Comparison of Proton Driver Schemes For Muon Collider and Neutrino Factory

Chuck Ankenbrandt[1,2] and Rol Johnson[1]
Muons, Inc[1] and Fermilab[2]
August 26, 2008

Why me?

Dear Chuck, Milorad, Dave (and Steve, Andreas and Yuri),

we've been asked to come out with (written) assessment of the (ultimate) Project-X parameters in the era when it will be used as Proton Driver for Muon Collider or/and Neutrino Factory. A comparison and advice on whether Linac option of PD is superior to the Synchrotron Ring one is needed, too. A short document is required by the end of the next week.
I 'd like to ask you - as people understanding the MC PD most - to prepare a short summary(ies) of your understanding of the issue and present this Friday (when Andreas, Steve and myself are back from MUTAC).

...

Thank you in advance, Vladimir

--
Vladimir D. Shiltsev
Director, Accelerator Physics Center

Proton Driver Beam Parameters for Muon Colliders and Neutrino Factories

Yu. Alexahin, C. Ankenbrandt, S. Geer, A. Jansson, D. Neuffer, M. Popovic, and V. Shiltsev
Fermilab

Abstract and Executive Summary

"There Are Three Kinds of People - Those Who Can Count and Those Who Can't" Anon

The requirements on proton drivers for muon colliders and neutrino factories are discussed. In particular, the requirements imposed on the Project X linac by the needs of a high-energy, high-luminosity muon collider at Fermilab are examined

The three most important conclusions are as follows:

1) If muon colliders and neutrino factories are separately designed and optimized, the front ends tend to diverge somewhat because muon colliders need luminosity whereas neutrino factories need flux. Nevertheless, there is considerable overlap between the proton beam power needs of energy-frontier muon colliders and those of neutrino factories based on muon storage rings. In many ways, muon colliders are somewhat more demanding on their front ends than neutrino factories, so any facility that meets the beam-power needs of the former is likely to meet the needs of the latter.

2) Several muon collider design efforts have generated parameter sets that call for proton beam power of several megawatts. The most common requests fall in the ballpark of 3 to 4 MW; however, most designs are optimistic and none have been fully vetted, so it is advisable to provide considerable performance contingency. The required proton beam power is not likely to be a strong function of the center-of-mass energy of the collider.

3) Several alternatives have been examined including synchrotron-based ones. The most promising front end is based on the Project X 8-GeV H^- linac upgraded to about 3 MW, with a further upgrade path to ~10 MW held in reserve. One or more 8-GeV storage rings will be needed to provide stripping and accumulation, formation of the appropriate number of bunches, and bunch shortening. Of course an appropriate multi-megawatt target station will also be necessary.

There are two main recommendations:

1) The performance requirements on the aforementioned 8-GeV storage ring(s) are severe. Accordingly, a design study should be initiated. The main goals should be to establish design concepts and explore potential limitations due to beam instabilities.

2) Planning should be initiated for an appropriately located muon test area that can evolve into a facility capable of handling several megawatts of proton beam power.

An excerpt from the P5 Report

Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for understanding the evolution of the universe. The US can build on the unique capabilities and infrastructure at Fermilab, together with the proposed DUSEL, the Deep Underground Science and Engineering Laboratory proposed for the Homestake Mine, to develop a world-leading program in neutrino science. Such a program will require a multi-megawatt proton source at Fermilab.

> **The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab.**

A neutrino program with a multi-megawatt proton source would be a stepping stone toward a future neutrino source, such as a neutrino factory based on a muon storage ring, if the science eventually requires a more powerful neutrino source. This in turn could position the US program to develop a muon collider as a long-term means to return to the energy frontier in the US.

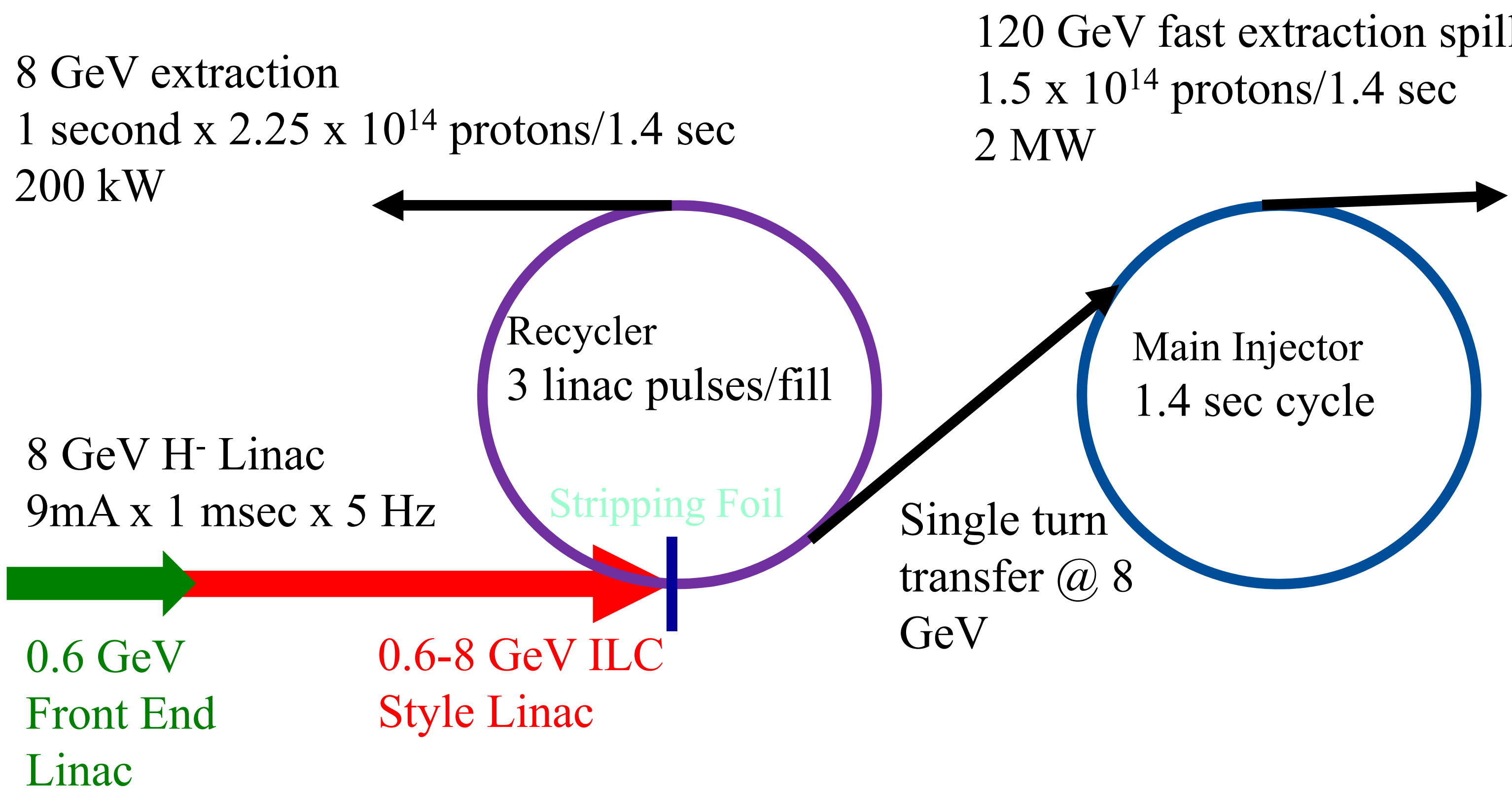
Introduction to Project X

- The heart of Project X is an 8-GeV H^- linac based on ILC technology.
- Project X will stack beam into the Recycler to allow Main Injector to accelerate 2.2 MW of beam to 120 GeV.
- Excess beam cycles will be available at 8 GeV.

