ZERO-ENERGY MUON COLLING METHOD FOR NEUTRINO FACTORY

— Complimentary Idea for Ionization Cooling, PRISM, etc —

NuFACT '00

Monterey, California

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KEK-MSL & RIKEN-MUON

1. KEK Method of Low Energy μ^+
   ; Present Status and Next Step
2. Towards Very High Intensity Low Energy μ^+
3. Advanced Neutrino Source with μ^+ Acceleration
4. Conclusion

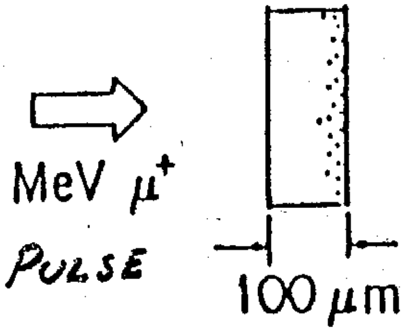
KEK METHOD OF LOW ENERGY μ^+

; PRESENT STATUS AND NEXT STEP

PROPOSED & REALIZED (☆) MUON COOLING METHOD

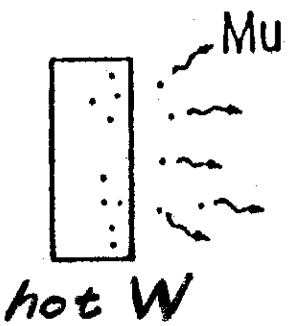
	IONIZATION COOLING	μ^+, μ^-
	PRISM	μ^+, μ^-
MeV	PHASE SPACE COMPRESSION	μ^+, μ^-
	μ^- RE-EMISSION FROM μCF	μ^-
KeV	☆ FRICTIONAL COOLING (PSI)	μ^+, μ^-
	☆ COLD MODERATOR (TRIUMF/PSI)	μ^+
eV		
	☆ THERMAL MUONIUM IONIZATION (KEK)	μ^+

1. THERMAL MUONIUM PRODUCTION IN VACUUM



STOPPING μ^+
AT REAR-SIDE OF
FOIL W

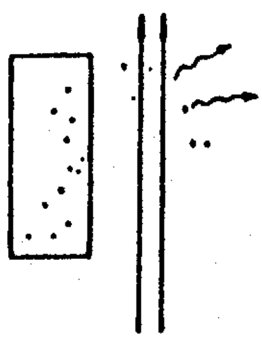
μ^+ DIFFUSION AND
REACHING TO FOIL SURFACE



Mu EVAPORATION

$\simeq 0.04$

2. MUONIUM IONIZATION AND SLOW μ^+ PRODUCTION



LASER IONIZATION OF Mu
PULSE

ULTRA-SLOW POSITIVE MUONS AND SURFACE SCIENCE

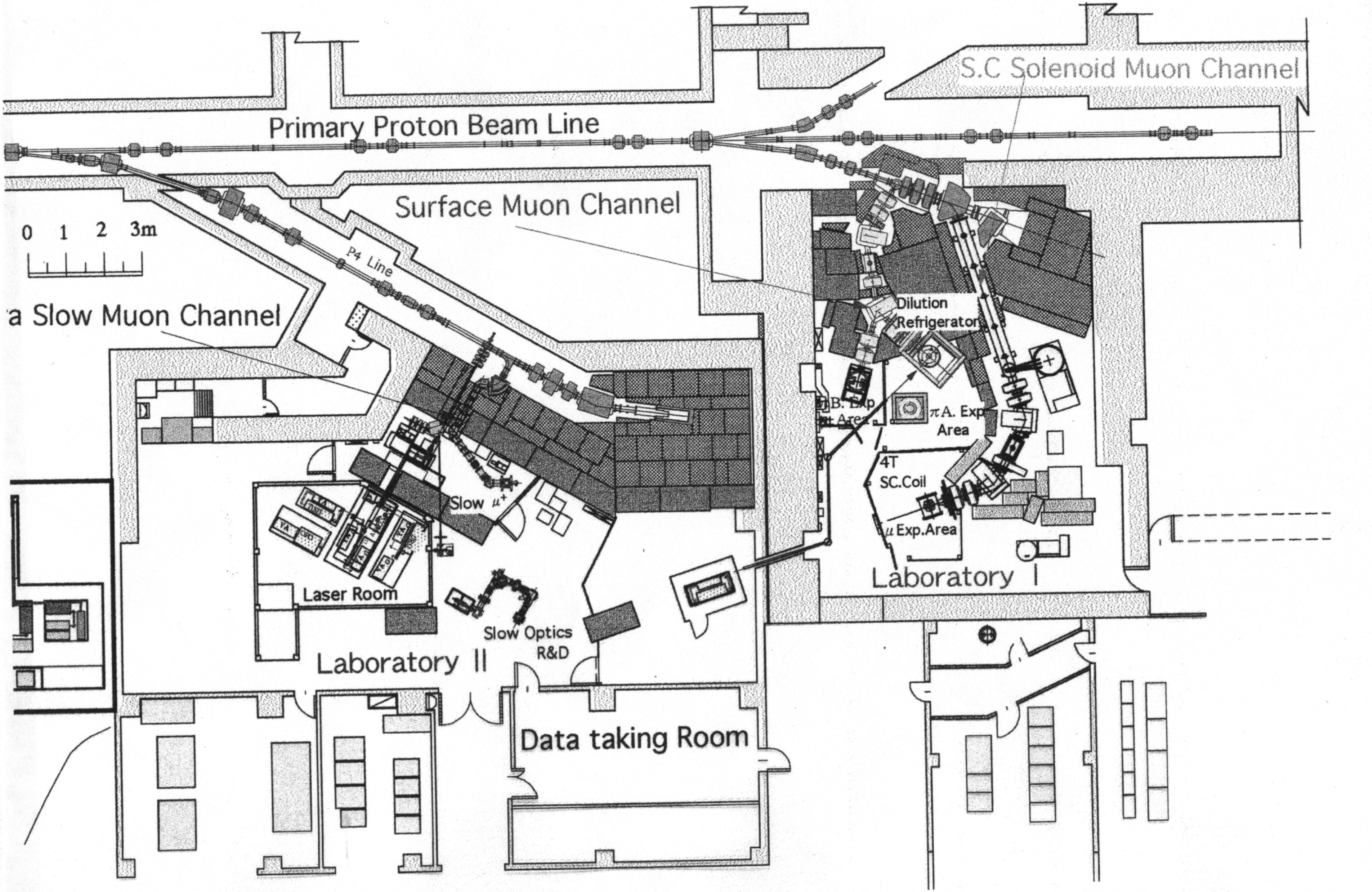
–Probing Dynamical Surface Layer–

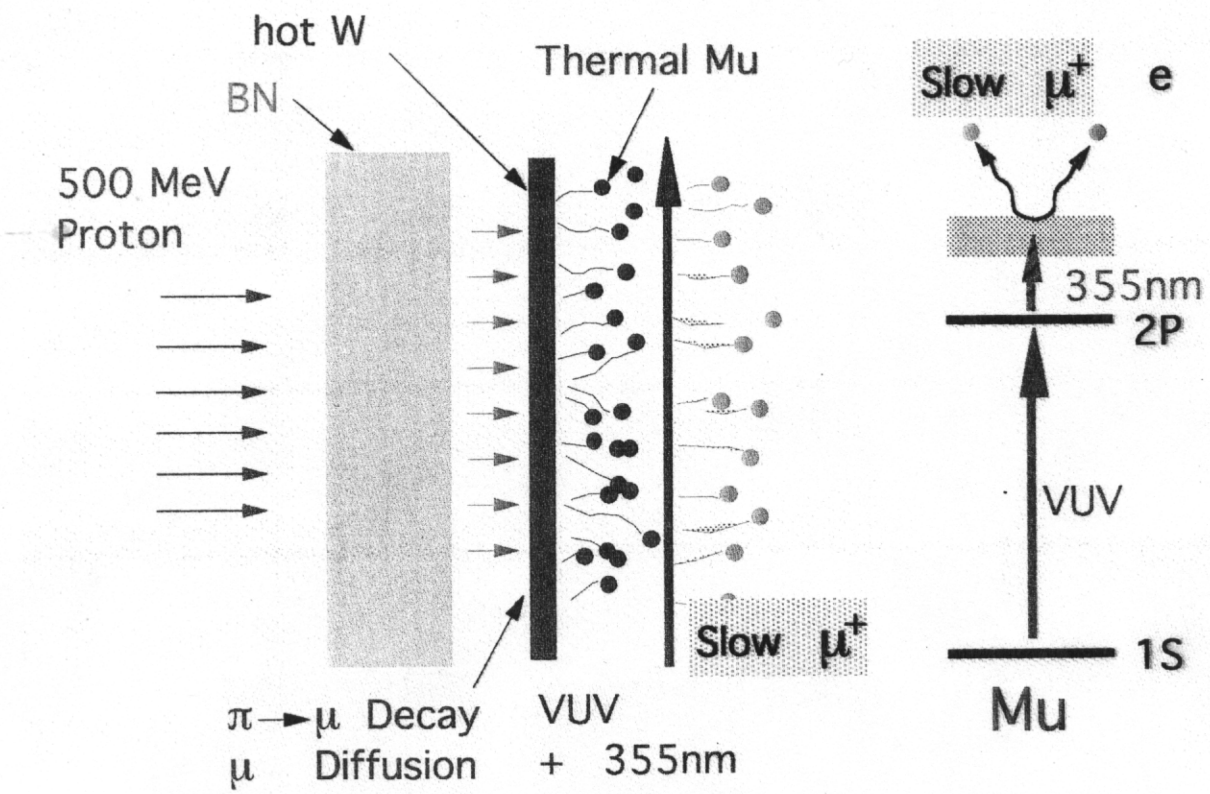
STEPS TOWARDS ULTRA-SLOW μ^+ BEAM AT KEK

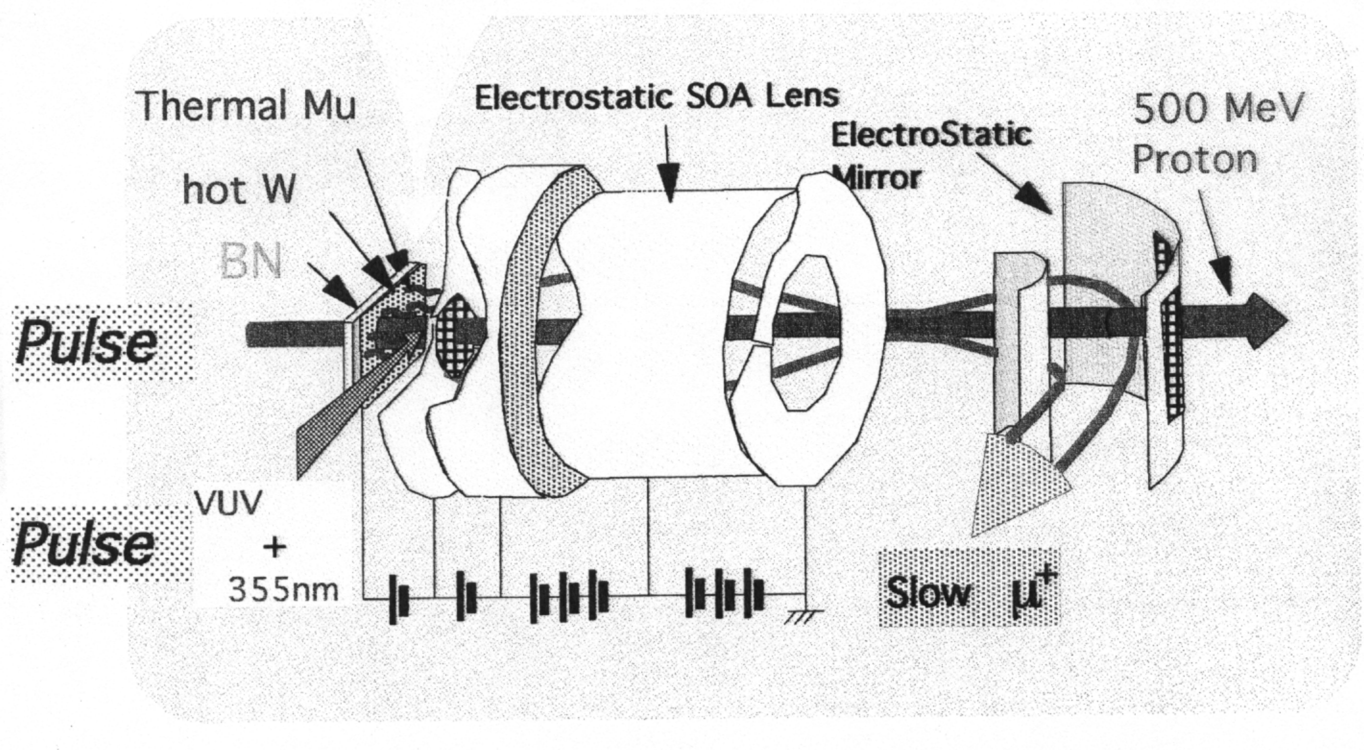
1) **Generation of Thermal Muonium ($\mu^+ e^-$) from Hot Tungsten in Vacuum**
   A.P. Mills Jr., K. Nagamine et al. (1986)

