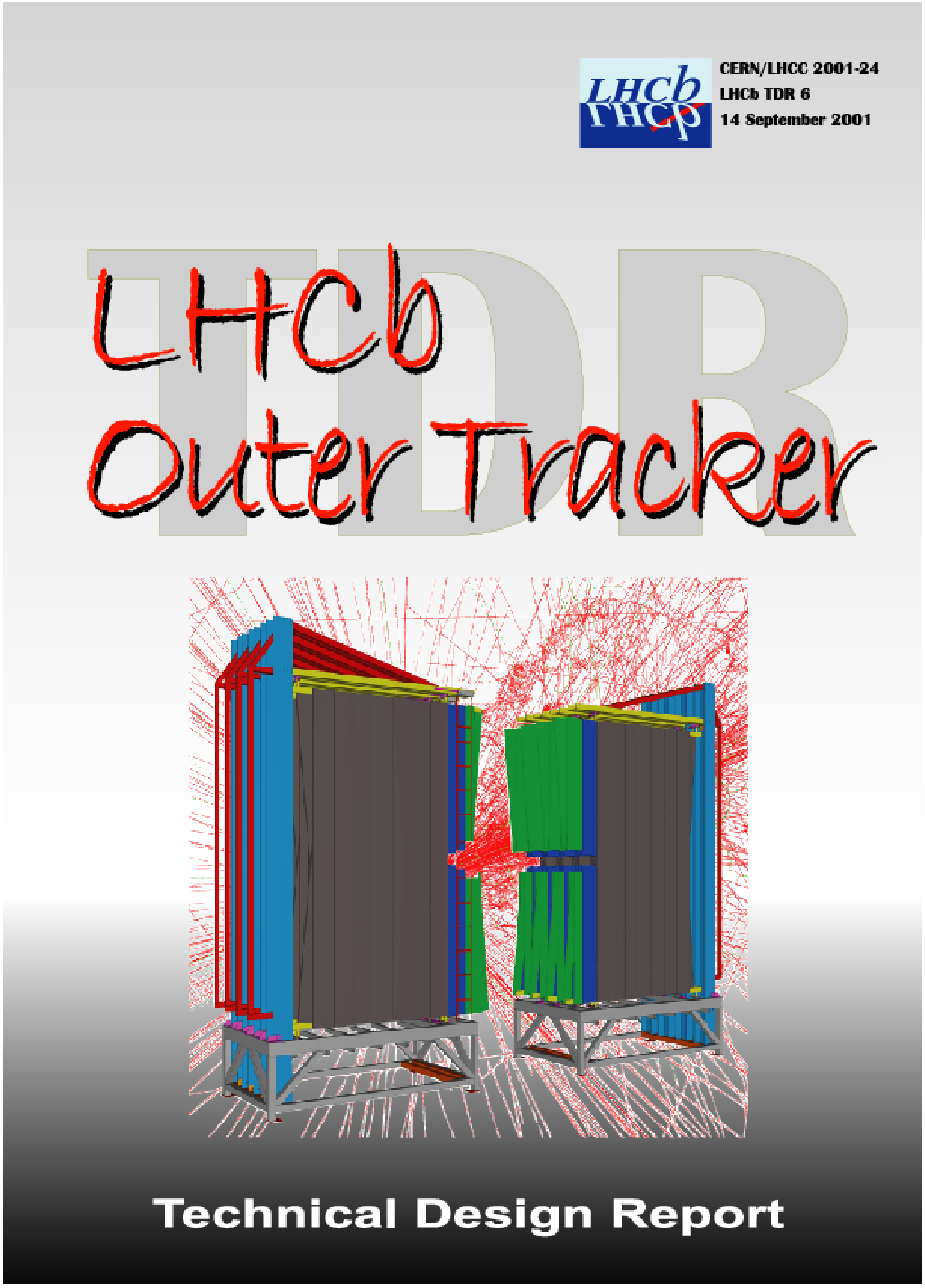
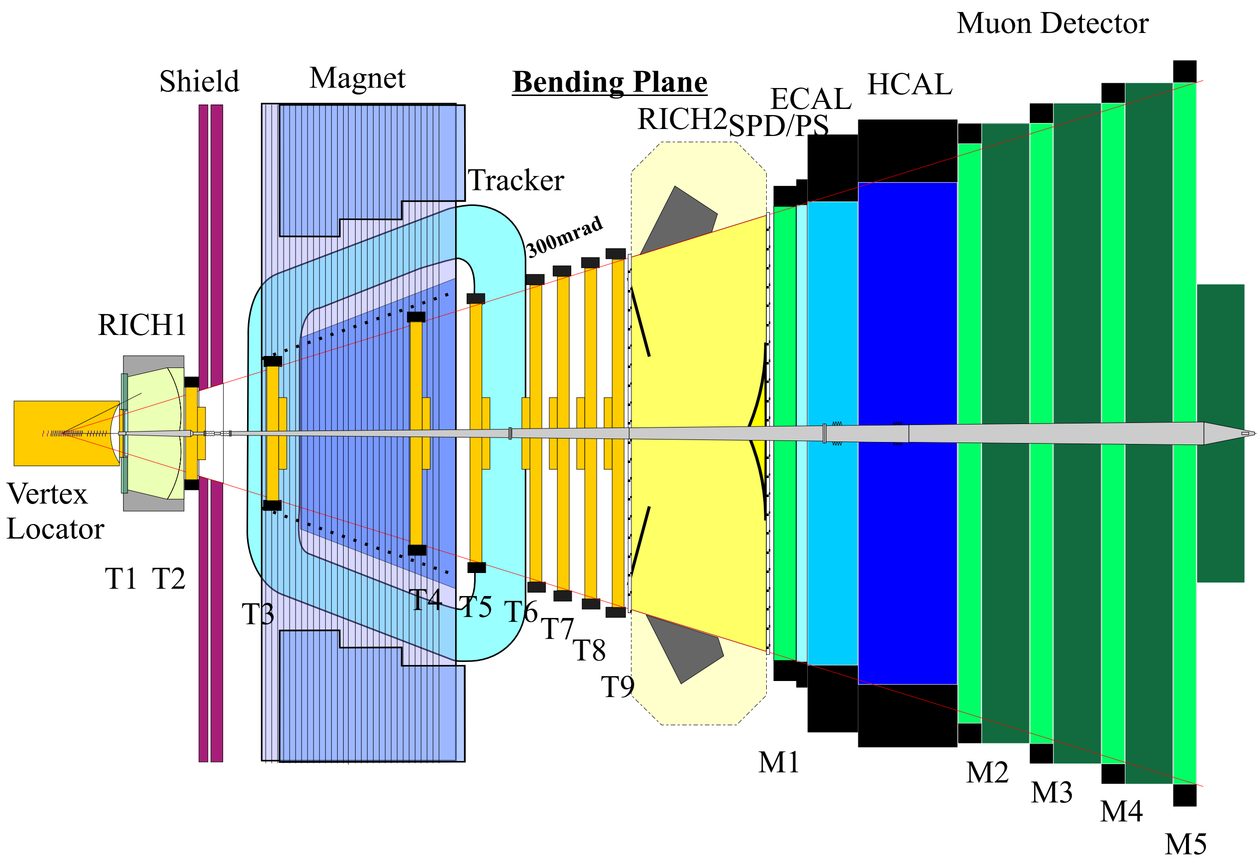


presented by Bert Koene

Topics

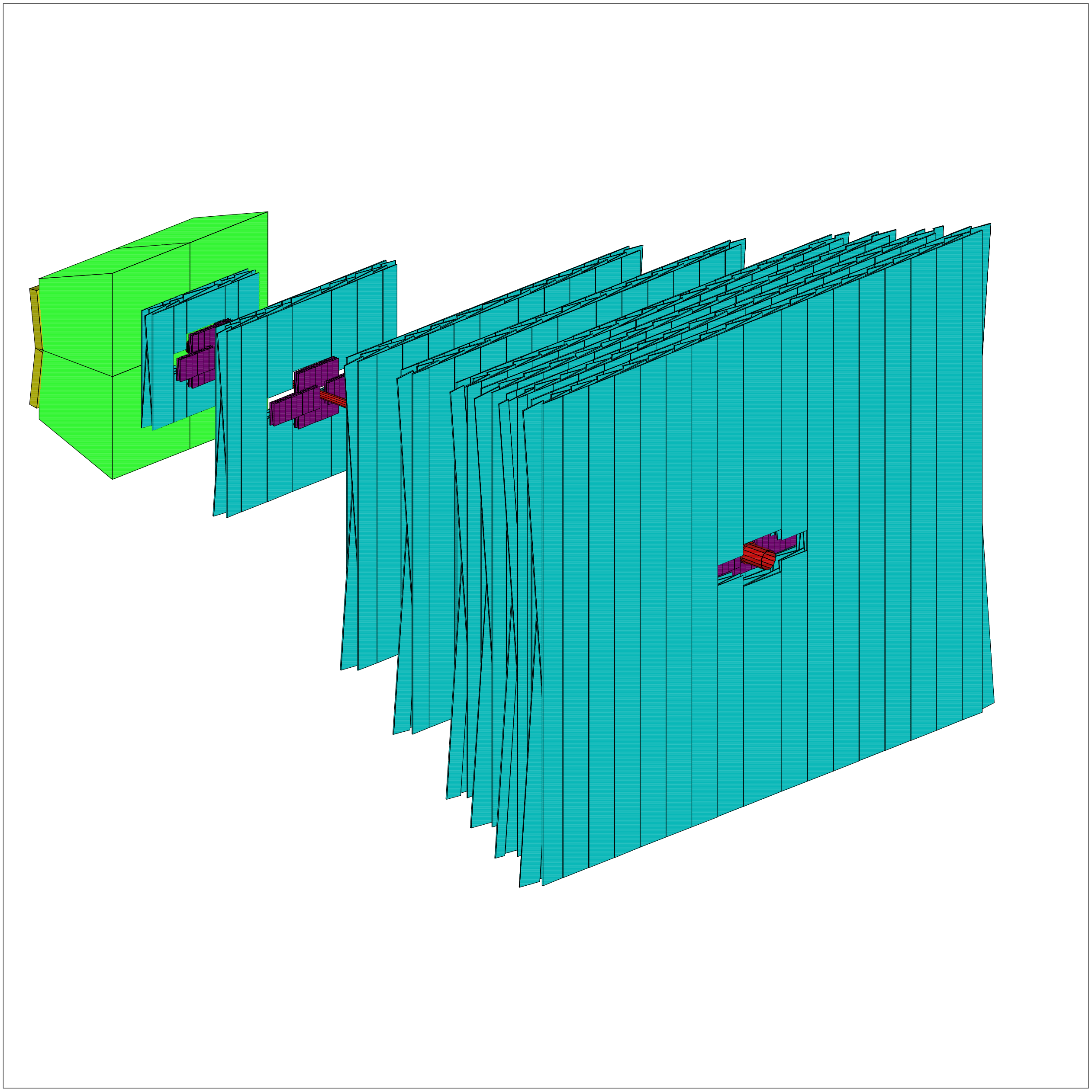
- Introduction
- Tracker layout
- Straw tube drift cells
- Detector modules
- Performance
- Stations
- Electronics
- HV, gas, alignment
- Project organization
- Summary

INTRODUCTION



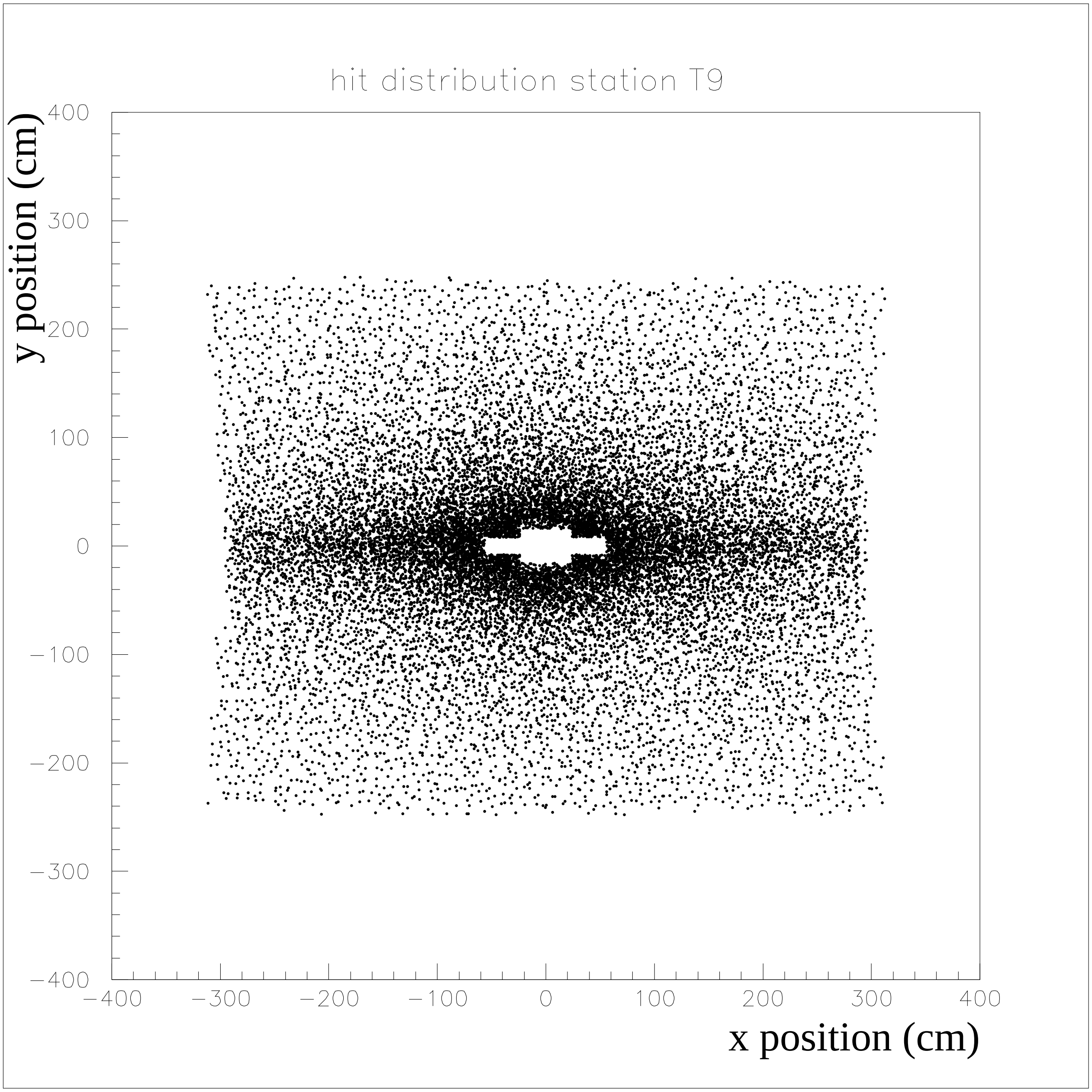
Momentum spectrometer	T2 – T9
Track slopes in RICH	T1 - T2
	T6 - T9

Link vertex $\Longleftrightarrow$ CAL/muon

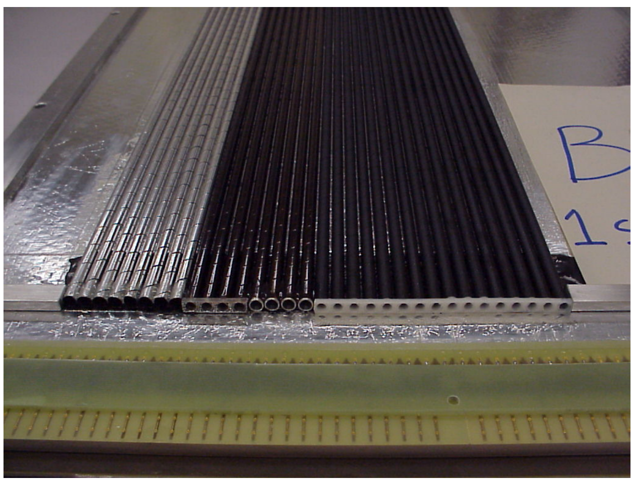


Tracker =	Inner Tracker +	Outer Tracker
	fine grained	coarse grained
surface	2 %	98 %

Boundary IT - OT:
cell occupancy $\longleftarrow$ track density $\otimes$ granularity

