Contribution of HEP Calorimeter Read out Electronics Techniques to the Medical Imaging Field

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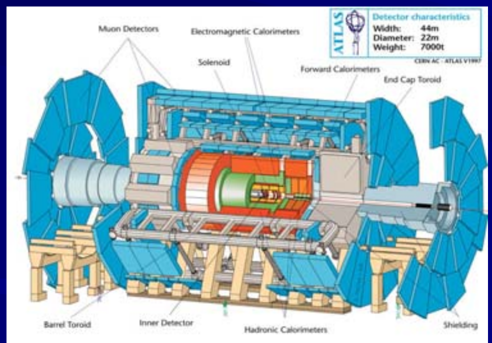
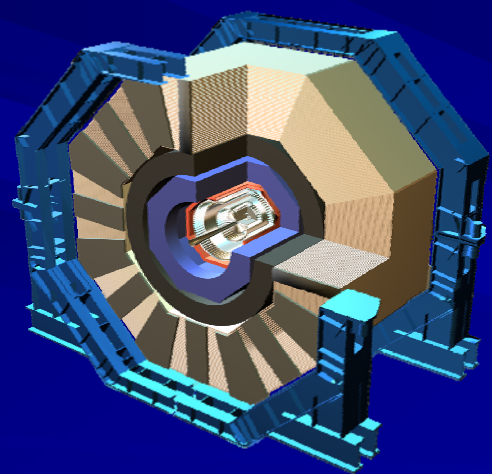


LHC/CERN



ILC

TEP

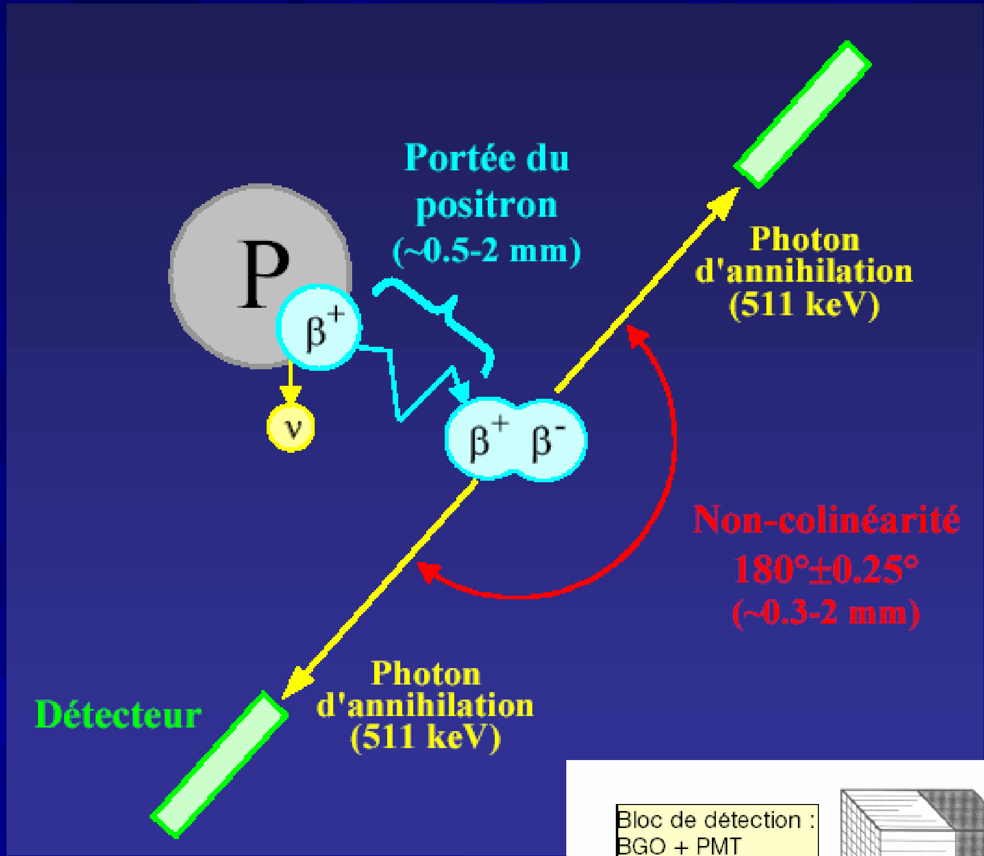
Goals of this presentation

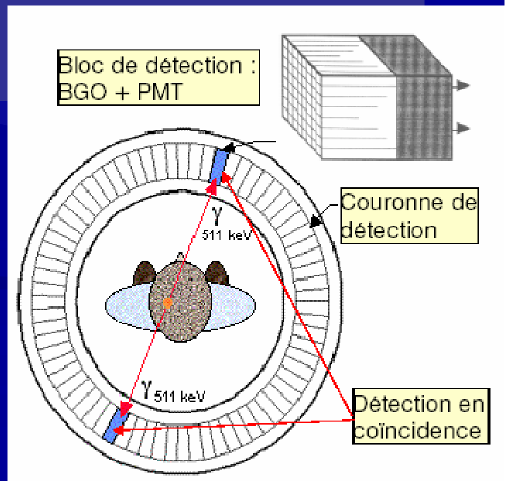
- An example of valorisation of Particle Physics R&D common to the medical imaging field
  - Can we use what we are developping for future experiments in another field ? (INNOTEP Col.)
- This is not a competition with the medical imaging industry but a demonstration of beyond the State of the Art technologies
- I illustrate that using the example of Positron Emission Tomography

Jeavons,Townsend & al.

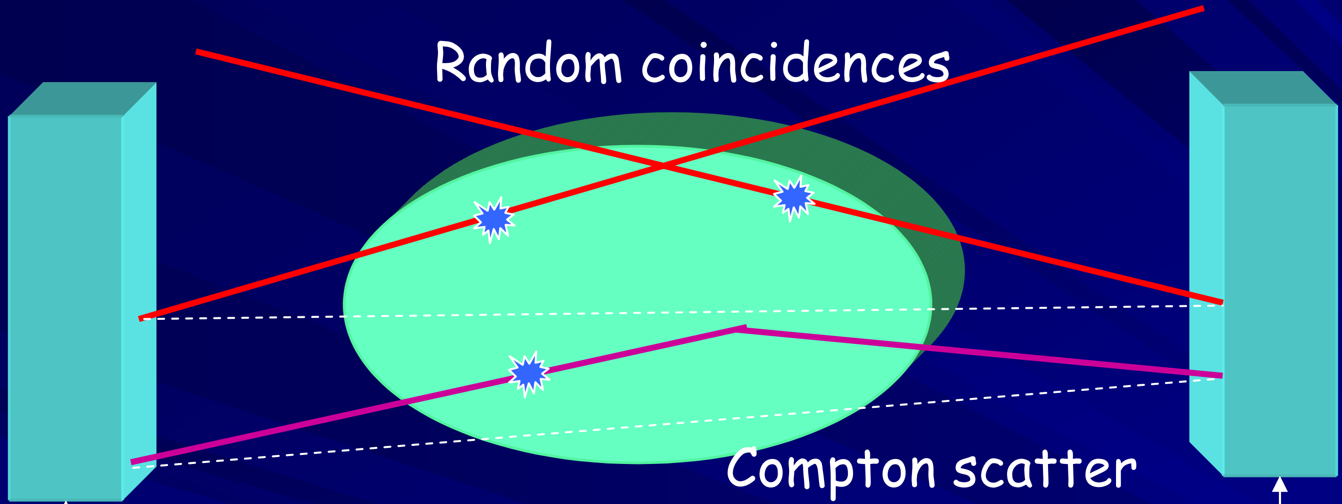
Positron Emission Tomography principle

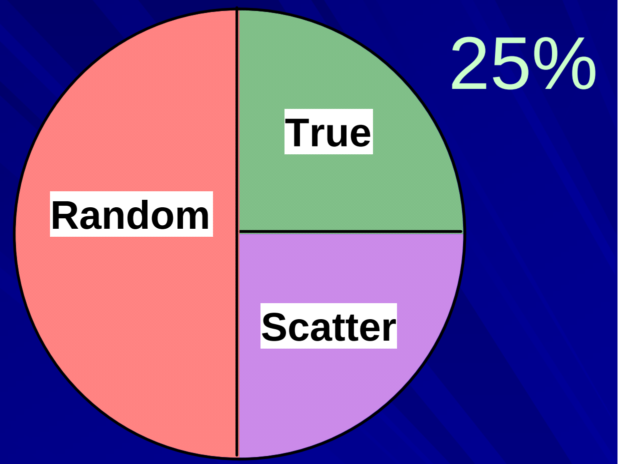
- Fonctional imaging using molecular tracers with doped beta + emitters
  - The most common → ^{18}F => ^{18}FDG fluoro-deoxy-glucose
    - Sign the degree of activity of an organ hungry of glucose
  - annihilation positron with an electron
  - emission of two 511 keV photons back to back



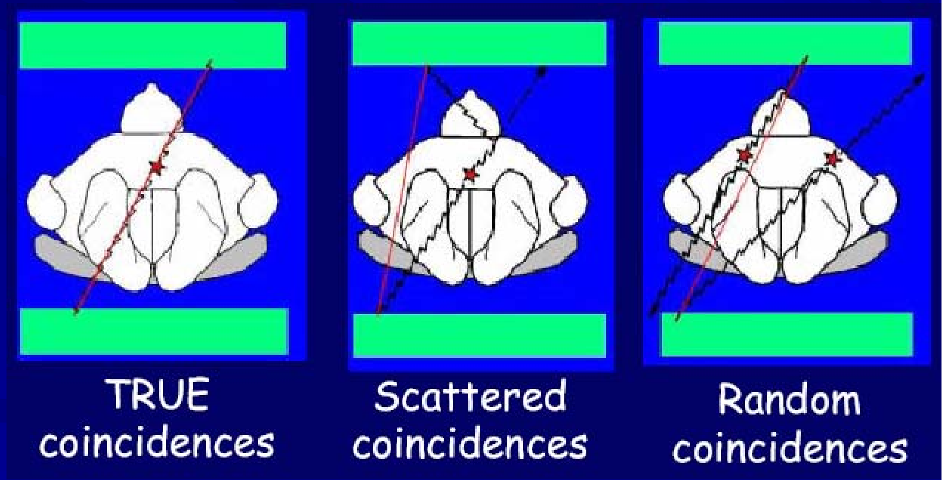


Source of errors in the source





Dector in coincidences
Energy window around 511keV
Time window 10-20 ns

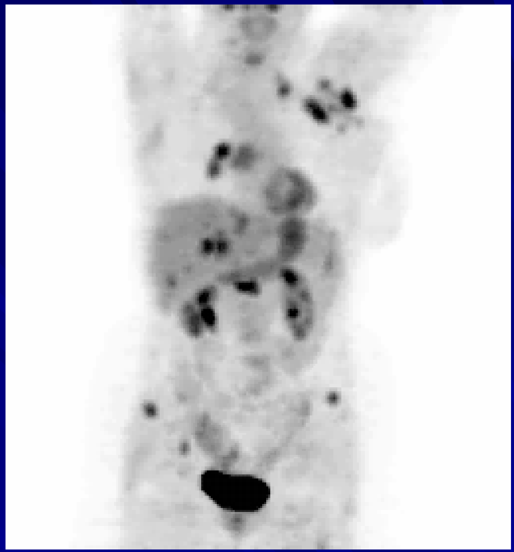


Signal : true concidences
Background: Compton + Random

Efficiency ≈ 0,01
(1 photon / 100)

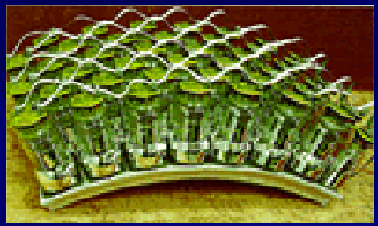
Clinical PET Imaging

- Whole body PET PET → Φ=90cm- FOV 20 cm
  - Oncology → market increase 30% per year !