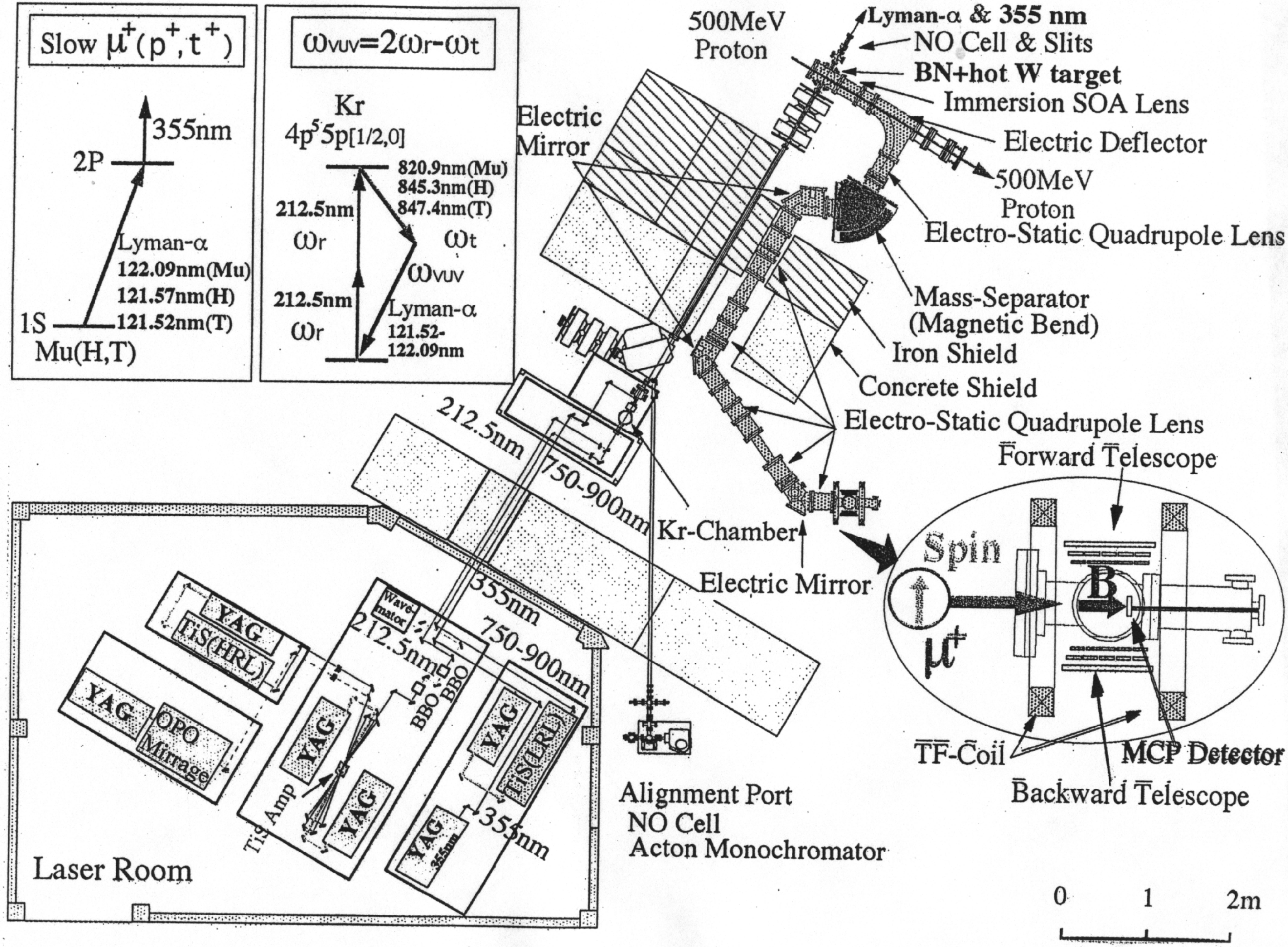
2) **Laser Ionization of Thermal Muonium**
   S. Chu, K. Nagamine et al. (1988)

3) **Ultra-Slow μ^+ Beam Production by Muonium Laser Ionization at Primary Proton Beam**
   K. Nagamine, Y Miyake, et al. (1995)

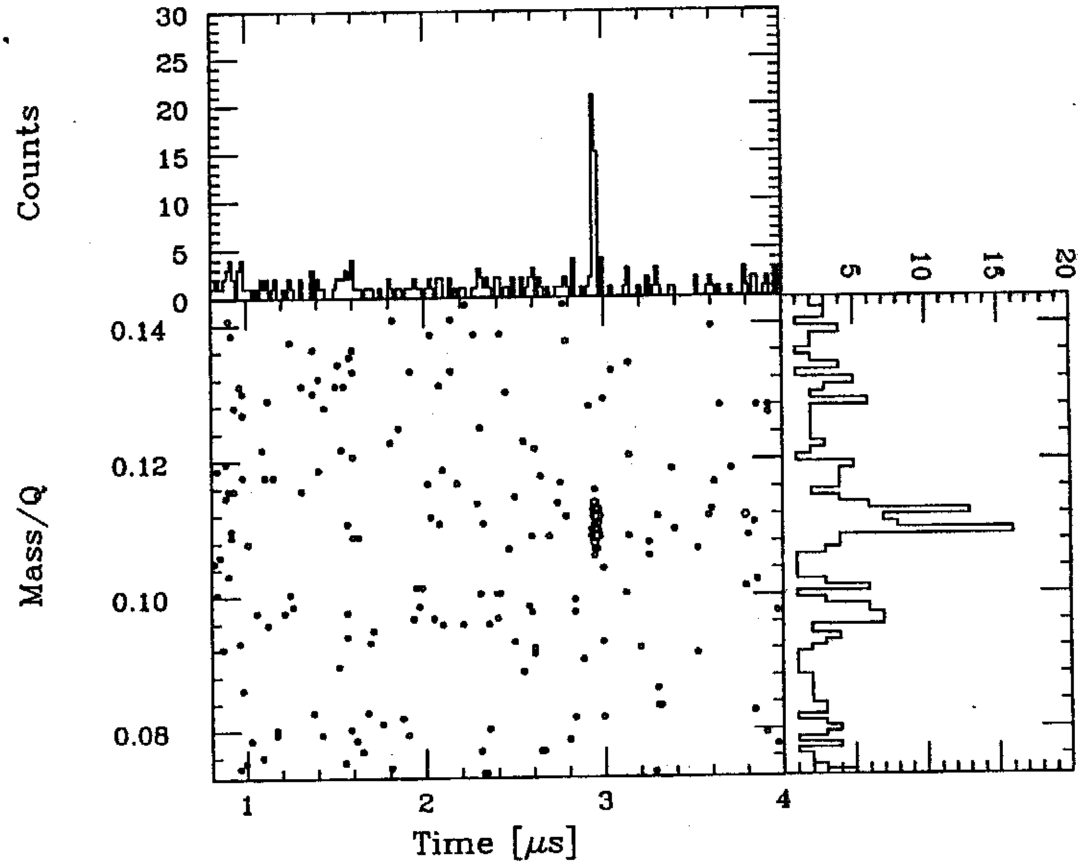

S.C Solenoid Muon Channel
Primary Proton Beam Line
Surface Muon Channel
0 1 2 3m
P4 Line
ra Slow Muon Channel
Dilution
Refrigerator
πA. Exp
Area
4T
SC.Coil
μ Exp.Area
Laboratory I
Slow μ+
Laser Room
Slow Optics
R&D
Laboratory II
Data taking Room


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

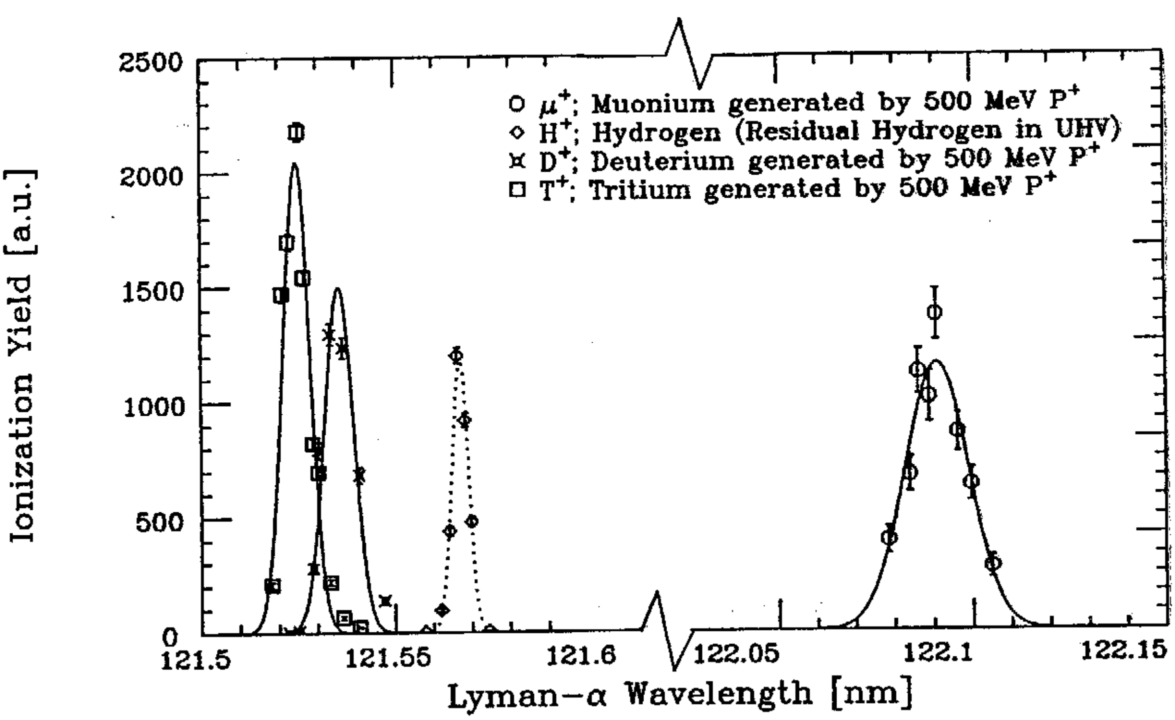

Thermal Mu
Electrostatic SOA Lens
ElectroStatic
Mirror
500 MeV
Proton
hot W
BN
Pulse
VUV
+
355nm
Pulse
Slow μ+



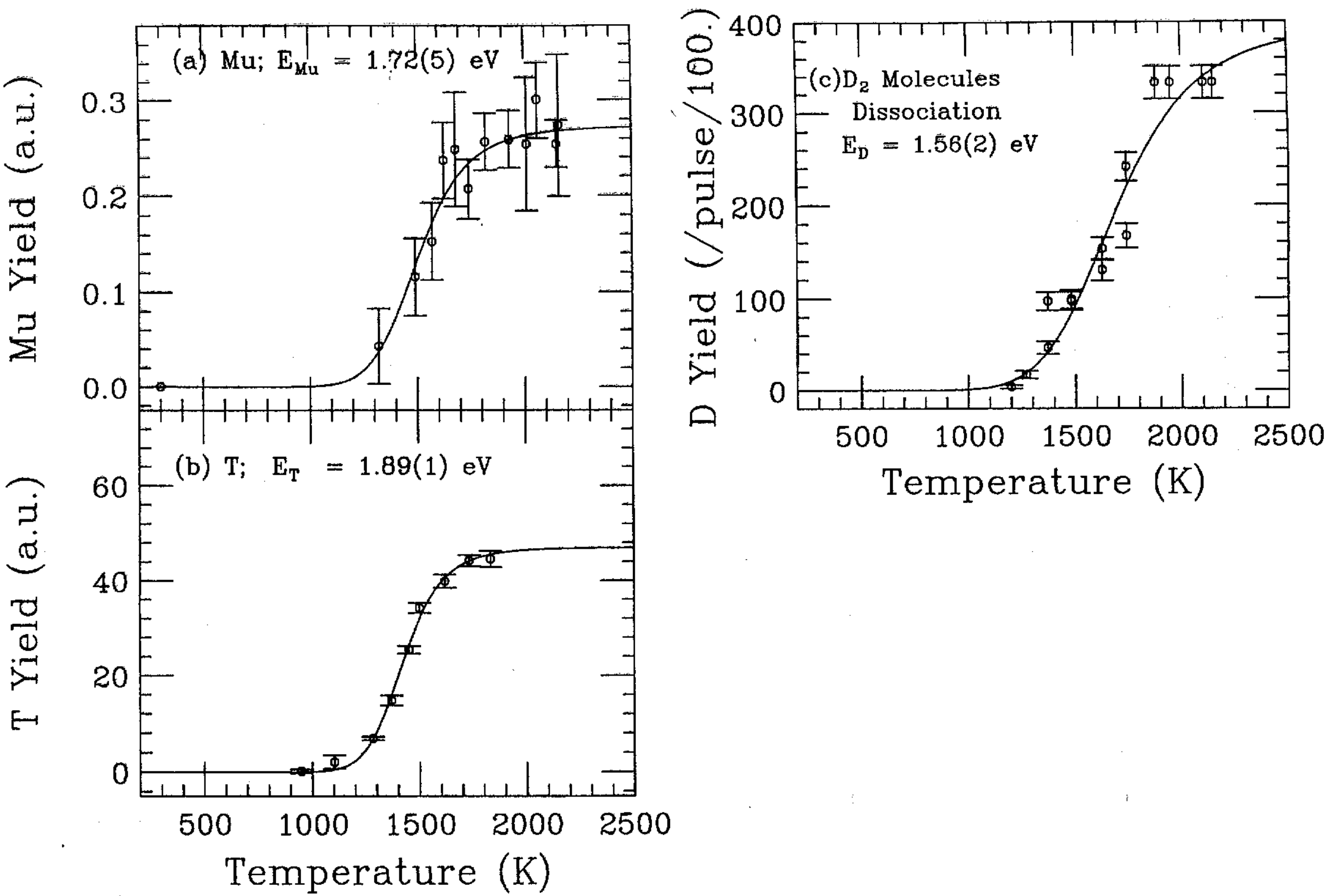
Slow μ+(p+,t+)
355nm
2P
Lyman-α
122.09nm(Mu)
121.57nm(H)
121.52nm(T)
1S
Mu(H,T)
ωvuv=2ωr-ωt
Kr
4p5 5p[1/2,0]
820.9nm(Mu)
845.3nm(H)
847.4nm(T)
212.5nm
ωr
ωt
ωvuv
212.5nm
Lyman-α
121.52-
122.09nm
ωr
500MeV
Proton
Lyman-α & 355 nm
NO Cell & Slits
BN+hot W target
Immersion SOA Lens
Electric Deflector
500MeV
Proton
Electro-Static Quadrupole Lens
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+
TF-Coil
MCP Detector
Backward Telescope
355nm
Wave-
mator
212.5nm
750-900nm
YAG
TiS(HRL)
YAG
OPO
Mirrage
BBO
BBO
YAG
YAG
YAG
TiS(LRL)
TiS Amp
YAG
355nm
355nm
Alignment Port
NO Cell
Acton Monochromator
Laser Room
0
1
2m



