Neutrino Factories: Accelerator Facilities

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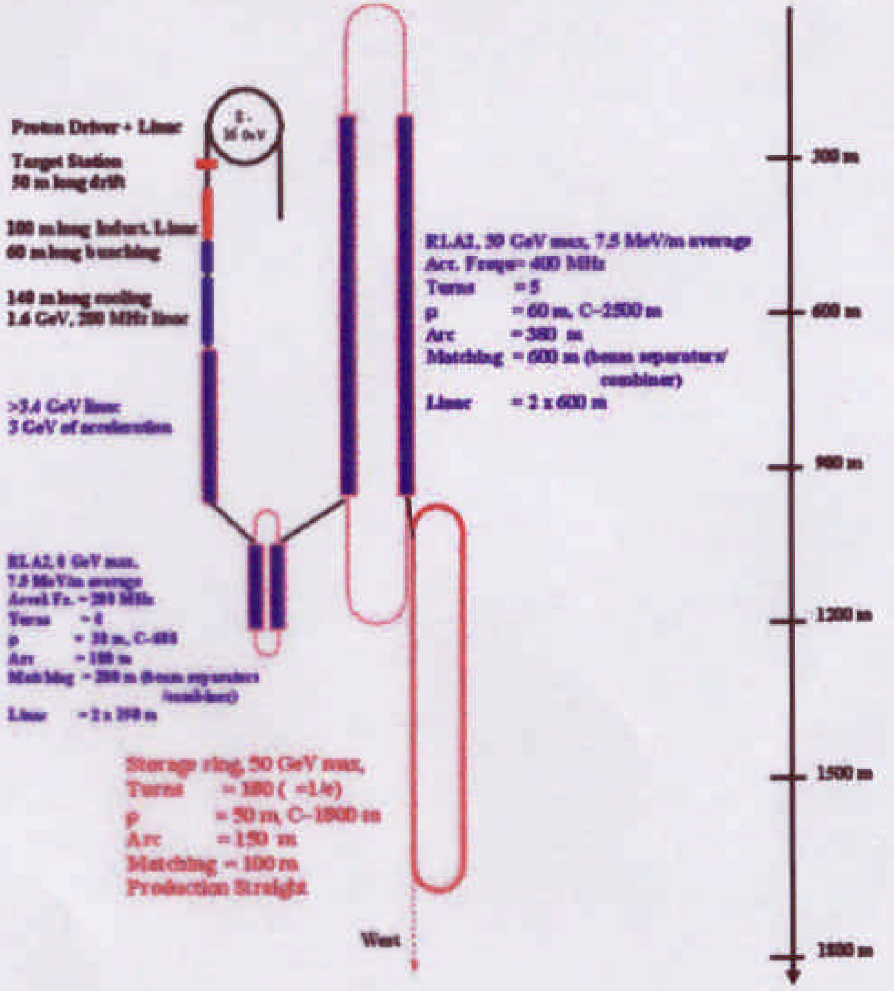
Fermilab Neutrino Factory Layout

