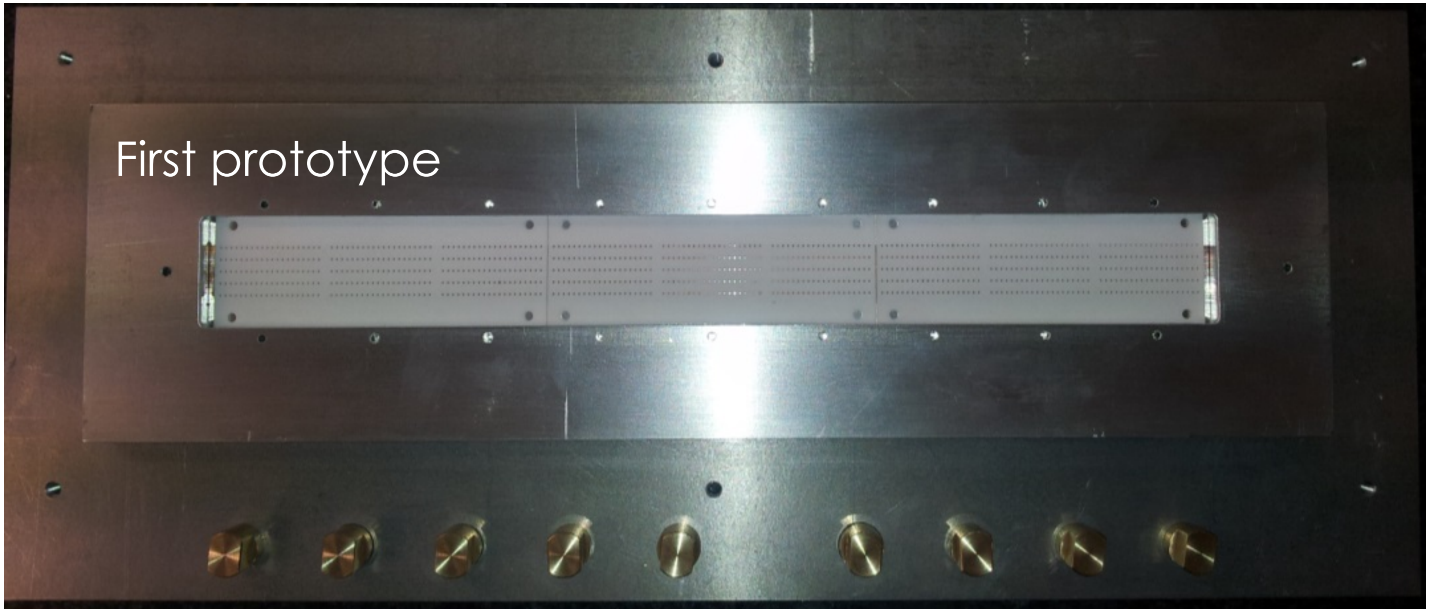



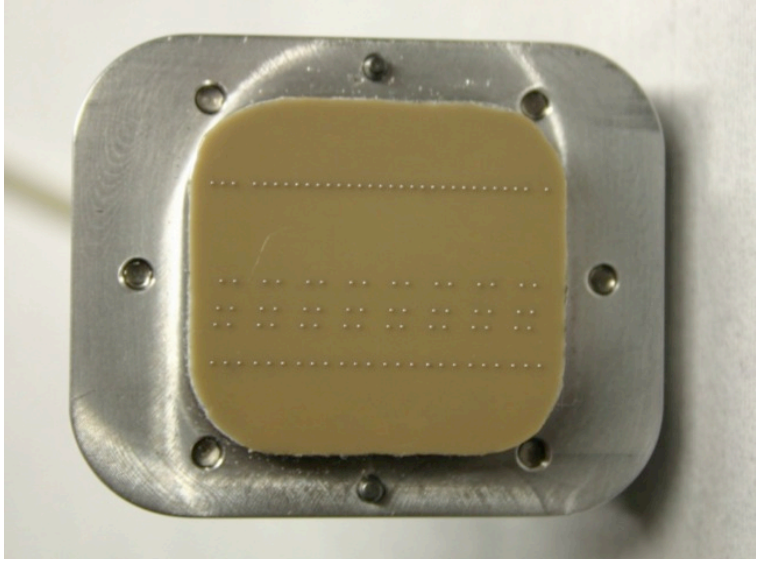
# HIC assembly - aligned pad chips



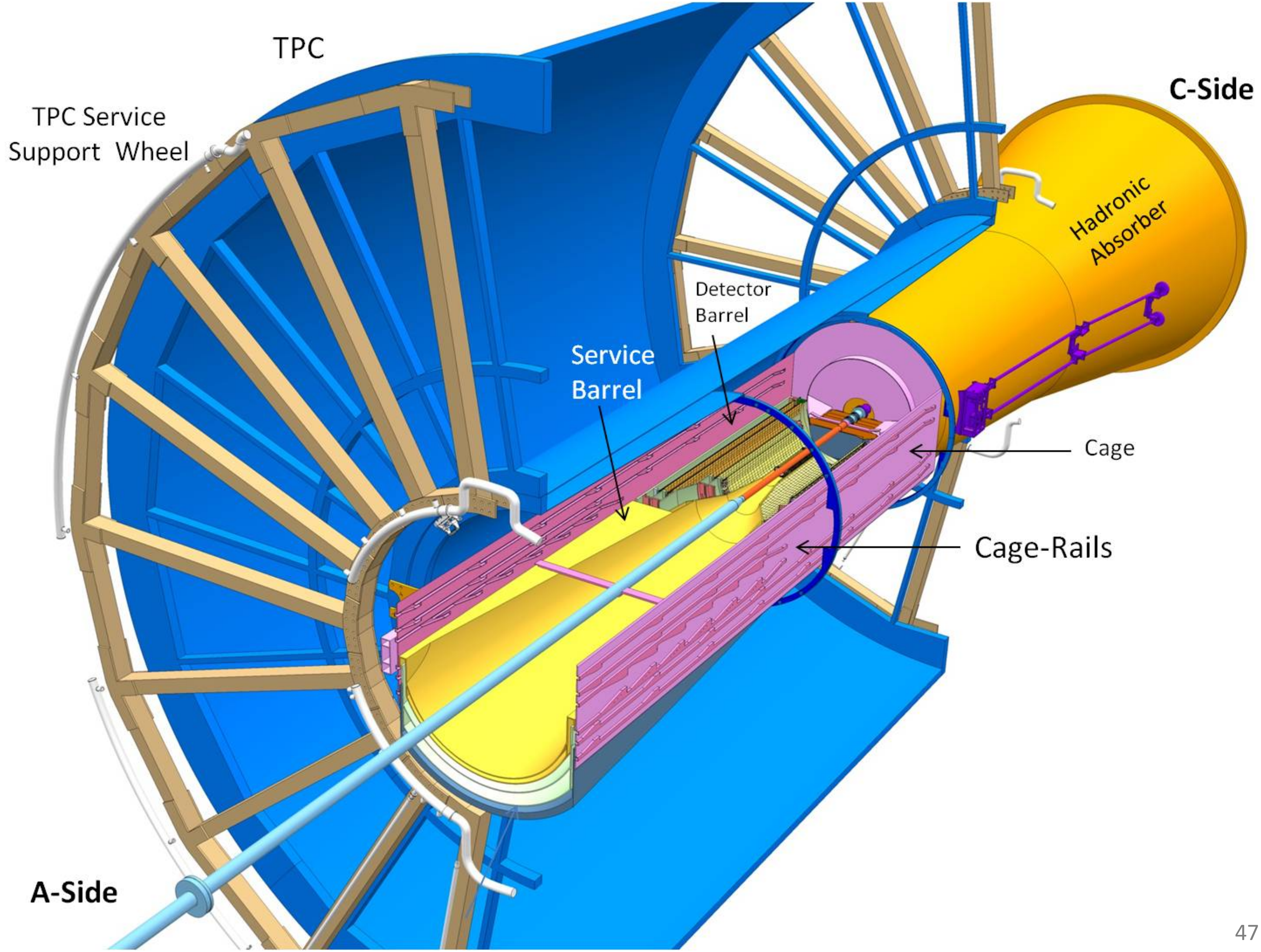


