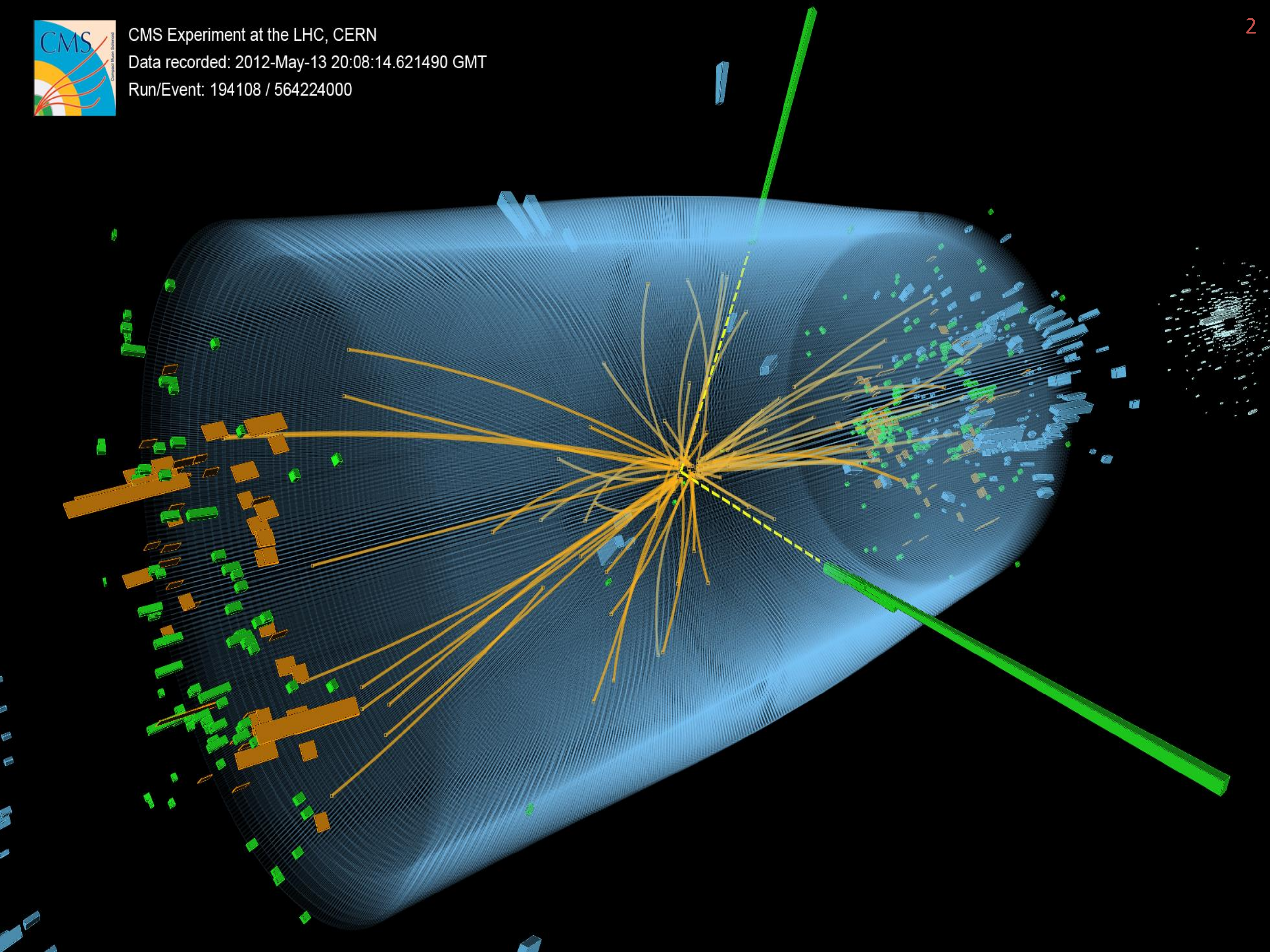
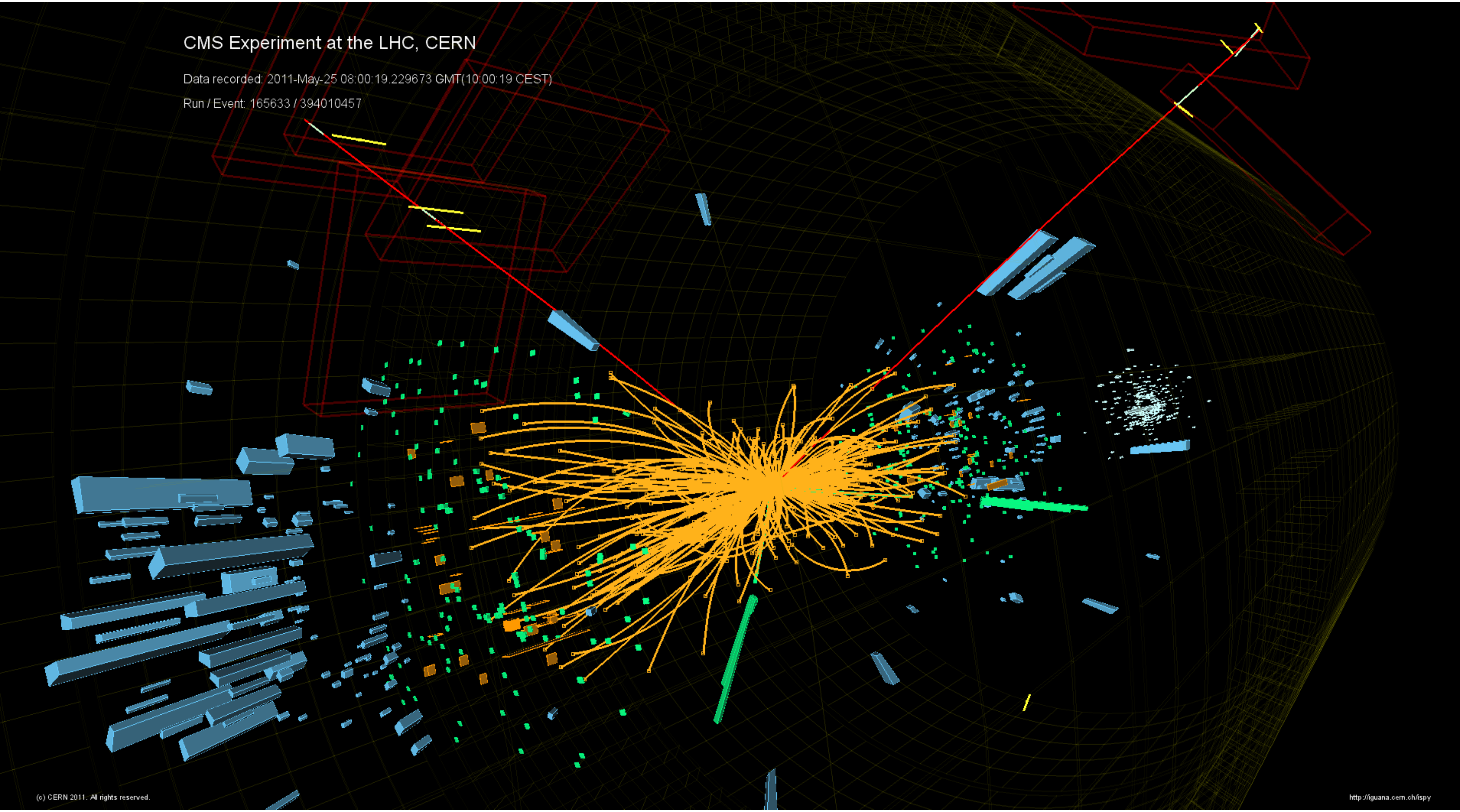
Roger Rusack The University of Minnesota

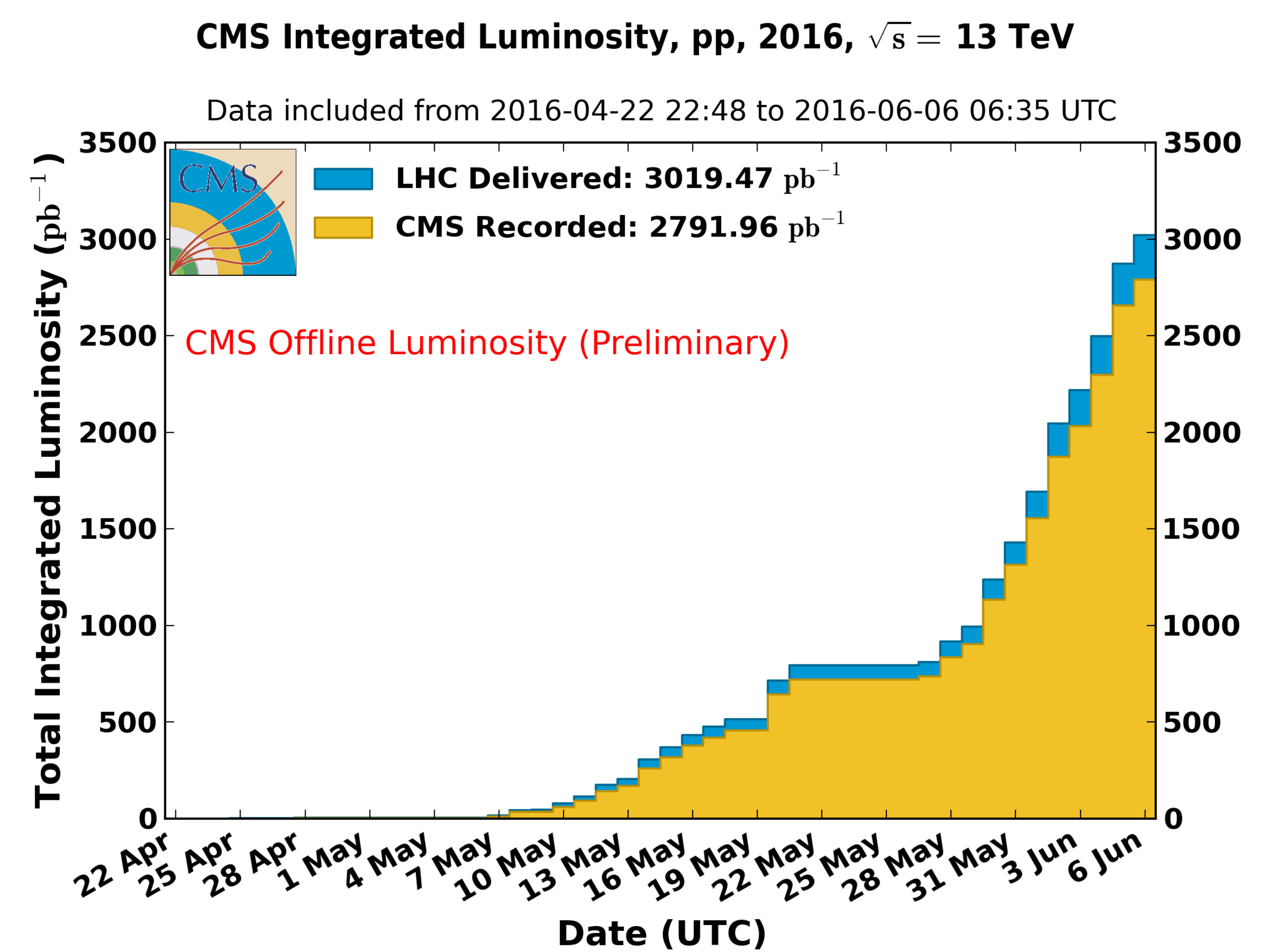
CMS - OVERVIEW


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
(c) CERN 2011. All rights reserved.
http://iguana.cern.ch/ispy

History:

- Aachen 1990:
  - Concept of a compact detector based on high B field superconducting solenoid first discussed in 1990 at Aachen,
- Evian 1992
  - Conceptual Design
- Letter of Intent, October 1992 [CERN/LHCC 92-3]
- Technical Proposal, Dec 1994 [CERN/LHCC 94-38]
- Memorandum of Understanding (MoU) 1998
- Technical Design Reports (available from the CMS secretariat)
  - Detectors 1997-98;
  - Lvl-1 Trigger: 2000;
  - DAQ/HLT: 2002
  - Computing & Physics TDR: 2005-06
- 2008: First data taking: LHC Incident. Restart in 2009.
- **2010-2013 Data taking [Run I]:**
  - 7 TeV (5fb^{-1})
  - 8 TeV (20 fb^{-1})
  - Heavy Ion: Pb-Pb and p-PB
- 2015 – 2016
  - 2.3 fb^{-1} + ...

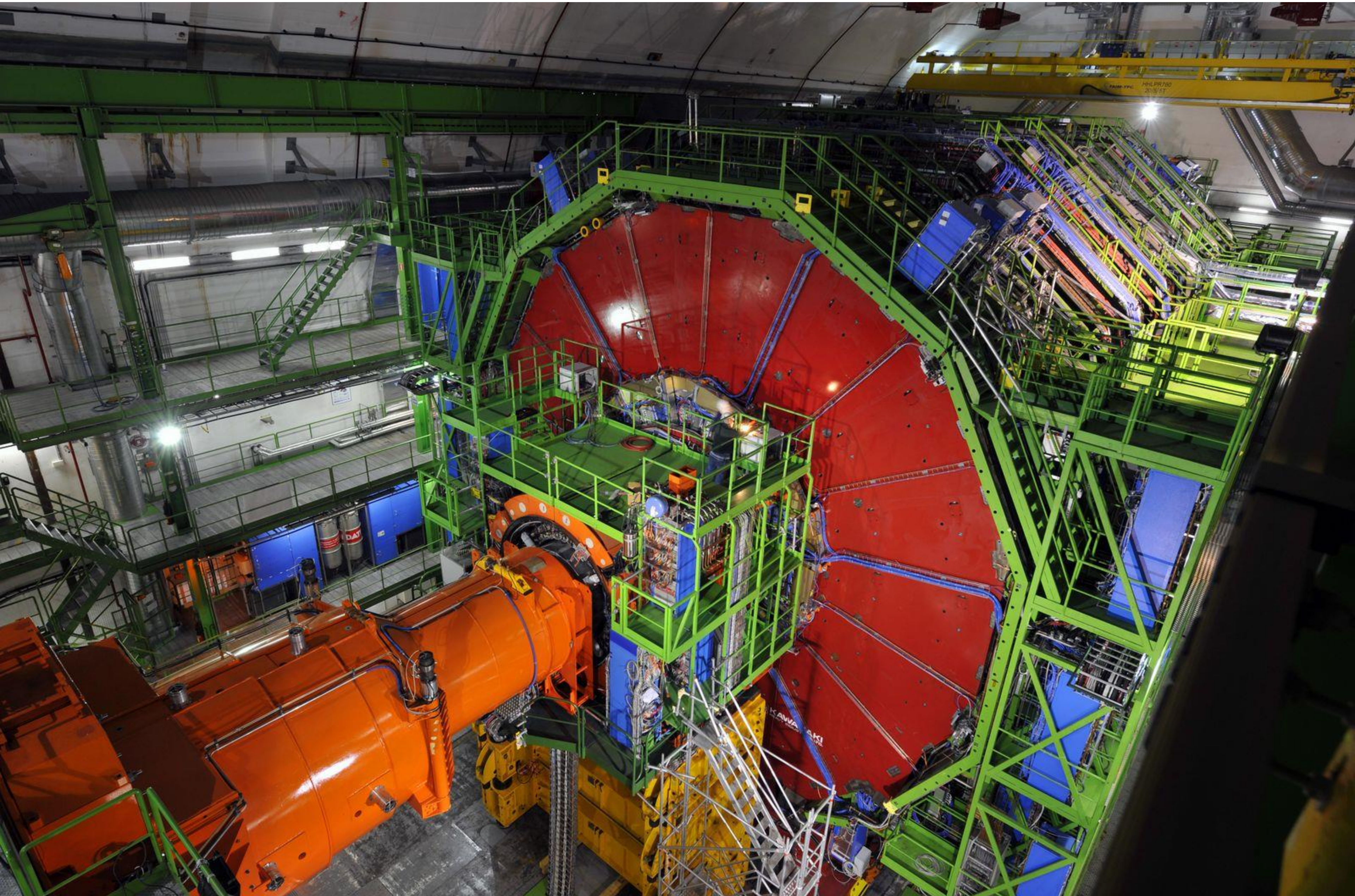

CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = 13$ TeV
Data included from 2016-04-22 22:48 to 2016-06-06 06:35 UTC
LHC Delivered: 3019.47 pb^{-1}
CMS Recorded: 2791.96 pb^{-1}
CMS Offline Luminosity (Preliminary)
CMS
Total Integrated Luminosity (pb^{-1})
0
500
1000
1500
2000
2500
3000
3500
22 Apr
25 Apr
28 Apr
1 May
4 May
7 May
10 May
13 May
16 May
19 May
22 May
25 May
28 May
31 May
3 Jun
6 Jun
Date (UTC)

CMS Primary Measurement Goals:

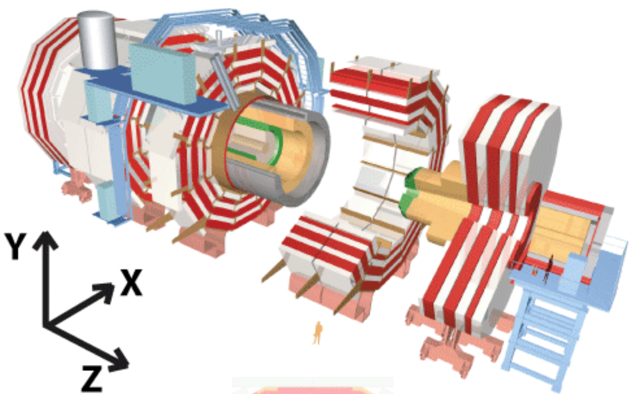
- Muon momentum resolution <10% at P~1TeV/c (reconstruction of mass of Z') translates into a requirement on μ-hit position resolution and chamber alignment.
- Good momentum resolution for low momentum particles.
- Efficiency at separating vertices close to beam line (pileup, heavy flavor identification): tracker resolution and alignment.
- Precision calorimetry for the $\gamma\gamma$ decay channel of the Higgs.

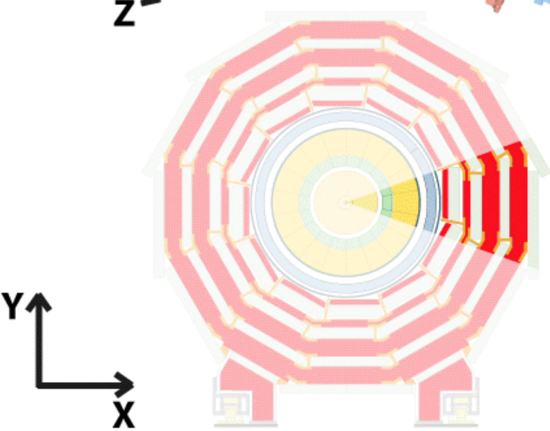
LHC Constraints

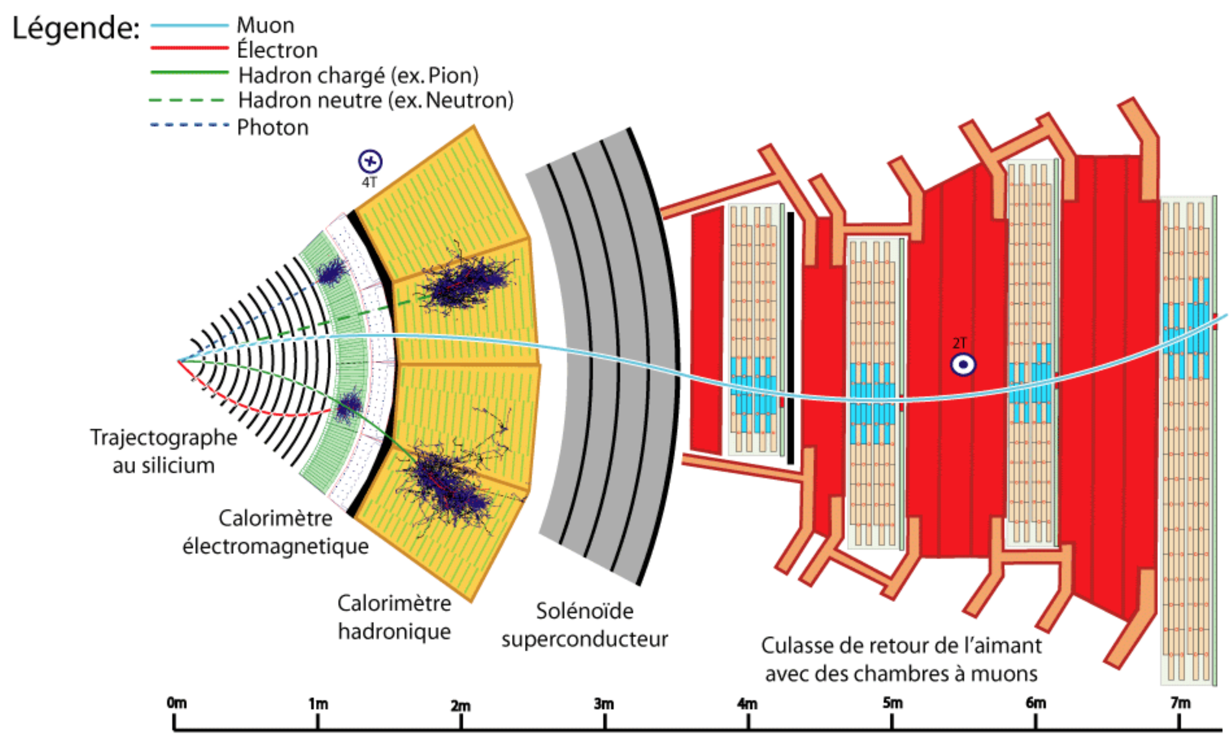
- Bunch separation 25 ns: a challenge for the readout electronics
  - Need of fast electronics to avoid piling up signals from one bunch to the next
  - Need of bunch identification (even a trigger level)
- Ultimate luminosity 2 10^{34} cm^2/s : ~ 40 interactions per crossing
  - Need highly granular detector to mitigate 'channel' pileup: many channels
- Radiation damage: the high rate hadron production in LHC requires development of radiation hard detector/electronics
  - Forward calorimeters elements will integrate in excess of 10^{16} neutrons/cm^2 over 10 years of LHC operation
  - Forward trackers will integrate in excess of 10^{16} charged particles over the operation of LHC



Basic Design







The CMS Magnet

Magnetic length 12.5m

Cold bore diameter 6.3m

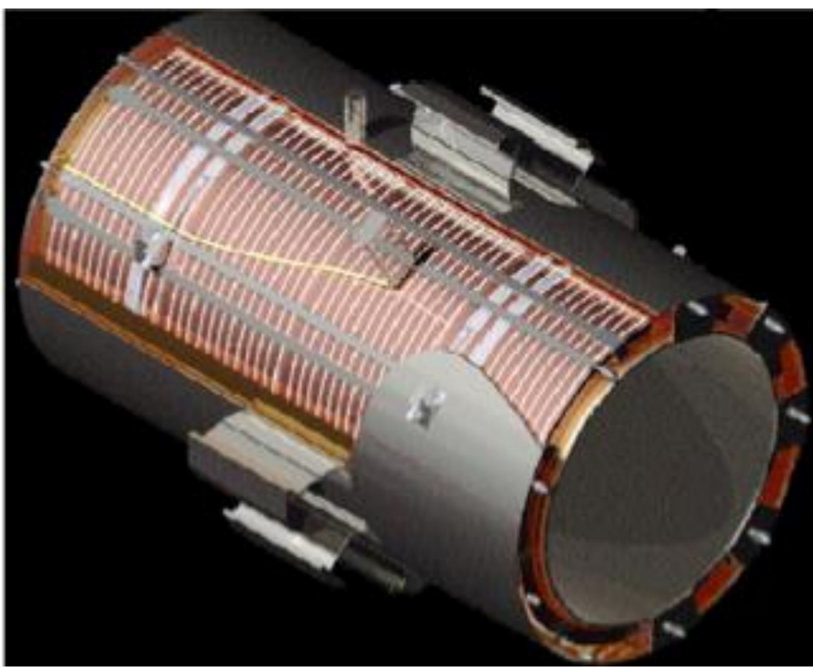
Central magnetic induction 4 T

Total Ampere-turns 41.7 MA-turns

Nominal current 19.14 kA

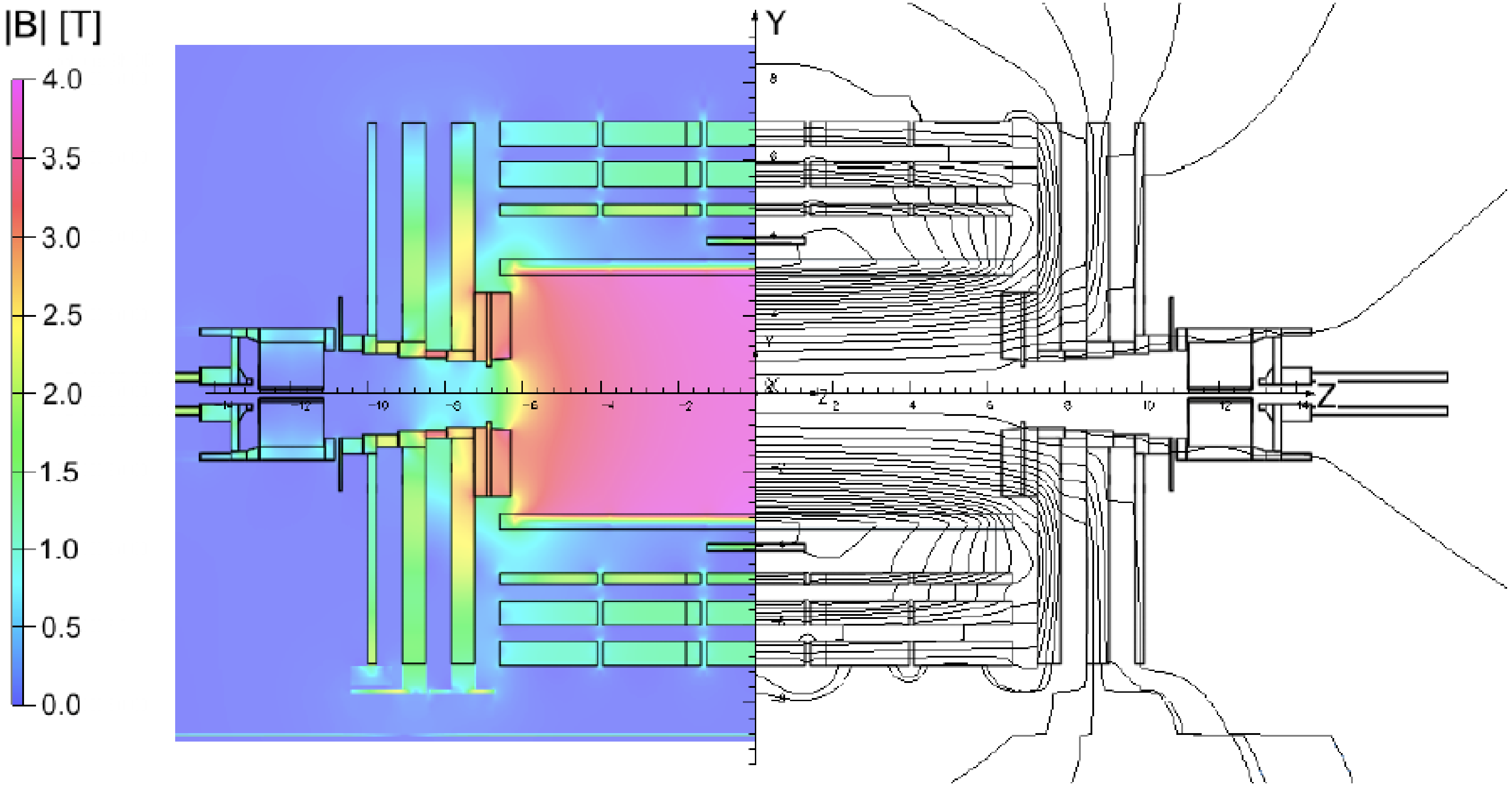
Inductance 14.2H

Stored energy 2.6 GJ



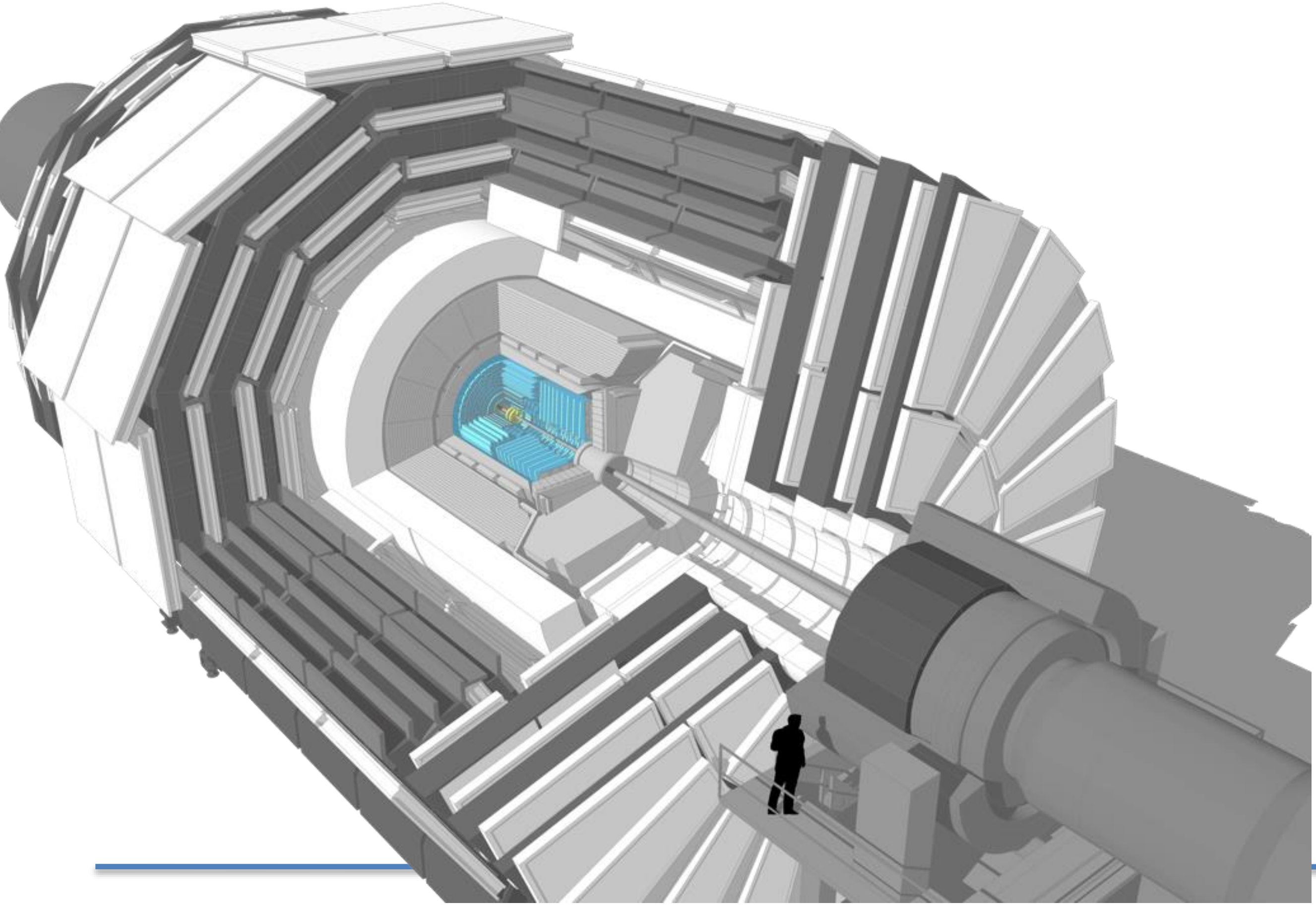
Return flux is through the iron of the muon detectors

