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LBL ν Meeting

Steve Geer

Muon Storage Ring Neutrino Source
A Preliminary Design Study

Steve Geer, Carol Johnstone, Dave Neuffer

(Fermilab–TM–2073)

- Motivation
- Scenario choice
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- Target & Decay Channel
- Cooling Channel
- Acceleration Scheme
- Storage Ring
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Muon Storage Ring Neutrino Source: Motivation

- **Pure ν flavor content with large ν_e component:**

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	50% ν_e ($\bar{\nu}_\mu$)
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	50% $\bar{\nu}_e$ (ν_μ)

- **Precisely known neutrino fluxes and kinematics:**

In the $\mu^\pm$ rest–frame, the distribution of neutrinos from muon decay is given by:

$$\nu_\mu : \quad \frac{dn}{dx\,d\Omega} = \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)\mathcal{P}\cos\theta\right]$$

$$\nu_e : \quad \frac{dn}{dx\,d\Omega} = \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)\mathcal{P}\cos\theta\right]$$

where $x = 2E_\nu/m_\mu$, θ is the angle between the neutrino and the muon spin, and $\mathcal{P}$ is the muon polarization.

- **A muon storage ring with a long straight section can be tilted at a large angle if needed –> very long (Trans–Earth) baseline experiments.**

History

- Using muon decays to generate muon beams has been discussed many times in the literature.

- There was an experiment proposed at Fermilab (P–860) in 1992 to search for neutrino oscillations using the Fermilab Antiproton Debuncher as a muon storage ring neutrino source. The P–860 sensitivity was interesting ... but the stored muon rates were not interesting enough to achieve sufficient sensitivity for approval.

- It has been realized that with the muon source required for a Muon Collider, the number of available muons would be so large that the muon storage ring neutrino source idea becomes very attractive : (*S. Geer, PRD 57, 6989 (1998)*).

–> What can one do with ~ 10^6 times the P–860 neutrino fluxes, using any baseline length up to Trans–Earth distances, and any beam energy up to ~50 GeV (say) ?

Scenario Choice

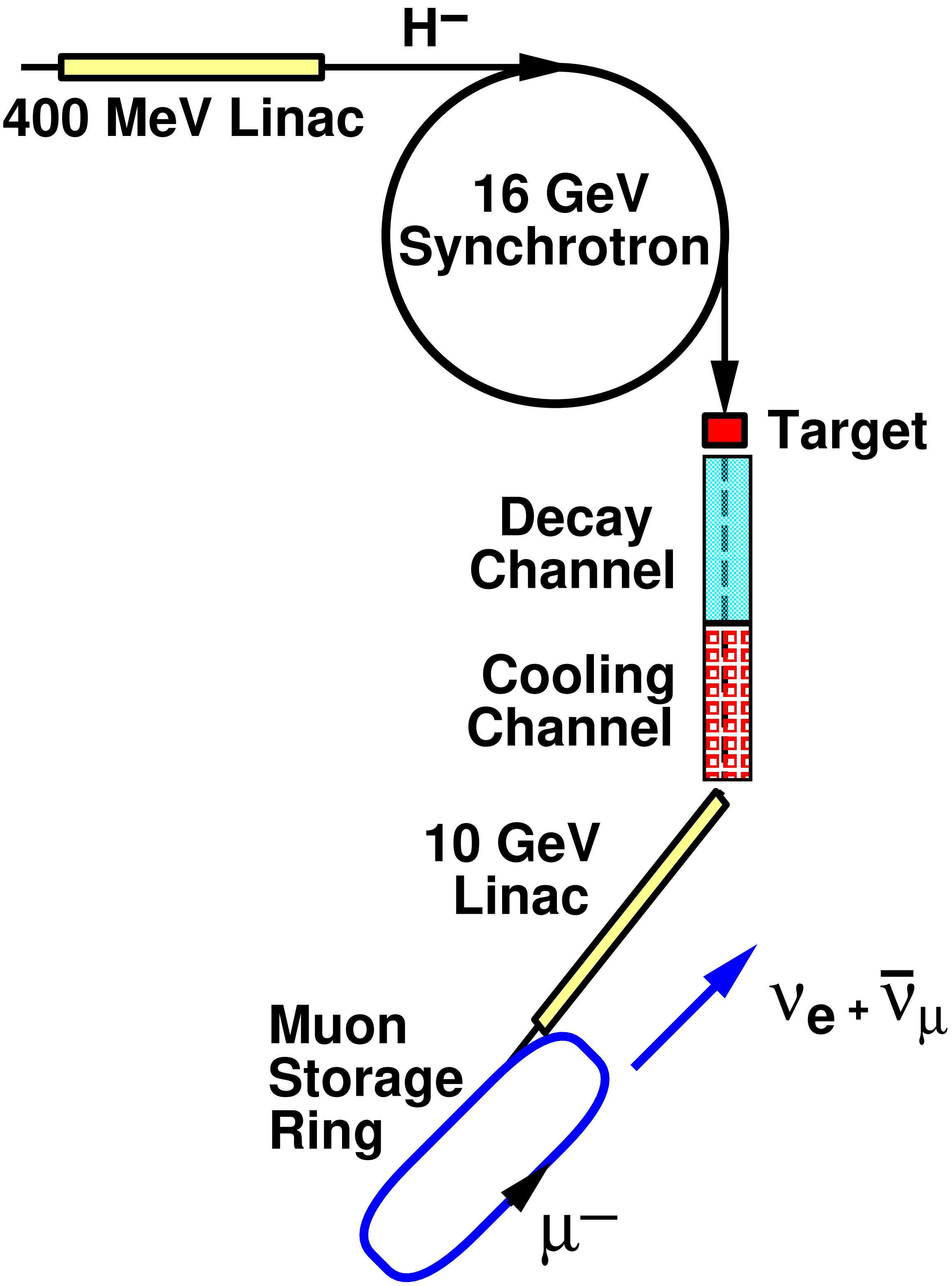
- **Two possible strategies:**

  1. **Design best possible muon storage ring neutrino source independent of its relevance to an eventual Muon Collider.**

  2. **Design a muon storage ring neutrino source that is in part motivated as a step towards a Muon Collider .... which means that the technology choices will be biased towards components od direct relevance to the First Muon Collider.**

- **We have chosen strategy 2 ..... to look at a neutrino source scenario that is designed to be a step towards the First Muon Collider.**

Neutrino Source Schematic



Proton Source – 1

- Source cycles at 15 Hz.

	Phase 1	Phase 2
Linac		
Kinetic Energy (MeV)	400	1000
Current (mA)	50	65
Pulse Length (μs)	100	300
H^- per pulse	3×10^{13}	1×10^{14}
Pre–booster		
Extraction K.E. (GeV)	–	3.0
Circumference (m)	–	158
Protons per bunch	–	2.5×10^{13}
Number of bunches	–	4
Trans. Emit. (mm–mr)	–	200π
Long. Emit. (eV–sec)	–	1.5
Booster		
Extraction K.E. (GeV	16	16
Circumference (m)	474.2	474.2
Protons per bunch	2.5×10^{12}	2.5×10^{13}
Number of bunches	12	4
Bunch length σ_t(ns)	2 – 10	2
Trans. Emit. (mm–mr)	50π	200π
Long. Emit. (eV–sec)	1.8	2.0

- Parameters from *S. Holmes et al; "A Development plan for the Fermilab Proton Source", Fermilab–TM–2021, Sep. 1997*.. updated to reflect current thinking.

