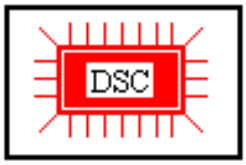
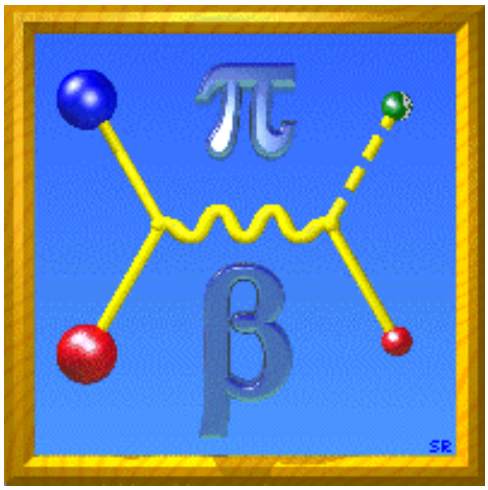


Waveform digitization with the Domino Sampling Chip in the $\pi\beta$ Experiment



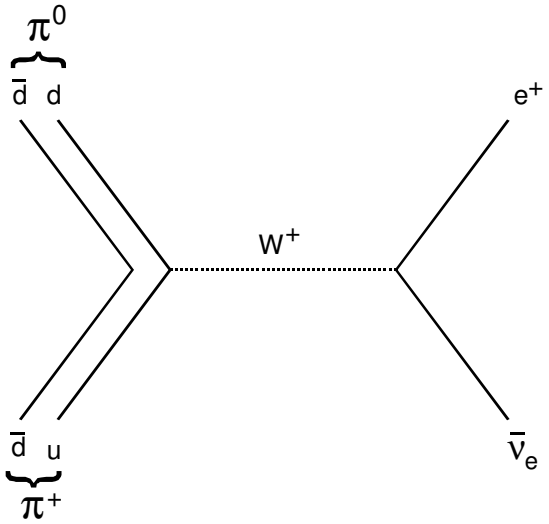
H.Peter Wirtz

Paul Scherrer Institute

Outline

- The $\pi\beta$ Experiment at PSI
  - Introduction, Motivation
  - Experimental Method
  - The $\pi\beta$ Detector
  - Detector Components
- The Domino Sampling Chip
  - Design Principles
  - Simple Setup
  - 48 Channel Boards for $\pi\beta$
- Results
  - Waveform Fitting
  - ADC/TDC Correlation
- Outlook

Pion-Beta Decay



- Analog to super-allowed Fermi decay
  - No nuclear corrections
  - No final state coulomb interaction
  - No screening effects
- Problem: small branching ratio BR

$$BR_{\pi\beta} = \frac{\Gamma\left(\pi^+ \to \pi^0 e^+ \nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right)} \approx 10^{-8}$$

$$V_{ud}^2 = \frac{K}{G_\mu^2 f (1+\delta) \frac{t_\pi}{BR}}$$

$$f = \frac{1}{30}\left(\frac{m_{\pi^+} - m_{\pi^0}}{m_e}\right)^5 \times corr \ .$$

$$\delta = 0.03230 \pm 0.00002$$

RC by W. Jaus (‘99) using light-front quark model

The standard model of electroweak interactions

Three generations of leptons and quarks

$$\begin{pmatrix} u \\ d \end{pmatrix};\begin{pmatrix} c \\ s \end{pmatrix};\begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix};\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix};\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Mass eigenstates are related to the electroweak eigenstates via the Cabbibo-Kobayashi-Maskawa (CKM) matrix [1)]

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

With three generations one can formulate the unitarity test:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

[1)] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973)

First row unitarity test

- V_{ud} can be obtained from:
  - Nuclear superallowed Fermi beta decays
  - Neutron decay
  - Pion beta decay

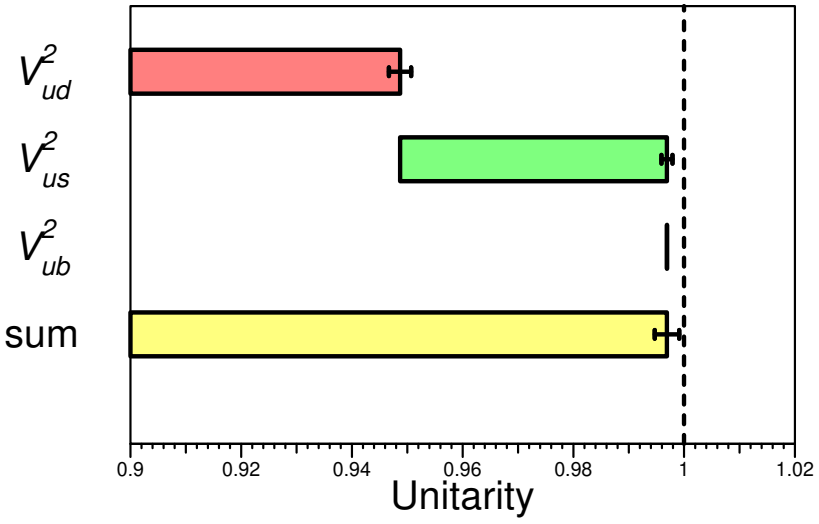
$$|V_{ud}| = 0.9740 \pm 0.0010$$

- V_{us} derived from K_{e3} decays [1], in agreement with K^+ and K^0 decays. Hyperon decays have larger theroretical uncertainties.

$$|V_{us}| = 0.2196 \pm 0.0023$$

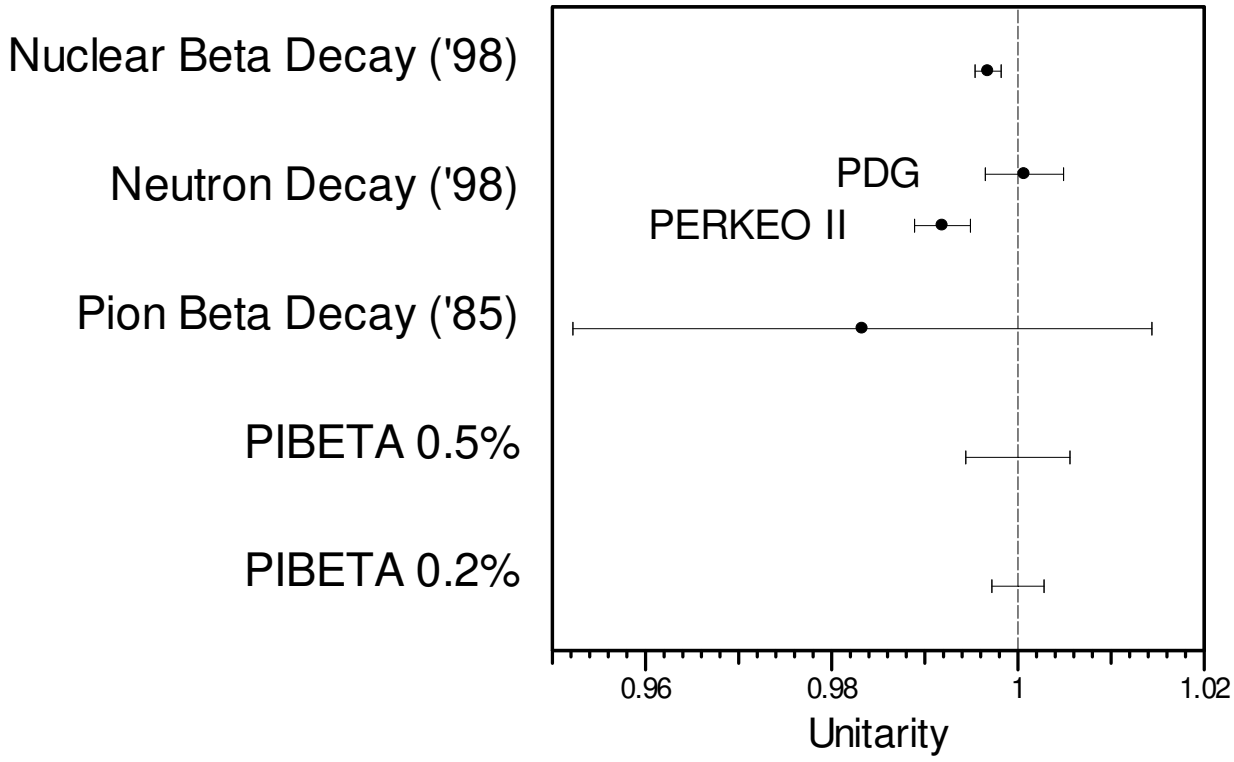
- V_{ub} is very small and has negligible impact on unitarity test.

$$|V_{ub}| = 0.0032 \pm 0.0008$$



[1] H. Leutwyler and M. Roos, *Z. Phys.* C **25**, 91 (1984)

Current Unitarity Data



- Test of Standard Model
  - at ≤1%: CVC and radiative corrections
  - at ≤0.5%: nuclear β decay vs. neutron decay
  - at ≤0.3%: CKM unitarity
- Implications of unitarity violation
  - Fourth generation $0.01 < V_{ub'} < 0.08$ at 90%CL[1)]
  - Additional neutral gauge bosons $m_{Z'} > 300$ GeV[2)]

1) W.J. Marciano and A. Sirlin, *Phys. Rev. Lett.* **56**, 22 (1986)
2) W.J. Marciano and A. Sirlin, *Phys. Rev. D* **35**, 1672 (1987)

Pion-Beta Experiment at PSI

E. Frlez, J. E. Koglin, W. Li, R. C. Minehart,
B. E. Norum, **D. Pocanic**, S. Ritt, O. A. Rondon Aramayo, L. C. Smith,
W. A. Stephens, K. O. H. Ziock
***University of Virginia**, Charlottesville, Virginia 22901-2458, U.S.A.*

J.F. Crawford, W. Bertl, Ch. Brönnimann, M. Daum,
R. Horisberger, D. Renker, R. Schnyder, D. Suwannakachorn, H.P. Wirtz
***Paul-Scherrer-Institut**, CH-5234 Villigen, Switzerland*

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V. V. Karpukhin, N.V. Khomutov, A. S. Korenchenko,
S. M. Korenchenko, N. P. Kravchuk, N. A. Kuchinsky, A. S. Moiseenko
*Joint Institute for Nuclear Research, **Dubna**, Russia*

D. Mzavia, Z. Tsamalaidze
*Institute for High Energy Physics, **Tbilisi** State, University, Georgia*

I. Supek
University of Zagreb and R. Boskovic Institute, Zagreb, Croatia

Pion-Beta Experiment at PSI

- First phase: 0.5% accuracy
- Stopped pion experiment:
- 10^6 π/s $\rightarrow$ 1 y beamtime
- Relative measurement

Γ_{π_i}	Process	$R = \Gamma_{\pi_i}/\Gamma$
Γ_{π_1}	$\pi^+ \rightarrow \mu^+ \nu_\mu$	$(99.98770 \pm 0.00004)\%$
Γ_{π_2}	$\pi^+ \rightarrow \mu^+ \nu_\mu \gamma$	$(1.24 \pm 0.25) \cdot 10^{-4}$
Γ_{π_3}	$\pi^+ \rightarrow e^+ \nu_e$	$(1.230 \pm 0.004) \cdot 10^{-4}$
Γ_{π_4}	$\pi^+ \rightarrow e^+ \nu_e \gamma$	$(1.61 \pm 0.23) \cdot 10^{-7}$
Γ_{π_5}	$\pi^+ \rightarrow \pi^0 e^+ \nu_e$	$(1.025 \pm 0.034) \cdot 10^{-8}$

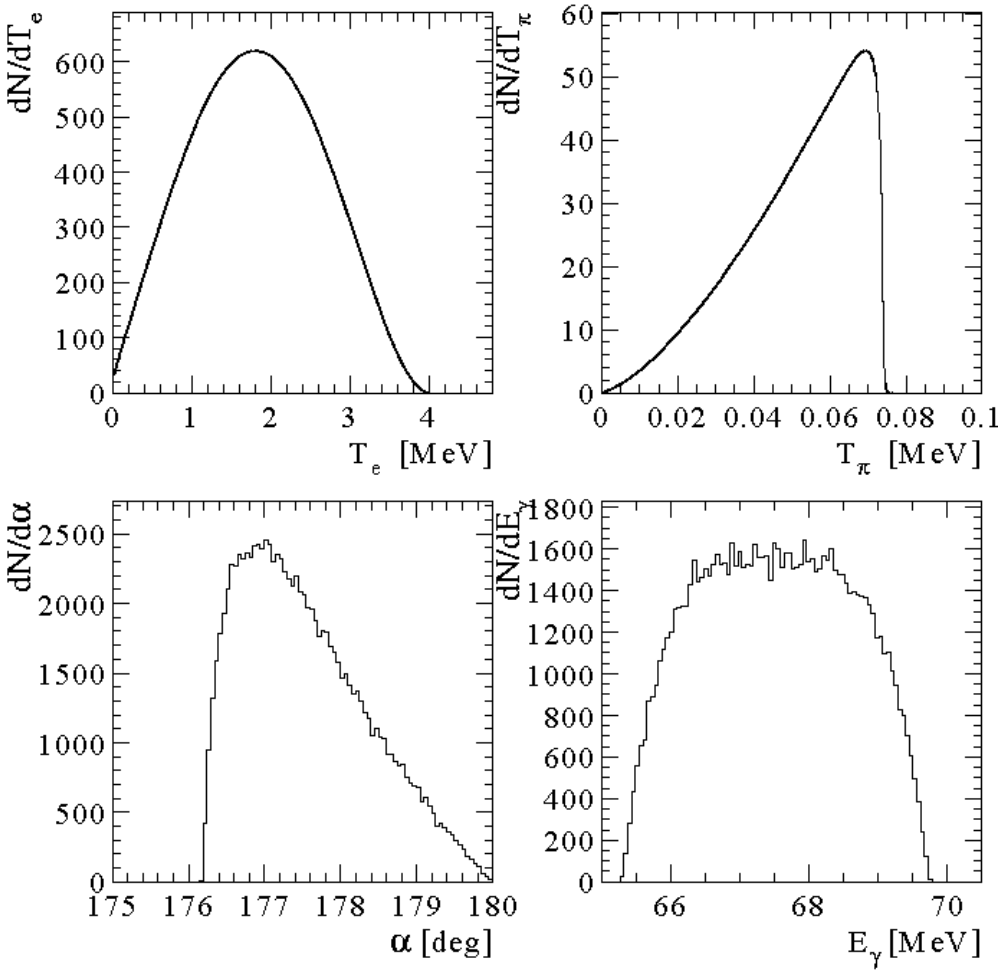
Pion decay modes

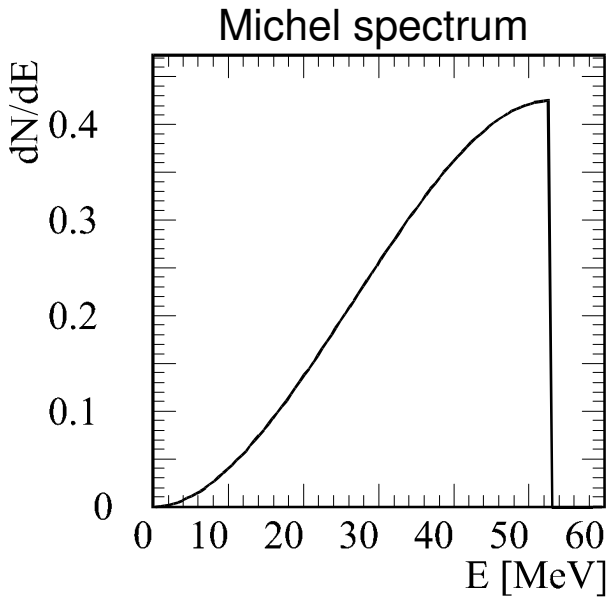
Γ_{μ_i}	Process	$R = \Gamma_{\mu_i}/\Gamma$	$\Gamma_{\pi_i^0}$	Process	$R = \Gamma_{\pi_i^0}/\Gamma$
Γ_{μ_1}	$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	$(98.6 \pm 0.4)\%$	$\Gamma_{\pi_1^0}$	$\pi^0 \rightarrow \gamma\gamma$	$(98.798 \pm 0.032)\%$
Γ_{μ_2}	$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$	$(1.4 \pm 0.4)\%$	$\Gamma_{\pi_2^0}$	$\pi^0 \rightarrow e^+ e^- \gamma$	$(1.198 \pm 0.032)\%$
Γ_{μ_3}	$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu e^+ e^-$	$(3.4 \pm 0.4) \cdot 10^{-5}$			

