Cost effective electronics for LAr and photo-detectors readout

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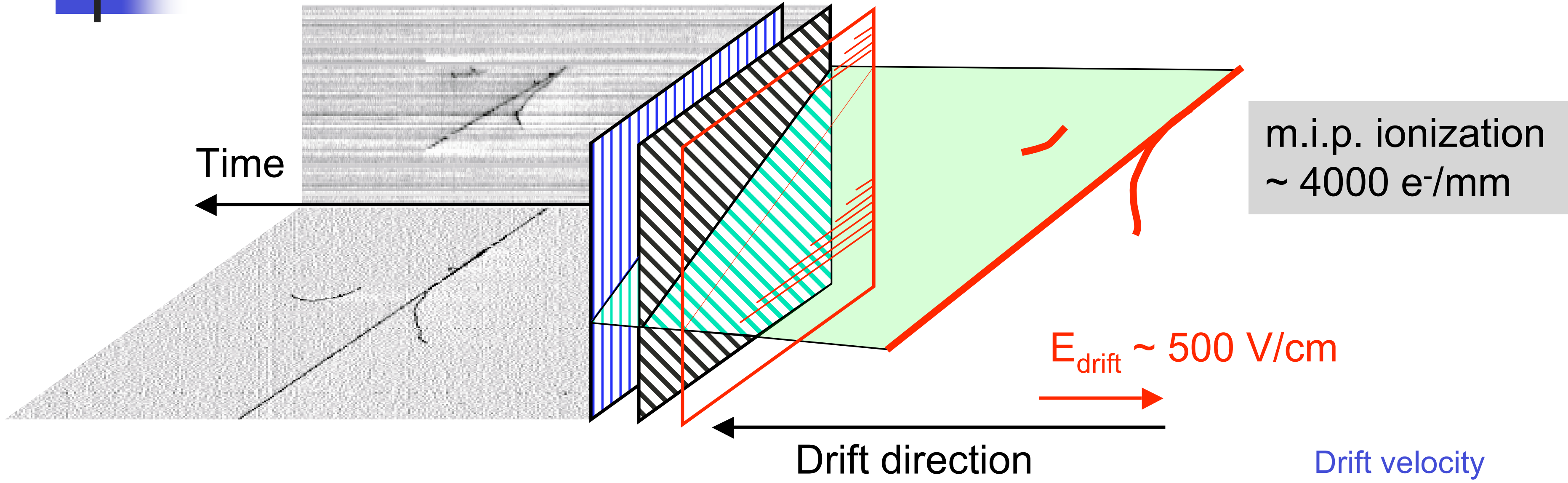
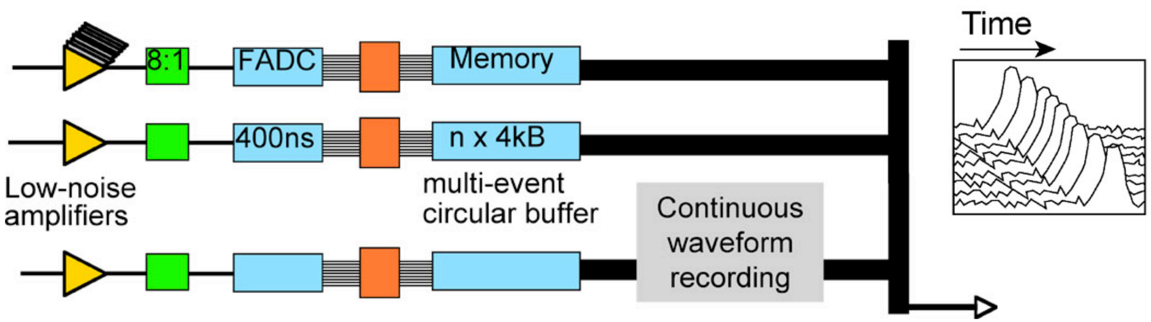
Outline

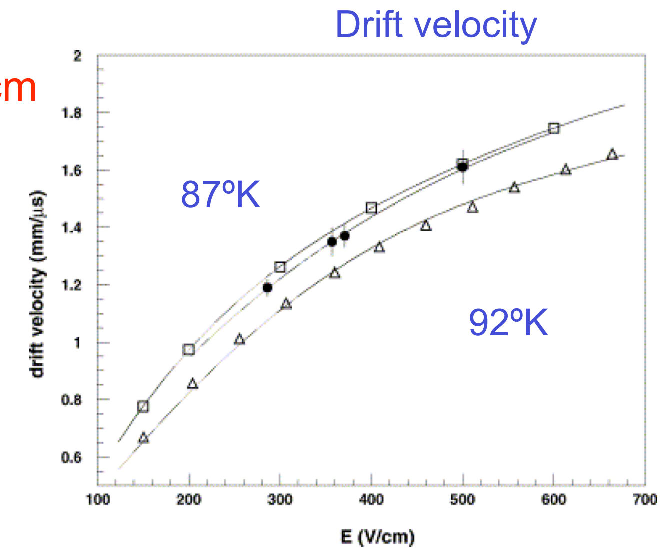
- Charge signals from *liquid* Argon TPC
  - Characteristics and critical issues
  - A proven architecture
  - Toward updated schemes
- Light signals from *liquid & gaseous* Argon
  - Characteristics and critical issues
  - Basic DAQ architecture