Proton Source – 2

- **Phase – 1:**
  - Replace FNAL Booster with 16 GeV synchrotron –> 2.5 x 10^{12} protons/bunch x 12 bunches/cycle
  - Cycles at 15 Hz –>

    4.5 x 10^{21} protons/year
    (1 year = 10^{7} secs)

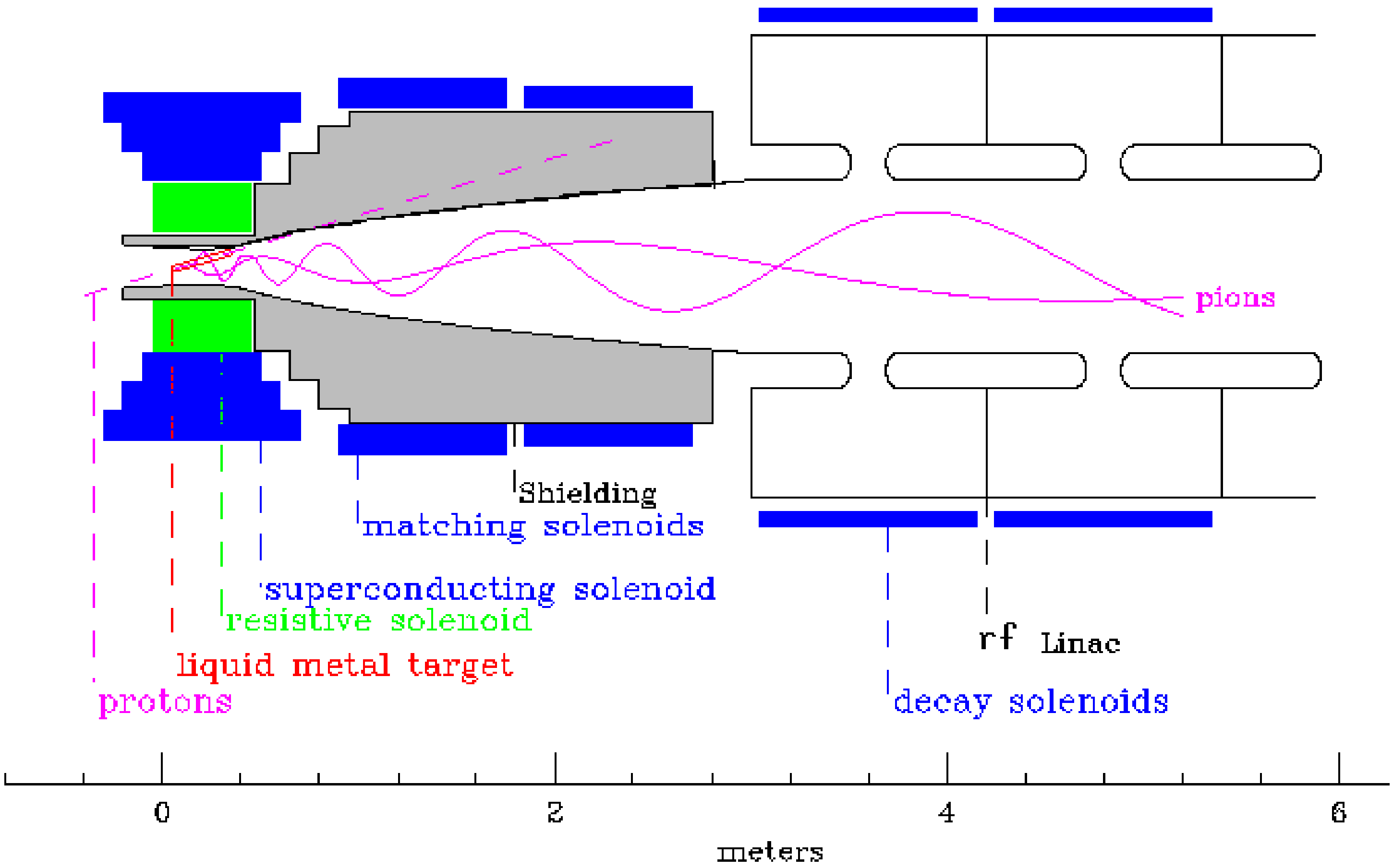
  - Assume the Phase – 1 proton source initially drives the muon storage ring neutrino source

- **Phase – 2:**
  - Upgrade FNAL Linac 400 MeV –> 1 GeV

    –> **1.5 x 10^{22} protons/year**

  - The Phase – 2 proton source would drive an upgraded neutrino source, & (with an added 3 GeV Pre–booster) eventually drive a muon collider.

Pion Capture & Decay



Section	L (m)	B (T)	Aperture (cm)	RF Frequency (MHz)	RF Gradient (MV/m)
1	3	20–>2	8–>24	–	–
2	3	2–>1.25	24–>30	60	5
3	29	1.25	30	30	4
4	5	1.25	30	60	4

0.6 π^+ captured / incident proton –>

0.2 μ^+ / incident proton at end of decay channel

Need for Cooling

- At the end of the decay channel:

No. muons/year	N	=	9×10^{20}
Mean Energy	E	=	250 MeV
Energy Spread	σ_E/E	=	0.15
Bunch length	σ_Z	=	1.5 m
Trans. Emittance	ε_N	=	0.017 m–rad

- The transverse emittance is too large to fit within an accelerator + storage ring ... need to reduce ε_N by a factor of ~3.

- Two options:

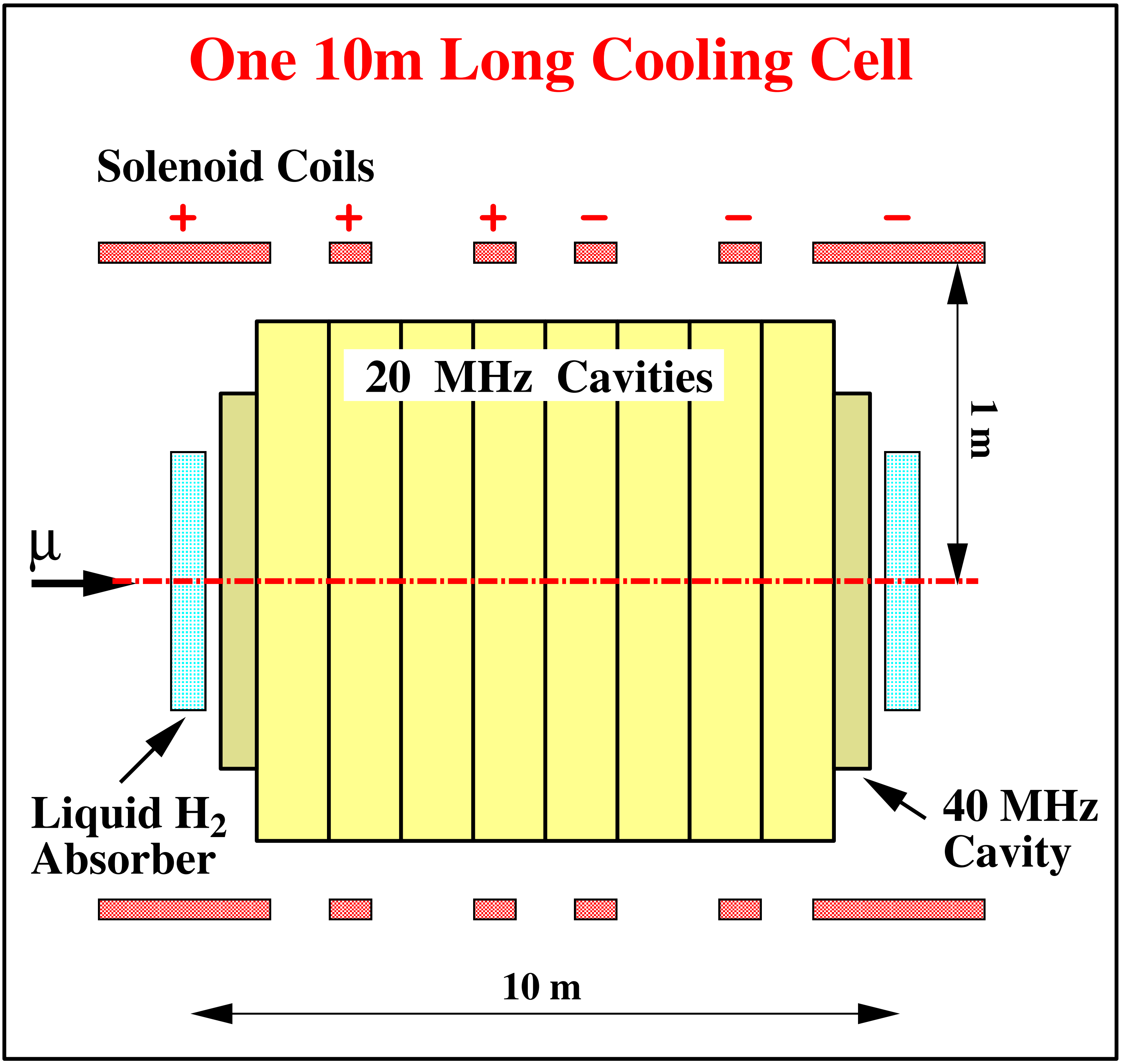
1. Use ionization cooling –> first stage of a muon collider cooling channel.

