CMS Pixel Upgrade

W. Bertl
Paul Scherrer Institut
5232 Villigen-PSI, Switzerland

Pixel upgrade – why?

- The pixel detector was designed from the very beginning to be replaced during the lifetime of the LHC experiments (because of degradation of the sensors by hadronic irradiations)
- After 2017 LHC luminosities beyond the original design are likely – incapable by the present readout electronics
- Stay compatible with current system and installation procedure as much as possible

An outline of the pixel upgrade
(phase I)

1) Pixel tracking ➡ • From 3 hits/track to 4

2) Material budget ➡ • Keep it small (smaller!)

3) Performance ➡ • impact par., vertex, b-tag

4) LHC Luminosity ➡ • Ready to $2x10^{34}$ $cm^{-2}s^{-1}$

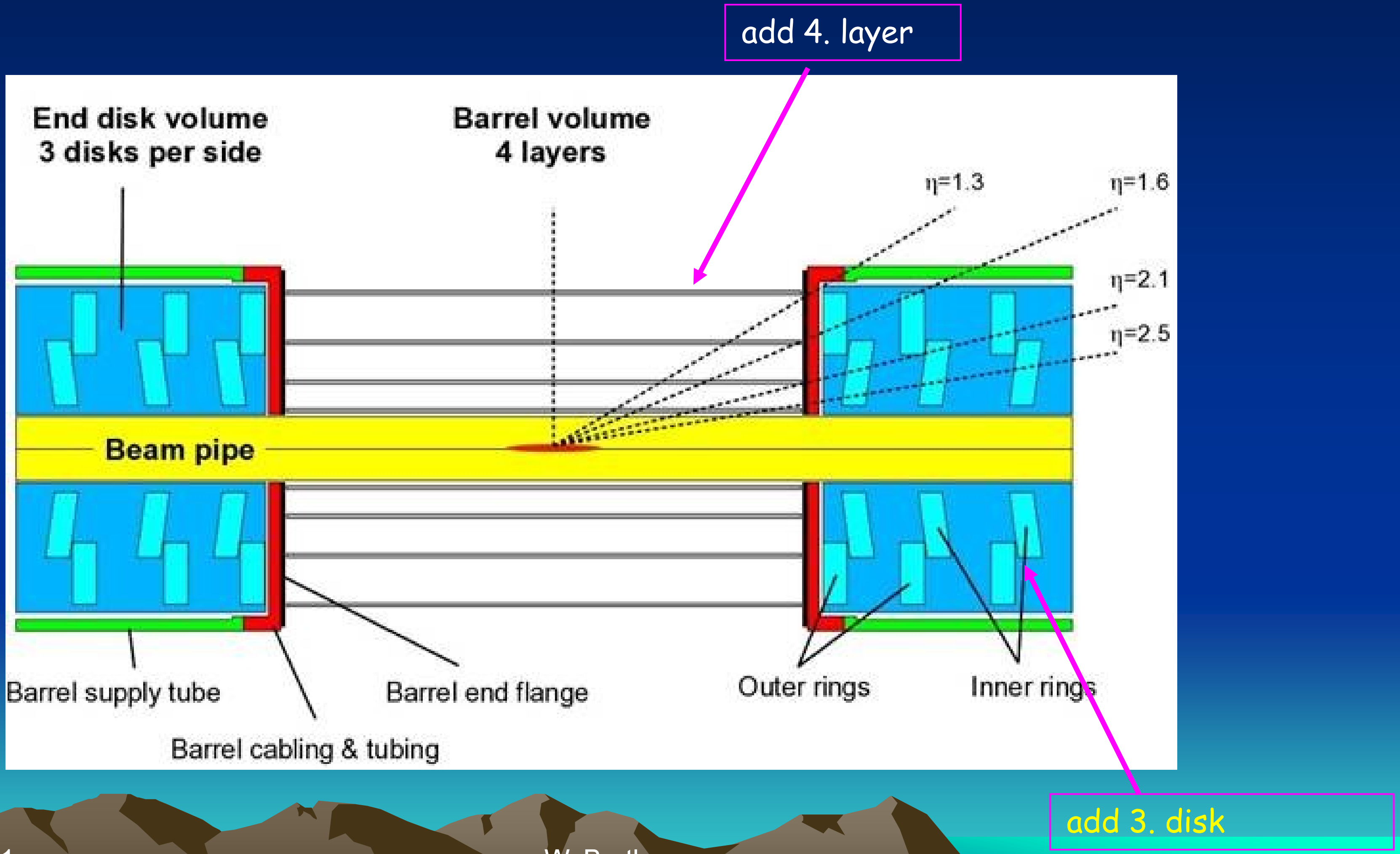
5) Total Power demands ➡ • Keep within pres. limits

6) Scheduling ➡ • use of LHC shutdowns

Constraints for the pixel upgrade

- CMS must be physics-ready after each shutdown used for upgrade work
- minimize risk of damage, radiation exposure and accidents
- minimize start-up time and risk of compromised detector performance
- ➡ consequently replacement impossible for power cables, readout fibers, pipes (from balcony to PP1)

Pixel tracking: from 3 to 4 hits



Benefits of 4 pixel track points

- Efficiency & resolution improvement for pixel-only tracks which are
  - important for High Level Triggering
  - seeds for full tracking → resulting in
    - higher full track efficiency
    - lower fake track rate
  - important for primary & secondary vertexing
    (pile-up) (b-tagging)

Material budget smaller !(?)

- Upgrade from 3 to 4 track points ➡
  ➡ means 50-60% more modules!
- Expected mass ratio $R_m \equiv m_{2017}/m_{2008}$:
  - BPIX: $R_m \sim 0.57$ ($\eta < 1.24$) (~0.8 in %RL)
    0.43* ($\eta < 2.15$)
  - FPIX: $R_m \sim 0.8$ ($\eta < 2.5$) (~0.5 in %RL)

How is this possible ?

➢ cooling by 2-phase CO_2 instead C_6F_{14}
➢ advanced mechanics + modified design

* barrel part only

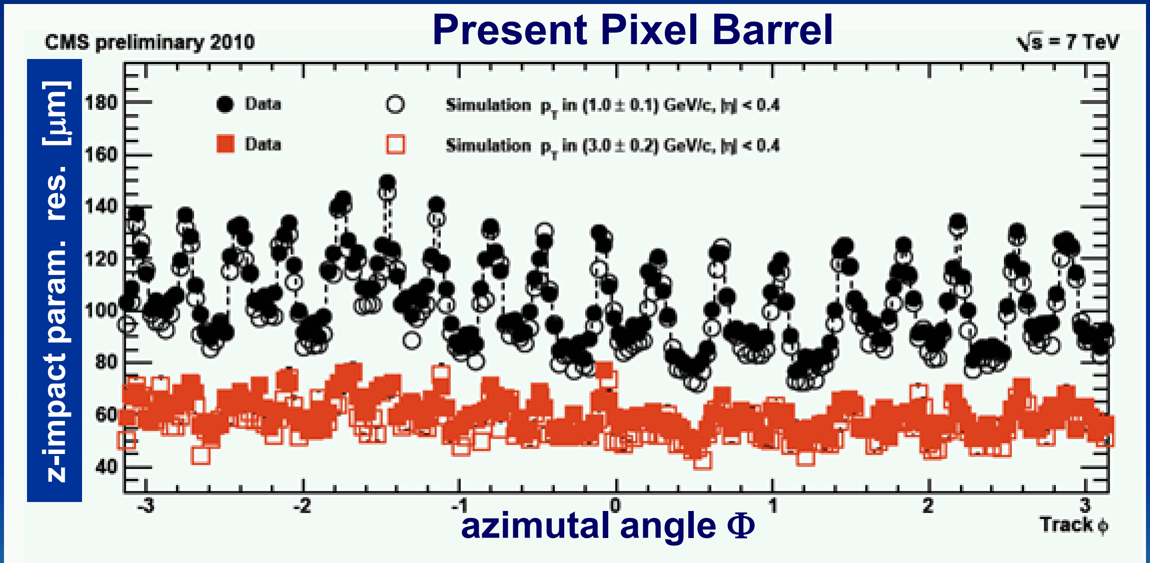
Mat. budget: "cool & mech"

- CO_2 cooling (total mass barrel layers):
  - 3 layers (2008): 3655g (1197g for cooling)
  - 4 layers (2017): 3029g (577g for cooling)
  - 4 layers (C_6F_{14}): 4473g (2021g for cooling)
- other layer mat.:

	2008(3L)	2017(4L)
– mechanics (w/o pipes)	186g	224g
– modules	870g	828g
– cables	159g	141g

Cooling aspects

Present cooling using C_6F_{14} contributes a major fraction to the mat. budget.



Two-phase CO2 cooling requires only small diameter tubing, despite high pressure operation (up to 70bar).

➡

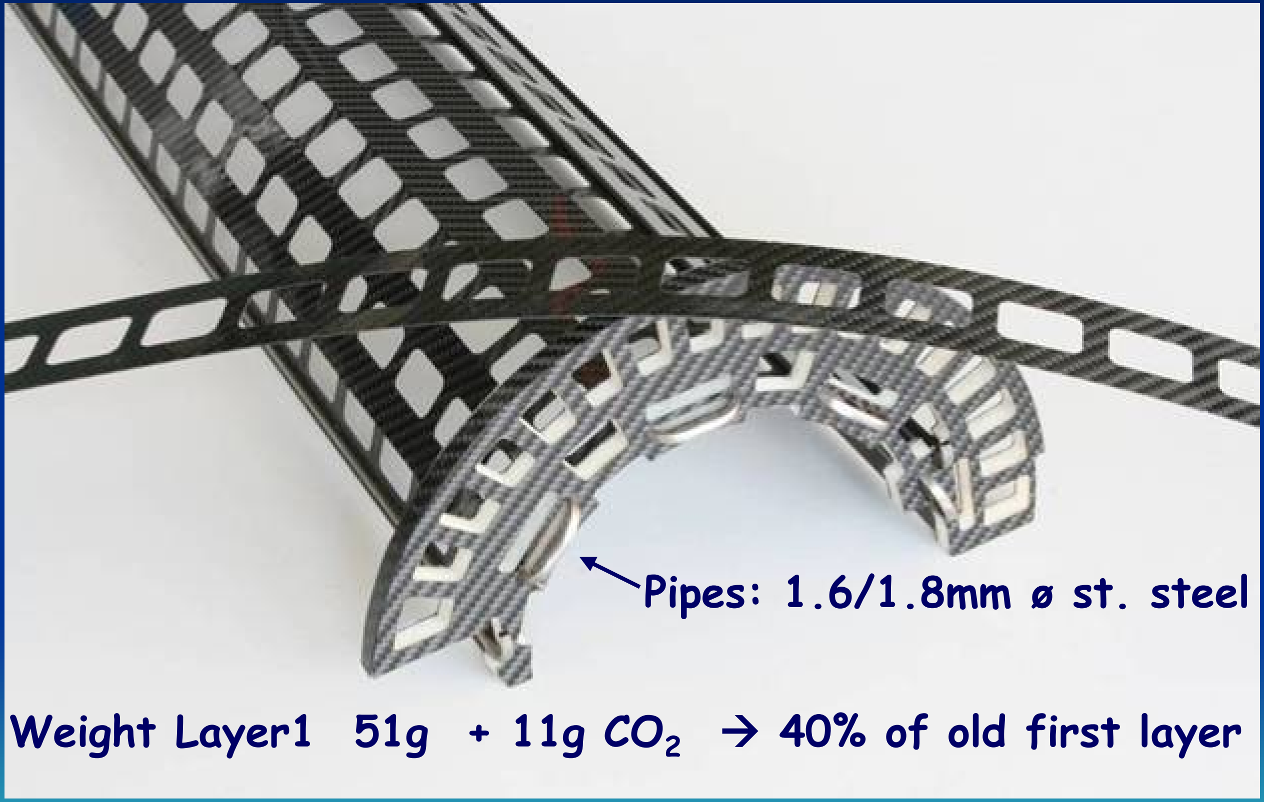
Therefore changing the C_6F_{14} cooling system into a CO_2 system is rewarded by the largest fraction of material savings.