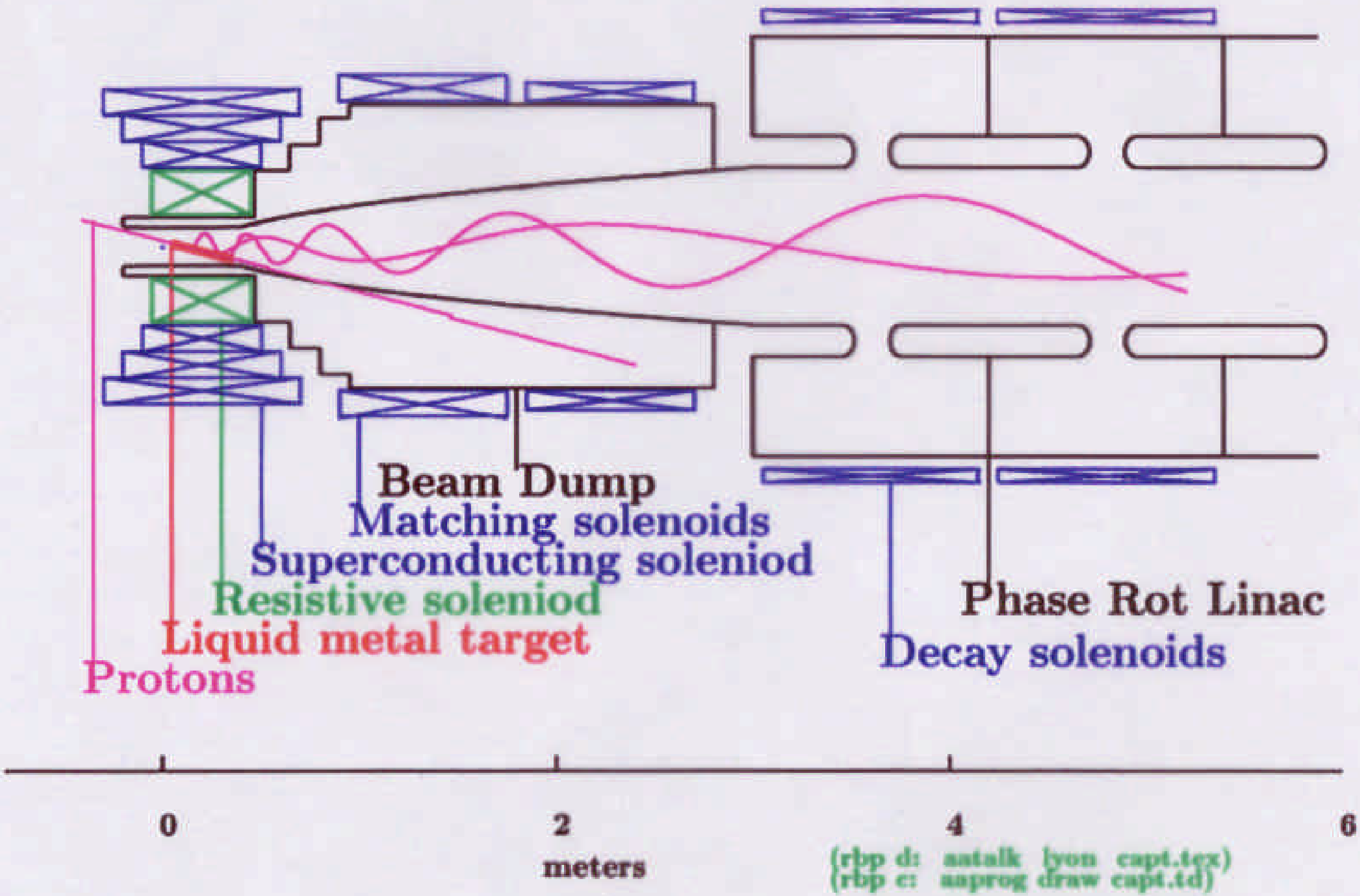
- p source
- p targetting
- π/μ collection
- μ cooling
- μ acceleration
- μ storage



Proton Sources

- Goals
  - A few short high-intensity bunches and not many long low-intensity bunches
  - Small proton losses for hands-on maintenance, avoiding remote handling
  - Beam power W a few MW
  - π/μ production insensitive to energy $2 \leq E \leq 30$ GeV at given beam power
  - At given W proton flux $\dot{N} \propto 1/E$
- Solutions
  - Inspired by existing synchrotrons and spallation neutron sources
  - SC linear accelerator with circular pulse compressor favoured at CERN
  - Rapid-cycling synchrotron(s) favoured elsewhere
  - Lower energy synchrotrons can cycle faster
  - All synchrotrons have equal numbers of protons N in a cycle if $f_{\mathrm{rep}}E$ and W are constant
  - Synchrotrons dominated by space charge

