II. LOW ENERGY PHYSICS WITH COLD $\mu^{\pm}$ BEAMS

Z. Parsa, Chair

II. LOW ENERGY PHYSICS WITH COLD $\mu^{\pm}$ BEAMS, *Z. Parsa* (BNL), Chair

Low Energy Studies with High Intensity Muon Sources (On the Road to the First Muon Collider) – *W. Marciano* (BNL)

Muon and Electron Lepton Number Nonconservation: The MECO Experiment to Search for $\mu^- N \rightarrow e^- N$ – *W. Molzon* (UC Irvine)

A $\mu \rightarrow e + \gamma$ Experiment at 10^{-14} Sensitivity? – *H.C. Walter* (PSI)

W. Marciano
12/10/97

Low Energy Studies With High Intensity Muon Sources
(On The Road To The First Muon Collider)

Outline

1. Introductory Perspective

2. Low Energy Studies
   - i) Muon-Number Non-Conservation
   - ii) Muon Electric Dipole Moment
   - iii) Neutrino Oscillations
   - iv) Other

   } Compelling "New Physics" Searches

3. Concluding Remarks

1. Introductory Perspective

Muon Collider Concept – "An idea whose time has come."

Still Needs: Creative Ideas
Clear Compelling Physics Goals
Aggressive R+D
Reality Checks!

$\mu^+\mu^-$, $\sqrt{s}$ = 100, 500, 3,000, 10,000 GeV ?

Build An Intense Muon Source

Study Muon Production, Collection, Polarization, Cooling ...
and
Carry Out – A Frontier Physics Program (More Important!)

1) Existing Facility eg. AGS 6×10^{13} p/pulse $\rightarrow 10^{11}\sim10^{13}\ \mu^{\pm}$/sec (relatively inexpensive)

2) Full Front End of Muon Collider $\rightarrow 7\times10^{13}\ \mu^{\pm}$/sec (clear)

Either Represents A Major Step Forward
(Current Facilities $\sim 10^{7}\sim10^{8}\ \mu$/sec)

Do Both

2. Low Energy Muon Studies (Most Compelling)

i) Muon-Number Non-Conservation

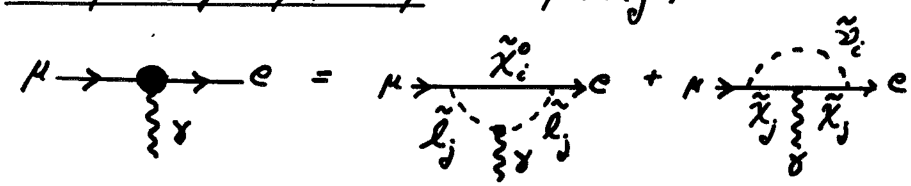
Reaction	Current Bound	Ongoing	Future
$B(\mu^- Ti \to e^- Ti)$	$< 7\times10^{-13}$	$\sim 2\times10^{-14}$	10^{-16} (10^{-18}?)
$B(\mu^+ \to e^+ e^- e^+)$	$< 1\times10^{-12}$	-	?
$B(\mu^+ \to e^+ \gamma)$	$< 4.2\times10^{-11}$	$\sim 5\times10^{-12}$	10^{-14}

Powerful Probes of "New Physics"

Robust Discovery Potential

Need Lots Of Muons! { W. Molzon et. al; $10^{+11}\mu^-$/sec }

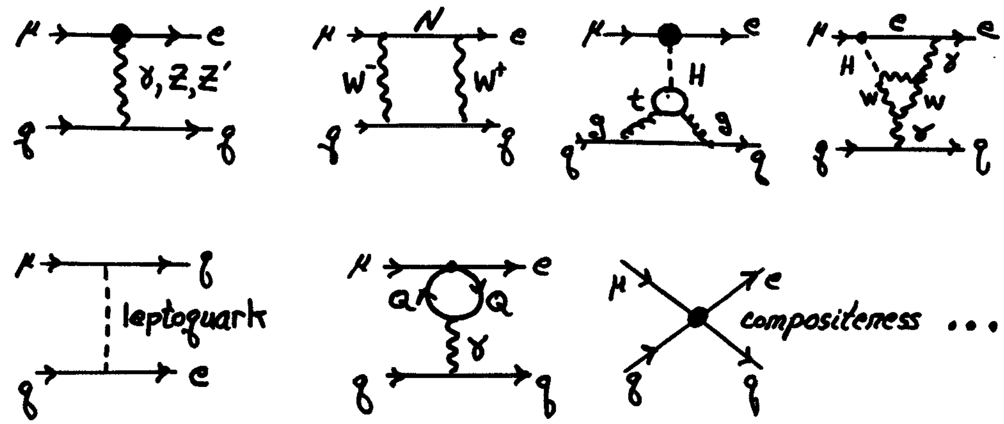
Example Supersymmetry (Compelling)



$B(\mu^+ \to e^+\gamma) : B(\mu^+ \to e^+e^-e^+) : B(\mu^- Ti \to e^- Ti)$

$1 : \frac{1}{150} : \frac{1}{200}$

All should be done!



Physics Probed By $B(\mu^- N \to e^- N) \lesssim 10^{-16}$ (10^{-18})

i) SUSY GUTS see fig. example

ii) Heavy Neutrino Mixing $|U^*_{\mu N} U_{eN}| \lesssim 8\times10^{-13}$ (10^{-15})

iii) Leptoquarks $M_{LQ} > 3000\sqrt{\lambda_{\mu d}}\sqrt{\lambda_{ed}}$ TeV!

iv) Compositeness $\Lambda_c > 3000$ (9000) TeV!

v) Higgs μe Coupling $< 10^{-4} H\mu\mu$

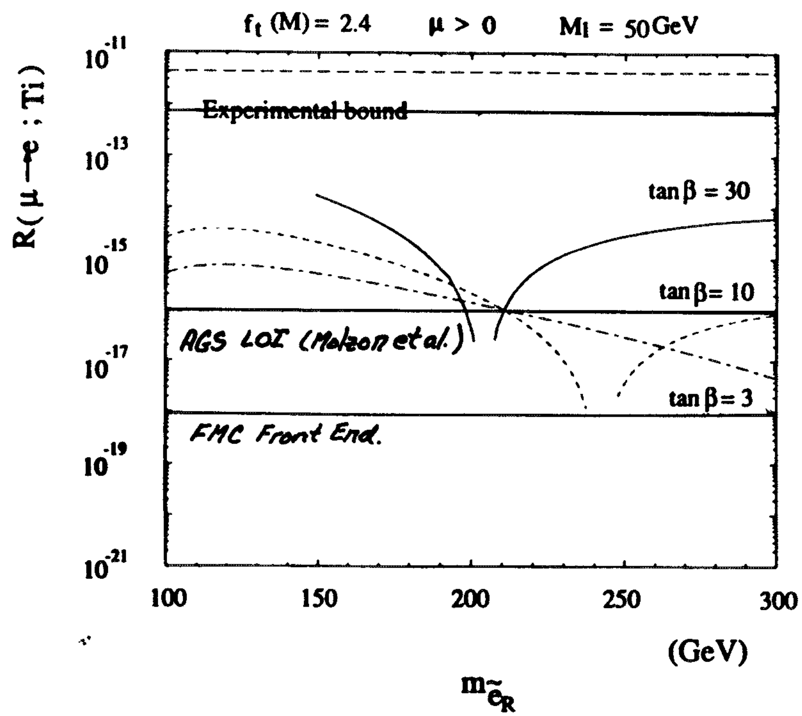
Equivalent to $B(H \to \mu e) < 10^{-12}$ (10^{-14})!

vi) $Z\mu e$ Coupling Equiv. $B(Z \to \mu e) < 10^{-17}$ (10^{-19})!

Anticipate Discovery!

$\mu^- Ti \to e^- Ti$ in SUSY SU(5) Model, (Hisano, Moroi, Tobe + Yamaguchi)

$\sim\left(\frac{m_\tau}{m_\mu}\right)^2$ larger is some SUSY SO(10) (Barbieri, Hall...)



(a)

ii) Muon Electric Dipole Moment (e.d.m.)

Brookhaven $g_\mu - 2$ Collaboration

Storage Ring Exists + Works (see fig)

$\rightarrow \Delta a_\mu = \Delta\left(\frac{g_\mu - 2}{2}\right) = \pm 40\times10^{-11}$ (or better)

AGS LOI Yannis Semertzidis et al.

Measure Muon e.d.m.

(Strong Focusing, High Intensity, Pol.)

Currently $|d_e| \lesssim 4\times10^{-27}$ e-cm
$|d_n| \lesssim 10^{-25}$ e-cm
$|d_\mu| \lesssim 7\times10^{-19}$ e-cm

} Violate P+T! (Baryogenesis)

Very Crudely Expect $d_e : d_n : d_\mu :: m_e : m_d : m_\mu ::$ 1 : 20 : 200

Currently Muon Not Competitive (But Pure)

BNL E821 LOI $\rightarrow |d_\mu| \sim 10^{-24}$ e-cm! (level of e + n)

6 Orders of Magnitude Improvement!

in an amplitude

Like 17 Orders of

$d_\mu \sim 10^{-24}$ e-cm requires: Polarization, $\sim 7\times10^{7}\,\mu$/sec, strong focusing } Being Studied

More Intense Source → 10^{-25} - 10^{-26} e-cm! (Exciting!)

Need 10^{10} - $10^{12}\,\mu$/sec (Challenging!)

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iii) <u>Neutrino Oscillations</u> (using muon storage ring)

Old Idea eg <u>Fermilab P860 W. Lee et al.</u>

$\bar{p}$ Debuncher

Contains μ^- $3\times10^{7}\,\mu$/sec!

Proposal → $6\times10^{8}\,\mu$/sec Study Osc.

$\mu^- \to e^- \nu_\mu \bar{\nu}_e$ Clean Well Known Spectrum

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<u>Extremely Compelling $\gtrsim 10^{11}\,\mu$/sec</u>

Highlight of Fermilab Workshop (November 1997)

S. Geer (preprint) $7\times10^{13}\,\mu$/sec!

(Worth Pursuing Near Term)

iv) <u>Other</u> (Under Study)

Muonium μ^+e^- H.F.S., $\mu^+e^- \to \mu^-e^+$

Muonic Atoms P+T violation μ^-N $|\psi_\mu(0)|^2 \sim \frac{m_\mu^3}{m_e^3} \sim 10^7$

Neutrino Mass

⋮

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3. <u>Concluding Remarks</u>

Intense Muon Source + Low Energy Exp. Program

Provide Path to First Muon Collider

$\mu^-N \to e^-N$
$(\mu^+ \to e^+\gamma)$
Muon e.d.m.
ν osc.
} Revolutionary Discovery Potential (Challenging)

<u>Start as soon as possible</u>! <u>Fast track!</u>

<u>Demonstrate</u>: μ Production, Collection, Pol., Cooling, Storage, Accel., Reliability …

<u>Do Fundamental Physics!</u>

Muon and Electron Lepton Number Nonconservation
The MECO Experiment to Search for $\mu^- N \to e^- N$

4th International Conference on Physics Potential and Development of $\mu^+\mu^-$ Colliders

December 10, 1997

W. Molzon
University of California, Irvine

- Physics Motivation
- Overview of Experimental Technique
- MECO Search for $\mu^- N \to e^- N$ with Sensitivity Below 10^{-16}
  - New Muon Beam
  - Backgrounds and Sensitivity
  - Status and Schedule

Search for Lepton Flavor Violation

Apparantly conserved additive quantum numbers associated with each *family* of leptons

- Rigorously true in SM if neutrinos are degenerate in mass

G=1	e	ν_e	u	d
G=2	μ	ν_μ	c	s
G=3	τ	ν_τ	t	b

- Not well motivated theoretically – not result of invariance with respect to gauge transformation as in electric charge conservation
- Tested experimentally in many processes
- Mass scale probed is very high –

$$\Gamma(\mu^- N \to e^- N)/\Gamma(\mu^- N \to \nu N') = 10^{-16} \Rightarrow$$
$$M = 1000\ TeV/c^2$$

- Essentially all extensions to Standard Model allow LFV processes
- Improved muon beams and experiments allow huge improvements in sensitivity

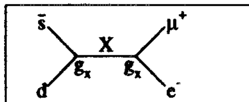
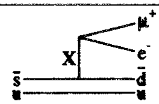
$\mu^- N \to e^- N$	$10^{-12} \to 10^{-16}$
$\mu^+ \to e^+\gamma$	$10^{-11} \to 10^{-14}$

Classify Decays by Change in Generation Number

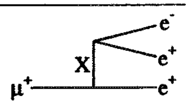
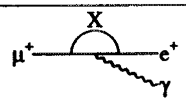
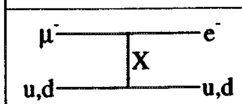
From the model of Cahn and Harari – basic dimensional analysis:

G=1	e	ν_e	u	d
G=2	μ	ν_μ	c	s
G=3	τ	ν_τ	t	b

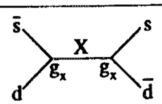
ΔG = 0(2) processes:

	$B(K_L^0 \to \mu e) < 2.4 \times 10^{-11}$ BNL871 $\to 10^{-12}$ axialvector or pseudoscalar	$M_X > 99\ TeV/c^2$
	$B(K^+ \to \pi\mu e) < 2.1 \times 10^{-10}$ BNL865 $\to 3 \times 10^{-12}$ vector or scalar	$M_X > 29\ TeV/c^2$

ΔG = $\pm$1 processes:

	$B(\mu \to eee) < 1.0 \times 10^{-12}$	$\Delta > 86\ TeV/c^2$
	$B(\mu^+ \to e^+\gamma) < 1.7 \times 10^{-11}$ MEGA $\to$ few $\times 10^{-12}$	$\Delta > 20\ TeV/c^2$
	$\frac{\Gamma(\mu^- A \to e^- A)}{\Gamma(\mu^- A \to \nu A)} < 8 \times 10^{-13}$ SINDRUM2 $\to 4 \times 10^{-14}$ MECO at BNL $\to 10^{-16}$	$\Delta > 240\ TeV/c^2$

ΔG = $\pm$2 processes:

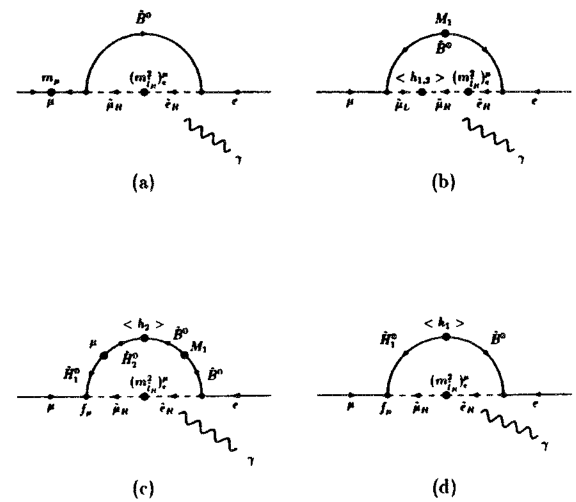
	$\Delta M_K < 3.5 \times 10^{-12} MeV/c^2$	$\Delta > 400\ TeV/c^2$