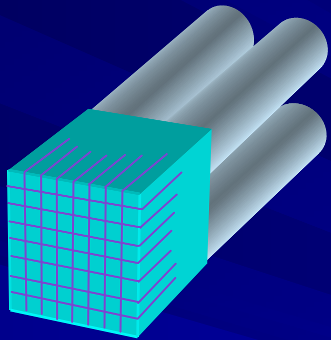


F. Bénard, UdeS

Extent of breast cancer with multiples metastases (Whole-body FDG-PET scan, CTI/Siemens EXACT HR+)



NaI curved CPET (Philips)



Detection block
Crystals 4x4x20 (or 30) mm^3
Block 8 x 8 crystals , 2 x 2 PM's

CTI Siemens LSO

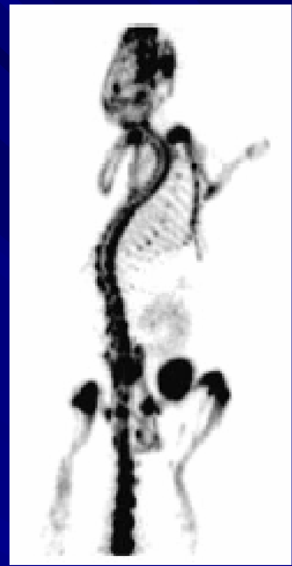
PET -CT Biograph

MicroPET → Φ=20cm- FOV few cm

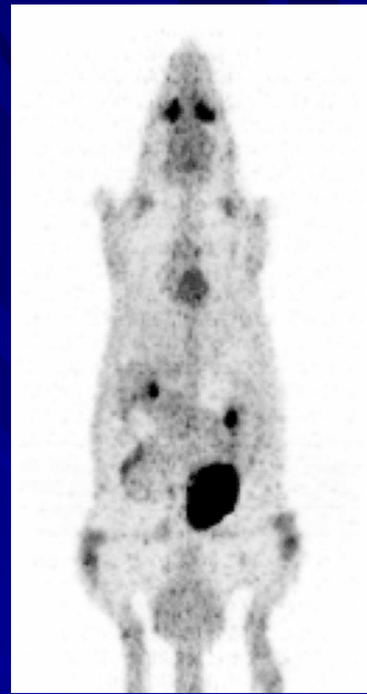
- Radio pharmacology
- Tracer development

LabPET

ClearPET

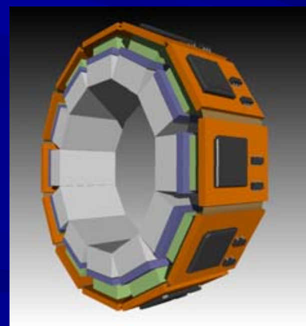


31 g mouse
1 mCi $^{18}F^{-}$



Whole-body
FDG-PET scan
250 g rat
(Sherbrooke APD)

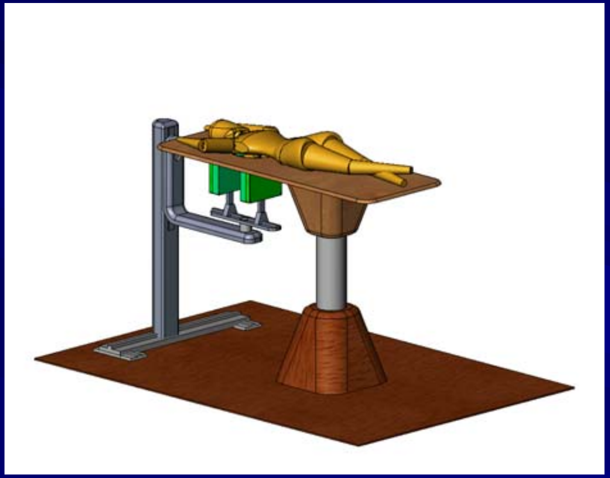
APD PET



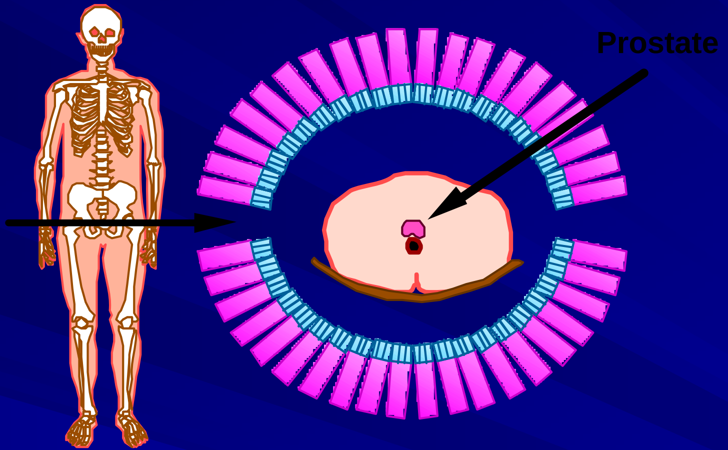
RatCap

Dedicated PET

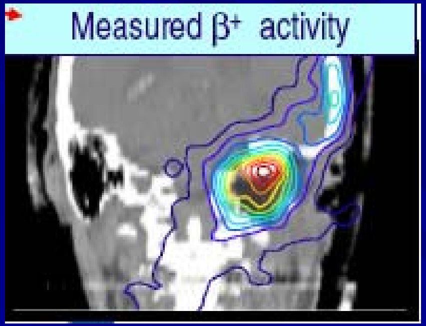
Mammography (CLEARPEM)

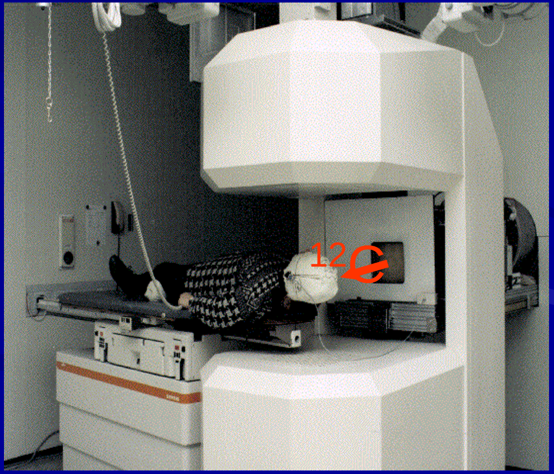


Prostate PET

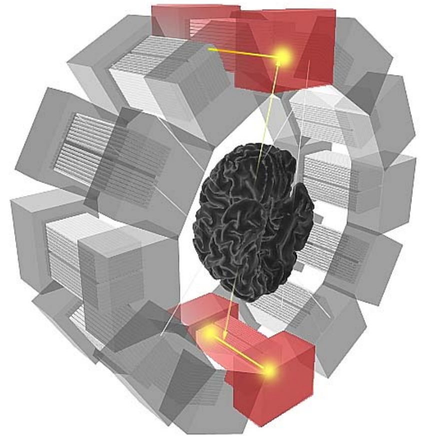


On Line PET for hadrontherapy



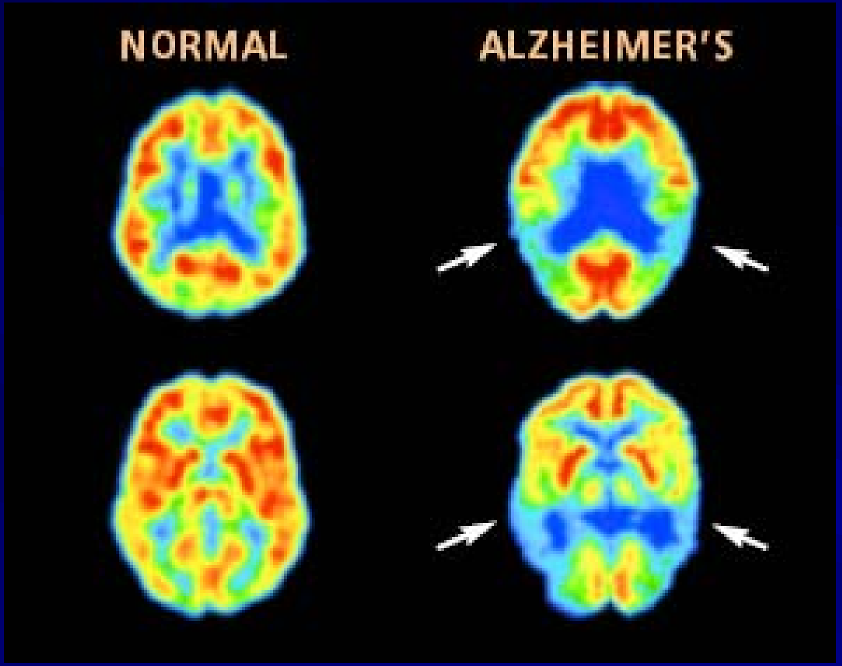


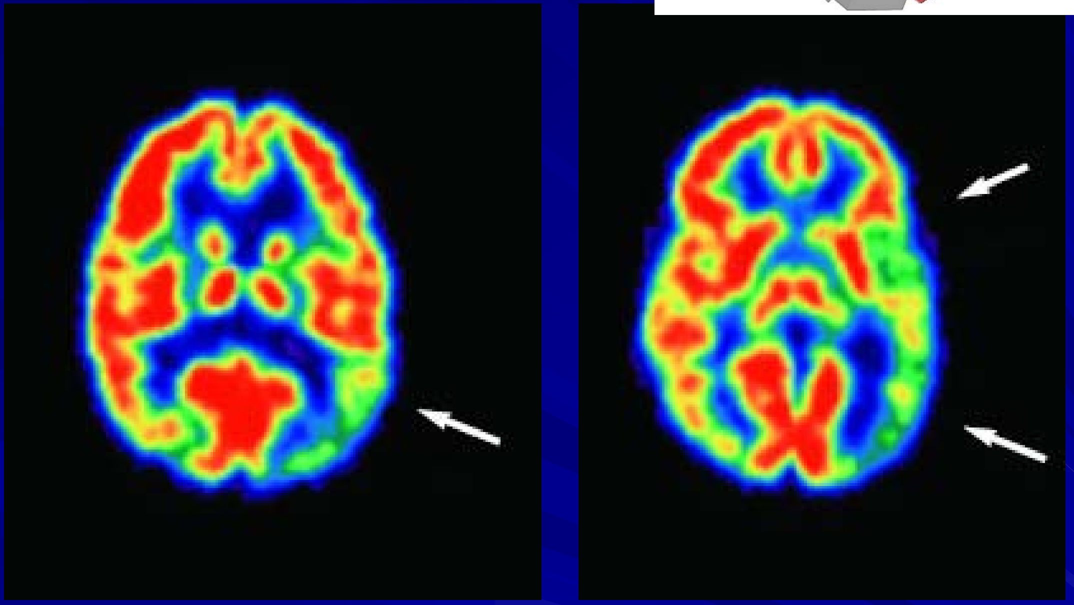
PET for neurosciences and brain diseases



Alzheilmer

Parkinson





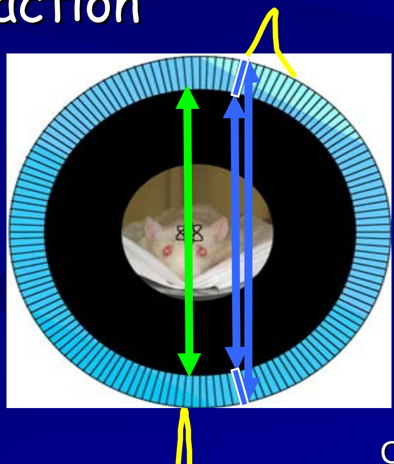
The PET shows decreased metabolism early in the desease!