- http://www.fnal.gov/directorate/Fermilab_AAC/AAC_July_07/

http://www.fnal.gov/directorate/Fermilab_AAC/AAC_July_07/Agenda_Aug_07_Rev4.htm

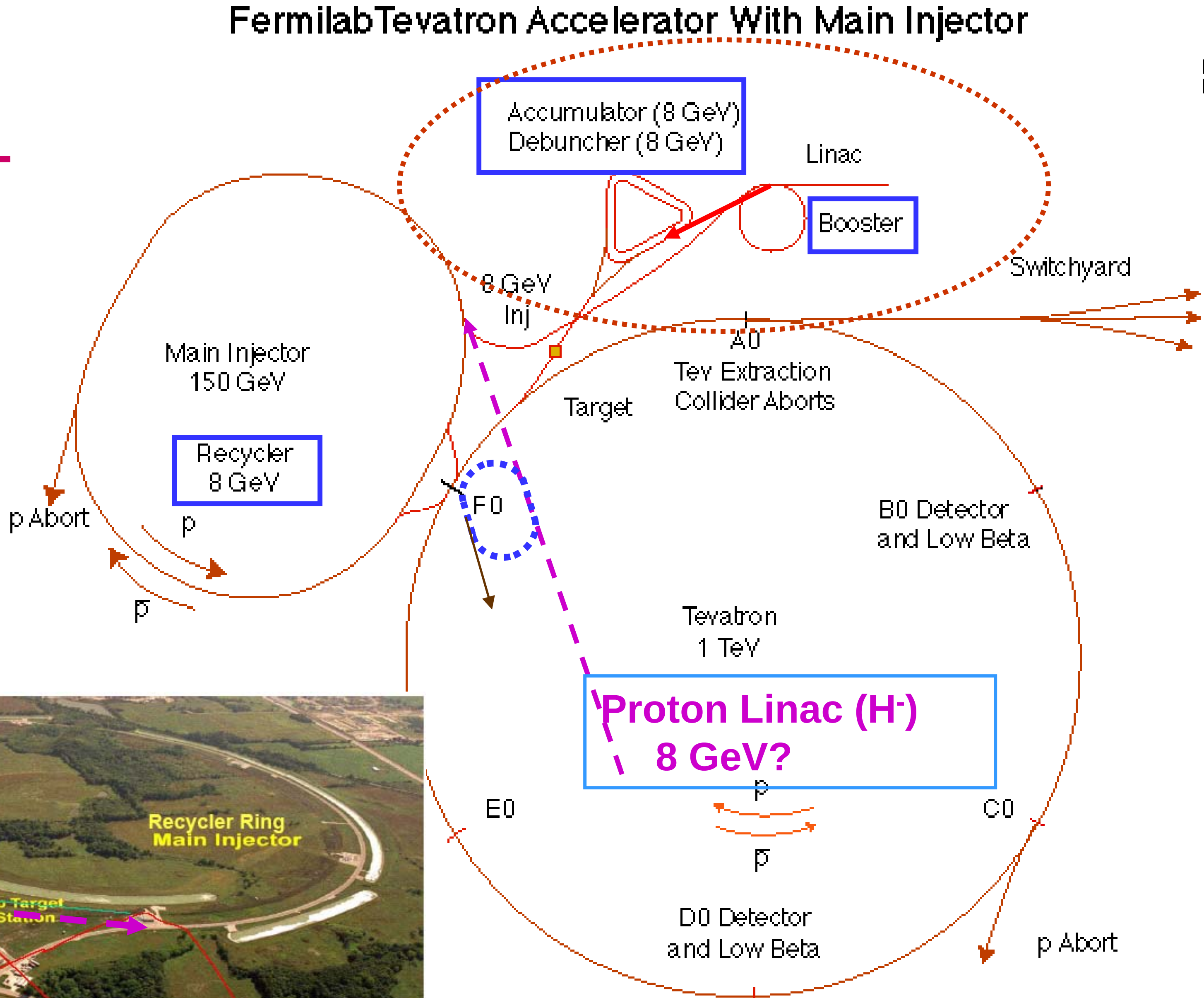
Overview of Project X

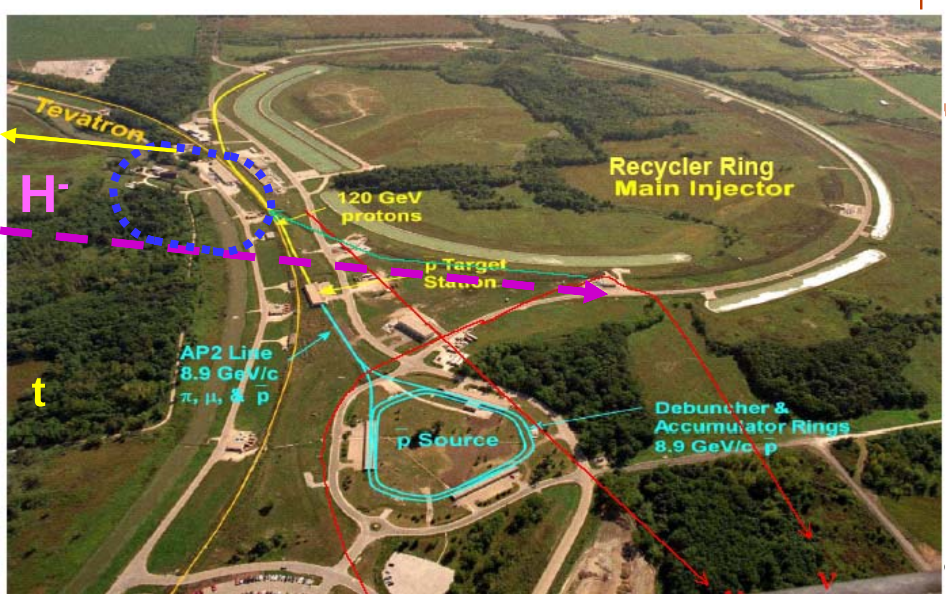


From Dave McGinnis' talk

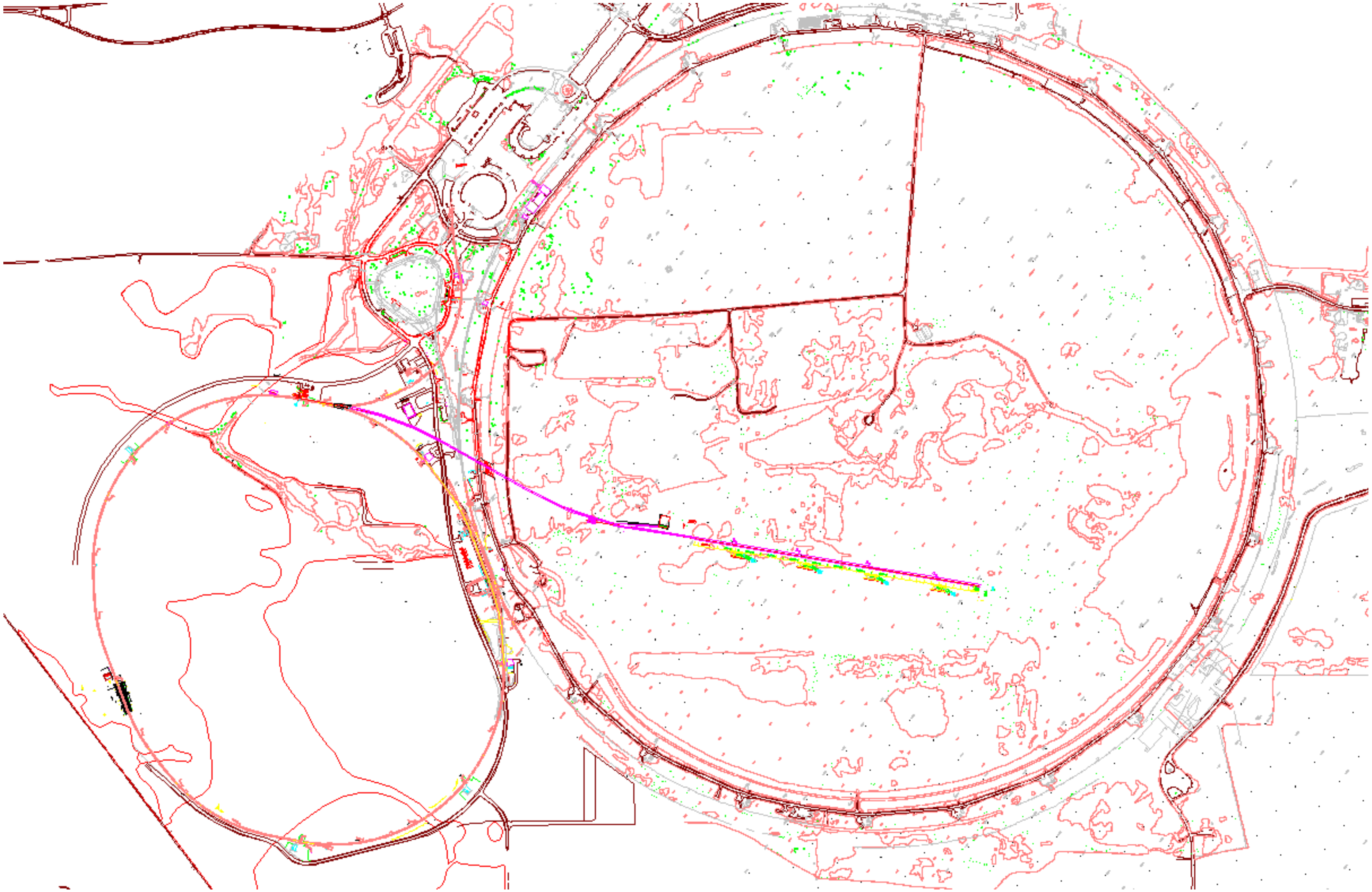
Muons, Inc.

8 GeV Proton sources



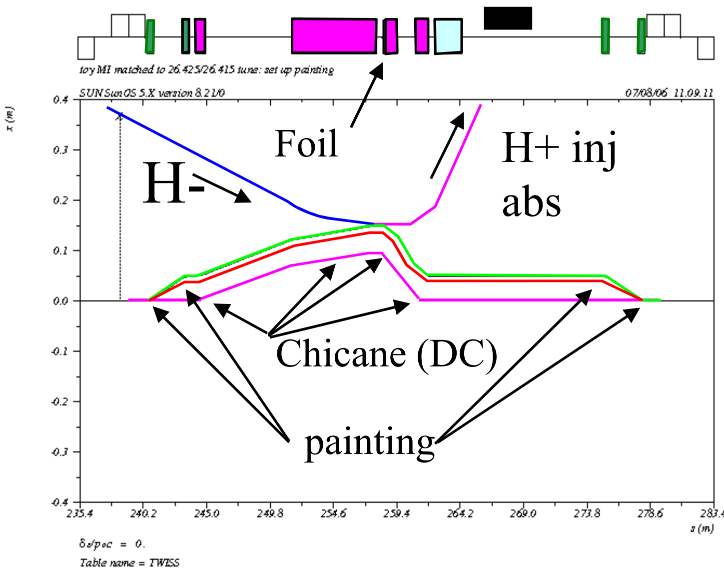


Possible site layout of Project X

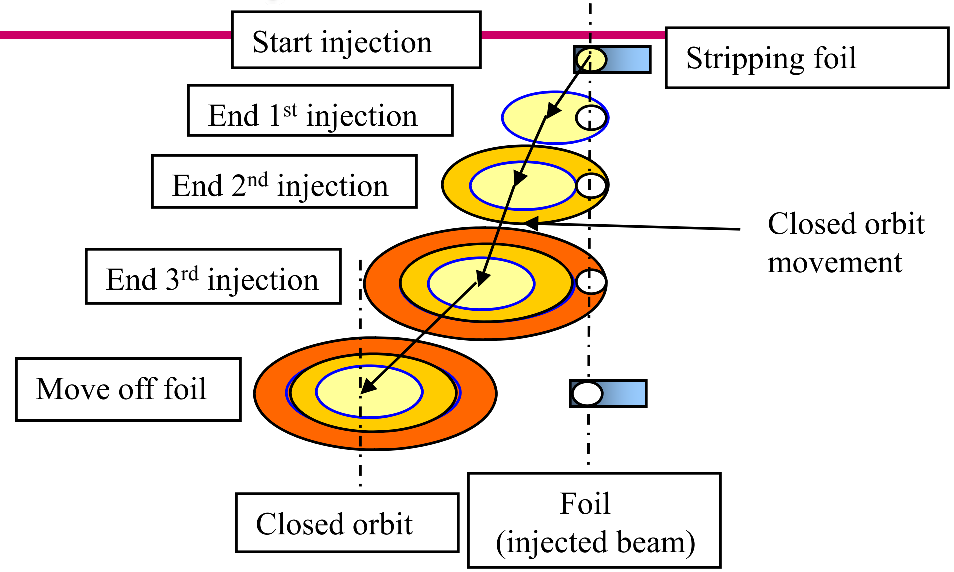


Muons, Inc.

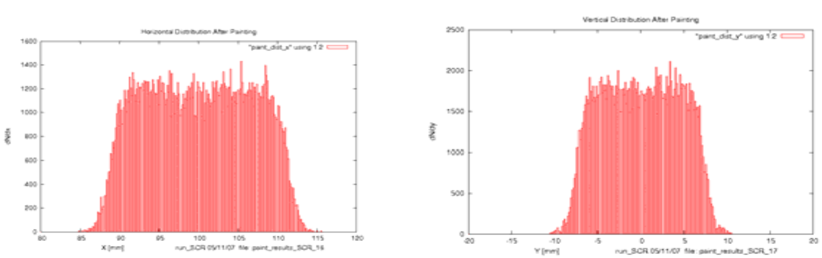
H- Injection – Transverse painting (Dave Johnson)



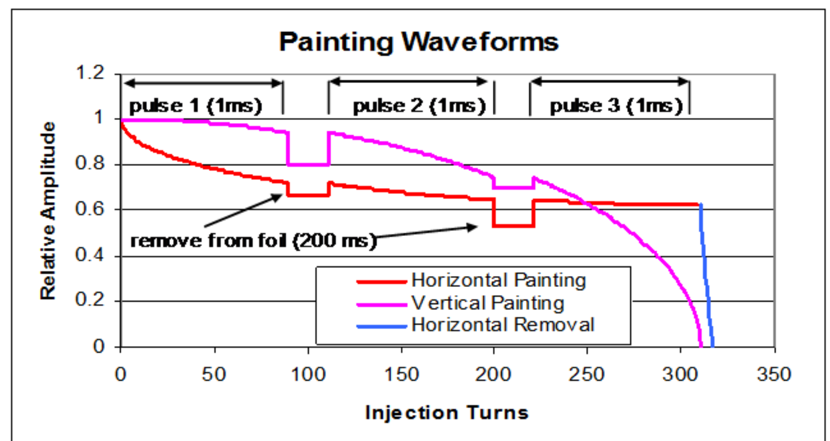
Horizontal orbit motion during painting



Cartoon of phase space painting with 3 linac pulses



Final distribution after painting to 25 π at β_H of 70 and β_V of 30 (STRUCT)



Painting waveform for Recycler Injection

Project X: Possible 8 GeV Upgrades

More extreme: 15Hz->

8 GeV Upgrade paths	Baseline	Extreme	Enough?
Pulse duration (msec)	1	3	1
Beam current (mA)	9	25	25
Repetition rate	5	10	10
Beam power (MW)	0.36	6.00	2.00

The last column has about the same Recycler intensity as when the baseline Project X accumulates 3 cycles for the Main Injector.