Supersymmetric GUTs Motivation for LFV

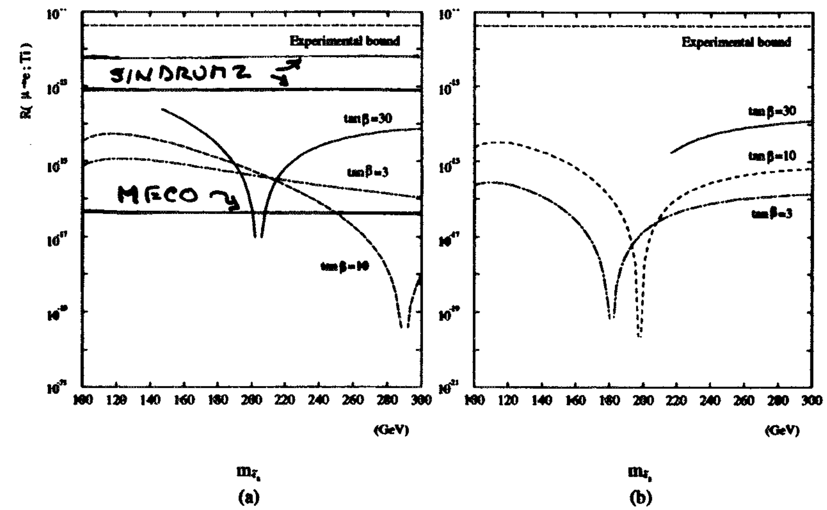
- Perhaps the most realistic possibility for physics beyond the SM
- Grand unified supersymmetric theories relate
  family structure of standard and supersymmetric sectors
- If supersymmetry is discovered,
  motivation for LFV searches is as strong as it ever was

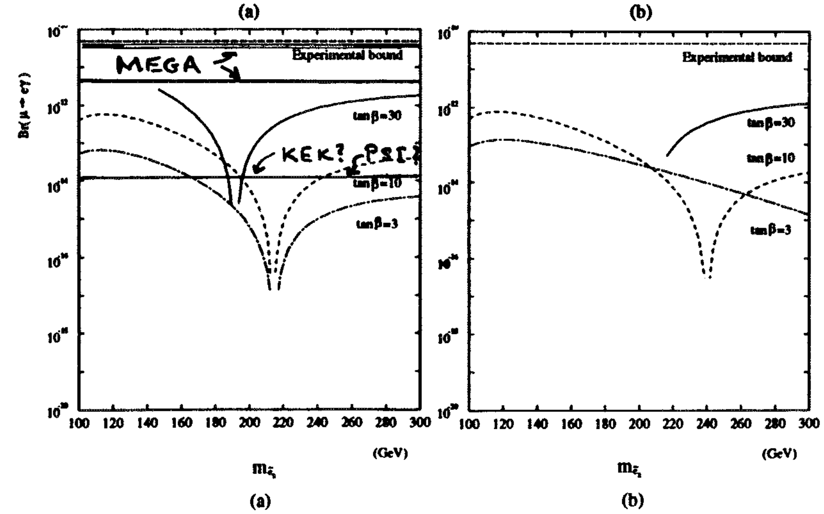
  $\Rightarrow$ the possibility of predictions for LFV rates

  $\Rightarrow$ the possibility of discovering something
- LFV occurs through mixing in supersymmetric sector



LFV Predictions From the Model of Hisano, et al.





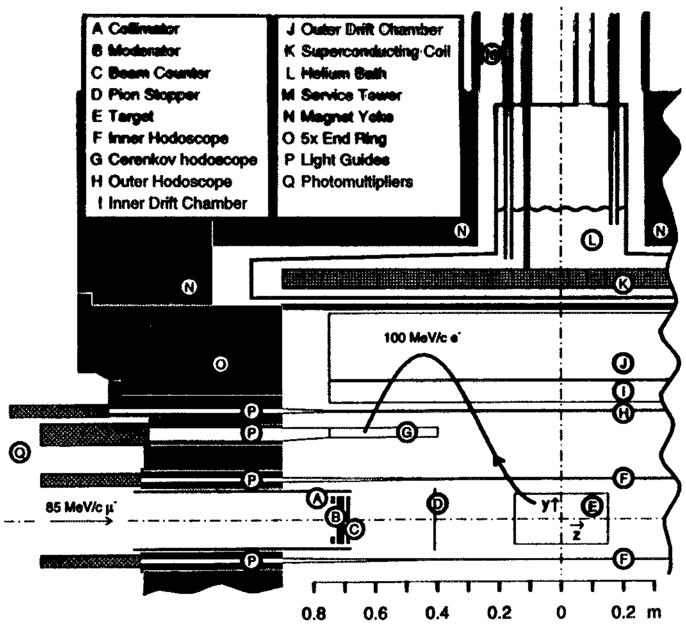
Outline of $\mu^- N \rightarrow e^- N$ Experiment

- Basic process:
  - Bring μ^- to rest in thin target
  - μ^- is captured in Coulomb orbit, cascades in
  - Can capture on the nucleus (inverse β decay)
  - Can decay in orbit
  - **May convert to electron**
- Interaction is coherent over the nucleus
  - Nucleus usually left in ground state
  - Rate for $\mu^- N \rightarrow e^- N$ enhanced for high Z nuclei
- For γ exchange, B($\mu^- N \rightarrow e^- N$) / B($\mu^+ \rightarrow e^+\gamma$) $\simeq$ 0.01
- For other mechanisms, $\mu^- N \rightarrow e^- N$ can be more sensitive
- Experimental issues
  - Signature is very simple – 105 MeV electron
  - No accidental coincidence backgrounds
  - Other sources of 105 MeV electrons heavily suppressed
  - Balance higher sensitivity at high Z vs. less experimental difficulties at low Z

Search for $\mu^- N \to e^- N$ with SINDRUM2 at PSI

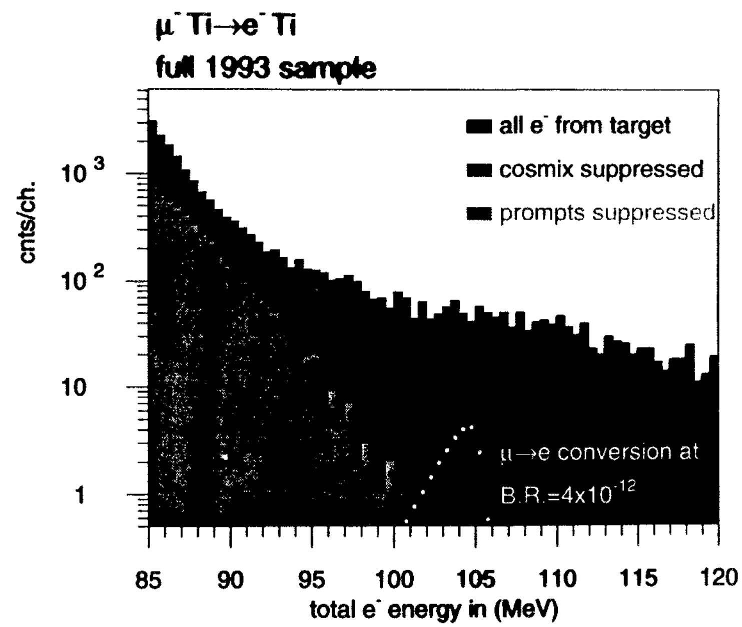
- μ^- beam derived from 1.5 mA, 590 MeV cyclotron (10^{16} protons per second at 1.2 GeV/c)
- Muon beam is a mixed 85 MeV/c π, μ, e beam with total flux $>\sim 10^7$ s^{-1}
- Data taking complete for first phase

$$\Gamma(\mu^- N \to e^- N)/\Gamma(\mu^- N \to \nu N') < 7.8 \times 10^{-13})$$



Search for $\mu^- N \to e^- N$ with SINDRUM2 ...

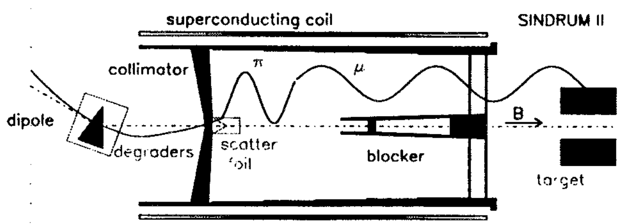
- Limited by "prompt" π, μ, e processes and detector rates
  - Eliminated with veto counter in beam
- Cosmic ray induced background eliminated by detecting throughgoing muon in detector
- Electron energy resolution limited by energy loss straggling and spectrometer resolution of FWHM$\sim$2.5 MeV



Expected Improvements from SINDRUM2

- New beam being built for SINDRUM2 at PSI
  - Reduce π beam energy below 70 MeV
    - eliminate prompt e backround
  - Absorb most pions
    - reduce prompt π background
  - Increase μ stop rate
    - no veto counter allows higher rate

the new muon channel



$10^9 \pi^- s^{-1}$ at 95 MeV/c

$10^8 \mu^- s^{-1}$ stops

high purity, no beam counter required

- Expected sensitivity of 4×10^{-14}
- Sensitivity then limited by available flux

P940

A Search for $\mu^- N \to e^- N$ with Sensitivity Below 10^{-16}

Muon – Electron COnversion

Proposal to Brookhaven National Laboratory AGS

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B.W. Mayes, L.S. Pinsky, J. Wilson, M. Youn
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A. Mincer, P. Nemethy, J. Sculli
New York University

W.D. Wales
University of Pennsylvania

D. Koltick, S. Carabello,
Purdue University

+ M. Brennan
BNL

PRIMARY BEAM	8-20 GeV proton beam pulsed at 1.11 MHz
	4×10^{13} per spill
	2-3 second repetition rate, 50% duty cycle
PRIMARY TARGET	Radiation cooled tungsten
SECONDARY BEAM	Low energy, negative μ
	5×10^{11} per pulse
SECONDARY TARGET	Aluminum
TIME REQUESTED	4000 hours
SPOKESPERSON	W. Molzon Department of Physics and Astronomy University of California Irvine, CA 92697-4574 714 824-5987 wmolzon@uci.edu

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September 1997

Physics Background Issues for $\mu^- N \rightarrow e^- N$

1. μ^- decay in orbit:
   - $E_e^{max} = E_e$ from $\mu^- N \rightarrow e^- N$
   - $dN/dE_e \propto (E_{max} - E_e)^5$
   - Sets electron energy resolution required
2. Radiative μ^- capture: $\mu^-(A,Z) \rightarrow (A, Z-1)\nu\gamma$
   - $E_e^{max} = 102.5$ MeV, $P(E_\gamma > 100.5) = 4 \times 10^{-9}$
   - $P(\gamma \rightarrow e^+ e^-, E_{e^-} > 100 \text{ MeV}) = 2.5 \times 10^{-5}$
3. Radiative π^- capture: $\pi^-(A,Z) \rightarrow (A, Z-1)\gamma$
   - Branching fraction ~1.2% with $E_\gamma > 105$ MeV
   - $P(\gamma \rightarrow e^+ e^-, 103.5 < E_{e^-} < 105 \text{ MeV}) = 3.5 \times 10^{-5}$
   - $\Rightarrow < 10^{-16}\ \pi^-/p$ at target during detection
4. μ^- decay in flight, e^- scatter in target
5. Beam e^-, scatter in target
   - $\Rightarrow < 10^{-7}\ e^-/p$ with $E_e > 100$ MeV
6. Cosmic ray induced e^-
   - primarily muon decay and interactions
   - requires active and passive shielding

1,2	require excellent energy resolution
3,4,5	eliminated with beam veto or pulsed beam
6	requires active and passive shielding

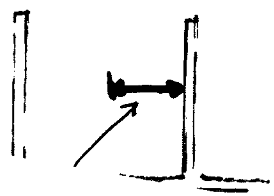
Background from Anti-protons

- Potential background from $\bar{p}$ annihilating in stopping target
- Concern is late arriving (and hence low energy) $\bar{p}$
  - High (> 80 MeV/c) momentum $\bar{p}$ are not transmitted
  - Low (< 80 MeV/c) momentum $\bar{p}$ arrive late
    not suppressed by pulsed beam
  - Production cross section near threshold not well measured
- Comments on $\bar{p}$ production
  - Threshold in pp collisions is 6.5 GeV/c
  - Threshold for Fermi momentum of 300 MeV/c is ~5 GeV/c
  - $\bar{p}$ produced at threshold have $p_{\bar{p}} \simeq p_p/4$
    $\Rightarrow$ no low energy production
  - $\bar{p}$ produced at threshold do not reflect in field
- Safest response is to work below threshold
  - FLUKA and Gheisha predict 40-50% loss in μ stop rate
  - some senstivity regained from increased rep rate
- Additional suppression from the following:
  - Crossed E and B field gives drift
    2 m long electrodes in beginning transport solenoid
    600 kV over 0.3 m, 2 T $\Rightarrow v_D$ is 10^6 m/s
    drift distance is ~13 cm – same direction as drift in torus
  - Use very thin absorber at second collimator location

Essential Features of MECO Experiment

- Much higher muon flux (idea from MELC at MMF)
  - High Z target for enhanced pion production
  - Capture most produced pions in graded solenoidal field
  - Produce $\sim 10^{-2}$ μ per proton with 8 GeV p beam (10^{-8} for SINDRUM2, 10^{-4} for MELC, 0.3 for μ collider)
  - μ^- transported in curved solenoid, new for MECO
    Suppress high momentum negatives, all positives

- Pulsed beam to eliminate prompt backgrounds (conversion electron detected in time with beam particle) used in PSI experiment (A. Badertscher, et al., 1981) $\tau_\mu(Al) \sim 880$ ns
  - Beam pulse length $<< \tau_\mu$
  - Time between pulses $\simeq \tau_\mu \simeq 1$ μsec
  - Large (50%) macro duty-cycle
  - Extinction between pulses $\simeq 10^{-10}$



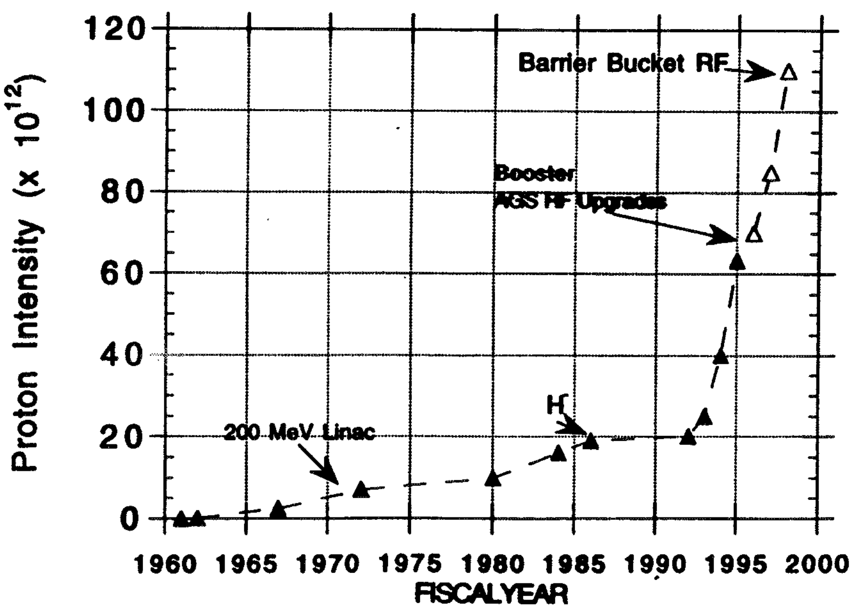
- Detector with improved resolution, backgroun(rate capabilities
  - Detector in graded solenoidal field for good acceptance, rate capabilities (M
  - Spectrometer with nearly axial detector very high resolution (MECO)