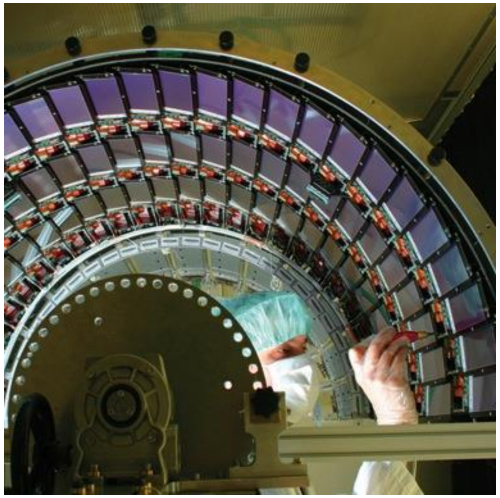
The Magnetic Field



The CMS Tracker

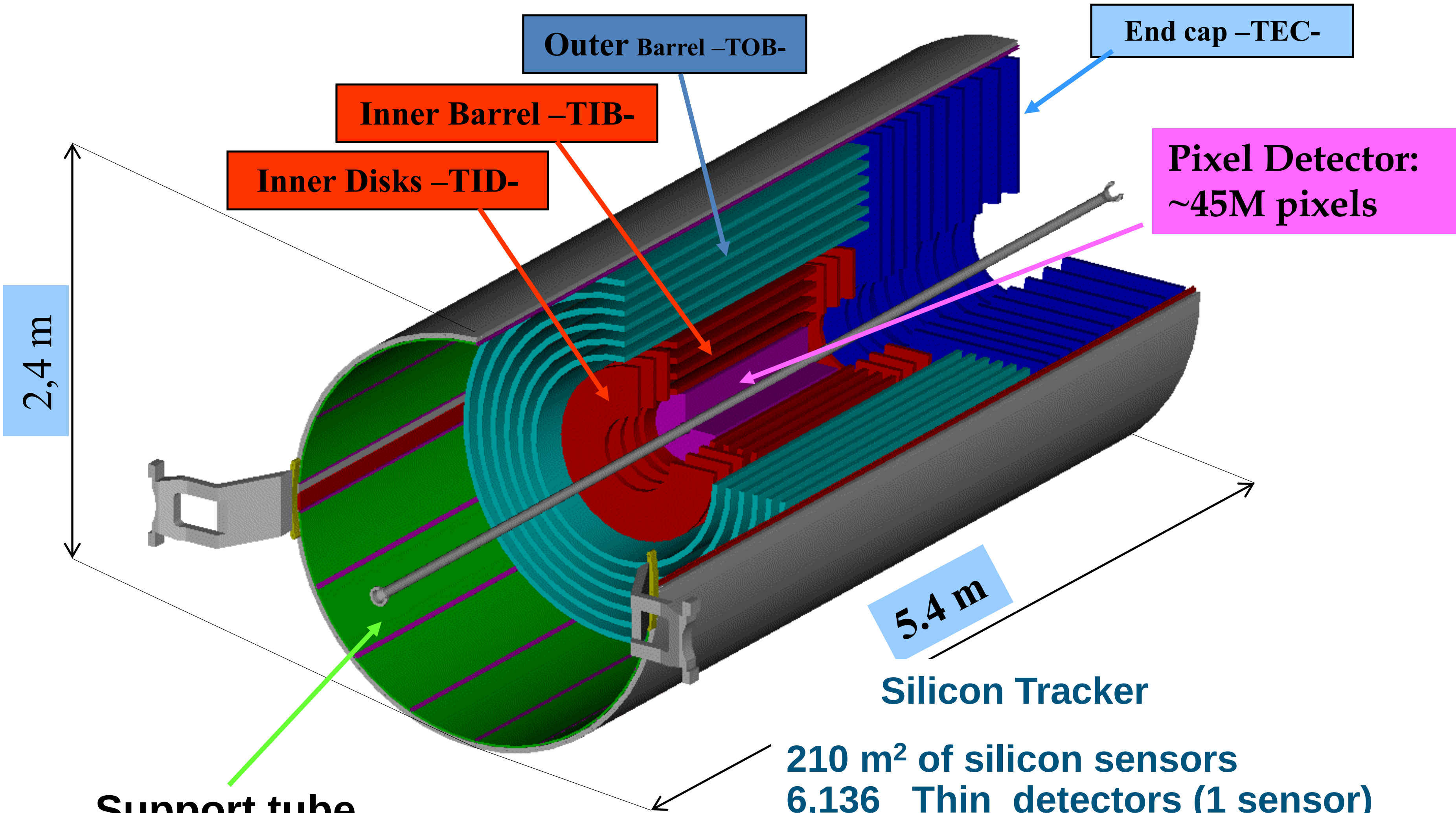
Finely segmented silicon sensors
Segmented into strips and pixels





66 Million Pixel
10 Million Strips

CMS Tracker

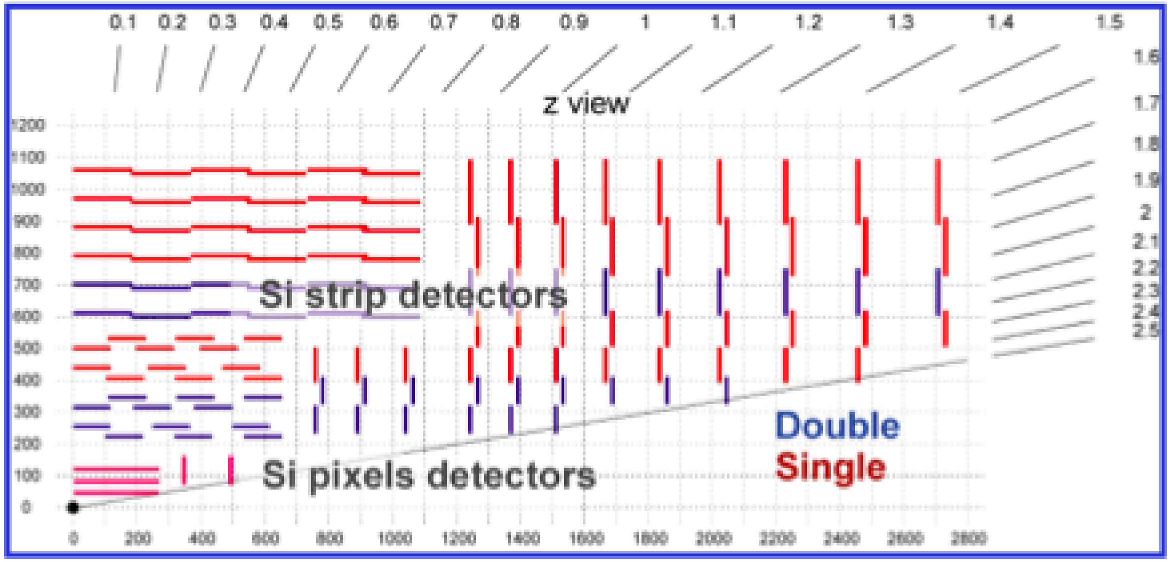


Silicon Tracker

210 m² of silicon sensors
6,136 Thin detectors (1 sensor)
9,096 Thick detectors (2 sensors)
10M channels

- Resolution goals:
  - $p_T/p_T \sim 0.1 p_T$[TeV]
  - Good resolution for narrow Signal ($H \to 4\propto$)
  - Match calorimeter resolution / Calorimeter calibration ($W \to e\{$)
  - ..and good isolation capability (2 particle separation etc.)
- CMS solution: 10 Si Strip (4 double) layers + 3 Si pixel layers & 2 fwd disks

CMS Tracker



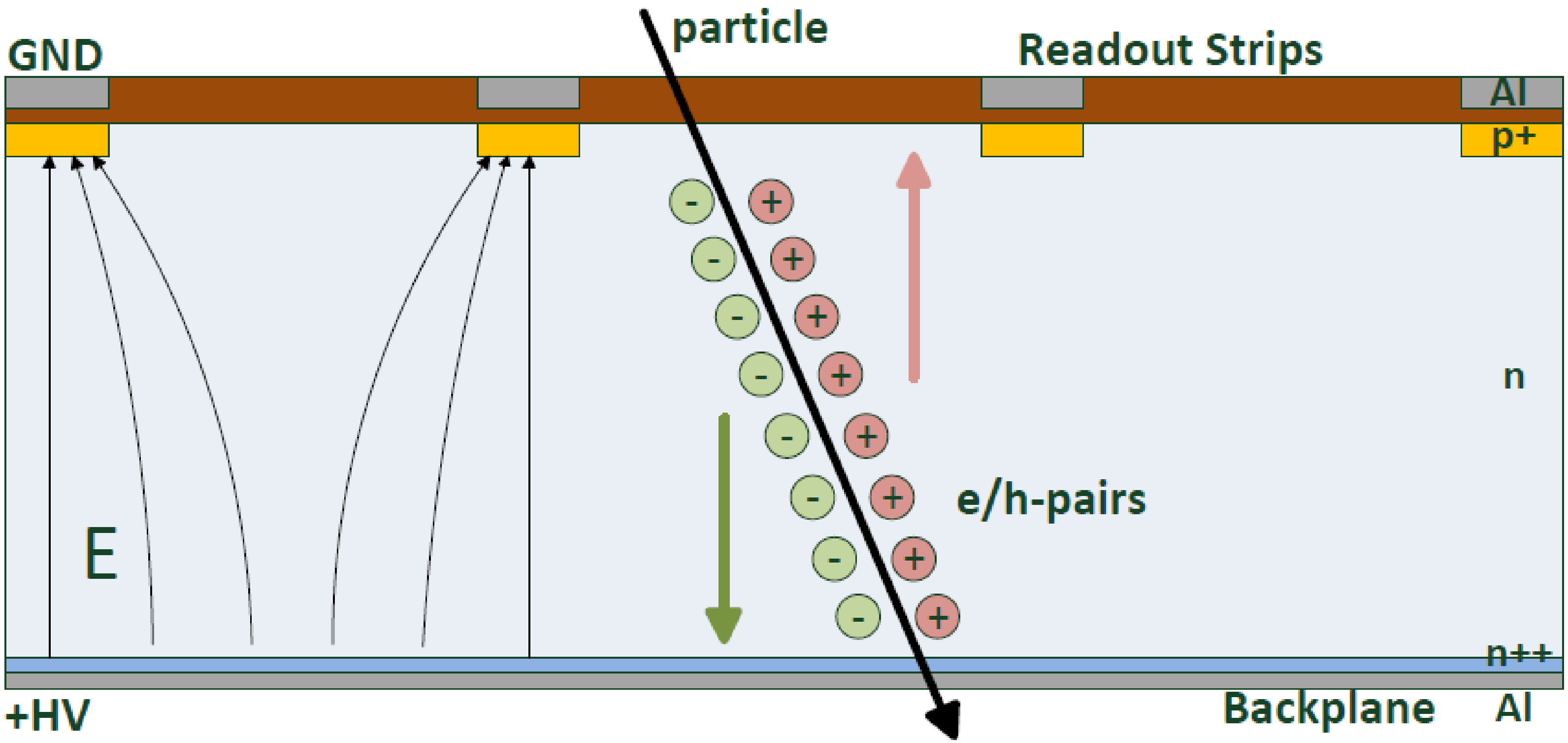
Outer radius: 110 cm
Length = 540 cm
On average 12 hits per track
Hit resol: pitch/√12

$$\frac{\Delta p}{p} \approx 0.12\left(\frac{pitch}{100\mu m}\right)^{1}\left(\frac{1.1m}{L}\right)^{2}\left(\frac{4T}{B}\right)^{1}\left(\frac{p}{1Tev}\right)$$

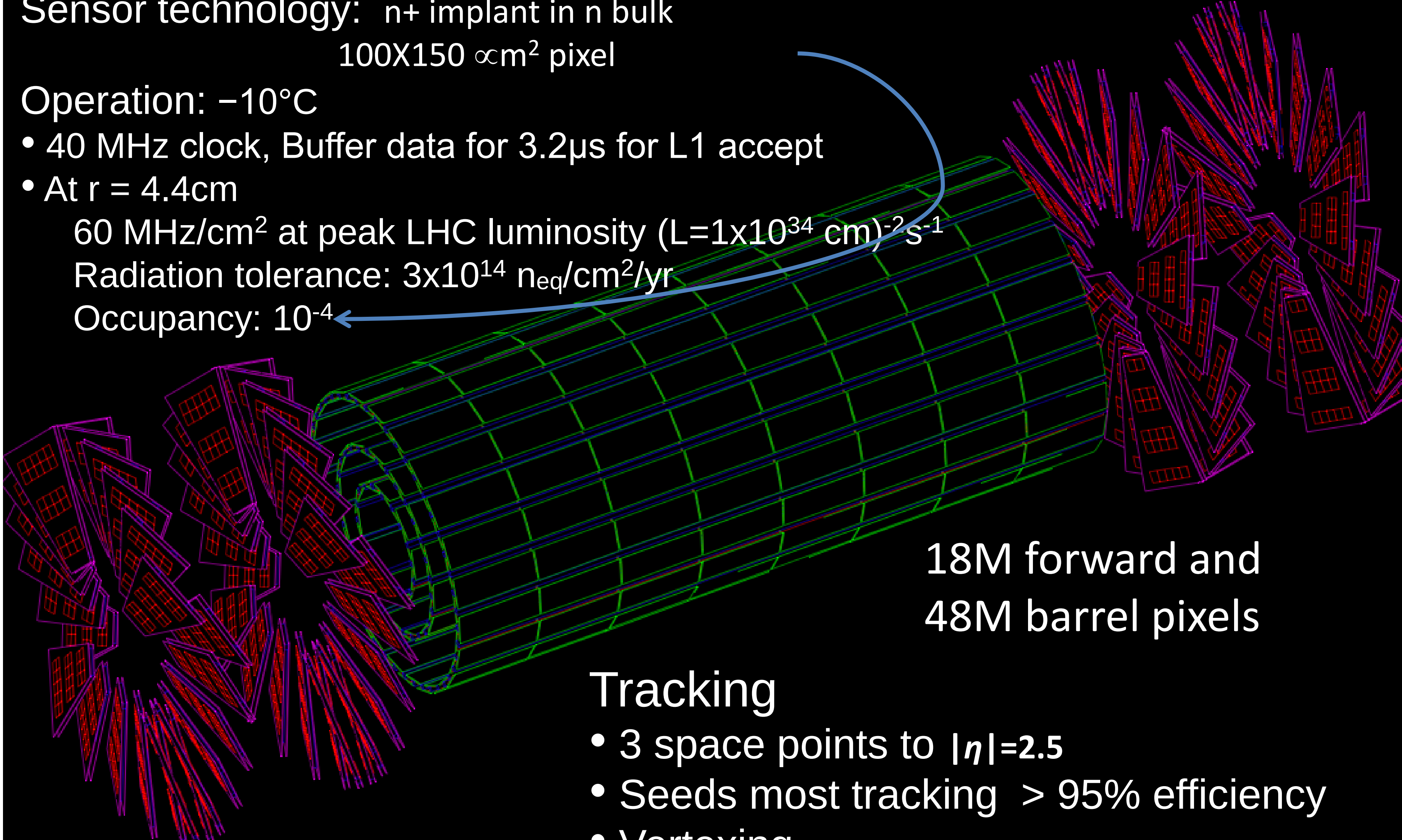
Pitch ~100 ∝m
66 Million pixels, 10 million strips: low occupancy at ultimate Lumi
Operate at <-10ºC for rad hardness

Operation of Silicon Detector

- Electron-hole-pairs generated by ionizing particles traversing the silicon are separated by E-field and ‘drift’ to the electrodes



CMC Silicon Pixel Detector



Sensor technology: n+ implant in n bulk
100X150 $\propto m^2$ pixel

Operation: −10°C

- 40 MHz clock, Buffer data for 3.2μs for L1 accept
- At r = 4.4cm
  - 60 MHz/cm^2 at peak LHC luminosity (L=1x10^{34} cm)$^{-2}$s^{-1}
  - Radiation tolerance: 3x10^{14} n_{eq}/cm^2/yr
  - Occupancy: 10^{-4}

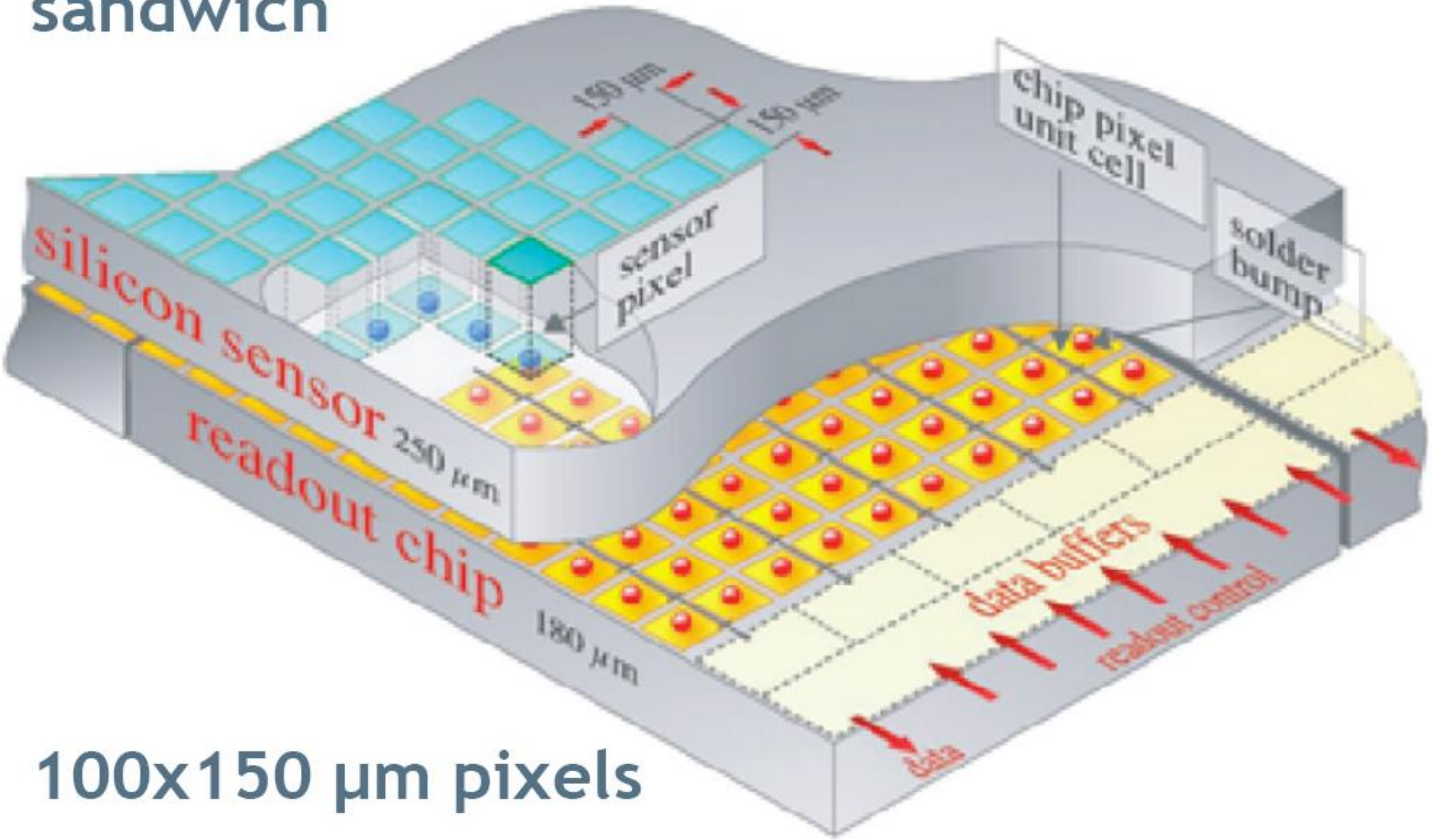
18M forward and
48M barrel pixels

Tracking

- 3 space points to $|\eta|$=2.5
- Seeds most tracking > 95% efficiency
- Vertexing