2. Use ε_N –> ε_L emittance exchange (*R. Palmer*).

In the spirit that a muon storage ring neutrino source provides a step towards a muon collider we choose to use ionization cooling.

Cooling Channel

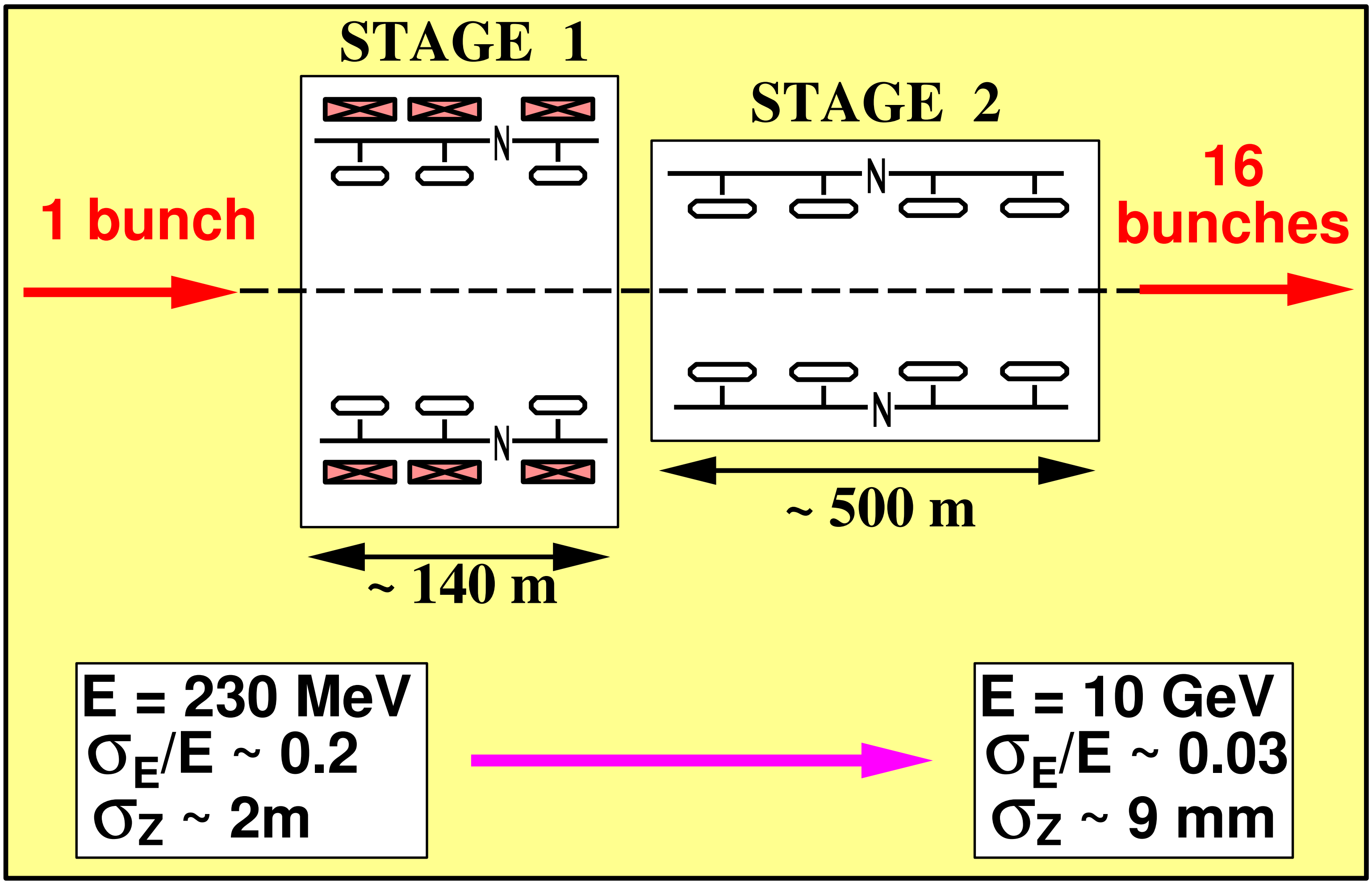
- Current concept: 150 m long cooling channel consisting of 15 Alternating Solenoid cooling cells : $\varepsilon_N = 0.017 \; -> \; 0.005$ m–rad



Acceleration Scheme

(*D. Neuffer*)

- Two–stage capture & acceleration using 805 MHz rf systems :