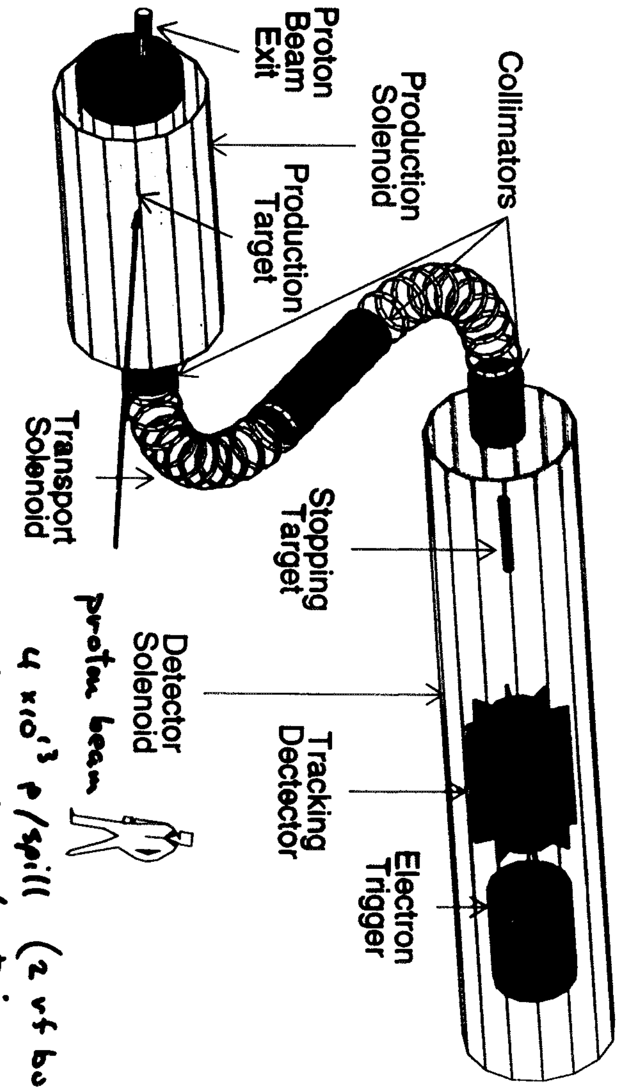
Advantages of Building Muon Source at BNL

- Much larger μ^- flux per proton than at low energy accelerators
- μ^-/μ^+ ratio near 1 – so lower rates wrt low energy accelerator
- More muons per incident energy – easier job with shielding
- μ^+, μ^- beams needed for muon collider R & D
- AGS will run as RHIC injector – modest cost to run experiment

M. BRENNAN

AGS PROTON INTENSITY HISTORY





proton beam
4 x10^{13} p/spill (2 rf bu
0.7 - 1.0 s cycle time
⇒ 4-6x10^{13} p/s

J SCULLI

J. Steinberger & H. Wolfe

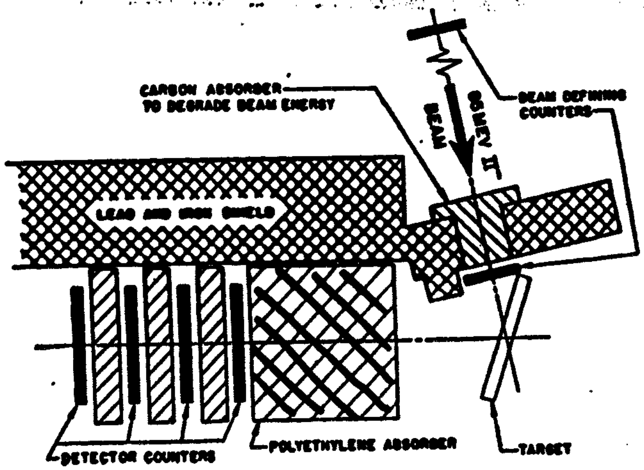


FIG. 1. Experimental arrangement.

Upper limit $\frac{\Gamma(\mu N \to e N)}{\Gamma(\mu N \to \nu N')} < 5 \times 10^{-4}$

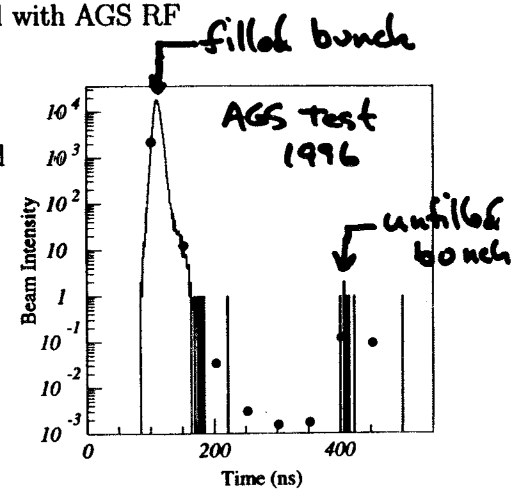
Running time 20 hrs

Poly In : 5 cts

Poly out 123 cts

Pulsed Proton Beams at BNL AGS

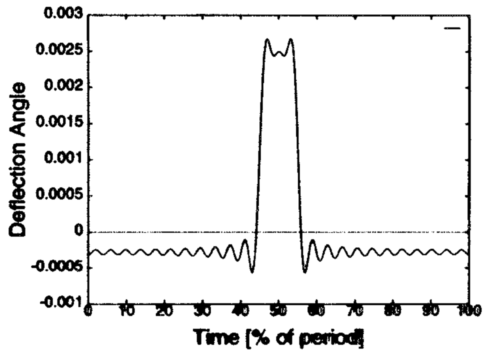
- Required to eliminate prompt background – extinction $< 10^{-10}$
  - beam electrons scatter in target
  - radiative π^- capture
  - μ^- decay in flight
- Extract proton beam bunched with AGS RF
  - 8 bunches
    2.7 μsec revolution time
  - Beam extinction measured one bunch extracted
  - Extinction $< 10^{-6}$ between bunches
  - Extinction $< 10^{-3}$ in unfilled bunches



- Require secondary extinction in extracted beamline
  - Pulsed electrostatic or magnetic kicker
    * Divert beam by 2.5 mrads
    * 4 MV/meter transverse field, 5 m long

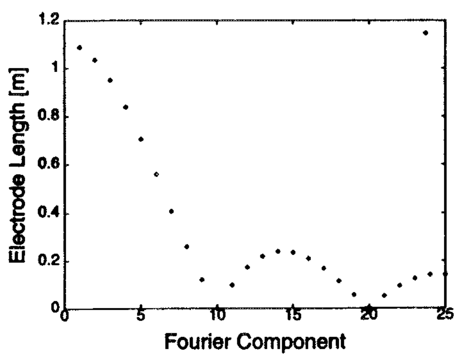
Electrostatic Kicker for Pulsed Beam

- Divert beam off muon production target between pulses with electrostatic kicker

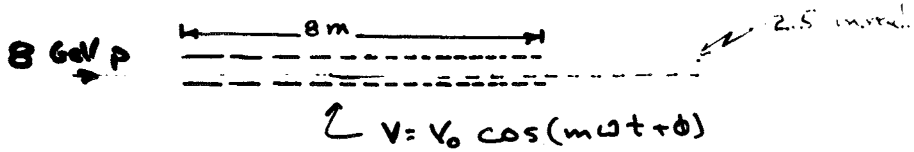


- 8 m long device, giving 20 MeV/c transverse momentum
- 25 m drift path giving ~8 cm deflection

- Get time structure by superposition of Fourier components of 10% DF square wave with ~1 MHz frequency
- Use ~20 electrodes, each driven resonantly with LRC circuit

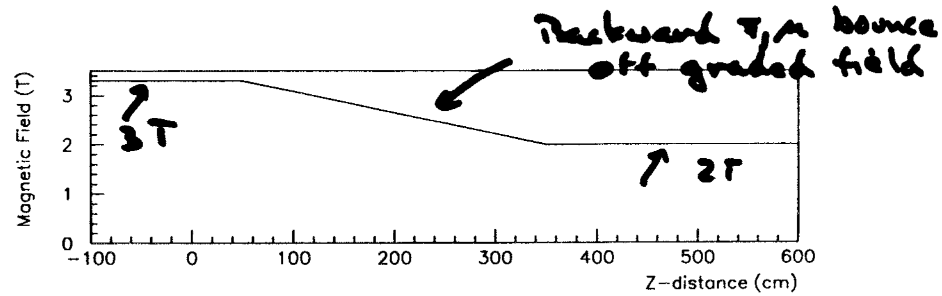


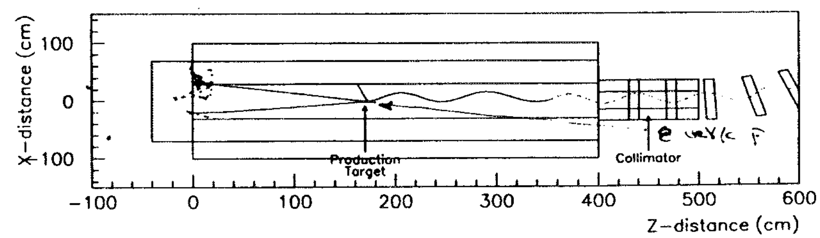
- Simple low power drivers give 4 MV/m field
- Length of electrode $\propto$ Fourier coefficient
- Adjust phase for proton transit time
- Feedback to inductor to stay on resonance



Muon Production for MECO

- Target in solenoid with graded field to increase solid angle acceptance to $\sim 4\pi$
- High Z target for improved low energy muon yield
- Target backwards to minimize problems with dump

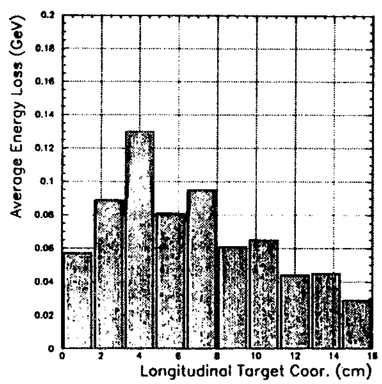


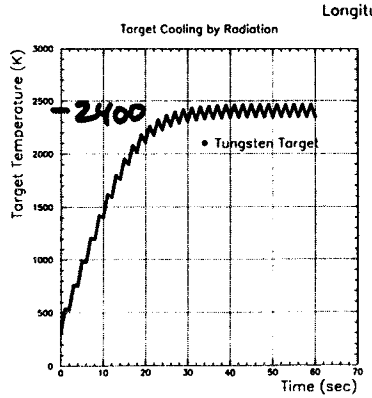


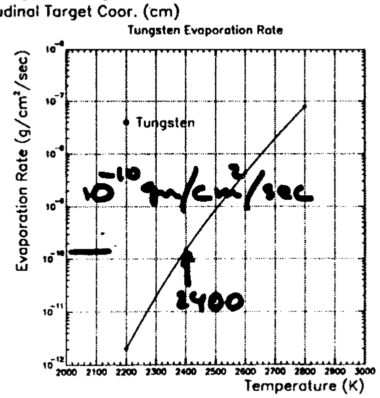
Radiation Cooled Tungsten Target

- Studied with GEANT simulation

Hadron Code	Average Current	Target Radius	Target Length	Average Loss	Peak Power	Average Power
GHEISHA	2×10^{13} p/sec	0.4 cm	16 cm	0.7 GeV	4.7 kW	2.35 kW
GHEISHA	-	-	20 cm	0.77 GeV	5.1 kW	2.55 kW
FLUKA	-	-	16 cm	0.7 GeV	4.7 kW	2.35 kW
FLUKA	-	-	20 cm	0.74 GeV	4.9 kW	2.45 kW

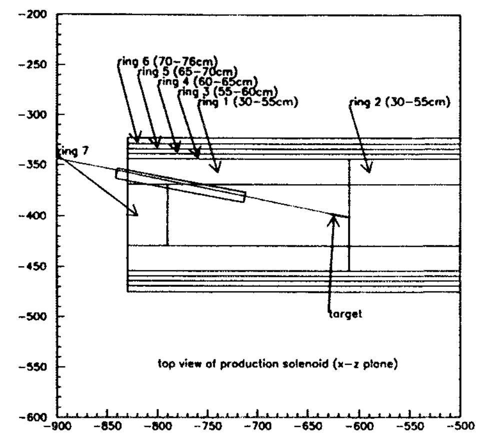


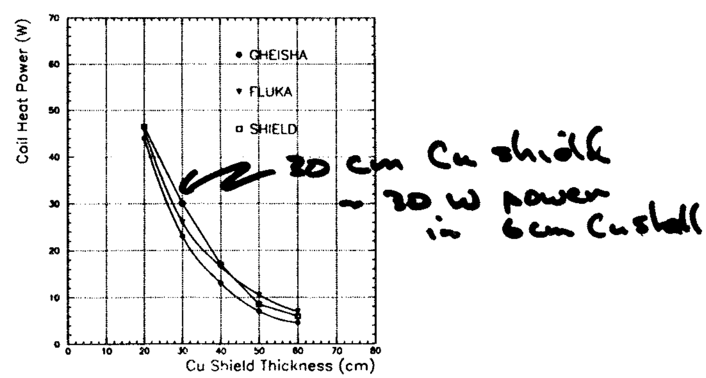




Production Solenoid Radiation and Heat Load

- Studied with GEANT simulation
- Radiation load is ~50 Mrad per year
- Total heat load on solenoid below 50W
- Local instantaneous heat load below 0.2 mW/gm well below quench limits



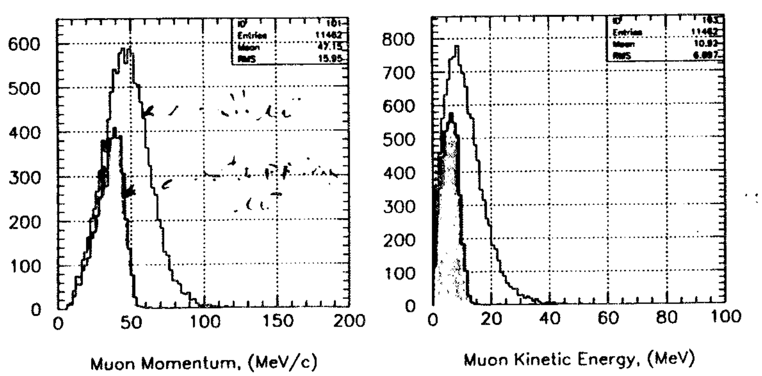


Studies of Muon Yield for MECO

- Not much information on low energy (0-10 MeV, 0-60 MeV/c) pion production cross sections with 8-20 GeV proton beams
- E910 at BNL has data, perhaps to below 100 MeV/c
- Production cross sections modeled with a number of codes – GHEISHA, FLUKA, SHIELD
- Study yield vs. target and production solenoid parameters

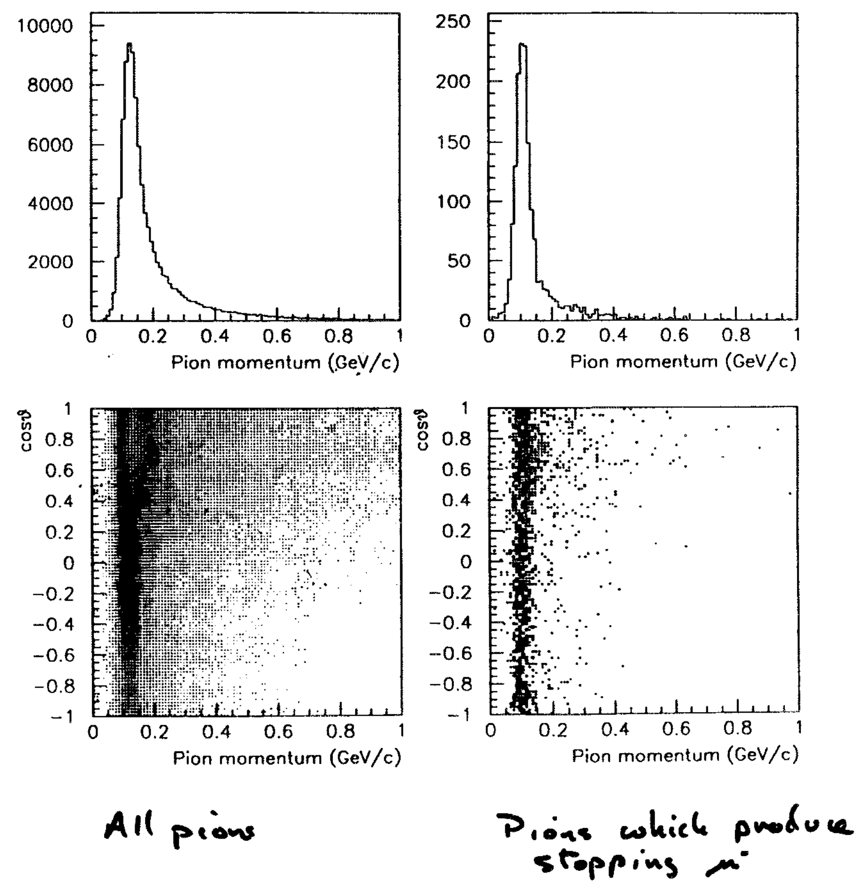
Hadron Code	Target Radius	Target Length	Target Angle	Pr. Sol. Radius	Tr. Sol. Radius	Total μ^-	Stop μ^-
GHEISHA	0.4 cm	16 cm	170°	30 cm	15 cm	1840	729
FLUKA						495	118
SHIELD						1983	563
GHEISHA				40 cm		1831	732
GHEISHA				20 cm		1597	662
GHEISHA					10 cm	585	410
GHEISHA	0.6 cm					1484	572
GHEISHA		20 cm				1784	717

without momentum selection collimator



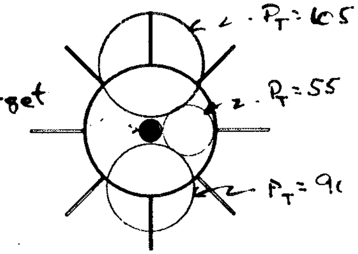
Where are the Stopping Muons Produced?