Sensor Construction

- bump-bonded sensor/readout chip sandwich

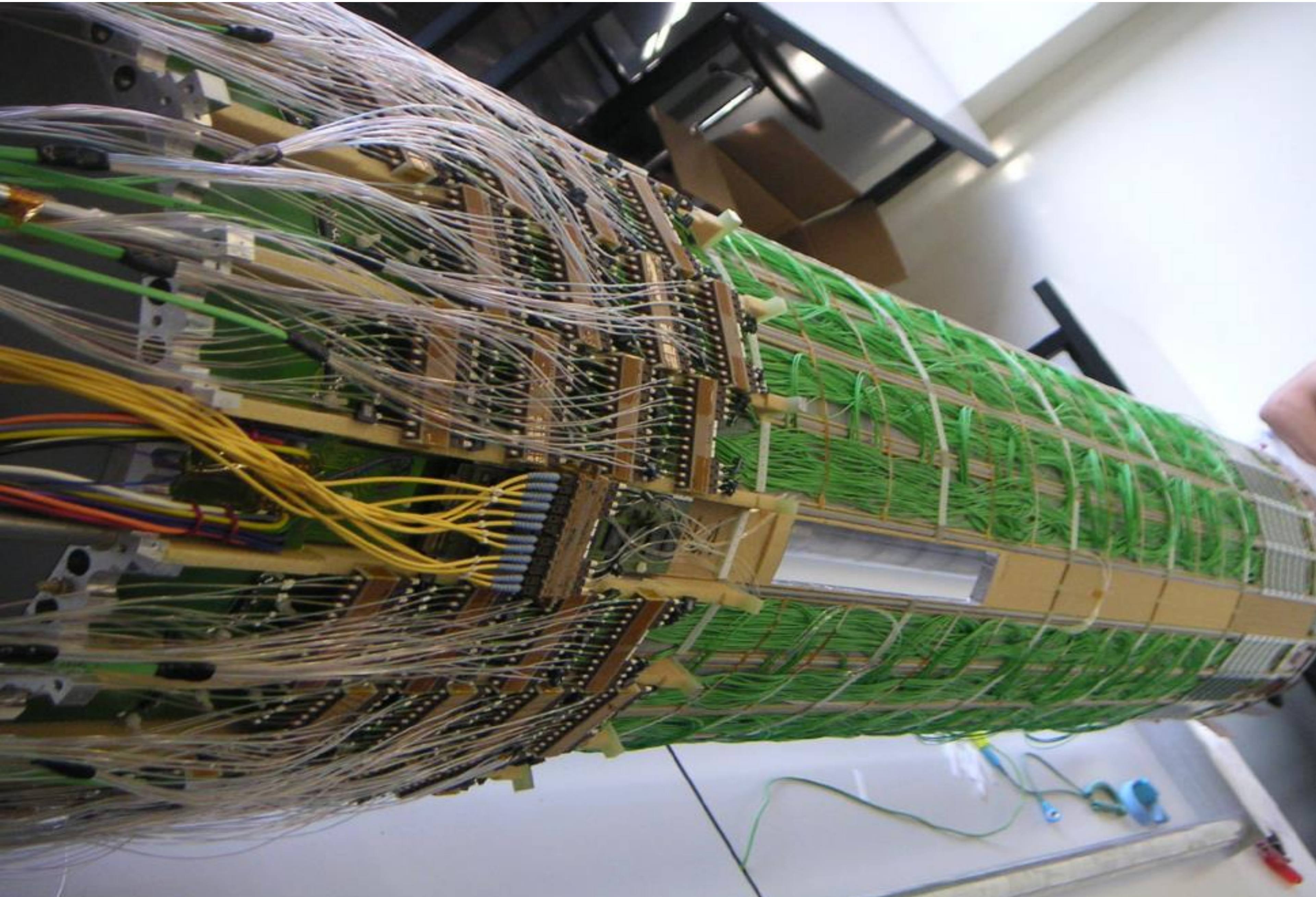


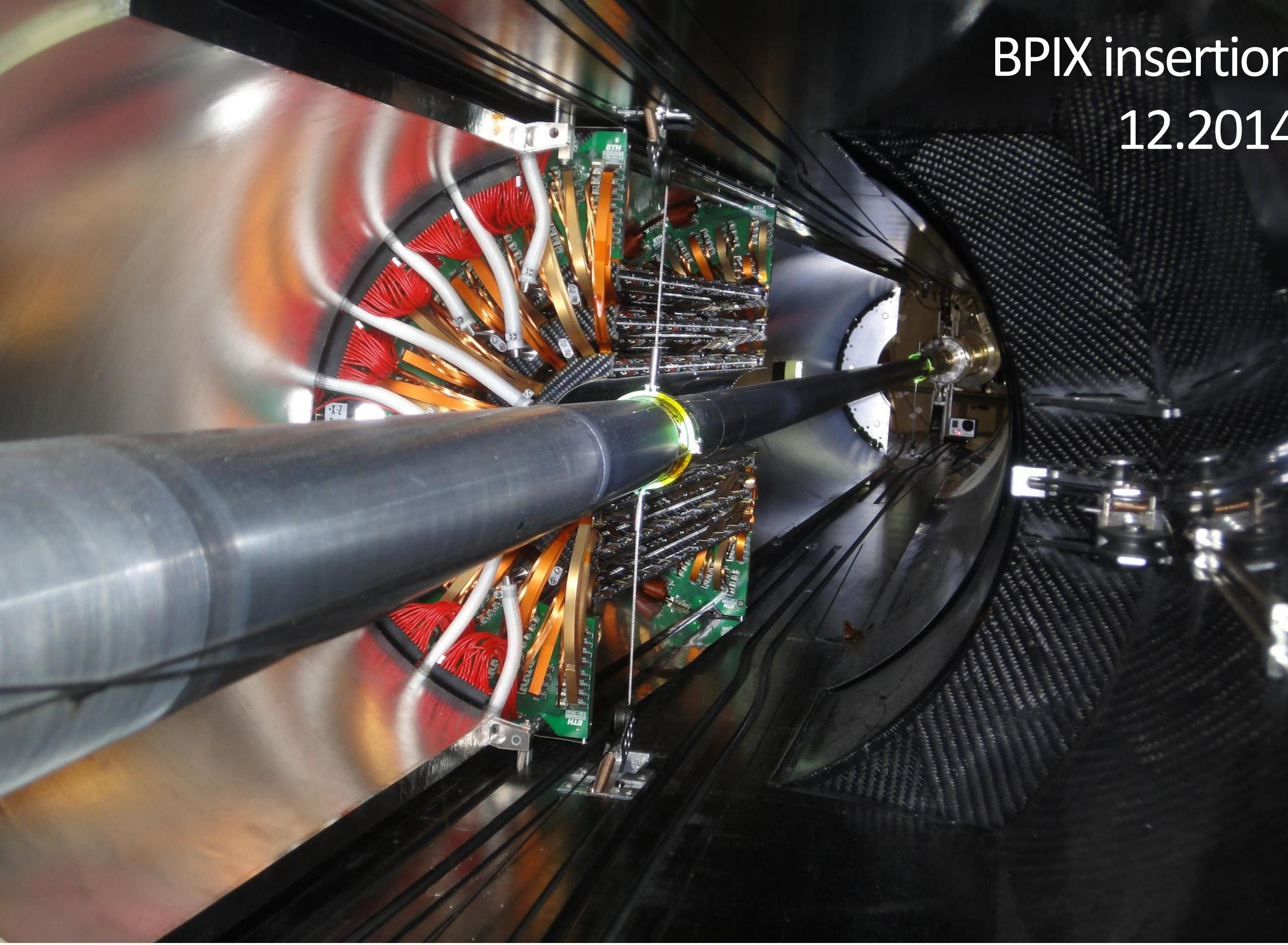
- 100x150 µm pixels

Half disc of Forward Pixels

Forward Pixel: 672 plaquettes installed

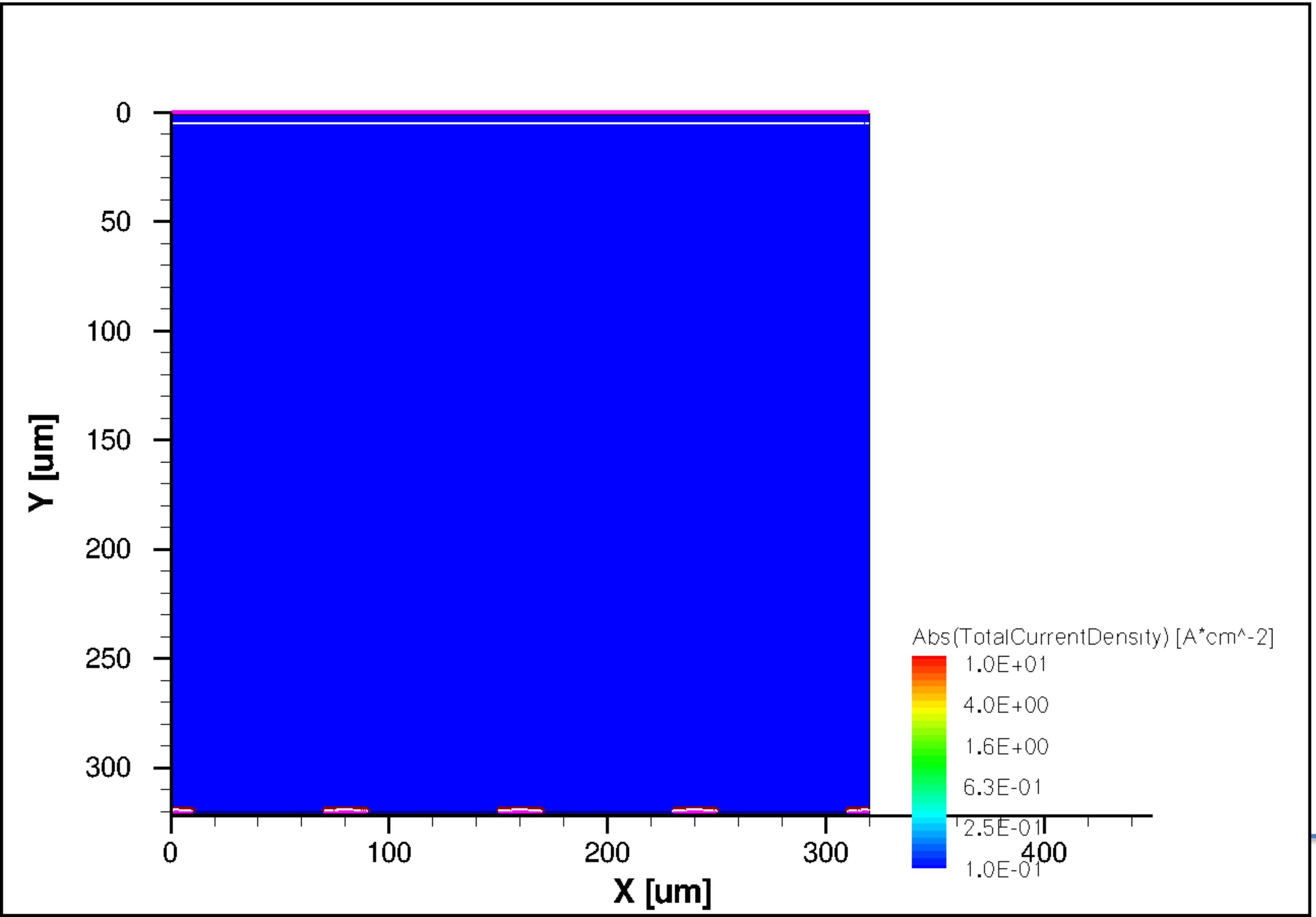
Pixel Barrel plus Endcaps



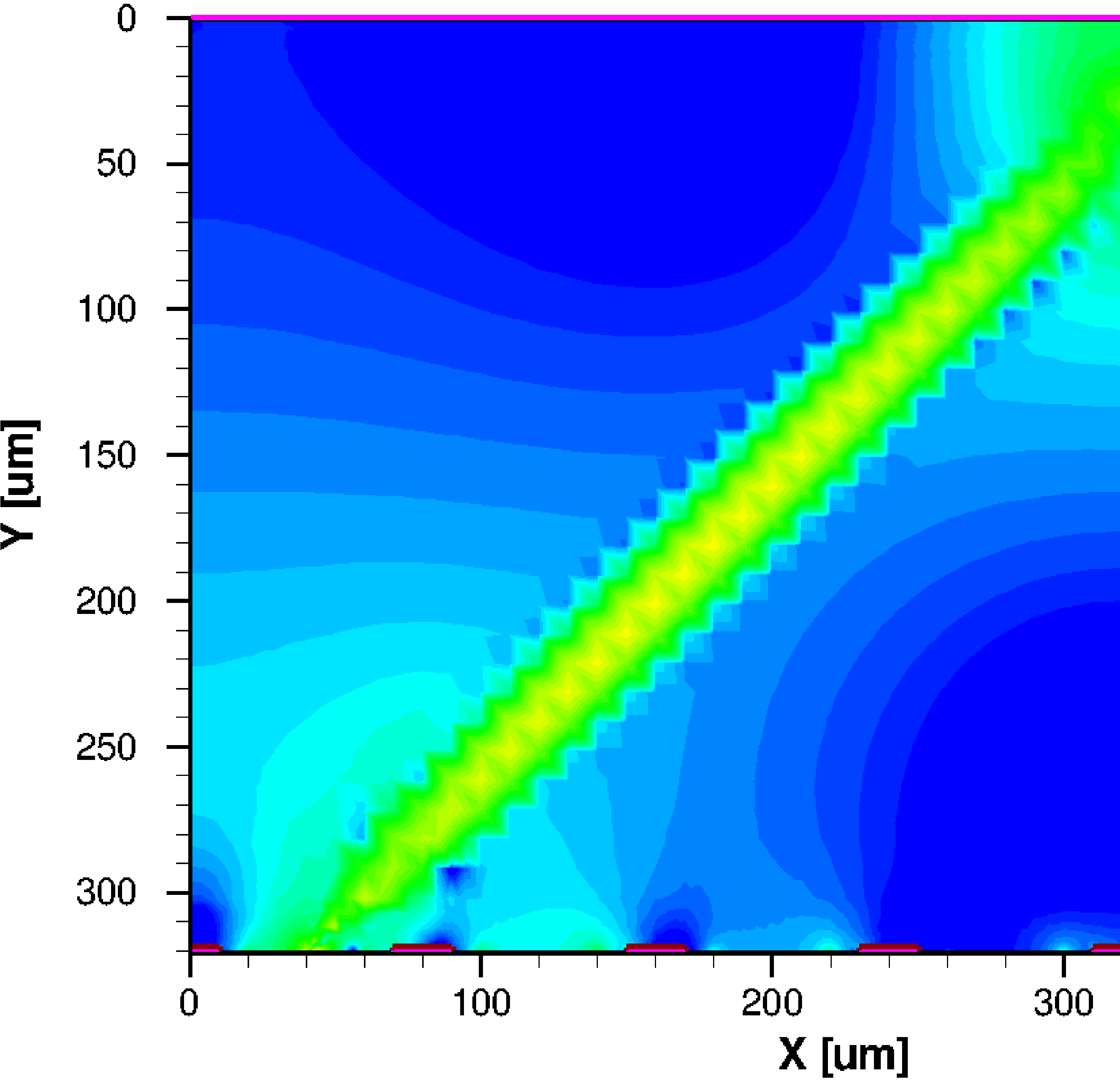

BPIX insertion
12.2014

Simulated Current Density

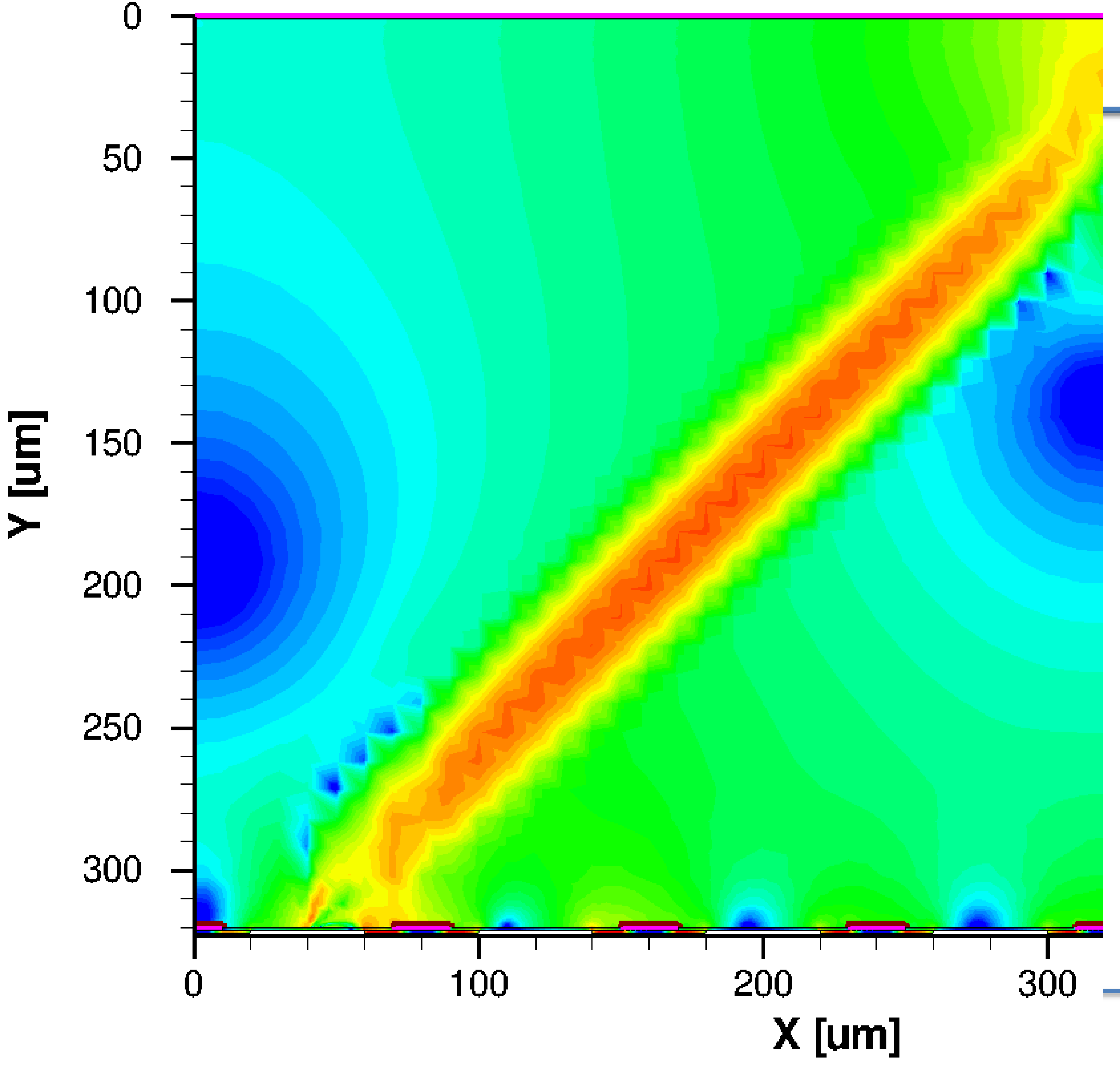
Ionizing particle with 45° angle t=0 s



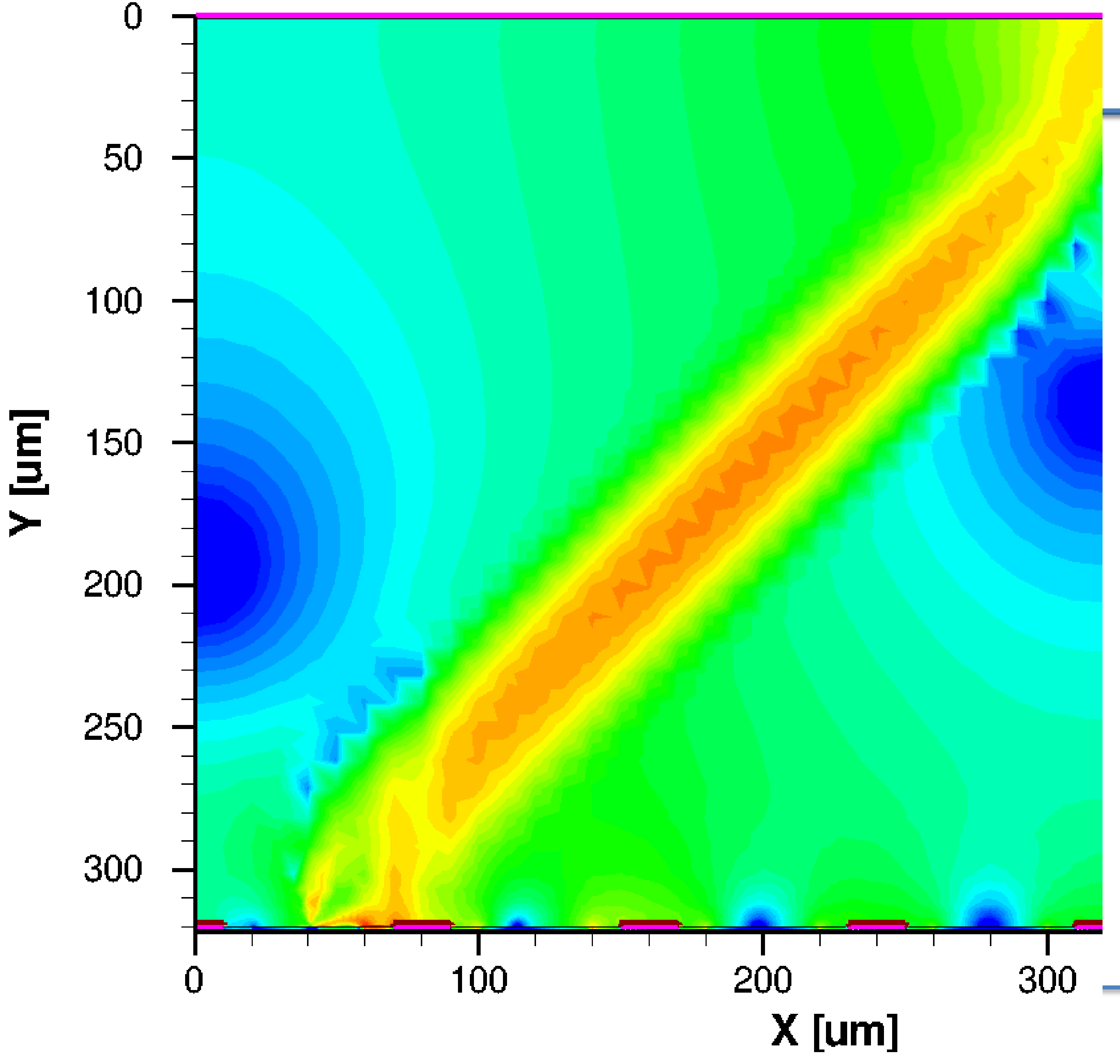
Simulation Thomas.Eichhorn@kit.edu



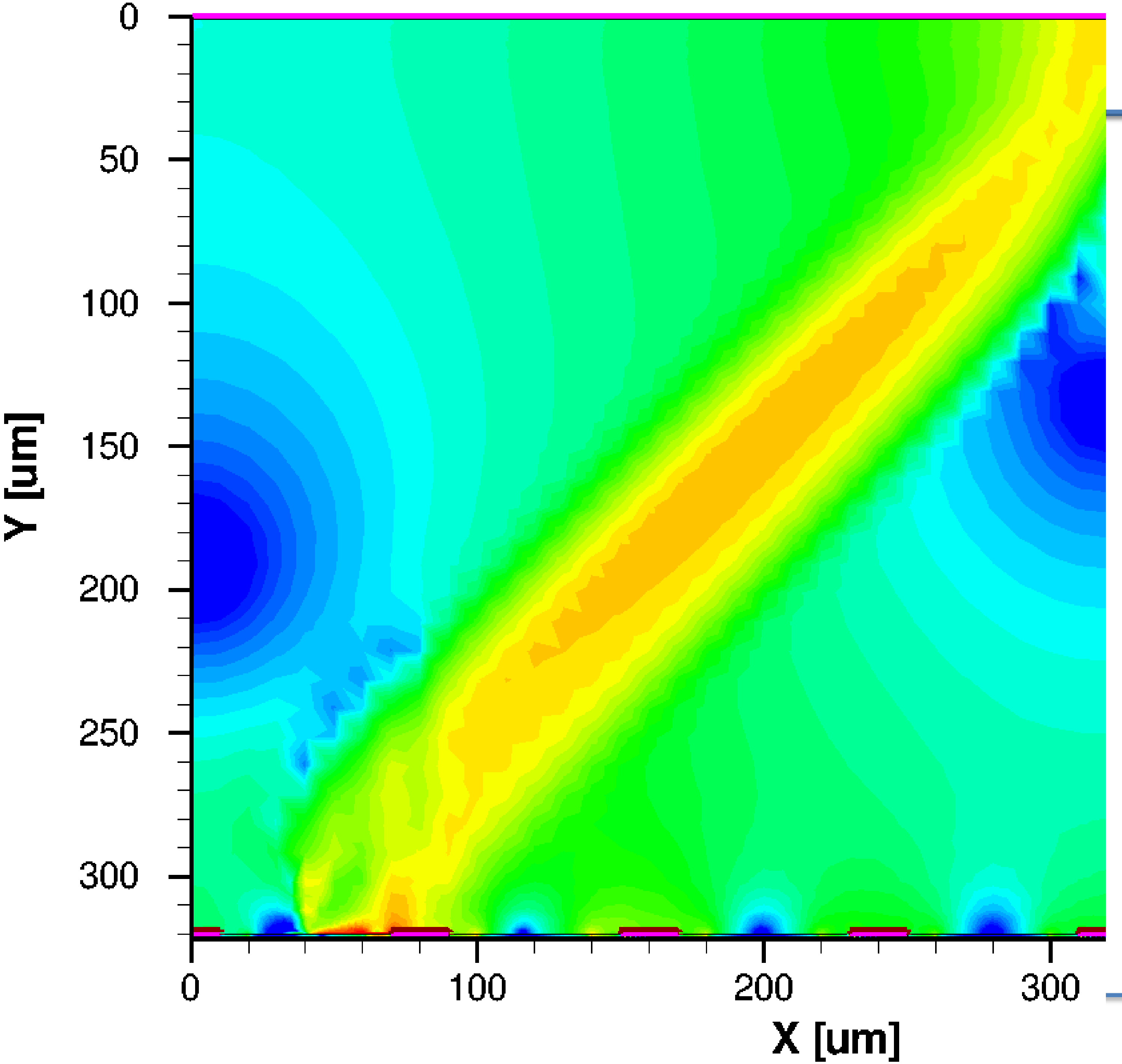
t=1 ns



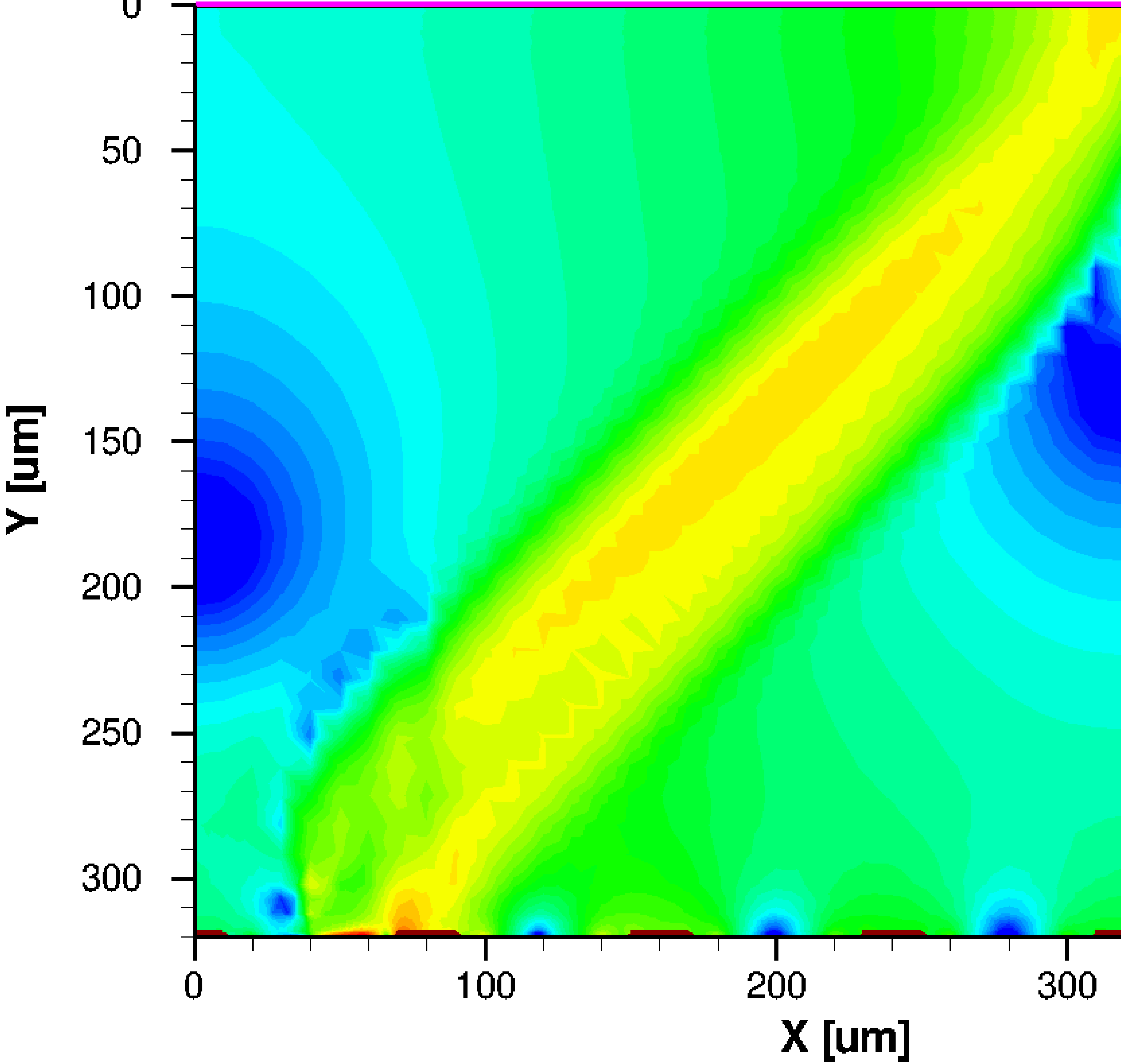
t=1,1 ns



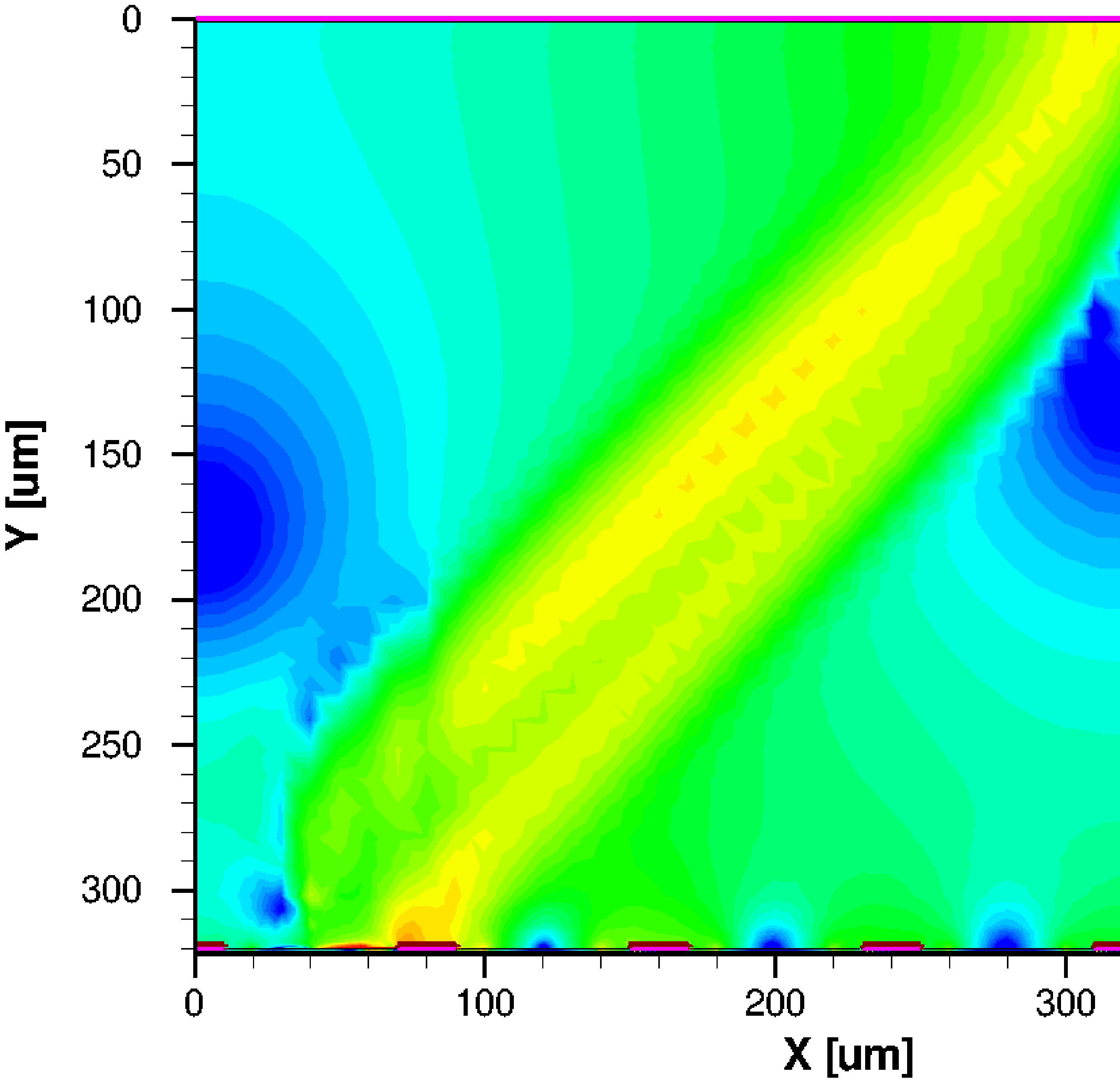
t=1,2 ns



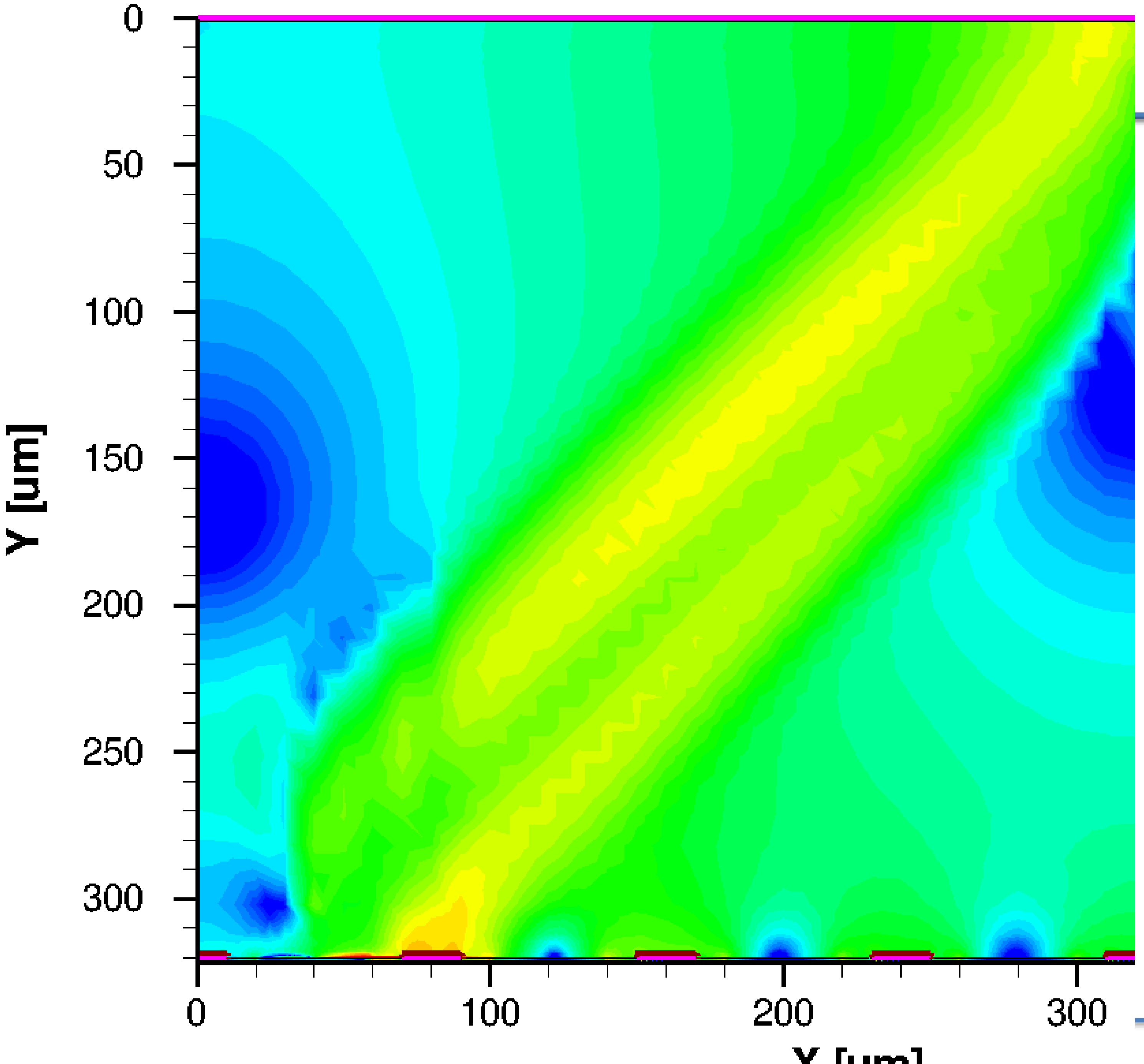
t=1,3 ns



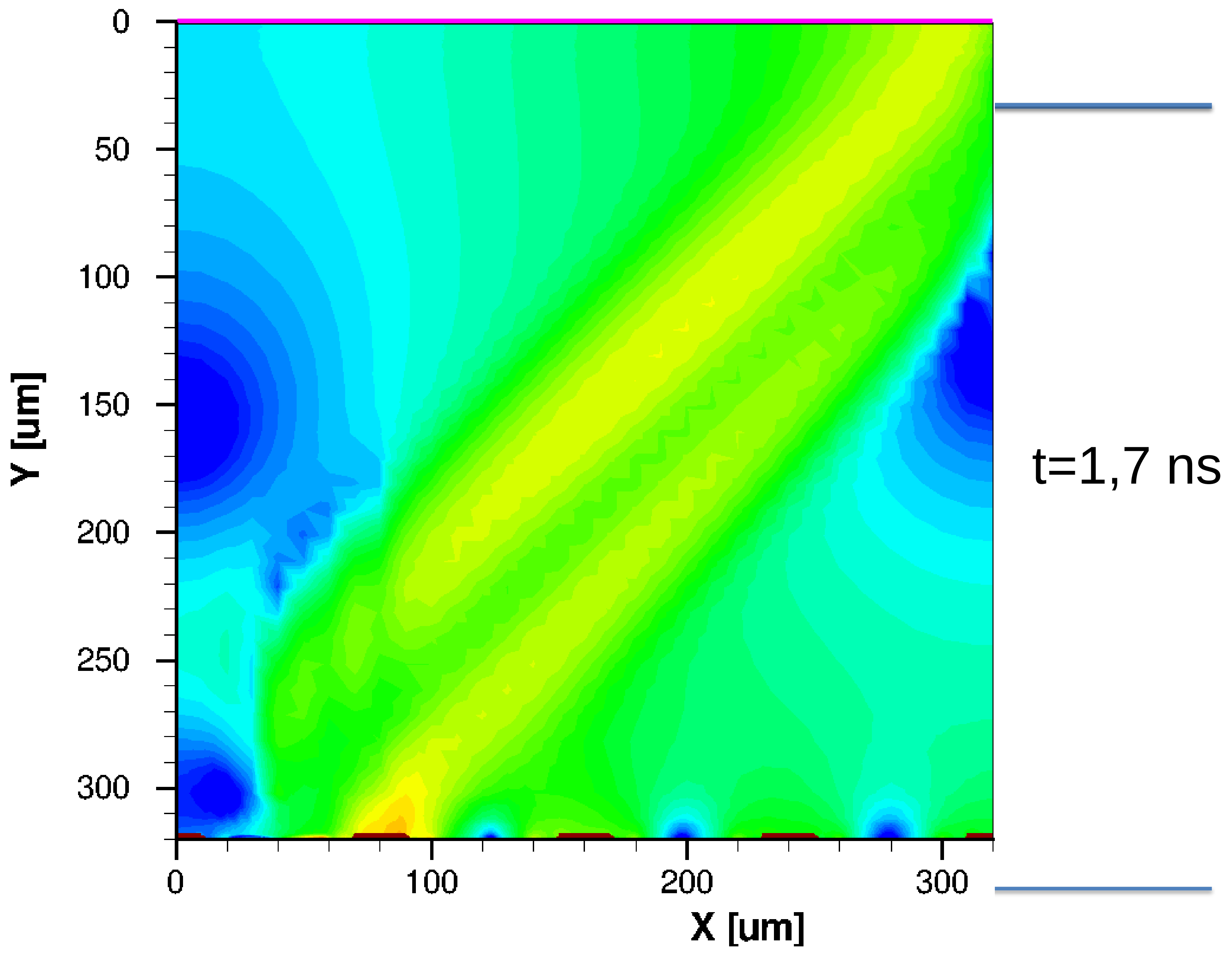
t=1,4 ns

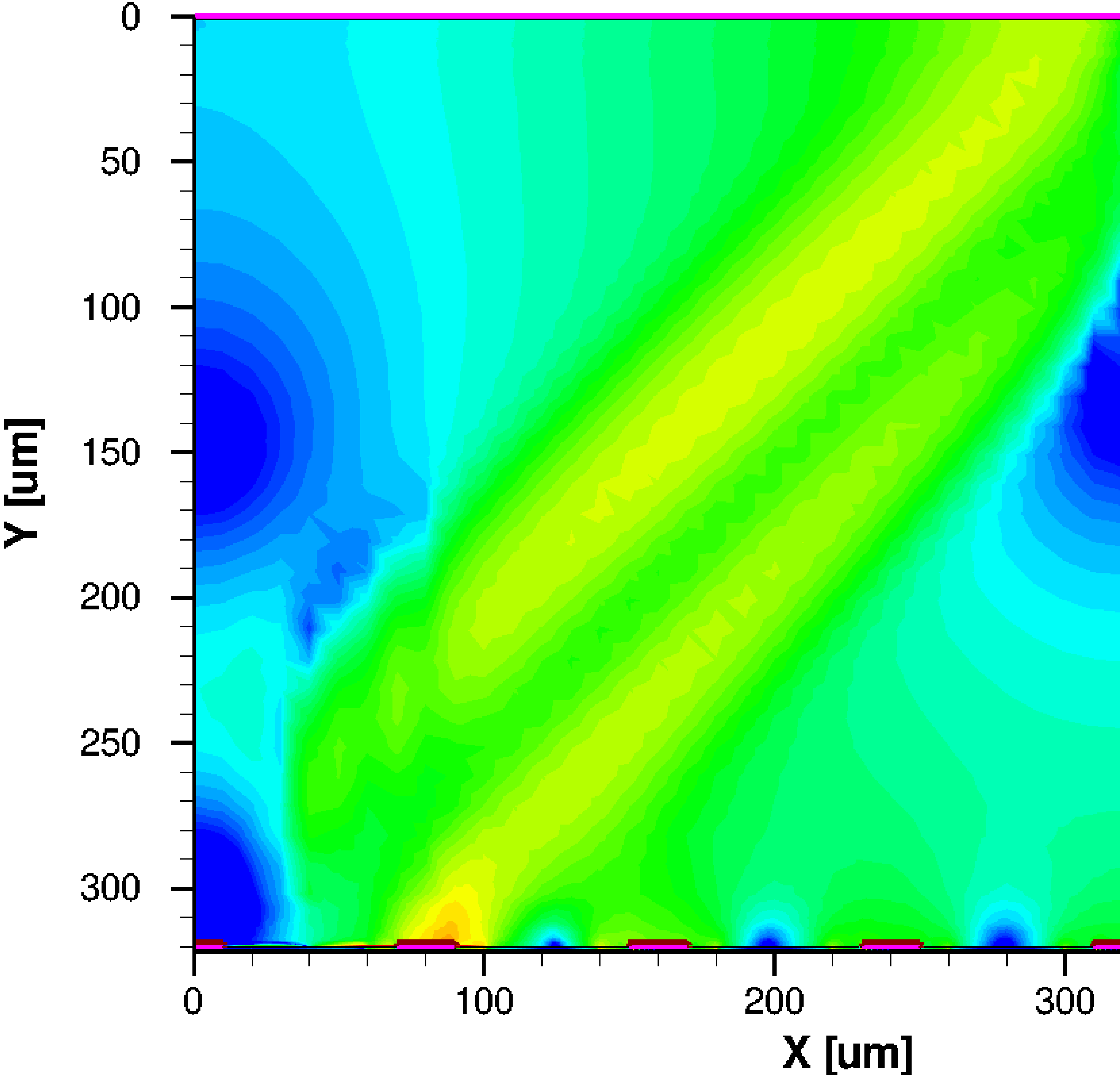


