Accelerator Scenario

and

Parameters for the Workshop

Chuck Ankenbrandt

Nov. 6, 1997

Accelerator Scenario

> Design Driven by $\mu\mu$ Collider Requirements

> {Compatible / Symbiotic} with other programs

> Concepts stable, numbers variable

> For this workshop, use same parameters as in summer study

Proton Driver Specs for $\mu\mu$ Collider

(Not a fixed target!)

Energy	16 GeV		
No. protons	10^{14} total		
No. bunches	4	$\longrightarrow$	2
Np / bunch	2.5×10^{13}		5×10^{13}
Rms bunch length	~ 1nsec		
Rep. Rate	15 Hz		

fermilab report

Fermi National Accelerator Laboratory Monthly Report

August 1986
September

It is a bad plan that admits of no modification.

(Malum est consilium, quod mutari non potest.)

Publilius Syrus
Sententiæ. No. 469
Circa 45 B.C.

A Two-Ring Proton Driver

for the

$\mu^+\mu^-$ Collider

Chuck Ankenbrandt

Fermilab

Nov. 6, 1997

> Argonne Workshop, Autumn '96
> Vancouver PAC, Spring '97
> Orcas Island, Spring '97
> Fermilab Summer Study, Summer '97

THE PROTON DRIVER FOR THE $\mu\mu$ COLLIDER*

J. Norem, Argonne National Laboratory, Argonne, IL, 60439 USA
C. Ankenbrandt, J. Griffin, C. Johnstone, S. Y. Lee, M. Popovic, K. Y. Ng, Fermilab, Batavia, IL 60510 USA
M. Brennan, T. Roser, D. Trbojevic, J. Wei, Brookhaven National Lab, Upton, NY 11973 USA

Abstract

The proton driver for the $\mu\mu$ collider might operate at about 15 Hz and produce four bunches of $2.5\cdot10^{13}$ protons/bunch at about 10 GeV (or half that number at 20 - 30 GeV) with an rms bunch length of about 1 nsec. A number of options have been considered to produce these bunches using: a) simple bunch rotation, b) energy slewing near γ_t followed by a fast increase of γ_t which facilitates bunching, and c) change of rf frequency in a ring-to-ring transfer. Flexible Momentum Compaction (FMC), or similar, lattices seem to offer control of γ_t even on short time scales. The large momentum spread, space charge tune shift and rapid bunching would tend to stabilize short, intense bunches, although I_{pk} ~ 1600 A. Both active (harmonic cavities) and passive (inductive wall) solutions have been considered to minimize high current beam effects. Magnet and vacuum systems would be similar to other high current designs.

1 REQUIREMENTS

The specifications on the proton driver for a $\mu\mu$ collider follow from the muon bunch parameters desired in the collider and from the capabilities of the systems for muon production, collection, cooling, and acceleration. Designs for these systems have been discussed at length in the "Snowmass Book" [1]. Although there is considerable latitude in the choice of system parameters, it is clear that a high-performance muon collider requires a high-performance proton driver. In general, delivery to the production target at a high repetition rate of a few short, intense proton bunches of moderate energy is necessary. The two parameter sets in Table I, adapted from reference [1], typify the formidable requirements on a proton driver for a 2 TeV x 2 TeV collider with luminosity of order 10^{35} cm^{-2}sec^{-1}. Of course the specifications on the proton driver and/or on the other systems can be relaxed for a less demanding collider, such as a demonstration machine at lower energy and luminosity.

Table I. Typical Proton Driver Requirements

Energy	30	10	GeV
Repetition Rate	15	30	Hz
Bunches	4	2	
protons/bunch	$2.5\cdot10^{13}$	$5\cdot10^{13}$	
Rms bunch length	1	1	nsec

Except for the short bunch lengths, these beam specifications are similar to those for recently designed medium-energy hadron facilities and spallation neutron sources, and so similar approaches are possible. (The short bunch lengths are needed to keep the initial longitudinal emittance of the muons as small as possible, thereby simplifying their collection and subsequent cooling; shorter bunches also allow production of muon beams of higher polarization.) The need for short bunches can be addressed either by adding systems such as a compressor ring or multiple chicanes downstream of the proton acceleration stage(s) or by integrating the short-bunch requirement into the acceleration stage(s). (A companion paper at this conference presents more detail on bunch-shortening strategies.[2])

2 THREE ALTERNATIVES

Three proton driver designs have been considered. The first two columns of Table II show major accelerator parameters of the first two approaches, a 30 GeV synchrotron loosely based on the AGS and a single 10 GeV synchrotron with a 1 GeV linac injector. These two options were described in the "Snowmass Book" [1], and so they will not be discussed further here. This paper presents a third alternative that has been developed since the Snowmass meeting: an 8 GeV, two-ring complex in which the bunch-shortening strategy is integrated into the design of the two synchrotrons. The last two columns of Table II show major accelerator parameters for the two rings of this latter option.

Table II. Major Synchrotron Parameters

Final Energy	30	10	8		GeV
Booster Energy	3.6		4	4	GeV
Injection Energy	0.4	1		1	GeV
Circumference	1080	580	474	158	m
Tune shift	0.1	0.2	0.4	0.4	
Transition energy	40	10-14	14	7	
RF Harmonic	12	8	84	4	
Long Emittance	4.5	2.5	1	0.5	eV-s
Voltage /turn	4	1.8	0.5	0.2	MV

*Work supported by US Department of Energy under contracts with the respective laboratories.

