The MEG Experiment: Search for $\mu \to e\,\gamma$ at PSI

For the MEG collaboration
Stefan Ritt
(Paul Scherrer Institute, Switzerland)

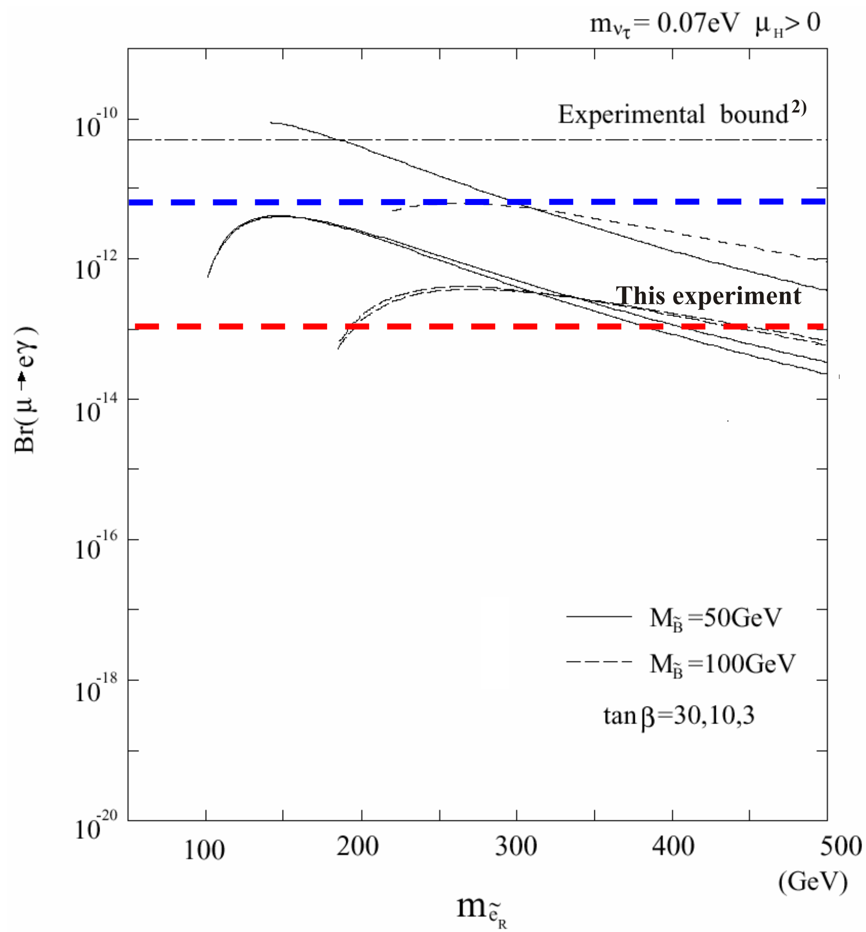
- Motivation
- Experimental Technique
- New Electronics
- Current status

Motivation

Physics Motivation

- Minimal SM: Conservation of Baryons (proton decay) and Lepton Flavour ($\mu^+ \rightarrow e^+ \gamma$, $\mu^+ \rightarrow e^+ \nu_e \nu_\mu \gamma$ ok)
- Super Symmetry (SUSY) theories generically predict LFV
- Processes like $\mu^+ \rightarrow e^+ \gamma$ are not "contaminated" by SM processes and therefore very clean
- Discovered ν oscillations are expected to enhance LFV rate
- The search for $\mu^+ \rightarrow e^+ \gamma$ is therefore a promising field to find physics beyond the SM

Prediction from SUSY SU(5)[1)]

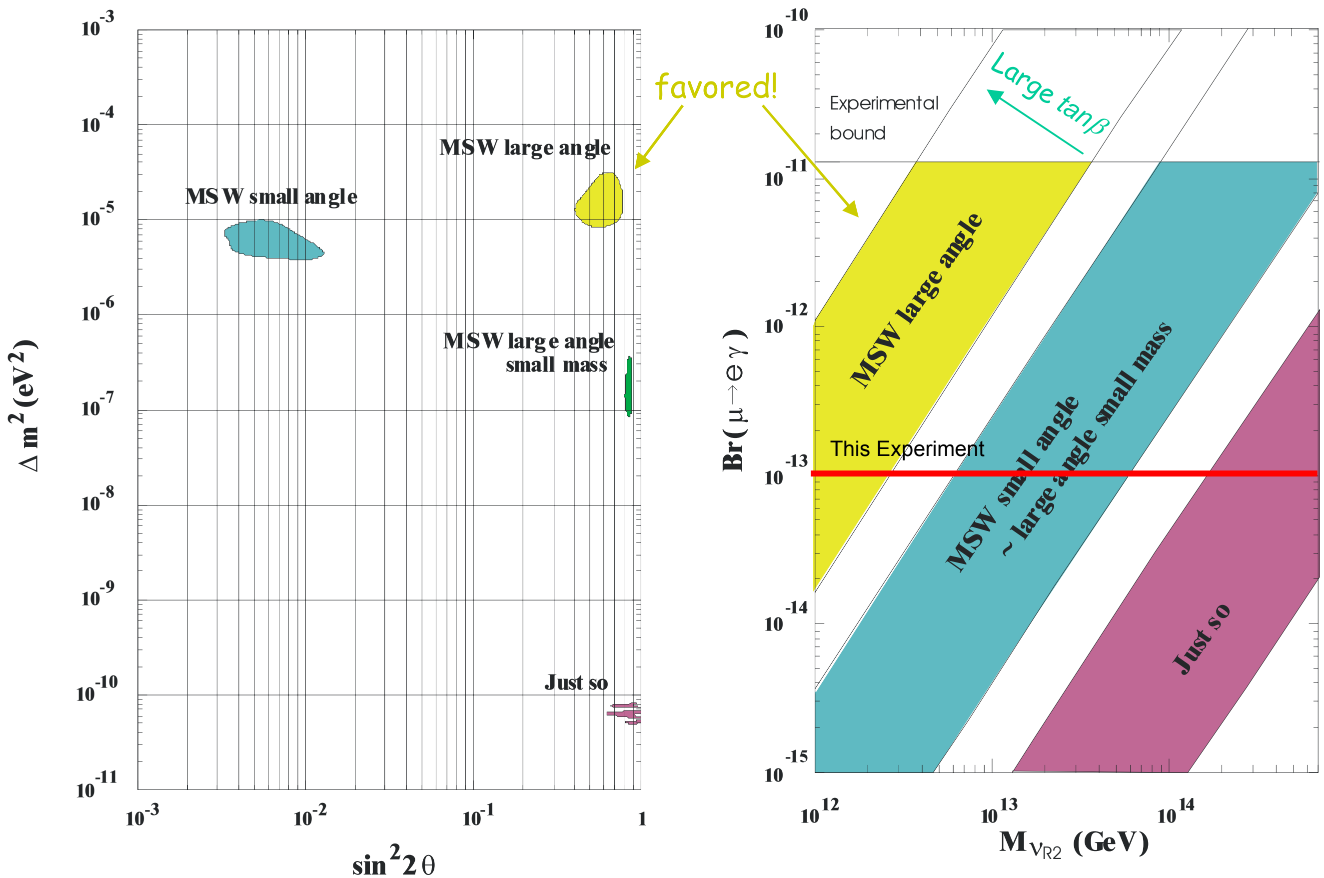


w/o SUSY: $BR(\mu^+ \to e^+ \gamma) \sim 10^{-24}$

- Based on observation of atmospheric neutrino anomaly
- $BR(\mu^+ \to e^+ \gamma) \geq 10^{-14}$
- $BR(\tau^\pm \to \mu^\pm \gamma) \geq 10^{-9}$
- Conversion$(\mu \to e) \geq 10^{-16}$

1) J. Hisano *et al.*, hep-ph/9711348
2) MEGA collaboration, hep-ex/9905013

Connection with ν oscillations[1)]



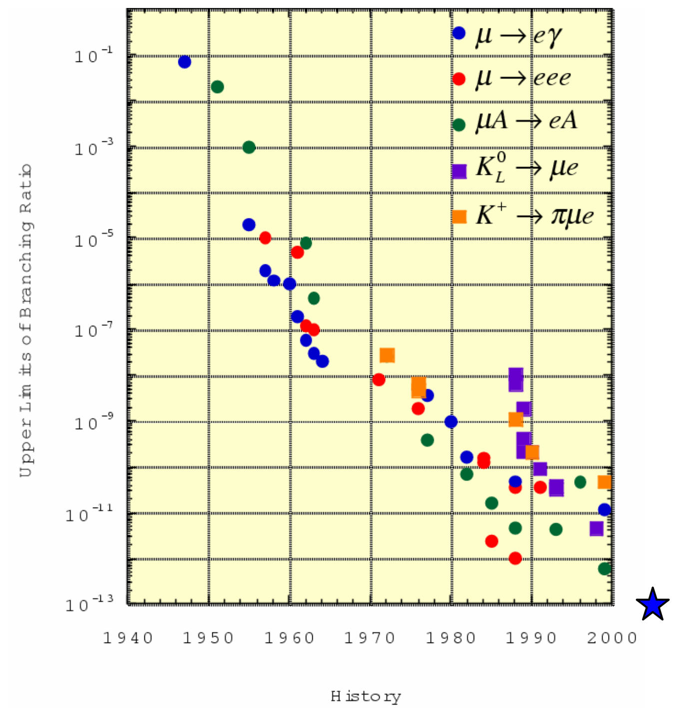
J. Hisano and D. Nomura, Phys. Rev. D59 (1999) 116005

Previous $\mu^+ \to e^+ \gamma$ Experiments

Place	Year	Upper limit	Author
SIN (PSI), Switzerland	1977	$< 1.0 \times 10^{-9}$	A. Van der Schaaf *et al.*
TRIUMF, Canada	1977	$< 3.6 \times 10^{-9}$	P. Depommier *et al.*
LANL, USA	1979	$< 1.7 \times 10^{-10}$	W.W. Kinnison *et al.*
LANL, USA	1986	$< 4.9 \times 10^{-11}$	R.D. Bolton *et al.*
LANL, USA	1999	$< 1.2 \times 10^{-11}$	MEGA Collab., M.L. Brooks *et al.*
PSI	~2005	$\sim 10^{-13}$	*This Experiment*

Two orders of magnitude improvement: Challenge!

Search for Lepton-Flavour Violation:



MEG Collaboration

Institute	Country	Main Resp.	Head	Scientists	Students
ICEPP, Univ. of Tokyo	Japan	LXe Calorimeter	T. Mori	12	2
Waseda University	Japan	Cryogenics	T. Doke	5	2
INFN, Pisa	Italy	Trigger, M.C.	A. Baldini	5	4
INFN, Pavia	Italy	e^+ counter	G. Cecchet	3	-
IPNS, KEK, Tsukuba	Japan	Supercoducting Solenoid	A. Maki	5	-
PSI	Switzerland	Drift Chamber, Beamline, DAQ	S. Ritt	4	-
BINP, Novosibirsk	Russia	LXe Tests and Purification	B. Khazin	5	-
Nagoya University	Japan	Cryogenics	K. Masuda	1	-

Σ 40 8

Time Table

now

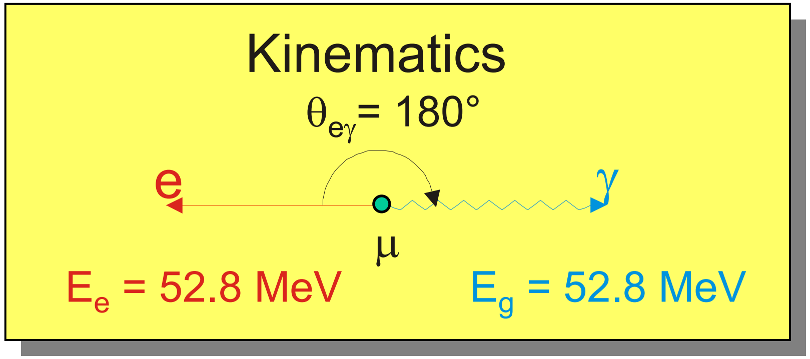
Planning	R & D	Assembly	Data Taking

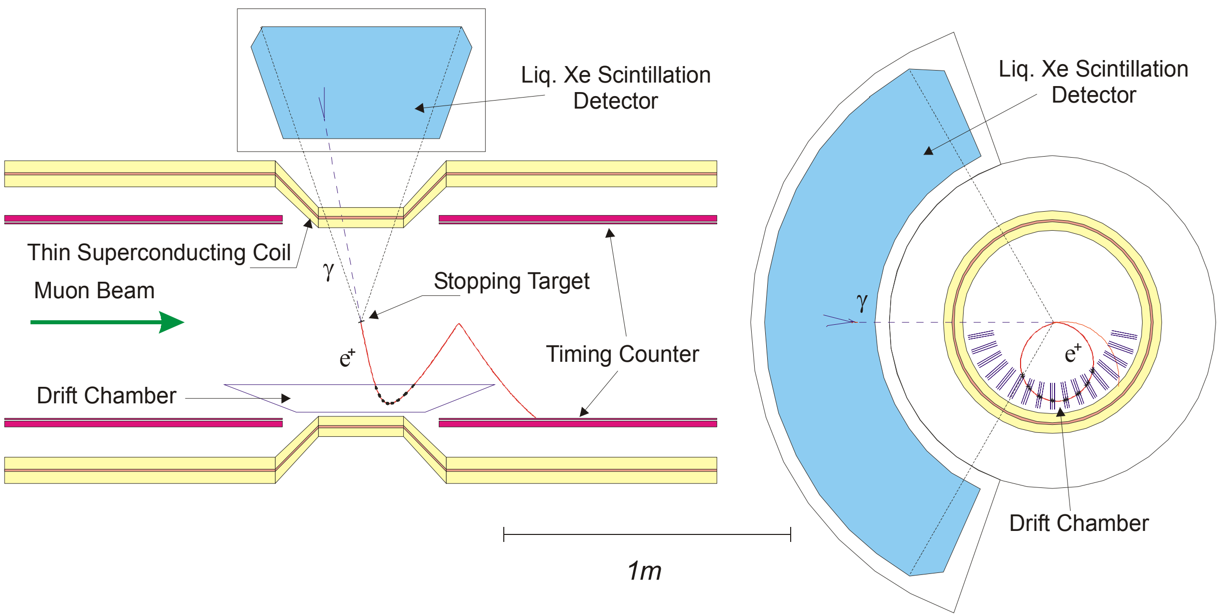
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

"large prototype"

Experimental Method

Detector Overview

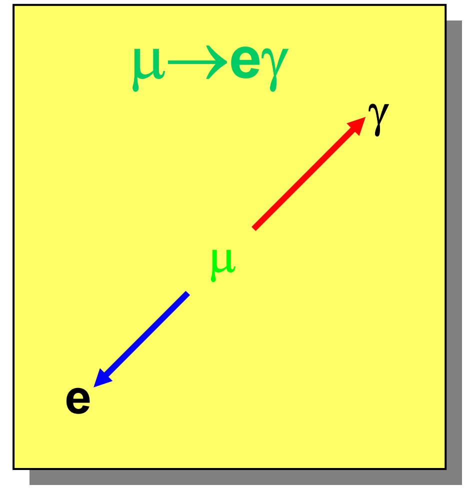


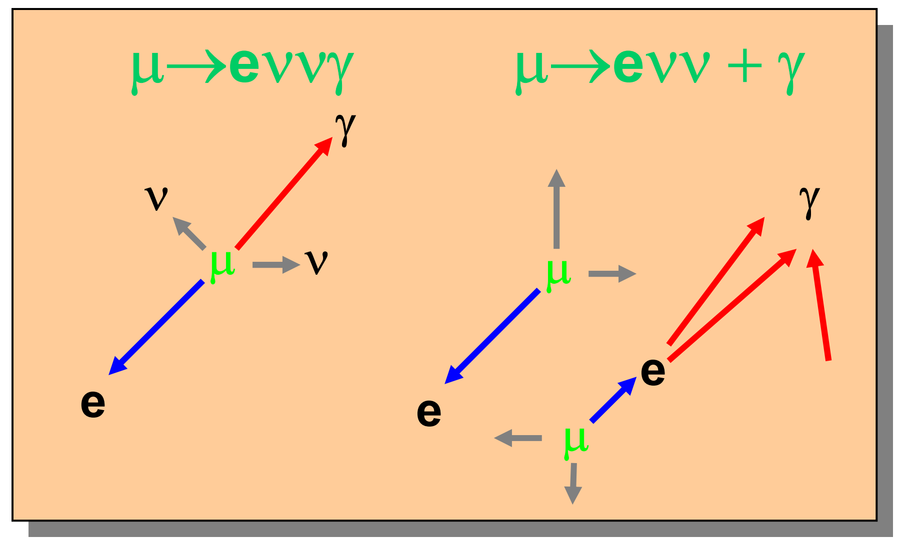


- Stopped μ beam of 10^7-10^8 s^{-1}, 100% duty factor
- Liquid Xe calorimeter for γ detection
- Solenoidal magnetic spectrometer with gradient field
- Radial drift chambers for e^+ momentum determination
- Timing counter for e^+

Signal and Background

- $\mu^+ \to e^+ \gamma$ signal very clear
  - $E_\gamma = E_{e+} = 52.8$ MeV
  - $\theta_{\gamma e+} = 180°$
  - e^+ and γ in time
- Background
  - Radiative μ^+ decays
  - Accidental overlap
- Detector Requirements
  - Excellent energy resolution
  - Excellent timing resolution
  - Good angular resolution

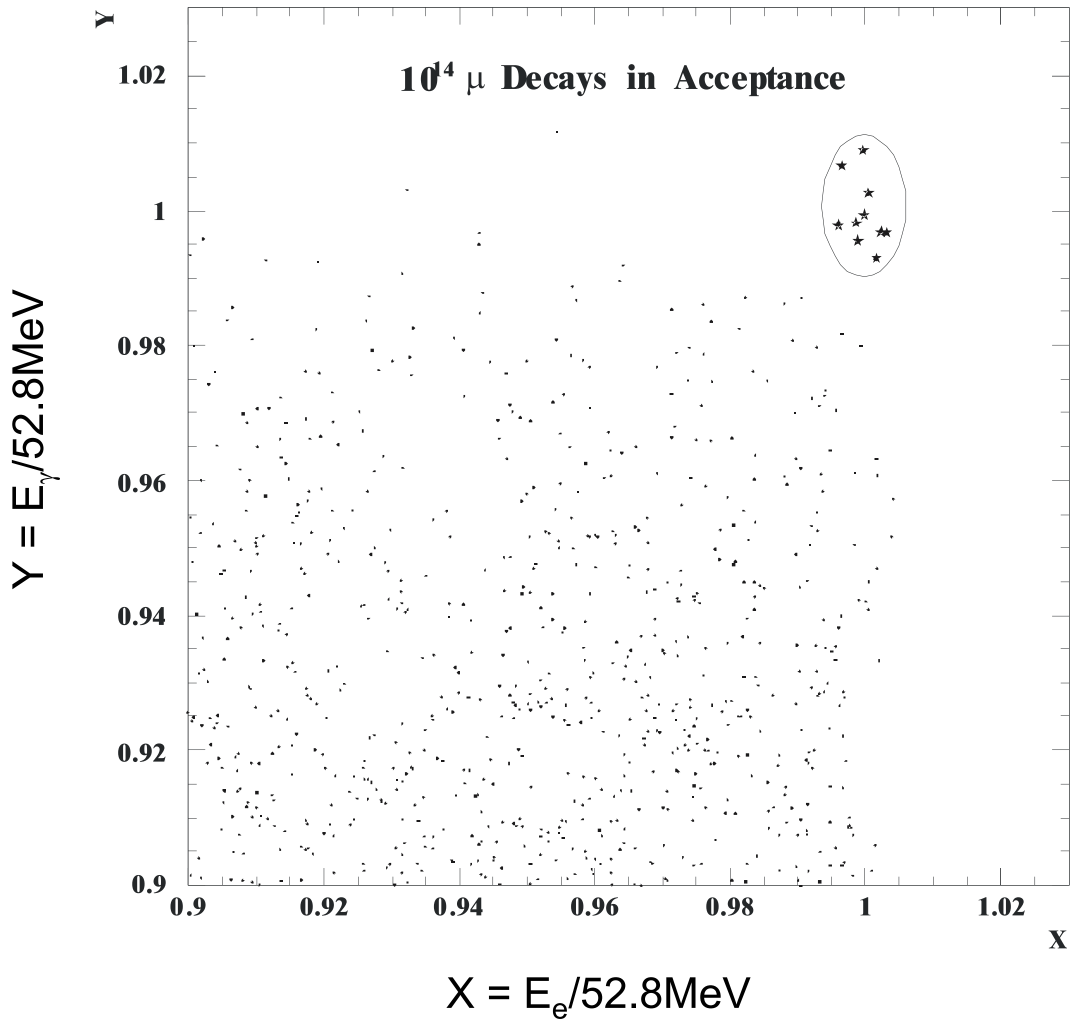




$\mu \to e\gamma$ Signature

$\mu \to e\gamma$
$E_e, E_\gamma = 52.8$MeV

$\mu \to e\gamma\nu\nu$
$E_e, E_\gamma < 52.8$MeV



Sensitivity and Background Rate

N_μ	2.5×10^7
T	2.6×10^7 s (~65 weeks)
$\Omega/4\pi$	0.09
ε_e	0.90
ε_γ	0.60
ε_{sel}	0.70