CO_2 cooling: pros and challenges

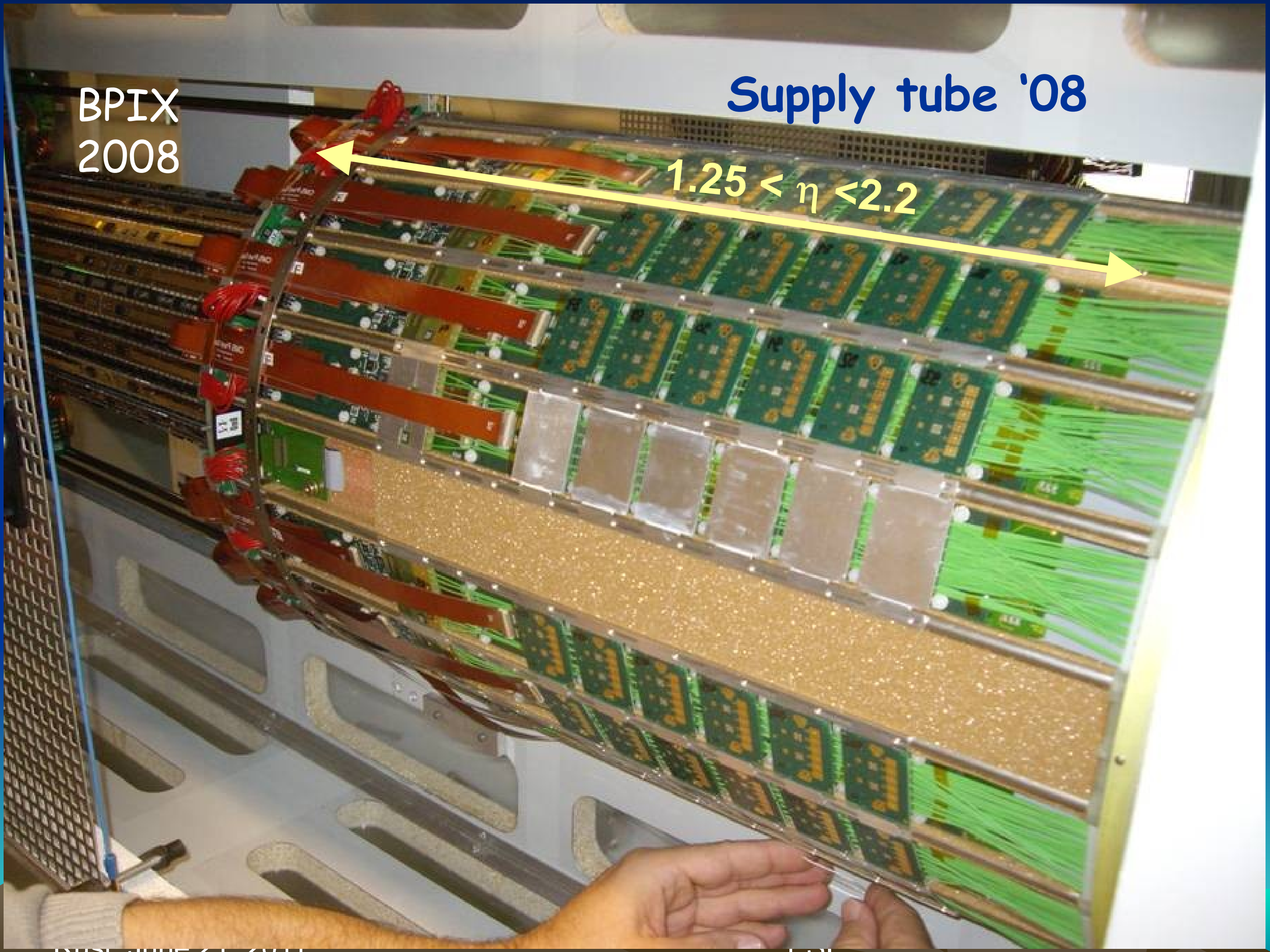
- Excellent thermodynamic properties:
  - small viscosity
  - high heat transfer
  - high latent heat
  - low liquid/vapor density ratio
  - ➡
  - small pipes (1.6/1.8mmø) possible
- low mass (~half of C_6F_{14})
- radiation hard
- cheap

- Challenges:
- Two-phase flow: predictions inaccurate; requires close co-operation between experimentalists and system designer.
- cooling plant design (~10kW @ -20°)
- primary cooling system
- pipe from plant → PP1 (pressure!)
- channels from PP1 → PP0 (space!)
- control & monitoring
- validation of system operation
- warm start-up
- safety issues

Prototype mechanics 1st layer



Mat. budget: “shift & save”



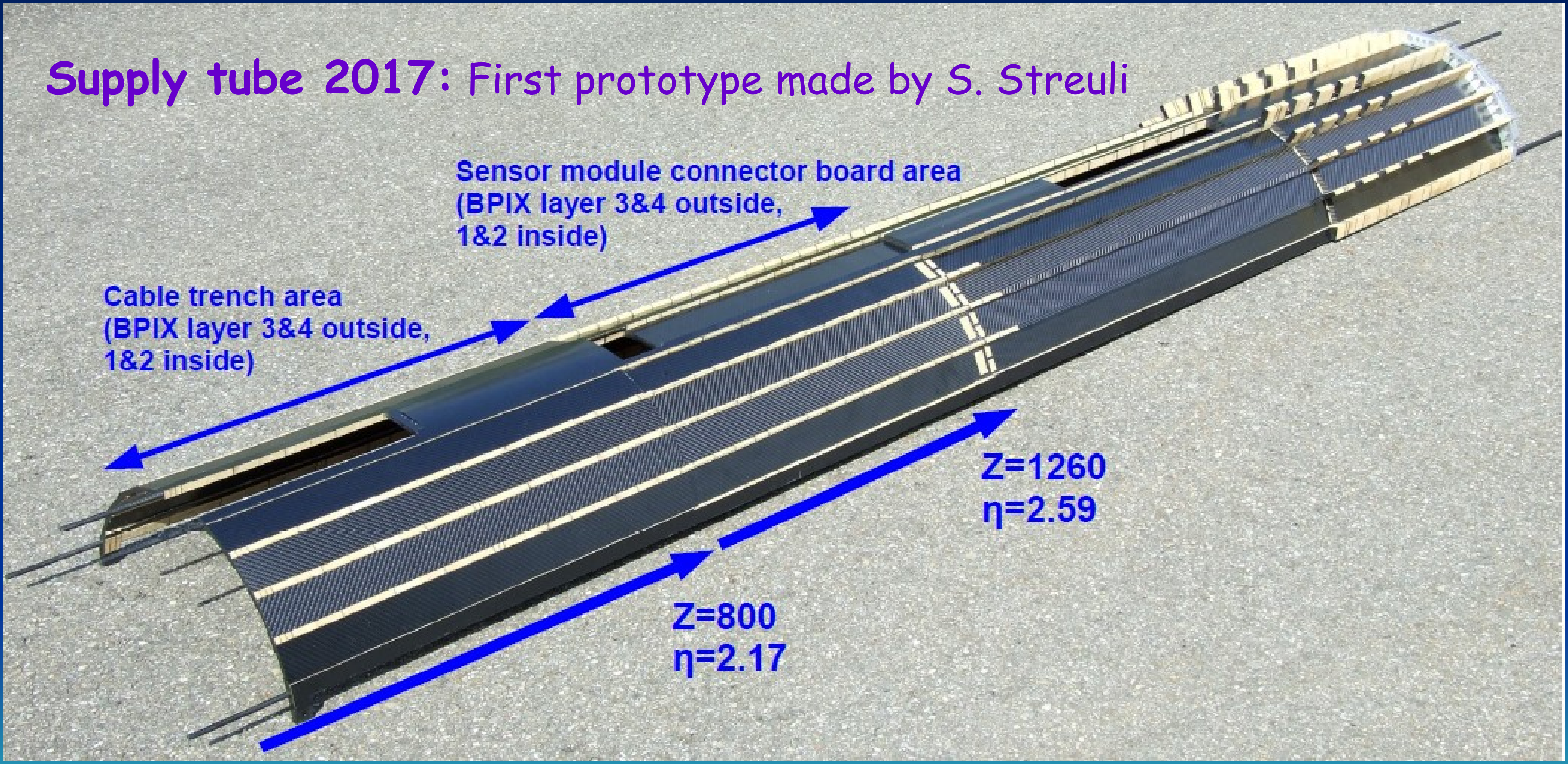
Innermost section of supply tube contains :

AOHs, DOHs, PCBs, cables, connectors, fibers

Total mass:

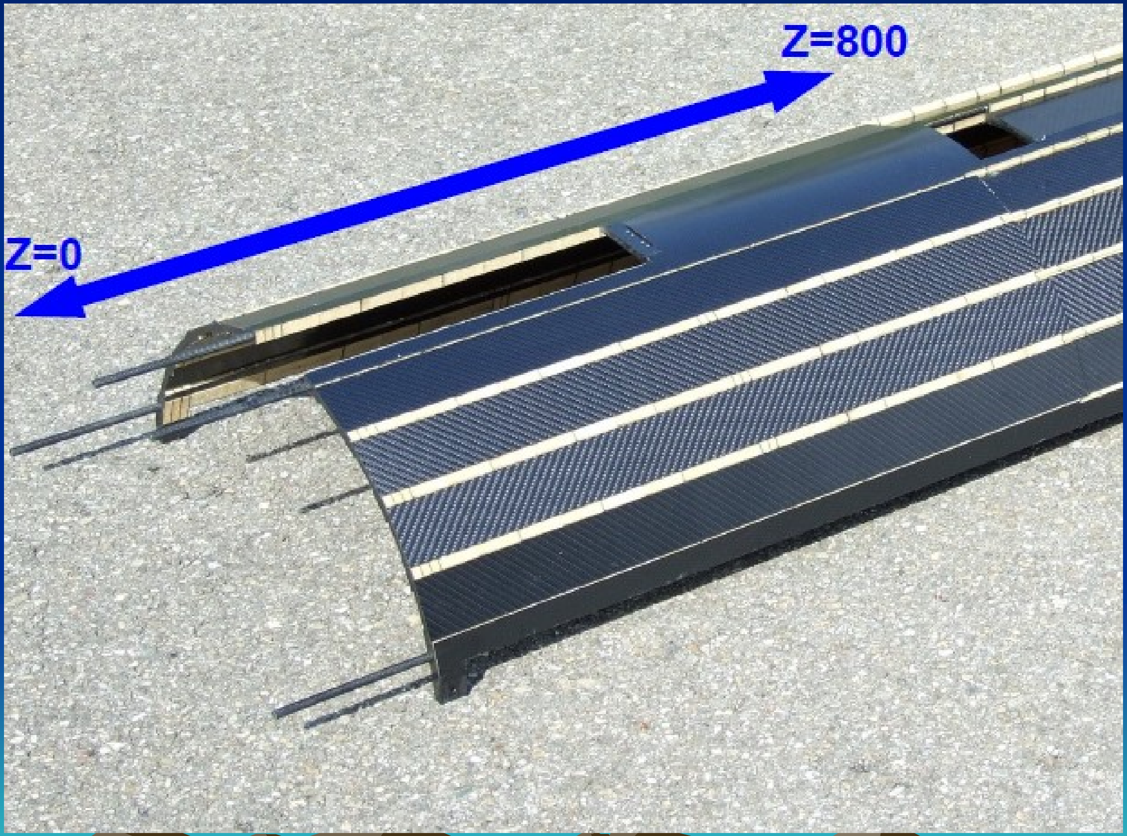
4 x 2289g

Mat. budget: “shift & save”



Mat. budget: "shift & save"

Supply tube 2017: Innermost section contains:



Material	Weight
Airex C70/55	83gr.
Carbon fiber ribs	11gr.
Carbon fiber tubes	27gr.
Carbon fiber wheel support	7gr.
Carbon fiber facets	180gr.
Epoxy glue	100gr.
Total weight	408gr.

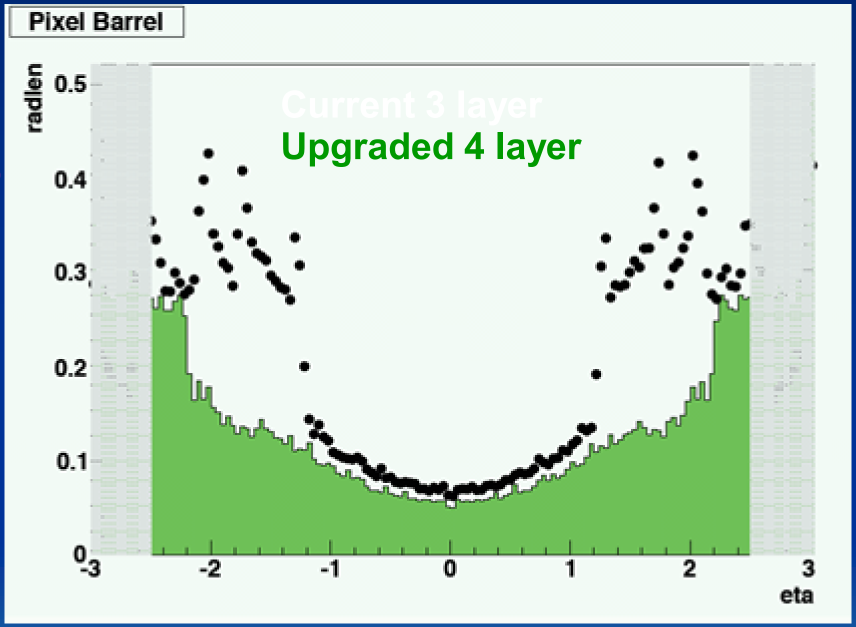
add:

CO2-pipes		38g
cables		280g
Total:	4 x	726g

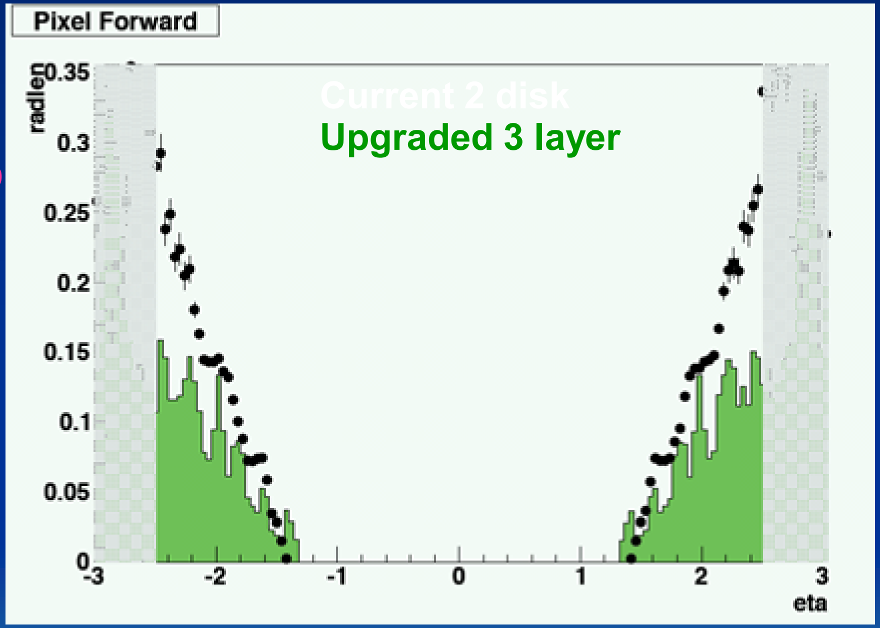
Material gain factor: 3.15 !!!

Expected effect on mat. budget

Radiation length



Radiation length



Remark: the shown budget for the upgrade is probably somewhat pessimistic !

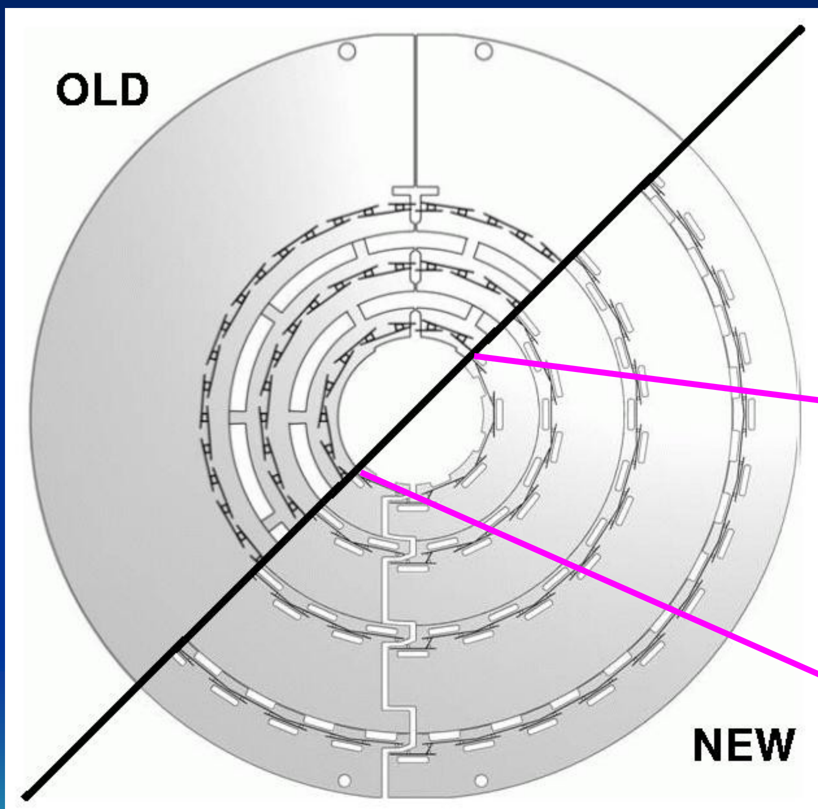
BPIX layout

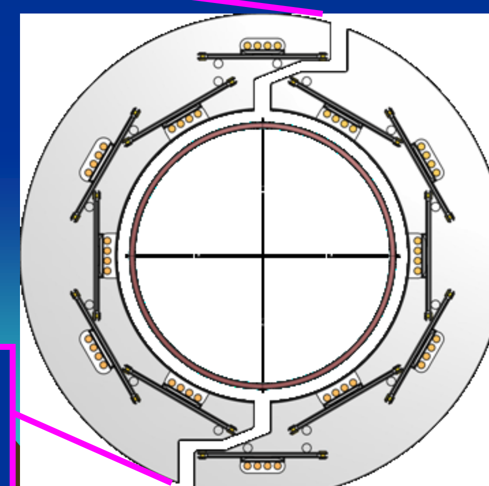
New layout: Full module type only !