ISS: Factors re Specs for PD

2.1 Introduction

Many factors influence the specifications for the proton driver. Among these are:

- the required production of $\approx 10^{21}$ neutrinos per year
- muon yields as a function of the proton energy
- muon yields as a function of the target material
- heating and stress levels for the target material
- muon capture as a function of proton bunch length
- maximum acceptable duration of proton pulses on the target
- peak beam loading levels in the $\mu^{\pm}$ accelerators
- bunch train stacking in the μ^{+} and μ^{-} decay rings

ISS Requirements (Feb. 3, 2008)

Table 2. Proton driver requirements.

Parameter	Value
Average beam power (MW)	4
Pulse repetition frequency (Hz)	50
Proton energy (GeV)	10 ± 5
Proton rms bunch length (ns)	2 ± 1
No. of proton bunches	3 or 5
Sequential extraction delay (μs)	≥ 17
Pulse duration, liquid-Hg target (μs)	≤ 40
Pulse duration, solid target (ms)	≥ 20

Comments on ISS-NF Requirements

- Energy:
  - ISS said 5 < Ep < 15 GeV ➔ 8 GeV is ~ ideal.
  - However, we should also consider using 50 GeV beam since it will be available.
  - Nμ/(Np*Ep) peaks around 8 GeV.
  - The amount of reduction at 50 GeV is controversial.
- Bunch delivery:
  - Cycle rate of proton accelerator: ISS said 50 Hz
  - Bunches per cycle: ISS said 3 or 5

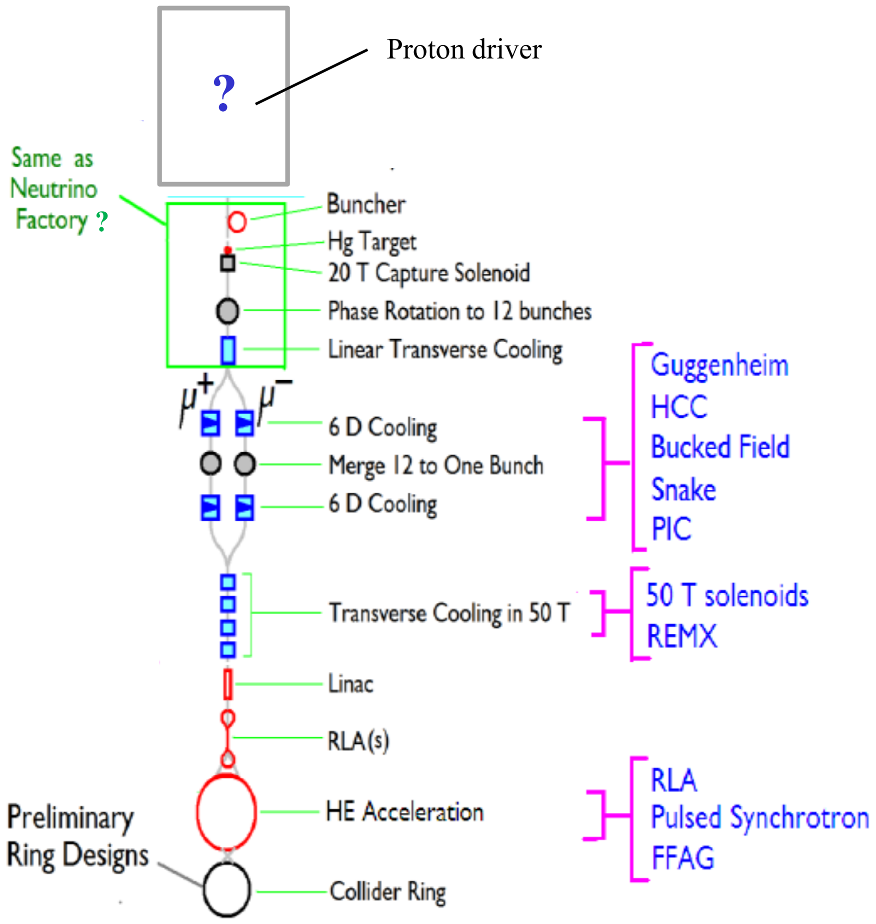
Interesting footnote in ISS report

[1]The use of multi-bunch trains at 50 Hz is a change made during the study from the original single, 15-Hz train. The change was made to ease the production of the 2 ± 1 ns (rms) proton bunches, and to reduce the heavy beam loading in the $\mu^{\pm}$ accelerators.

Muon Collider Proton Driver Requirements

Andreas Jansson
Fermilab

Muon Collider Scenarios



R. Palmer

- *All Muon Collider scenarios are variations on a theme*
  - ***Proton driver***
  - *Target, capture and phase rotation*
  - *6D cooling section*
  - *Transverse cooling section*
  - *Muon acceleration*
  - *Collider ring*

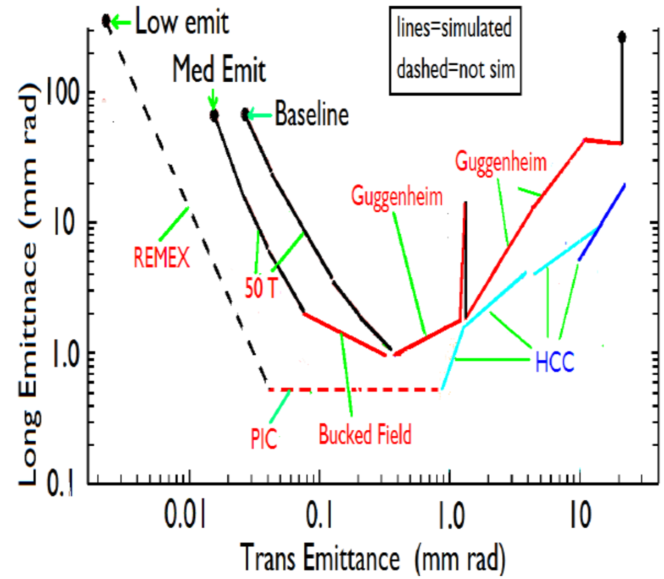
Muon Collider Parameters

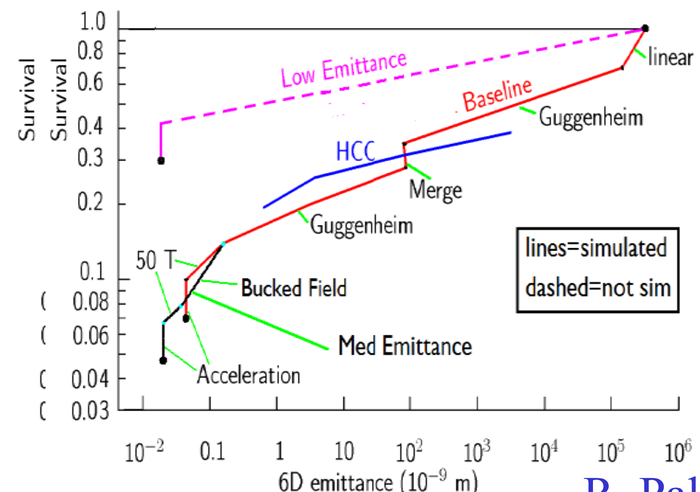
	Low ε (Johnson)	Med ε (Alexahin)	High ε (Palmer)	
CM Energy	1.5	1.5	1.5	TeV
Luminosity	2.7	1	1	10^{34}cm^2/s
Muons/bunch	0.1 *10	1	2	10^{12}
Ring circumference	2.3	3	8.1	km
$\beta^* = \sigma_z$	5	10	10	mm
dp/p (rms)	1.0	0.1	0.1	%
Ring depth	35	13	135	m
Muon survival	30	4	7	%
ε_T	2.1	12	25	π mm mrad
ε_L	370,000	72,000	72,000	π mm mrad
PD Rep rate	**65**	**24**	**12**	**Hz**
PD Power	**≈4**	**≈6**	**≈4**	**MW**

R. Palmer, LEMC

PD Power Requirements

- Required proton driver power depends strongly on the performance of the cooling channel.
  - Rely on simulations, not yet fully end-to-end.
- Average estimate is ~4MW
  - May need more





R. Palmer

Proton Driver Energy

Muon yield at the end of the initial cooling channel

H. Kirk

Proton energy (GeV)	μ+ per proton (%)	μ- per proton (%)	μ+ yield normalized to power	μ+ yield normalized to power
10	8.3	7.7	100	92.8
24	19.4	17.9	97.5	89.7
50	36.5	30.7	87.8	73.9
100	64.2	49.4	77.2	59.5

- Beam power requirement is not a strong function of energy
  - Pion production efficiency goes down ~20% in going from 8GeV to 50GeV.
  - Less intensity is needed at higher energy.
  - Higher energy tends to come with lower rep rate.

