A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring

NUFACT00 May 23, 2000

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(Norbert Holtkamp)

- Introduction
- Charge
- Basic Parameters
- Technical Feasibility
- Cost Drivers
- Site Dependence

Accelerator Study:

http://www.fnal.gov/projects/muon_collider/nu-factory/

Physics Study:

http://www.fnal.gov/projects/muon_collider/nu/study/study.html

Seven Challenges

Making Protons

Making Muons

Making Small ΔE/E

Cooling the Muon Beam

Accelerating Muons

How to Handle the Neutrino Radiation

Providing a Useful Physics Tool

The Two Charges

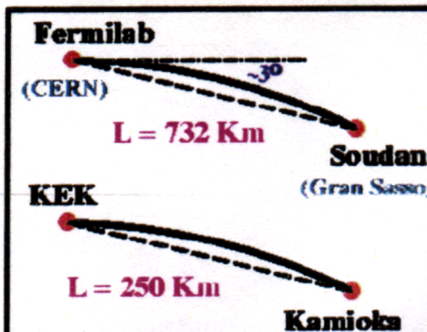
- **Accelerator Study (N. Holtkamp/D. Finley)**
  - **design concept for a muon storage ring - associated support facilities - compelling neutrino based research program (see next charge)**
  - **cost drivers**
  - **R&D program**
  - **specific environmental, safety, and health issues**

- **Physics Study (H. Schellman/S. Geer)**
  - **Physics motivation for a neutrino source based on a muon storage ring - beyond the current set of neutrino oscillation experiments.**
  - **A physics program that could be accomplished at a neutrino factory as a function of:**
    - stored muon energy, with the maximum energy taken to be 50 GeV.
    - number of muon decays per year in the beam-forming straight section, taken to be in the range from 10^{19} to 10^{21} decays per year.
    - presence or absence of muon polarization within the storage ring.
    - oscillation experiments
  - **Investigations evaluating matter effects**

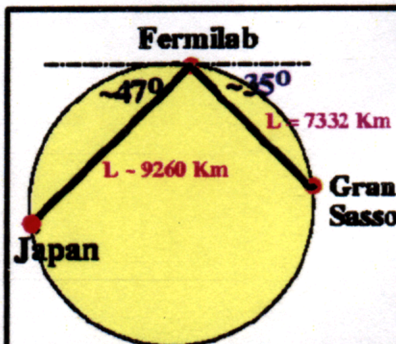
The Energy Choice, the Experiment and the Options

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

- Choice of baseline beam line angle are connected

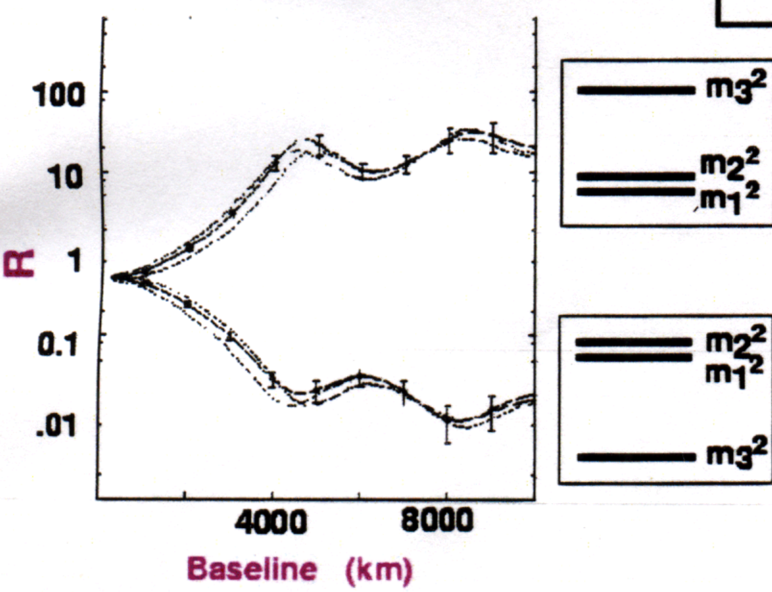


E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3
50	14.6	5.0



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

Barger, Geer, Raja, Whisnant ... Fermilab–PUB 00/049–T



- What is the right baseline length ??

- Large splitting: matter effects -> sign of δm^2
- Small splitting: CP violation
- Error bars: Statistics for 10^{20} muon decays

The Choices We Made

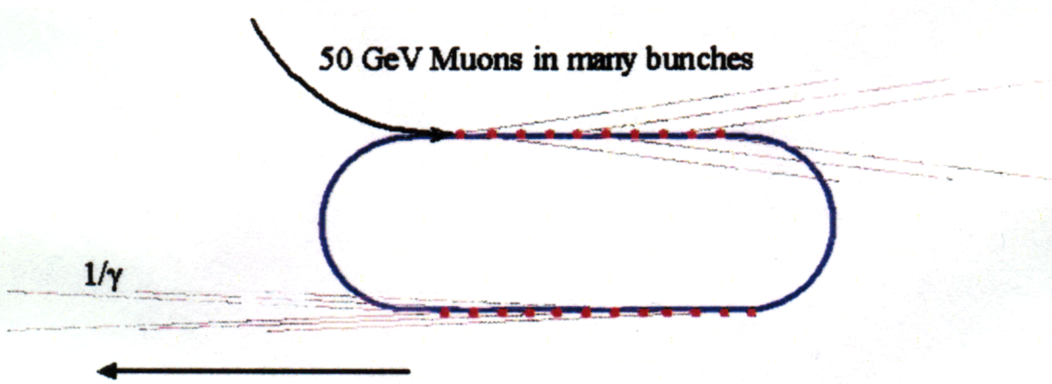
Parameters for the Neutrino Source		
- Energy of the ring	50	GeV
- Number of neutrinos / straight	$2x10^{20}$/y	
- ignore polarization		
- capability to switch between $\mu^+ \mu^-$		
- FERMI to SLAC / LBNL → West Coast (L ~ 3000 km)		

- Basic Calculation
  - 1/3 of the muons decay in the straight section (39%)
  - 10 protons for 1 μ into the storage ring (>10; >20-50)
  - $2x10^7$ sec in a year
    - $2x10^{13}$ proton on target per pulse @ 16 GeV and 15 Hz
      - $3x10^{13}$ proton because of carbon target → 1.5 MW
    - $2x10^{12}$ μ per pulse to be accelerated and injected into the ring
      - places demand on cooling channel
    - Longer bunch in the proton driver and on target (1 nsec → 3)
      - helps, but still need a few bunches ⇒ induction linac !!
    - Ring tilt angle is 13deg (22 %) instead of 35 deg (57 %)
      - ring with these parameters is not a cost driver
      - tilt angle is manageable

The Neutrino Source

- First experiment based on an intense muon source -> Does it have to be 50 GeV??
  - Example: 10 GeV & 50 kT or more magnetized water detector
  - Balance detector cost with Accelerator: $E*M_{Detector}*I$=const.
  - Start with $2x10^{19}$/year (Sessler, Geer)?

Muon Storage Ring as a Neutrino Source



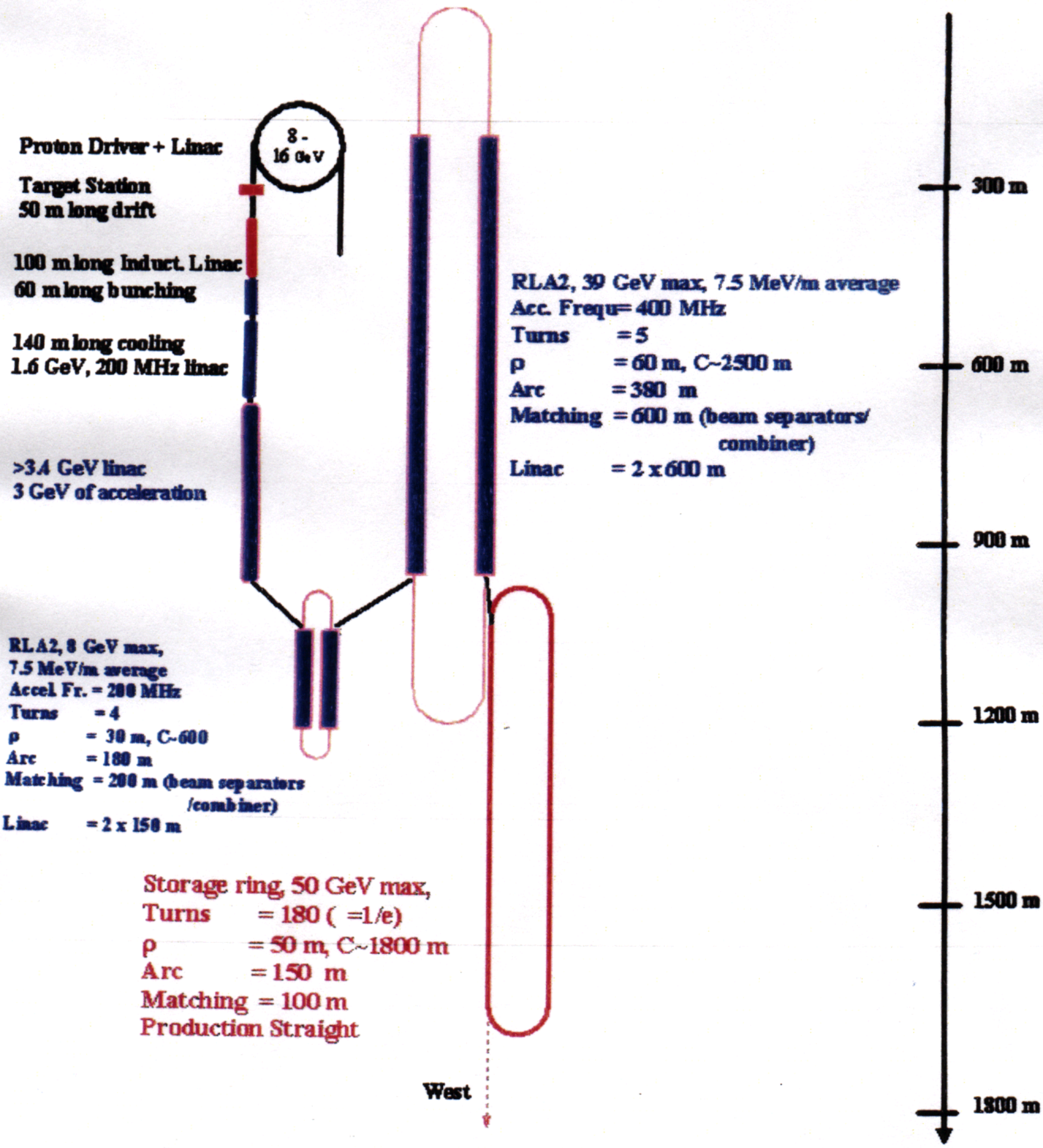
Medium baseline experiment eg Fermi -> SLAC/LBNL 2900 km

Parameters for the Muon Storage Ring		
Energy	GeV	50
decay ratio	%	>40
Designed for inv. Emittance	m*rad	**0.0032**
Cooling designed for inv. Emitt.	m*rad	**0.0016**
β_{MAX} in straight	m	400
N_μ/pulse	10^{12}	~~6~~ → 2
typical μ decay angle = $1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon/\beta_o}) = (\sqrt{\varepsilon\,\gamma_{Twiss}})$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	$3x10^5$

$\gamma_{Twiss} = (1-\alpha^2)/\beta$

Footprint for a 50 GeV Neutrino Source

- Infrastructure is very close together …⇒ It fits under a small site
  - bends between different sub-system is minimized
  - beam loading is kept equal on both sides of the RLAs
- ⇒ Direction of proton beam on target defines layout

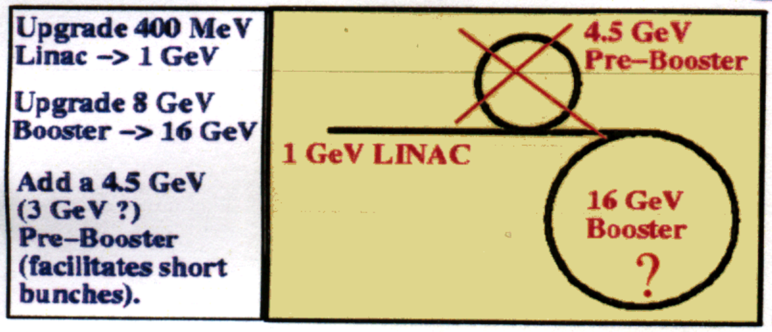


The Neutrino Source

- Approach:
  - **<u>go more conventional where ever possible</u>**
  - <u>Oak Ridge, FHML</u>, Brookhaven ⇒ the target
    - most people bought the solid target
  - <u>Jefferson Lab</u> / <u>Cornell</u> ⇒ sc rf and re-circulating linacs
    - progress continues
  - <u>LBNL</u> , DUBNA ⇒ induction linacs
    - went much better than expected but it's not cheap
  - <u>IHEP Protvino</u> ⇒ sc solenoid channels (+Fermilab)
    - so far very good job, but expensive magnet channels even if built in Russia
  - <u>SLAC</u>/Industry ⇒ power sources
  - specific design and engineering (cooling channel, target collection, beam manipulation, beam tracking and simulation) → Muon Collider group (12 people @FNAL) + the collaboration
    - (Thanks to Andy Sessler for the enormous support)
  - general engineering (large scale rf systems, sc magnets, sc solenoid channels, ps, vacuum, beam lines, tunnel, water) (20 FTEs for 6 months)

R & D Issues for the Proton Driver Design Study

- **R & D groups (Internal Review 4/17-18):**
  - **RF, beam loading, feedback, Collective effects, magnet, power supplies, vacuum, lattice, H^- source and linac / linac upgrade, Collaboration with KEK/Japan and LANL)**

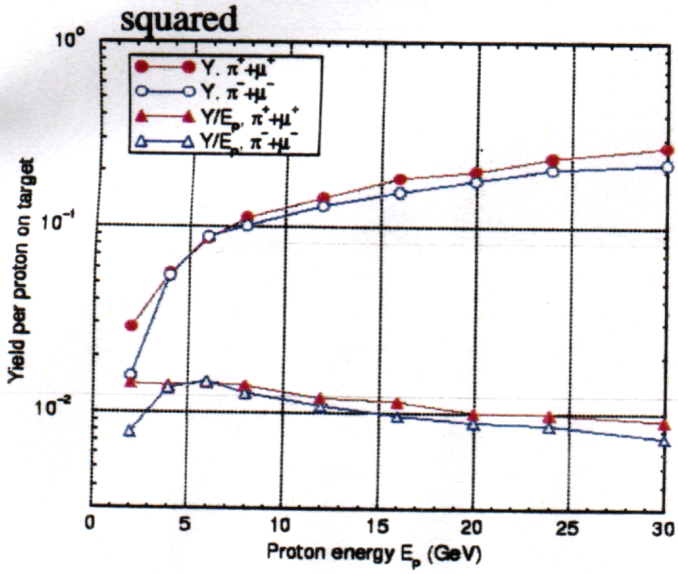


Goal:

- **$4 \times 0.75 \times 10^{-13} = 3 \times 10^{13}$ @ 15 Hz**
- **8 GeV versus 16 GeV versus higher energies?**
- **Achieve 1.5 MW**
- **Number of bunches 4 or more? Induction Linac?**

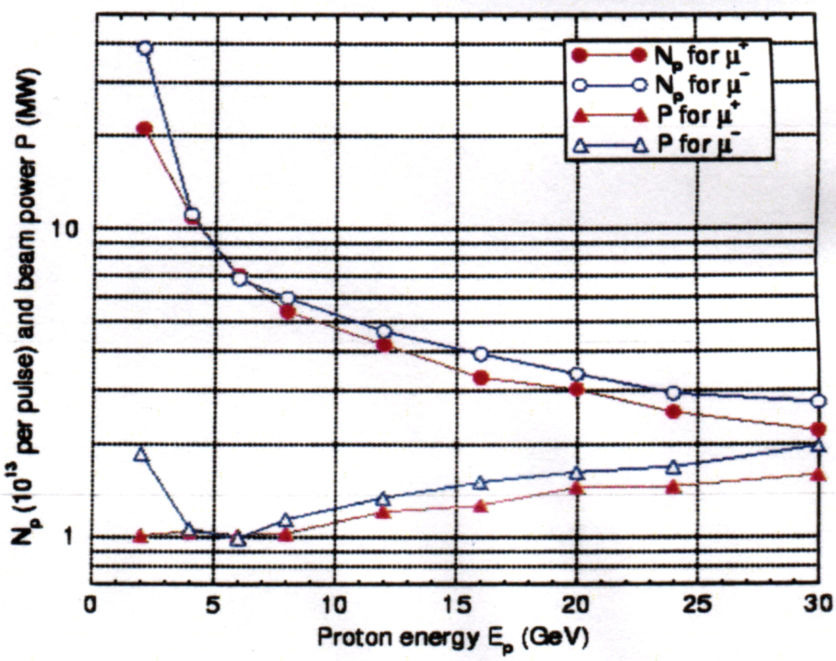
Pion production on Carbon

- Neutrino Source: Physics ∝ number of muons produced.
- MC: Physics ∝ number of muons squared



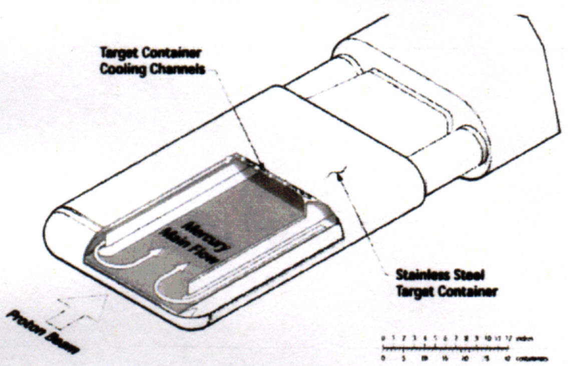
Beam power required?