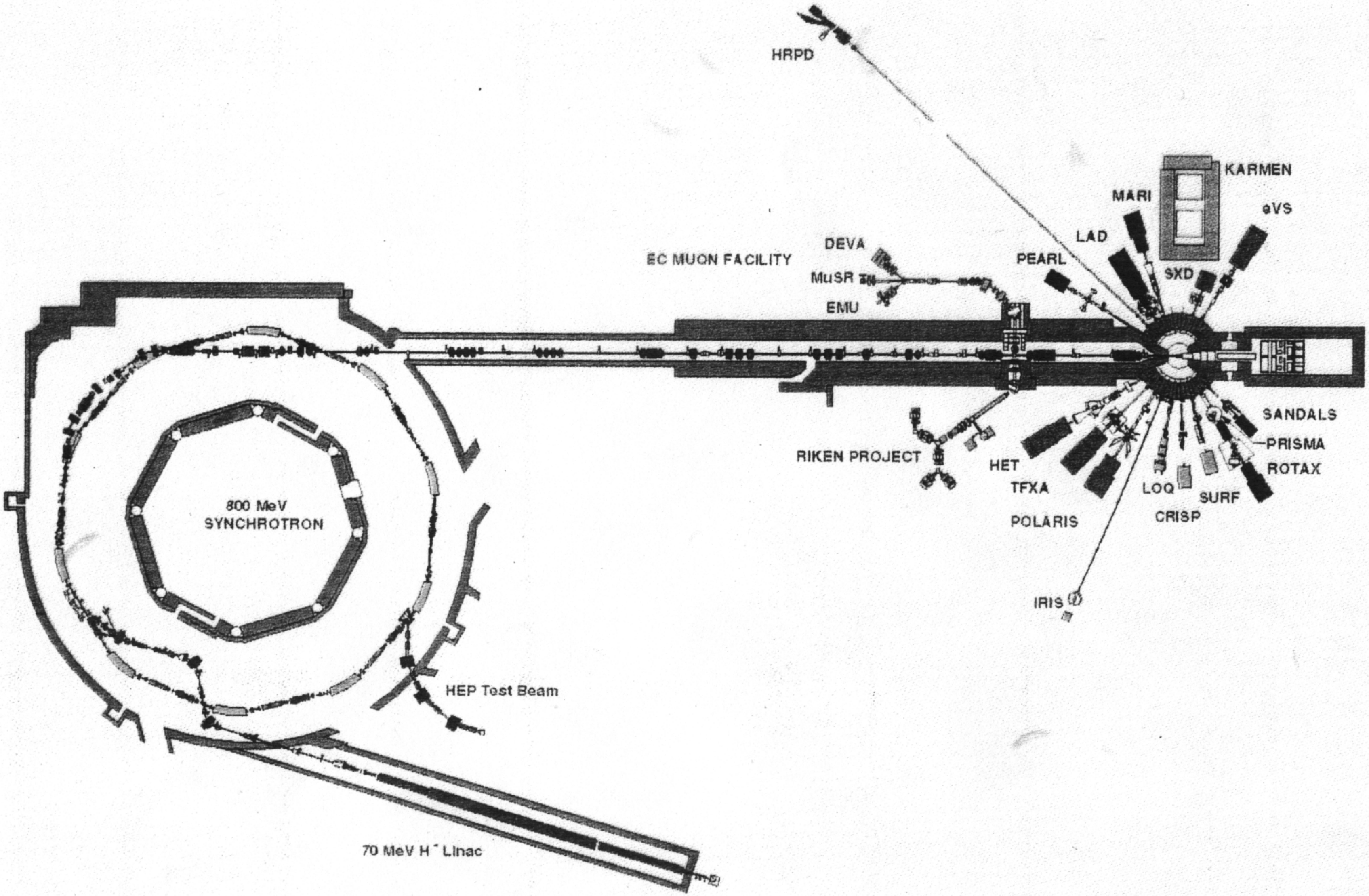
Counts
Mass/Q
Time [μs]

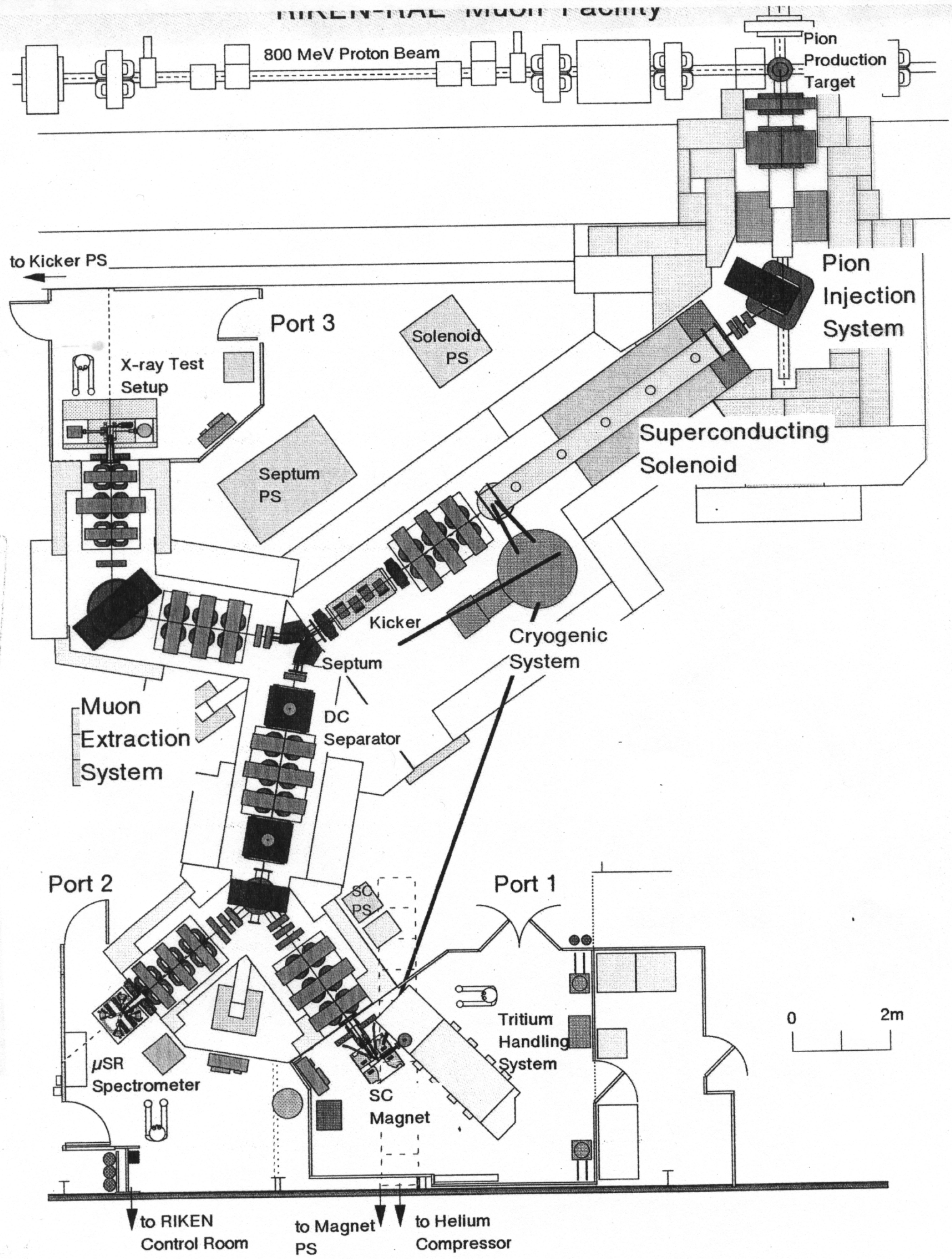


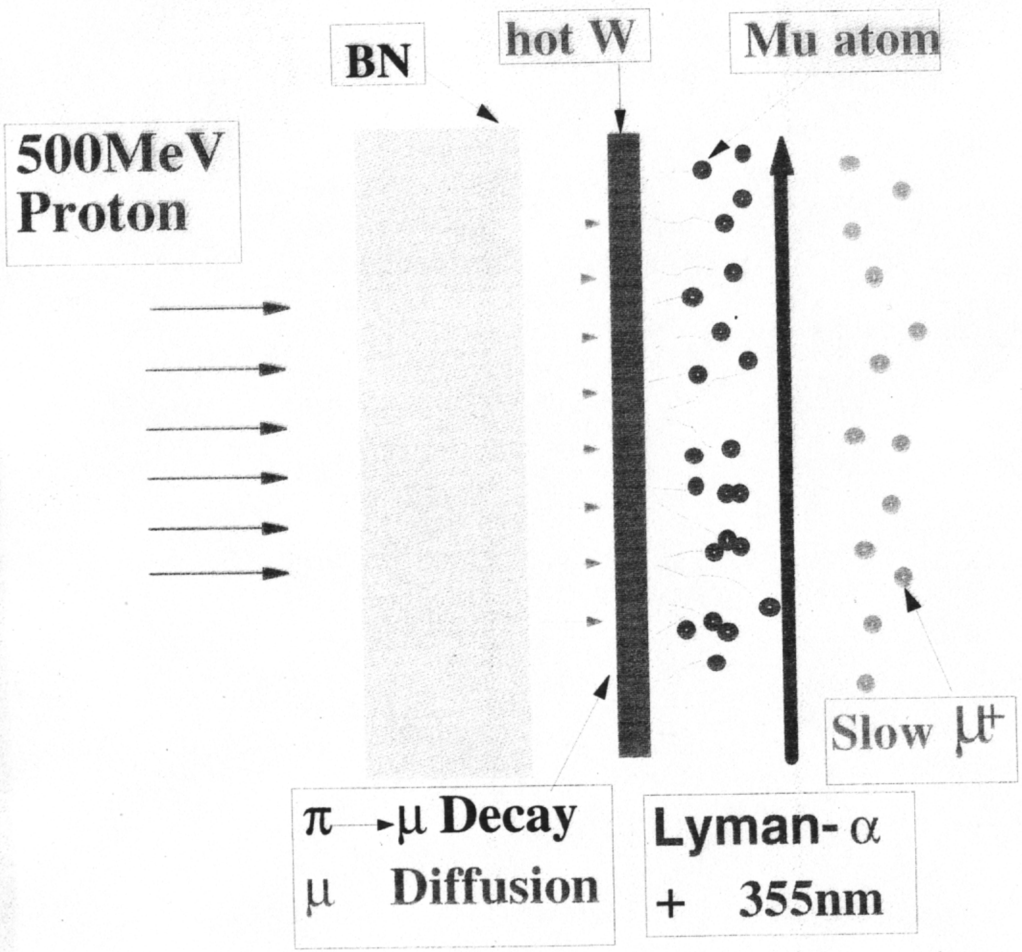
μ+; Muonium generated by 500 MeV P+
H+; Hydrogen (Residual Hydrogen in UHV)
D+; Deuterium generated by 500 MeV P+
T+; Tritium generated by 500 MeV P+
Ionization Yield [a.u.]
Lyman−α Wavelength [nm]