The PET scan showed abnormal glucose metabolism in the back of the right emisphere Folloing surgical removal of the dysfonctional brain area the child was seizure free

μPET vs whole body PET → different requirements

- **High Spatial resolution →fundamental**
  - Objective ~ 1mm or less
  - Today → 1,2 mm
- **High sensitivity**
  - Less Compton event
  - Small dose
- **Paralax correction**

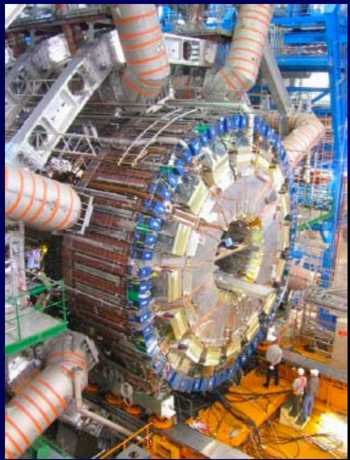
→ Deph Of Interaction Technique



- **High Efficiency** (>85%)
- **Good Spatial Resolution** (<5 mm)
- **Low Cost** (<$100/cm2)
- **Short Dead Time** (<1 μs)
- **High Timing Resolution** (<5 ns fwhm)
- **Good Energy Resolution** (<100 keV fwhm)

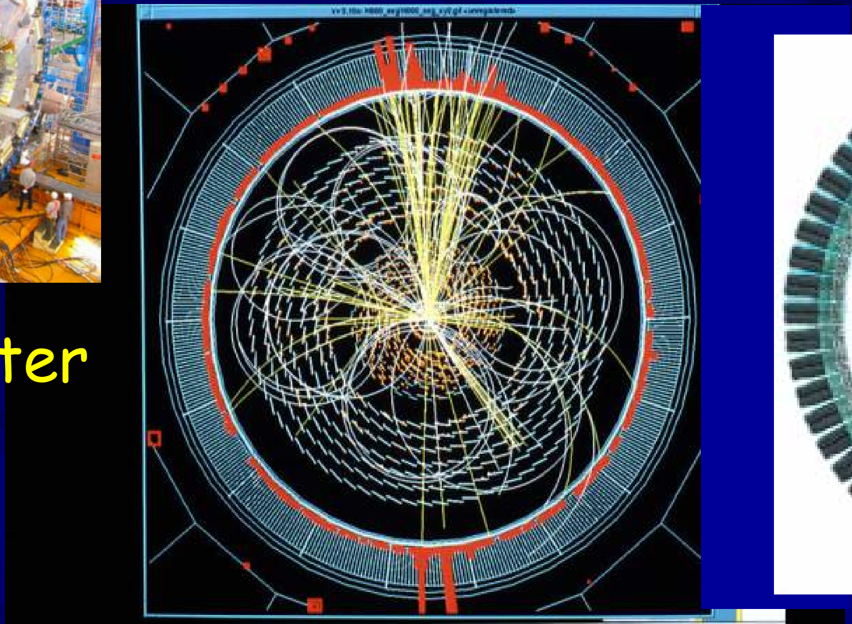
Why PET ?

Similarities and differences

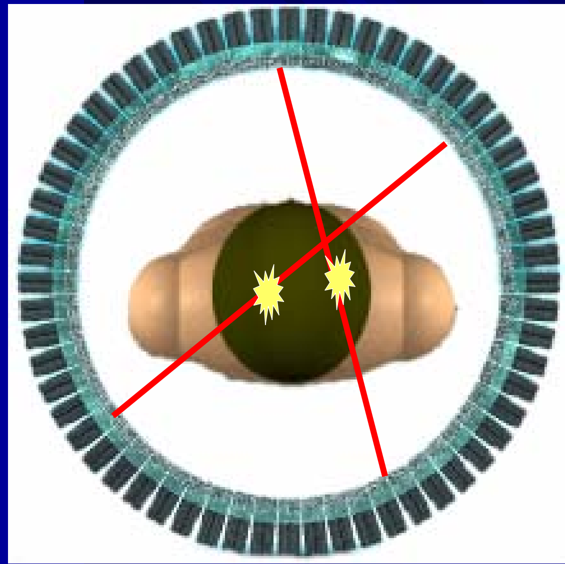


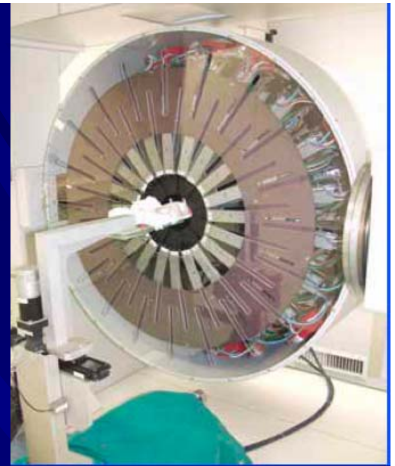
Calorimeter

HEP



M_{Higgs} = 100 GeV





PET Camera

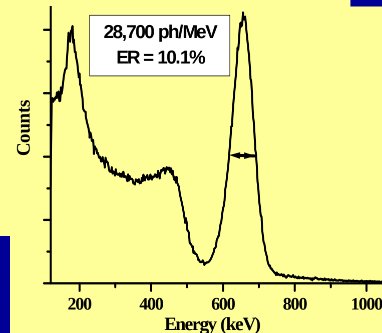
Biomedical Imaging

Similarities

Geometry and granularity
Detector (Crystals & scintillator)
Photo Sensor (PM,APD)
Electronics:Fast and compact
Event rate & Data volume

Differences

Energy range (10GeV-511keV)
No synchronisation
--> free running electronics



From HEP to Medical

*Where **techniques** are transfered to developments in bio- medical field*

Medical Imaging has only partially benefited from new technologies developed for telecommunications and High Energy Physics detectors

- **New scintillating crystals and detection materials →**
  - CMS (WPbO4) → Luap …(Crystal Clear col),
- Photodetectors : **Highly segmented and compact** → PMT → APD → SiPM
  - APD : SSC/SDC (1991) → CMS (1996) → MicroTEP→ TEP
- Electronics & signal treatemnt→ Highly integrated
  - Fast, low noise,low power preamp
  - Digital filtering and signal analysis
- Trigger/DAQ →
  - **High level of parallelism and event filtering algorithms**
  - Pipeline and parallel read-out, trigger and on-line treatment
- Computing
  - Modern and modular simulation software using worldwide recognized standards (GEANT)

Scintillators for PET

	1962	1977	1995	medical 1999	μPET 2001	Next
	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce	?
Density (g/cm^3)	3.67	7.13	6.71	7.40	8.34	$PbWO_4$
Atomic number	51	75	59	66	65	
Photofraction	0.17	0.35	0.25	0.32	0.30	
Decay time (ns)	230	300	30-60	35-45	17	$LaBr_3$
Light output (hν/MeV)	43000	8200	12500	27000	11400	LuI_3
Peak emission (nm)	415	480	430	420	365	
Refraction index	1.85	2.15	1.85	1.82	1.97	
Hygroscopic	Yes	No	No	No	No	
Natural radioactivity	No	No	Yes	Yes	Yes	

