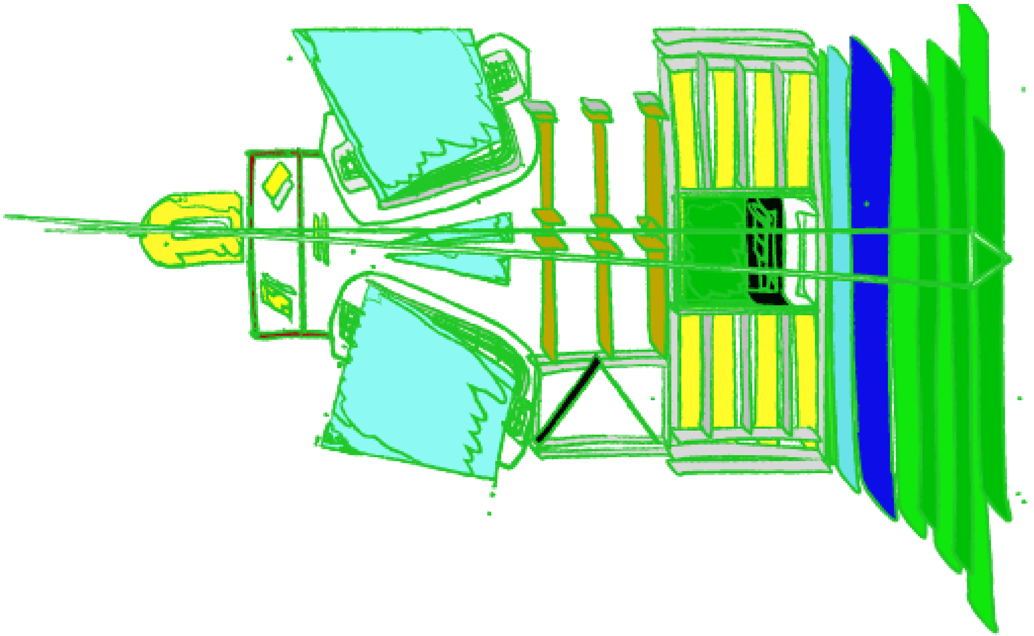


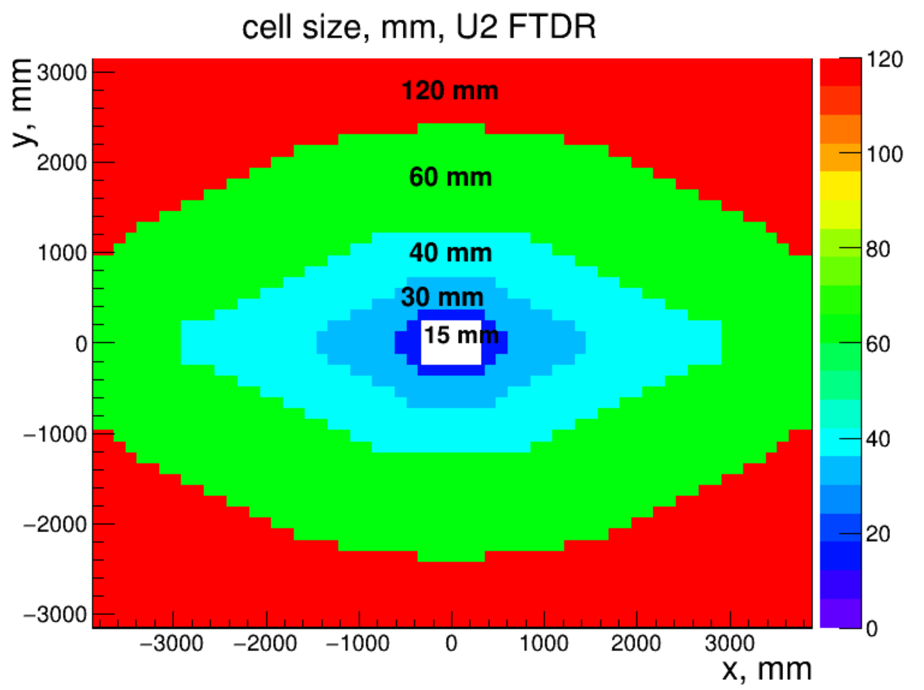
PMTs Photon detectors and cables

E. Picatoste

ECAL Upgrade II Workshop
at ICJLab (Orsay)

13/12/2022

PMTs for the Calorimeter Upgrade II



Gain values expected from ageing

Cell size case	Channel technology	High G (Imax lim.)	Low G (Imax lim.)
15 mm	SPACAL W	4k	1k
30 mm	SPACAL Pb	4k	500
40, 60, 120 mm	Shashlik	100k	11k

- Different detector zones, different needs (gain, ageing, geometry)
  - Inner part:
    - High doses
    - 2 channel technologies: SPACAL-W, SPACAL-Pb
  - Outer zone
    - Shashlik technology
    - Somehow more relaxed requirements due to lower radiation doses
- Stringent geometry in the innermost zone (15mm)
- Ageing is an important limit
  - Needs of high number of photoelectrons → maximum amount of integrated charge before degrading the device characteristics
  - Total integrated charge ≥ 10^3 C (to be confirmed/evaluated for MCD)

PMT Measurements

- PMTs?
  - R11187 (TILECAL), R14755U-100, R7600U-20 (MCD), FEU115M,…
- Perform measurements to check PMT characteristics at detector expected gains
  - Time resolution ~20 ps
  - Energy resolution
  - Signal linearity
- Other measurements
  - Ageing
  - Radiation hardness

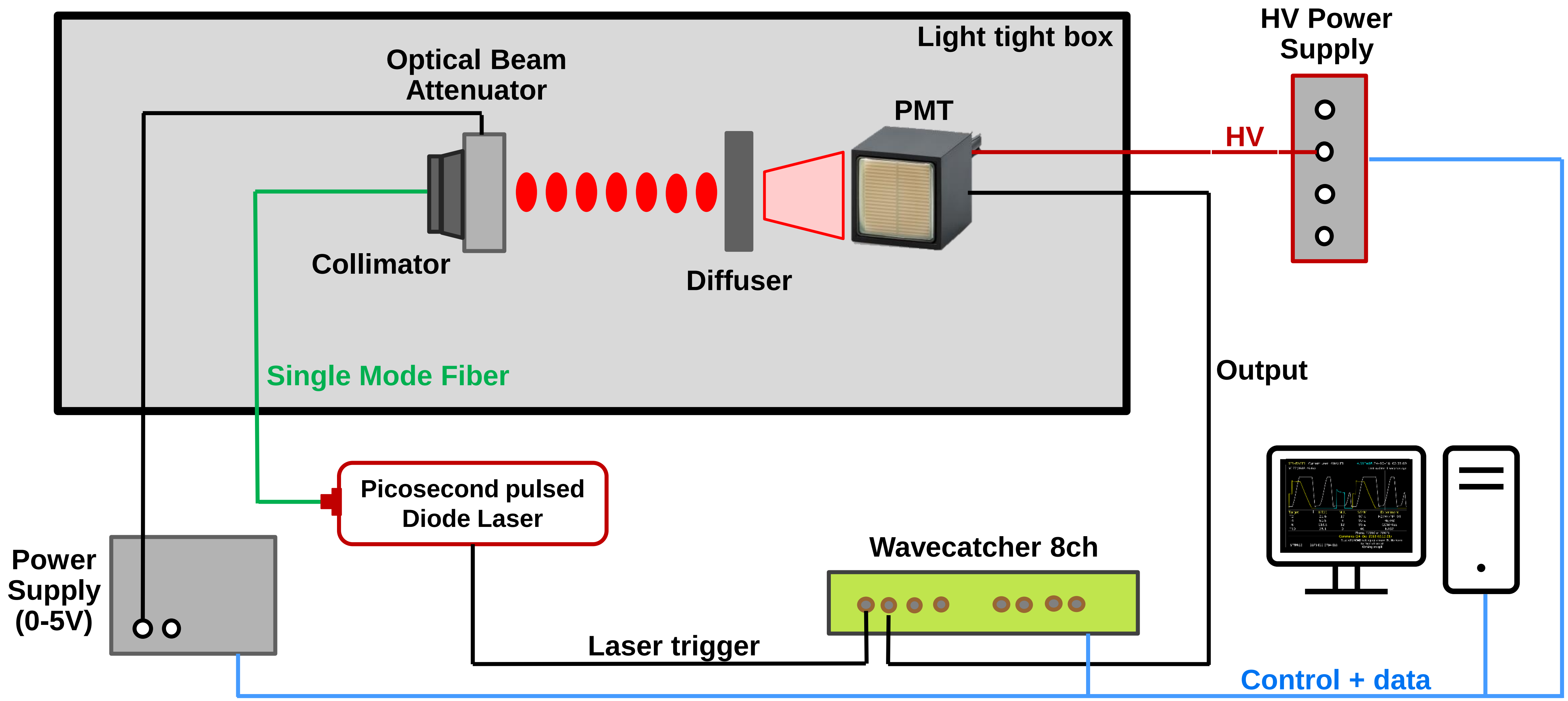
PMT: R11187

- TILECAL
- Good timing
- Lower gain (8 dynodes)