PTr

A DEVELOPMENT PLAN FOR THE FERMILAB PROTON SOURCE

Edited by S. D. Holmes

for the Proton Source Summer Study Group:

C. Ankenbrandt, C. Bhat, B. Brown, W. Chou, N. Gelfand, J. Griffin, D. Herrup, S. Holmes, J. Holt, D. Johnson, C. Johnstone, I. Kourbanis, J. Lackey, P. Martin, E. McCrory, F. Mills, N. Mokhov, C. Moore, A. Moretti, D. Neuffer, K-Y. Ng, R. Noble, J-F. Ostiguy, M. Popovic, C. Schmidt, S. Shukla, J. Steimel, I. Terechkine, R. Tomlin, R. Webber, and D. Wildman

August 1997

TABLE OF CONTENTS

Design Concepts for Proton Driver

- ≥ 2 Rings in Series
- Rapid (15 Hz) cycling, resonant p.s.
- Manage $\Delta\nu_{sc}$ by large ε_L and ε_T
- Avoid transition (FMC lattices)
- Bunch rotations at extraction from each stage
- Bypass first stage(s) to fill Main Injector
- Stretcher ring for slow spill from last Booster

Two rings are better than one

- The bunch area is smaller

$$A_b = \Delta p \cdot C/h$$

- High line density at the space charge limit

$$\Delta \nu_{sc} = -\frac{3}{2} \frac{r_p}{\varepsilon_n} \frac{N_{tot}}{\beta \gamma^2 B}$$

- Can do two bunch rotations
- Smaller apertures

$$s_{1/2} = \sqrt{\frac{\varepsilon_n \beta_L}{\beta \gamma}}$$

First ring: smaller β_L
Second ring: higher β_L

- Fewer rf cavities

First ring: Small $E_{max} - E_{min}$
Small Radius

2[nd] ring: Small $f_{rf,max} - f_{rf,min}$
$\Rightarrow$ High voltage cavities

Space-charge tune shift formula

$$\Delta\nu_{sc} = -\frac{3}{2}\frac{r_p\, N_{tot}}{\varepsilon_n \beta\gamma^2 B}$$

$B \equiv$ Average Beam Current / Peak Cur.

N_{tot} = No particles in ring

$r_p = 1.54\times10^{-18}\,m$

$$\beta\gamma^2 = pE/m_p^2$$

Use p or E for scaling, not K.E.

K.E.	1	3	8	24
E	2	4	9	25

One factor of p for circumf. ratio;
one factor for compression ratio

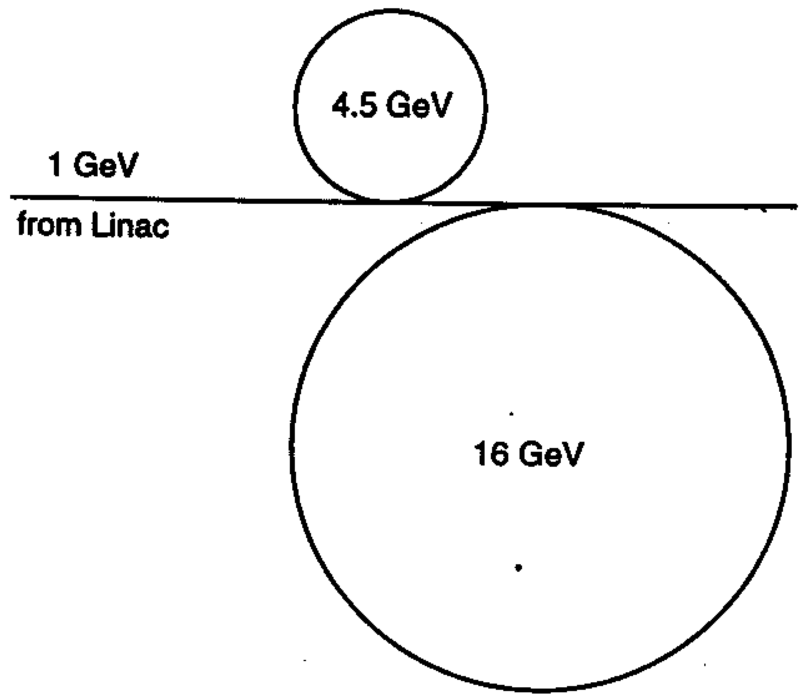


Figure II.1: Geometry of a new proton source. The 4.5 GeV pre-booster is situated to allow injection into the 16 GeV booster either directly from the linac or via the pre-booster.

II.2 Linac

At present the Linac delivers 1.6×10^{13} protons per pulse at a 15 Hz rate through the low energy linac for NTF treatment. This represents a pulse of 45 mA for 57 μs. This same current passes through the high energy linac to 400 MeV but with a pulse length seldom longer than 30 μs at 15 Hz. Since the high energy system runs continuously at 15 Hz with more than a 100 μs rf pulse length, operating at 1.6×10^{13} p/pulse at a 15 Hz rate for the full Linac is easily done.

The requirement for support of muon collider operations is 1×10^{14} protons per pulse at a 15 Hz at 1.0 GeV. The average current is a factor of six-to-ten beyond current capabilities, depending upon the extent of pre-bunching, while the energy is 600 MeV higher than the current facility. The upgrade strategy currently envisioned is a modest increase in the operating current, a significant increase in the pulse length, and construction of an additional 600 MeV of 805 MHz, side coupled linac identical in structure to the downstream end of the current linac. It is currently assumed that the linac would be relocated as part of this upgrade, although a plan to leave the existing structure where it is and extend through the to-be-abandoned Booster enclosure might be feasible.

Upgrading the existing linac

With a small effort it is likely that a pulse of 60 mA and 90 μs could be achieved. This represents a beam of 3.4×10^{13} protons, which at a 15 Hz rate provides 5×10^{14} p/sec. Increasing the ion source to reach this current has been studied and appears possible. The pulse length would at most need some correction for the voltage droop on the Pre-accelerator using a bouncer

Accelerator Experiments

Fermilab Booster: Bunch shortening

Los Alamos PSR: Inductive Inserts

cf talk by J. Griffin this afternoon

Brookhaven AGS: Bunch shortening

Bunching Near Transition in the AGS

Short bunches with bunch area of ~1.3 eV-sec and $\sigma = 2.85$ ns have been produced in the AGS by flattopping the machine near transition and reducing the transition energy to the beam energy using the γ_t jump system. A charge of 3 x 10^{12} protons/bunch was used in these tests.