- Minimum at 5-6 GeV for Carbon target



A Target for the Neutrino Factory

- Comparable Targets:
  - RAL & ISIS
  - CERN/ FNAL: pbar
  - SNS Oak Ridge
  - NuMI
  - for Muon sources



- Power deposition (C, Al, Cu, W, Pb)

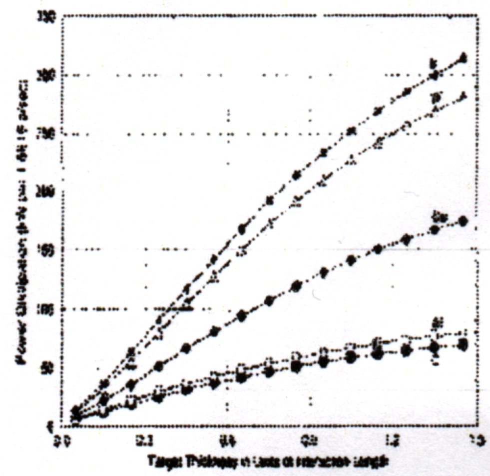
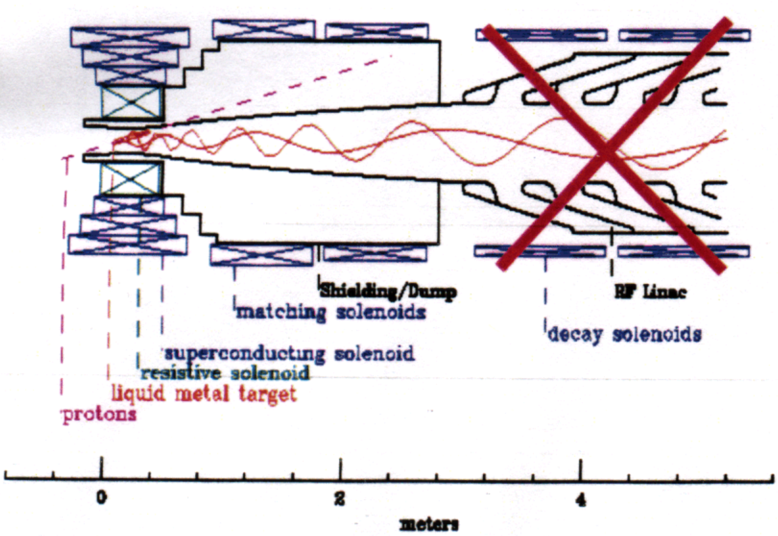


Figure 4.12: Average power dissipation in different 1 cm radius targets due to 8 GeV incident beam of 6×10^{13} protons at 30 Hz. Beam rms spot size $\sigma_x = \sigma_y = 4$ mm.

•MC Target Experiment



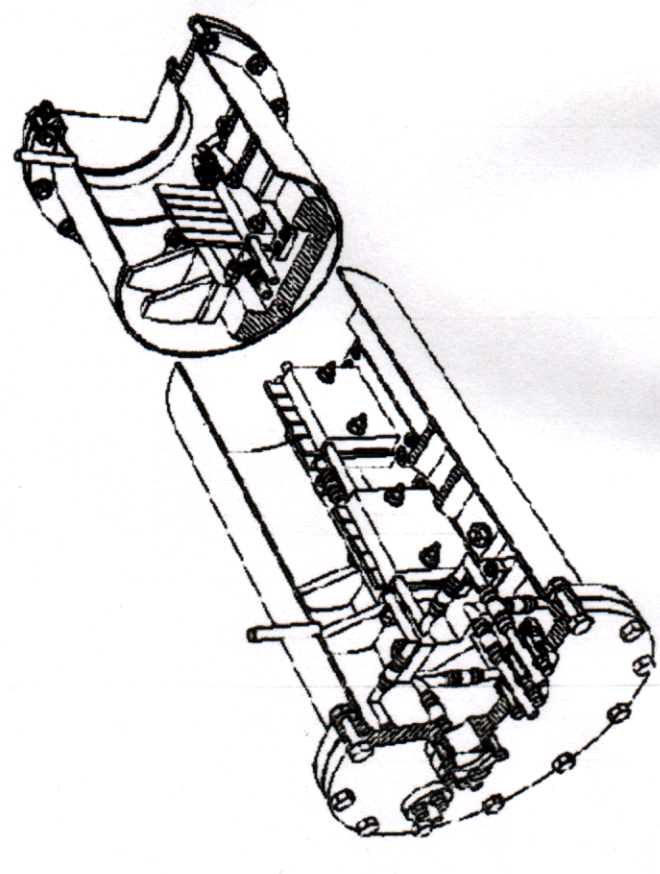
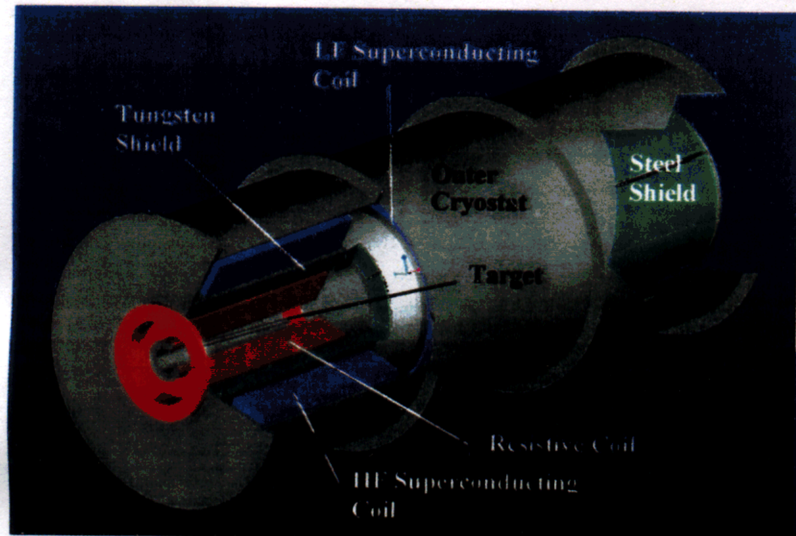
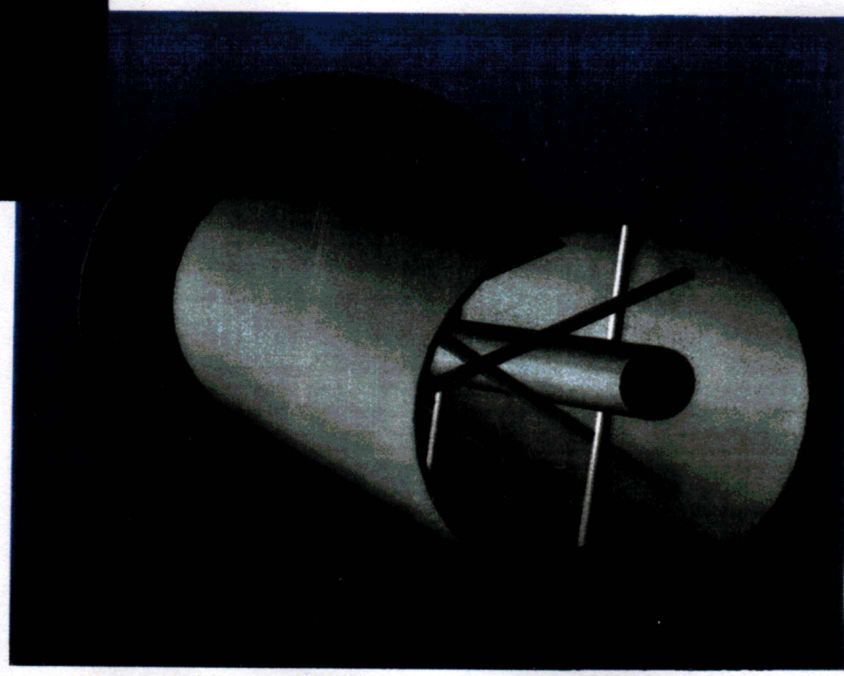
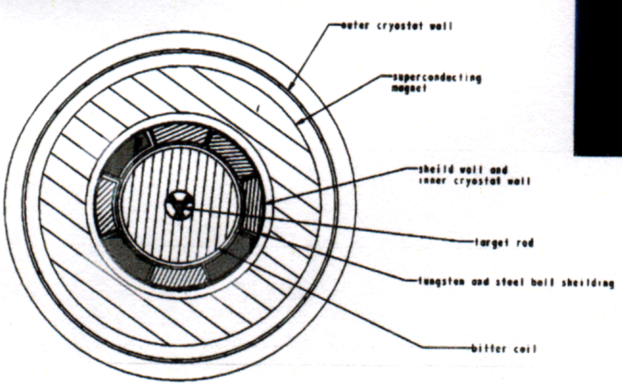


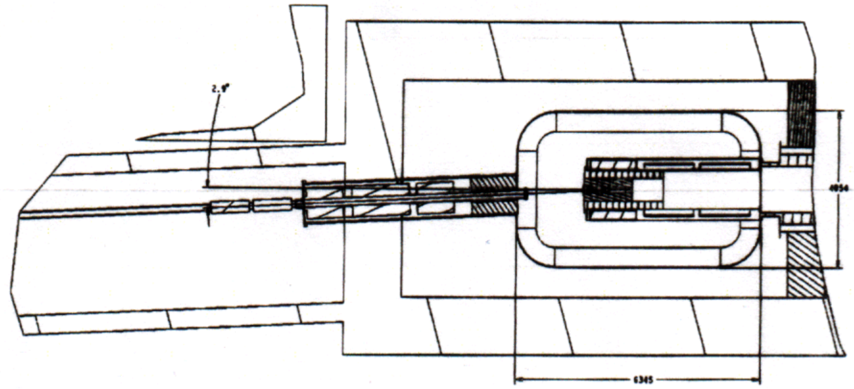
Figure 1.16: Perspective view of the target design.

Make the Target as simple as possible

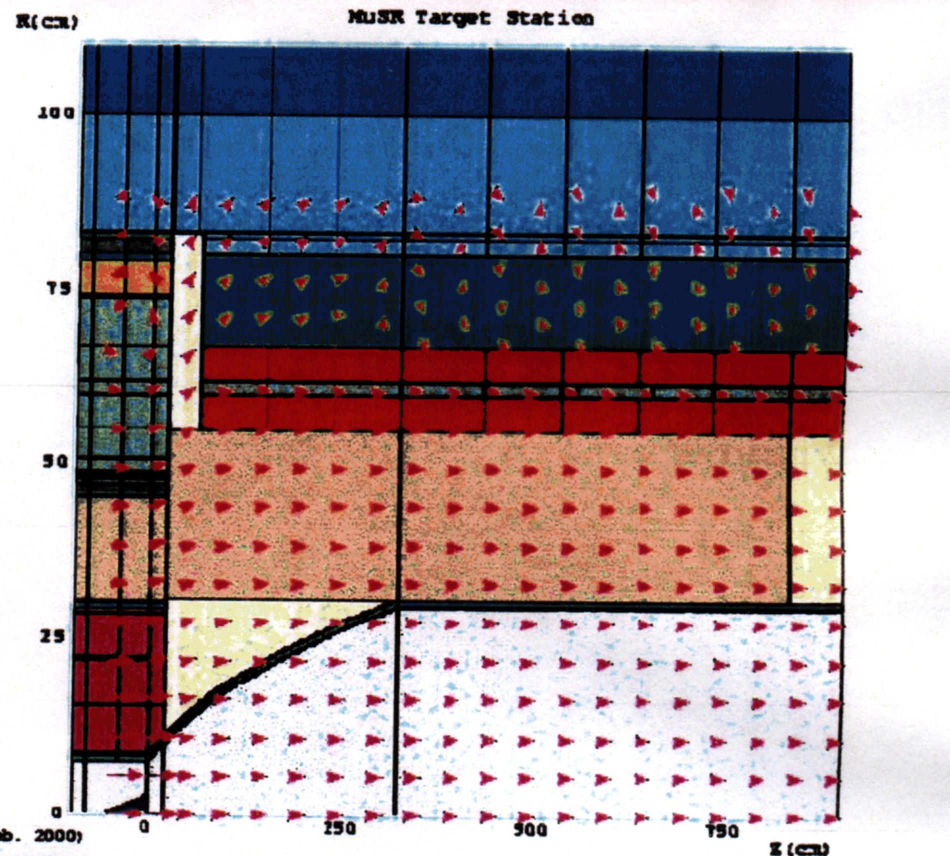








Target Station Energy Deposition (Mokhov)



Iron shielding

Air

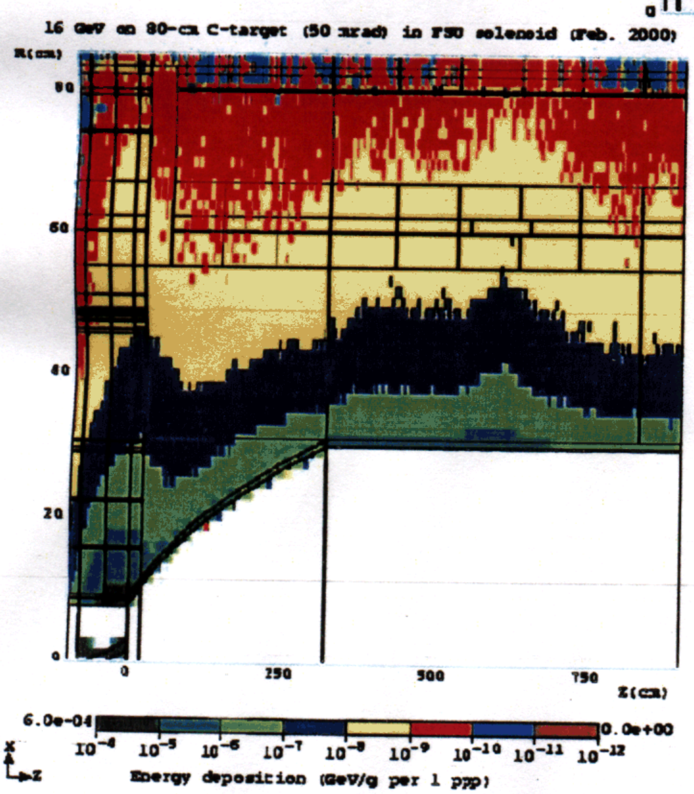
Cryostat

sc coil

tungsten-carbide
+water

nc coil (=10 MW)

rod tilted, 50 mrad



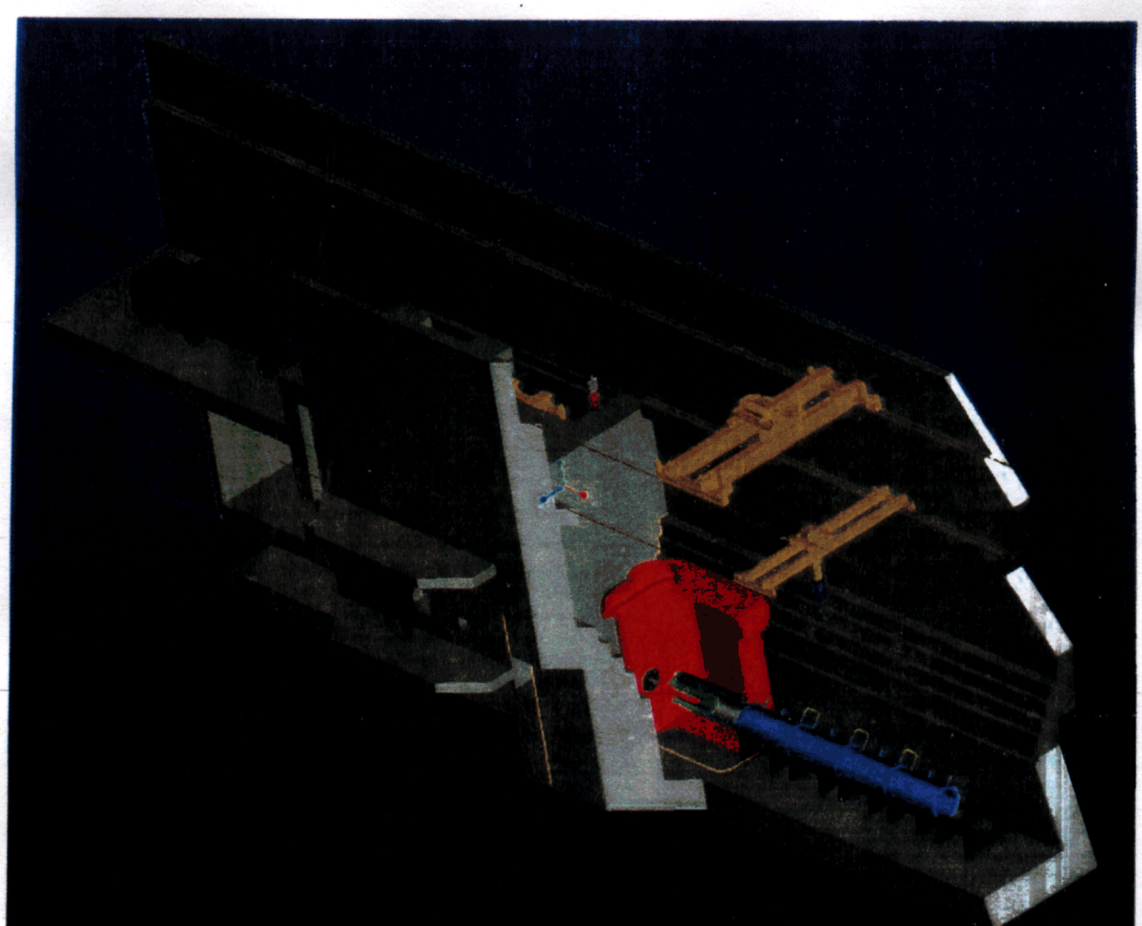
- Flux: few x 10^{10} Gy (0.01 Gy=1 rad)
- very hot area

Target for a Neutrino Factory

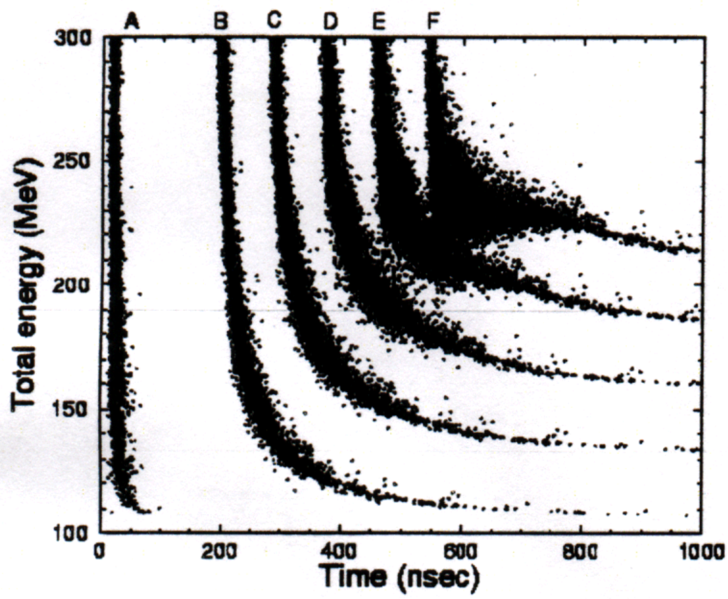
- 1.5 - 4 MW target station and infrastructure for it
- Reduce power in the target → low Z → compromise yield
- Designed a 1.5 MW target (80 cm long, 2 cm radius carbon rod)
- Lifetime: limited by cavitation in nc Coil: 10 MW dissipated power