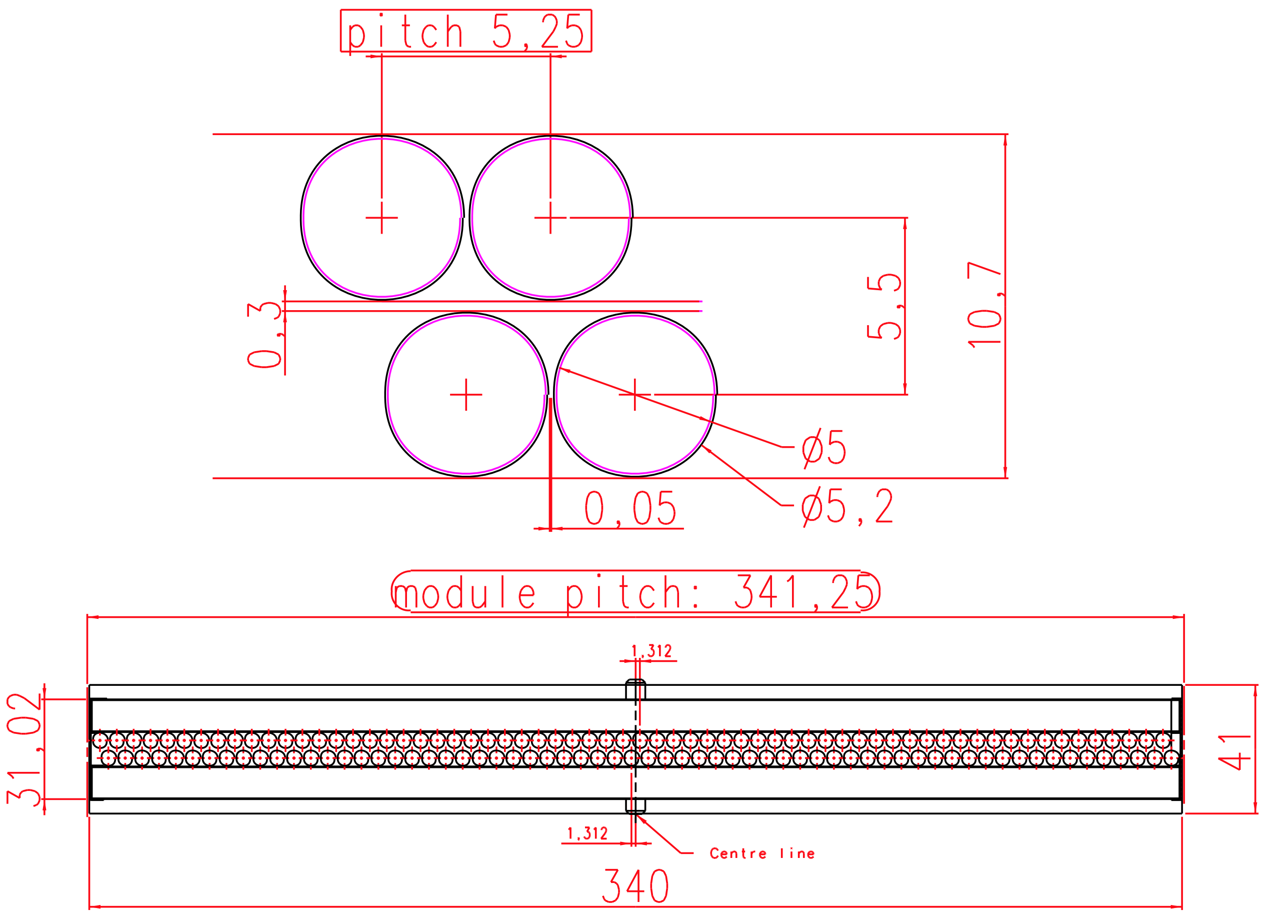


TRACKER LAYOUT



Detection elements

5 mm diameter straw tubes packed in double-layered modules

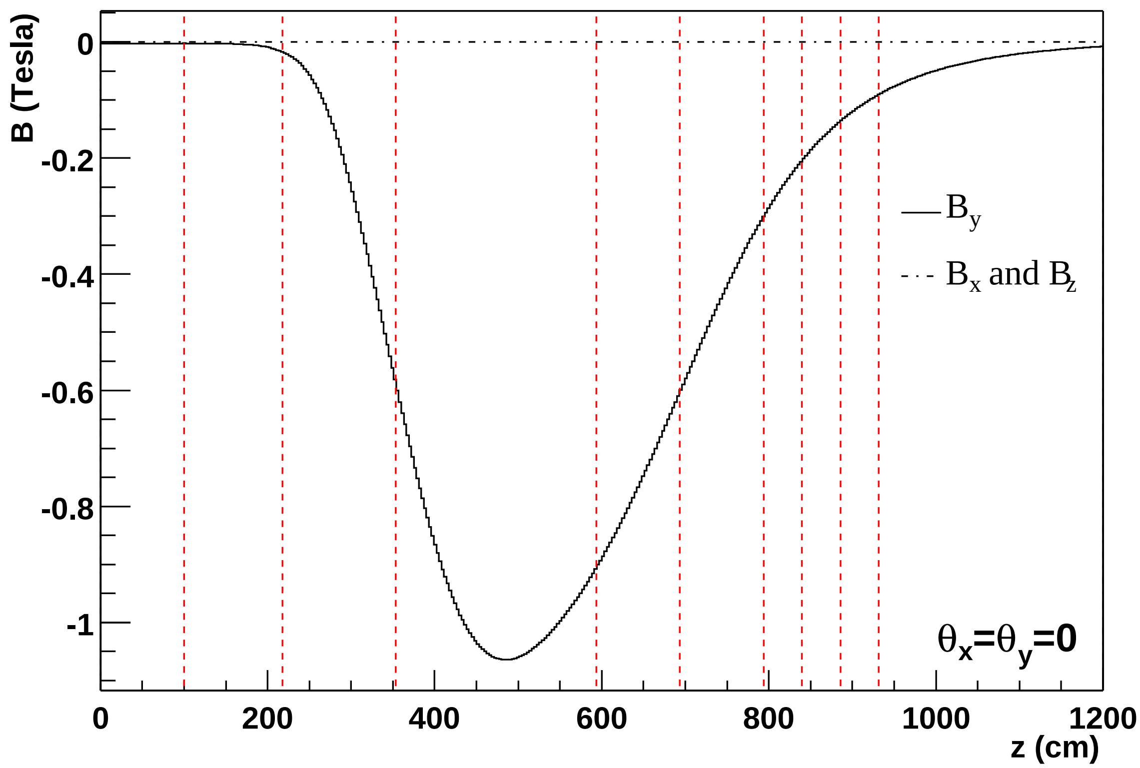


Module cross section

Station = 4 planes of modules arranged as X U V X views

		active area		
station	z_{max} (mm)	x_{max} (mm)	y_{max} (mm)	channels
2	2275	704	581	4.3 k
3	3635	1125	929	6.8 k
4	6035	1867	1541	11.4 k
5	7035	2176	1796	13.1 k
6	8038	2486	2052	15.1 k
7	8497	2628	2170	16.0 k
8	8956	2770	2287	16.8 k
9	9415	2912	2404	17.5 k
				101.0 k

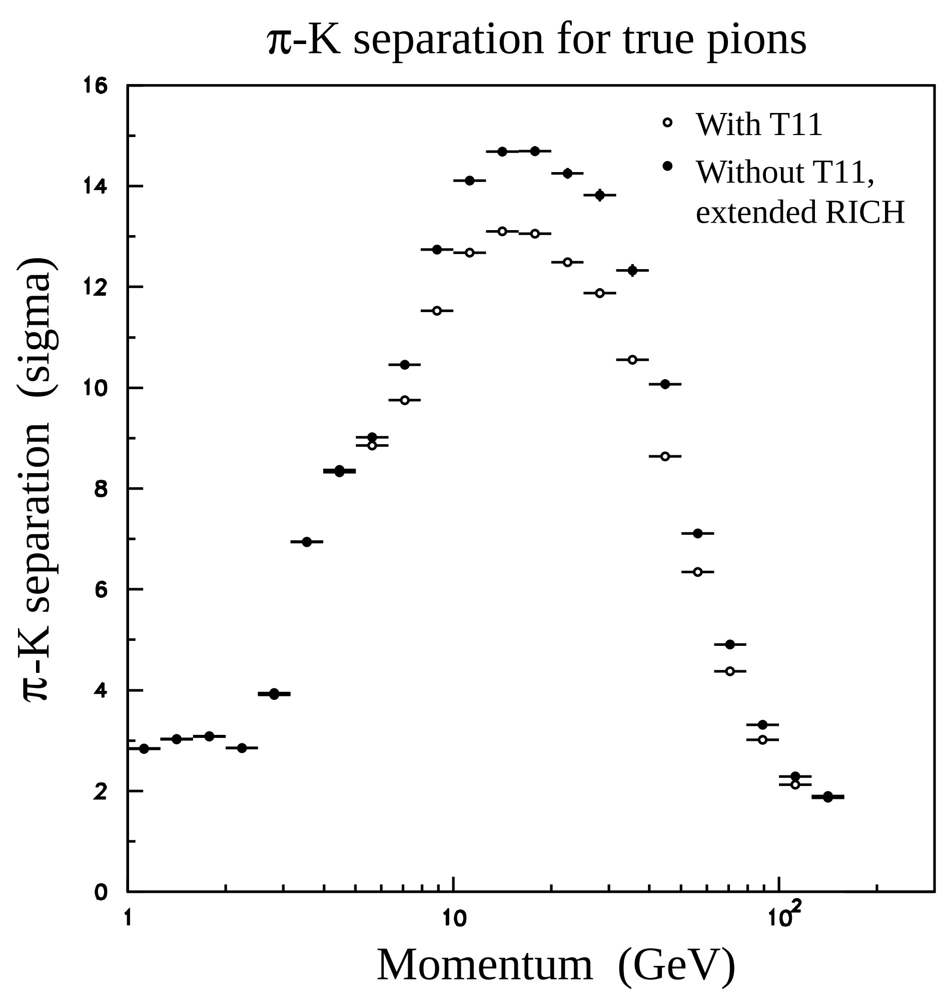
Stereo angle $\pm 5^o$ optimised for
$\varepsilon_{seeding} \otimes \varepsilon_{following} \otimes$ RICH slopes



R1 ← following → seeds R2

Economised since Techn. Proposal:

- No station behind RICH 2
- No Y planes at RICHes
- One magnet station less



STRAW TUBES

Cell size limited by:

occupancy

signal collection time

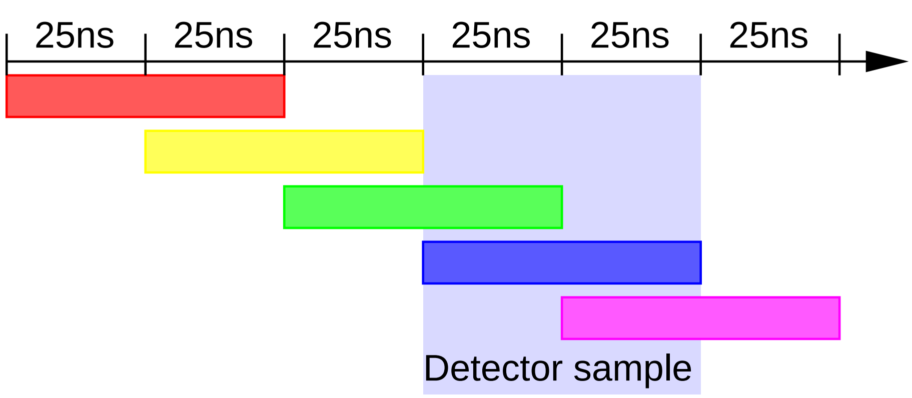
clean electrostatics (tube)

fast drift gas

$T_{max} < 25$ ns ideal

$T_{max} < 50$ ns realistic

consequence: time overlap with hits from neighbouring BX



Use Ar / CF_4 / CO_2 for fast drift

Large electron capture c.s. of CF_4 at few eV:

- degrades drift resolution insignificant
- breakup to free fluorine radicals

Cathode surface of noble metal or carbon loaded polymer (ATLAS, HERA-B, COMPASS)

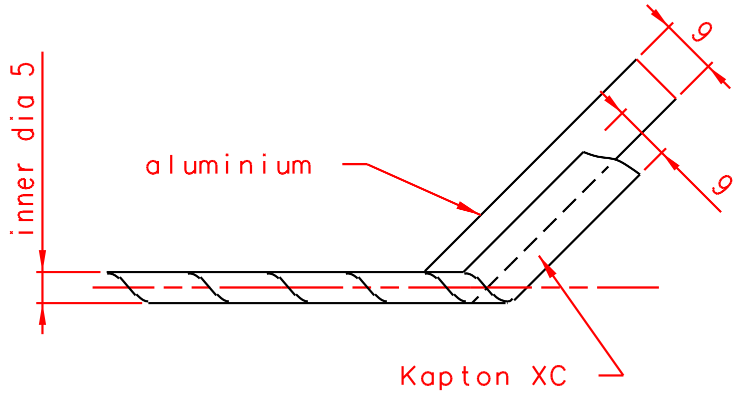
Technical Proposal: "drift cells of straw tube geometry built with honeycomb chamber technique"

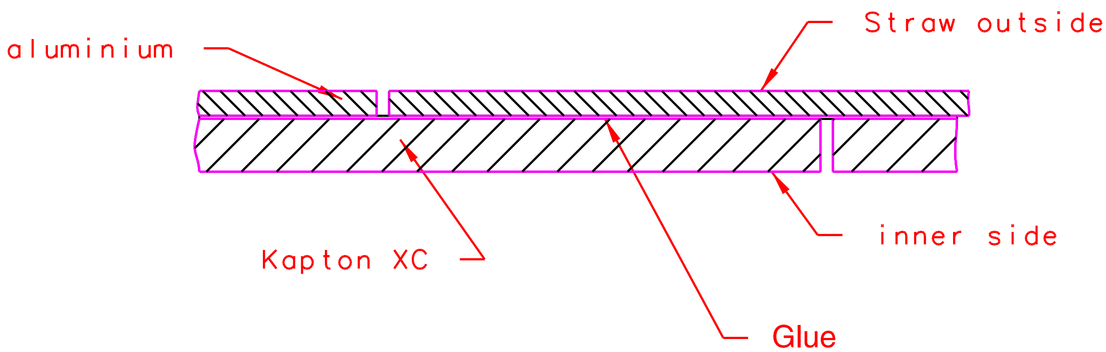
HC proto's of C-doped polycarbonate foil (Pokalon)
Switched to real straw tubes of C-doped Kapton because:

1. Pokalon-C very expensive
2. doubts about Pokalon-C 'aging' in Ar / CF_4 / X
3. slow drift in HC cell corners
4. better precision of cell shape

Channel density increase: 5 + 1 mm HC cell pitch
5.25 mm tube pitch

Less planes $\Longrightarrow$ stayed at 100 k channels





Inner layer = 40 μm Kapton XC with 30 % volume doping

Tested in Ar / CF_4 / CO_2 to

1.2 C/cm (realistic: p beam)

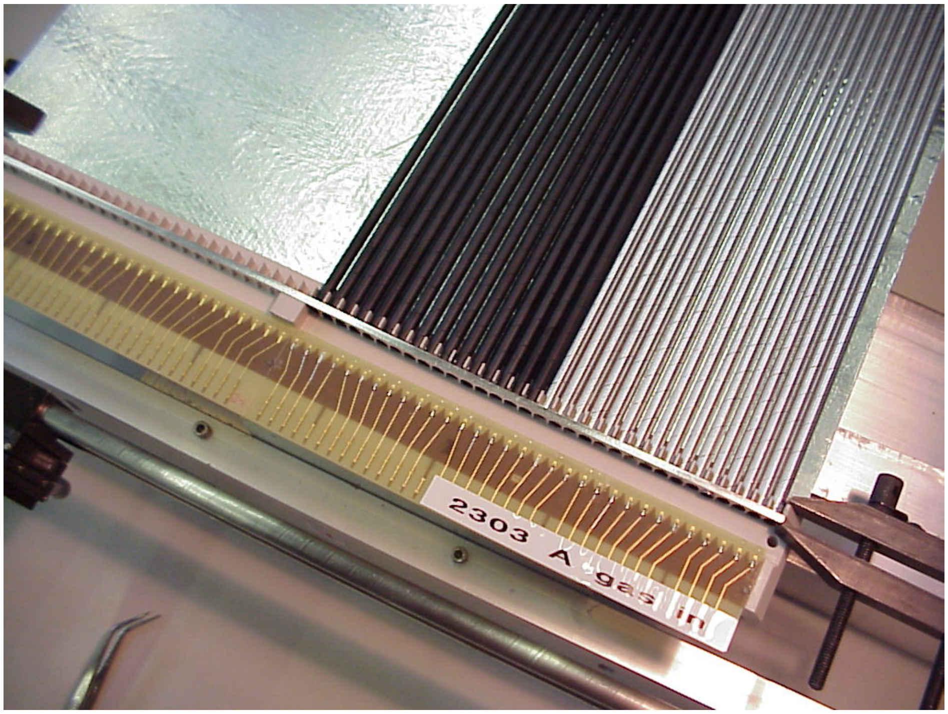
several C/cm (extreme: glow discharge)

Estimate hottest OT regions: 0.25 C/cm per year

Module aging tests in HERA-B and with X-ray source

realism accelerated

Outer layer = 25 μm Al $\Longleftarrow$ X-talk suppression



Tested 1. Kapton XC

2. aluminium

3. pure Kapton

4. aluminised Mylar

1 & 2 cathode to HV GND via outer layer

X talk by amplitude:

0.5 % aluminium

1.8 % Kapton XC

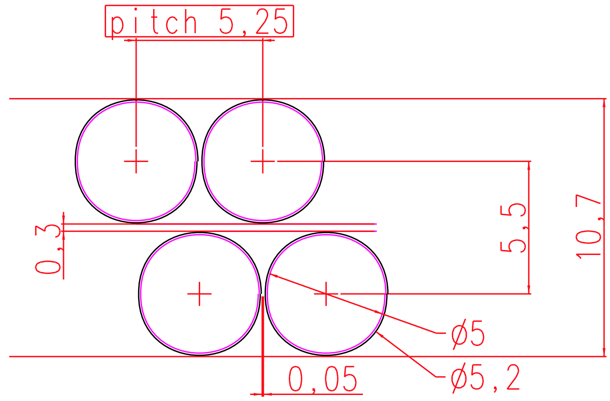
stays worse with shielding foils

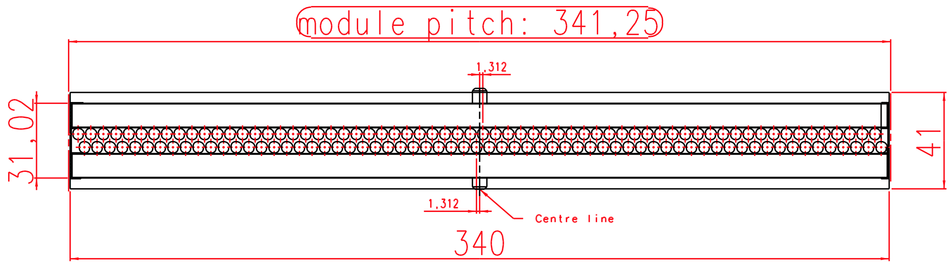
Pair of Al-XC tubes acts as $1/4\lambda$ resonator if only sees GND at preamp