red: before bunching
blue: after bunching
green: fitted $\sigma = 2.85$ ns

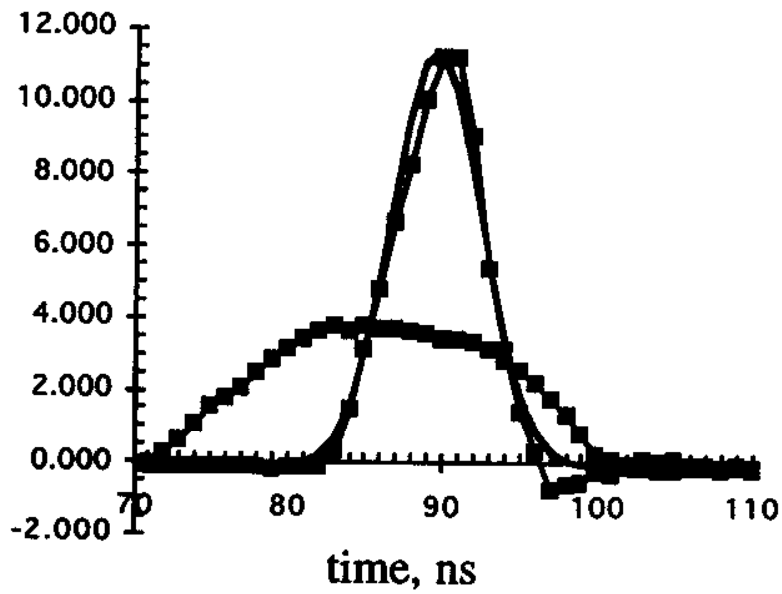


Table III.1: Operational parameters for the Proton Source at each implementation step.

	Boo Step 1 Scenario 1	Liu Step 1 Scenario 2	Step 2	Step 3 PreBoo	
Linac					
Energy (Kinetic)	400.0	1000.0	1000.0	1000.0	MeV
Current	48.0	48.0	48.0	65.0	mA
Pulse Length	45.0	67.1	112.0	328.5	μsec
Chopping Fraction	0.75	0.75	0.75	0.75	
N_{TOT}	1.0E+13	1.5E+13	2.5E+13	1.0E+14	H-
Momentum Spread (95% FW)	1.0	1.0	1.0	1.0	MeV
Repetition Rate	15.0	15.0	15.0	15.0	Hz
Pre-Booster					
Bunches				2	
N/bunch				5.0E+13	protons
Circumference				180.6	m
Injected Turns				477	
Transverse Acceptance (normalized @ injection)				450π	mm-mr
Emittance (95%, normalized)				200π	mm-mr
Physical Aperture (Half-height)				61	mm
Bunching Factor				0.25	
Space-charge Tune Shift				0.40	
Longitudinal Emittance (95%, per bunch)				1.8	eV-sec
Extraction Energy (Kinetic)				4.50	GeV
Repetition Rate				15	Hz
Booster					
Bunches	84	84	84	2	
N/bunch	1.2E+11	1.8E+11	3.0E+11	5.0E+13	protons
Bunch Length (rms)	2.7	2.2	2.2	8.6	nsec
Circumference	474.2	474.2	474.2	474.2	m
Injected Turns	20	37	62	1	
Transverse Acceptance (normalized @ injection)	80π	68π	142π	450π	mm-mr
Emittance (95%, normalized)	50π	30π	50π	240π	mm-mr
Physical Aperture (Half-height)	49	27	49	49	mm
Bunching Factor	0.26	0.26	0.26	0.02	
Space-charge Tune Shift	0.40	0.39	0.39	0.39	
Longitudinal Emittance (95%, total)	2.2	1.8	1.8	4.0	eV-sec
Extraction Energy (Kinetic)	16.0	8.0	16.0	16.0	GeV
Bunch Length at Extraction (95%, HW)	4.9	4.9	4.9	2.3	nsec
Momentum Spread at Extraction (95%, HW)	0.0%	0.0%	0.0%	1.2%	
Repetition Rate	15	15	15	15	Hz
Main Injector (Booster Batch)					
Bunches	84	84	84		
N/bunch	1.2E+11	1.8E+11	3.0E+11		protons
Bunch Length (rms)	2.0	2.0	2.0		nsec
Circumference	3319.0	3319.0	3319.0		m
Trev	11.1	11.1	11.1		μsec
Transverse Acceptance (normalized @ injection)	76π	40π	76π		mm-mr
Emittance (95%, normalized)	50π	30π	50π		mm-mr
Space-charge tune shift	0.01	0.11	0.03		

Table I.2: A possible allocation of Proton source cycles based on 15 Hz operations.

	Booster Intensity	Rate (Hz)	
Near Term Hadron Program			
Required upgrades: Booster shielding			
Booster supercycle: 28/15 sec			
Antiproton production	5×10^{12}	0.536	Run II goal
NUMI	5×10^{12}	2.678	NUMI request
MiniBooNe	5×10^{12}	4.821	MiniBooNe request
Booster Muons	5×10^{12}	6.964	
Booster supercycle: 43/15 sec.			
Antiproton production	5×10^{12}	0.349	Run II goal
KAMI	5×10^{12}	1.744	Available for slow spill
MiniBooNe	5×10^{12}	4.884	MiniBooNe request
Booster Muons		8.023	
Longer Term Hadron Program			
Required upgrades: Linac upgrade, new (relocated) Booster			
Booster supercycle: 28/15 sec.			
Antiproton production	2.5×10^{13}	0.536	Antiproton production × 5
MIST	2.5×10^{13}	2.678	MIST × 5
Booster Neutrinos	2.5×10^{13}	4.821	MiniBooNe × 5
Booster Muons	2.5×10^{13}	6.964	
Muon Collider Era			
Required upgrades: Pre-booster, linac rf upgrade, Booster rf upgrade			
Booster supercycle: 30/15 sec.			
Muon production	1×10^{14}	5.000	FMC requirement
Main Injector Fixed Target	2.5×10^{13}	2.000	MIST × 5
Booster Fixed Target	1×10^{14}	8.000	

Table II.1: Parameter list for a Proton Source capable of supporting muon production requirements for a First Muon Collider