Muon and π^0 decay modes

$$BR_{\pi\beta} = \frac{BR_{\pi e \nu}}{N_{\pi e \nu}} \cdot \frac{N_{\pi\beta}}{BR_{\pi^0 \gamma\gamma}} \times corrections$$

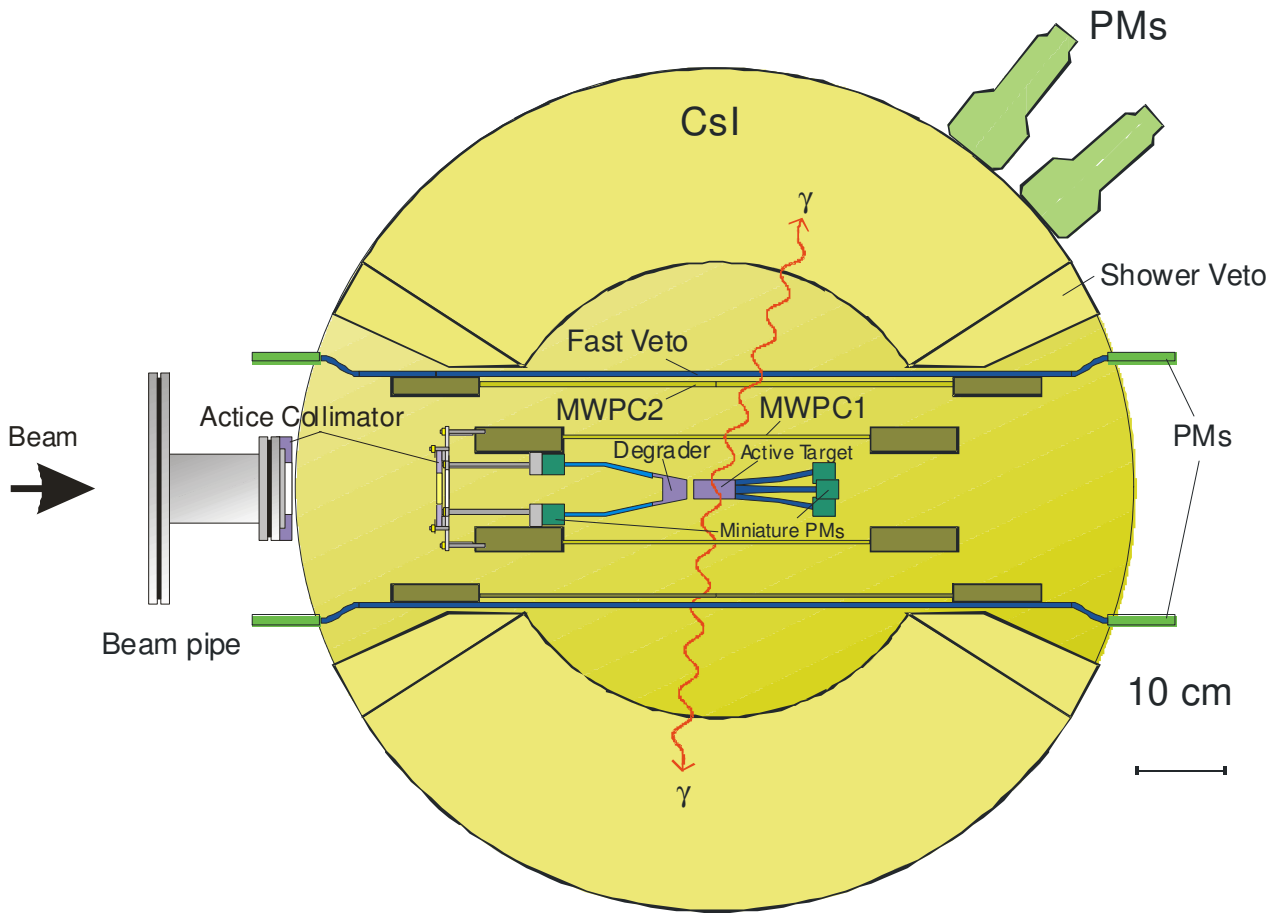
Kinematics


dN/dT_e
T_e [MeV]
dN/dT_π
T_π [MeV]
dN/dα
α [deg]
dN/dE_γ
E_γ [MeV]


Michel spectrum
dN/dE
E [MeV]

Pion-Beta Detector

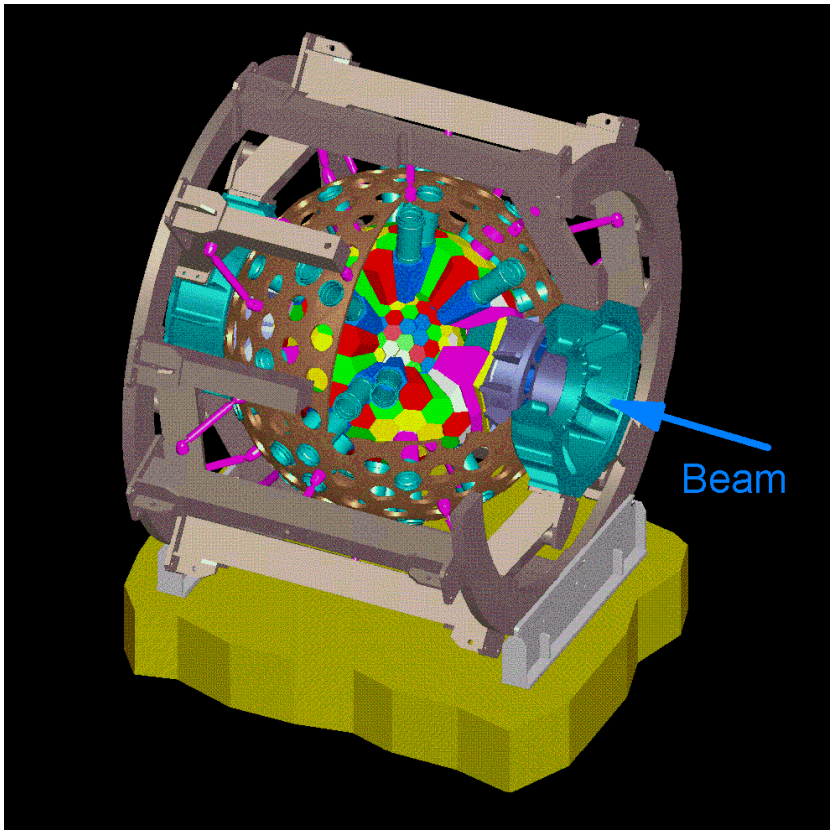
Cross-section



- Pion momentum: 114 MeV/c
- After degrader: 20 MeV/c
- AT: 9 Elements (orig. 77 planned)
- 2 CMWPC: 640 wires
- Fast Veto: 20 segments
- 3” PMs

Pion-Beta Detector

The Sphere



Pion-Beta Detector

The Calorimeter

240 pure CsI crystals

Length: 22 cm (12 RL)

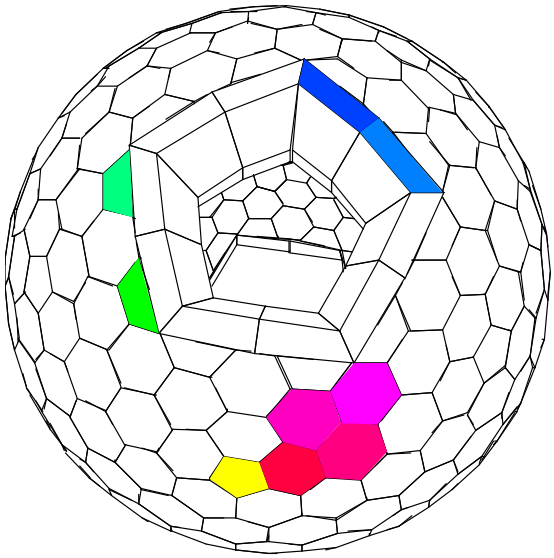
9 different shapes:

1 pentagonal type

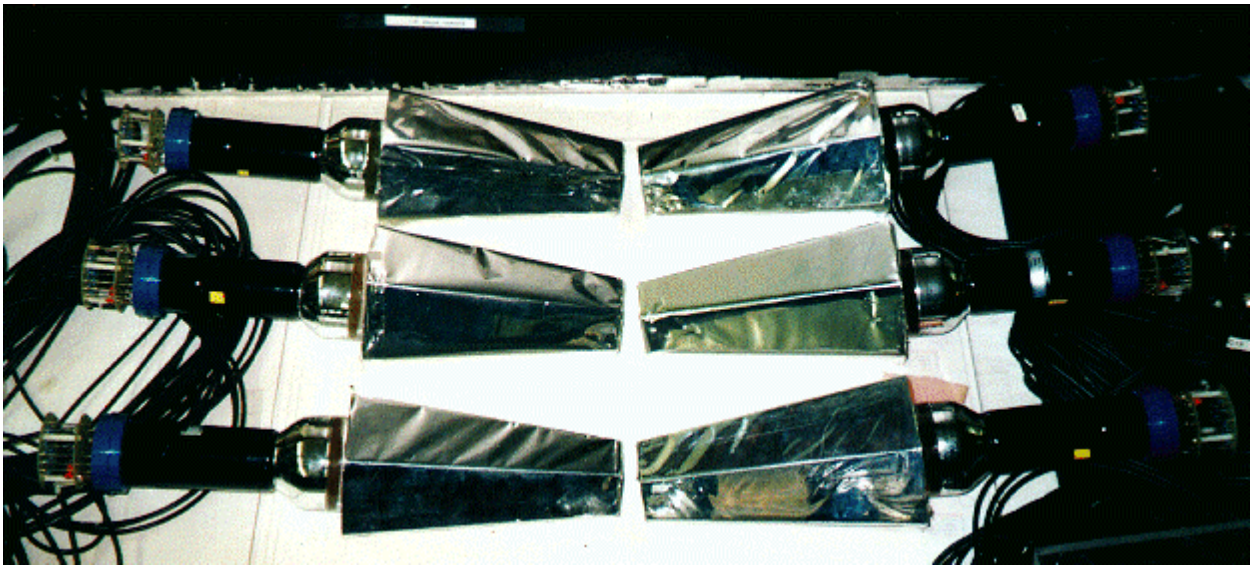
4 hexagonal types

2 half-hexagons (Trapezoids)

2 veto types

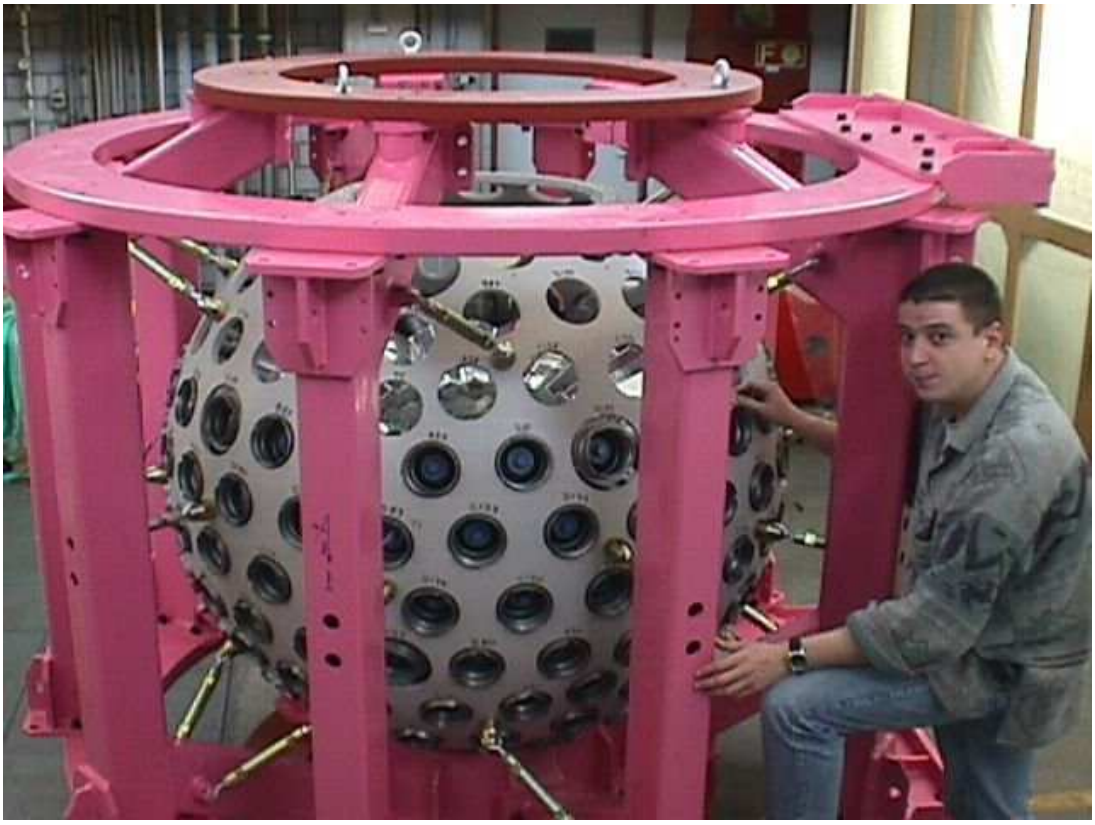


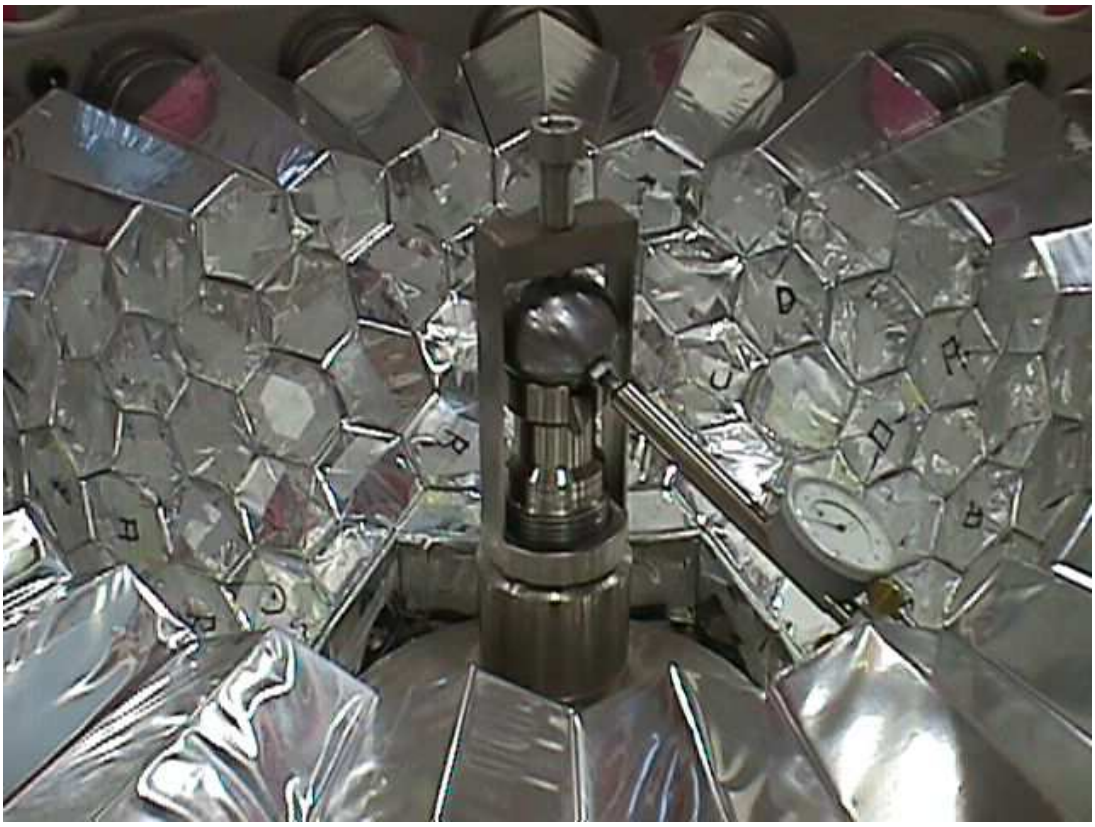
- inner radius: 260mm
- outer radius: 480mm
- volume of CsI: 346'000 cm^3
- weight: ~1.5 t
- Solid angle coverage: ~77%
- spatial resolution: ~5°