PMT: R14755U-100

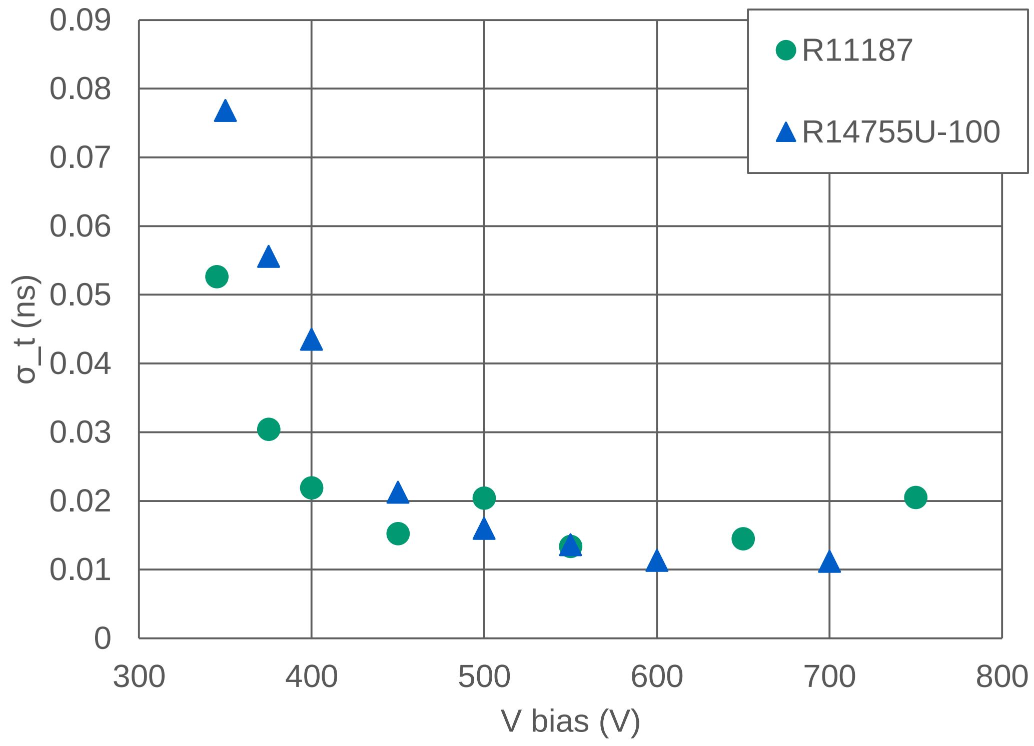
- Lower gain (6 dynodes)
- Good timing
- Smaller but still 1-2 mm large

PMT Laboratory Setup

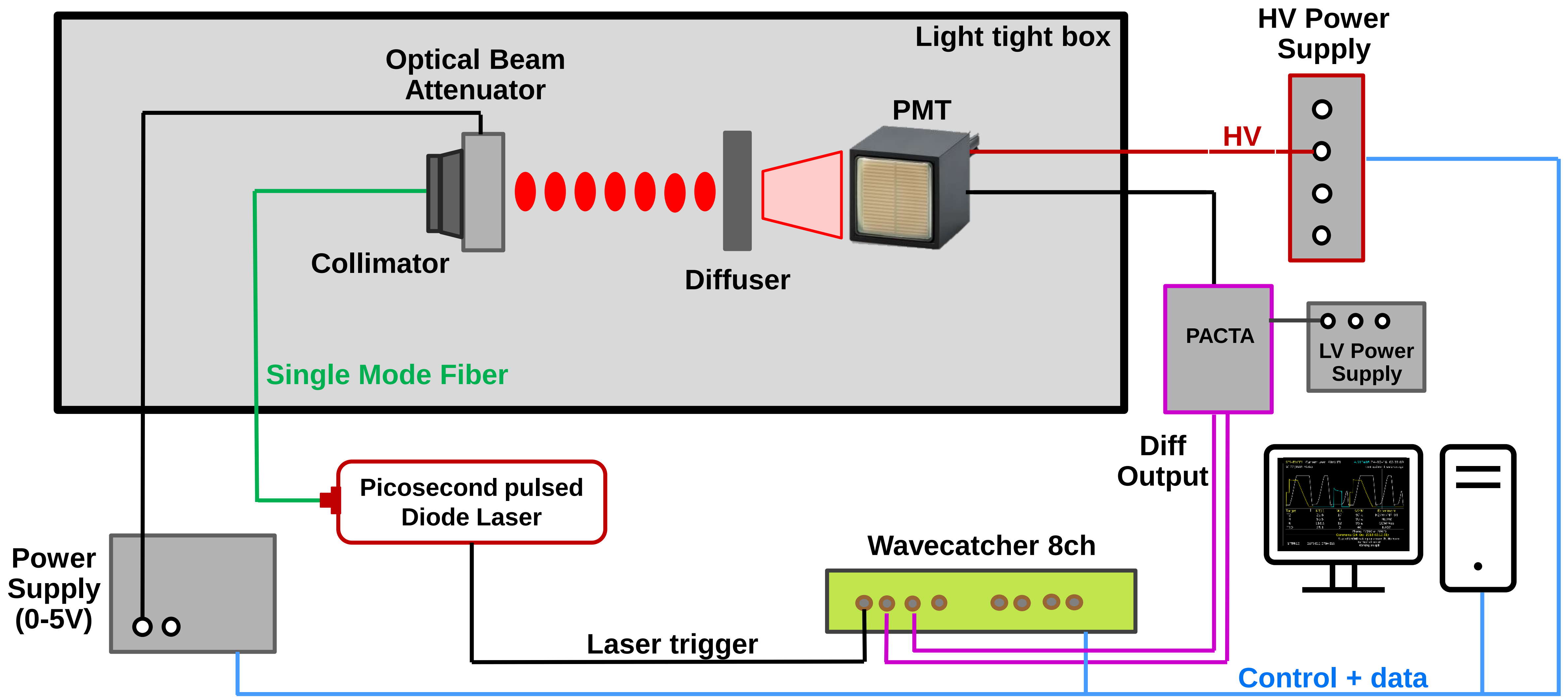


PMT Measurements at the Laboratory

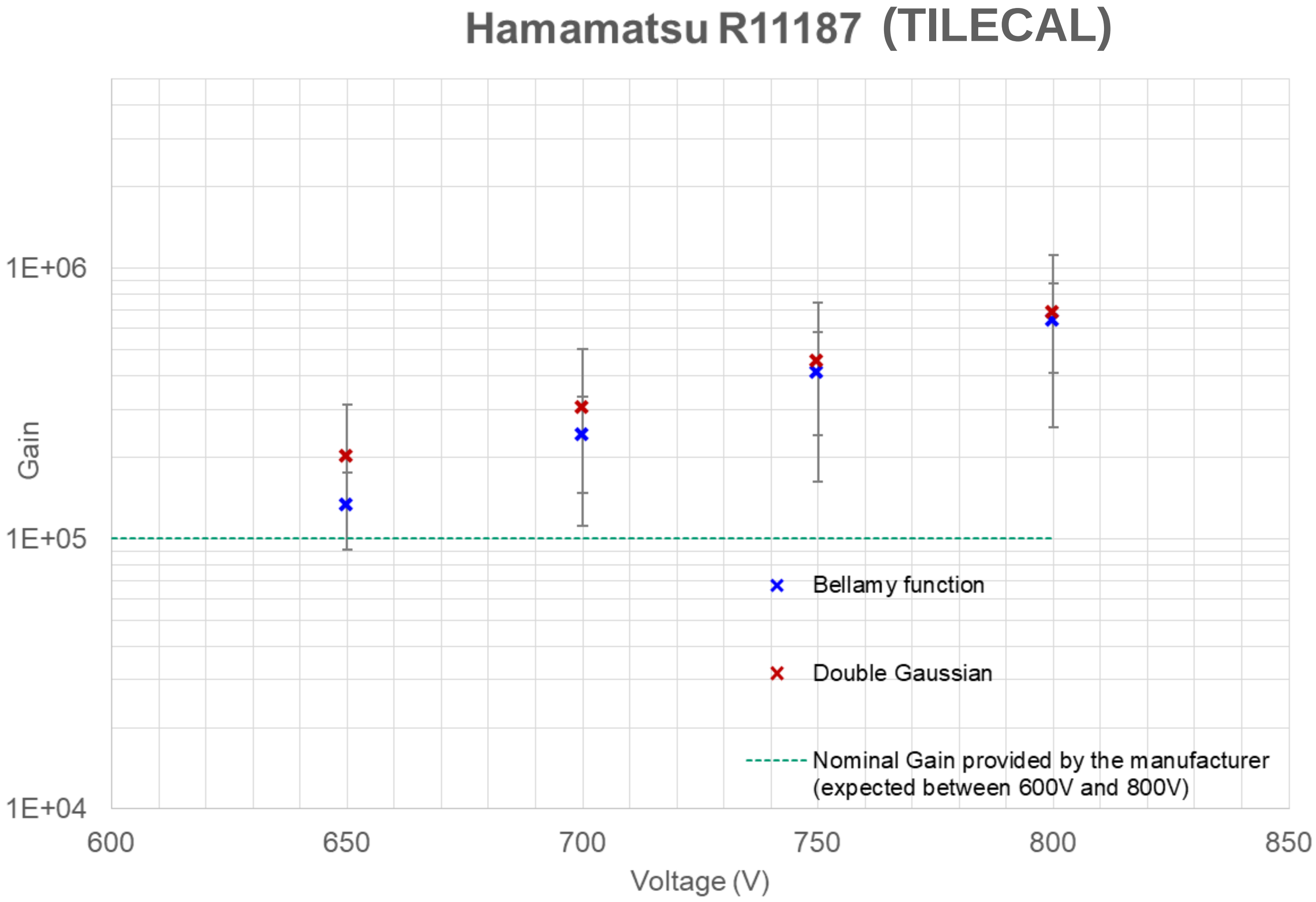
- First good results on time resolution, BUT
- Gain at laboratory using statistics and pulsed light method is not well understood
  - Need to use same Nphe and PMT bias voltage (HV) as test beam for comparison
    - Higher Nphe reduce time resolution!
- Try 1-Phe method
  - Use PACTA transimpedance amplifier (from CTA) to amplify PMT signal
  - Analyze data with double Gaussian fit or *Bellamy* function (E.H. Bellamy et al.INucl. Instr. and Meth. inPhys . Res. A 339 (1994) 468-476)
  - Estimate N_{phe} from the measured (1-Phe) gain?