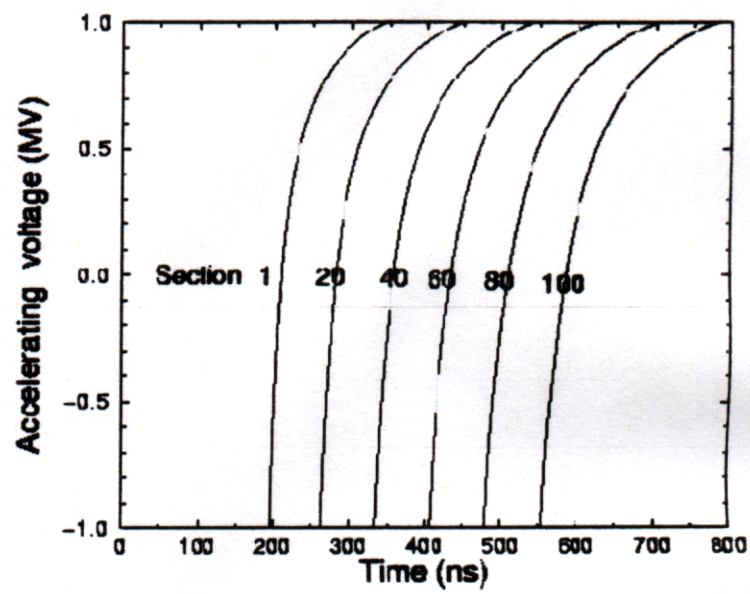
- Very intense radiation in target area
- Beam dump is integrated in magnet shielding
- Target lifetime due to radiation ~ 3 months

- Target hall designed by ORNL
- 1.5 - 4MW Target infrastructure
- Radiation cooled strained fiber carbon target (2400 C°)



Decay Channel, Induction Linacs, and Rebunching





50 m drift before ϕ rotation

For carbon target:

0.10 μ/p between 225 - 240 MeV

0.13 μ/p between 220 - 250 MeV

0.18 μ/p between 200 - 270 MeV

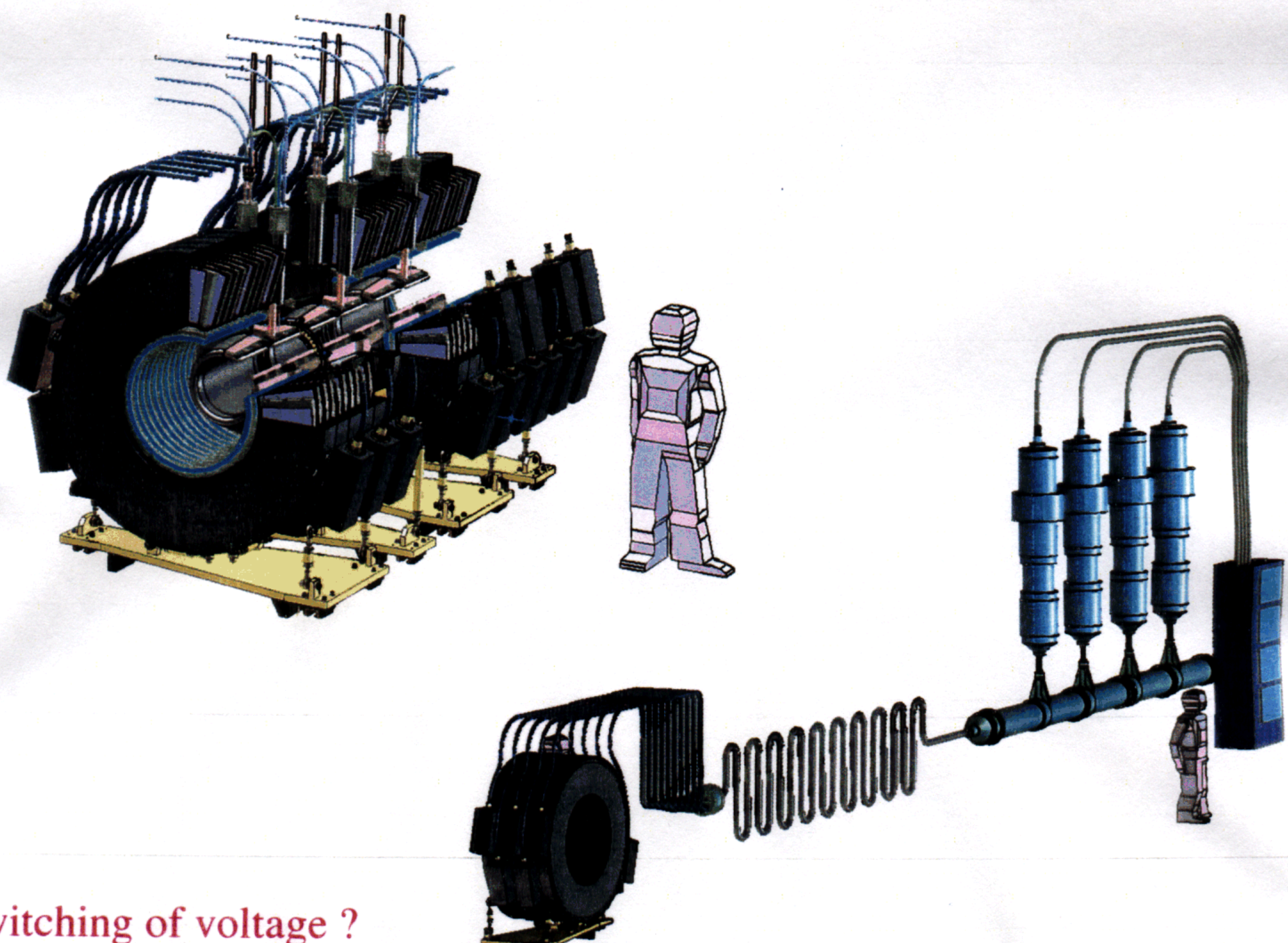
Trade off:

Energy Spread after rotation⇔ drift channel length [loss]

Particle capture⇔length(voltage) in induction linac [loss]

Induction Linac Layout

- Strong Effort at LBL for DAHRT + Fermilab: 4 pulses per cycle in 2 μsec (Proton booster circumference.)
- Higher field 2-3 T and smaller cores may be better solution
  - saturation in the cores is under control
  - switching is the main problem
  - sc coil inside of an induction linac



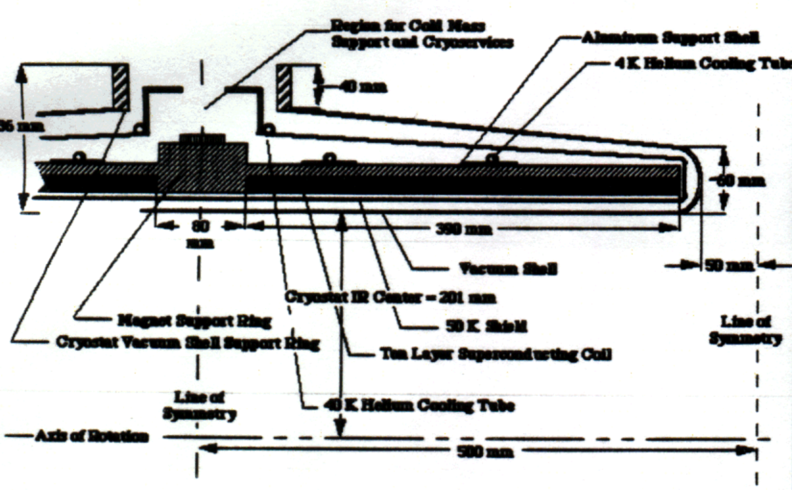
Switching of voltage ?

Induction Linac Construction

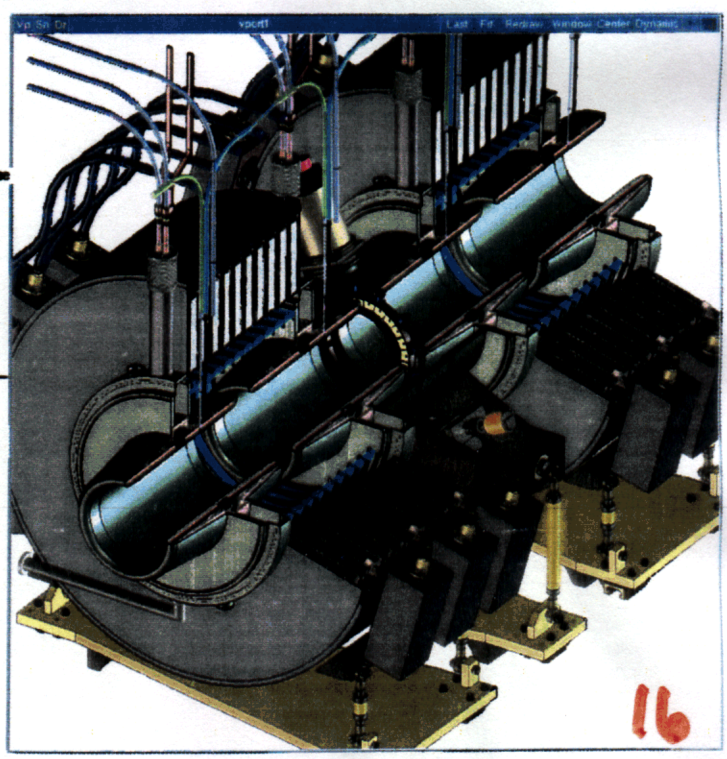
- Induction cell with 1.5-3.0 Tesla coil inside
  - high gradient -- 4 pulses -- sc solenoid inside
  - Power consumption: 4 pulses 15 Hz→8 MW

ΔV	V_{eff}	τ_r	τ_{flat}	τ_{eff}	$v\tau$	Type	δ	PF_r	ΔB_{max}	Cost	
kV	kV	μs	μs	μs	mV-s		gm/cc		T	Norm	
200	142	0.070	0.030	0.07	12.6	Finemet	7.32	0.70	1.95	1.00	<-- Finemet
200	142	0.070	0.030	0.07	12.6	2605SC	7.32	0.70	2.90	0.36	<-- 2605SC
200	142	0.070	0.030	0.07	12.6	2605SC	7.32	0.70	1.10	2.00	<-- 2714A

ΔB	A_{Met}	A_{Core}	$\Delta B/\Delta t$	L		Δr	r_i	r_o	r_o/r_i	r_{Mean}	H	I_{Core}	E_{core}	k	U_{Met}	V_{Met}	W_{Met}	System $
T	cm²	cm²	T/μs	•	cm	cm	cm	cm	cm	cm	kA/m	kA	J	J-μs/T-m³	J/m³	cm³	kgm	Norm
0.97	130	185	13.2	2.28	5.8	32.0	45	77	1.71	61.0	0.65	2.50	31.5	107	634	49670	363.6	1.00
0.82	154	220	11.1	2.28	5.8	37.9	45	83	1.84	64.0	0.55	2.23	28.1	107	454	61744	452.0	1.02
1.48	85	122	20.1	2.28	5.8	21.0	45	66	1.47	55.5	0.98	3.41	42.9	107	1445	29688	217.3	1.07
0.82	154	220	11.1	2.28	5.8	38.0	45	83	1.84	64.0	0.98	3.94	49.6	282	801	61946	453.4	1.13
2.20	57	82	29.8	2.28	5.8	14.1	45	59	1.31	52.1	2.53	8.28	104.4	282	5571	18736	137.1	2.07
0.82	154	220	11.1	2.28	5.8	38.0	45	83	1.84	64.0	0.37	1.50	18.9	41	306	61946	453.4	1.35
0.86	147	209	11.7	2.28	5.8	36.1	46	82	1.79	64.1	0.39	1.59	20.0	41	339	58981	431.7	1.33

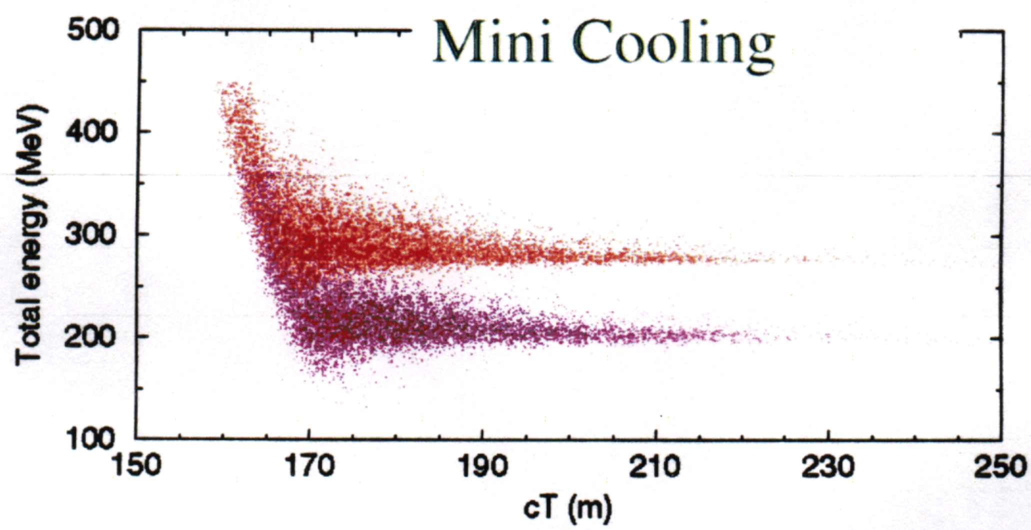


Quarter Section of a 3.0 T Solenoid for the Phase Rotation System

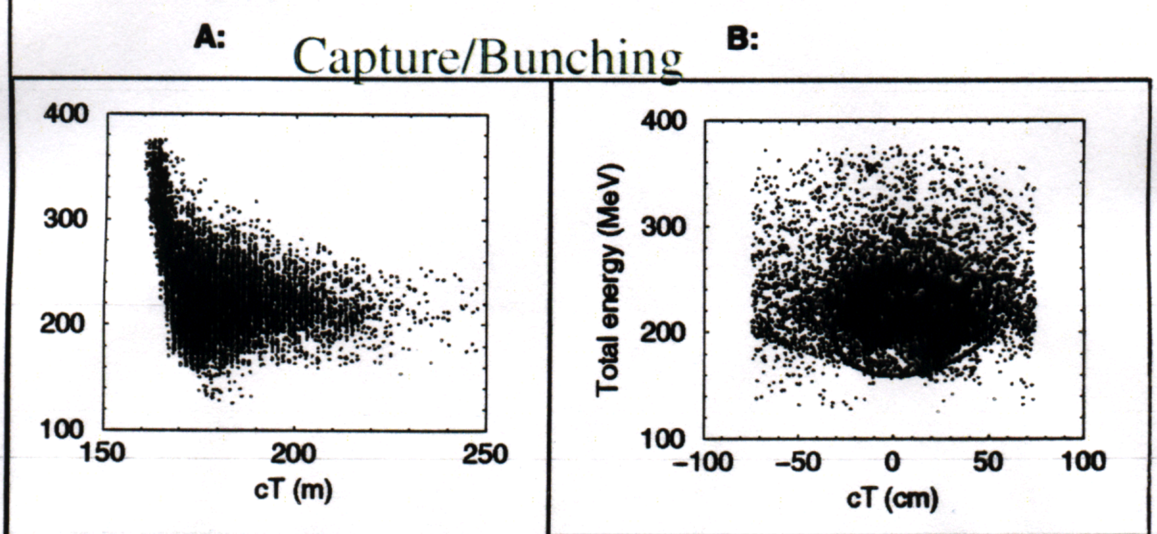


Bunching and Capture

- ΔE/E after phase rotation
- bunching into string of 35 bunches or so



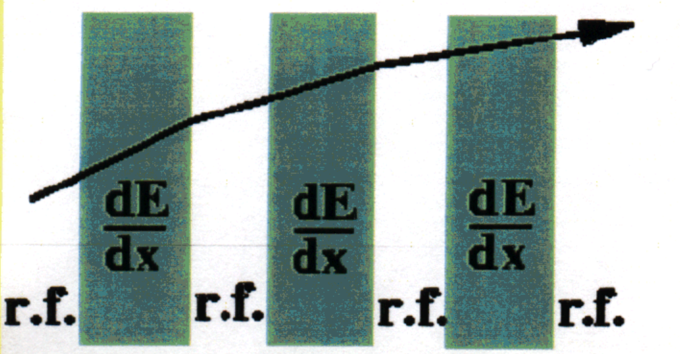
Longitudinal phase space distributions of the μ=beam before (above, red) and after (below, violet) the minicool energy loss insert.



Beam distributions in energy –distance coordinates. A shows the full beam length; B shows the distribution folded over the 201.25 MHz periodicity, with an RF bucket for 200 MeV, 200 MHz cooling.

Cooling Principle

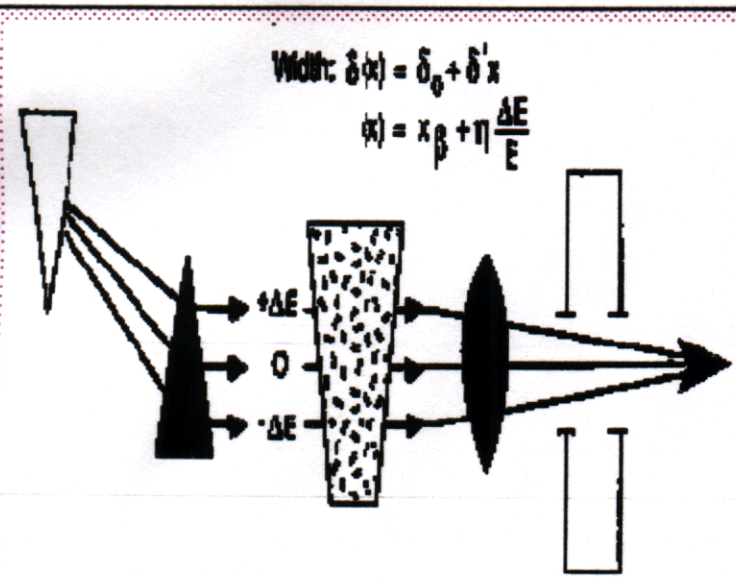
Ionization Cooling



Transverse Cooling

Muons lose energy by dE/dx and long–itudinal momentum replaced by r.f.

- **To Minimize heating from Coulomb Scattering:**
  - Small $\beta_\perp$ (strong focusing) : High–field solenoids or Lithium Lenses
  - Large L_R (low–Z absorber) : Liquid H_2



Energy "Cooling"

Ionization cooling using a wedge plus dispersion.