No Scintillator with Superior Properties in *All* Aspects

New pixellised Photodetectors

CMS

Hamamatsu single channel APD

LHCB

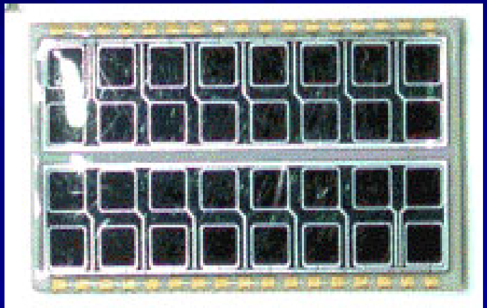
BrainPET

HPD tube manufactured at CERN: 2048 channels

Opera

ClearPET

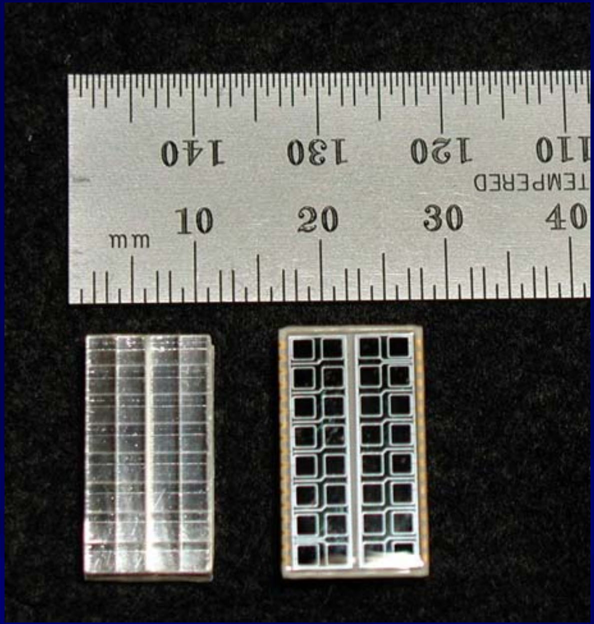
ClearPEM



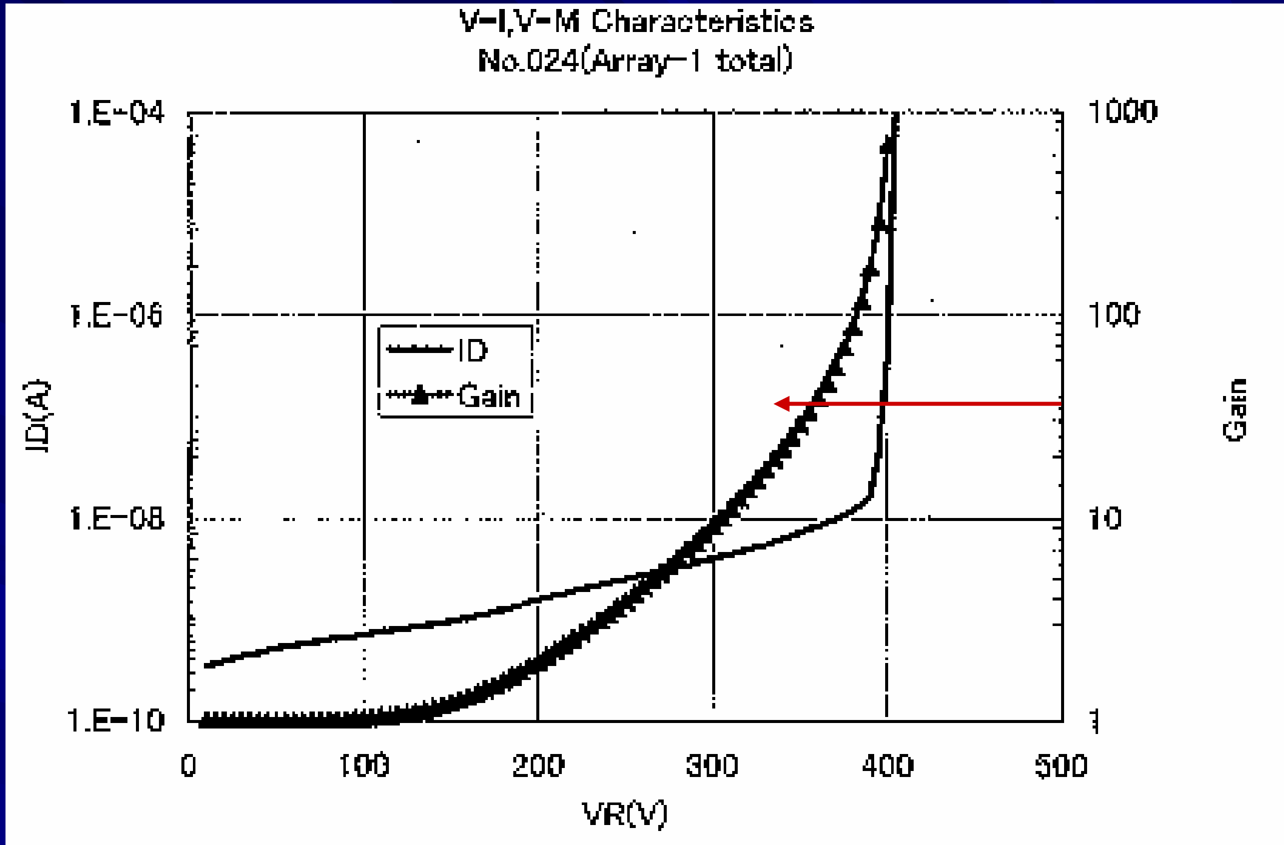
Hamamatsu 32 channels APD array

Mammography

Hammamatsu PM flat pannel



APD's



Hamamatsu S8550

4x8 array

1.6 x 1.6 mm^2

active pixel area

C_T~ 10 pF

Typical G ~ 50

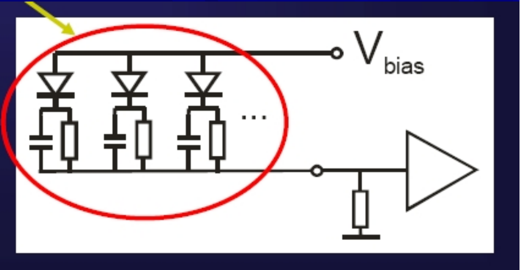
N_{pe} ~ 1200

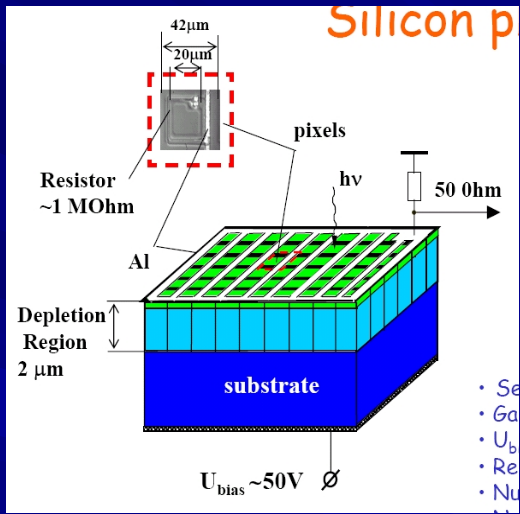
~ 60K signal electrons

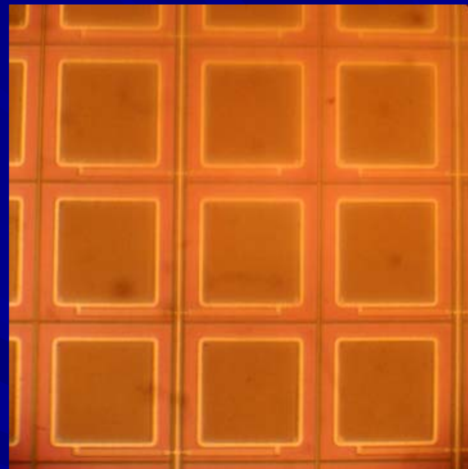
Expected noise in final ASIC ~ 500-600 e's

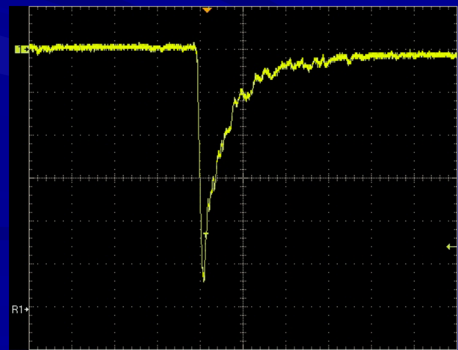
Next step --> SiPM (Geiger mode APD)

- operating low bias voltage ~ 50 V
- power consumption < 50 µW/mm²
- single-photon response ~ 105-106e
- optical cross-talk ~ 10%
- peak detection efficiency ~ 25% at 520nm
- timing resolution ~ 100 psec
- typical size ~ few mm2
- dynamic range ~ 1000
- non-sensitivity to magnetic field
- low temperature dependence
- mechanical and electrical robustness
- cheap (CMOS process)
- large dynamic range
- compact, rugged and show no aging,









511 Kev on LSO

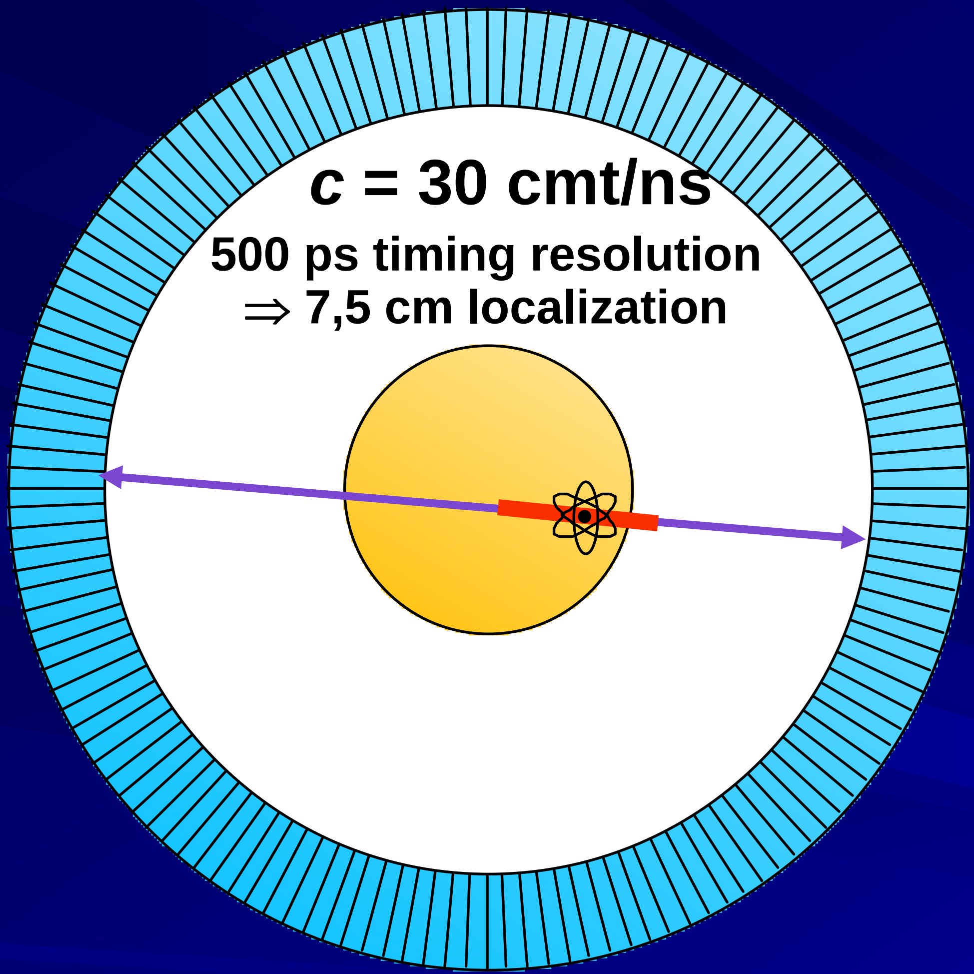
BUT:

Significant dark count rate (~10^5-10^6 Hz / mm²)

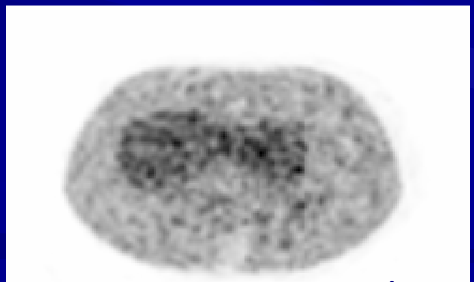
Enhanced optical cross-talk (~10%)

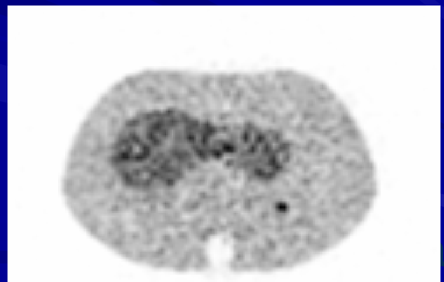
Therefore area is practically limited to few mm²

Next → Time-of-Flight in medical PET



- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Time of flight cameras built in the 80's with BaF2 & CsF.
- These scintillators forced compromises that prevented TOF from flourishing
- Today new crystals (LaBR3) and new MHz electronics/DAQ