t=1,5 ns

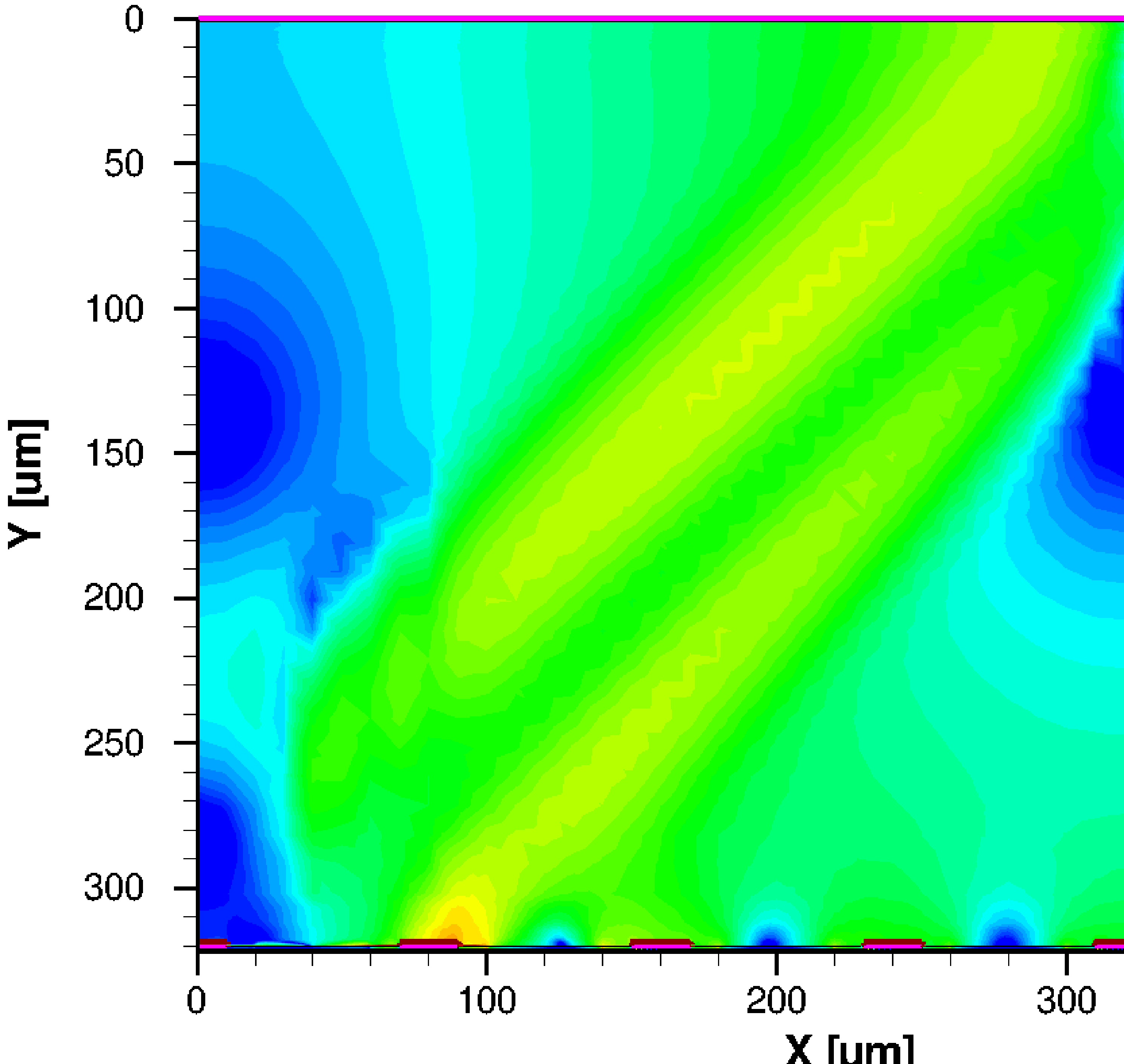


t=1,6 ns

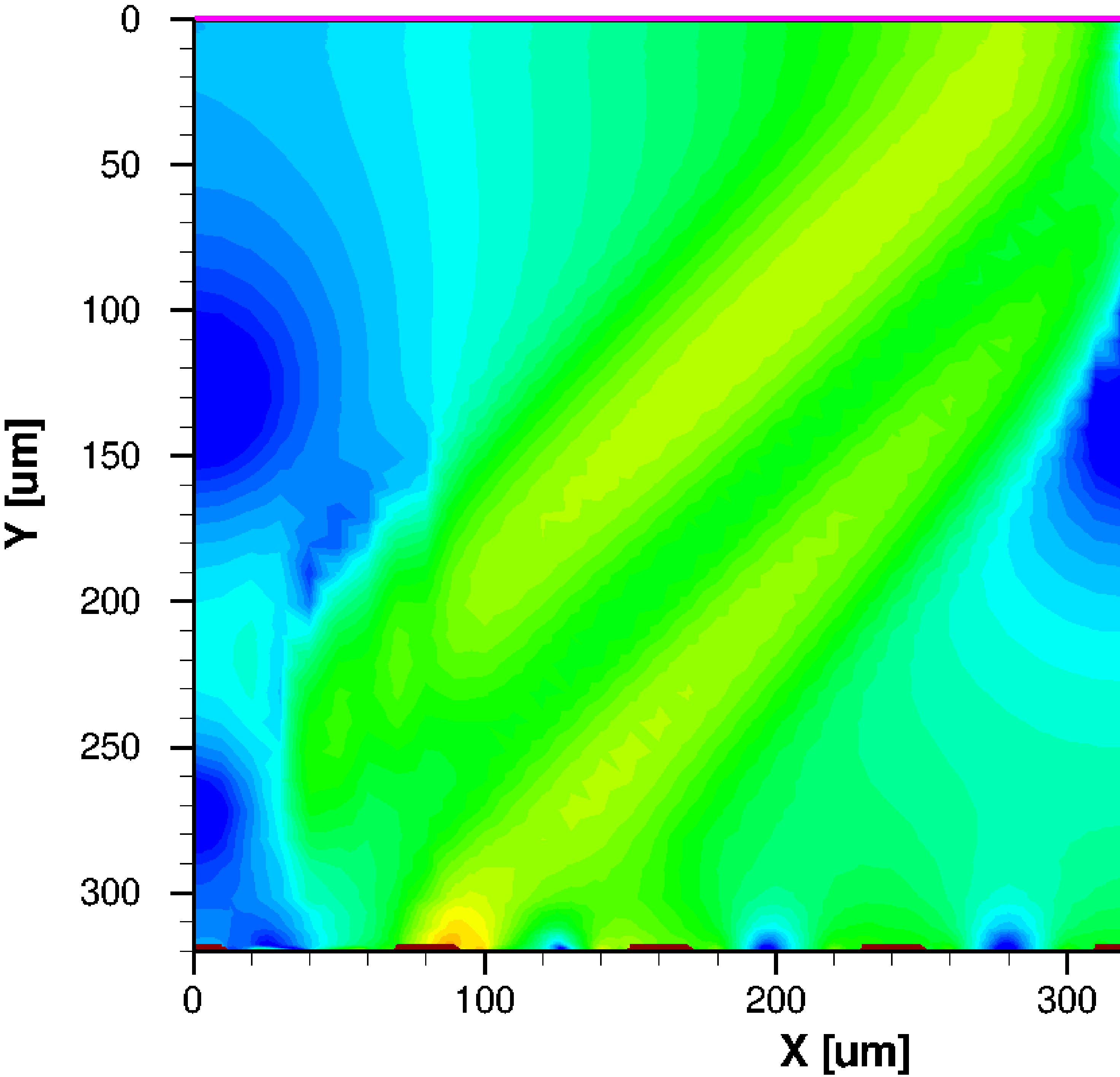

0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=1,7 ns



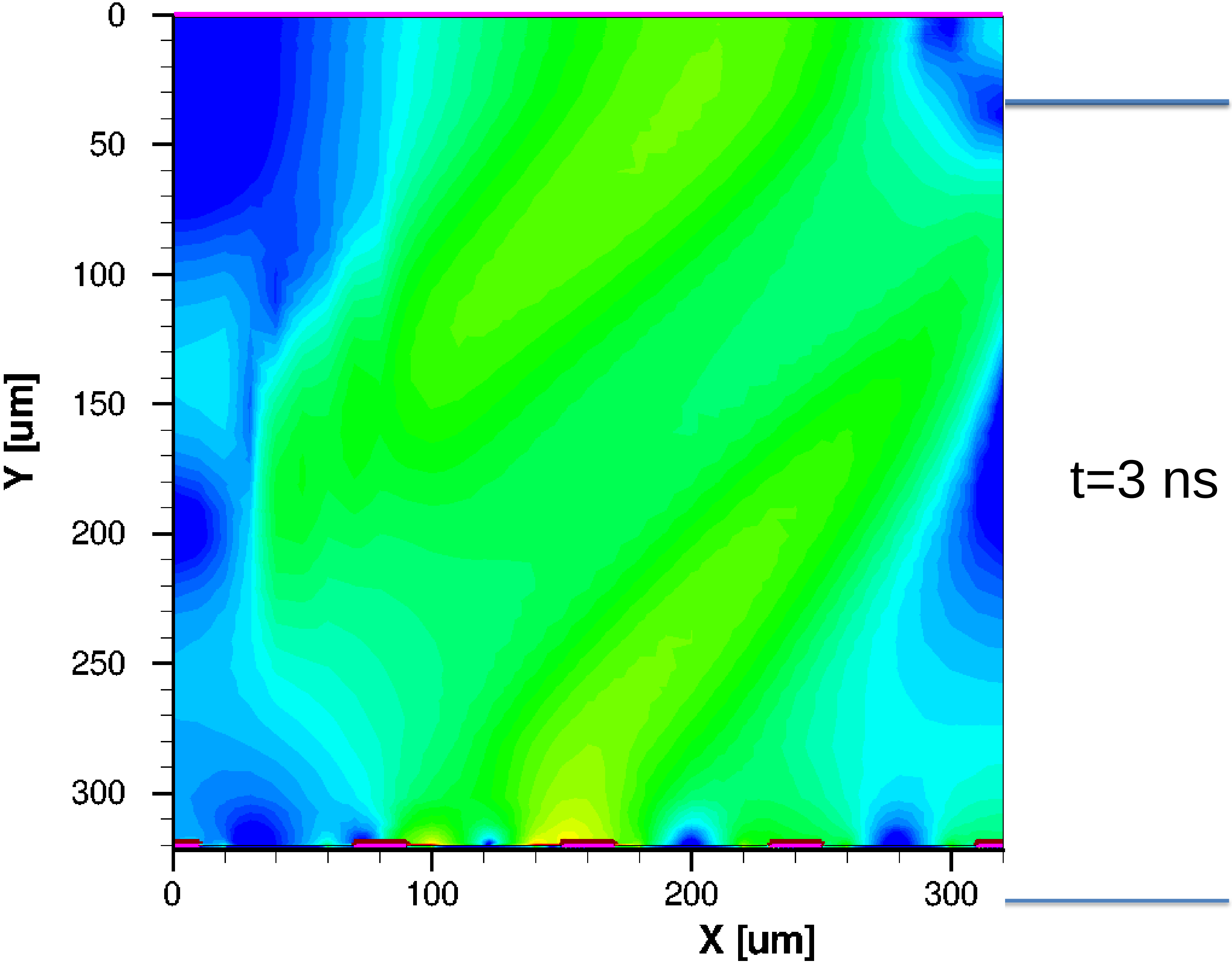
t=1,8 ns



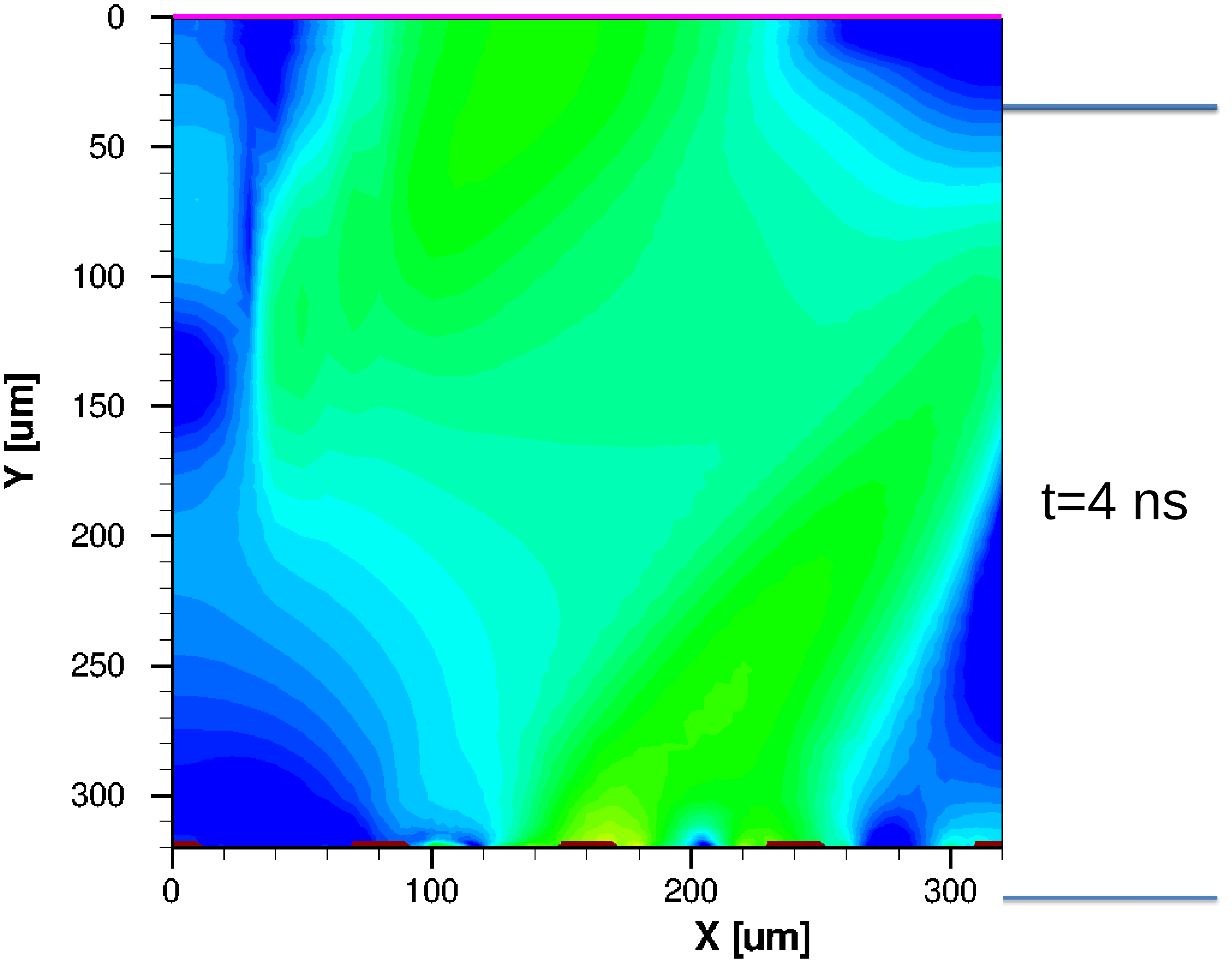
t=1,9 ns



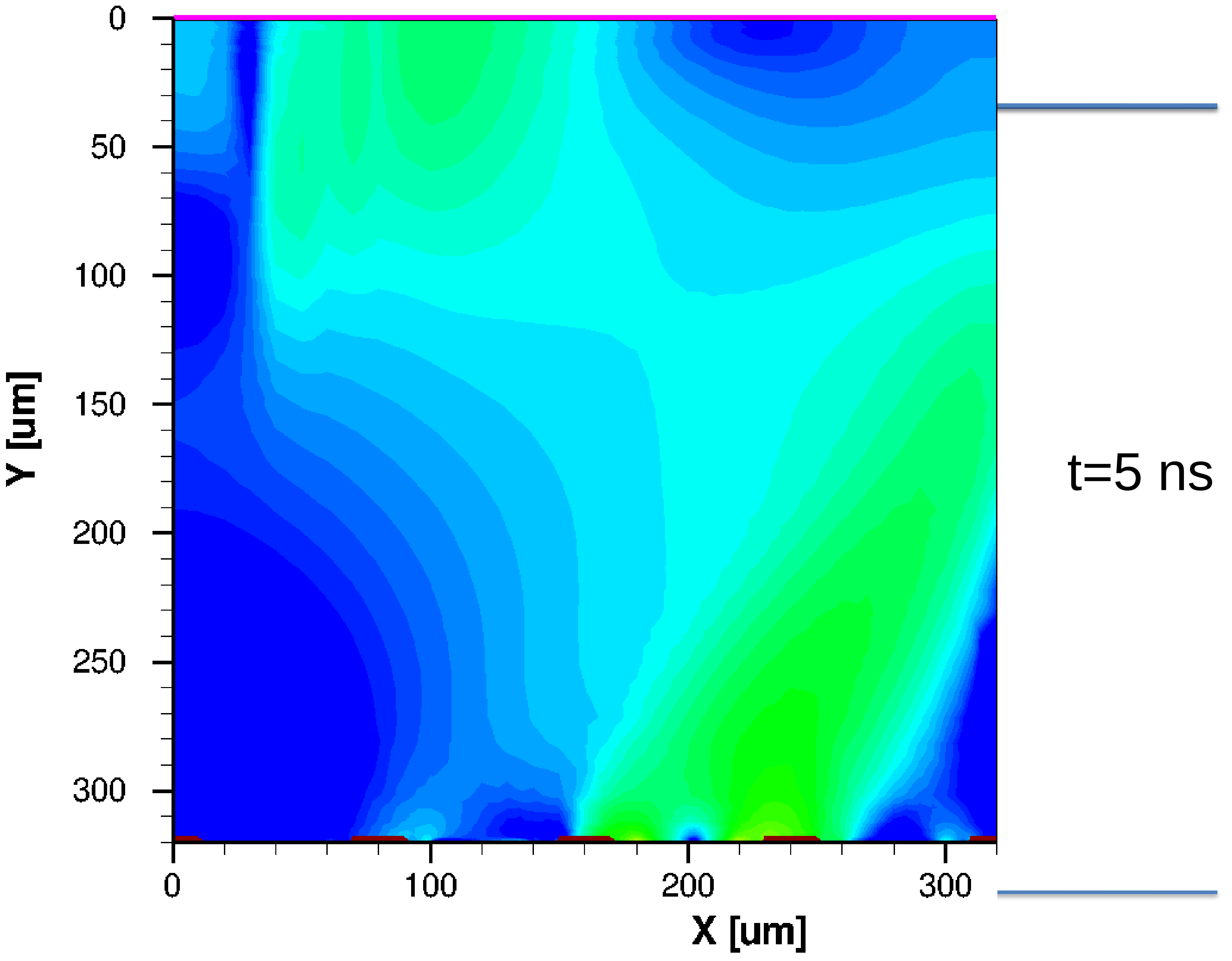
t=2 ns



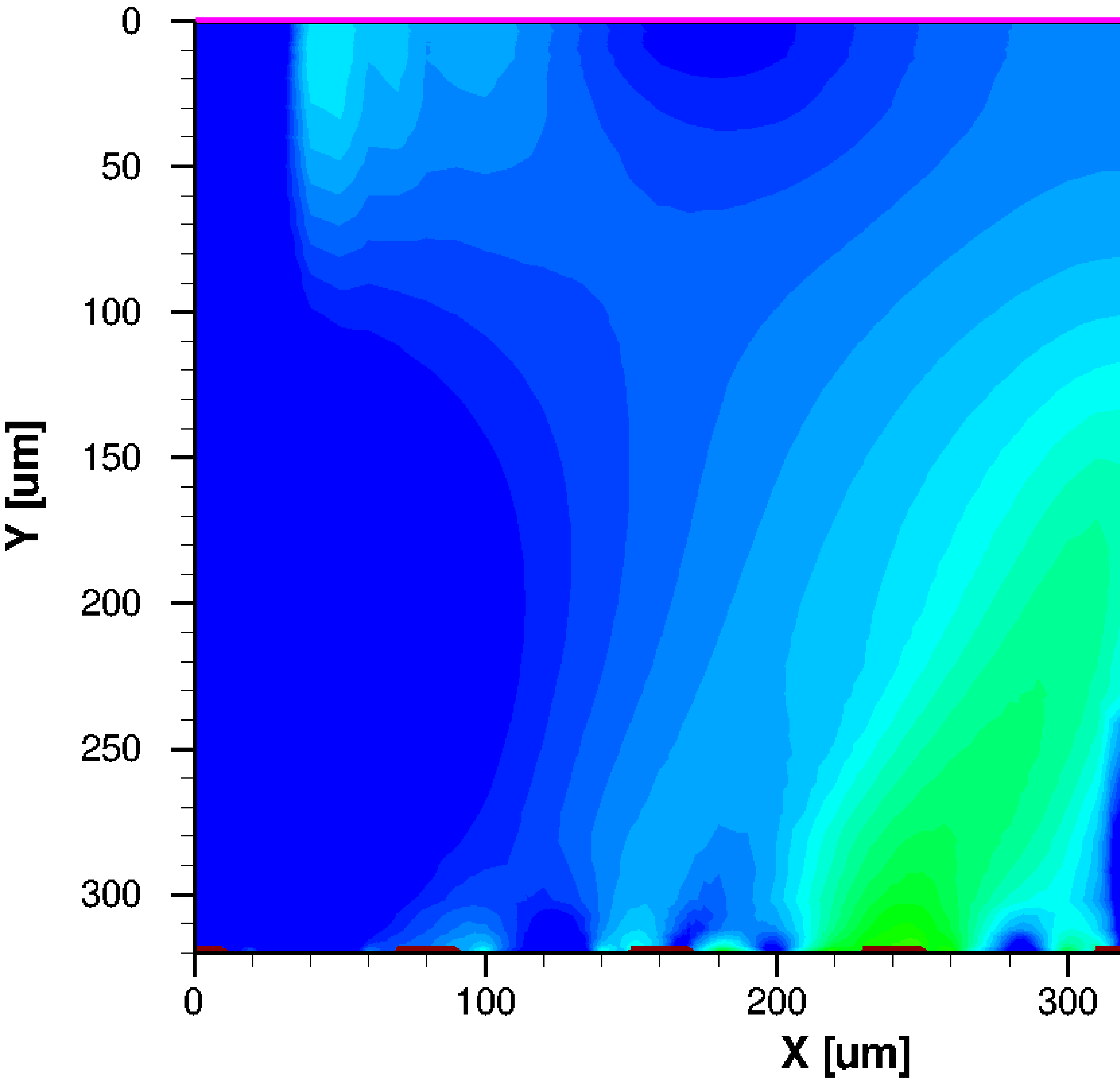
0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=3 ns



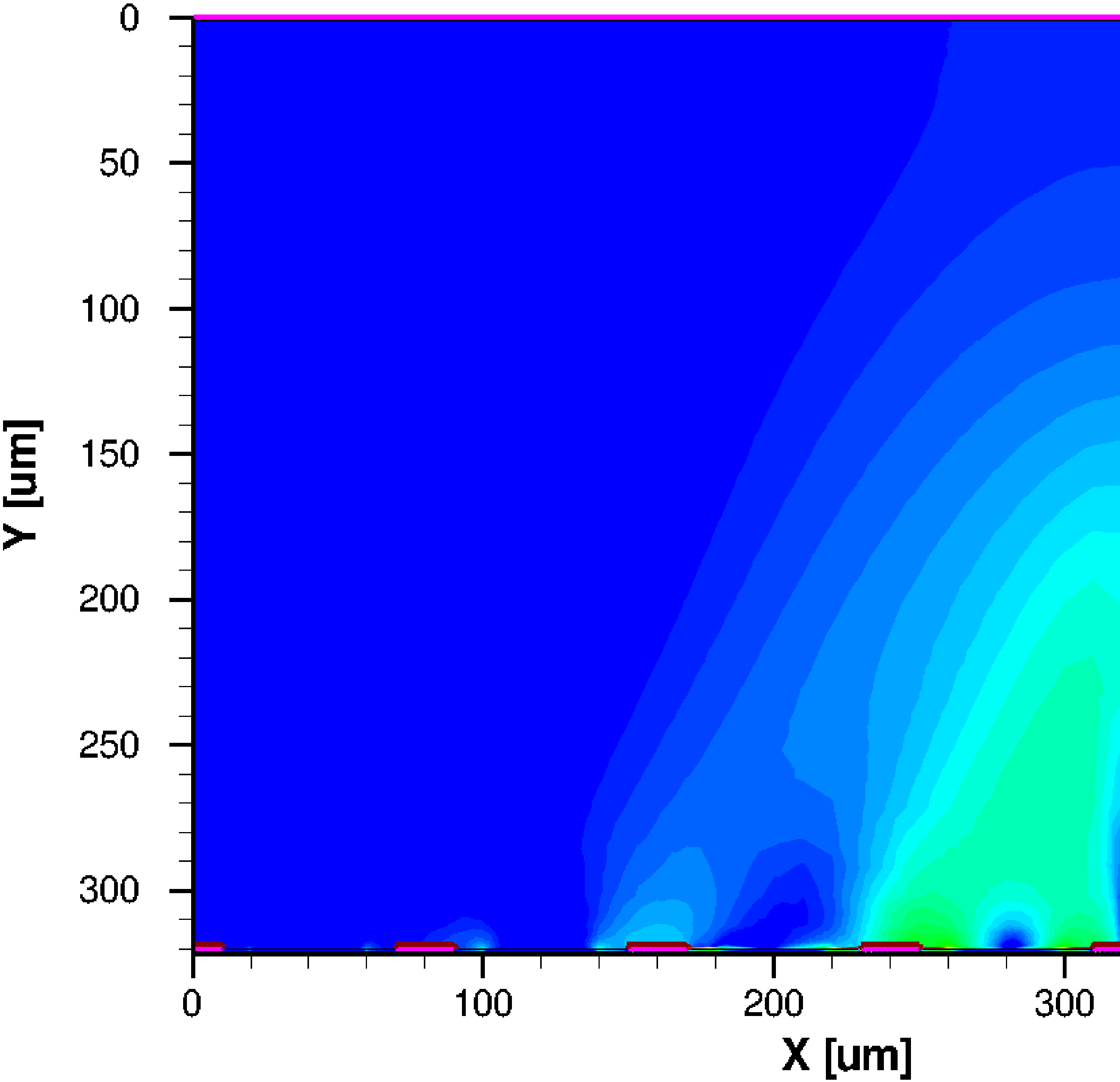
0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=4 ns



t=5 ns



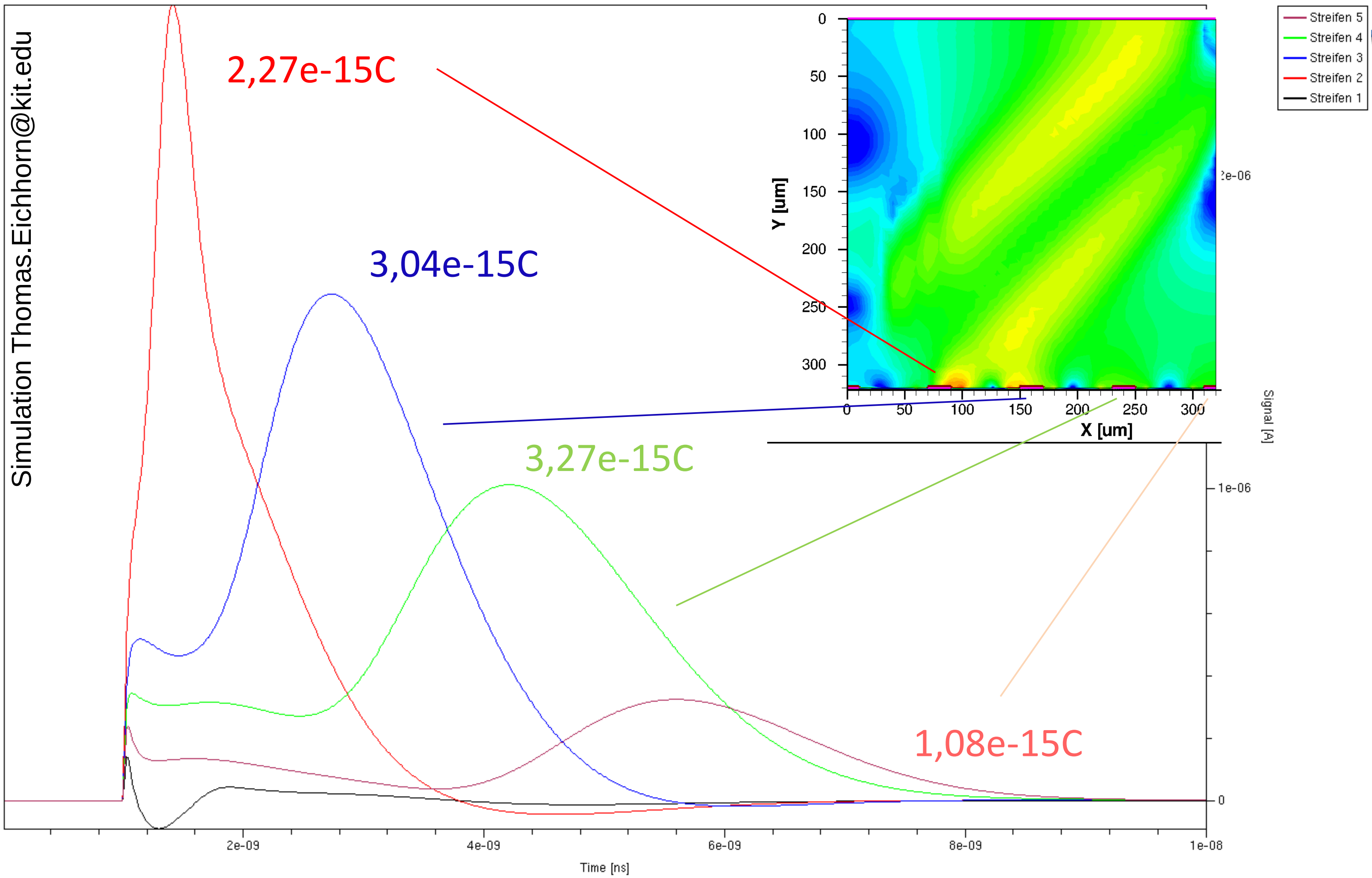
t=6 ns

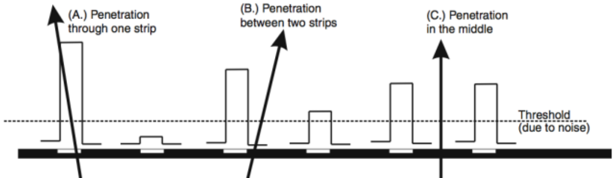


t=7 ns

All electrons collected

Charge Collection (channel & time resolved)

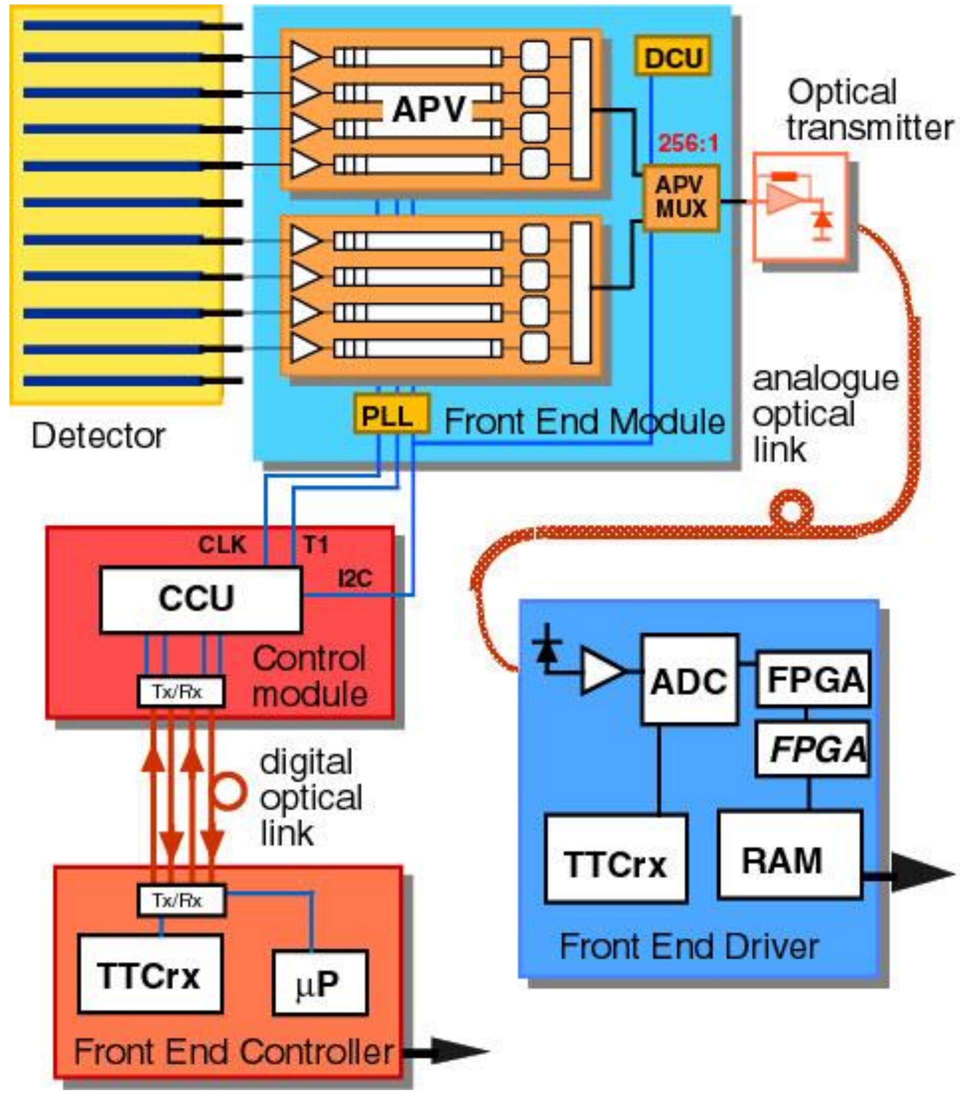




Readout of the Strip Detector

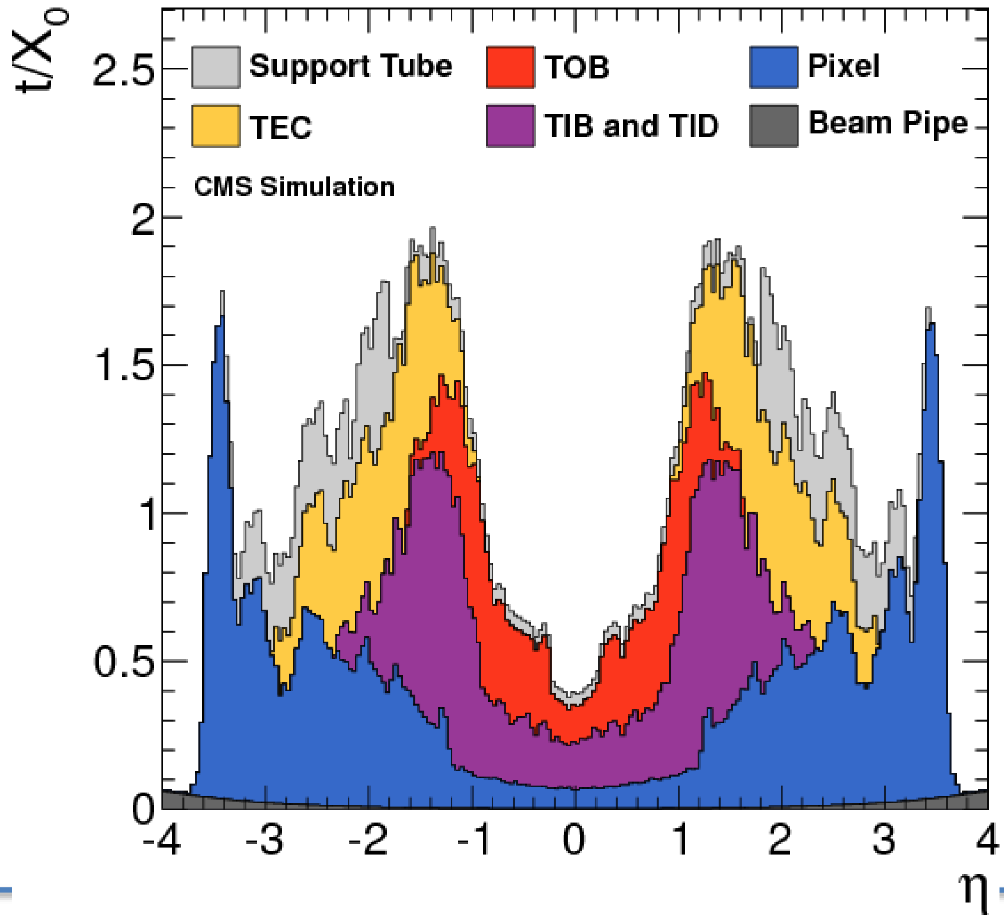
Bunch crossings occur at a rate of 40 MHz.