Exchanges emitt–ance between transverse & long–itudinal directions

Cooling Principle

- Limit on Performance of Cooling

$$\varepsilon_x^2 = \langle x^2\rangle\langle\Theta^2\rangle - \langle x\Theta\rangle^2$$

$$\varepsilon_{xN} = \beta\gamma\varepsilon_x$$

$$\frac{d\varepsilon_{xN}}{dz} = \varepsilon_x \frac{d(\beta\gamma)}{dz} + \beta\gamma\frac{d\varepsilon_x}{dz}$$

$$-\frac{1}{\beta^2}\frac{\varepsilon_{xN}}{E}\left|\frac{dE}{dz}\right|$$

$$-\frac{\beta\gamma}{2\varepsilon_x}\left[\langle x^2\rangle\langle\Theta^2\rangle' + \langle\Theta^2\rangle\langle x^2\rangle' - 2\langle x\Theta\rangle\langle x\Theta\rangle'\right]$$

- near waist (no correlation)+strong focusing (no $\langle x^2\rangle$growth)

$$-\frac{\beta\gamma}{2\varepsilon_x}\left[\langle x^2\rangle\langle\Theta^2\rangle'\right]$$

- with:

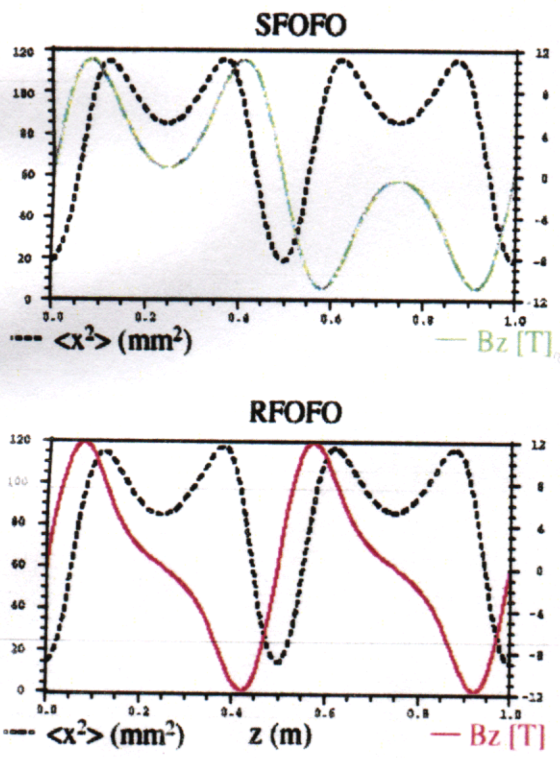
$$\langle x^2\rangle = \beta_\perp\varepsilon_x \quad , \quad \Theta = \frac{E_s}{pc\beta}\sqrt{\frac{z}{L_R}}$$

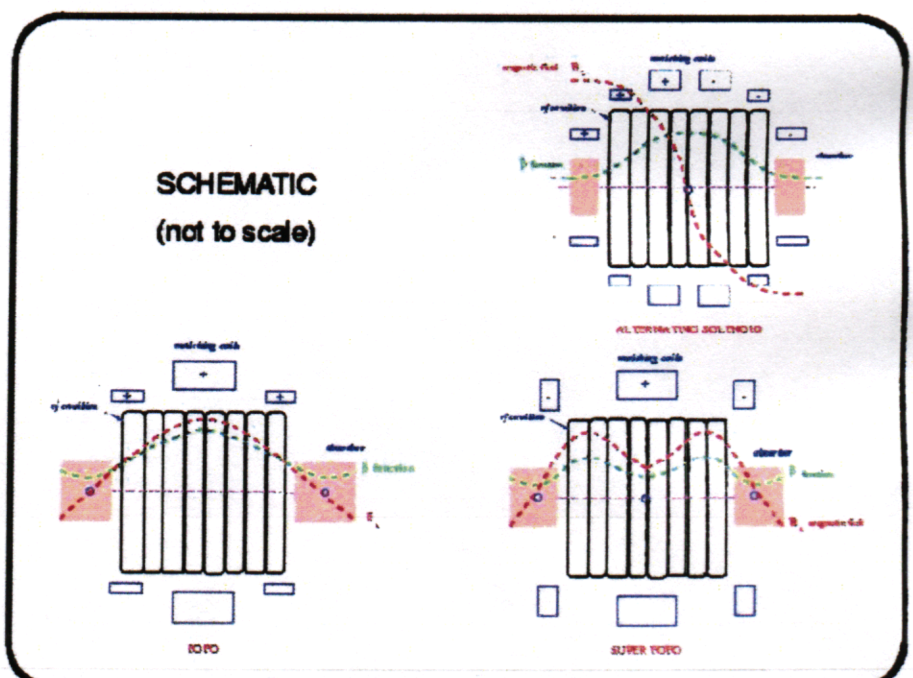
$$\min\varepsilon_{xN} = \frac{\beta_\perp E_s}{2\beta\cdot mc^2\cdot L_R\left|\frac{dE}{dz}\right|}$$

Simulation Effort

- "From the Target through the Cooling" (LBNL)
  - Different Lattice types
  - Cell length ~ Coil diameter ⇒ non efficient use of H_{crit}
  - Field 3.5-7 T or more ⇒ Ni_3Sn with this size diameter
  - Analytical description ⇒ G. Penn, LBNL / K. Kim ANL+U of Chicago/ Y. Derbenev, Michigan State/Fermilab
  - Joint design among FNAL-LBNL-BNL on cooling channels

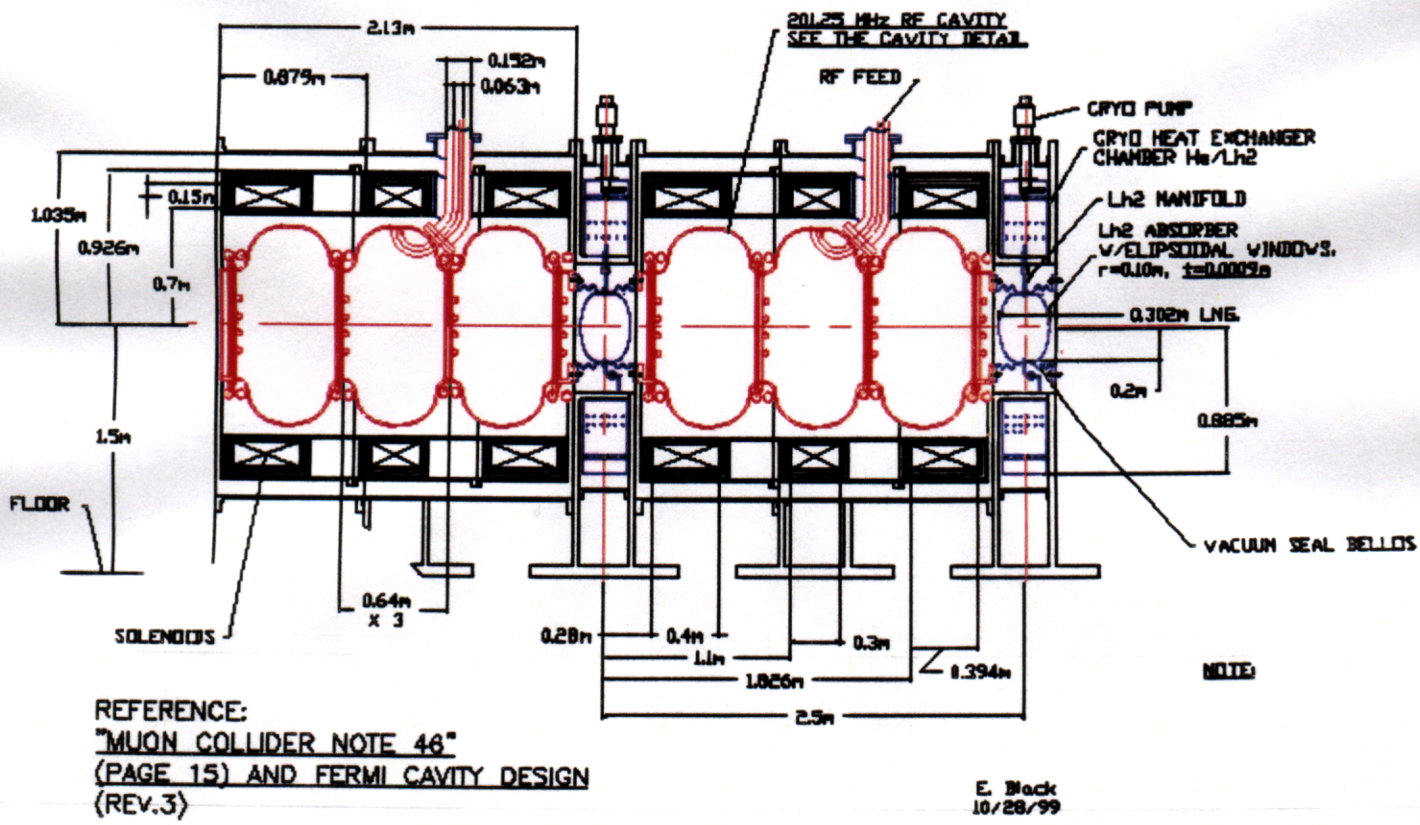
Fields and beta functions: two examples
(note $\langle x^2 \rangle \propto \beta$)





The Heart of the Cooling Channel for a Neutrino Factory

- IIT, BNL, LBNL, FNAL: go through an engineering design
- Goal: Do all the cooling with one set of hardware

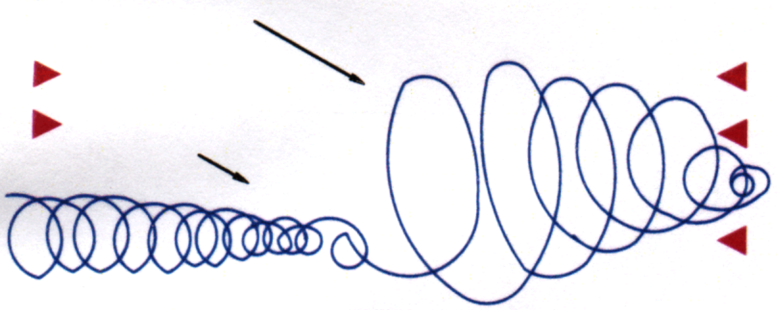


B_z ~ 3.5 T max

E_{acc} ~ 15 MV/m @ 200 MHz

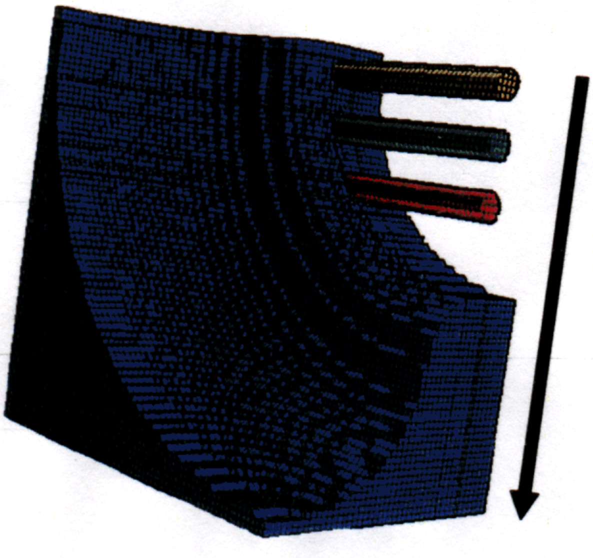
Other Cooling Channels

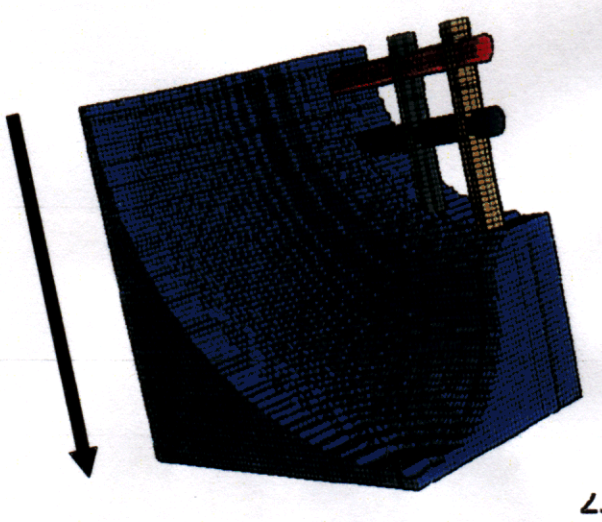
- Single Flip



Cavity Parameter

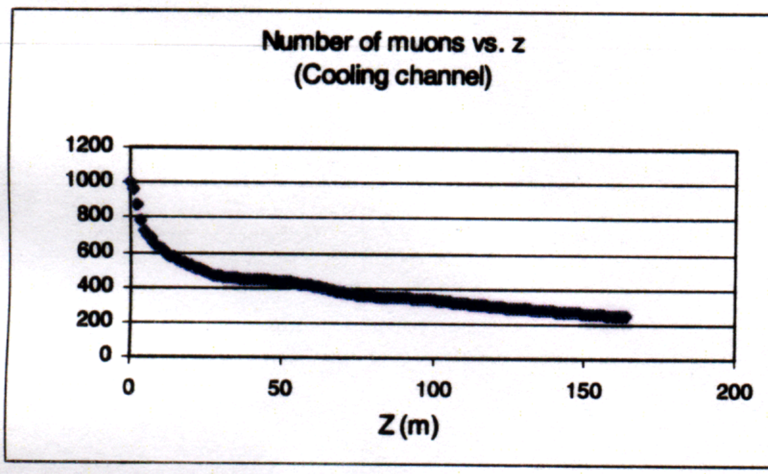
Parameter	Crossed Tube	Pill Box
Frequency	201.25 MHz	201.25 MHz
Accelerat. Phase Angle	Sin(25 degrees)	
Peak Accelerating Field	15.0 MV/m	15 MV/m
Peak Surface Field	22.5 MV/m	15 MV/m
Kilpatrick Limit	14.8 MV/m	14.8 MV/m
Cavity Type	crossed tubes	Beryllium foil windows
Shunt Impedance	20.3 M? /m	23.3
Transit Time Factor T	0.845	0.827
Peak Voltage per Cell	6.5 MV	5.7 MV
Q	47,500	52,600
Fill Time	38 µs, critic. coupled	42 µs
rf Pulse	114 µs	125 µs
Peak Power per Cell	3.45 MW	2.8 MW
Average Power per Cell	8.0 kW	5.3 kW
Window Type	4 cm diameter Al crossed tubes	15 cm radius, 127 µm thick Be foil
Average Power on Tubes	30 W (worst tube)	53 W (heated from both sides)



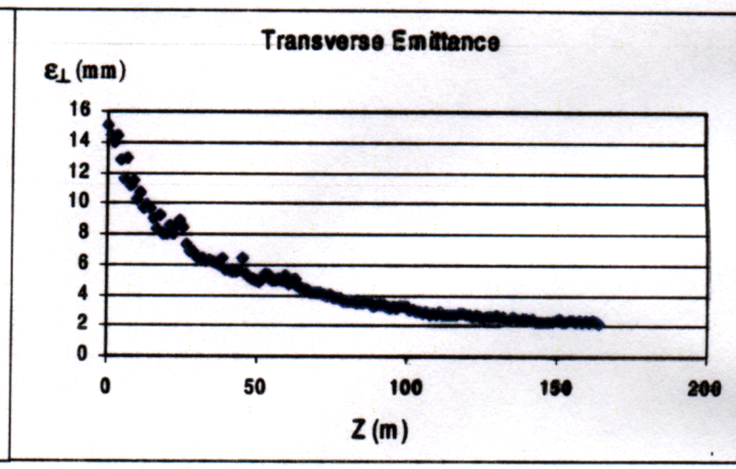


Ideal Cooling Channel

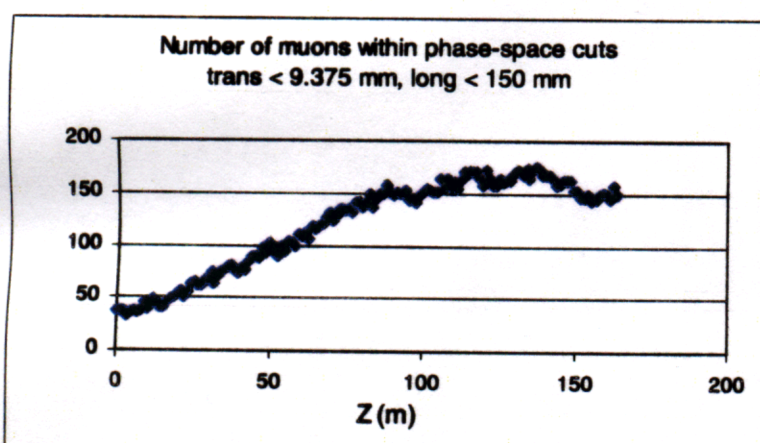
- Small enough $\Delta p/p$ and σ_z
- no correlation between transverse position and longitudinal momentum



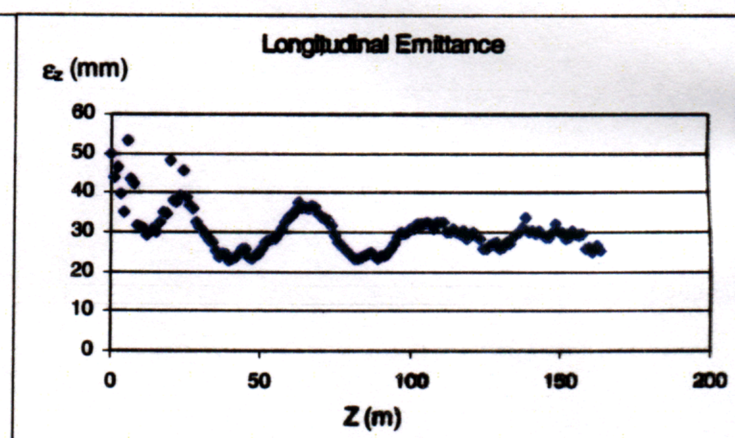
a: Transmission in the FOFO channel vs. distance using the idealized beam described in the text.



b: Transverse emittance vs. distance for the idealized beam.



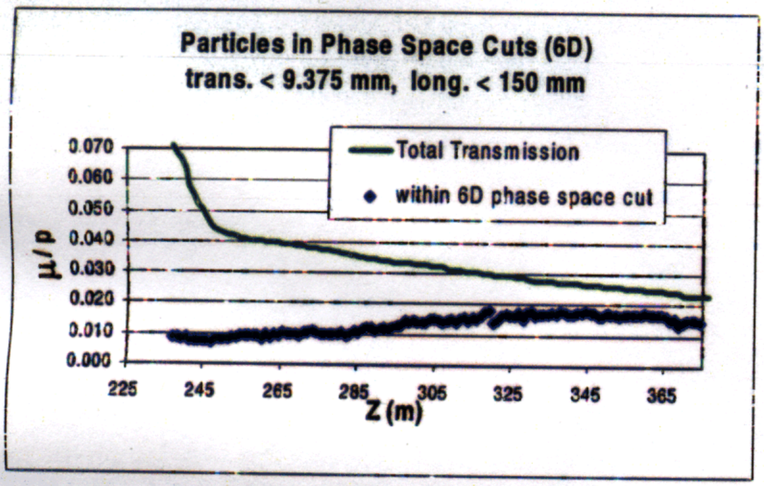
c: Relative yield increase within the acceptance of the accelerator (9.375π mm.rad transverse, 150π mm longitudinal) using the idealized beam.



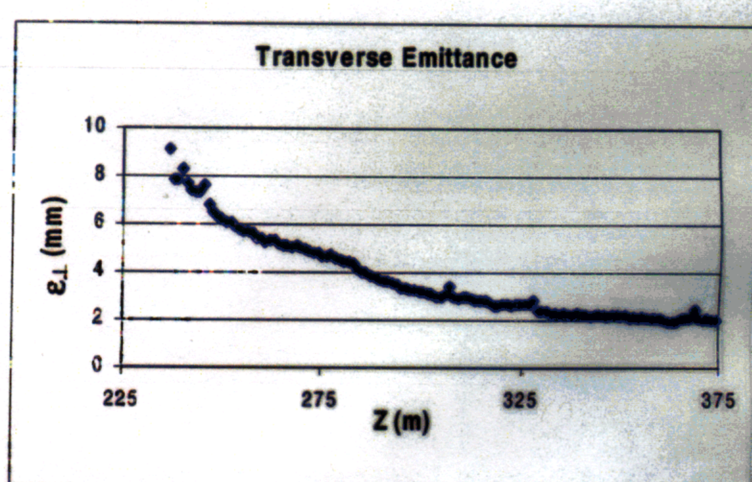
d: The longitudinal emittance of the idealized beam in the FOFO channel

Did We Achieve The Goal?