Pion-Beta Detector

Calorimeter Assembly



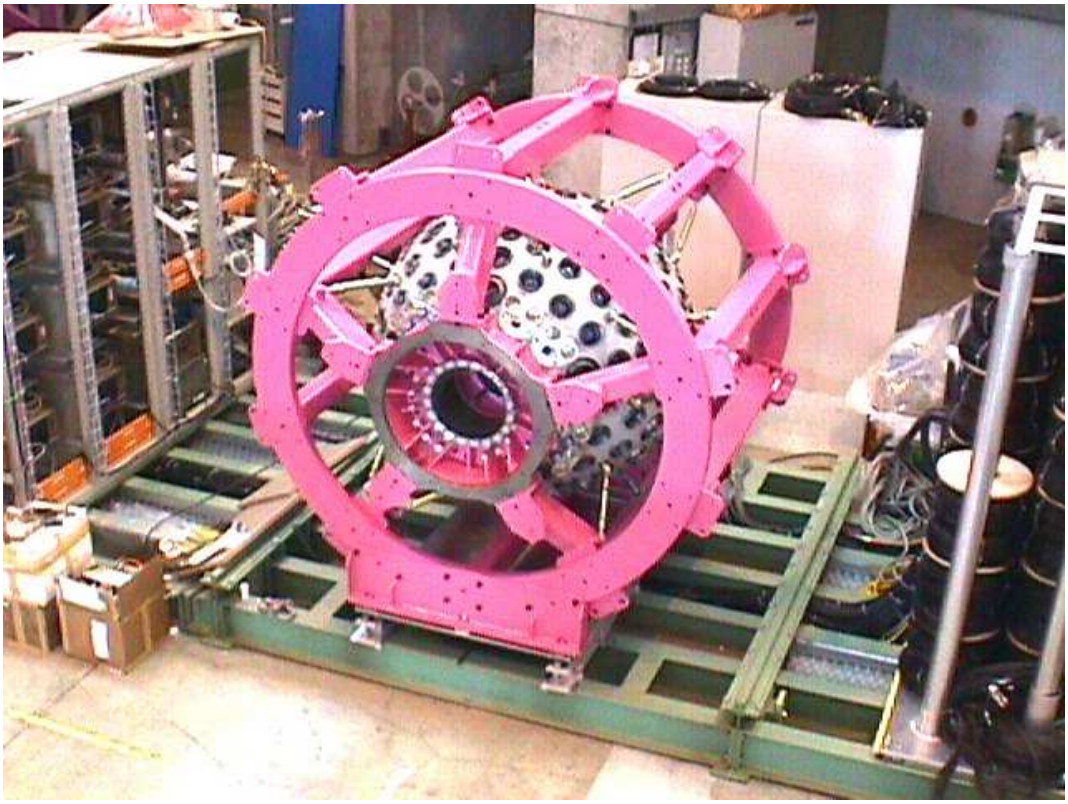


Pion-Beta Detector

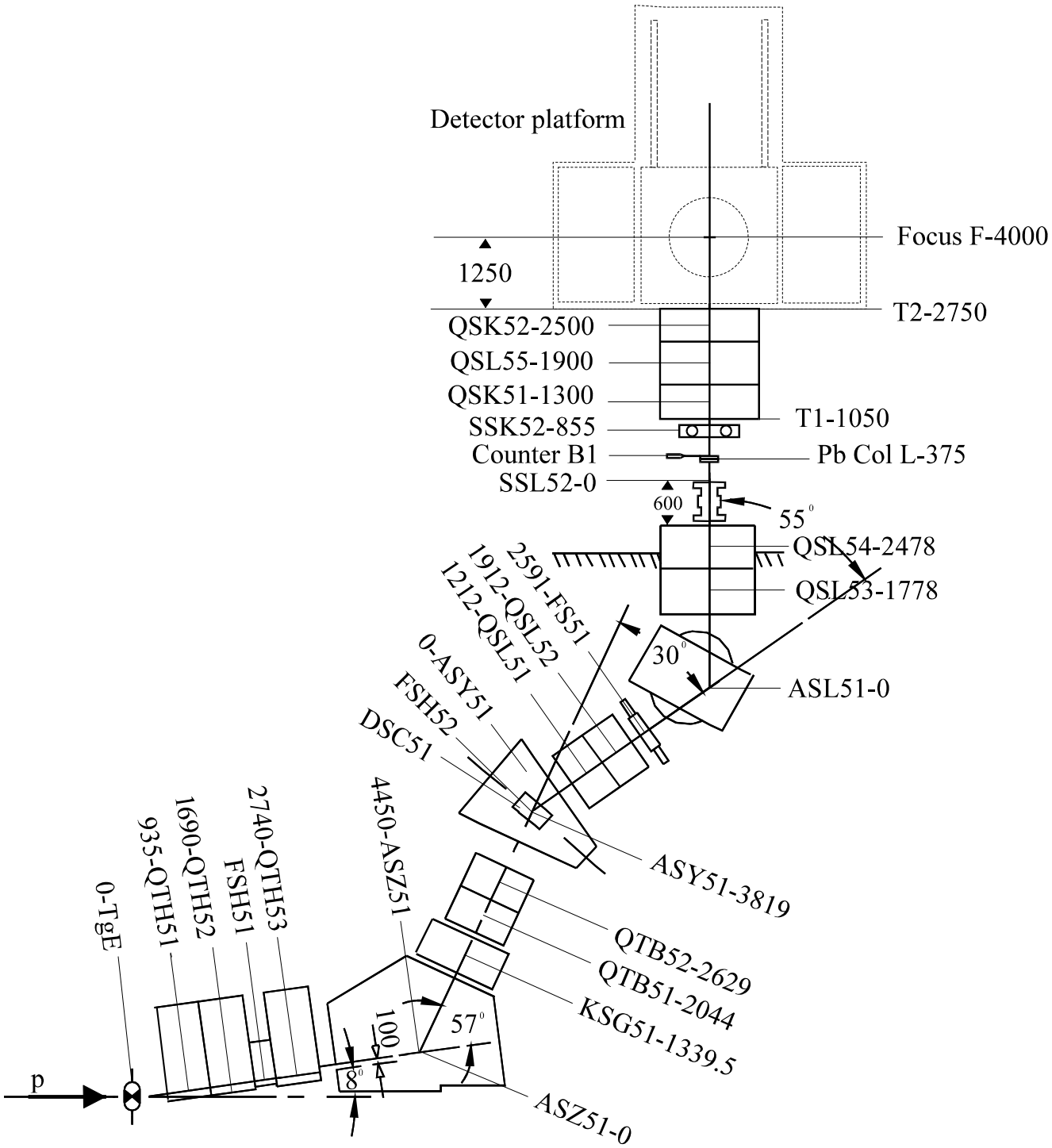
Transport and Rotation

Pion-Beta Detector

Detector Platform

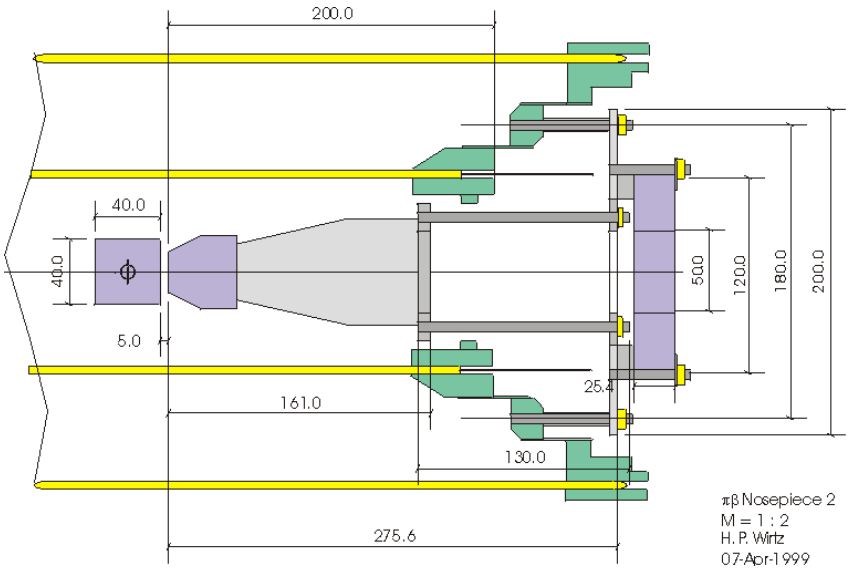


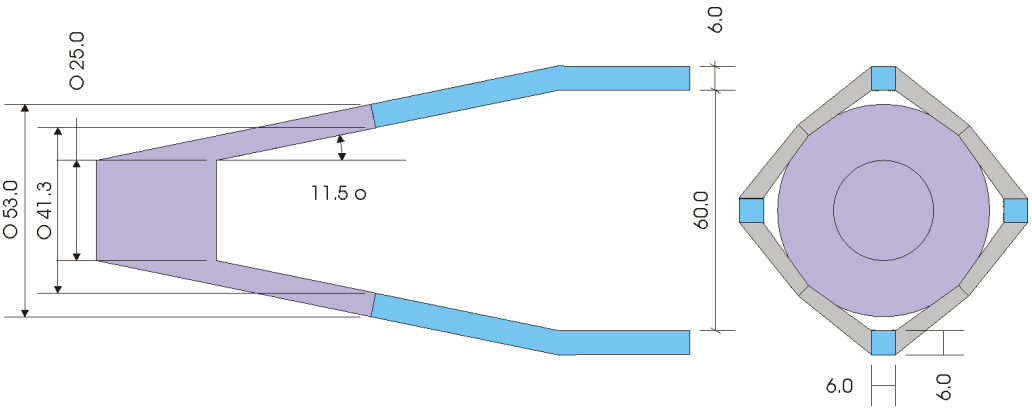
πE1 Beamline at PSI



Pion-Beta Detector

Active Degrader





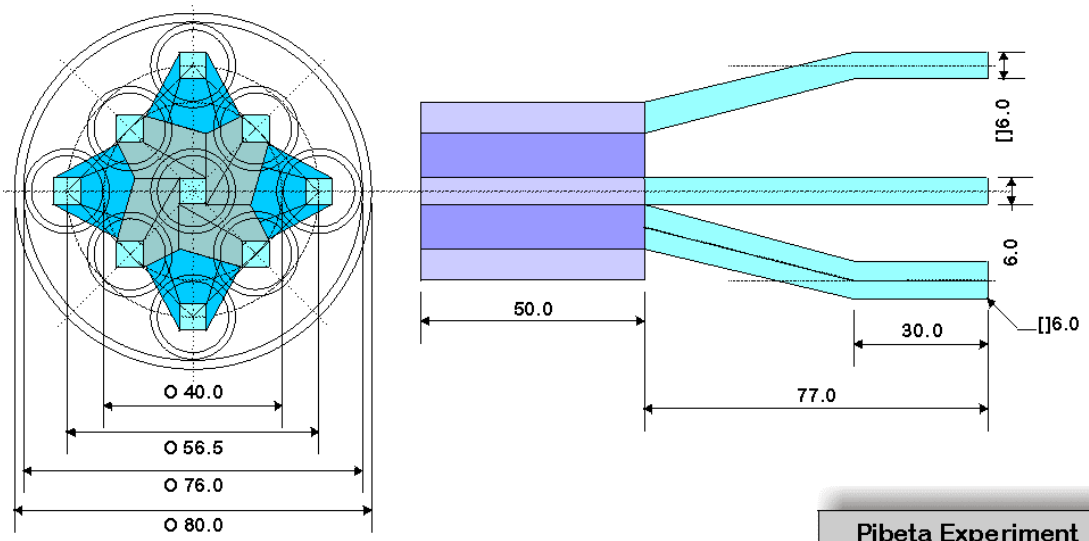
Pibeta Experiment
Degrader Version 2.1

Massstab 1:1
H.P. Wirtz
04-Feb-2000

- Pion momentum: 114 MeV/c
- After degrader: 20 MeV/c

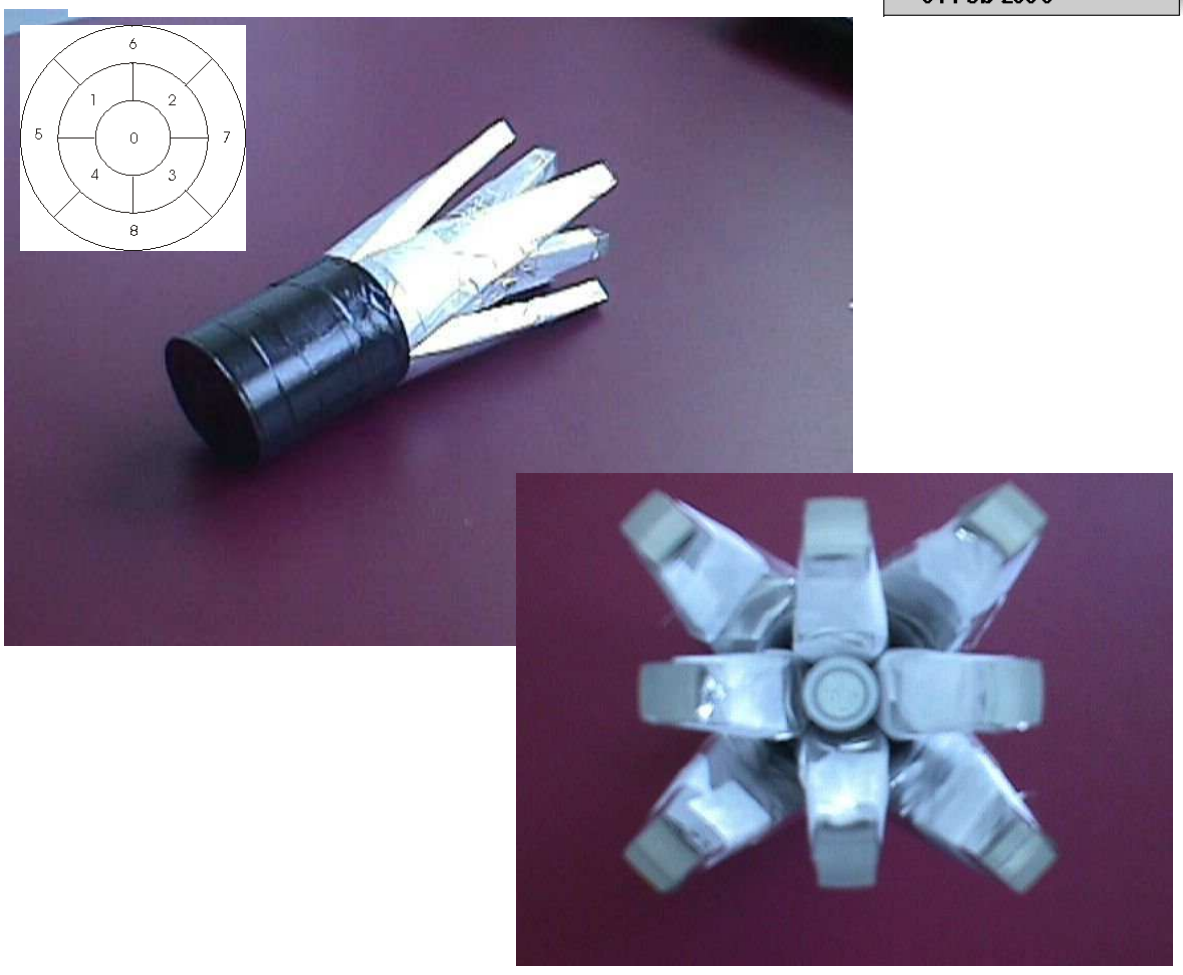
Pion-Beta Detector

Active Target



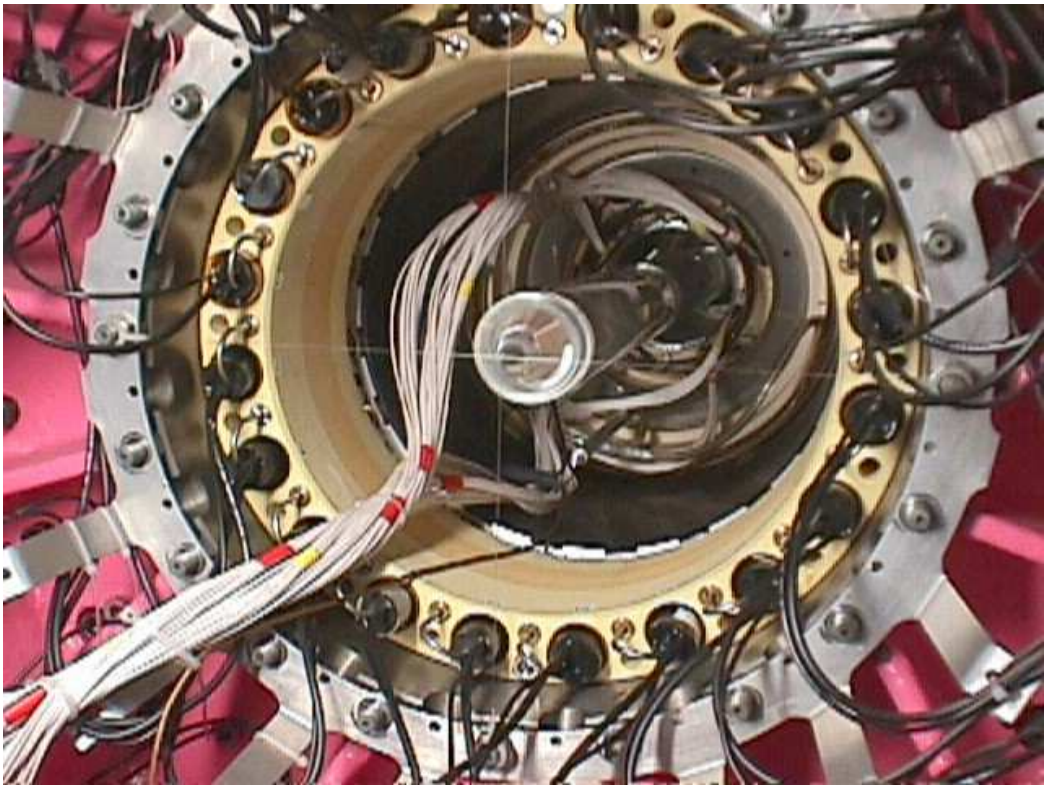
Pibeta Experiment
Target Version 4

Massstab 1:1
H.P. Wirtz
04-Feb-2000

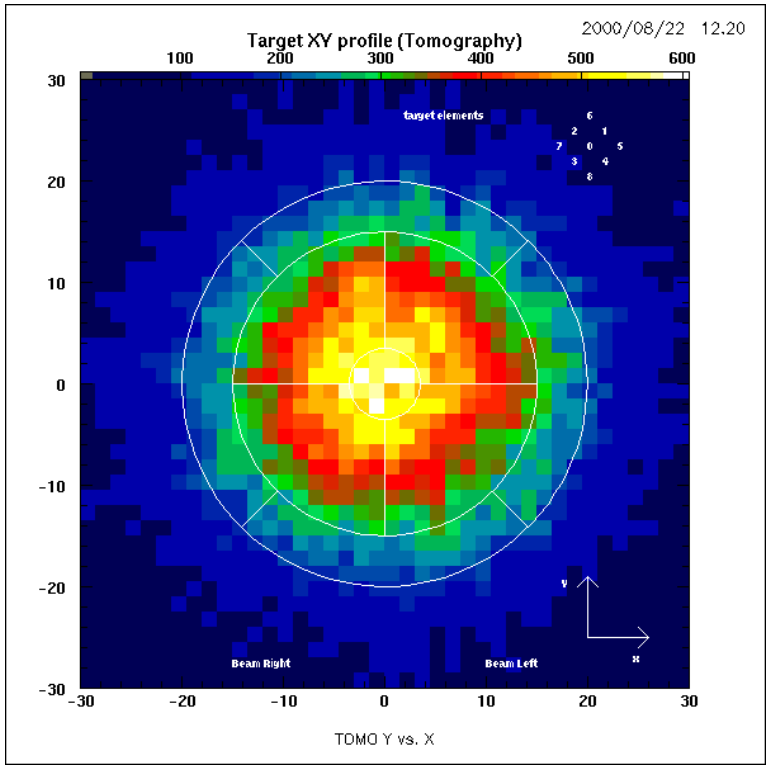


Pion-Beta Detector

Active Target

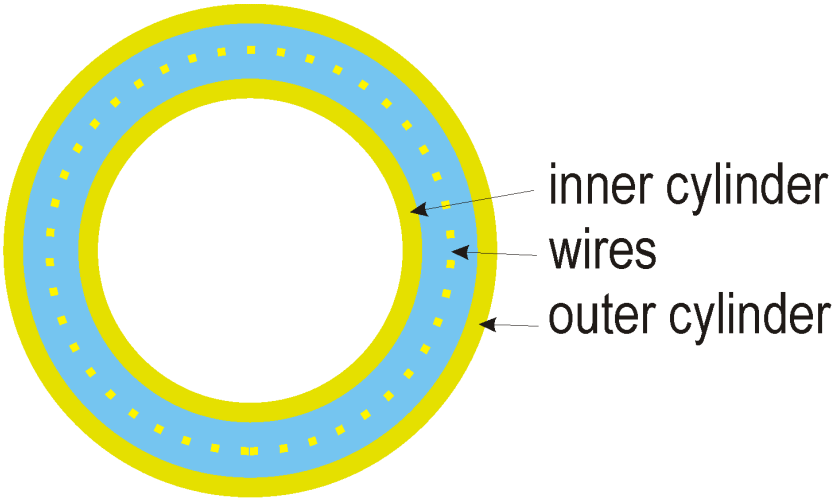


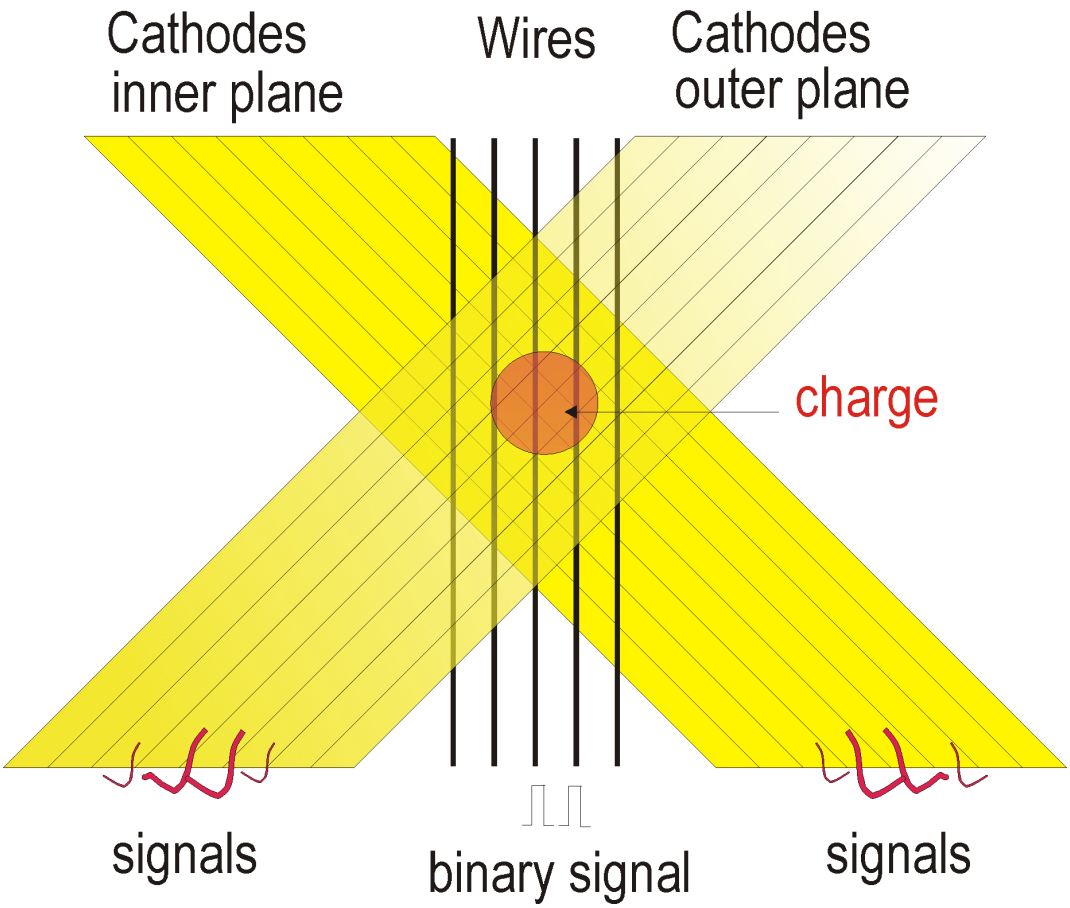
- Accuracy: ± 0.5 mm
- Position reproducible



Pion-Beta Detector

Multi Wire Proportional Chambers (MWPC)





Double pulse resolution ~1-2 mm

Pion-Beta Detector

Multi Wire Proportional Chambers (MWPC)

Chamber	**1 (inner)**	**2 (outer)**

Dimensions

Active length [mm]	350	540
All length [mm]	580	730
Min. diameter [mm]	90	206