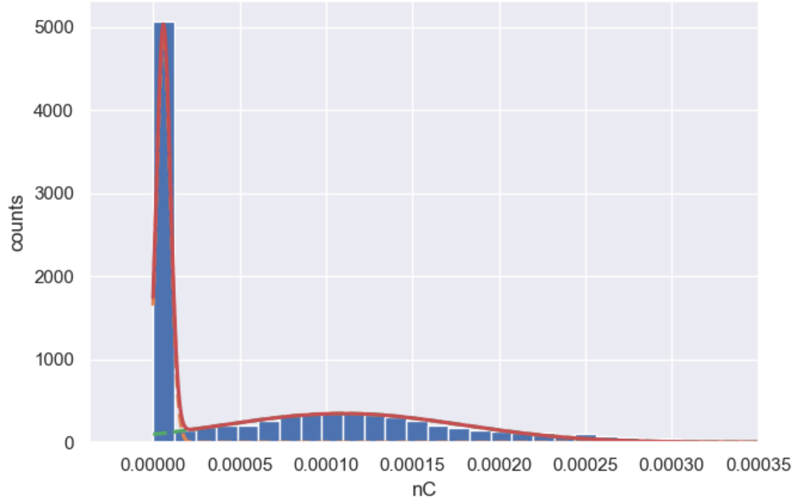
PMT Laboratory Setup 1-Phe

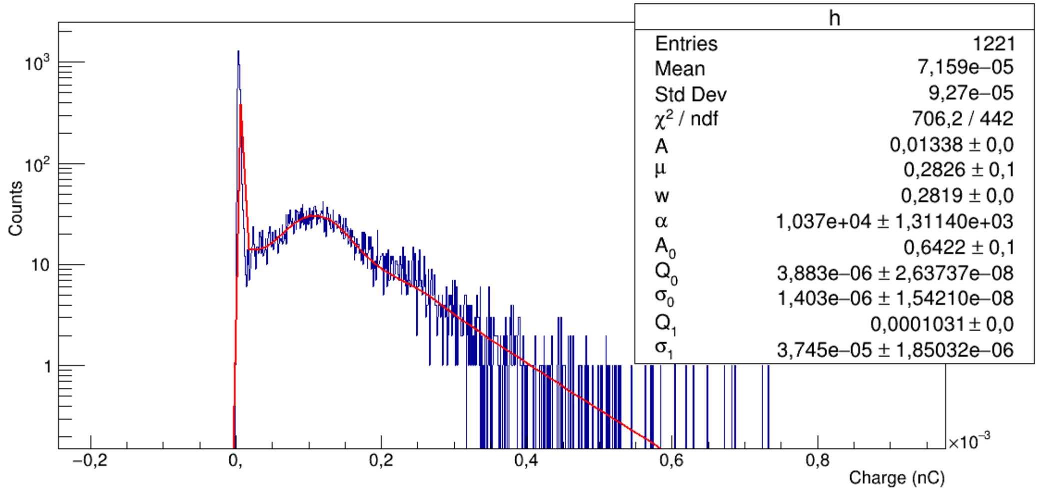


PMT Measurements: 1-Phe Gain

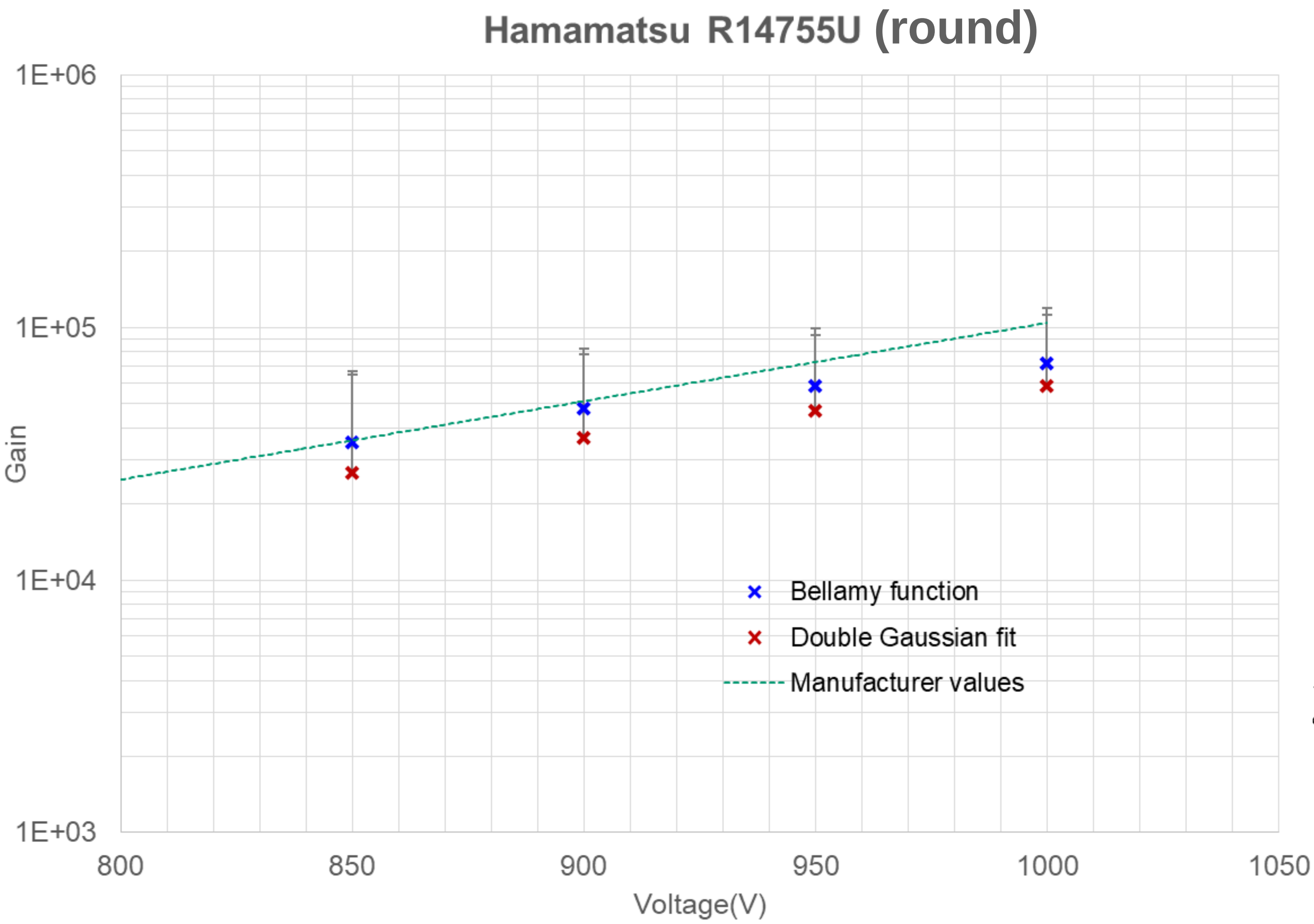


PMT R11187 – 800 V (HV)