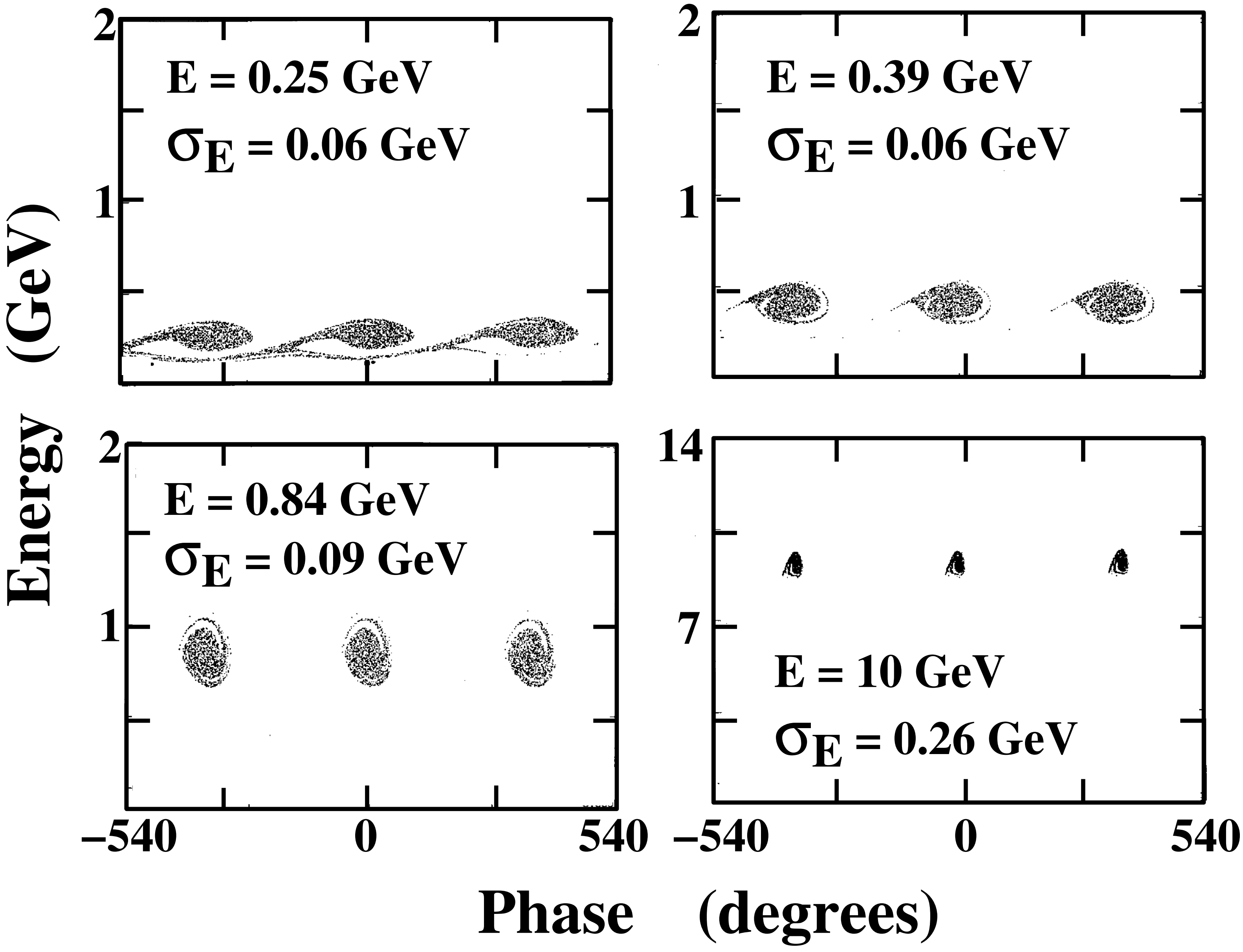


Stage 1: 140 m long 5T solenoid channel. Captures each long bunch into 16 stable bunches & accelerates to 1 GeV with a V_{rf} = 15 MV/m, $\phi_S = 30^o$, capture loss ~ 35%.

Stage 2: 500 m long FODO channel. Accelerates to 10 GeV with V_{rf} = 20 MV/m, $\phi_S = 60^o$. Decay & aperture losses ~ 10%

Simulation of capture & acceleration

(D. Neuffer)



Book–Keeping

Phase 1 Proton Source	
Protons/year	4.5×10^{21}
Decay Channel	
muons/proton	0.2
muons/year	9×10^{20}
Cooling Channel	
Decay + Aperture loss	0.9
muons/year	8×10^{20}
Acceleration System	
Capture efficiency	0.65
Decay + Aperture loss	0.9
10 GeV muons/year	4.7×10^{20}
Storage Ring	
Fraction in Straight Section	0.33
Useful muon decays/year	1.6×10^{20}

- Note: The Phase 2 proton source would increase the number of protons by x 3.3 –> 5.3×10^{20} useful muon decays/year.

Storage Ring Requirements

- **Storage Ring –> two long straight sections joined together with two arcs. One straight section forms the neutrino beam, and the other is used for injection. To maximize the fraction of muon decays that contribute to the neutrino beam make the straight sections long & the arcs compact.**

- **The beam–forming straight section must be a high–β region so that beam divergence small compared to typical decay angle which is, for example, O(10 mr) at 10 GeV.**

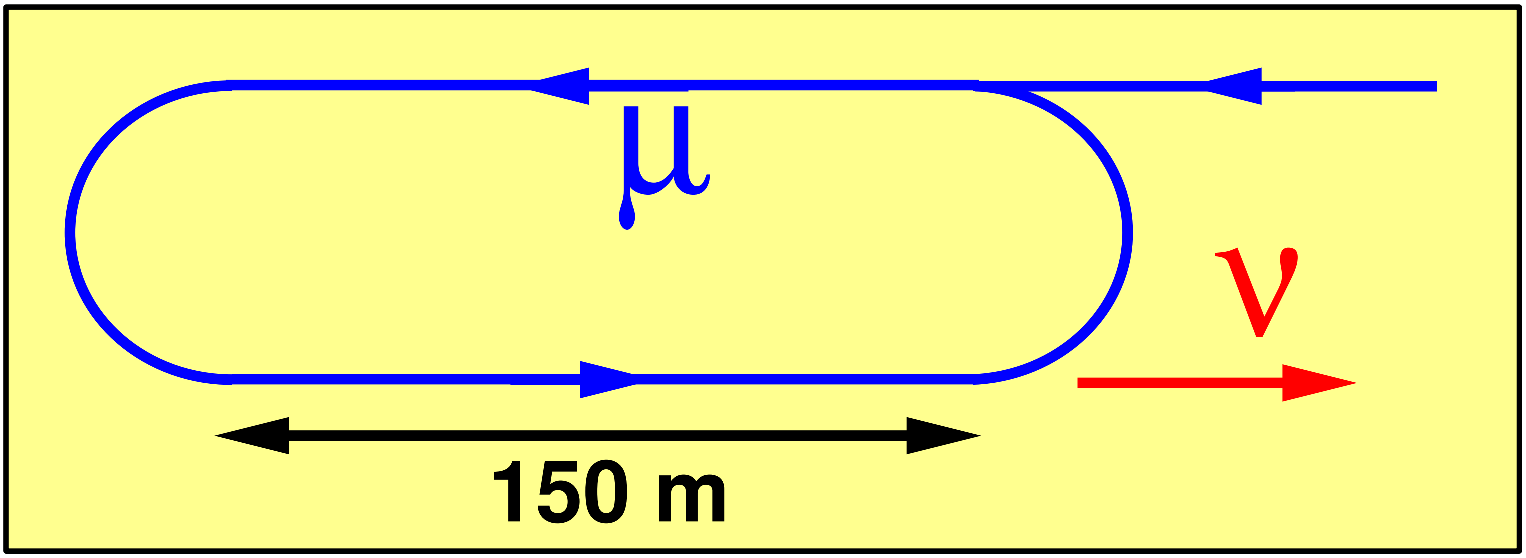
- **The lattice must accommodate a large moment–um spread ($\Delta p/p \sim 0.03$) & transverse beam size ($\varepsilon_N \sim 0.005$ m–rad).**

- **The ring must have large apertures to accom–modate large ε_N and large off–momentum orbit excursions.**