Aimed resolutions:

	FWHM
ΔE_e	0.8%
ΔE_γ	4.3%
$\Delta\theta_{e\gamma}$	19 mrad
$\Delta t_{e\gamma}$	140 ps

Single event sensitivity $(N_\mu \bullet T \bullet \Omega/4\pi \bullet \varepsilon_e \bullet \varepsilon_\gamma \bullet \varepsilon_{sel})^{-1} = 4.5\times10^{-14}$

Prompt Background $B_{pr} \cong 10^{-17}$

Accidental Background $B_{acc} \propto \Delta E_e \bullet \Delta t_{e\gamma} \bullet (\Delta E_\gamma)^2 \bullet (\Delta\theta_{e\gamma})^2 \rightarrow 3\times10^{-14}$

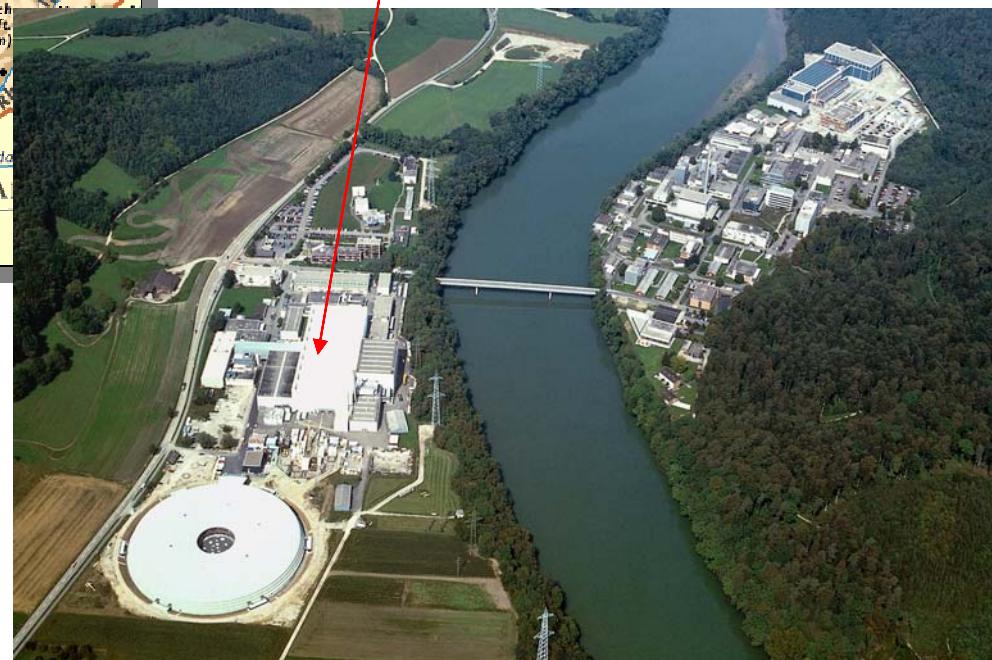
90% C.L. Sensitivity $\rightarrow 1.5\times10^{-13}$

Comparison with previous experiments

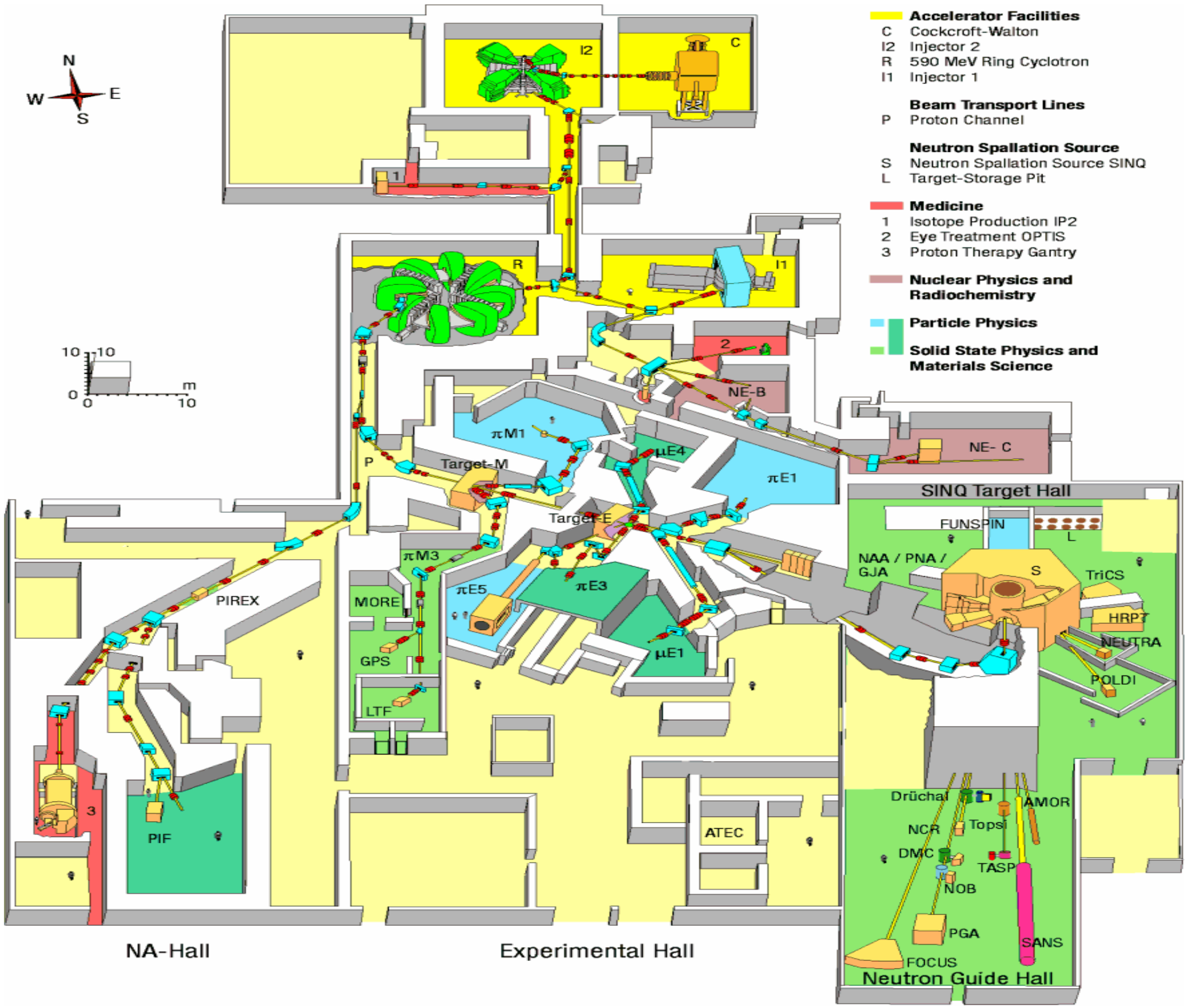
Exp./Lab	$\Delta E_e/E_e$ %FWHM	$\Delta E_\gamma/E_\gamma$ %FWHM	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Inst. Stop rate (s^{-1})	Duty cycle (%)
SIN (PSI)	8.7	9.3	1.4	-	$(4..6) \times 10^5$	100
TRIUMF	10	8.7	6.7	-	2×10^5	100
LANL	8.8	8	1.9	37	2.4×10^5	6.4
Crystal Box	8	8	1.3	87	4×10^5	(6..9)
MEGA	1.2	4.5	1.6	17	2.5×10^8	(6..7)
MEG	0.8	4.3	0.14	19	2.5×10^7	100

Paul Scherrer Institute

Experimental Hall

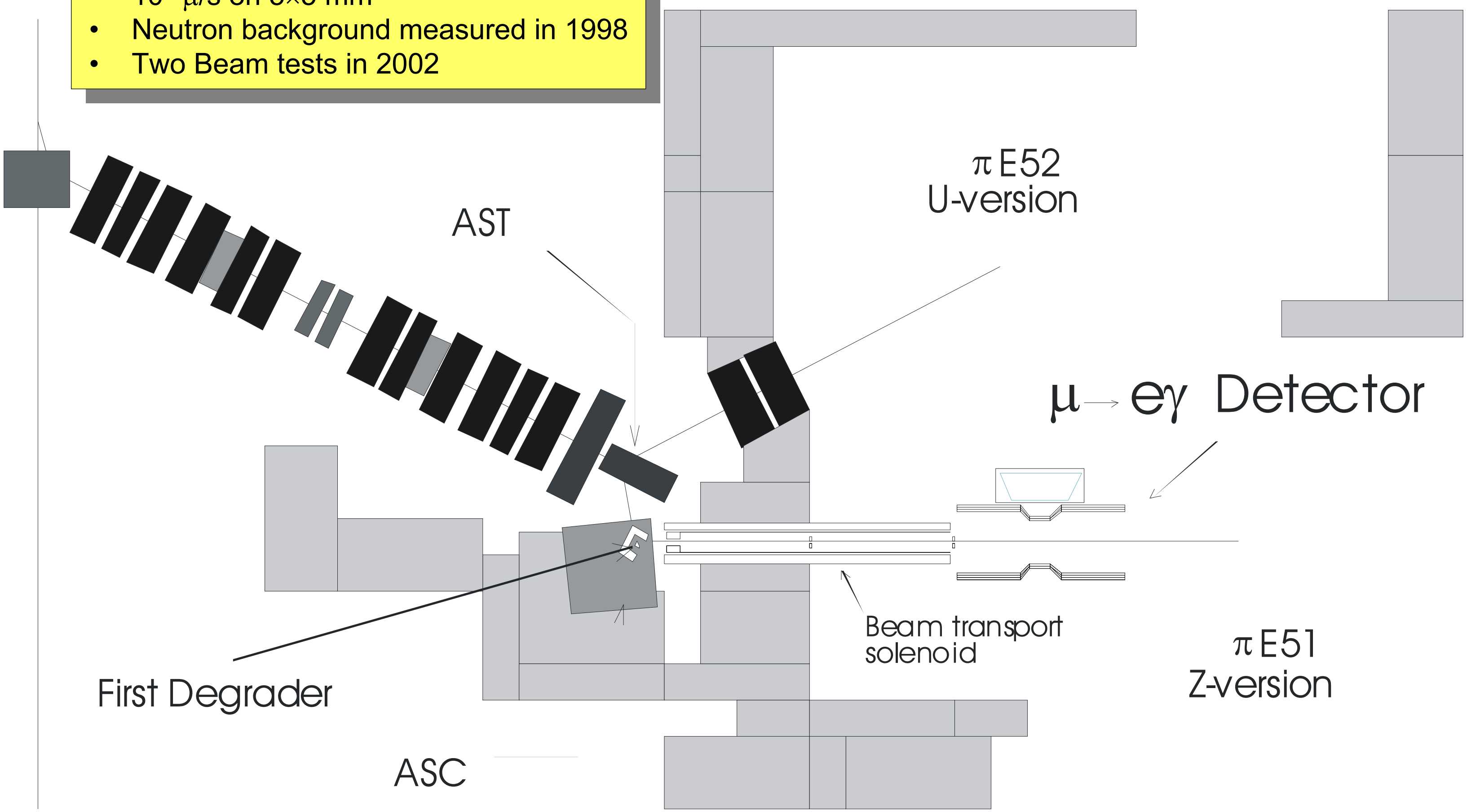


Experimental Hall

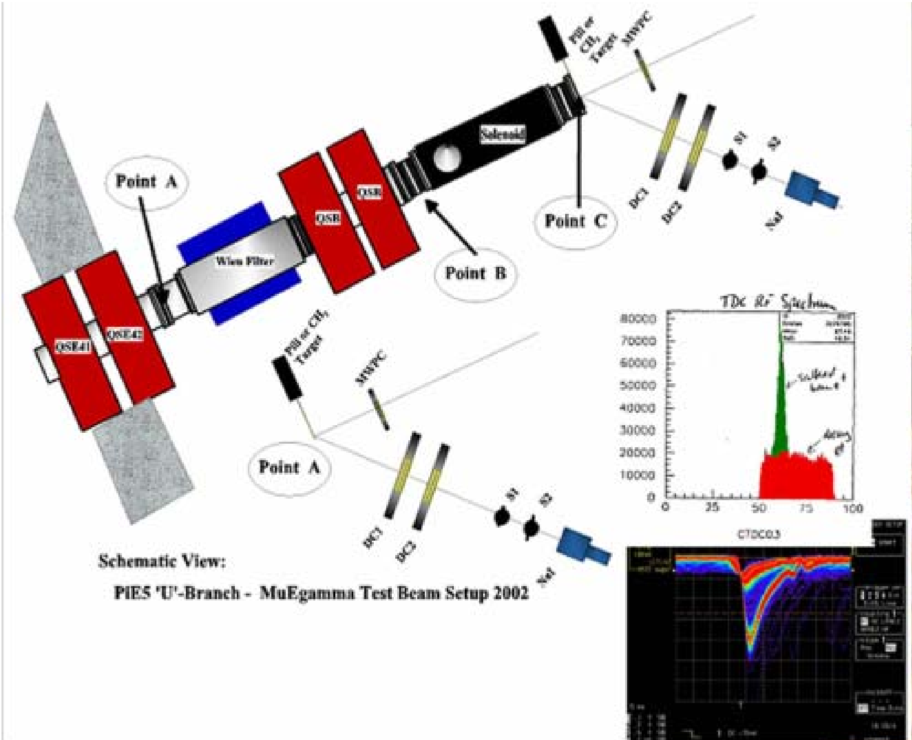


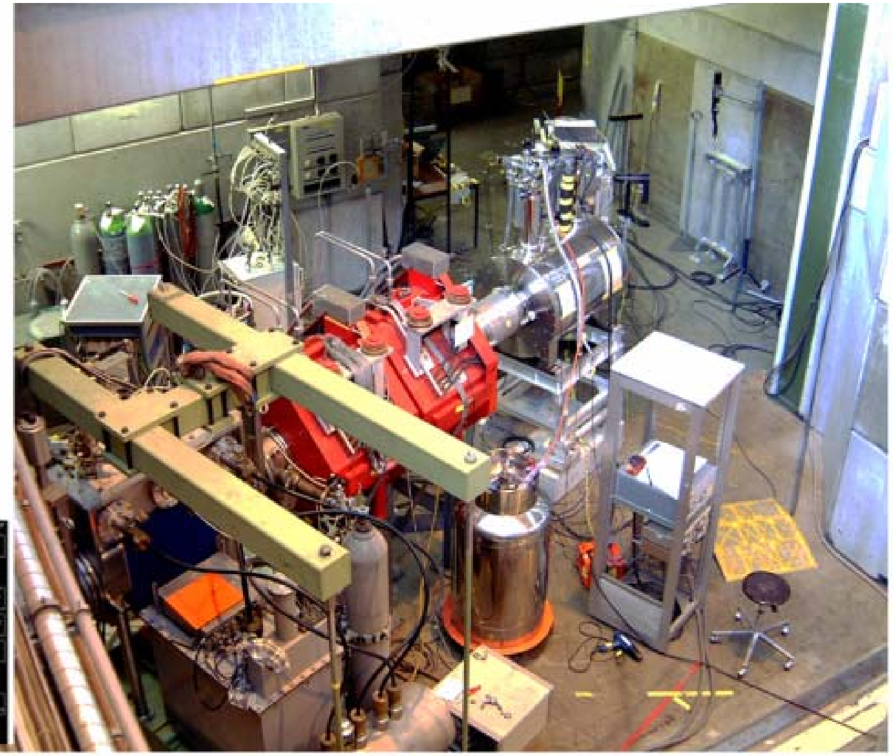
πE5 Beam Line

- 10^8 μ/s on 5×5 mm^2
- Neutron background measured in 1998
- Two Beam tests in 2002



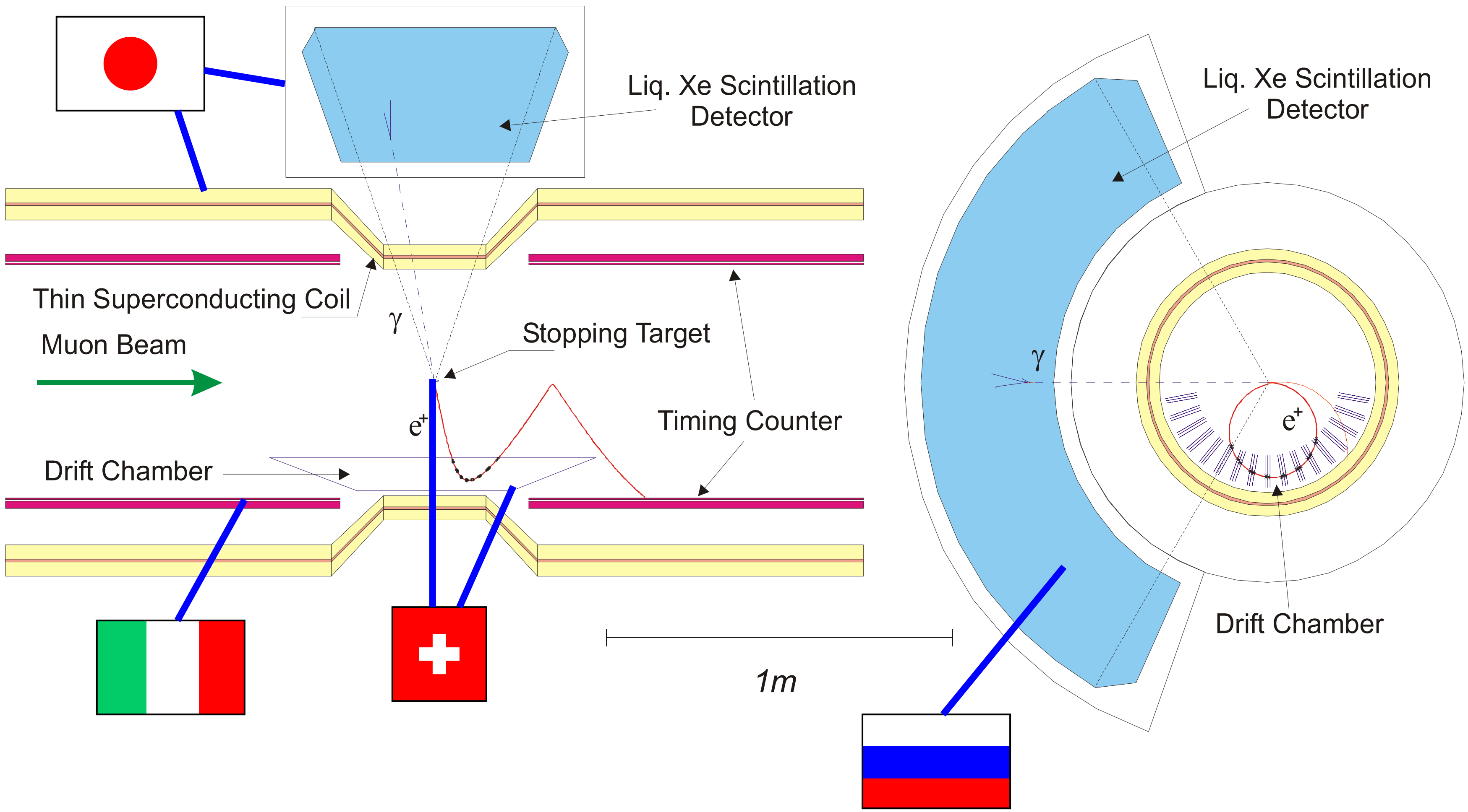
2002 beam line tests





- Electrostatic separator shows excellent background suppression (7 – 11 σ)
- Beam spot size at target ~6mm σ
- Stopping rate ~0.5-0.8 x 10^8 (short production target)