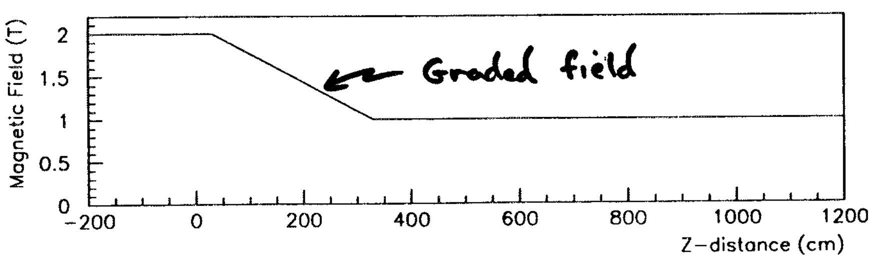
Pions which result in muons stopping in the target
– produced over wide range in angle
– typically at 100 MeV/c

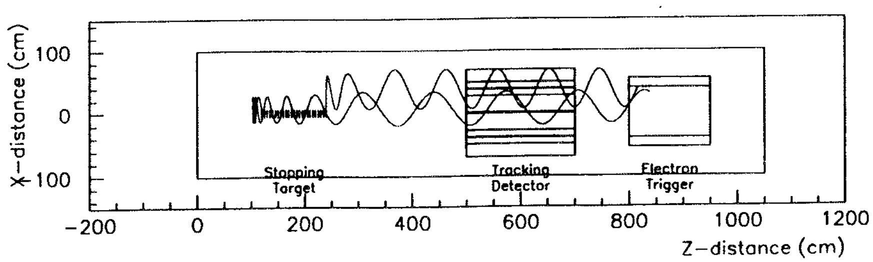


Stopping Target, Solenoid and Detector

- Stopping target and detector in solenoid with graded field
- Stopping target – 25 layers of .02 cm aluminum
- Tracking detector consist of axial detectors
  - Cylinder is either 5 mm straws or 0.5 μm scintillating fibers
  - Vanes are 5 mm straws (electrically semi-transparent)
  - Axial coordinate from cathode pads (straws) or stereo (fibers)
- Electron scintillator/calorimeter
  - Primarily used in trigger
  - Fully absorbing solid plastic scintillator





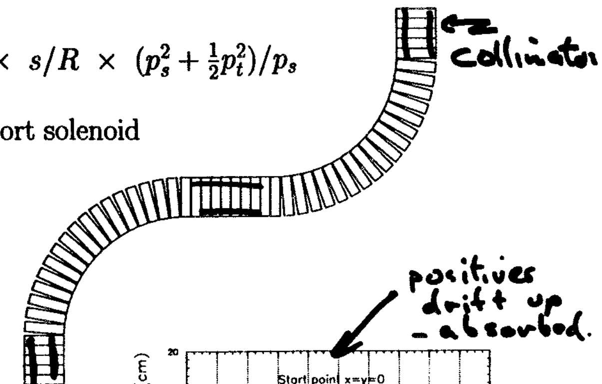


Charge and Momentum Selection in Muon Transport

- Transport in curved solenoid results in drift ⊥ to bend plane

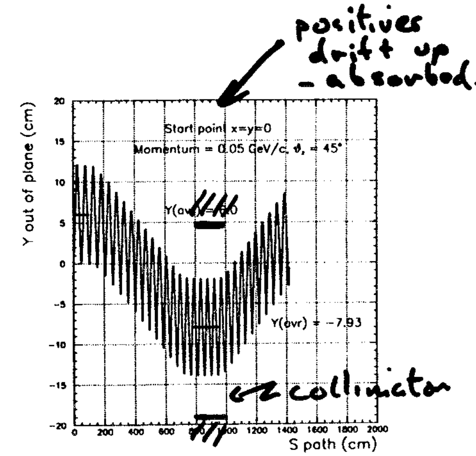
Drift = $1./(0.3B) \times s/R \times (p_s^2 + \frac{1}{2}p_t^2)/p_s$

Curved muon transport solenoid



D is drift distance ⊥ to bend plane
B is magnetic field
s/R is bend angle of solenoid
p_t and p_s are ⊥ and || momenta

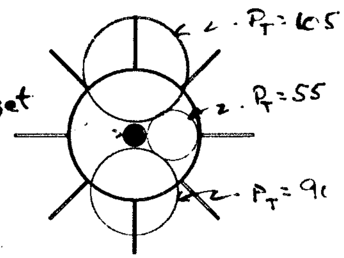
for $s/R = \pi/2$ $p_t = 0.035$ GeV/c,
$p_s = 0.035$ GeV/c, $B = 2T$
$\Rightarrow$ $D = 14$ cm

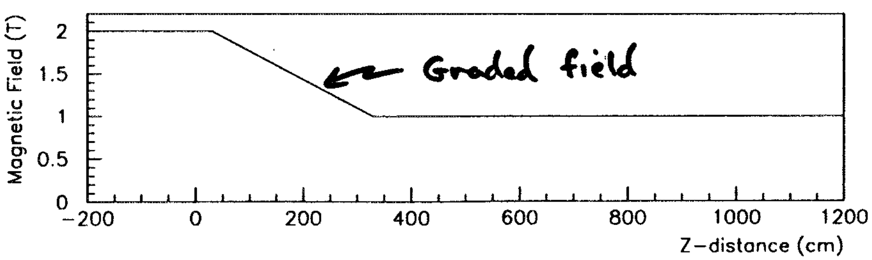


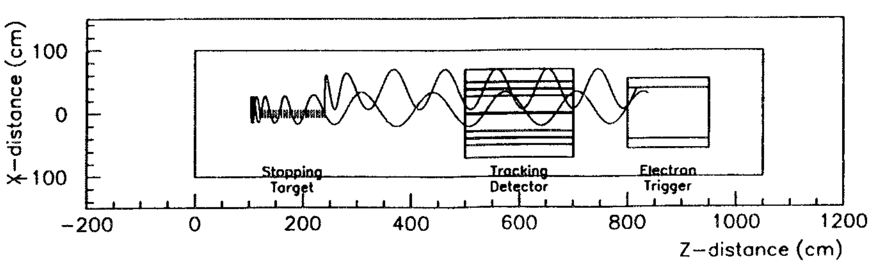
- Positive muons are absorbed in collimator after $\pi/2$ bend – reduces rates in detectors
- Particles above 100 MeV/c are similarly abosrbed – important for beam electron background rejection
- Particles returned to axis after second bend – maintains well collimated beam

Stopping Target, Solenoid and Detector

- Stopping target and detector in solenoid with graded field
- Stopping target – 25 layers of .02 cm aluminum
- Tracking detector consist of axial detectors
  - Cylinder is either 5 mm straws or 0.5 μm scintillating fibers
  - Vanes are 5 mm straws (electrically semi-transparent)
  - Axial coordinate from cathode pads (straws) or stereo (fibers)
- Electron scintillator/calorimeter
  - Primarily used in trigger
  - Fully absorbing solid plastic scintillator

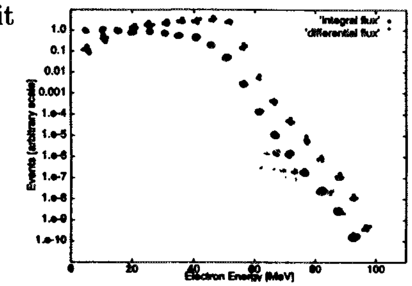




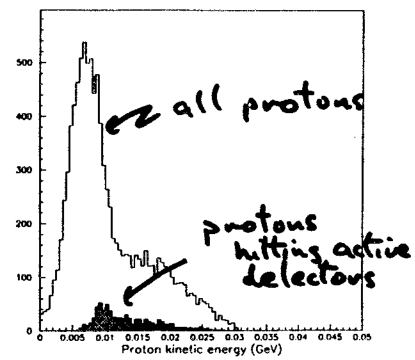


Particle Flux Issues for Detectors

- Electrons from μ^- decay in orbit
  - $E_{e^-} > 53$ MeV
  - Trapped at small radii
  - ~40 kHz / channel



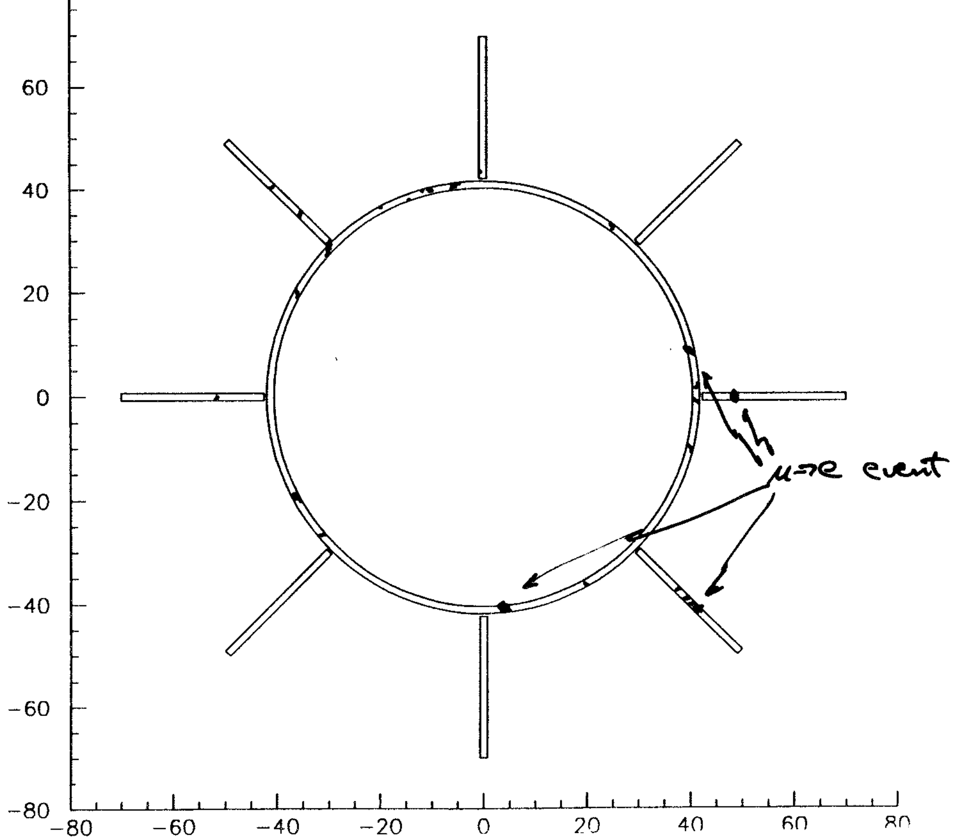
- Protons from μ^- capture
  - About 10^{-2} per μ^- capture
  - Low kinetic energy
  - High momentum
  - Absorbed in target
  - Absorbed in 0.1 mm CH_2
  - ~150 kHz / channel



- Photons from μ^- capture
  - About 2 per μ^- capture
  - Conversions in detector
  - ~100 kHz / channel
- Neutrons from μ^- capture
- Flash from stopping pulse – gate detector HV

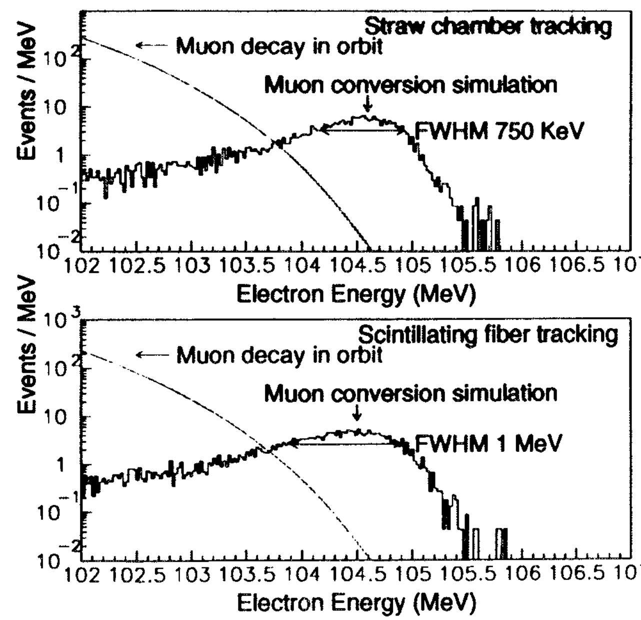
Pattern Recognition and Pileup Issues

- Rates of order 200,000 per detector element
- Tracking detector integration time (~30 ns)
- Local information on track angle (~50 mrad)
- Local timing information (~3 ns)
- Position and energy in trigger counter



MECO Detector Resolution Studies

- Important in eliminating μ^- decay in orbit background
- Full GEANT simulation of detector response
  - Energy loss in target (large effect, low energy tail)
  - Multiple scattering (dominates intrinsic resolution)
  - Position resolution (small contribution)
- No pattern recognition, effects of noise not yet incorporated
- Electron energy fitted by maximum likelihood method
- Signal and background plotted for $R_{\mu e} = 10^{-16}$



Expected MECO Sensitivity

- Expect ~5 $\mu^- N \rightarrow e^- N$ events for 10^7 s run, $R_{\mu e} = 10^{-16}$

Running time (s)	10^7
Proton flux (s^{-1}) now 4-6 with 0.7-1.0 s cycle time	2×10^{13}
μ/p entering solenoid ×0.6 if 8 GeV, non yield uncertain	0.012
Stopping probability	0.37
μ capture probability	0.60
Fraction of μ which capture in time window	0.31-0.54
Electron trigger efficiency	0.90
Fitting and selection criteria	0.25
Detected events for $R_{\mu e} = 10^{-16}$	3.7-6.5

few × 10^{11} μ/sec

- Expect ~0.4 background events for 10^7 s run, $R_{\mu e} = 10^{-16}$

Source	Events	Comment
μ decay in orbit	0.190-0.330	S/N = 20 for $R_{\mu e} = 10^{-16}$
Radiative μ capture	$<< 0.050$	
μ decay in flight	< 0.003	without scatter in target
μ decay in flight	0.004	with scatter in target
Radiative π capture	0.007	from out of time protons
Radiative π capture	0.014	from late arriving π
π decay in flight	$<< 0.001$	
Beam electrons	< 0.020	← further suppressed by 0.1
Cosmic ray induced	0.004	10^{-4} CR veto inefficiency
Total background	0.290-0.410	

Possible MECO Timeline

Scientific approval	**October 1997**
HEPAP recommendation to proceed	March 1998
Detector prototypes	1998 - 1999
Pulsed extraction tests	summer 1998
Beam emittance tests	fall 1998
Kicker prototype tests	fall 1998
Solenoid design	early 1999
Technical design	mid 1999
Detector and beam construction	1999-2001
Pulsed beam tests	early 2000
First muon beam	early 2001
Physics data	late 2001

Summary and Prospects

The MECO $\mu^- N \to e^- N$ experiment can make a major advance in searching for muon and electron number violation

- There is a robust discover potential in many scenarios for physics beyond the Standard Model, e.g. supersymmetry
- A new high intensity pulsed muon beam has been designed using the BNL AGS operating at up to 4×10^{13} p/s
- A detector with high acceptance and good background rejection has been described
- A new experiment –BNL E940–has been approved to search for $\mu^- N \to e^- N$ with sensitivity below 10^{-16}
- Executing the experiment will depend on a commitment by the DOE to operate the AGS for particle physics
- The Gilman HEPAP subpanel is charged with recommending the level of support for particle physics research at the AGS

A $\mu \rightarrow e + \gamma$ experiment with 10^{-14} sensitivity ?