The ICARUS-like read-out

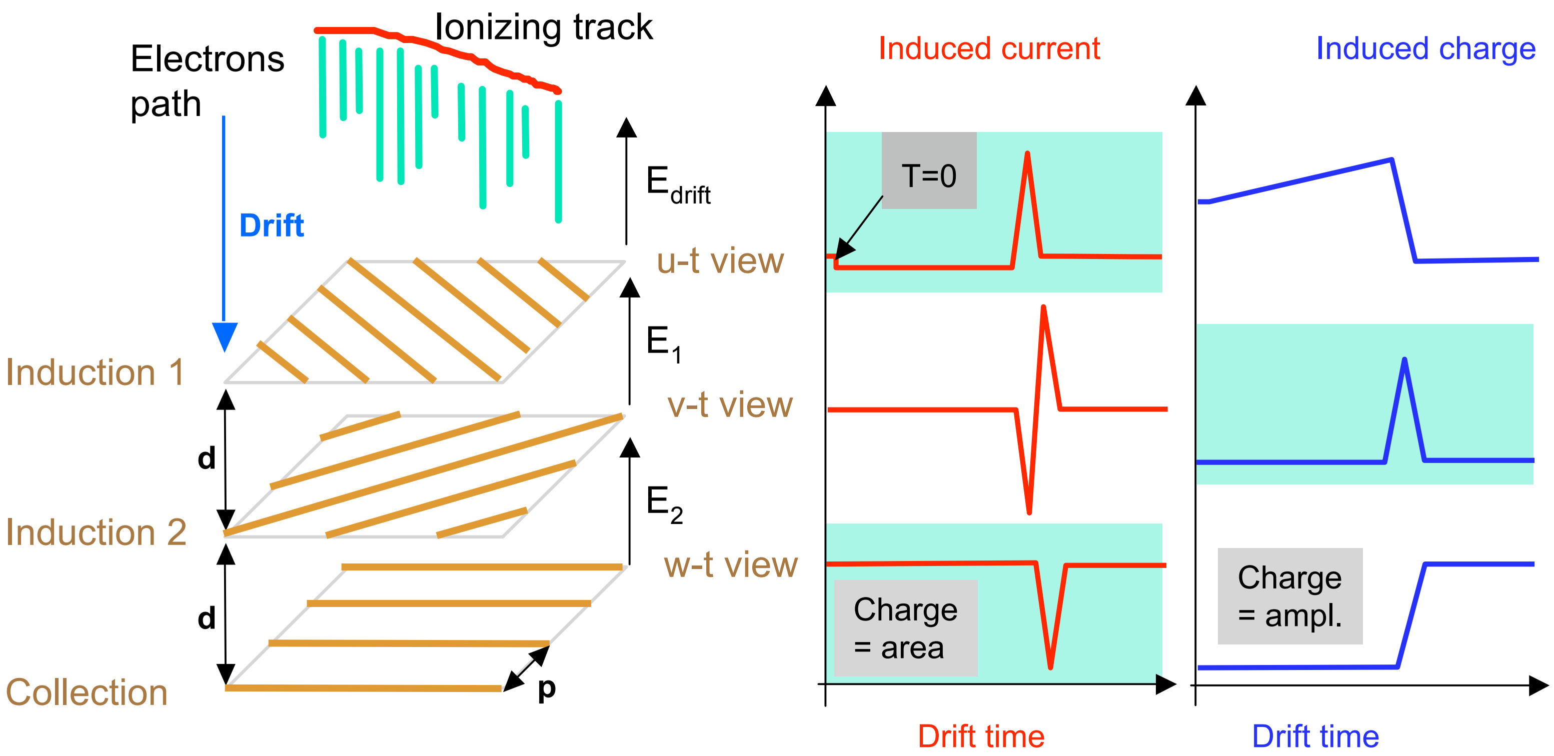


~1.5mm/μs @ 500V/cm





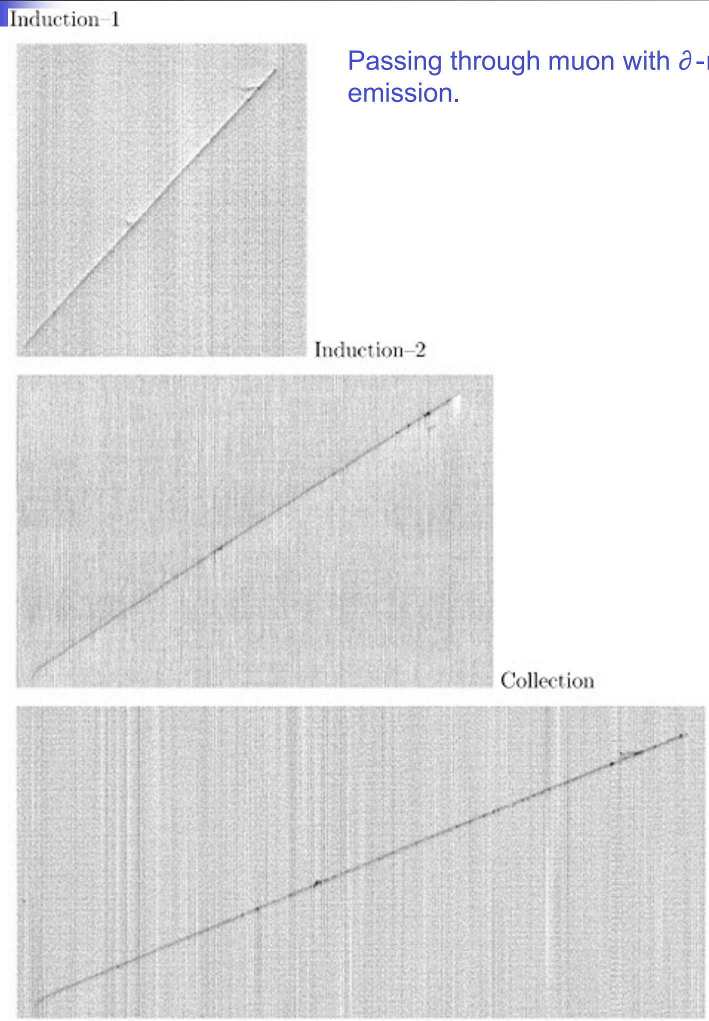
The induction/collection signals



- ICARUS T600: three wire planes (pitch 3mm, separation 3mm)

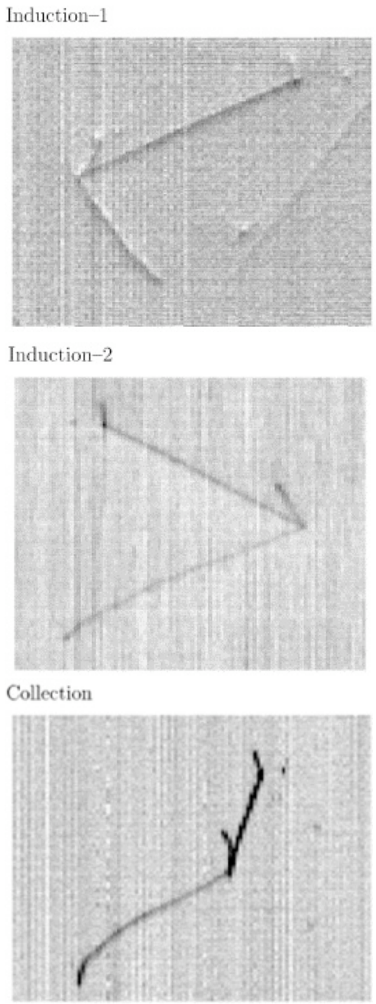
E_{drift} = 500 V/cm
Mip signal ~ 12000 e^- (inc. recombinantion)
Electron drift velocity ~ 1.5 mm/μs
Typical grid transit time ~ 2-3 μs

Induction signals require different treatment, but proper filtering makes the signal shape very much the same.



Passing through muon with ∂-ray emission.