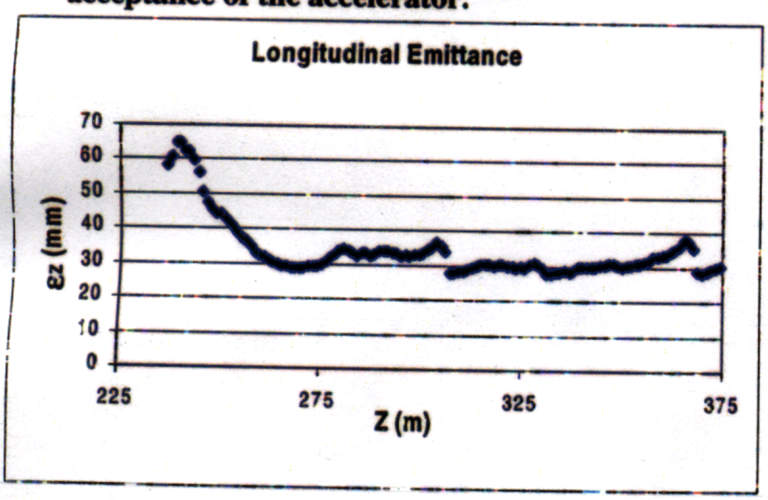
- Tough question:
  - partially: 5.8×10^{19} shown in the study; no errors included but full simulation. 2×10^{20} goal



The transmission and the muon yield within the acceptance of the accelerator.



The transverse emittance versus z in the FoFo cooling channel.

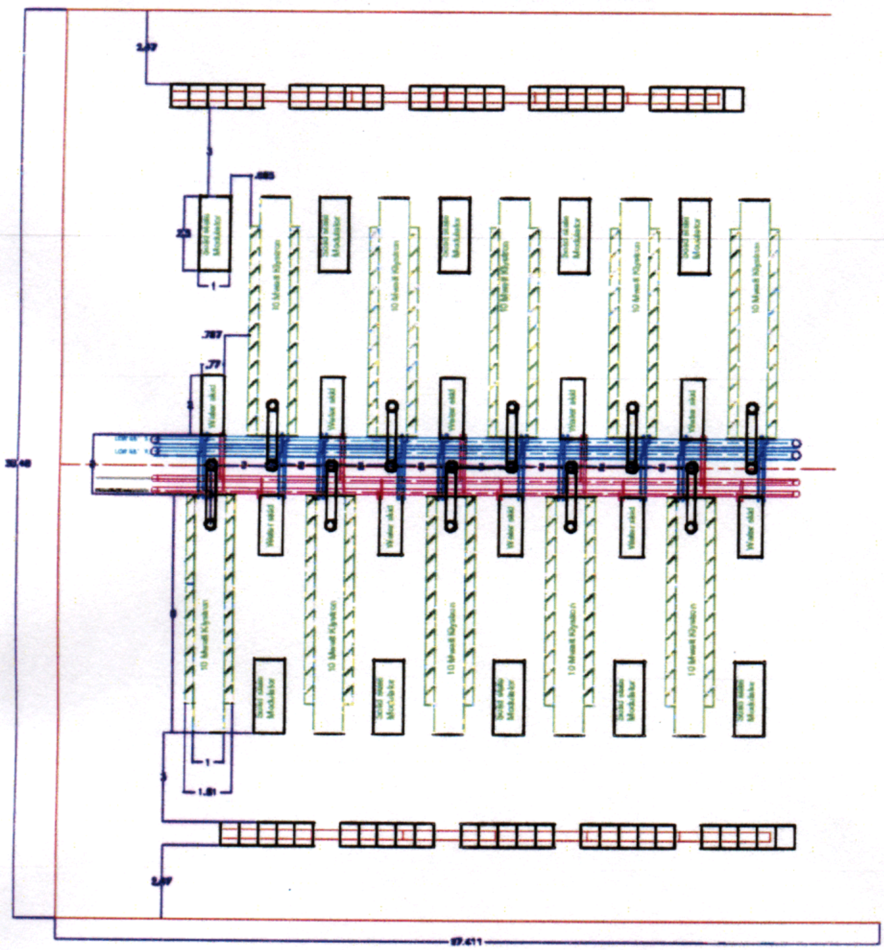


The longitudinal emittance.

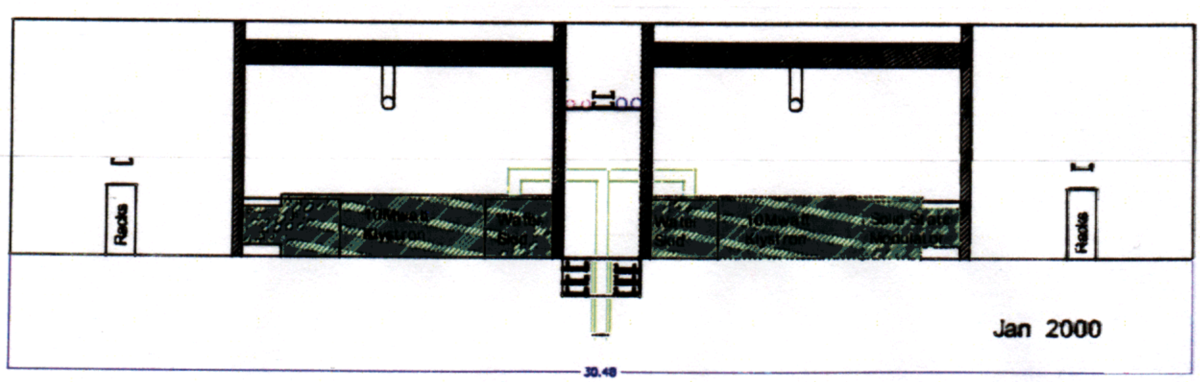
The Cooling Linac

- 100-150 m of 200 MHz High Gradient RF

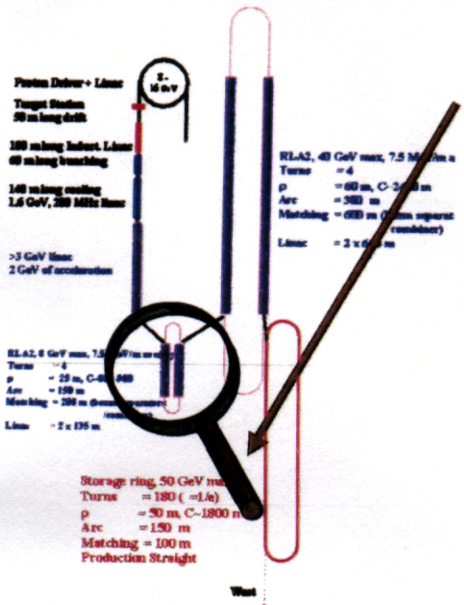
Cooling Channel Linac Equipment Gallery Layout Jan 2000



Cross Section - Cooling Channel Linac
Equipment Gallery



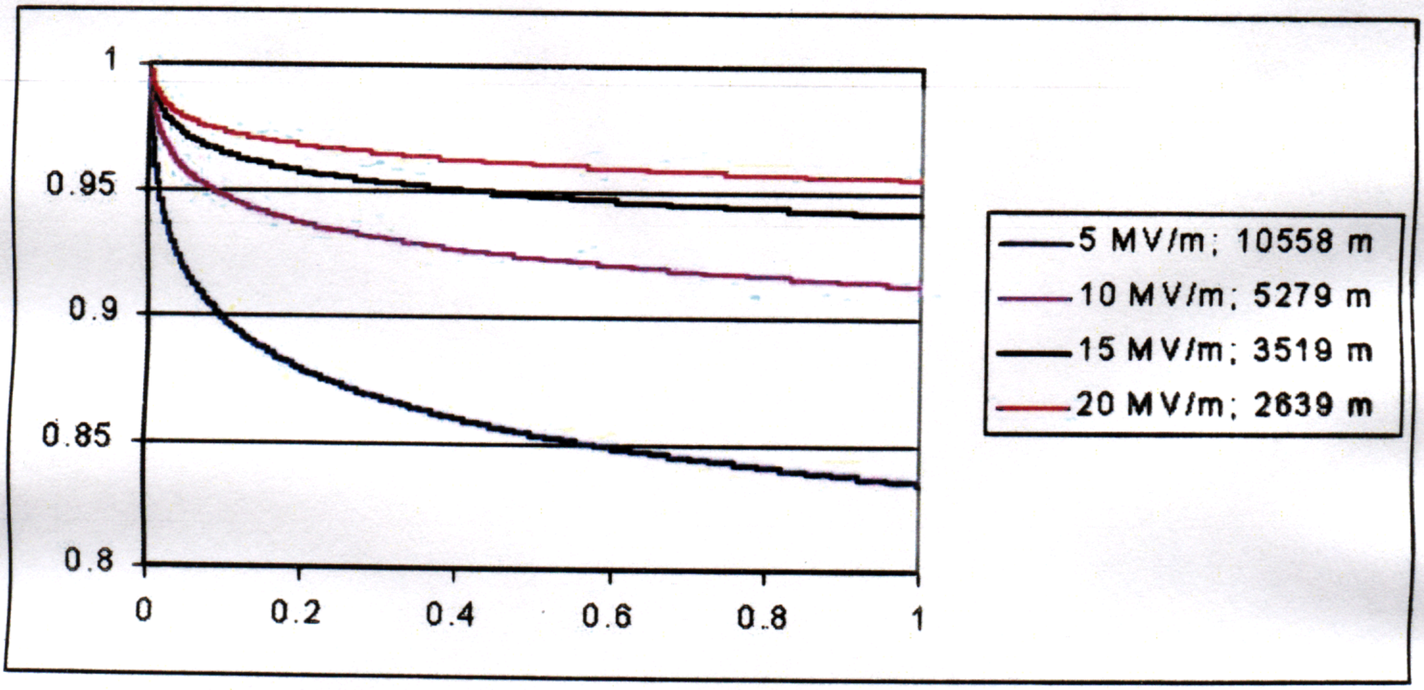
Basic Result from Accel. Meeting



- Acceleration Scenario (TJNAF):
  - 3 GeV linac, sc solenoids, 200 MHz
  - RLA1: 3-11 GeV, 200 MHz, nc arcs, 4 turns
  - RLA2: 11-50 GeV,400 MHz, sc arcs, 5 turns
  - cost model was agreed on
  - (32+23) 200 MHz and 25 400 MHz klystrons with Tp=2 msec and 15 Hz are required + 80 Modulators for acceleration
  - <u>issue</u>:$\Delta F \approx 80$ Hz per cavity which gives loaded Q ~ 3×10^6

- Cavity R&D (Cornell Univ.,NSF ⇒Tigner, Padamsee):
  - build 200 MHz model and measure microphonics
  - coupler development is relaxed (800 kW (200 MHz) 200 kW (400 MHz))
- Klystron (SLAC ?):
  - ~ 70 Klystrons or so are needed for the whole scrf acceleration
  - big R&D plan: 10 MW @ 2 msec, 200 MHz+400 MHz.
  - Modulator: TESLA type

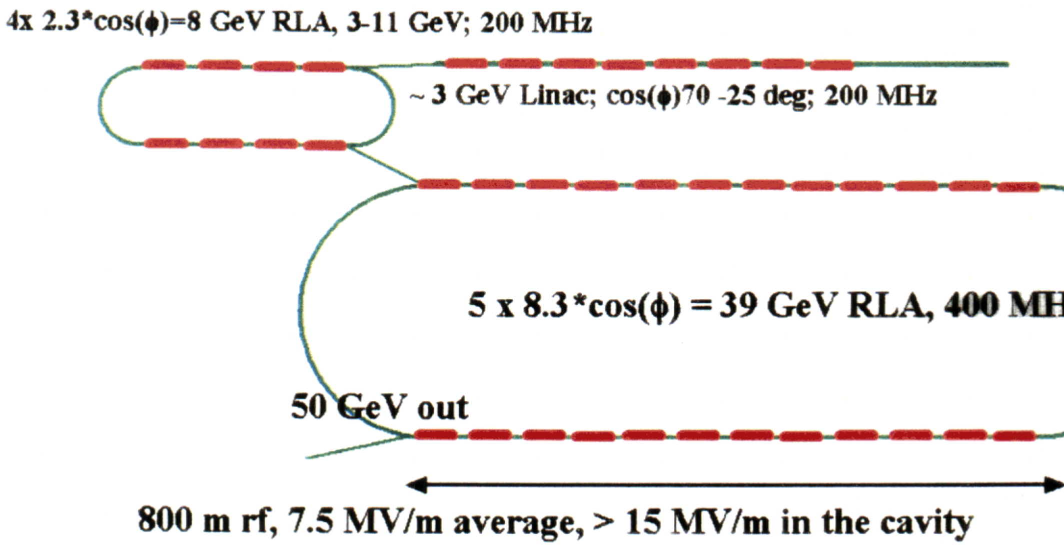
Acceleration of Muons



- Muon Survival
  - requires high gradient
  - large aperture

Acceleration

- Low Frequency Linacs and RLAS (Jefferson Lab, BNL, Cornell, Fermilab, Meeting at Fermilab Feb 17th+18th)
  - RF systems at 200 MHz (175)
  - at this emittance -> linac, 1st RLA at 200, 2nd=400 MHz
  - can be sc here, because no solenoids required



Based on cooling assumption		
incoming norm.emittance $\varepsilon_{x,y}$	π mm rad	1.5
outgoing emittance at 50 GeV	π mm rad	3.2
energy spread at 50 GeV (95%)	%	+/- 2
incoming momentum	MeV/c	190
incoming norm. emittance ε_{long}	π mm	28
bunch length	mm	120
momentum spread (rms)	%	11
$\beta\gamma$ at start	~	2
pulse length	~	150 nsec (4x(150+250))
number of bunches in one pulse	~	30 (4x30)
number muons per pulse	10^{12}	2.5
repetition rate	Hz	15
acceleration I (linac)	GeV	3
RLA_1 + RLA_2	GeV	47

Acceleration based on RLA

- Why not nc?
  - Peak power limited already
  - in normal conducting cavity: too much power required to build up the gradient
  - gradient is not a free parameter for optimization:
    - muon decay +longitudinal acceptance
- SC structures at 200 MHz (100 MHz) and 10 MV/m (7.5 MV/m real estate)
  - almost no power to build up gradient --> beam
  - loaded Q's are similar to nc structures ->fill time short but how to do the coupler ? -> comparatively efficient !
  - 4 x 30 bunches per RLA, 2.5×10^{12} total
  - P_{linac} ~ 6 MW, P_{RLA1} ~ 2 MW, P_{RLA2} ~ 12 MW
  - ~20 MW power for RF acceleration at ~25 % overall efficiency (AC → RF)
  - Problem is the required peak power, not average power !

RLA Energy	L_{tot} m	L_{linac} m	I_{beam} mA	R_{loaded} MΩ/m	Q_{loaded}	Nr of turns	$T_{pulse} = T_{fill}+T_{acc}$ /μs	Peak Power MW/m
2-10	800	2x135	120	83	80 x10^3	4	132+10	1.2
10-50	2400	2x700	40	252	240 x10^3	4	400+32	0.4

Limits for Peak Power and Frequency

- What determines the physical size of a klystron?

ideal situation with no space charge:

$$z_{opt} = 1.84 \cdot \frac{u_o(V)}{2\pi \cdot f} \cdot \frac{2}{\alpha \cdot \beta}$$

u_o := velocity of electrons $= \beta * c = (1 - 1/\gamma^2)^{0.5} * c$
α := modulation gap voltage/beam voltage
β:= transit time

f = 200 MHz, U_{gun} = 175kV , uP=1.2 , 15 MW Beam power ->
10 MW rf power,

z_{opt} := 10 meter only for the rf part
+ gun + collector ---> easily a 11-12 meter long klystron with a standard approach.