Max. diameter [mm]	152	255
Diameter anode [mm]	120.3	240.2
Diameter inner cathode [mm]	115.2	235.2
Diameter outer cathode [mm]	125.0	245.2
Inner cathode - anode gap [mm]	2.55	2.5
Volume of chamber [cm^3]	660	2035
Total chamber thickness [mg/cm^2]	53.9	74.8
Total chamber thickness [rad.length]	1.4E-3	2.0E-3

Anode wires

Number of anode wires	192	384
Anode wire spacing [mm]	1.96	1.96
Anode wire tension (min-max) [N]	0.44-0.48	0.44-0.51
Resistence of anode wire [Ohm]	110	155
Resistance between anode-anode [Ohm]	560k	560k
Capacity between anode-ampl. [pF]	1000	1000

Cathode strips

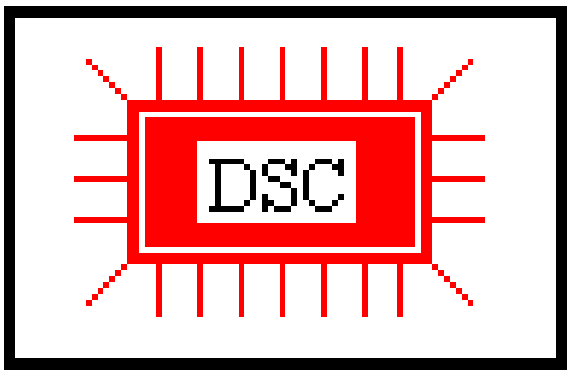
Number of inner cathode strips	2 x 64	192
Angle of slope inner cathode [deg]	36.960	44.602
Number of outer cathode strips	2 x 64	192
Angle of slope outer cathode [deg]	33.650	42.339
Width of cathode strips [mm]	3.0	2.4
Gap between strips [mm]	0.4	0.3
Resistance of strips (6u Al) [Ohm]	~1.5	~2.0

Pion-Beta Detector

Plastic Veto

Domino Sampling Chip

Waveform Digitizing System



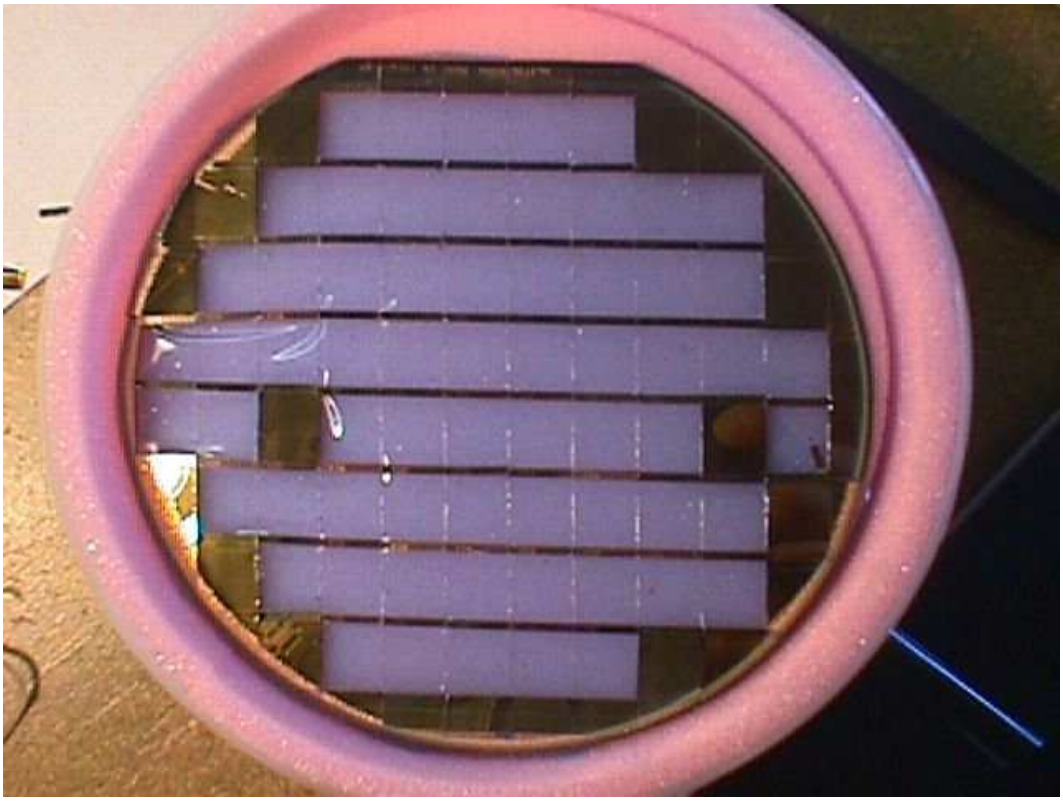
DSC: Fast Analog Memory

in CMOS Technology

- Sampling speed: 500 – 1200 MHz
- Readout at 5 MHz with Flash ADC
- Readout daisy chaining of 48 DSC's
- Costs: <100 CHF/channel