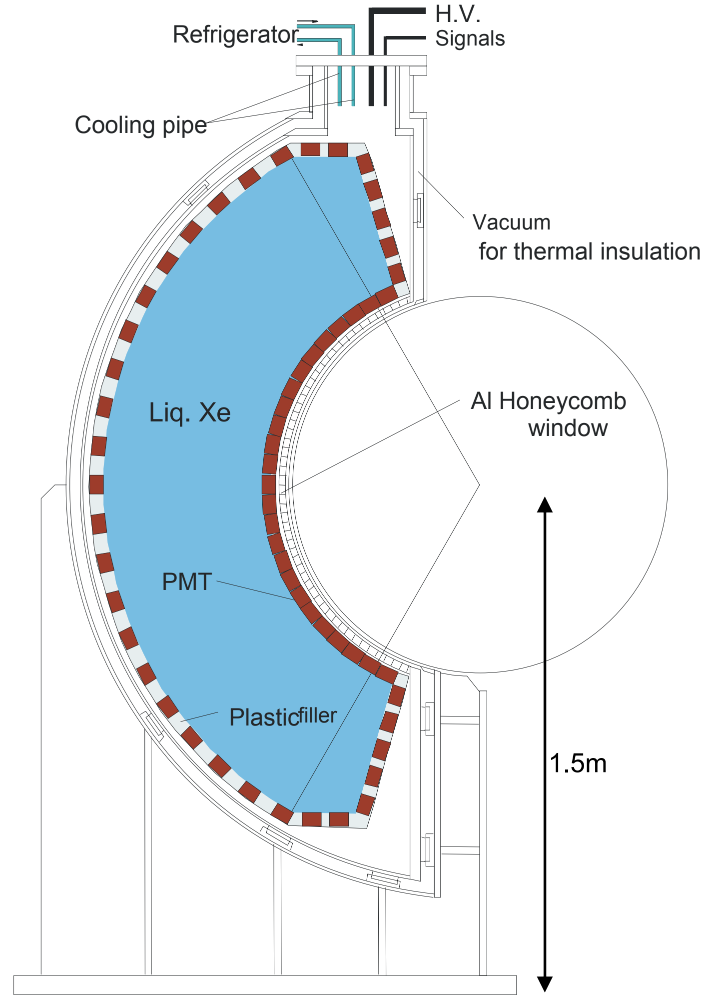
Detector


Liq. Xe Scintillation Detector
Thin Superconducting Coil
Muon Beam
γ
Stopping Target
e+
Timing Counter
Drift Chamber
1m
Liq. Xe Scintillation Detector
γ
e+
Drift Chamber

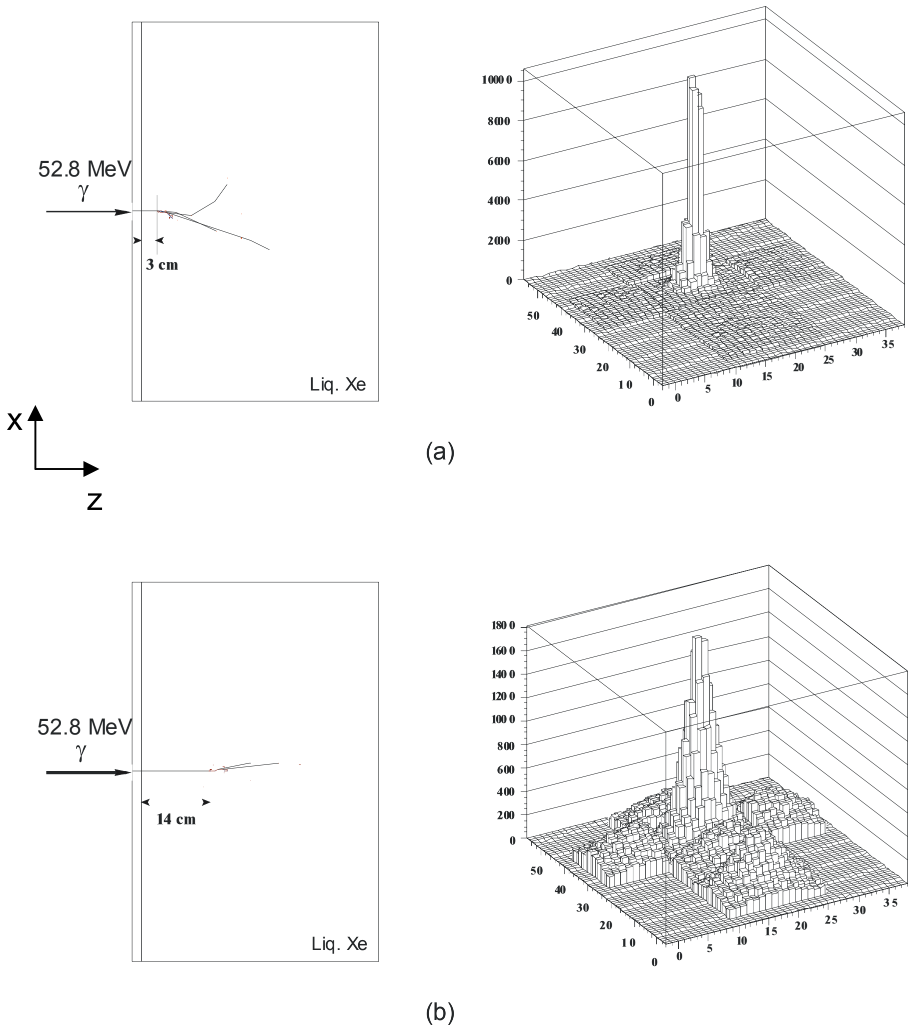
LXe Calorimeter

- ~800l liquid Xe (3t)
- ~800 PMTs immersed in LXe
- Only scintillation light detected
- Fast response (45 ns decay time)
- High light output (70% of NaI(Tl))[1)]
- High uniformity compared with segmented calorimeters
- High channel occupancy will be accommodated by special trigger scheme

1) T. Doke and K. Masuda, NIM A 420 (1999) 62



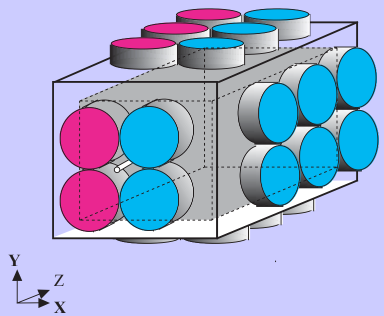
γ Response



- Signal is distributed over many PMTs in most cases
- Weighted mean of PMTs on the front face
  → δx ~ 10mm FWHM
- Broadness of distribution
  → δz ~ 16mm FWHM
- Timing resolution
  → δt ~ 100ps FWHM
- Energy resolution
  ~ 4.3% FWHM
  depends on light attenuation in LXe

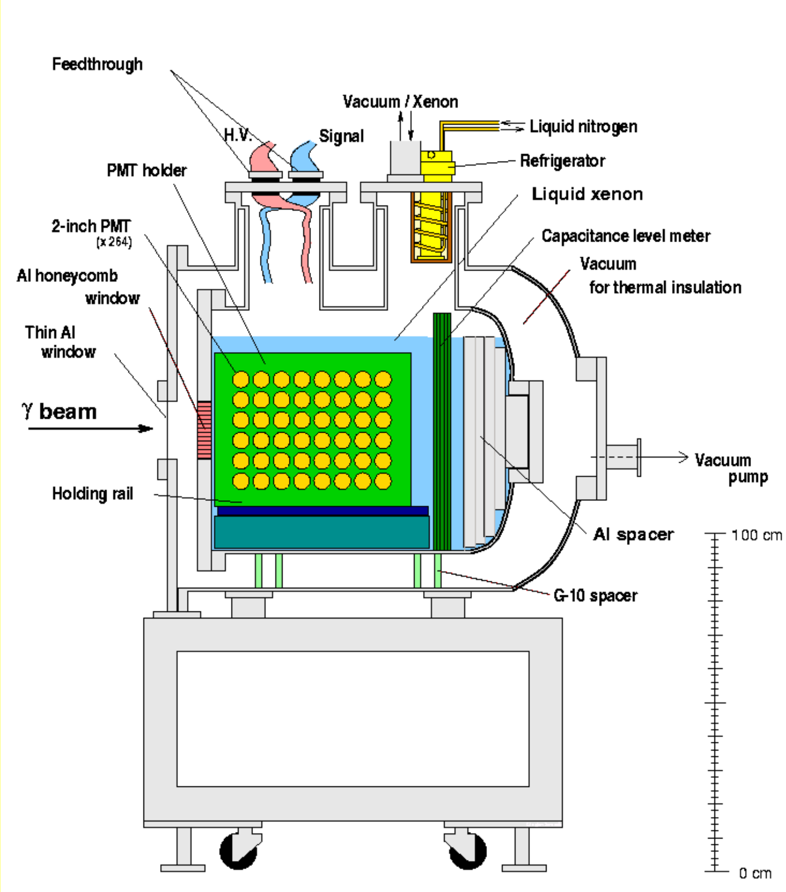
Calorimeter Prototypes

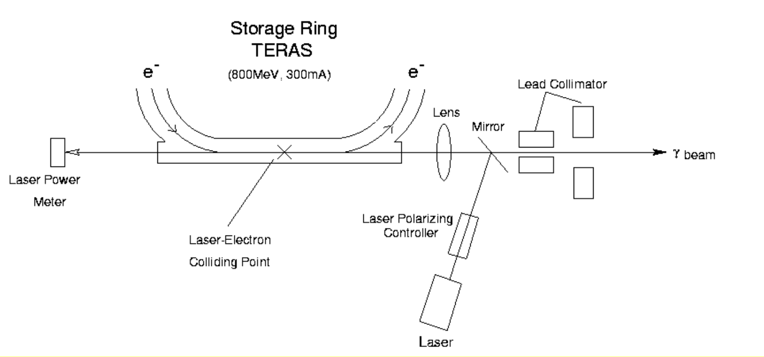
"Small"



- 32 PMTs, 2.3 l LXe
- Tested with radioactive sources ^{51}Cr, ^{137}Cs, ^{54}Mn, ^{88}Y
- Extrapolated resolutions at 52.8 MeV in agreement with quoted numbers

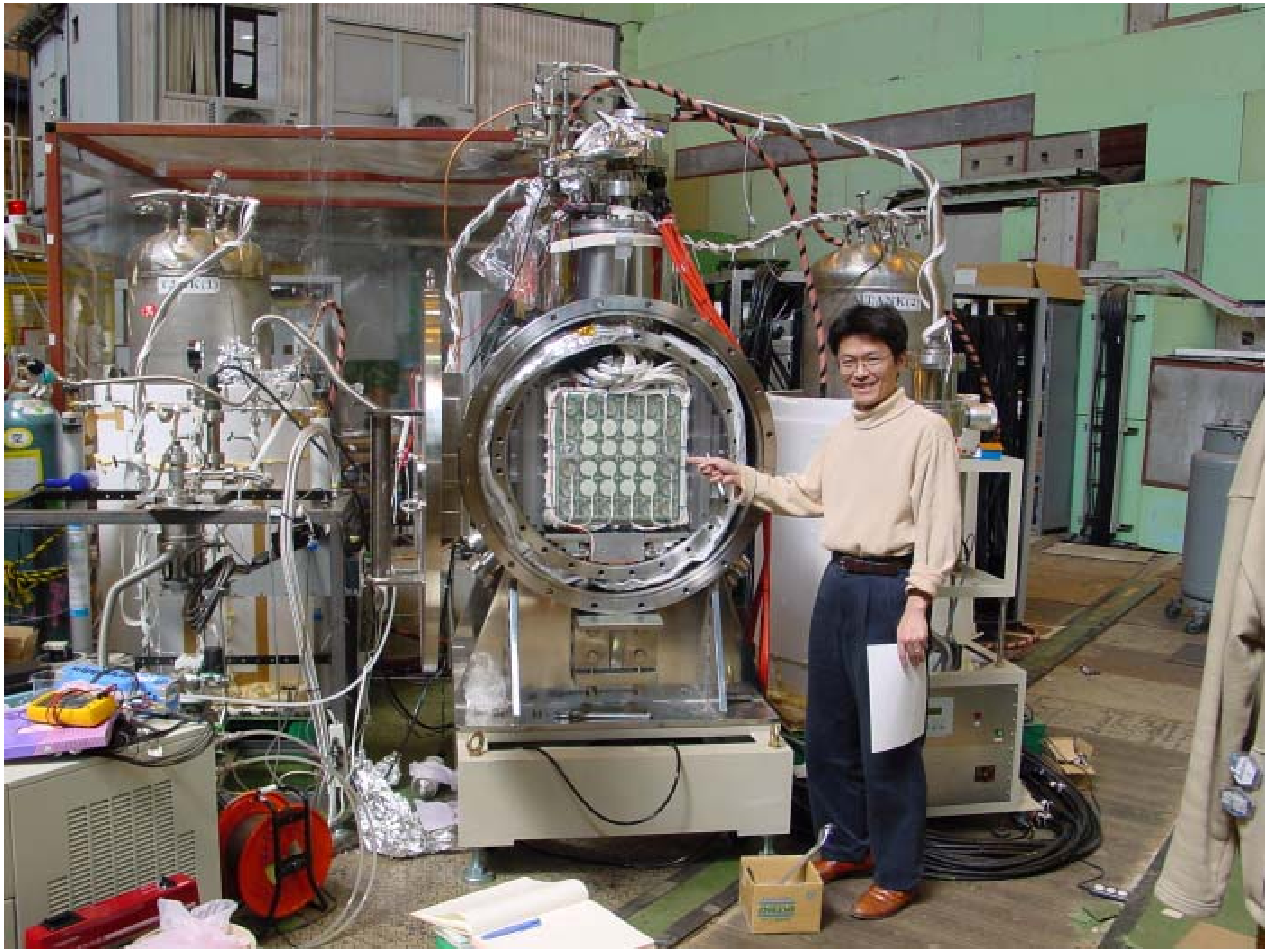
"Large"





Measure resolutions with 40 MeV photon beam at ETL, Tsukuba, Japan

Large Prototype

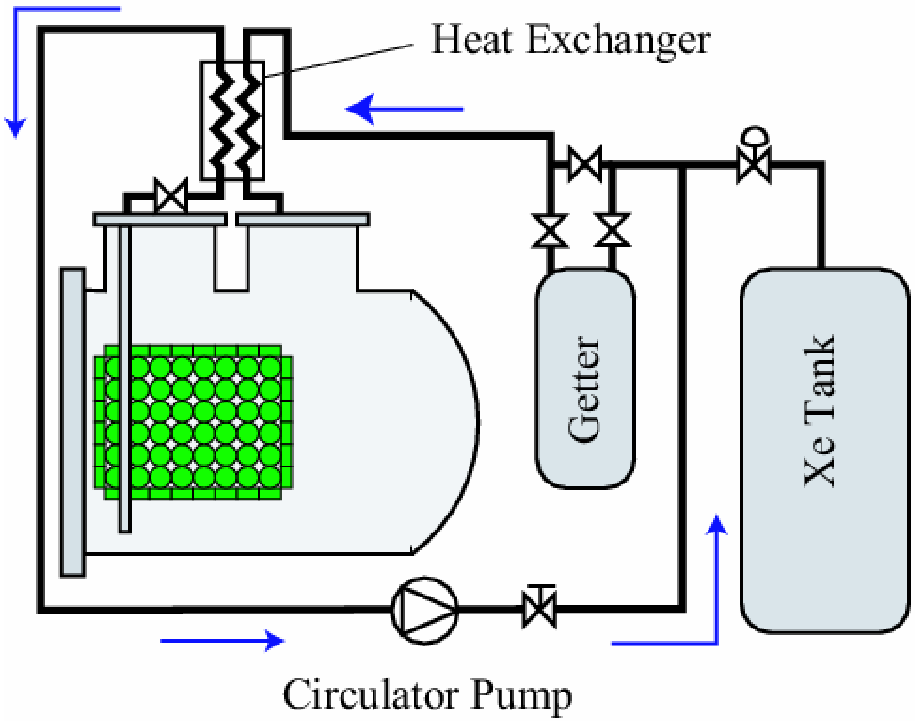


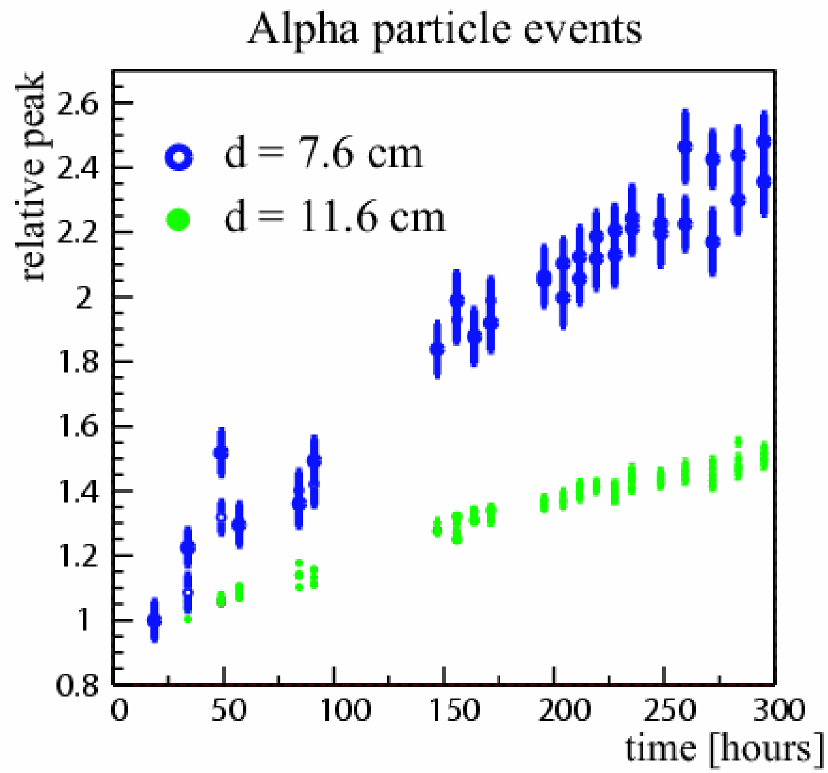
- Currently largest LXe detector in the world (224 PMTs, 150l),
- Contains all critical parts of final detector
- Can measure light attenuation length up to ~1m

Light attenuation

- Two beam tests, many α-source and cosmic runs in Tsukuba, Japan
- Light attenuation much too high (~10x)
- Cause: ~3ppm of Water in LXe
- Cleaning with "hot" Xe-gas before filling did not help
- Water from surfaces is only absorbed in LXe
- Constant purification necessary
- Filter system works, attenuation length can be improved with a time constant of ~350 hours

Purification System

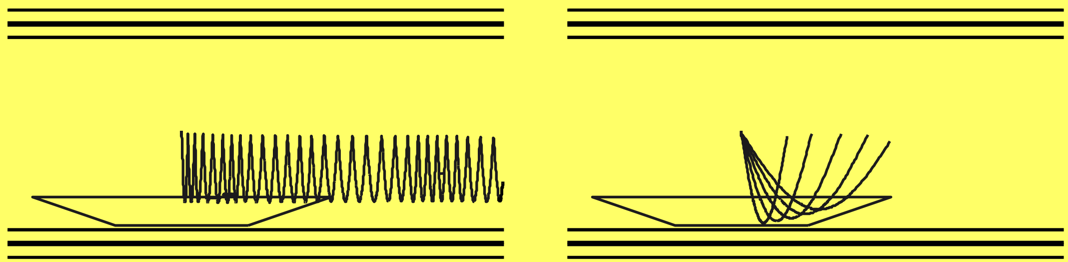




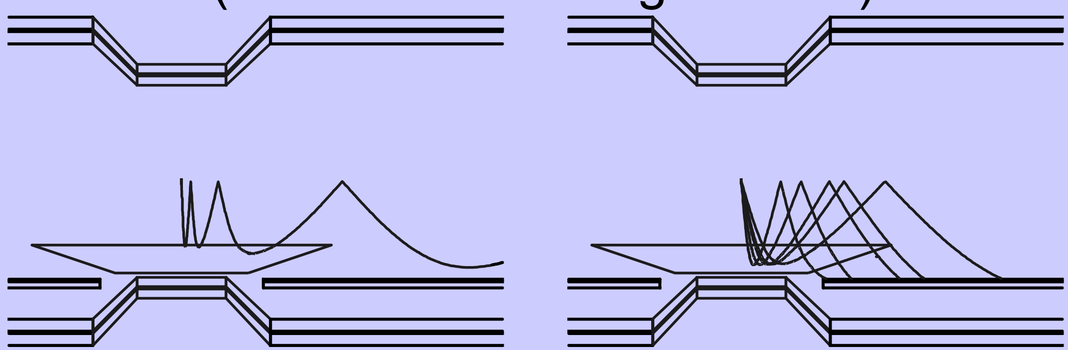
- Works acceptable in gas mode, τ = 350h
- Should be much faster in liquid mode
- Redesign in progress