4 th Int. Conf. on
Physics Potential and
Development of
$\mu^+ \mu^-$ Colliders
Dec. 10 - 12, 1997
San Francisco

H. K. Walter
Paul Scherrer Institut

- Why $\mu \rightarrow e \gamma$ and why at PSI ?
- General detector considerations
- Specific detector proposals
- Future plans

Experiments to probe Supersymmetric GUT

"Violations of lepton flavour and CP in supersymmetric unified theories"

R. Barbieri, L. Hall and A. Strumia, Nucl. Phys. B 445 (1995) 219,
and R. Barbieri et al., Erice- and Gran Sasso workshops 1995

Abstract

As a consequence of the large top quark Yukawa coupling, the supersymmetric unified theories with soft supersymmetriy breaking terms generated at the Planck scale predict lepton flavour and CP violating processes with significant rates.
The flavour violating parameters of the low energy theory are derived in both SU(5) and SO(10) theories, and are used to calculate the rate for $\mu \dashrightarrow e\gamma$. The sensitivity of the search for $\mu \dashrightarrow e\gamma$ is compared with that for μ - e conversion in atoms, $\tau \dashrightarrow \mu\gamma$ and the electric dipole moment of the electron. The experimental search for these processes is shown to provide a very significant test of supersymmetric unification, especially in SO(10) but also in SU(5).

	SU(5)	SO(10)	MSSM	
$\mu \dashrightarrow e+\gamma$	●	●		● very important search
μ - e conv.	●	●		
$\tau \dashrightarrow \mu+\gamma$	○			
d_e		●		○ important search
d_n		●		
ε'/ε		○		● dominant constraint on parameters
ε_B		○		
ε_K	○	●	○	
Δm_B	○	○	○	○ constraint on parameters
$b \dashrightarrow s+\gamma$	○	○	○	

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Recent theory papers on $\mu \rightarrow e\gamma$

- **R. Barbieri et al. Nuclear Phys. B 445 (1995) 219**
  "Violations of lepton flavour and CP in supersymmetric unified theories"
  $B(\mu \rightarrow e\gamma) = 10^{(-13\pm1)}$

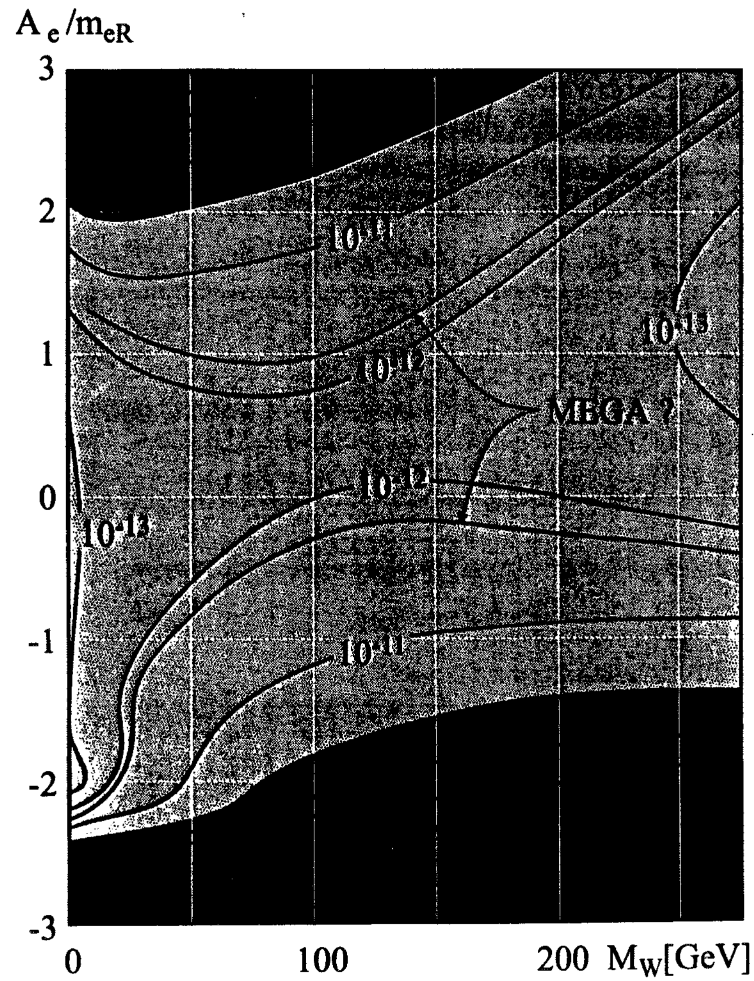
- **J. Hisano et al. Phys. Rev. D 53 (1996) 2442**
  "Lepton-flavour violation via right-handed neutrino Yukawa couplings in the supersymmetric standard model"
  $B(\mu \rightarrow e\gamma) \lesssim 10^{-11}$

- **Y. Kuno and Y. Okada KEK-TH-478, April 1996**
  "$\mu \rightarrow e\gamma$ Search with Polarized Muons"
  Reduction of accidental background

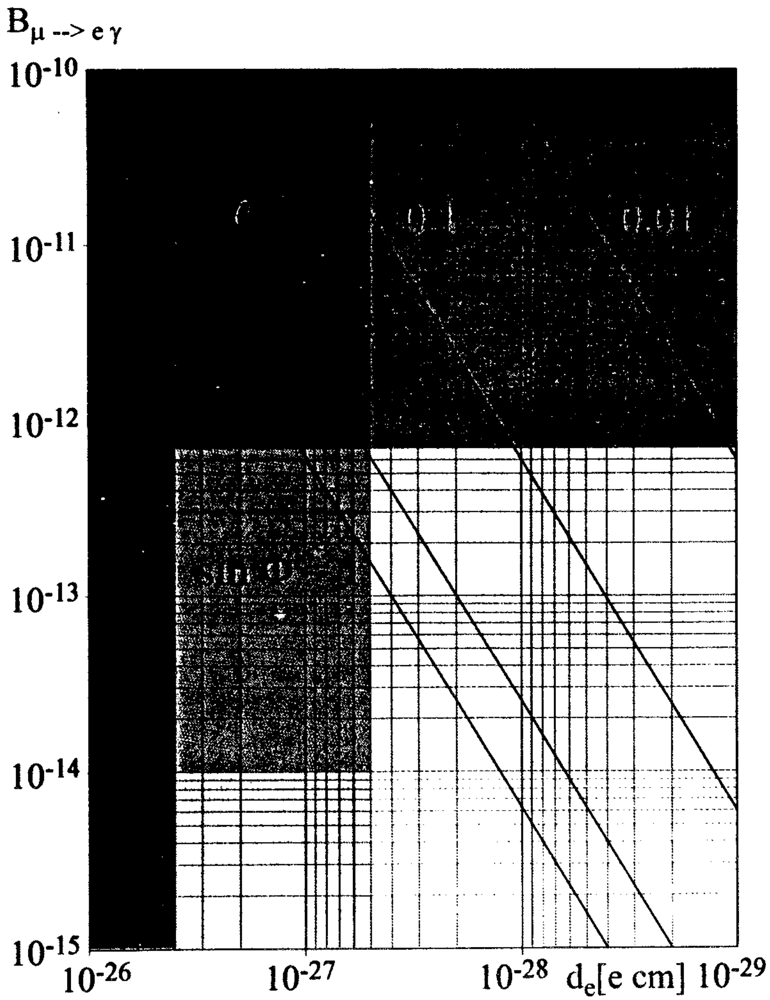
- **B. de Carlos et al. Phys. Rev. D 53 (1996) 6398**
  "Constraints on supersymmetric theories from $\mu \rightarrow e\gamma$"
  $(\text{gaugino mass})^2 / \mu\text{-e mass mixing} \gg 34$ TeV

- **M.E. Gomez and H. Goldberg Phys. Rev. D 53 (1996) 5244**
  "Lepton flavor violation in SUSY SO(10) with predictive Yukawa texture"
  $B(\mu \rightarrow e\gamma) = 10^{(-12\pm2)}$

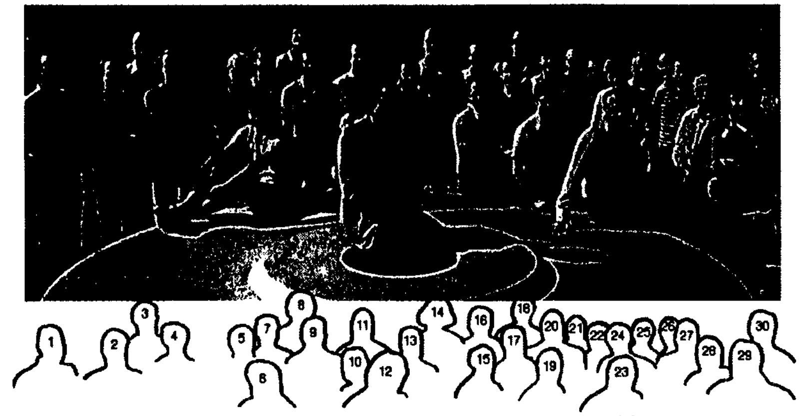
B.R. ($\mu \rightarrow e\gamma$) in SO (10) (Barbieri et al.)



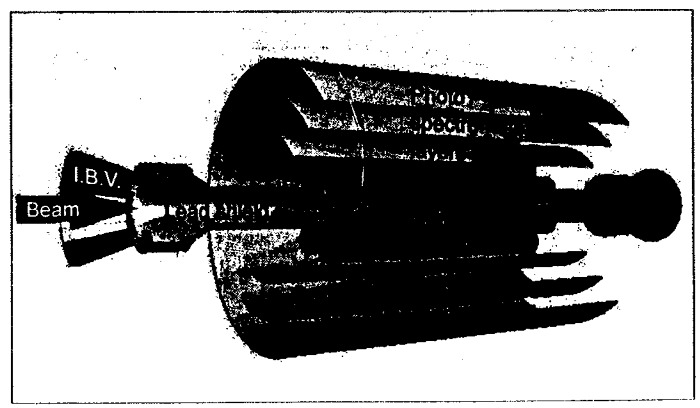
μ --> e γ versus d_e (Barbieri et al.)

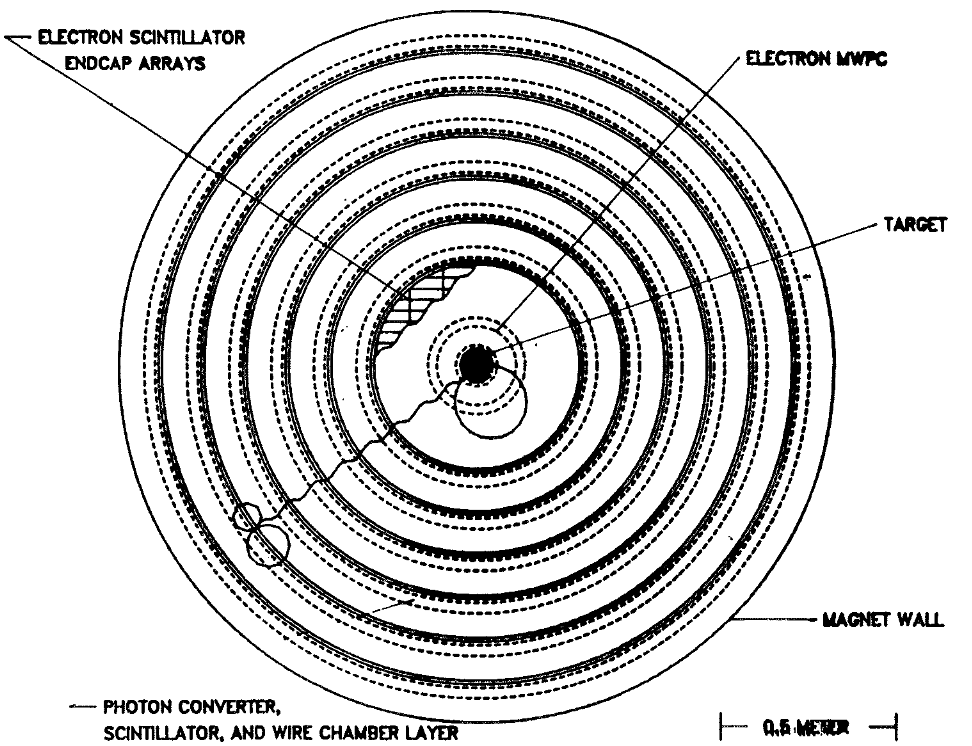


The MEGA (search for μ --> e+γ) experiment at LAMPF

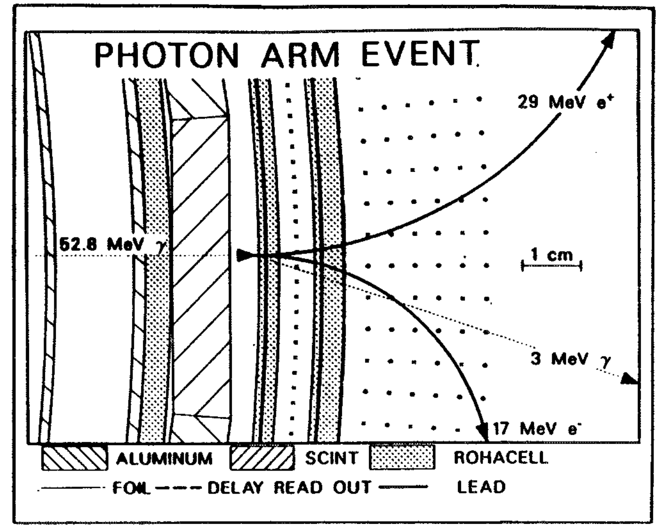


1. Don Koetke (Valparaiso)
2. John Otis (Stanford)
3. Barrie Hughes (Stanford)
4. Brad Tippens (Virginia)
5. Joe Van Dyke (LANL, MP-8)
6. Charles Jui (Stanford)
7. Kevin Black (LANL, MP-4)
8. John Markey (Yale)
9. Ron Harrison (LANL, MP-8)
10. Rick Bolton (LANL, MP-4)
11. Ben Nefkens UCLA)
12. Martin Cooper (LANL, MP-4)
13. Cy Hoffman (LANL, MP-4)
14. Jim Amann (LANL, MP-10)
15. Peter Cooper (Yale)
16. Mike Oothoudt (LANL, MP-1)
17. Leo Piilonen (LANL, MP-4)
18. Courtenay Wright (Chicago)
19. Dick Mischke (LANL, MP-4)
20. Tom Kozlowski (LANL, MP-1)
21. Val Hart (LANL, MP-8)
22. Del Kercher (LANL, MP-1)
23. Gary Hogan (LANL, MP-4)
24. Jim Little (LANL, MP-1)
25. Louis Rosen (Past Director, LAMPF)
26. Gerry Garvey (Director, LAMPF)
27. Ed Hungerford (Houston)
28. Lew Agnew (MP Deputy Div Leader)
29. Larry Pinsky (Houston)
30. Wolfram v. Witch (Houston/Bonn)