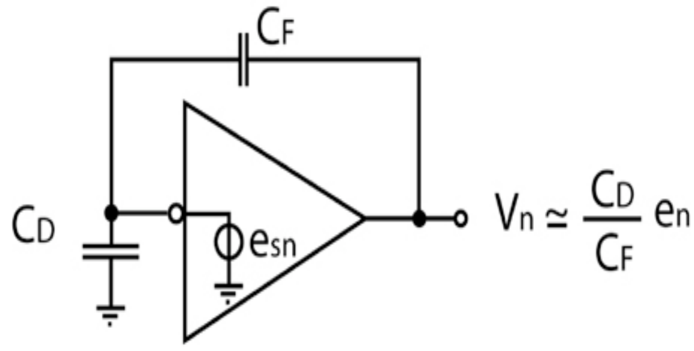
Low-multiplicity hadron interaction



Drift time vertical
Wires horizontal

Preamplifier for LAr TPC

- Need of very low noise amplifier:
  - No amplification around sense wires
    Collected charge ~ 10^4 electrons/mip
  - Large input capacitance (C_D)
    - Wires (20 pF/m)* + cables (50 pF/m)
    - In T600 C_D ~ 300-400pF
    - Serial noise (proportional to C_D) dominates over parallel noise (proportional only to signal bandwidth)
  - High trans-conductance (g_m) input devices are required to ensure acceptable Signal-to-Noise level (S/N ≥ 10)



$$e_{sn}^{\;2} \propto \frac{1}{g_m} T$$

* 3mm wire pitch

Choice of the active input device

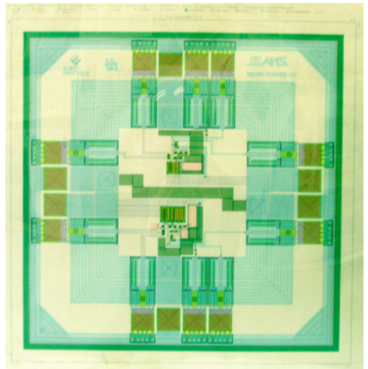
- Bipolar transistors
  - $g_m \approx$ 400mS @ $I_c \approx$ 10 mA (Amplification **merit factor** $g_m \cdot Z_{out} \approx 10^5$)
  - BUT: **parallel noise** density ≈ 2 pA / √ Hz **too high** (with a typical LAr signal bandwidth of ~ 1 MHz gives **unacceptable noise contribution**)
- jFET
  - Good $g_m \approx$ 40mS @ $I_{ds} \approx$ 10 mA (Amplif. **merit factor** $g_m \cdot Z_{out} \approx 10^4$)
  - **negligible parallel noise** density ≈ 0.001 pA / √ Hz
- VLSI-CMOS
  - Lower $g_{m,}$ (Amplif. **merit factor** $g_m \cdot Z_{out} \approx 10^3$)

jFET was the ICARUS choice :
charge sensitive preamplifier with high g_m **2-jFET input stage**

The ICARUS T600 preamplifier

- **Custom IC in BiCMOS technology**
  - Classical **unfolded** cascode integrator
  - External input stage jFET's
    - Two IF4500 (Interfet) or BF861/2/3 (Philips) in parallel to increase g_m (50-60 mS)
  - External feedback network
    - Allow sensitivity and decay time optimization
    - High value f.b. resistor (100MΩ) reduce parallel noise
- Two channels per IC
  - symmetrical layout guarantees identical electrical behavior

Two versions:
"quasi-current" mode: $R_fC_f \approx 1.6\mu s$ (collection + first induction)
"quasi-charge" mode: $R_fC_f \approx 30\mu s$ (mid induction)



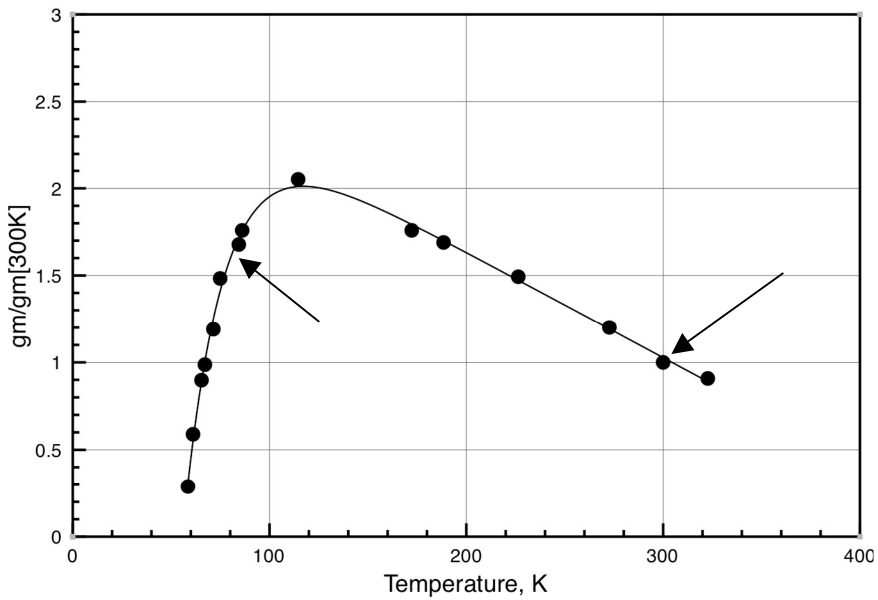
Sensitivity ≈ 6 mV/fC
Dynamic range > 200 fC
Linearity < 0.5% @ full scale
Gain 6.5±.5 mV/fC,
Gain uniformity < 3%
E.N.C. ≈ (350 + 2.5 x C_D) el ≈ 1200 el. @ 400pF
Power consumption ≈ 40 mW
1LSB = 1 mV

Electronics in LAr ?

Deeply investigated within ICARUS collaboration (since 1988)

- Limited choice of active devices working at LAr temperature
  - GAs-jFET (High Electron Mobility Transistor technology)
  - Silicon jFET (High Resistive Substrate technology)
  - CMOS very low temp. **now** available but…
  - **Issues:**
    - Better S/N due to improved g_m at cryogenic temperature
    - Reliability at LAr temperature
    - Availability on the market

U310 jFET

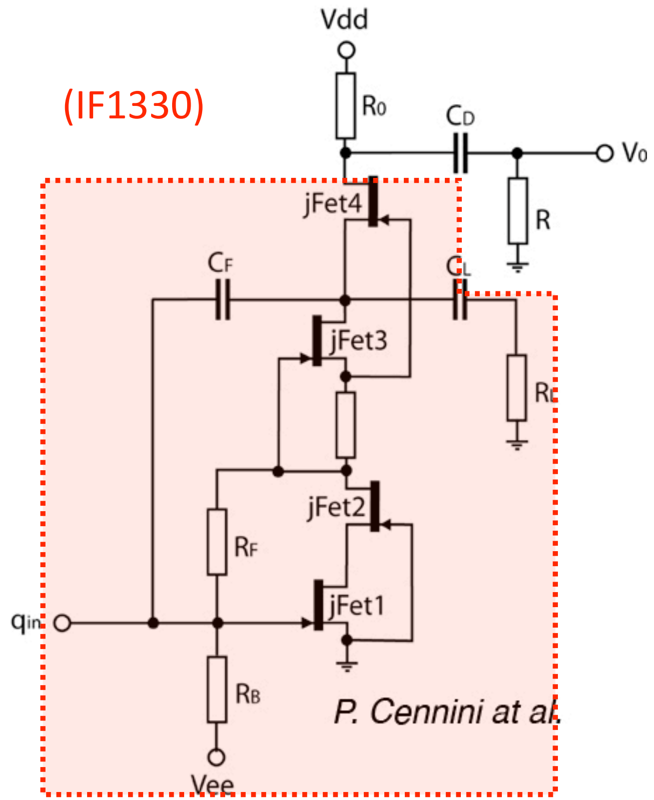


The TOTEM architecture

- Charge Integrator made on Thick Film Hybrid technology with discrete jFET only
  - Minimum active and passive components
  - Ability to drive long transmission line
  - Reduced power consumption
  - Minimum cable connections
    - Current signal from Positive Power Supply
    - Common Negative polarization
- Characteristics
  - Optimized for low detector capacitance