Conventional

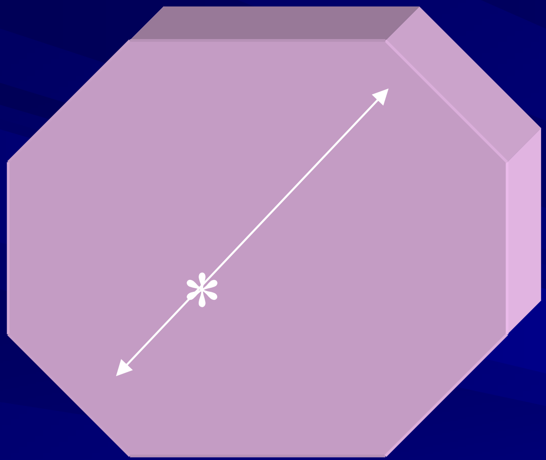

300 ps

Simulation of liver cancer

- Objective :
  - < 500 ps Timing Resolution

Future Challenges

Medical Whole-Body High-Resolution PET



Phi = 75 cm
L= 75 cm

- Model Geometry
  - Hexagonale : 8 wedges of 25x75 cm = 30000 crystals of 2,5x2,5 mm2
  - Trigger by 'Region Of Interest' (ROI) 25x25 cm2
    - 24 ROI with 10000 crystals
- Total : 240 000 electronic channels

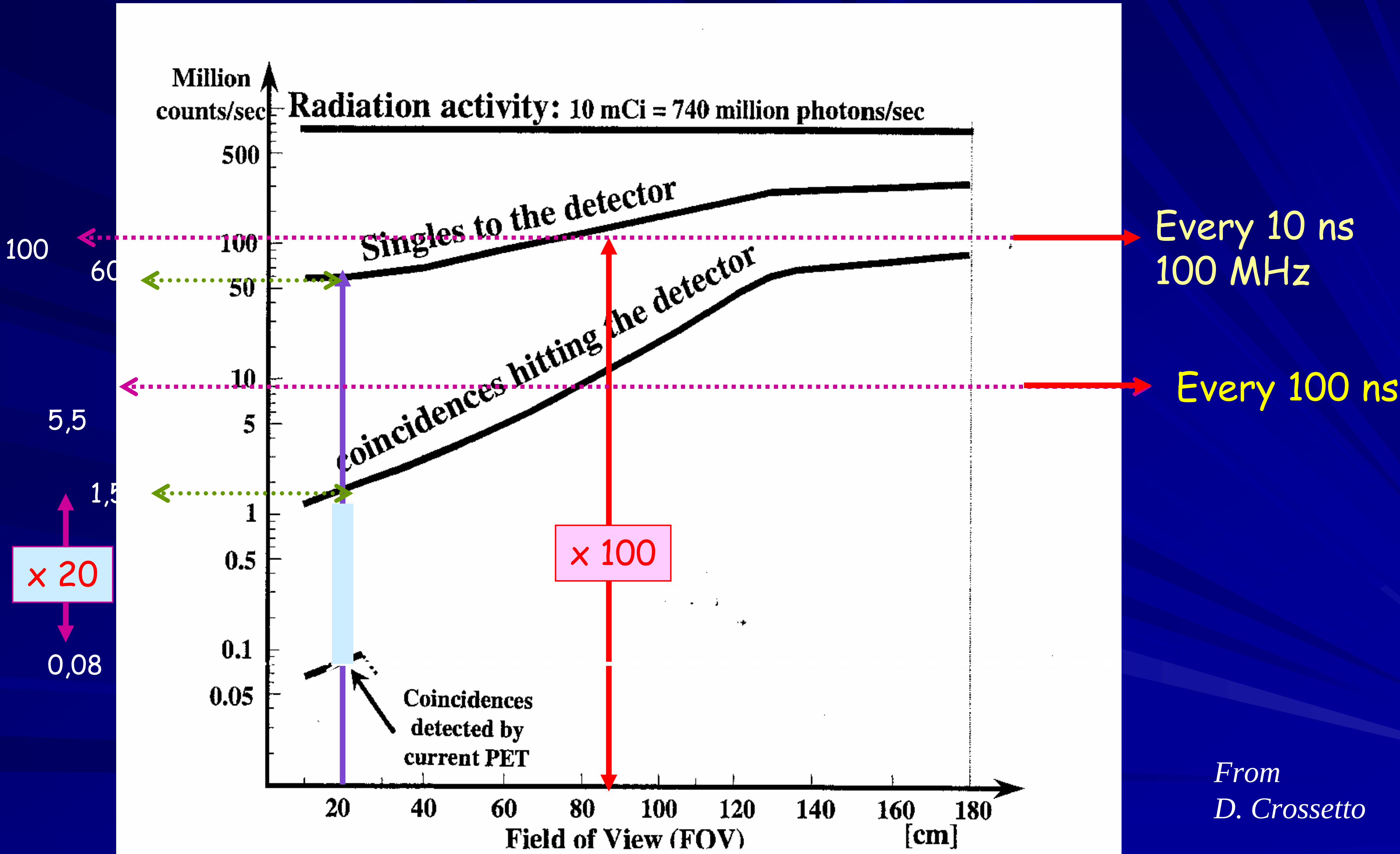
Improve spatial resolution ?

- Near theoretical limit = few mm (4mm with FDG)
- Can Increase SNR by Reducing Backgrounds
- Keep exam time short (30 min → few min!)

Sensitivity → significant room for improvment!

- Compact and hermetic design → large Field Of View
- Fast and high light yield crystal (LaBr3?)
- Fast and low noise electronics with TOF capability
- Built-in intelligence in the Data Acquisition system
- Make the best use of "good" events (TRIGGER)
- Use Compton events instead of rejecting them?
- Efficiently throw away "bad" events (better timing resolution!)

Counting rate estimate (preliminary)



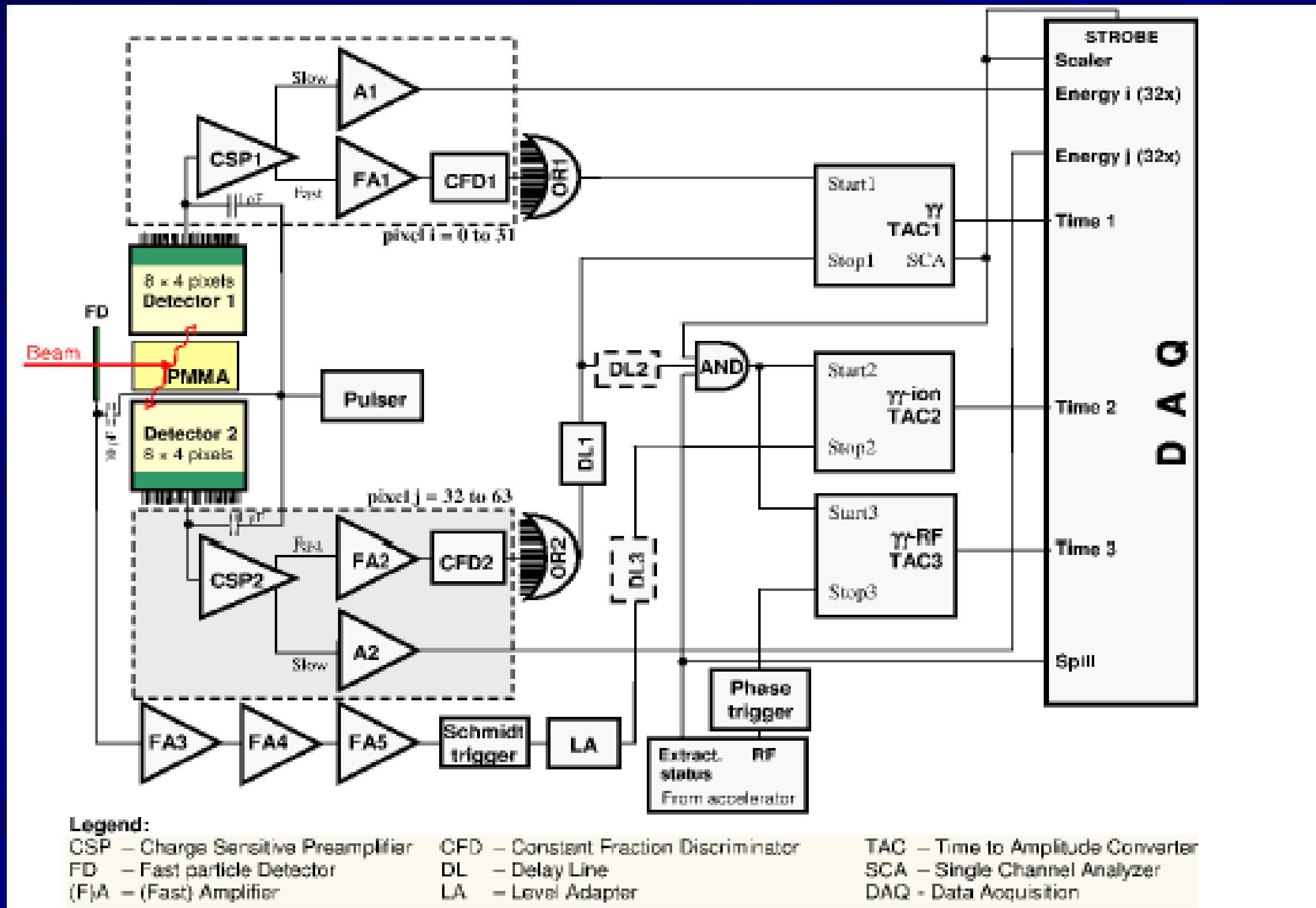
From
D. Crossetto

Basic requirements

- Very large number of channels (20 → 80 cm FOV)
  ~ 300 k channels (2x2 mm2 pixels)
- High trigger rate
  - ~ 10 MHz
- High data rate
  ~ 10 Gbyte/s
- Large number of events
  ~ 10^9 events (10^6 voxels, 1000 events/voxel)
- Large data volume per image
  ~ 1000 Gbytes (list mode)
- High computer power for image reconstruction

Standard PET electronics chain

- PA/SH + CFD + TDC + ADC



Dead Time

Time during which the detector can not accept and record new events

$R = \text{Rate}\,(s^{-1})$

$\delta = \text{Absolute dead time per event}\,(s)$

$DT = \text{Relative dead time}\,(\%)$

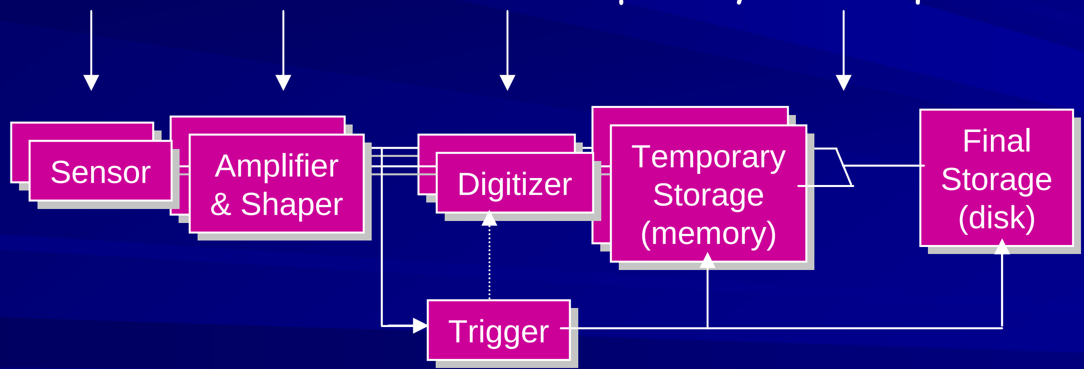
$AR = \text{Acquisition rate}\,(s^{-1})$