Muon Storage Ring

- 10 GeV muon storage ring:
  circumference = 448 m
  Straight sections = 150 m

  } 33% of the muons decay in beam–forming straight section



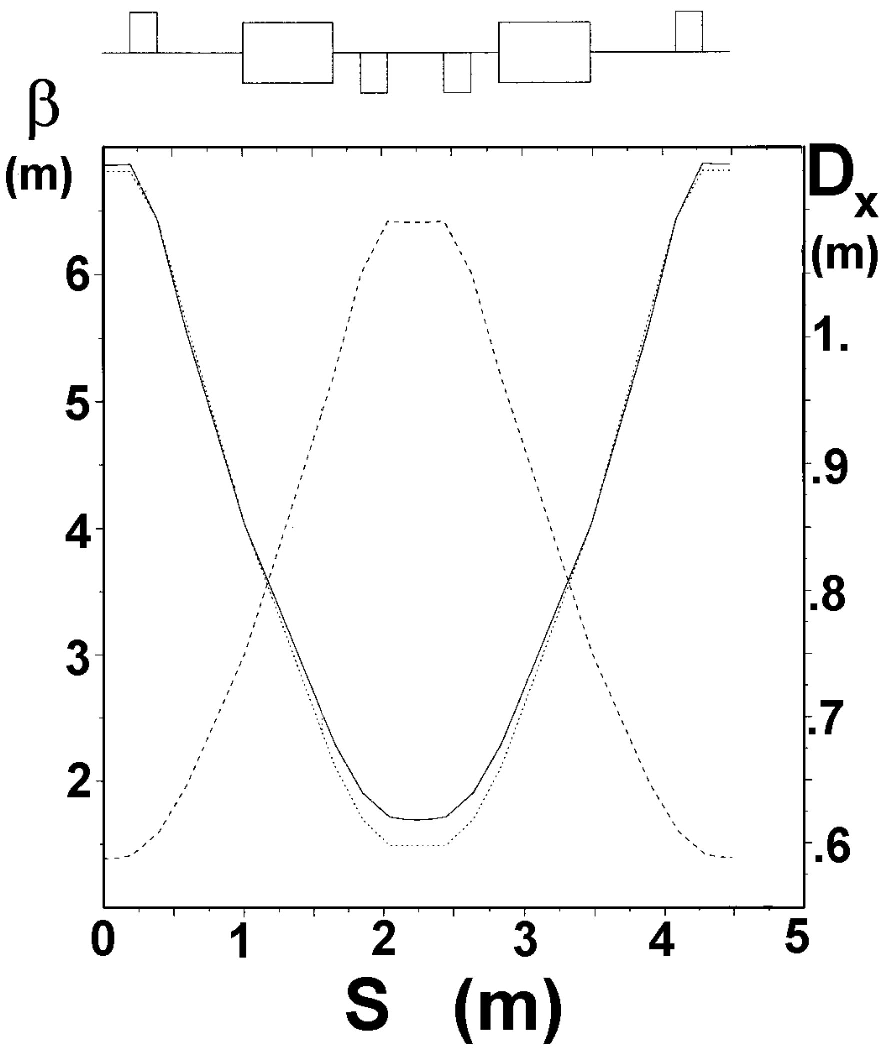
- 4.7 x 10^{20} Muons injected per year (10^7 secs)
- 1/3rd decay in beam–forming straight section

1.6 x 10^{20} ν_e per year 1.6 x 10^{20} $\bar{\nu}_\mu$ per year		μ^+ stored
1.6 x 10^{20} $\bar{\nu}_e$ per year 1.6 x 10^{20} ν_μ per year		μ^- stored

Storage Ring: Arc Design

(*Carol Johnstone*)

Arc –> 6 + 1/2 FODO cells plus two cells at each end with reduced deflections to suppress disper–sion in matching & high–β straight sections.



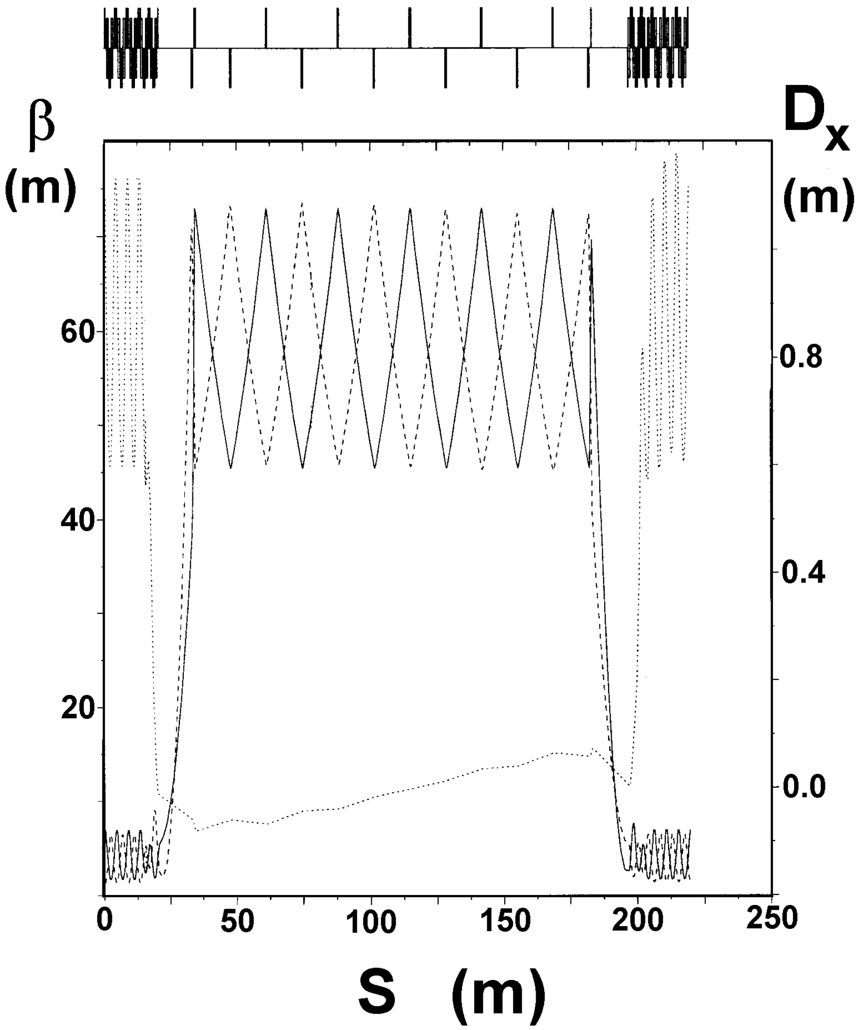
Arc cells keep off–momentum excur–sions under 8 cm.

Quad. strengths are tuned to give nearly $\pi/2$ phase advance per cell –> accomm–odates sextupoles that reduce the momentum dependence of the tune (ν_x = 8.252, ν_y = 8.741).

Dipoles:			
Field	9 T	Length	0.645 m
Bend	0.174 rad	Aperture	6 x 15 cm
Quadrupoles:		**Sextupoles:**	
Length	0.387 m	Horiz.	2.3 T
Bore	15 cm	Vert.	3.5 T

Storage Ring: Straight Section Design

(*Carol Johnstone*)



Beam–forming section –> 5 + 1/2 weak focusing FODO cells –> 150 m long.