Packaging (rep rate)

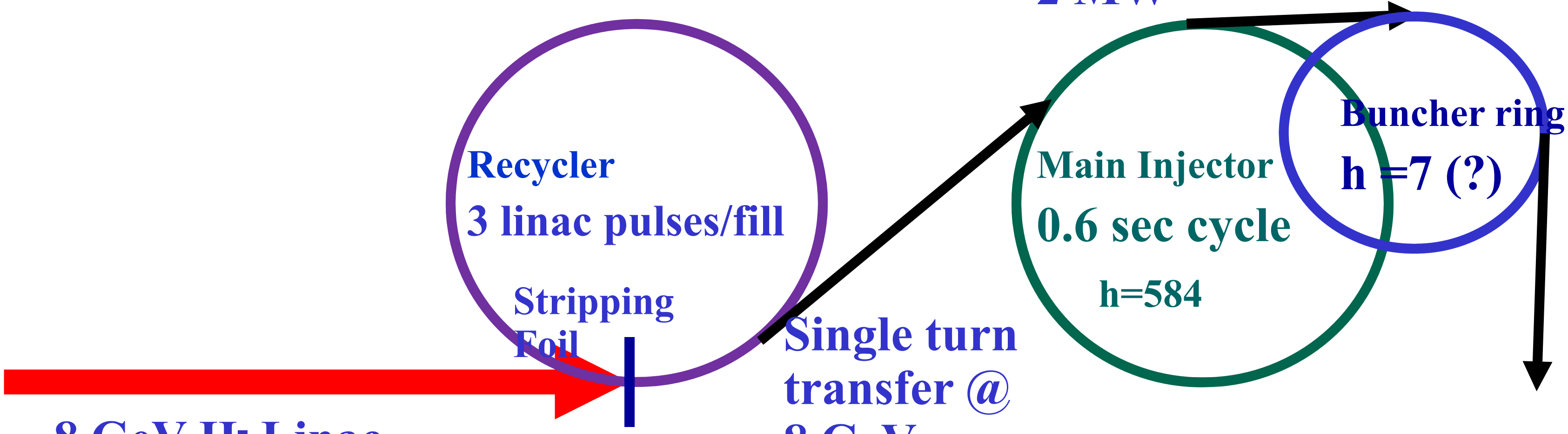
- Bunch rep rates range from 12-65Hz
  - Note that this is not necessarily the same as the proton driver rep rate.
- Flexibility here would be useful, also for operations
  - This can be achieved using one or more intermediate fixed energy rings.

A 56 GeV 4MW scenario

56 GeV fast extraction spill

3×10^{14} protons/0.6sec

2 MW



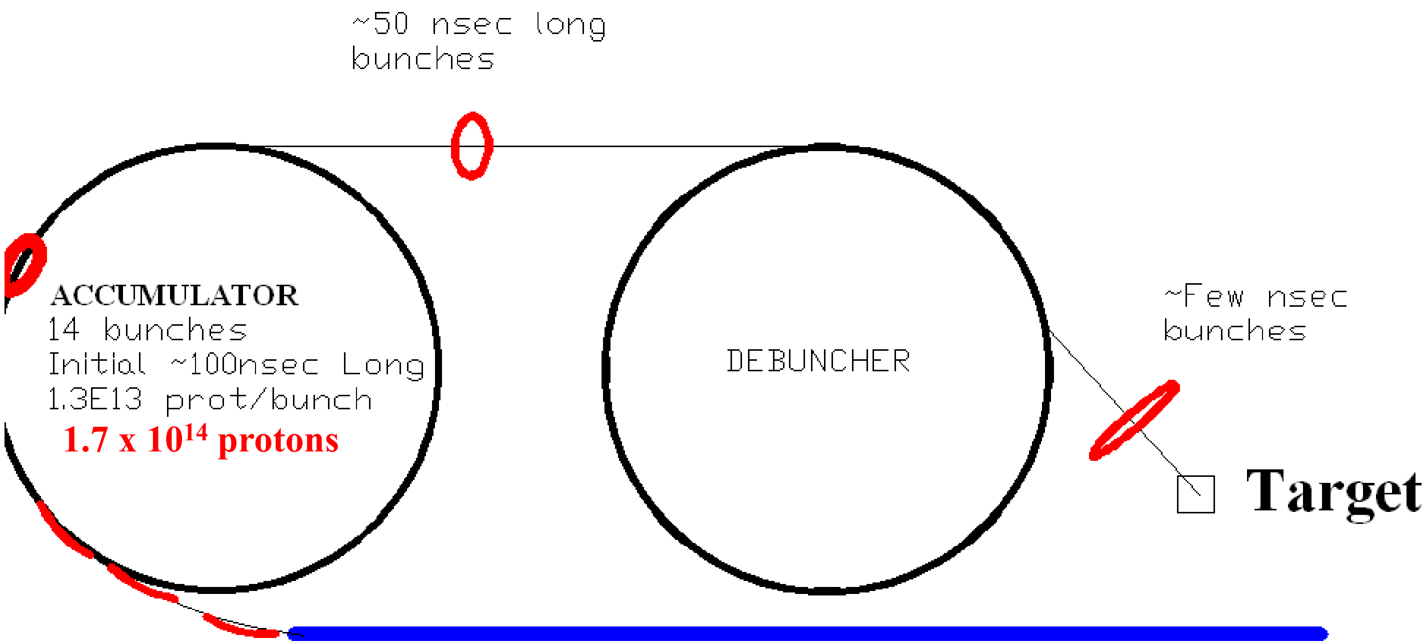
8 GeV H^- Linac
(e.g. upgraded Project X)

9mA current		18mA
2 ms pulse	or	1ms
5 Hz rep rate		5 Hz

To μμ Collider

D. Neuffer's 2MW scheme
with R. Palmer's "upgrades"

An 8GeV 4MW scenario



8 GeV LINAC
(e.g. upgraded Project X)

11mA		**25mA**
3ms	**or**	**1.3ms**
15Hz		**15Hz**

C. Ankenbrandt

Thoughts on 8GeV vs 50 GeV at Fermilab

- 4MW at 50GeV would require only "modest" upgrades to Project X beyond the planned 2MW, but
  - Bunch packaging would require a new (perhaps two) 50GeV fixed energy rings. These are costly.
  - Could 4 10^{14} protons (5 Amps in MI) be accelerated through transition and rebunched with acceptable losses?
  - Is there any further upgrade potential?
- 4MW at 8GeV would require significant upgrades to Project X linac (factor ~10 in power), but
  - Bunch packaging could probably be done using (some of) the 3 existing 8GeV fixed energy rings.
  - No acceleration -> Each linac pulse handled separately -> Lower intensity (1.7 10^{14}, or 18 Amps in Accumulator), but still a challenge.
  - No acceleration -> no rebunching
  - **Possible upgrade path** (linac to 25mA, 3ms, 15Hz).

Synergies with NF

- Power requirements are similar for NF and MC, but required bunch packaging different.
- Strong synergies possible, but if PD optimized separately requirements may diverge
  - Neutrino Factories mainly need flux
  - Muon Colliders need luminosity (bunch brightness)
- In many ways, muon colliders are more demanding than neutrino factory.
  - Any MC proton driver could also feed a NF, but not necessarily the other way around.
- MC requirements should be taken into account when designing NF proton driver.
  - Try to maintain synergies

Conclusions

- A muon collider would likely need ~4MW of proton power
  - Should plan for a further upgrade potential of factor ~2 to cover shortfalls in cooling efficiency and future luminosity upgrades
- Bunch rep rate on target ranges from 12-65 Hz
  - Not necessarily the same as linac rep rate. Flexibility can be achieved with intermediate fixed energy rings.
- Proton driver energy is flexible, but at least at Fermilab 8GeV seems most attractive
  - Need more detailed study of intensity limitations.
  - Need to weigh cost of new 50GeV ring(s) against cost of Project X linac upgrades

Scaling of Muon Collider Requirements

$$\mathcal{L} \sim \frac{R_b N_\mu^2}{\varepsilon_\perp \beta^*} f(\sigma_z / \beta^*) \sim \frac{R_b N_\mu \xi}{\beta^*} f(\sigma_z / \beta^*) \qquad \xi = \frac{r_\mu N_\mu}{4\pi\varepsilon_\perp} \leq \xi_{\max}$$

The luminosity of a muon collider is given by the product of:
the integrated luminosity per muon bunch pair injected, times
the rep. rate R_b of injecting bunch pairs into the collider.

Designers often assume (optimistically?) that the muon bunches can be made bright enough to reach the beam-beam limit. Then:

$$\mathcal{L} \propto \frac{R_b \xi_{\max}^2 \varepsilon_\perp}{\beta^*} f(\sigma_z / \beta^*)$$

and for given luminosity, energy, and beam-beam tune shift:

1) the rep. rate scales inversely with the trans. emittance;
2) the proton beam power is independent of the trans. emittance.

Scaling of PD params with collider energy

- For given muon bunch parameters, the luminosity of an optimistically designed collider tends to scale like s.
  - There's one factor of energy in the non-normalized emittance;
  - The bunch length can also be reduced as the energy is raised, allowing smaller β^*.
- The cross sections for pointlike processes scale as 1/s.
- As a result, the event rates depend only weakly on s.
- Therefore, the requirements on the front end of an optimistically designed muon collider are approximately energy-independent.

Desire for performance contingency

- Advocates of low-emittance designs worry that very high intensities per bunch (of protons and/or muons) will not be feasible due to various intensity-dependent effects.
- Advocates of high intensities per bunch worry that very low emittances will not be achievable.
- What if both camps are right!?! Then a face-saving compromise path is needed:
  - A) Punt, or
  - B) Settle for lower luminosity, or
  - C) Raise the proton beam power (rep rate) if necessary.
- Option C is most attractive.

Consider the possibilities… for the proton driver

What are some possibilities?

- Project X linac feeding 8-GeV storage ring(s)
- Few-GeV linac feeding 8-GeV synchrotron, etc.
- Project X linac feeding MI as 50-GeV synchrotron
- A CW 8-GeV linac (instead of pulsed).
- (Various options invented elsewhere (NIH))

The short document

- Proton Driver Beam Parameters for Muon Colliders and Neutrino Factories
- Yu. Alexahin, C. Ankenbrandt, S. Geer, A. Jansson, D. Neuffer, M. Popovic, and V. Shiltsev
  - Fermilab
- **Abstract and Executive Summary**
- The requirements on proton drivers for muon colliders and neutrino factories are discussed. In particular, the requirements imposed on the Project X linac by the needs of a high-energy, high-luminosity muon collider at Fermilab are examined.
- The three most important conclusions are as follows:

First Conclusion

If muon colliders and neutrino factories are separately designed and optimized, the front ends tend to diverge somewhat because muon colliders need luminosity whereas neutrino factories need flux. Nevertheless, there is considerable overlap between the proton beam power needs of energy-frontier muon colliders and those of neutrino factories based on muon storage rings. In many ways, muon colliders are somewhat more demanding on their front ends than neutrino factories, so any facility that meets the beam-power needs of the former is likely to meet the needs of the latter.

Second Conclusion

Several muon collider design efforts have generated parameter sets that call for proton beam power of several megawatts. The most common requests fall in the ballpark of 3 to 4 MW; however, most designs are optimistic and none have been fully vetted, so it is advisable to provide considerable performance contingency. The required proton beam power is not likely to be a strong function of the center-of-mass energy of the collider.

Third Conclusion

Several alternatives have been examined including synchrotron-based ones. The most promising front end is based on the Project X 8-GeV H- linac upgraded to about 3 MW, with a further upgrade path to ~10 MW held in reserve. One or more 8-GeV storage rings will be needed to provide stripping and accumulation, formation of the appropriate number of bunches, and bunch shortening. Of course an appropriate multi-megawatt target station will also be necessary.

First Recommendation

The performance requirements on the aforementioned 8-GeV storage ring(s) are severe. Accordingly, a design study should be initiated. The main goals should be to establish design concepts and explore potential limitations due to beam instabilities.

Second Recommendation

Planning should be initiated for an appropriately located muon test area that can evolve into a facility capable of handling several megawatts of proton beam power.