Layer	radius	# faces	# modules	# ROCs
1*	39mm	16	128	2048
2	68mm	28	224	3584
3	109mm	44	352	5632
4	160mm	64	512	8192
		Total:	1216	19456

* Clearance to beam pipe 4mm

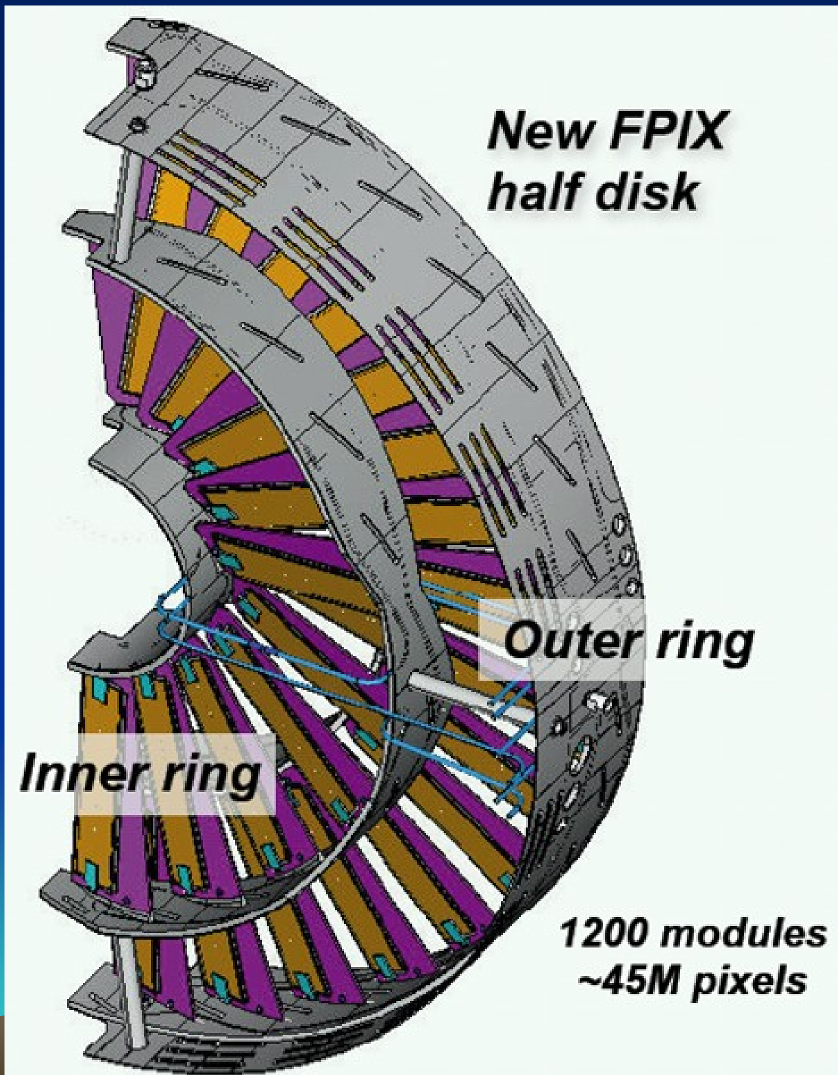
~81M pixel (~1.7x old BPIX)

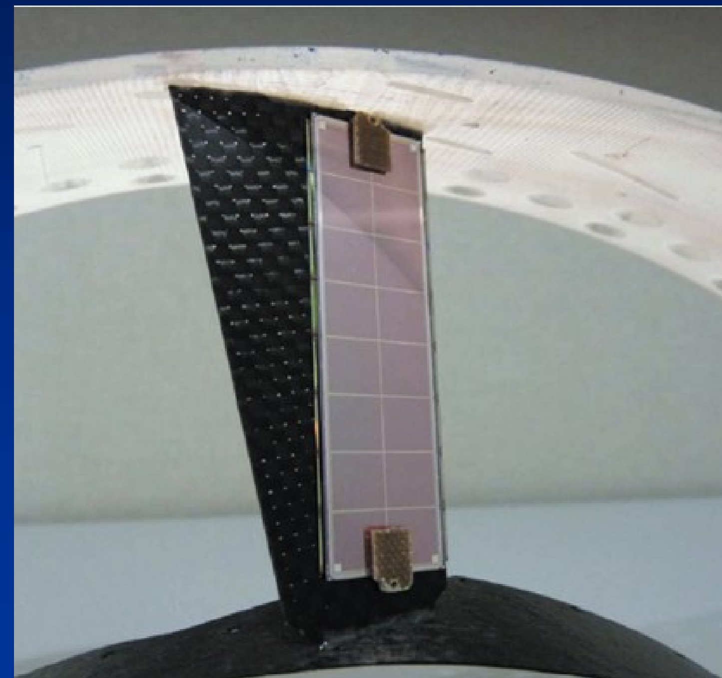




If beam pipe r < 22.5 mm → 1st Layer: 12 faces
<R>=29.5mm (32 modules and 512 ROCs less → 1184 / 18944)
beam pipe clearance 2.25 mm (~79M pixel)

FPIX disk design





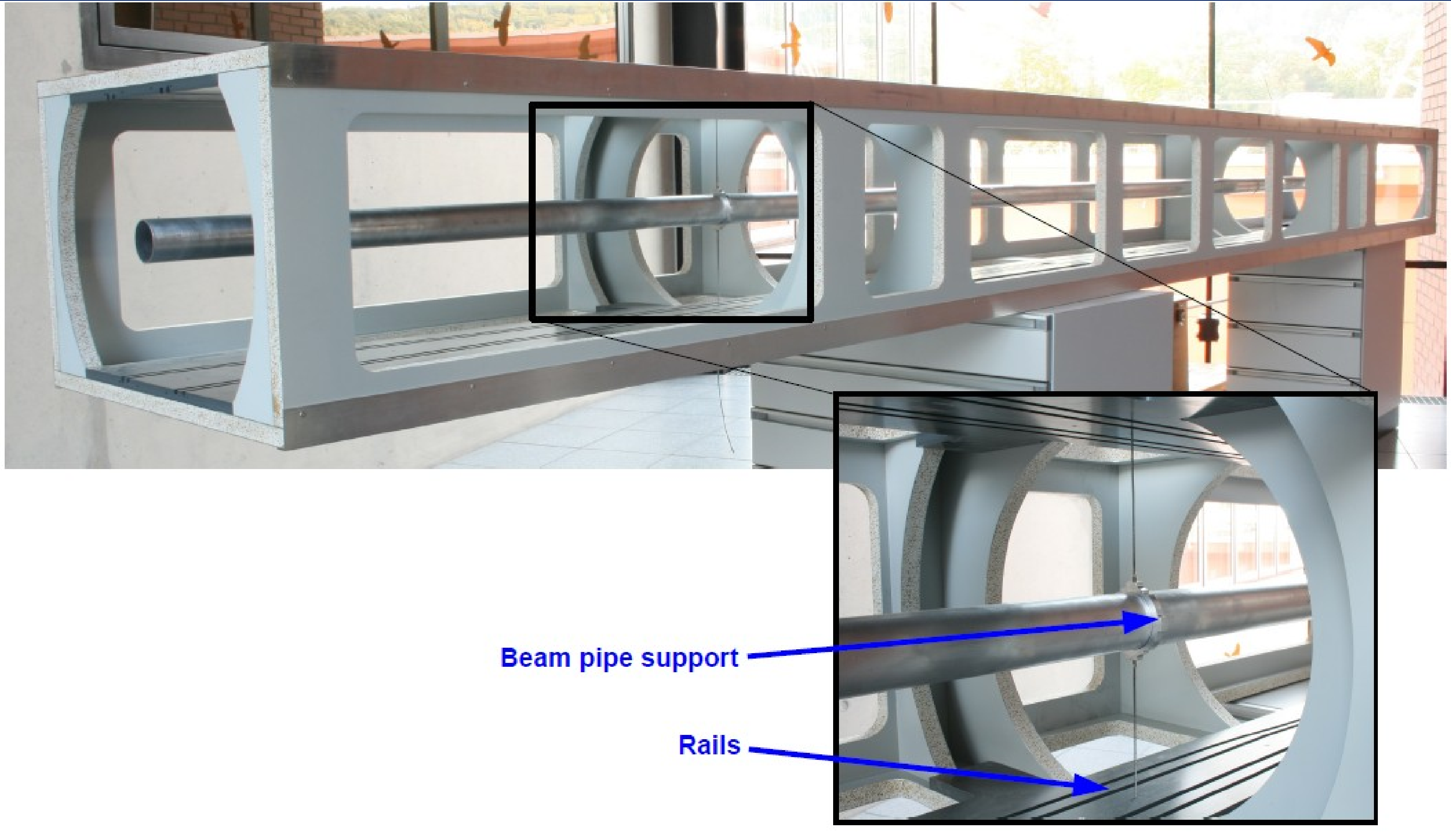
- **inner & outer ring for easier replacement**
- **6 disk of 112 sensors each → 672 modules**
- **one module size with 2x8 ROC / module**

→ 10'752 ROC's **~ 44M pixel** (2.5 x old FPIX)

