VERY LOW ENEGRY COOLING POSSIBILITIES TOWARDS MUON COLLIDERS

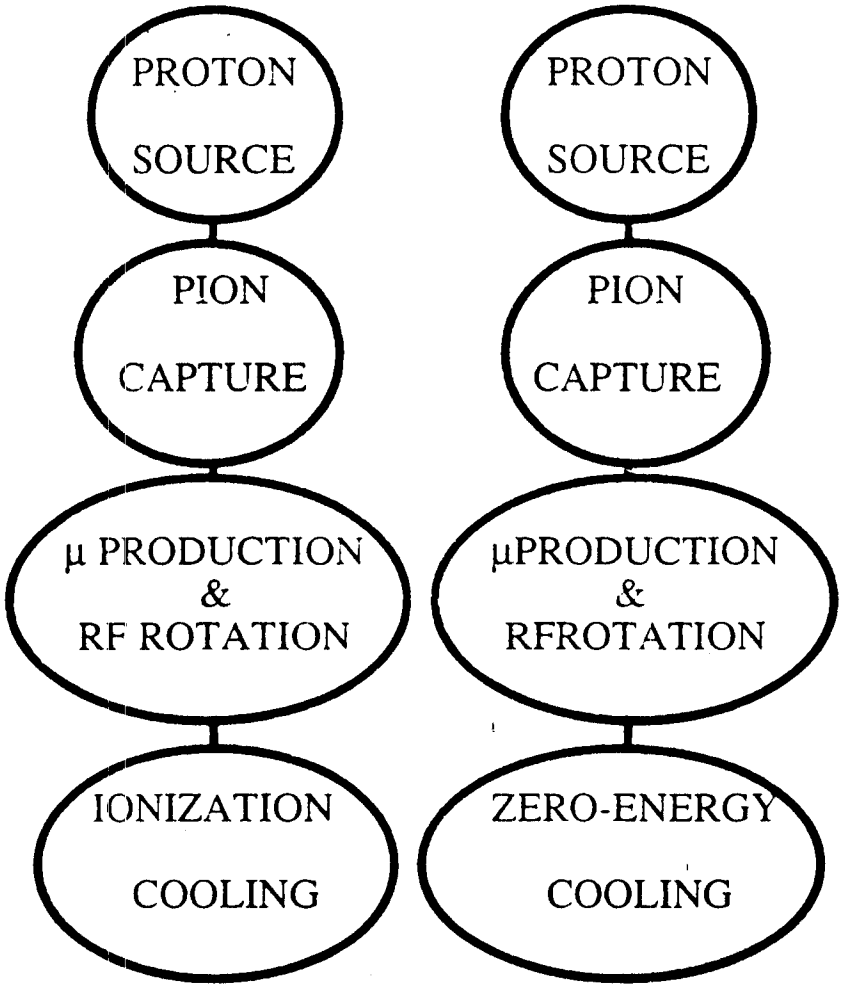
Workshop on 10-100 TeV Muon Colliders & Collider Physics

1 October, 1999
Montauk, N.Y.

K. Nagamine
Meson Science Laboratory, IMSS-KEK
Muon Science Laboratory, RIKEN

1. Introduction
2. Possible Very Low Energy Muons
3. KEK Method of Low Energy μ^+
   ; Present Status and Next Step
4. Collider Option
5. Neutrino Source Option
6. Conclusion

INTRODUCTION



3×10^{12} μ/bunch	5×10^{12} μ^+/s
20 MeV	10 keV
ε_N : 4×10^{-5} m-rad	ε_N : 8×10^{-8} m-rad

POSSIBLE VERY LOW ENERGY MUONS

PROPOSED & REALIZED (☆) MUON COOLING METHOD

	IONIZATION COOLING	μ^+, μ^-
MeV	PHASE SPACE COMPRESSION	μ^+, μ^-
	μ^- RE-EMISSION FROM μCF	μ^-
KeV	☆ FRICTIONAL COOLING (PSI)	μ^+, μ^-
	☆ COLD MODERATOR (TRIUMF/PSI)	μ^+
eV	☆ THERMAL MUONIUM IONIZATION (KEK)	μ^+

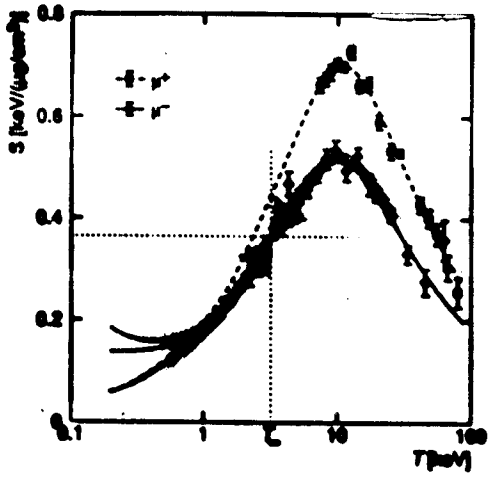


Figure 1. Average stopping power $S(T)$ of carbon measured for both, positive muons and negative muons as a function of energy T [12,13]. Smooth curves are fitted according to the parameterization given in [14]. There is strong evidence that $S(T)$ for μ^- stays constant or even increases at energies below 0.8 keV [15–18]. The arrows show the region where we expect an increase in the spectral density for an equilibrium energy $T_{eq} = 3$ keV.

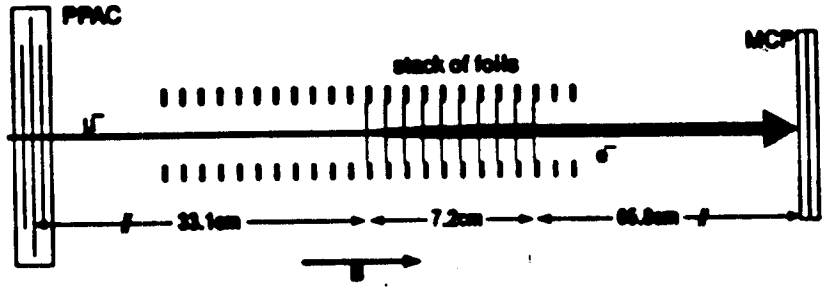


Figure 2. Schematic view of the experimental set-up as it is inserted into a superconducting solenoid (not shown) generating a high magnetic field in beam direction (PPAC: parallel-plate avalanche counter, MCP: microchannel plate).

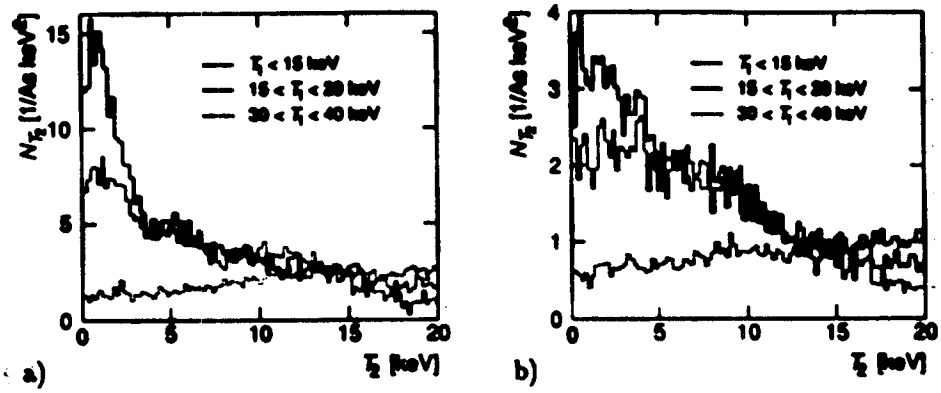


Figure 3. Energy spectra of the outgoing muons for different slices in the energy T_1 of the incident muons (10 foils ≈ 5 μg/cm² C each, $U_{down} = -3$ kV and (a) $\Delta U = 1.4$ kV, (b) $\Delta U = 1.00$ kV.

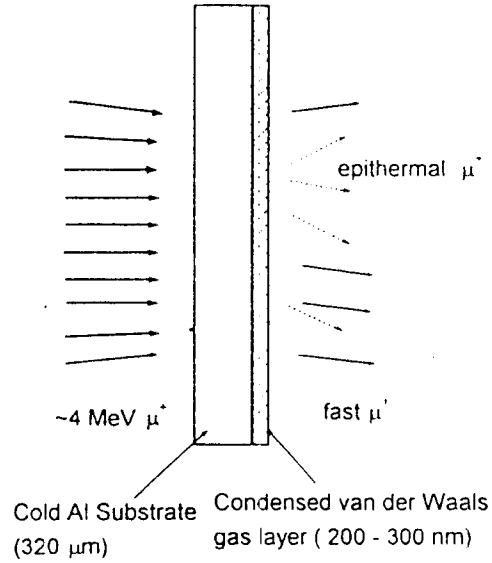


Fig. 1. Principle of the moderation technique for the production of very slow polarized μ^+. The total thickness of the moderator is chosen to maximize the yield of epithermal muons.