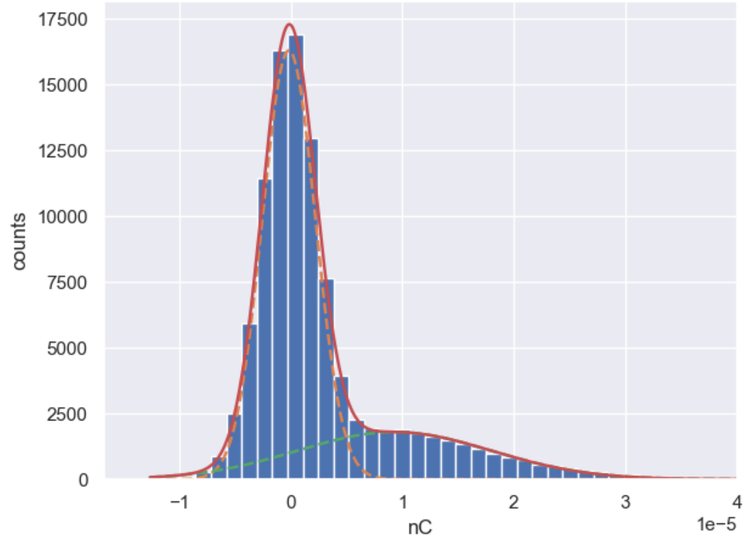


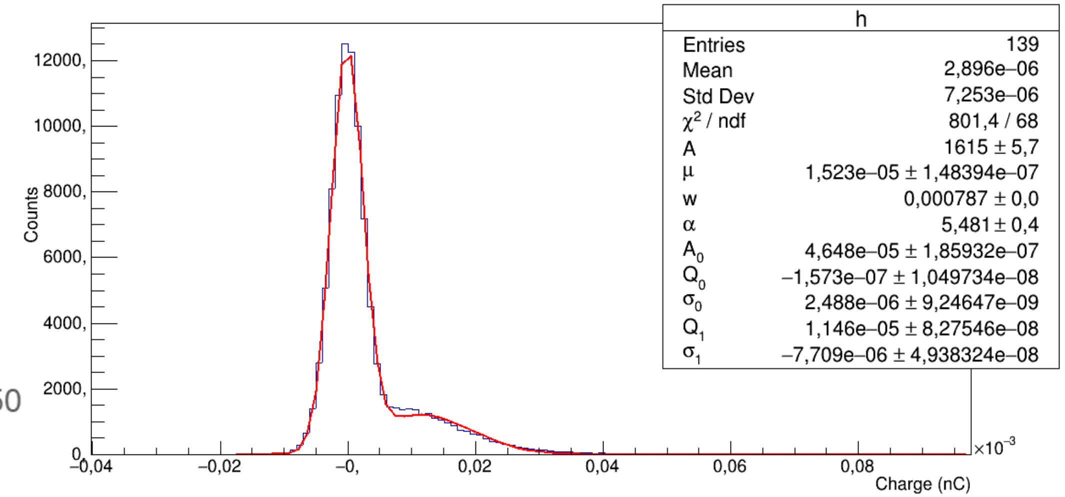


PMT Measurements: 1-Phe Gain



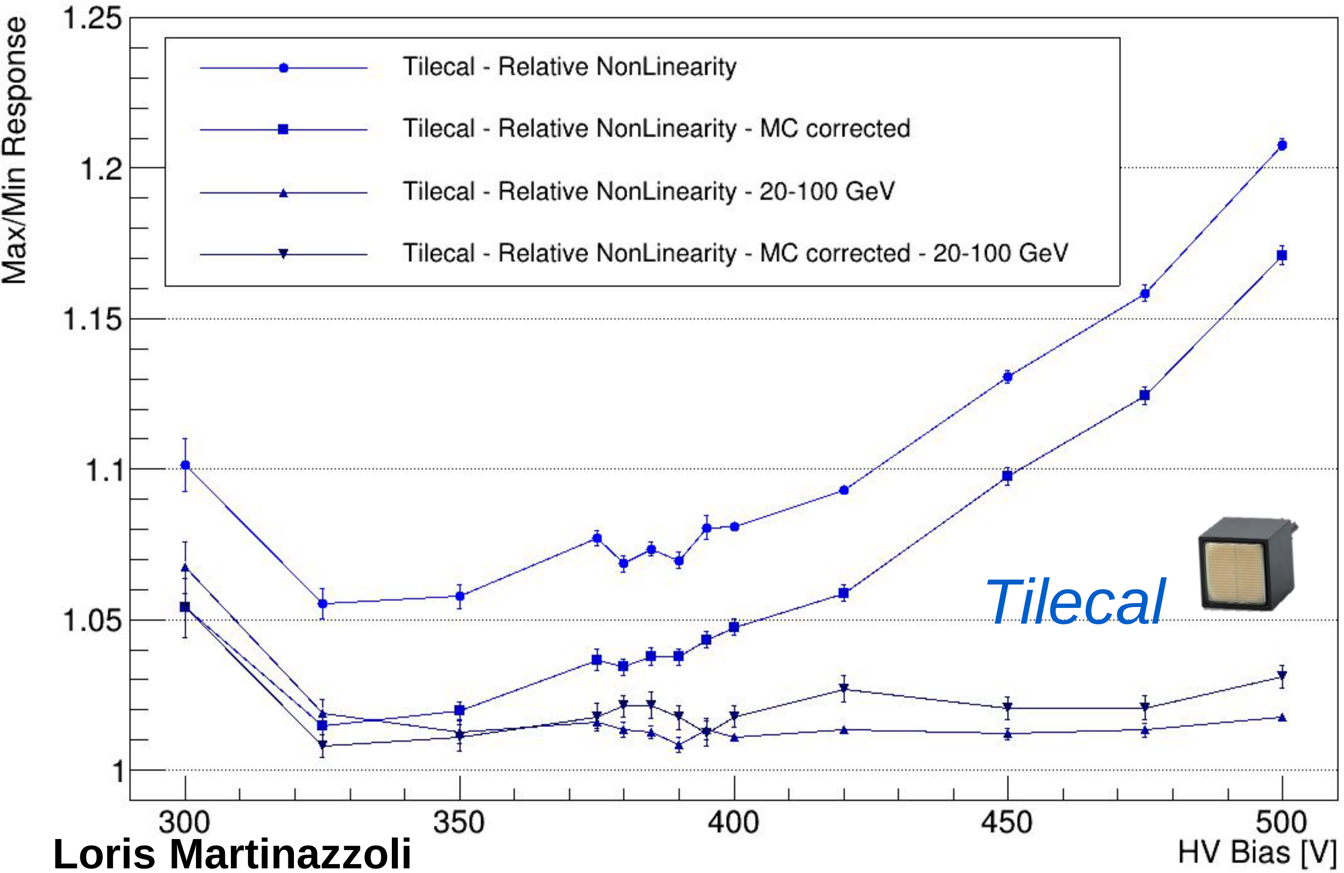
PMT R14755U – 1000V (HV)



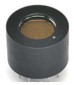


PMT Linearity Measurements at SPS Test Beam (2022)

$$NL = \frac{R_{max}}{R_{min}} \text{, where } R = \frac{\langle Ampl \rangle}{E_{beam}}$$

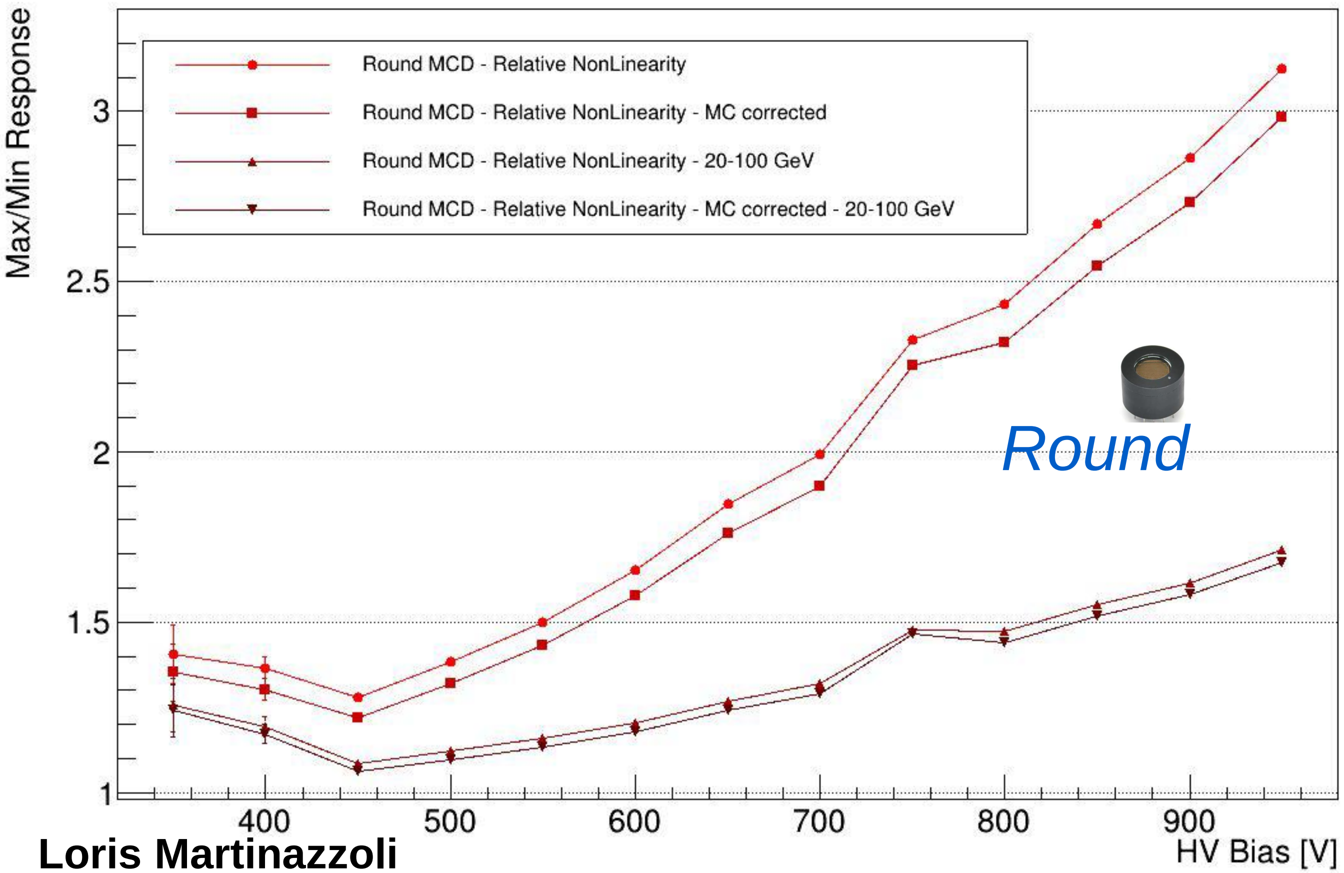


Loris Martinazzoli

- R11187 (Tilecal) 
  - Max/Min response ~1% in the 20-100 GeV range
  - 8 dynodes, tapered board to help against space-charge effects
  - More linear than Round MCD
- R14755U-100 (Round MCD) 
  - Max/Min response significantly worse than Tilecal
    - 10-30% in the 20-100 GeV range at the useful HVs
  - Max/Min response ~2.5% even in the 20-40 GeV range at reasonable voltages.
  - 6 dynodes
  - R&D needed
    - Tapered board?
    - Transistorized base?
    - Asking some more dynodes?

PMT Linearity Measurements at SPS Test Beam (2022)

$$NL = \frac{R_{max}}{R_{min}}, \text{ where } R = \frac{\langle Ampl \rangle}{E_{beam}}$$