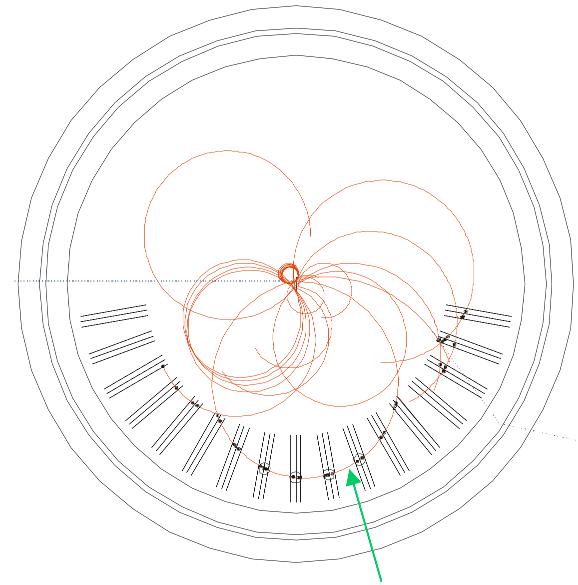
Positron Spectrometer

Homogeneous Field



Gradient Field (COnstant-Bending-RAdius)



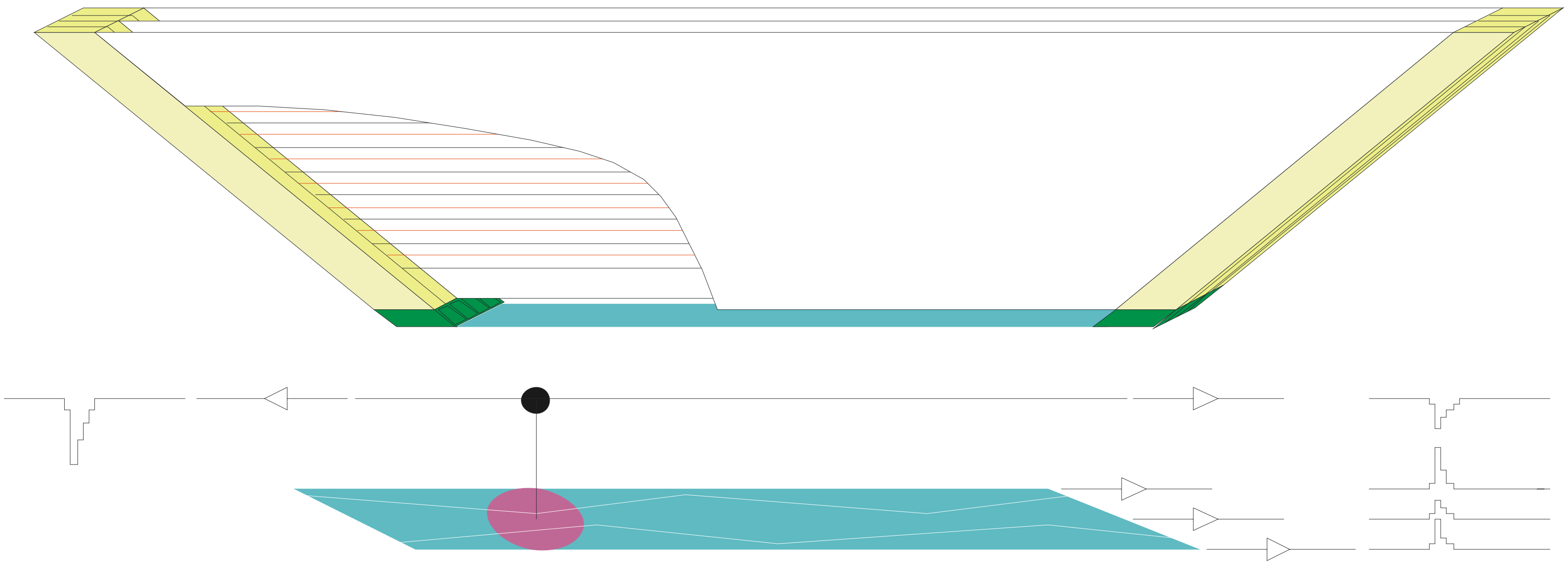


e⁺ from $\mu^+ \rightarrow e^+ \gamma$

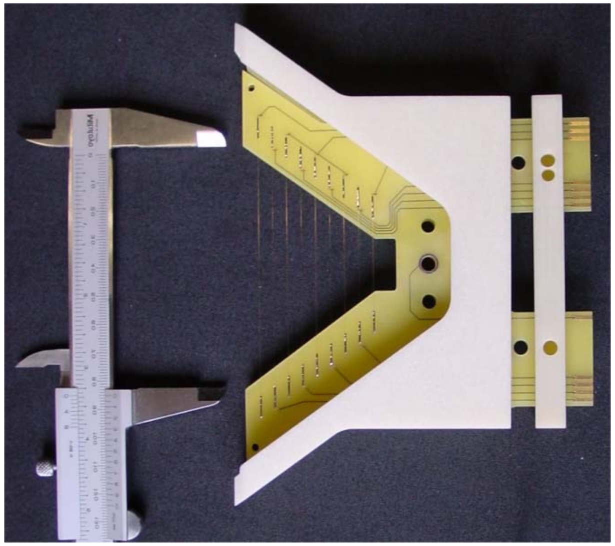
Ultra-Thin (~3g/cm2) superconducting solenoid with 1.2 T field

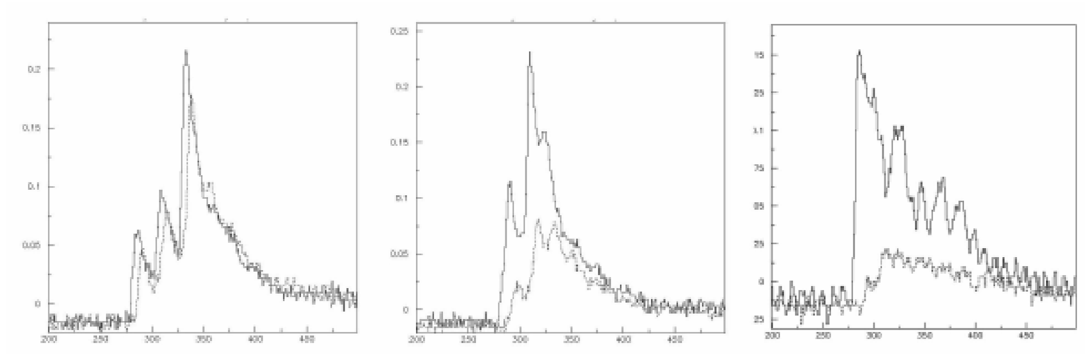
Drift Chamber

- 16 radial chambers with 20 wires each
- Staggered cells measure both position and time
- He – C_2H_6 gas to reduce multiple scattering
- Vernier pattern to determine z coordinate

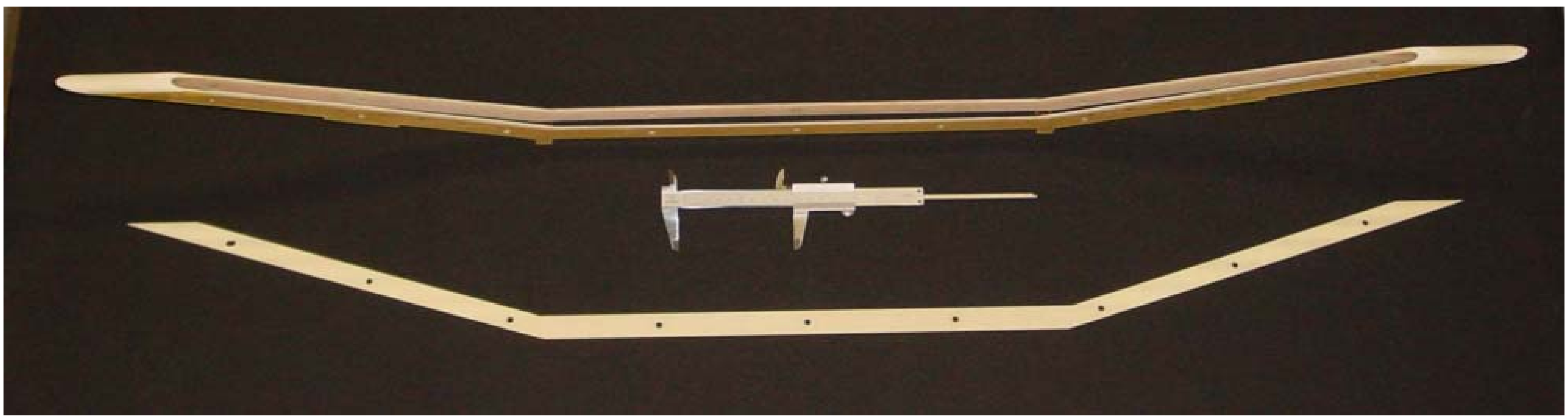


Prototype Tests at PSI

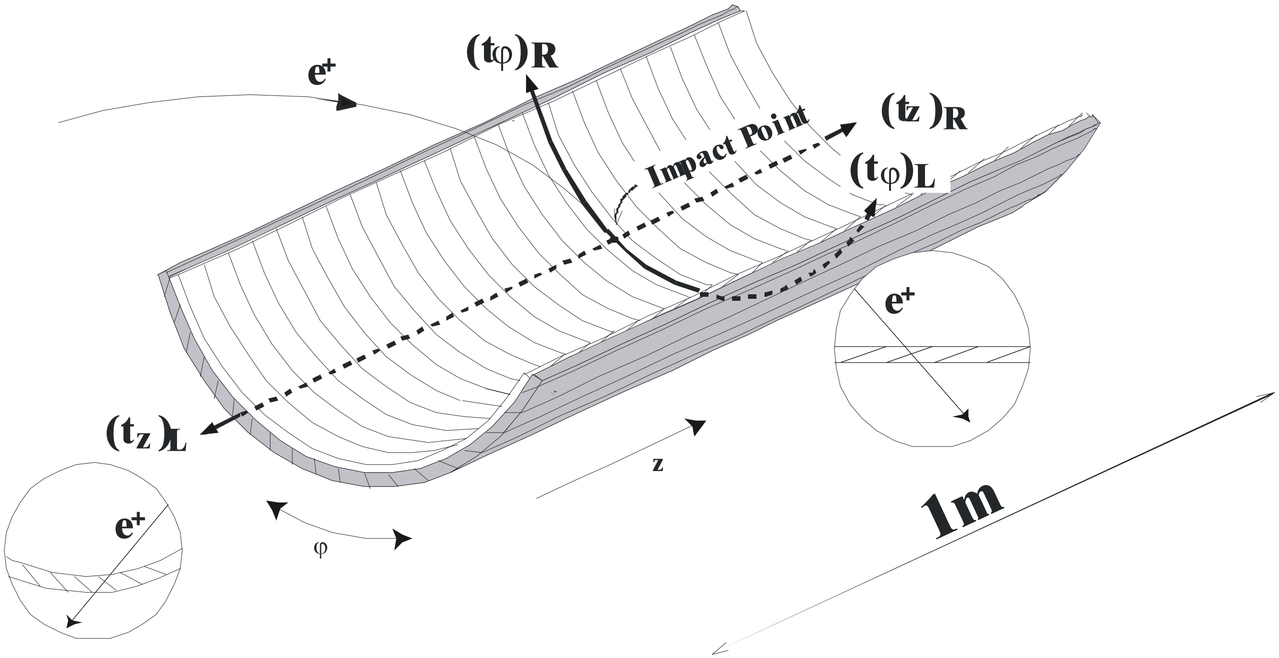




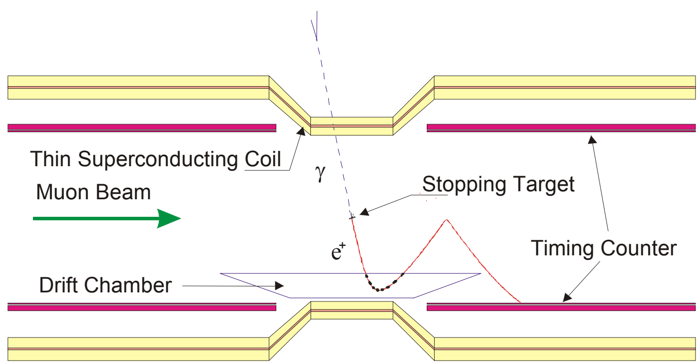
- Anode charge division tests successful
- Fast preamplifier with FADC (~200MHz)



Positron timing counter



- Aimed resolution ~100ps FWHM
- Tests with cosmic μ confirmed 100ps FWHM



http://meg.psi.ch/subprojects/tcount/

Status of R & D

- Complete MC, much improved compared to original proposal
- Beam line mode found with high rate and low contamination
- Positron detector prototype confirms 100ps resolution
- Large prototype LXe detector shows that originally planned resolution cannot be reached ($10^{-14} \rightarrow 10^{-13}$)
- Drift chamber seems to meet design goal
- We are confident that the experiment can be made at the 10^{-13} level with current technologies
- Start building full detector, develop electronics

Sensitivity Calculator

Electronics

Trigger

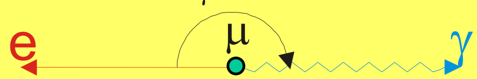
DAQ

Slow-Control

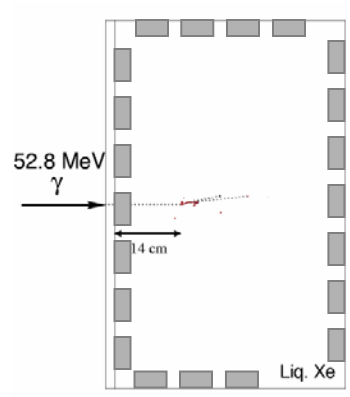
Trigger Requirements

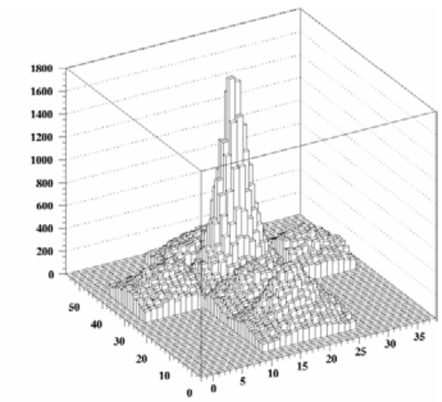
Kinematics

$\theta_{e\gamma} = 180°$



E_e = 52.8 MeV E_g = 52.8 MeV



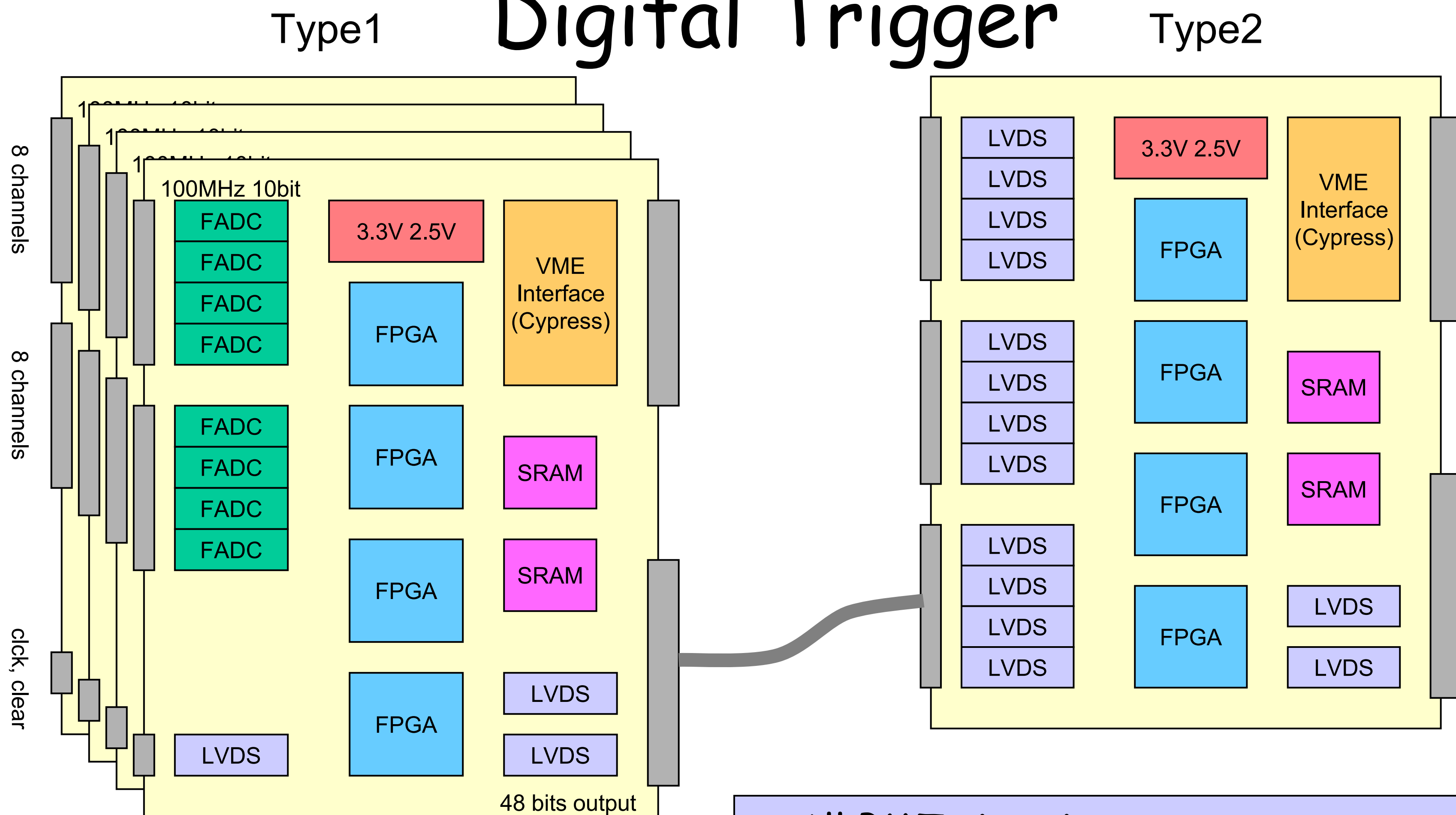


❖ Beam rate	10^8 s^{-1}
❖ Fast LXe energy sum > 45MeV	2×10^3 s^{-1}
❖ γ interaction point	
❖ e^+ hit point in timing counter	
❖ time correlation $\gamma - e^+$	200 s^{-1}
❖ angular corrlation $\gamma - e^+$	20 s^{-1}

M.C.

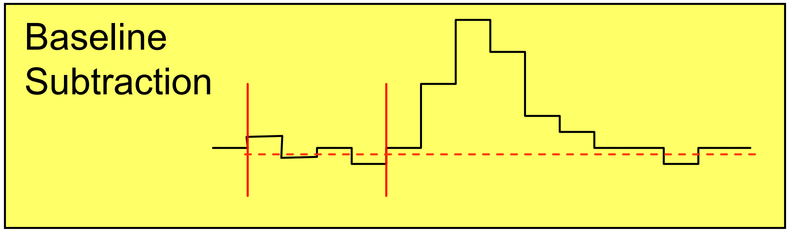
- Total ~800 PMTs
- Common noise contributes significantly to analog sum
- AC coupling → Baseline drift
- How to evaluate θ,φ of shower center?