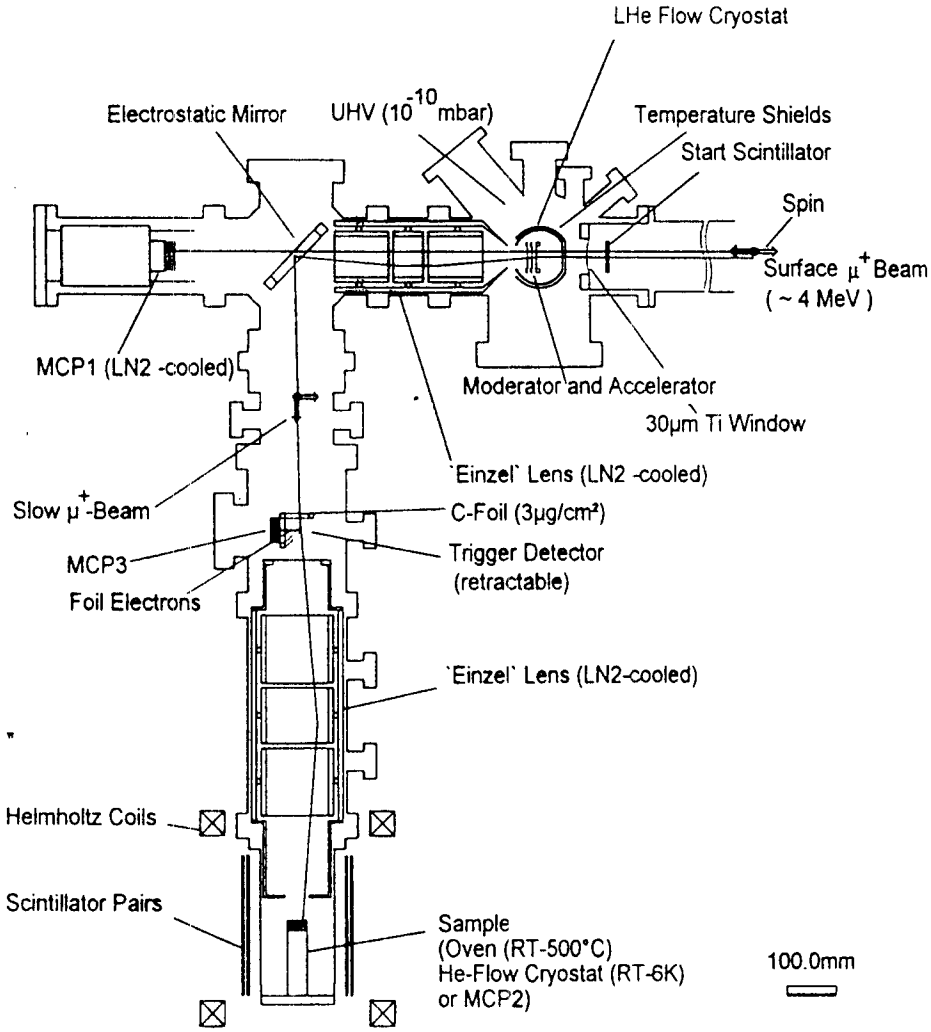
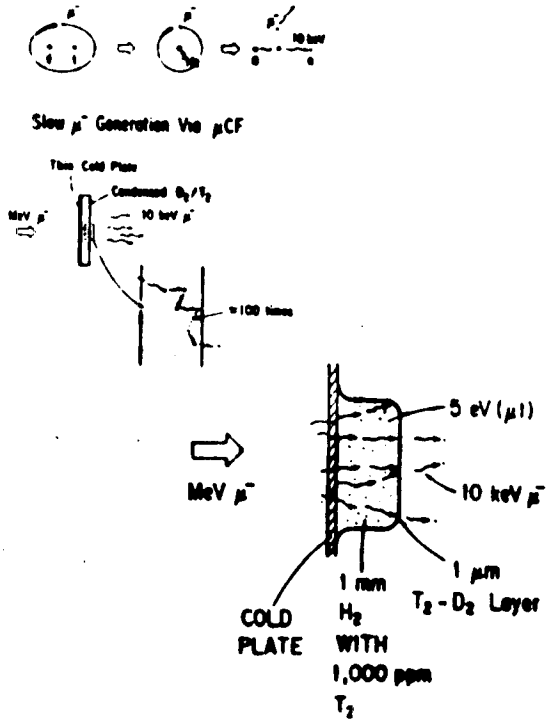
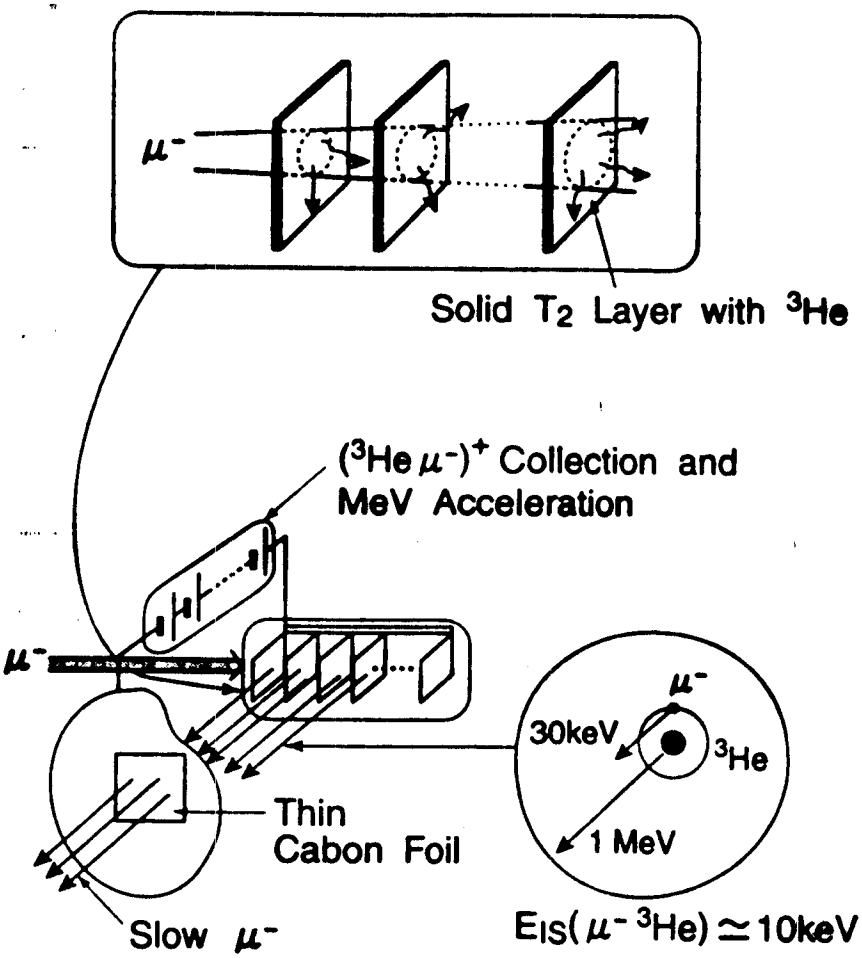
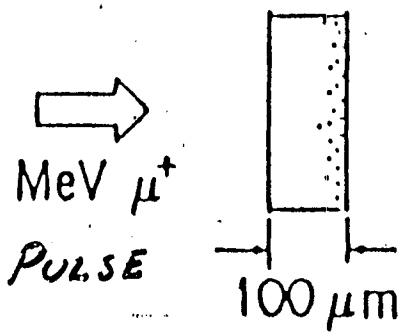


Fig. 2. Apparatus for low energy μSR at the Paul Scherrer Institute.


Slow μ⁻ Generation Via μCF
Thin Cold Plate
Condensed D₂/T₂
MeV μ⁻
10 keV μ⁻
≈100 times
5 eV (μ1)
MeV μ⁻
10 keV μ⁻
1 mm
H₂
WITH
1,000 ppm
T₂
1 μm
T₂ - D₂ Layer
COLD
PLATE

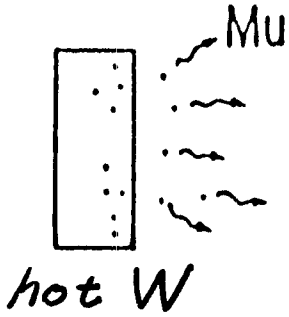

μ⁻
Solid T2 Layer with ³He
(³He μ⁻)⁺ Collection and
MeV Acceleration
μ⁻
Thin
Cabon Foil
Slow μ⁻
μ⁻
30keV
³He
1 MeV
EIS(μ⁻ ³He) ≃ 10keV

1. THERMAL MUONIUM PRODUCTION IN VACUUM



STOPPING μ^+
AT REAR-SIDE OF
FOIL W

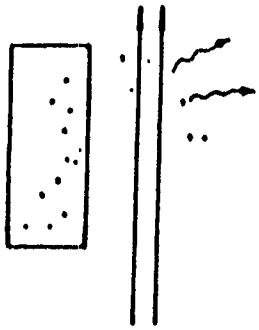
μ^+ DIFFUSION AND
REACHING TO FOIL SURFACE



Mu EVAPORATION

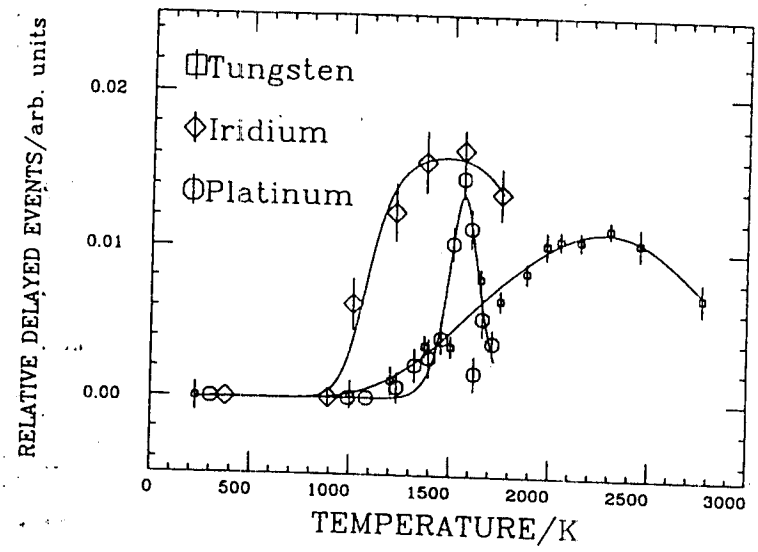
: 0.04

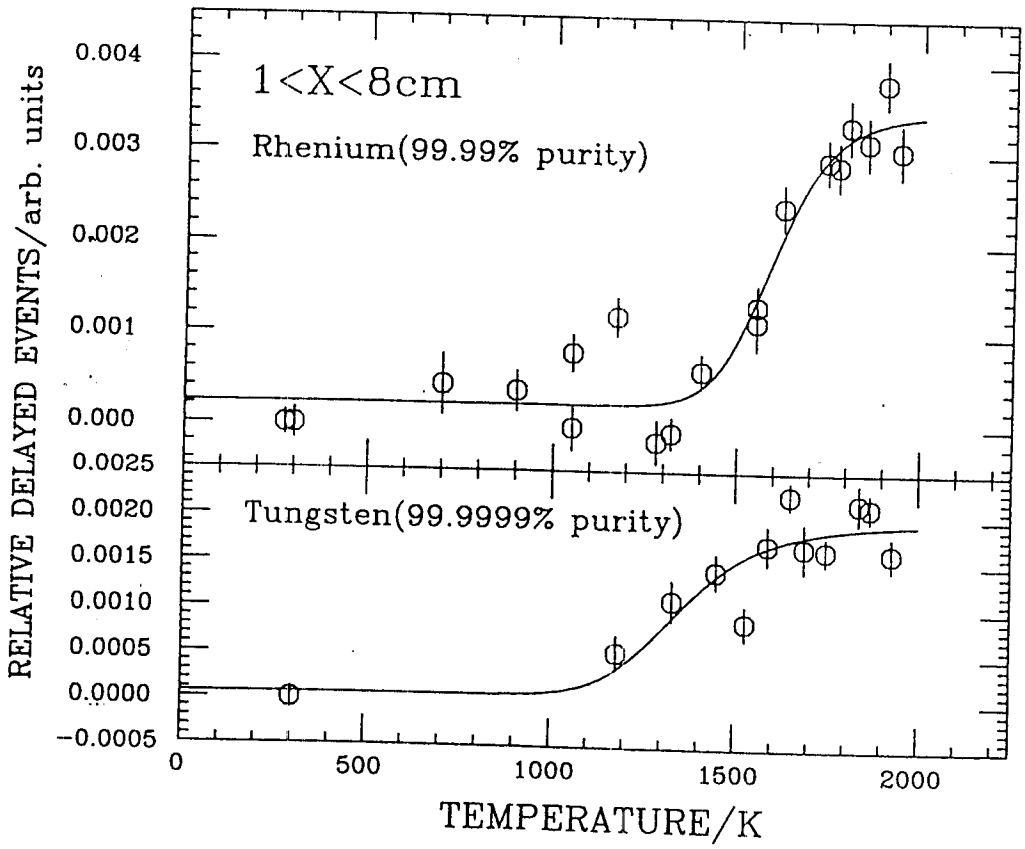
2. MUONIUM IONIZATION AND SLOW μ^+ PRODUCTION



LASER IONIZATION OF Mu

PULSE


Tungsten
Iridium
Platinum
RELATIVE DELAYED EVENTS/arb. units
0.02
0.01
0.00
0
500
1000
1500
2000
2500
3000
TEMPERATURE/K


1<X<8cm
Rhenium(99.99% purity)
Tungsten(99.9999% purity)
RELATIVE DELAYED EVENTS/arb. units
0.004
0.003
0.002
0.001
0.000
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
0
500
1000
1500
2000
TEMPERATURE/K

KEK METHOD OF LOW ENERGY μ^+

; PRESENT STATUS AND NEXT STEP

LIST OF COLLABORATORS

THE KEK METHOD

Y.Miyake, K.Shimomura

P.Birrer, J.P.Marangos, M.Iwasaki,
P.Strasser, T.Kuga, A.P.Mills,Jr,
E.Widmann,

S.Chu, K.Ishida.