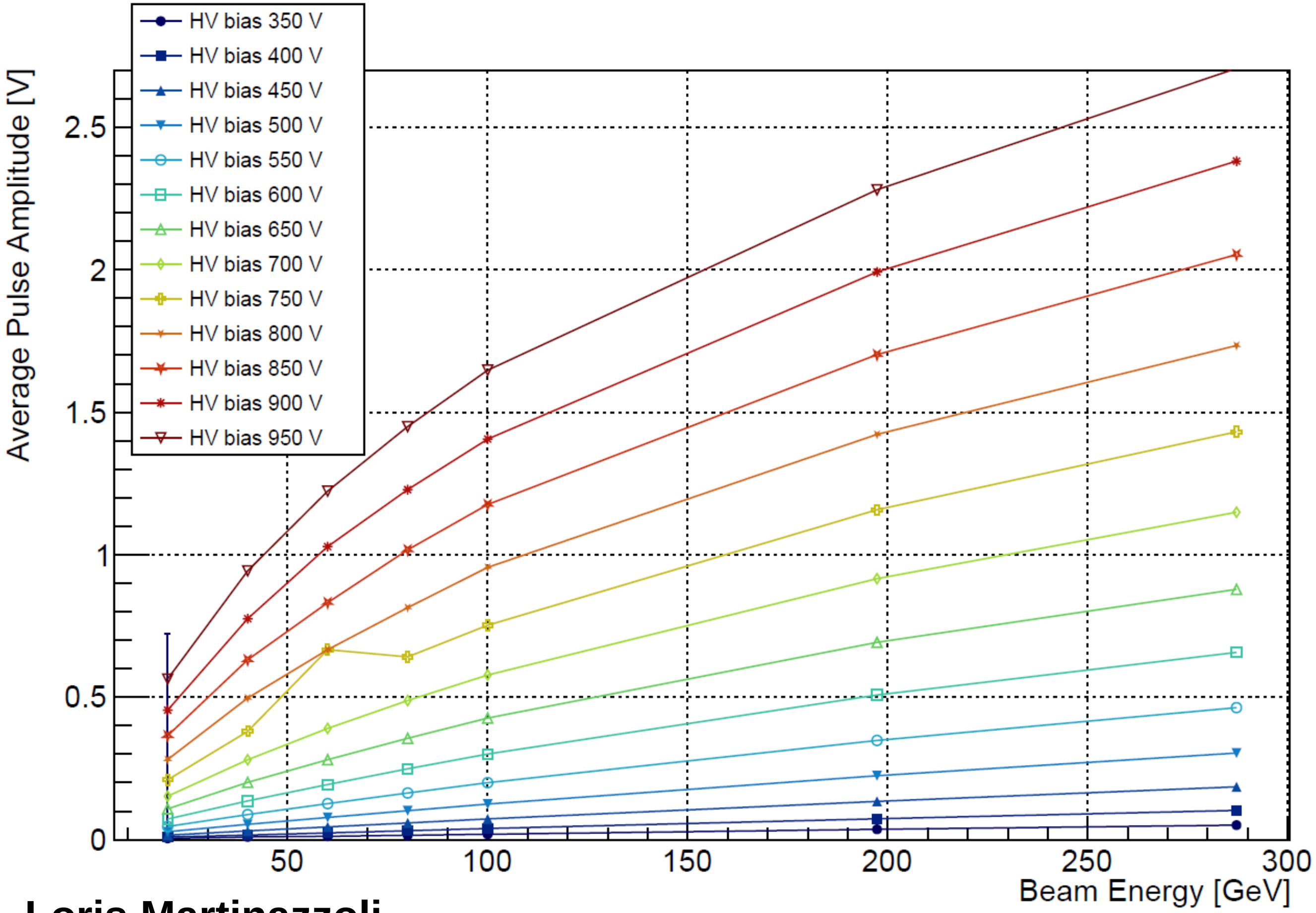


Loris Martinazzoli

- R11187 (Tilecal) 
  - Max/Min response ~1% in the 20-100 GeV range
  - 8 dynodes, tapered board to help against space-charge effects
  - More linear than Round MCD
- R14755U-100 (Round MCD) 
  - Max/Min response significantly worse than Tilecal
    - 10-30% in the 20-100 GeV range at the useful HVs
  - Max/Min response ~2.5% even in the 20-40 GeV range at reasonable voltages.
  - 6 dynodes
  - R&D needed
    - Tapered board?
    - Transistorized base?
    - Asking some more dynodes?

PMT Linearity Measurements at SPS Test Beam (2022)

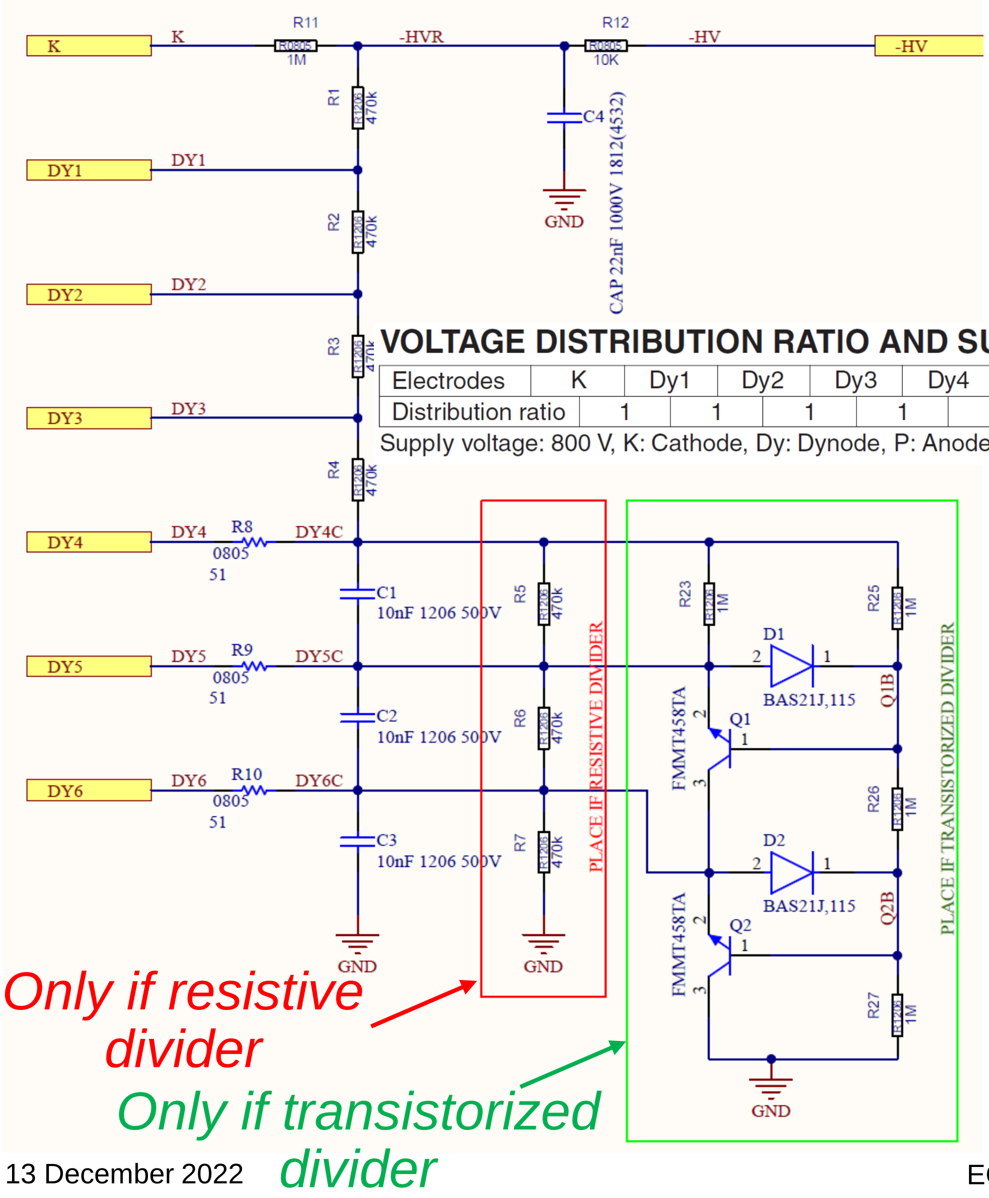
Round PMT ampliudes Vs. HV Vs. E



Loris Martinazzoli

- Round PMT non-linearity causes?
- PMT DC output current should be lower than 1/100 the voltage divider current (I_{bias})
  - ➢ I_{bias} = 30-100µA
- Estimate PMT $I_{out,DC}$ from
  - – Amplitudes
  - – Rates: 10kHz to ~200Hz (at different E)
- $I_{out,DC} \geq I_{bias}/100$ for $V_{bias} \geq 600$V
- Plan:
  - ➢ Reduce base resistors (2MΩ to 470kΩ or lower)
  - ➢ Test transistorized base

PMT Linearity Measurements at SPS Test Beam (2022)

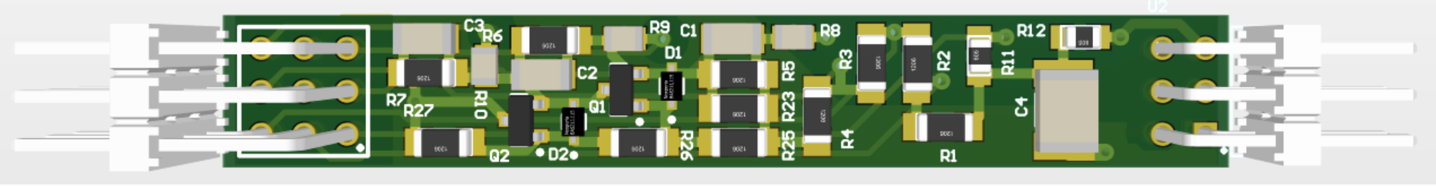


VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrodes	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	P
Distribution ratio	1	1	1	1	1	1	1	

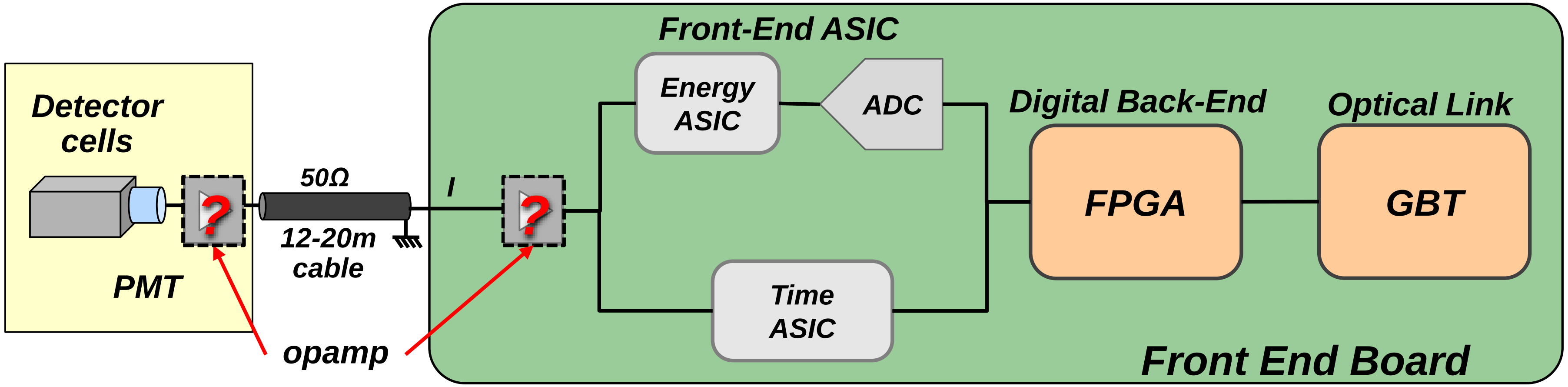
Supply voltage: 800 V, K: Cathode, Dy: Dynode, P: Anode

- Round PMT non-linearity causes?
- PMT DC output current should be lower than 1/100 the voltage divider current (I_{bias})
  - ➢ I_{bias} = 30-100μA
- Estimate PMT $I_{out,DC}$ from
  - – Amplitudes
  - – Rates: 10kHz to ~200Hz (at different E)
- $I_{out,DC} \geq I_{bias}/100$ for $V_{bias} \geq 600V$
- Plan:
  - ➢ Reduce base resistors (2MΩ to 470M or lower)
  - ➢ Test transistorized base