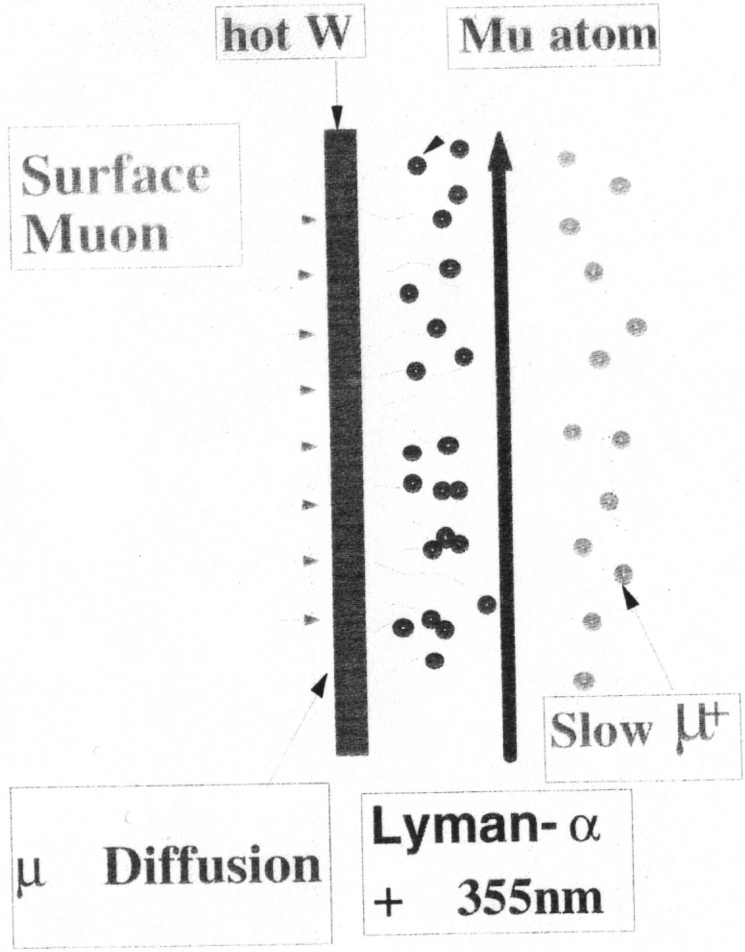


(a) Mu; E_{Mu} = 1.72(5) eV
Mu Yield (a.u.)
0.0
0.1
0.2
0.3
(b) T; E_T = 1.89(1) eV
T Yield (a.u.)
0
20
40
60
500
1000
1500
2000
2500
Temperature (K)
(c) D_2 Molecules Dissociation
E_D = 1.56(2) eV
D Yield (/pulse/100.)
0
100
200
300
400
500
1000
1500
2000
2500
Temperature (K)


HRPD
KARMEN
MARI
eVS
LAD
DEVA
EC MUON FACILITY
PEARL
MuSR
SXD
EMU
SANDALS
PRISMA
RIKEN PROJECT
HET
ROTAX
TFXA
LOQ
SURF
800 MeV
SYNCHROTRON
CRISP
POLARIS
IRIS
HEP Test Beam
70 MeV H⁻ Linac


RIKEN-RAL Muon Facility
800 MeV Proton Beam
Pion
Production
Target
to Kicker PS
Pion
Injection
System
Port 3
Solenoid
PS
X-ray Test
Setup
Septum
PS
Superconducting
Solenoid
Kicker
Cryogenic
System
Septum
DC
Separator
Muon
Extraction
System
Port 2
Port 1
SC
PS
Tritium
Handling
System
0
2m
μSR
Spectrometer
SC
Magnet
to RIKEN
Control Room
to Magnet
PS
to Helium
Compressor



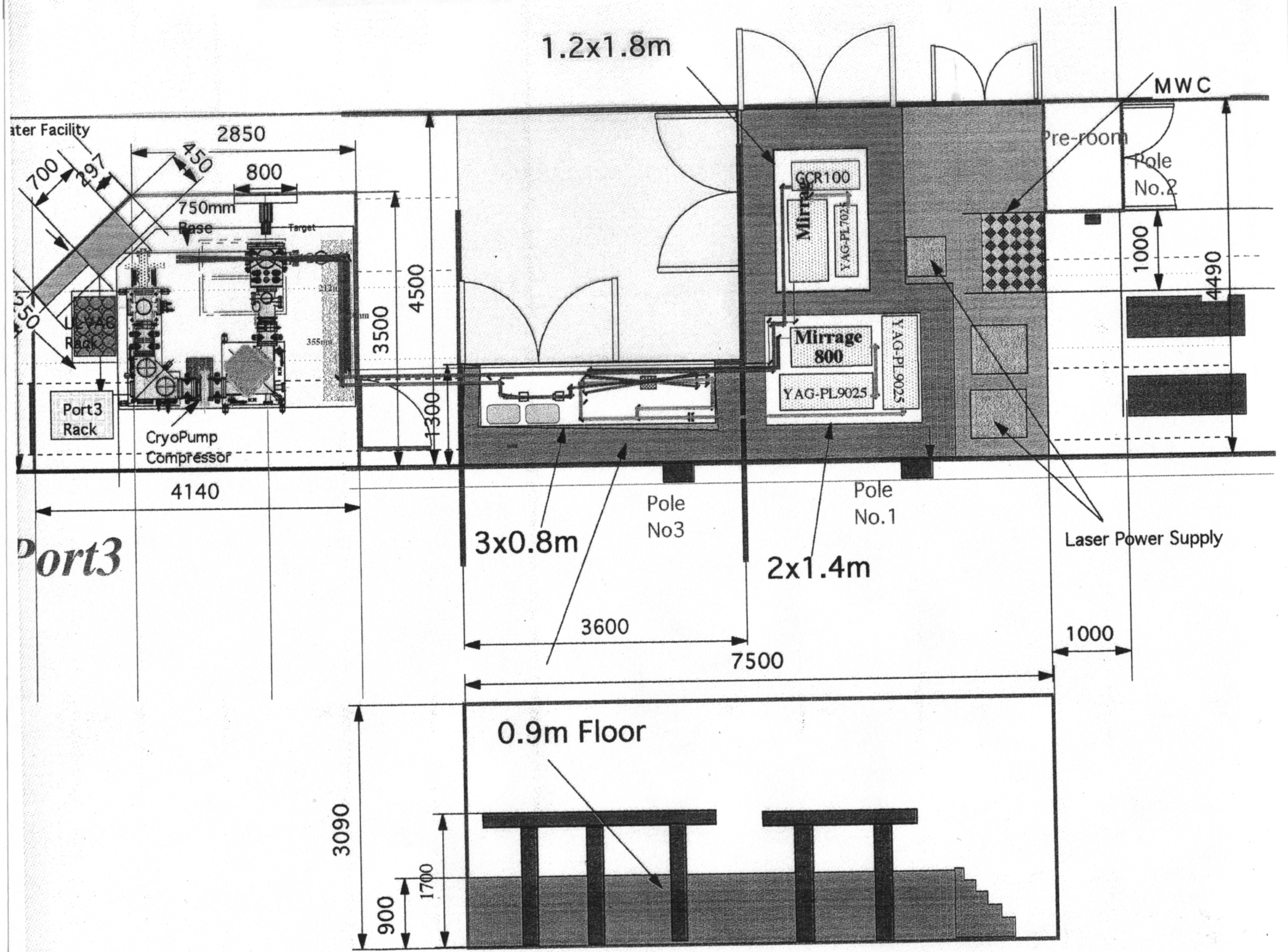


KEK-MSL

Primary Protons

RIKEN/RAL

Surface Muons



1.2x1.8m
MWC
ater Facility
2850
450
700
297
800
750mm
Base
Target
Pre-room
Pole
No.2
GCR100
Mirrage
YAG-PL7025
1000
4490
4500
3500
212mm
355mm
Mirrage
800
YAG-PL9025
YAG-PL9025
Rack
Port3
Rack
CryoPump
Compressor
1300
4140
Pole
No3
Pole
No.1
Laser Power Supply
Port3
3x0.8m
2x1.4m
3600
1000
7500
0.9m Floor
3090
1700
900

TOWARDS
VERY HIGH-INTENSITY LOW-ENERGY μ^+

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

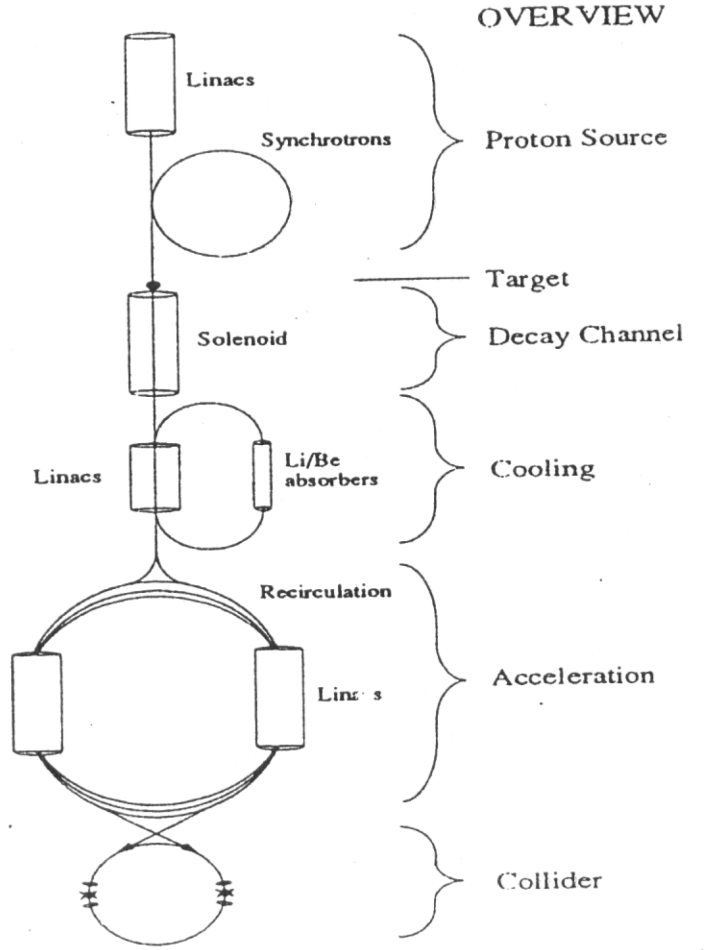
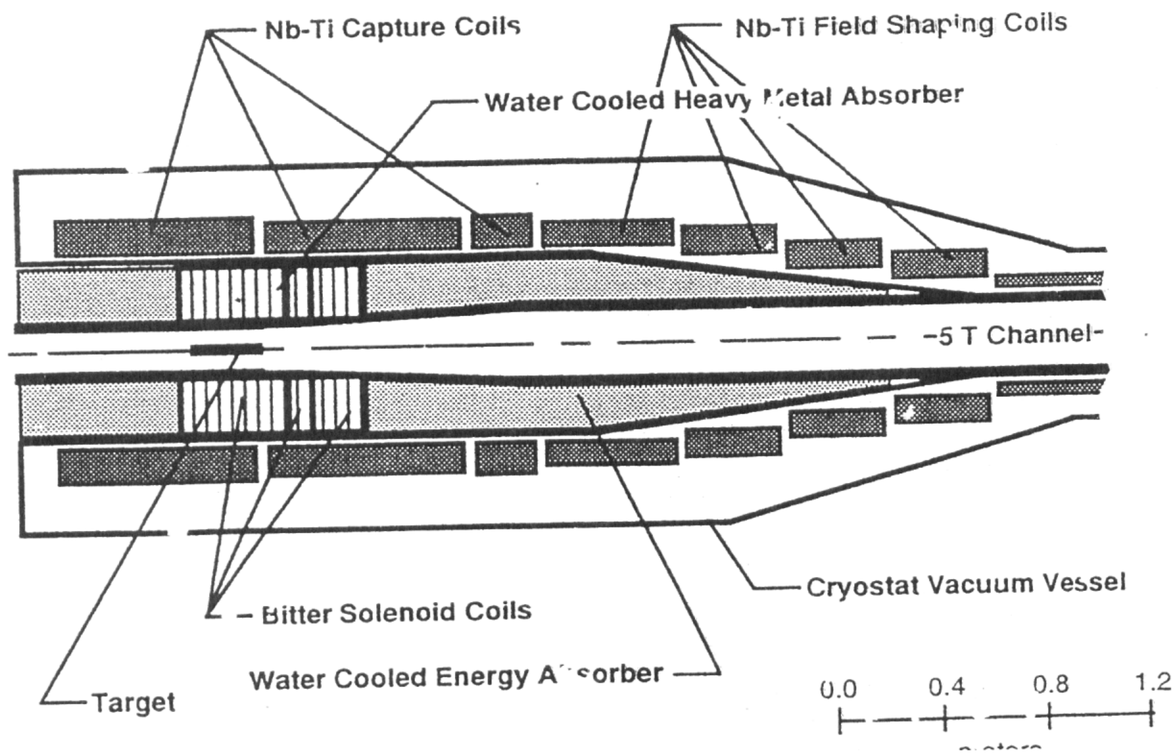
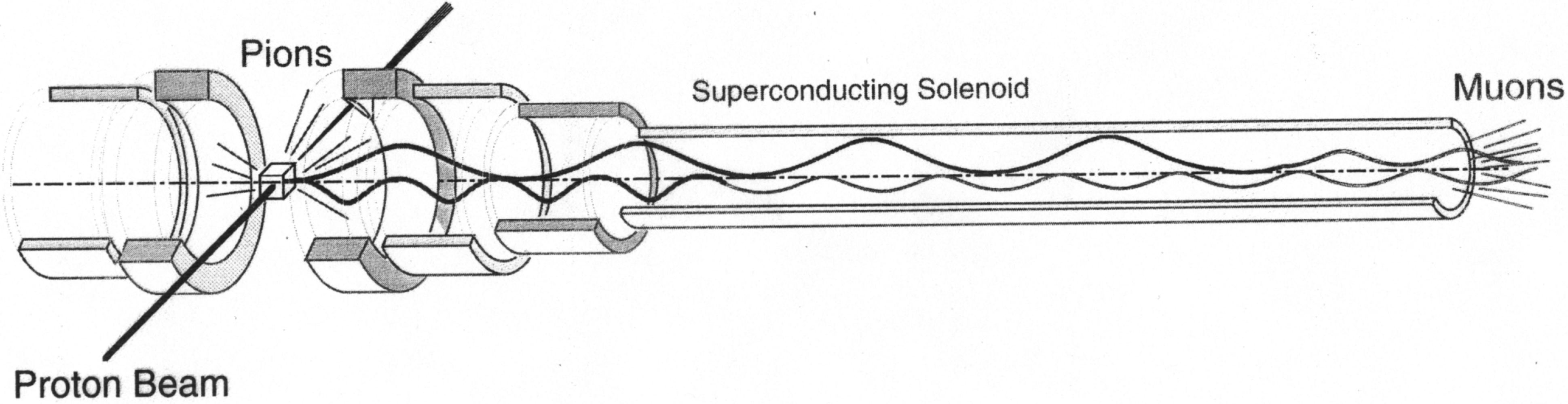
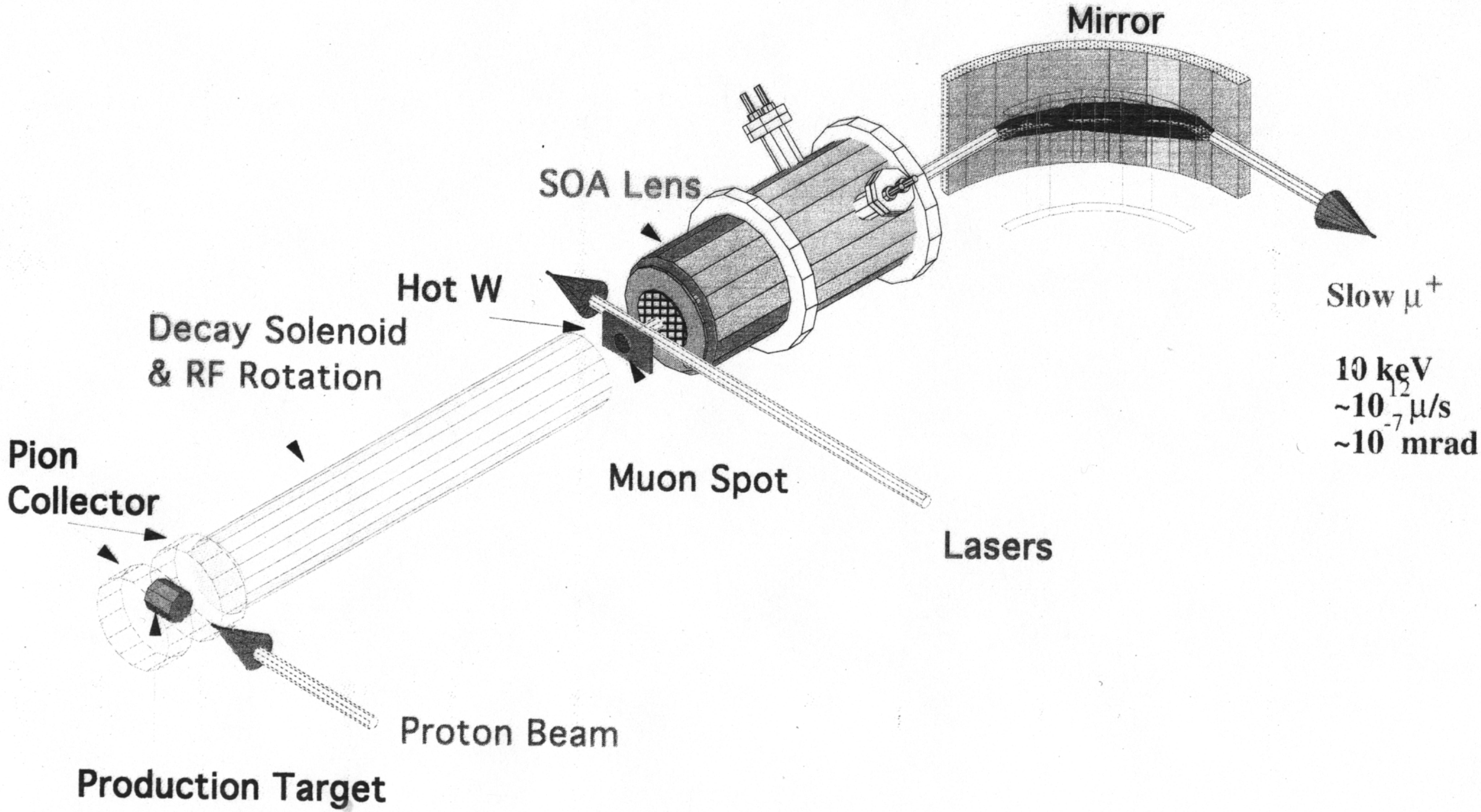