RIKEN_RAL_KEK PROJECT

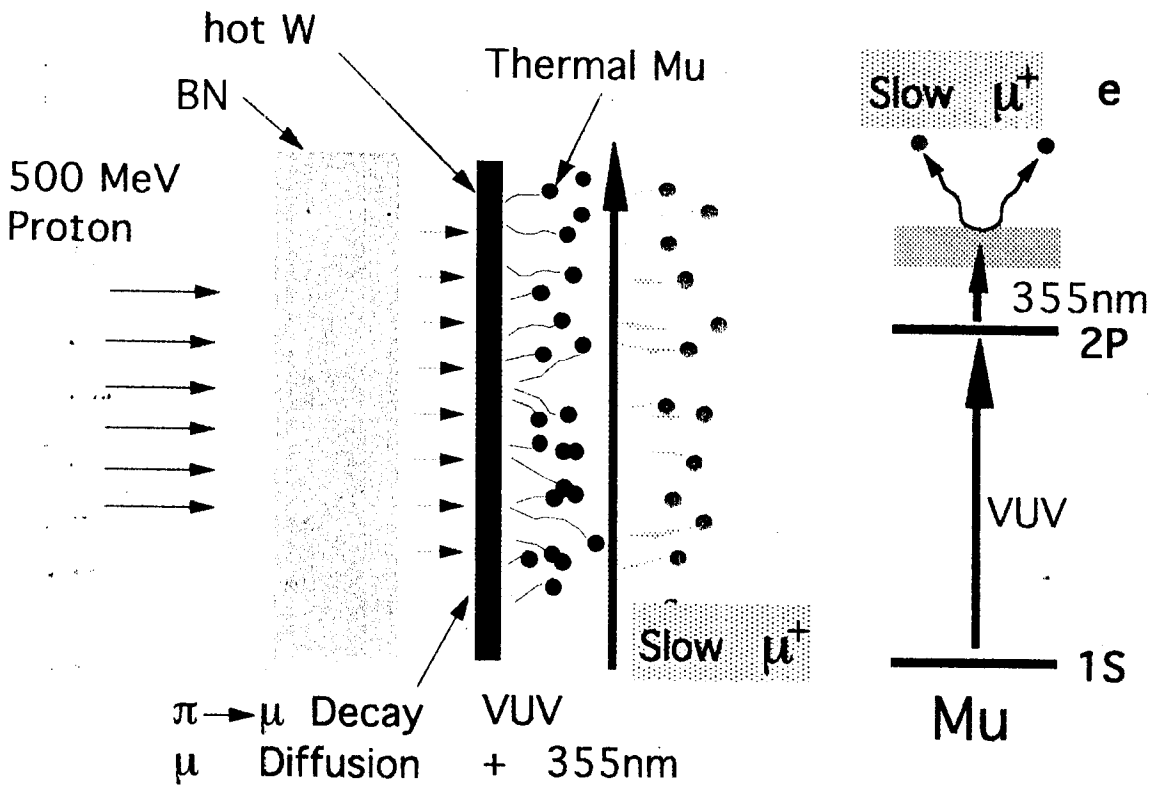
Y.Miyake, K.Shimomura,Y.Matsuda, P.Bakule,
R.Scheuermann,

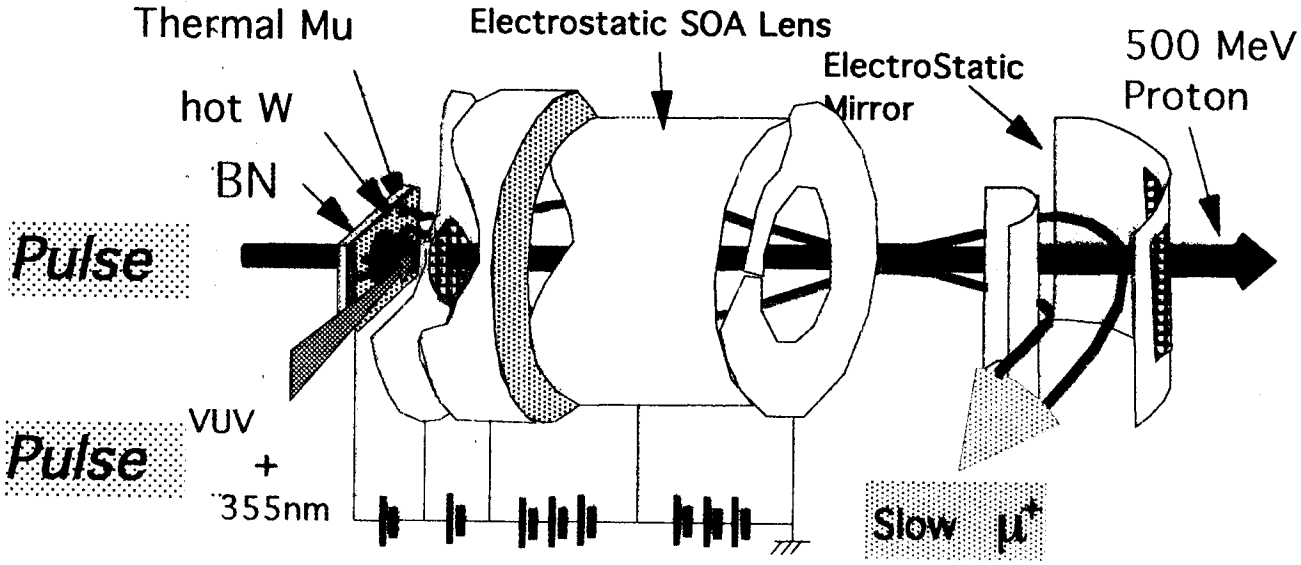
G.H.Eaton, S.Makimura, S.N.Nakamura,
K.Ishida, T.Matsuzaki

