R&D Needs for a Neutrino Factory

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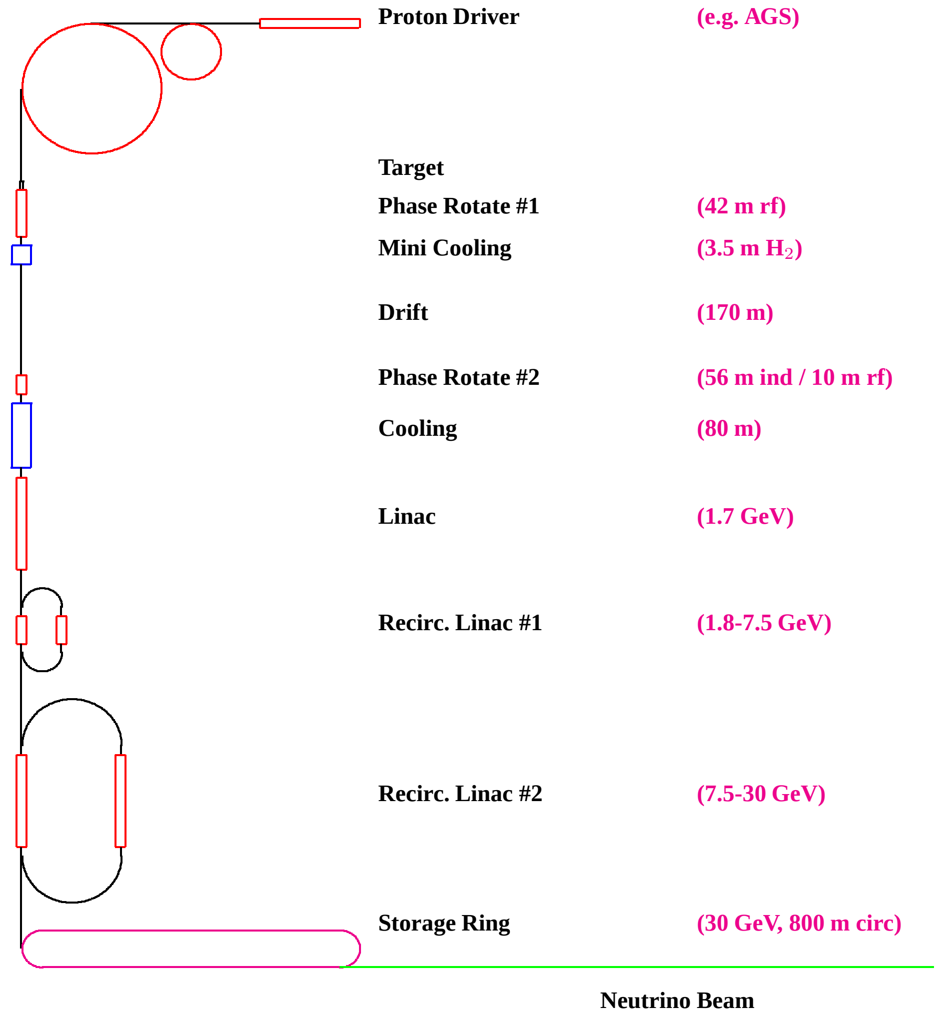
Abstract

The R&D needs for a neutrino factory, based on a muon storage ring, are presented. Such a neutrino factory consists of several modules, that all must be developed, namely: Intense proton source, pion production target and collection system, ionization cooling, acceleration and storage. R&D on these modules will be discussed in terms of theory and simulation, engineering prototypes, and experiments in particle beams.

Neutrino Factory Layout



Why do we need R&D?

- Neutrino factory NF design uses novel concepts for **several different** modules, e.g.
  - p sources
  - targetting
  - π/μ collection
  - μ cooling
  - acceleration
  - storage

  with a peak of novelty in the middle of the list
- R&D on NF must be done on many fronts at the same time
- Linear e^+e^- colliders LC and very large hadron colliders VLHC use novel concepts on a few types of modules that are repeated many times, e.g. accelerating sections, wave guides and RF power sources for LC, arc magnets for VLHC, and tunnel construction techniques for both
- If we could work out a conceptual design for a NF of adequate performance without R&D we would do it

Goals of R&D?