$$V_0 = \frac{R_0}{R_L} * \frac{q_{in}}{C_F}$$

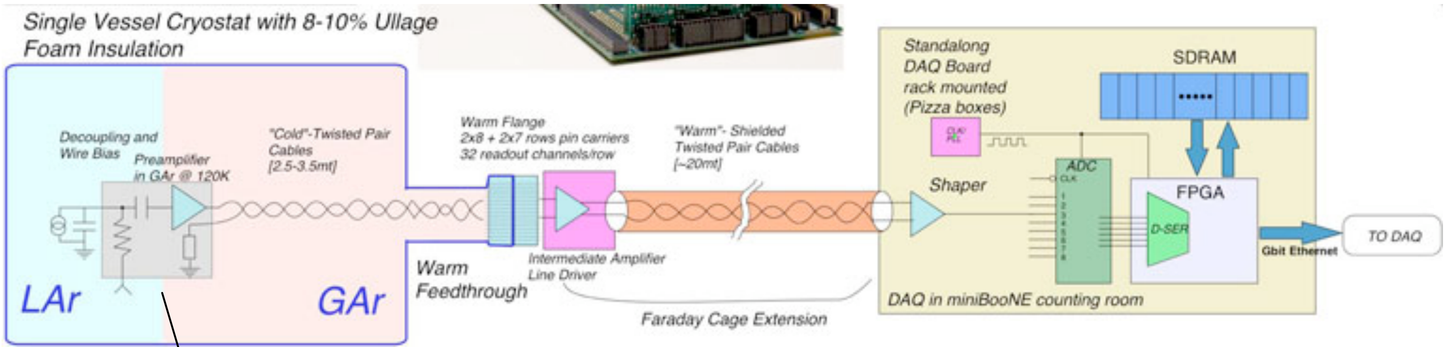
(IF1330)



Sensitivity ≈ 0.45 mV/fC (0.9 μA/fC)
Dynamic range ±1.5 pC
Linearity < 0.5% @ full scale
Input impedance ≈ 420 Ω
Input capacitance ≈ 20 pF
E.N.C. ≈ (390 + 7 x C_D) el
Power consumption ≈ 11 mW

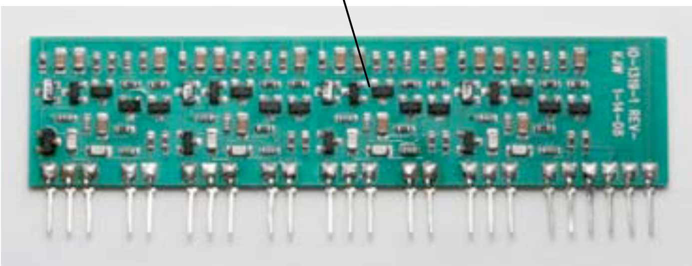
MicroBooNE: cryogenic front-end

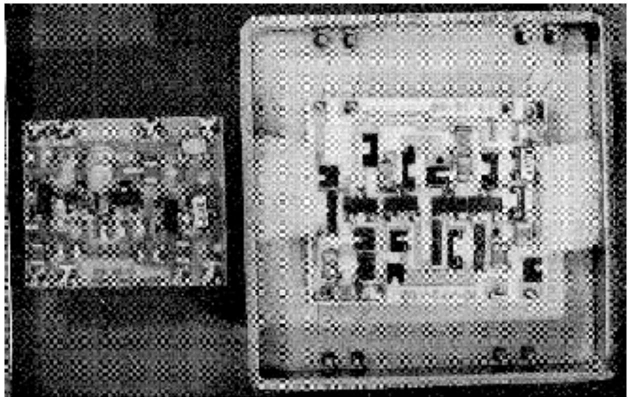
Electronics chain



Several years of experience in NA-34 & NA-48

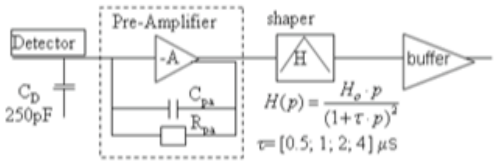
JFet discrete amplifier



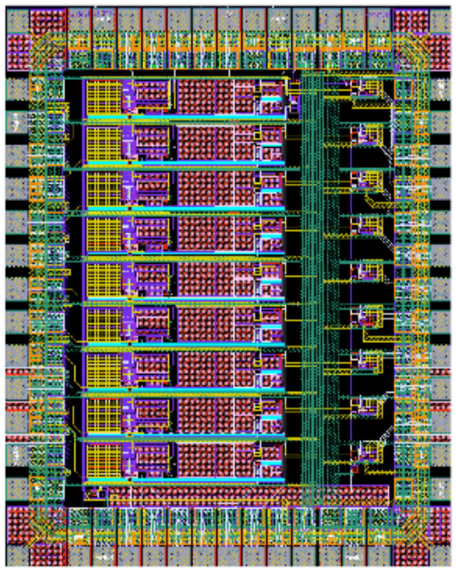


Step 2) (2008) on the basis of the experience acquired during the first phase, new version (TOPEST) integrating also the shaper+buffer, 8 channels + single components for characterization.

Received at the end of July 2008. Tests at IPNL. Typical total gain 7.5 mV/fC, 40 mip dynamic range.



- selectable:
  feedback capacitance (500 fF-1 pf)
  feedback resistor (2 - 10 MΩ)
- selectable shaping times (0.5 - 4 μs range)
- power switching on-off