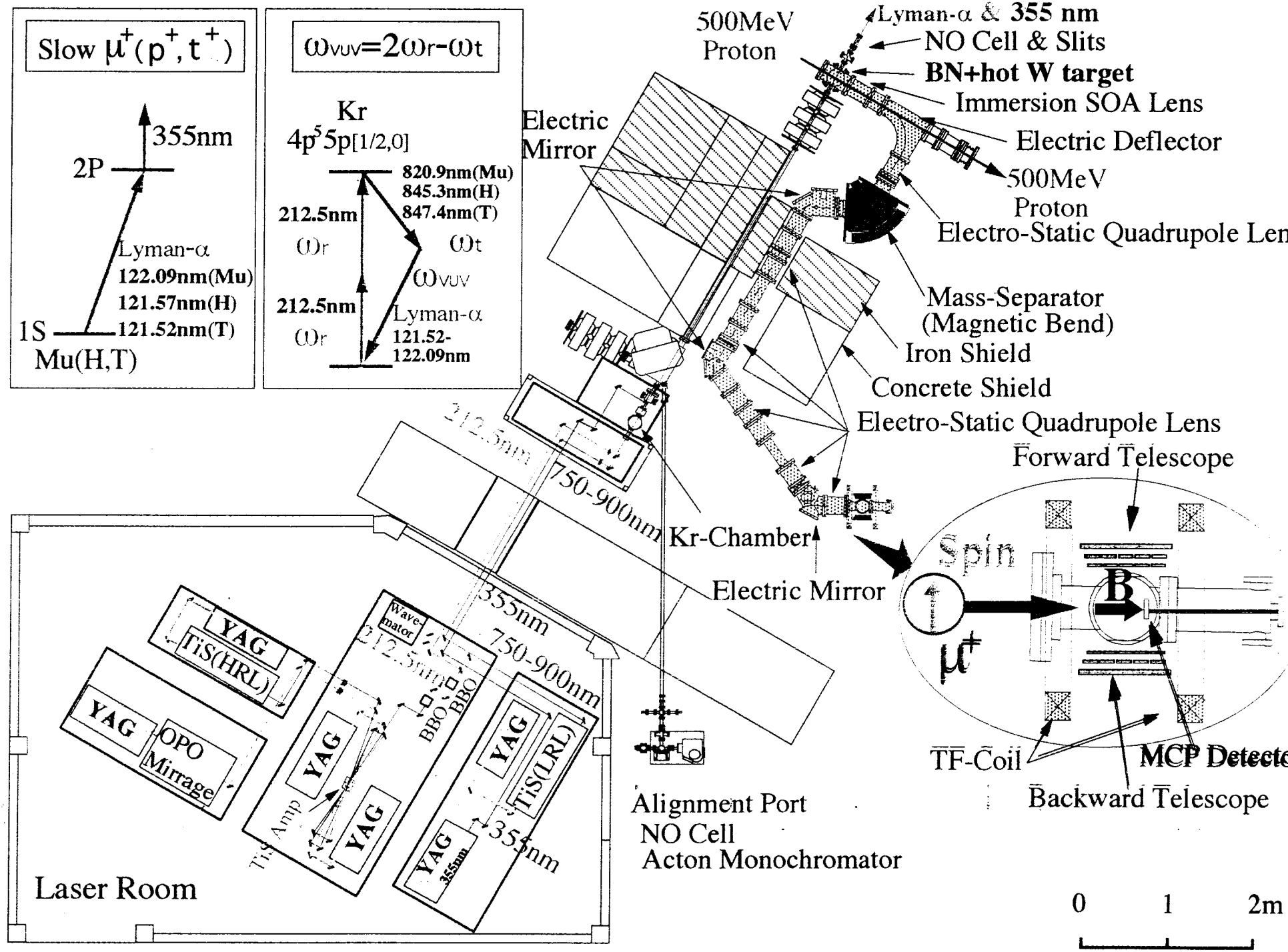
Thermal Mu PRODUCTION EXPERIMENT

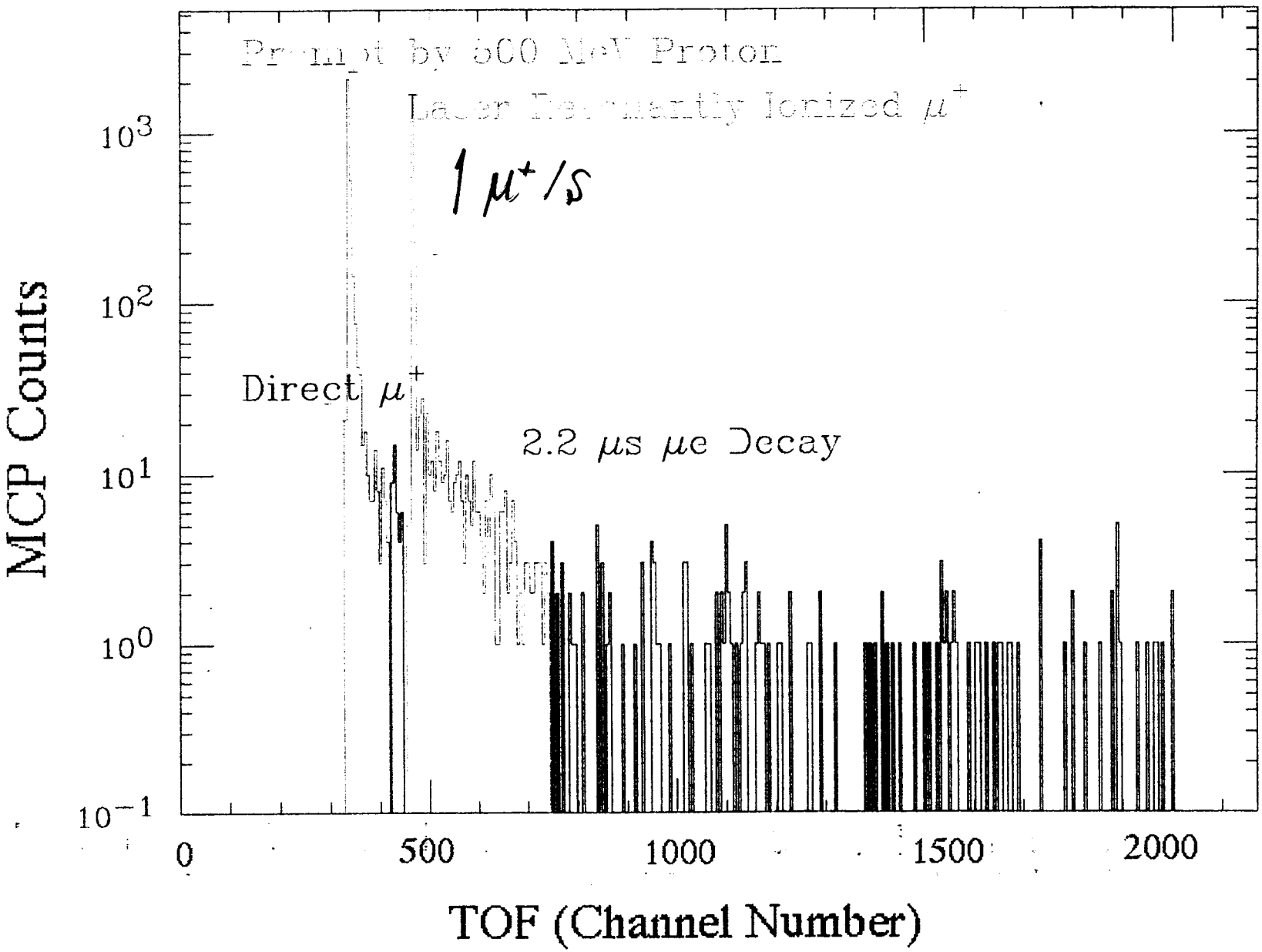
A.Matsushita

S.N.Nakamura, Y.Miyake, K.Ishida
I.Watanabe, T.Matsuzaki


hot W
BN
Thermal Mu
500 MeV
Proton
Slow μ+
e
355nm
2P
VUV
1S
Mu
Slow μ+
π→μ Decay
μ Diffusion
VUV
+ 355nm

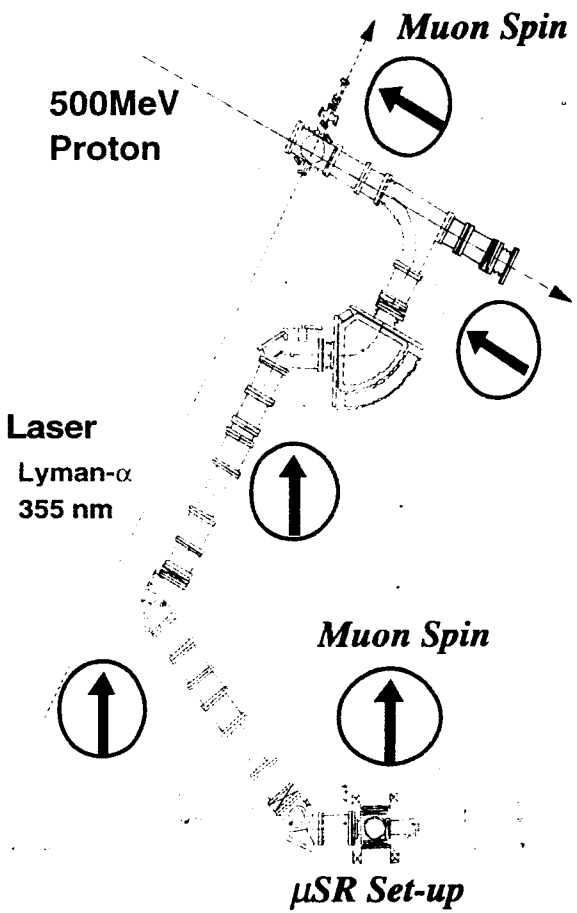

Thermal Mu
Electrostatic SOA Lens
ElectroStatic
Mirror
500 MeV
Proton
hot W
BN
Pulse
Pulse
VUV
+
355nm
Slow μ+

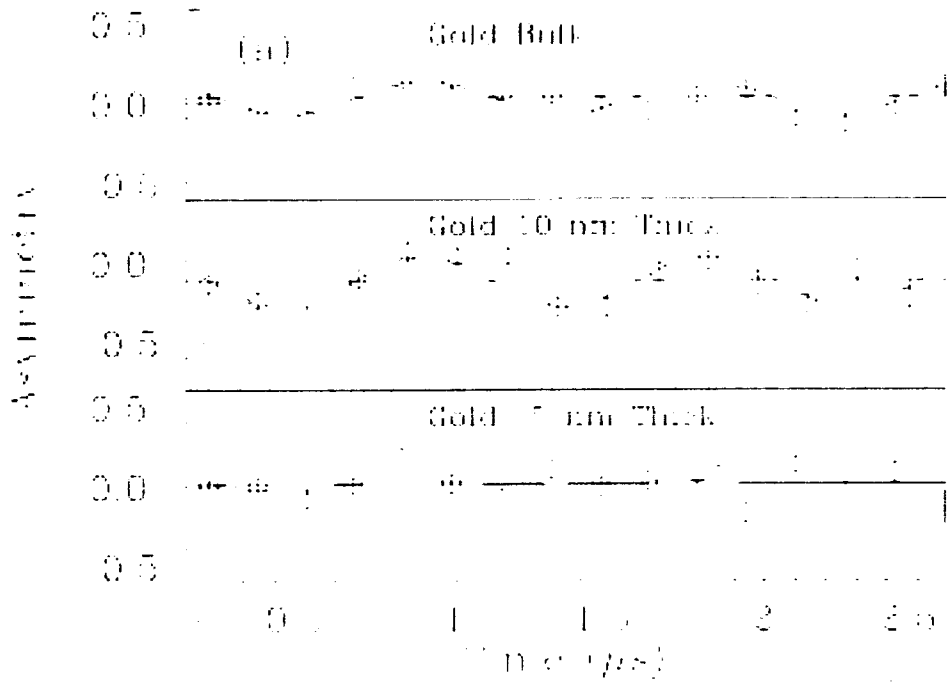

Slow μ+(p+,t+)
355nm
2P
Lyman-α
122.09nm(Mu)
121.57nm(H)
121.52nm(T)
1S
Mu(H,T)
ωvuv=2ωr-ωt
Kr
4p55p[1/2,0]
820.9nm(Mu)
845.3nm(H)
847.4nm(T)
212.5nm
ωr
ωt
ωvuv
212.5nm
ωr
Lyman-α
121.52-
122.09nm
500MeV
Proton
Lyman-α & 355 nm
NO Cell & Slits
BN+hot W target
Immersion SOA Lens
Electric Deflector
500MeV
Proton
Electro-Static Quadrupole Len
Electric
Mirror
Mass-Separator
(Magnetic Bend)
Iron Shield
Concrete Shield
Electro-Static Quadrupole Lens
Forward Telescope
212.5nm
750-900nm
Kr-Chamber
Electric Mirror
Spin
B
μ+
355nm
750-900nm
Wave-
mator
YAG
TiS(HRL)
YAG
OPO
Mirrage
YAG
YAG
BBO
BBO
YAG
TiS(LRL)
YAG
355nm
355nm
TiS Amp
Laser Room
TF-Coil
MCP Detecto
Backward Telescope
Alignment Port
NO Cell
Acton Monochromator
0
1
2m

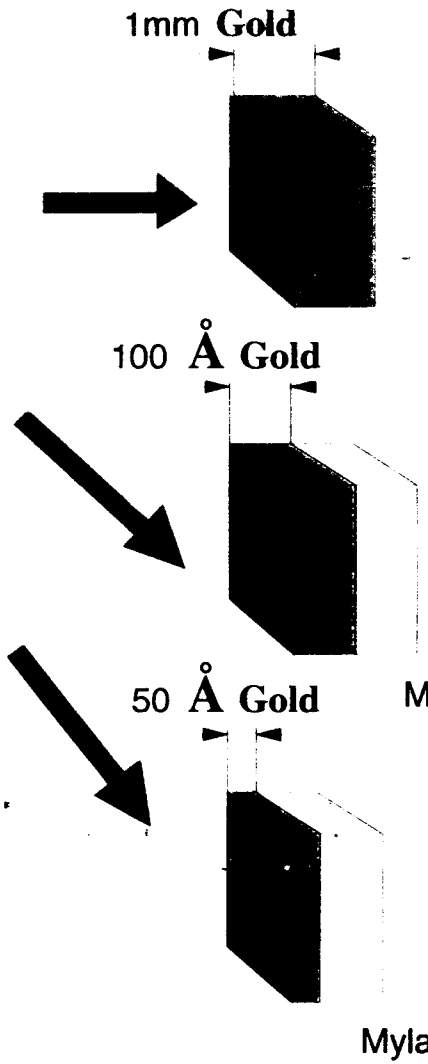

Prompt by 800 MeV Proton
Laser Permanently Ionized μ^+
1 μ^+/s
Direct μ^+
2.2 μs μe Decay
MCP Counts
10^3
10^2
10^1
10^0
10^{-1}
0
500
1000
1500
2000
TOF (Channel Number)