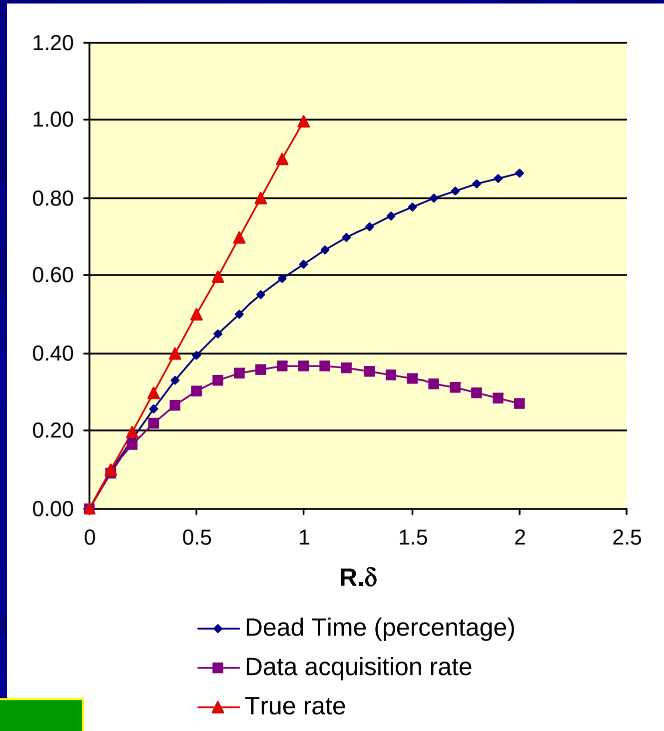
$$DT = 1 - e^{-R\delta}$$

$$AR = R \cdot e^{-R\delta}$$

Dead time sources:

Detector signal formation	Signal shaping	Conversion time	Readout time
20-100 ns	100-500 ns	10 ns-100 μs	System dependent



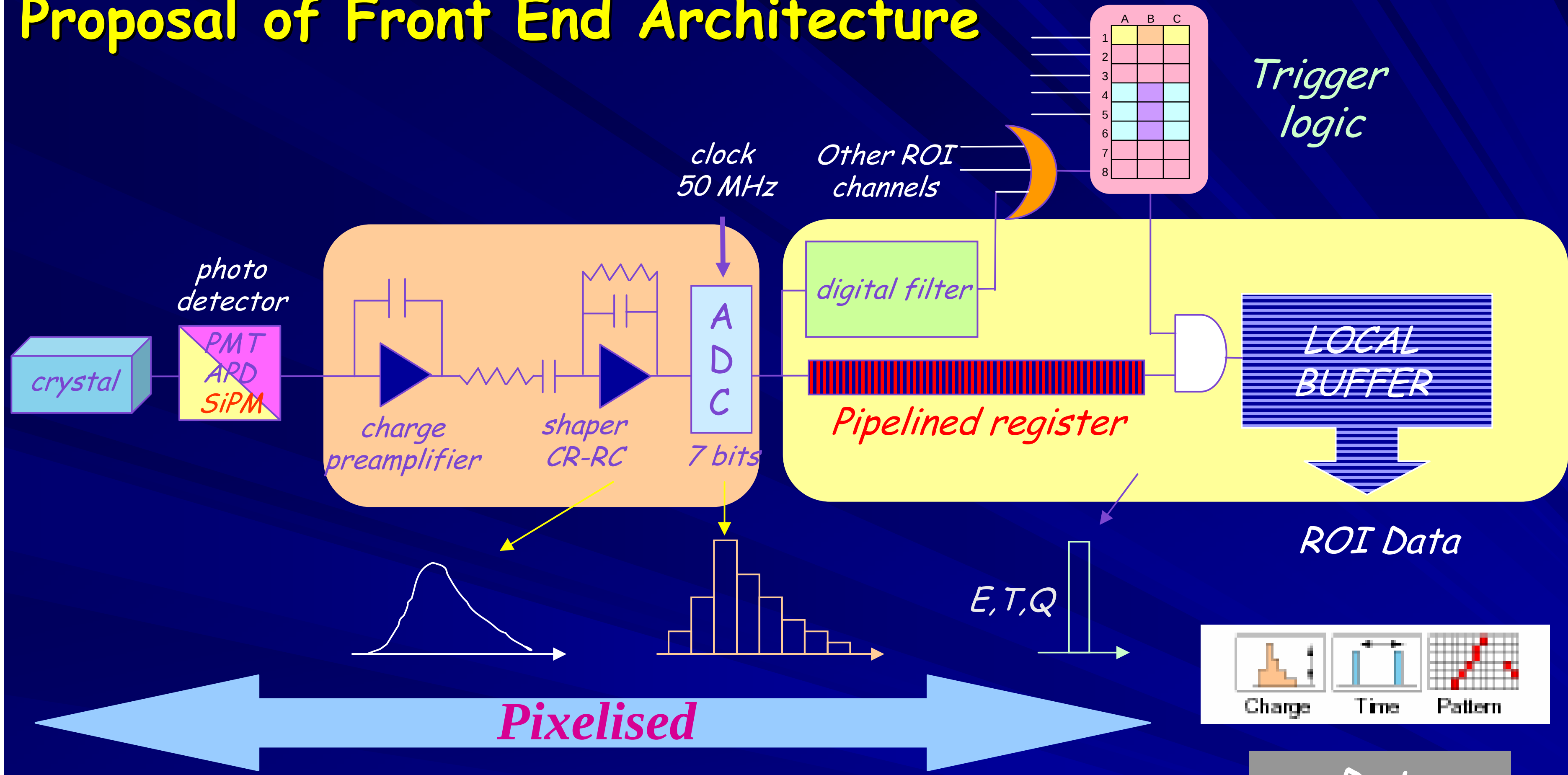


Towards an innovative read out electronics concept (INNOTEP)

- ♦ Fully pixellated detector yields to a considerable number of channels to be considered, each having its own reading electronics
- ♦ size and speed have been a real issue for years but progress in the microelectronics field have made ASICs of high integration readily available
- ♦ besides this, they appear as a cost effective solution
- ♦ no possible CFD implementation on chip (shared constant network / derivation are noisy…!) in agreement with the expected time resolution.
- ♦ High resolution TDCs require complex architecture, large surface area and appearno

→ need to find another solution for time measurement … to be inspired by HEP experiments

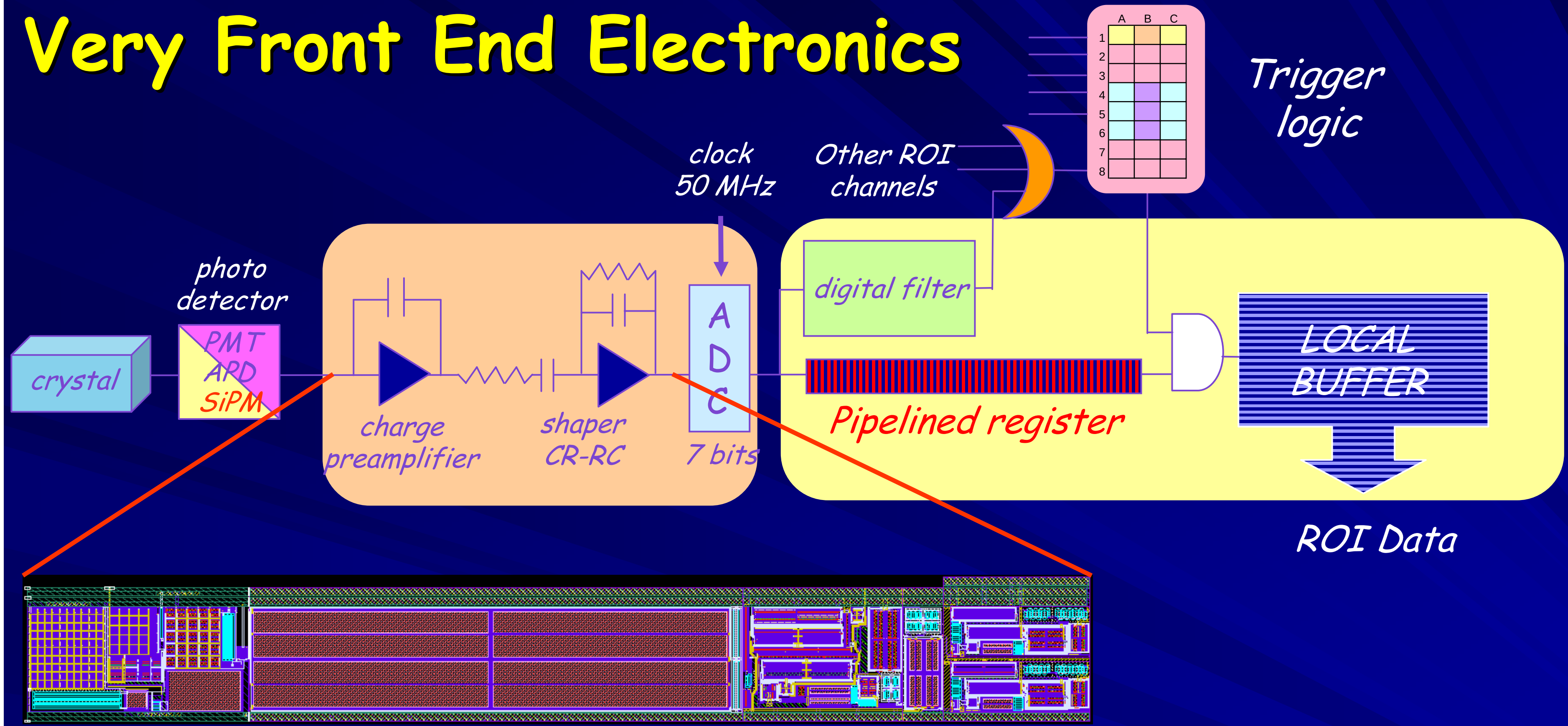
Proposal of Front End Architecture



Data Acquisition

- Trigger logic processes "raw fast information"
- Free-running sampling ADC
- Digital filter used to extract pulse amplitude and high resolution timing
- Pipelined processing architecture to avoid deadtimes
- Only one "channel" to compute either the energy and time

Very Front End Electronics



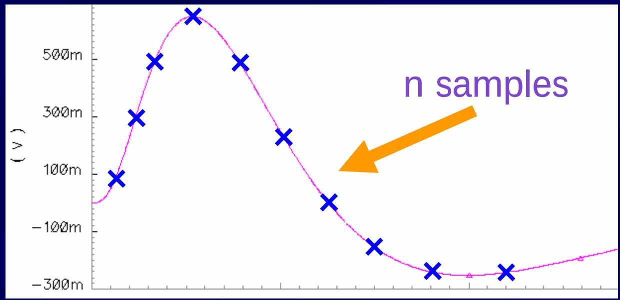
→ The design of the very front end electronics is complete (charge preamplifier + shaper)