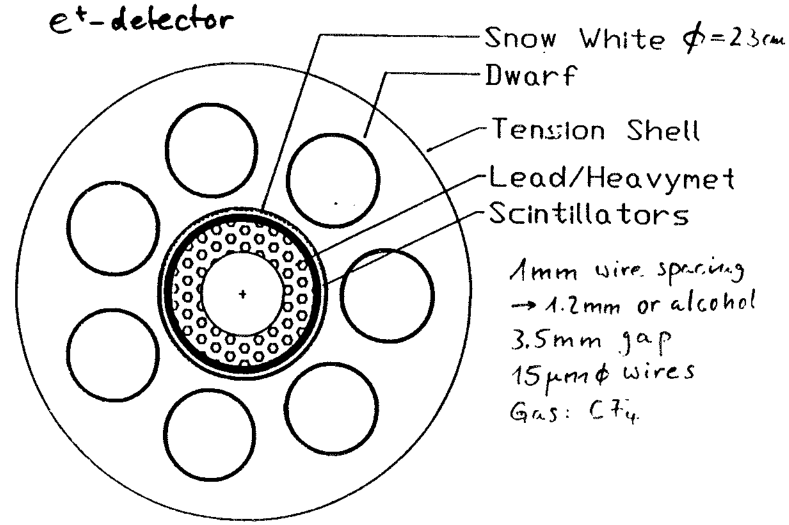




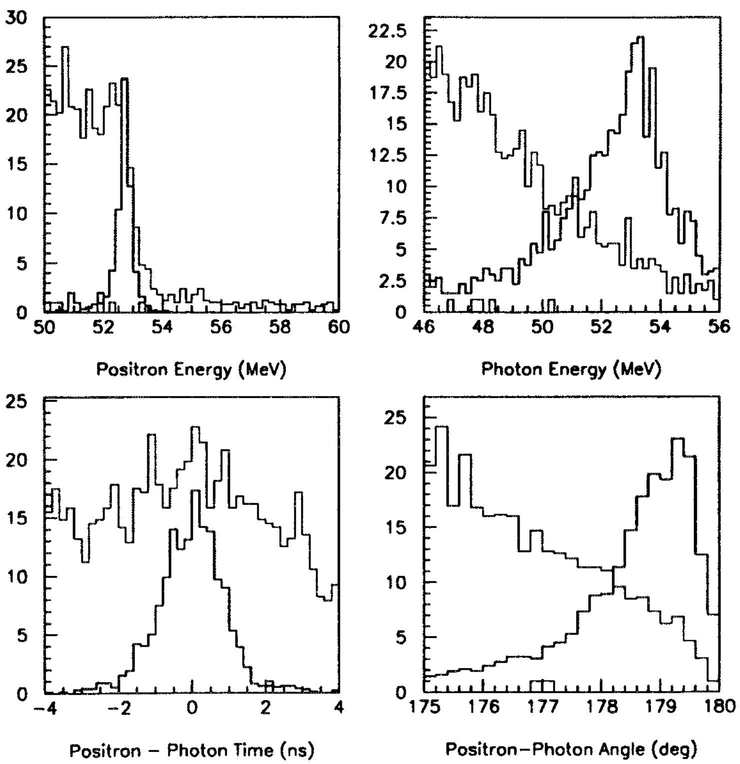
γ-detector



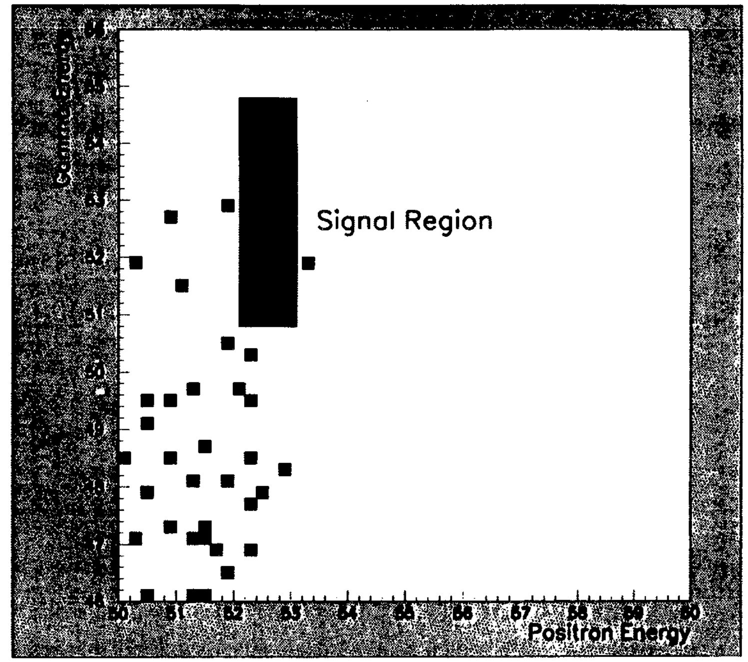
e^+-detector



Results from MEGA



Results from MEGA



Results from ~16 % of data

BR $_{90\%}$ ($\mu \rightarrow e\gamma$) < 3.8 x 10 $^{-11}$

compare to current world limit from crystal box

BR $_{90\%}$ ($\mu \rightarrow e\gamma$) < 4.9 x 10 $^{-11}$

Expectation from all MEGA data

BR $_{90\%}$ ($\mu \rightarrow e\gamma$) < 3-6 x 10 $^{-12}$

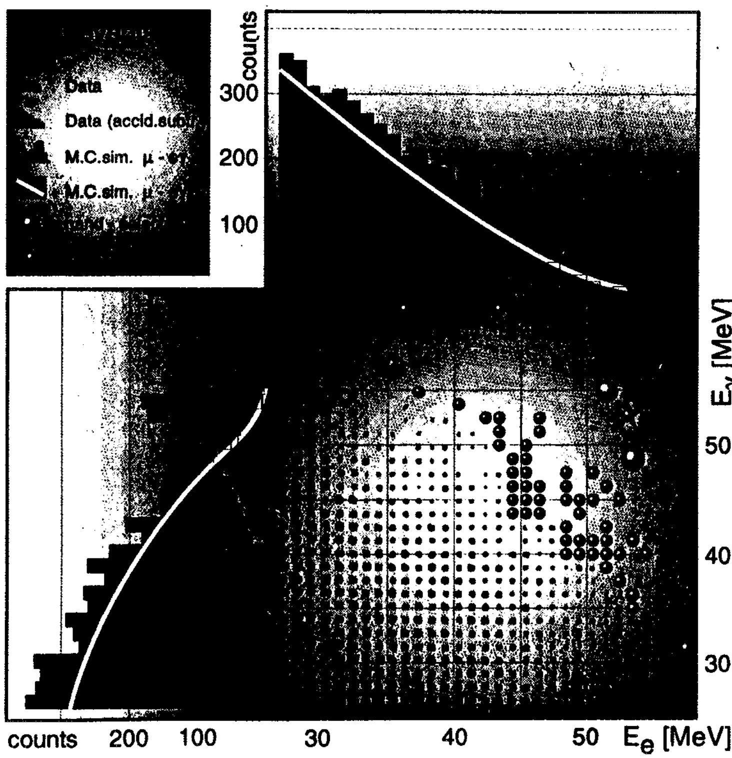
or evidence for the decay

The famous μ - eγ experiment at SIN

$B_{\mu - e\gamma} <$ 10^{-9} (SIN 1978)

$< 5\ 10^{-11}$ (X-tal Box LAMPF)

$5\ 10^{-13}$ (MEGA LAMPF)



Sensitivity and background for μ-->eγ

Single event sensitivity:

$$B_{\mu\to e\gamma}^{\text{sing.event}} = (N_\mu \cdot T \cdot \tfrac{\Omega}{4\pi} \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot f_{pol} \cdot \varepsilon_{cut}^{5})^{-1}$$

N_μ = muon stop rate
T = measuring time
Ω = solid angle
ε_i = efficiencies
f_{pol} = gain factor for polarized muons

Physical background:

$$B_{\mu\to e\gamma\nu\bar{\nu}}^{\text{phys}} = 5.8 \cdot 10^{-4} \cdot (\delta x)^2 \cdot \delta y \cdot [\delta y + \tfrac{\delta x}{3}] \cdot (\delta z)^2$$

x = $2E_e/m_\mu$
y = $2E\gamma/m_\mu$
z = $\pi-\theta_{e\gamma}$
δ = signal box half width

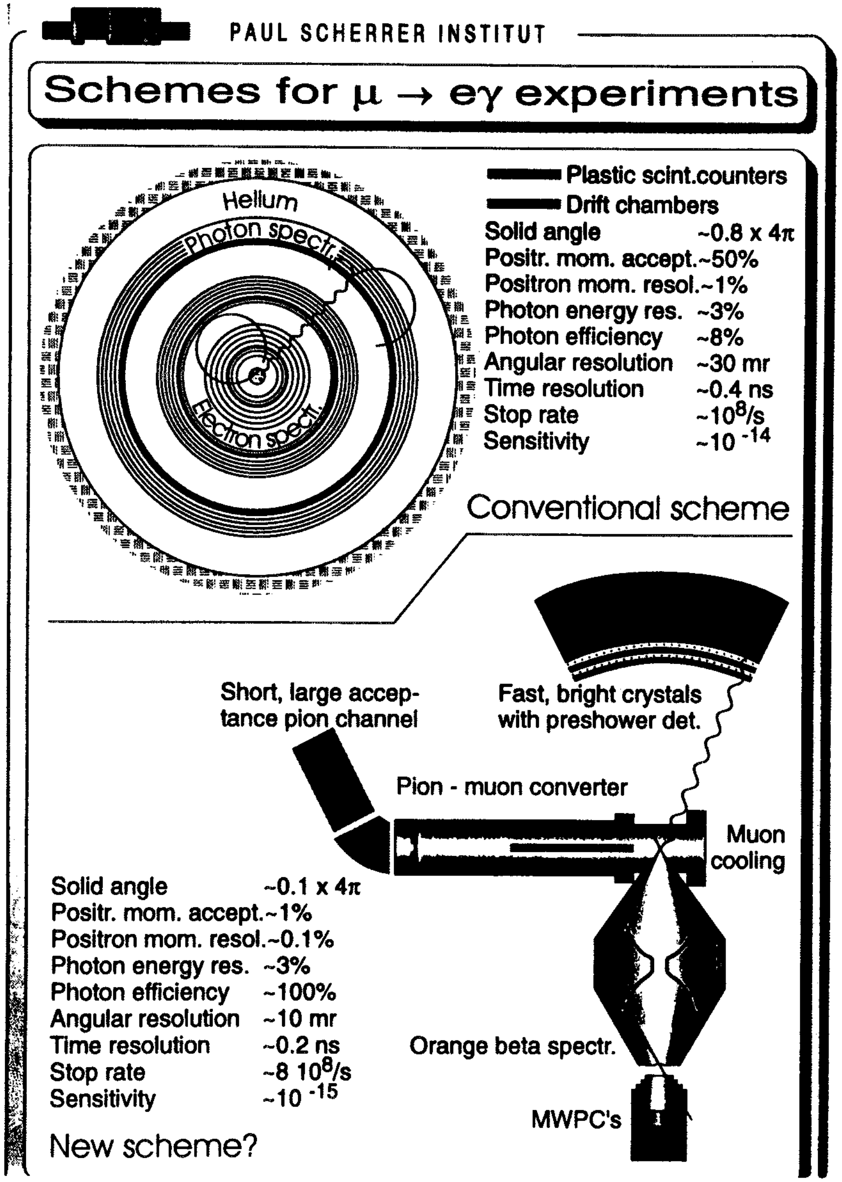
$$\delta x_i = \tfrac{1}{2} \cdot (\Delta x_i)_{cut}^{\varepsilon_{cut}=0.9} = \tfrac{1}{2} \cdot 1.4 \cdot \Delta x_i^{FWHM}$$

Accidental background:

$$B^{acc} = R_\mu \cdot f_e^0 \cdot f_g^0 \cdot (\tfrac{\delta\omega}{4\pi}) \cdot 2\delta t \cdot \varepsilon_{cut}^{-5}$$

With
$$f_e^0 = 2\delta x$$
$$f_\gamma^0 = \tfrac{\alpha}{2\pi} \cdot (\delta y)^2 \cdot (\ln \delta y + 7.33) = 1.16 \cdot 10^{-3} \cdot (\delta y)^2 \cdot (\ln \delta y + 7.33)$$
$$\tfrac{\delta\omega}{4\pi} = \tfrac{\pi(\delta\theta_{e\gamma})^2}{4\pi} = \tfrac{(\delta\theta_{e\gamma})^2}{4}$$

$$B^{acc} = R_\mu \cdot \tfrac{\alpha}{2\pi} \cdot \delta x \cdot (\delta y)^2 \cdot (\ln \delta y + 7.33) \cdot (\delta\theta)^2 \cdot 2\delta t \cdot \varepsilon_{cut}^{-5}$$



Characteristics of the πE5 channel at PSI

Solid angle Ω	150 msr
Length L	10.5 m
Resolution δp/p	1.5 %
Momentum band Δp/p	10 % FWHM
Max. momentum p_{max}	120 MeV/c

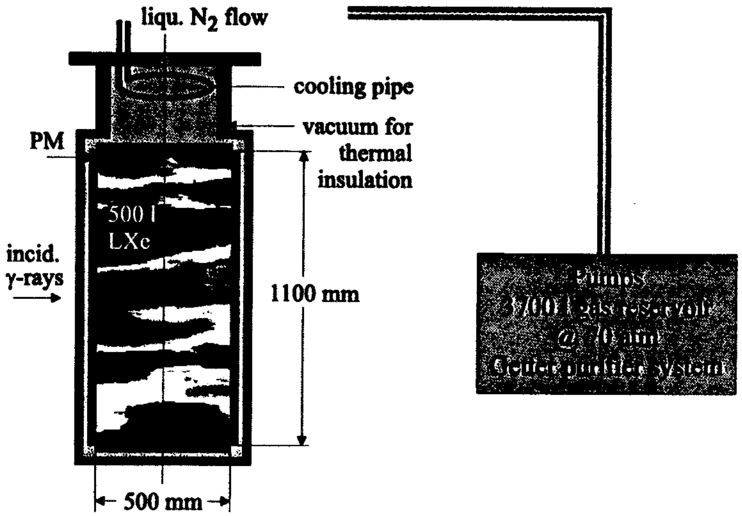
Spot size for pions

x	=	1.5 cm	FWHM
y	=	2.0 cm	"
x'	=	300 mrad	"
y'	=	100 mrad	"

Spot size for muons

x	=	3.1 cm	FWHM
y	=	3.3 cm	"
x'	=	300 mrad	"
y'	=	100 mrad	"

LXe calorimeter for μ --> e γ, R&D (T. Doke)

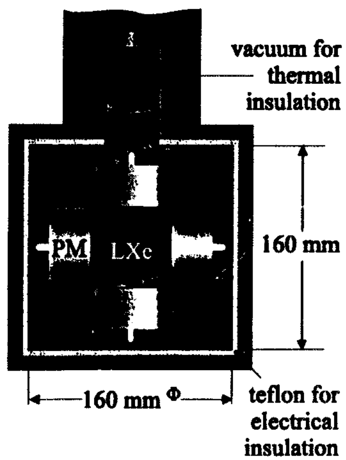


VUV Sensitive Photomultiplier R6041Q

Diameter:	2"
Height:	1.6"
Dynode:	Metal Channel Diodes
Photo-cathode:	Sb - Rb - Cs *
diameter:	1.8"
Quantum eff.:	0.1 ** for 175 nm

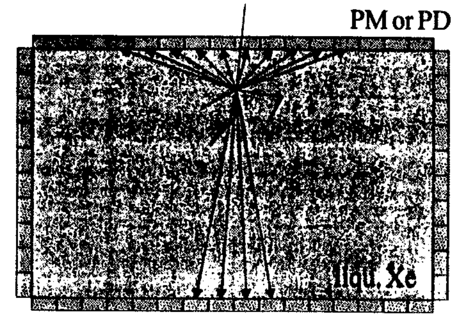
* This is the same as used in R 1668, so this multiplier can be operated at liquid Xe temperature

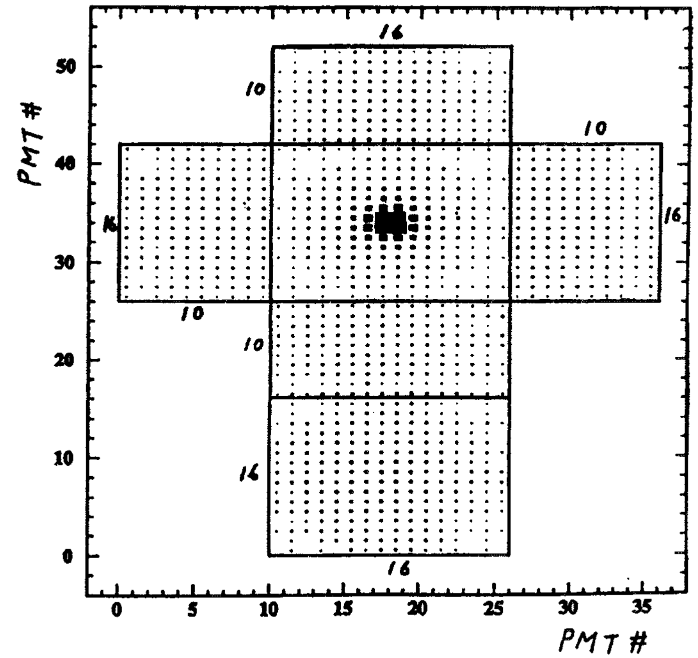
** This value includes the absorption effect due to the quartz window.