# The soldering mask and ball transfer tool



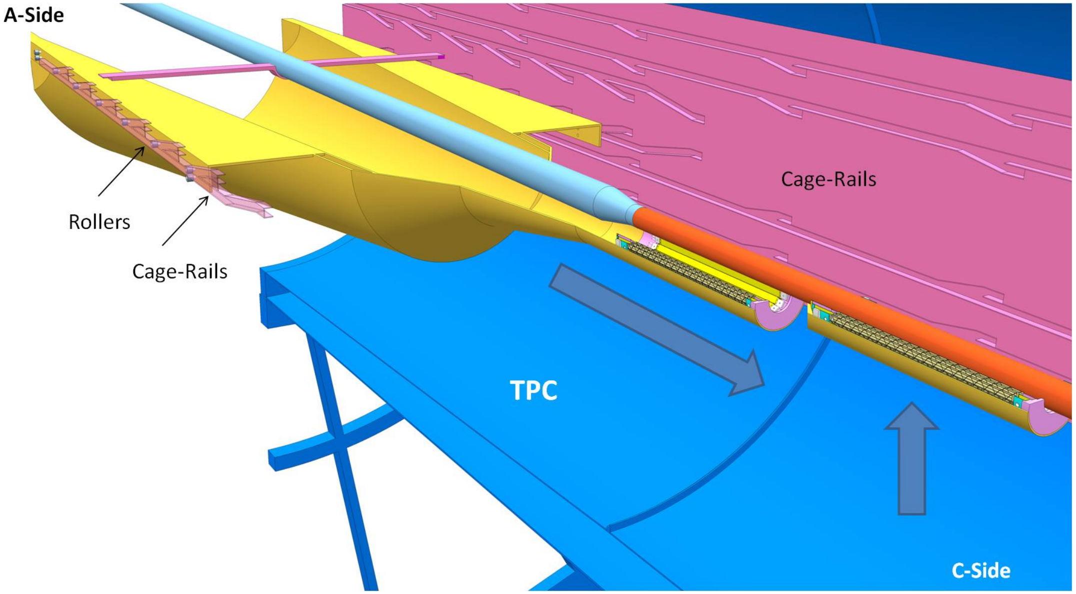



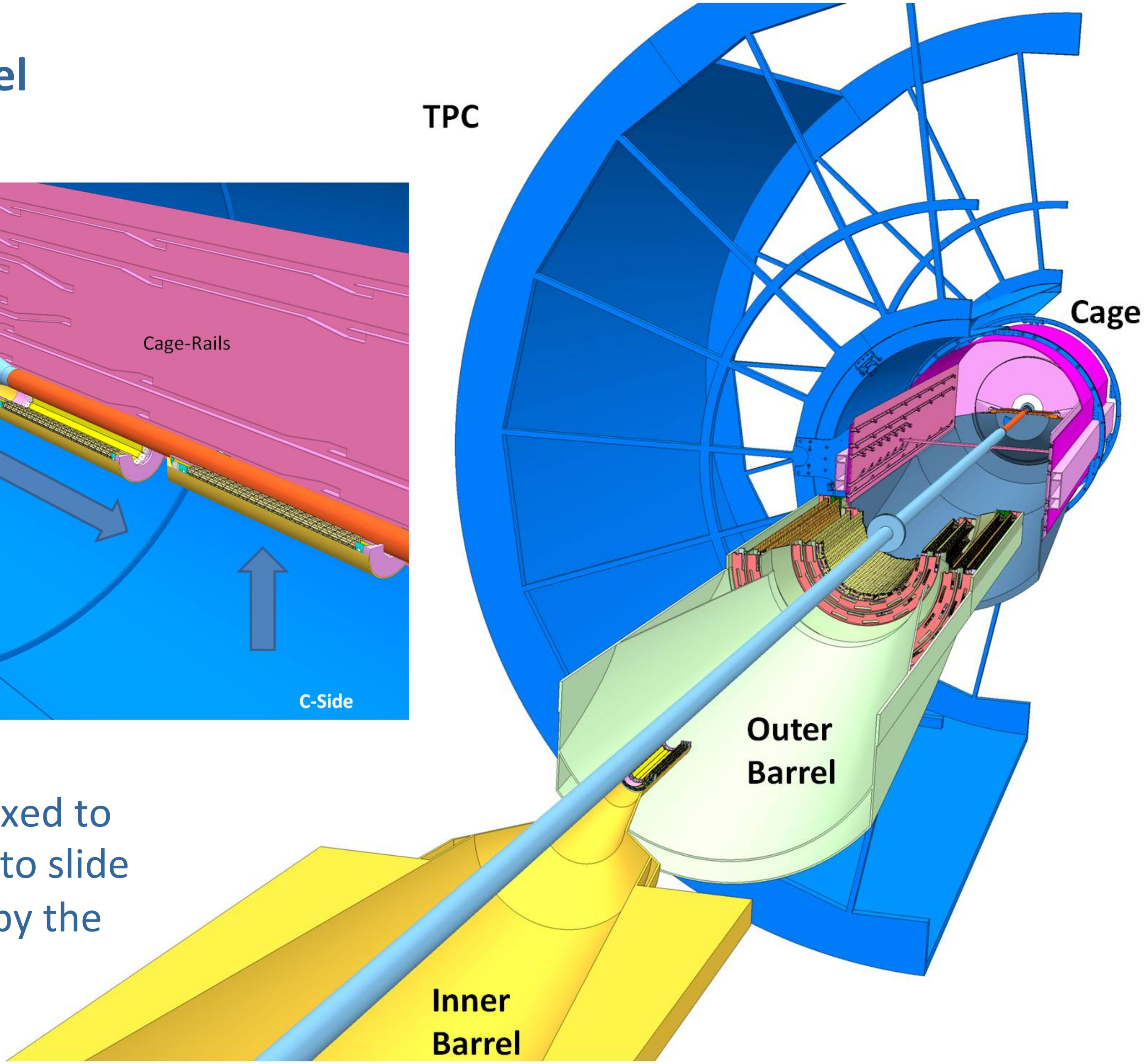
# Mechanical Integration



# Mechanical Integration

## Installation of IB half-barrel




half-barrel are utilizes rollers fixed to the Cylindrical Structural Shell to slide along a rail system supported by the cage

# Mechanical Integration