Targetting and Capture



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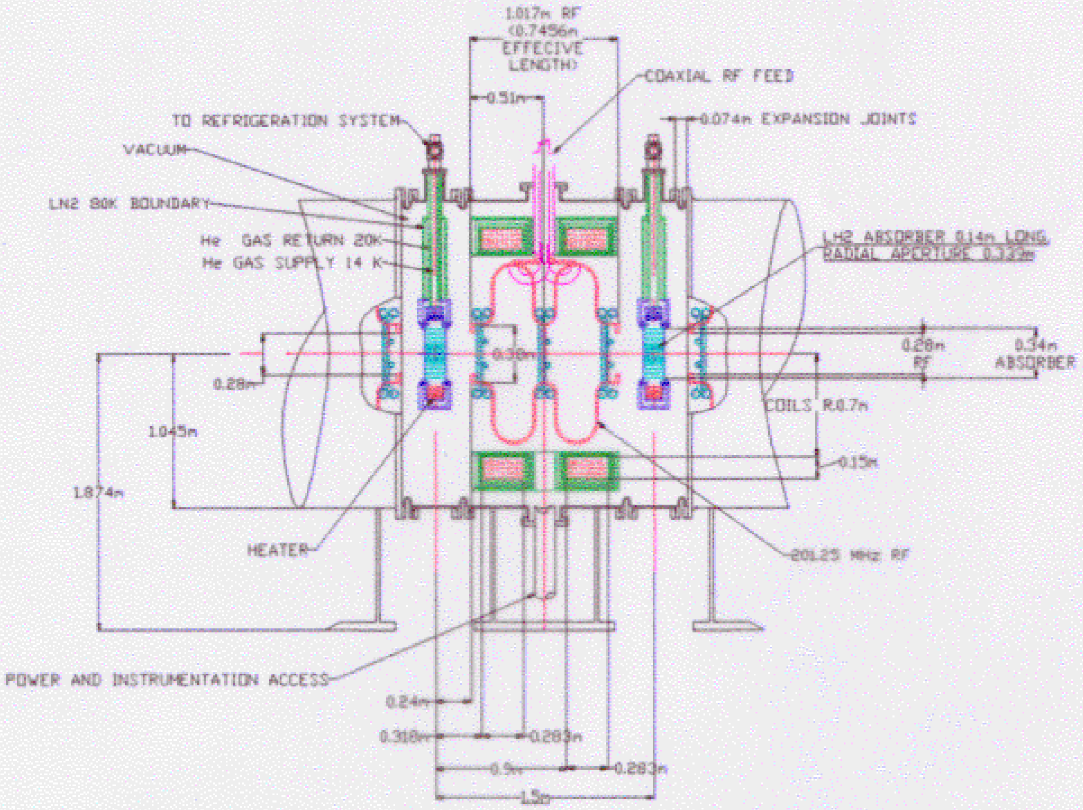
Targetting and Capture Issues

- Target material: Solid graphite or liquid Hg jet
- Magneto-hydrodynamic effects on moving conductor in magnetic field
- Field level and lifetime of Bitter solenoid surrounded by s.c. solenoid
- Radiation damage & heating & stresses in coils – shielding & dump
- Choice between solenoid channel and magnetic horns
- Maximum $p_\perp \approx 250$ MeV/c in solenoid given by field and aperture
- Maximum $p_\perp / p_\parallel$ in horn given by outer radius
- Capture μ with $200\ \text{MeV}/c < p_\parallel < 400\ \text{MeV}/c$
- Use correlation between $p_\parallel$ and t for "phase rotation", i.e. to reduce energy spread either with induction linac at FNAL or with RF systems at CERN
- This correlation makes p bunch length ≈ 1 ns desirable

Targetry experiment E951 at BNL

- Approved experiment coordinated by Kirk McDonald Princeton U
- Goals
  - Demonstrate performance of 1 MW target in high-field solenoid
  - Measure particle yield and compare to Monte Carlo codes
  - Demonstrate lifetime of solid and liquid targets
- R&D activities
  - Complete beam line A3 at BNL
  - Assess mechanical behaviour of target by thermal calculations
  - Develop 20 T solenoid and 70 MHz high-gradient RF cavity
  - Test solid target in beam
  - Test liquid Hg jet in high magnetic field at NHMFL in Florida
  - Complete tests with beam at 10^{14} p/pulse
- Tests of Hg jet at High Magnetic Field Laboratory in Grenoble?
- Particle production experiment HARP at CERN to include 2.2 GeV protons