Domino Sampling Chip

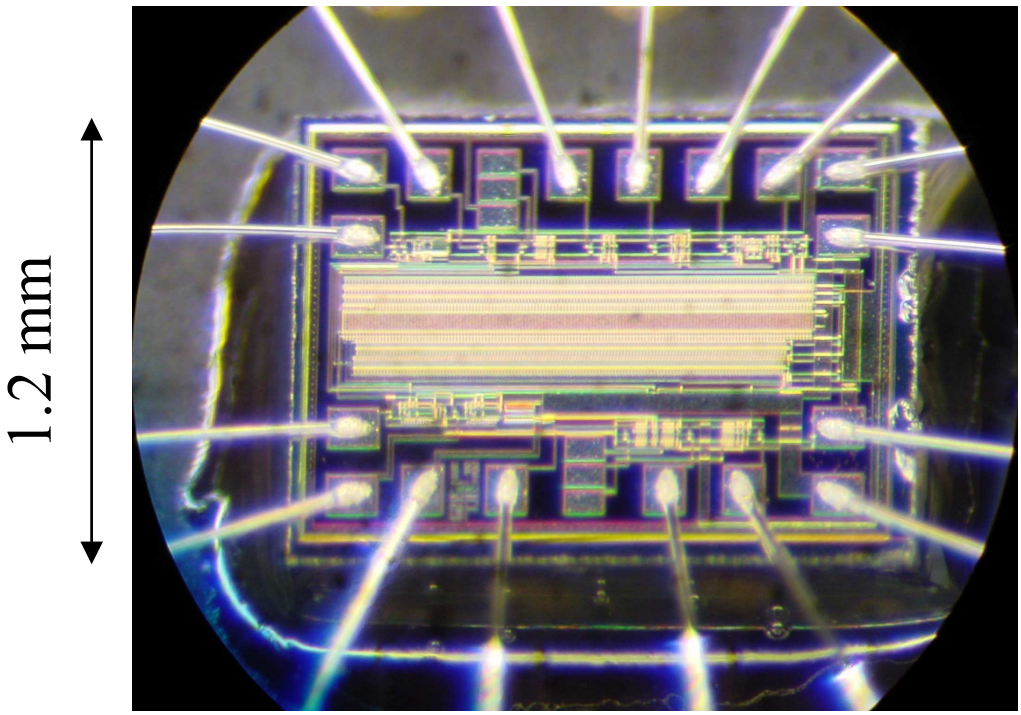
Wafer

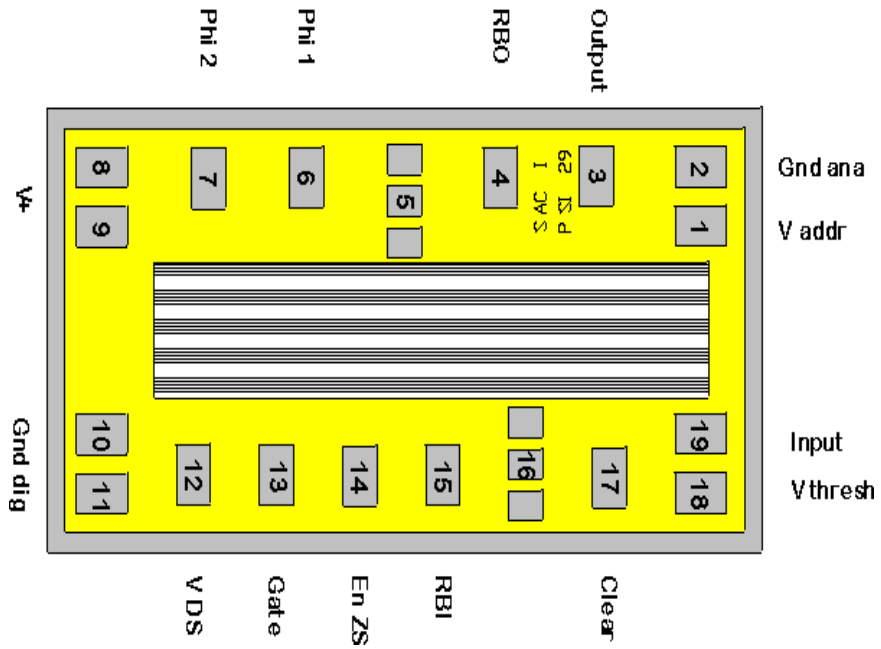


Domino Sampling Chip

Bond Pads

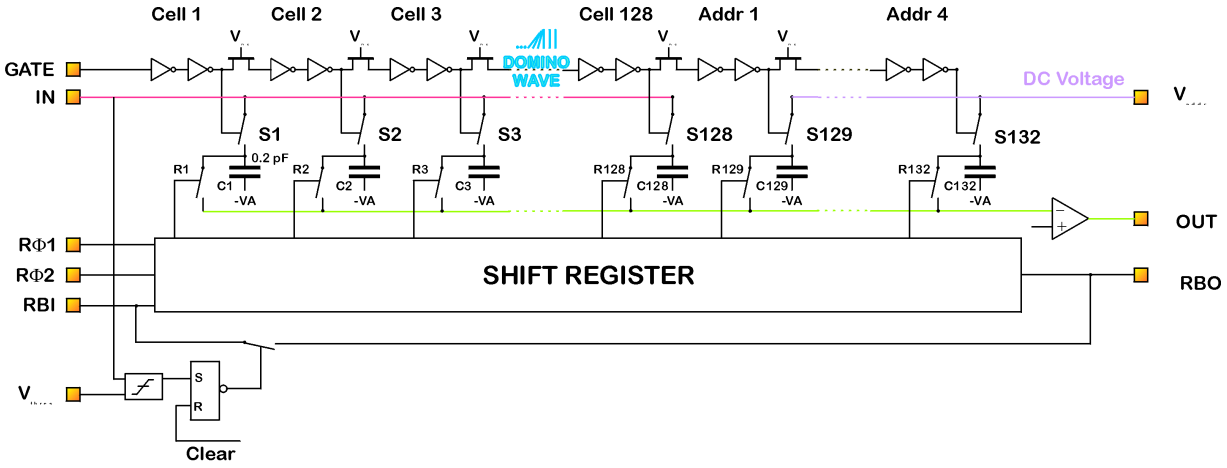
Chip realized in S1DM (1µm SACMOS double metal)
technology by FASELEC, Switzerland





Domino Sampling Chip

Design Principles



Sampling Phase:

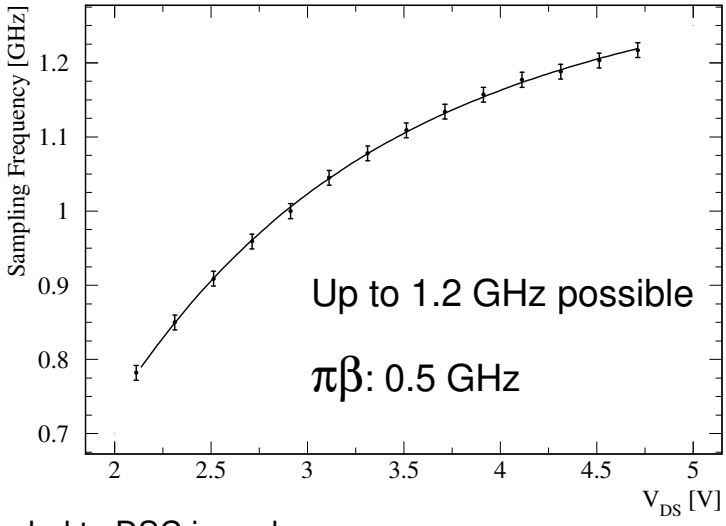
- Transmission of a logic pulse through two sequential CMOS inverters
- 800 ps delay per inverter pair
- Inverter chain: logical Signal: **DOMINO WAVE**
- Every 2 inverters: IN connected via **S1..128** to **C1…128**
- Charge is proportional to **momentary voltage level at** IN
- **4 additional cells A1…4 sampling** V_{addr} (**S129..132**) -> *ZS*

Readout Phase:

- 2 phase SHIFT REGISTER: RBI is clocked through (non-overlapping clock phases RΦ1, RΦ2)
- On phase RΦ2: switching R1…132 -> Capacitor connected to charge sensitive output amplifier
- 132th clock cycle: RBI appears as RBO at the shift register end
- RBO indicates successful readout
- RBO disconnects amplifier from output pad
- RBO is RBI to the next DSC in the chain

Domino Sampling Chip

Parameters



Input: DC coupled to DSC in pad

Input Capacitance 1 pF

max. Readout frequency ~ 5 MHz

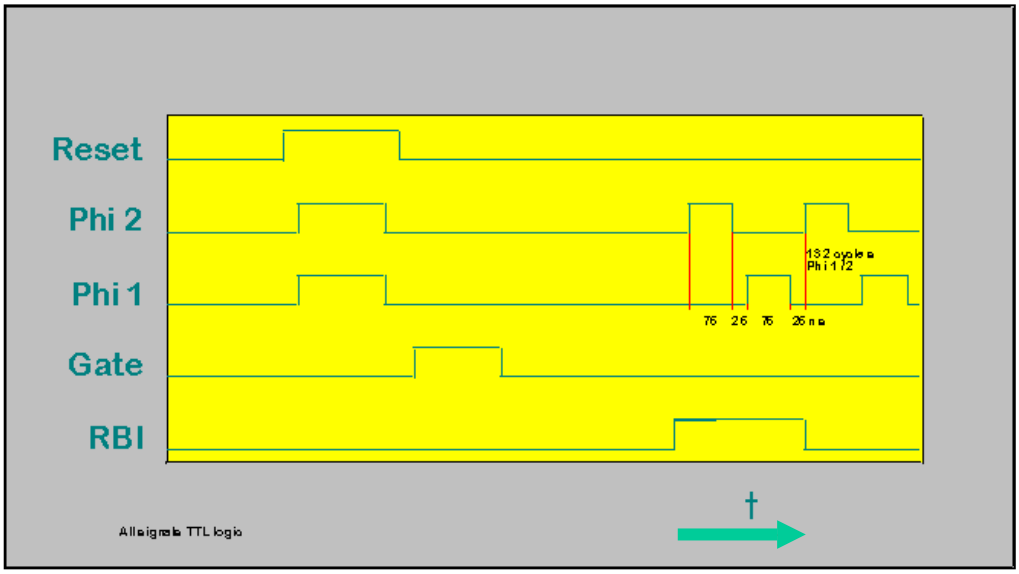
Noise: ~ 4mV

Amplitude non-linearity: 0.2 %

Timing non-linearity: < 0.8 %

Reference: Broennimann et al, NIM A 420 (1999) 264-269

Simple Readout Scheme

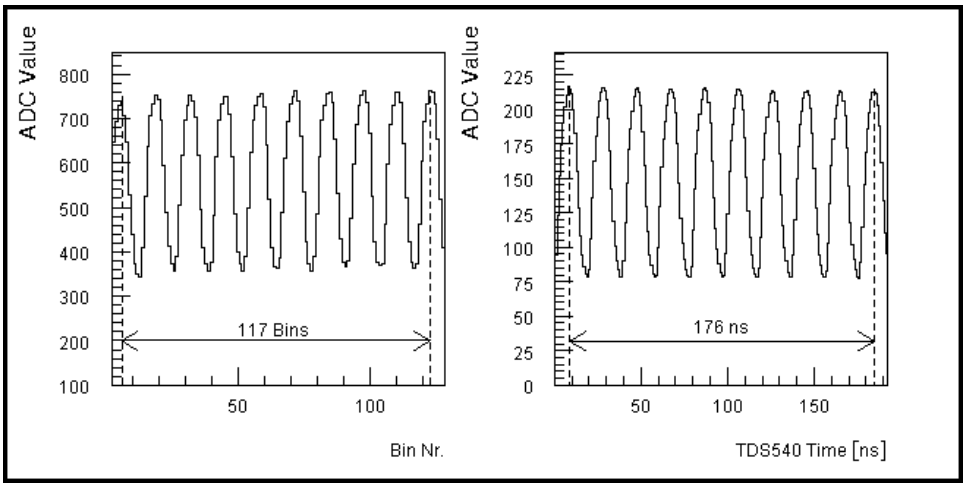


Domino Sampling Chip

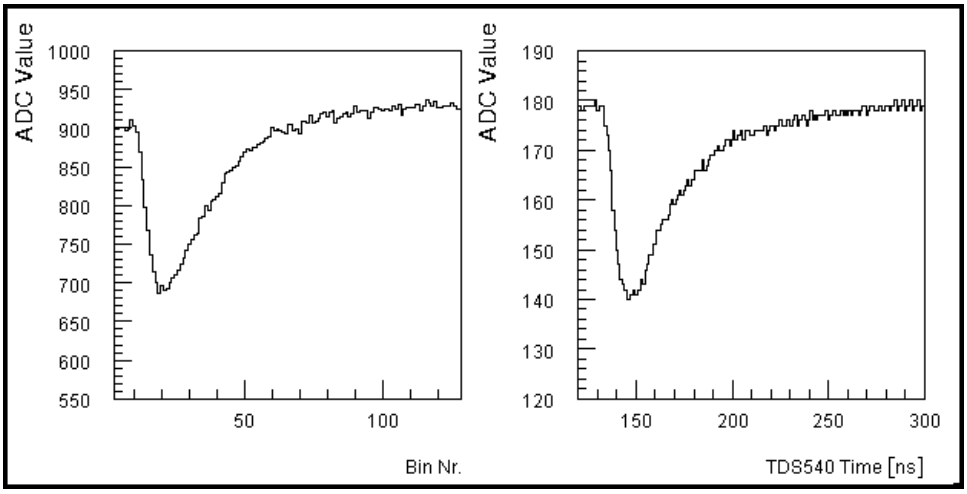
DSC Response

Comparison: DSC + Sirocco / Tektronix TDS 540

Response to 50 MHz Sine Wave, Domino Speed 665 MHz



Pure CsI crystal on EMI 9821QB PM

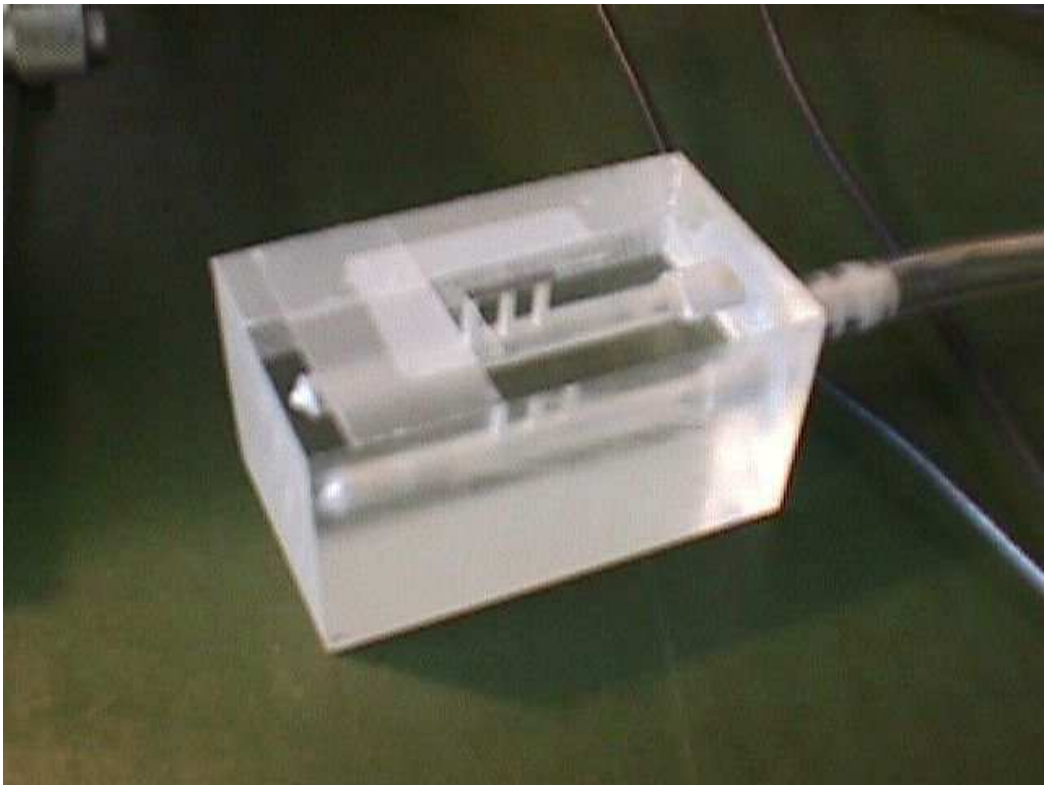


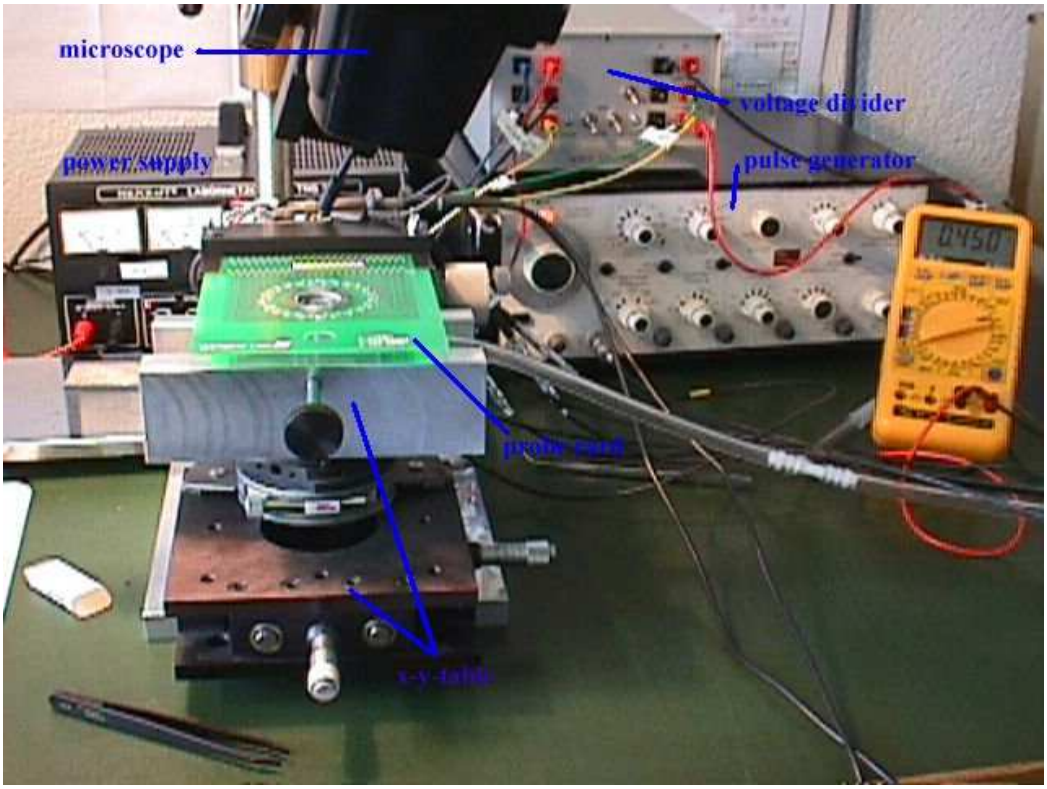
Excellent agreement of main parameters
- rise time
- decay time
- charge integral