The synchrotron-based options

- ~2.5 GeV linac plus 8-GeV synchrotron
- Project X linac plus Recycler plus Main Injector (at ~ 50 GeV) plus one or two 50 GeV storage rings for bunch transformation

Compare schemes w/wo synchrotron

- Beam losses are a major technical risk.
- Beam losses in synchrotron (not in storage ring):
  - Uncaptured beam lost at start of magnet ramp
  - Various resonant conditions at particular energies
  - Transition crossing losses (in MI case)
- Beam losses in synchrotron (less in storage ring):
  - Time of occupancy less in storage ring -> less vulnerable to instabilities
  - Beam collimation is easier and more effective in a fixed-energy storage ring.
- Storage ring(s) provide more flexibility (variable number of bunches, variable rep. rate to target)

LE Linac + 8-GeV Synchrotron

- Main motivation: purported cost savings vs. Project X. However:
- For ~ 2 MW from MI, need a high-energy linac to overcome space-charge limit in the synchrotron with ~ 25 π mm-mrad.
  - E_L ~ 2.5 GeV by scaling from Booster performance
  - Need to use Recycler as accumulator ring as in Project X
- The new rapid-cycling synchrotron needs large aperture (normalized acceptance ~ 250 π mm-mrad) in order to provide multi-megawatt beam also at 8 GeV.
- Cost hand-waving:
  - Low energy part of a linac is the most expensive part.
  - A high-performance rapid-cycling synchrotron with that aperture is also quite expensive.
- Conclude:
  - Costs are comparable.
  - Performance risk is higher.
  - There's less flexibility (e.g. number of bunches)

Rapid-cycling Synchrotrons vs Storage Rings

- In storage rings, many systems are easier:
  - The beam pipe
  - The rf systems
  - The magnets
  - The power supply for the magnets

Comments/conclusions on using MI

- The yield/power is somewhat lower at 50 vs 8 GeV.
- MI intensity proposed in Project X is already more than 5 times its design intensity; its beam power is about an order of magnitude higher.
- Perhaps can "only" make 1.5 MW at 50 GeV.
- Need expensive 50 GeV storage ring(s).
- Twice as many cycles/sec -> twice the beam losses at injection and transition compared to 120 GeV.
- This would use the full output of the whole facility; diversity has been a strength of Fermilab's program heretofore.

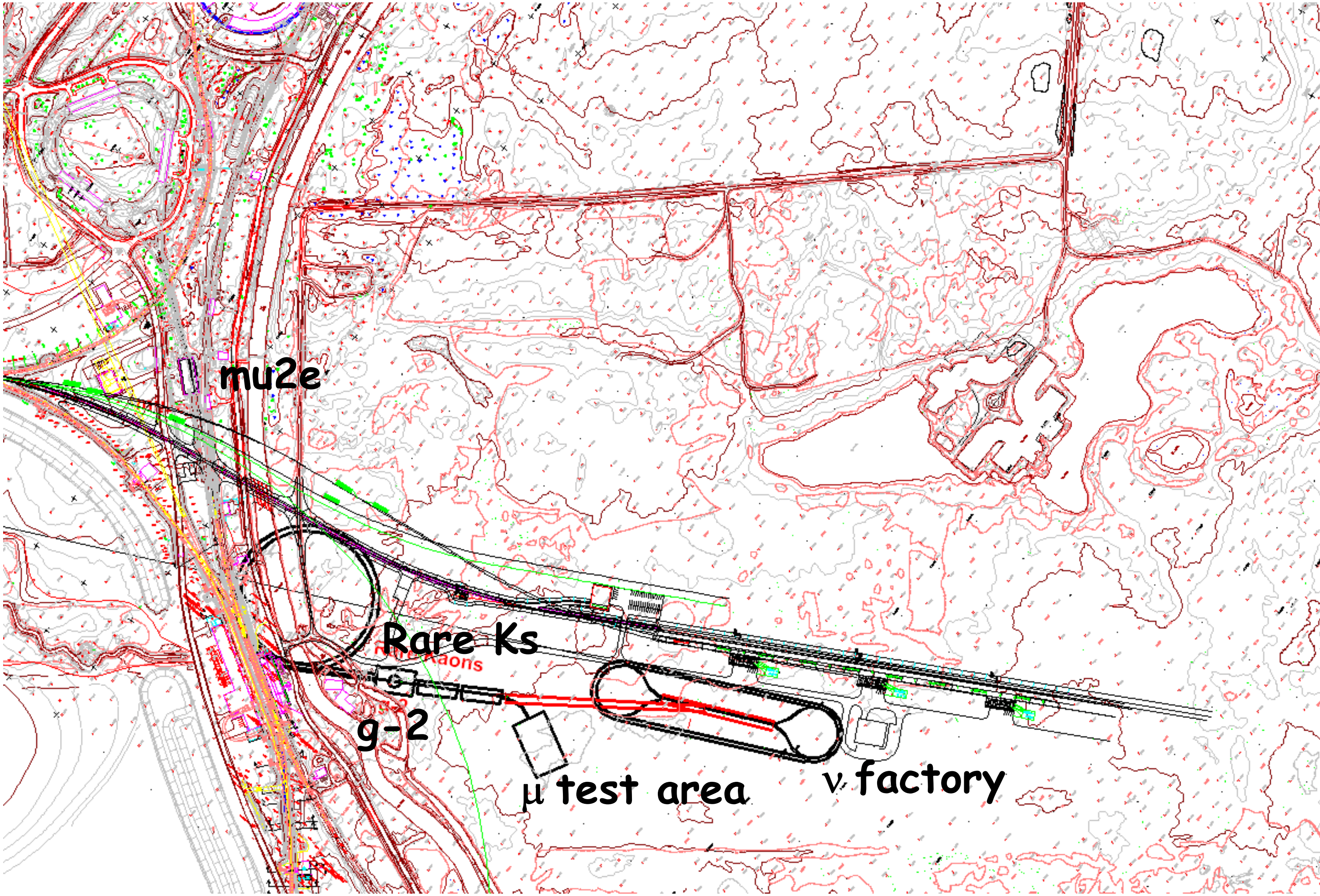
What are some possibilities?

- → Project X linac feeding 8-GeV storage ring(s) ←
- Few-GeV linac feeding 8-GeV synchrotron, etc.
- Project X linac feeding MI as 50-GeV synchrotron
- A CW 8-GeV linac (instead of pulsed).

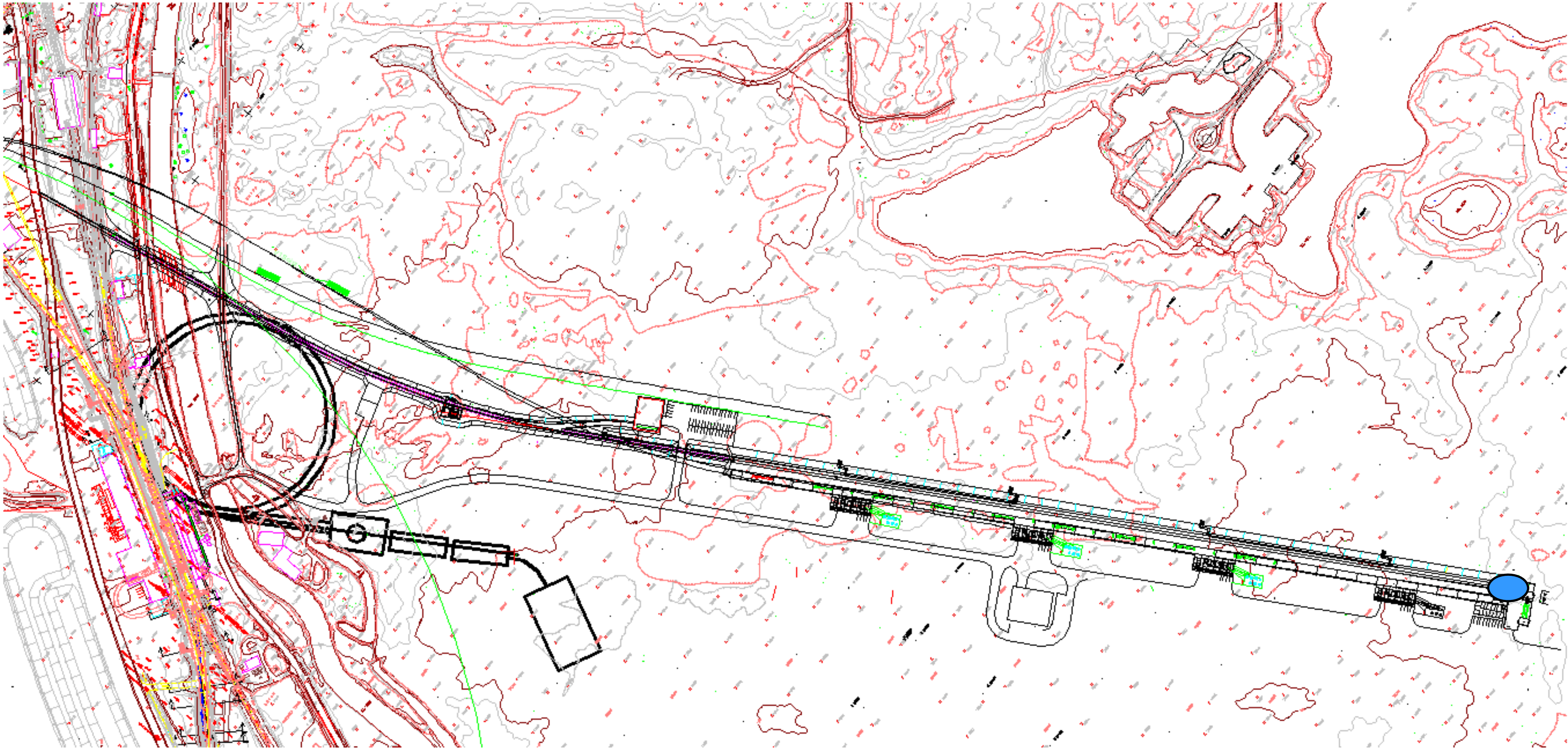
Layouts & Beam Transfer Schemes

- Booster Era
- Project X Era (Beam Power = 200 kW @ 8 GeV)
- Upgraded (2MW) Project X Era (aka Project XLR8 Era?)