- Advance understanding of NF in order to be ready for Conceptual Design Report CDR in a few years
- R&D done in cycles, reconciling two conflicting aims:
  - consistency
  - openness for better ideas
- In each cycle define a scenario, i.e. a set of parameters for the beam, modules and performance of a neutrino factory which
  - is consistent, i.e. beam parameters at module boundaries agree more or less
  - has module parameters that are either within reach now or will be in future
  - orients engineering of prototypes
- Replace modules and/or scenarios by better ones at any time
- Cycle ends when scenario, performance, and engineering parameters of components/modules are consistent

Classes of R&D

R&D: Analytical calculations and simulation leading to ‘scenario’

- Develop and verify theory
- Find or develop and verify simulation tools
- Find module parameters, using theory, simulation and advice from engineers
- Optimise module parameters
- Optimise NF by shifting module boundaries

Prototyping: Engineering activity developing prototypes for modules

- Conceive
- Engineer
- Build
- Test

Experiments: Testing of components in beam

- Assemble system of modules that fit together
- Perform experiment within the boundaries of machine schedule
- Convince funding agencies that NF is worth funding

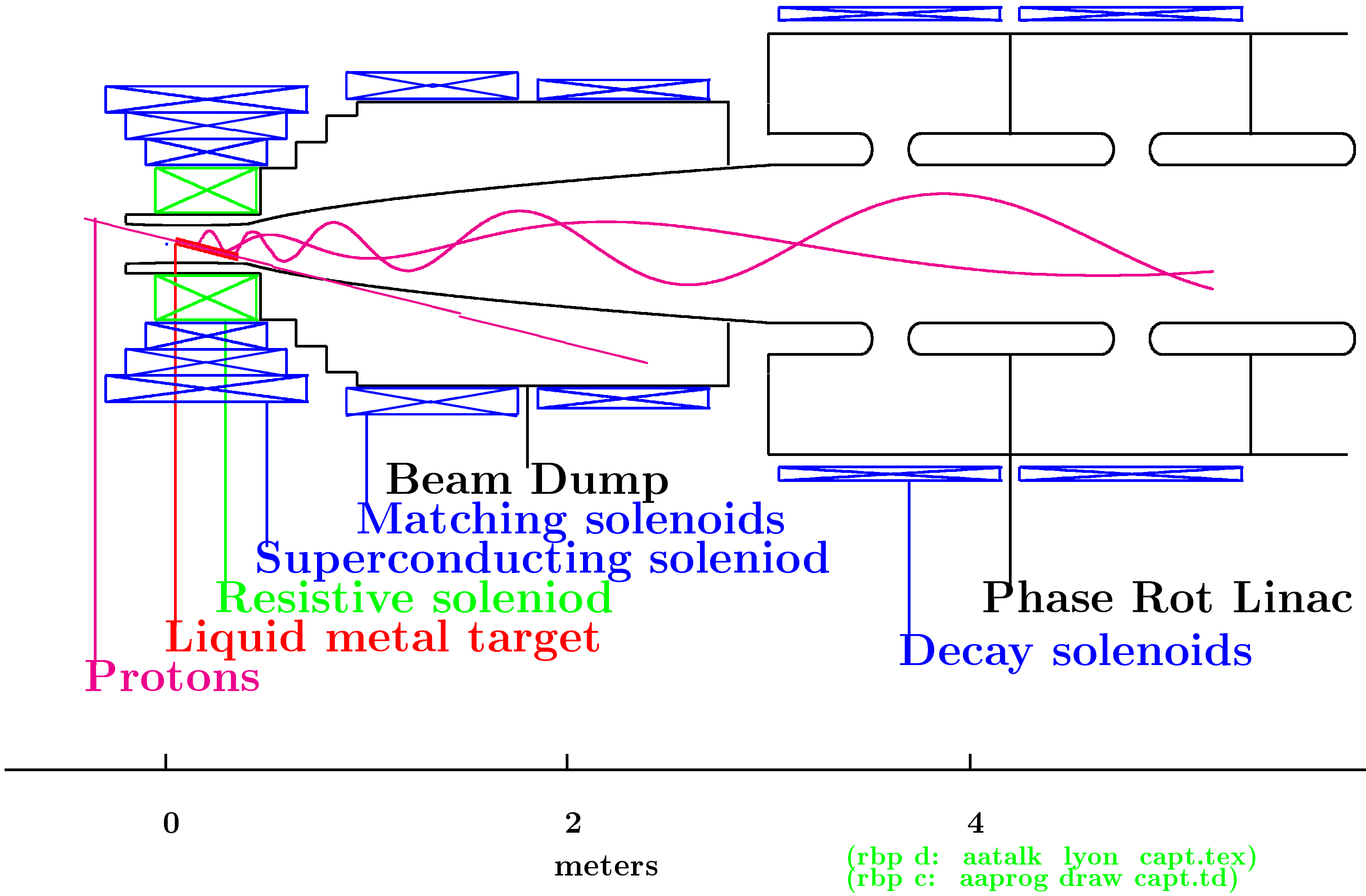
Relations between Classes of R&D

- Splitting R&D into 3 classes is a simplification
- Many problems in more than one class
- Use simulation to verify theory and vice versa
- Use insight into future engineering possibilities
- Choose parameters in ranges that might be achieved in practice
- Mutual understanding between theoreticians and engineers about their respective problems