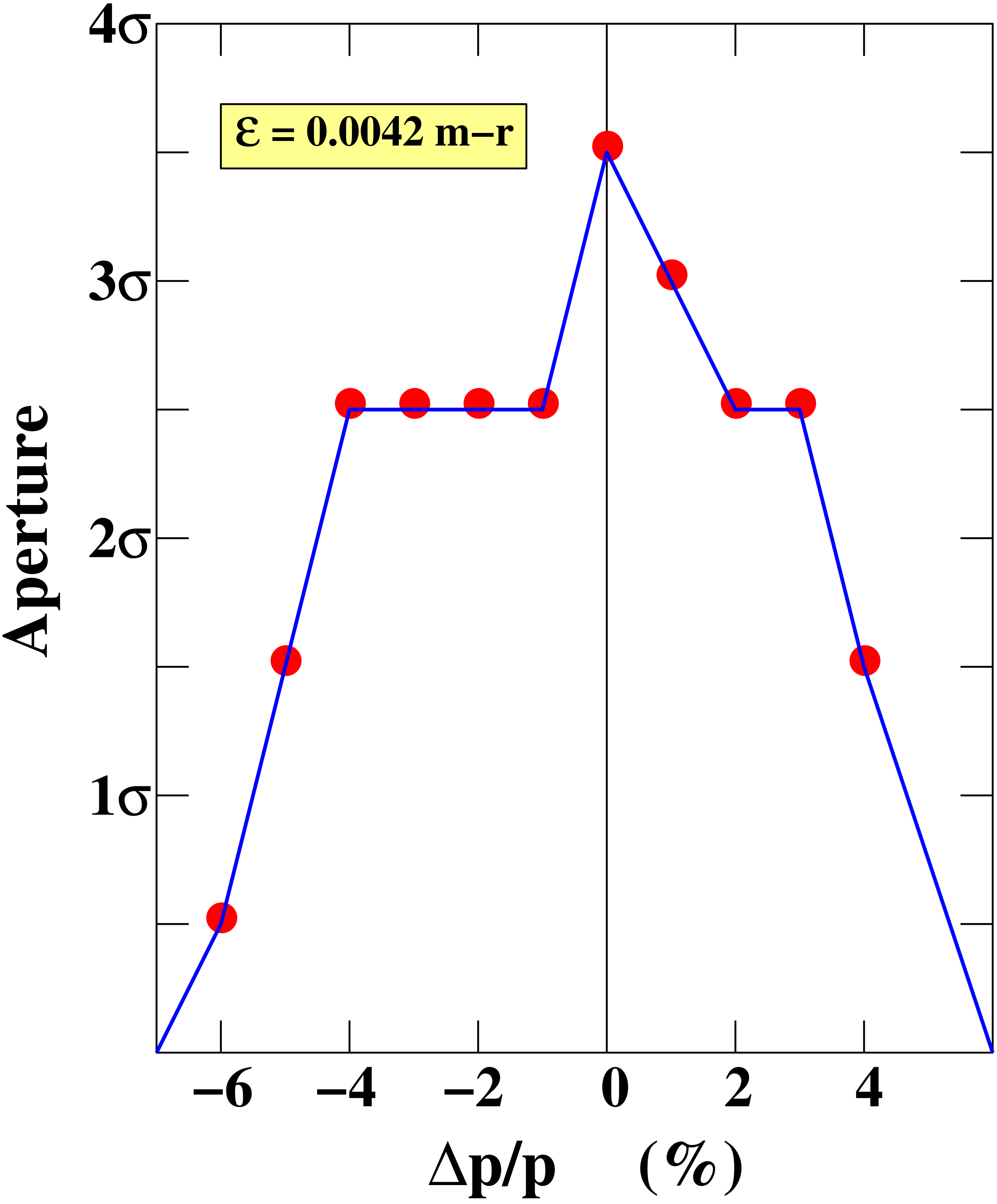
FODO cells are periodic units ... so straight section length flexible.

The weak focusing high–β section is matched to the strong focusing arcs with 20 m long matching sections.

Straight Section Length	147.9 m
Matching Section Length	2 x 20 m
High–β Quadrupole Radius	20 cm
β_x(max)	73 m
β_y(max)	73 m

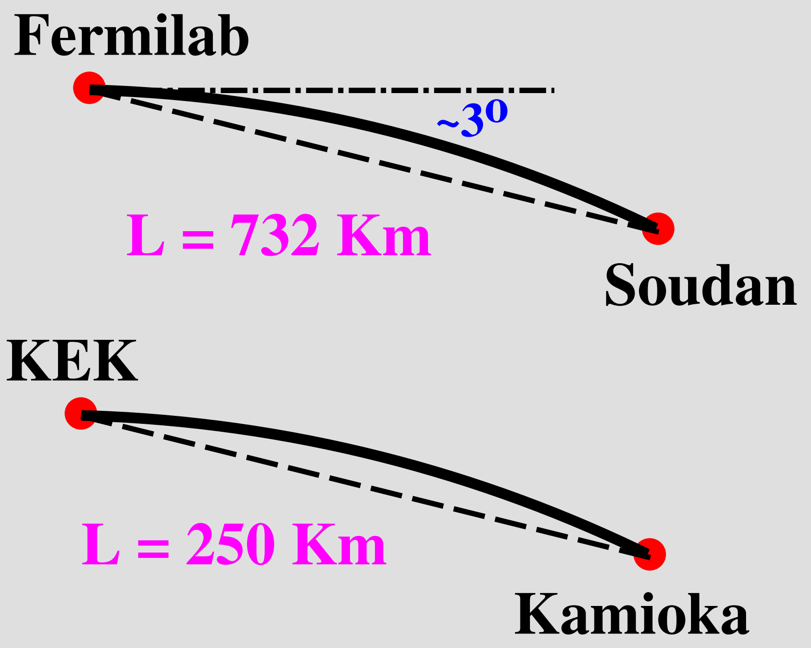
The finite divergence of the muon beam traveling within the straight section has been calculated to decrease the ν flux at a distant site by ~10%.

Storage Ring Momentum Acceptance

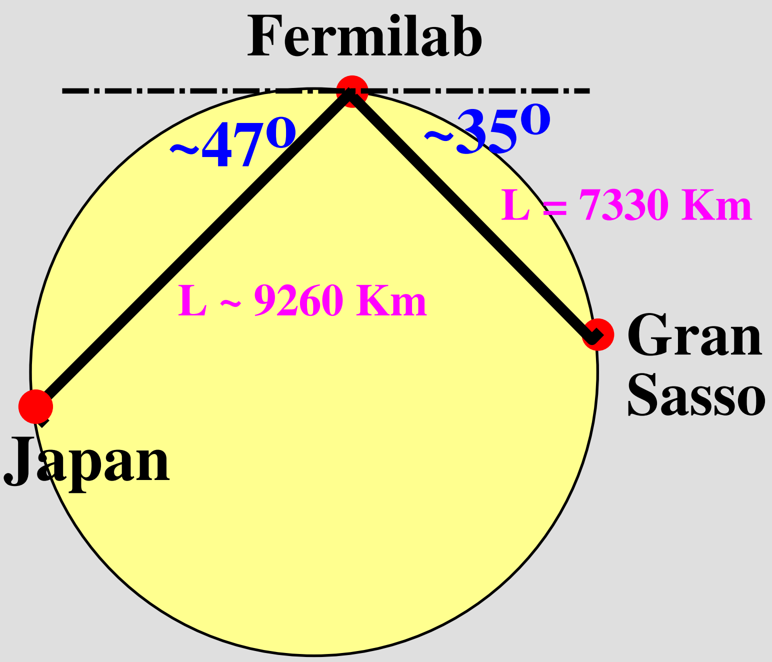


Geography

	L (km)	Dip (Deg.)	Heading (Deg.)
FNAL –> Soudan	732	3	336
FNAL –> Gran Sasso	7332	35	50
FNAL –> Kamioka	9263	47	325



E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	L/E (Km/GeV) KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3