- scaling shows : $z_{opt} \sim 1/f$ klystron becomes longer
- infrastructure in industry can not mechanically accommodate this easily
- test stands are not available

Klystrons as high peak power sources are only feasible below 200 MHz if multi beam tube is used.
SLAC and CPI: preliminary discussion going on

Klystron R & D

- Multi Beam Tubes can be “compact”
- Highly efficient
- Very long lifetime

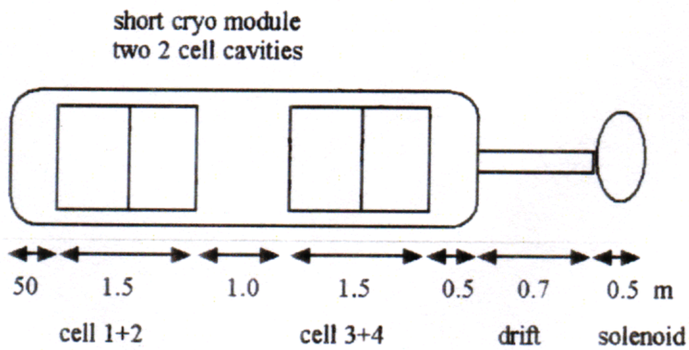
- Alternative: IOT’s, Tubes (see linac)

Frequency, MHz	200			
RF Power, MW	10			
µPerveance , $A/V^{1.5}$	2			
Efficiency, %	44			
Item	Value	Value	Value	Units
Type	ring	3 pole	2 ring+1	-
Number of beams	6	12	19	-
Vb	81	62	51	kV
Itotal	279	368	442	A
Bz	233	251	264	G
Total anode dia	53.3	58.4	60.9	cm
l_q	6.201	5.279	4.759	m
Gun + collector len	1.05	0.87	0.77	m
Total length is from	2.6	2.18	1.96	m
to	4.15	3.51	3.15	m

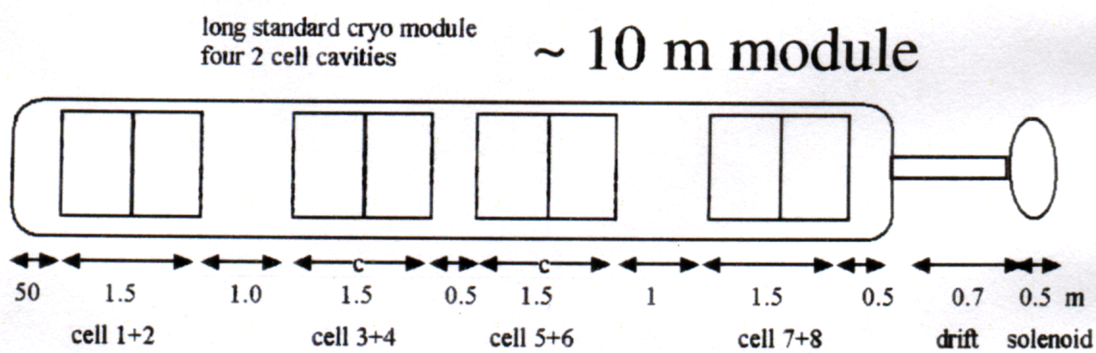
Proposal by SLAC for a klystron design

NSF-Cornell-Jlab-FNAL-TESLA-SLAC

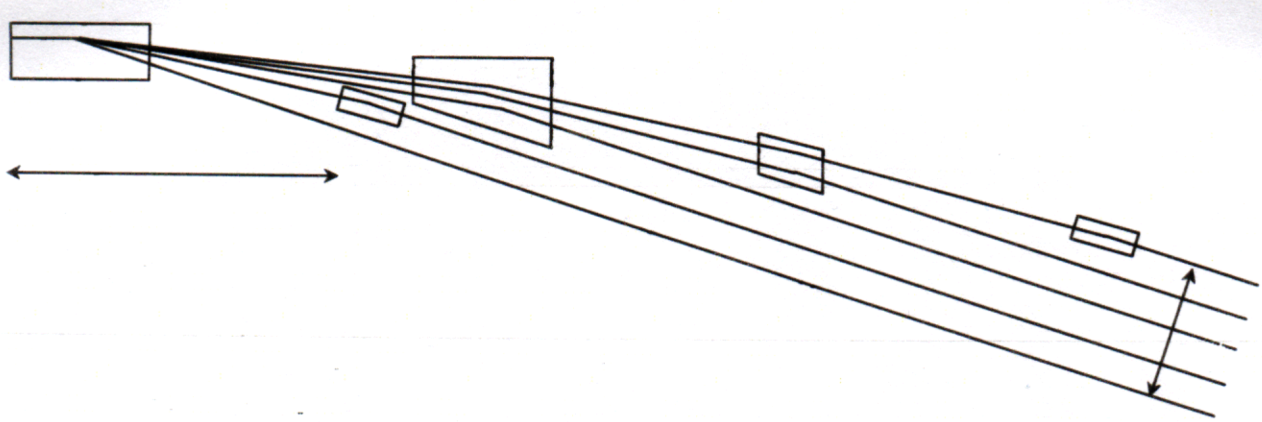
- Super Conducting Cavities and RF Power Sources



  - Acceleration starts 70deg off crest
  - 1st part of the linac
  - 2nd part of the linac & RLAs
  - double # of cells
  - 400 MHz



- Arcs and Beam Spreaders (need work here)

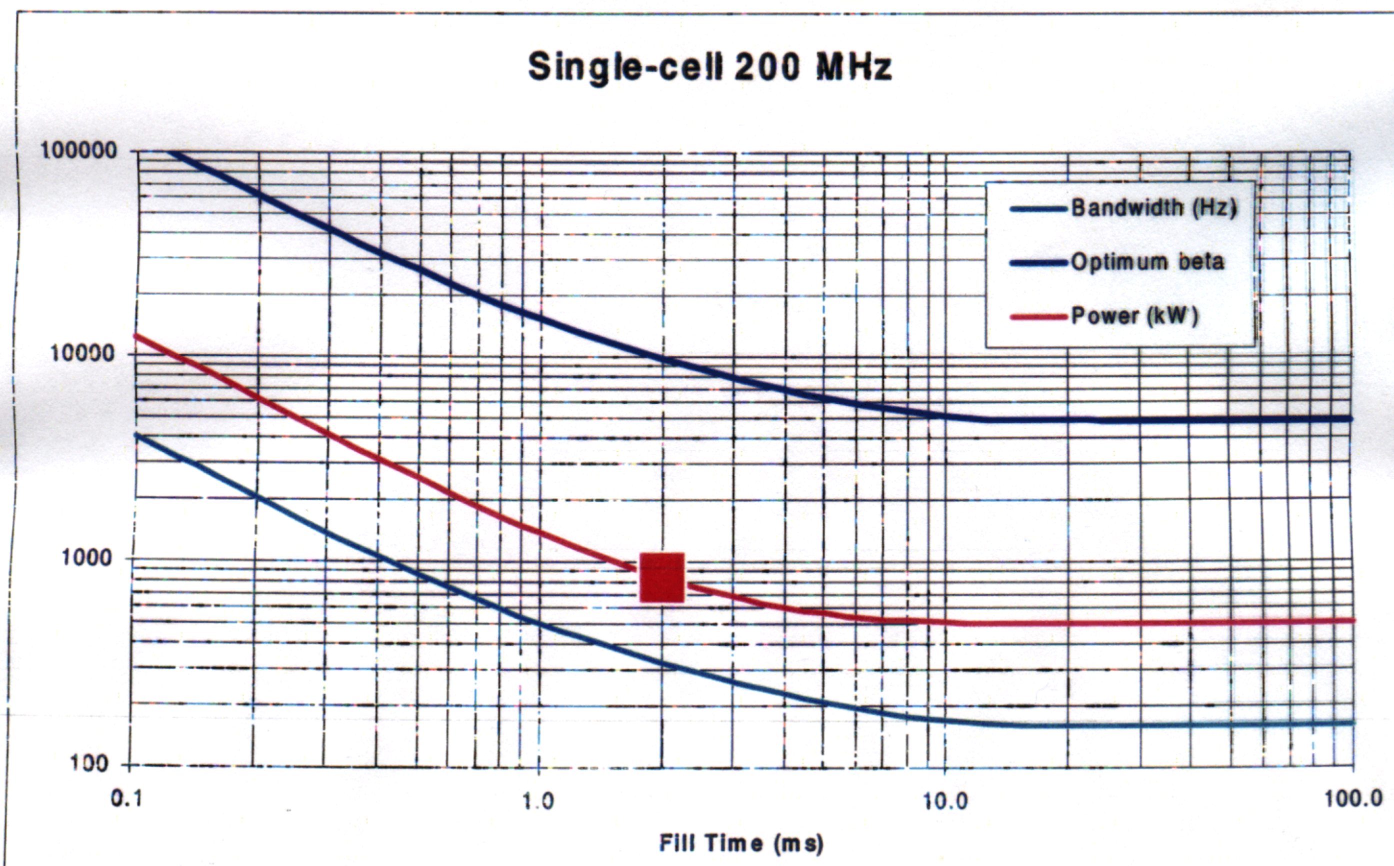


Acceleration with Low Frequency SC Cavities

Machine Segment	# passes	$I_{ave.}$ (μA)	V (MV)	$P_{average}$ (W)	U_{stored}/ cell (J)	$P_{control}$ for 80 Hz bandwidth, (kW)
Preaccelerator	1	7.2	11.25	81	1000	503
RLA1	4	28.8	11.25	324	1000	503
RLA2	5	36	5.625	203	125	63

Power extracted per turn: 3.6 J for 200 MHz
1.8 J for 400 MHz

Microphonics + "Lorentz Force Detuning"
especially in large cavities



8. The Muon Storage Ring

8.1 Introduction

The 50-GeV storage ring for neutrino production has been designed using a racetrack configuration. A racetrack is the optimal geometry for maximizing the proportional length of a single straight section to circumference, hence maximizing the number of muons converted into a neutrino beam. Although this particular ring was designed to meet limitations and target physics detectors specific to the Fermilab site, its design concepts, parameters, components, and dynamics are generally applicable. The racetrack design is simple, containing a downward straight, called the production straight, a return straight pointed towards the surface and two arcs with their associated matching and dispersion suppression sections.

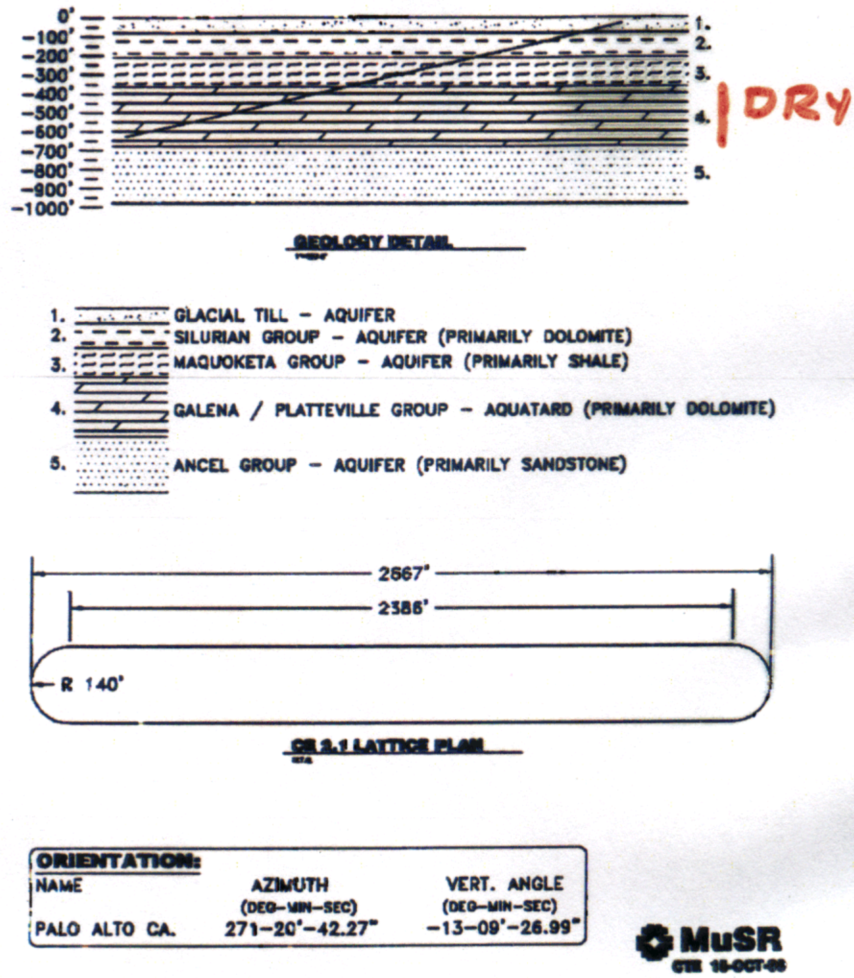


Figure 1: Constraints on the storage ring due to the geology under the Fermilab site. The 2667' (or 813 meter) limit on the cross-section profile of the ring shown in the lower drawing is given by the 600 foot available for the ring's vertical drop the and 13 degree angle between Fermilab and the West Coast.

One of the parameter constraints of the design arises from the underlying geology of the site as shown in Figure 1. The vertical distance between the surface of the site and the bottom of the Galena Platteville rock layer is approximately 680 feet. Below this dolomite layer is a sandstone layer, which must be avoided because it is a poor substrate for tunnel construction and it contains the water supply for the municipalities surrounding Fermilab. Of the 680 feet, 600 have been allocated to the ring for its vertical drop (Table 1). The "vertical drop" is the vertical distance between two parallel planes: one plane through the topmost part of the ring and a second plane through the bottommost part of the ring.

This vertical constraint is a limitation because at least part of the ring must be tilted at a vertical angle to direct the neutrino beam through the earth to a long-baseline detector. Tilting the entire ring obviates the need for additional, "out-of-plane" bending. For a significant angle of declination and vertical height restriction, tilting increases the relative arc

What is Specific to Fermilab Site?

Is 22 % steep?

- 17 % into a quarry
- there is water !
- incremental cost small compared making more ν
- extend the ring up to the surface

Further down the ramp

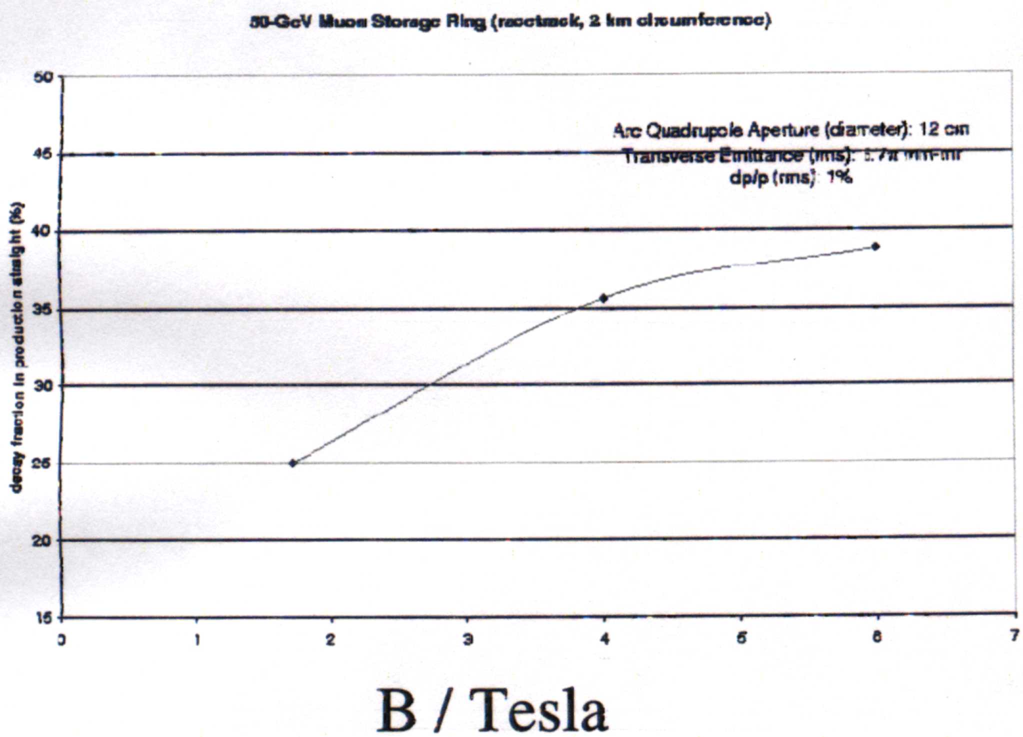
Use vehicles

Optimization of the Storage Ring

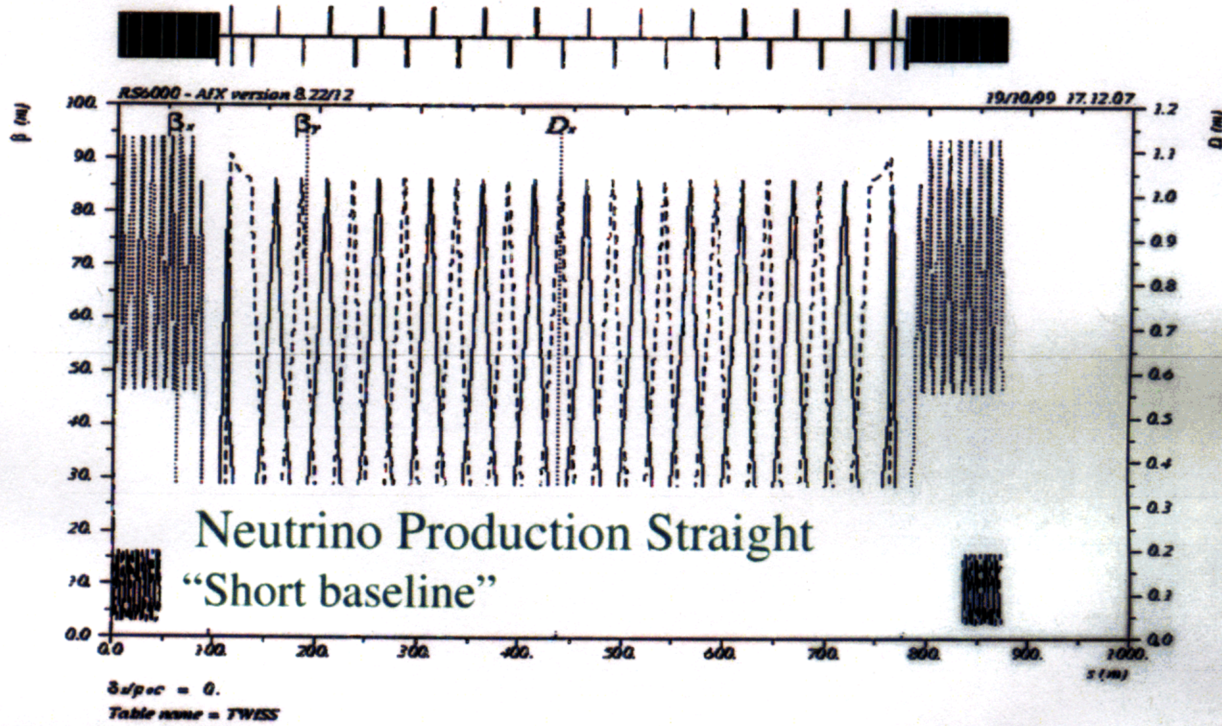
- The cheapest way to produce muons in the straight section is to make them as long as possible !