$\mathcal{L}$ = O (2 m) $\Longrightarrow$ ν = O (40 MHz), inside preamp bandwidth

Remedy: tube grounding at short intervals

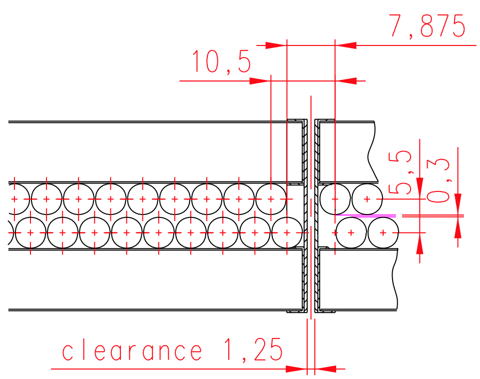
STRAW TUBE MODULES



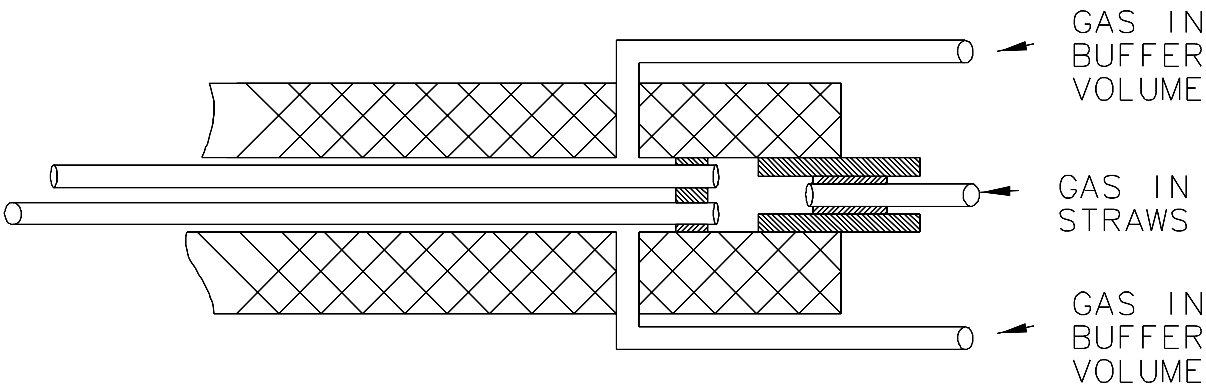


64 cells wide

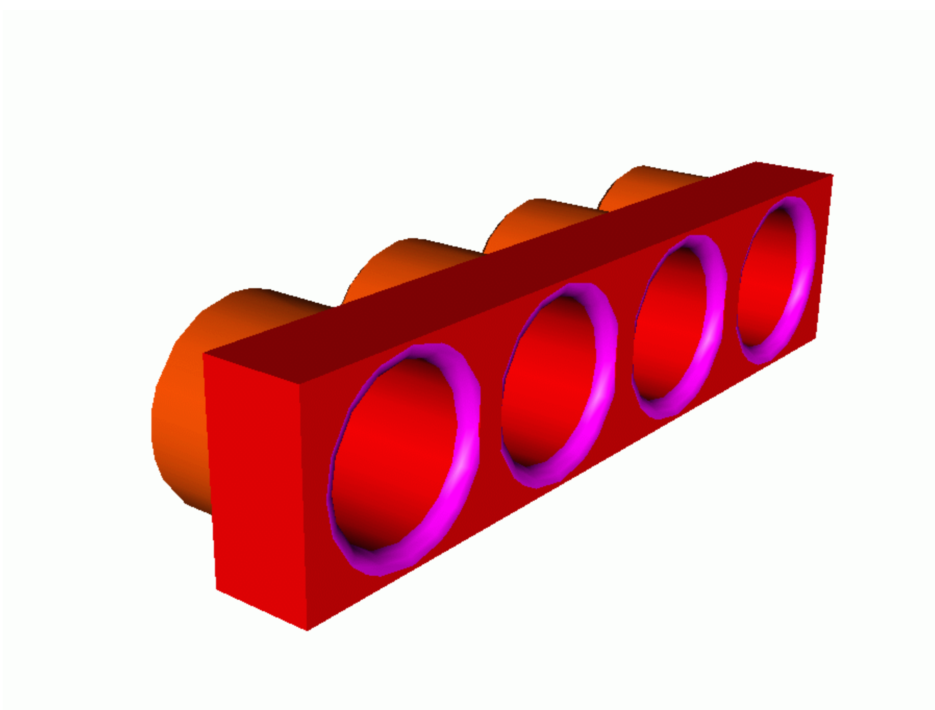
sandwich plates of HC core + 100 μm carbon facings + 20 μm Al foil



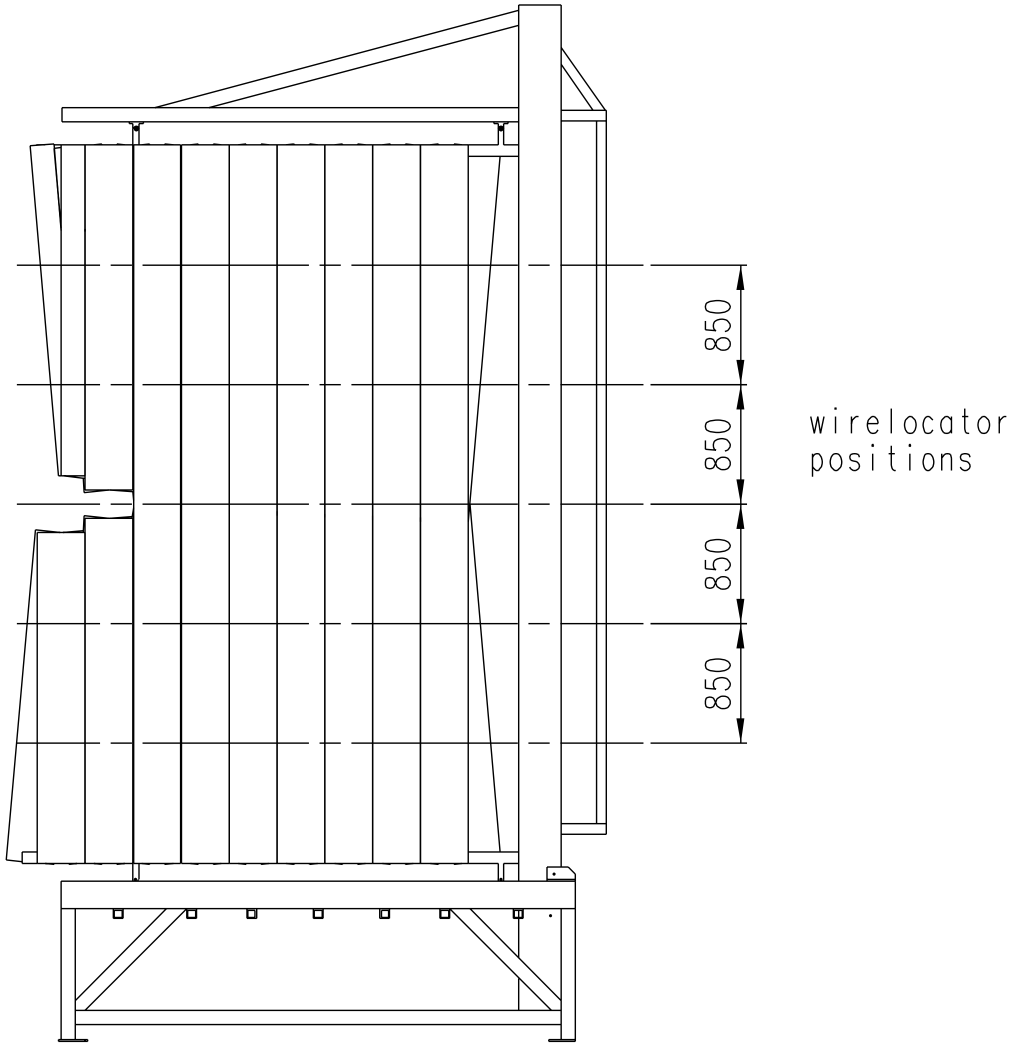
no module overlap $\Longrightarrow$ loose 1/2 cell at border



drift gas flows through and around the tubes

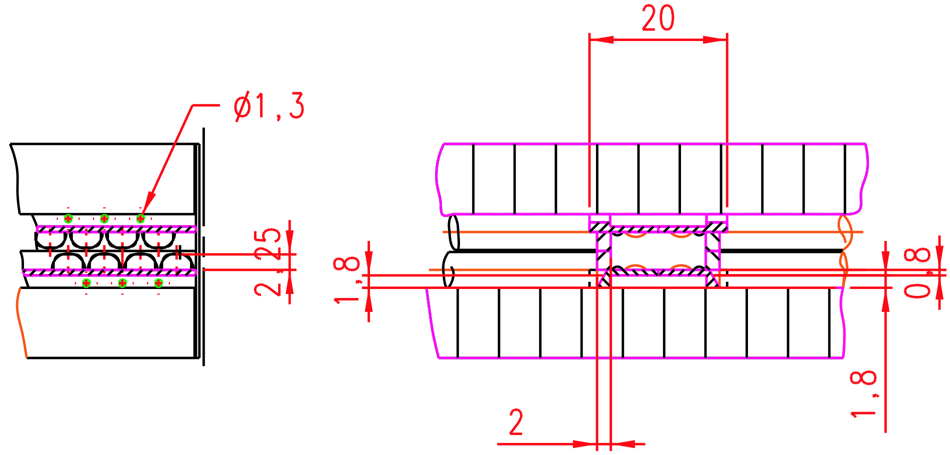


gas distribution into tubes



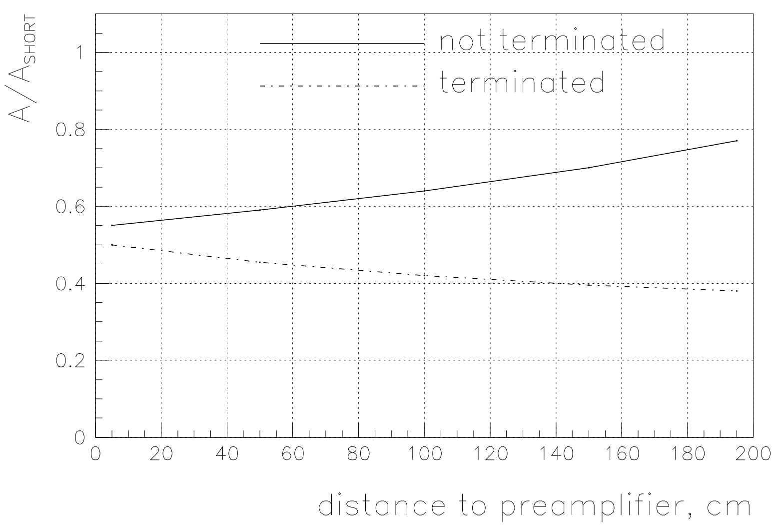
Electrical split near y = 0 to limit cell occupancy and signal propagation time

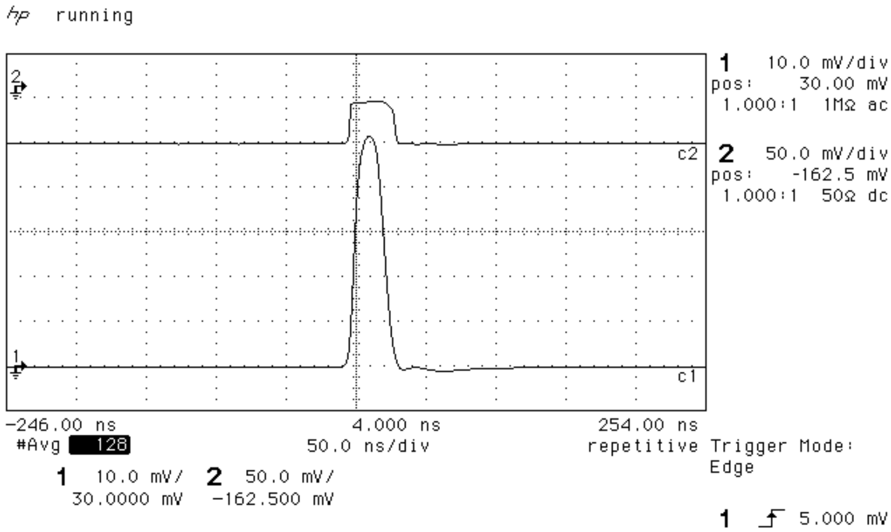
Wire centering supports every 80 cm

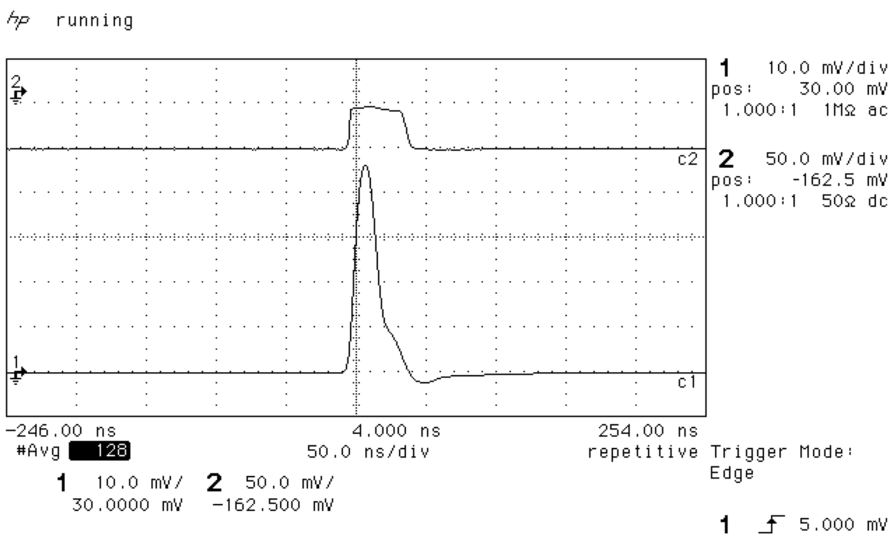


midway splitter

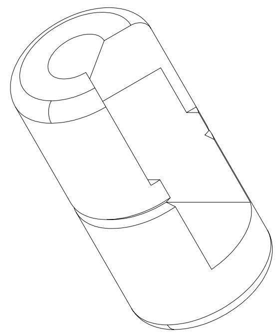
boost far-end amplitude: no terminating impedance