Cooling Cell



LBNL LATTICE WITH FNAL RF CAVITY

E. L. Black
12/09/99

BERKLATTICE

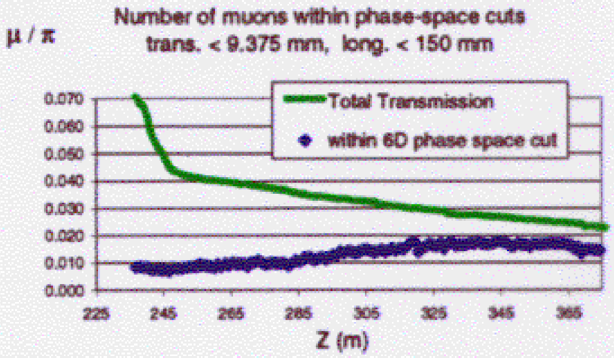
μ Cooling

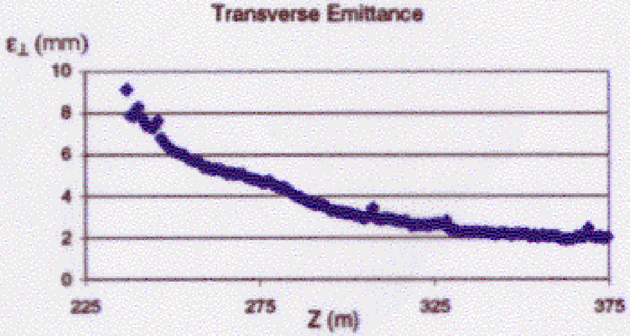
- Equation for cooling of normalised transverse emittance ε_n with characteristic scattering energy $E_s \approx 13.6$ MeV and radiation length L_r

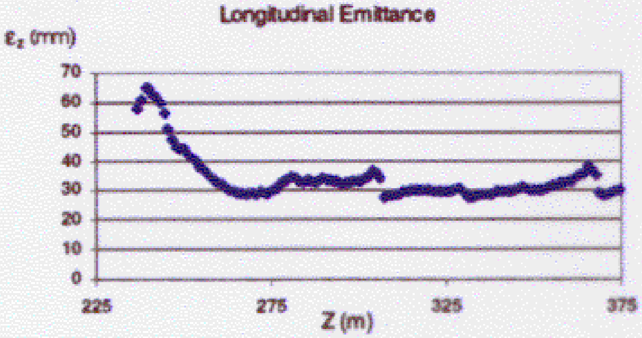
$$\frac{\mathrm{d}\varepsilon_n}{\mathrm{d}s} = -\frac{\varepsilon_n}{\beta^2 E}\frac{\mathrm{d}E}{\mathrm{d}s} + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_r E}$$

- Liquid H_2 absorbers with Al or Al-Be alloy windows 4 MeV
- Challenging fluid dynamics and thermal modelling of absorber heating 100 W
- Compensate ionization loss by high-gradient RF system with Be windows or grids of Al tubes across beam aperture
- Surround absorber and RF cavities with solenoid focusing to achieve small $\beta_\perp$
- Muon scattering experiment at TRIUMF by U Birmingham IC RAL Riken UCLA collaboration aims at distinguishing between scattering theories
- Everybody I know believes that ionization cooling works

Cooling Simulation







- Particles with large $\varepsilon_{\|}$ lost at entrance of cooling channel
- Constant $\varepsilon_{\|}$ downstream
- Cooling of $\varepsilon_{\perp}$ by factor $\approx$ 5 is less than hoped for
- Improve cooling