Step 3) (End 2008), detector tests 64 channels:

study noise vs track reconstruction as a function of angles and shaping times

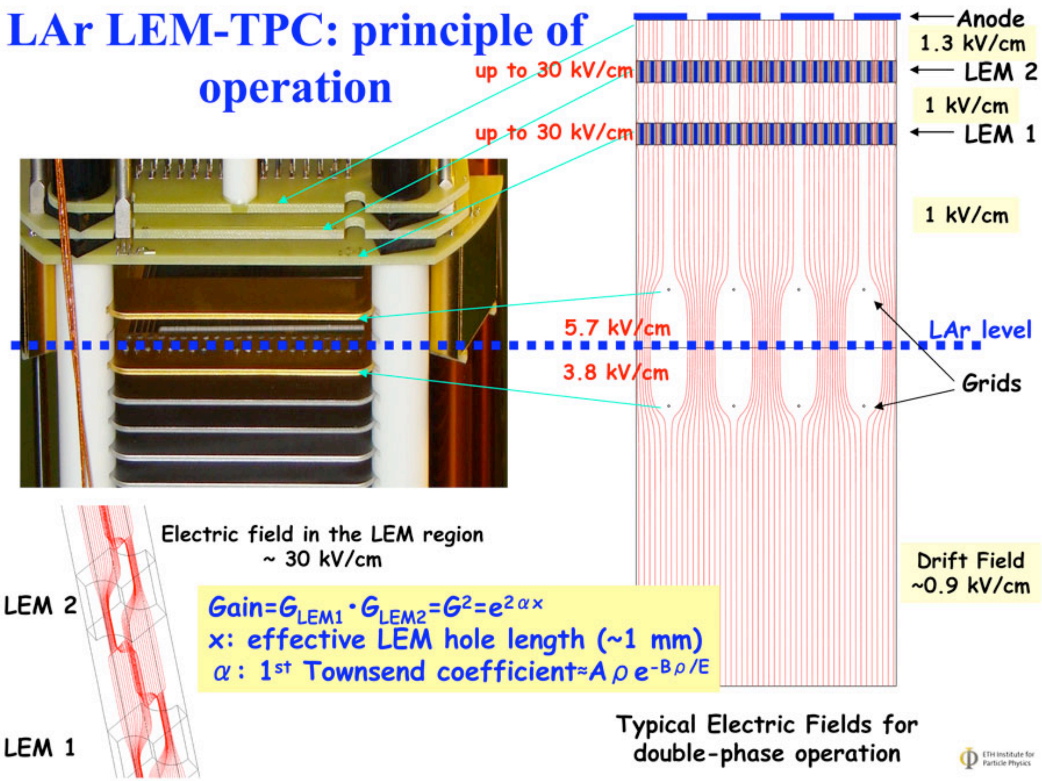
Private communication:

g_m = 117 mS
i_d = 8.655mA
W_{tot} = 8100μW
L = 0.35μ
g = 10 (gates)

Noise=1000e
@ Cd 250pF
??

Double phase Ar detectors

Double phase detectors enhance charge generated in liquid.



Similar signal shape

S/N intrinsically higher

Previous issues also apply

Pro & Contra cold amps

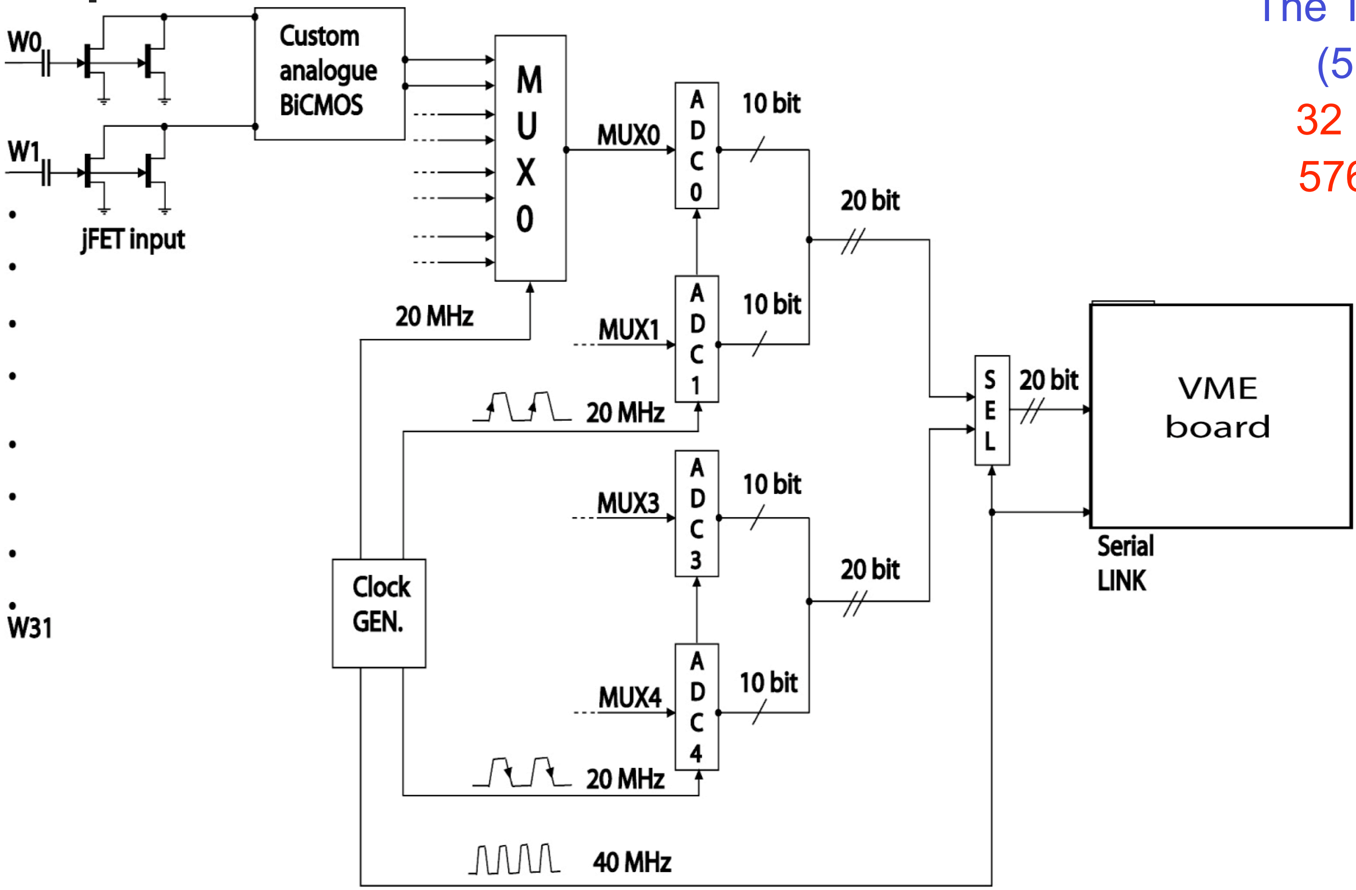
- Advantages
  - Reduction of input capacitance due to cable absence
  - Reduction of micro-phonic noise (detector = Faraday cage)
  - Improvement of S/N [~ **2.4**] due the **combined effect** of lower [~1.9] Johnson noise and higher [~1.26] g_m @ 86ºK
- Disadvantages
  - Inaccessibility during detector operation
  - Need of careful selection of components, extensive burn-in and temperature cycles before installation to minimize components failure
  - Design architecture and technology restricted by limited choice of active components
  - Limit on power dissipation (< 100 mW/cm^2 to avoid LAr boil-off)

The ICARUS T600 experience

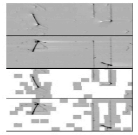
- **Analogue front-end** followed by a multiplexed ***ADC*** (1LSB≅1000e^-) whose output is stored in RAM: **waveform recorder**.