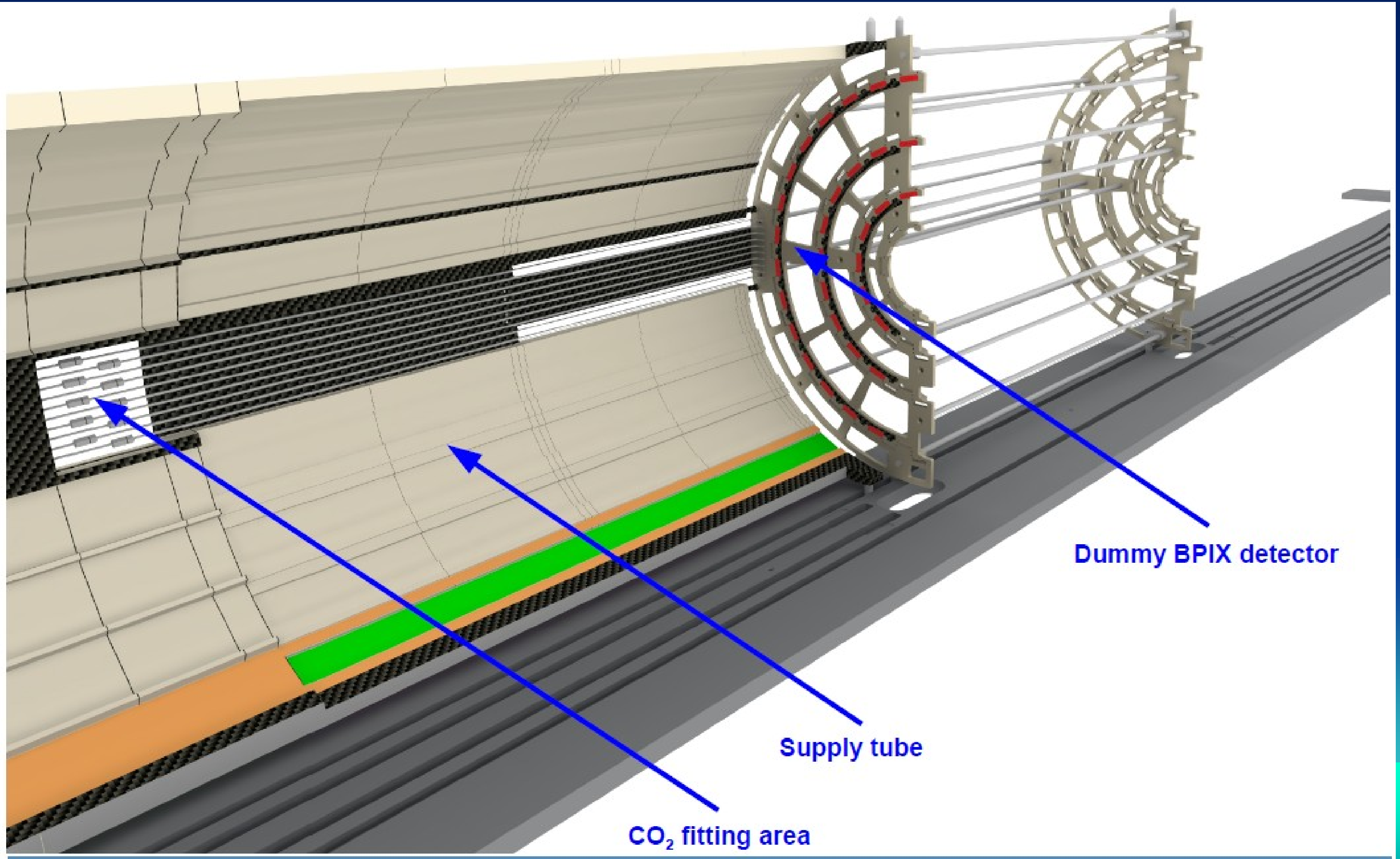
Impact parameter

- Improvements by:
  - more hits / lower mass (see above)
  - smaller 1st layer radius (beam pipe radius?)
  - closer approach to beam pipe (difficult and a potential threat to CMS / LHC)
    - ➡
    - direct "blind" insertion into CMS to risky
    - final adjustment system needed
    - test on mock-up

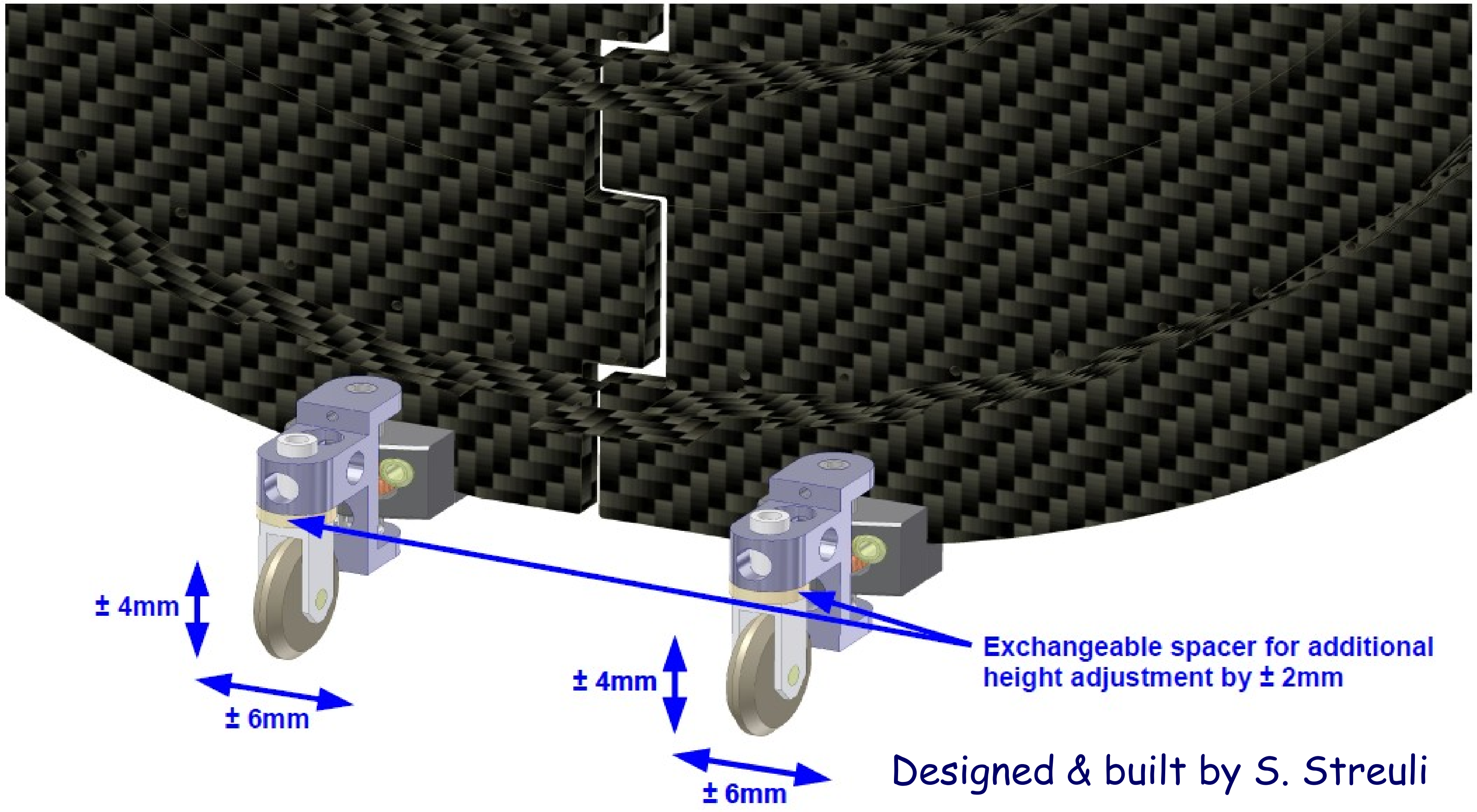
Installation mock-up



BPIX dummy + Supp. Tube

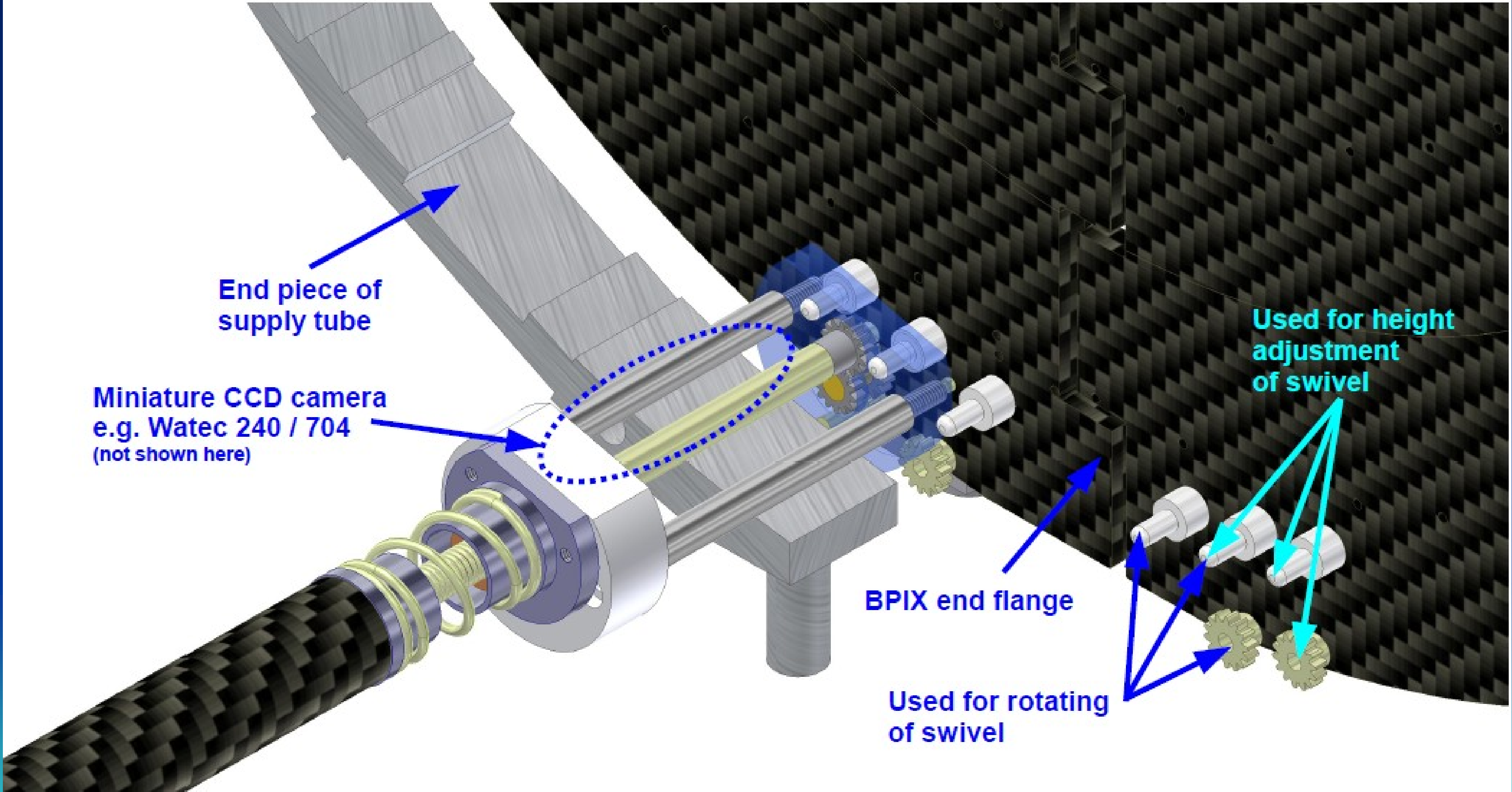


Adjustable wheel set for BPIX



Designed & built by S. Streuli

Precise BPIX shell adjustment



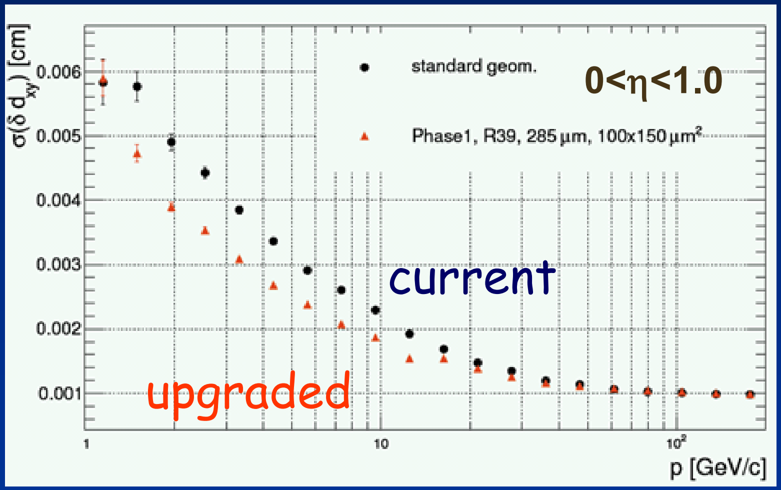
- Only one kind of remote tool V#2 necessary to adjust all wheel sets in pivoting, lifting/lowering on BPIX.