PROBING 100Å THICK SURFACES WITH 9 keV μ^+

μSR Pattern



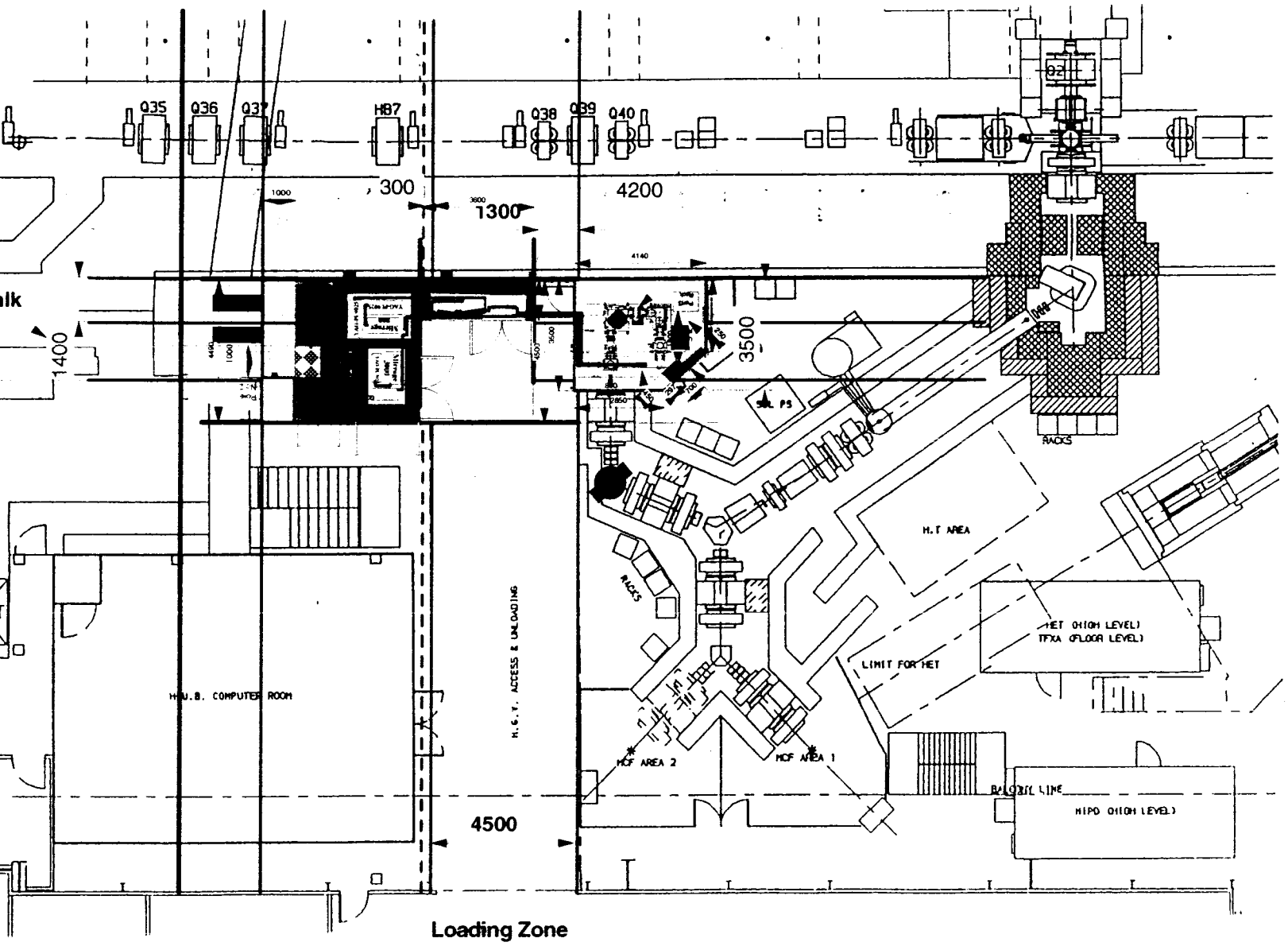




KEK-MSL 500 MeV		RIKEN/RAL 800 MeV	
Intensity	5 μA	Intensity	200 μA
Beam	500 MeV Proton	Beam	Surface Muon
Radiation	Very High	Radiation	Negligible
Laser System Distance	10-12 m	Laser System Distance	2-4 m
Mirror	Damage	Mirror	can be reflected

KEK-MSL → RIKEN/RAL

Comparison between KEK-MSL and RIKEN/RAL



Layout to try to install a laser room interrupting a loading zone as less as possible

Evaluation of Yield

At Port 3 at RIKEN-RAL

1) 23.5 MeV/c Surface Muon 5×10^5 per sec

10^4 positve muons per pulse

2) **Mu formation; 80(12) per pulse out of 2600** inthe case of SiO_2 Powder target(1s-2s Exp.)

Mu yield from W is assumed to be 4 %. about one third of SiO_2 Powder target

$10^4 \times 80/3 / 2600 = 102.5$ Muonium in vacuum per pulse

3) Effective Extraction Probability from D_2 experiments

1.3×10^{-4} Efficiency for D

4) **$1.33\ 10^{-2}$ slow muons per pulse**

0.33 slow muons per sec for 25 Hz

But,

- Laser Intensity and quality can be increased by the use of CLBO to be 3 to 10 times

- Laser transmission can be increased by one order, due to easiness of alighnment at PORT 3

- **Beam Optics can increased by 3 times at least.**

We may expect 3.3/s to 33/s slow muons.