	Linac	Pre-Booster	Booster	
Injection Energy (Kinetic)	---	1.0	4.5	GeV
Extraction Energy (Kinetic)	1.0	4.5	16.0	GeV
Circumference	---	180.65	474.20	m
Current	65	---	---	mA
Pulse Length	328	---	---	μsec
Protons/bunch	---	5×10^{13}	5×10^{13}	
Bunches	---	2	2	
Total Protons	1×10^{14}	1×10^{14}	1×10^{14}	
Repetition rate	15	15	15	Hz
Transverse Beam Emittance (95%, normalized)	7π	200π	240π	mm-mr
Bunching Factor	---	0.25	0.25×2/21	
Space-charge tune shift (injection)	---	0.39	0.39	
Longitudinal Emittance (95%, per bunch)	---	1.8	2.0	eV-sec
RF Voltage		0.148	1.23	MV
RF Frequency (injection)	805	2.90	13.08	MHz
RF Frequency (extraction)	805	3.27	13.26	MHz
Harmonic number	---	2	21	
Transition Gamma	---	7	25	
Synchrotron Frequency	---	473	378	Hz
Bunch Length (injection, 95% half-width))		83	21	nsec
Bunch length (extraction, 95% half-width)		21	2.3	nsec
Momentum spread (Injection , 95% half-width)	---	0.1	0.5	%
Momentum spread (Extraction , 95% half-width)	0.1	0.5	1.2	%

The transfer energy of 4.5 GeV between the two rings is chosen to equalize the space-charge tune shift in the two rings. In the tune shift formula, there are two factors of γ. Roughly speaking, one factor of γ is used to make up for the larger circumference of the second ring; the other factor of γ is used to compensate for the shorter bunch length resulting from the bunch rotation. Both effects reduce the bunching factor in the second ring.

The design of the required 1-GeV linac is discussed elsewhere; here only a brief overview is given. H^- injection is used. It is assumed that the injected beam will be chopped and injected

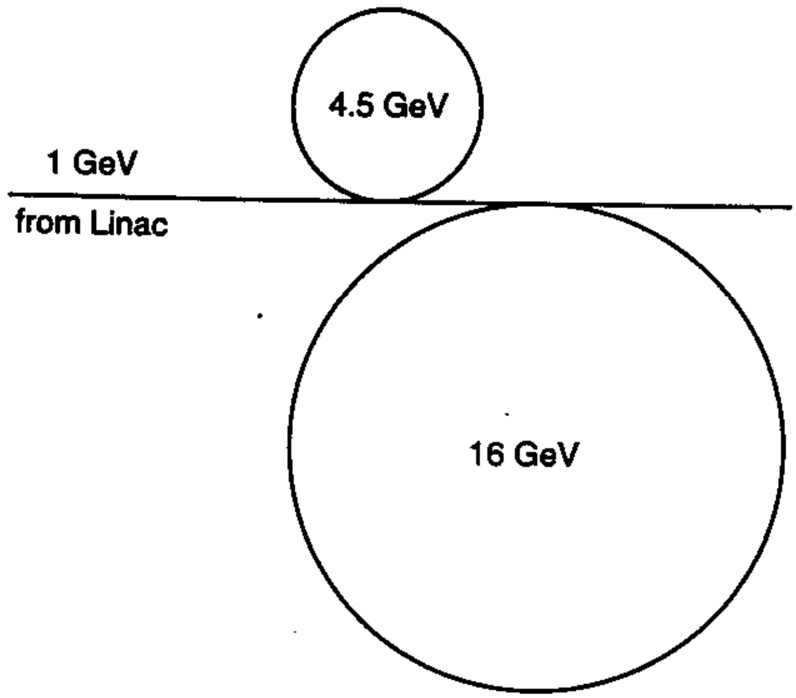


Figure II.1: Geometry of a new proton source. The 4.5 GeV pre-booster is situated to allow injection into the 16 GeV booster either directly from the linac or via the pre-booster.

II.2 Linac

At present the Linac delivers 1.6×10^{13} protons per pulse at a 15 Hz rate through the low energy linac for NTF treatment. This represents a pulse of 45 mA for 57 μs. This same current passes through the high energy linac to 400 MeV but with a pulse length seldom longer than 30 μs at 15 Hz. Since the high energy system runs continuously at 15 Hz with more than a 100 μs rf pulse length, operating at 1.6×10^{13} p/pulse at a 15 Hz rate for the full Linac is easily done.

The requirement for support of muon collider operations is 1×10^{14} protons per pulse at a 15 Hz at 1.0 GeV. The average current is a factor of six-to-ten beyond current capabilities, depending upon the extent of pre-bunching, while the energy is 600 MeV higher than the current facility. The upgrade strategy currently envisioned is a modest increase in the operating current, a significant increase in the pulse length, and construction of an additional 600 MeV of 805 MHz, side coupled linac identical in structure to the downstream end of the current linac. It is currently assumed that the linac would be relocated as part of this upgrade, although a plan to leave the existing structure where it is and extend through the to-be-abandoned Booster enclosure might be feasible.

Upgrading the existing linac

With a small effort it is likely that a pulse of 60 mA and 90 μs could be achieved. This represents a beam of 3.4×10^{13} protons, which at a 15 Hz rate provides 5×10^{14} p/sec. Increasing the ion source to reach this current has been studied and appears possible. The pulse length would at most need some correction for the voltage droop on the Pre-accelerator using a bouncer the higher repetition rates. They were not designed for continuous high duty factor operation. Slow spill would require a complete re-design of the septum magnet and power supply as the existing system can operate in pulsed mode only.