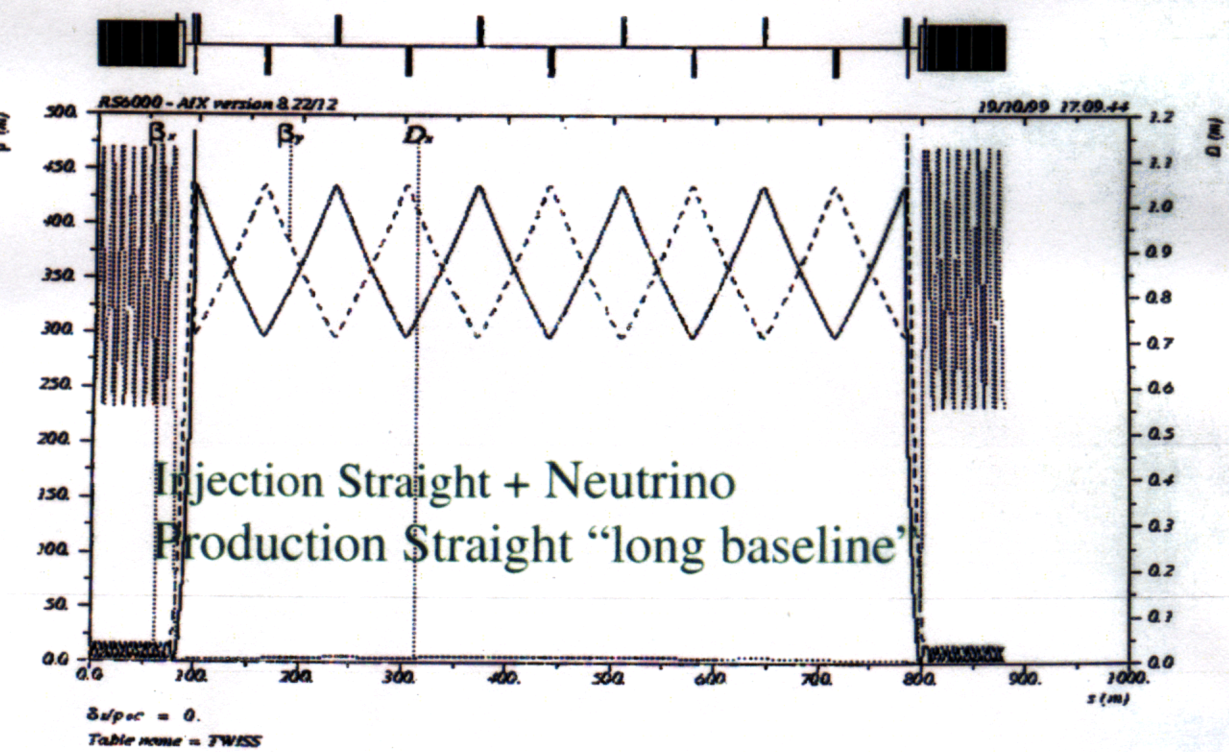
$$\eta = \frac{\text{Nr of } \mu \text{ decaying in straight section}}{\text{Nr of } \mu \text{ injected}}$$

L=length of straight $\qquad \eta = \frac{1}{2\,(1+\pi\,\rho\,/L)} = \frac{1}{2\,(1+0.2)}$



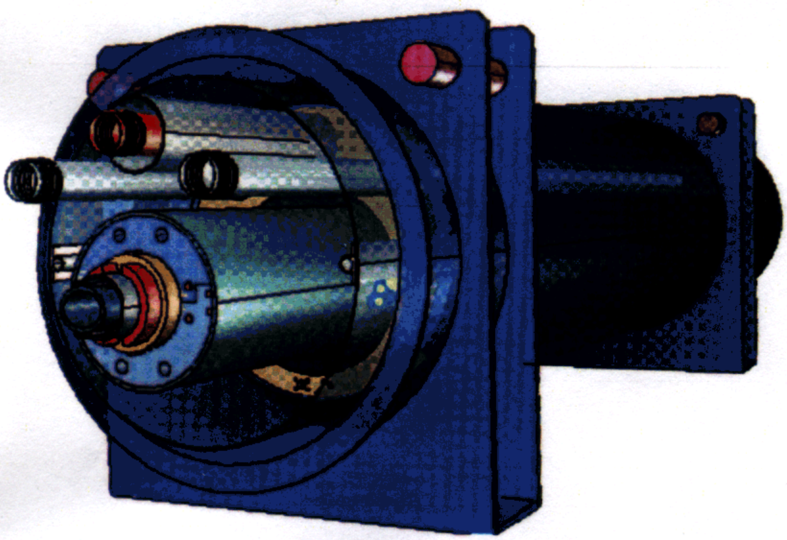
A Storage Ring for 2 Experiments

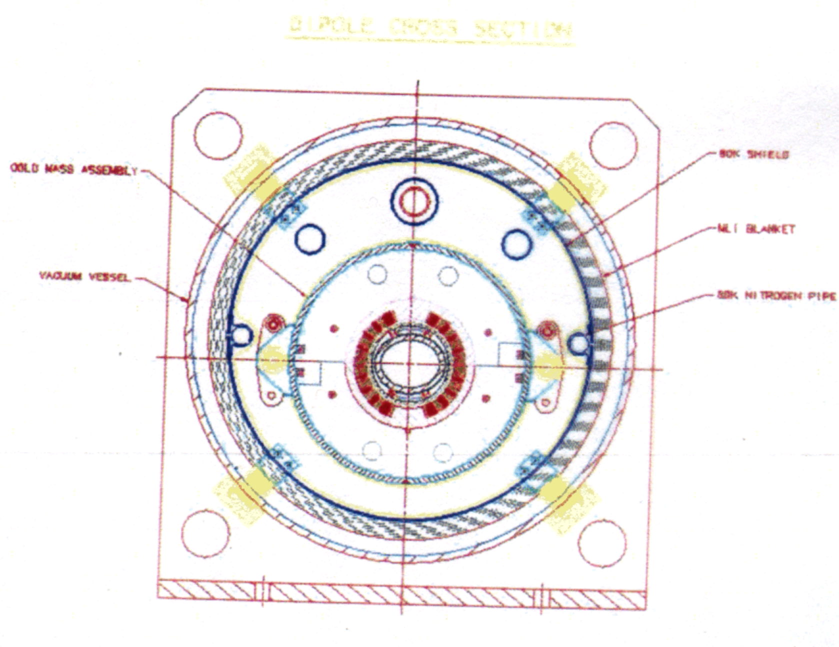




SC Large Bore Magnets

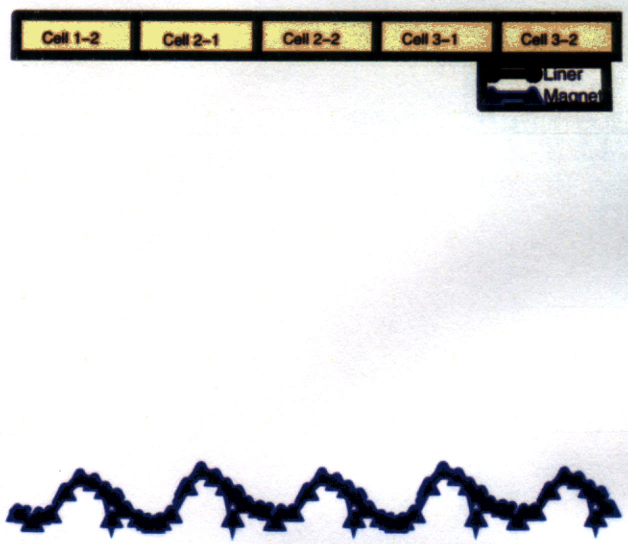
- Low field quality (reduce cost), large aperture (increase cost)
- 7 Watts/m into LHe due to electrons from muon decay
- 1 cm tungsten liner (3 cm was considered)
- Design tied to choice of muon intensity

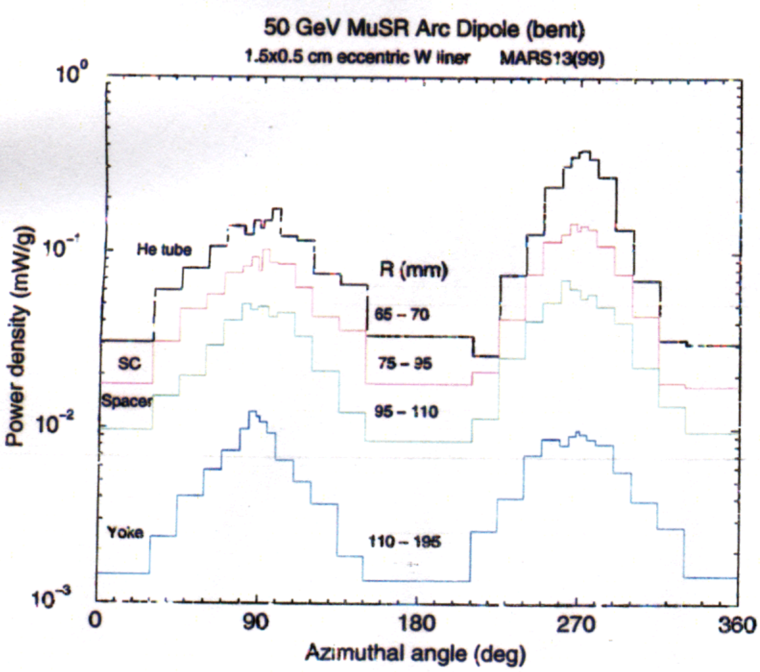




Decay Electrons

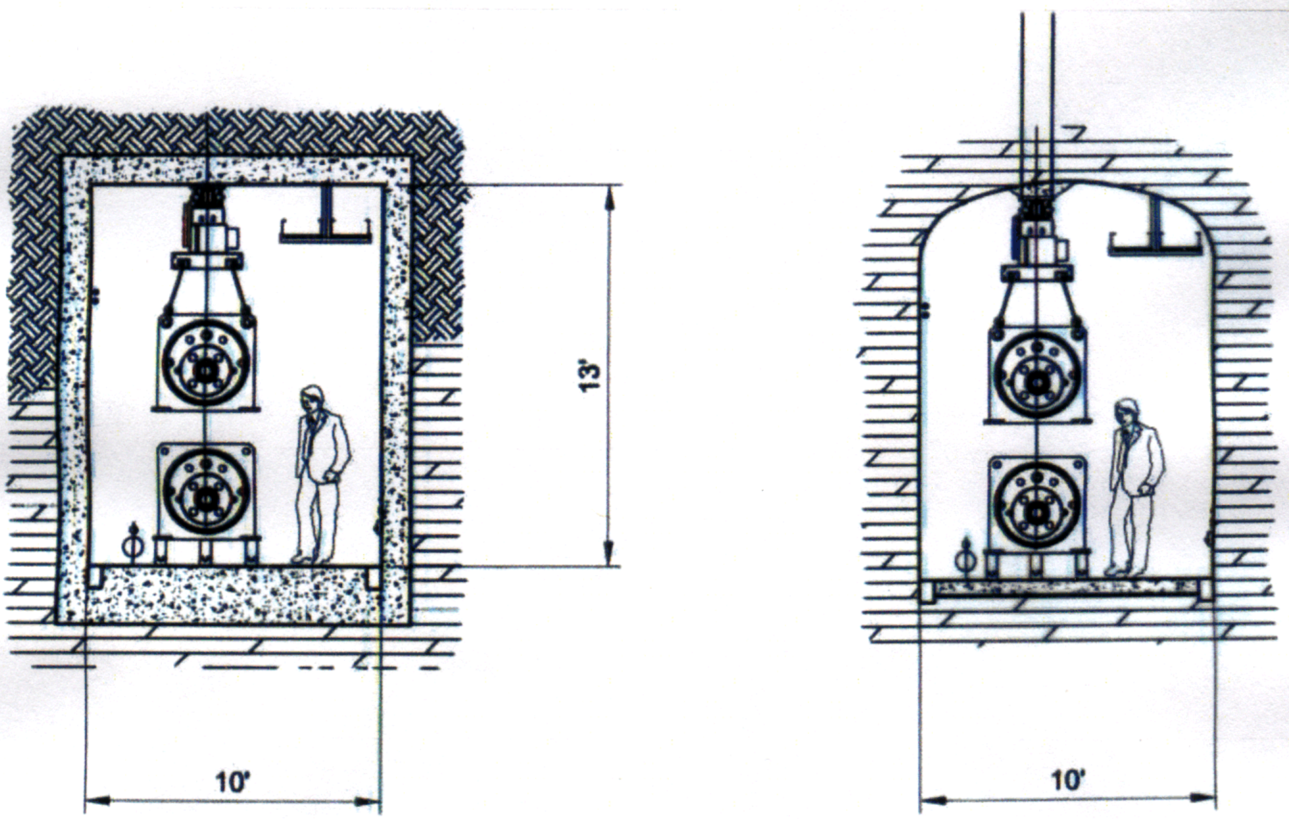
- Beam power
  - 240 kW muon beam → 80 kW deposition due to electrons
  - long racetrack → helps: 22 % decays in arcs
  - ~ 50 Watt/m in arcs + 1 cm tungsten shielding ~ 7 W/m into LHe





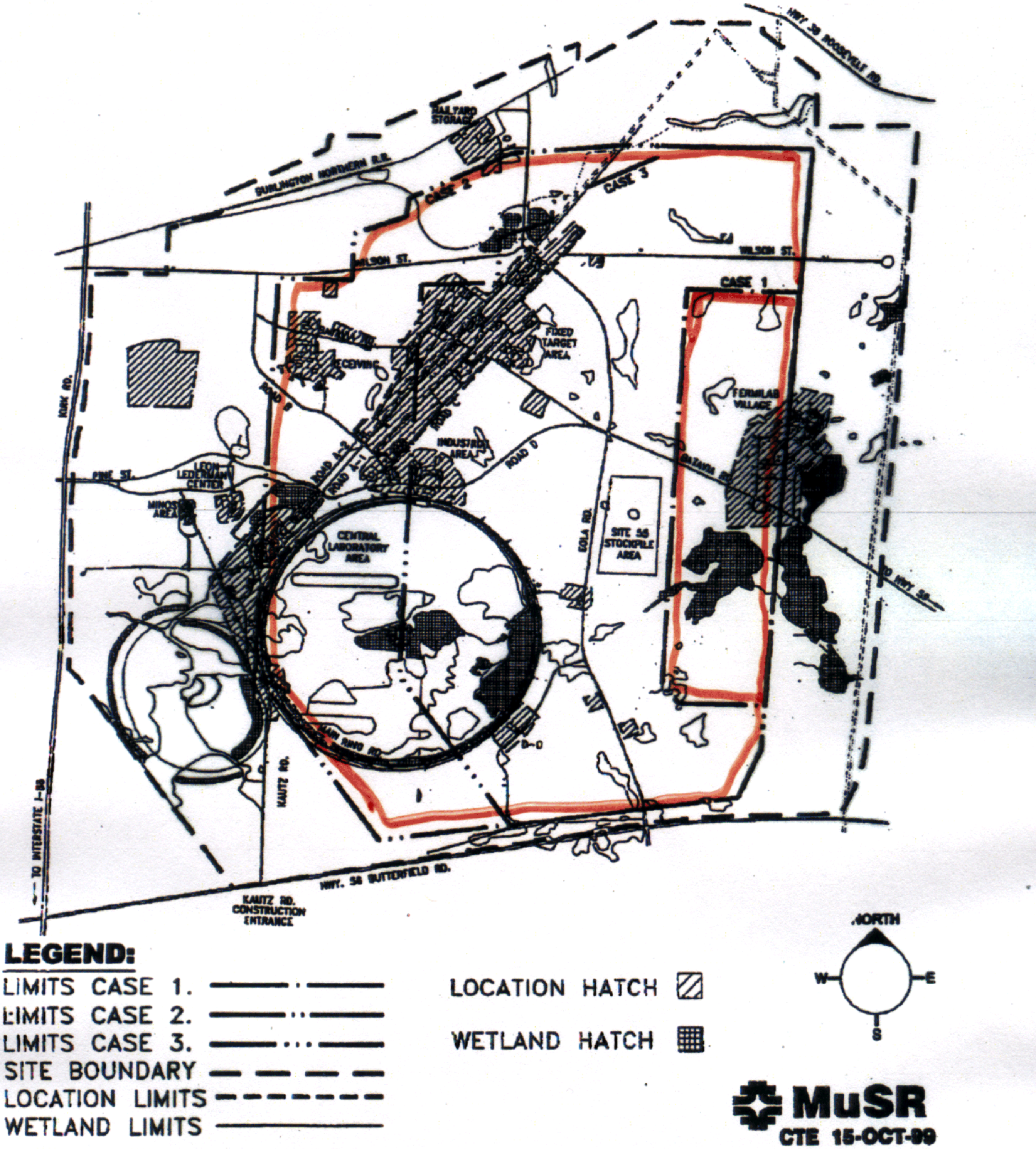
Civil Engineering for the Storage Ring

- Tunnel for very different environments



SECTION G
MuSR (SHALLOW)

SECTION H
MuSR (DEEP)



LIMITS:		mrem/year	CONTROL CYL.	
CASE 1.	50GeV	10	4.5KM	RADIUS=4.0M
CASE 2.	50GeV	100	1.4KM	RADIUS=1.2M
CASE 3.	30GeV	10	2.5KM	RADIUS=5.0M

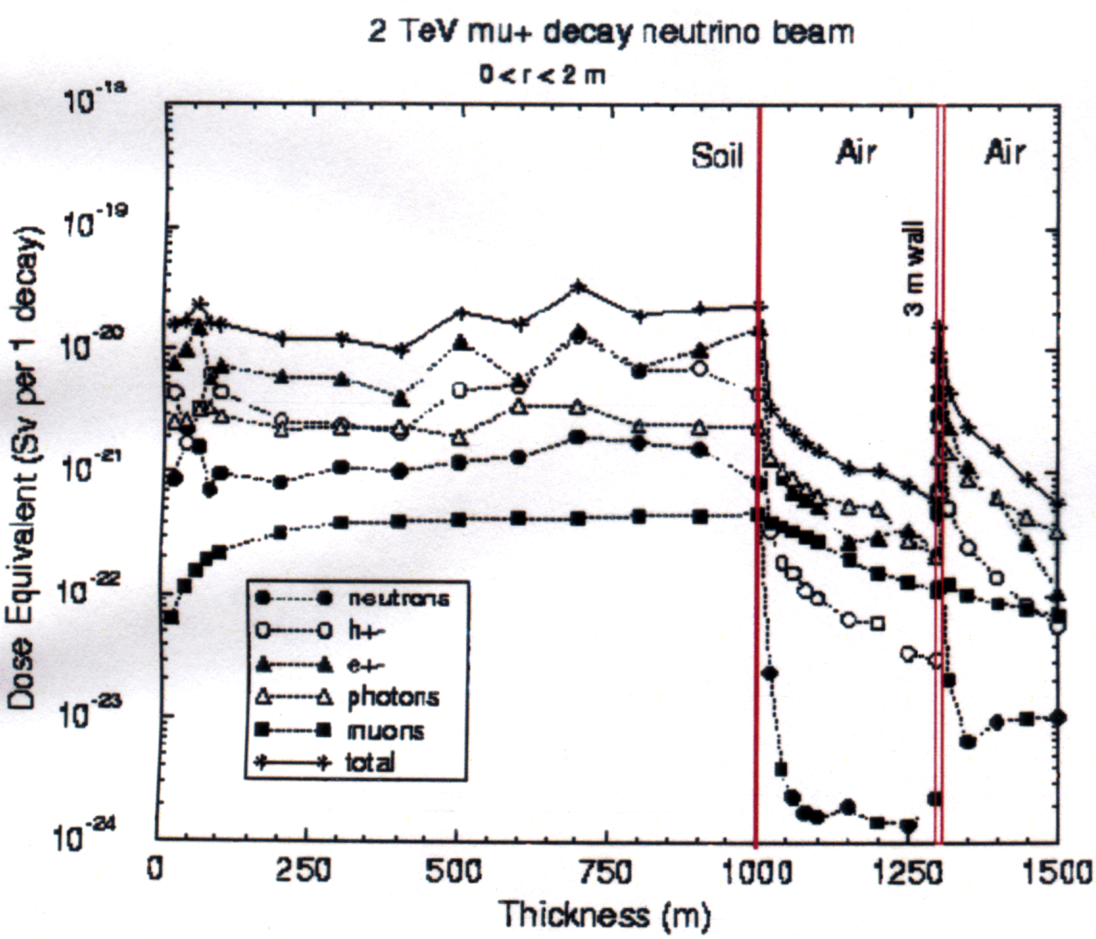
– SMALL BOX
– BIG BOX

Figure 5: Map of the Fermilab site that displays the siting constraints for locating the MuSR explained in the text for two different choices of annual dose equivalent and two different choices of muon energy.

Radiation from the Neutrino Source @ FNAL

Neutrino Radiation from the μ Storage Ring: Max E_μ ?