Domino Sampling Chip

Quality Assurance

400 Chips individually cut and measured





Domino Sampling Chip

The DSC in the Experiment

Power Module:

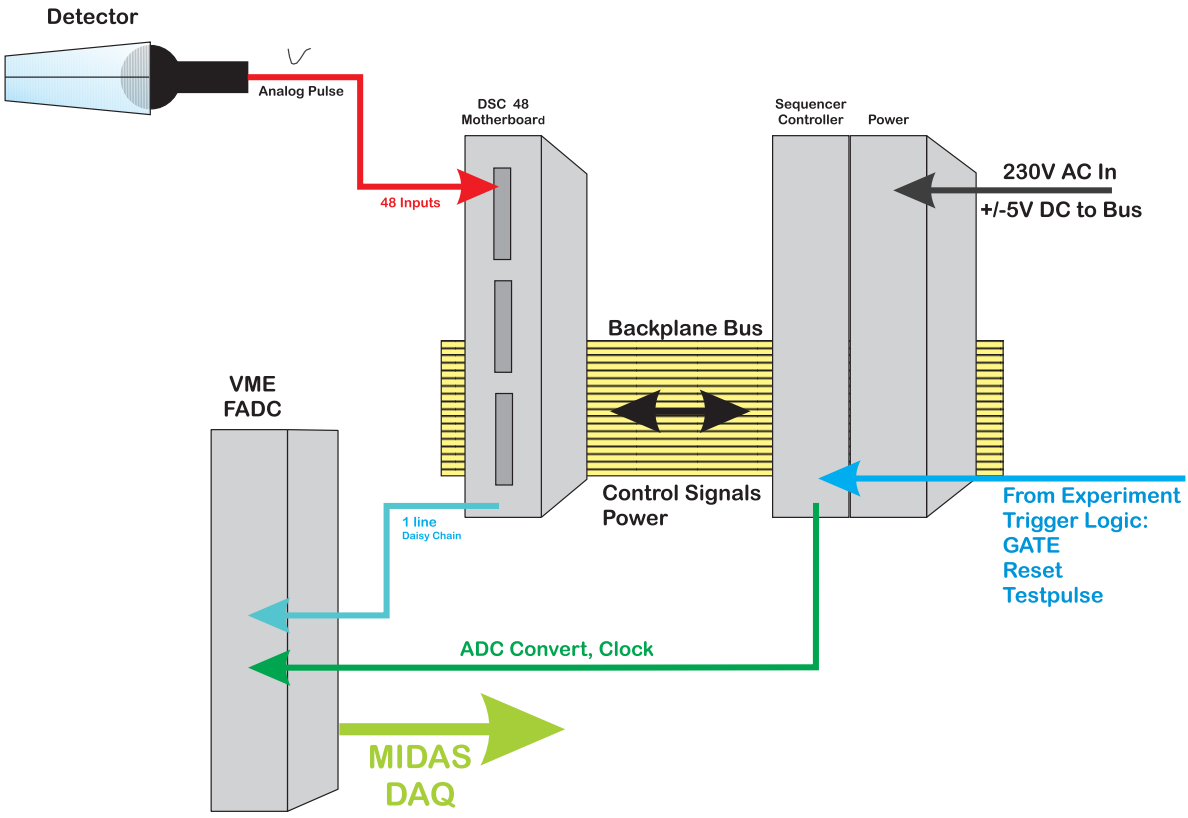
•2 Transformators 230V AC to +/-5V DC , Filters
•Backplane Bus -> Controller, Motherboards

Sequencer / Controller

• FPGA: Altera EPM 7032SLC44-6
• Input Gate, Reset, Testpulse (Trigger Logic)
• Input Response 'DSC finished'
•Output control signals to DSC
•Output Flash ADC Gate and Converts

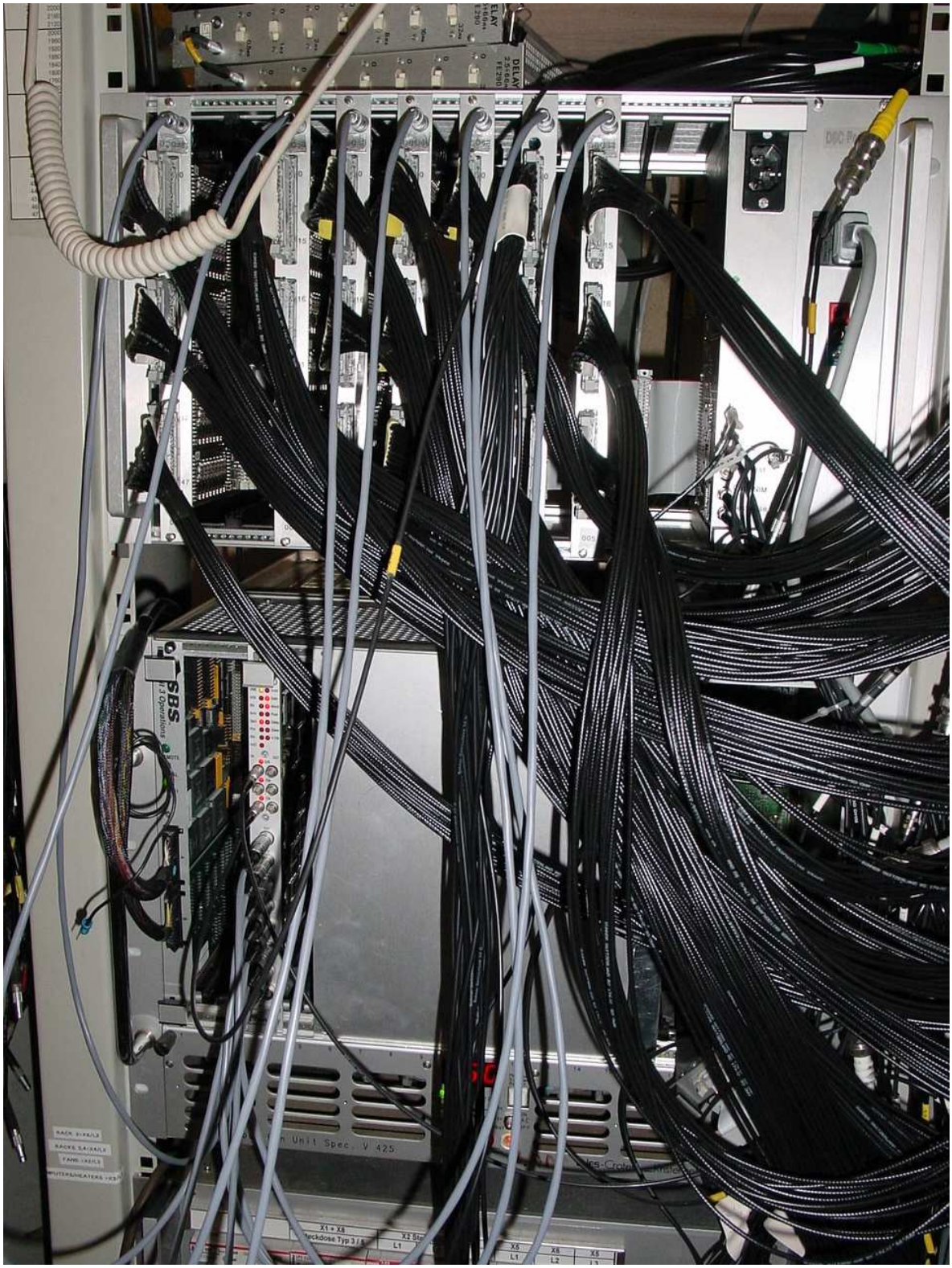
Flash ADC:

•VME Flash ADC (Batech 7510 / D, 12 bit, 10 MHz)



Domino Sampling Chip

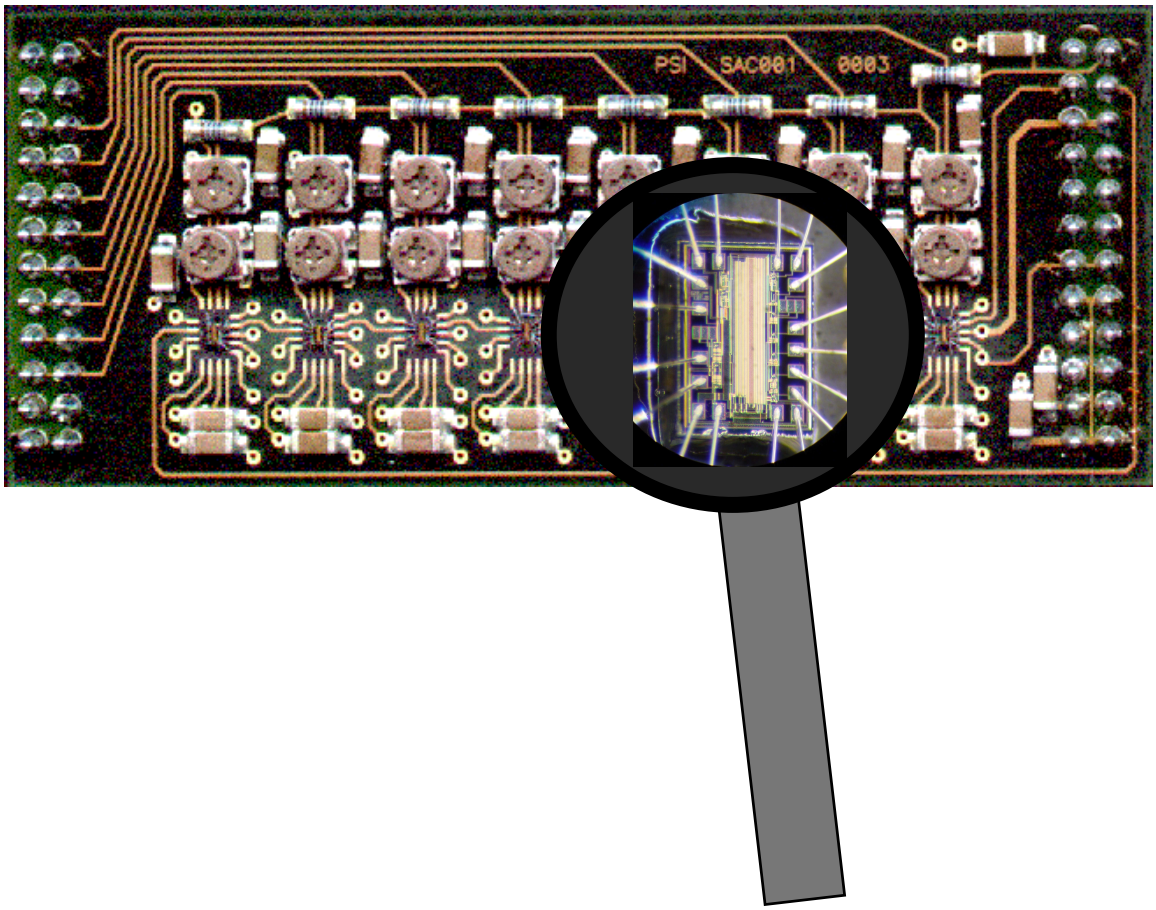
The DSC in the Experiment



Domino Sampling Chip

The Carrier

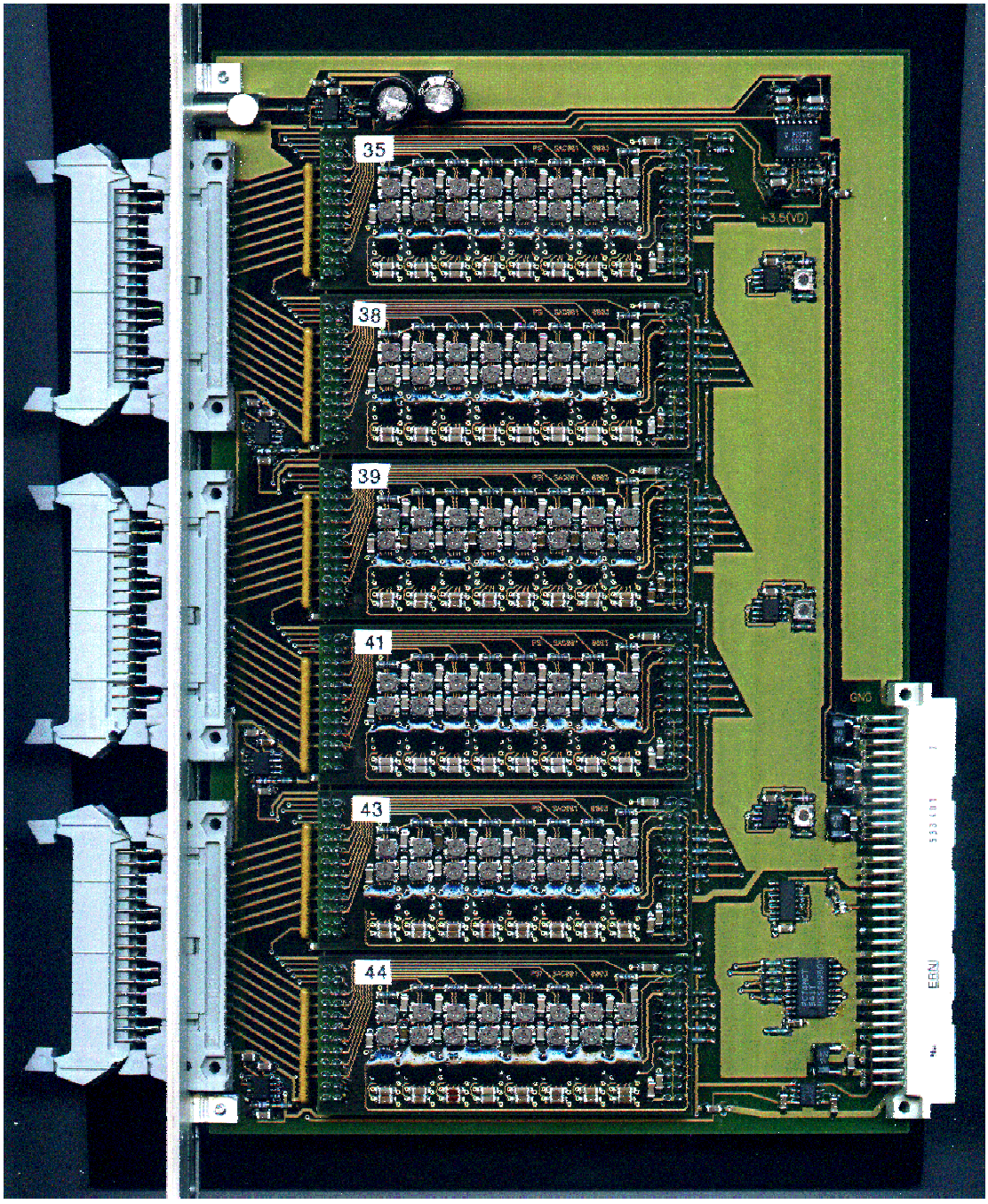
The Carrier



- **8 DSC channels per carrier**
- **Multi-layer Board (4 layer)**
- **Address voltage divider chain**
- **Address adjustment potentiometer**
- **V_{thres} adjustment (Zero Suppression)**

Domino Sampling Chip

The Motherboard



Multi Layer Board (4 Layers)
48 channels, 6 x 8 DSC
Testpulse Refresh
Output Line Drivers
Setpoint Domino Speed

DSC Addresses

Readout Speed 5 MHz -> 26.4 µs / DSC
300 channels: 7.9 ms deadtime: NOT ACCEPTABLE!