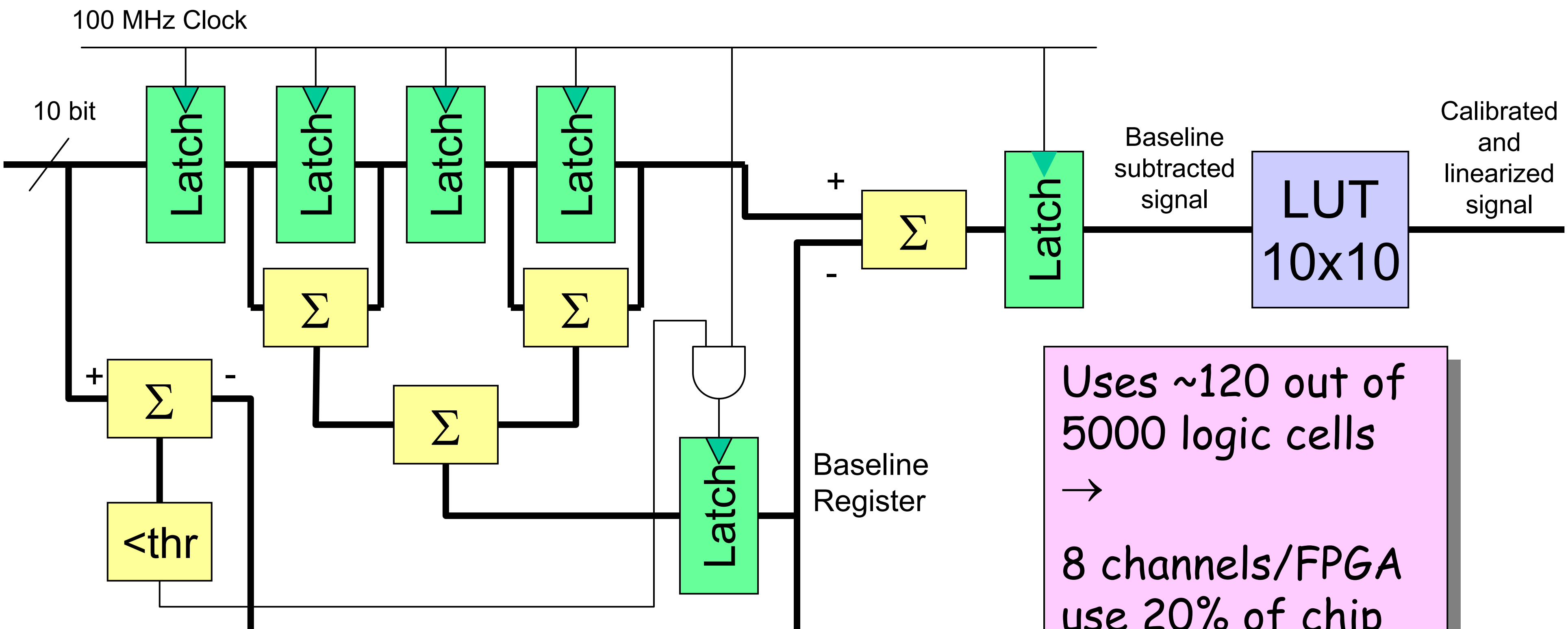
Digital Trigger



- All PMTs in trigger
- Board hierarchy with LVDS interconnect
- Use FPGA with double capacity

Baseline Subtraction



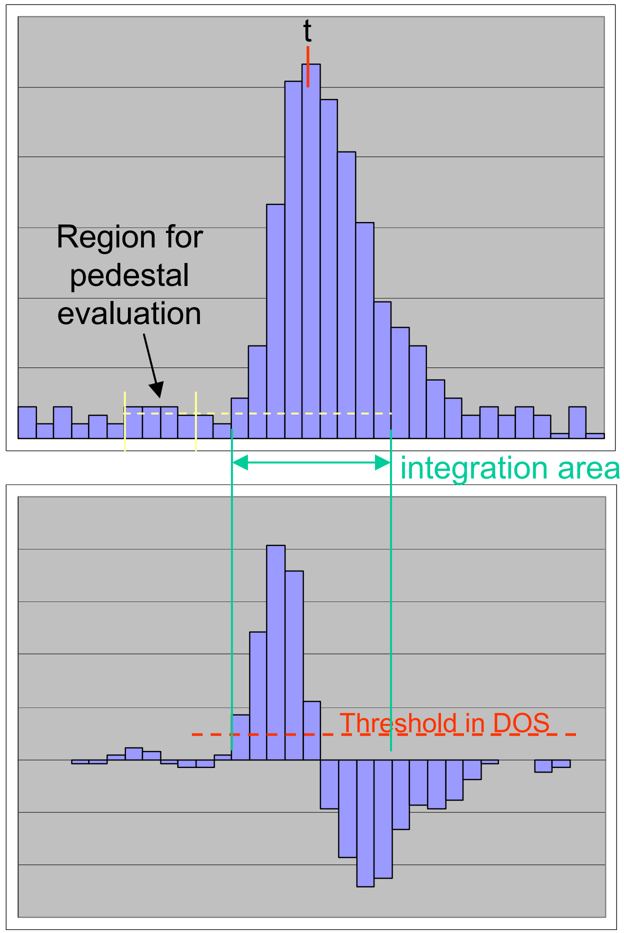


Uses ~120 out of 5000 logic cells
→
8 channels/FPGA use 20% of chip

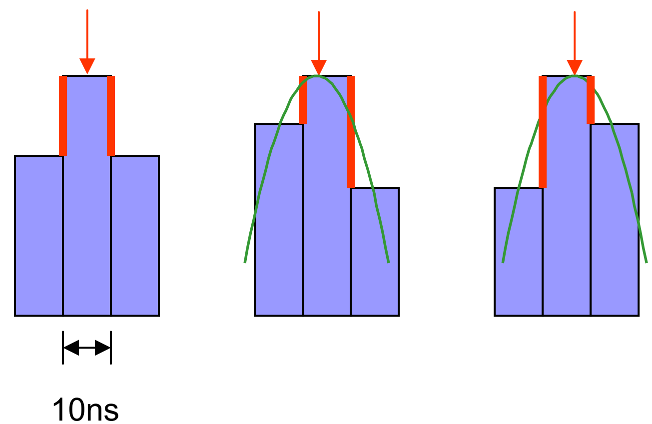
QT Algorithm

original waveform

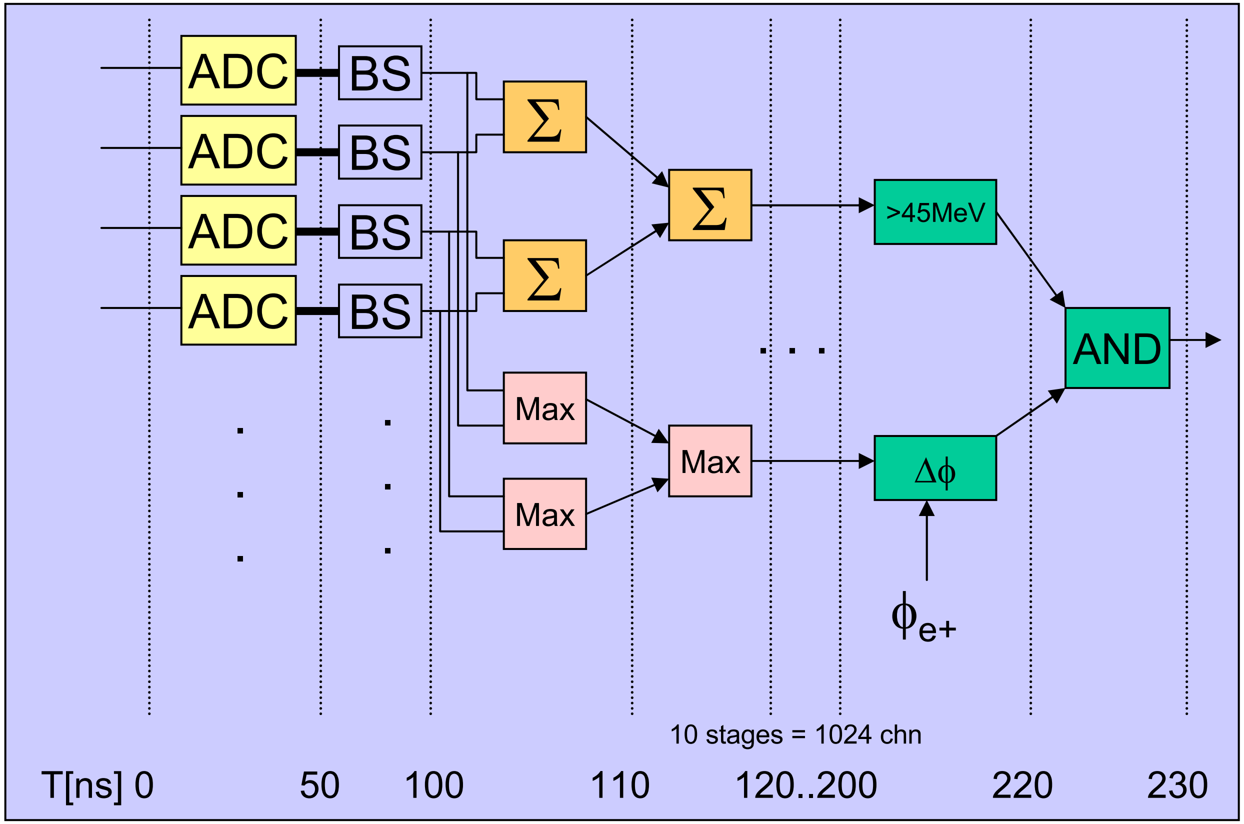
smoothed and differentiated (Difference Of Samples)



- Inspired by H1 Fast Track Trigger (A. Schöning)
- Hit region defined when Difference of Samples is above threshold
- Integration of original signal in hit region
- Pedestal evaluated in region before hit
- Time interpolated using maximum value and two neighbor values in LUT → 1ns resolution for 10ns sampling time



Trigger latency

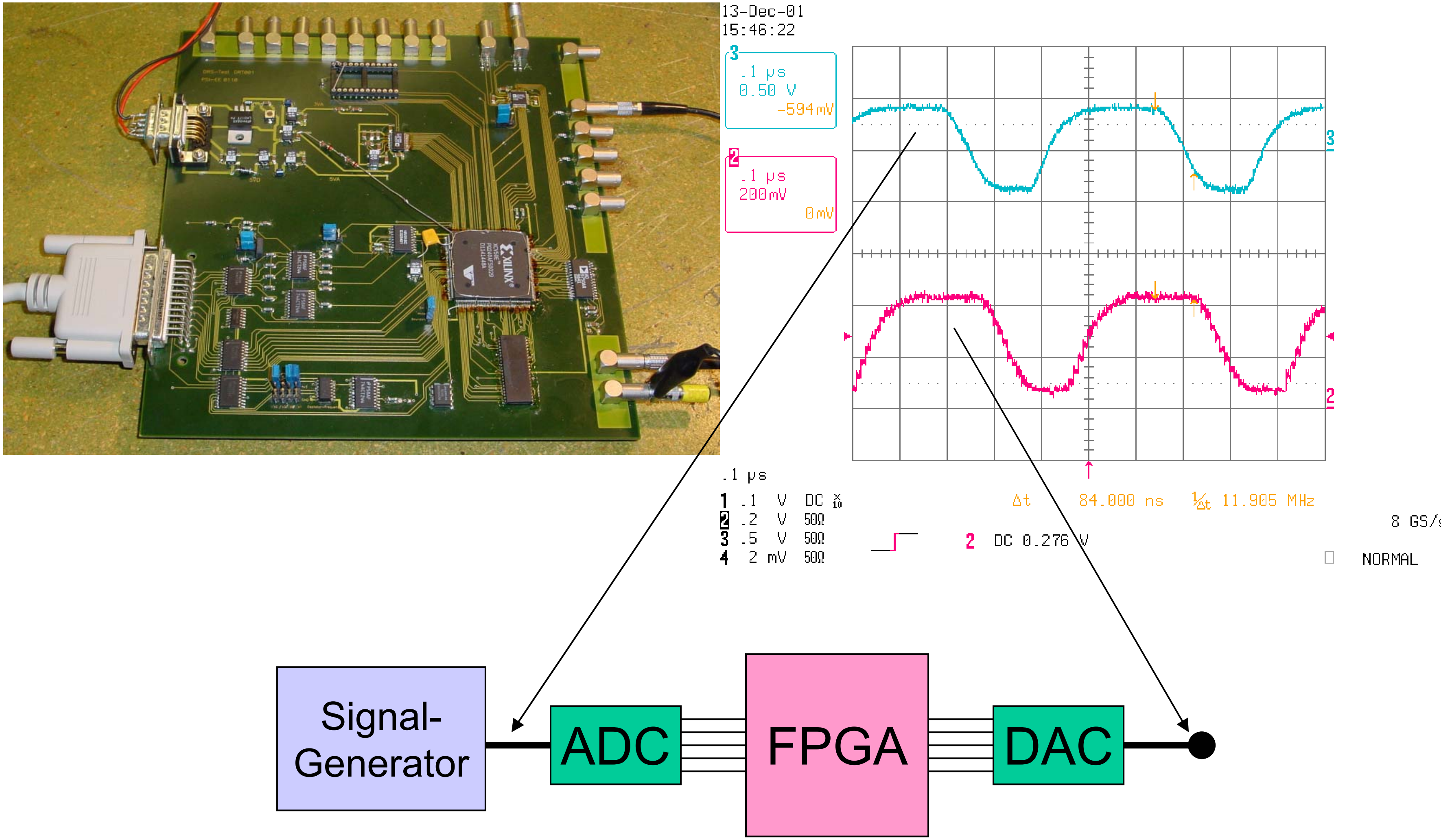


~600 chn. / 10 bit
At 100 MHz

→ 75 GB/s
processing power
In 2 VME crates

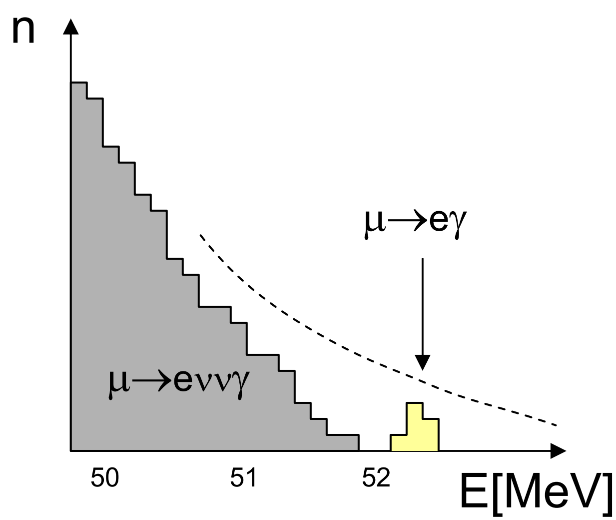
Inter-board communication: 120ns
Total: 350ns (simulated)

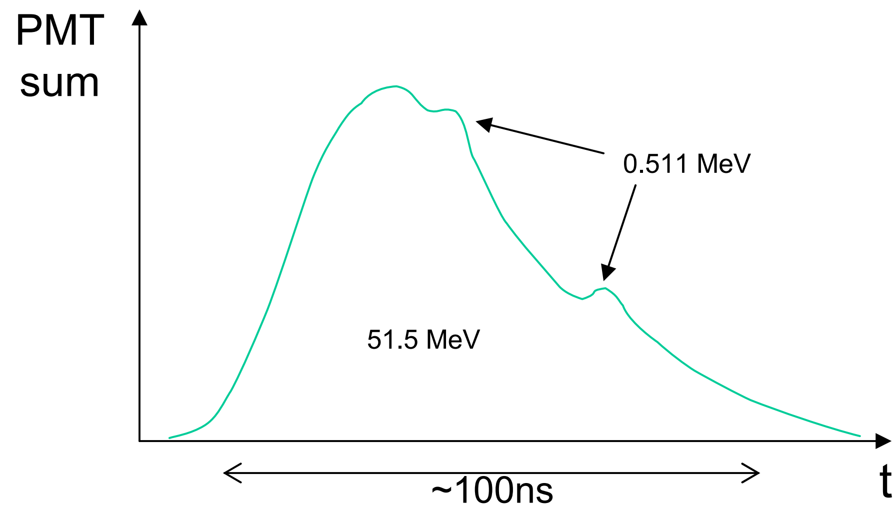
Prototype board

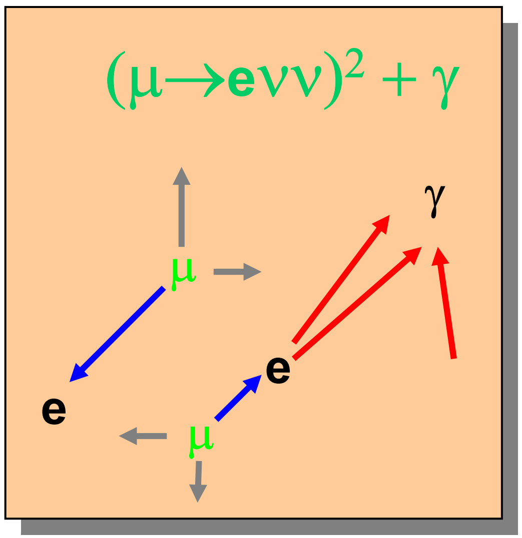


DAQ Electronics

DAQ Requirements

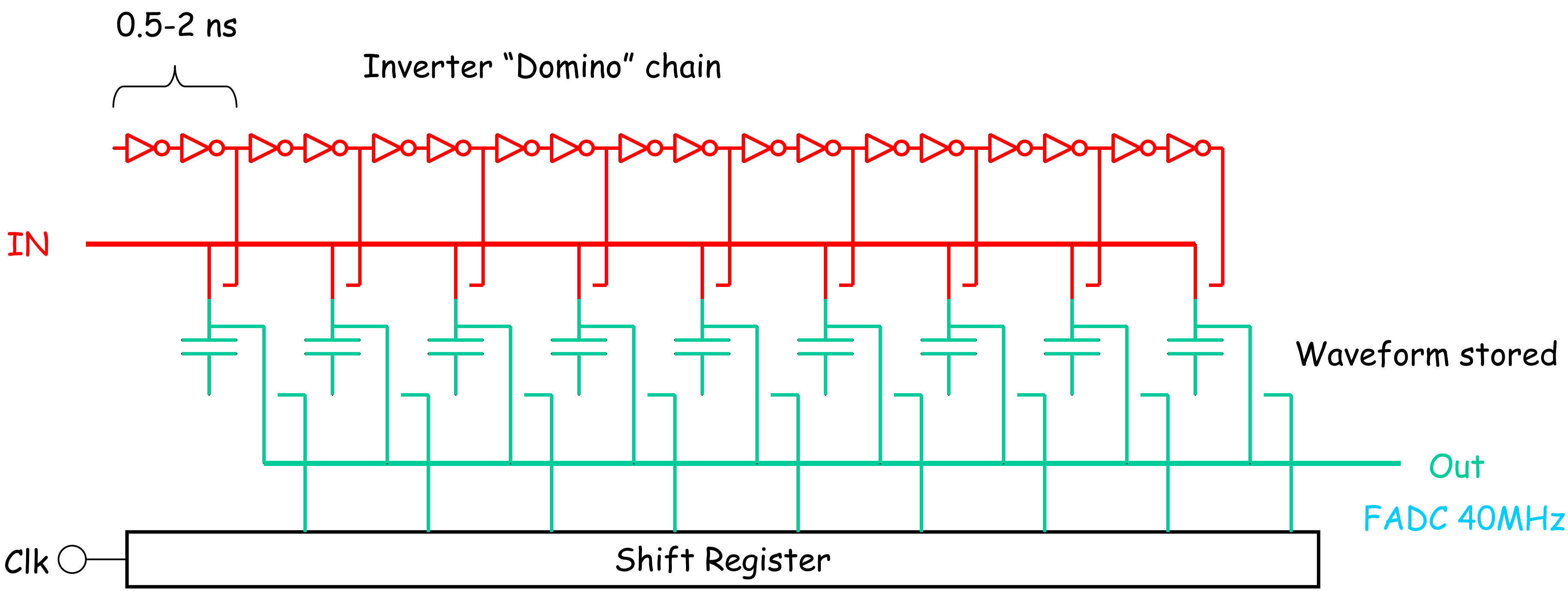






- γ's hitting different parts of LXe can be separated if > 2 PMTs apart (15 cm)
- Timely separated γ's need waveform digitizing > 300 MHz
- If waveform digitizing gives timing <100ps, no TDCs are needed