Siting of mu2e, g-2, Kaons, μ test area, 4GeV ν Factory

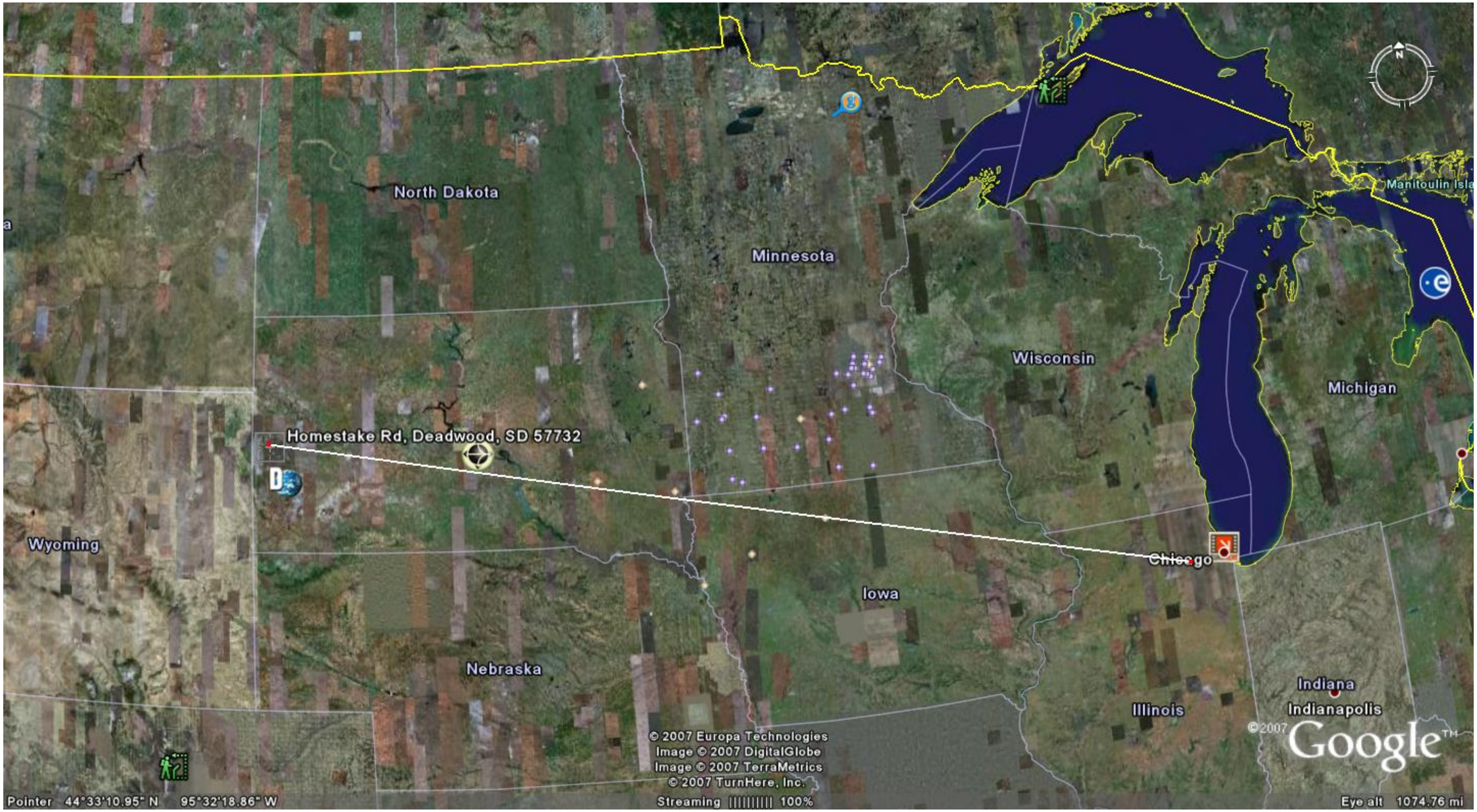


Beam Path to 2 MW target in Project XLR8 Era

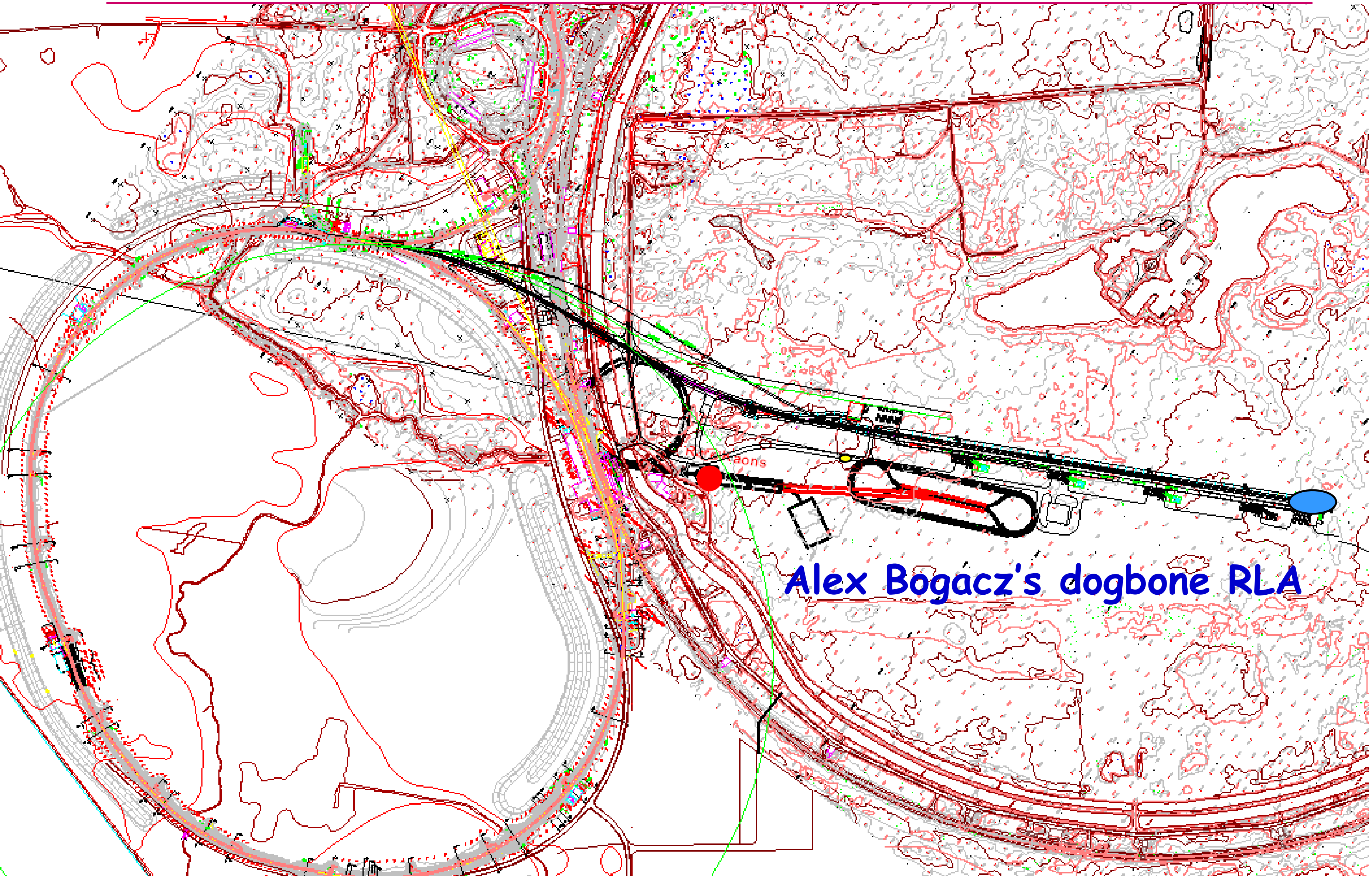


Including a 2 MW target station was Steve Geer's idea

FERMI-DUSEL, 802 miles



Path of Beams to ν Factory in Project XLR8 Era



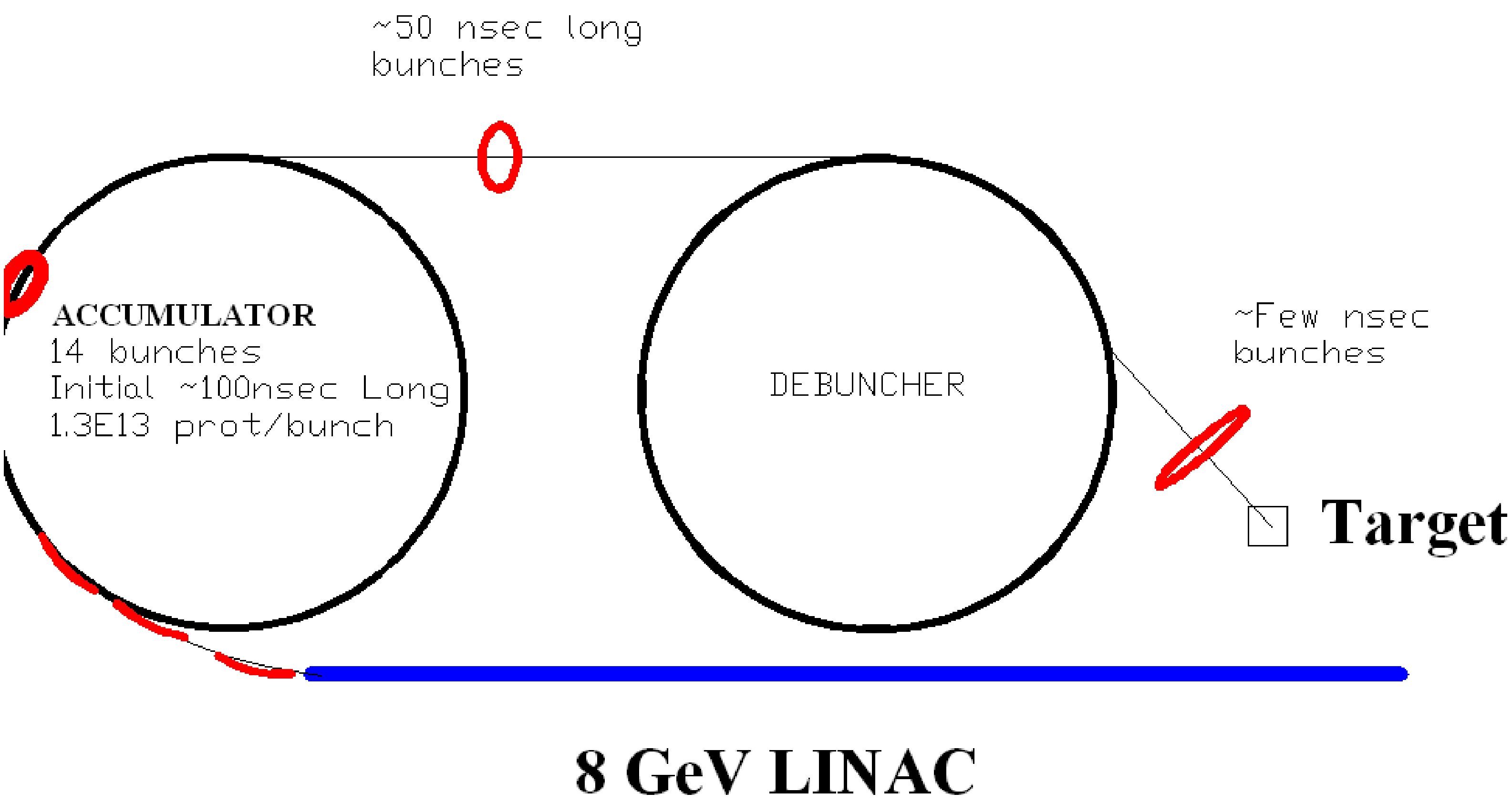
Making muons for a MC/NF with Project X

- Proton beam power of 2 MW may be enough to drive a high-luminosity, low-emittance muon collider.
- The challenge is to "repackage" the protons into a useful form for a muon collider.
  - It's not clear what will work best for a muon collider or a neutrino factory, so flexibility would be nice at the conceptual design stage.
    - The rms bunch length should be 3 nsec or less.
    - A repetition rate of 60 Hz would match the muon lifetime at 750 GeV. (However, we may end up at a different energy.)
    - Will we use one or two proton bunches to make each pair of muon bunches? Or to make multiple pairs?
    - How many pairs of muon bunches will we make at a time?
  - "Buffer rings" (two 8 GeV storage rings with large acceptances and small circumferences) could provide the needed flexibility.

