Accelerator Facility Design: 1, 3, 8 GeV Beam Transport

David Johnson
Project X Machine Advisory Committee
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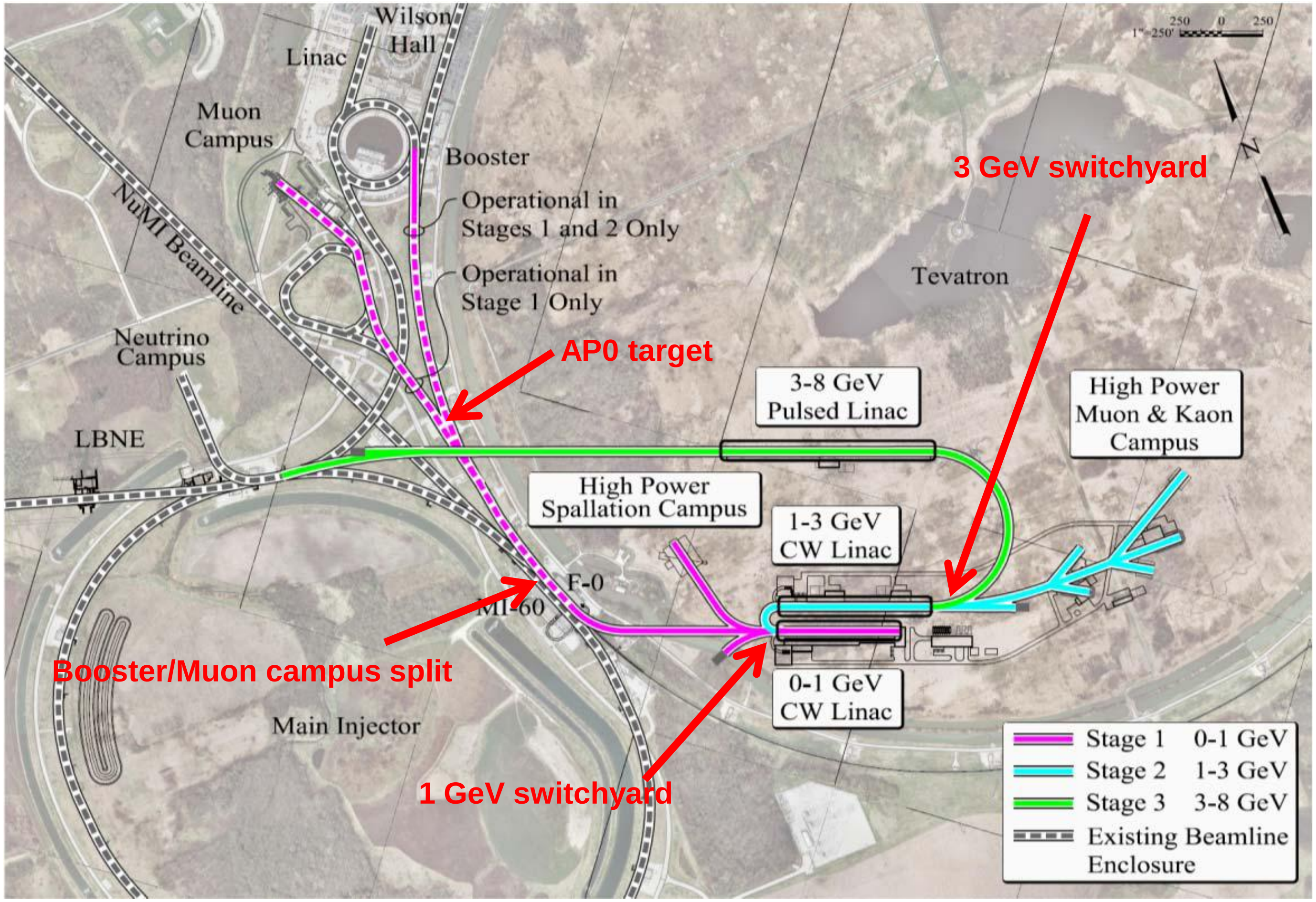
Organization of Talk