"Min - Kam" liqu. Xe cal. for μ --> e γ (S. Orito)

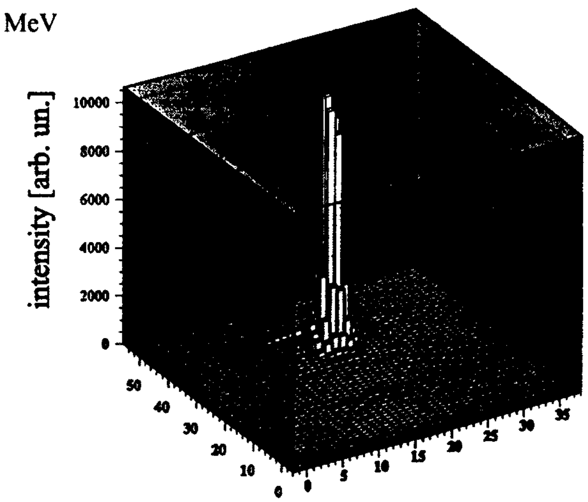
1 / 50'000 volume of Superkamiokande

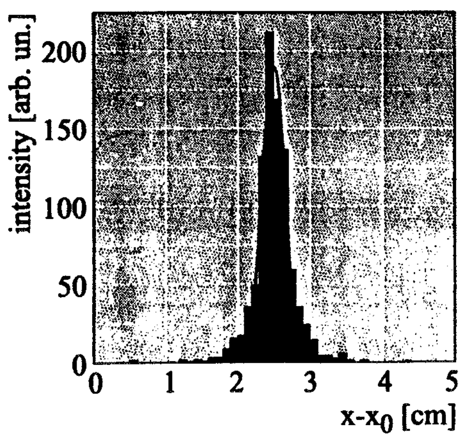




50 MeV photon in Min - Kam (S. Orito)

Trial event 50 MeV

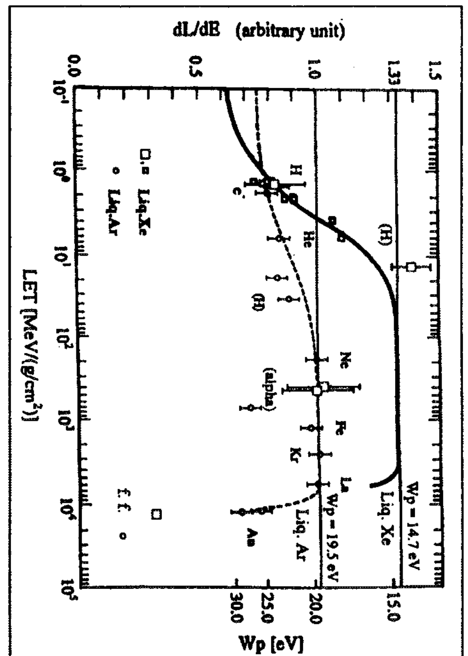




x-resolution by crude weighted mean for 5" x 5" PMT
σ_x = 1.7 mm
FWHM = 4 mm
(will improve by proper fitting algorithm)

Liquid Xe Scintillation Calorimeter for μ --> e γ Decay (T. Doke)

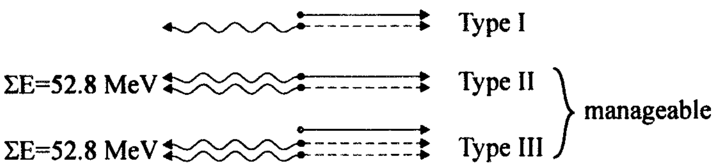
Physical Properties of Liquid Xe	
Atomic number	54
Atomic weight	131.3
Boiling point at 1 bar	165 K
Melting point at 1 bar	161 K
Temperature at triple point	161.4 K
Pressure at triple point	612.2 Torr
Liquid density	3.0 g/cm^3
Solid density	3.4 g/cm^3
W-value	15.6 eV
W_{ph}-value	24.0 eV
for 1 MeV electrons	
Decay time constants:	
τ_f (fast component)	4.2 ns
τ_s (slow component)	22.0 ns
τ_r (recombination)	45 ns
Ratio of scintillation from direct excited atoms to that from recombination	0.25
Attenuation length of scintillation light	30 cm

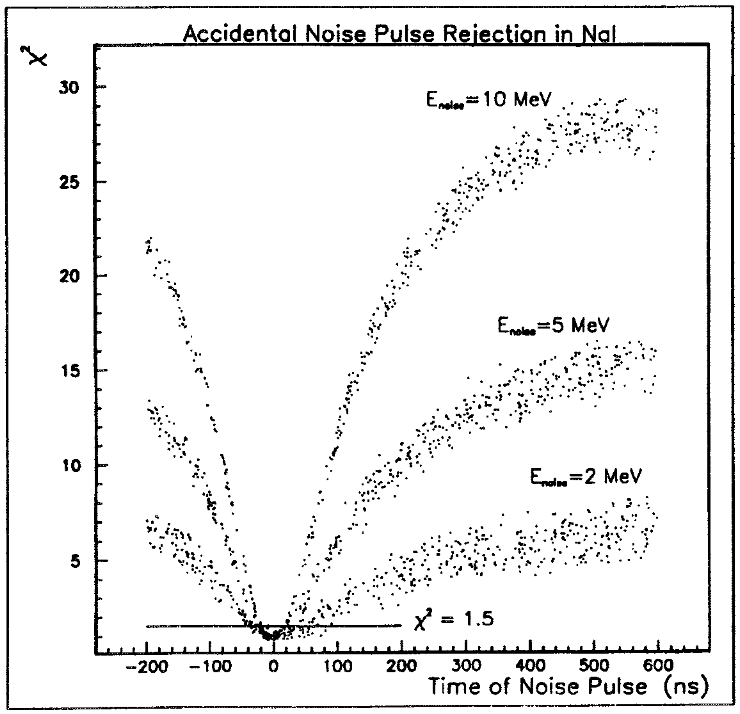


(fast + slow) / recombination	~25 / 75
W_{ph} (liqu. Xe / NaI)	~24 eV / 17.2 eV
Peak wave length	174 nm
Measured attenuation length	29 (2) cm
(since mainly caused by Rayleigh scattering no problem)	
Refraction index	1.56 for 175 nm

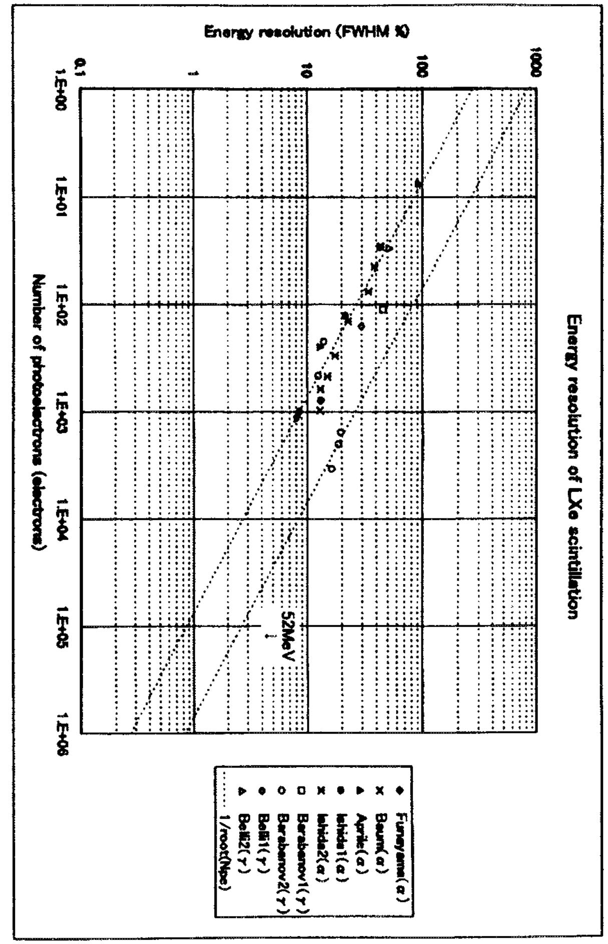
Photon detection, granularity, pile-up (R.Marlow)

Tower geometry: position resol. ~ 1 cm
Pile-up rej. ~0.1 τ by waveform analysis





Energy resolution of liquid Xe (T. Doke)



Estimated energy resolution for 52 MeV gamma - rays is ~2.5 % (FWHM), where Qeff = 0.1 and light collection = 0.5 are assumed

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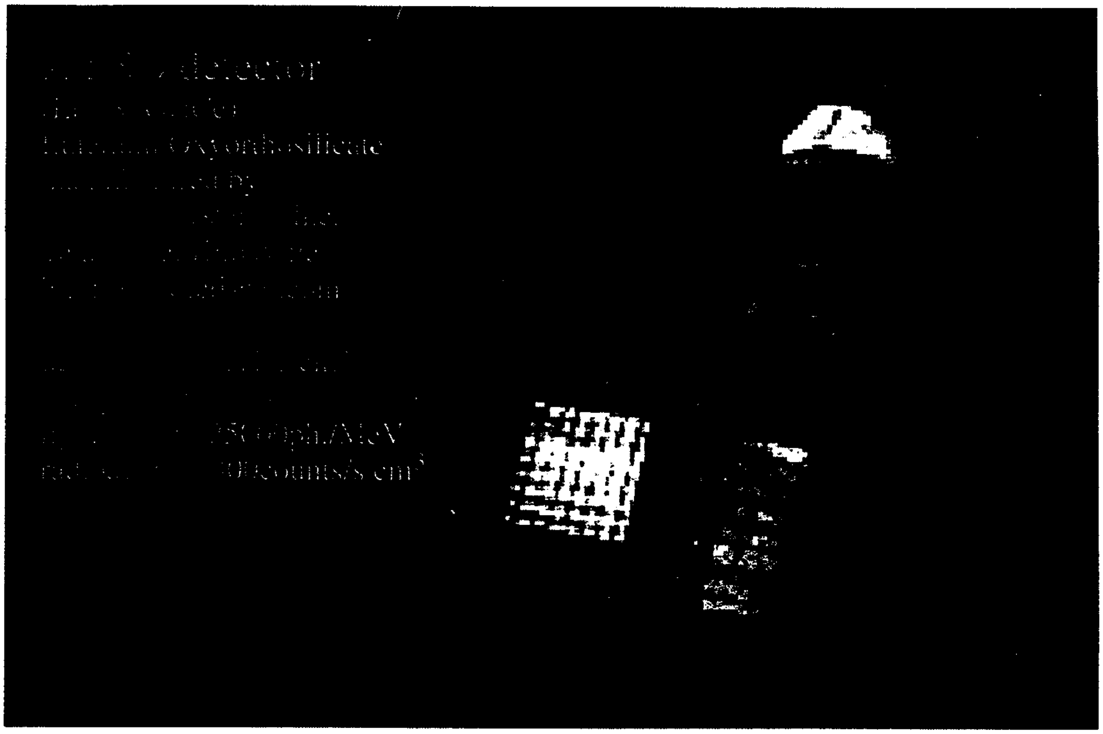
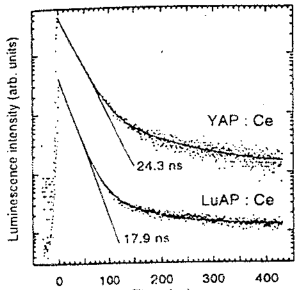
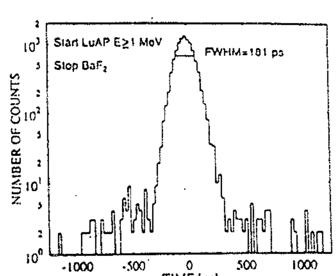


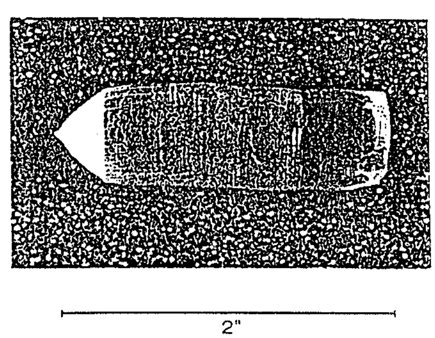
Walter-20.Juni 98-LSOctl-PSI7970

Crystal properties

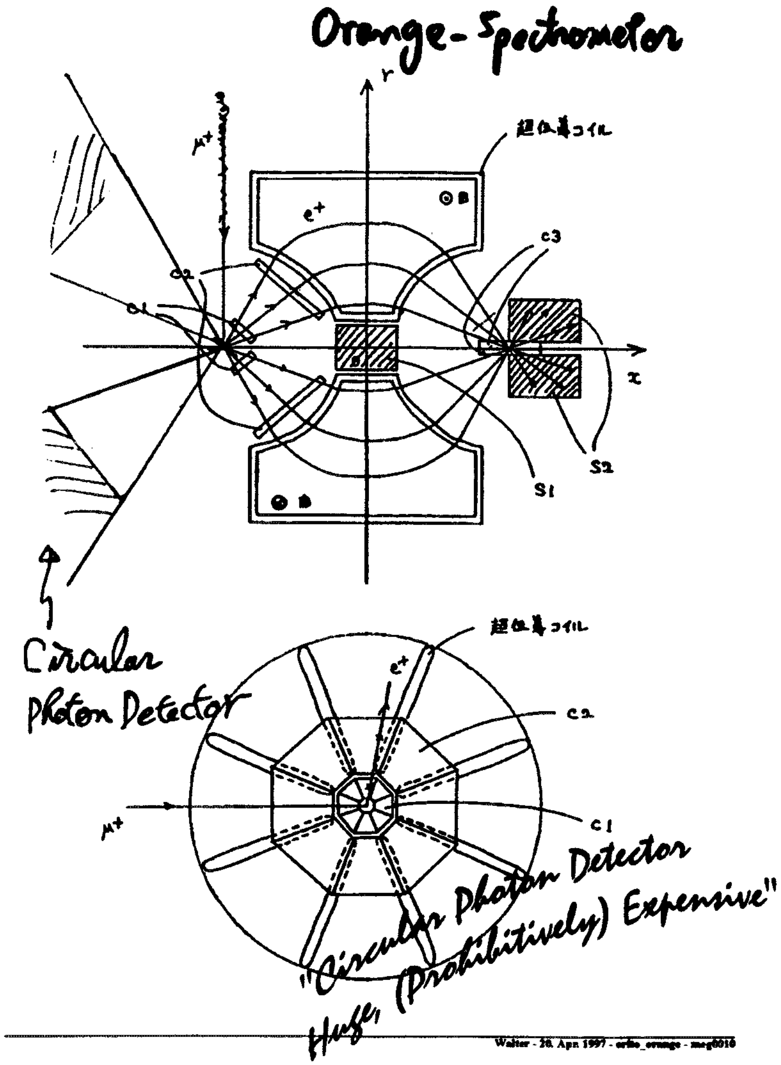
		γ energy	YAP	LuAP	LuAP	LSO	GSO	BGO	NaI(Tl)
Ce concentration	10^{-3}		10	0.35	1.05	2.2	10		
light yield	ph/keV		14	12	23	23	9	9	40
fall time	ns		24	17	16	47	41	300	230
density	g/cm^3		5.5	8.4	8.4	7.4	6.7	7.1	3.7
peak wave length	nm		380	365	365	420	430	480	415
energy resolution	10^{-2}	0.66 MeV	7.2		6.5	7.9	7.8	9.3	6.5
time resolution	ns	1 MeV	0.3	0.25	0.16	0.16	0.7	1	0.35
mass att. length	cm	0.51 MeV	2.63	1.05	1.05	1.05	1.38	1.11	3.05
refractive index			1.94	1.94	1.94	1.82	1.85	2.15	1.85