A specific hi rep. rate, 8 GeV example

- Use Accumulator(-like) and Debuncher(-like) rings.
  - Acc and Deb are leftovers from Fermilab's Antiproton Source
  - They are not very deep underground; maybe move to new tunnel?
- Paint to large (~200 pi) transverse emittances in rings with small circumference to control space charge.
  - Could strip directly into "Accumulator" or do multi-turn transverse stacking from Recycler to "Accumulator".
  - Small circumference means more favorable bunching factor.
  - Scale from space charge tune shift (~0.04) in Recycler ring.
- Use h=12 and h=24 rf to make 12 ~rectangular bunches.
- (Note possible constraints on h_1, h_2: Circumference ratio)
- Transfer two bunches at a time to the "Debuncher".
- Do a bunch rotation in the "Debuncher".
- Deliver two bunches at a time to the target at 60 Hz.

Providing p Bunches for a ν Factory or a μ Collider



Longitudinal emittance scaling

- In the Recycler, beam will be painted to a longitudinal emittance of about 0.25 eV sec per (53 MHz) bunch
- After transfer via transverse stacking to the Accumulator, the total longitudinal emittance will be ~ 84 times 0.25
- If we form 12 bunches, each will have 84(0.25)/12 = 1.75 eV sec.
- If we reduce the bunch length to a total Δt of about 10 nsec, then ΔE will be about 0.175 GeV = +/- 0.09 GeV
- So $\Delta E/E$ = +/- 1% , well within the momentum aperture.
- Note that much smaller longitudinal emittances can be achieved if we inject
  - without longitudinal painting
  - into a smaller ring (than the Accumulator)

Space-charge tune shift scaling

- Scale from incoherent tune shift of 0.04 in Recycler

$$\Delta \nu \sim \frac{N_{tot}}{\varepsilon_n \beta \gamma^2 B}$$

- The energy (8 GeV) and the total number of protons are the same in the Recycler and the Debuncher.
- The transverse stacking into the Debuncher raises the transverse emittances by a factor of eight.
- The bunching factor goes down (worse) by a factor of nine.

$$B_{ar} = \sqrt{2\pi}\,\frac{\sigma_l}{C} \qquad B_{br} = \frac{1}{2}\frac{\lambda_{rf}}{C} \qquad \frac{B_{ar}}{B_{br}} = \sqrt{8\pi}\,\frac{\sigma_l}{\lambda_{rf}}$$

Flexibility

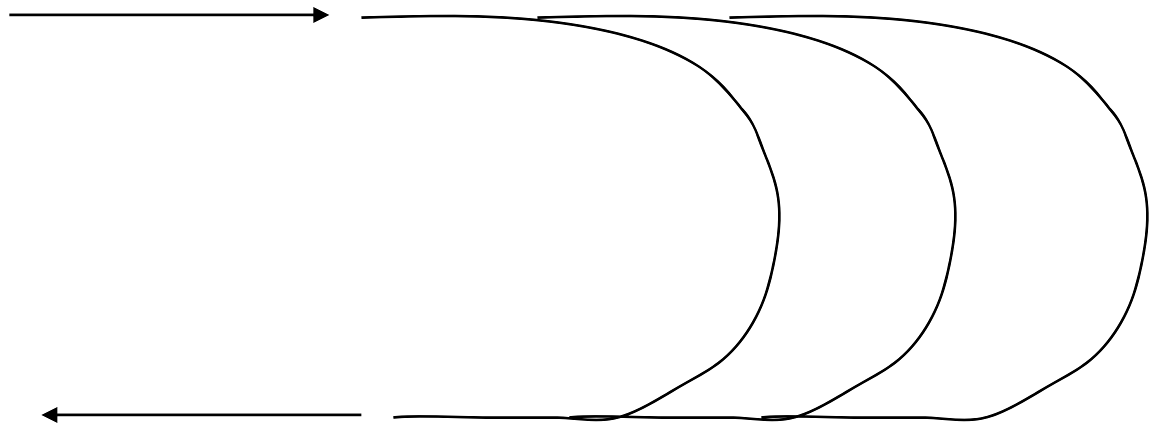
- Above example was for 60 Hz; however…
  - Could form fewer bunches in rings
  - Could combine bunches externally (cf. next slide)
  - Rep rate as low as 10 Hz (once per linac cycle) may be feasible
- Analogy: Tevatron Collider
  - Started with one pair of bunches at design luminosity of 10^{30}
  - Went to 3x3, mainly to reduce events per crossing
  - Implemented electrostatic separators and went to 6x6
  - Now at 36x36

What if lower rep. rates are desired?

- The Fermilab Debuncher handles 4% momentum spread.
- We wouldn't have to paint to such a large longitudinal emittance in a dedicated 8-GeV ring with no acceleration.
- We can combine bunches in an external "trombone".

An external combiner ("trombone") to reduce rep rate at target

Several bunches enter



Bunches exit simultaneously

Summary

- A flexible way to deliver short intense 8-GeV proton bunches to a muon collider target station has been found.
- The scheme uses the full capability of Project X upgraded to 2 MW of beam power.
- The scheme makes good use of other Fermilab resources.

<3 MW is recommended;
10 MW may be necessary.

Backup slides

Dave Neuffer's Draft: 56 GeV

56 GeV Synchrotron proton driver for Collider/Factory

The neutrino factory and muon collider scenarios require a proton source of 2 MW or more. The initial application of the 0.36 MW 8 GeV Project X Linac is to increase the deliverable power of the Fermilab Main Injector (MI) to more than 2 MW at 50 to 120 GeV, and it is of interest whether that source can be used for a Collider or Factory. The major difference in requirements is that the Collider/factory (C/F) scenarios require that the 2 MW beam must be bunched in a relatively small number of bunches, while the MI produces beam in 53 MHz bunches (h=584). For the C/F scenarios the MI beam must be rebunched into a smaller number of bunches, which would then be single-bunch extracted to produce $\pi \rightarrow \mu$ on a high-intensity target. Also the higher-energy proton beams would be less efficient in producing the ~0.3GeV/c $\pi \rightarrow \mu$ beams required for C/F scenarios, where the optimal proton energies are ~8 to ~40 GeV, and it is desirable to reduce the maximal energy toward this range.

Dave Neuffer's Draft: 56 GeV

For 2+ MW operation the MI spends its entire cycle time in its acceleration cycle, with no flat-top for injection/extraction, and with the ramp rate for acceleration/reset at 80 GeV/s. In the 120 GeV cycle, 3 linac blasts of 5×10^{13} 8 GeV protons are transversely stacked in the Recycler and a 1.4s cycle produces 120 GeV beam for single-turn extraction. Only 3 of 7 linac blasts are used in that scenario. A lower-energy high-power cycle is obtained by using all of the linac blasts, but acceleration only over a 0.6s cycle, obtaining 56 GeV protons for single turn extraction, which would be more efficient in soft π production.

Dave Neuffer's Draft: 56 GeV

The single turn from the MI would be injected into a buncher ring, where the beam would be rebunched into a small number of bunches. 9 bunches would obtain a 15 Hz C/F scenario and 30 bunches would match a 50 Hz scenario; these match the range of C/F designs under consideration. While the buncher could be the same circumference as the MI, a better rf scenario is obtained with a smaller circumference; for example, a buncher ring with ¼ the MI circumference, filled using transverse phase-space stacking. The bunching to short bunches (< ~2ns) can occur in a fraction of a second (<0.1), and would not be space charge limited. Parameters for the 9 bunch scenario are presented in table 1.

Dave Neuffer's Draft: 56 GeV

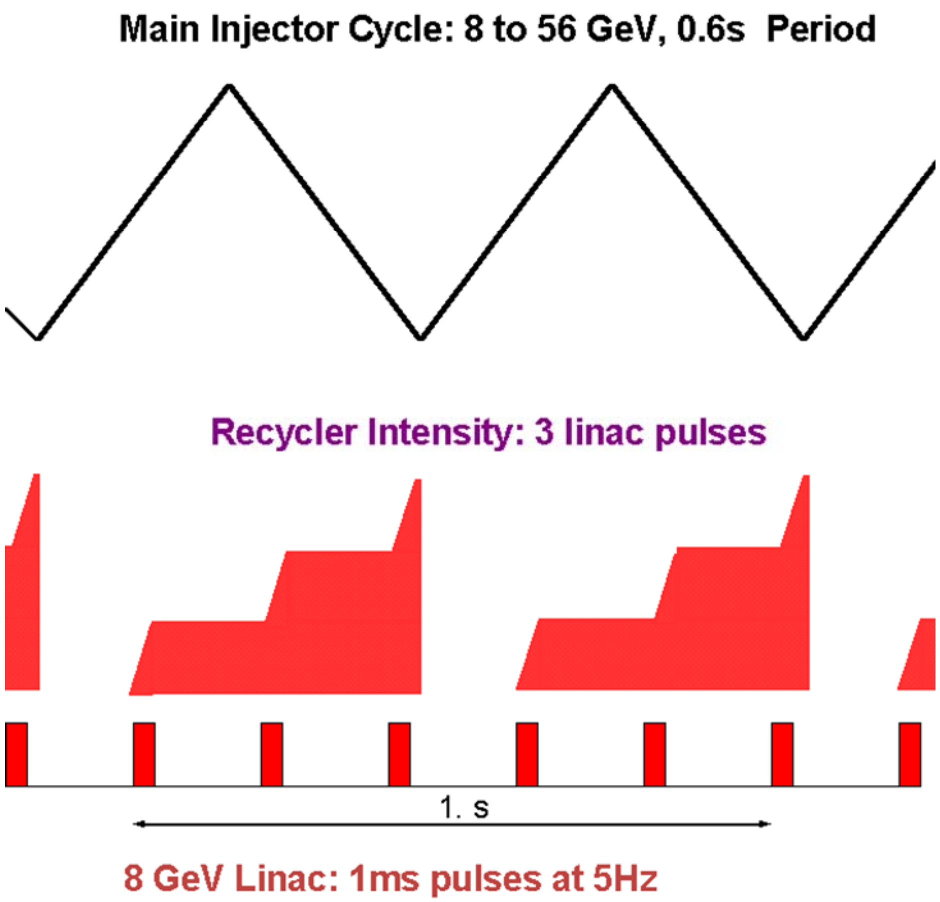
Upgrade/Variations

The project X linac could be upgraded by a factor of three in pulse length, peak current and repetition rate. The increase in pulse length and peak current would lead to a corresponding increase in output power, provided the MI can handle the additional beam. The baseline MI rf power system is designed to allow an increase of a factor of 3 in power; that increase would give us 7^{+} MW. A repetition rate increase is not as helpful since the cycle time is set by the MI ramp, but one may be able to increase the number of injection blasts/cycle.