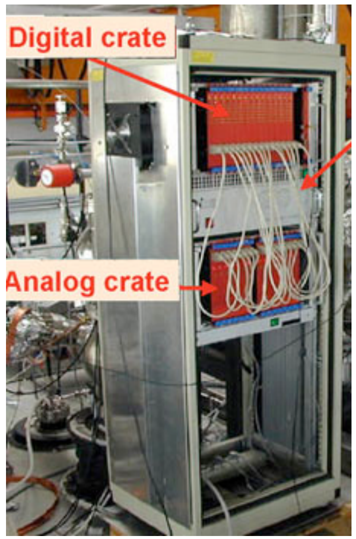
- Digital VME module performs local storage, **hit finding** and **facor 4 data compression** (*recent improvement*).

T600 DAQ block diagram



The T600 DAQ system
($5 \cdot 10^4$ channels)
32 channels/board
576 channels/rack





Signals and noise in **large** TPC

- In a multi-kton TPC we can foresee wires with a pitch larger than the ***3mm*** used in the T600
  - The adoption of ***6mm*** pitch for a large TPC seems reasonable and
  - A realistic capacitance value for 10*m* electrode wires, 6*mm* pitch, and average 8*m* of cable is ~600*pF* (cfr.: 300-400*pF* in the T600)
- It follows that the Signal to Noise Ratio should be very similar to that of the T600.

  - **Hence a completely new design of the analogue front-end would hardly improve the performance**

AD conversion

- Serial ADC are **now** preferable over Flash ADC.
  - To reach the 3*MHz* sampling rate, AD must be clocked at 48*MHz*.
  - Mini Small Outline Package (MSOP) smaller than 5*x*5 mm^2. Many house **2 or even 4 channels. Competitive in price and power consumption.**
- We can assume a resolution of 10*bit* but 12*bit* ADCs are also available at reasonable cost. More components available soon.

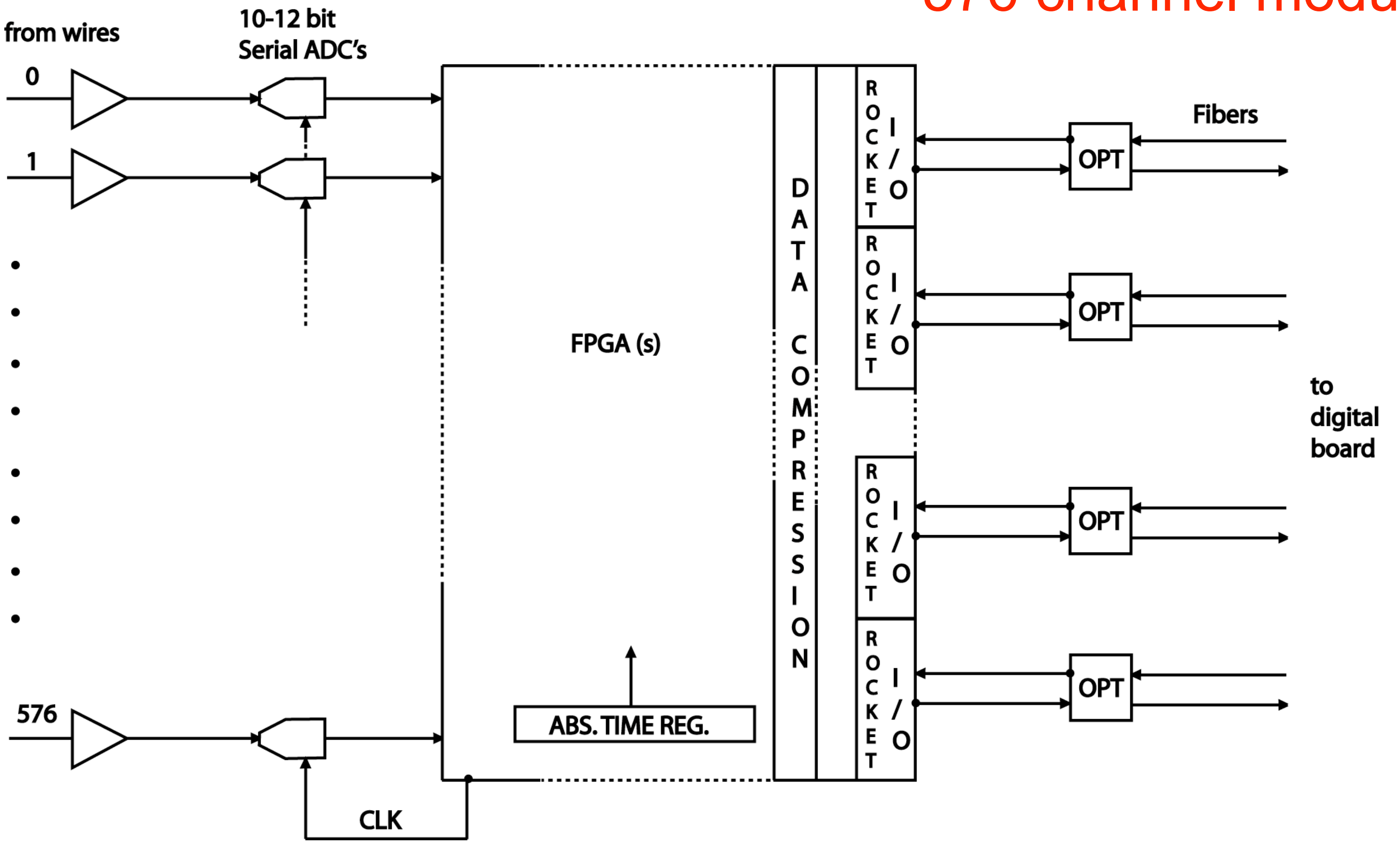
Available Serial ADC

Manufacturer	Res	Part. Num.	Freq. *MHz*	Power mW typ.	Supply	Cost $ 1000 pcs
Analog Devices	10	AD7273	3	11.4	2.35 – 3.6	3.75
Analog Devices	10	AD7277	3	10.5	2.35 – 3.6	3.60
Maxim	10	MAX1334	4.5	40	5, 3.3	NA
Maxim	10	MAX1335	4	40	3.3	NA
Analog Devices	12	AD7274	3	11.4	2.35 – 3.6	3.75
Analog Devices	12	AD7276	3	10.5	2.35 – 3.6	4.0 – 6.25
Linear Technology	12	LTC1403-1	2.8	14	2.7 – 3.3	4.00
Maxim	12	MAX1332	3	38	5, 3.3	NA
Linear Technology	14	LTC1403A-1	2.8	14	2.7 – 3.3	7.00
Analog Devices	16	AD7621	3	86	2.5	29.95

The frequency given in the table refers to the sampling rate.