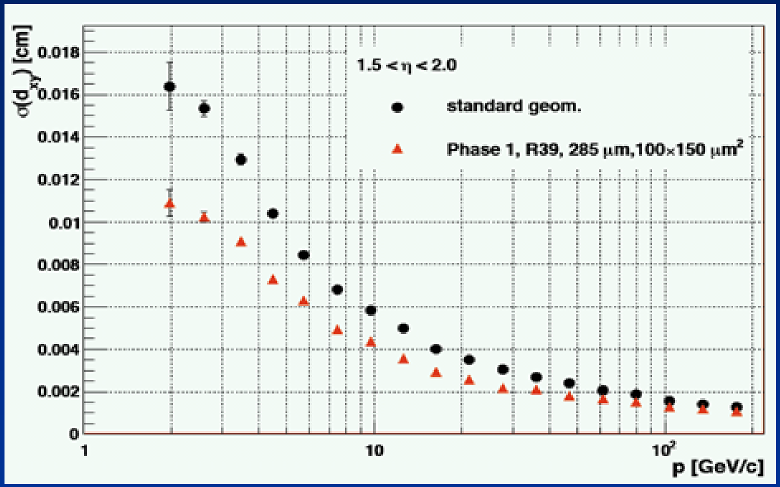
Improved Impact parameter

Barrel region

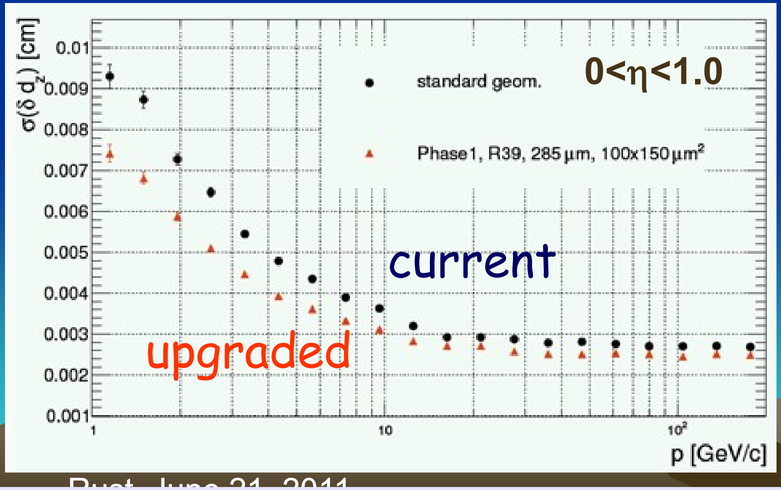
Forward region

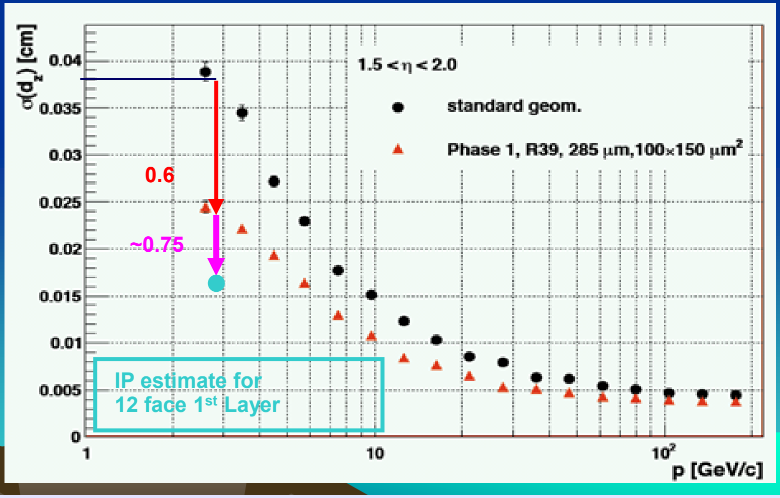
transverse IP





longitudinal IP

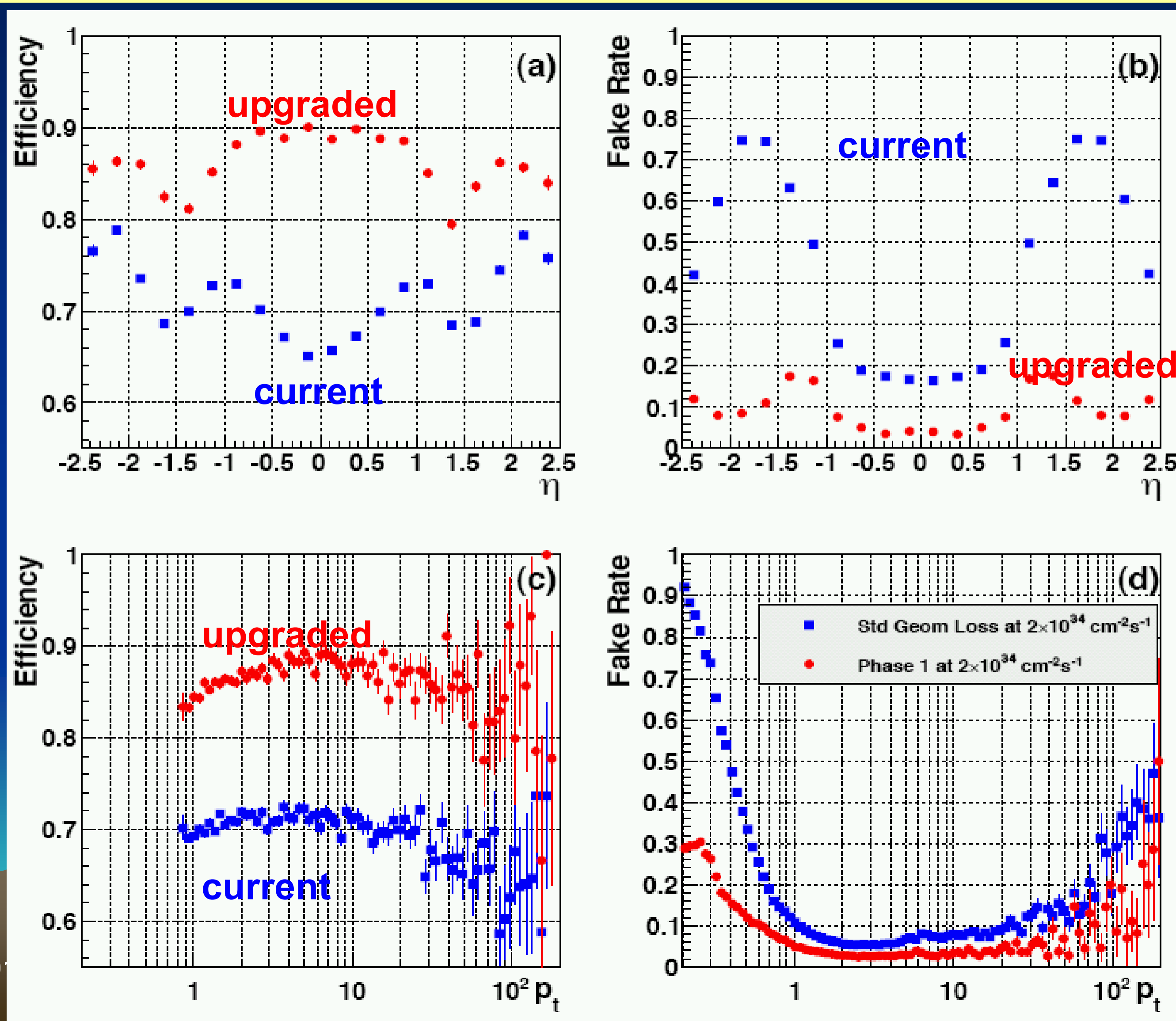




Beam pipe r<23mm : 16 faces to 12 faces → reduce MS term by ~0.75 → total 0.75x0.6 = 0.45 !

Pixel Track seeding

Prediction for 2×10^{34} $cm^{-2}s^{-1}$ luminosity

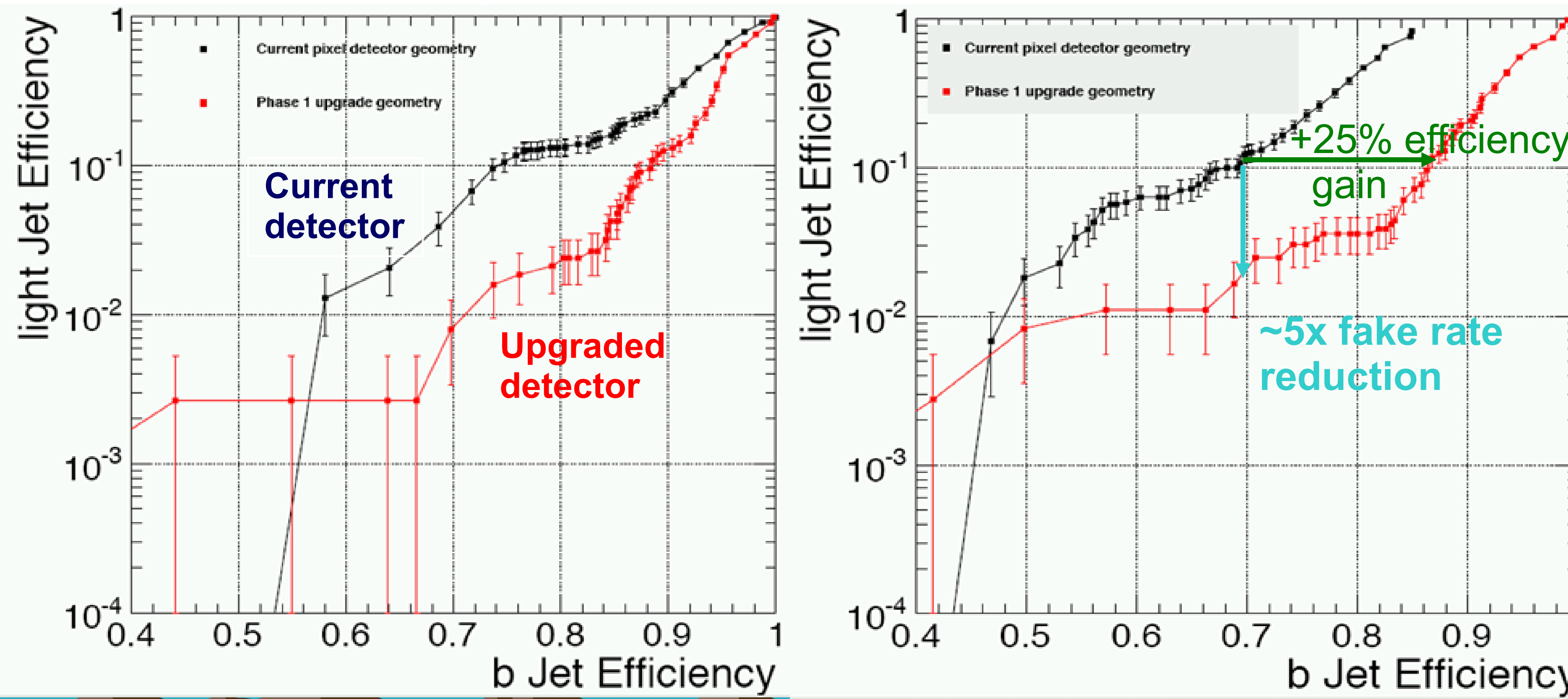


Reduced data loss and quadruplet seeding improves efficiency and reduces fake rate !

b-tagging

ttbar 80 < p_t < 120 GeV Combined Secondary Vertex Tagger

No pile up — Lumiosity = 1E34 $cm^{-2}s^{-1}$



ROC ready for the upgrade?