Dave Neuffer's Draft: 56 GeV

The 56GeV scenario obtains 2MW beam from MIX (Main Injector + Project X) without upgrading any linac/MI parameters. However, it does require addition of a ~50 GeV storage ring. It may be possible to avoid an additional ring by accelerating to a constant energy "flat-top" in the MI, bunching the beam to ~30 bunches and extracting these one (or a few) at a time. With plausible timings, a "flat-top" would require doubling the MI cycle time, reducing the output power by a factor of two to ~1MW, and the constraints on bunching scenarios and densities would be more severe then in a new ring, and all duty cycles are a factor of two worse. (A doubling of linac peak current could restore the intensity to 2MW, with the 50% duty cycle.)

Dave Neuffer's Draft: 56 GeV



Beam Power from MI at ~50 GeV

Fermilab Proton Projections for Long-Baseline Neutrino Beams

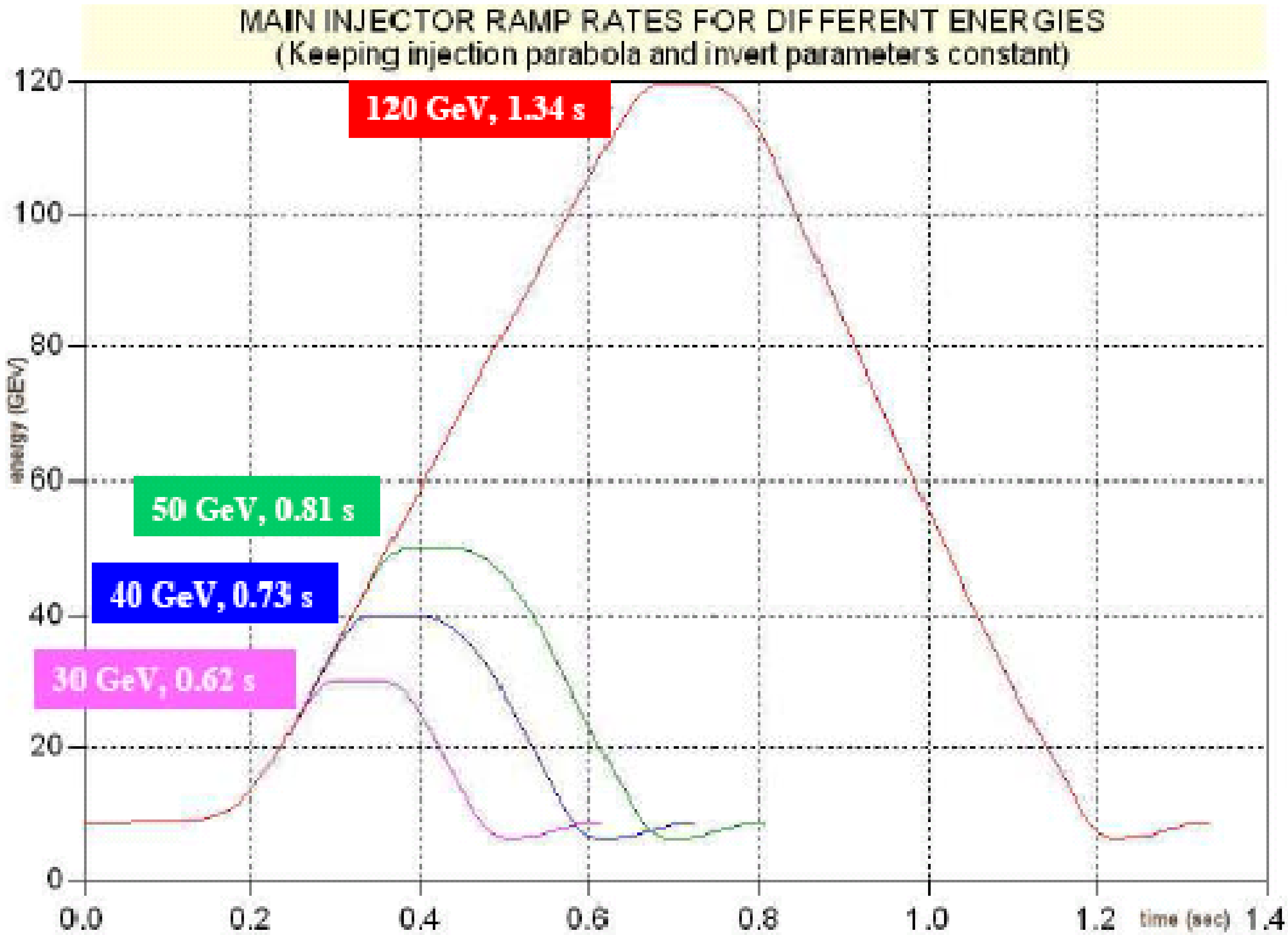
Robert Zwaska
for the SNuMI Planning Group

July 17, 2006

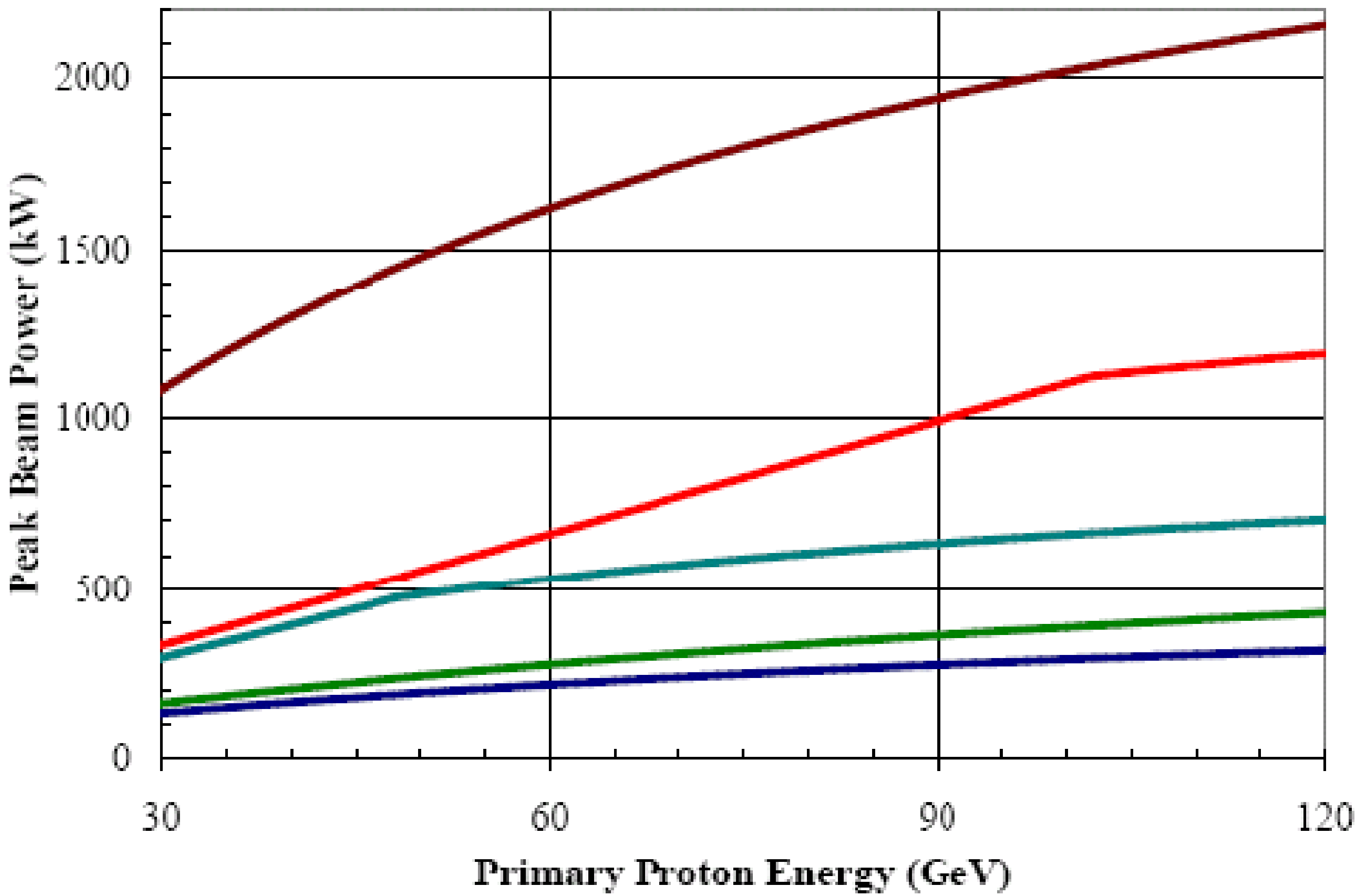
Abstract

This note describes the rates of proton delivery that may be available in the future for long-baseline neutrino experiments. Several potential accelerator configurations are briefly described and analyzed in terms of their potential proton rates and schedules. Beam power is considered for variable primary proton energies between 30 and 120 GeV, delivered by the Main Injector.

Zwaska's Figure 1



Zwaska's Figure 2



Muon Collider parameters

- **Low emittance option** (advanced): owing to ideas by Yaroslav Derbenev (HCC, PIC) much lower 6D emittances seem to be feasible than previously thought of.
- **High emittance option** (baseline): conceptually follows 1999 PRSTAB Muon Collider Collaboration report

	Low Emitt.	*High Emitt.*
Energy (TeV)	0.75+0.75 (γ=7098.4)	
Average Luminosity (1e34/cm^2/s)	2.7	1
Average bending field (T)10	8.33	
Mean radius (m)	361.4	363.8
Number of IPs	4 (350m/2 each)	2 (200m each)
P-driver rep.rate (Hz)	65	60
Beam-beam parameter/IP, ξ	0.052	0.1
$\beta*$ (cm)	0.5	3
Bunch length (cm), σ_z	0.5	2
Number of bunches/beam, n_b	10	1
Number of muons/bunch (1e11), N_μ	1	12
Norm.transverse emittance (μm), $\varepsilon_{\perp N}$	2.1	13
Energy spread (%)	1	0.1
Norm.longitudinal emittance (m), $\varepsilon_{\parallel N}$	0.35	0.14
Total RF voltage (GV) at 800MHz	$406.6 \times 10^3 \alpha_c$	$0.26 \times 10^3 \alpha_c$
RF bucket height (%)	23.9	0.6
Synchrotron tune	$0.723 \times 10^3 \alpha_c$	$0.02 \times 10^3 \alpha_c$
μ+ μ- in collision / proton	0.15 /2	0.15
8GeV proton beam power (MW)	1.1	0.6

2 MW Target Station for ν Factory or μ Collider