Cooling Experiments

- MUCOOL experiment at FNAL originally planned to demonstrate cooling at low emittance needed for $\mu^+\mu^-$ collider, adaptation to high emittance under way
- Any cooling experiment will be difficult because of needed accuracy of tracking devices
  - Expected emittance reduction is a few %
  - RMS scattering angles ≈ 1 mrad
  - Straggling small compared to 4 MeV
  - Mimimum material in tracking devices
- Some cooling demonstration essential for NF
  - MUCOOL was once proposed and funding agencies know about it
  - Provides focus for activity of study
  - Serves as basis for design of cooling section in NF
  - Demonstrates diagnostics for setting up real NF, not only cooling
- Failure of experiment would be a severe blow for NF

μ Acceleration

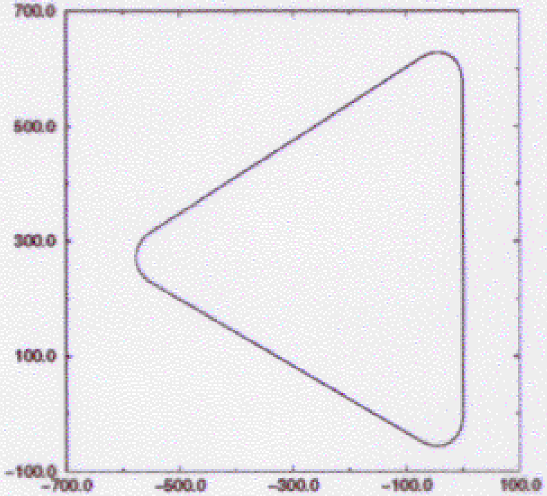
- Accelerating with a linear accelerator and one or more recirculating linear accelerators RLA similar to CEBAF is expensive
- RLA1 and RLA2 at CERN have 0.7 and 3.8 km of linear accelerators and 1 and 5 km circumference
- Super-conducting RF only way of avoiding too large peak RF power
- R&D towards desirable higher gradient: smaller RLA, smaller decay losses, less beam loading, but also shorter bunch trains
- Larger normalised emittance and/or lower injection energy implies lower f_{RF}
- Larger initial energy spread implies fewer passes in RLA
- Severe beam loading at repetition rates of few tens of Hz
- Alternatives
  - An-isochronous RLA accelerating off crest of RF waveform
  - Isochronous RLA accelerating on crest of RF waveform

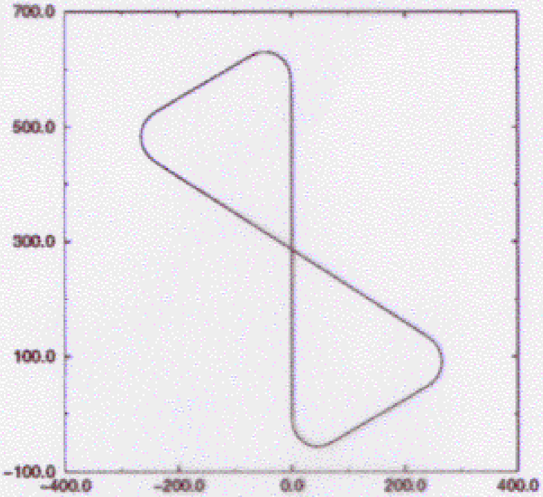
μ Storage Ring Parameters

	FNAL	CERN	
Energy	50	50	GeV
Shape	Racetrack	Triangle or Bowtie	
Distance to detector(s)	≈ 3000	1000 & 3000	km
Year	$2 \cdot 10^7$	10^7	s
Design ν fluence/detector	$2 \cdot 10^{20}$	$2.8 \cdot 10^{20}$	1/y
Normalised emittance ϵ_{xn}	3.2	1.67	mm
Relative RMS energy spread σ_e	1.0	0.5	%
Circumference	1753	2075 or 2008	m