Present ROC :

Luminosity	bx-spacing	Data loss
$cm^{-2}s^{-1}$	ns	(@ 1st layer)
1×10^{34}	25	4%
	50	16%
2×10^{34}	25	15%
	50	~50%

Approx. 50% more ROCs in new pixel detector.

Limited number of readout fibers ➔ boost readout frequency

This bx-mode was not foreseen in 1998 when ROC architecture has been designed

Clearly, the present ROC is not appropriate for luminosities expected in phase-1

New ROC : Hit rate capability

Unchanged: front-end amplifier, threshold + trimming, column drain

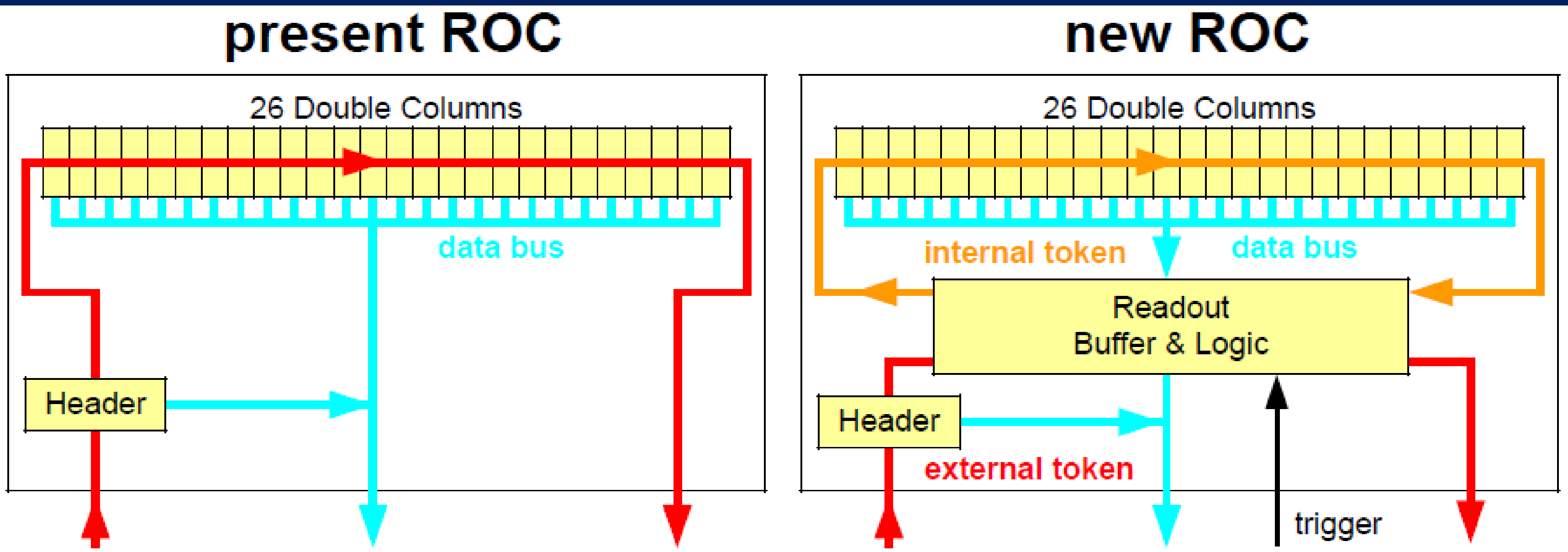
0.25μm technology

Present ROC:		New ROC:
32 data buffer	→	80 data buffer
12 timestamp buffer	→	32 timestamp buffer
no readout buffer (8 ROC seq.)	→	64 x 24 bit static RAM as readout buffer
		space for 96 cells (set after simulation)
		readout buffer storage:
		simultaneous read/write (6 bit counters)

Design/simulation done;

integration into ROC "to do"

Buffered Readout



- Double columns with verified data stops → no more events accepted
- Double columns have to wait for external token → long dead time
- Sequential readout of of 8/16 ROCs → high token delay

- DCol readout parallel in all ROCs after trigger → reduced waiting time
- ROC readout buffer: read/write simultaneous; data with different time stamps
- Easy implementation in separate buffer on ROC → keep present DCol logic

ROC : Readout bandwidth

Present ROC: 40 MHz analog (6 levels ≅ 2.5 bits)

raising frequency risky because limited rise time!

Solution: "GO DIGITAL"

➡➡➡➡

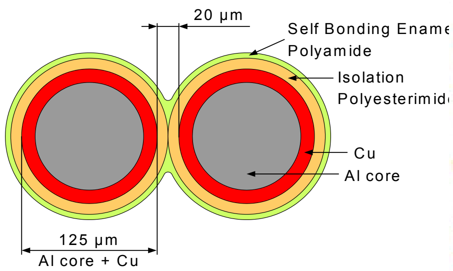
on-chip 8-bit ADC, clock = 80 MHz

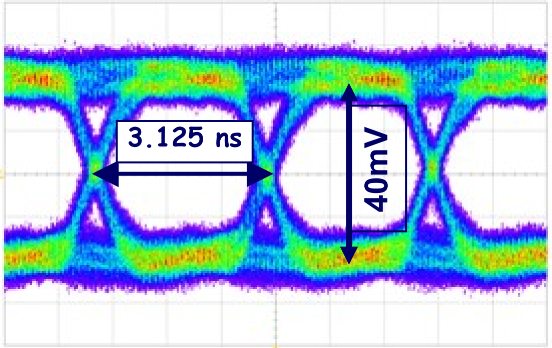
ROC readout: 160 MHz

TBM readout: 320 MHz

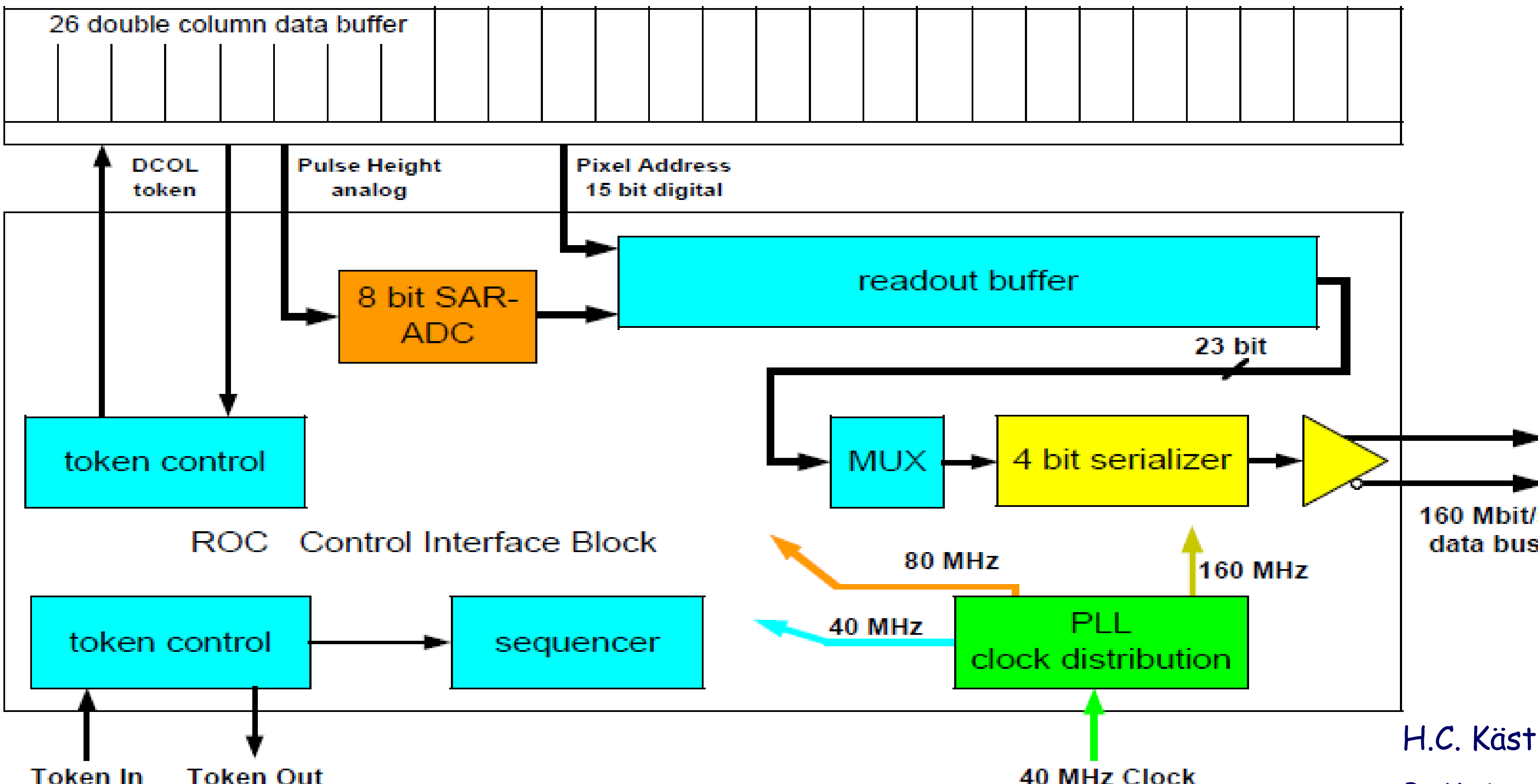
μ twisted CCA pair (Copper-Cladded Aluminum)