Domino Sampling Chip Principle

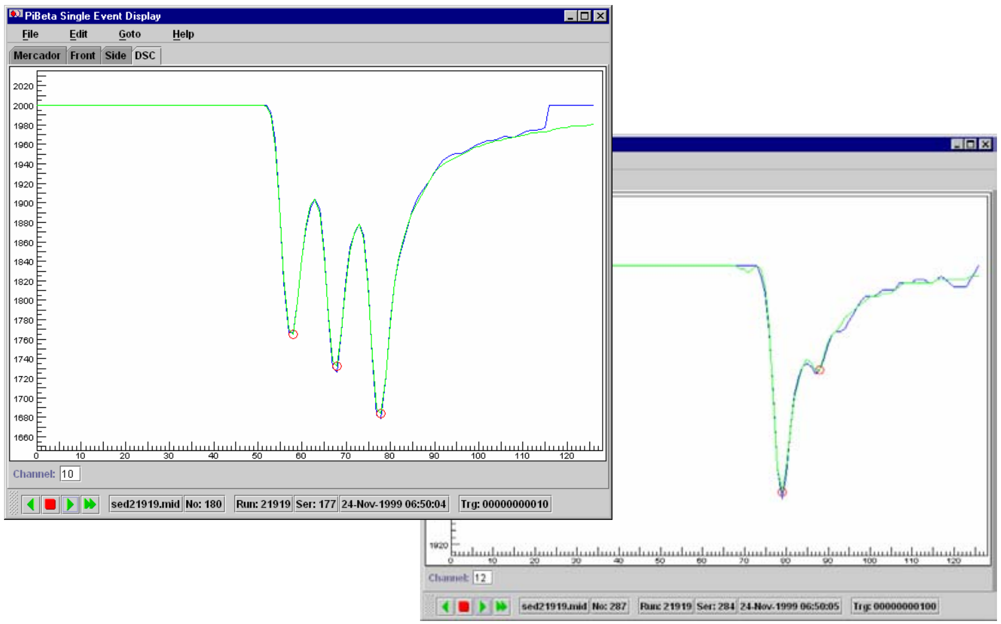


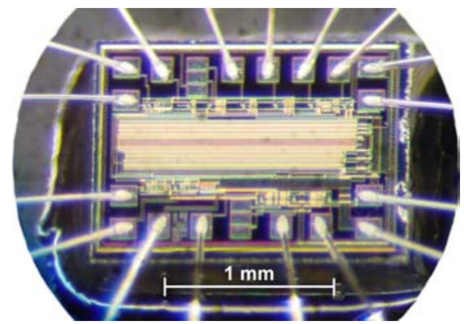
"Time stretcher" GHz → MHz

πβ Domino Sampling Chip

Existing:
- 0.5 – 1.2 GHz sampling speed
- 128 sampling cells
- Readout at 5 MHz, 12 bit
- ~ 60 $/channel

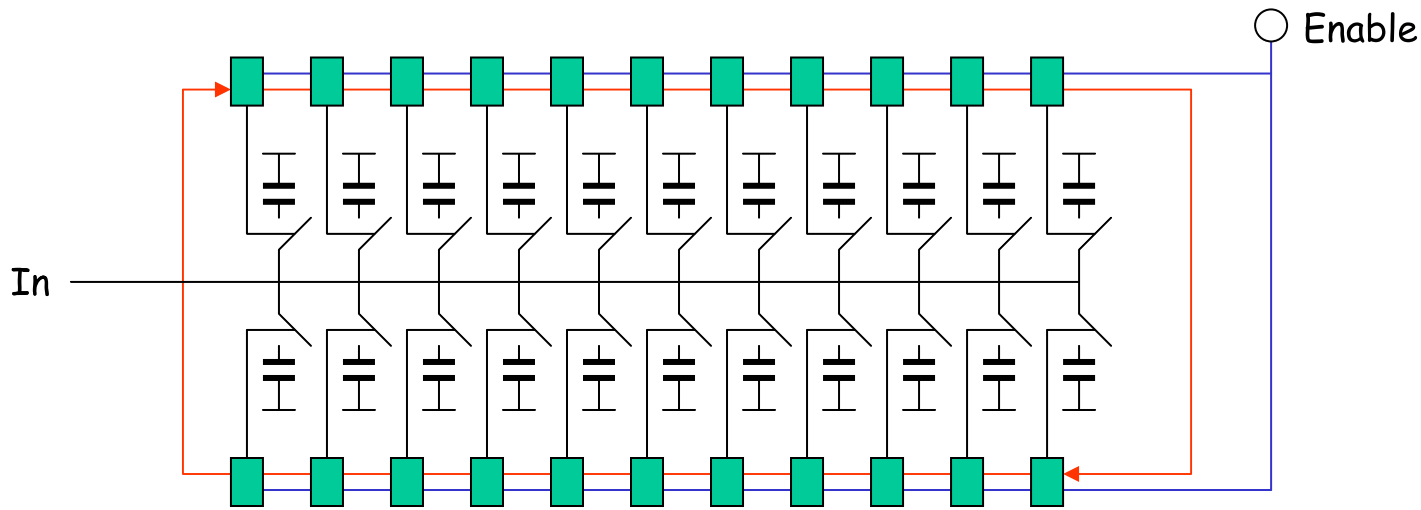
Needed:
- 2.5 GHz sampling speed
- Circular domino wave
- 1024 sampling cells
- 40 MHz readout
- < 100ps accuracy





C. Brönnimann *et al.*, NIM A420 (1999) 264

Domino Ring Sampler (DRS)

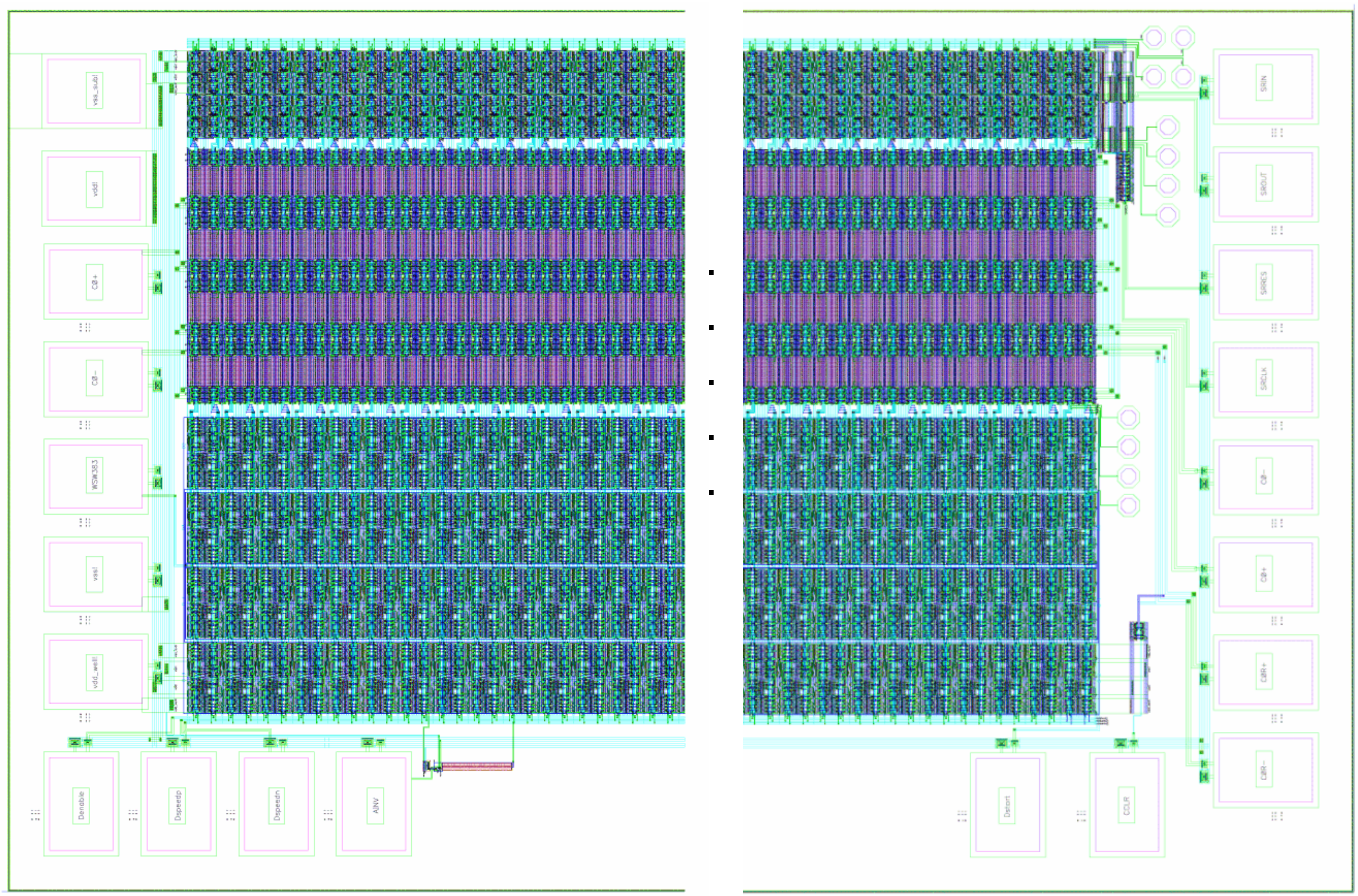


- Free running domino wave, stopped with trigger
- Sampling speed 2 GHz (500ps/bin), trigger gate sampling gives 50ps timing resolution
- 1024 bins → 150ns waveform + 350ns delay

First DRS Prototype

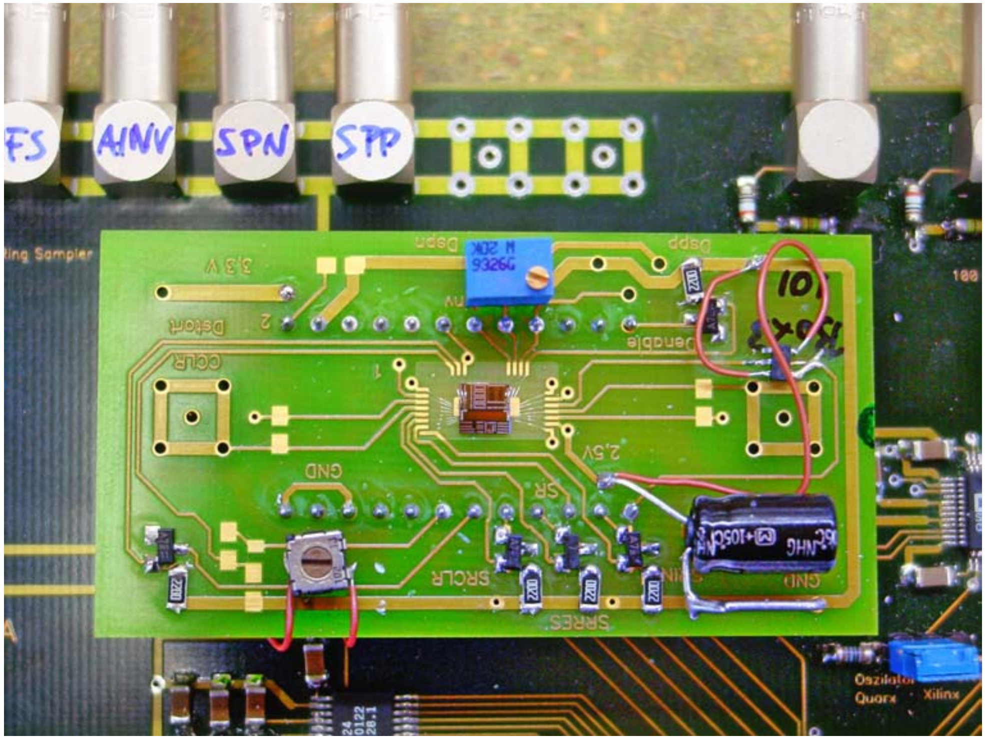
4mm

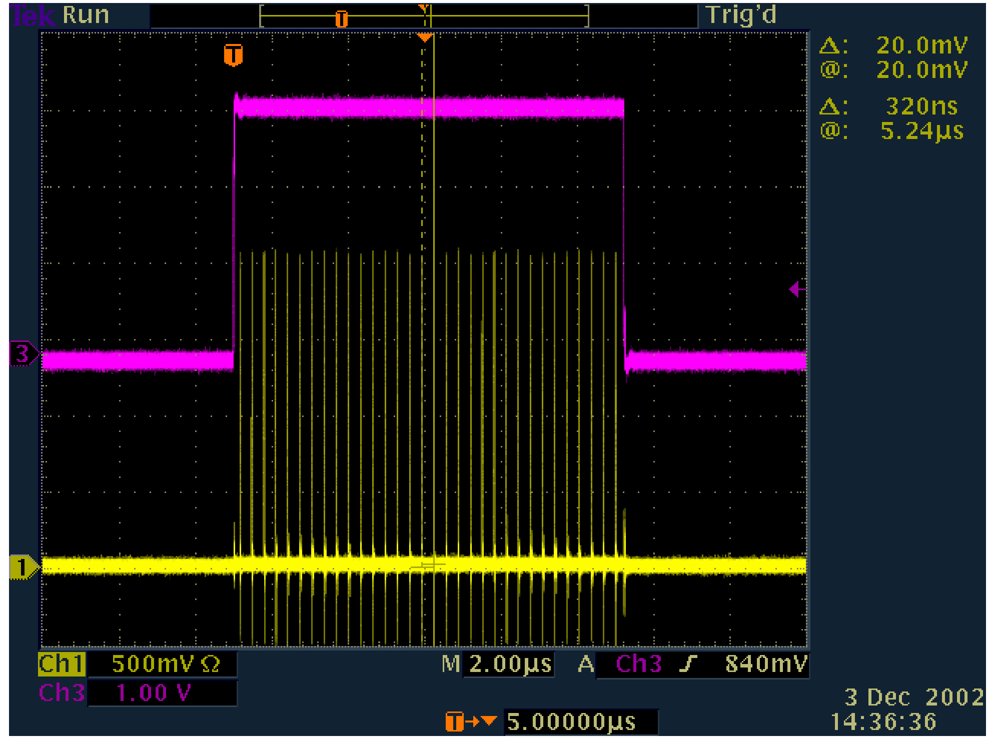
1mm



- 0.25μm Process
- Radiation Hard
- Single Channel
- 768 cells

DRS Tests

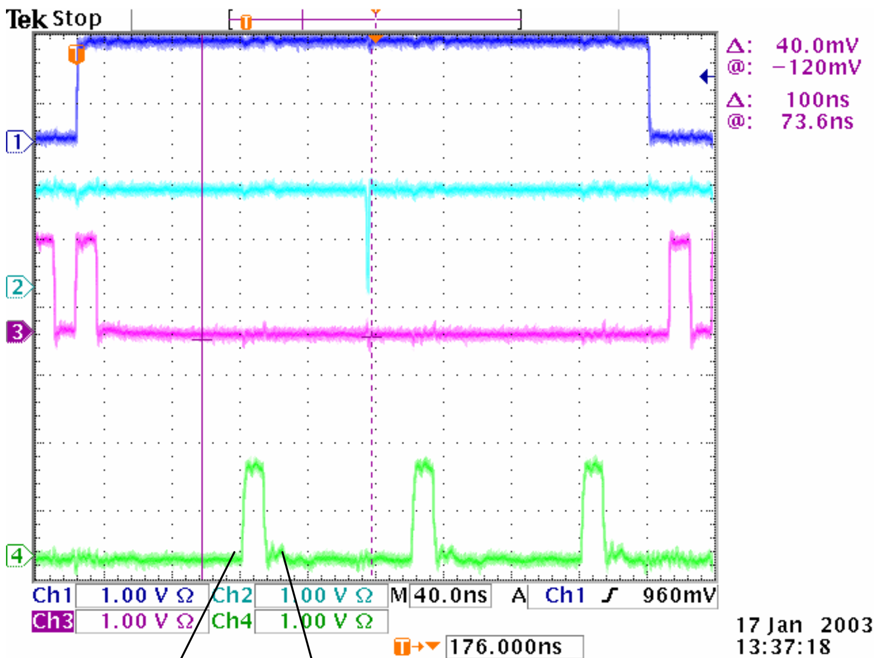




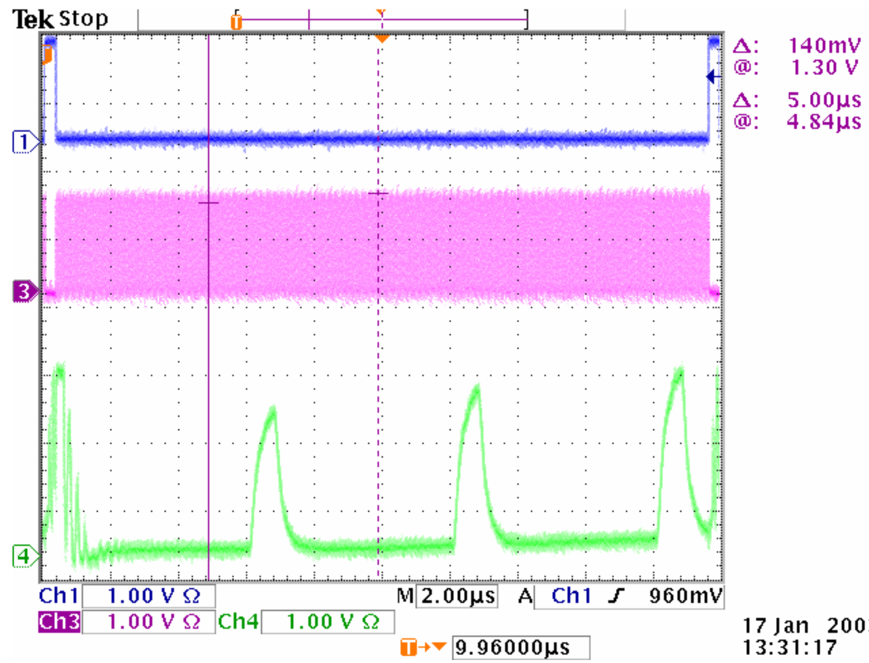
- Sampling Speed 0.7 – 2.5 GHz
- Power Supply 35mW (@2.5V), 6mW (@1.8V)
- Timing jitter: 100ps

- Readout stable at 40 MHz
- TC: 0.2% / deg. C

Test Pulse Readout



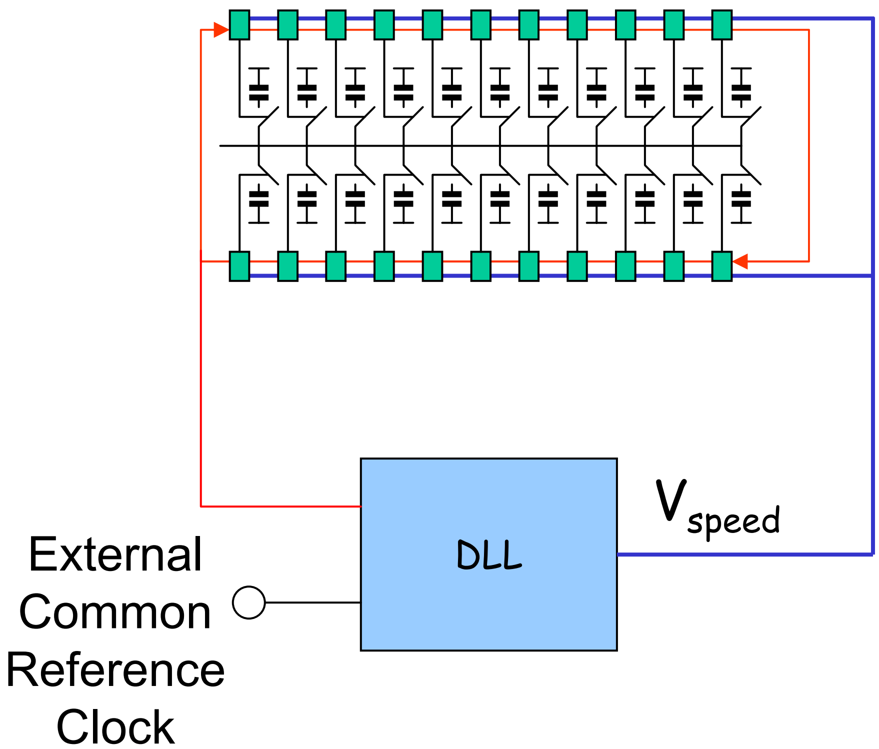
12ns
Input pulses



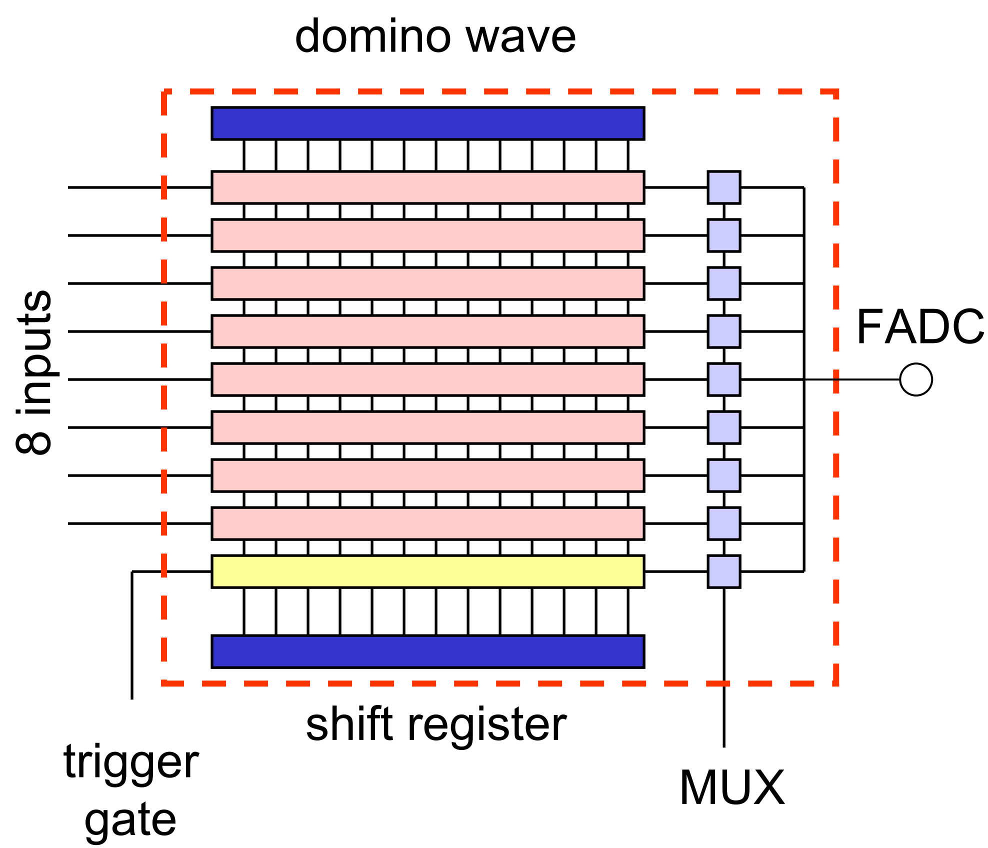
Limited by readout cirquitry!