Data are stored on-detector until a L1 trigger is received and then sent by optical links to the off-detector electronics.

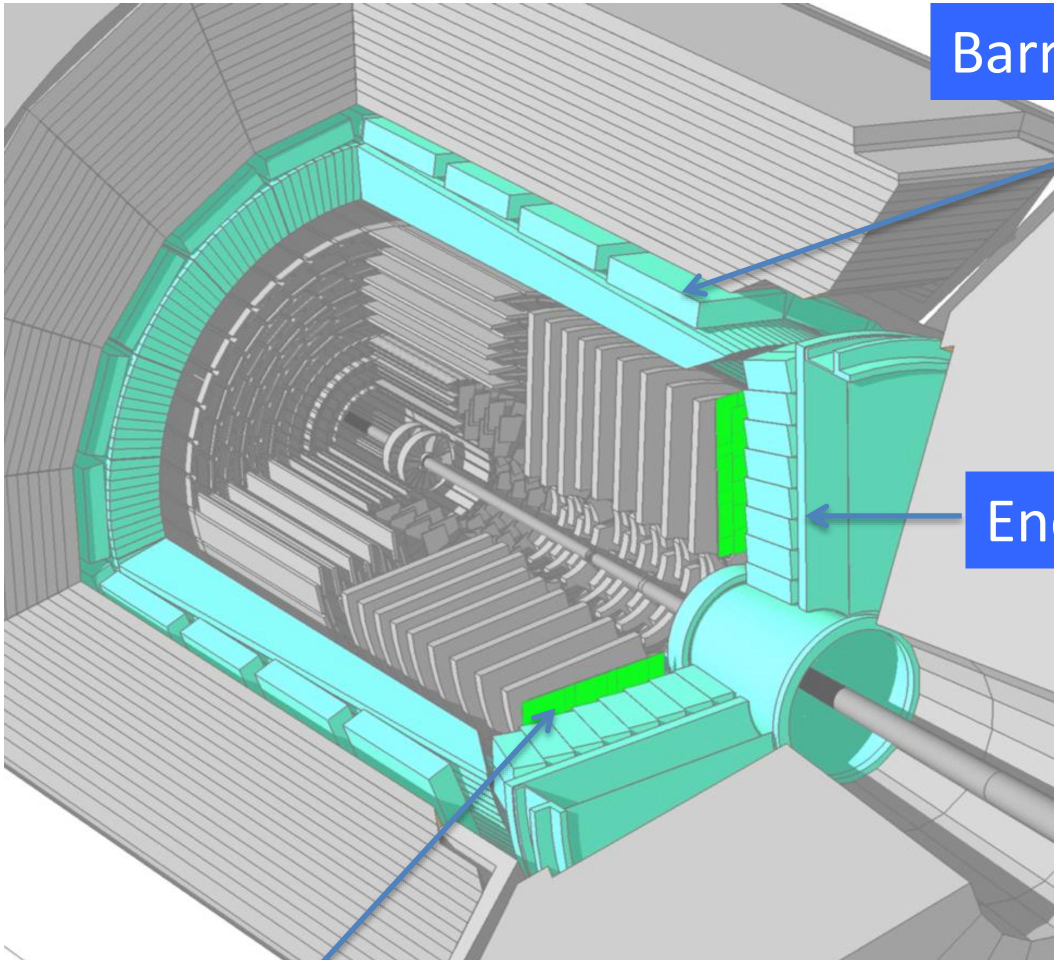


Material Budget

The CMS tracker is a major technological achievement that makes CMS a highly competitive detector compared with ATLAS. The price is the amount of material in the tracker that converts photons or degrades the energy of the electrons.



The Electromagnetic Calorimeter



A new scintillating crystal was developed for CMS – Lead Tungstate ($PbWO_4$).

ECAL

- Incident electron/photon generates EM shower (spread laterally over several crystals) in the heavy PbWO4 material
  - Charged particles in the shower produce scintillation light isotropically
  - Amount of scintillation light is proportional to incident particle energy
  - Scintillation light detected by photodetectors with internal amplification:
    Silicon Avalanche PhotoDiodes - APDs (in EB) or Vacuum PhotoTriodes - VPTs (in EE).
- There is no longitudinal segmentation – so no information about shower's direction.

ECAL by the numbers

- Barrel (EB): |η| < 1.48
  - 36 Supermodules: 1700 crystals
    (1 supermodule = 4 modules):
    61200 crystals total, of 17 shapes
  - (2.2×2.2×23 cm3) ~26X0

- Endcaps (EE): 1.48 < |η| < 3.0
  - 4 Dees (2 per endcap): 3662 crystal (mostly in 5x5 supercrystals)
  - 14648 crystals total
  - 3.0×3.0×22 cm^3 ~25X_0

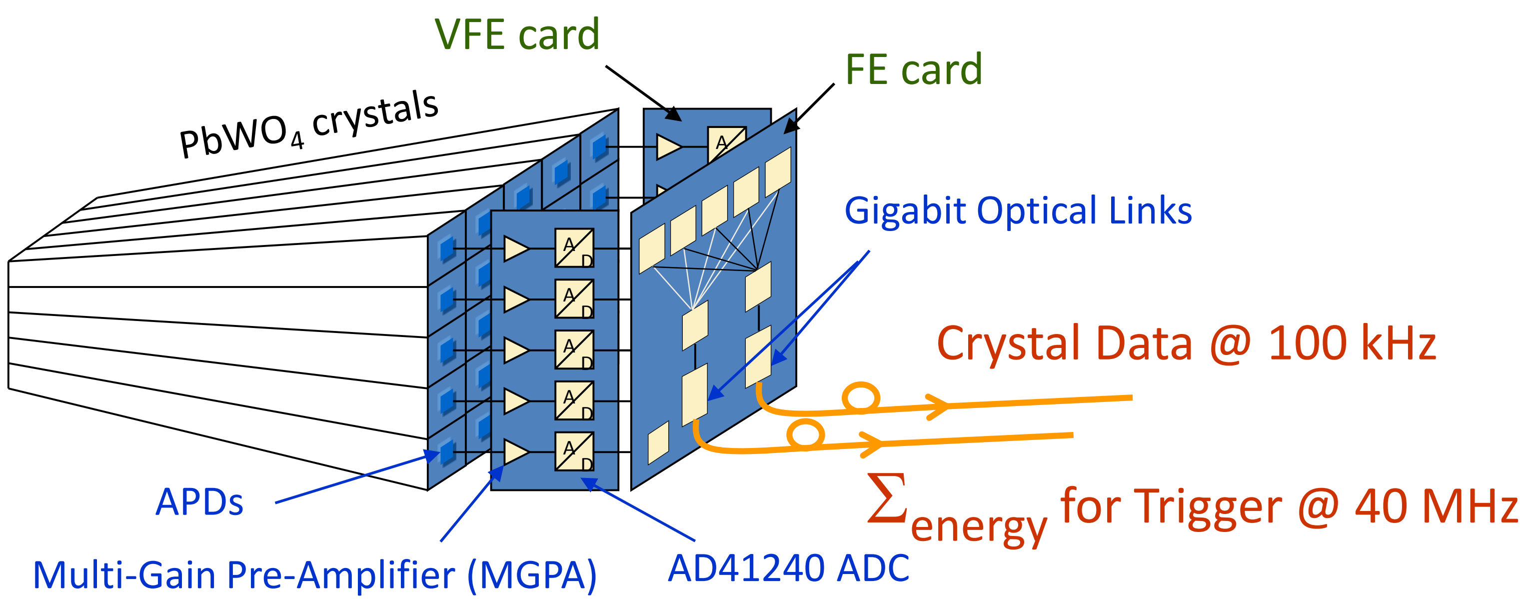
- Preshower (ES): 1.65 < |η| < 2.6
  - 4 planes (2 per endcap): 1072 Si sensors
    1 sensor = 6.3 x 6.3 x 0.032 cm3, 32 strips 137,216 strips total
    2X_0 + 1X_0 of Pb interspersed with Si strips
- 1.90 × 61 mm2 x-y view

Readout ECAL

Like the tracker we cannot readout all the data from a the 72,000 crystals every bunch crossing.

Electrical signals from the APDs are converted for every bunch crossing in three gain ranges and data are stored until L1 accept is received.

The sum of the signal from 25 crystals is also sent for every bunch crossing. This is used to make the L1 trigger.



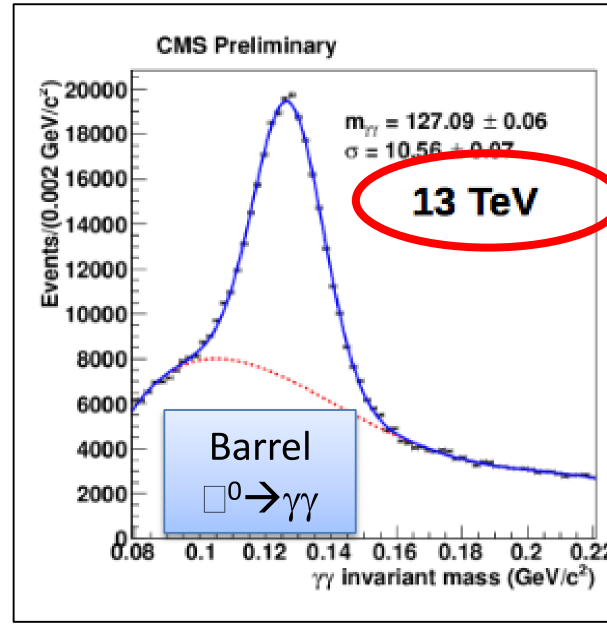
(Inter)Calibrating the ECAL

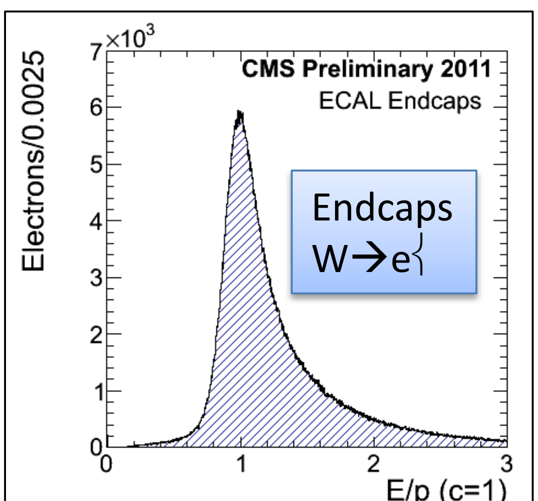
- ϕ- and time-invariance of energy flow in crystals at given |
  - Short calibration periods ~ 2 days
  - Excellent for checking ECAL stability
- □^{0}/| → γγ invariant mass
  - Average calibration periods ~weeks

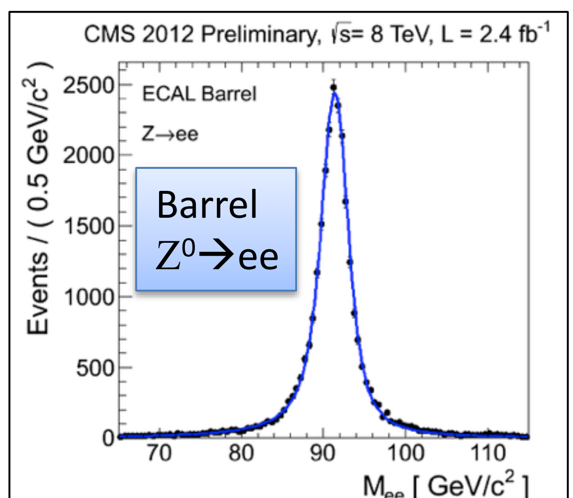
Dedicated high-rate (~10 kHz) trigger streams

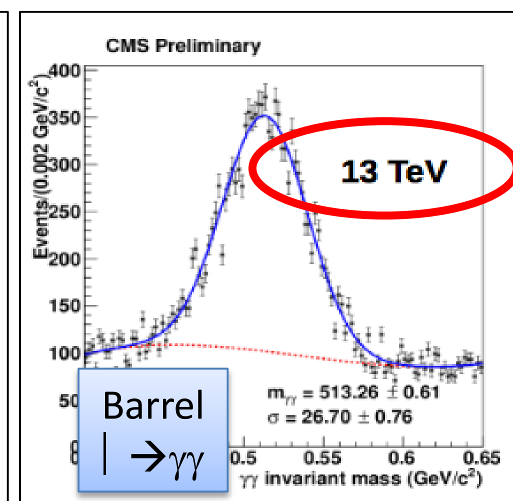
- Z→e$^+$e$^-$ invariant mass and E/p with electrons from W→e{
  - Long calibration periods ~months
  - Z peak also → absolute energy scale

Non pre-scaled analysis triggers

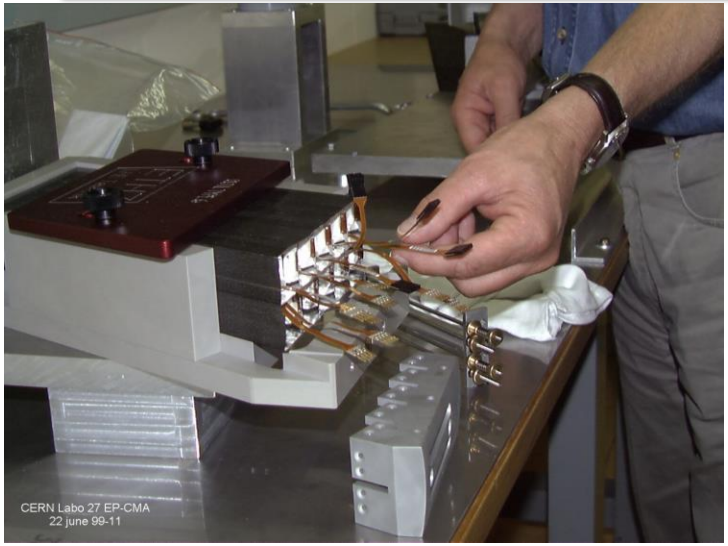


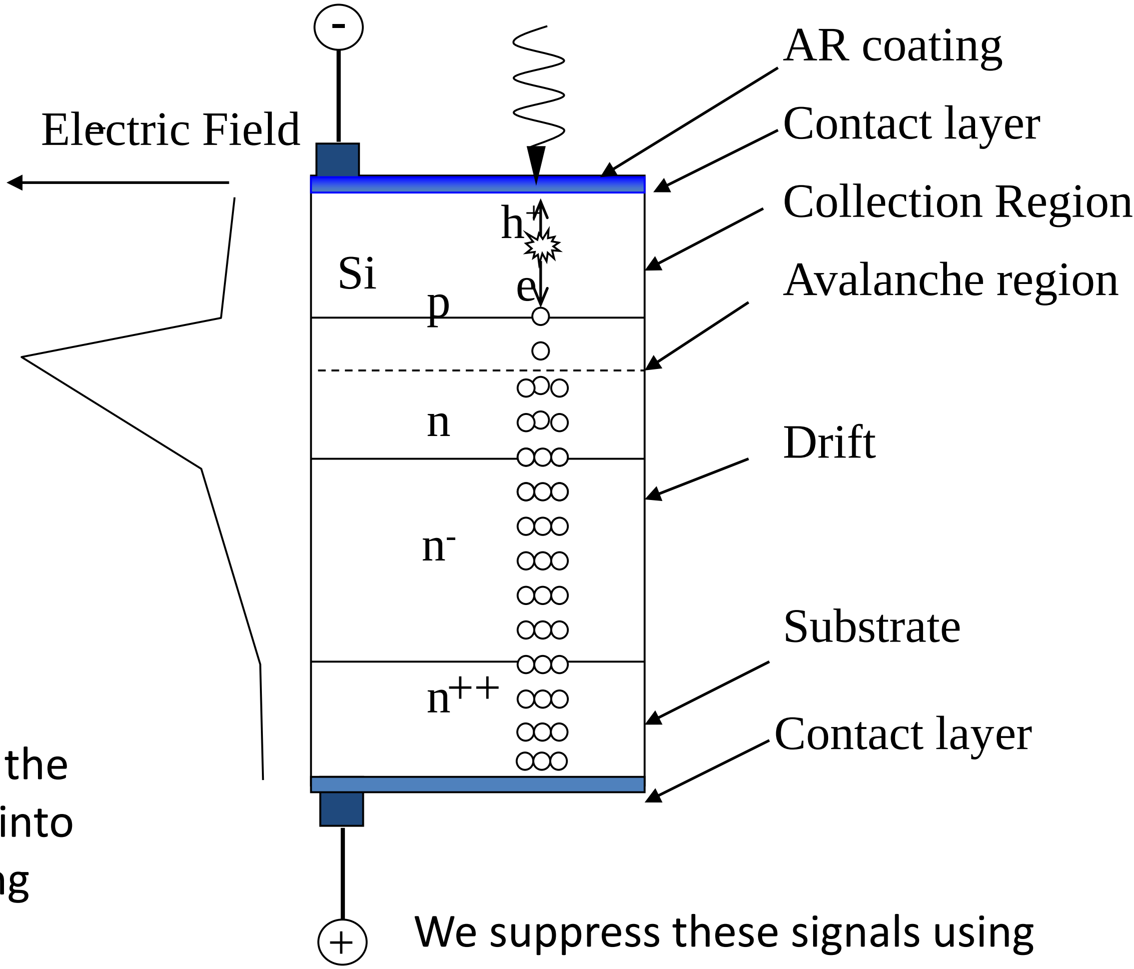






Spikes and all that



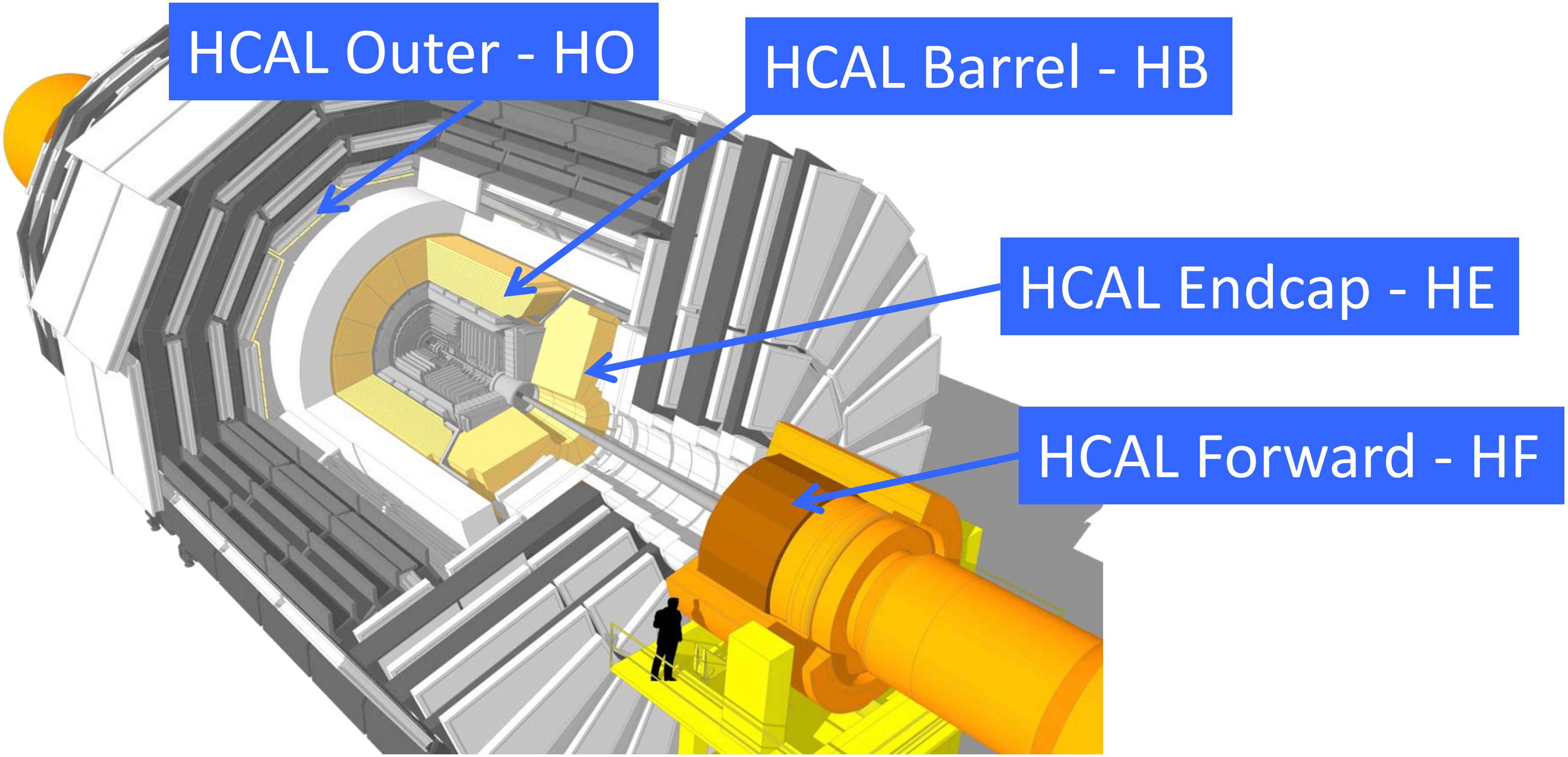


The APDs are silicon diodes with a high gain at the junction.

Interactions with the glue that bonds the APD to the crystal knocks on protons into the junction giving a very large ionizing signal similar to the signal form the scintillation light

We suppress these signals using the time and the isolation of the APD signal.

The Hadron Calorimeter



The hadron calorimeters HB and HE are brass-scintillator sampling calorimeters.

The forward calorimeter – HF – covers $3.0 < |\eta| < 5.0$ and signals are from Čerenkov light in quartz fibers.

Operation of HB and HE

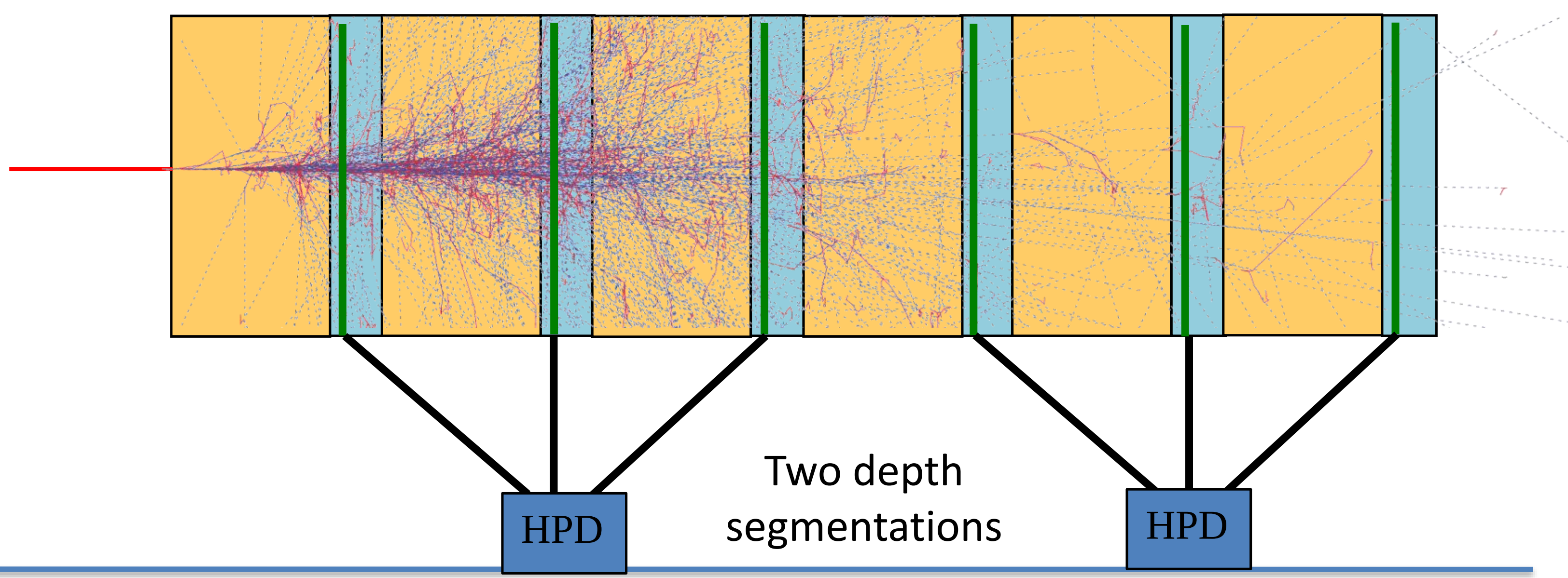
- Incident charged/neutral hadron generates hadronic shower in the heavy brass absorber
  - Charged particles in the shower produce **scintillation** light in the plastic
  - Amount of scintillation light is **proportional to incident particle energy**
  - Scintillation light shifted in wavelength & transported to **Hybrid PhotoDiodes**

Brass

Plastic scintillator

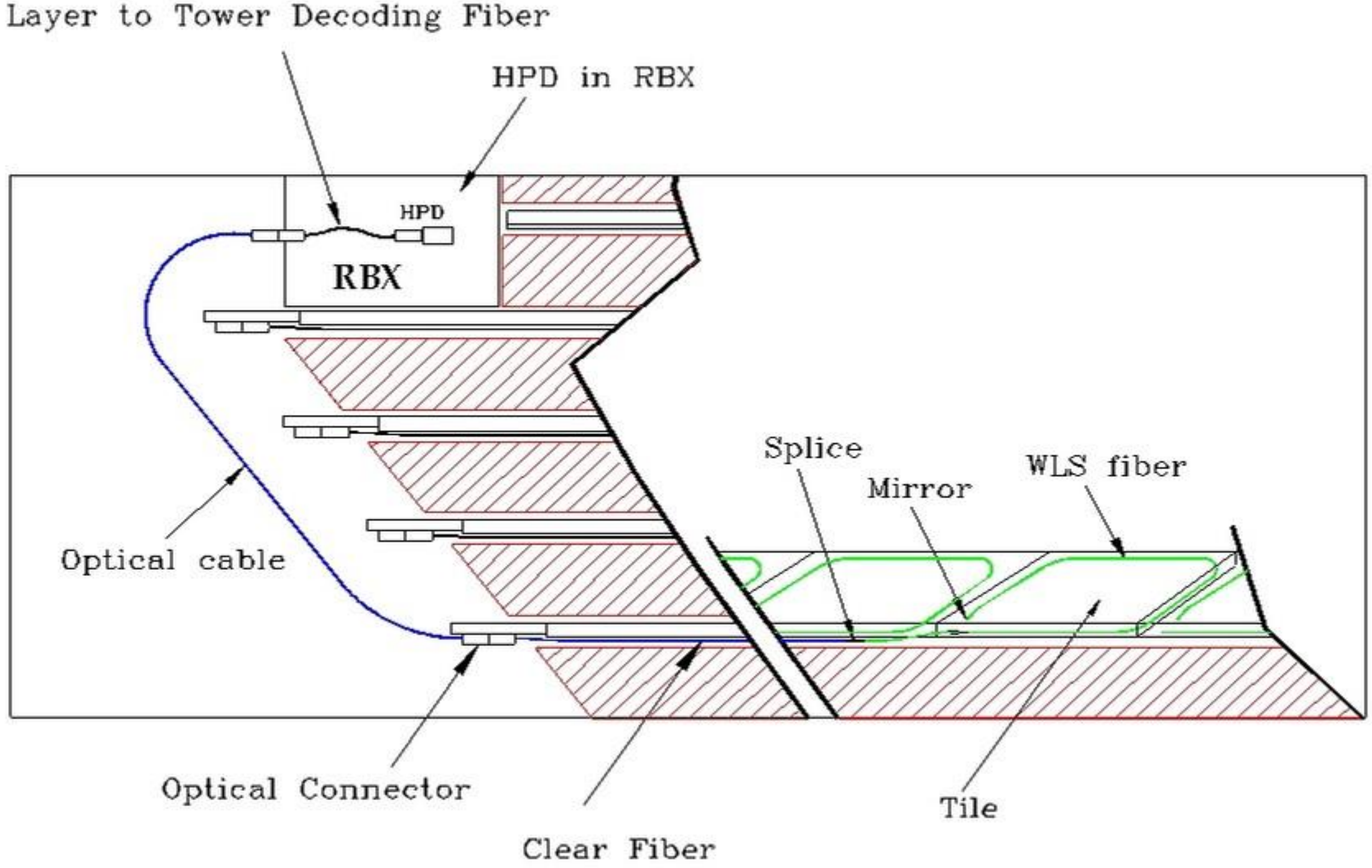
Wavelength-shifting (WLS) fibre

Clear fibre for light transport to HPD



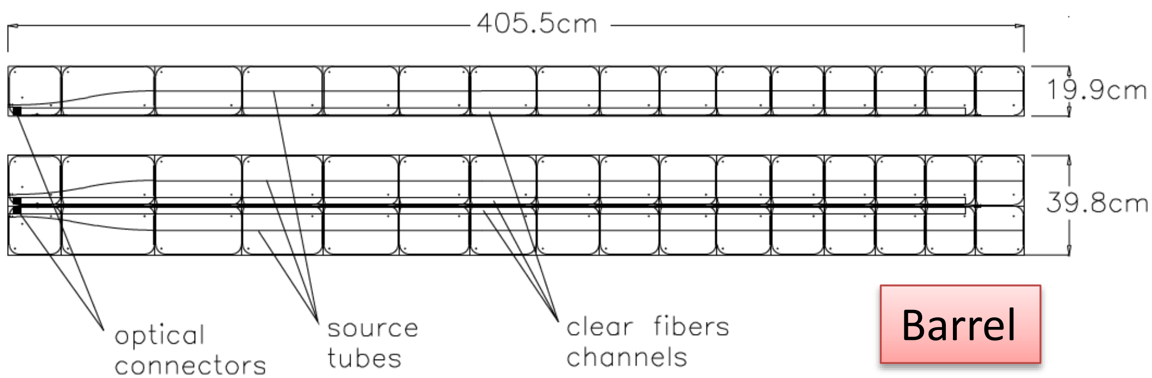
Optical Design for HCAL

Common Technology for HB, HE, HO

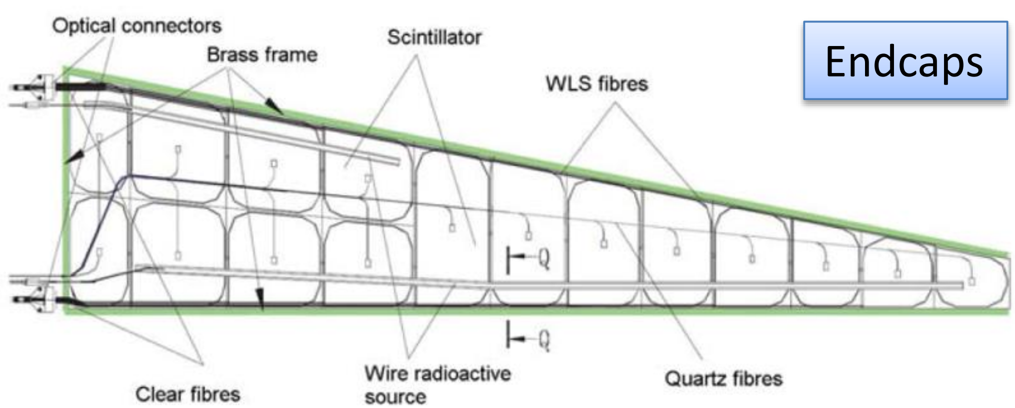


Scintillator in HE and HB

- Plastic scintillator + WLS + clear fibres
- Different sizes for the different layers in HB/HE
- Individual tile sizes vary with | $/\phi$