E_ν (GeV)	L/E (Km/GeV) Gran S.	L/E (Km/GeV) Japan
10	~733	~926
20	~367	~463
30	~244	~309
40	~183	~232
50	~145	~185

Neutrino Fluxes & Charged Current Interaction Rates

1.6×10^{20} muons decays per year (10^7 secs)

Annual ν_e, ν_μ Fluxes (10^{10} m^{-2} yr^{-1})

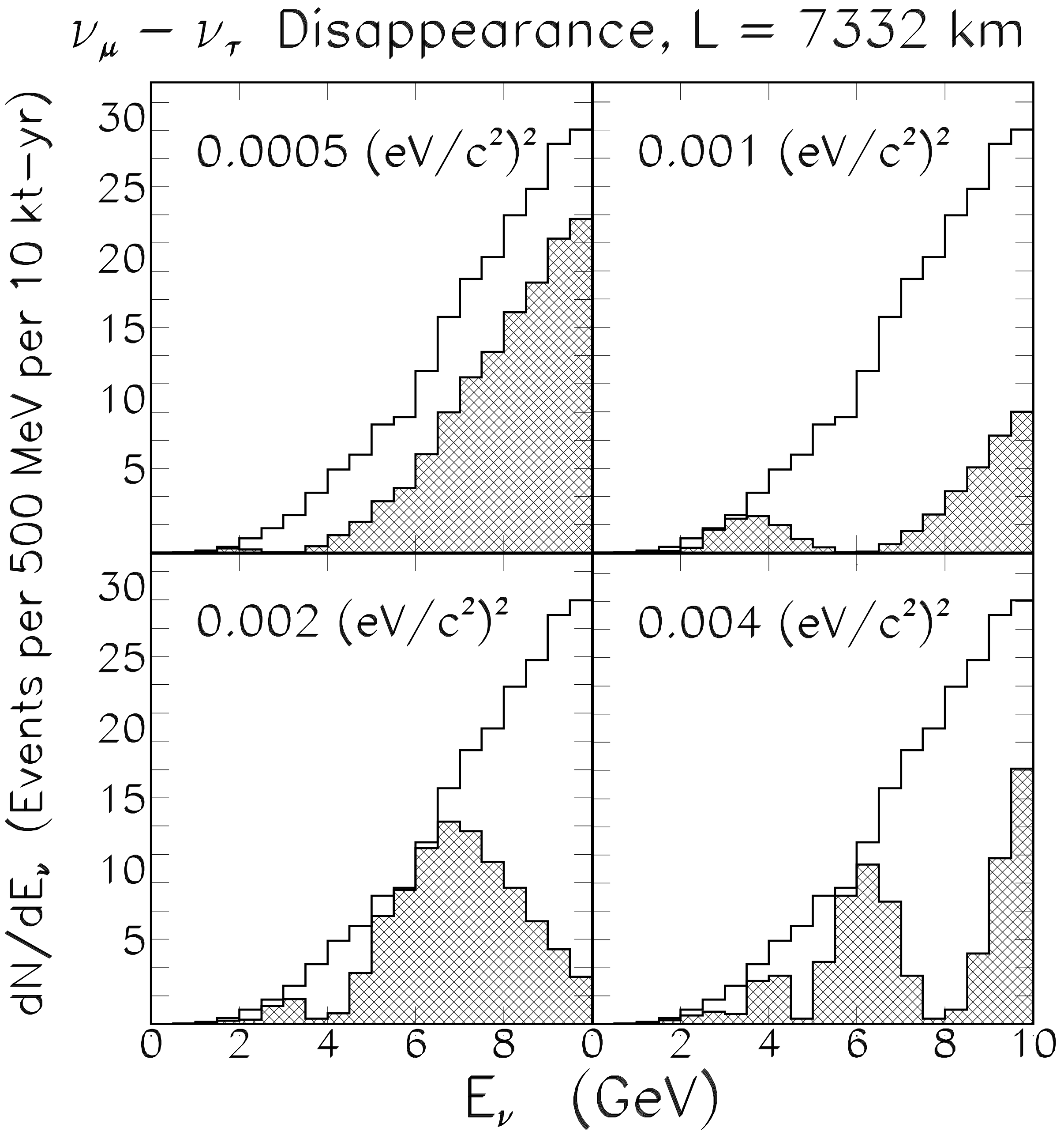
L (km)	E_μ (GeV) 10	15	20	25	30
732	79	190	330	510	740
7332	0.79	1.8	3.3	5.1	7.4

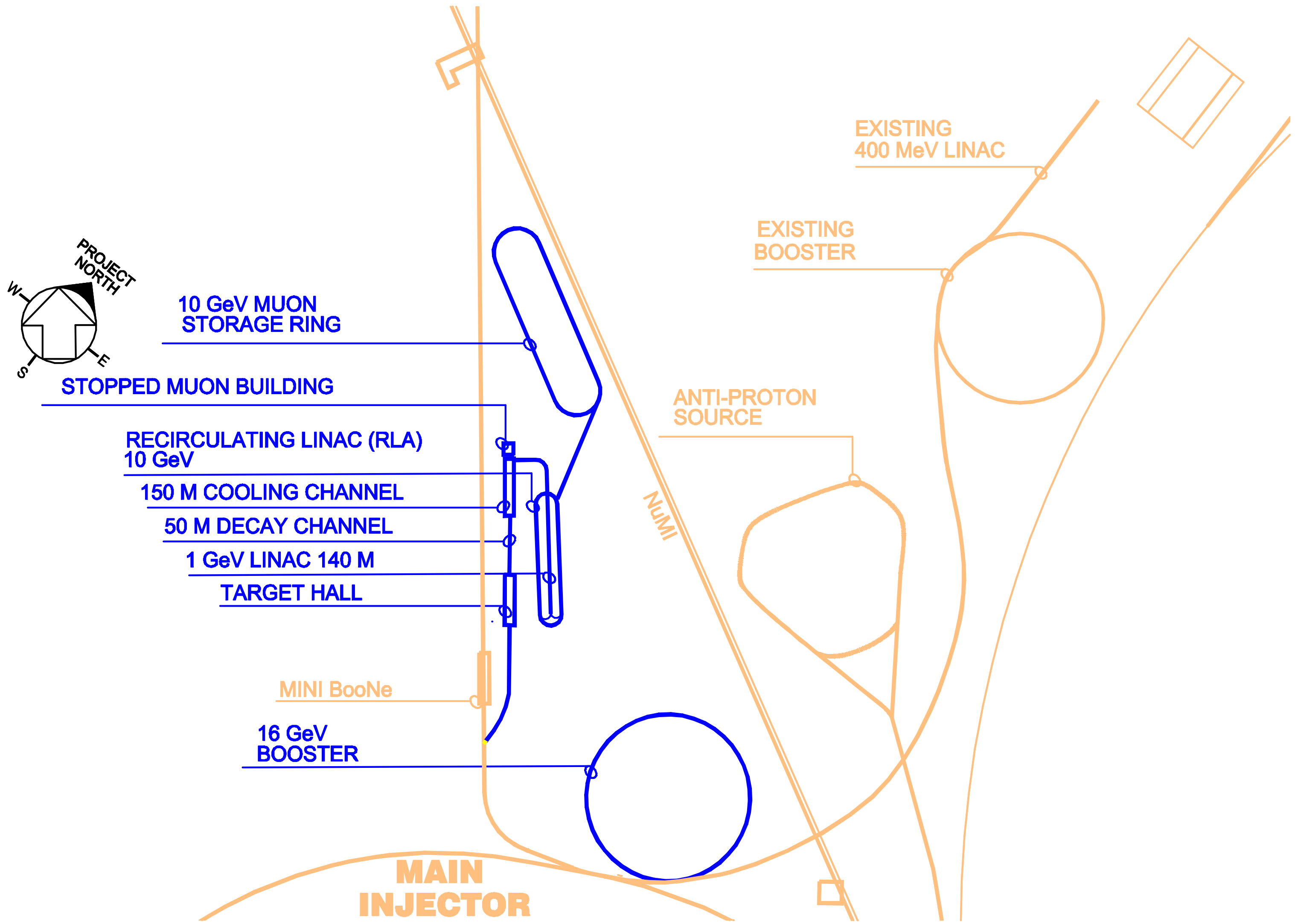
Annual CC Rates (per kt–yr)