Domino Wave Stabilization

Phase and Frequency Stabilization

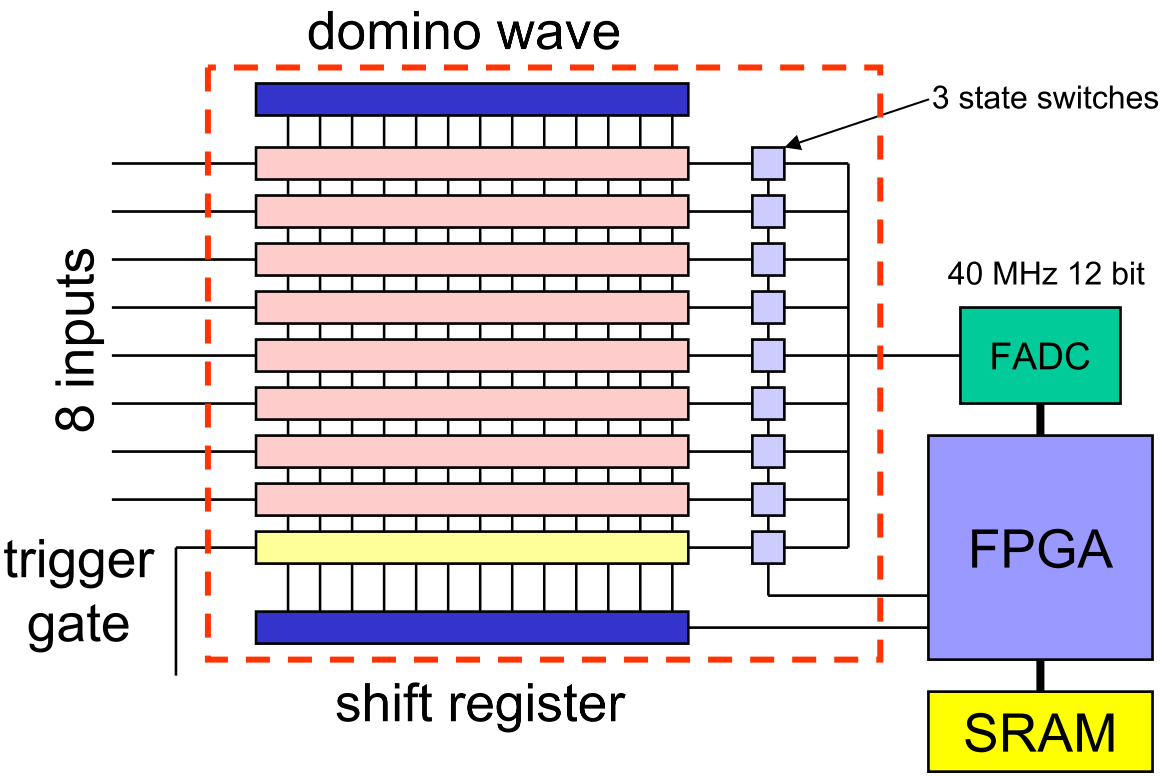


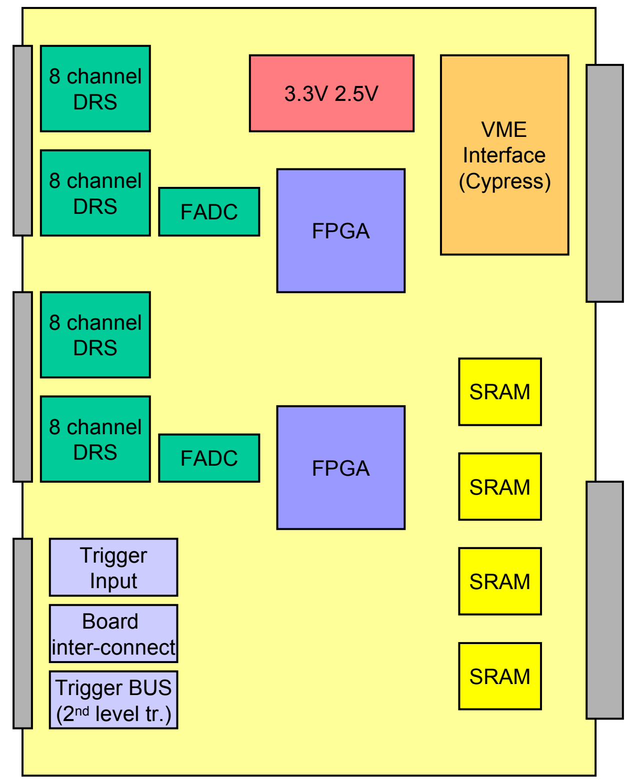
Trigger Signal Sampling



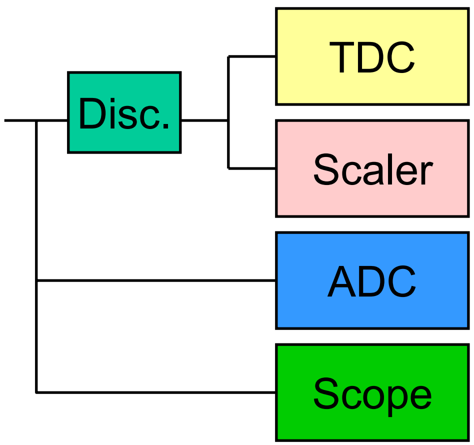
DAQ Board

- 9 channels × 1024 bins / 40 MHz = 230 μs → acceptable dead time
- Zero suppression in FPGA
- QT Algorithm in FPGA (store waveform if multi-hit)
- Costs per channel: ~25$ (board) + 6$ (chip)

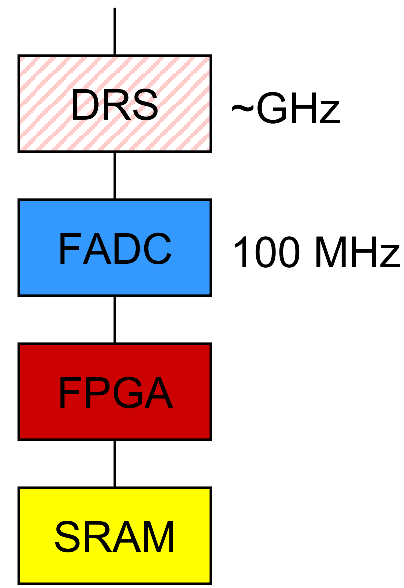




"Redefinition" of DAQ

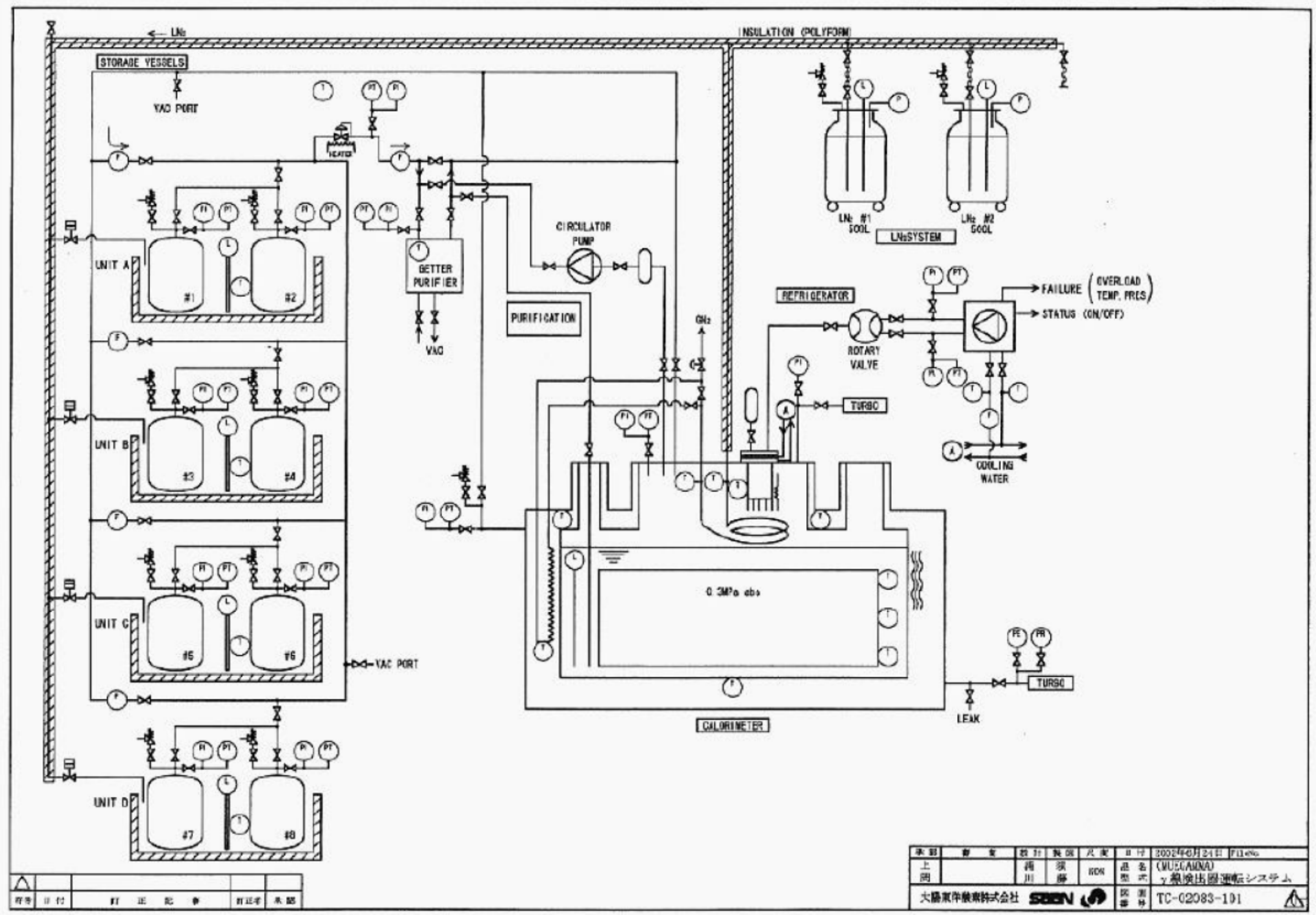


Conventional	New
AC coupling	Baseline subtraction
Const. Fract. Discriminator	DOS – Zero crossing
ADC	Numerical Integration
TDC	Bin interpolation (LUT) Waveform Fitting
Scaler (250 MHz)	Scaler (50 MHz)
Oscilloscope	Waveform sampling
400 US$ / channel	50 US$ / channel