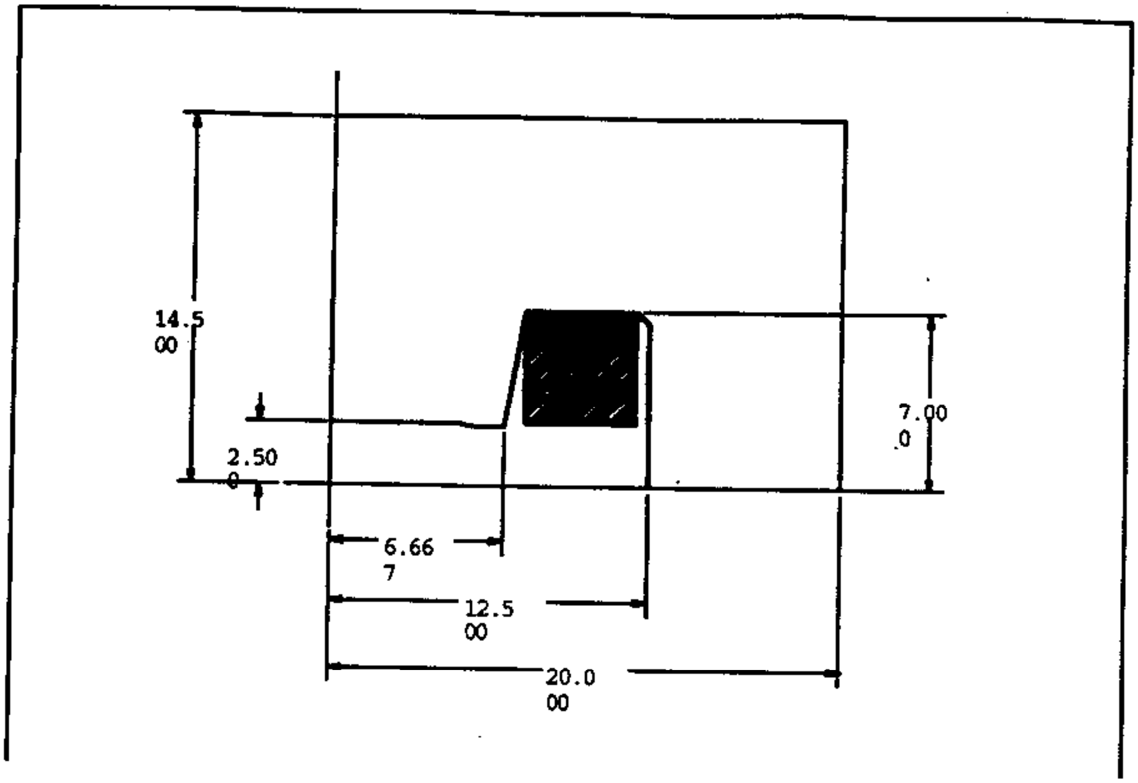
Lattices

Lattice designs for both the pre-booster and the new booster have been initiated. Both lattices are of the "flexible momentum compaction" type, allowing for setting of the transition energy above the peak energy of the accelerator. This is particularly important in the case of the new Booster as it expedites the bunch rotation performed at the end of the acceleration cycle to produce the required 2 nsec bunches.

Lattice parameters are summarized in Table II.2. Lattice functions are shown in Figures II.2 and II.3. As shown the lattices incorporate sufficient straight section space for injection and rf. Yet to be incorporated are extraction areas and space for correction elements. Approximately 25/42 meters of circumference are available in the pre-booster/new booster lattices shown in Figure II.2/3 for incorporation of such space.

Table II.2: Pre-Booster and new Booster initial lattice parameters

	Pre-Booster	Booster	
Energy (kinetic)	4.5	16	GeV
Circumference	180.65	474.20	m
Straight sections	2×12	2×12	m
		14×6	m
Dipole Field	1.3	1.3	Tesla
Dipole length	1.5	1.25	m
Dipole gap (full height)	12.5	10.0	cm
Number of dipoles	60	112	
Quadrupole length	0.5	0.25-0.5	m
Number of Quadrupoles	56	120	
Tune			
Transition gamma	7.5	48	
Maximum beta function	31	37	m
Maximum dispersion	3.8	1.65	m
Natural Chromaticity	-5	-12	



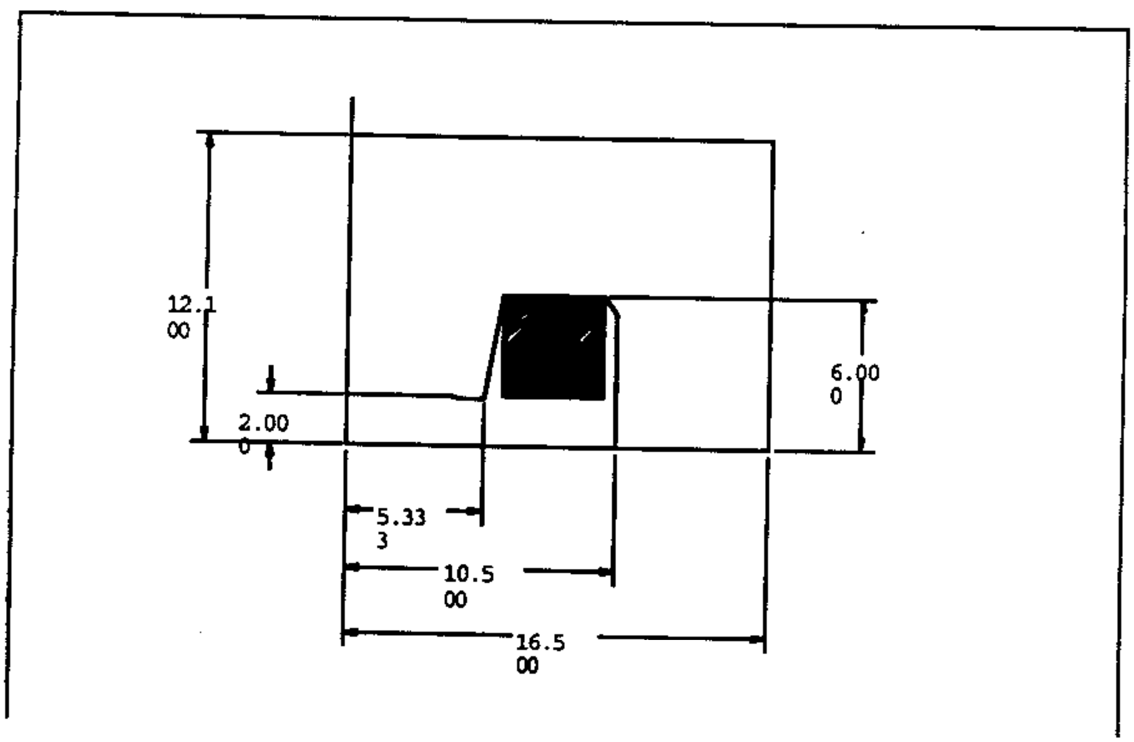


Figure II.4: Cross sections for the Pre-Booster (top) and New Booster (bottom) dipole magnets. One quadrant is shown. All units are in inches.