PMT Signal Conditioning

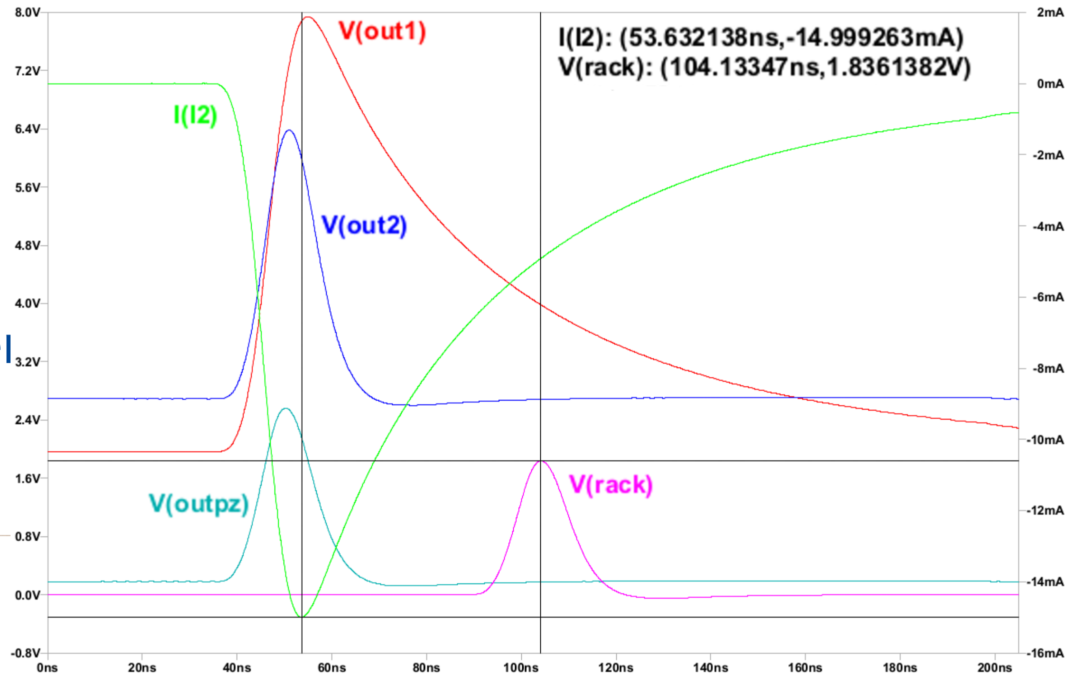
- Photodetectors readout solution follows the same scheme as in current ECAL:
  - Minimal light transport with PMT sensors near modules,
  - All electronics in crates on top of the detector (reduced radiation),
  - Connection via analog link (coaxial) ~12m long (up to 20m considered).
- ASIC/chipset in TSMC 65nm with separate energy and timing processing paths

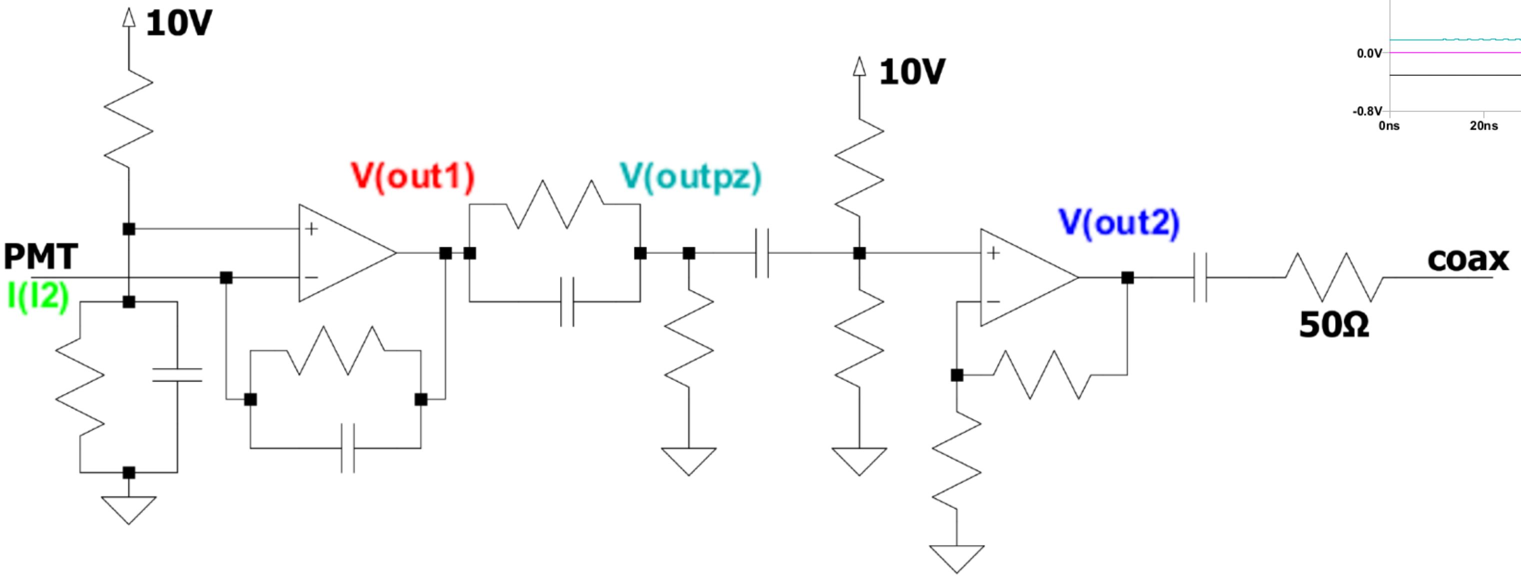


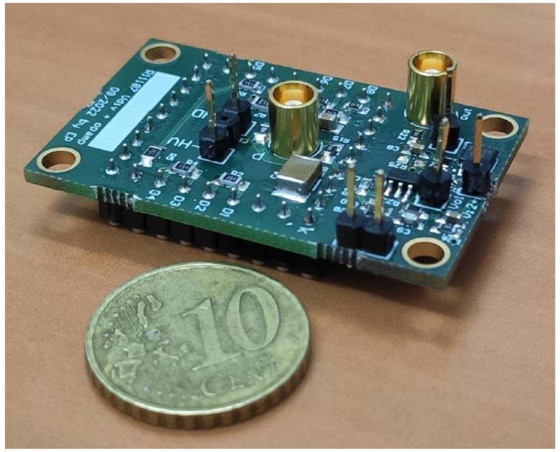
- Amplifier + Shaper circuit included on the PMT base or FEB under consideration
  - To compensate cable attenuation, improve SNR, if necessary, and reduce spill-over effort
  - To act as a buffer to help split the signal between paths
  - Different ASIC requirements (signal range, gain, noise, BW): add dedicated passive attenuator for each path.
  - If at FEB, use differential outputs to ASICs

PMT signal Conditioning: Opamp Circuit

- Two stage OpAmp based circuit on PMT divider:
  - Transimpedance amplifier(OPA847) boost SNR.
  - PZ cancellation network reduce pulse width.
  - High slew rate coaxial cable driver(OPA695).
- Radiation damage limits available commercial componen
  - ➢ design dedicated ASIC or integrate in front-end board.
- Board designed and produced, now under test.







Summary

- Different detector zones, different needs (gain, ageing)
- Main PMTs under study: R11187 (Tilecal) and R14755U-100 (round)
- PMT tests
  - Laboratory: gain, linearity, time resolution
    - Gain has been measured with 1-Phe method with reasonable results
    - Need to define a method to define the N_{phe} to be able to compare results
  - TB: energy resolution, time resolution, linearity, gain
    - Energy and time resolution routinely measured at TB
    - Linearity problems with R14755U-100 → review PMT base
  - Other: ageing, radiation hardness
- PMT signal conditioning is considered with operational amplifier-based circuit
  - To compensate cable attenuation, improve SNR and reduce spill-over effort
  - To act as a buffer to help split the signal between paths

Thank you for your attention!

PMT characteristics summary

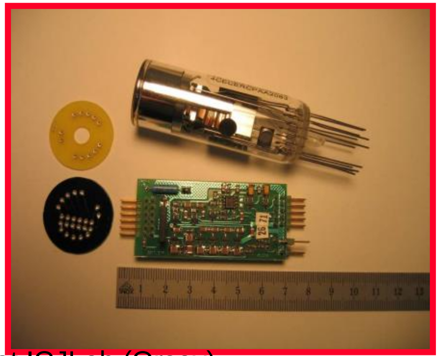
PMT	Ø outer (mm)	Ø Eff area (mm)	Photocathode [1]	λ range (nm)	λ peak (nm)	<QE> PMT*GFAG (%)	Gain ~800V	Dynodes	Dark Current ~800V (nA)	t rise (ns)	T.T.S. (ns)	Price (€)
R14755U-100	16	8	SBA	300-650	400	9.5	2.5 x 10^4	6	0.1	0.4	?	798
R11187 (TILECAL)	25.7x25.7	18x18	BI	300-650	420		1.0 x 10^5	8	0.25	1.5	?	
R7600U-20 (MCD 2020)	30x30	18x18	ERMA	300-920	530	**15.3**	1.0 x 10^6	10	20	1.6	0.35	1750
R12421 (2018)	13.5	10	EGBI	300-700	420	10	2.0 x 10^6	10	1	1.2	1.4	
R7899-20 (ECAL)	25	22	BI	300-650		10.3	2.0 x 10^6	10	2	1.6	0.6	

(1) SBA: Super bialkali, BI: bialkali, ERMA: Extended red multialkali, EGBI: Extended green bialkali

PMT: R14755U-100

PMT: R11187, R7600U-100

PMT: R7899-20



PMT: R12421

PMTs being studied

PMT: R7899-20

- Used on ECAL/HCAL runs ½
- Low timing uniformity over photocathode
- 10 dynodes

PMT: 7600U-20

- MCD 2020
- Good timing
- Relatively high gain (10 dynodes)

PMT: R11187

- TILECAL
- Good timing
- Lower gain (8 dynodes)

PMT: R14755U-100

- Lower gain (6 dynodes)
- Good timing
- Smaller but still 1-2 mm large

PMT gain calculation for test beam at CERN

for digitizer

- E is the beam energy (E=150 GeV)
- ξ is the max fraction of energy in one cell (ξ=0.4)
- Y is the photoelectron yield (Y=20000 GeV^{-1})
- τ is the effective decay time of scintillation (τ=60 ns)
- U is the signal amplitude (U=1V)
- R is the digitizer input impedance (R=50 Ohm)
- e is the electron charge ($e=1.6\cdot10^{-19}$ C)
- G is the PMT gain