ν's from the μ's in the up-pointing straight section exit the surface: ϕ~13 deg (22%)

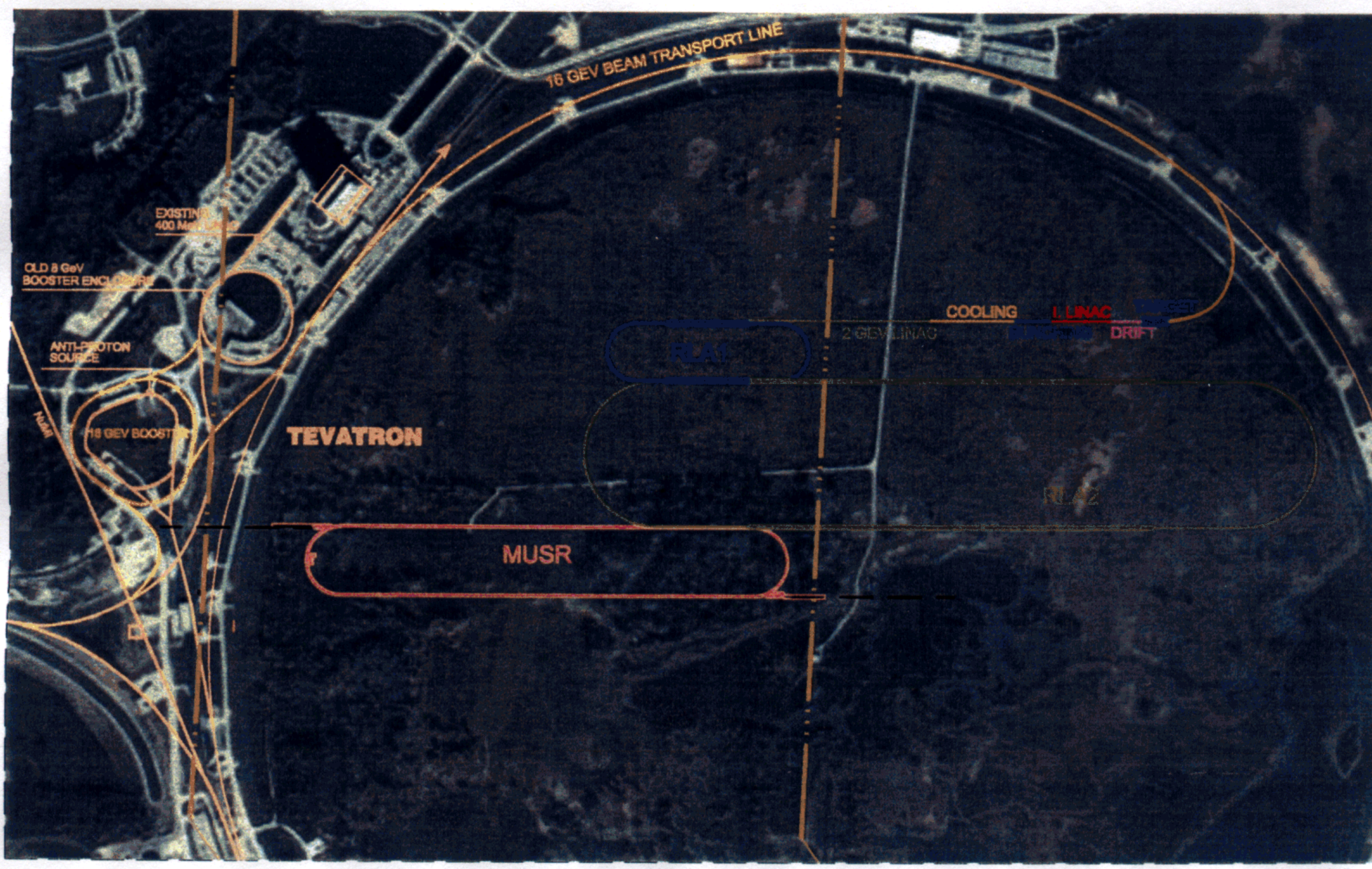


Fermi limit
0.1 mSv/year

Federal Limit
1.0 mSv/year

Layout on Fermilab Site

- Features
  - Fits neatly inside Tevatron footprint
  - Proton Driver feeds Target or Main Injector
  - Uses Tevatron tunnel to transport protons to Target
  - Meets extremely conservative interpretation of radiation limits



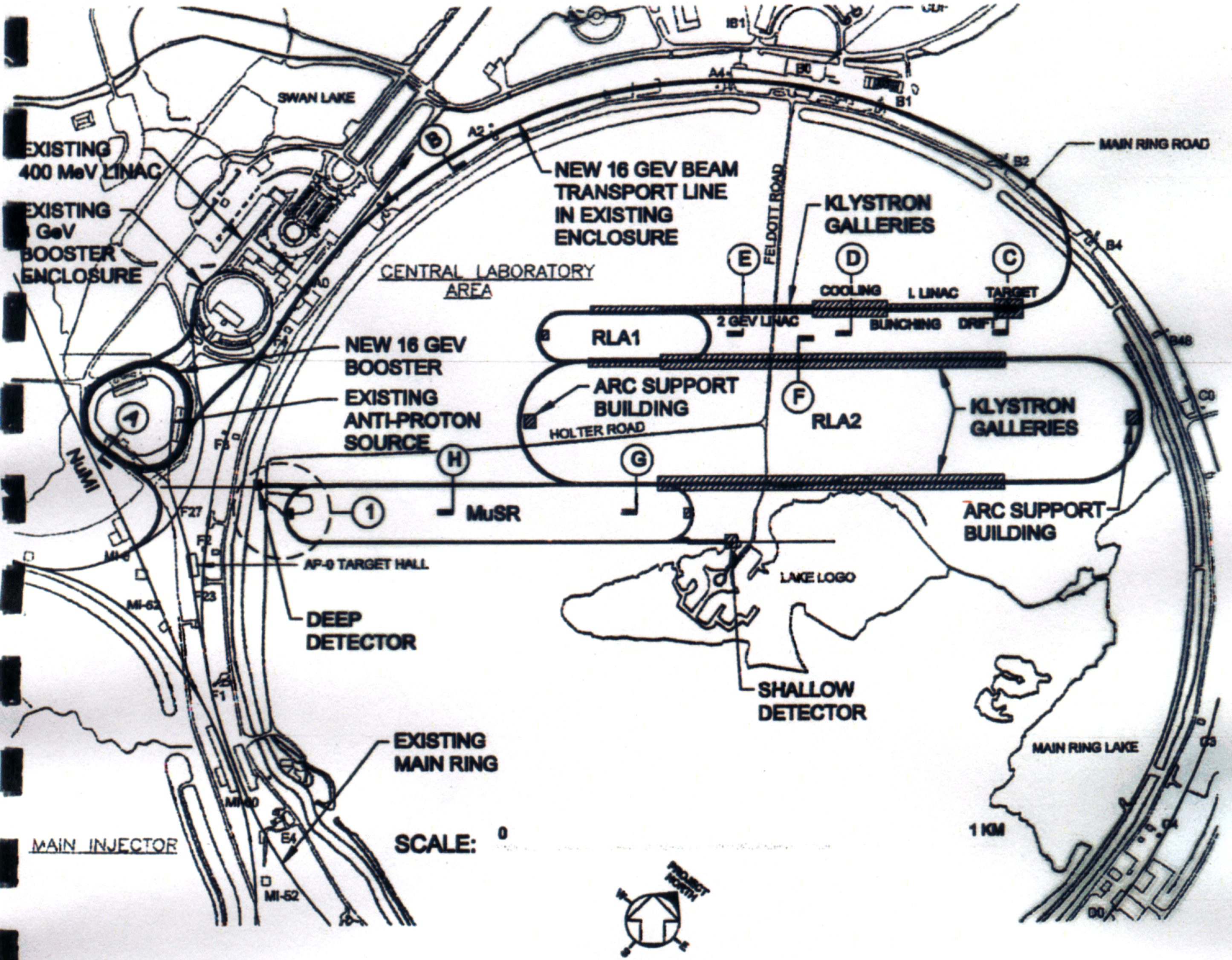


Figure 2: Sketch of the Neutrino Factory layout on the Fermilab site. The sections (A through F) and details (1 and 2) are shown in the Figures which follow. The hashed areas indicate new surface buildings.

Technical Feasibility

- Ten Subsystems

Table I made for myself at the beginning of the study

Sub-Component	Status Can we build it?	Risk	Save money? Make it easier?	right / wrong
Proton Driver	ok yes	moderate	yes less intensity longer bunches	right
Target	not ok no	high	power on target	right fixed it
Decay channel + ϕ rot	not ok may be	high	no back off in present design	right fixed it
mini cooling (factor of 3) (3 m LH2)	ok yes	low	no for this design less intensity	right
2[nd] ϕ-rotation (induct) linac	not ok may be	very high	only in exchange with low frequ. RF	wrong easier
capture	not ok mainly rf problem	high	no (a little) lower Frequ. rf	yes and no
cooling (factor of 50)	not ok mainly rf problem	high	no (a little) lower Frequ. rf	right more than rf problem
1[st] stage linac together with next row (RLAS)	½ ok yes	moderate	no	wrong not sure we can build it
RLA's	½ ok yes	moderate	no	wrong not sure
Storage Ring	ok yes	moderate	no compromise flux	easy
Diagnostic	not ok	moderate	no	right

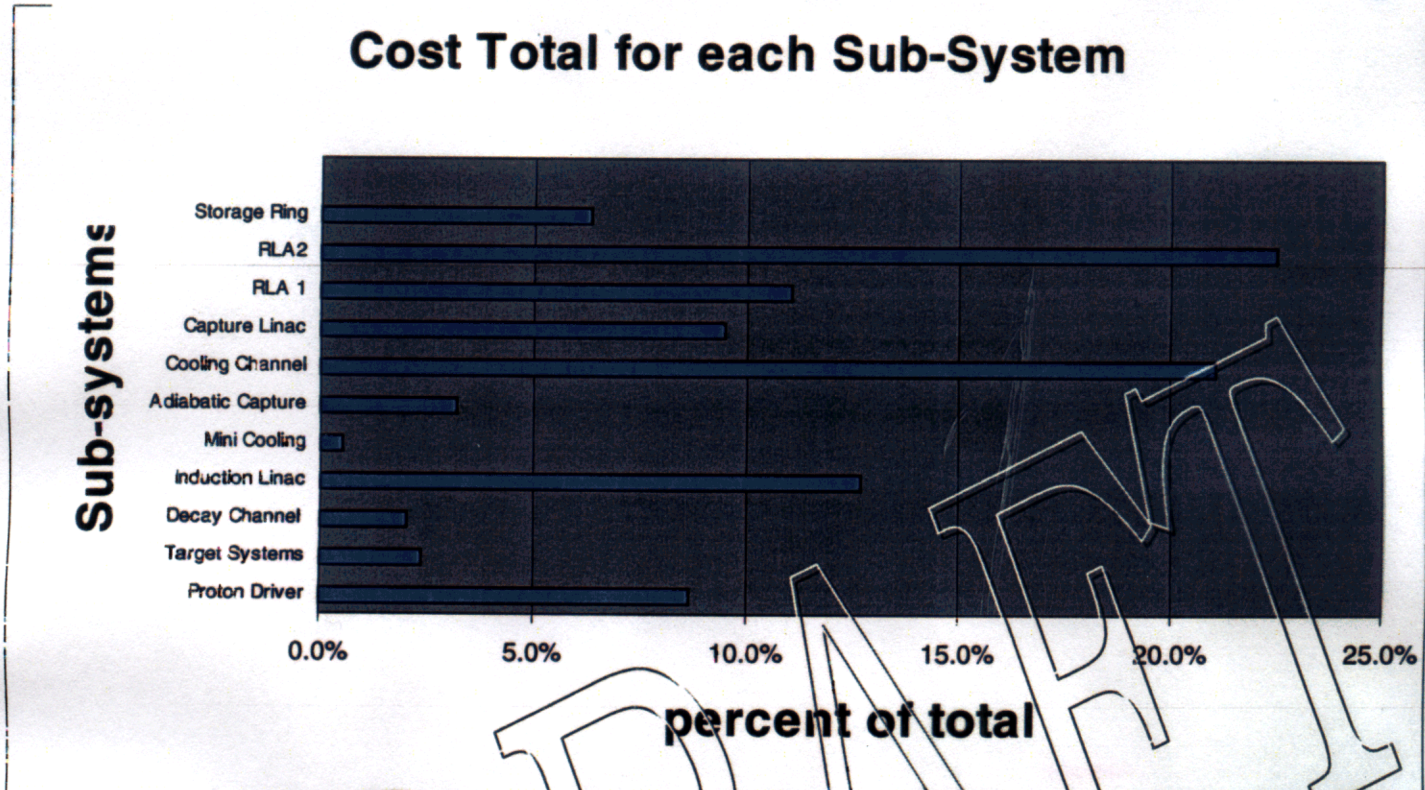
- **Cooling Performance limits the achievable flux**: 10^{19} ok, ~ $2*10^{20}$ only with working cooling channel -> intellectual R&D program
- **Acceleration is major cost driver**:Fast Acceleration of large emittance beams requires expensive rf sytems and beam transport channels.-> Aggressive hardware R&D program

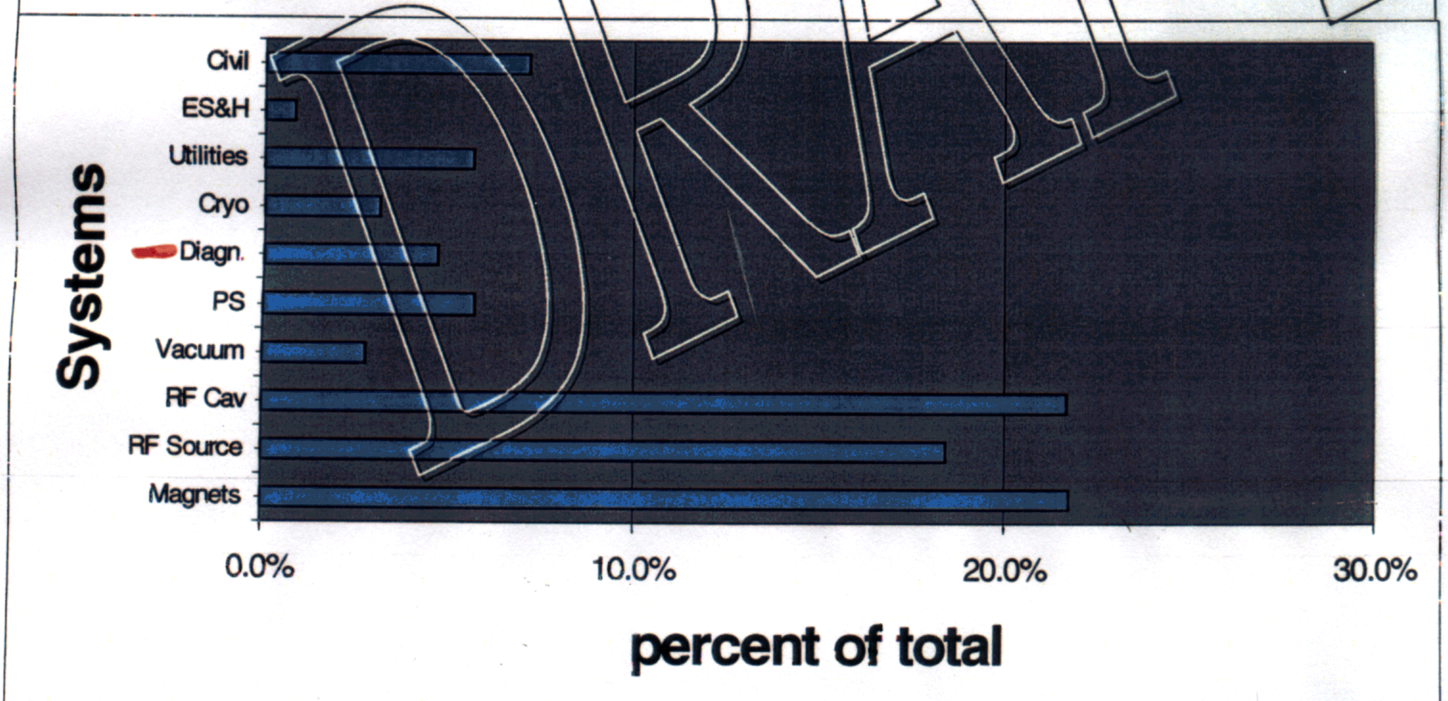
Technical Summary

- Aspects Coming out of of the Study
  - Worldwide Unique facility
  - Detector cost and Accelerator cost can be balanced
  - Long Term program ⇒ can be staged
  - Can fit under many existing sites
  - Diverse organizational and funding base: DOE / NSF / University / State (Illinois) / MCNF Collaboration ...

Cost Driver Analysis

- Presented at Fermilab April PAC Meeting





Initial Thoughts / Reactions

- Acceleration is a cost driver
  - no choice with this scenario ⇒ limited by transverse cooling we can achieve without emittance exchange
  - emittance exchange (exchange of longitudinal and transverse emittance): no solution available
  - more cooling does not necessarily mean less money
- Two possibilities:
  - stay with this scenario and develop the technology to accelerate this kind of an emittance
    - aggressive R&D program might bring us into a position to have a ZDR in a couple of years (~5)
    - make sure that we doen't exclude further improvements in the cooling
    - start with "minimal" scenario for number of Muons/year
    - may be start without cooling ~ 10^{19} μ/Y
  - go into a longer term R&D program and work on conceptual designs for better cooling channels.
    - No hardware R&D required now
    - Shift the ZDR stage an unknown number of years

Where Did We Fall Short?

- Diagnostics:
  - "How do you measure the emittance of the muons in a solenoid with pions, electrons etc going down the same channel?"
  - Required resolution: One cooling cell reduces $\varepsilon_{\perp}$ by ~ few % → thus need to measure at least 1/5th of that
- RLA Arcs:
  - need a lot more attention and is very preliminary
- Power consumption:
  - going to be a >100 MW facility

Where Did We Excel?

- Charge = Feasibility, Cost Drivers, R&D, ES&H
- Developed concept and demonstrated feasibility
  - Likely to go with a staged plan to fit various budget scenarios
  - Addressed ESH issues and concluded: If the new issues (MW beam power for Fermilab, and neutrino radiation hazards) are folded into the baseline design properly, it won't be a problem … but it will cost money.
  - Presented basically a long upgrade route: This is a program not a project
  - First cut on cost drivers indicates what needs to be controlled
- Involvement
  - NF and MC collaboration played a major role
  - Universities and NSF became part of this
  - other Laboratories got heavily involved

What is the Plan?

- R&D Plan for 5+ years
  - Proton driver ZDR (Fermilab's and BNL's)
  - Target test (Fermilab, ORNL, BNL, NHMFL)

  - Induction linac (LBNL)
  - Develop high gradient nc (Fermilab, LBNL, Cornell)
  - Cooling cell prototyping (IIT +++)
  - Prototyping of high field solenoids (Protvino, Fermilab)
  - RF power source development (SLAC)
  - SC RF development (Cornell, JLAB, CERN)

  - Prototyping of tungsten shielded chamber (Fermilab)

  - Diagnostics (Universities, NSF) (more money than CRYO ~~or~~ PS)
  - Simulation FNAL, LBNL, BNL, Universities, NSF

  - Detectors (NSF, Universities) → Balance cost: bigger detector