SUPER-SUPER MUON GENERATOR

Super High Intensity

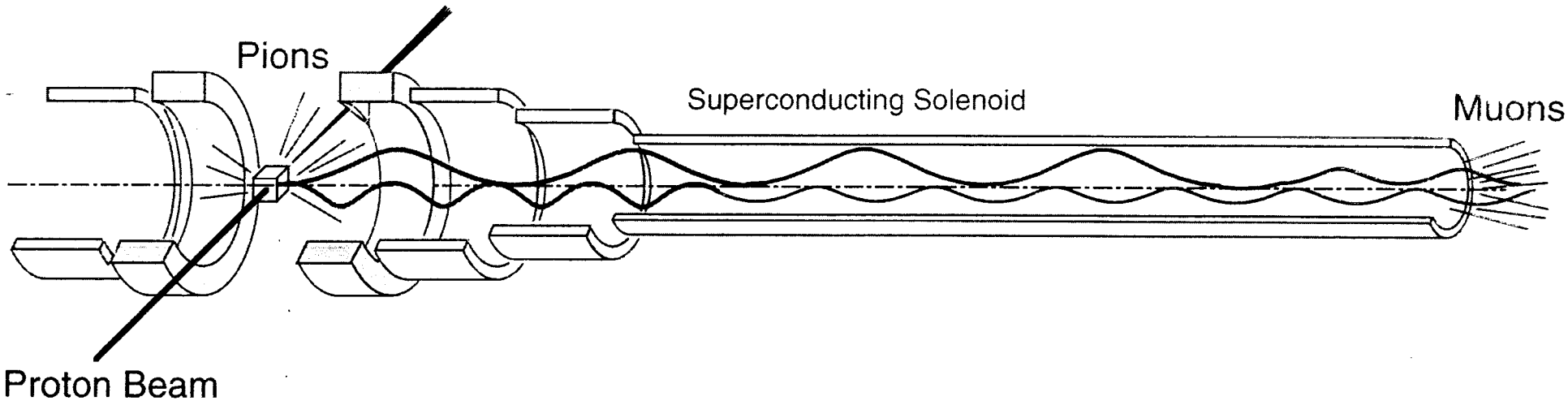
Superconducting Muon Generator

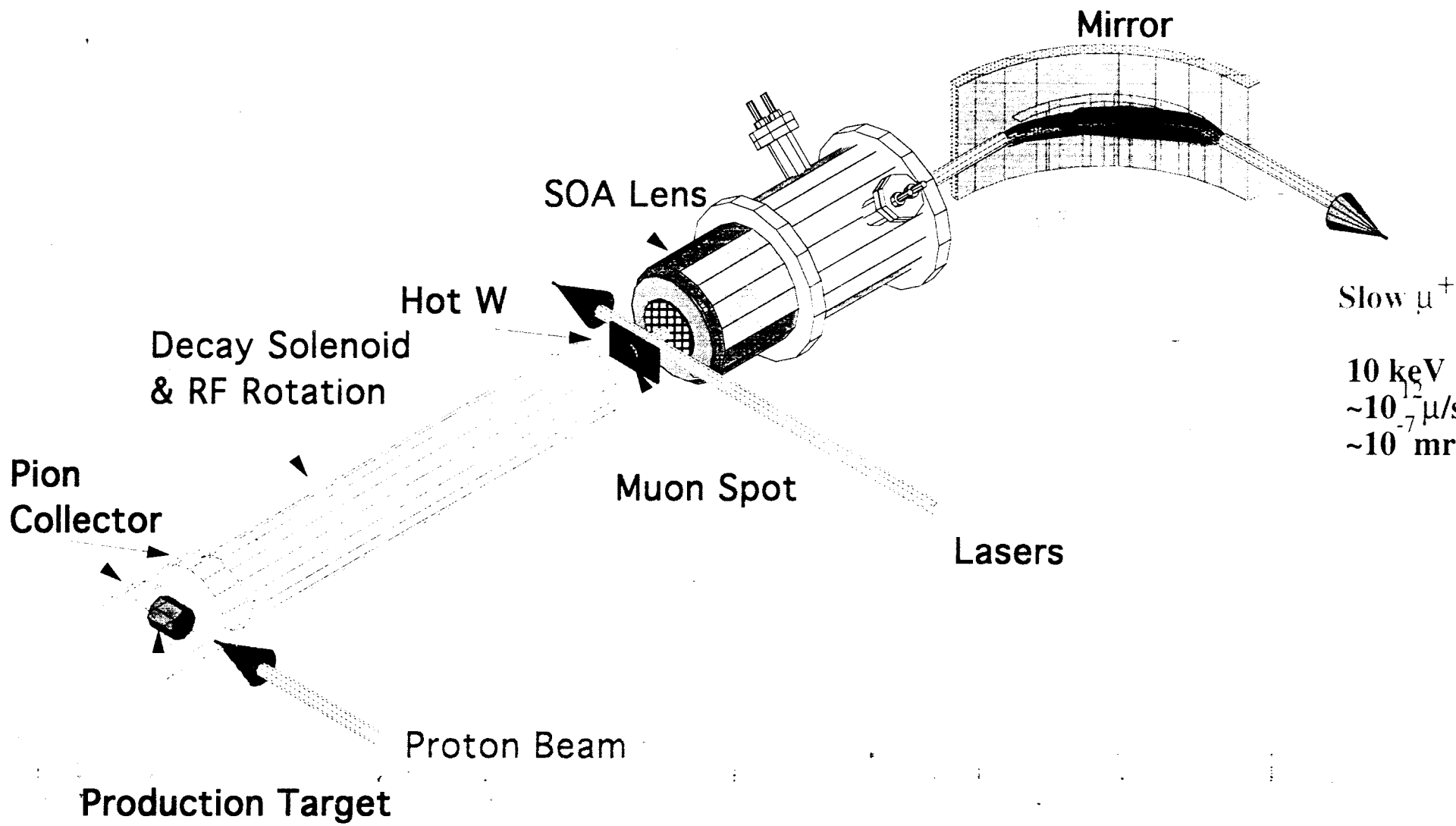
Intensity > 10^{10} μ^+, μ^-/s

Divergence $\ll$ mrad

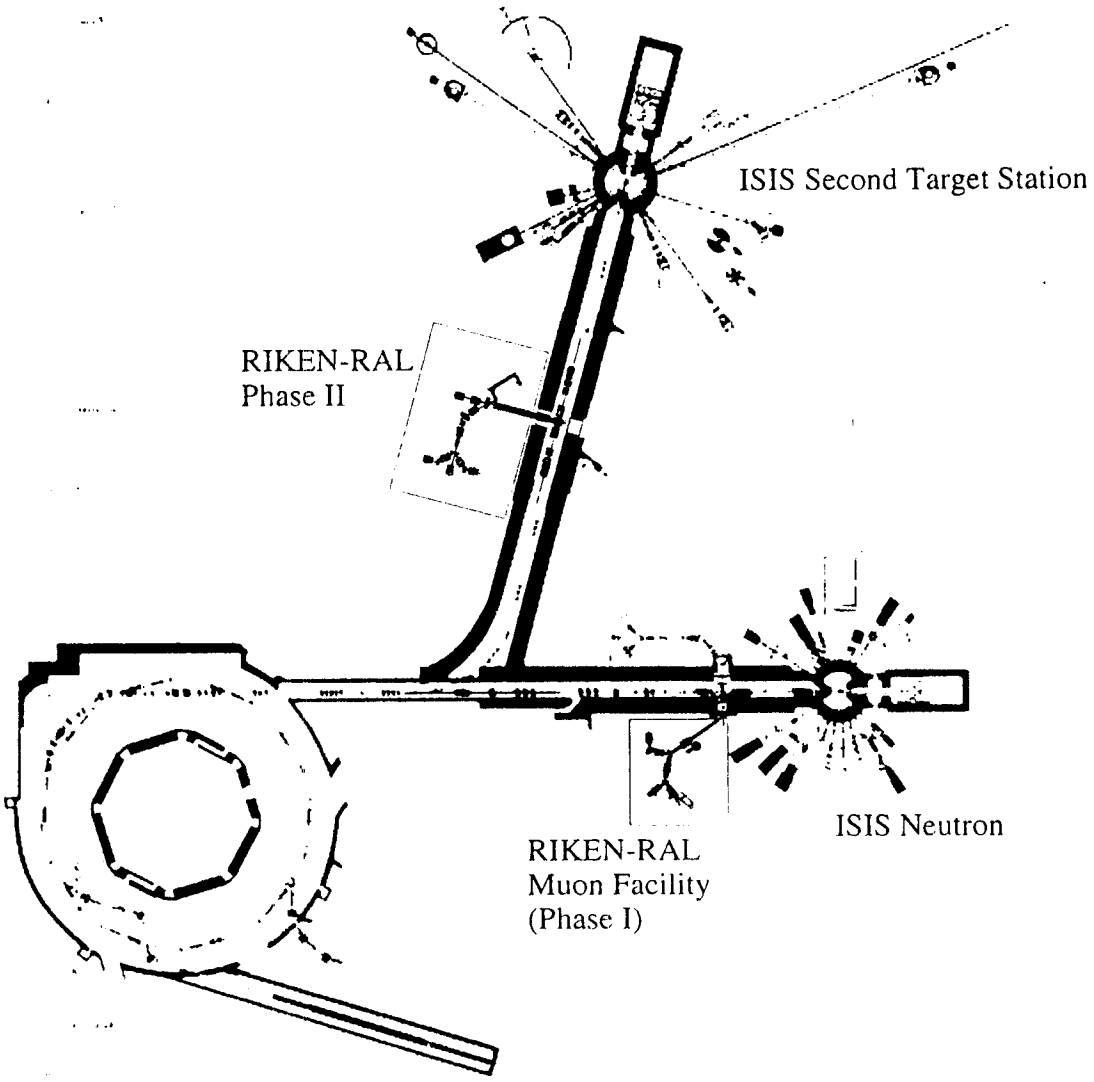
Realized at JHF etc.

In 21st Century


Pions
Superconducting Solenoid
Muons
Proton Beam


Mirror
SOA Lens
Hot W
Decay Solenoid
& RF Rotation
Pion
Collector
Muon Spot
Lasers
Proton Beam
Production Target
Slow μ+
10 keV
~10-12 μ/s
~10-7 mr

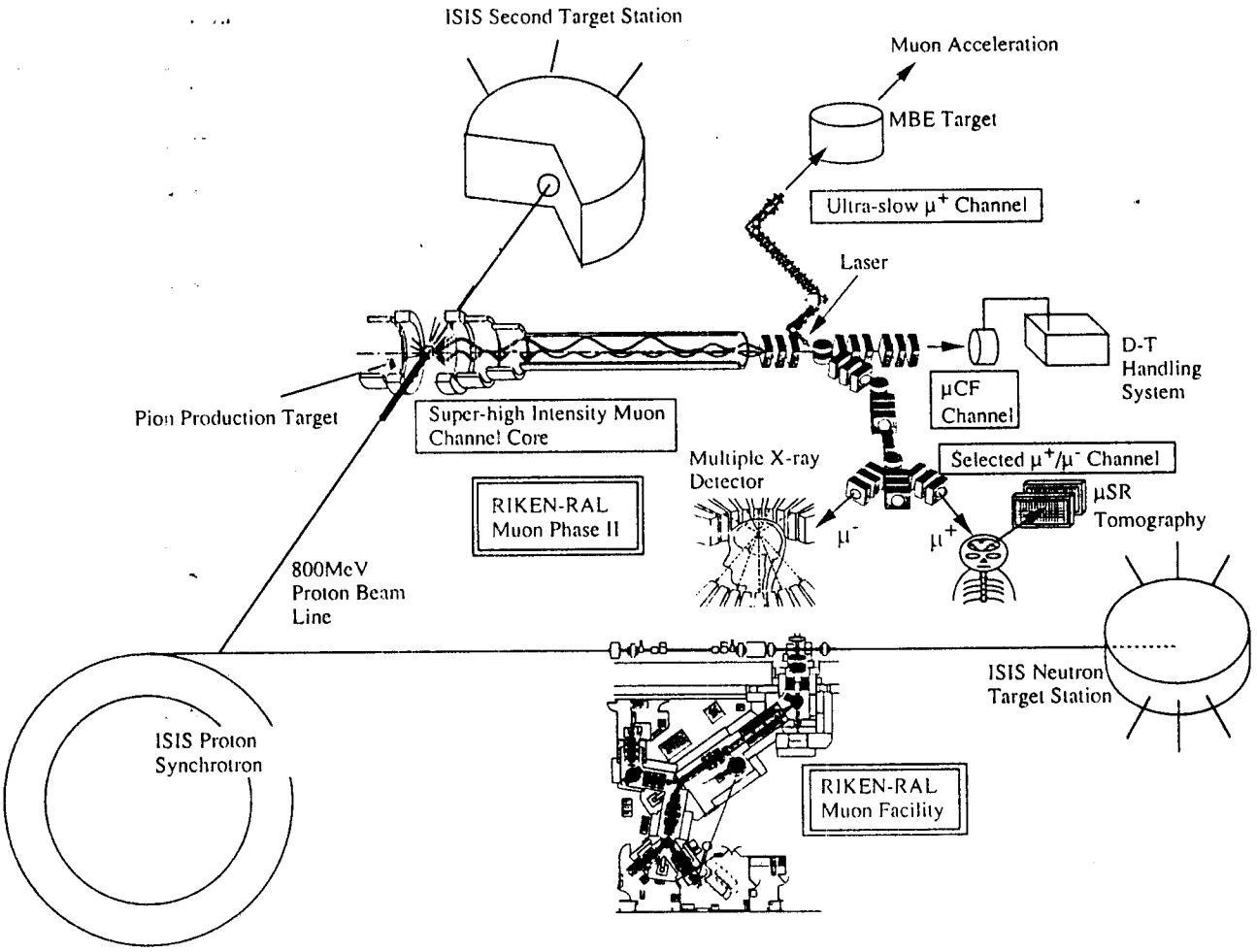
RIKEN-RAL
Phase II Project
(2000-2009)



July 1999

Muon Science Laboratory, RIKEN
RIKEN RAL-Branch

3. Contents of the RIKEN-RAL Phase II Project



Schedule

Items	2000	2001	2002	2003	2004~
RIKEN-RAL II Facility					
(1) Super-high Intensity Muon Channel Core	design and construction			tuning	
(2) Ultra-slow μ^+ Channel	design and construction			tuning	
(3) μCF Channel	design and construction			tuning	
(4) Selected μ^+/μ^- Channel	design and construction			tuning	
Facilities & Instruments					
(1) Super-high Intensity Muon Channel Core	500	500	600	500	
(2) Ultra-slow μ^+ Channel		200	200	200	
(3) μCF Channel		200	200		
(4) Selected μ^+/μ^- Channel			100	200	
Consumable Items		20	30	50	
Operational Cost					
RIKEN-RAL I Facility Operation	325.7	325.7	325.7	244.3	244.3
RIKEN-RAL II Facility Operation				192.1	192.1
SUM	825.7	1,245.7	1,455.7	1,386.4	436.4

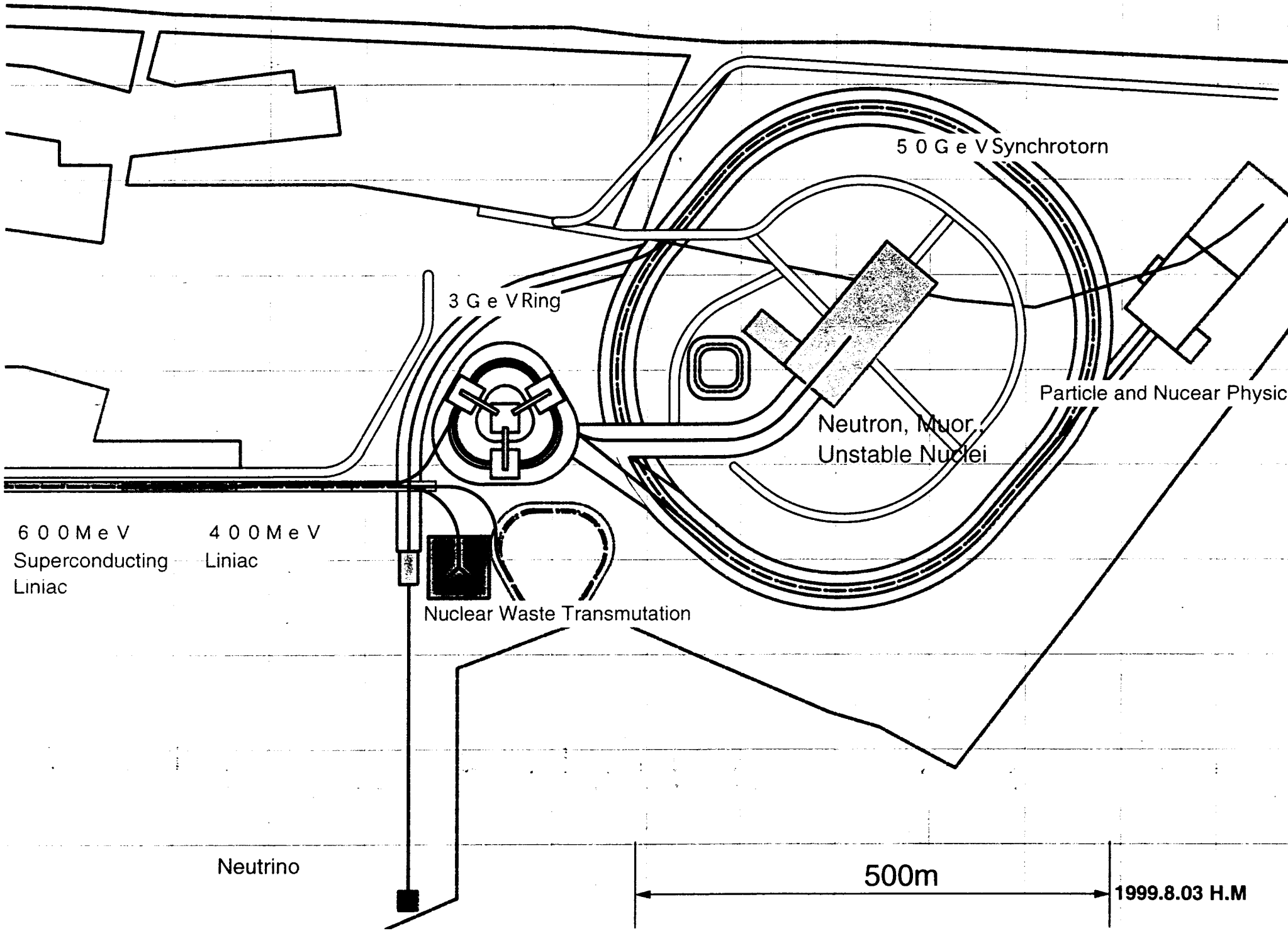
(unit : M yen)