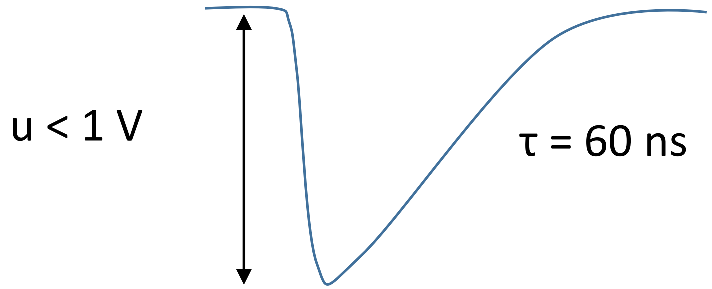
The signal charge

$$Q = \frac{U\tau}{R} = Y\xi EGe$$

then

$$G = \frac{U\tau}{R\xi YEe} = 6250$$

then, V_{R7600} = 410V (750V if -40dB attenuation)



for integrating ADC

- E is the beam energy (E=150 GeV)
- ξ is the max fraction of energy in one cell (ξ=0.4)
- Y is the photoelectron yield (Y=20000 GeV^{-1})
- Q^{max} is the max input charge (200 pC for LeCroy 1182)
- e is the electron charge ($e=1.6\cdot10^{-19}$ C)
- G is the PMT gain

The signal charge

$$Q^{max} = Y\xi EGe$$

then

$$G = \frac{Q^{max}}{\xi YEe} = 1042$$

then, V_{R7600} = 290V (530V if -40dB attenuation)

PMT gain calculation for the LHCb operation

gain is limited by maximum anode current
considering the very central spacal cells ($\sin\theta = 0.03$)

- I^{max} is the max anode current (Imax=100 μA)
- $\mathbb{L}$ is the total integrated luminosity ($\mathbb{L}$=300 fb^{-1})
- L is the instantaneous luminosity (L=$1.5\cdot10^{34}$ $cm^{-2}s^{-1}$)
- D is the TID dose for 300 fb^{-1} (D=1 MGy)
- M is the cell weight (M=0.5 kg)
- Y is the photoelectron yield (Y=20000 GeV^{-1})
- e is the electron charge (e=$1.6\cdot10^{-19}$ C)
- G is the PMT gain

The dose rate

$$\frac{dD}{dt} = L\frac{D}{\mathbb{L}} = 0.05\frac{J}{kg\cdot s} = 3\cdot10^{8}\frac{GeV}{kg\cdot s}$$

then

$$I^{max} = \frac{dD}{dt}\cdot MYGe$$

$$G = \frac{I^{max}}{\frac{dD}{dt}MYe}$$

The max transverse energy $E_T^{max} = 20\ GeV$
at the very central cell $\sin\theta = 0.03$

- the $E^{max} = E_T^{max}/\sin\theta$≈600 GeV
- ξ is the max fraction of energy in one cell (ξ=0.4)
- Y is the photoelectron yield (Y=20000 GeV^{-1})
- τ is the effective decay time of scintillation (τ=60 ns)
- R is the input impedance (R=50 Ohm)
- e is the electron charge (e=$1.6\cdot10^{-19}$ C)
- G is the PMT gain

The signal charge

$$Q = Y\xi EGe \approx 12\ pC$$

the signal amplitude:

$$U = \frac{QR}{\tau} = 0.01\ V$$

Then, within the Spacal section, the PMT gain should scale proportionally to sinθ.

i.e. G=156*sinθ/0.03

The Upgrade-2 FTDR configuration: gain limited by ageing

Lumi=$1.5\cdot10^{34}$ $cm^{-2}s^{-1}$.
SPACAL light yield (zone 15mm and 30mm): 20 ph.el/MeV
Shashlik light yield: 3 ph.el./MeV

The signal charge:

$$Q = Y\xi E G e$$

The signal amplitude:

$$U = \frac{QR}{\tau}$$

cell size(mm)	Y (phe/GeV)	ξ	Emax (GeV)	τ (ns)
15	20000	0.4	698.4	60
30	20000	0.4	453.1	4
40	3000	0.4	291.5	10
60	3000	1	140.8	10
120	3000	1	63.2	10

- Maximum signal amplitudes are orientative
  - If too high, the gain of the PMT can be lowered and PMT lifetime extended
- LSB is calculated divident maximum signals by the minimum ADC step (4096 for 12 bit)
- LSB in Calo I is $4.9\cdot10^{-4}$ V
  - and noise is about 1-2 LSB

PMT gain limited by I^{max}

GAIN

cell size (mm)	G_{PMT} channel	G_{PMT} REAR	G_{PMT} FRONT
15	568	812	1894
30	381	544	1270
40	8210	11729	27367
60	21868	31240	72893
120	21367	30524	71223

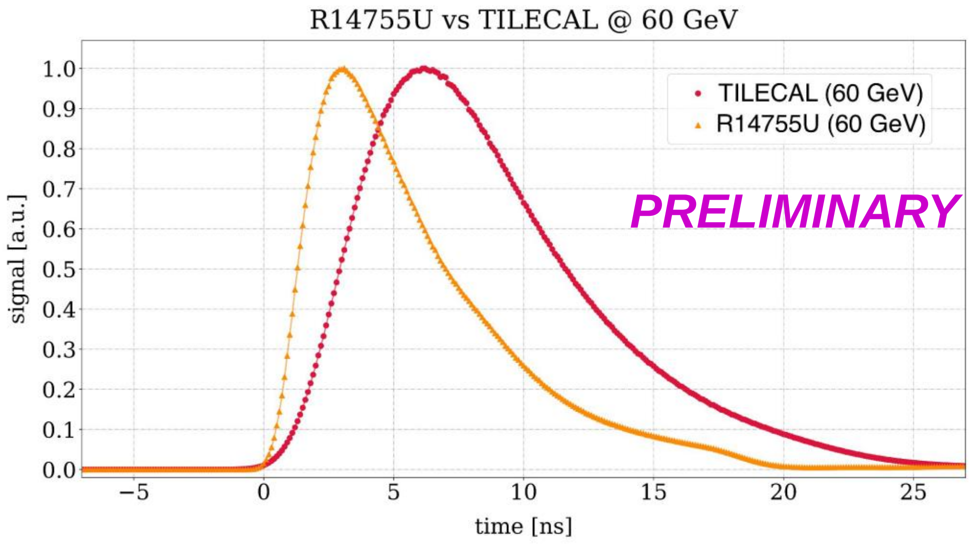
Max signal

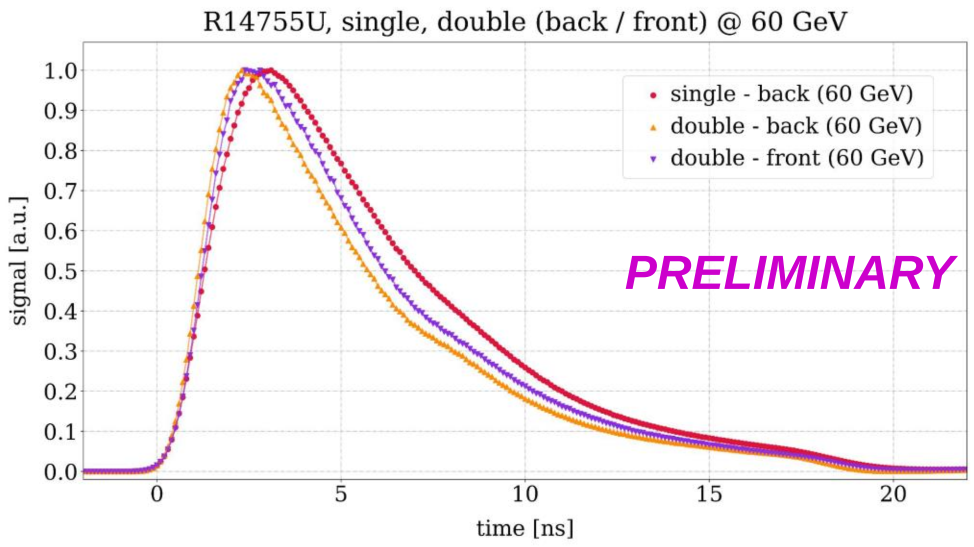
cell size (mm)	U (V) channel	U (V) REAR	U(V) FRONT
15	0.42	0.60	1.41
30	2.76	3.95	9.21
40	2.30	3.28	7.66
60	7.39	10.56	24.63
120	3.24	4.63	10.80

LSB

cell size (mm)	LSB (V) channel	LSB (V) REAR	LSB (V) FRONT
15	1.03×10^{-4}	1.48×10^{-4}	3.44×10^{-4}
30	6.75×10^{-4}	9.64×10^{-4}	2.25×10^{-3}
40	5.61×10^{-4}	8.01×10^{-4}	1.87×10^{-3}
60	1.80×10^{-3}	2.58×10^{-3}	6.01×10^{-3}
120	7.91×10^{-4}	1.13×10^{-3}	2.64×10^{-3}

W/Poly - Pulse shape





- Studied the average pulse at 60 GeV
  - R14755U pulses are shorter than TileCal's with faster rise and decay time
    - Better containment within the bunch crossing

Single side readout	Rise time (10-90%) [ns]
R11187 (TILECAL)	3.6
R14755U-100 (round)	1.8

  - Average pulse shape affected by the readout configuration
    - Slower pulse in single side readout due to the light reflected by the mirror in front
    - Studies ongoing with Monte Carlo simulations