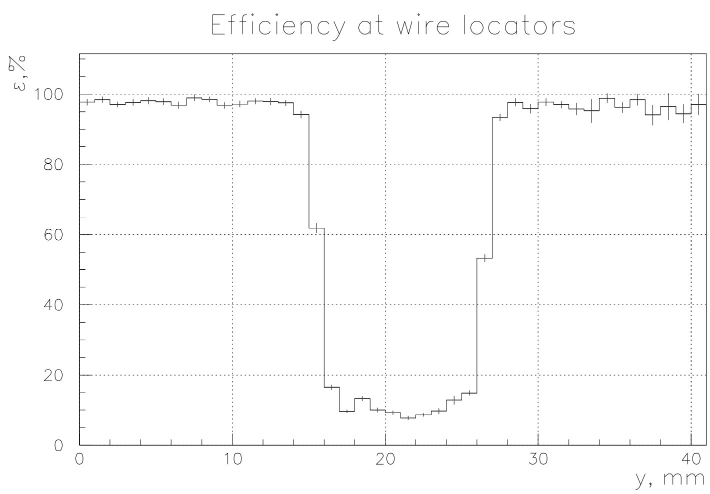


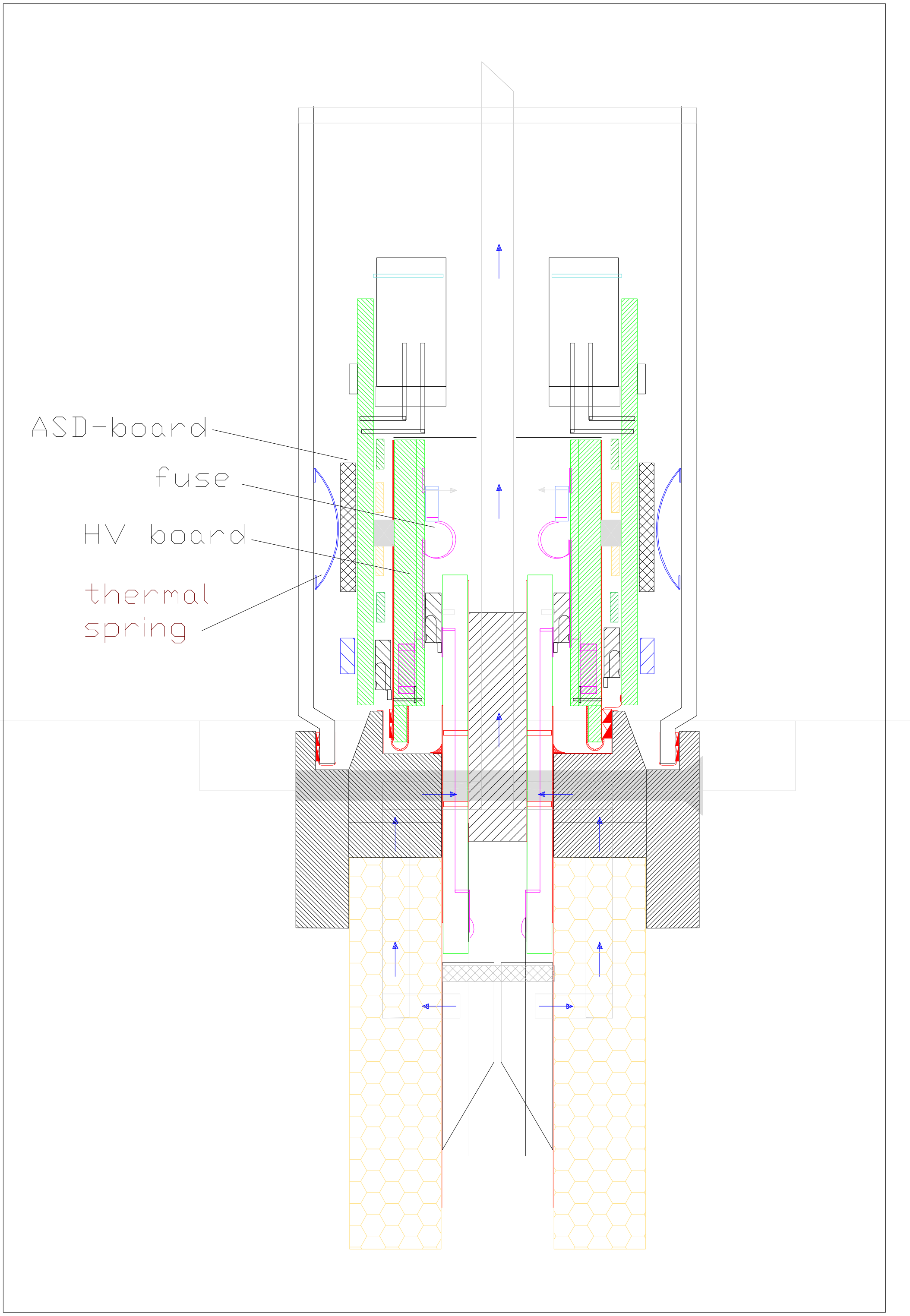


signal round trip $\leq$ 20 ns $\simeq$ shaping time



10 mm long wire support $\Longrightarrow$ 12 mm insensitive region





assembly of end piece and front end boards

MATERIAL BUDGET

Module elements: 0.67 % X_0

2 tube layers	0.276 %
4 x 0.1 mm facing	0.14 %
2 x 10 mm HC core	0.11 %
2 x 20 μm Al foil	0.045 %
gluings (est.)	0.1 %

Break down for tube layers:

aluminium	0.165 %
glue	0.02 %
Kapton XC	0.091 %

Add localised materials $\Longrightarrow$ 0.75 % per module

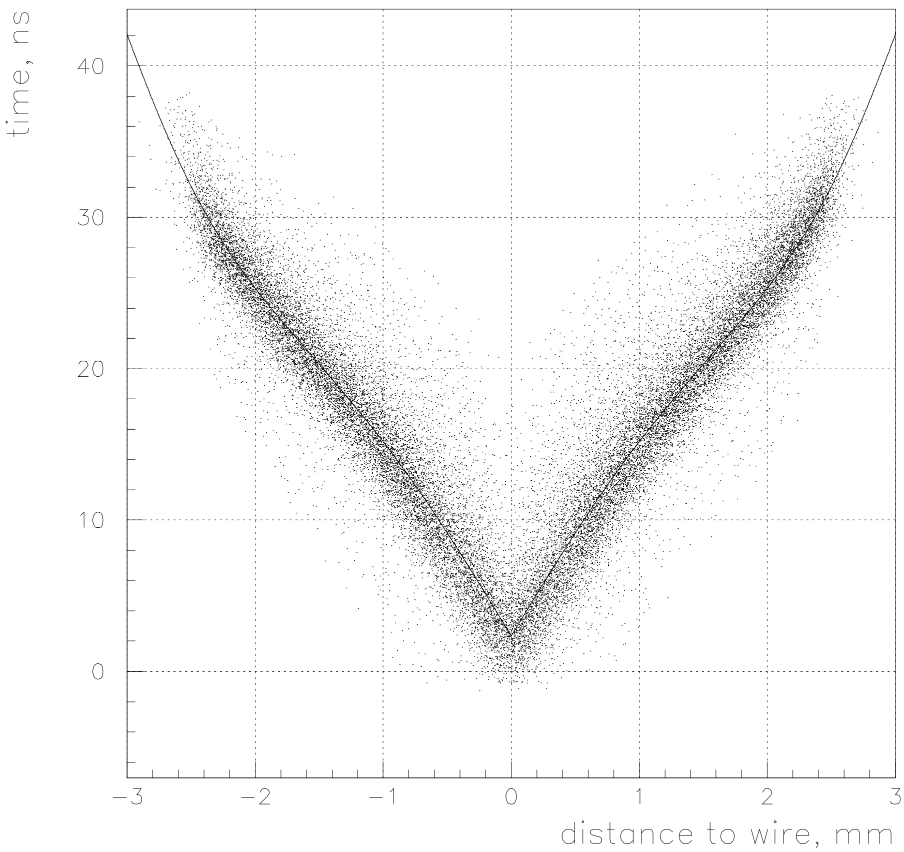
4 x 0.75 % = 3.0 % X_0 per station

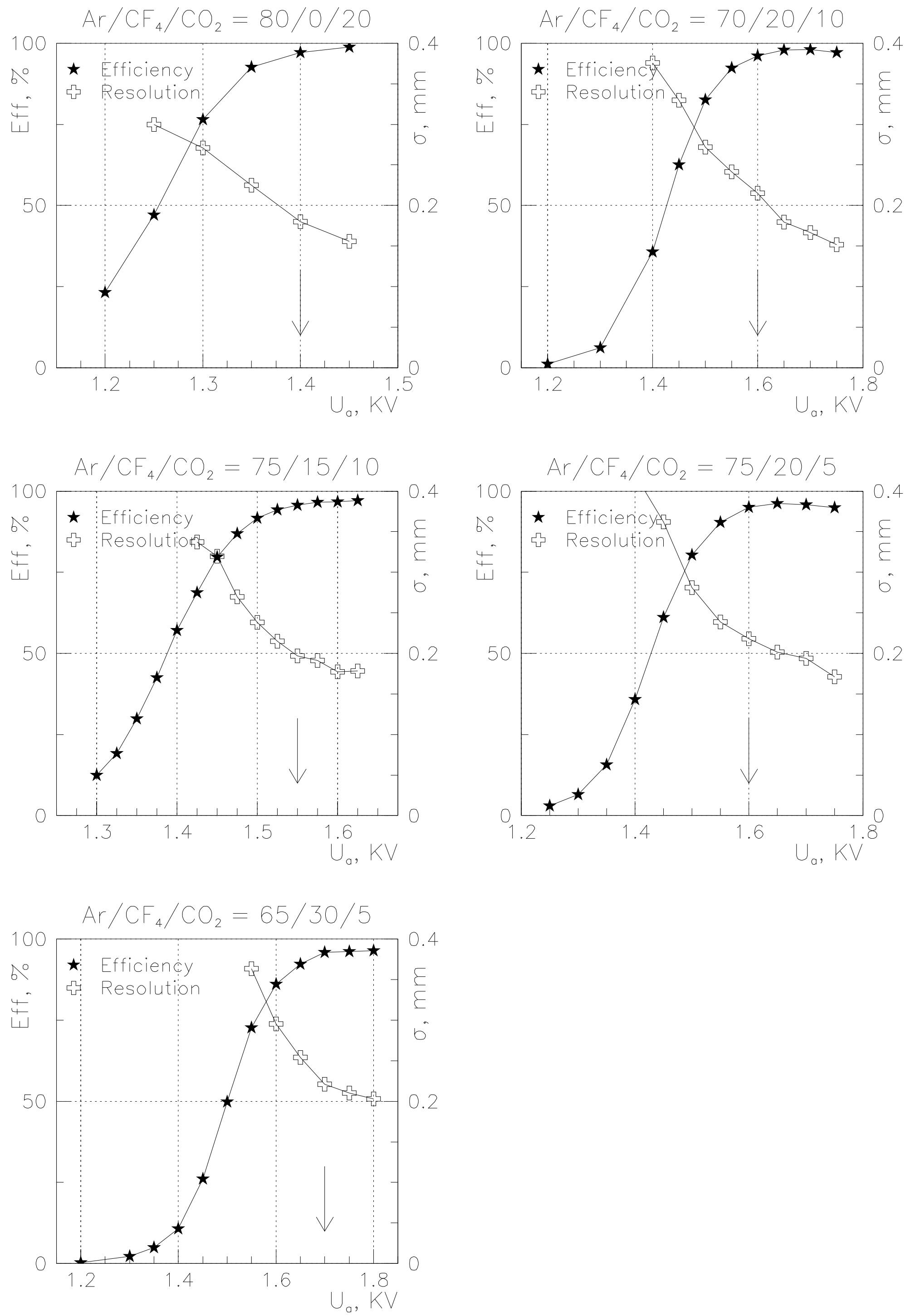
Sum for Outer Tracker:

24 % X_0

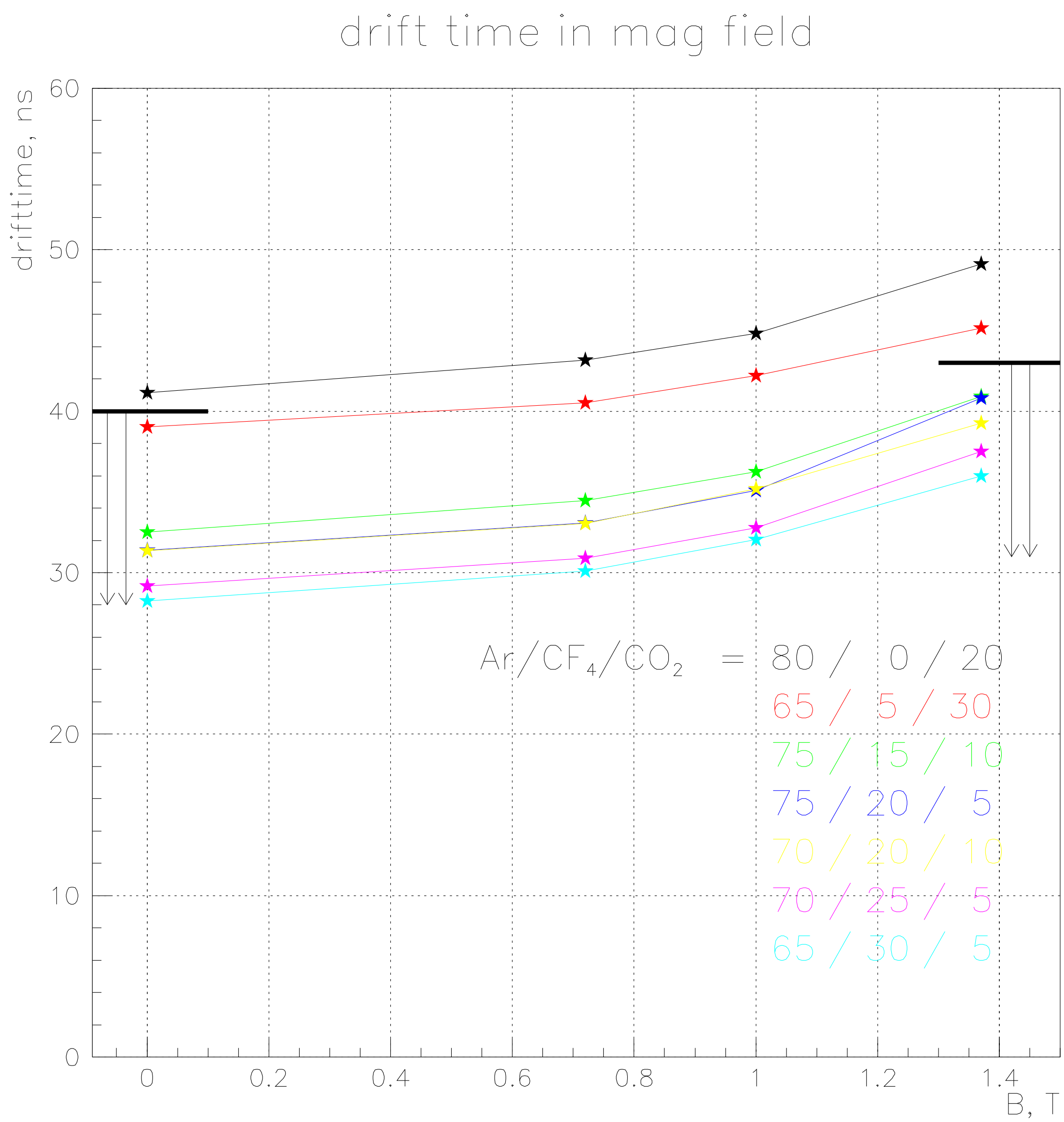
10 % λ_I

TEST BEAM RESULTS

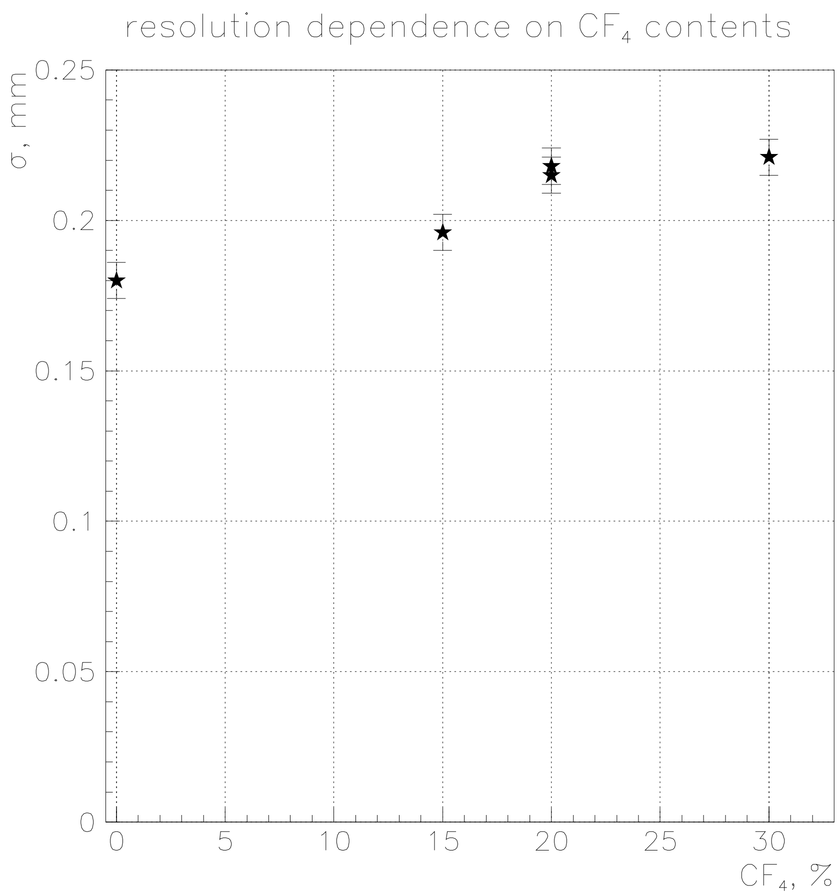




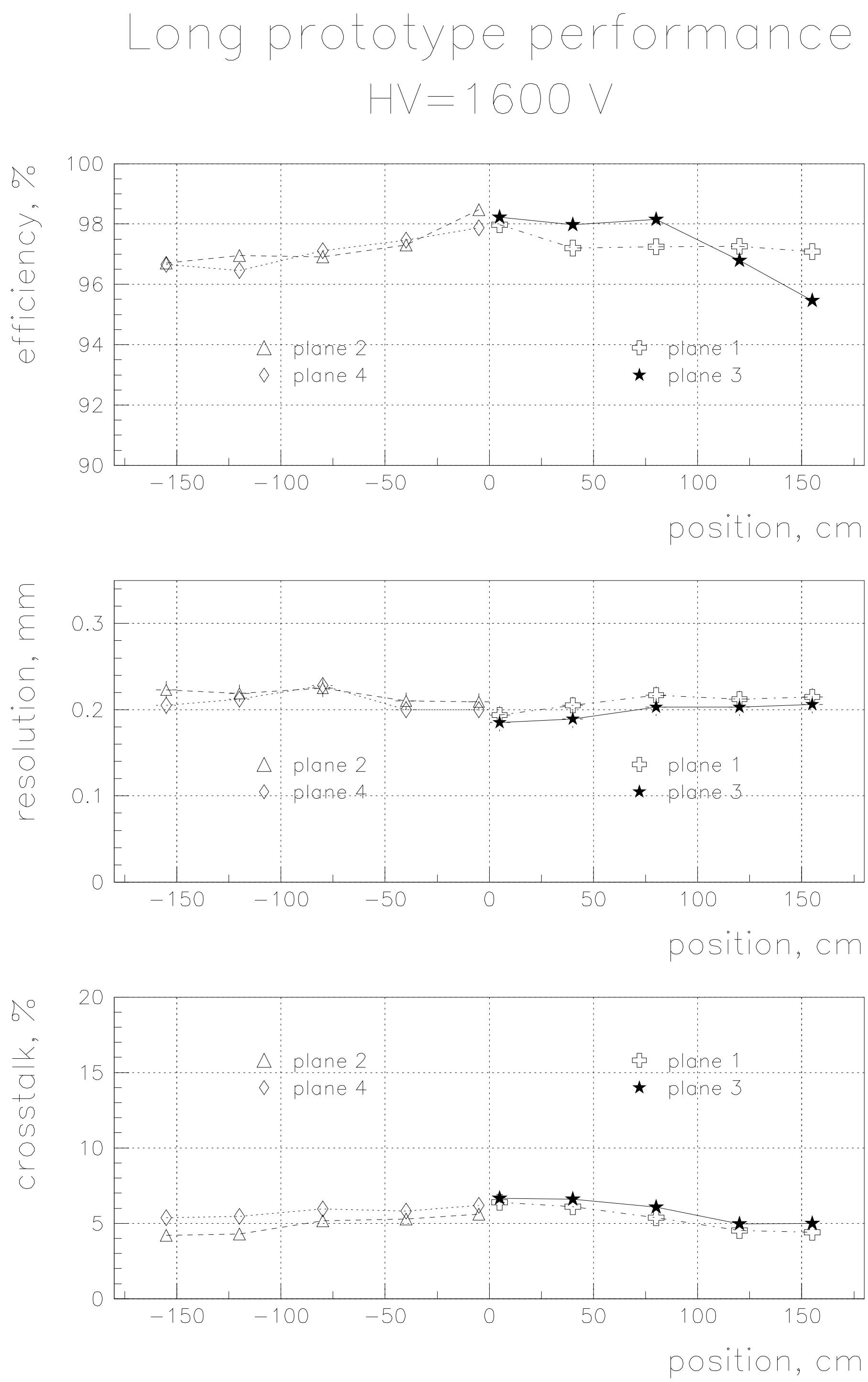
plateau curves and cell resolution at different CF$_4$ concentrations