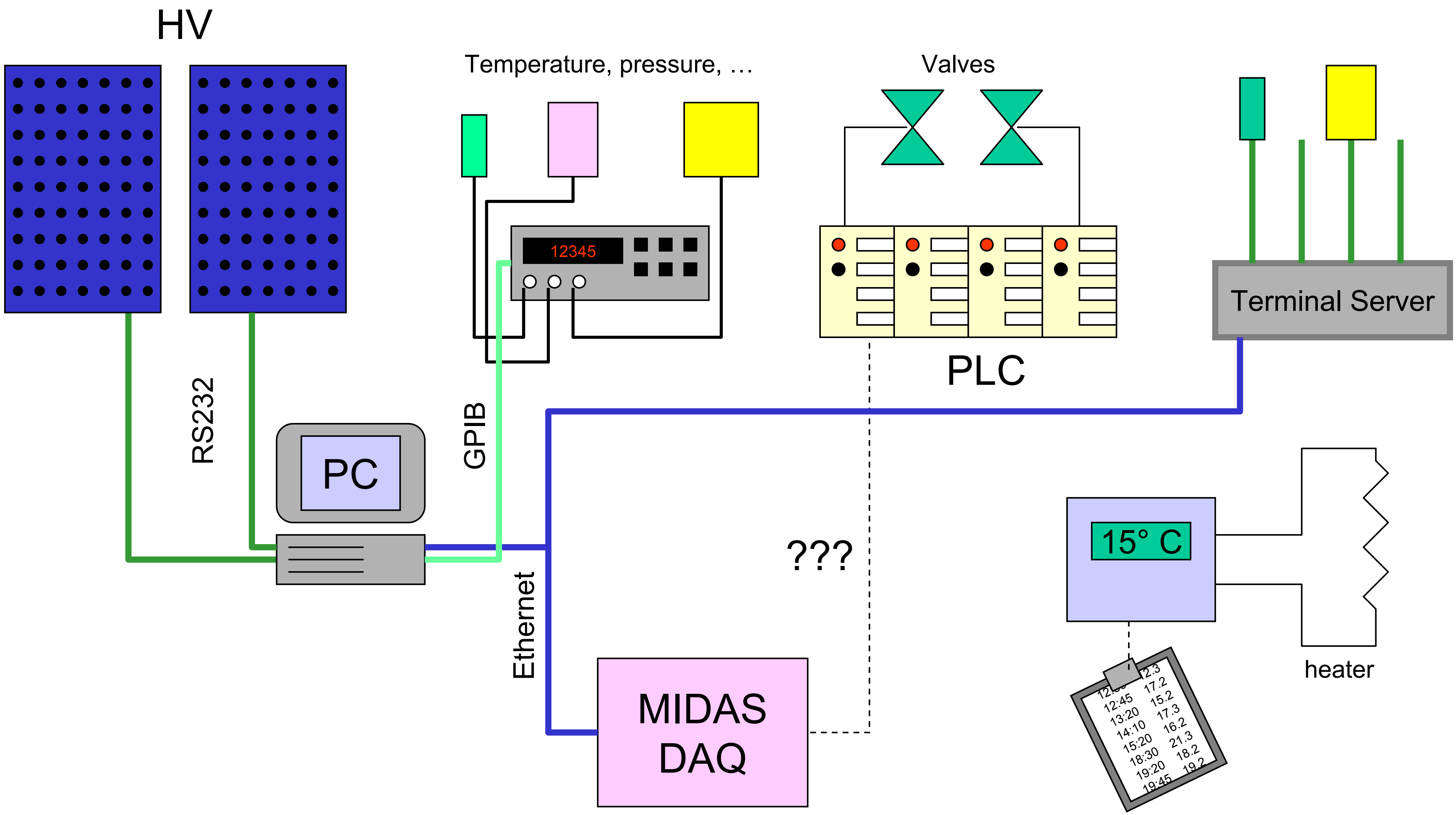


Slow Control

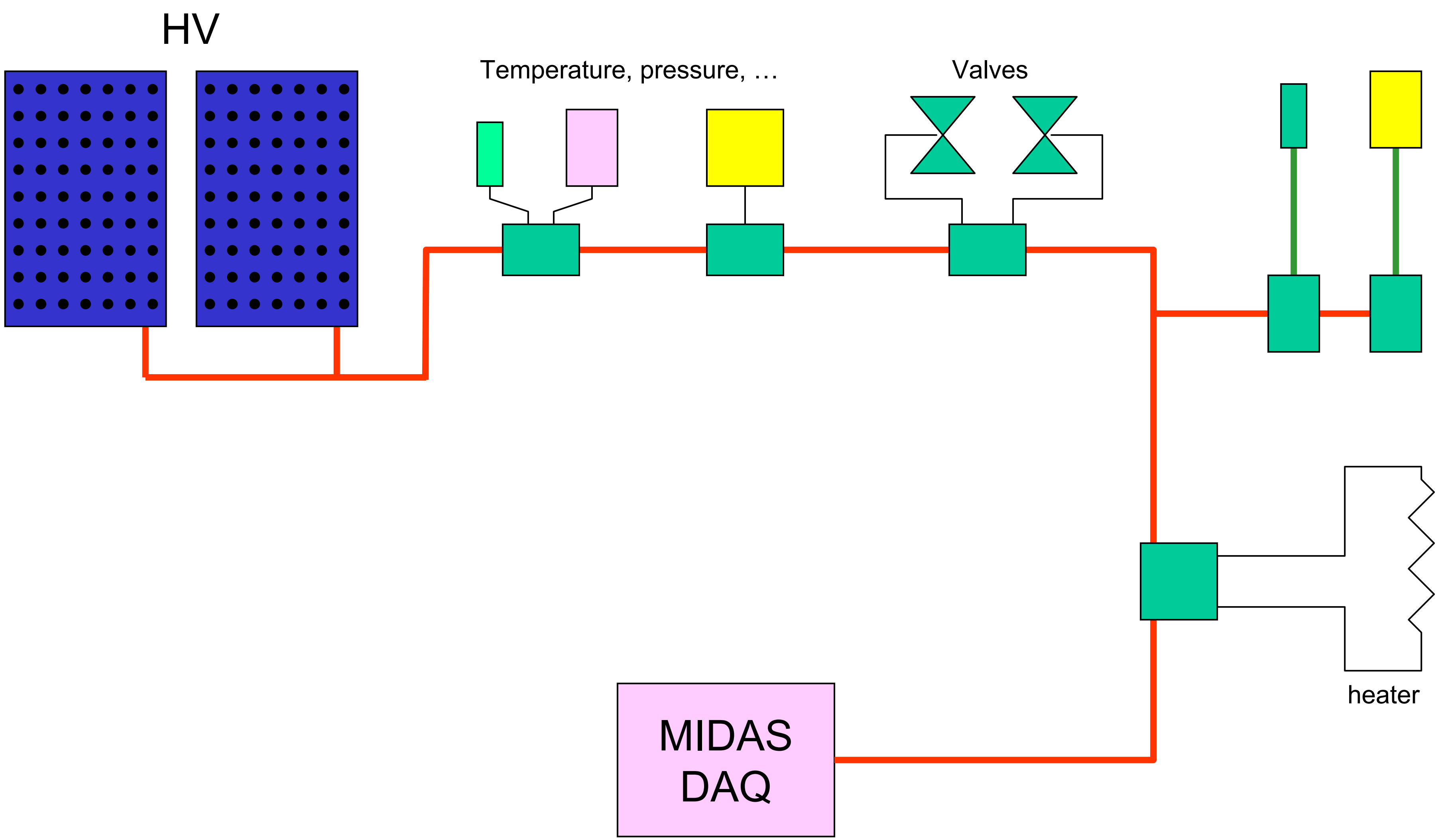
Cryogenics Design



Slow Control

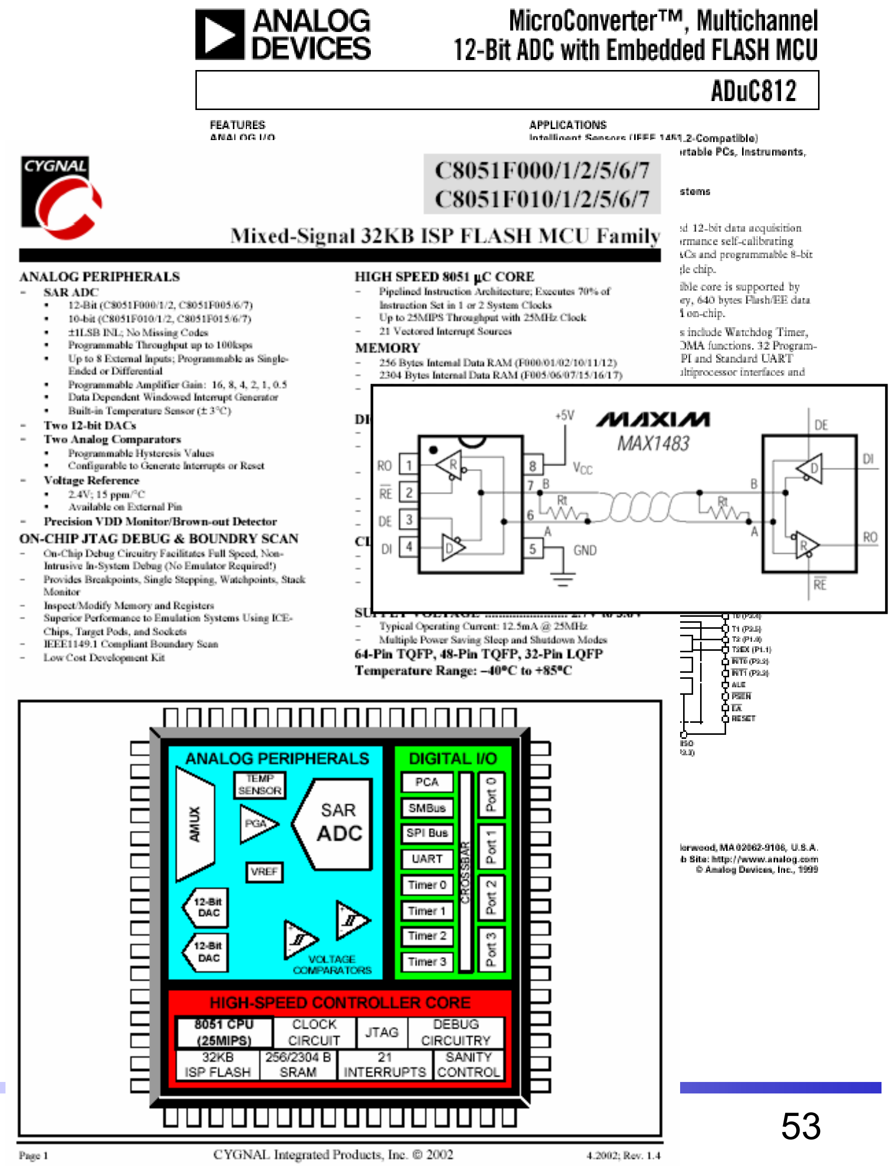


Slow Control Bus



Field Bus Solutions

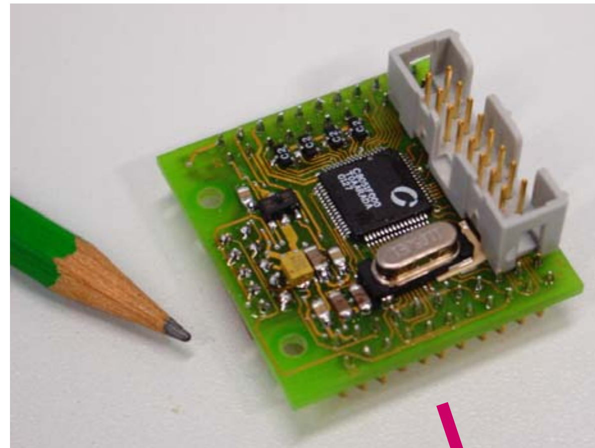
- CAN, Profibus, LON available
- Node with ADC >100$
- Interoperatibility not guaranteed
- Protocol overhead
- Local CPU? User programmable?
- How to integrate in HV? (CAEN use CAENET)

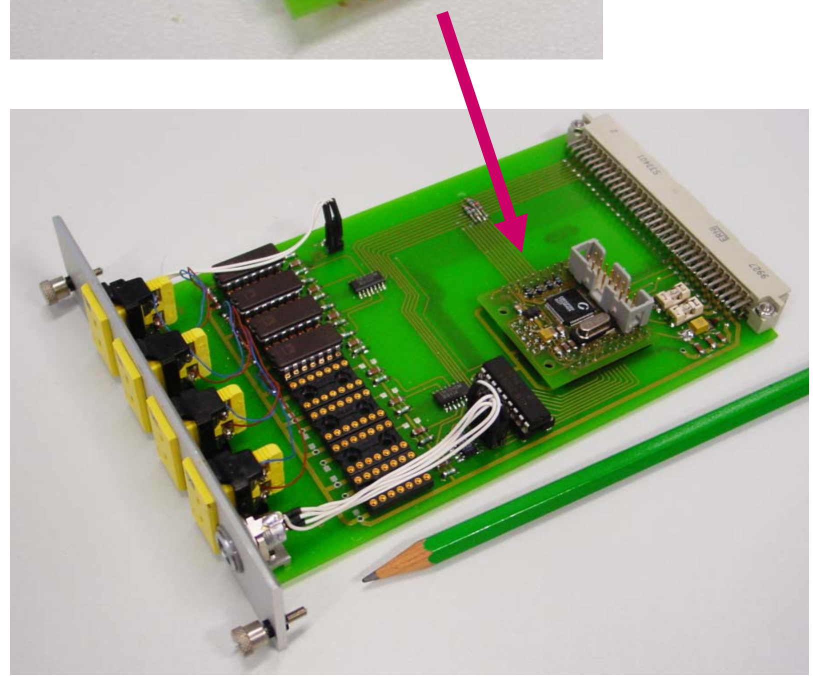


Generic node

- ADuC812 / C8051Fxxx Micro controllers with 8x12 bit ADC, 2x12 bit DAC, digital IO, 8051 μC and Flash Memory
- RS485 bus over flat ribbon cable
- Powered through bus
- Costs ~30$
- Piggy back board for signal conditioning cards

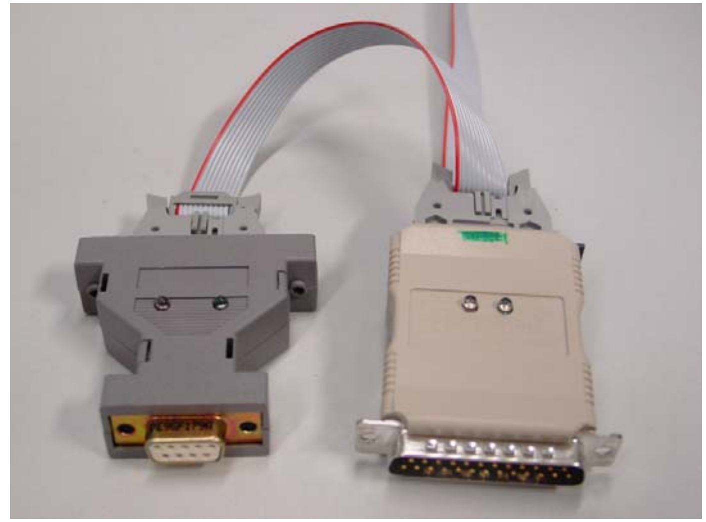
www.cygnal.com





2 Versions

BUS Oriented



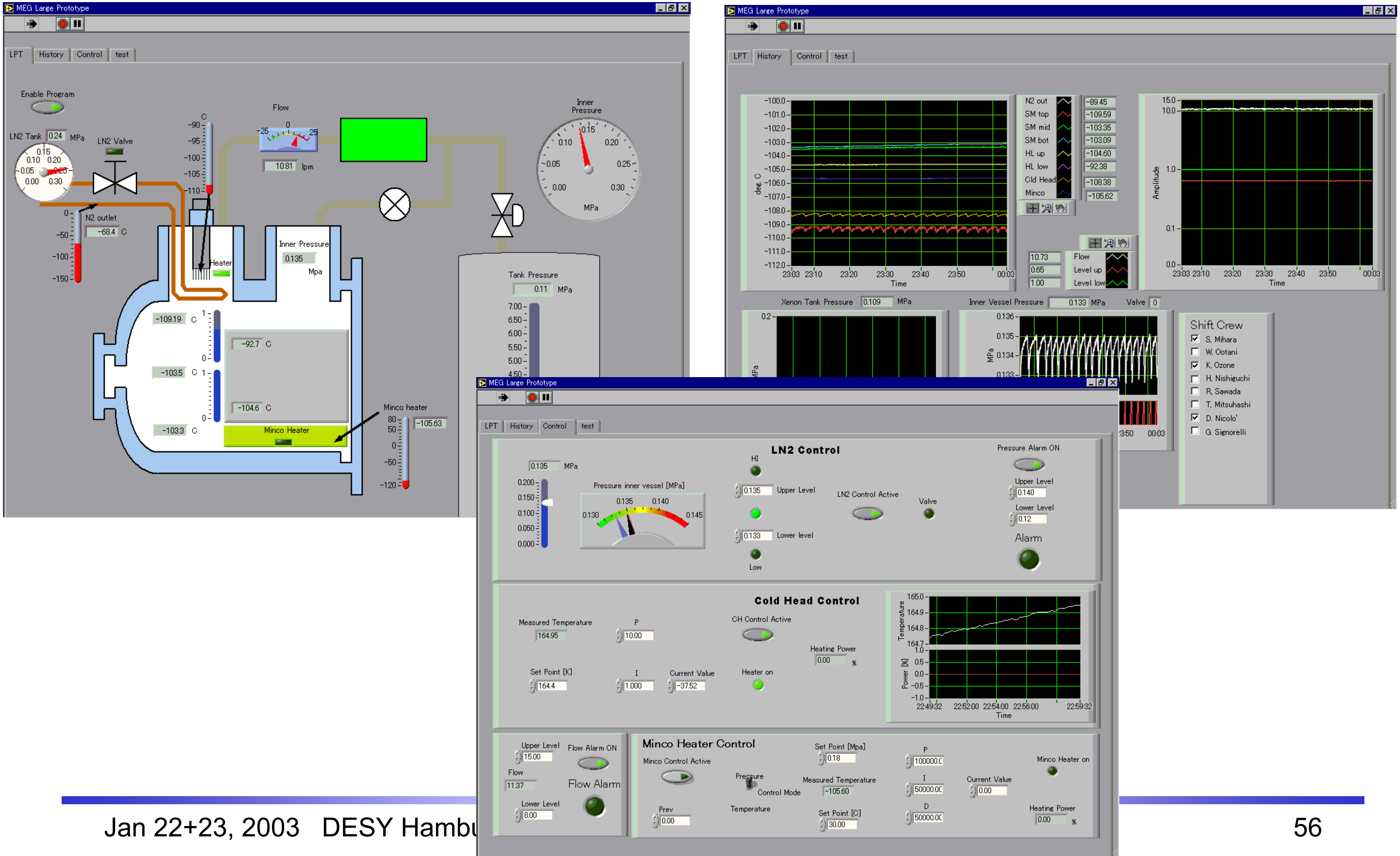
- Generic node with signal conditioning
- RS232 node with protocol translator
- PC connection to parallel port (USB planned)
- Integration on sensors, in crates

Can be mixed

Crate Oriented

- 19" crate with custom backplane
- Generic node as piggy-back
- Cards for analog IO / digital IO / °C / 220V
- Used in 3 experiments at PSI

Labview control of Large Prototype



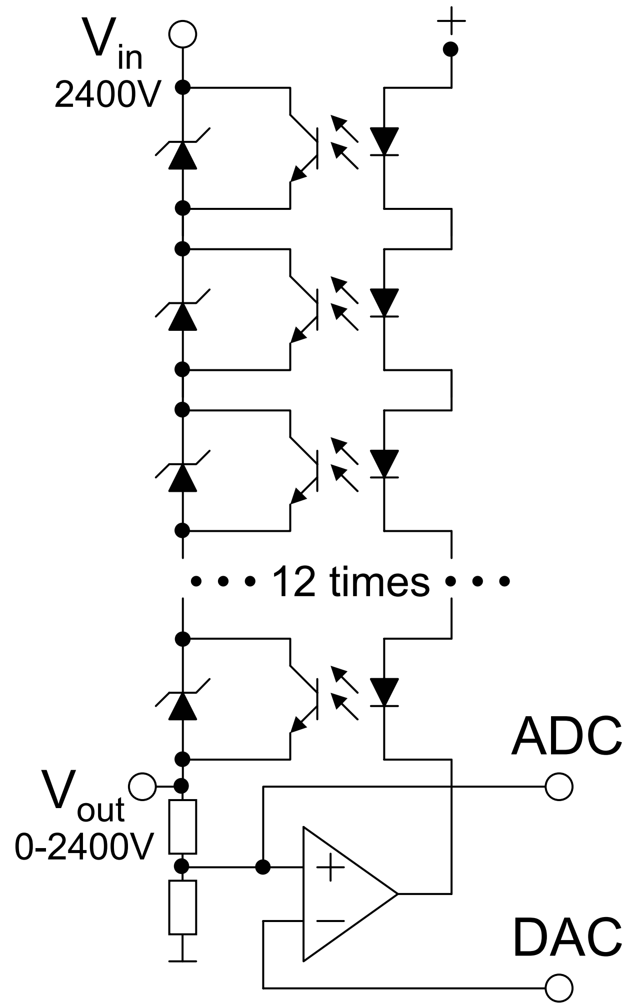
Midas Slow Control Bus

- 256 nodes, 65536 nodes with one level of repeaters
- Bus length ~500m opto-isolated
- Boards for voltage, current, temperature, Digital IO, 220V
- Readout speed: 0.3s for 1000 channels
- C library, command-line utility, Midas driver, LabView driver
- Nodes are "self-documenting"
- Configuration parameters in EEPROM on node
- Node CPU can operate autonomously for interlock and regulation (PID) tasks (C programmable, floating point library)
- Nodes can be reprogrammed over network

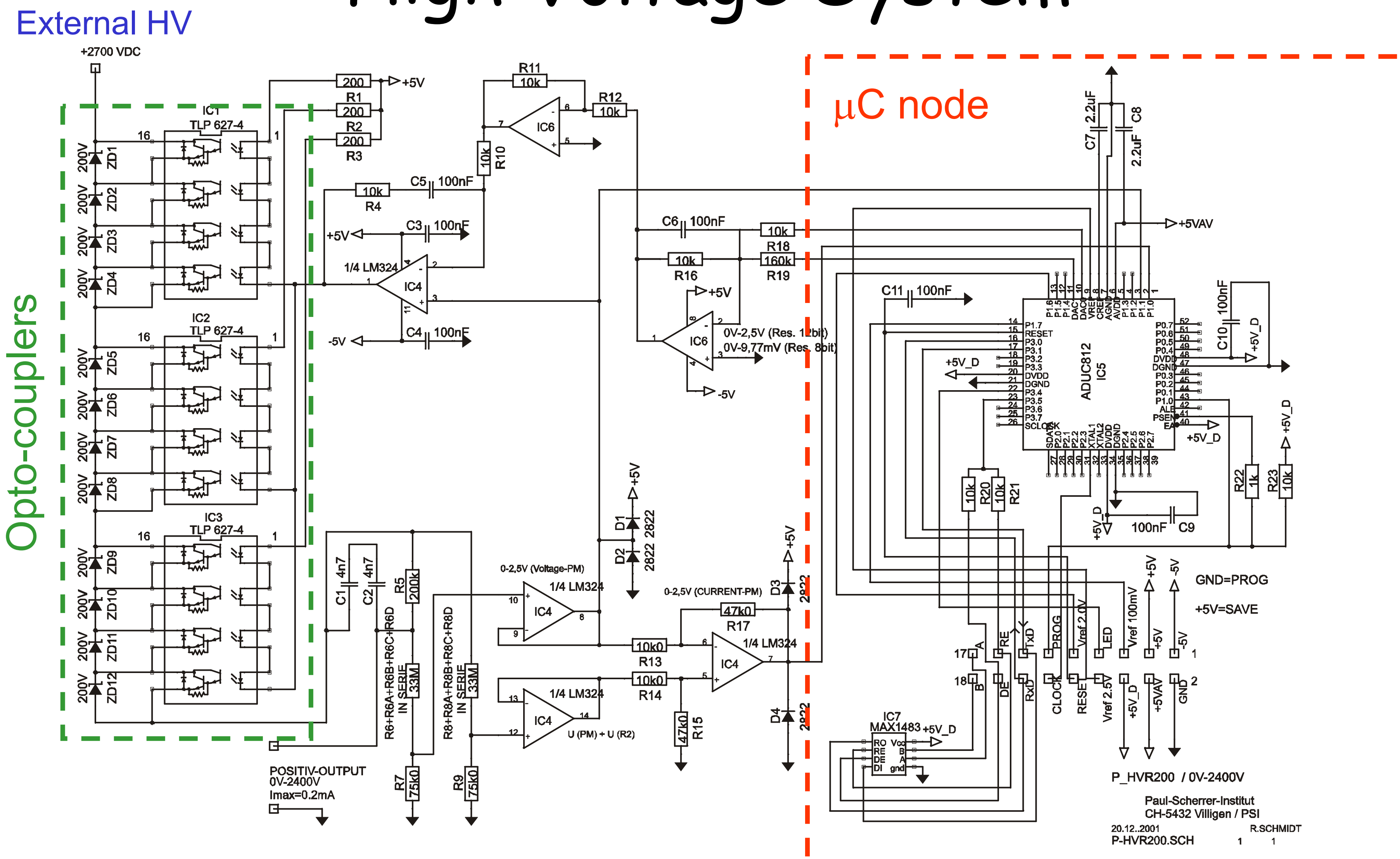
`http://midas.psi.ch/mscb`

HV System Design

- Cheap and stable (<0.3V) HV system
- Regulate global external voltage
- Use series of opto-couplers
- Compensate non-linearities of opto-couplers by regulation loop
- ADC and DAC from slow control node

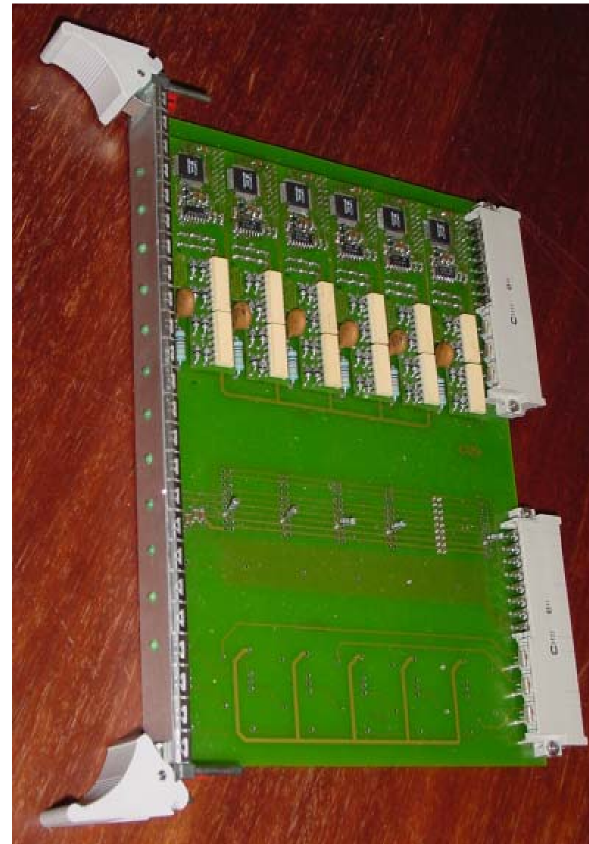


High Voltage System



HV performance

- Regulates common HV source
- 0-2400V, ~1mA
- DAC 16bit, ADC 15bit
- Current trip ~10μs
- Self-calibration with two high accuracy reference voltages
- Accuracy <0.3V absolute
- Boards with 12 channels, crates with 192 channels
- 30$/channel (+ext. HV)



Prototype

Conclusions

Current Status

- R & D is going well, we are confident that we can do the experiment at the 10^{-13} level
- Assembly of main experiment has been started
- Physics runs expected in 2005
- Innovative electronics useful for other experiments
  - FPGA-based trigger with 100MHz FADC
  - 2 GHz cheap waveform sampling
  - New slow control system MSCB

http://meg.psi.ch