Figure 1.1: Schematic of a Muon Collider.

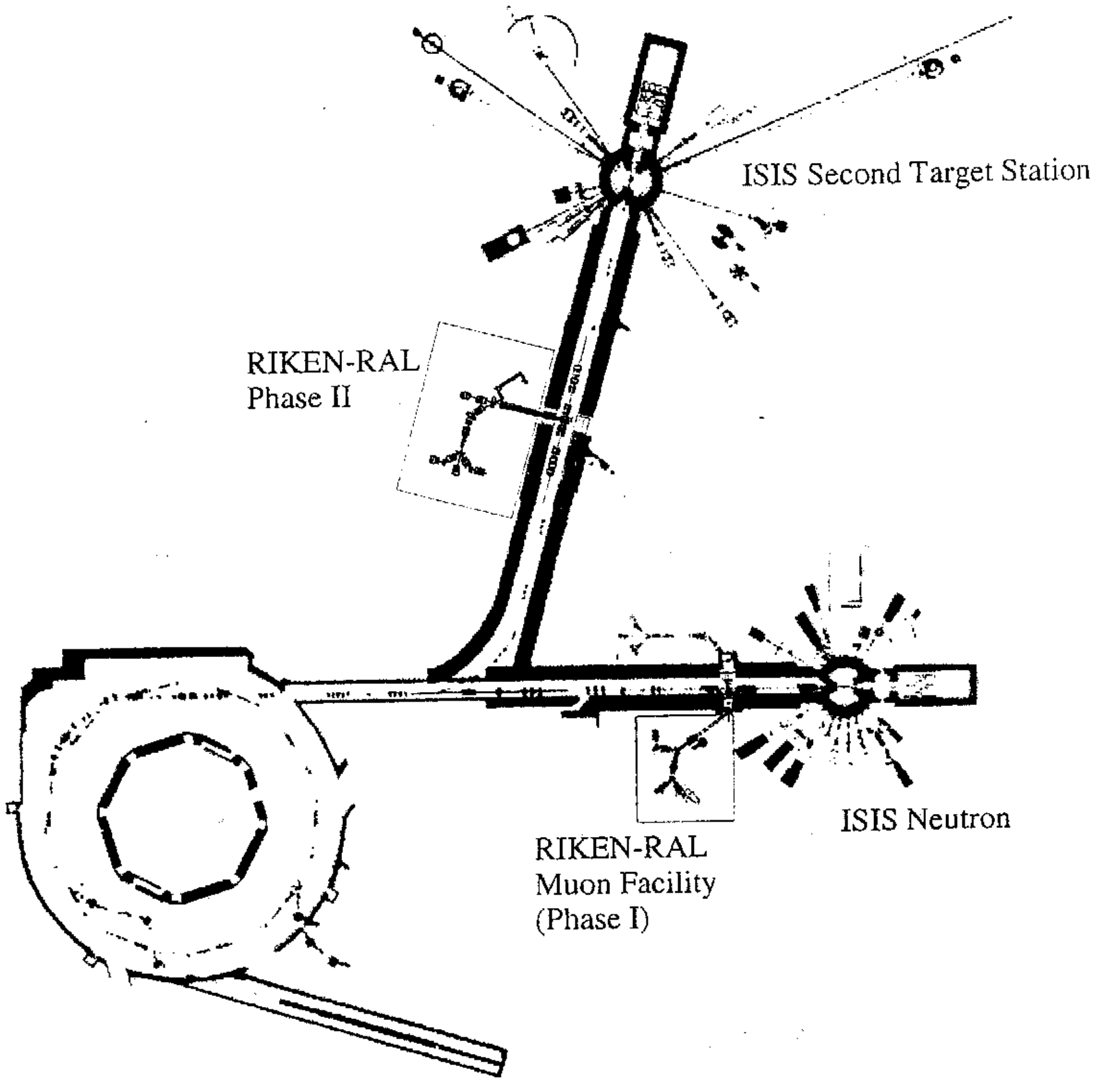



Pions
Superconducting Solenoid
Muons
Proton Beam

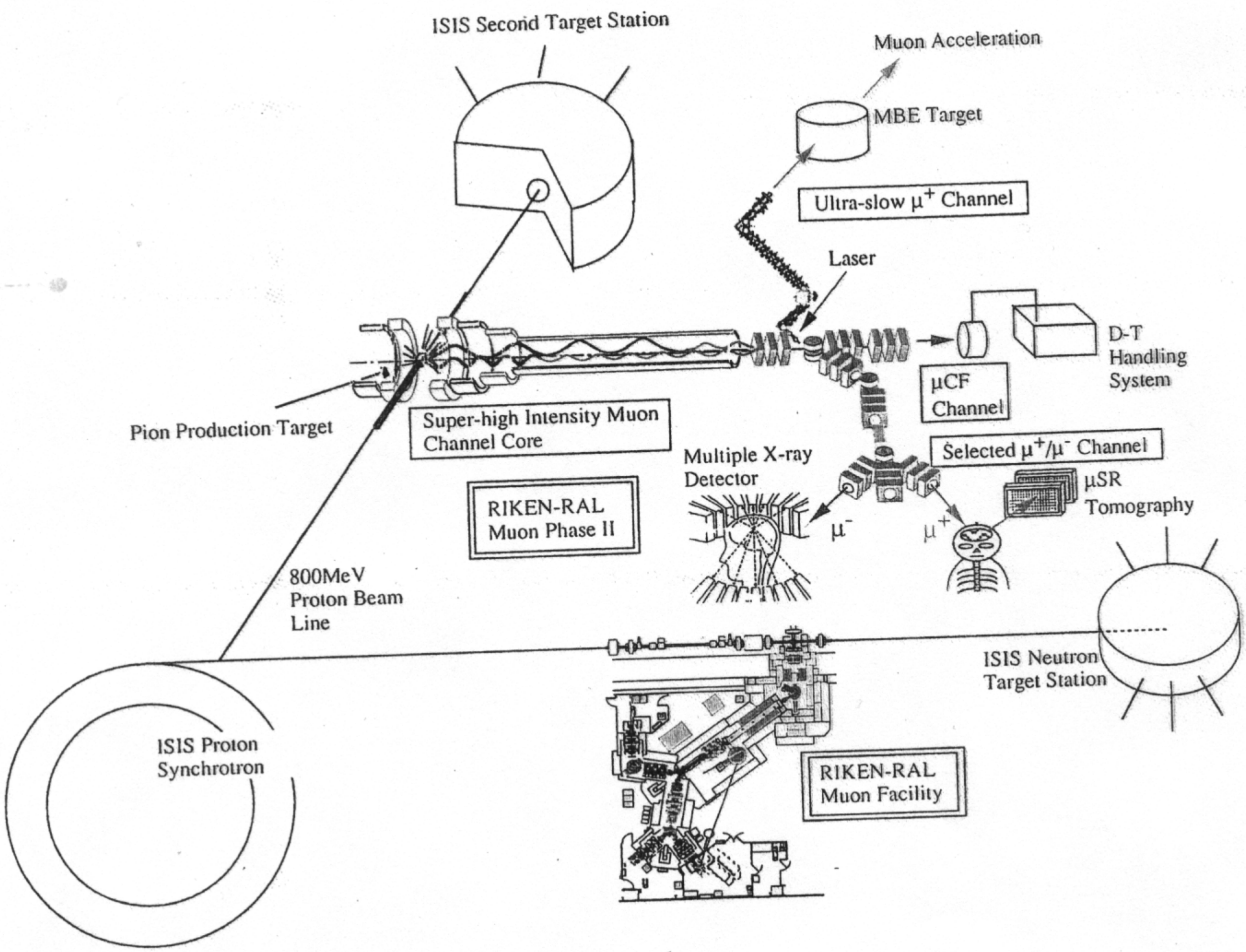
	KEK-BSF	RAL-II	JHF
陽子ビームエネルギー	500MeV	800MeV	3GeV
陽子ビーム強度	$5\mu A$	$60\ \mu A$	$200\ \mu A$
炭素標的厚み	3cm	4cm	1cm
標的での負パイオン発生効率	0.0014	0.0032	0.0072
パイオン発生総数	$3.3 \times 10^{10}/s$	$1.2 \times 10^{12}/s$	$9 \times 10^{12}/s$
ソレノイド出口ミュオン総数	$1.3 \times 10^{9}/s$	$3 \times 10^{10}/s$	$2.2 \times 10^{11}/s$
選択後ミュオン総数	$6 \times 10^{5}/s$	$1.3 \times 10^{7}/s$	$8 \times 10^{7}/s$


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

RIKEN-RAL
Phase II Project
(2000-2009)