T_{max} vs B field: 15 % CF_4 is enough



smallish effect of CF_4 concentration on resolution



homogeneous response along 3.3 metre long and fully realistic prototype

PERFORMANCE STUDIES

OT configuration optimization

Track reconstruction on simulated $b\bar{b}$ events + min. bias bkg events

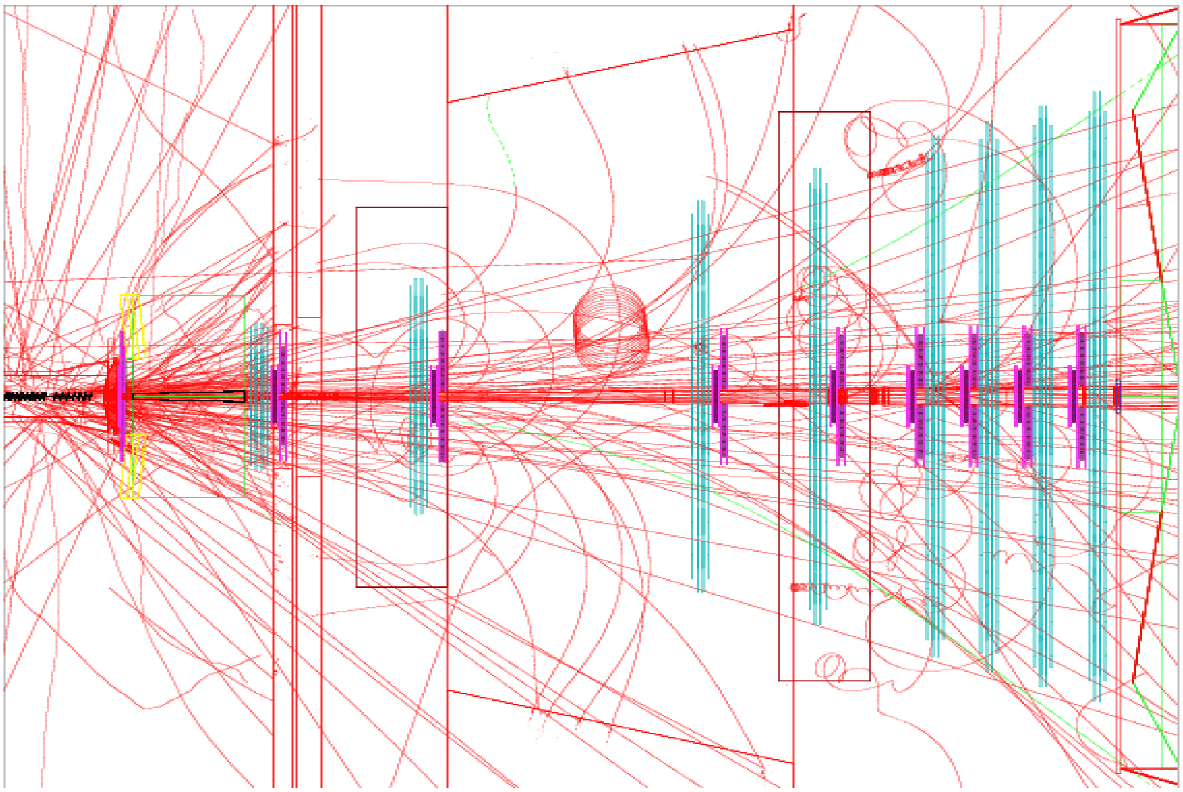
pp interactions at $\sqrt{s}$ = 14 TeV	Pythia
particle decays	QQ package
follow through LHCb	GEANT based SICB
Outer Tracker response	GAUDI
tuned to test data, incl. dead time etc.	
track reconstruction	TRAIL package

Background mixed into $b\bar{b}$ events :

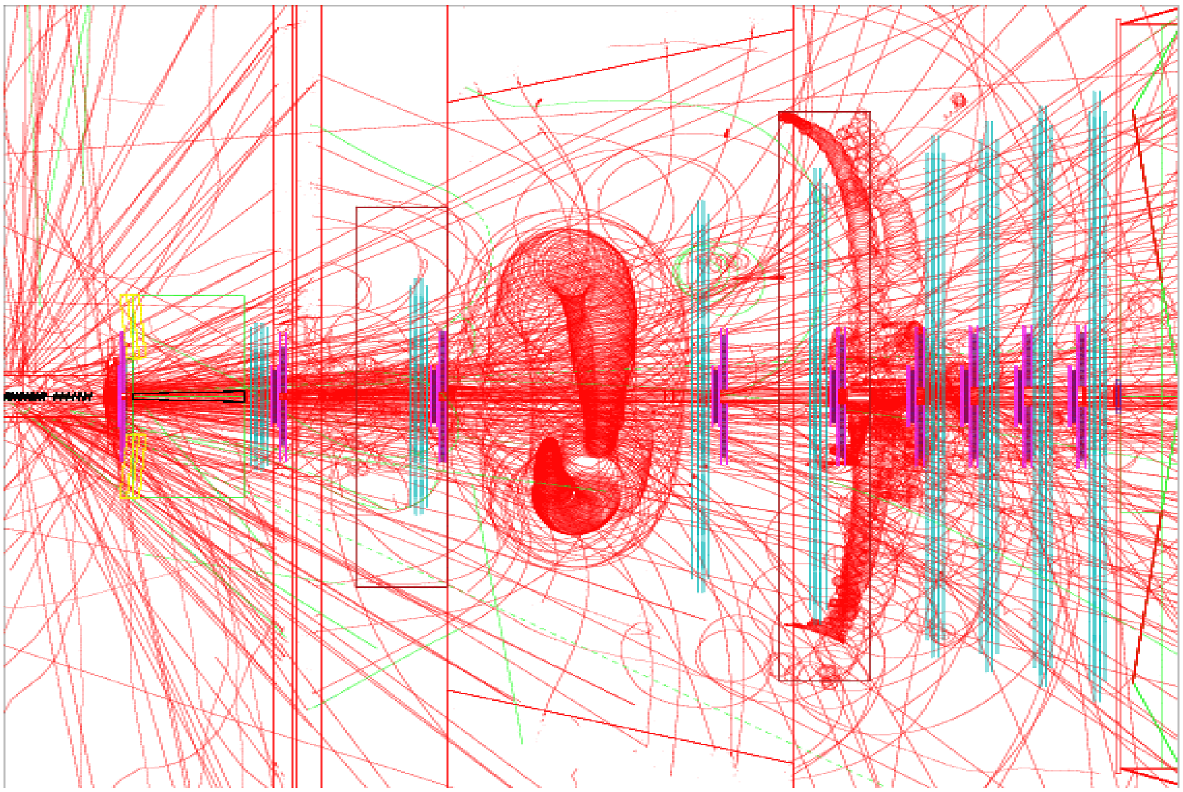
PILE UP: min. bias in same BX (average 0.53)

SPILL OVER: hits due to different BX

1. overlap of 50 ns OT time windows per BX
2. long-lived curling tracks



quiet $B_d \rightarrow \pi^+\pi^-$ event



busy $B_d \to \pi^+\pi^-$ event

OCCUPANCY

Def: fraction of channels hit within the 50 ns event window

importance:

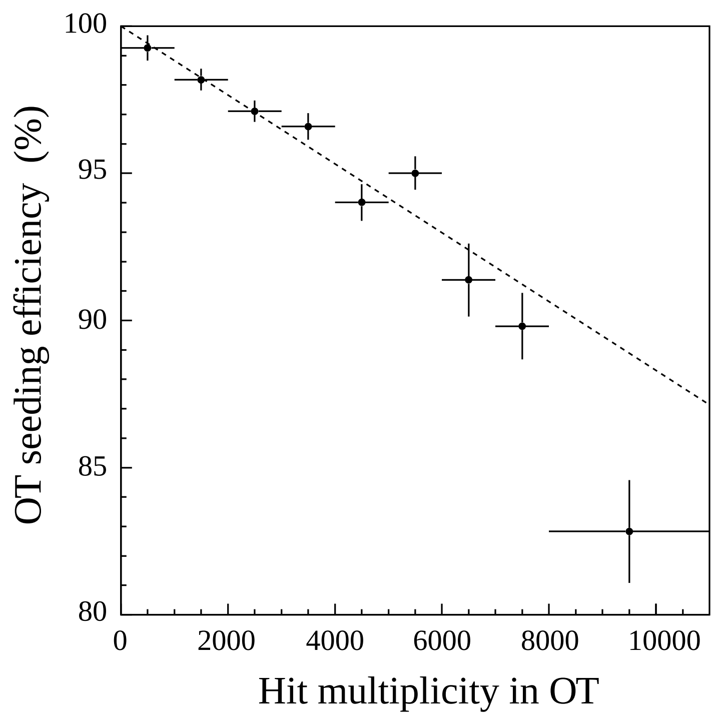
- pattern recognition efficiency & ghost rate requires mean occupancy

  seeding $\lesssim$ 10 %

  other $\lesssim$ 15 %

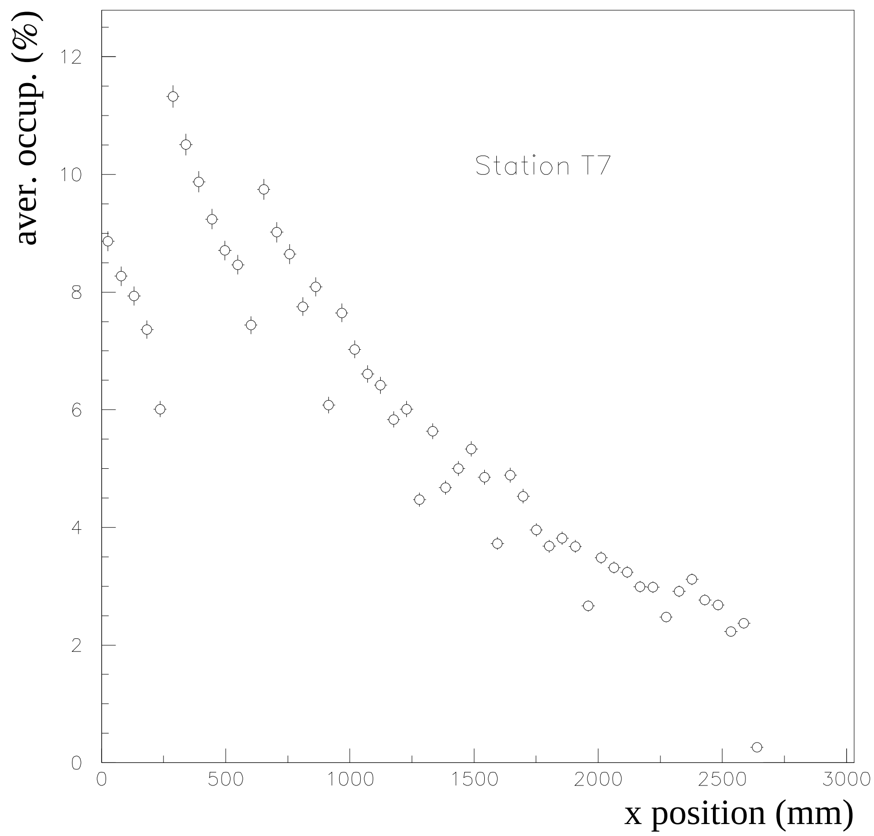
- f.e. dead time $\simeq$ 35 ns / hit

  occupancy $\Longrightarrow$ inefficiency

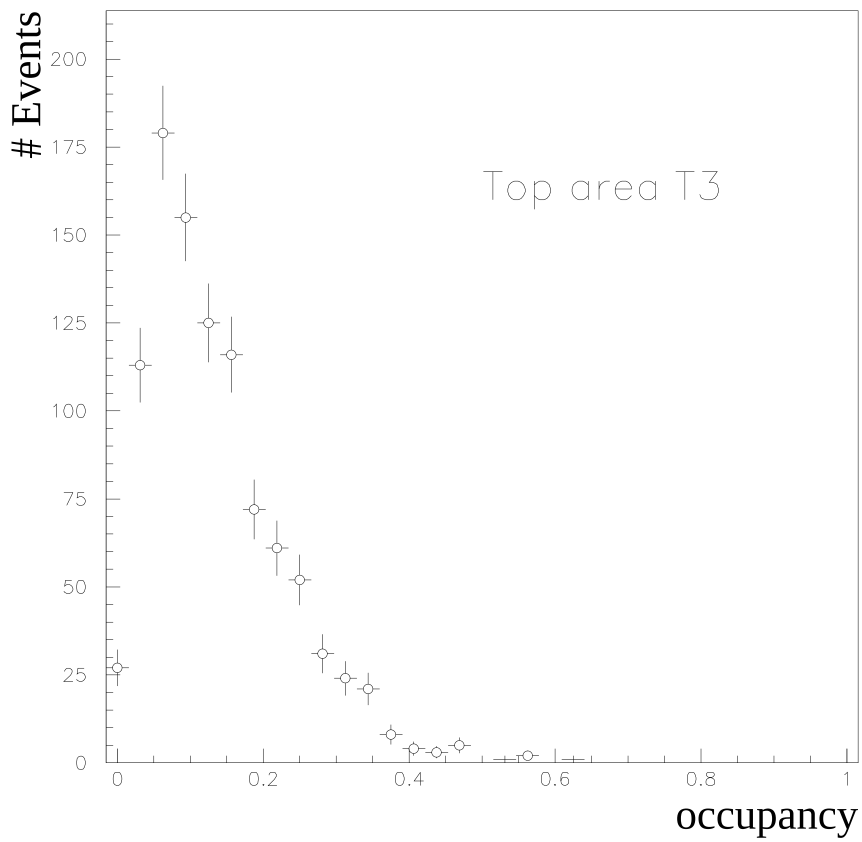


seeding eff. vs number of hits in T6 – T9

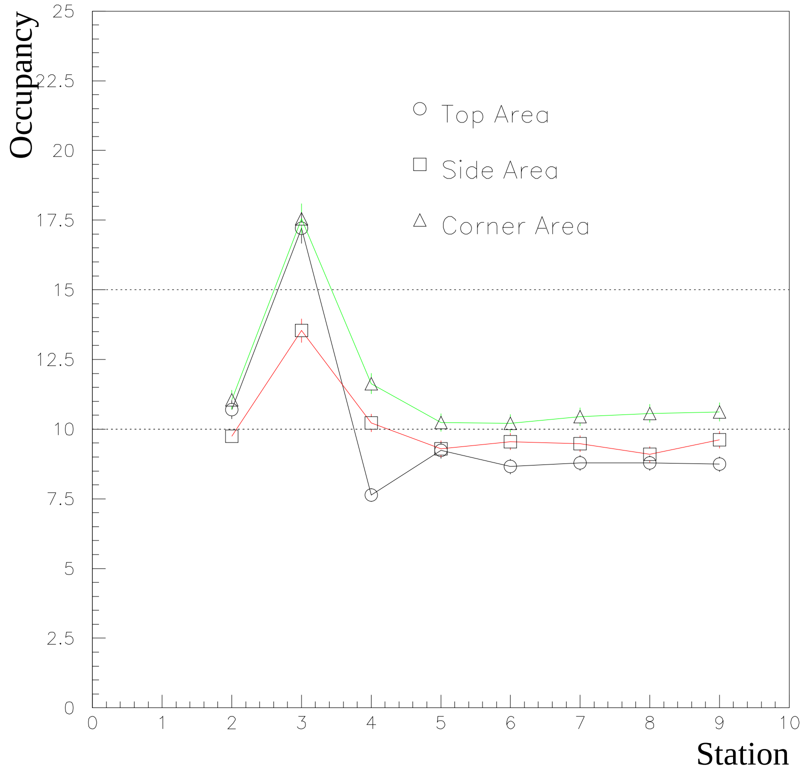
Tuning of IT - OT boundary

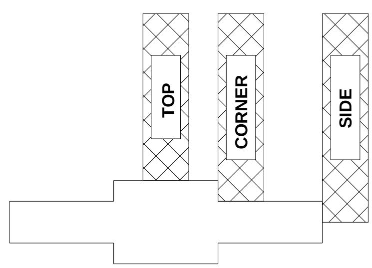


average occupancy vs cell position in T7



event-to-event occupancy fluctuation in hottest region of T3





Average occupancies in the hottest regions of each station at $\mathcal{L} = 2 \times 10^{32} cm^{-2} s^{-1}$