Compact architecture

576 channel module

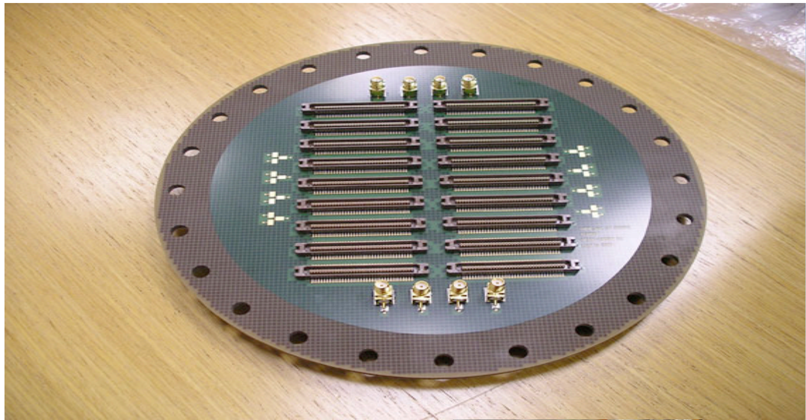
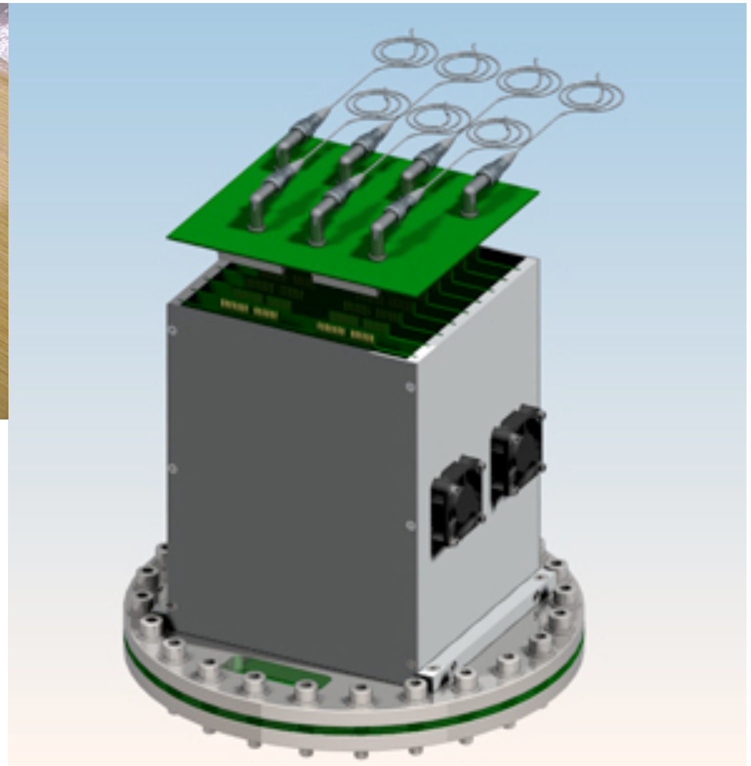
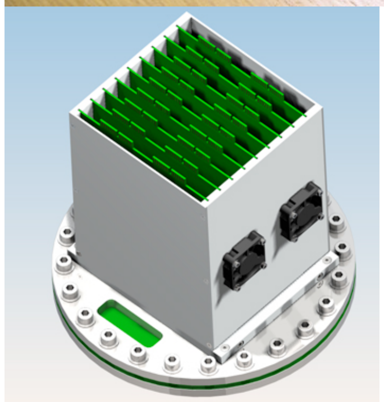
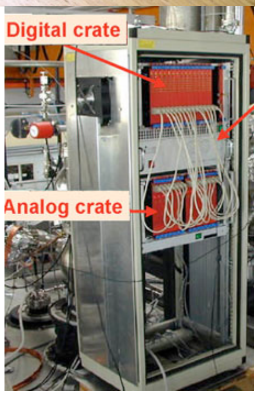


New data distribution

- A set of a few FPGA for 576 channels (one flange) will be used to handle, filter, and organize the serial information provided by the serial ADC's.
- Assuming a sampling frequency of 1.5*Mhz*, 10*bit* ADC's we need to transmit ~8 G*bit/s*, (including error correction redundancy).
- Optical links with 1.5*Gbit/s* data rates are standards and can be driven by suitable interfaces available on FPGA from different vendors.
- **Six optical links could serve all the channels of one module (576) and convey also extra information as absolute time.**
- The architecture of the DAQ system can be enhanced through the adoption of a modern switched I/O allowing the parallelization of the serial data flows.

New electronics layout

- The whole electronics of ~600 channels can be hosted in a compact crate (~12 liter volume) incorporating the feed-through flange that forms a sort of backplane.
- External cables will be essentially eliminated.

Conclusions on charge read-out

- The ICARUS DAQ ***basic*** architecture is well suited even for larger size LAr-TPC (*single phase*);
- Similar structures adopted by other projects. Differences limited to the front-end choice: ***cold versus warm*.**
- Main upgrades concern:
  - More compact version of the front-end amplifier
  - Adoption of high frequency serial ADCs
  - **Housing and integration electronics on detector**
  - Optical links for Gbit/s transmission rate

Photo-detectors readout

Ionization in **liquid** Argon (LAr) is accompanied by **scintillation light emission**.

The two processes are **complementary** through recombination and their relative weight depends on the strength of **the electric field** and **dE/dx**.

Electron and photon yield similar (Y_{ion} = ~$2.9*10^4$ e^-/MeV, Y_{ph} = ~$2.4*10^4$ γ/MeV @ 500v/cm for *mip*).