1 m long link at 320 MHz from TBM to POH; chips done





Digital ROC Readout



H.C. Kästli

B. Meier

ROC : Other improvements

- Lower signal threshold (~3000e- >> ~150e- amp.noise)
  - chip internal X-talk (analog: identified, easy to solve →layout
    digital: identified, more simulation req.)
- Linearity of pulse height (understood)
- Power-up behavior
- Removal of unused DACs
- Submission planned for Sept. 2011
- 2nd submission possible in 2012

TBM (Token Bit Manager)

Staged development (Ed Bartz, Rutgers)

1. Step: keep analog data handling, replace digital TBM core *
   - correct minor impracticability's
   - install handling of PKAM events
2. Step: replace analog section by digital version (160MHz)
3. Step: shift ROC data to 400(320)MHz, 4/5 bit encoding

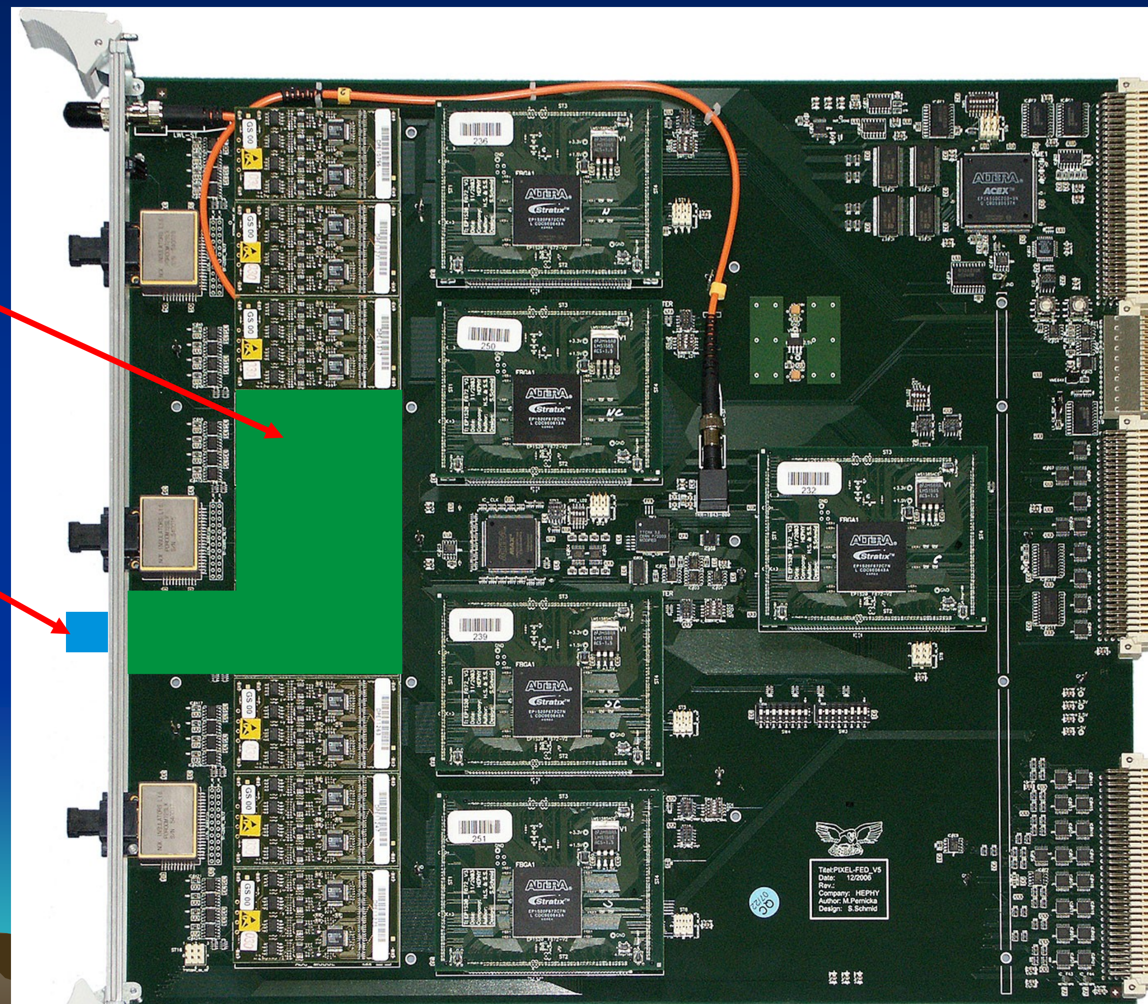
* mount few TBM's in 2013 on 1. barrel layer

Modification of Pixel-FED

- Keep single slot size
- Keep VME base board

New daughter board
(instead of 3 ADC cards)
including Zarlink receiver

- Don't need to remove current ARx12 → allows easy swapping between old and new systems
- Need new front panel in any case



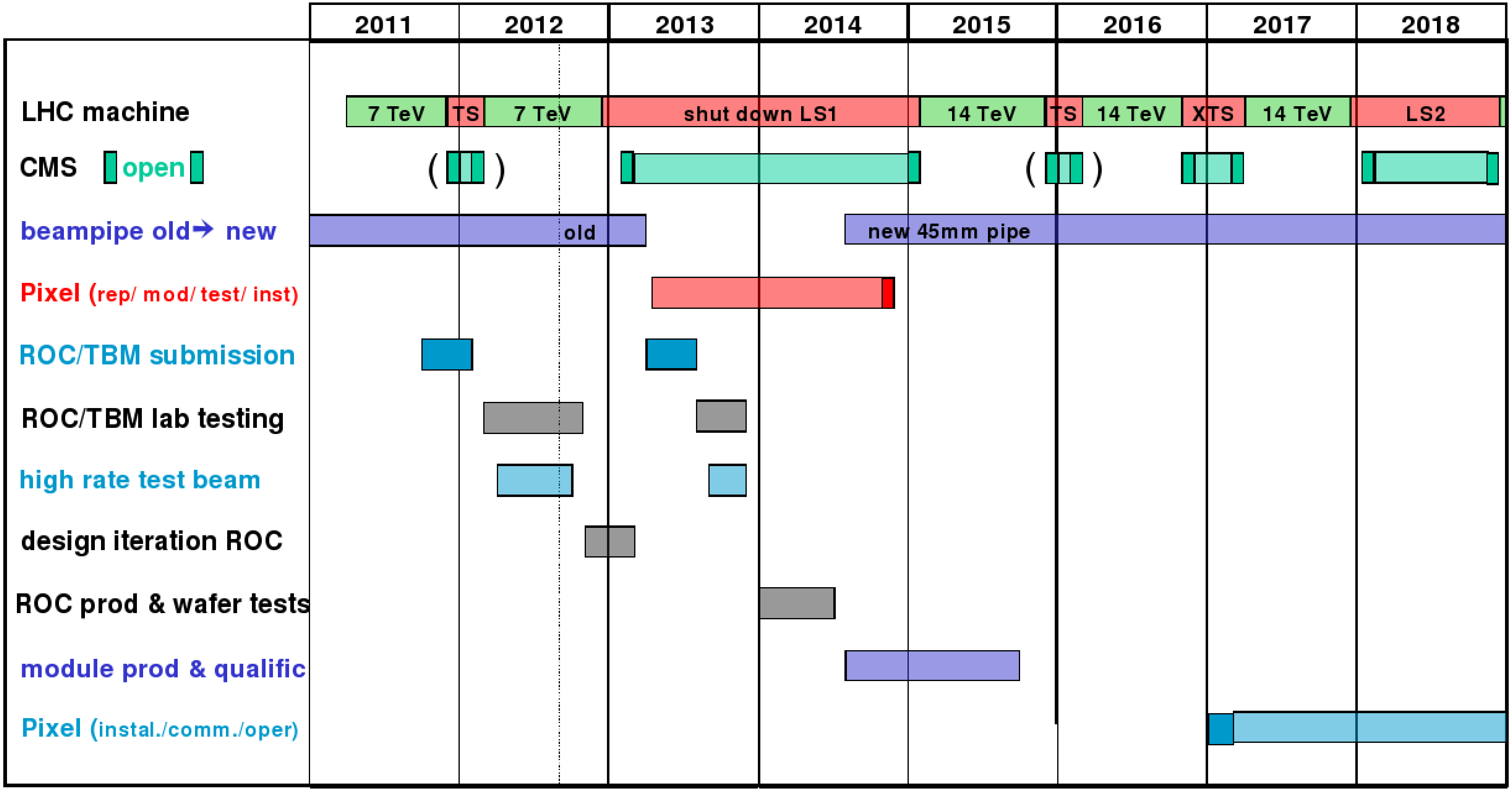
H. Steininger, M. Pernicka, HEPHY

Powering aspects

- LV power demands are based on present ROC data and up scaled
- up scaling existing power system leads to large cable losses (cable overheating !) and lack of power
- ➡
- employ DCDC-converter close to detector and modify power supplies (A4603 from CAEN) to operate at higher voltage (→ less cable losses)

(for details of the converter see talk by Katja Klein)

ROC/TBM submission & Pixel Testbeams



Some duties for LS1 (proposal)

- repair work if needed (BPIX, FPIX)
- install "Pilot system" on 3rd disk place
  - few blades with new FPIX design (2x8 mod.)
  - new HDI, new Al cables, new port card, POHs instead AOHs
  - ➡ test new electronics readout chain, DAQ handling (2014-2016)
- "pixel-cooling-insertion" device
  - full BPIX dummy, correct cooling loops, resistive loads
  - ➡ CO_2 cooling test at TIF (2013-2016)
  - ➡ mechanical insertion test into CMS (2013)
  - ➡ equip few ST-slots with DCDC-conv. test new power system (upgraded A4603 PS-modules + dummy ROCs) (P5 & TIF)
  - ➡ final P5 cooling commissioning in 2017 just before insertion of new BPIX

Summary

- Roots of the CMS pixel upgrade project:
  - limitations for high luminosity & non-stand. LHC modes
  - partial detector replacement (after ~150 fb^{-1})
- Project has been detailed & enlarged:
  - 4 hit system (improve tracking seed, vertexing, track efficiency)
  - reduce material budget (improve impact parameter, b-tagging)
  - keep inefficiencies low (up to $2x10^{34}cm^{-2}s^{-1}$, also for >25ns mode)
- Mandatory constraints:
  - minimize impact on other CMS detectors (no new piping, cabling...)
  - minimize changes of DAQ, DCS and other CMS-global software
  - minimize radiation exposure of service personnel