統合計画の現状

Status of Joint Proposal Between KEK and JAERI

Meson Science Laboratory/KEK (KEK-MSL) *Y. Miyake*

- Two Past Proposals
  - Japan Hadron Facility (JHF) at KEK
  - Neutron Science Project (NSP) at JAERI
- Joint Project between KEK and JAERI
- Recent Progress
- Tandem-type M-arena Version at JAERI

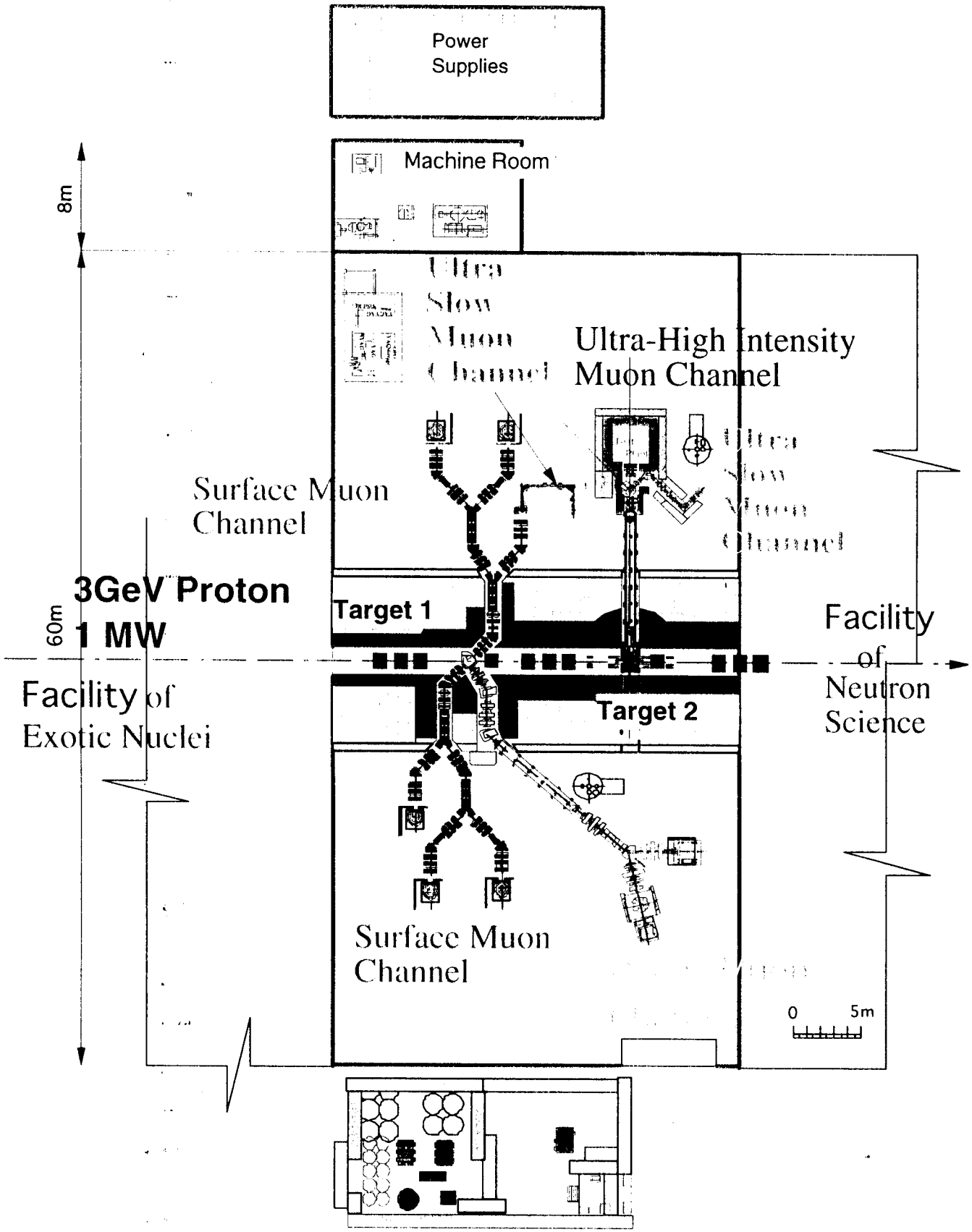

5 0 G e V Synchrotorn
3 G e V Ring
Particle and Nucear Physic
Neutron, Muor.,
Unstable Nuclei
6 0 0 M e V
Superconducting
Liniac
4 0 0 M e V
Liniac
Nuclear Waste Transmutation
Neutrino
500m
1999.8.03 H.M

Designated Accelerator

Linac 200-400 MeV Now 600 MeV
30 mA
Beam Pulse 500 μs

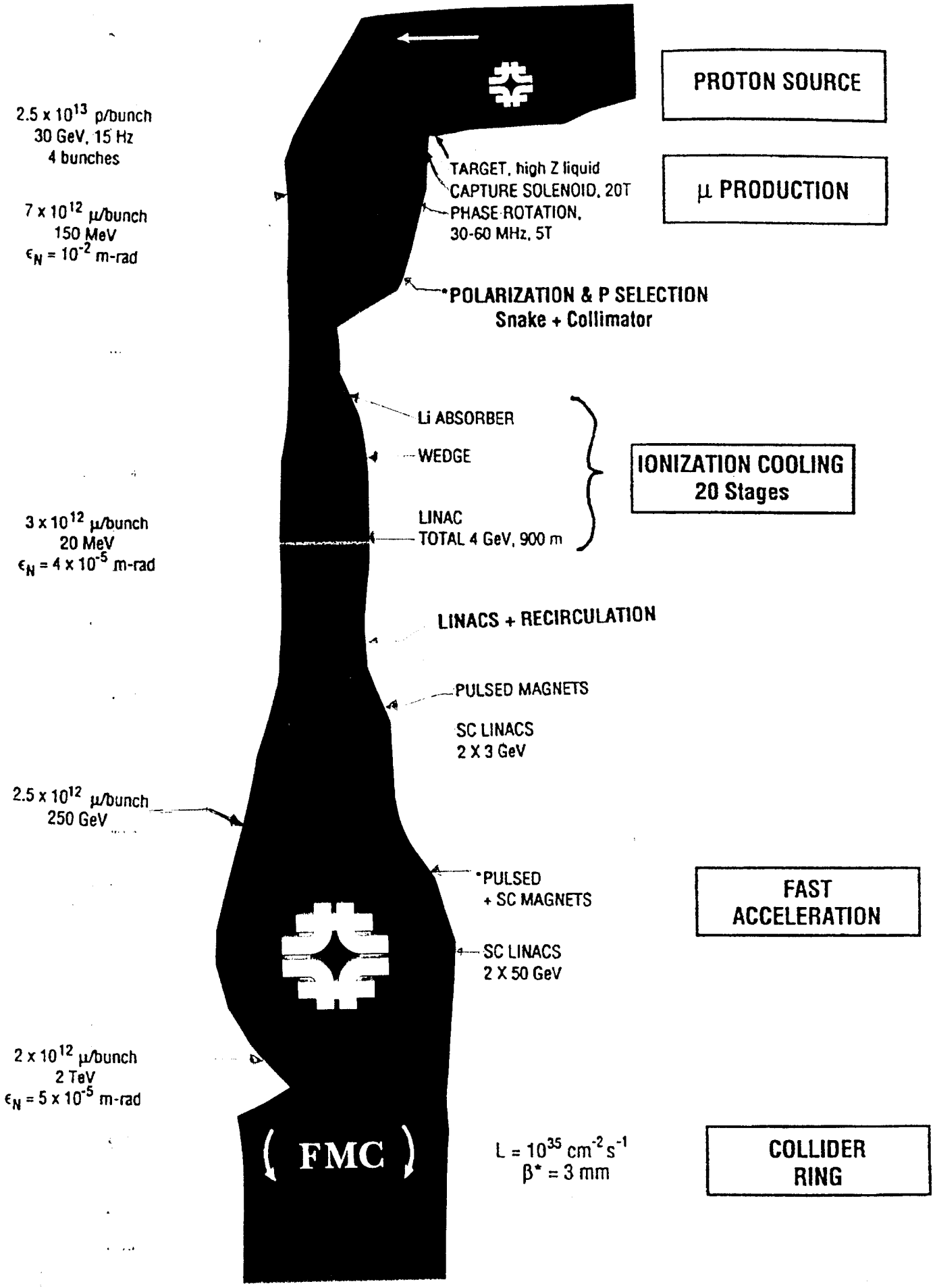
Rapid-cycling Synchrotron
3GeV, 25 Hz 1 MW (1st Stage)
5-6GeV as 2nd stage
(or 1GeV with storage Rings)
5 MW (2nd Stage)