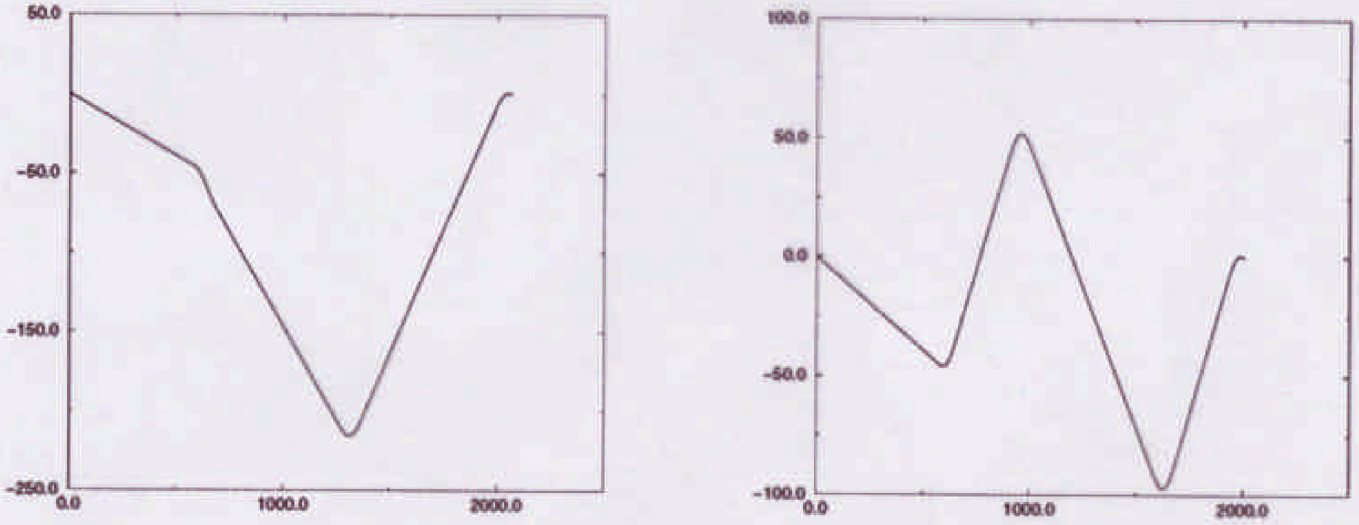
- CERN designs aim for 2.8 times the ν fluence/s of FNAL design
- CERN designs are more demanding than FNAL design on p source, targetting, collection, cooling, shielding
- CERN designs are less demanding on emittance ϵ_{xn}, momentum spread σ_e, physical and dynamic aperture for acceleration and storage