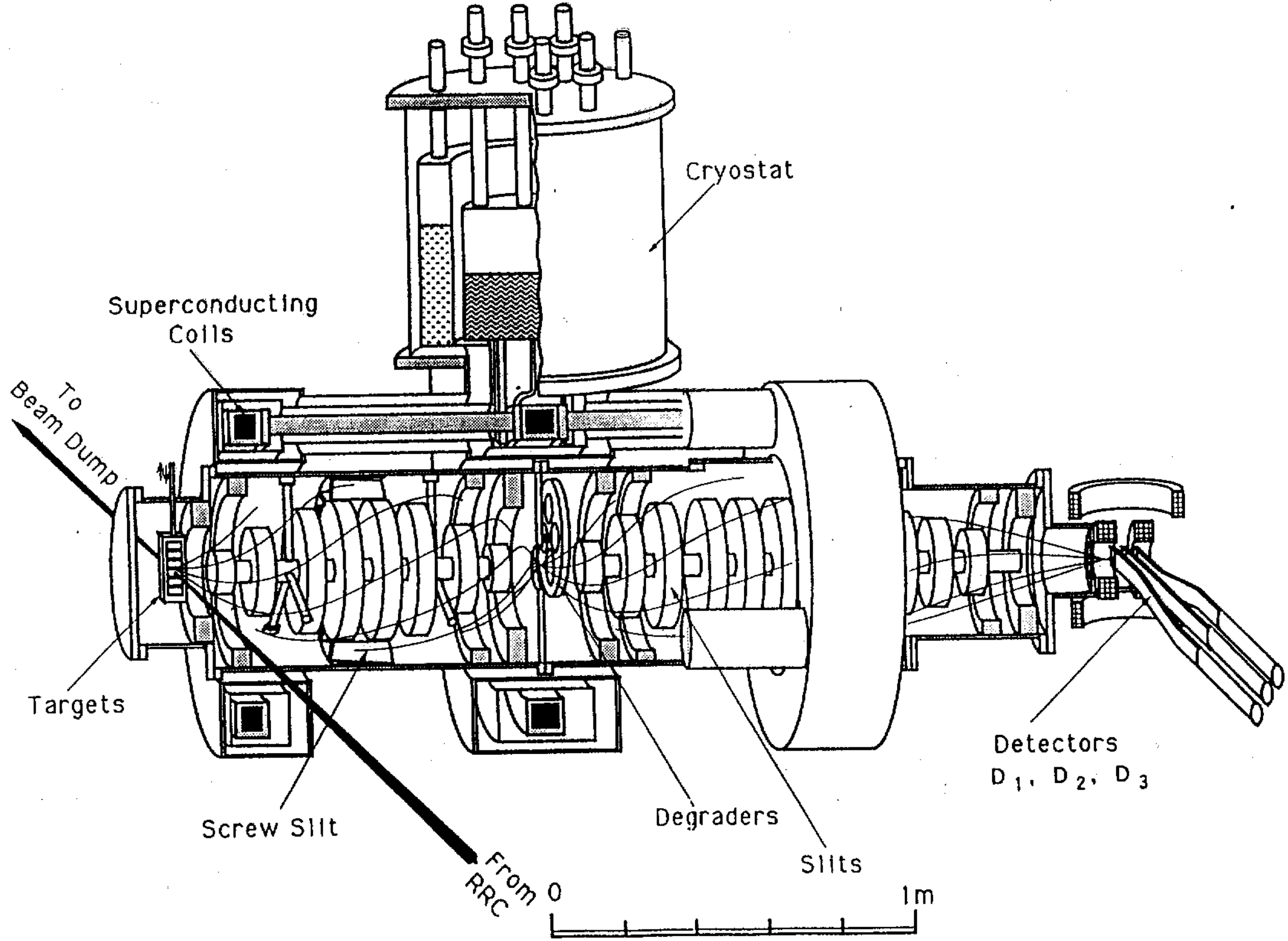
3. Contents of the RIKEN-RAL Phase II Project

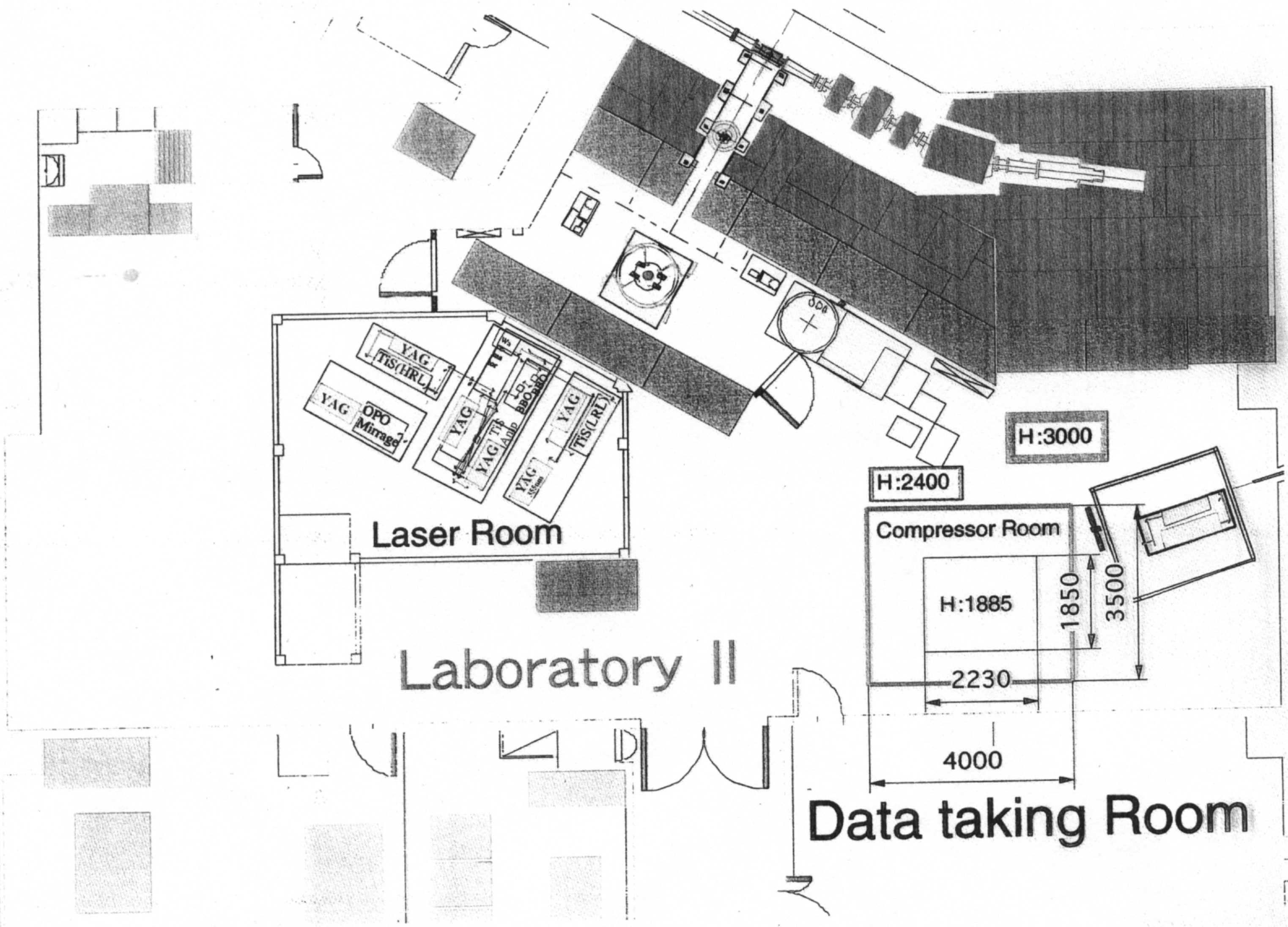


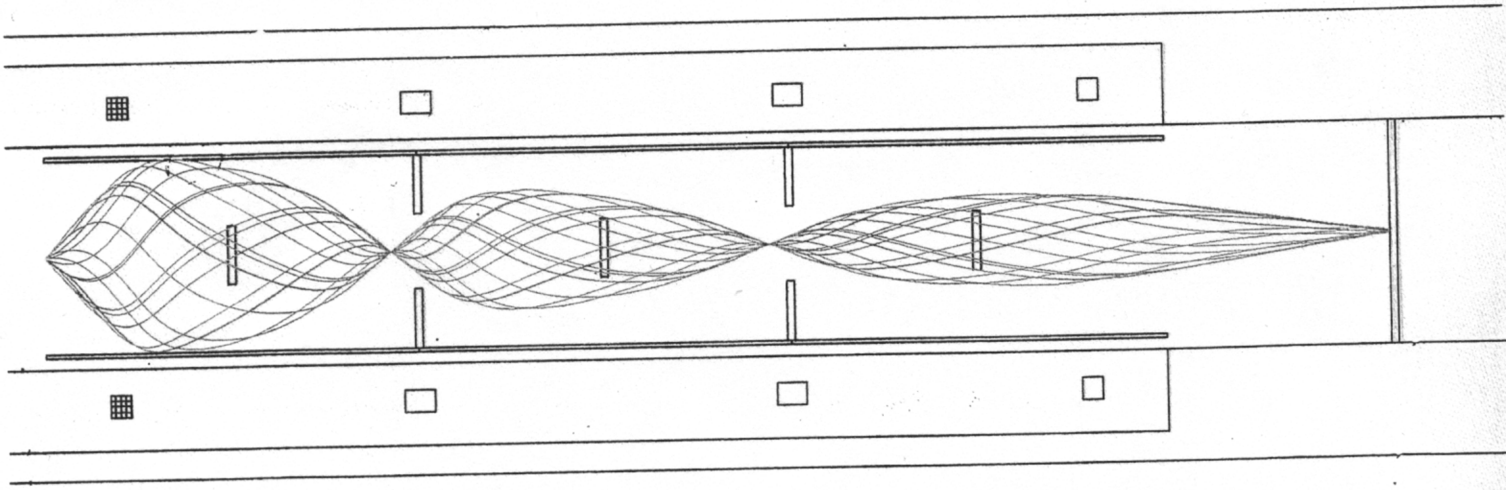
Schedule

Items	2000	2001	2002	2003	2004~
RIKEN-RAL II Facility					
(1) Super-high Intensity Muon Channel Core	design and construction	design and construction		tuning	
(2) Ultra-slow μ^+ Channel	design and construction	design and construction		tuning	
(3) μCF Channel	design and construction	design and construction		tuning	
(4) Selected μ^+/μ^- Channel	design and construction	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)


Cryostat
Superconducting Coils
To Beam Dump
Targets
Screw Slit
From RRC
Degraders
Slits
Detectors D 1, D 2, D 3
0
1m


YAG
TiS(HRL)
YAG
OPO
Mirrage
YAG
YAG
YAG
TiS(LRL)
YAG
Laser Room
H:3000
H:2400
Compressor Room
H:1885
1850
3500
2230
4000
Laboratory II
Data taking Room



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
2005	**RIKEN-RAL-II** (800MeV, 300 μA) Super-Super Decay μ^+	**10^{7-8}**	μ^+ Acceleration Bio-medical Application
2010	**KEK-JAERI** (3GeV, 330 μA) Super-Super Decay μ^+	**10^{10}**	Possible Extension to ν-Factory, $\mu^+\mu^-$ Colliders

ADVANCED NEUTRINO SOURCE WITH μ^+ ACCELERATION

1. Muon Decay Section

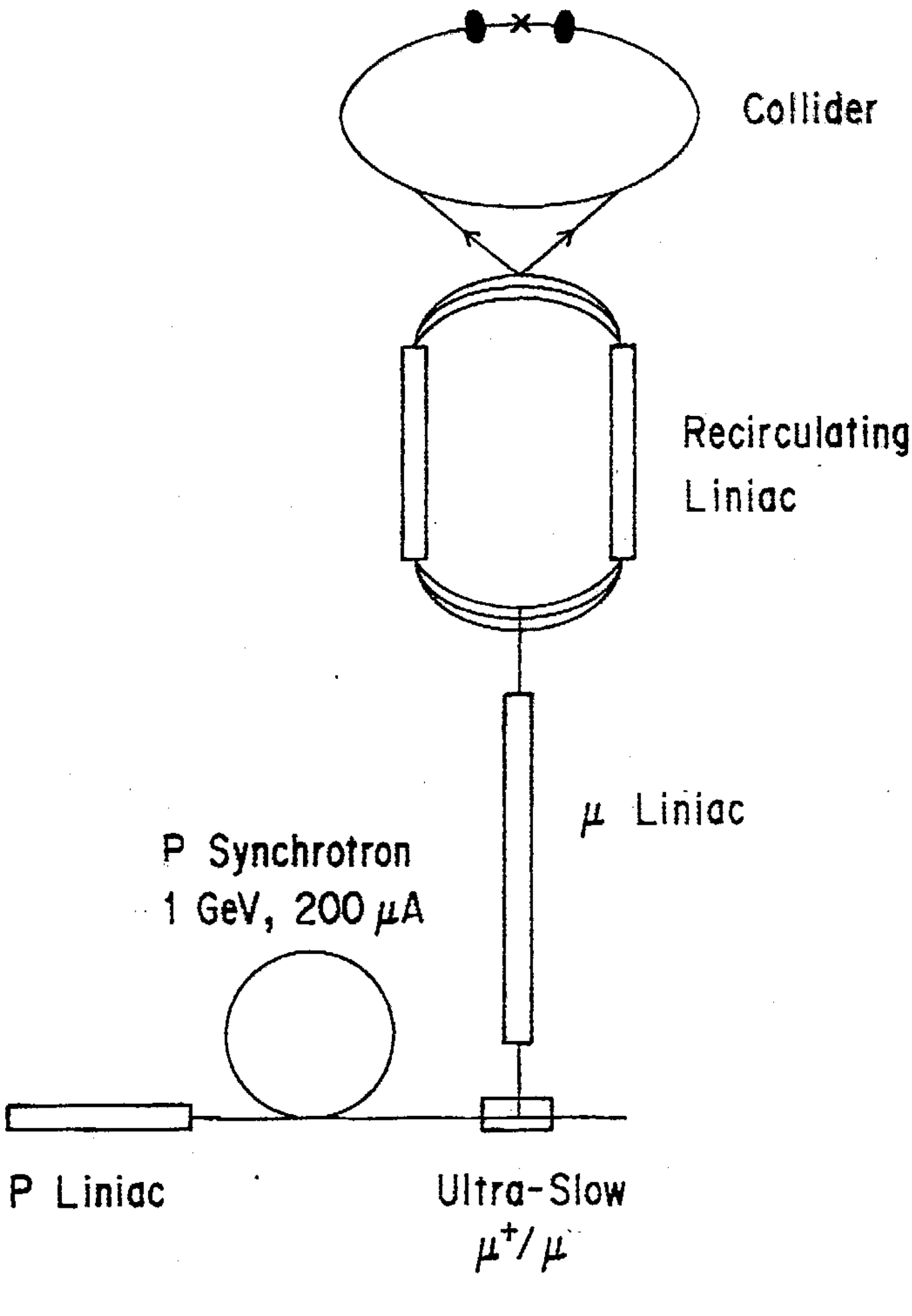
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