R&D on 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



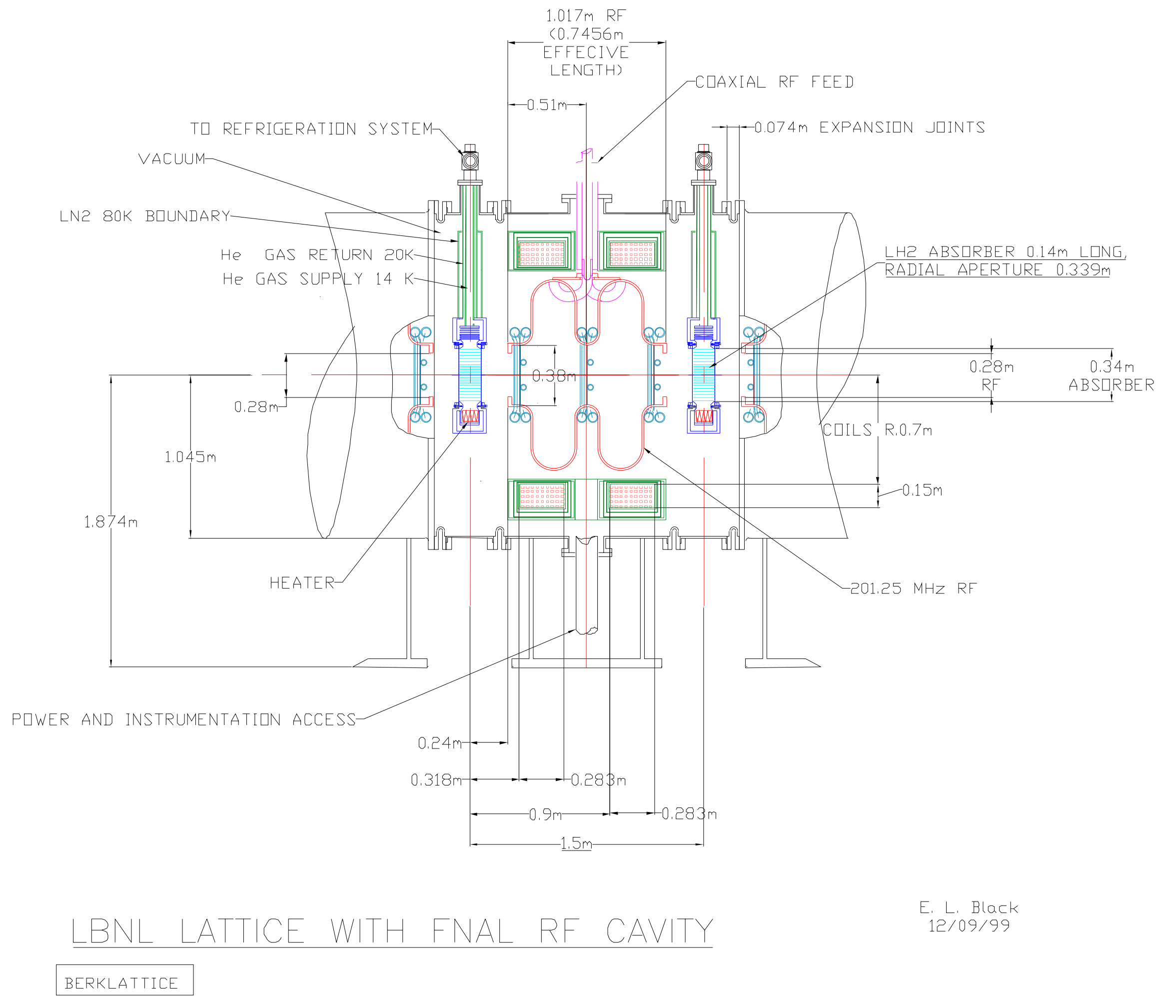
R&D on Targetting and Capture

- Target material: Solid graphite – liquid Hg jet – levitated moving band
- Magneto-hydrodynamic effects on moving conductor in magnetic field
- Field level and lifetime of Bitter solenoid surrounded by s.c. solenoid
- Radiation – heating – stresses in coils – shielding
- Choice between solenoid channel and magnetic horns
- Use correlation between E and β for "phase rotation", i.e. to reduce energy spread either with induction linac in FNAL study or with RF systems in CERN study

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 π and n 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
- Similar target tests in Europe?
- Particle production experiment HARP at CERN