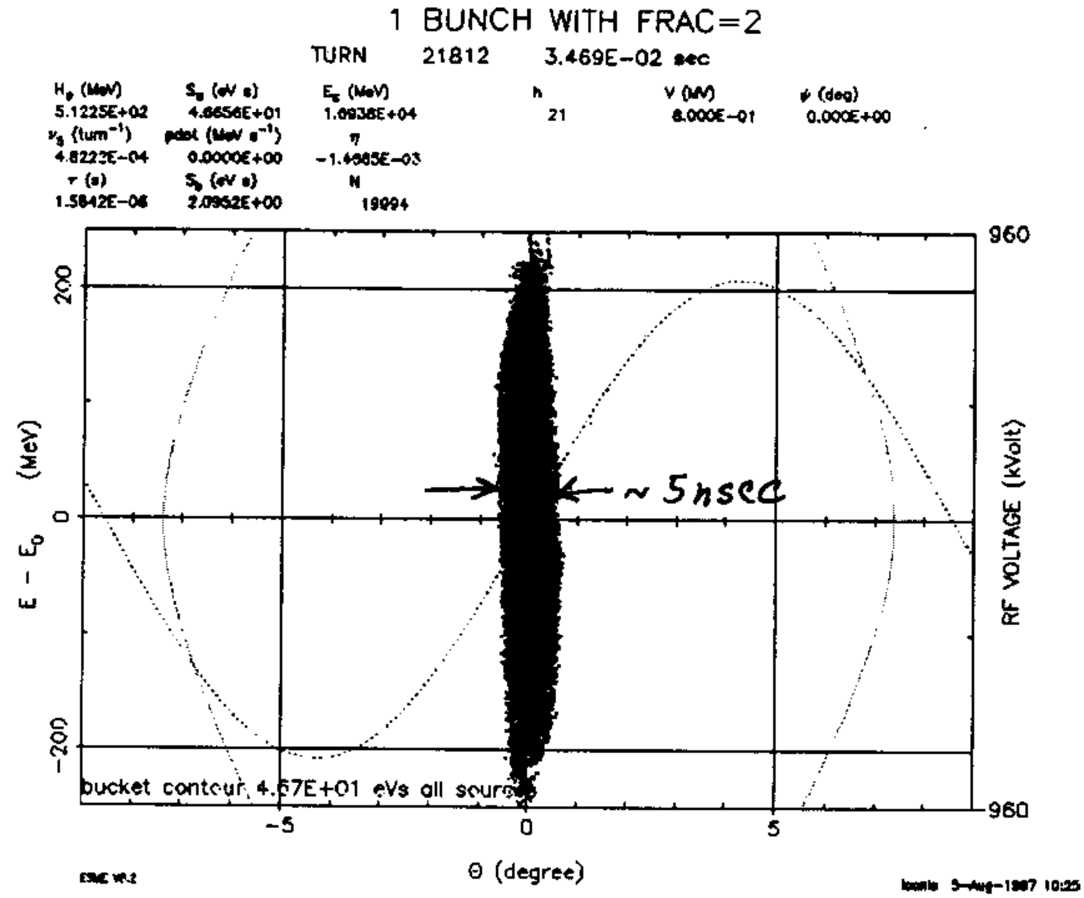


Figure II.9: Beam distribution at the end of bunch rotation in the Booster Ring.

Beam Loading

The current Booster RF cavities must ramp their resonant frequencies from 37 MHz to 53 MHz and provide 300 kW of power for the beam in order to maintain the orbit during the highest slope of the magnet ramp. The 18 cavities provide the beam with 800 kV/turn of RF to maintain the bucket area necessary to contain the entire longitudinal emittance of the beam.

One limitation of the current cavities is beam loading. When the voltage produced in the cavity by the beam becomes equal to or greater than the acceleration voltage, a beam instability could develop. The shunt impedance of the cavities at resonance is approximately 22 kΩ. With a beam intensity of about 1×10^{13} protons, the voltage produced by the beam is close to the acceleration voltage. If the cavities are to drive a more intense beam, the shunt impedance should be reduced, or the RF source impedance needs to be reduced.

With the current local feedback systems on the cavity voltage, any large increase in intensity will destabilize the beam because of Robinson instabilities. A rule of thumb used to avoid Robinson instabilities is to dump as much power into the cavity and amplifier as is dumped into the beam. At an intensity of 1×10^{13}, the beam begins to take a majority of the power from the system.

One way to get more power to the cavity is to add swamping resistors in parallel with the ferrite cavities. This will reduce the impedance of the cavity as seen by the beam, and raise the intensity threshold for Robinson instabilities. The drawback to this technique, however, is that it

V. NEXT STEPS

The design presented here is a first look at a possible evolution of the Fermilab Proton Source. Further development and optimization of this concept is required before a conceptual design report and more accurate associated cost estimate could be produced. During this study several features of the design were identified as worthy of further consideration over the course of developing a more complete concept. These are listed below along with identified areas that will require R&D before finalizing any design.

V.1 Design Issues

There are clearly a large number of design issues relating to the very demanding performance specifications of the proton source described in this report. The performance is well beyond current state-of-the-art and is comparable to accelerator based neutron spallation sources that are currently under design at a number of laboratories. Among the outstanding issues we would identify as requiring particular attention are:

1. The rf system. The system required is very high power and suffers from significant beam loading. Concepts for rf feedback need to be brought to maturity.
2. The vacuum system. A concept must be developed for a vacuum chamber that can satisfy the dual demands of surviving in a 15 Hz magnetic field while presenting a low impedance to the circulating beam.
3. The magnet system. A high field, large aperture, 15 Hz magnet is called for in this facility. The technology is challenging.
4. Residual activation and shielding. Little has been done on this, but it is a major issue in spallation sources and requires analysis.
5. Beam stability. Concepts for impedance minimization and development of innovative damper systems must be pursued.
6. The power supply system. In a resonant system addition of a second harmonic provides significant relief in the 16 GeV Booster rf system. It is probably also worth investigating a programmable power supply in the Booster if some of the more complicated operating modes involving mixed muon collider/Main Injector cycles are required.