Geometries of μSR – (x, z)-Projection

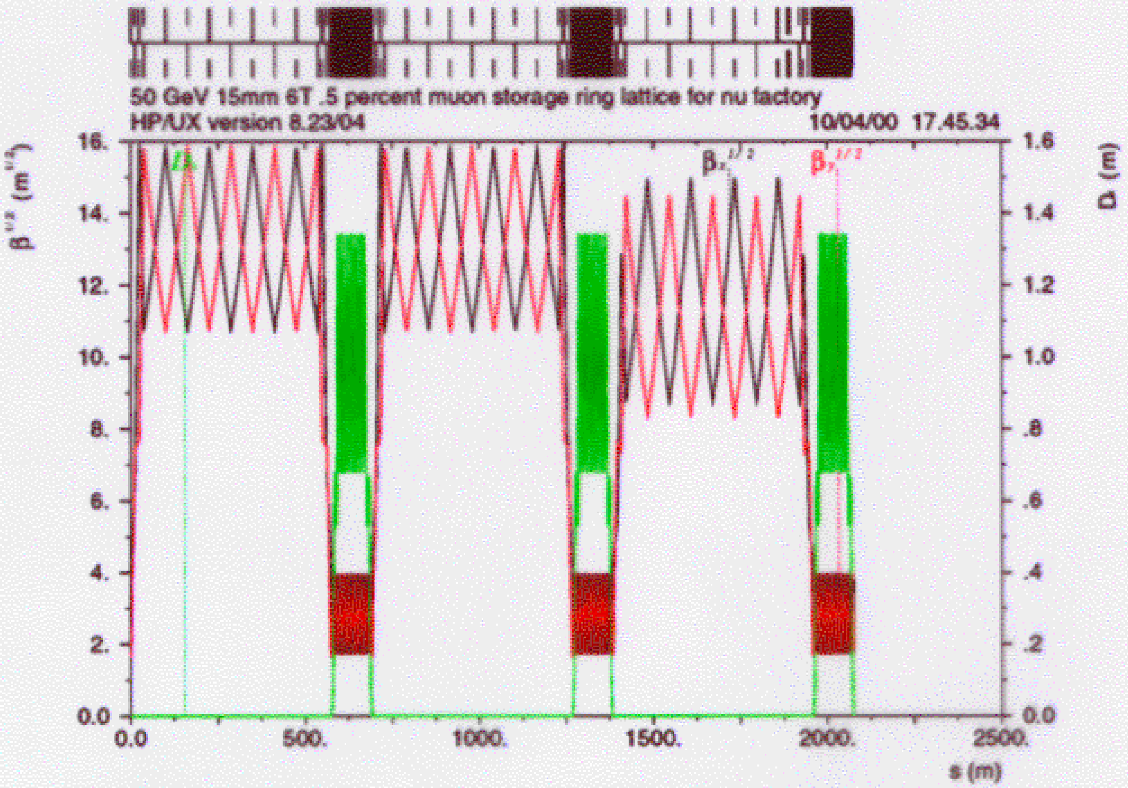




Geometries of μSR – $y(s)$



Optical Functions of Triangular μSR



$\delta_E/p_0c = 0.$

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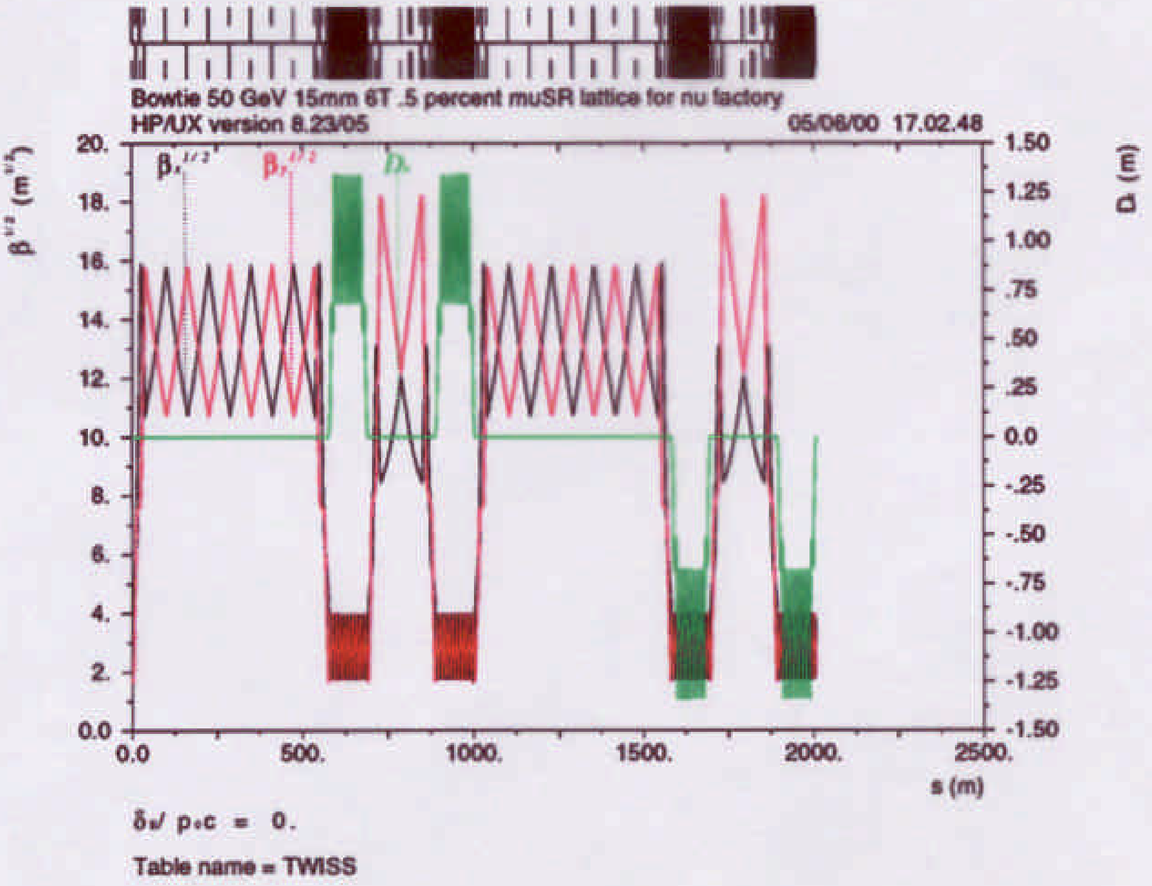
Optical Functions of Bowtie μSR