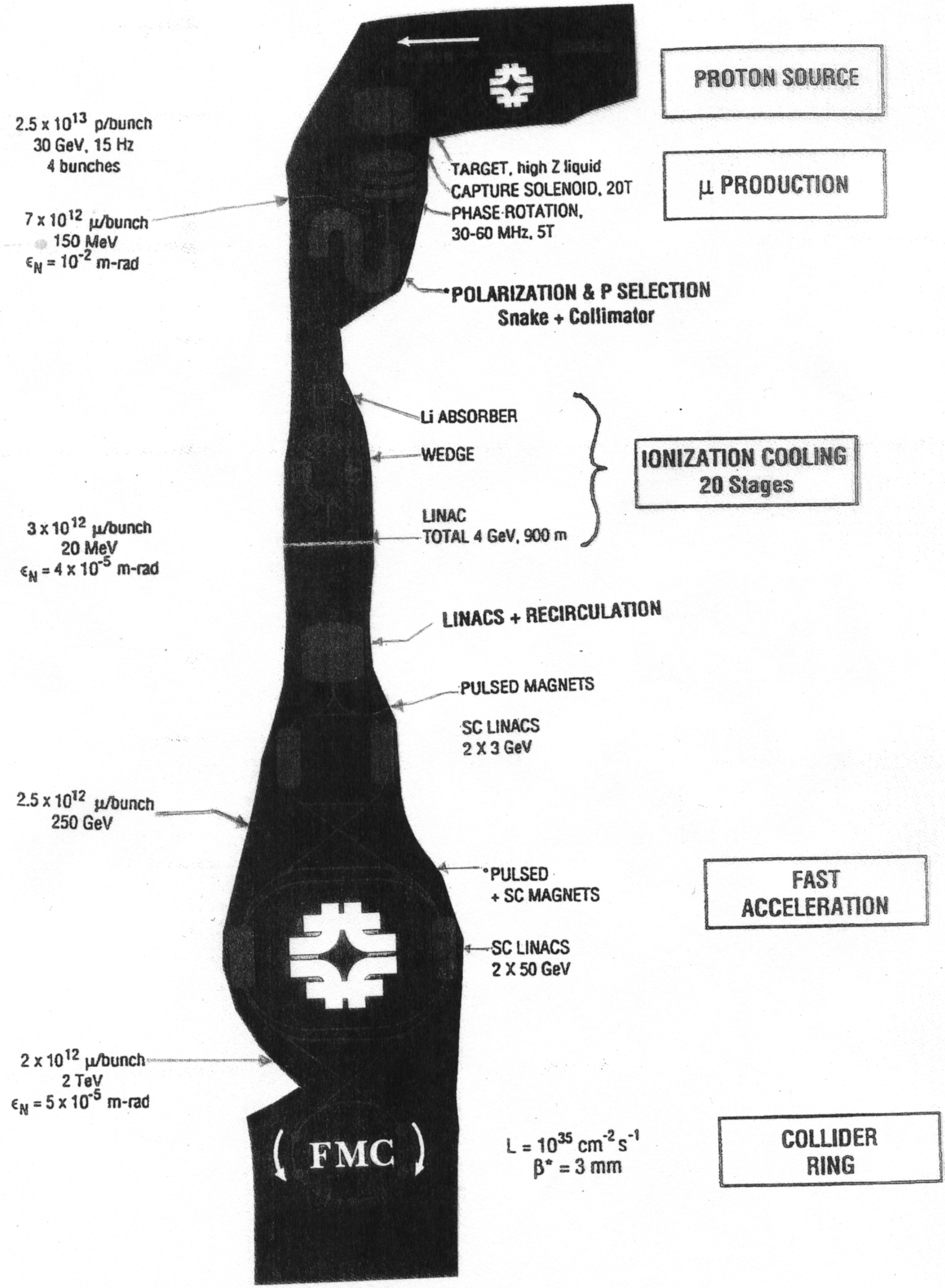
2. Expected Intensity and Phase Space

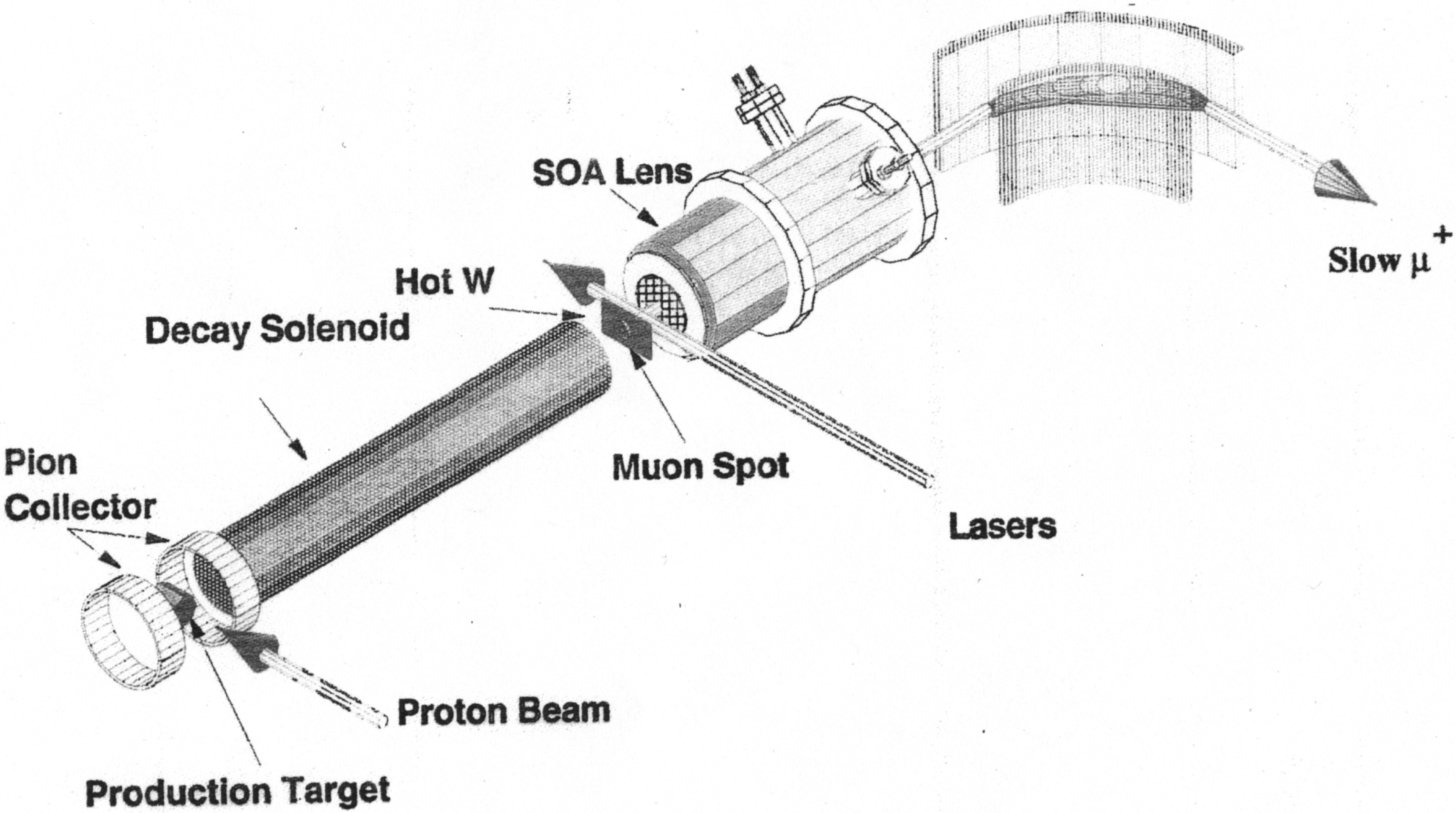
3. Comparison with Other Methods

   Proposed ν Sources, So far

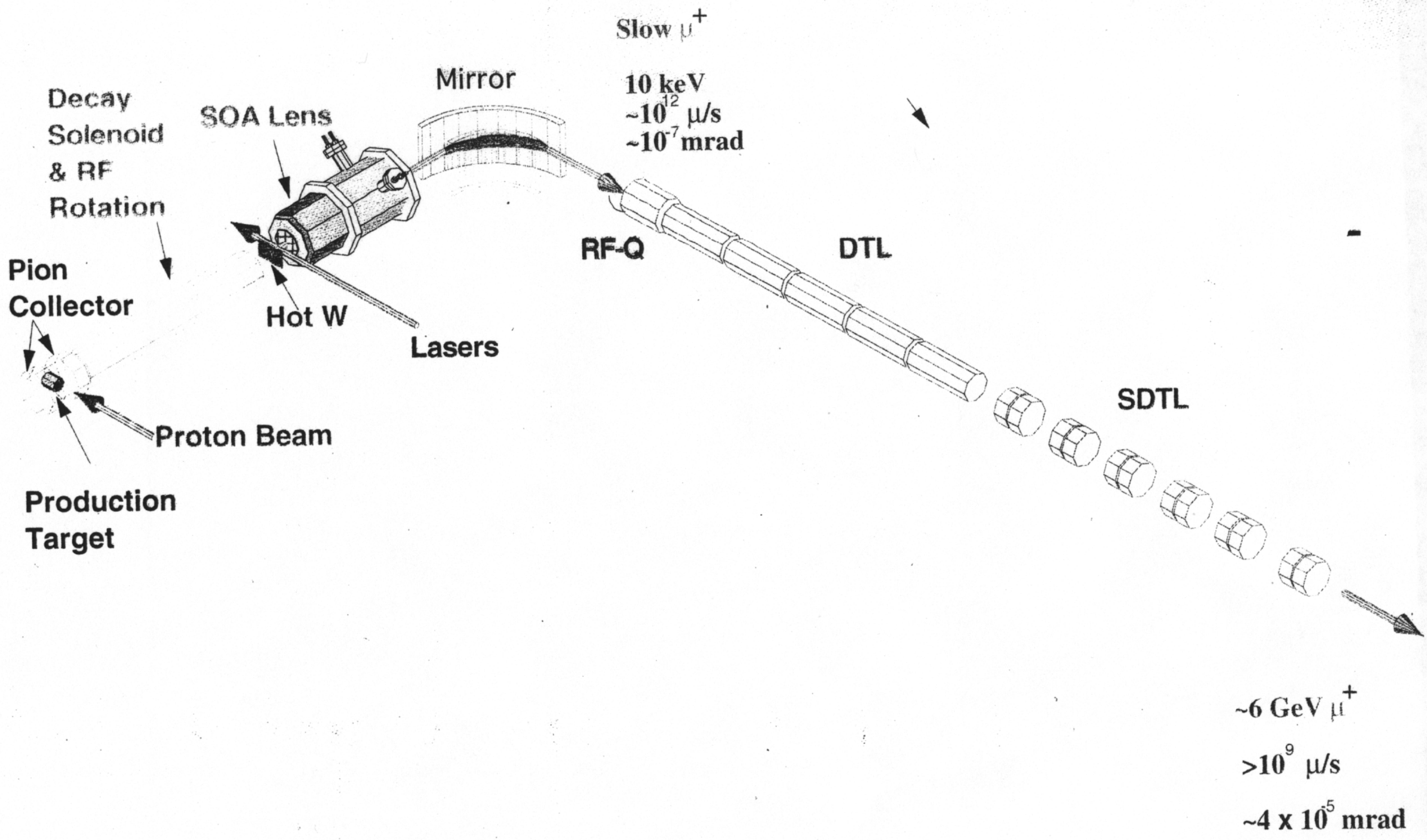
   Long Base-Line ν Oscillation Experiment