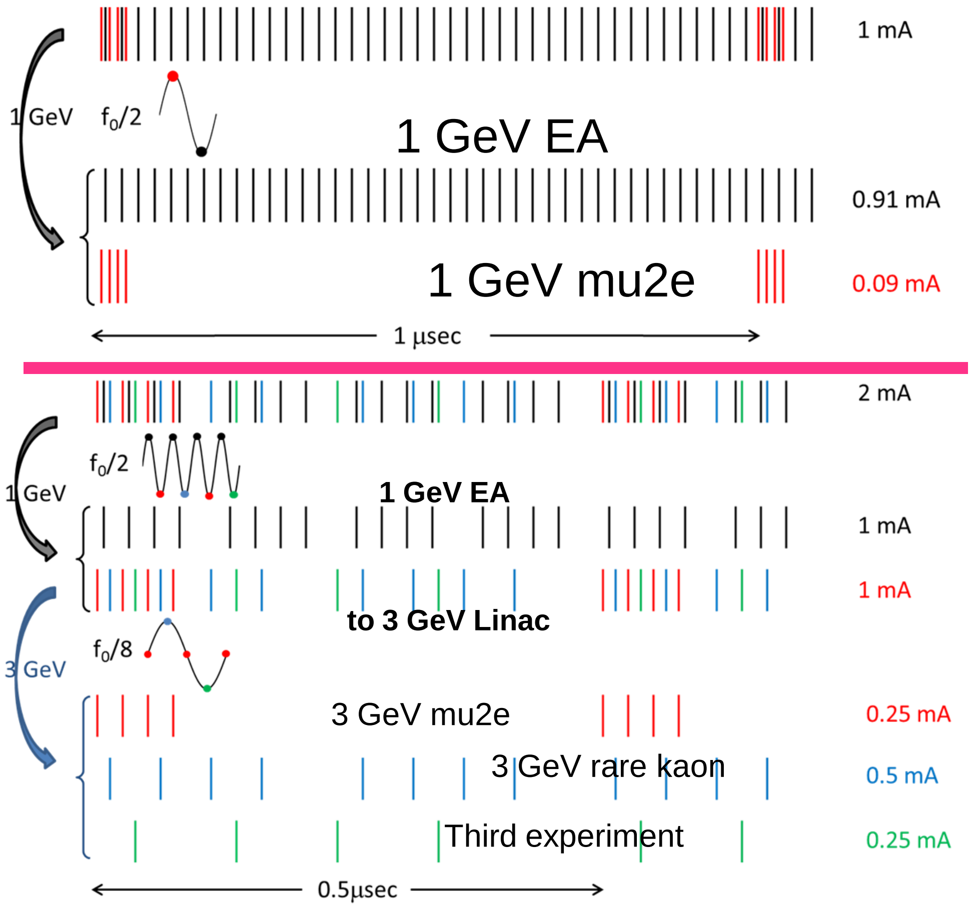
- Current layout
- Beam distribution
- Performance requirements
- Transport lines
  - 1 GeV transport to Booster, 1 GeV EA (Spallation Target) , Muon Campus, and to 1-3 GeV Linac
  - 3 GeV transport to Experimental Area and 3-8 GeV Pulsed Linac
  - 8 GeV transport to Recycler
- Losses
- Hardware requirements

- General Comment: The aperture, optics, vacuum level, and beam pipe temperature will be designed to minimize both single particle and macro beam losses. Instrumentation and correction elements will be provided to monitor and facilitate orbit and lattice control.