V.2 Design Alternatives

A number of alternative implementations of the design concepts developed here were identified during our study as worthy of further consideration. These include:

7. Possible addition of a third ring. This has the potential benefit of allowing operation of the proton source at an energy above Main Injector transition.

8. Increasing the linac energy and eliminating the pre-booster. The feeling is that this is likely very expensive but it probably warrants a further look.

9. Lowering the rf frequency in the new Booster to 7.6MHz (h=12). This would allow longer bunches and reduce the space charge tune shift thereby allowing a reduction of the

pre-booster energy and/or reduction of the aperture. It would also provide bunches to the Main Injector with a spacing of 132 nsec, eliminating the need for coalescing during collider operations.

10. Possible use of chicanes to consolidate bunches for muon production targeting. This would allow the total charge in the pre-booster and the new booster to be distributed over a greater number of bunches.

11. Lowering the repetition rate, say to 10 Hz. This eases many problems in the rf, magnet, power supply, and vacuum systems. and is still twice the muon collider requirement. A cost-benefit analysis might be valuable.

12. A more detailed analysis of mixed operational modes is also called for. As presently envisioned the existence of the pre-booster does nothing to enhance Main Injector operations, and could actually be an impediment.

V.3 R&D Initiatives

A number of areas worthy of immediate R&D are derived from the above, and other, considerations identified during the course of our study:

- Linac ion source development program to address what the maximum H^- current that is likely to be available.
- Linac test station, including a prototype 350 μsec modulator, klystron, and cavity, to conduct investigations into utilization of long pulse lengths.
- Prototype pre-booster rf cavity to verify operational characteristics as described in this report.
- Prototype magnets to lead to an optimized design and matching between dipoles and quadrupoles.
- Prototype vacuum chamber to validate design concepts.
- Development of a direct feedback rf system.

Proton Source Parameters for the Workshop

	Step 1		Step 2	Step 3
	Scenario 1	Scenario 2		
Linac				
Kinetic Energy (MeV)	400	1000	1000	1000
Momentum Spread (95% FW)	1	1	1	1
Current (mA)	45	67.1	112	328.5
Pulse Length (μs)	0.75	0.75	0.75	0.75
H^- per pulse	1×10^{13}	1.5×10^{13}	2.5×10^{13}	1×10^{14}
Repetition Rate (Hz)	15	15	15	15
Pre–Booster				
Extraction Kinetic Energy (GeV)				4.5
Momentum Spread (95% HW)				0.5%
Circumference (m)				180.6
Protons per bunch				5×10^{13}
Number of Bunches				2
Repetition Rate (Hz)				15
Extracted bunch length (ns)				21
Transverse Emittance (mm–mr)				200π
Longitudinal Emittance (eV–sec)				1.8
Booster				
Extraction Kinetic Energy (GeV)	16	8	16	16
Momentum Spread (95% HW)	< 0.1%	< 0.1%	< 0.1%	1.2%
Crcumference (m)	474.2	474.2	474.2	474.2
Protons per Bunch	1.2×10^{11}	1.8×10^{11}	3.0×10^{11}	5×10^{13}
Number of Bunches	84	84	84	2
Repetition Rate (Hz)	15	15	15	15
Extracted bunch length (ns)	4.9	4.9	4.9	2.3
Transverse Emittance (mm–mr)	50π	30π	50π	240π
Longitudinal Emittance (eV–sec)	2.2	1.8	1.8	4.0

Muon Source Parameters for the Workshop

Parameters of muon bunches downstream of the ionization cooling channel

	Narrow σ_p	Broad σ_p
muons per bunch	5×10^{12}	5×10^{12}
μ^+ bunches per cycle	1	1
μ^- bunches per cycle	1	1
momentum (MeV/c)	200	200
σ_p/p	5%	10%
bunch length (cm)	1.5	10
normalized $\varepsilon_\perp$ (mm–mr)	$200\ \pi$	$60\ \pi$
repetition rate (Hz)	15	15
μ^+ per year (10^7 secs)	7.5×10^{20}	7.5×10^{20}
μ^- per year (10^7 secs)	7.5×10^{20}	7.5×10^{20}

Recirculating LINAC Parameters

The muons are accelerated in 3 recirculating LINACS (RLAs). Each RLA consists of two long straight LINACs connected by two arcs. Muon decays produce collimated neutrino beams downstream of each LINAC, giving sub–nanosec neutrino pulses in a train of ~10 pulses. Each pulse comes from muon decays at a given energy, with the energy increasing with pulse number.

	RLA 1	RLA 2	RLA 3
Input Energy (GeV)	1.0	9.6	70
Output Energy (GeV)	9.6	70	250
No. of Turns	9	11	12
LINAC Length (m)	100	300	533.3
Arc Length (m)	30	175	520
Bunch Length (cm)	4.8	1.3	0.6
Bunch Length (ps)	158	43	19
Revolution Time (μs)	0.9	3.1	7.0
Decay Losses	9.0%	5.2%	2.4%
Initial muons per bunch	5×10^{12}	4.6×10^{12}	4.3×10^{12}
μ^+ bunches per sec	15	15	15
μ^- bunches per sec	15	15	15