Track reconstruction

OT $\oplus$ IT

Upstream tracking

- find track seeds in T6 – T9
- assume origin in vertex $\Rightarrow \delta p/p$ to O(2 %) from p_t kick
- follow into the gently rising B field

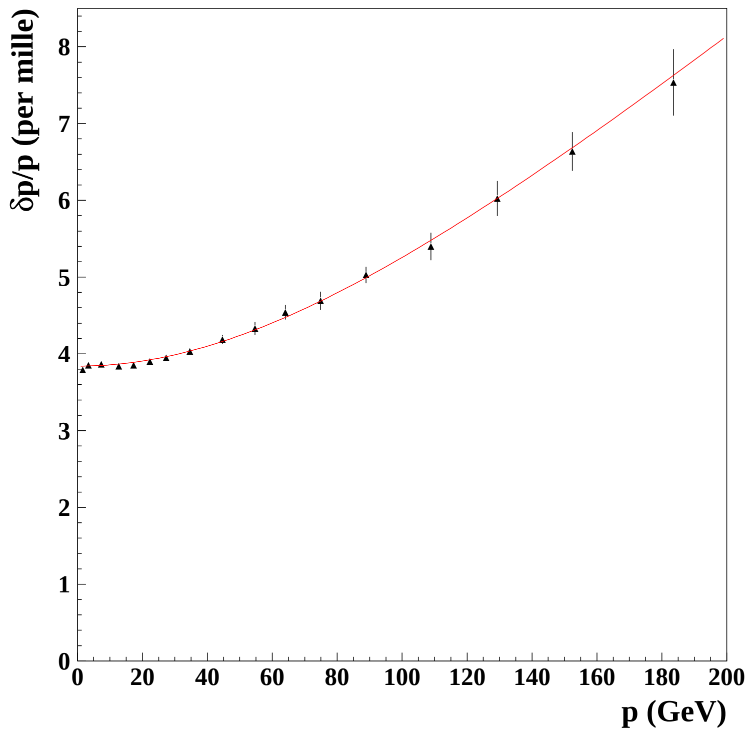
Fast variant for L2 trigger

- match track seed with VELO track, p from kink
  $\delta p/p$ = 1.3 %
  matching eff. = 92 % for $p >$ 5 GeV/c

Downstream tracking

- follow VELO track into the magnet (T4)
  $\delta p/p \simeq$ 0.6 %
  ε = 80 % – 90 % depending on p

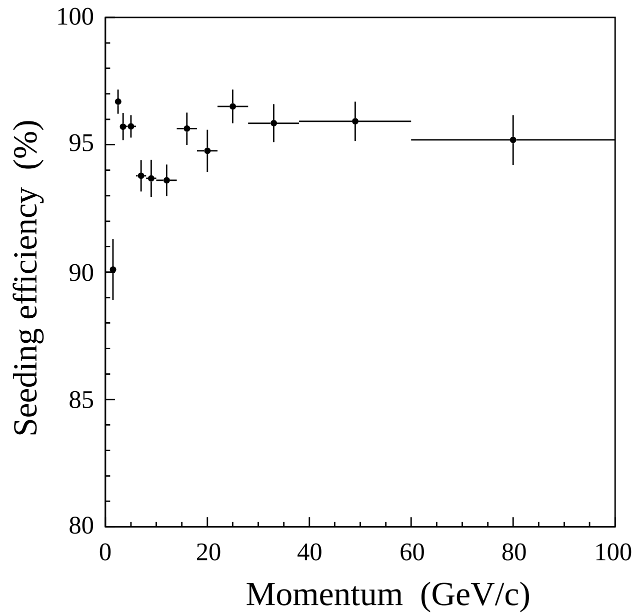
Upstream tracking



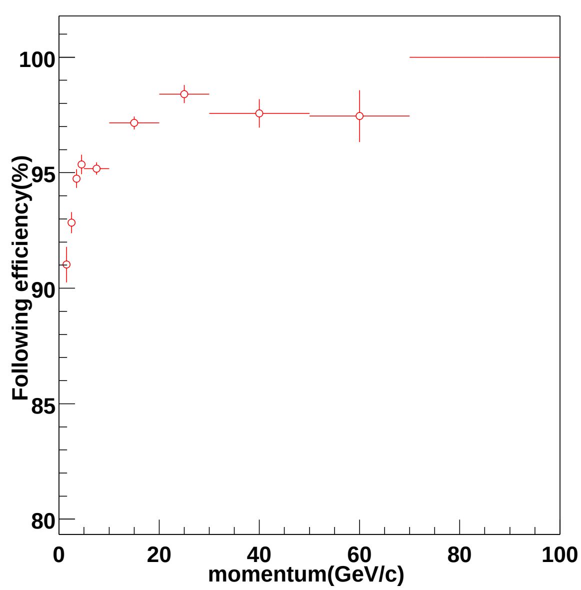
m.s. term (constant) and resolution term ($\propto p$) are equal at 100 GeV/c

$< \delta p/p >$ = 0.39 % for $p > 1$ GeV/c

Upstream tracking efficiencies

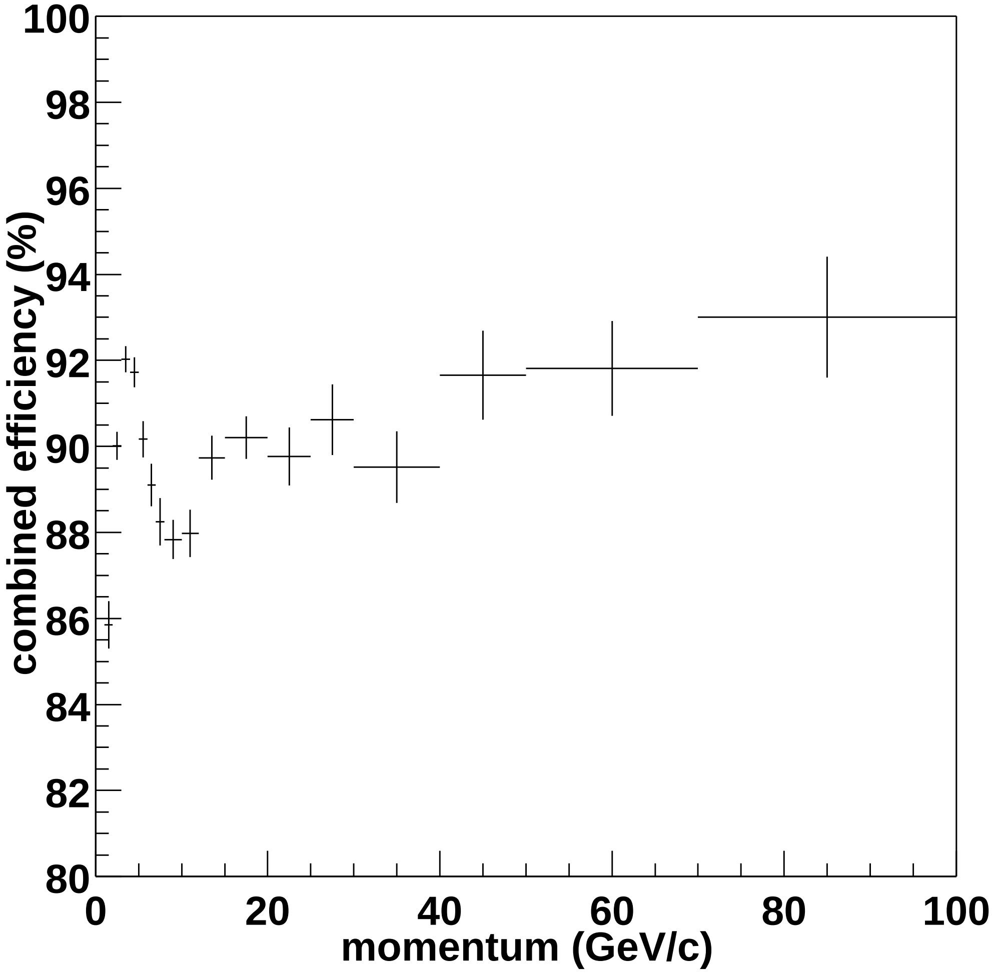


seeding



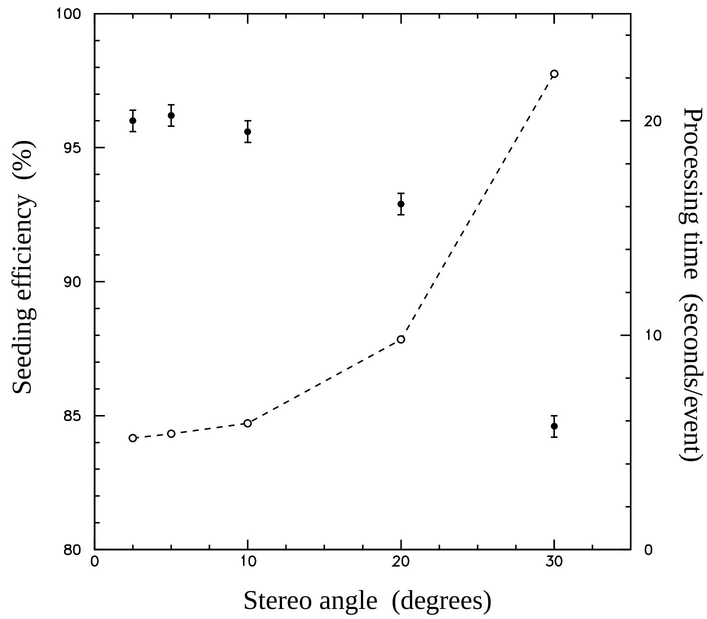
following

requiring $>$ 70 % purity and efficiency of hit assignment

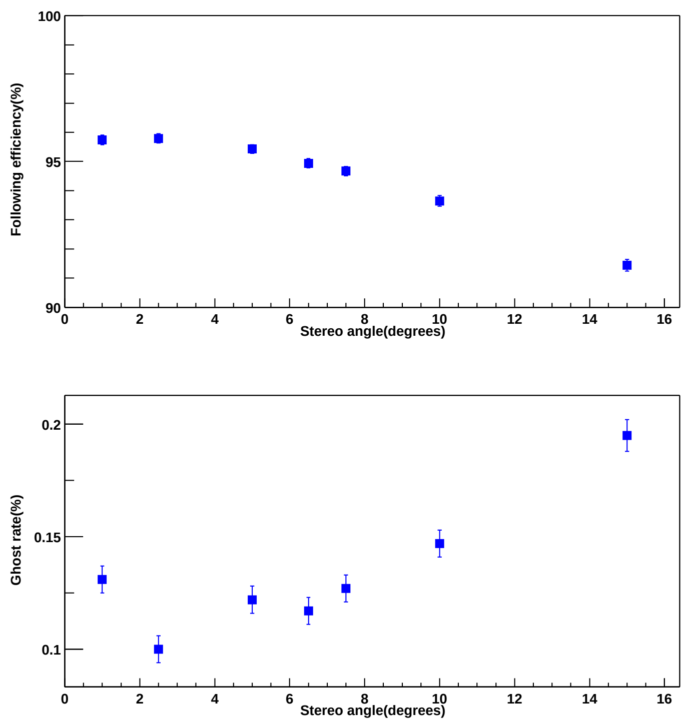

100
98
96
94
92
90
88
86
84
82
80
combined efficiency (%)
0
20
40
60
80
100
momentum (GeV/c)

Stereo angle

track following	$\leq 5^o$
track seeding	$\leq 10^o$
RICH slopes	not too small, 5^o still OK ($\Rightarrow$ 0.09 mrad on track vs 0.58 mrad per photon)



seeding eff. vs stereo angle



following eff. and ghost rate vs stereo angle

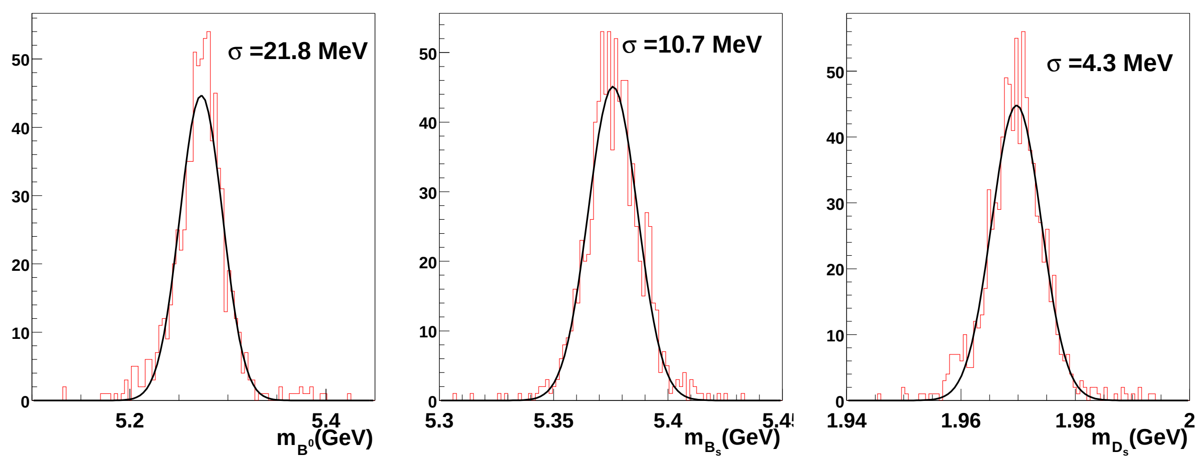
Physics performance illustration

Tracking efficiency

$B_d \to \pi\pi$ 94 % ($\Leftarrow$ 97 % per track)

$B_s \to D_s(KK\pi)K$ 80 % ($\Leftarrow$ 95 % per track)

Mass resolution



$B_d \to \pi\pi$ $B_s \to D_s K$ $D_s \to KK\pi$

comment to mass resolution

Tracker $\Longrightarrow$ track momenta
VELO $\Longrightarrow$ track angles

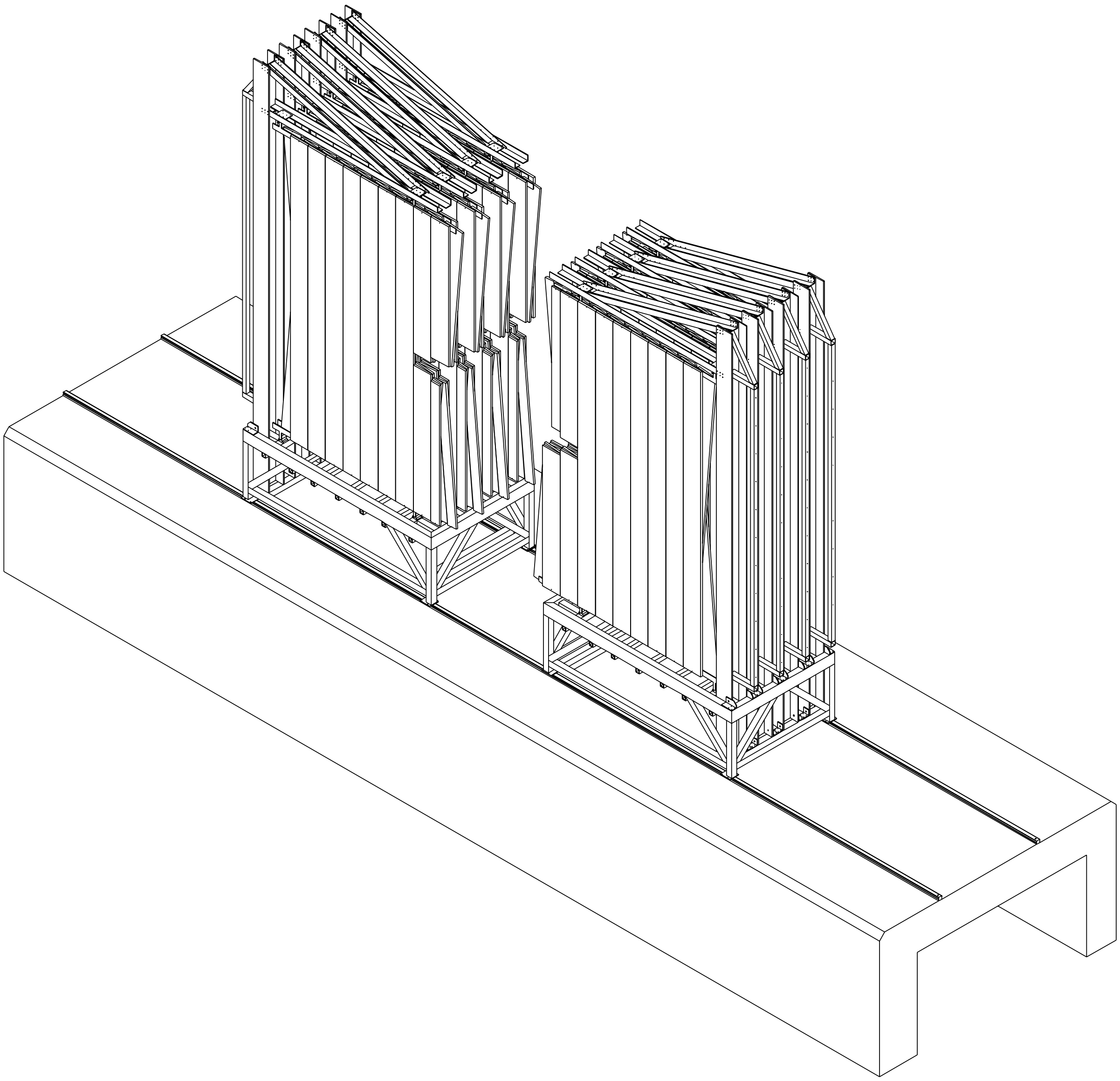
$\delta M/M \propto \delta p/p$ and $\propto \delta\alpha/\alpha$