Energy Deposition along μSR

- *All* muons arriving in μSR decay there
- Power in $\mu^\pm$ beam ≈ 0.8 MW, hence power in $e^\pm \approx 0.28$ MW or ≈ 140 W/m or 70 kW from 500 m of straight section in CERN design
- Warm W liner inside super-conducting arc magnets absorbs most of this power
- Shower simulations by Mokhov show about 7 W/m in cold mass mass at FNAL
- Possible local enhancement of power deposition at entrance of arcs, because $e^\pm$ travel through long straight section and get lost in dipoles at entrance of arcs by energy loss due to synchrotron radiation
- Simulations for CERN design show that
  - 45 kW deposited in long straight section at room temperature
    $\Rightarrow$ use water cooled vacuum chamber with thick walls or absorbers
  - 21 kW deposited in matching section with mixture of room temperature and super-conducting magnets $\Rightarrow$ use absorbers
  - 3.5 kW deposited in 3 or 4 first $\Rightarrow$ special dipoles of dispersion suppressors
  - Negligible extra power beyond 140 W/m deposited in remainder of arcs

μ Storage Ring Issues

- First cycle of optical work essentially done
- Tracking realistic distributions of more than 10^4 muons through acceleration and storage ring for full life time is easy
- Automated generation of data with *Mathematica* procedures that guarantee correct geometry, thin-element strengths for most optical modules, and feed data into optical programs for finite-element matching, tracking, etc., implemented
- Engineers study components and their packaging, recommend magnetic fields B, propose cheaper alternatives, etc.
- Reconsider values for normalised emittance ε_n, relative momentum spread δ, muon fluence $\dot{N}$, etc.
- Another round of optical studies, using results of engineering and optimisation, and decisions on ν-factory and detector sites

Status of Neutrino Factory Studies

Parameter	pjk	FNAL	CERN	Units
Proton beam power	4	1	4	MW
Proton beam energy	24	16	2.2	GeV
Conversion factor	0.004	0.0011	0.0023	μ/p·GeV
Year	10^7	$2 \cdot 10^7$	10^7	s
Observed muon fluence into μSR	10^{21}	$1.6 \cdot 10^{20}$	$5.8 \cdot 10^{20}$	1/a
Expected muon fluence into μSR	10^{21}	$5.3 \cdot 10^{20}$	10^{21}	1/a

- Preliminary CERN figures
- High-performance ν factory study launched at BNL

Future Neutrino Factory R&D

- Assume that proof of principle will be achieved soon
- Put less emphasis on existence proofs and internal optimisation of modules
- Put more emphasis on optimisation across modules
- Consider shifting module boundaries
- Vary muon energy E
- Overall optimisation including detector(s), using product IM of muon fluence I and fiducial detector mass M far away
- Consider building NF in stages, increasing muon fluence I and energy E in steps
- R&D for NF offers wide scope for collaboration on global scale