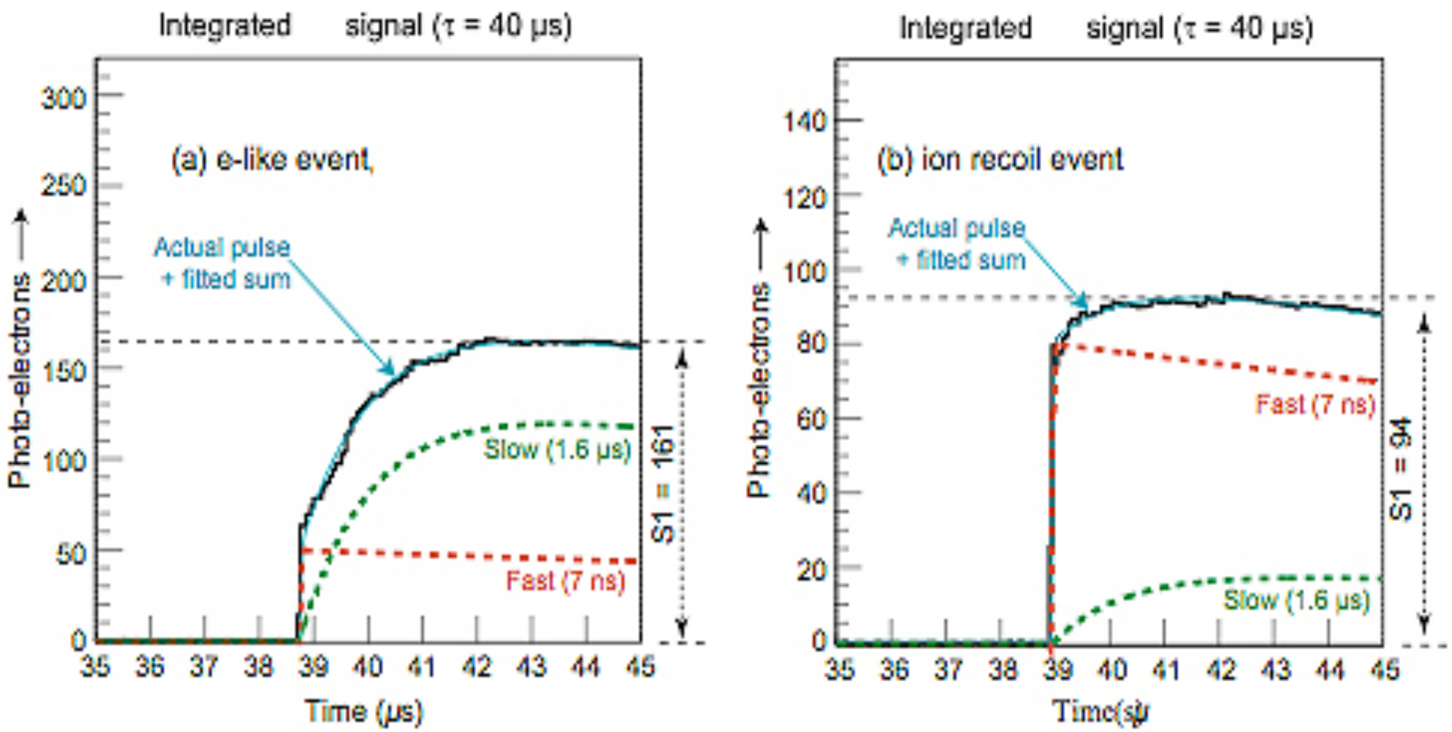
Light is emitted at 128nm (detection generally through wave-shifting) with **two-component** exponential decay (τ_s ~ **6 ns** and τ_L ~ **1.5 μs).**

Prompt light signal typically used for **trigger** (eg. Icarus) or for **calorimetry/particle identification** (eg. WArP).

Example of light coll. in WArP

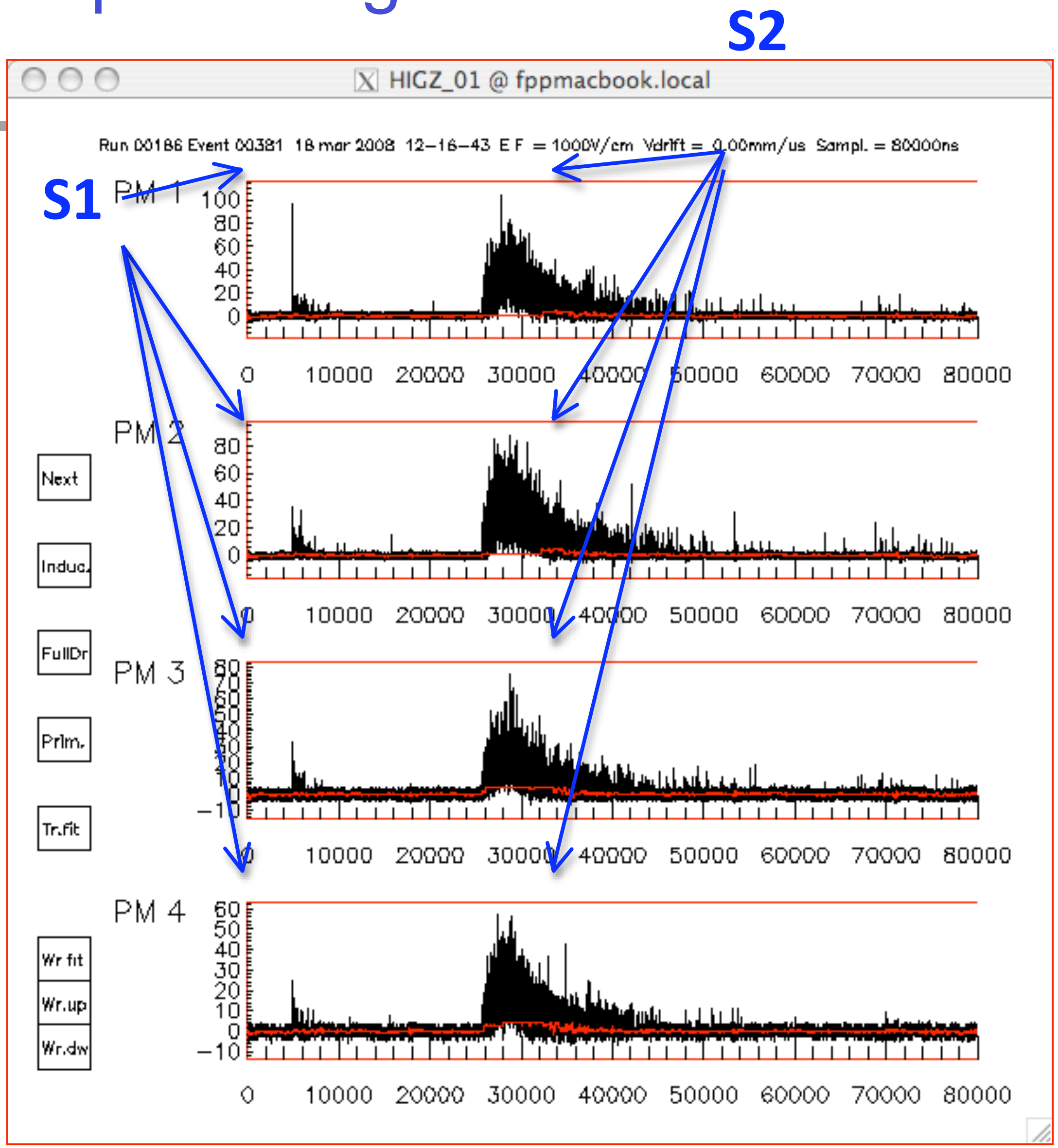
mip: ~25% of light **short time** constant ~75% **long time** constant.

recoil: ~75% of light **short time** constant ~25% **long time** constant.



Double phase signals

- S1 primary scintillation.
- S2 scintillation in gas phase proportional to extracted ionization electrons.
- Ionization electrons identified individually.
- Efficient alternative to direct charge measurement for tiny signals (few electrons)
- S1 and S2 have similar characteristics.



Conclusion

Waveform recording based on **high performance** (expensive) commercial solution (≥1GHz-≥8bit, multi buffering) is well suited for signals provided by PMTs in single and double phase Ar detectors, allowing full measurement of the signal structure.

Investment required:
for low cost waveform recorders for experiments requiring high number of channels;
for **on line data reduction, signal recognition, and trigger pre-processing** through high speed FPGAs.

Also **onto detector integration** would be a benefit (see first part).