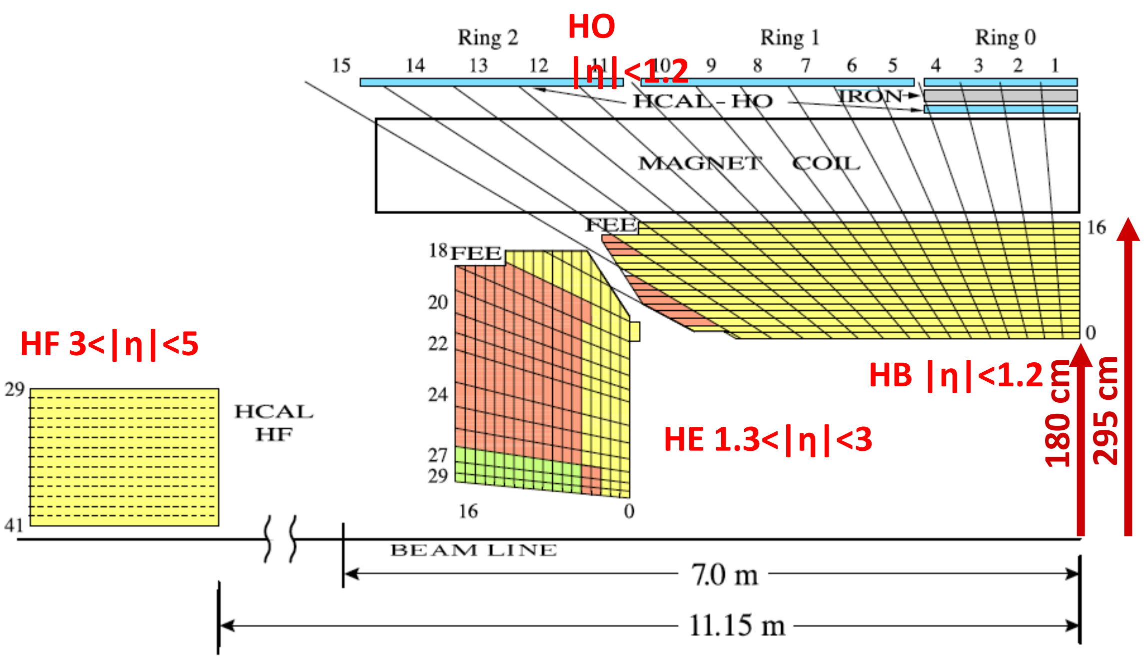
Barrel



Endcaps

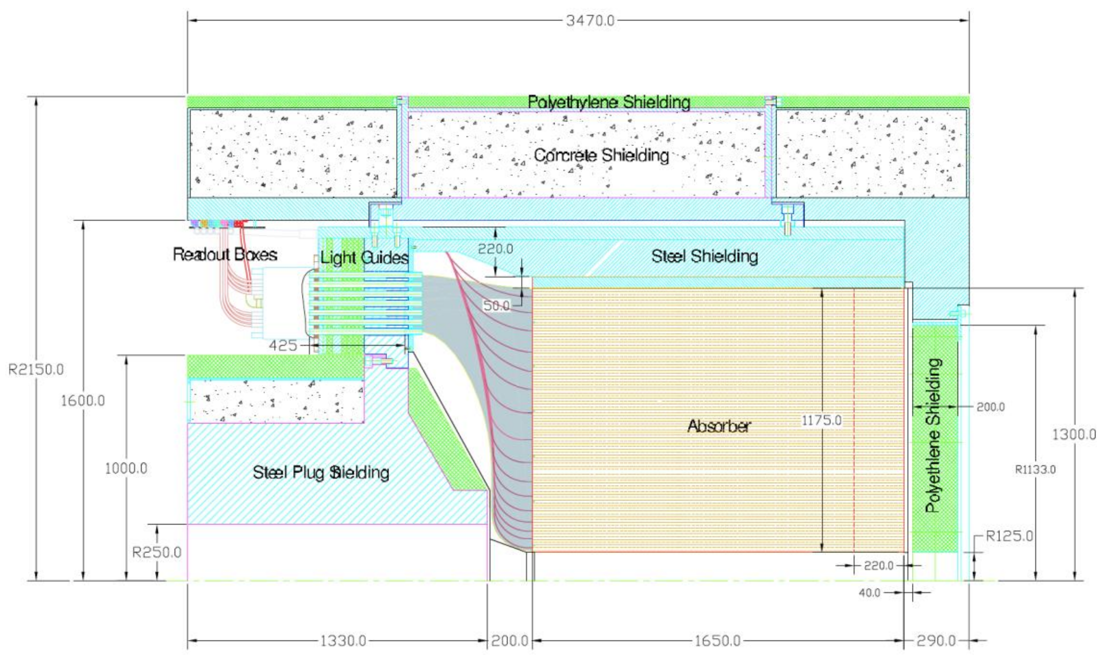
HB and HE

- Barrel (HB): |η|<1.3, 36 wedges (18 HB+, 18 HB-)
  - 14 layers of brass + steel front/back plates → ~10⌊
  - 16 megatile layers; 16| and 4 ϕ divisions per wedge
- Endcaps (HE): 1.3<|η|<3.0, 36 petals per endcap
  - 17 layers of brass → ~10⌊
  - 17 megatile layers; 12| and 1 or 2 ϕ divisions per wedge
  - 2 or 3 (high η) longitudinal segments



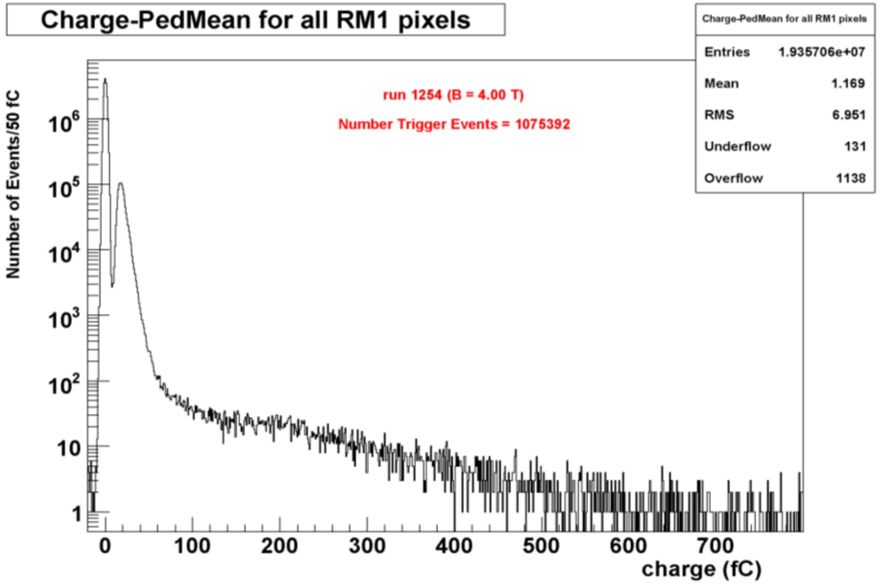
HF

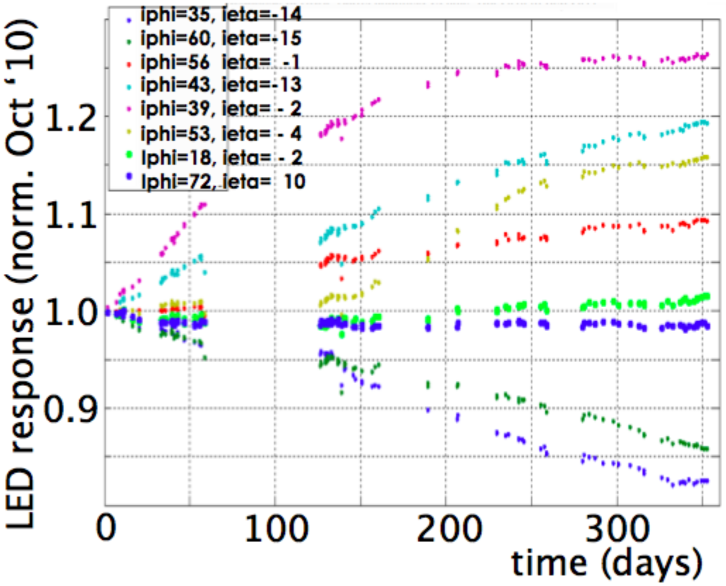
- Forward (HF): 3.0<|η|<5.0, 18 wedges per end
  - **Grooved steel plates**, 5mm thick, 165cm long → ~10 λ
  - ~square grid of holes spaced 5mm apart
  - 1mm diameter **fibres** (600μm **quartz core** + cladding + buffer)
  - **2 fibre lengths** (read out separately) to distinguish e/γ from hadron showers:
    - Half are **165cm long**
    - Other half start **after a depth of 22cm**



Readout of HB and HE

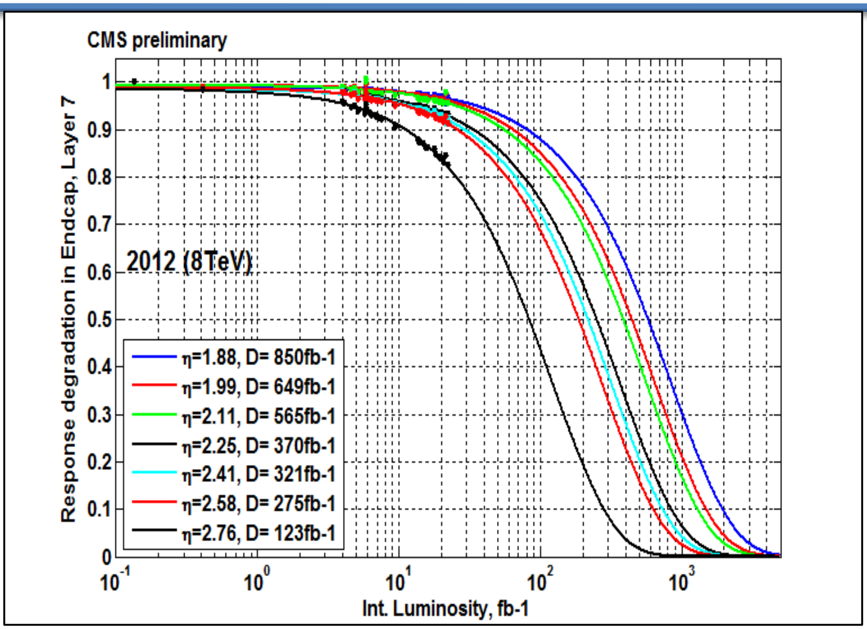
- The readout of HB and HE is currently done with Hybrid Photomultipliers.
- Due to discharge problems with these photodetectors we are changing them to Silicon Photomultipliers.
  - Improve signal to noise.
  - Solve discharge problem
  - Solve instability at B < 3.8 T.



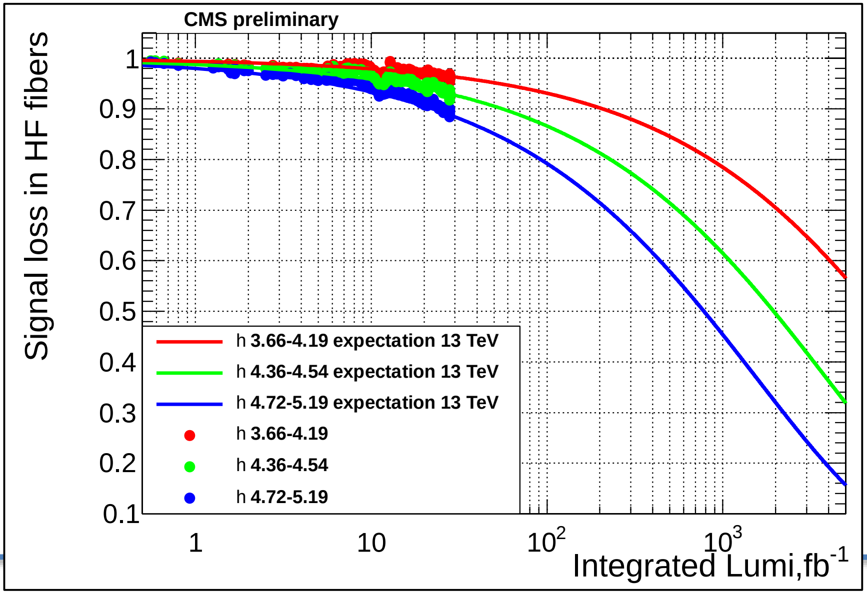


Radiation Effects in HCAL

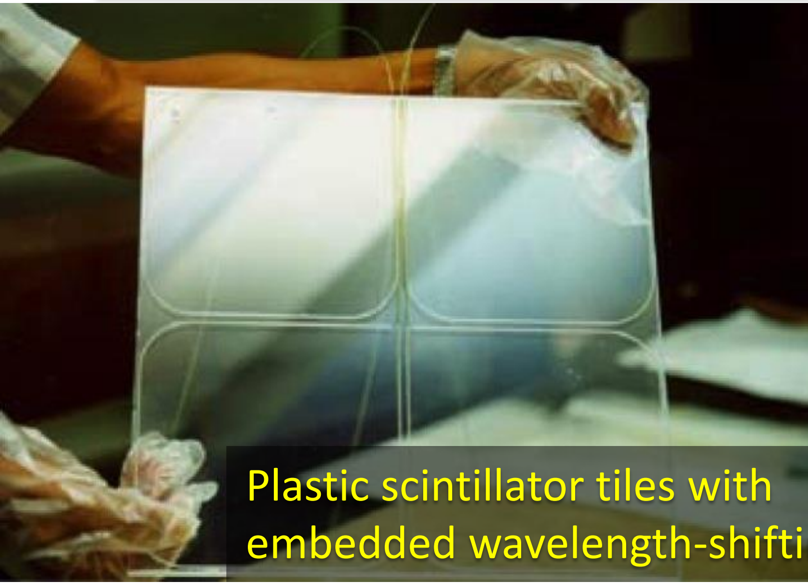
HE:
- Loss of scintillation and reduced transmission of light
- Effect observed in Run1 at the level of 30% in the highest η region of HE (η=3)



HF:
- Reduced light transmission in quartz fibres
- Effect observed during Run1 at the level of 10% in the highest η region of HF (η=5)



Assembly of brass wedges + megatiles for HB



Plastic scintillator tiles with embedded wavelength-shifting fibres

One of 36 brass wedges showing gaps for the scintillators

Assembled HB wedges, showing the optical cabling

Inserting the final wedge to form one half of HB

Swords into Ploughshares The HCAL Brass

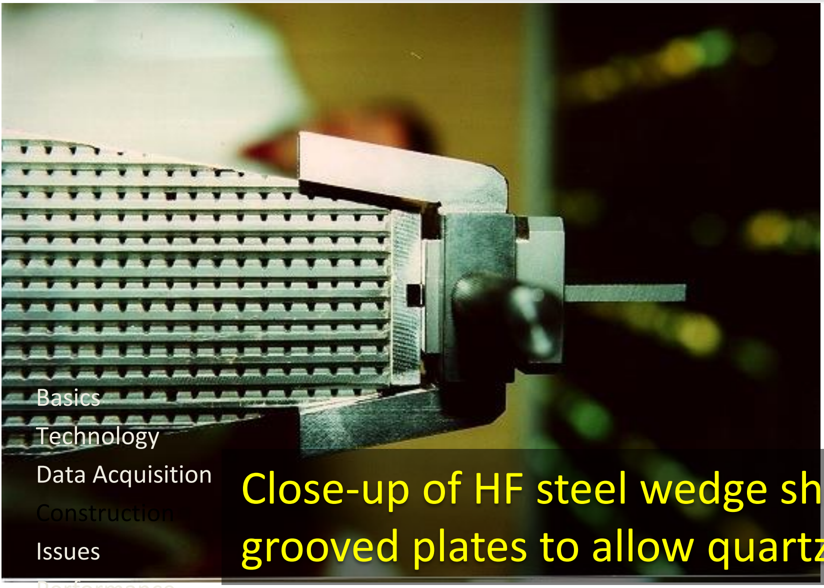
Brass for the HE came from Russian artillery shells

Melting the shells

Recycled brass plates

Trial assembly of HE brass "petals"

Assembly of the 350-tonne HFs



Close-up of HF steel wedge showing grooved plates to allow quartz fibres

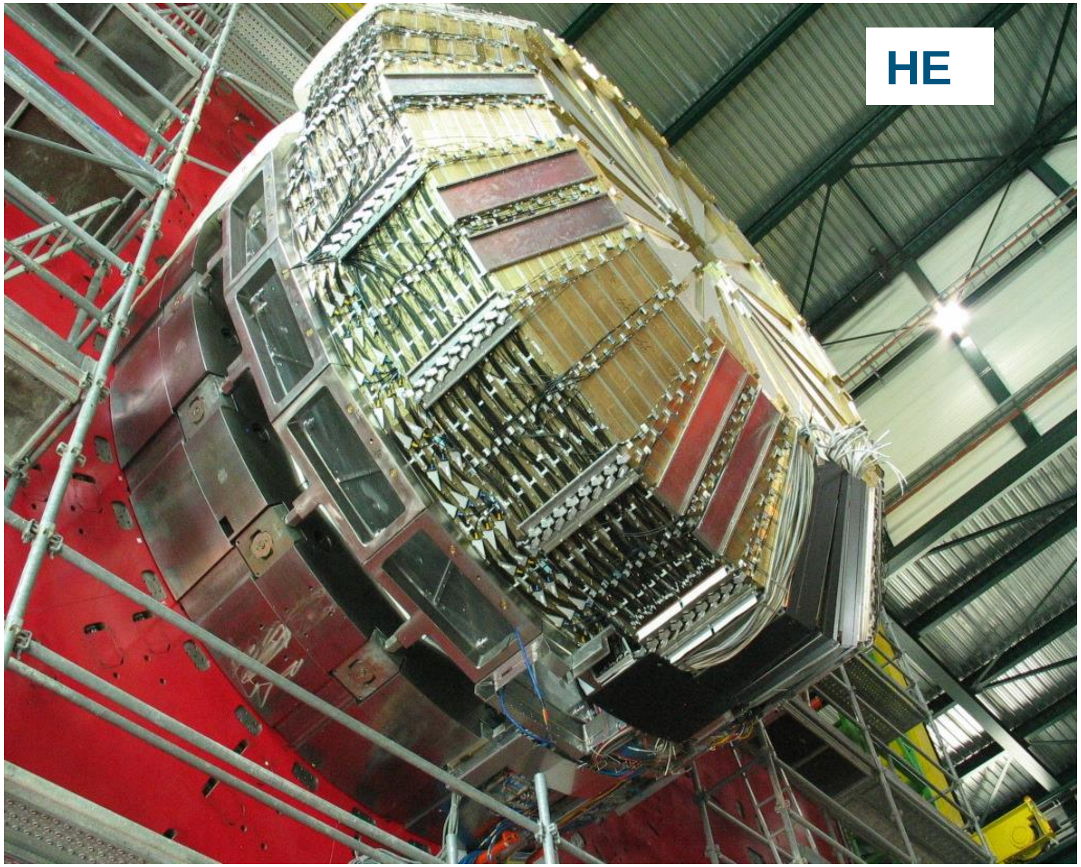
Basics
Technology
Data Acquisition
Construction
Issues
Performance
Long-term
Organization

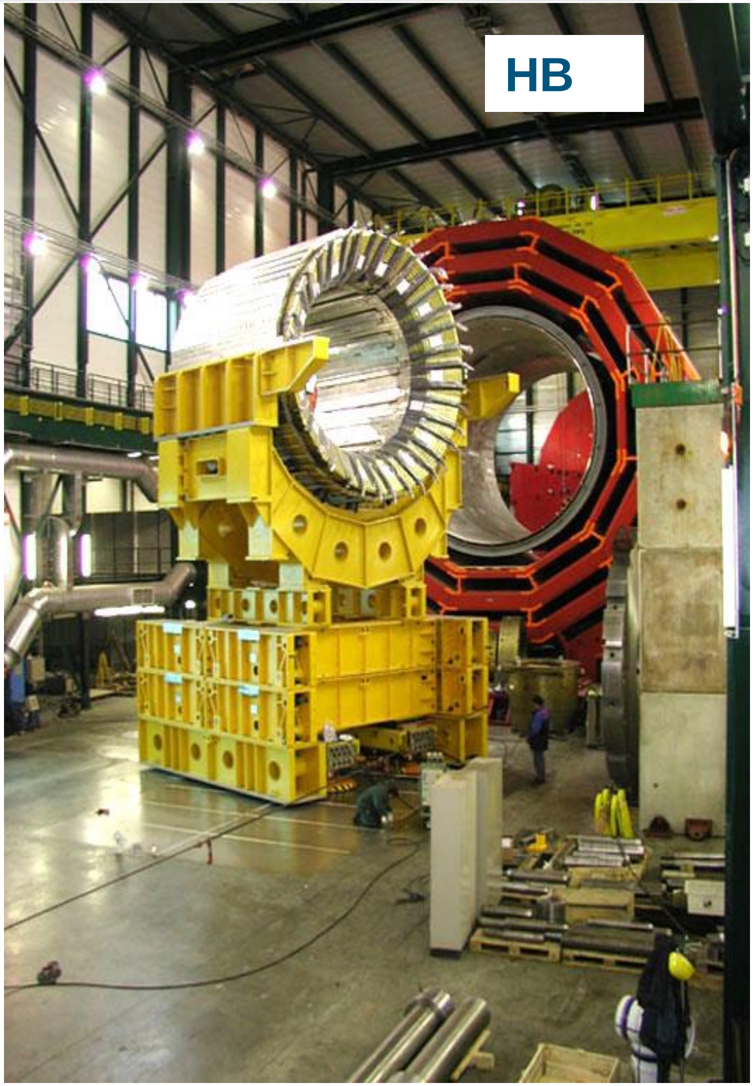
Inserting quartz fibres into a steel wedge

Wedges being assembled into Dees

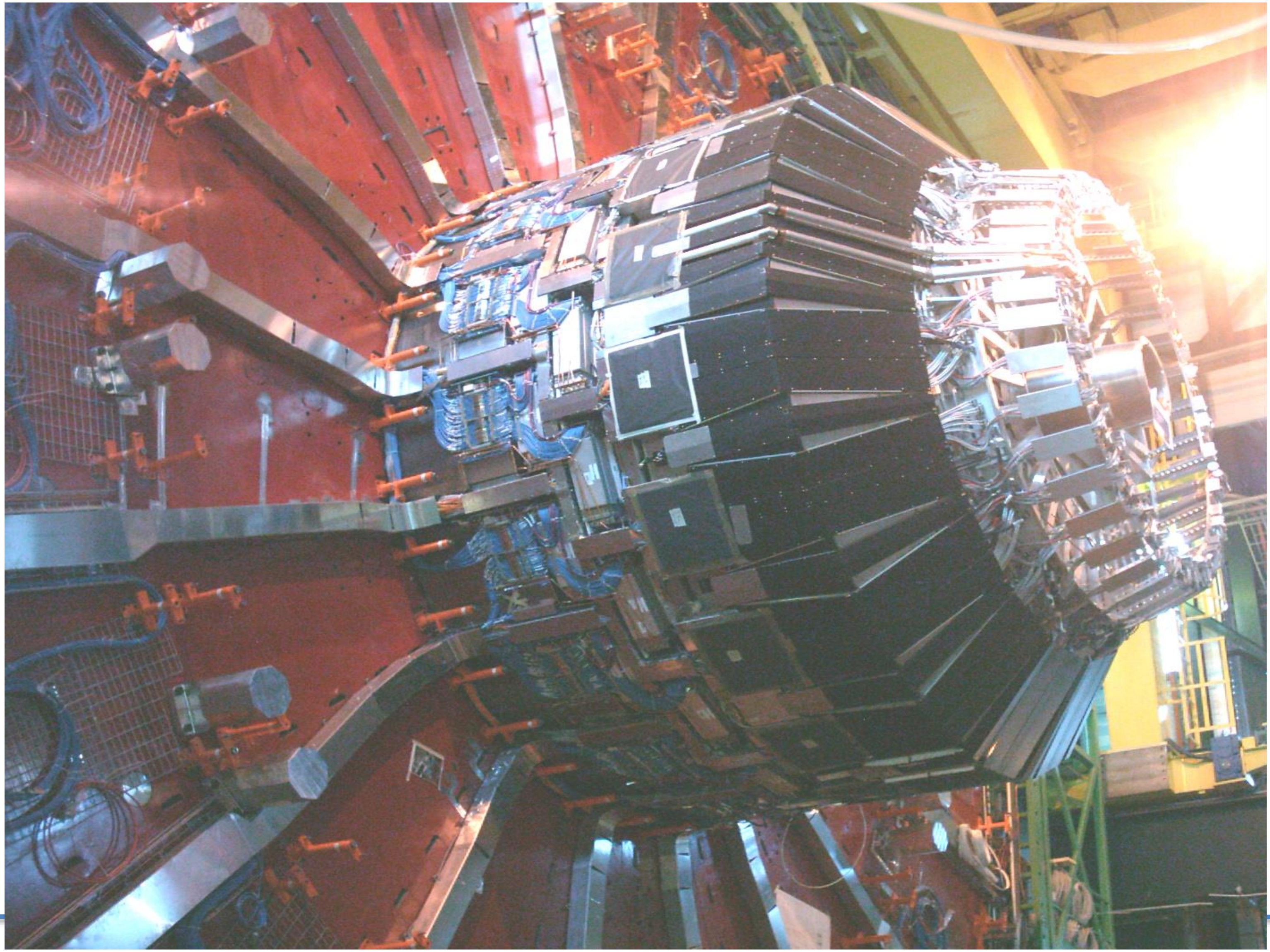
Completed HF ready for installation

HCAL-Absorbers Complete

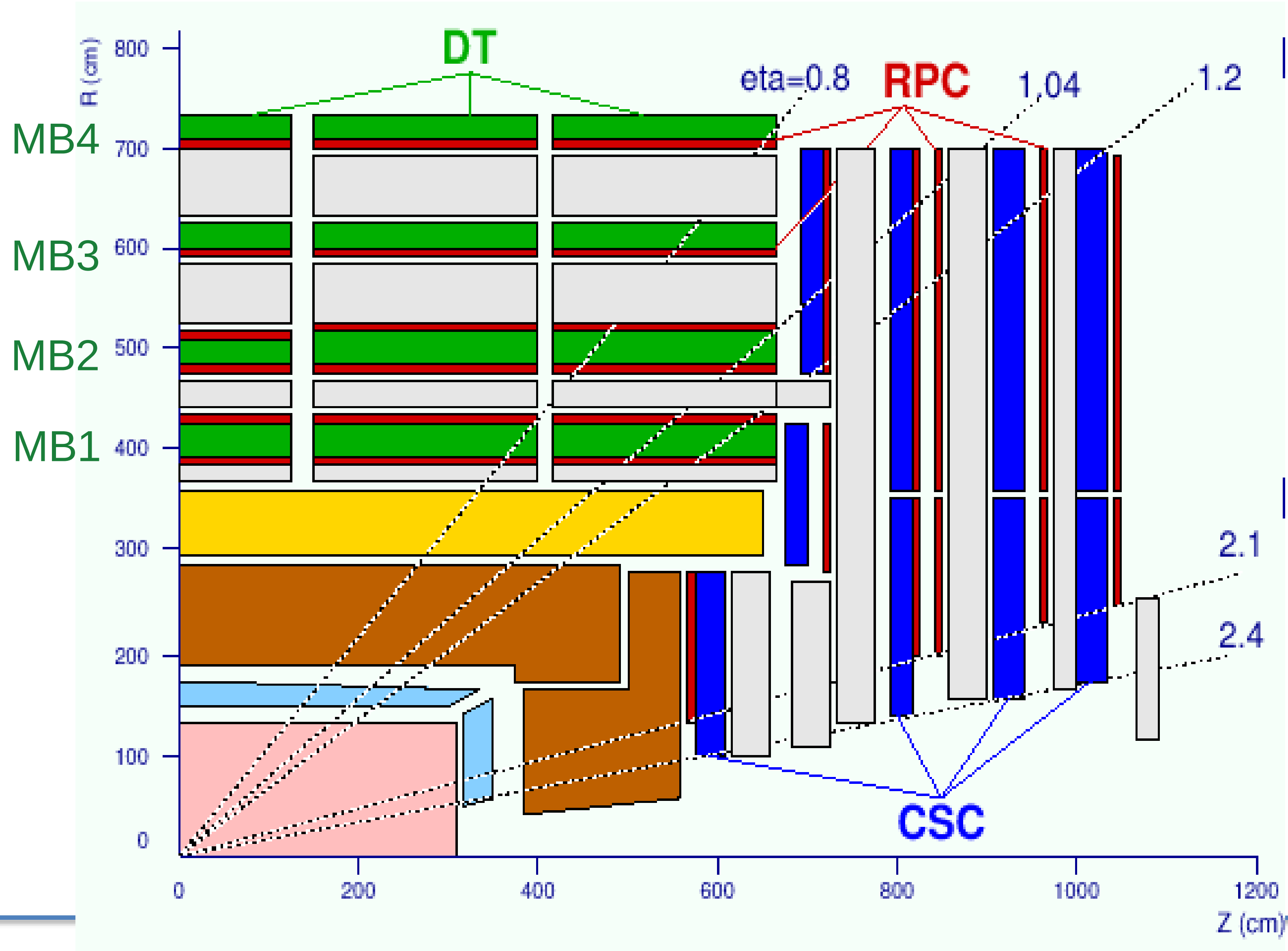




HE Right Now

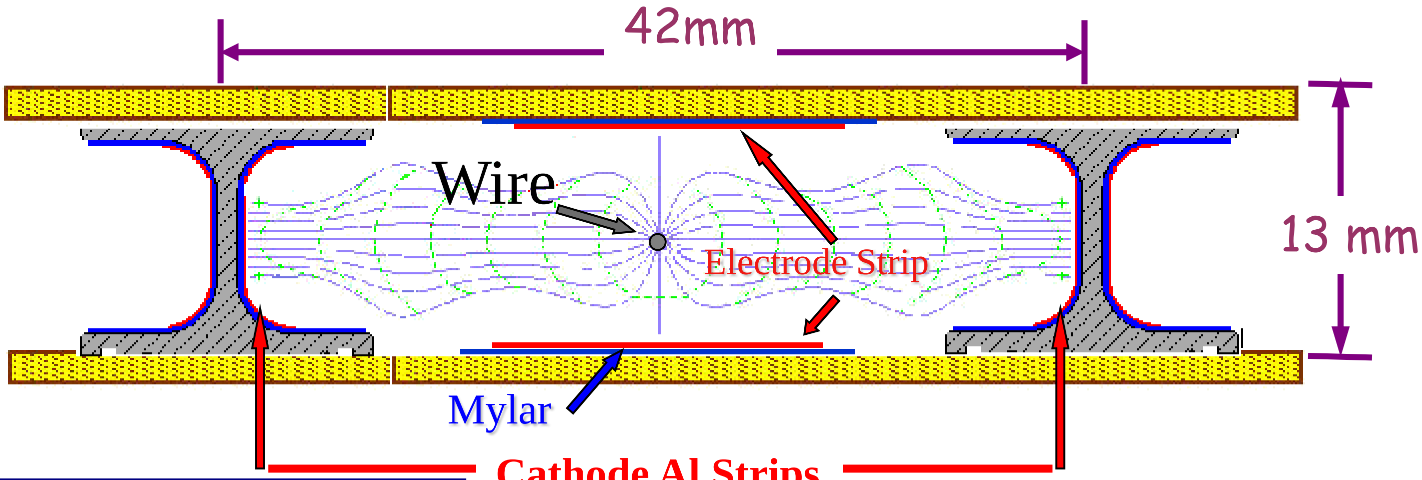


Muon System



DT
eta=0.8
RPC
1.04
1.2
MB4
MB3
MB2
MB1
R (cm)
800
700
600
500
400
300
200
100
0
2.1
2.4
CSC
0
200
400
600
800
1000
1200
Z (cm)