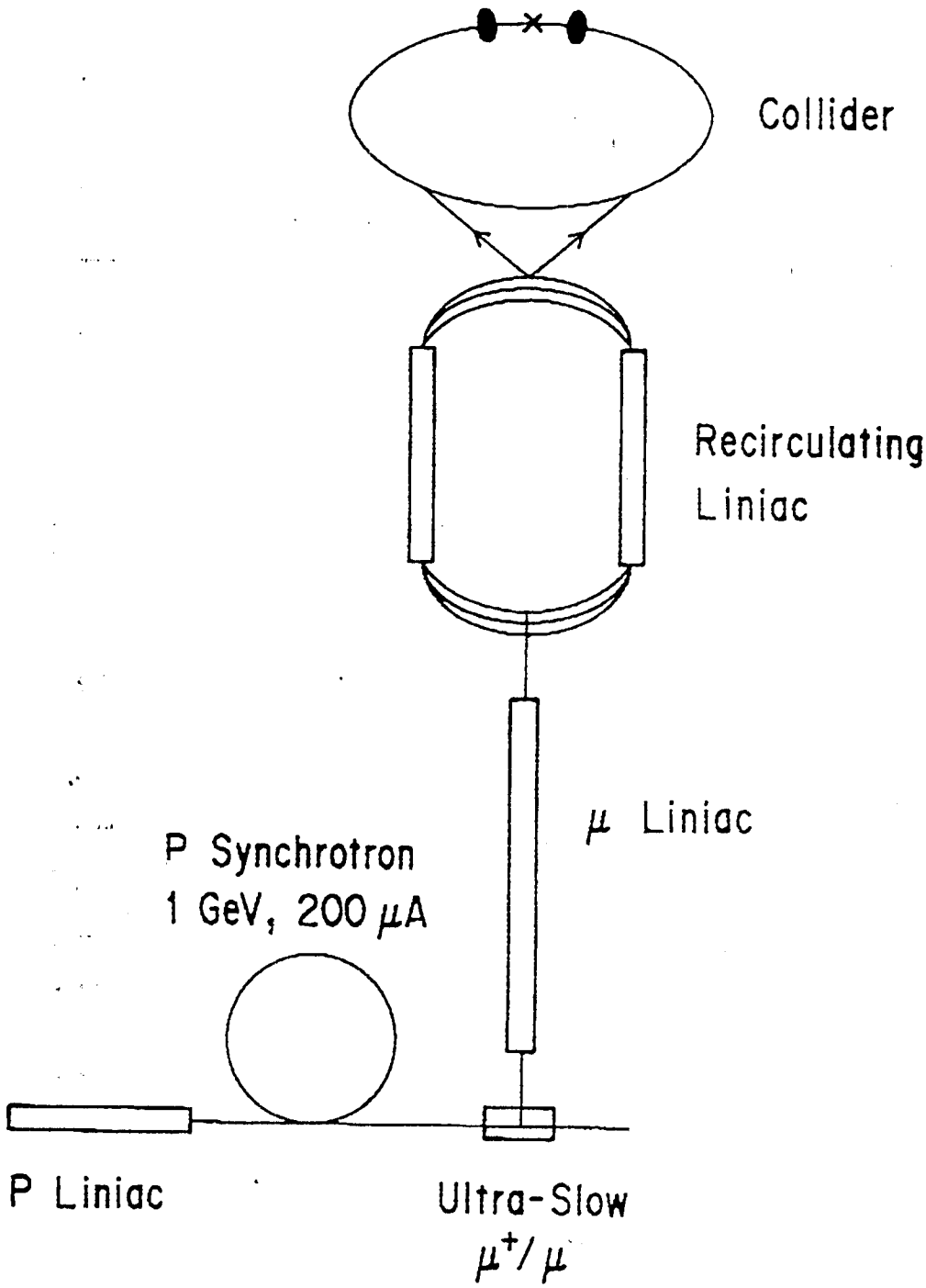
50 GeV Ring
10 μA



Muon Science Facility

COLLIDER OPTION


PROTON SOURCE
2.5 x 10^13 p/bunch
30 GeV, 15 Hz
4 bunches
TARGET, high Z liquid
CAPTURE SOLENOID, 20T
PHASE ROTATION,
30-60 MHz, 5T
μ PRODUCTION
7 x 10^12 μ/bunch
150 MeV
ε_N = 10^-2 m-rad
*POLARIZATION & P SELECTION
Snake + Collimator
Li ABSORBER
WEDGE
IONIZATION COOLING
20 Stages
LINAC
TOTAL 4 GeV, 900 m
3 x 10^12 μ/bunch
20 MeV
ε_N = 4 x 10^-5 m-rad
LINACS + RECIRCULATION
PULSED MAGNETS
SC LINACS
2 X 3 GeV
2.5 x 10^12 μ/bunch
250 GeV
*PULSED
+ SC MAGNETS
FAST
ACCELERATION
SC LINACS
2 X 50 GeV
2 x 10^12 μ/bunch
2 TeV
ε_N = 5 x 10^-5 m-rad
(FMC)
L = 10^35 cm^-2 s^-1
β* = 3 mm
COLLIDER
RING


Collider
Recirculating
Liniac
μ Liniac
P Synchrotron
1 GeV, 200 μA
P Liniac
Ultra-Slow
μ+/μ

NEUTRINO SOURCE OPTION

ADVANCED NEUTRINO SOURCE WITH μ^+ ACCELERATION

1. Muon Decay Section

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

2. Expected Intensity and Phase Space

3. Comparison with Other Methods

   Proposed ν Sources, So far

   Long Base-Line ν Oscillation Experiment

MUON DRIVEN NEUTRINO
with ULTRA-SLOW μ^+

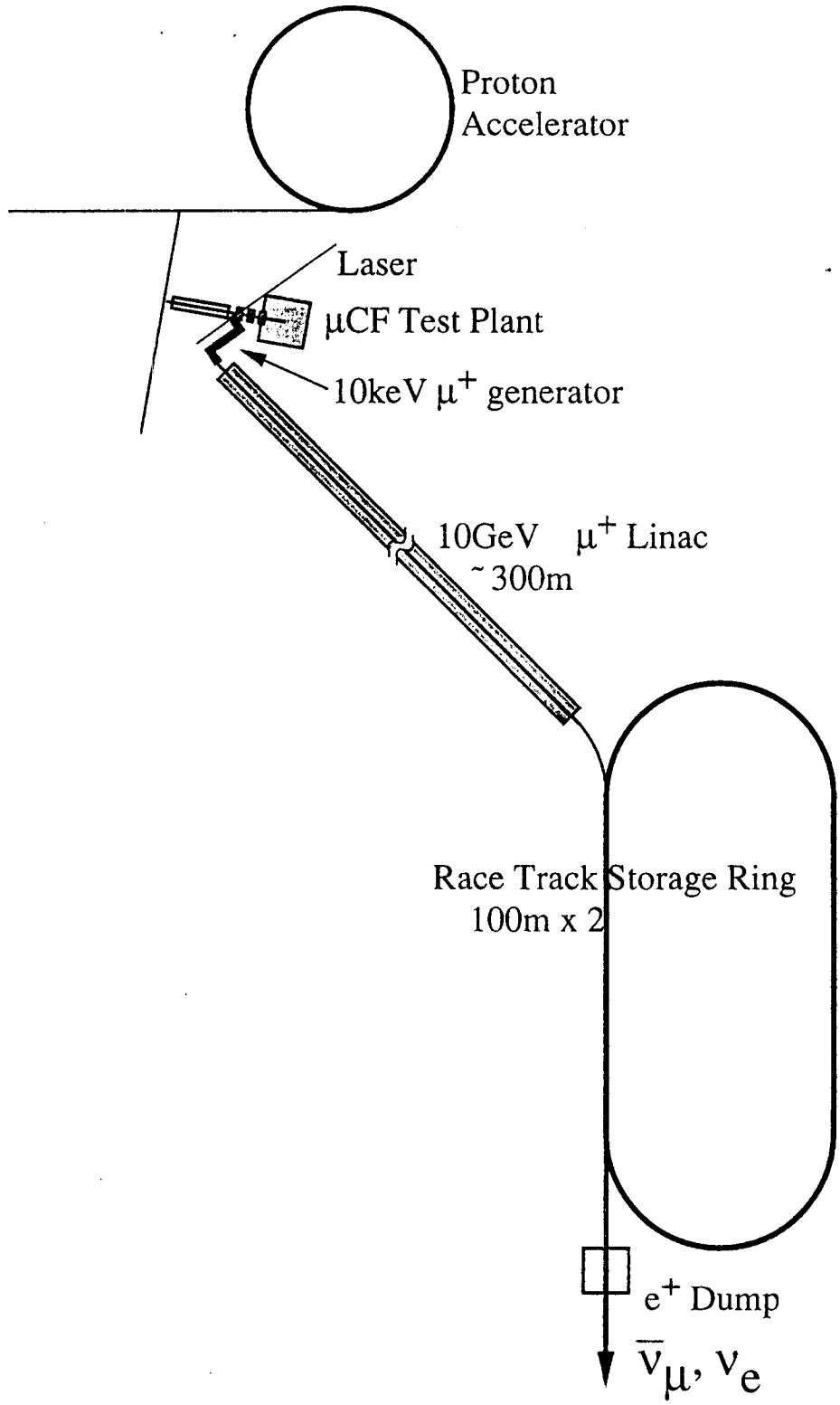


Table 1. Field estimations for advanced neutrino source

	Expected Numbers (s^{-1})	Conditions	Remarks
N_p	1.9×10^{15}	0.8 GeV × 300μA	
$N_{\pi^+}^{tot}$	2.4×10^{13}	4 cm Carbon	$\sigma_{\pi^+}^{tot}$: 28 mb
N_{μ^+}	6.0×10^{11}	Pion Capture: 2.9T, 20cm bore × 1.5m	Ref.(7)
		Muon Decay: 3.0T, 25cm bore × 10m	p_μ: 88(42) MeV
N_μ^{stop}	2.9×10^{11}	20 × 100 μm W	
$N_{th.Mu}$	1.2×10^{10}	$\varepsilon_{th.Mu}$: 0.04	2000 K. hot W
$N_{u.s.\mu^+}$	1.0×10^{10}	ε_{ion}: 0.8	Laser Resonant Ionization
$N_{\mu^+}^{Acc.}$ (10 TeV)	10^{10}	ε_{cap}: 1.0	
		ε_{acc}: 1.0	
$N_{\bar{\nu}_\mu, \nu_e}$	0.5×10^{10}	Full conversion in	$\bar{E}_\nu \approx 3.3$ TeV
		Race-Track Storage Ring	$\theta_\nu \approx 10^{-5}$

$N_{\pi^+}^{tot}$: total π^+ at production target

N_{μ^+} : total μ^+ at the exit of decay solenoid

N_μ^{stop} : μ^+ stopping number at thermal Mu producing material

$N_{th.Mu}$: thermal Mu yield

$N_{u.s.\mu^+}$: ultra-slow μ^+ yield after thermal Mu ionization

CONCLUSION

TIME SCHEDULE FOR INTENSITY (s^{-1}) UPGRADING of COLD μ^+ (KEK METHOD)

	KEK-MSL (500MeV, 2 μA) Direct Proton	**0.1**	Feasibility Studies
2000	**RIKEN-RAL** (800MeV, 200 μA) Surface μ^+	10^2	Surface Science Laser/Optics Development
	RIKEN-RAL-II (800MeV, 300 μA) Super-Super Decay μ^+	$10^{7\text{-}8}$	μ^+ Acceleration
2005			Bio-medical Application
	KEK-JAERI (3GeV, 330 μA) Super-Super Decay μ^+	10^{10}	Possible Extension to
2010			ν-Factory, $\mu^+\mu^-$ Colliders

1. REALISTIC TIME SCHEDULE FOR VERY INTENSE COLD μ^+ BEAM.

2. μ^+ PART OF APPLICATION TO $\mu^+\mu^-$ COLLIDERS IS POSSIBLE .
   NEED BRILLIANT IDEA OF COLD μ^-

3. $\bar{\nu}_\mu$ SOURCE APPLICATION IS POSSIBLE.

4. NICE COEXISTENCE WITH PULSED PROTON SOURCE FOR SPALLATION NEUTRONS.