Zero Suppression:
Only DSC above a certain threshold are read out

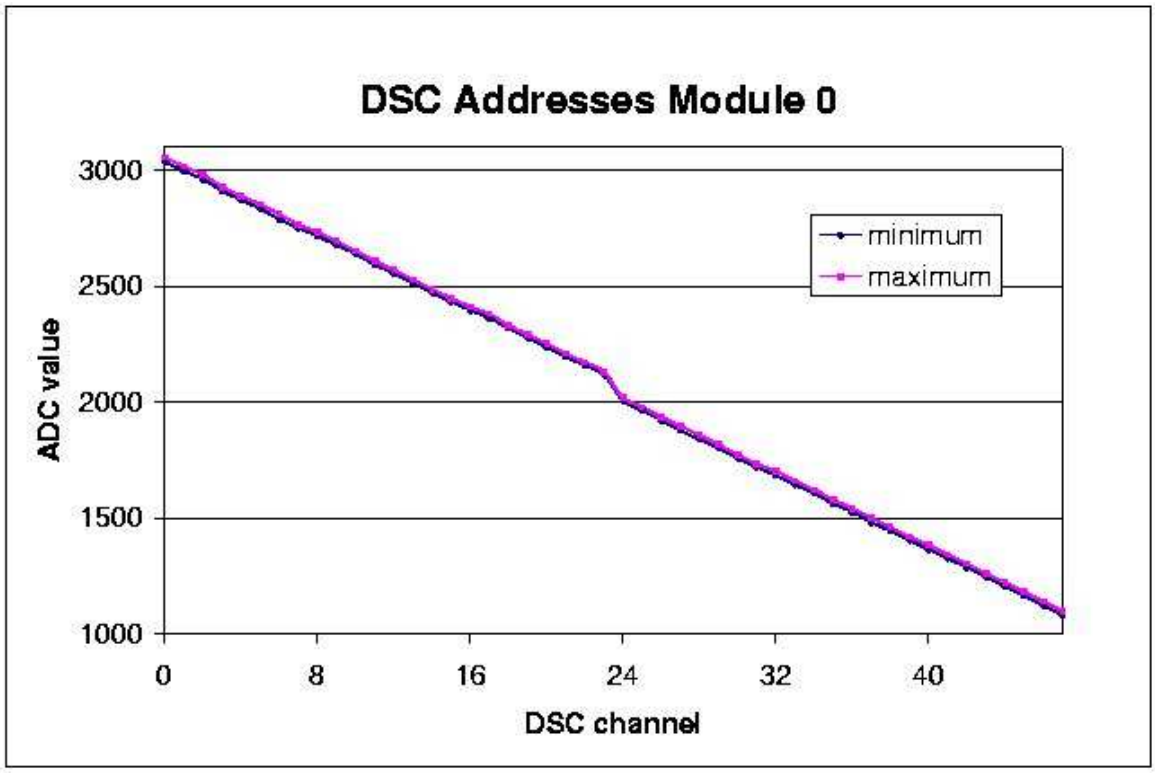
Identification via 4 Address Cells
DC Value sampled

DC Voltage: +0.9V…-0.9V -> ~40 mV between neighbour channels

Additional baseline offsets: can get 40 ADC bins distance

Function: address = 3040 - 40 * channel (channel 0…23)
address = 2000 - 40 * channel (channel 24…47)
'baseline' ~ 2050...2080

Addresses are written into Lookup Table for channel decoding

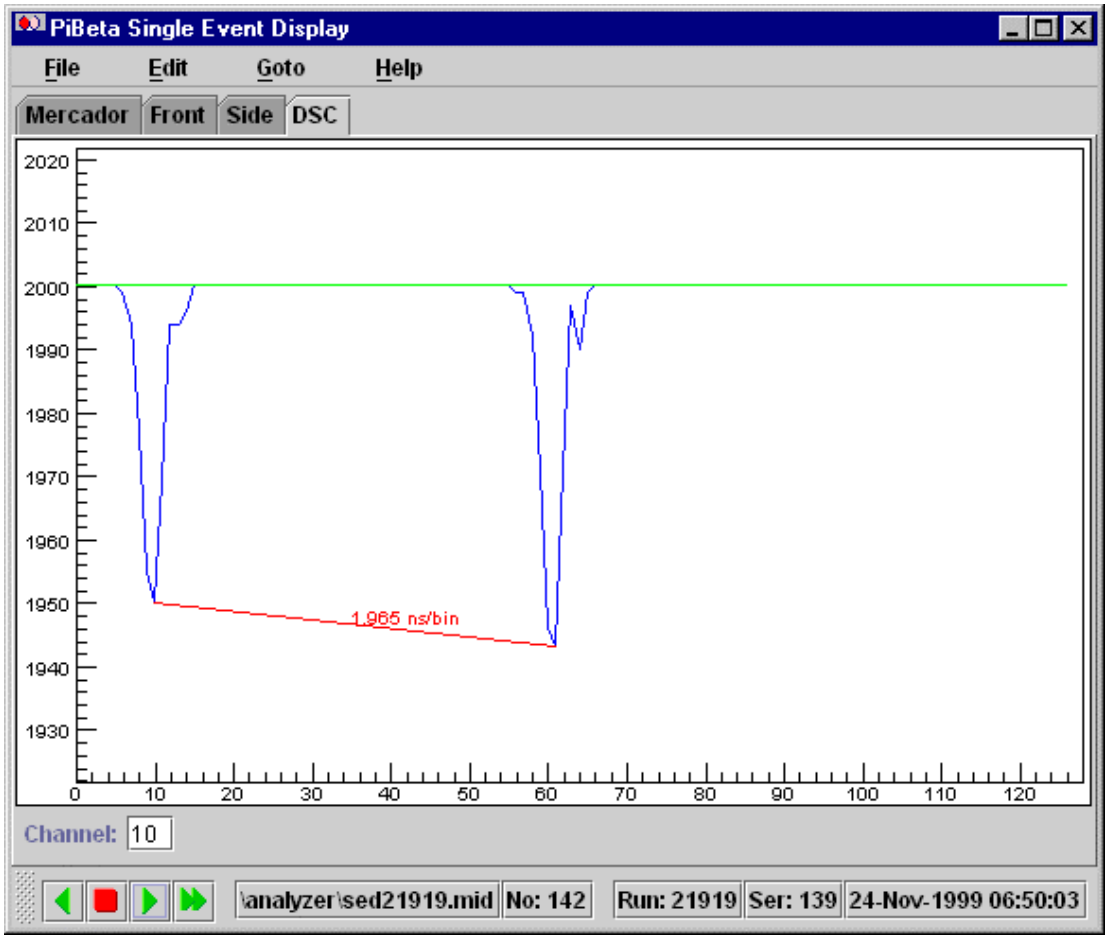


Domino Speed Calibration

Testpulse on 'Random Trigger':
100 ns wide TTL pulse
AC coupled to the DSC inputs

Position: Fit 2nd order parabola around peak (3 points)

1999: 16 channels, max. deviation: 0.3%



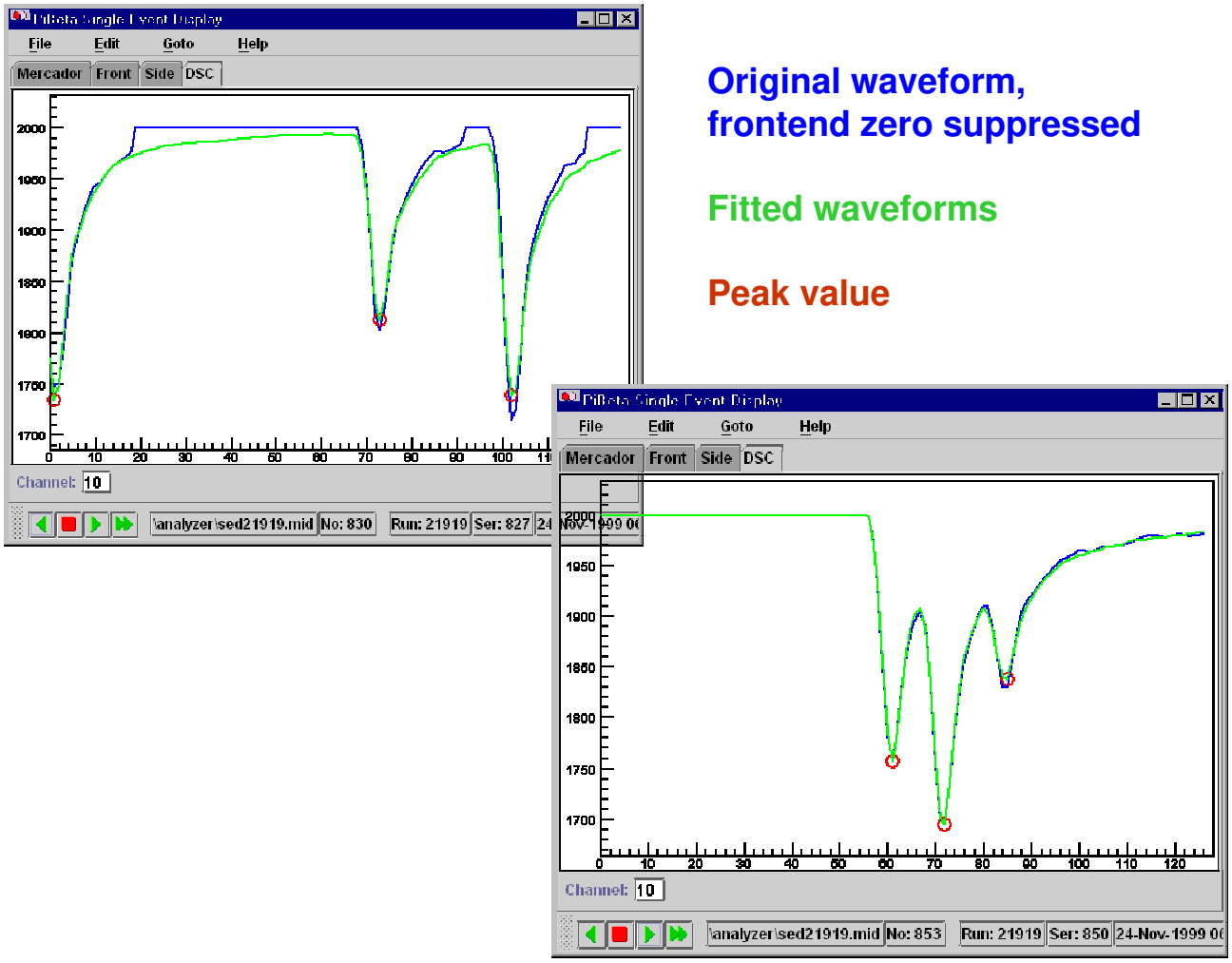
Waveform Fitting

Assumption:
Pions and Positrons produce identical waveforms

Determine exact shape of an average waveform ('system function') for each channel, fit (chi-square) all events with that waveform

More than 1 hit: Sum of N system functions with different factor (ADC) and offsets (TDC), g(x) is system function:

$$f(x) = \sum_{i=1}^{N} ADC_i \bullet g(x - TDC_i)$$

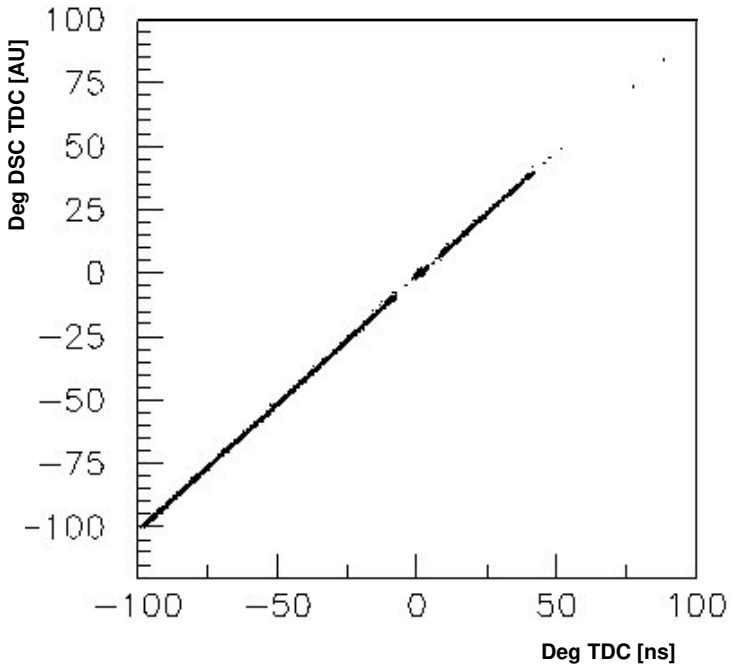


Original waveform, frontend zero suppressed

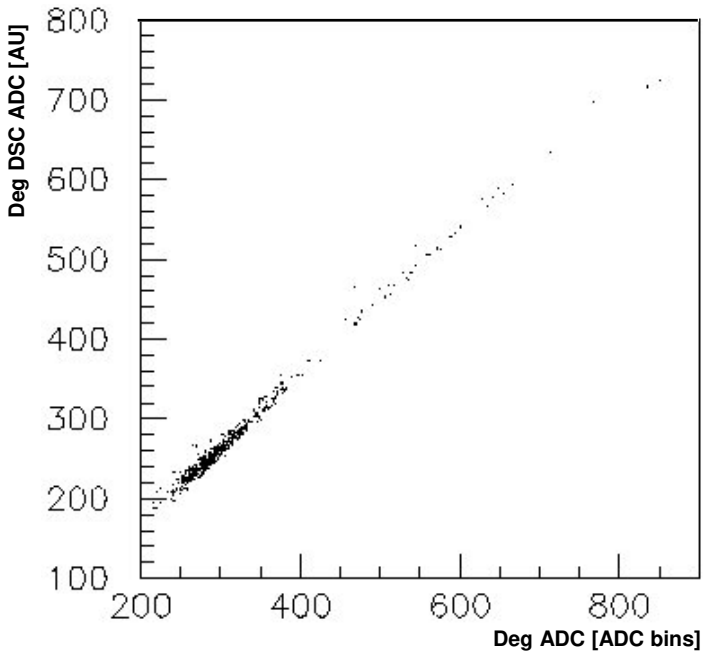
Fitted waveforms

Peak value

ADC/TDC Correlation



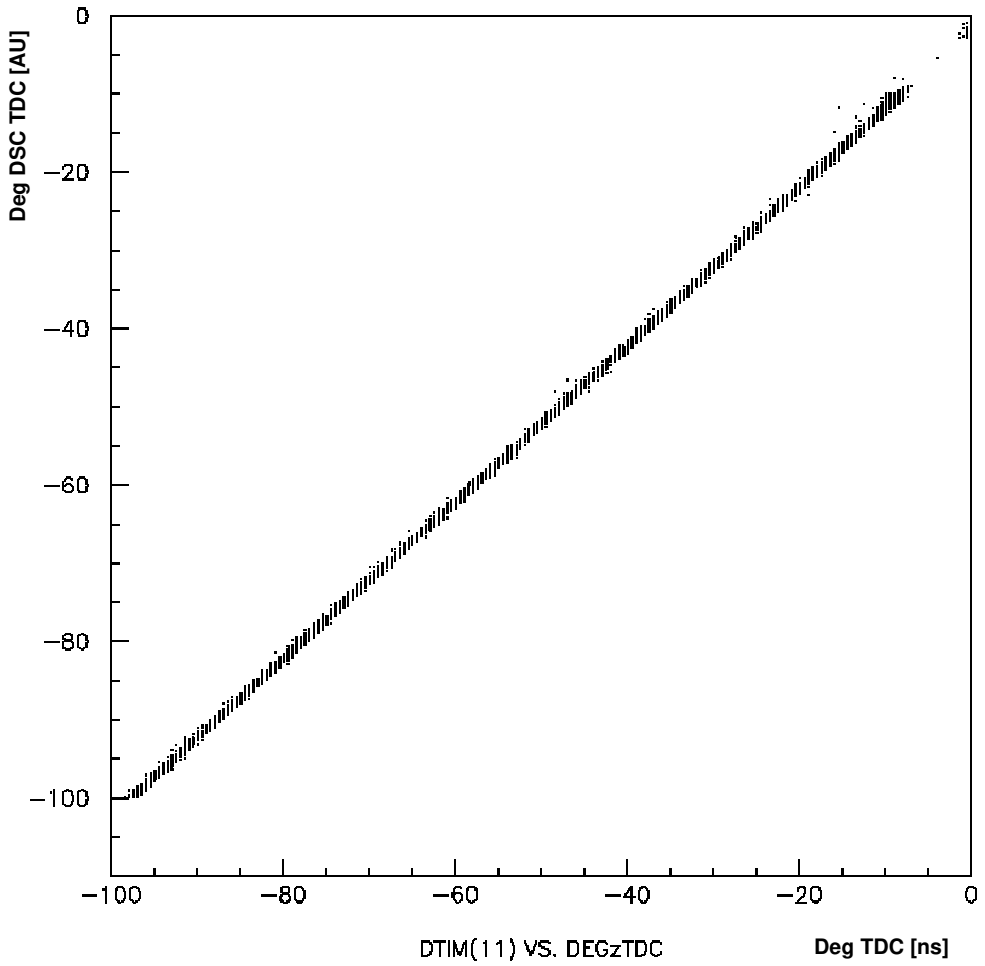
DSC TDC vs. Fastbus LRS 1877 TDC



DSC ADC vs. CAMAC LRS 2249 ADC

Cut: prompt -> signal completely inside ADC Gate

Timing Resolution



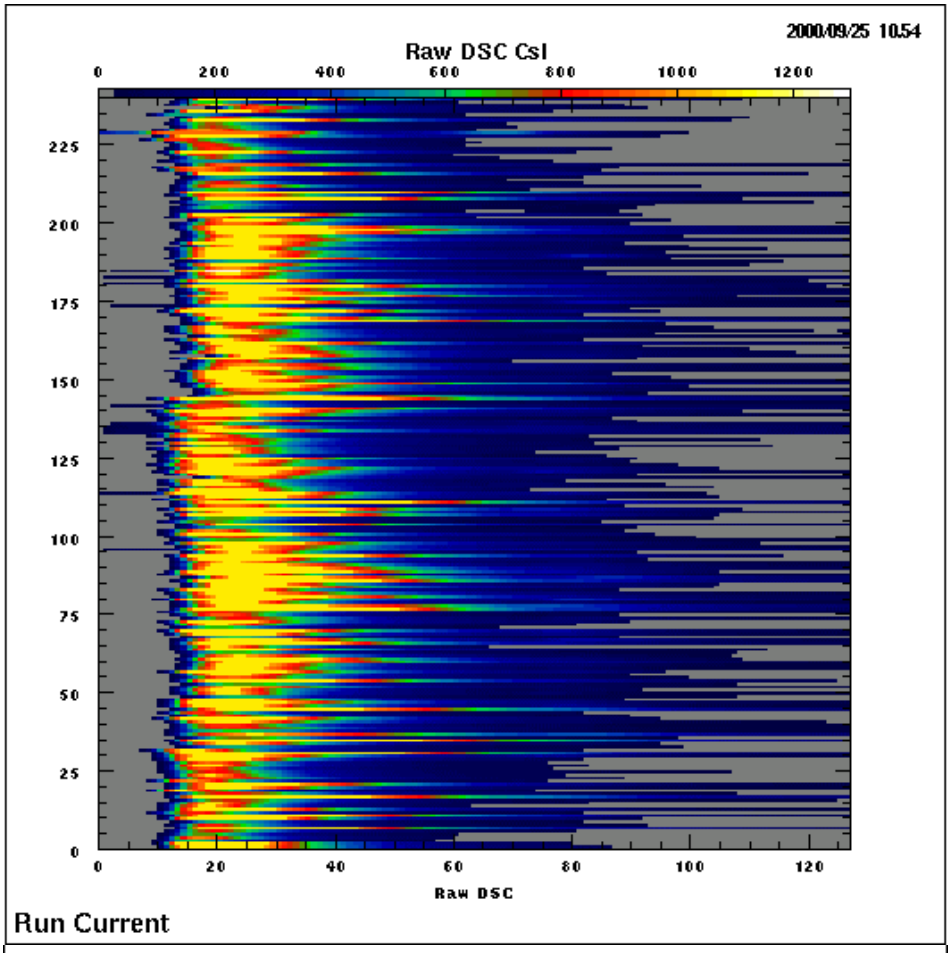
Zoom of previous Pane 1: One can see the 0.5 ns resolution of the LRS1877 TDC.

To make a more careful study of the DSC timing resolution one would need TDCs with a better timing resolution.

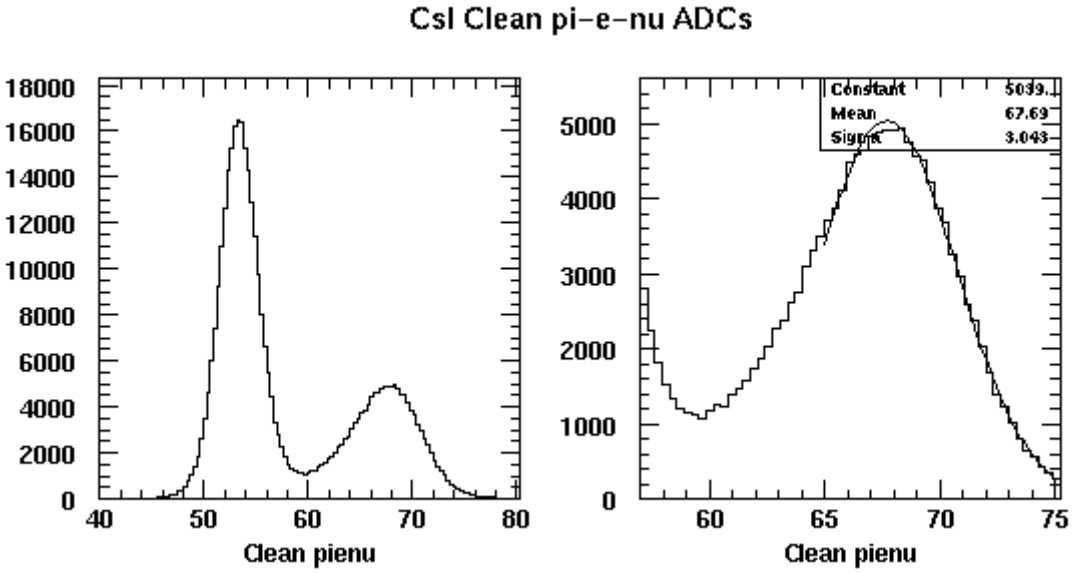
A rule of thumb is that with a sampling speed of 2ns one can obtain a time accuracy of 0.2ns, taken into account the full waveform during the fitting process.

Raw Data

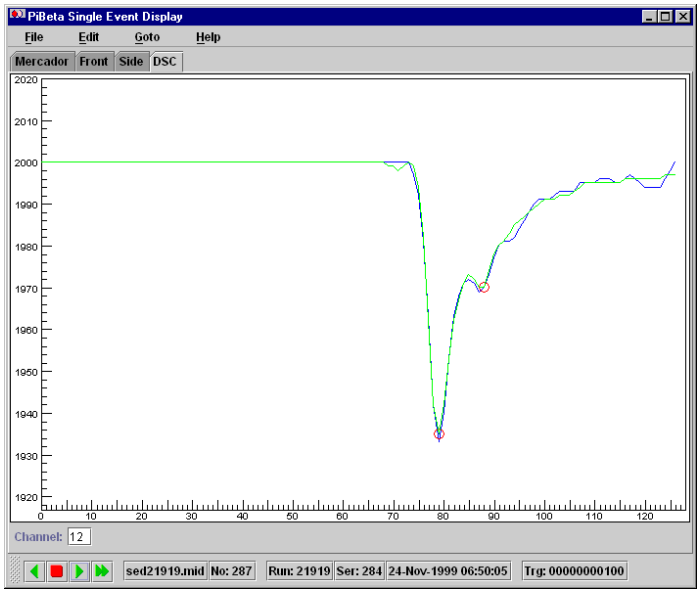
296 channels on DSC



πeν spectra



- Clearly separated from Michels, FWHM = 10.2%
- Will be improved by (need DSC data)
  - adding energy loss in active target and plastic veto hodoscope
  - subtracting baseline shift from pile-up in CsI



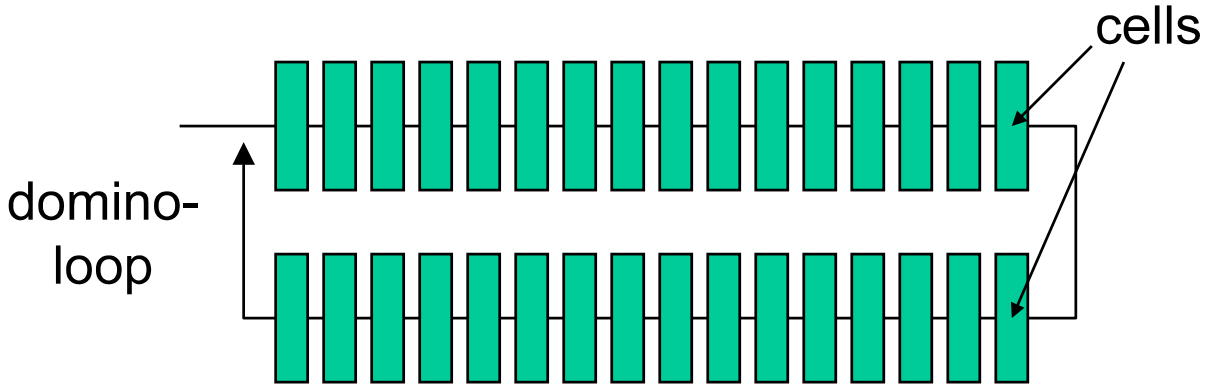
Outlook

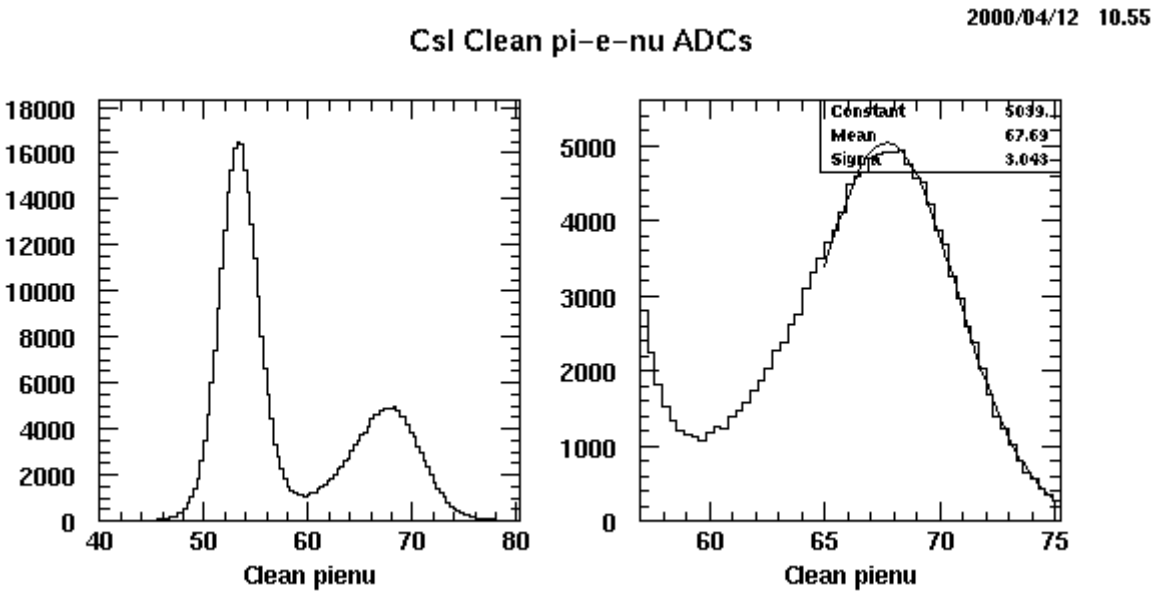
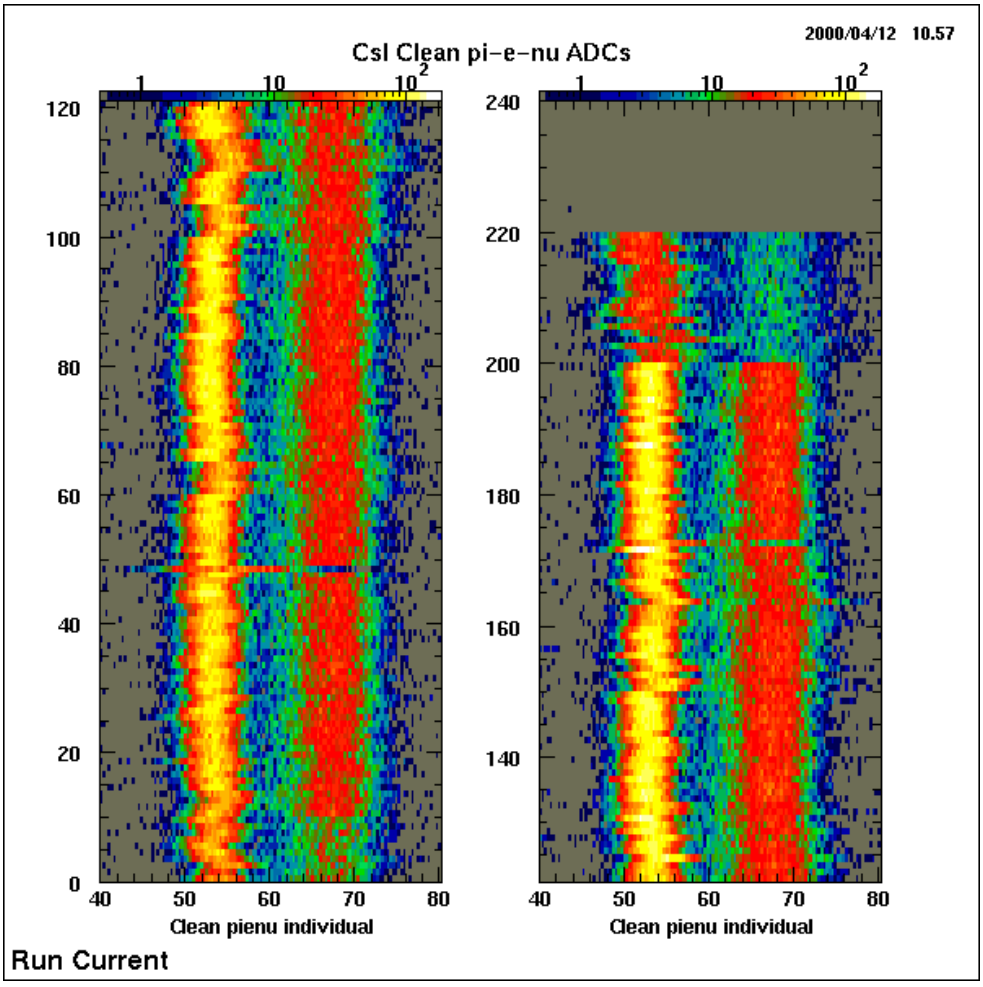
- The $\pi\beta$ Experiment at PSI produces now excellent data for a whole series of publications.
- We expect to get >50'000 $\pi\beta$ until end of the year.
- First phase (0.5% measurement) finished in 2001, second phase (0.2%) needs re-measurement of $\pi \rightarrow e\ \nu$ decay.
- Calorimeter, Plastic Veto and Beam Counters are equipped with DSC.
- Offline Waveform Analysis is started, but not completed yet.
- Expect improvement of time and energy resolution. Improvement of data cuts possible.
- New DSC design starts end of the year.

Transparencies:

http://pibeta.psi.ch/docs/talks/dsc_pibeta_00/dsc_2000.html

Next generation sampling chip



- “Free running mode”
- Switch in return path of storage capacitor
  8bit → 11bit resolution
- New AMS process: 2.5GHz → 40ps resolution, 512/1024 bins
- Improved readout 40MHz
- Fast online processing necessary

Online histograms