Neutrino Beam Pulses from Recirculating LINACs

	Turn Number											
	1	2	3	4	5	6	7	8	9	10	11	12
RLA 1												
E_μ(start) (GeV)	1.0	1.96	2.92	3.88	4.84	5.8	6.76	7.72	8.68	9.64		
E_μ(end) (GeV)	1.48	2.44	3.4	4.36	5.32	6.28	7.24	8.2	9.16			
$\langle E_\mu \rangle$ (GeV)	1.24	2.2	3.16	4.12	5.08	6.04	7.0	7.96	8.92			
$\langle \gamma \rangle$	11.7	20.8	29.9	39.0	48.1	57.2	66.3	75.3	84.4			
$\gamma c\tau$ (km)	7.72	13.7	19.7	25.7	31.7	37.8	43.8	49.6	55.7			
f_{decay}=100m/$\gamma c\tau$ (%)	1.3	0.73	0.51	0.39	0.32	0.26	0.23	0.20	0.18			
N_{decay}/bunch (x10^{10})	6.5	3.7	2.6	2.0	1.6	1.3	1.2	1.0	0.9			
N_{decay}/year (x10^{18})	9.8	5.5	3.8	2.9	2.4	2.0	1.7	1.5	1.4			
RLA 2												
E_μ(start) (GeV)	9.6	15.1	20.6	26.1	31.6	37.1	42.6	48.1	53.6	59.1	64.6	70.1
E_μ(end) (GeV)	12.4	17.9	29.4	28.9	34.4	39.9	45.4	50.9	56.4	61.9	67.4	
$\langle E_\mu \rangle$ (GeV)	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0	60.5	66.0	
$\langle \gamma \rangle$	104	156	208	260	312	364	416	469	521	573	625	
$\gamma c\tau$ (km)	68.7	100	140	170	210	240	270	310	340	380	410	
f_{decay}=300m/$\gamma c\tau$ (%)	0.44	0.30	0.21	0.18	0.14	0.13	0.11	0.097	0.088	0.079	0.073	
N_{decay}/bunch (x10^{10})	2.0	1.4	0.97	0.83	0.64	0.60	0.51	0.45	0.40	0.36	0.34	
N_{decay}/year (x10^{18})	3.0	2.1	1.5	1.2	0.96	0.90	0.77	0.68	0.60	0.54	0.51	
RLA 3												
E_μ(start) (GeV)	70	85	100	115	130	145	160	175	190	205	220	235
E_μ(end) (GeV)	77.5	92.5	108	123	138	153	168	183	198	213	228	243
$\langle E_\mu \rangle$ (GeV)	73.8	88.8	104	119	134	149	164	179	194	209	224	239
$\langle \gamma \rangle$	698	840	982	1124	1266	1408	1550	1692	1834	1976	2118	2260
$\gamma c\tau$ (km)	460	550	650	740	840	930	1000	1100	1200	1300	1400	1500
f_{decay}=533m/$\gamma c\tau$ (%)	0.12	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
N_{decay}/bunch (x10^{10})	0.52	0.42	0.35	0.31	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15
N_{decay}/year (x10^{18})	0.78	0.63	0.53	0.46	0.41	0.37	0.34	0.31	0.28	0.26	0.25	0.23

Parameter lists for 100 GeV, 200 GeV, 350 GeV and 500 GeV Muon Colliders

	Low Energy		Medium Energy	Top Factory	Higher Energy
	Narrow σ_p	Broad σ_p			
$\sqrt{s}$ (GeV)	100	100	200	350	500
beam energy (GeV)	50	50	100	175	250
σ_p/p	3×10^{-5}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
muons per bunch	3×10^{12}	3×10^{12}	2×10^{12}	2×10^{12}	2×10^{12}
number of bunches	1	1	2	2	2
repetition rate (Hz)	15	15	15	15	15
norm. $\varepsilon_\perp$ (mm–mr)	297π	85π	67π	56π	50π
Collider Circum (m)	380	380	700	864	1000
f_{rev} (Hz)	7.9×10^5	7.9×10^5	4.3×10^5	3.5×10^5	3.0×10^5
turns/lifetime	820	820	890	1260	1560
β^* (cm)	13	4	3	2.6	2.3
σ_z (cm)	13	4	3	2.6	2.3
σ_r (μm)	286	85	47	30	22
$\mathcal{L}_{peak}$ (cm^{-2} s^{-1})	6×10^{32}	7×10^{33}	6×10^{33}	1×10^{34}	2×10^{34}
$\mathcal{L}_{av}$ (cm^{-2} s^{-1})	5×10^{30}	6×10^{31}	1×10^{32}	3×10^{32}	7×10^{32}

Parameter lists for neutrino beams from straight scraping sections in 100 GeV, 200 GeV, 350 GeV and 500 GeV Muon Colliders

	Low Energy		Medium Energy	Top Factory	Higher Energy
	Narrow σ_p	Broad σ_p			
$\sqrt{s}$ (GeV)	100	100	200	350	500
beam energy (GeV)	50	50	100	175	250
$\gamma c\tau$ (Km)	311	311	622	1088	1554
muons per bunch	3×10^{12}	3×10^{12}	2×10^{12}	2×10^{12}	2×10^{12}
number of bunches	1	1	2	2	2
repetition rate (Hz)	15	15	15	15	15
Collider Circum (m)	380	380	700	864	1000
f_{rev} (Hz)	7.9×10^5	7.9×10^5	4.3×10^5	3.5×10^5	3.0×10^5
turns/lifetime	820	820	890	1260	1560
$L_{straight}$ (m)	5	5	7	9	10
Decays/cycle (straight)	2.5×10^{10}	2.5×10^{10}	2.5×10^{10}	2.6×10^{10}	2.5×10^{10}
<Decays/bunch/turn>	3.1×10^7	3.1×10^7	1.4×10^7	1.0×10^7	8.0×10^6
Decays/year (straight)	3.8×10^{18}	3.8×10^{18}	3.8×10^{18}	3.9×10^{18}	3.8×10^{18}

Note: The lengths of the straight sections in the collider rings iare educated guesses. They scale approximately with ring circumference .... hence the total number of muon decays per proton accelerator cycle ends up being roughly independent of collider energy.

Parameter list for 200 GeV x 1000 GeV $\mu - p$ Collider

$\sqrt{s}$ (GeV)	894
proton energy (GeV)	1000
protons per bunch	1.25×10^{12}
number of proton bunches	4
proton norm. $\varepsilon_{\perp}$ (mm–mr)	12.5π
proton β^* (cm)	15
proton beam–beam shift	0.02
muon energy (GeV)	200
muons per bunch	2×10^{12}
number of bunches	4
muon norm. $\varepsilon_{\perp}$ (mm–mr)	50π
muon β^* (cm)	7.5
muon σ_r (μm)	40
muon storage turns	2000
muon beam–beam shift	0.026
repetition rate (Hz)	15
$\mathcal{L}_{av}$ ($cm^{-2}\ s^{-1}$)	1.3×10^{33}