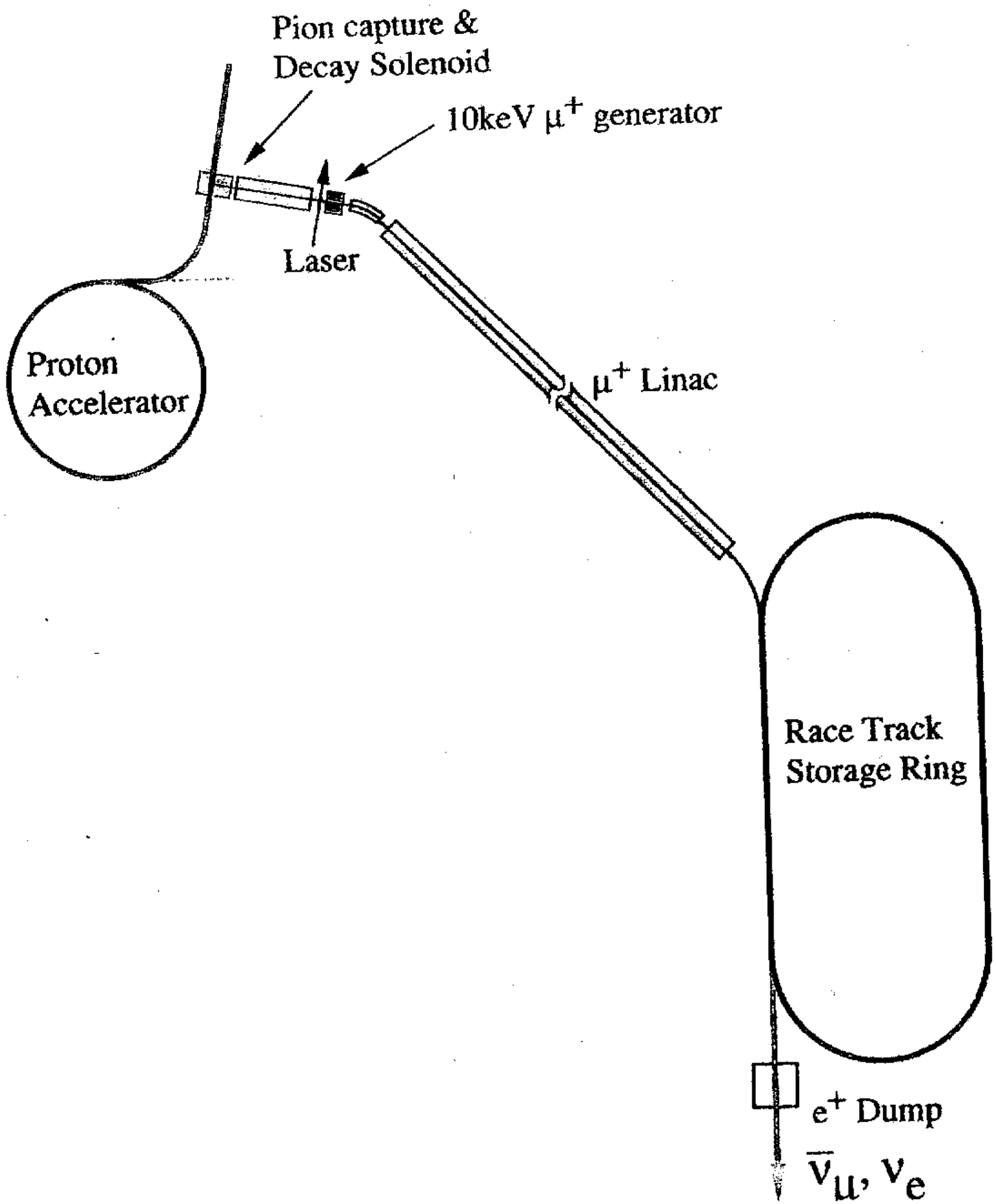

Collider
Recirculating
Liniac
μ Liniac
P Synchrotron
1 GeV, 200 μA
P Liniac
Ultra-Slow
μ+/μ-


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



Intense ultra-slow μ^+ production by employing the high-intensity muon production via a large acceptance pion collection.


Slow μ+
10 keV
~10^12 μ/s
~10^-7 mrad
Mirror
Decay
Solenoid
& RF
Rotation
SOA Lens
RF-Q
DTL
Pion
Collector
Hot W
Lasers
SDTL
Proton Beam
Production
Target
~6 GeV μ+
>10^9 μ/s
~4 x 10^-5 mrad



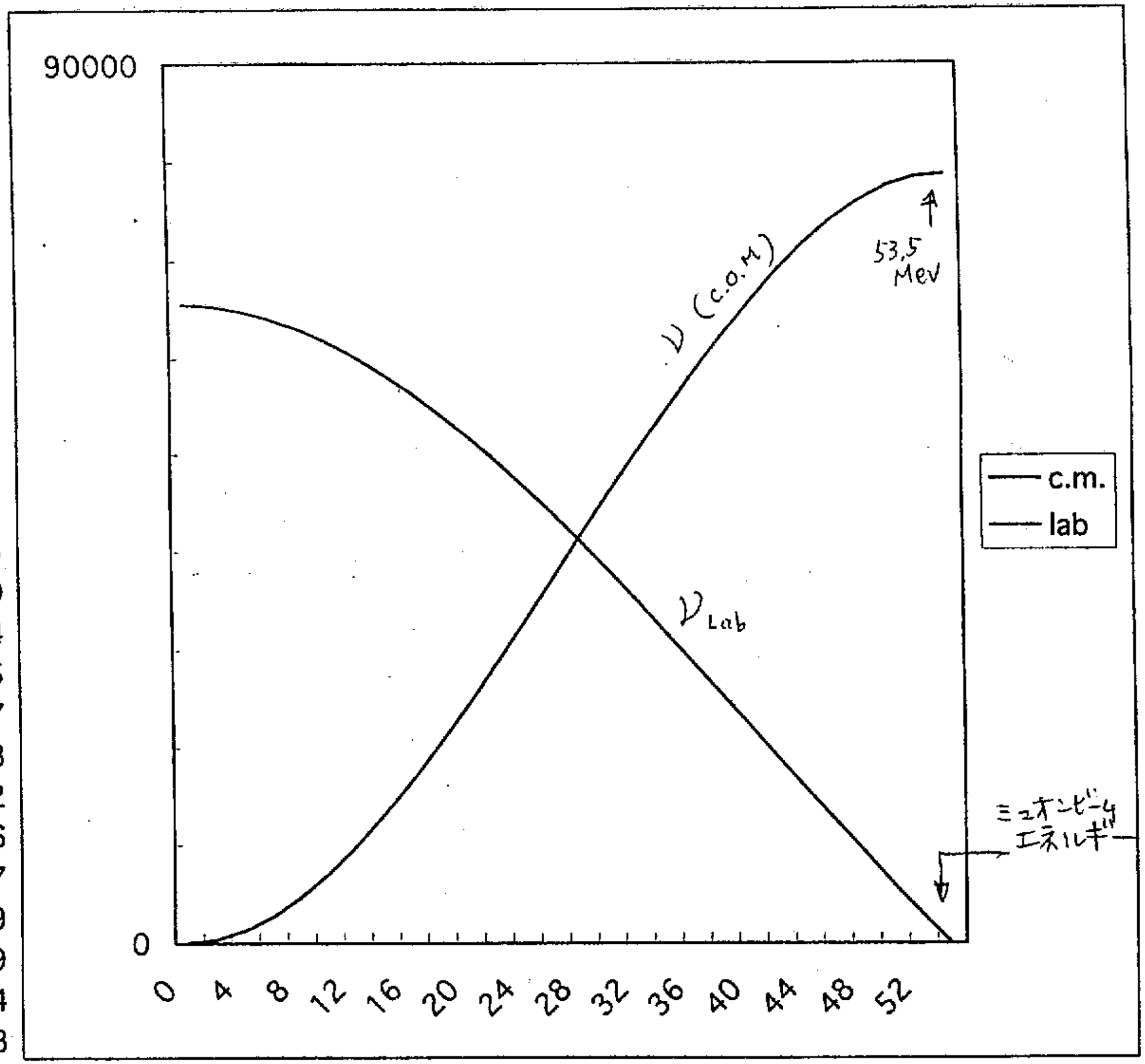
Proposed scheme of the advanced generation of neutrino beam based upon a decay of the muons accelerated from the ultra-slow μ^+ ion-source.

MUON LOSS DURING ACCELERATION

— *Very Preliminary Estimation* —

Energy Region	Remarks	Required Time	Survaival
Non-relativistic Region $0 \rightarrow E_0$ (<< 100 MeV)	$\ell\sqrt{\frac{2m_\mu}{E_0}}$ vs τ_μ	0 - 1 MeV in 1 m, 50 ns - 100 MeV in 50 m, 250 ns vs τ_μ	0.87
Relativistic Region $\rightarrow E_\mu$ ($\geq$ 10 GeV)	$\frac{\ell}{c}$ vs $\tau_\mu \gamma$ $\cong \tau_\mu \frac{E_\mu}{m_\mu}$	1 GeV ~ 10 GeV in 300 m, 1 μs vs 45 τ_μ	0.99

p	c.m.	lab/2γ
0	0	65615
2	316	65456
4	1232	64989
6	2700	64229
8	4672	63194
10	7100	61899
12	9936	60359
14	13132	58592
16	16640	56612
18	20412	54437
20	24400	52082
22	28556	49562
24	32832	46895
26	37180	44095
28	41552	41180
30	45900	38164
32	50176	35065
34	54332	31897
36	58320	28678
38	62092	25422
40	65600	22146
42	68796	18867
44	71632	15599
46	74060	12359
48	76032	9164
50	77500	6028
52	78416	2968
54	78732	0



Yield estimations for advanced neutrino source

	Expected numbers (s^{-1})	Conditions	Remarks
N_p	1.9×10^{15}	0.8 GeV × 300 μA	
$N_{\pi^+}^{tot}$	2.4×10^{13}	4 cm Carbon	$\sigma_{\pi^+}^{tot}$: 28 mb
N_{μ^+}	6.0×10^{11}	Pion Capture: 2.9 T, 20 cm bore × 1.5 m	Ref. (7)
		Muon Decay: 3.0 T, 25 cm bore × 10 m	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 Ioni
$N_{\mu^+}^{Acc.}$(10 TeV)	10^{10}	$\varepsilon_{cap.}$: 1.0 $\varepsilon_{acc.}$: 1.0	
$N_{\bar{\nu}_\mu, \nu_e}$	0.5×10^{10}	Full conversion in Race-Track Storage Ring	$E_\nu \approx 3.3$ TeV, $\theta_\nu \approx 10$

$N_{\pi^+}^{tot}$: total π^+ at production target, N_{μ^+}: total μ^+ at the exit of decay solenoid, $N_\mu^{stopp.}$: 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

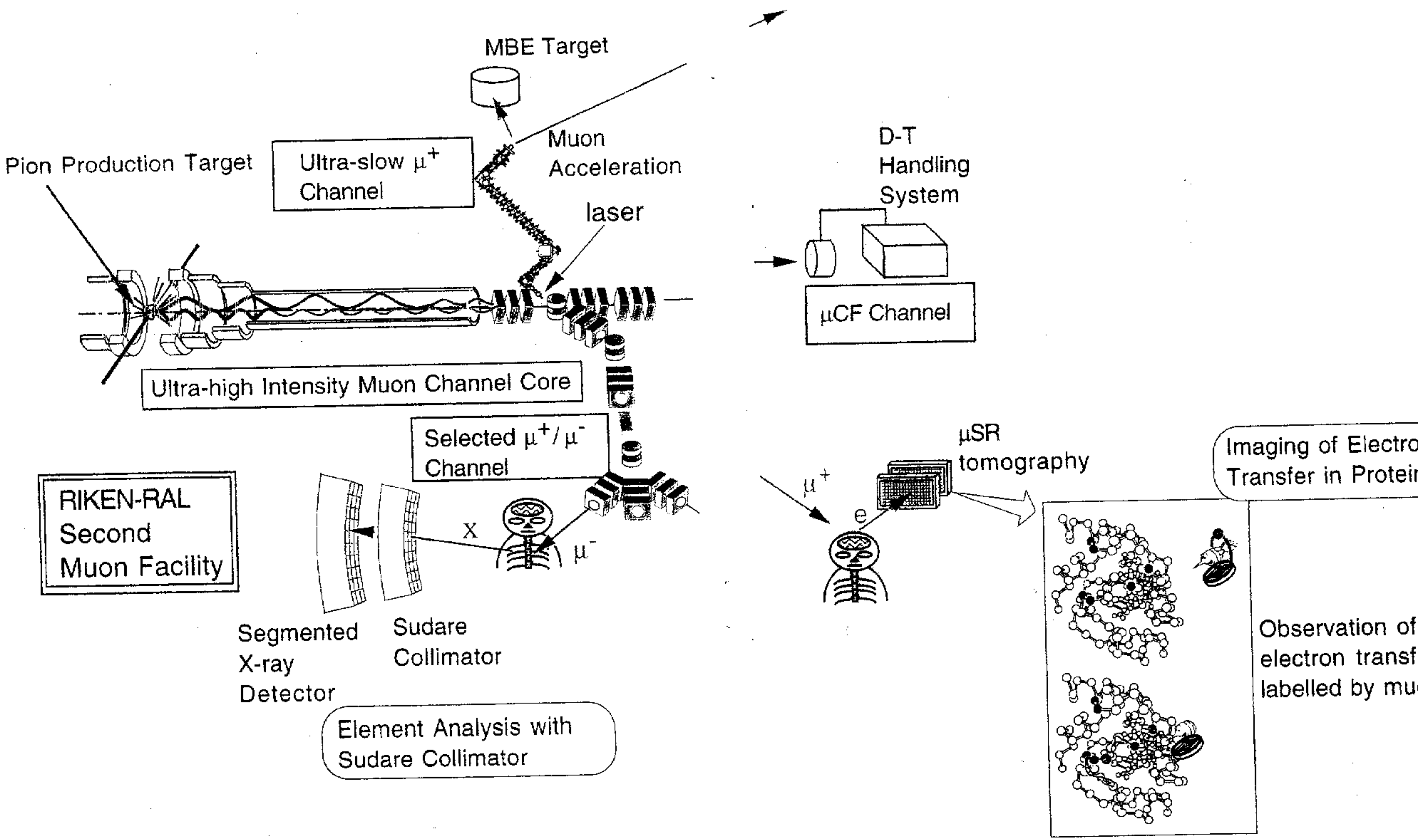
1. REALISTIC TIME SCHEDULE FOR VERY INTENSE COLD μ^+ BEAM.

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

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

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

New Scientific Research Opened by RIKEN-RAL Phase II Project



LIST OF COLLABORATORS

THE KEK METHOD

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RIKEN_RAL_KEK PROJECT

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Thermal Mu PRODUCTION EXPERIMENT

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