$B \to \pi\pi$ hard tracks, large opening angle
momentum error dominates

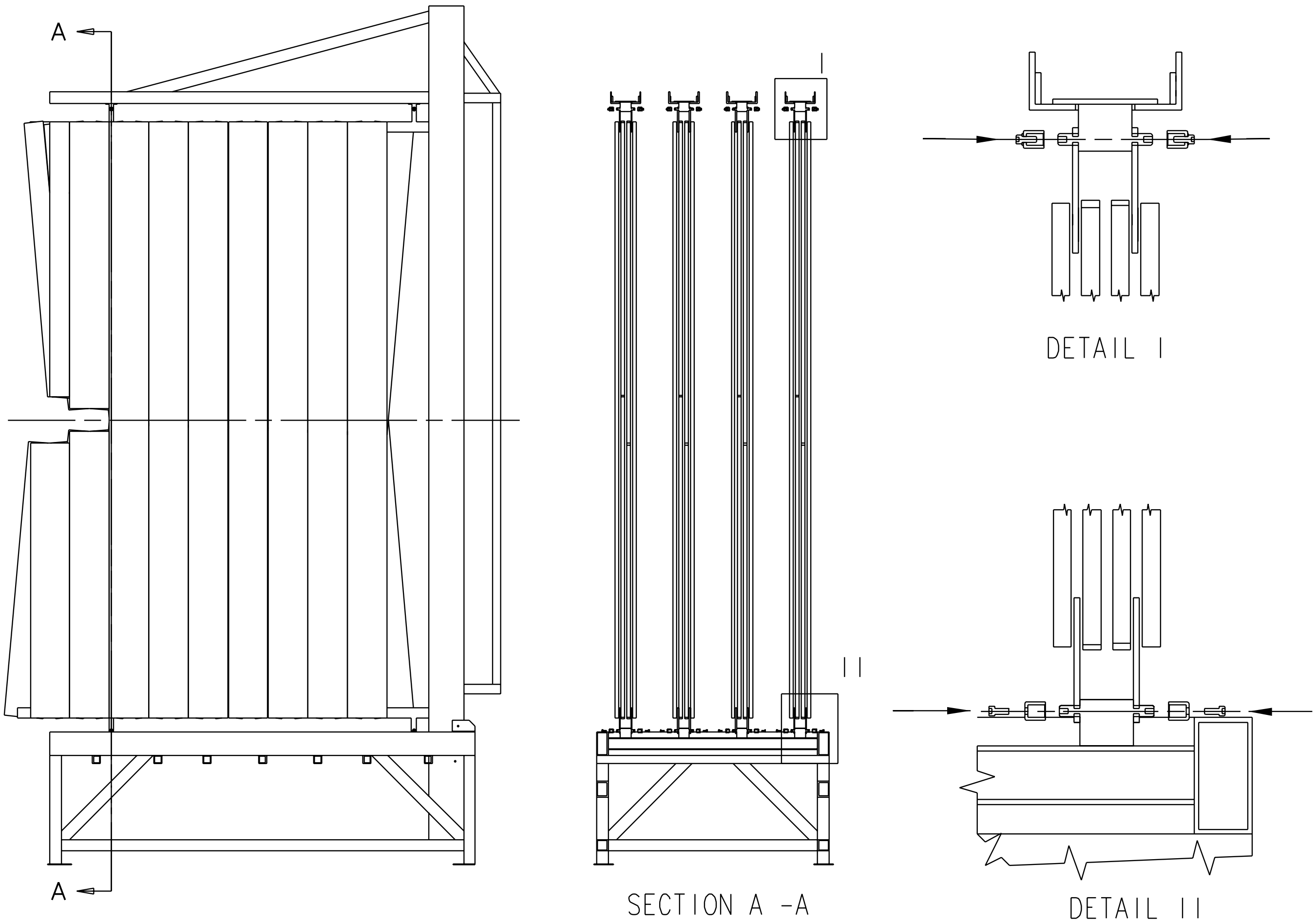
$D_s \to KK\pi$ soft tracks, small opening angle
errors on momenta and angles contribute equally

cp. Techn. Proposal:
assumed $\delta p/p$ = 0.3 %
$\delta M(B_s \to D_s K)$: unchanged
$\delta M(B_d \to \pi\pi)$: 17 MeV/c^2 $\times$ (0.39 % / 0.3 %) = 22 MeV/c^2

STATION DESIGN

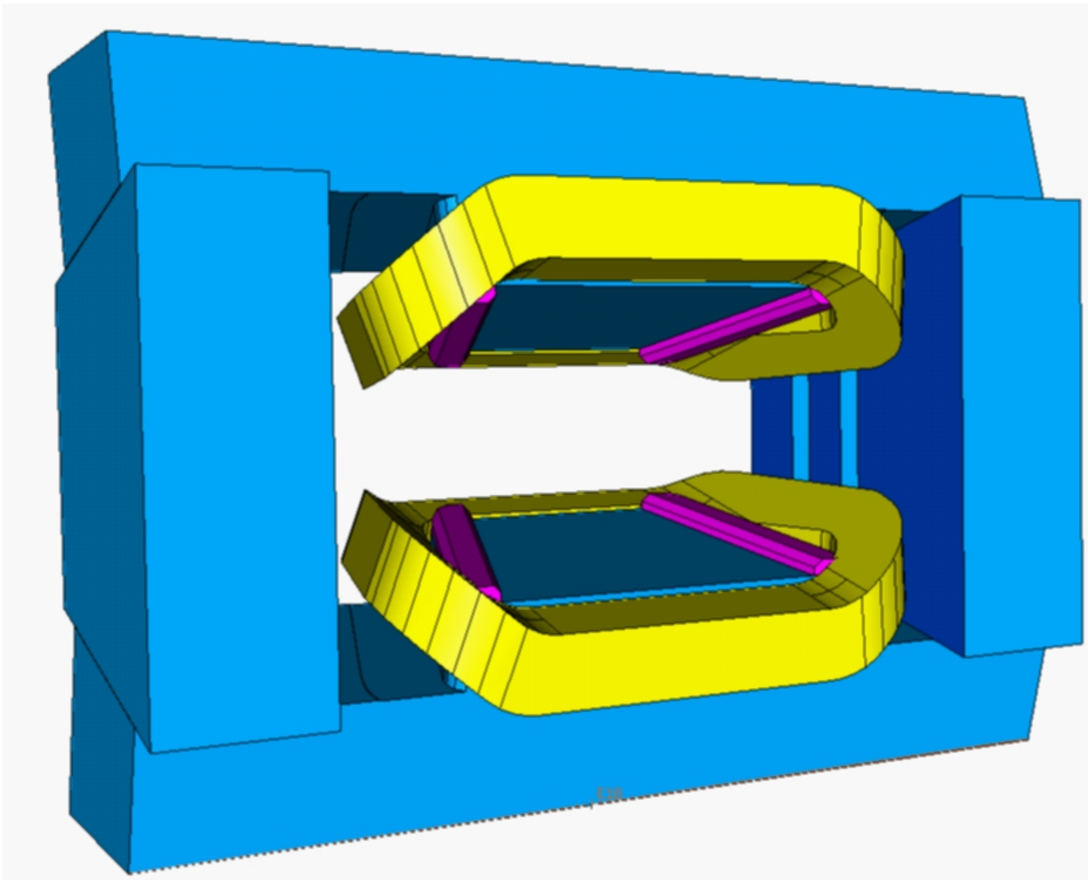


seeding stations T6 – T9 are identical

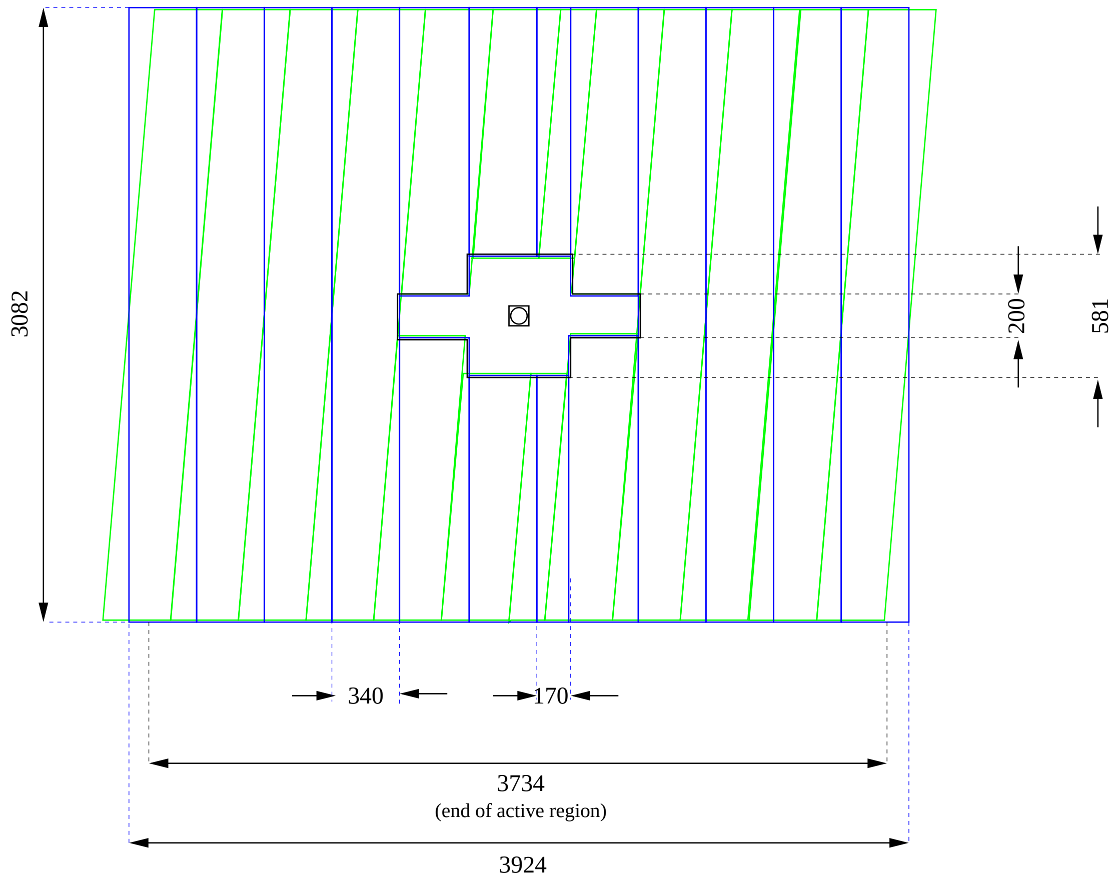


L/R station halves

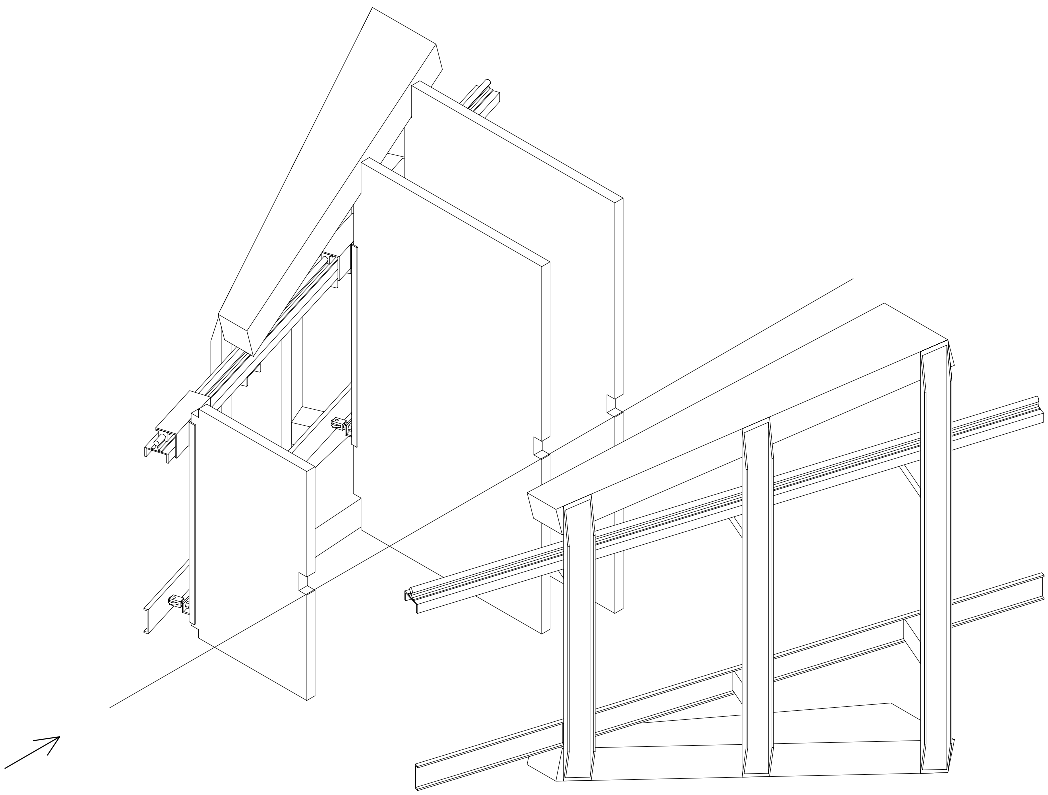
modules mounted on top/bottom precision bars



10 cm between pole faces and $\pm$ 250 mrad acceptance limit



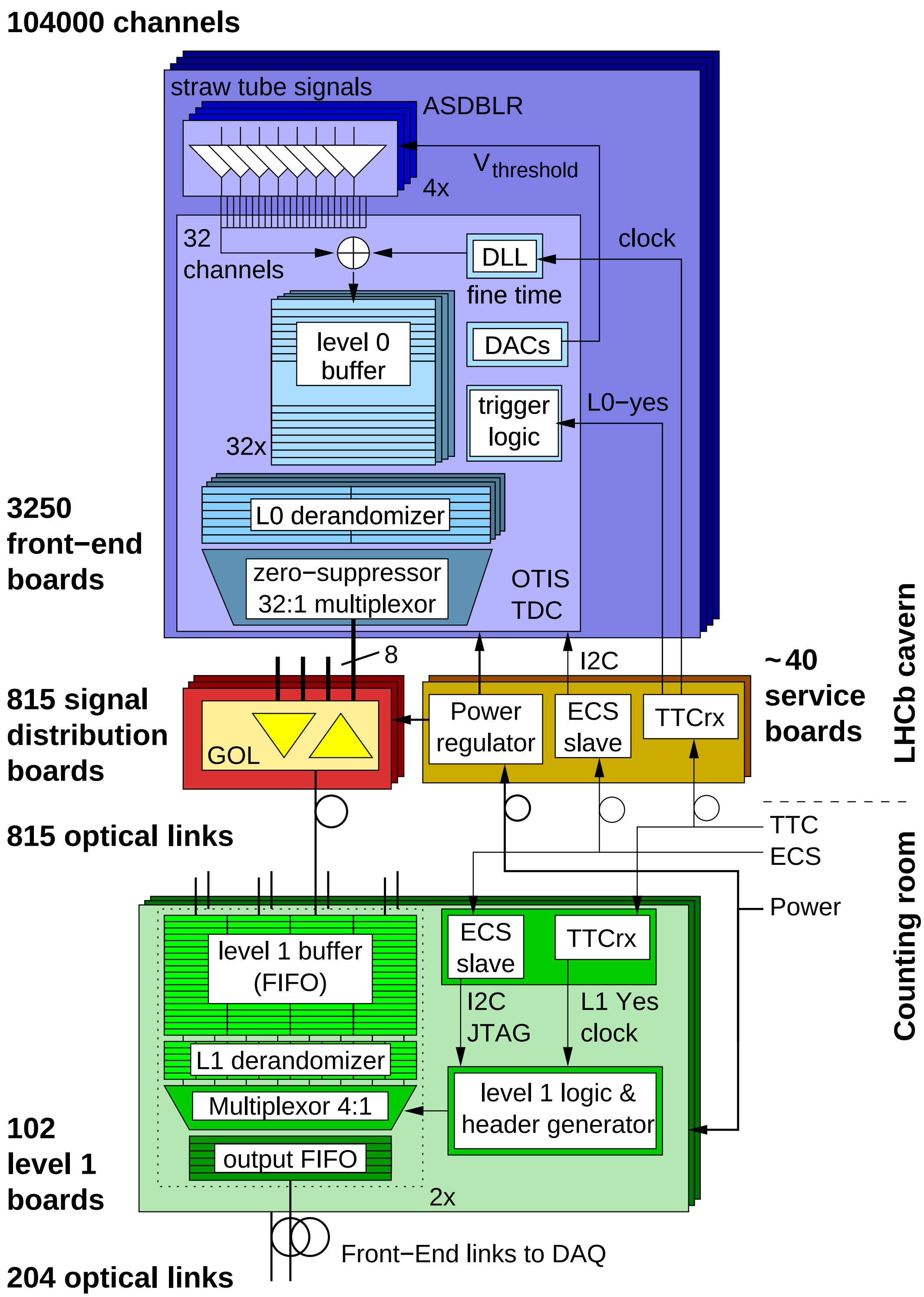
so cut sawtooth of stereo planes away



T3 – T5 mounted on rails fixed to magnet yoke

L/R halves separate when moving out

ELECTRONICS



Front end:

- Hit rates locally up to 4 MHz at $\mathcal{L} = 5 \times 10^{32} cm^{-2} s^{-1}$
- radiation dose O(10 krad/yr) $\Longrightarrow$ rad. tolerant / hard

Preamp: 8-channel ASDBLR chip

DMILL $\rightarrow$	radiation hard
peaking time	8 ns
shaping time	20 ns

Custom designed TDC

OTIS chip, ASIC lab Heidelberg

- rad hard 0.25 μm CMOS
- clock driven (via TTC system from LHC clock)
- DLL adds 5 bits fine time
- 32 channels / chip
- each channel has its own clock-synchronous L0 buffer
- on L0 accept two buckets to derandomizer

OTIS development steps

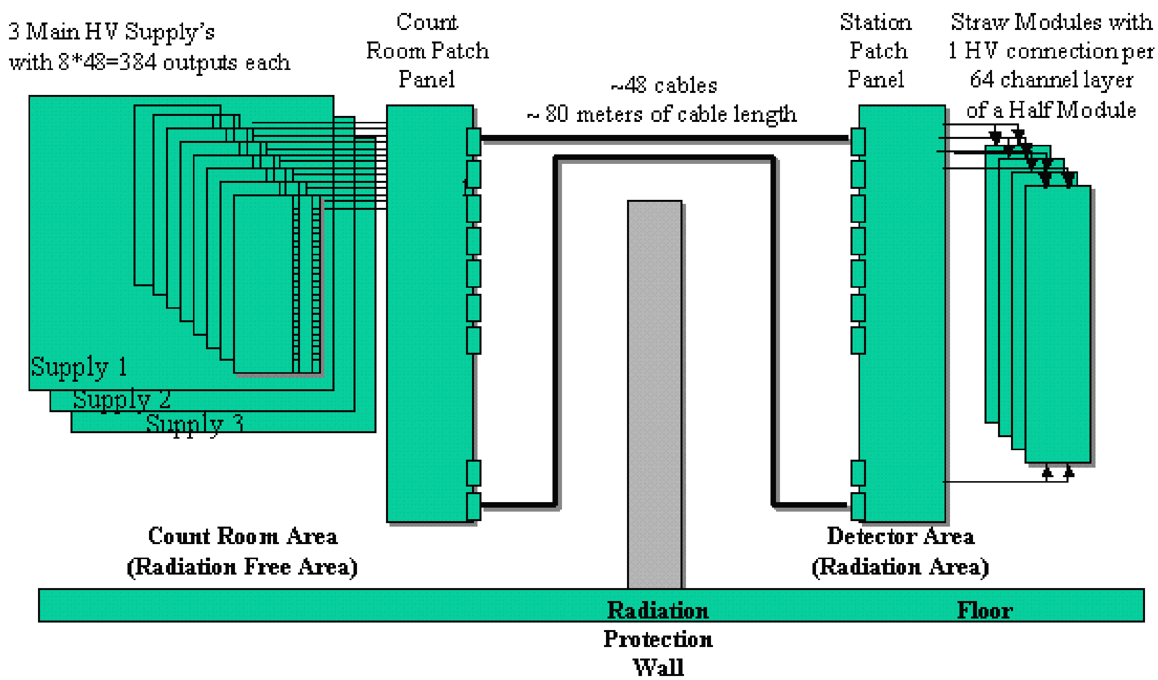
submits of TDC core and memory tested	July 2001
first submit of full chip	April 2002
final evaluation	May 2003

fall-back solution: already existing HPTDC chip

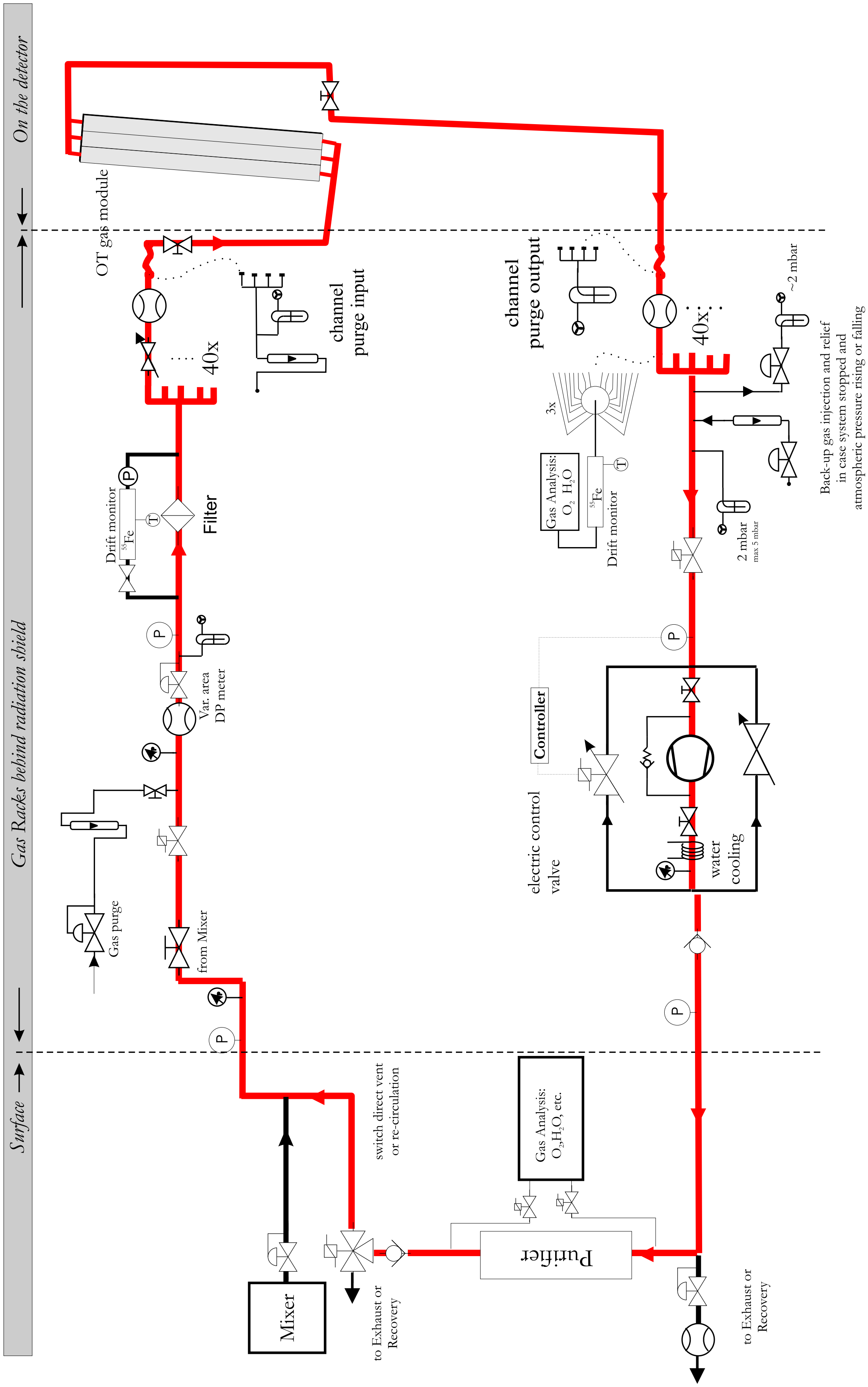
- 32 channels share 1 L0 buffer $\Rightarrow$ in hot regions use only 16 channels/chip
- limited radiation tolerance $\Rightarrow$ not on f.e. boards (racks near detector)
- FPGAs convert data to OTIS format $\Rightarrow$ same L1 electronics

Can do the job at added cost of crates and cabling

HV DISTRIBUTION



2 $\times$ 64 ch per HV branch



On the detector
Gas Racks behind radiation shield
Surface
OT gas module
channel purge input
channel purge output
40x
40x
Drift monitor
Filter
Var. area DP meter
Gas purge
from Mixer
Mixer
to Exhaust or Recovery
switch direct vent or re-circulation
Gas Analysis: O_2,H_2O, etc.
Purifier
to Exhaust or Recovery
electric control valve
Controller
water cooling
Gas Analysis: O_2 H_2O
Drift monitor
3x
2 mbar
max 5 mbar
~2 mbar
Back-up gas injection and relief in case system stopped and atmospheric pressure rising or falling

Drift gas system

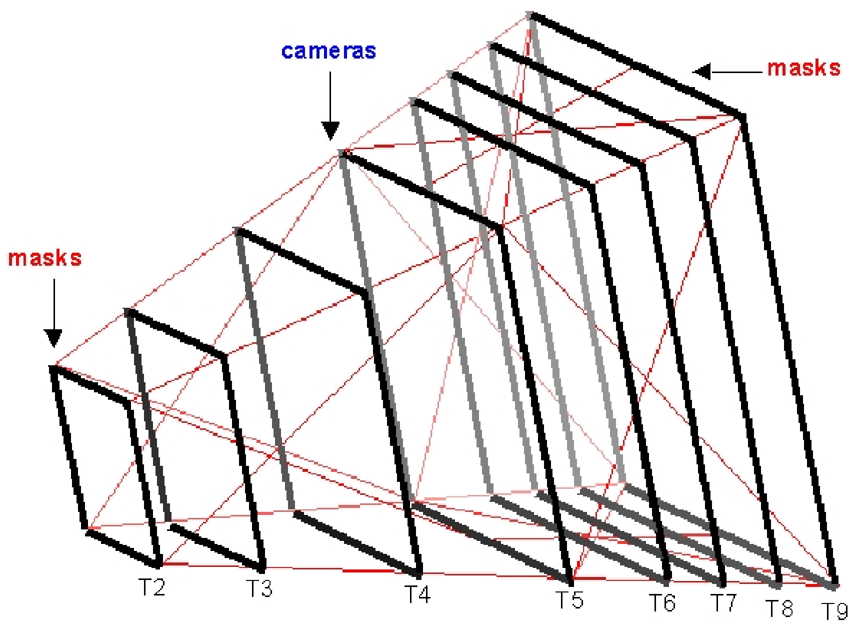
recirculating $\Leftarrow$ CF_4 cost

90 % regeneration per cycle

flow rate O(1 vol/ 2 h)

Hardware alignment monitoring

(if it fits in)

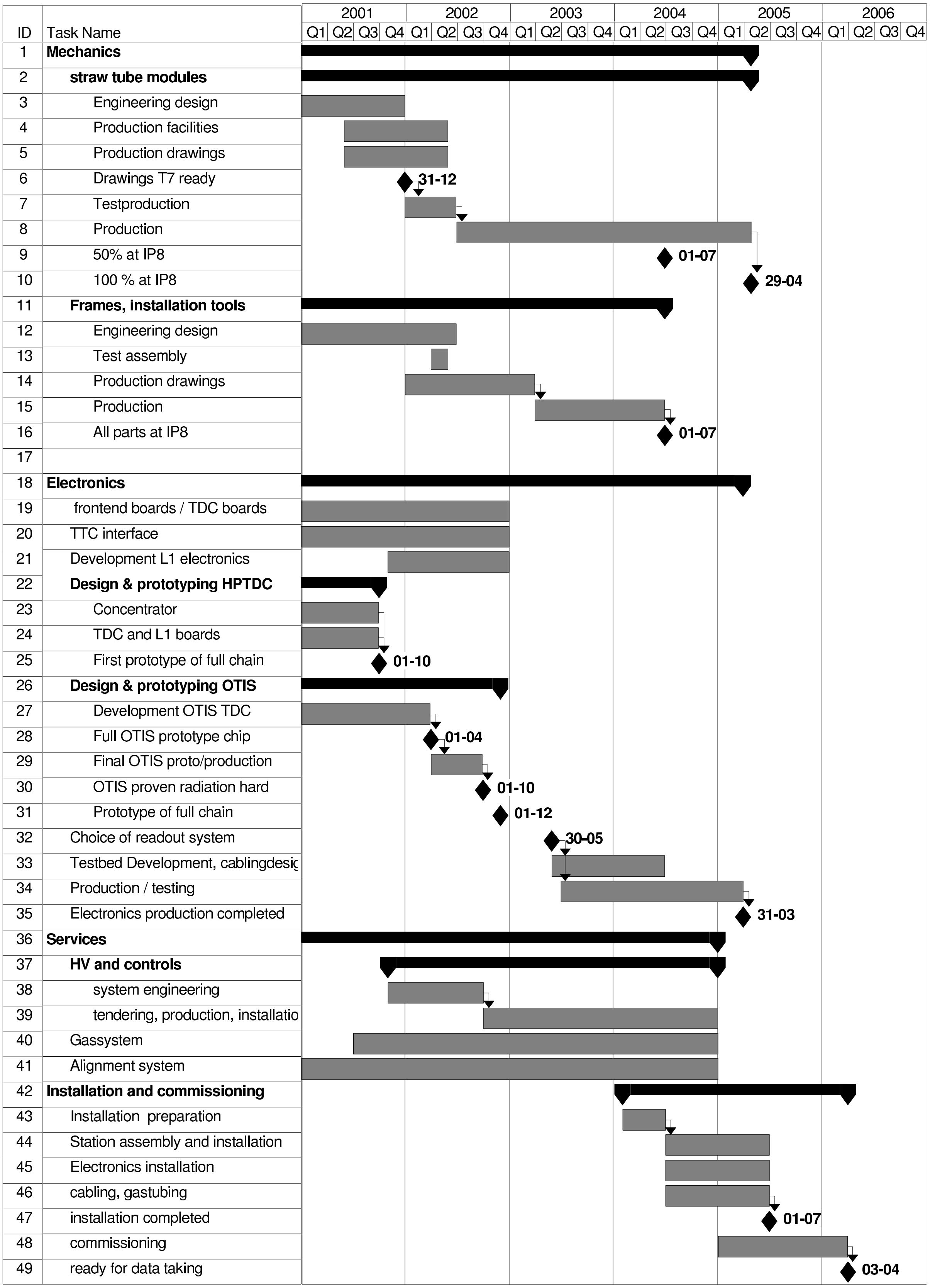


RASNIK system logs movements within station triplets

MASK (1) $\rightarrow$ LENS (2) $\rightarrow$ CCD CAMERA (3)

PROJECT ORGANISATION

Milestone	Date
Mechanics	
Engineering design of modules completed	12/2001
Engineering design of frames completed	6/2002
Start of module production	6/2002
Start of frame production	3/2003
All frame parts at IP8; start of station assembly	6/2004
Last modules to IP8	4/2005
Last station installed	6/2005
Electronics	
TDC choice	5/2003
Start of electronics production	6/2003
All electronics produced and tested	3/2005
Project	
Commissioning completed	3/2006


2001 2002 2003 2004 2005 2006
ID Task Name
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
1 Mechanics
2 straw tube modules
3 Engineering design
4 Production facilities
5 Production drawings
6 Drawings T7 ready
31-12
7 Testproduction
8 Production
9 50% at IP8
01-07
10 100 % at IP8
29-04
11 Frames, installation tools
12 Engineering design
13 Test assembly
14 Production drawings
15 Production
16 All parts at IP8
01-07
17
18 Electronics
19 frontend boards / TDC boards
20 TTC interface
21 Development L1 electronics
22 Design & prototyping HPTDC
23 Concentrator
24 TDC and L1 boards
25 First prototype of full chain
01-10
26 Design & prototyping OTIS
27 Development OTIS TDC
28 Full OTIS prototype chip
01-04
29 Final OTIS proto/production
30 OTIS proven radiation hard
01-10
31 Prototype of full chain
01-12
32 Choice of readout system
30-05
33 Testbed Development, cablingdesig
34 Production / testing
35 Electronics production completed
31-03
36 Services
37 HV and controls
38 system engineering
39 tendering, production, installatio
40 Gassystem
41 Alignment system
42 Installation and commissioning
43 Installation preparation
44 Station assembly and installation
45 Electronics installation
46 cabling, gastubing
47 installation completed
01-07
48 commissioning
49 ready for data taking
03-04

Task	Institutes
Mechanics	
T2 – T5	Heidelberg, Krakow
T6 – T9	Beijing, NIKHEF, Warsaw
Electronics	
Before TDC	NIKHEF
From TDC to DAQ	
Baseline design	Dresden, Heidelberg, NIKHEF
Fall-back design	Krakow, NIKHEF
Production & testing	Beijing, Dresden, Heidelberg, NIKHEF
Services	
Drift gas	CERN, Krakow
High voltage	CERN, NIKHEF
Alignment	Warsaw
Controls	NIKHEF

Comments

620 modules includes 10 % spares

assembly of large stations at CERN

tracking software and performance studies:
common for OT + IT by Tracking Task Force

PROJECT COST

detector modules	2720 kCHF
electronics	5570
frames and installation	560
services	450
TOTAL	9300 kCHF

SUMMARY

- Module design: ready and proven
- Known how to assemble into stations
- Electronics is designed; TDC still under development, fall-back is on the shelf
- Tracker layout simplified: two stations less than in Technical Proposal
- Track reconstruction efficiency through entire spectrometer $\geq$ 90 %
- Momentum resolution 0.39 %
  (T.P. assumed 0.3 %)
- Outer Tracker represents 0.24 X_0
  (T.P. idealized design 0.18 X_0)
- Resources of people, time and money match the present project size

Further LHCb optimization: trend to ‘less is even better’

May drop another station, but no effect on technical design