→ 2 versions have been submitted to the foundry

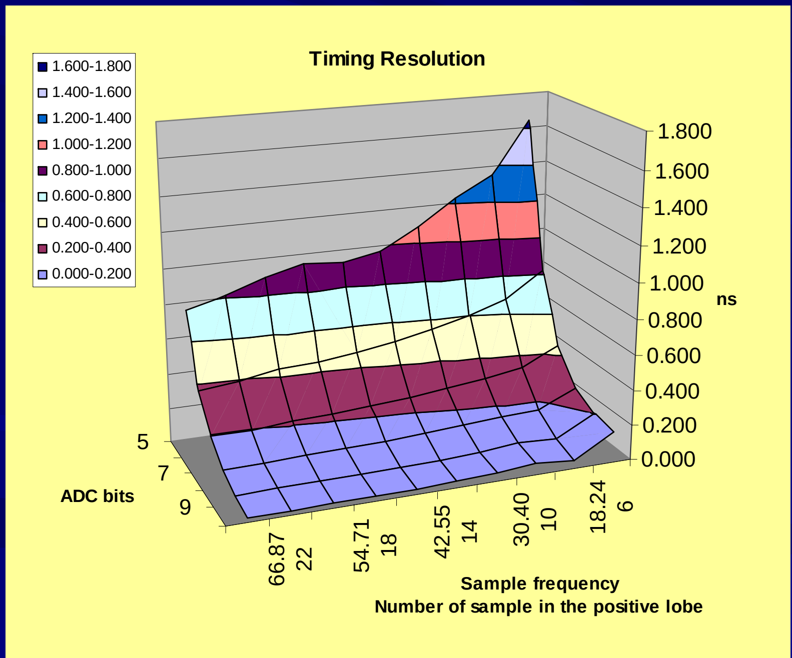
→ Consumption: 23mW

→ Surface area: 205μm^2

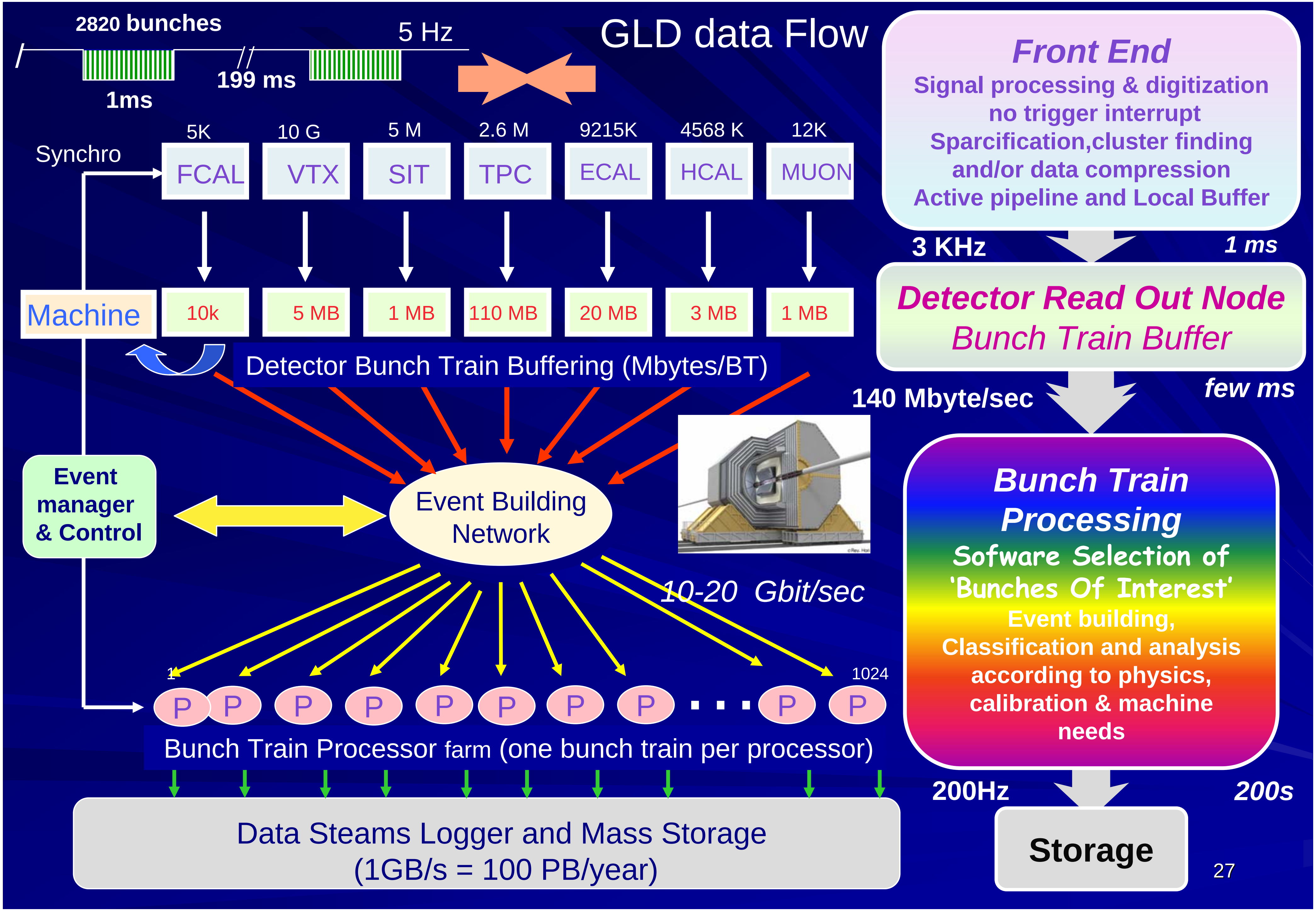
Digital filtering

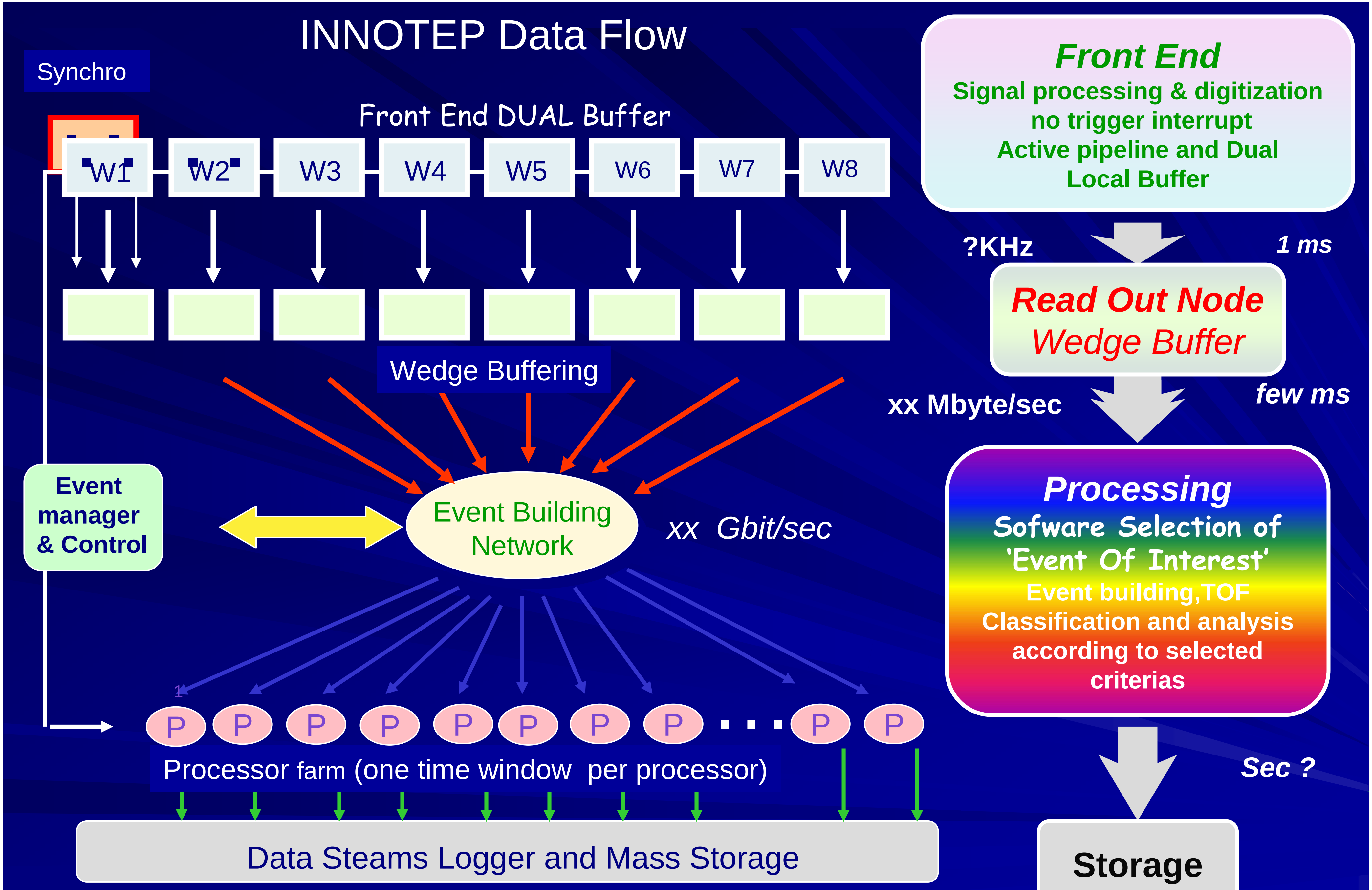


Samples.	4	6	8	10	12	14	16	18	20
Frequency/MHz	12,16	18,24	24.32	30.4	36.47	42.55	48.63	54.71	60.79
n bits ADC									
4	7,33	5,27	4,51	4,18	3,69	3,55	3,36	2,96	2,56
5	4,46	2,75	2,25	2,05	1,81	1,62	1,54	1,58	1,49
6	3,35	1,37	1,13	1,00	0,92	0,84	0,78	0,75	0,72
7	3,03	0,73	0,57	0,51	0,46	0,42	0,39	0,37	0,35
8	2,96	0,45	0,28	0,26	0,24	0,21	0,20	0,19	0,18
9	2,94	0,34	0,15	0,16	0,13	0,11	0,10	0,10	0,09
10	2,94	0,30	0,08	0,11	0,08	0,06	0,06	0,05	0,05



- ♦ For one channel, a timing resolution of 500ps is obtained with:
  - → 7 bits at 30MHz
  - → 8 bits at 19MHz
- ♦ Those results are the mathematical limits that can be attained. In practice, we have noisy signals that will weaken those figures.
- ♦ To combine both the energy accuracy requirement and the potential added noise, we will consider a 7 bits ADC working at say 50MHz.