Orange Spectrometer for μ --> e γ (S. Orito)



Walter - 26. Apr 1997 - orito_orange - meg0010

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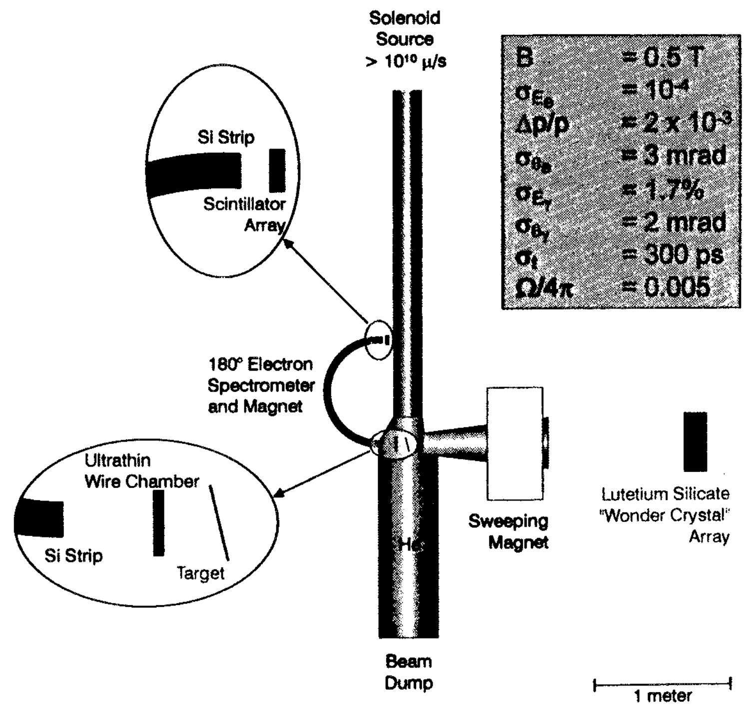
New Proposal for μ --> eγ by M. Cooper (Los Alamos)

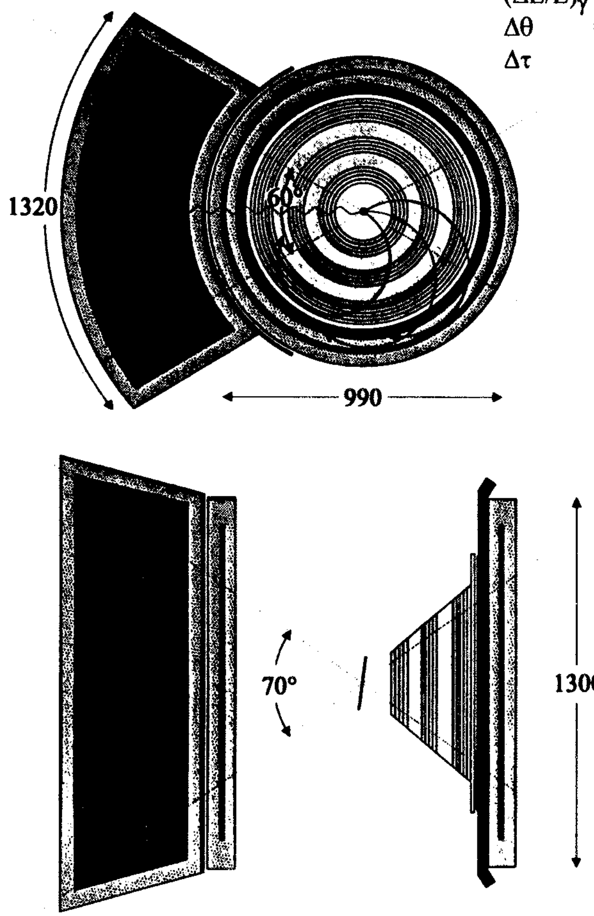
Schematic Layout for a new $\mu^+ \to e^+ \gamma$ Experiment



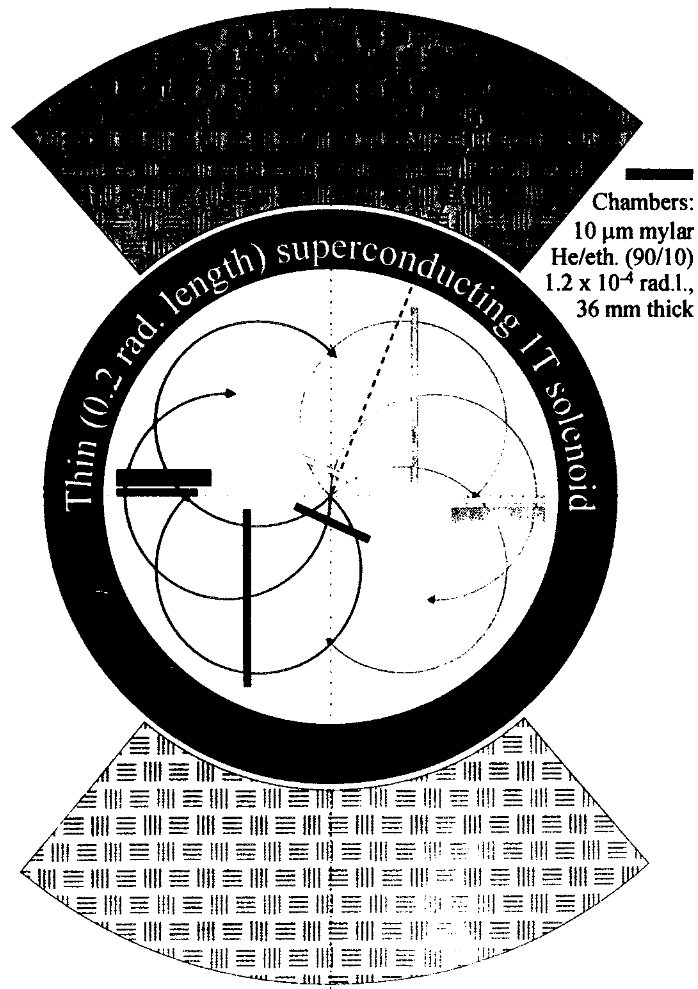
B	= 0.5 T
σ_{E_e}	= 10^{-4}
$\Delta p/p$	= 2×10^{-3}
σ_{θ_e}	= 3 mrad
σ_{E_γ}	= 1.7%
σ_{θ_γ}	= 2 mrad
σ_t	= 300 ps
$\Omega/4\pi$	= 0.005

Possible μ --> e γ set-up (S. Orito)

$\Omega/4\pi$ = 0.1 - 0.6
$(\Delta E/E)_e$ = 0.7 %
$(\Delta E/E)_\gamma$ = 3 %
$\Delta\theta$ = 7 mrad
$\Delta\tau$ = 50 ps

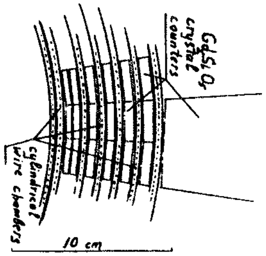


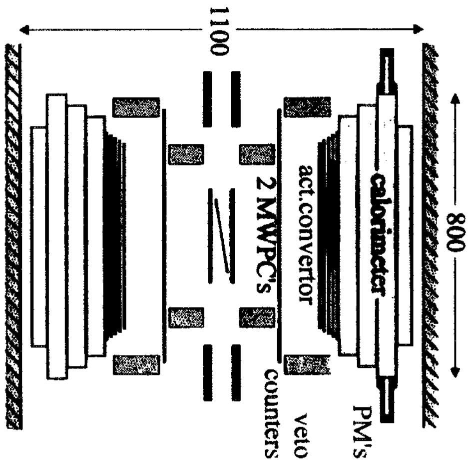
Possible μ --> eγ set-up (A. Maki)

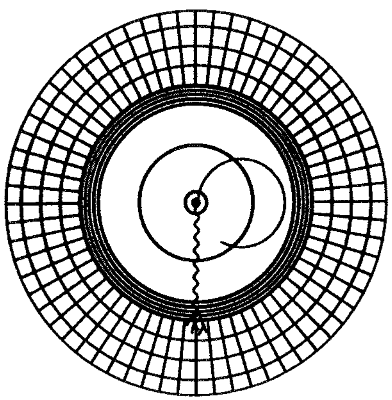


Set-up (MEG - 14M) to search for μ --> e γ (S. Korenchenko)

$\Omega = 2\pi$ sterad
B = 1.5 T
Ecal: 14.8 R.L.
Gd_2SiO_5:Ce
370 l, 2.5 tons
Active Convertor:
2 R.L. ~5 layers
26 l, 174 kg
1152 P.M. or APD
MWPC's: 7
10'000 wires
7'000 strips







$\Delta E_e/E_e \sim 0.7\,\%$ $\Delta E_\gamma \sim 3.5\,\%$
$\Delta\theta \sim 18$ mrad $\varepsilon_\gamma \sim 75\,\%$

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μ - eγ III (LAMPF) [at 10^{-12}]

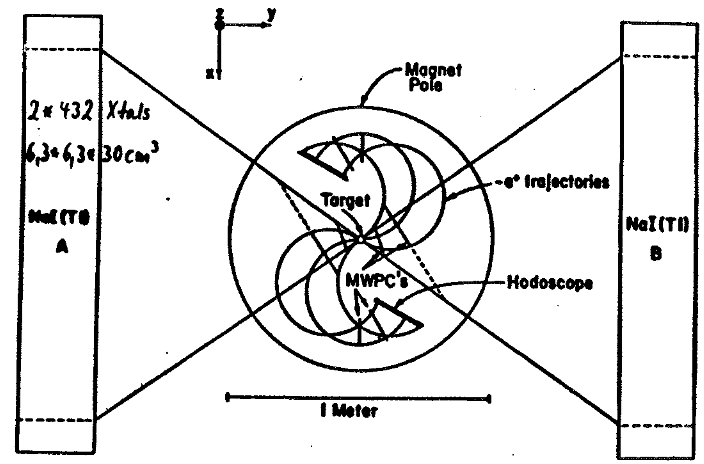
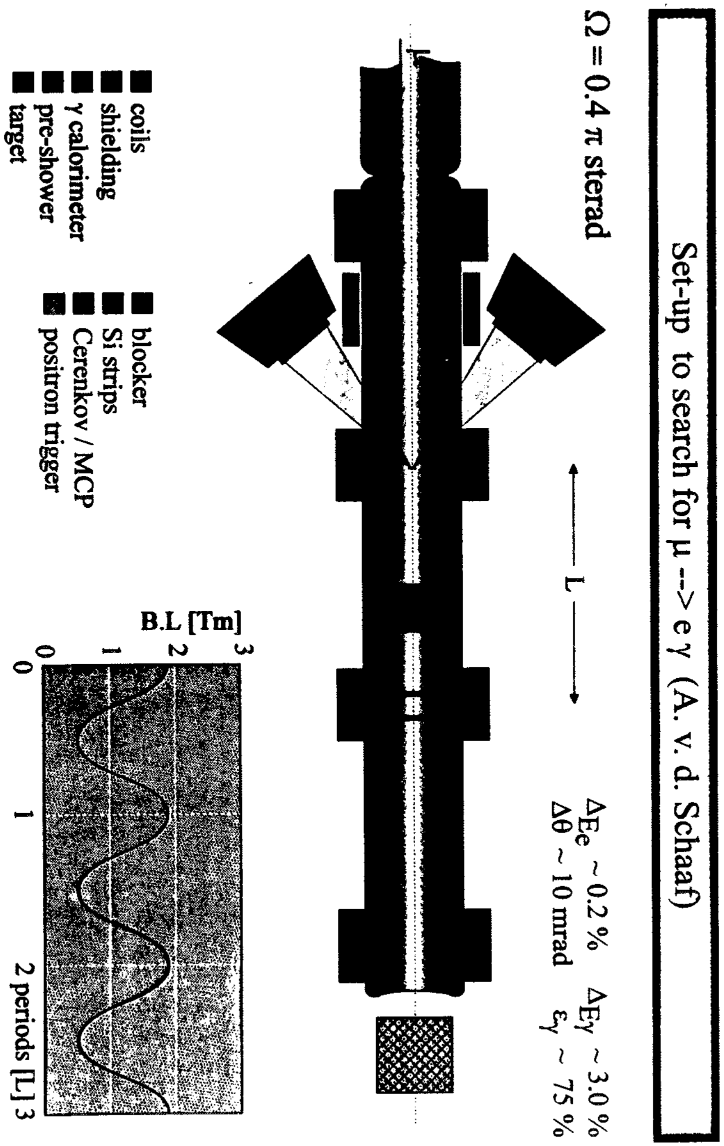


Fig. 14. Design of the future LAMPF $\mu^+ \to e^+\gamma$ (III) experiment.

Acceptance	16 %
Stop rate	$2.5\cdot10^7$ average
$\Delta E_\gamma/E_\gamma$	4%
$\Delta E_e/E_e$	0.6 %
Δt	0.7 ns



Possible Participants in a LoI at PSI

Possible Collaborators

Enrico Conti	Padua
Tadayoshi Doke	Waseda University
Spartak Korenchenko	Dubna
Yoshitaka Kuno	KEK
Akihiro Maki	KEK
David Mzavia	Tbilisi
Shuji Orito	Tokyo University
Dino Zanello	Rom

Tetsuro Mashimo, ? Miyazawa, Toshinori Mori, Hiroyuki Okada, Shuji Tanaka, Kazuhiro Terazawa, Koji Yoshimura

Conclusions

- A new $\mu \rightarrow e\gamma$ experiment (together with μ - e conversion and the EDM of the neutron) is recommended by many theorists as one of the most promising low energy tests to see supersymmetric unification and undoubtedly has high priority
- It has to have a sensitivity of $\sim 10^{-14}$ in order to be sufficiently decisive
- It can be done with the required sensitivity at the edge of present day technology and with the existing πE5 beam at PSI
- Best energy, angular and time resolutions are required for the detector in order to overcome the main accidental background
- These best performances probably will forbid a 4π detector from price arguments, therefore the intrinsic efficiency of the photon side should be high, suggesting a calorimeter
- Ce doped highly luminous crystals or liquid Xe/Kr are being studied and a photon resolution of 2-3 % FWHM at 50 MeV is strived for
- The positron (magnetic) spectrometer should have <0.5% energy resolution (FWHM) at 50 MeV/c and a limited momentum acceptance
- Positron polarization and inner bremsstrahlung vetos should be exploited as far as possible
- There is still room for good ideas, good R&D on new crystals and liquids and good collaborators
- There will be competition (complementation) from μ - e conversion (BNL) and EDM of the neutron (LANSCE and PSI)

Conclusions R. Barbieri

What if $\mu \rightarrow e\gamma$ is not seen at a few x 10^{-14} level?

- Supersymmetric unification is false

or

- Accelerator searches of SUSY particles reoriented:

γ's from "LSP" - decays

"stable" charged tracks rather than huge missing E