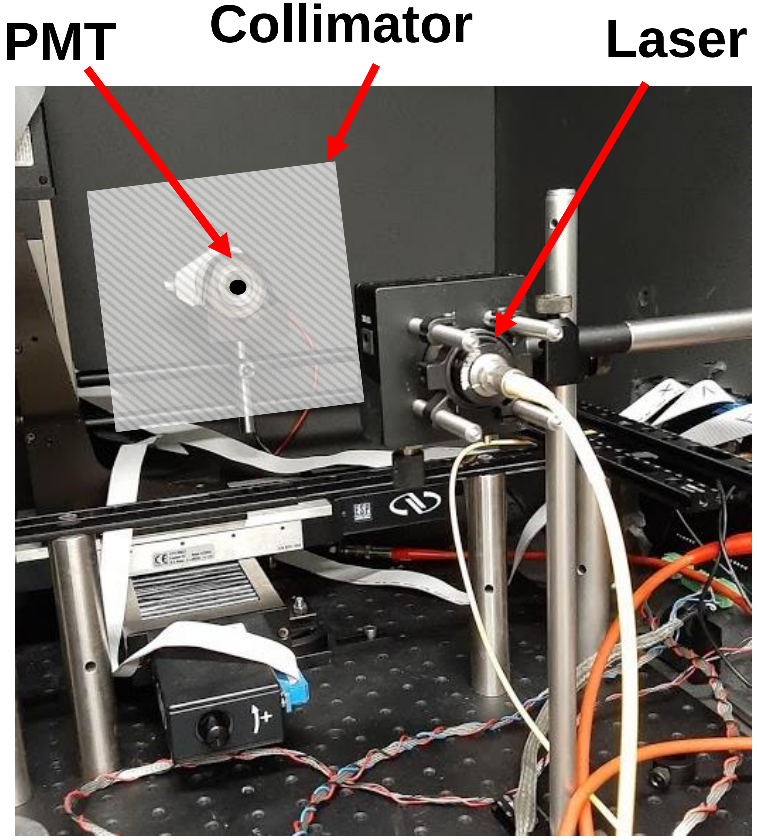
Transient time measurements

- Objective: study the transient time uniformity over the photocathode of R7600U-20

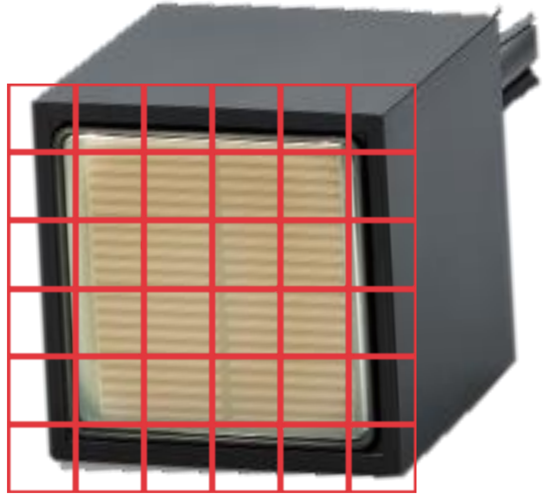
- Measurements:
  - PMT signal output amplitude
  - Transient time: time between laser trigger and PMT output pulse
  - Transient time spread: standard deviation at a given photocathode position

- PMTs:
  - R7600U-20: ZF0002, TS0340
  - ECAL R7899-20

EXPERIMENTAL SETUP



PMT: R11187



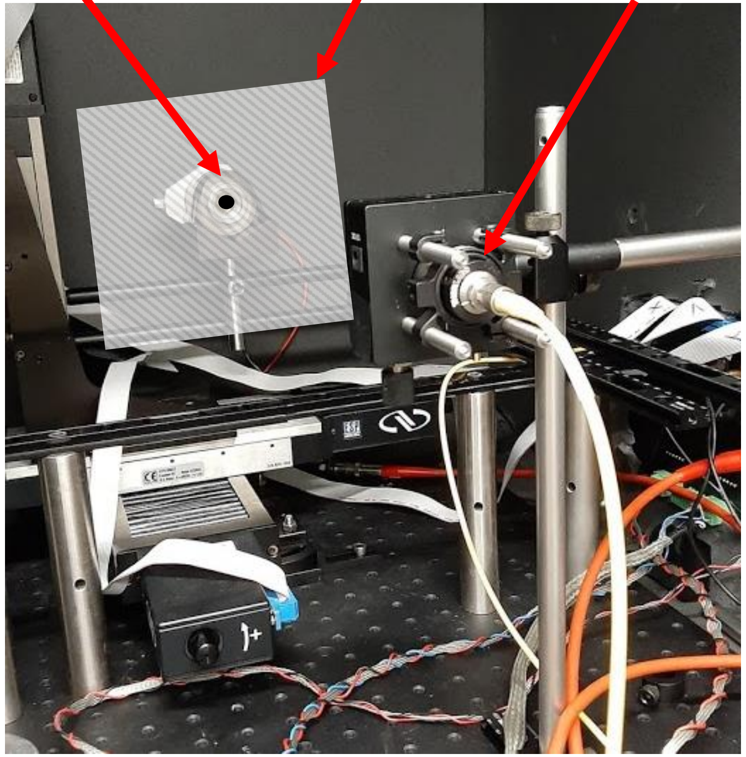
Grid of points, (laser)

- 12x12 matrix, 1.5mm separation
- 500 waveforms per point
- Bias voltage = 800V
- 'Cardboard' collimator

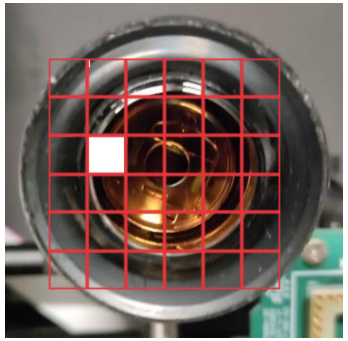
Light readout: PMTs time resolution and TTS uniformity

- Non uniformity may increase the time resolution
- The use of light guides would reduce the uniformity requirement
- Scan over photocathode with laser light

PMT **Collimator** **Laser**

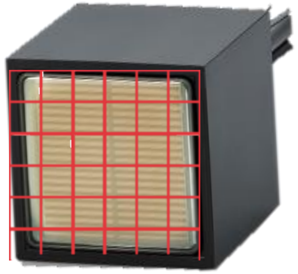


PMT: R7899-20



Grid of points, (laser)

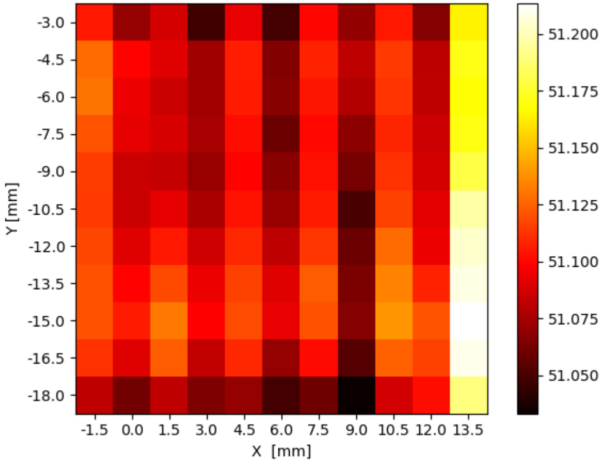
PMT: R7600U-20 or R11187



Grid of points, (laser)

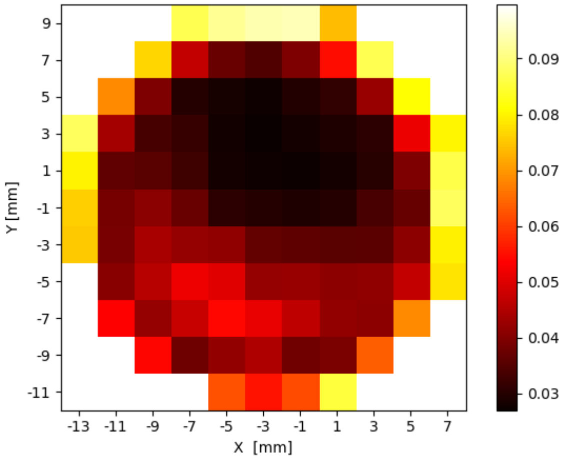
Arrival time uniformity over R7600U-20

✓ CFD 0.5 → total std = 41 ps



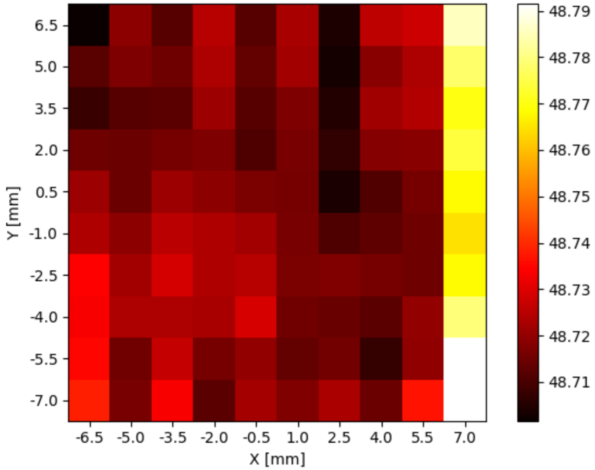
Arrival time uniformity over R7899-20

× CFD 0.5 → total std = 1.36 ns



Arrival time uniformity over R11187

✓ CFD 0.5 → total std = 32 ps



Timing and amplifier at PMT base

- 20 ps time resolution is mandatory to distinguish interactions → maintain physics performance.
- Time path self-trigger threshold could be set for 5GeV depositions in channel.
  - Testbeam 2020 results assure 20 ps time resolution above 5GeV of beam energy (E_T = 2GeV).
  - Time measurement for 2x2 cluster or each channel, depending on occupancy.
- Theoretically, time jitter above time resolution for smaller signals.
  - Assume
    - Dynamic Range=1V, for $E_{T,max}$ = 40GeV and $E_{T,max}$ = 2GeV → min signal 50mV ;
    - Rise time (10%-90%) of SPACAL GFAG and MCD: 5ns ;
    - noise = 1mV,
  - therefore → jitter = noise/slope = 1mV/(50mV/5ns) = **100ps rms**
- Can we increase the Slope by a factor 5 to achieve 20ps?
  - reduce scintillator rising time?
  - increase gain, but then pulse saturates at SCA so no CFD correction.
    - external time walk correction using energy path measurement?
    - external baseline correction with initial SCA samples/event
- Alternative to measure time with MCP-PMT layer.
  - Sampling rate specification would increase by some factor.
  - Sample pattern for digitization may change wrt module PMTs.