GLD data Flow
2820 bunches
5 Hz
1ms
199 ms
Synchro
5K
10 G
5 M
2.6 M
9215K
4568 K
12K
FCAL
VTX
SIT
TPC
ECAL
HCAL
MUON
Machine
10k
5 MB
1 MB
110 MB
20 MB
3 MB
1 MB
Detector Bunch Train Buffering (Mbytes/BT)
Event manager & Control
Event Building Network
10-20 Gbit/sec
1
1024
P P P P P P P P . . . P P
Bunch Train Processor farm (one bunch train per processor)
Data Steams Logger and Mass Storage
(1GB/s = 100 PB/year)
Front End
Signal processing & digitization
no trigger interrupt
Sparcification,cluster finding
and/or data compression
Active pipeline and Local Buffer
3 KHz
1 ms
Detector Read Out Node
Bunch Train Buffer
140 Mbyte/sec
few ms
Bunch Train Processing
Sofware Selection of
'Bunches Of Interest'
Event building,
Classification and analysis
according to physics,
calibration & machine
needs
200Hz
200s
Storage
27


INNOTEP Data Flow
Synchro
Front End DUAL Buffer
W1
W2
W3
W4
W5
W6
W7
W8
Wedge Buffering
Event manager & Control
Event Building Network
xx Gbit/sec
1
P
P
P
P
P
P
P
P
. . .
P
P
Processor farm (one time window per processor)
Data Steams Logger and Mass Storage
Front End
Signal processing & digitization
no trigger interrupt
Active pipeline and Dual
Local Buffer
?KHz
1 ms
Read Out Node
Wedge Buffer
xx Mbyte/sec
few ms
Processing
Sofware Selection of
'Event Of Interest'
Event building,TOF
Classification and analysis
according to selected
criterias
Sec ?
Storage

ATCA in one page

(Advanced Telecommunications Computing Architecture)

Courtesy of R.Larsen (SLAC), R.Downing (FNAL), S.Dahwan (Yale), B.Martin (CERN)

ITER, AGATA

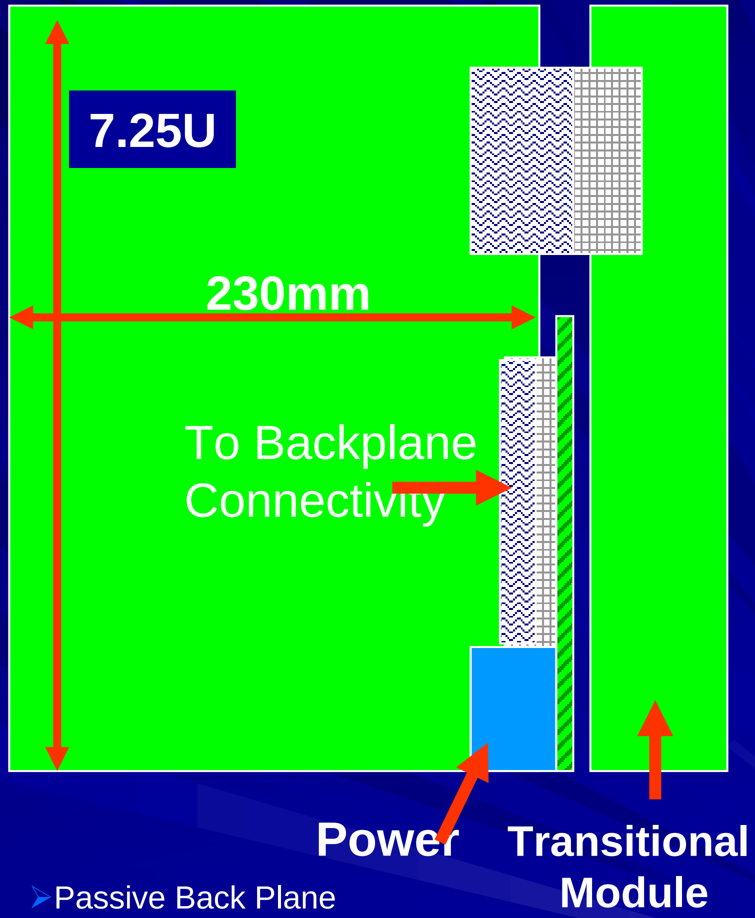
- Coming from Telecom industry
  - System throughput to 2 Tb/s
  - System Availability 99.999% (~5 min/yr)
  - Sponsored by the PIC Industrial Computer Manufacturers Group (PICMG)

- Basics elements and features
  - Crate & subrack (Shelf) : Backplane, Shelf Manager,Air Cooling,Power, Entry Modules
    - "Shelf Manager" manages all module, crate, system utilities
  - Module /Board (Blade) 14 to 16 units 8U .!,2 inch x 280 mm - 200W, vertical/horizontal
  - Backplane : redundant dual star and full mesh (point to point)
    - Multiprotocols : Ethernet,Fiber channel, PCI express, Infiniband, rapidIO ….
    - Synchronization and Clock Interfaces buses (6)
  - Rear Transition Module for user up 20 W
  - Carrier (Daughter Card, Plug-in Module, Advanced Mezzanine Card)
  - Software (Linux based)

Compare ATCA* & Bus systems

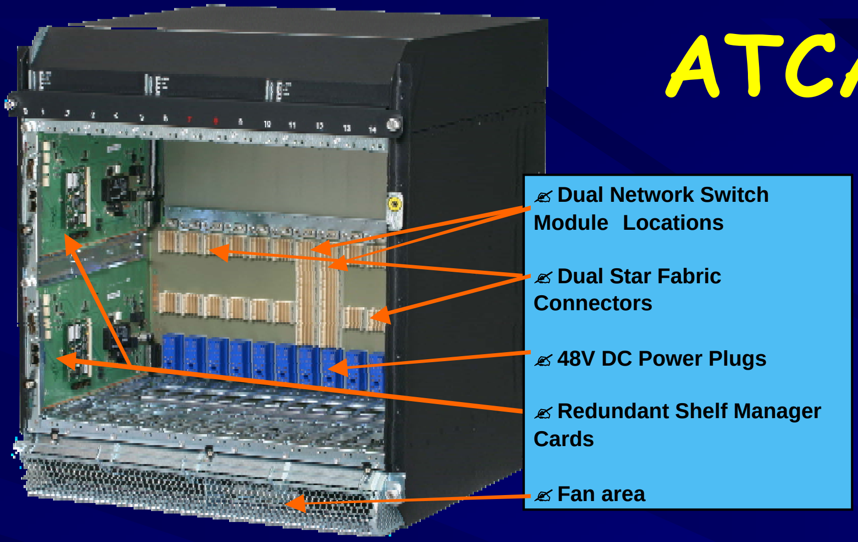
**Advance Telecom Computing Architecture*

	ATCA	PCI Long	VME (6U)
Board Area cm^2	995	316	373
Power Watts	200	10/25	30
Bandwidth I/O Gb/s	20 Full Duplex	4.3 66 Mhz 64 bits	2.4 VME 2eSST
Front Panel H*W cm	30 * 23	8 * 1.2	21.5 * 23
Component height mm	21.33	14.48	13.72

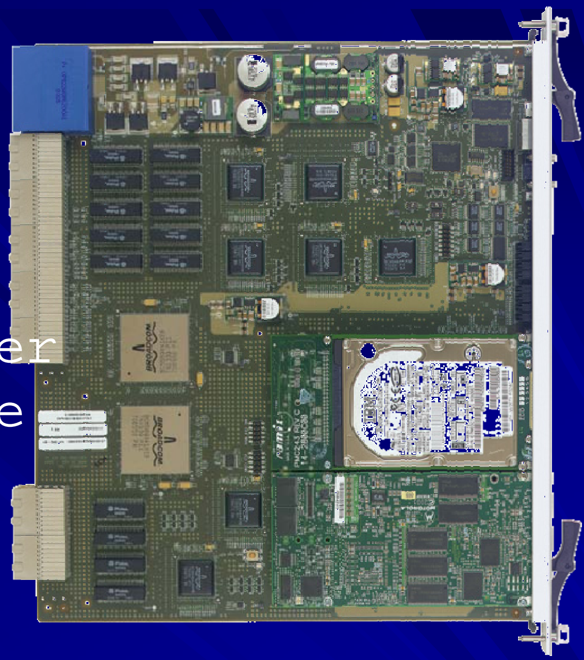


- Passive Back Plane
- - 48 Volt Power in
- Specifications for PCIe, Infiniband, GigE using the same Back plane
  - AMC (Advanced mezzanine Card)
  - mTCA based on ATC specifications - 4 U PCB
  - Interconnections for Servers

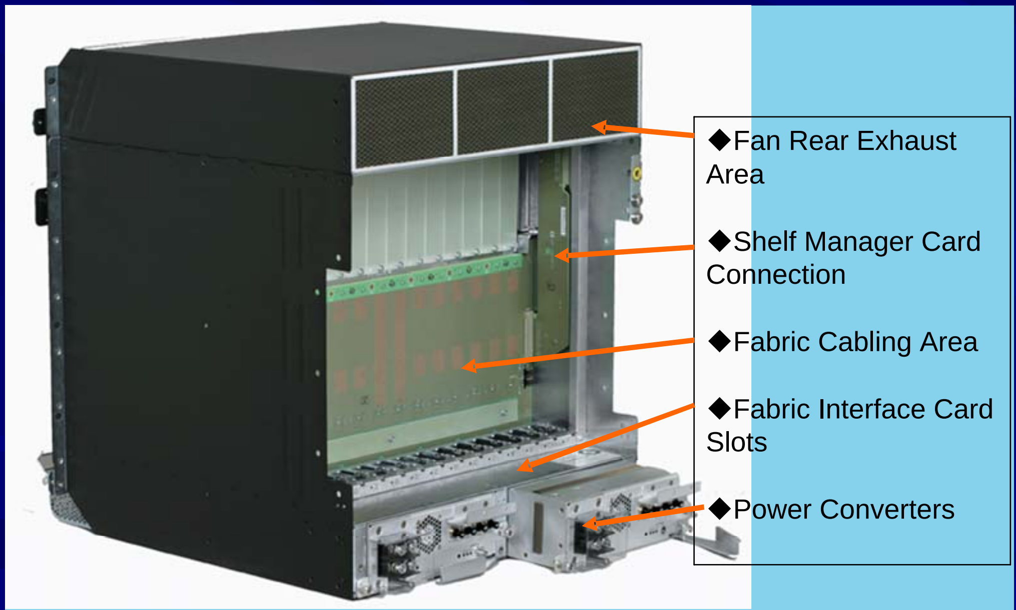
ATCA elements



Shelf front



System Controller and Switch Blade



Shelf rear

System processor

Conclusions

- The well-tried concepts of HEP experiments may successfully be transferred to the medical imaging field…

- The pixelisation of the detector and the subsequent pipelined independent reading electronics scheme will enable:
  - → to attain the highest count rates by suppressing deadtime
  - → to cancel out the time contributions of CFD and TDC
  - → to compute both energy and time by using the same channel

- The power and the flexibility of the digital filter will enable to suit future needs if the TOF accuracy is to be increased

- A powerful trigger DAQ system based on modern telecom technologies can make a real time treatement of the data.

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- C.Woody (BNL)
- P.E. Vert (INNOTEP collaboration)
- ....and many others