Barrel Muons Drift Tubes



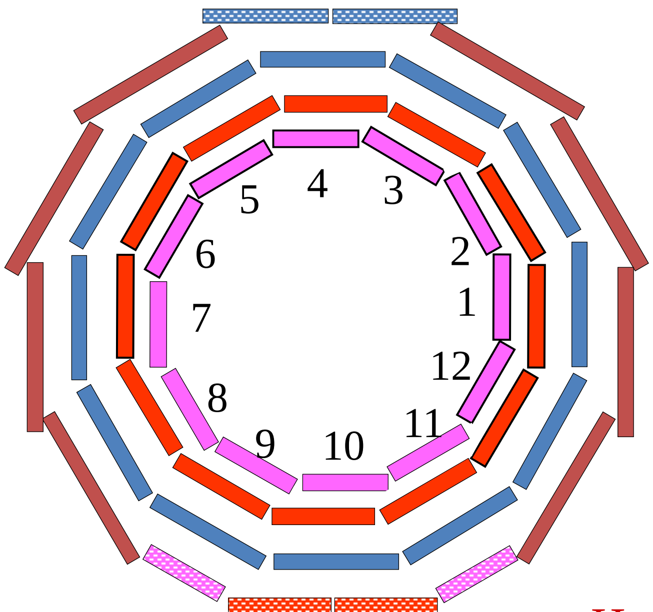
GAS: Ar/CO_2 (85/15)

HV: Wires 3600 V
Strips 1800 V
I-beams -1200 V

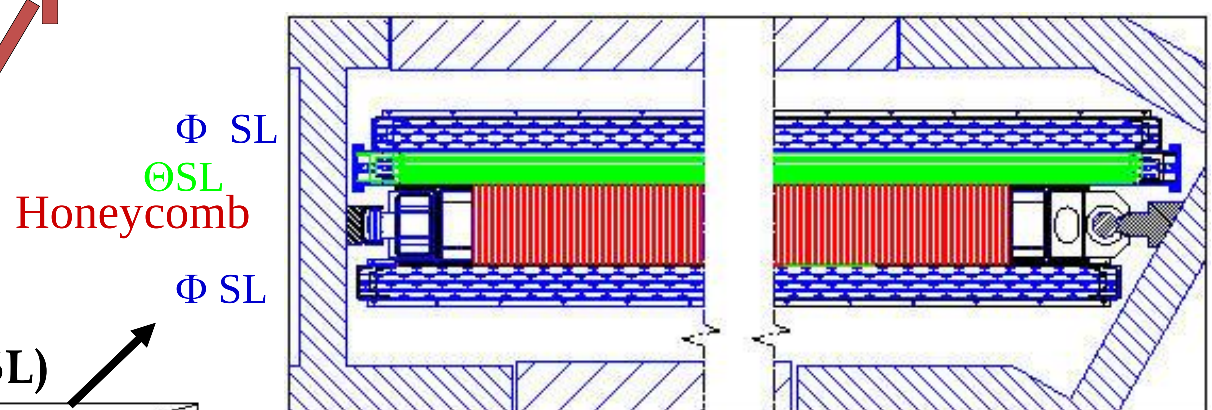
Tmax: < 400 ns
Drift Velocity : ~ 55μm/ns

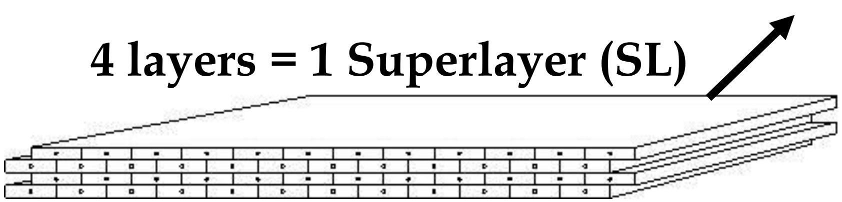
Single Wire
Resolution : < 300 μm ➡ 100μm Φ
150μm θ

Barrel Drift Tubes



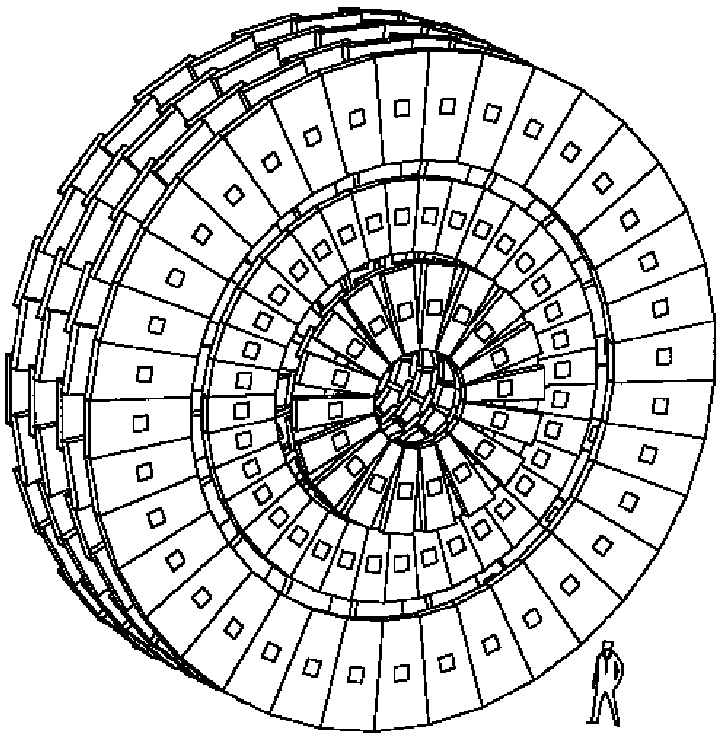
60	MB1	3SL	2 RPC ~2.0 x 2.54 m^2	960kg
60	MB2	3SL	2 RPC ~2.5 x 2.54 m^2	1200kg
60	MB3	3SL	1 RPC ~3.0 x 2.54 m^2	1300kg
40	MB4	2SL	1 RPC ~4.2 x 2.54 m^2	1800kg
10	MB1	2SL	1 RPC	
10	MB2	2SL	1 RPC	
10	MB3	2SL	1 RPC	





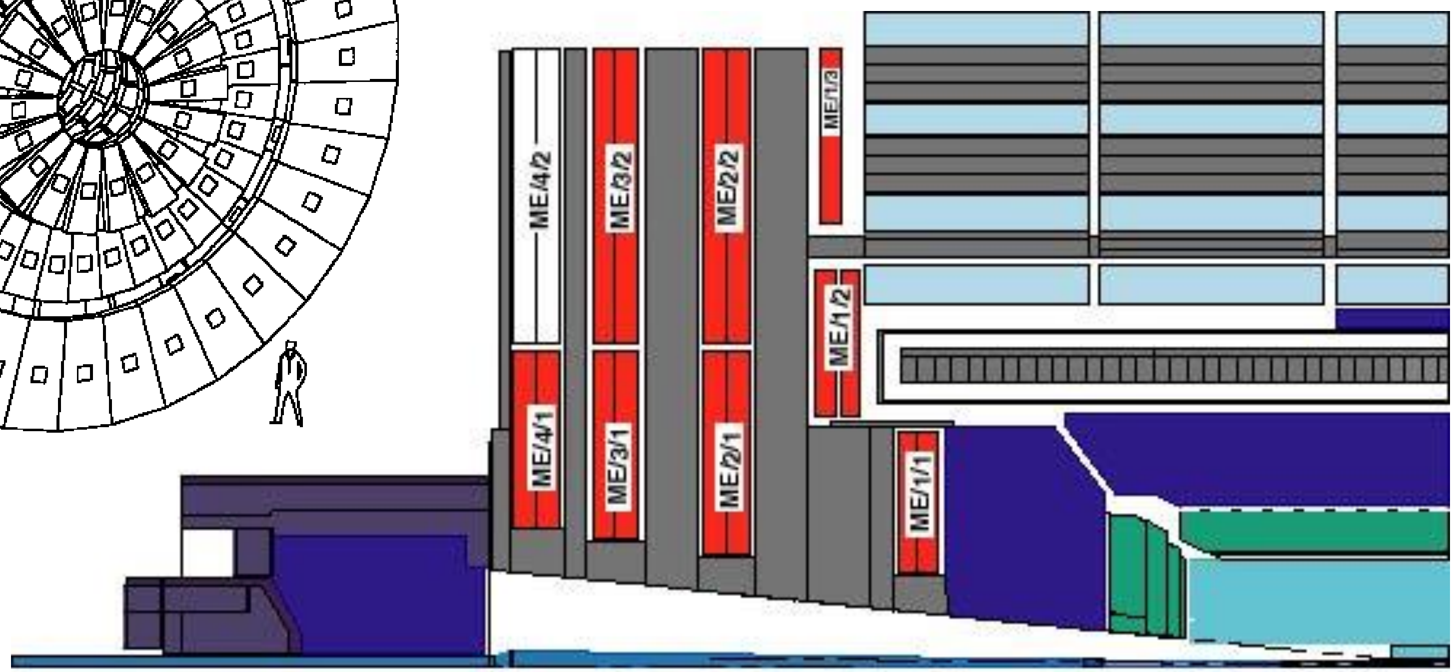
The Barrel Muon system comprises 250 chambers for 5 wheels: Total 1700 SqM. Each Chamber has 2*4 Φ and 1*4 Θ layers

Endcap Muon Cathode Strip Chambers

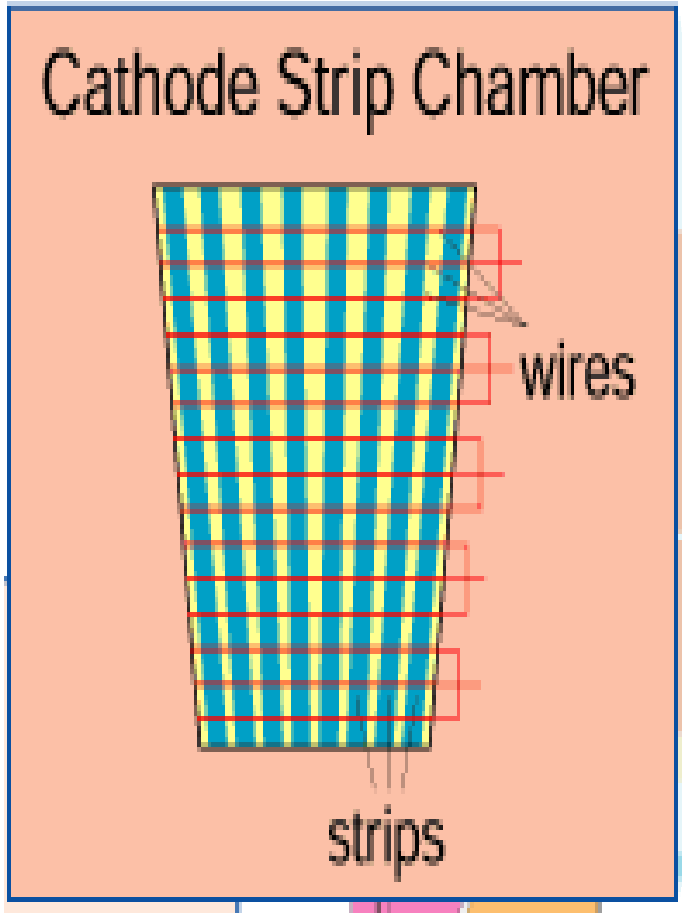


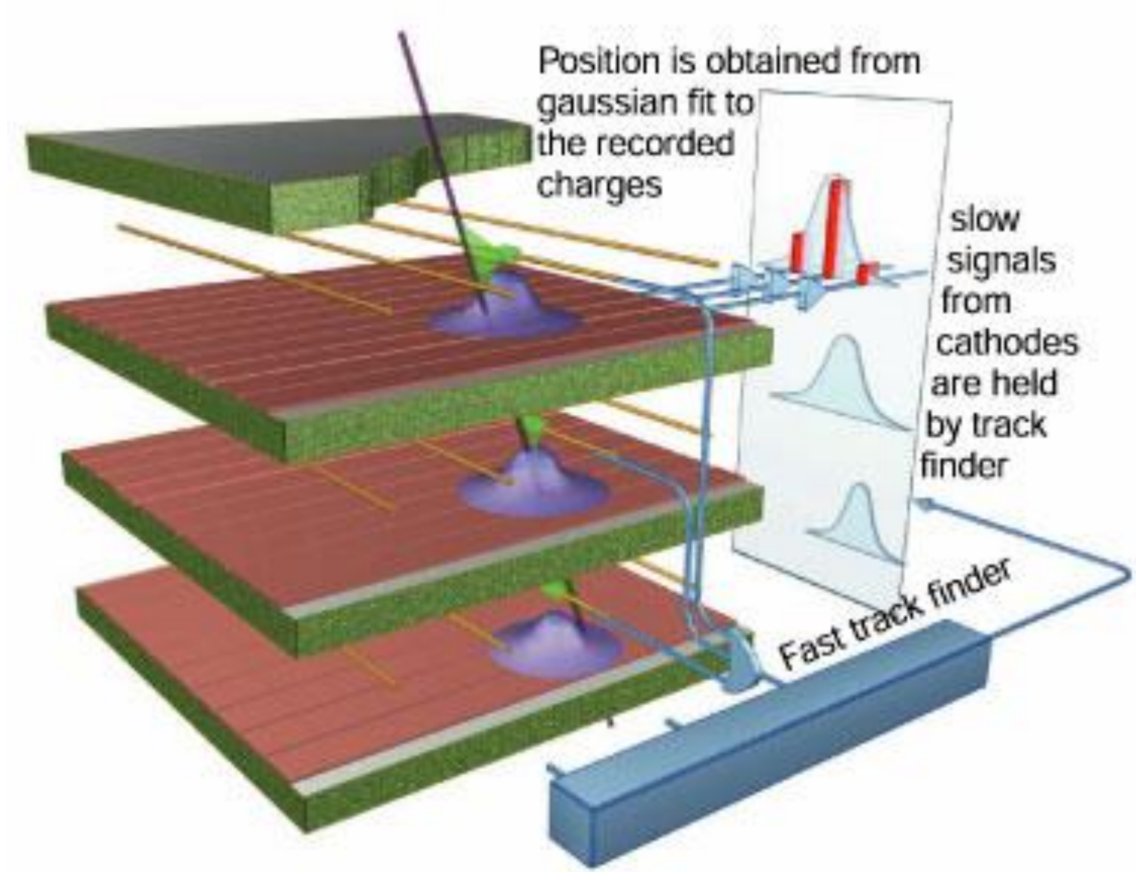
468 Cathode Strip Chambers

~2,000,000 wires
~6,000 m^2 sensitive area



CSC Construction



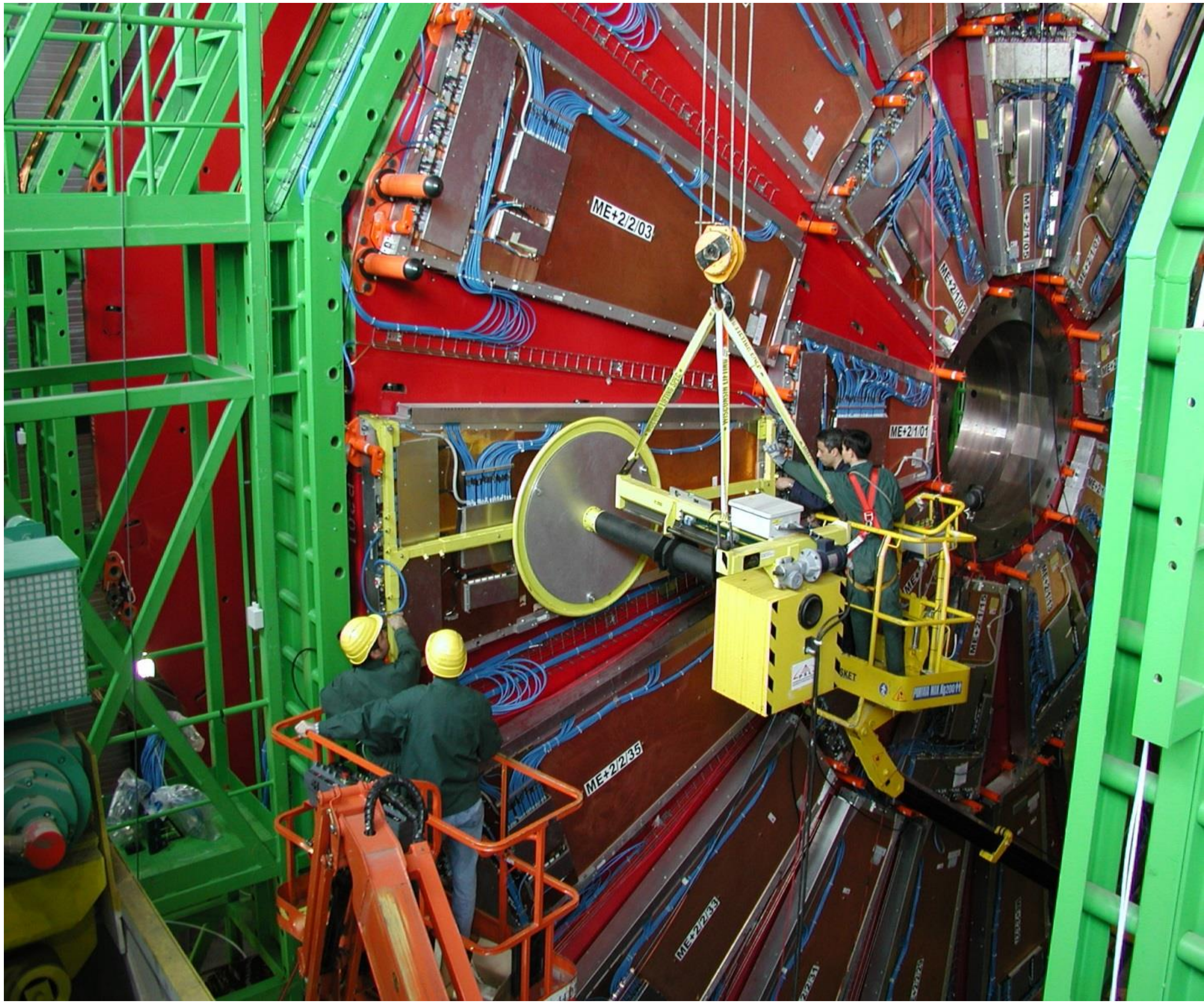


6 layers in each chamber

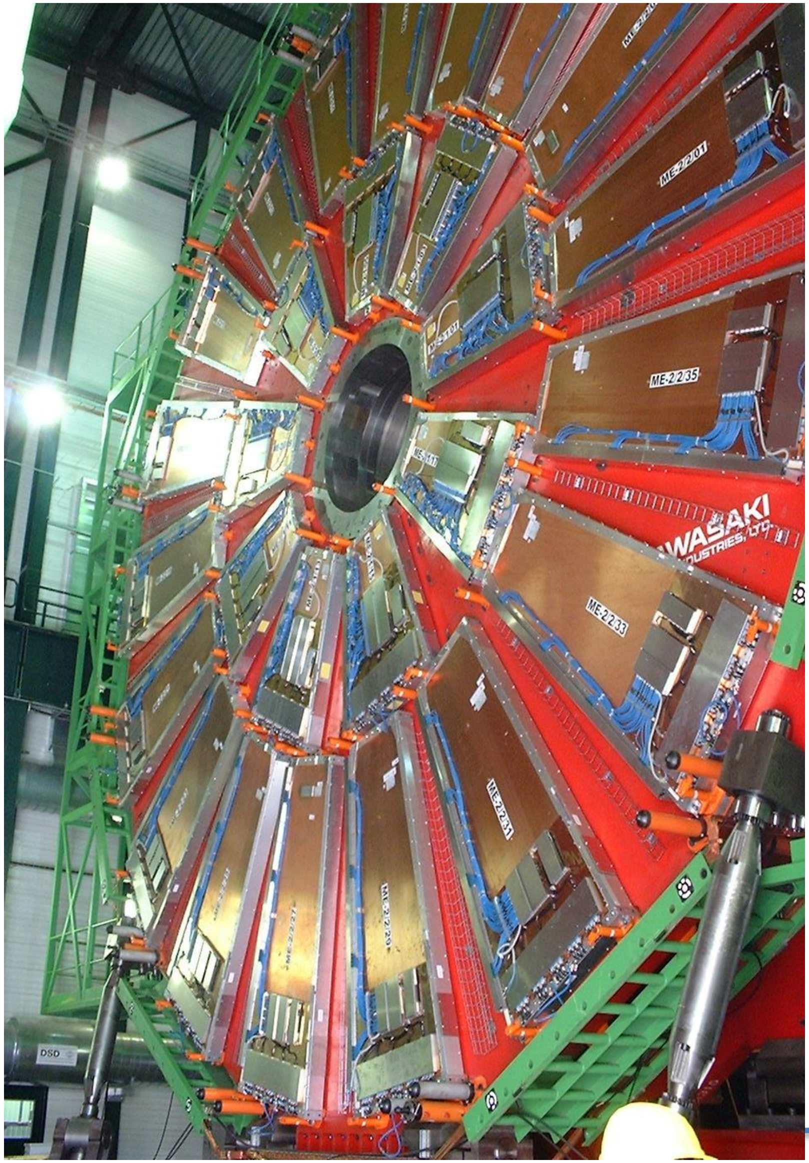
Position resolution ~ 50 microns (from strips)
Timing resolution better than 25ns (from wires)

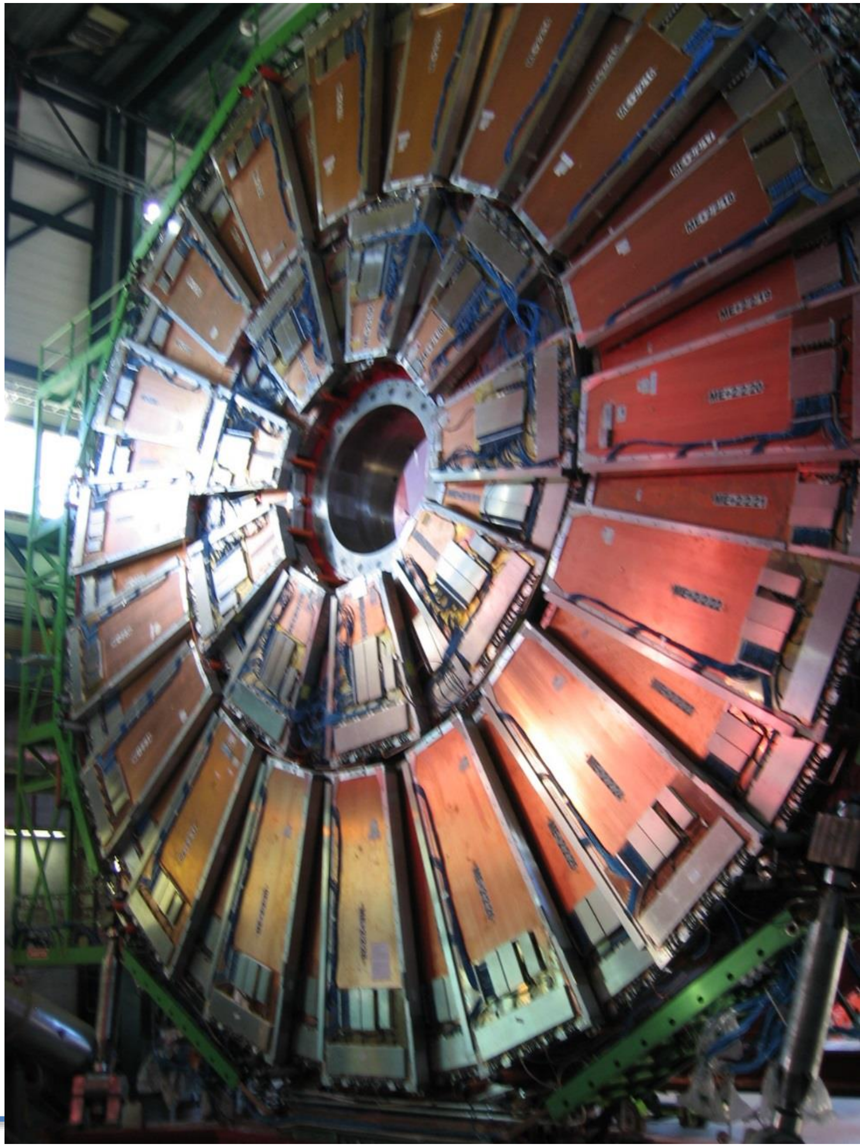
Endcap CSC Installation

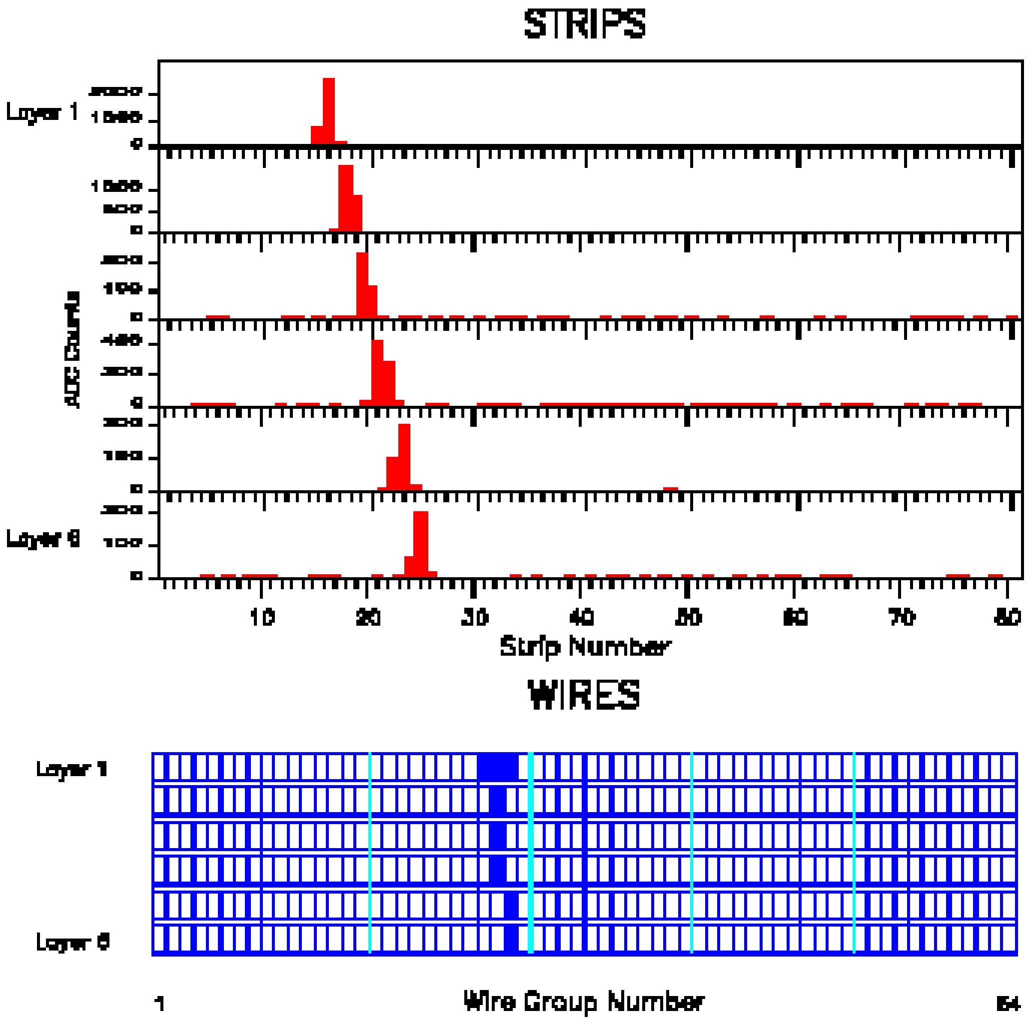
468 chambers needed
100% tested and at CERN
67% installed
65% commissioned



CSC's mounted on endcaps







Single muon track in one CSC

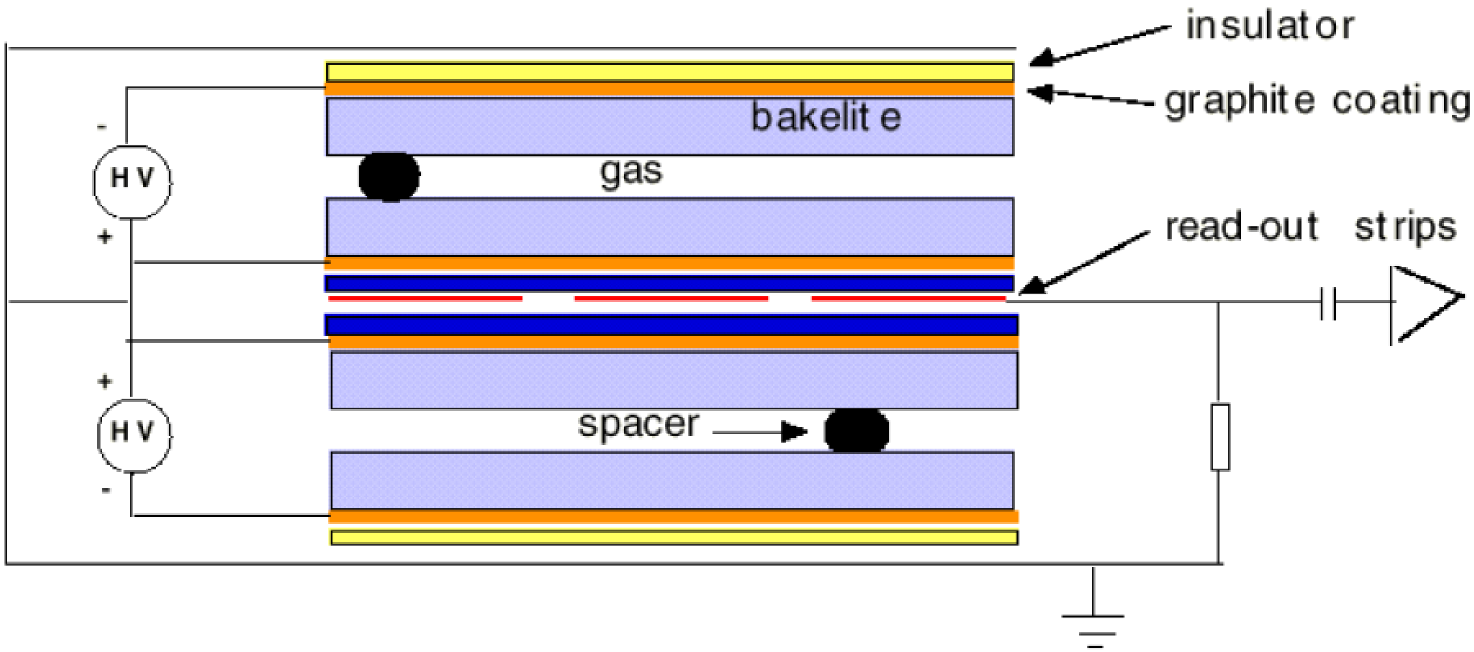
Resistive Plate Chambers

Dedicated trigger detector, with fast timing response

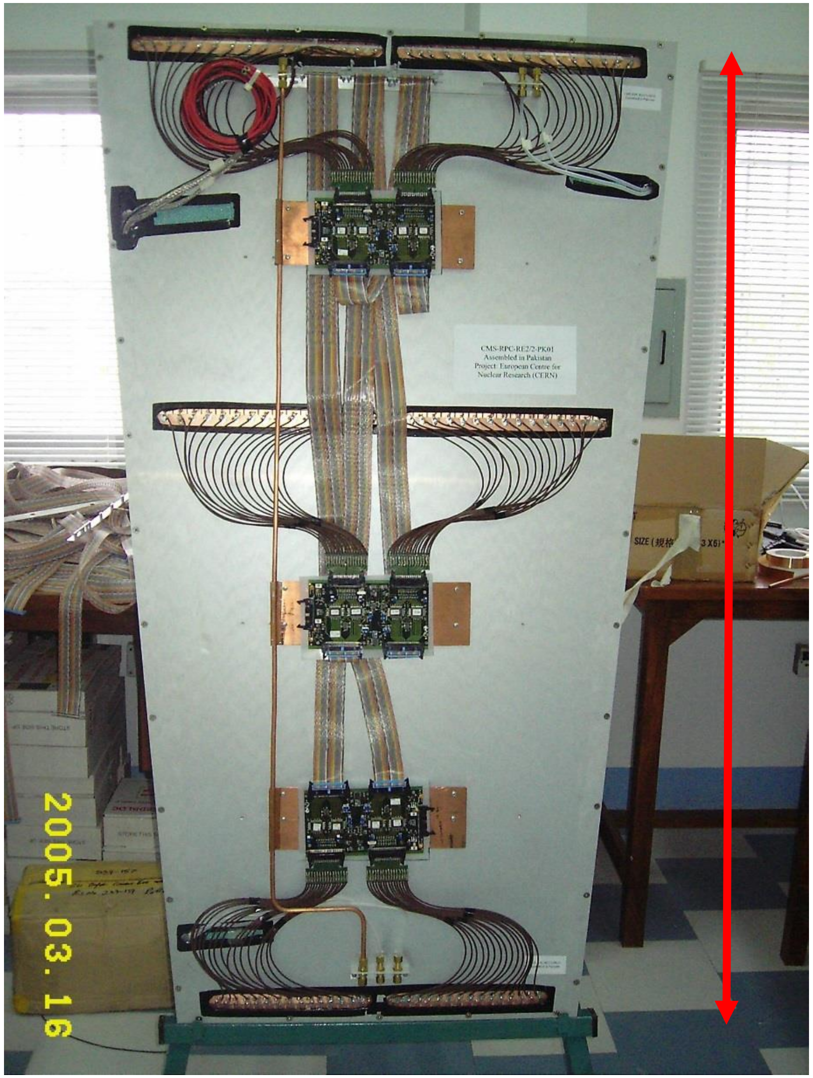
Basic functions:

- identify candidate muon track
- assignment of bunch crossing to the candidate track(s)
- estimate their transverse momenta

An RPC module is made self-supporting, mounted outside the muon chambers (barrel and endcap) to match the active area of the tracking chambers

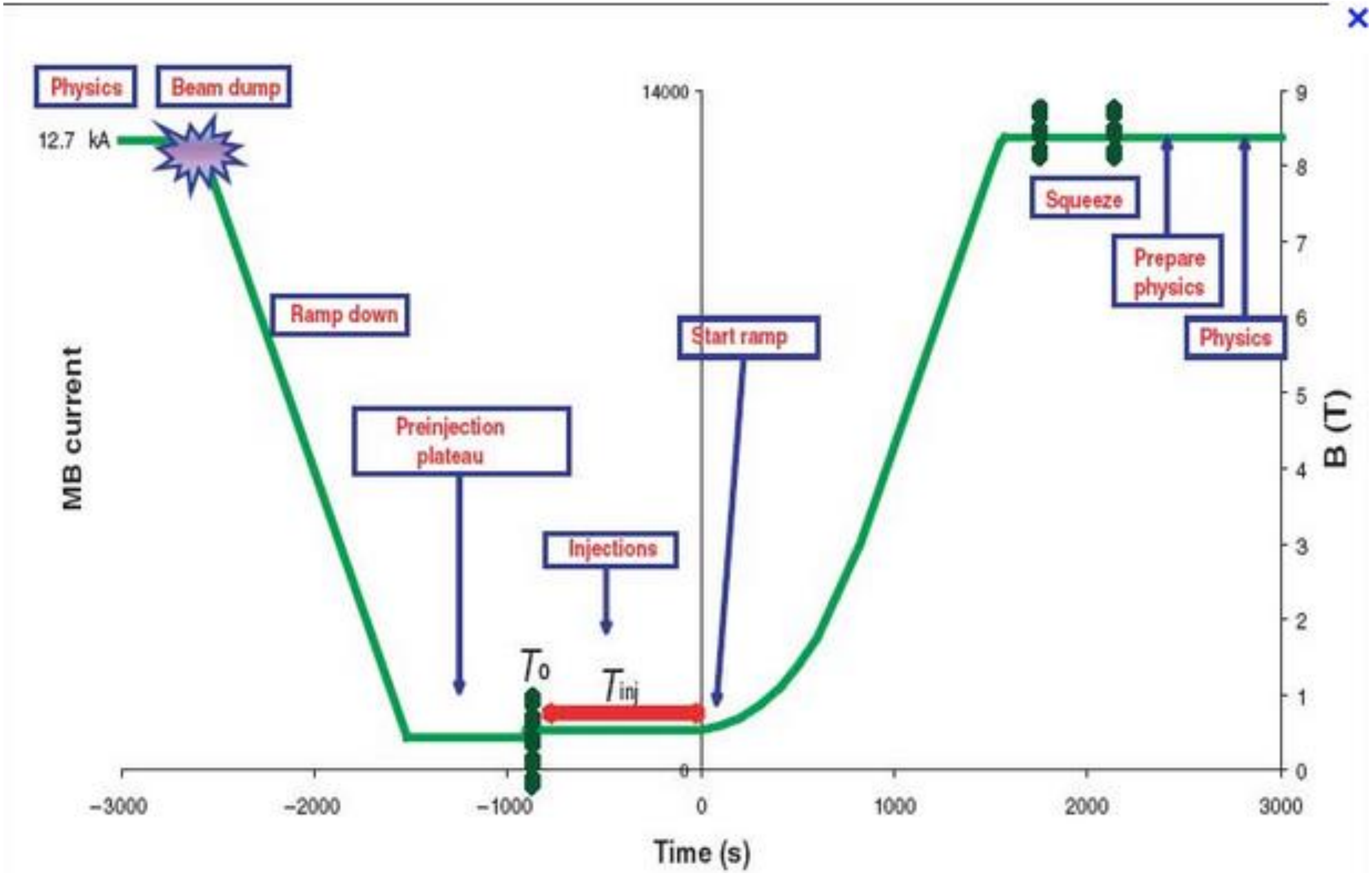


Endcap RPC



3.2 m

LHC operation

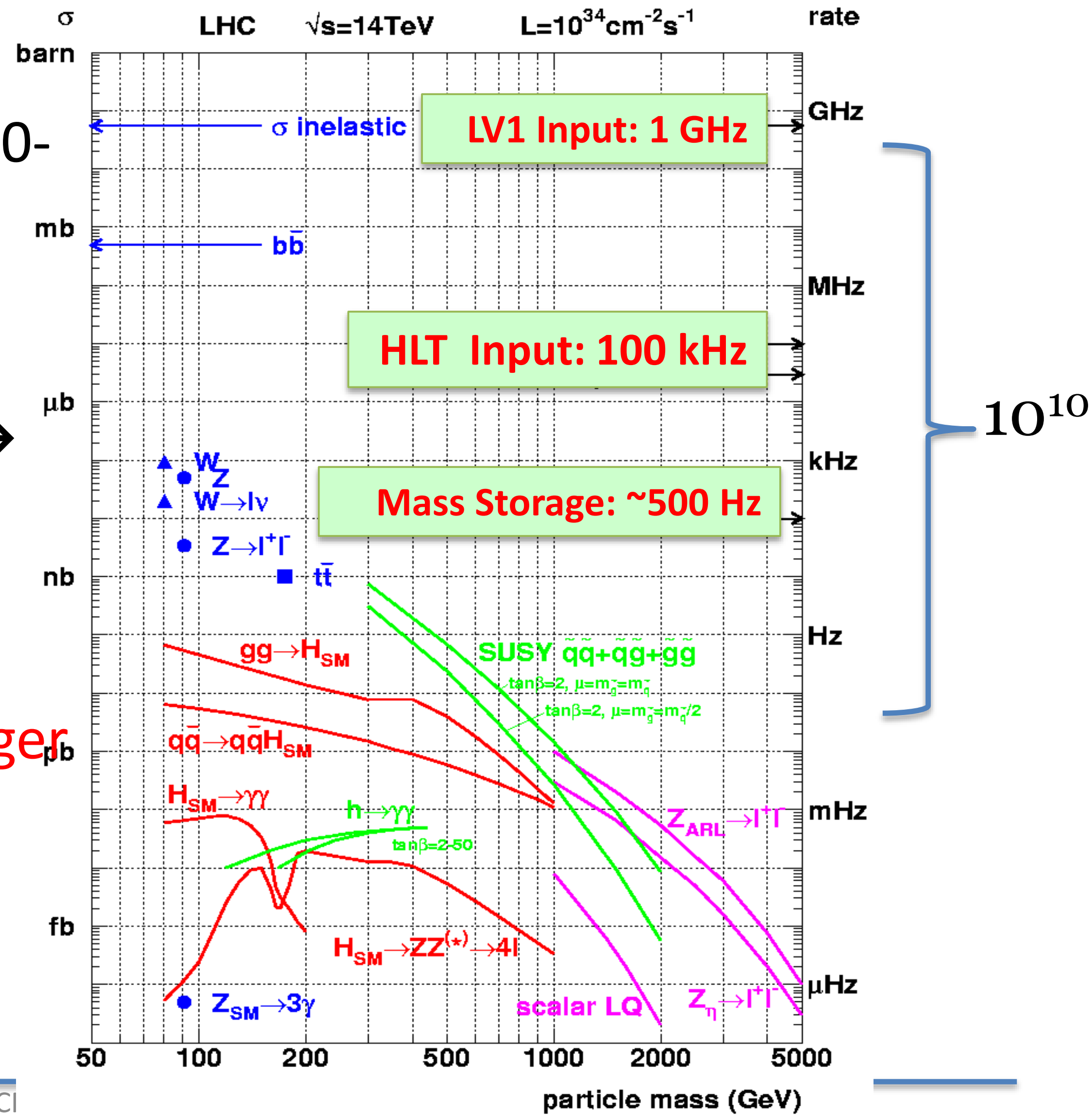


Towards physics: CMS triggers

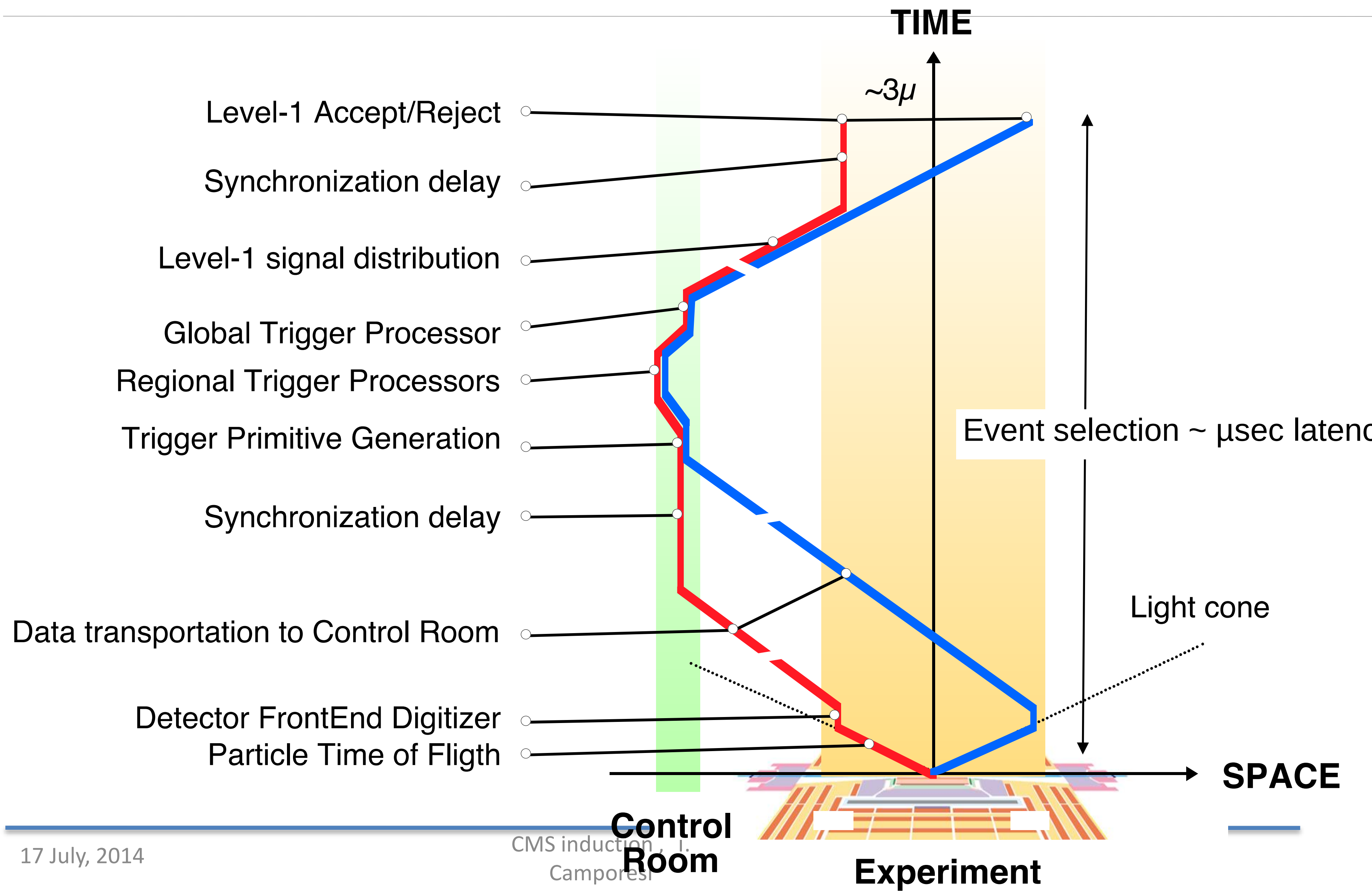
At LHC the collision rate is 20-40 MHz
The Event size <1 Mbyte

Band width limit ~ 200 GB→
Mass storage rate
~300-500 Hz

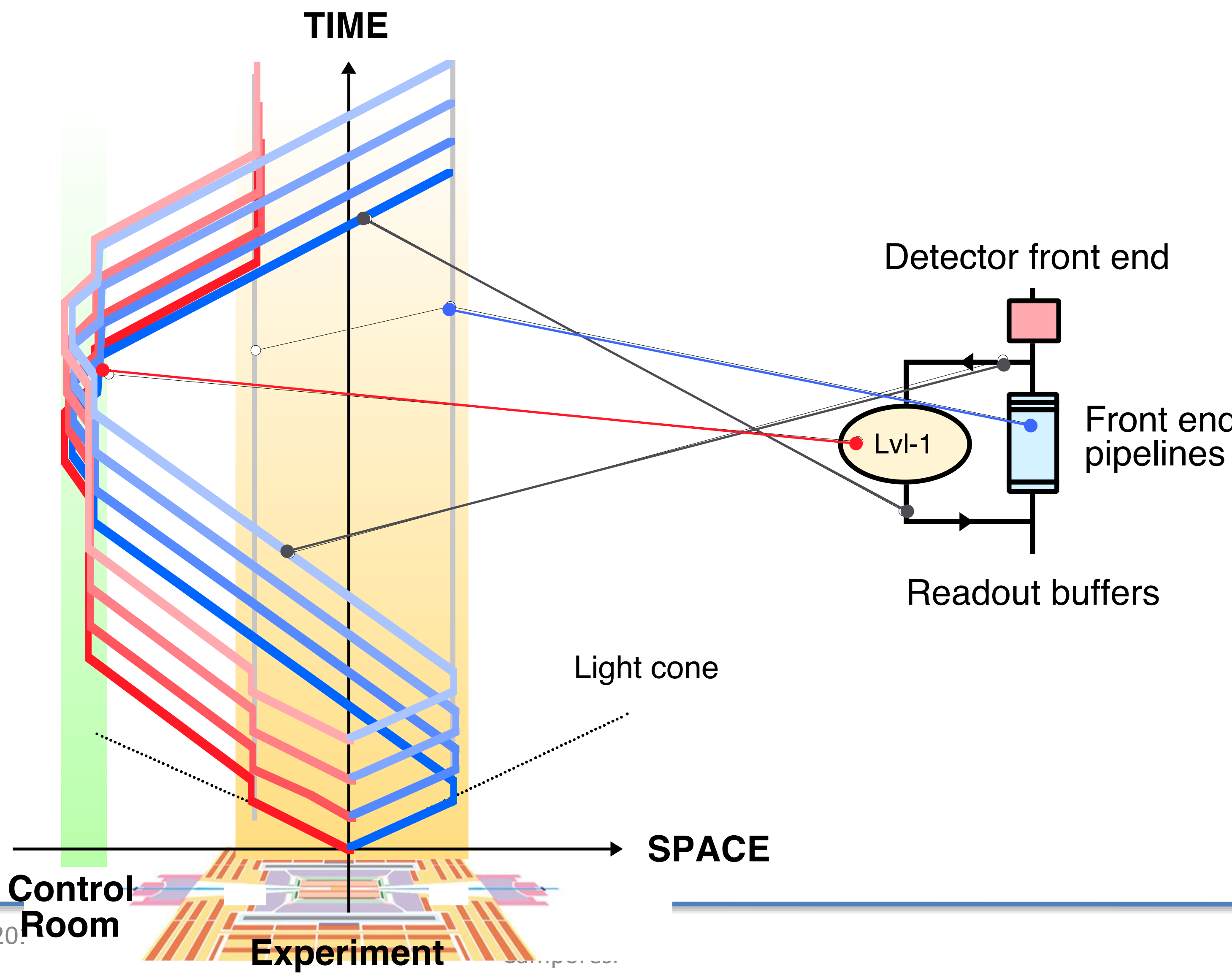
First step in ‘analysis’ is trigger



Event signals kinematic



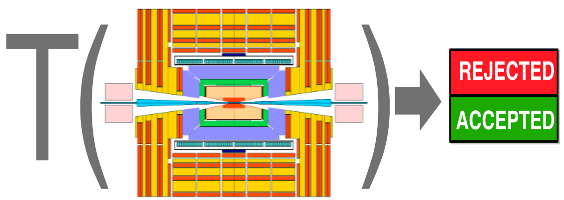
Events signal handling



Trigger levels

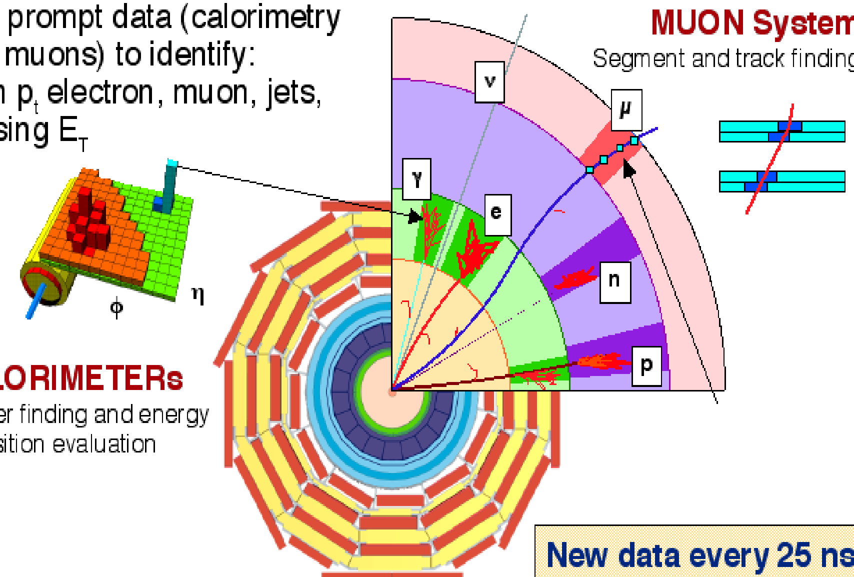
L1 trigger

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T

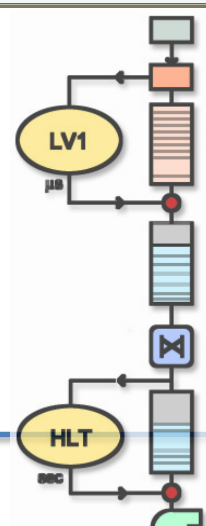


Since the detector data are not all promptly available and the function is highly complex, T(...) is evaluated by successive approximations called :

TRIGGER LEVELS

(possibly with zero dead time)

New data every 25 ns
Decision latency ~ μs



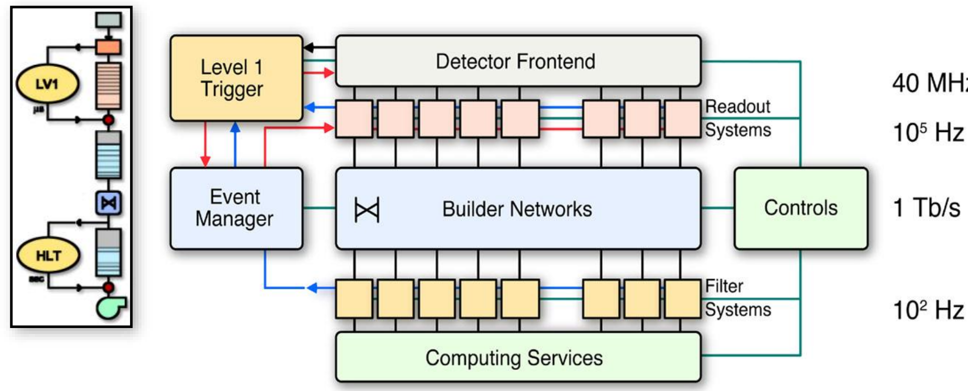
On-line requirements

Collision rate	**40 MHz**
Event size	**1 Mbyte**
Level-1 Trigger input	**40 MHz**
Level-2 Trigger input	**100 kHz**
......	
Mass storage rate	**~300 Hz**
Online rejection	**99.999%**
System dead time	**~ %**

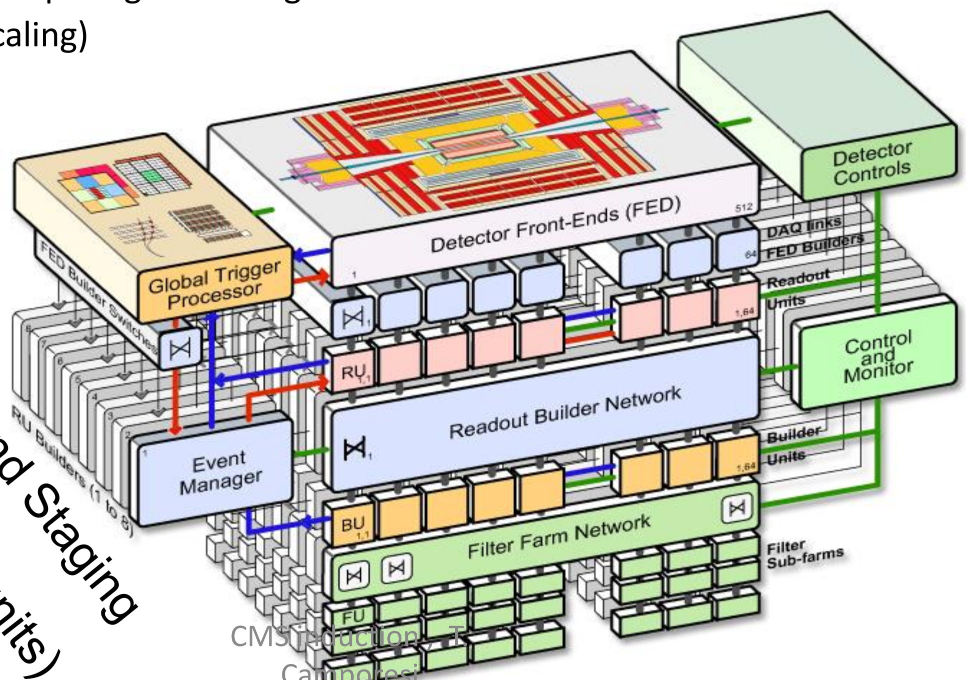
DAQ

DAQ design issues

Data network bandwidth (EVB)	~ Tb/s
Computing power (HLT)	~ 10 Tflop
Computing cores	~ 10000
Local storage	~ 300 TB



Minimize custom design
Exploit data communication and computing technologies
DAQ staging by modular design (scaling)

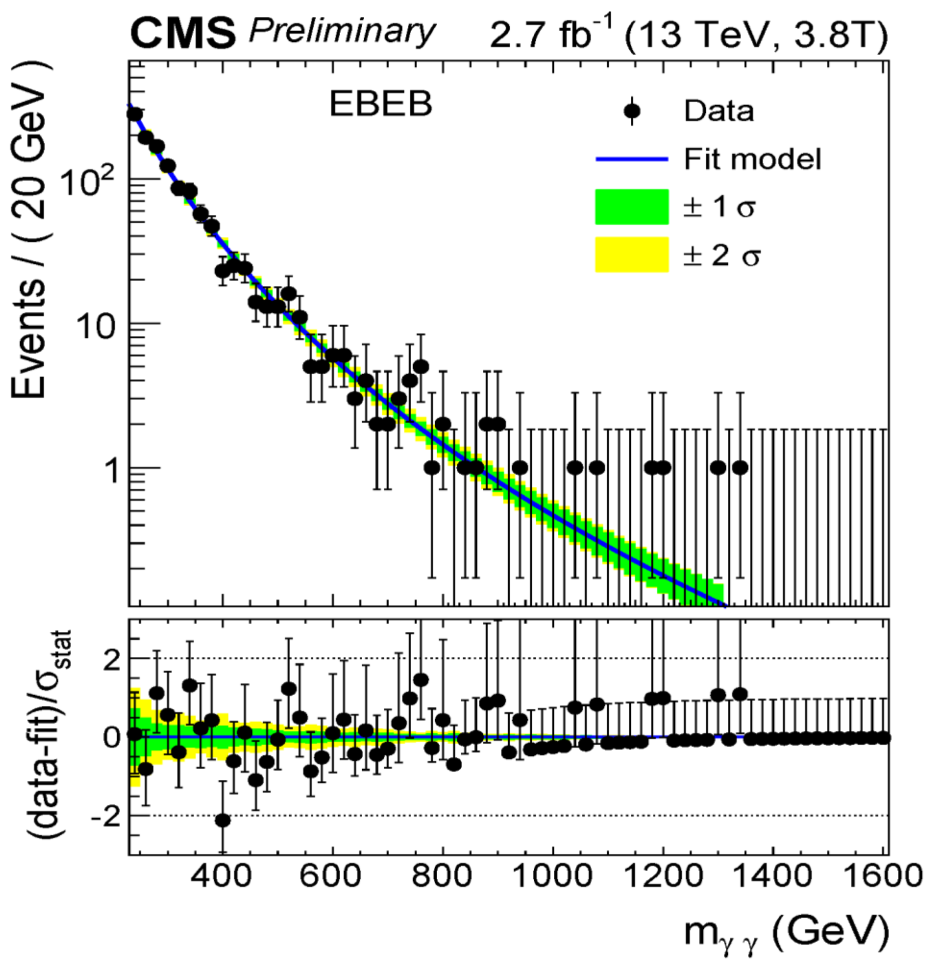


Scaling and Staging

8 x (12.5 kHz DAQ units)

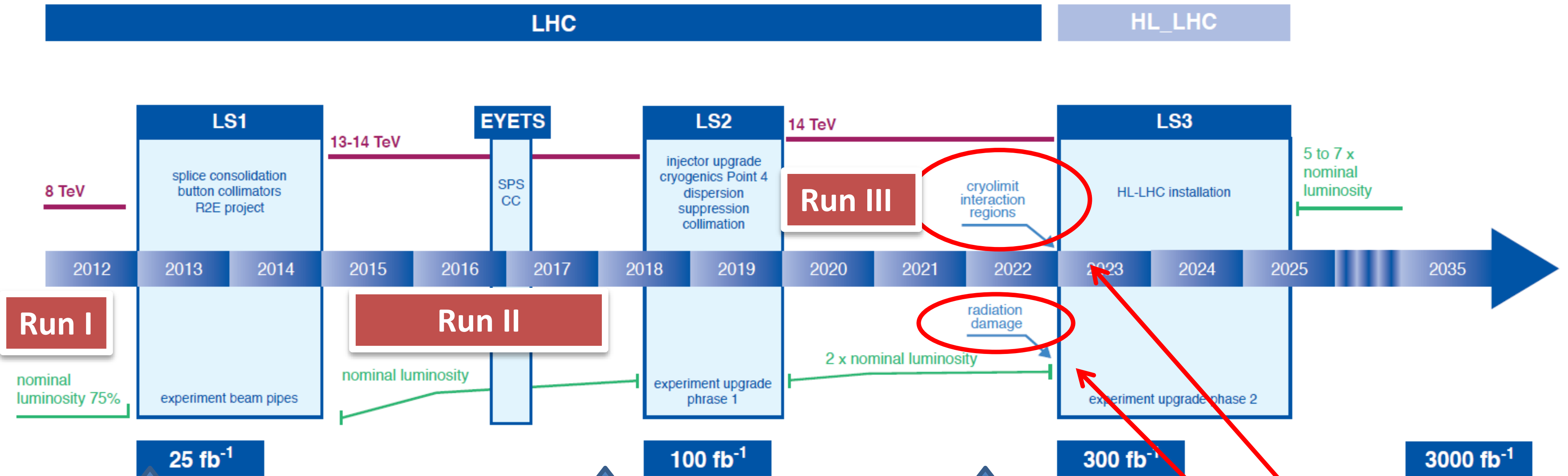
and that’s where the data comes from.

A brief word about the future….



CMS Preliminary
2.7 fb-1 (13 TeV, 3.8T)
EBEB
Data
Fit model
± 1 σ
± 2 σ
Events / (20 GeV)
(data-fit)/σstat
mγ γ (GeV)

New LHC / HL-LHC Plan



$0.75\ 10^{34}\ cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

50 & 25 ns

$1.5\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

$1.7\text{-}2.2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits
(experiments,
too) like :

CMS Phase 2 Upgrades (construction 2017-2022)

Tracker

- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons

- Replace DT FE electronics
- Complete RPC coverage
- Investigate Muon-tagging up to η ~ 4

Endcap Calorimeters

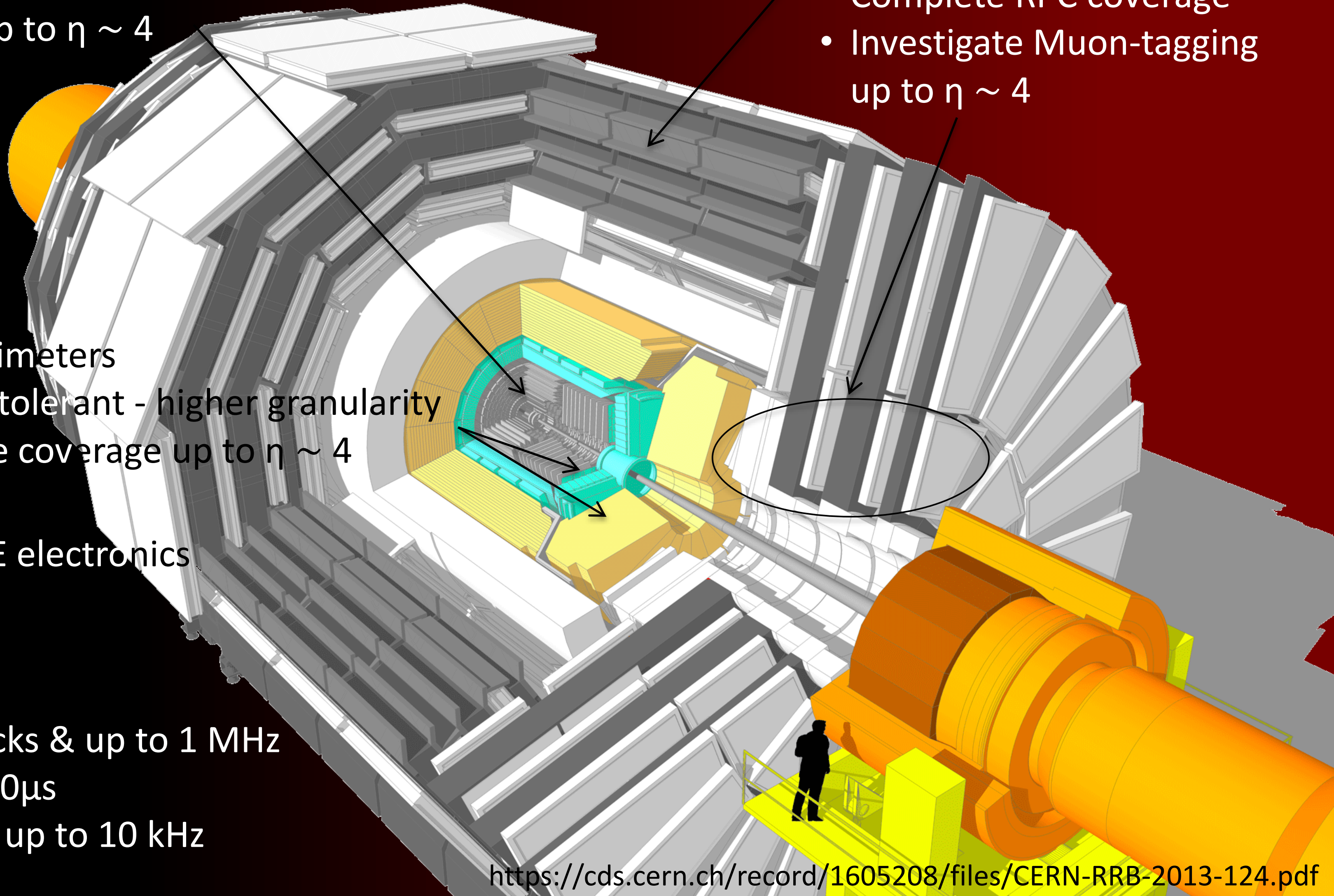
- Radiation tolerant - higher granularity
- Investigate coverage up to η ~ 4

Barrel ECAL

- Replace FE electronics

Trigger/DAQ

- L1 with tracks & up to 1 MHz
- Latency ≥ 10µs
- HLT output up to 10 kHz



https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf


CMS
CMS LHC - P5
June 2014