Cooling Cell



R&D on 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

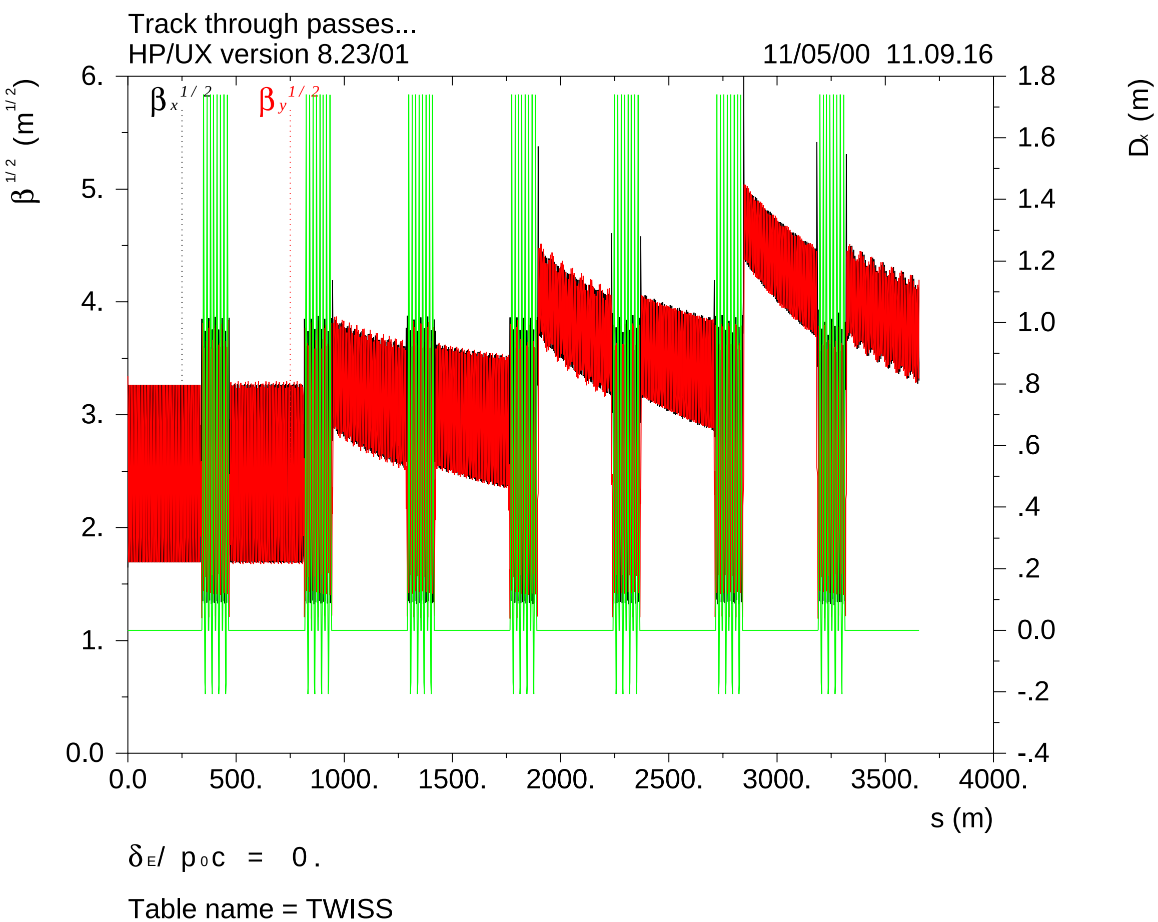
$$\frac{\mathrm{d}\varepsilon_n}{\mathrm{d}s} = -\frac{\varepsilon_n}{\beta^2 E}\frac{\mathrm{d}E}{\mathrm{d}s} + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_r E}$$

- 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 theories
- Everybody I know believes that ionization cooling works

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
- Accuracy of tracking devices in cooling experiment determined by
  - Expected emittance reduction is a few %
  - RMS scattering angles $\approx$ 1 mrad
  - Straggling small compared to 4 MeV
- Any cooling experiment will be difficult
- Some cooling demonstration essential for NF
  - Provides focus for activity of study
  - Demonstrates beam diagnostics needed for setting up a real NF, not only cooling
  - Serves as basis for design of cooling section in NF
- Failure of experiment would be a severe blow for NF