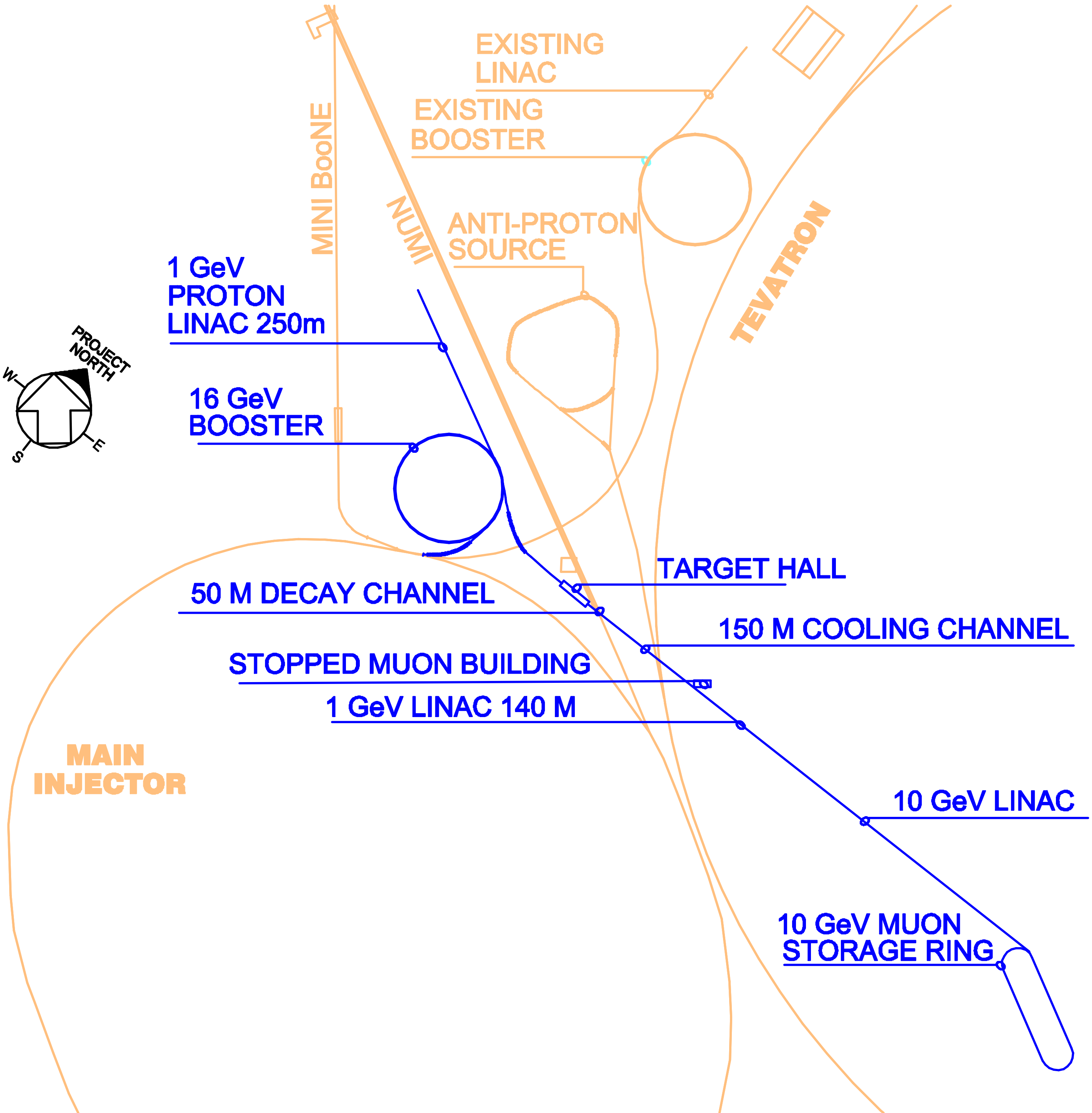
	E_μ (GeV) 10	15	20	25	30
L = 732 km					
ν_μ	2220	7830	18500	36400	62200
$\bar{\nu}_e$	958	3380	7890	15700	26800
ν_e	1940	6670	15600	30900	53100
$\bar{\nu}_\mu$	1210	3980	9530	18700	32500
L = 7332 km					
ν_μ	22.1	77.6	187	360	620
$\bar{\nu}_e$	9.5	33.7	80.2	155	266
ν_e	20.2	66.3	158	309	530
$\bar{\nu}_\mu$	12.1	39.5	94.3	187	325

Example: ν_μ dissappearance between FNAL and Gran Sasso, with 10 GeV muons

Δm^2 (eV^2/c^4)	ν_μ CC Event Rate (per 10 kt–yr)
0.0005	139
0.001	44.5
0.002	103
0.004	82.7




PROJECT NORTH
W
E
S
10 GeV MUON STORAGE RING
STOPPED MUON BUILDING
RECIRCULATING LINAC (RLA) 10 GeV
150 M COOLING CHANNEL
50 M DECAY CHANNEL
1 GeV LINAC 140 M
TARGET HALL
MINI BooNe
16 GeV BOOSTER
EXISTING 400 MeV LINAC
EXISTING BOOSTER
ANTI-PROTON SOURCE
NuMI
MAIN INJECTOR



EXISTING
LINAC
EXISTING
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MINI BooNE
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SOURCE
TEVATRON
1 GeV
PROTON
LINAC 250m
PROJECT
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16 GeV
BOOSTER
TARGET HALL
50 M DECAY CHANNEL
150 M COOLING CHANNEL
STOPPED MUON BUILDING
1 GeV LINAC 140 M
MAIN
INJECTOR
10 GeV LINAC
10 GeV MUON
STORAGE RING

Further Work

- Establish realistic rf parameters for decay & cooling channels –> update design.

- More complete simulations of the pion capture, and decay channel, and the cooling channel, with optimization of the optics, & a study of how the muon population in 6–d phase–space at the end of the cooling channel.

- Explore the possibility of using an RLA for the 2nd acceleration stage, and make a more detailed simulation of the muon acceleration.

- Establish realistic large–bore super–conducting magnet parameters for the storage ring –> update the storage–ring lattice design.

- Explore the trade–offs between getting more muons by investing more in the proton source compared with more in the decay channel, or cooling channel, etc.

Summary

- The physics potential of muon storage ring neutrino sources built as a step towards the first muon collider is sufficiently promising to justify the next level of design studies.

- BUT there is a lot of basic stuff to do.
If we are to have something more solid
by Lyon we will need an expanded effort :

  - More detailed cooling study.
  - Stage 2 acceleration –> RLA ?
  - Preliminary Storage Ring Magnet Study –> realistic parameters.
  - RF reality check.

PLEASE HELP !