Optical Functions in μRLA1 at CERN



R&D on μ Acceleration

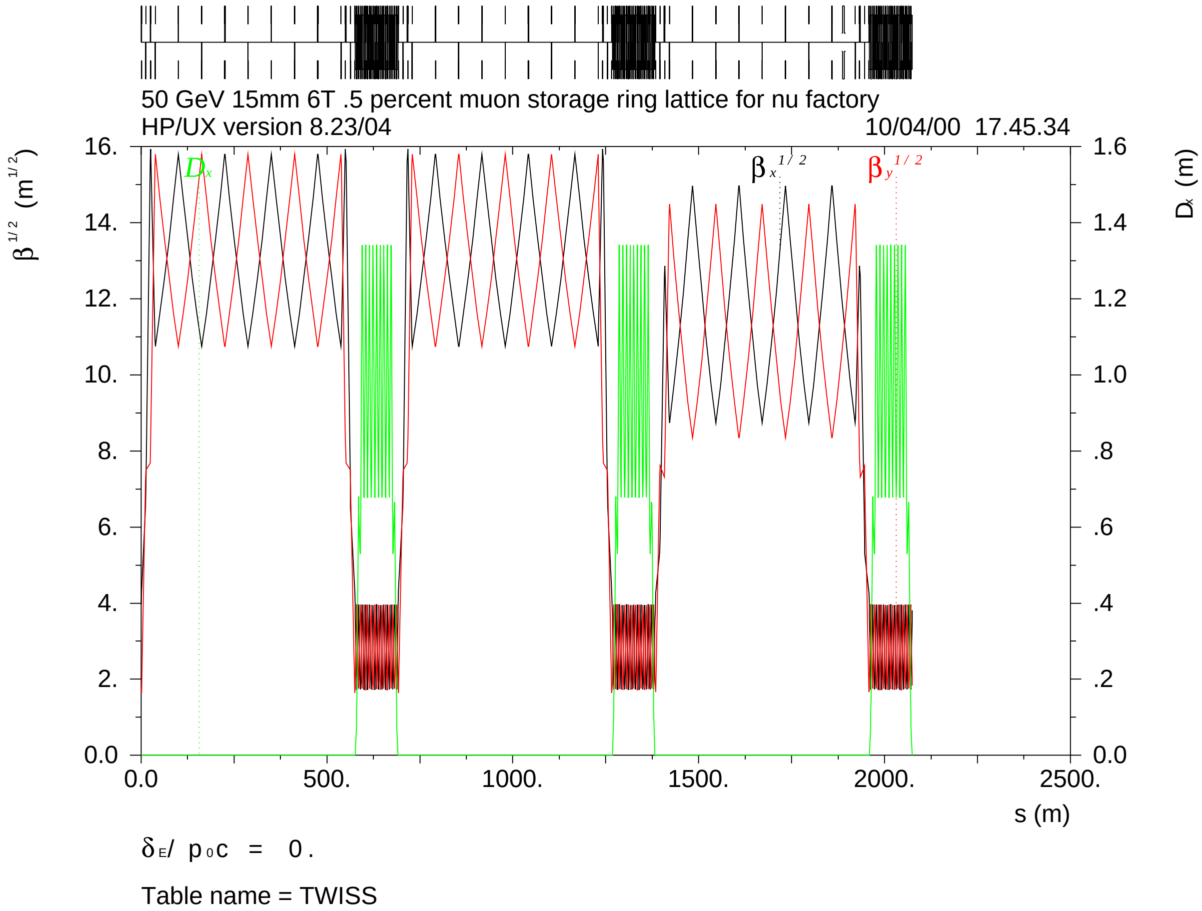
- Accelerating with a linear accelerator and one or more recirculating linear accelerators RLA similar to CEBAF is expensive
- Super-conducting RF only way of avoiding too large peak RF power
- R&D towards desirable higher gradient: smaller RLA, smaller decay losses, less beam loading, but also shorter bunch trains
- Larger normalised emittance and/or lower injection energy implies lower RF frequency
- 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	
Distance to detector(s)	≈ 3000	1000 & 3000	km
Year	$2 \cdot 10^7$	10^7	s
Neutrino 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	1.753	2.075	km

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

Optical Functions of μSR at CERN



R&D on μ Storage Rings

- First cycle of optical work essentially done with few outstanding items:
  - Study effects of alignment and field shape errors
  - Improve chromatic behaviour
- Tracking realistic distributions of more than 10^4 muons through acceleration and storage ring for full life time is easy
- Engineers study packaging of components, propose cheaper alternatives, etc.
- Reconsider values for normalised emittance ε_n, relative momentum spread δ, muon fluence $\dot{N}$, magnetic fields B, etc.
- Another round of optical studies, using results of engineering and optimisation
- Automated generation of data with *Mathematica* procedures that guarantee correct geometry, thin-element strengths for most optical modules, and feed data into optical program MAD for finite-element matching, tracking, etc.

Future Directions for Neutrino Factory R&D

- Assume that proof of principle will be achieved soon
- Less emphasis on internal optimisation of modules
- More emphasis on optimisation across modules
  - shifting module boundaries
  - include cost of detector(s)
  - vary muon energy
- Overall optimisation including detector(s), using product EIM of energy E, fluence I and fiducial detector mass M far away
- Consider staging in muon fluence I and energy E
- R&D for NF offers wide scope for collaboration on global scale