Current Layout



Beam Distribution

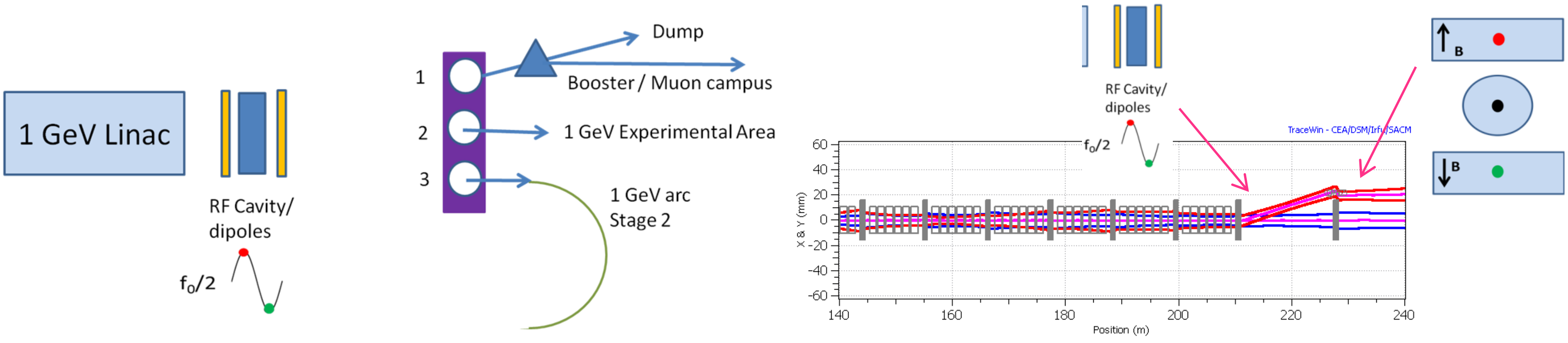


- MEBT chopper produces desired bunch pattern for delivering bunches simultaneously to multiple Experimental Areas at multiple energies with bunch frequencies sub-harmonic to natural 162.5 MHz bunch frequency.
- Injection into Booster at 1 GeV or injection into the Recycler at 8 GeV requires the full 162.5 MHz bunch structure
  - Implies turning off the experimental program during the time required for injection. ~ 3% impact at 1 GeV and ~5% impact at 8 GeV
  - Requires pulsed dipoles to steer the beam into 1-3 GeV linac and the 3-8 GeV pulsed linac.

Performance Requirements

- Transverse emittance requirements
  - Not expected to be a limiting factor for targeting, no specifications given – it is assumed the final targeting optics will be fully capable of meeting targeting requirements
  - For injection into Booster and Recycler need to keep the ratio of ε/A as small as possible to minimize number of parasitic hits ($\varepsilon/A < 0.1$) where ε is the linac beam emittance to be injected and A is the final painted emittance in the ring.
    - For Booster (inj. time ~ 1ms) $A_{95} \sim 20$ π-mm-mr implies $\varepsilon_{rms} < 0.33$ π-mm-mr
    - For Recycler (inj. time 6 x 4.3 ms) $A_{95} \sim 25$ π-mm-mr implies $\varepsilon_{rms} < 0.42$ π-mm-mr
- Longitudinal emittance requirements
  - No requirements for Experimental area targeting
  - Injection into Booster and Recycler use micro bunch injection into both rings. Longitudinal emittance (both Δt and ΔE) of linac beam is much smaller than the already formed RF buckets in the ring – should not be a problem.
  - The main requirement on longitudinal emittance is matching between linacs and
  - Longitudinal phase shear at RF transverse deflection cavities (particularly 3 GeV)
- Bunch train frequency
  - Experimental program - typically a sub-harmonic of 162.5 MHz bunch frequency, typically 1 to 40 MHz
  - Ring injection - use the full bunch train frequency minus removing bunches which land outside the central bucket phase and gaps for extraction kickers

1 GeV: Splitting Configuration



- Splitting accomplished by combination of
  - Transverse RF superconducting cavity and ramped dipoles (to give same bend center) which will produce a vertical deflection of ~ 20 mm at Lambertson (+/- 1.5 mr)
  - Three way Lambertson (35 mr)
- The cavity sends bunches simultaneously to either
  - the Muon Campus and 1 GeV EA, or
  - the 1 GeV EA and 1-3 GeV Linac
- For injection, the cavity is turned off and the dipoles are energized to select either
  - the Booster aperture in the Lambertson
  - the arc to the 1-3 GeV linac for further acceleration and injection into Recycler

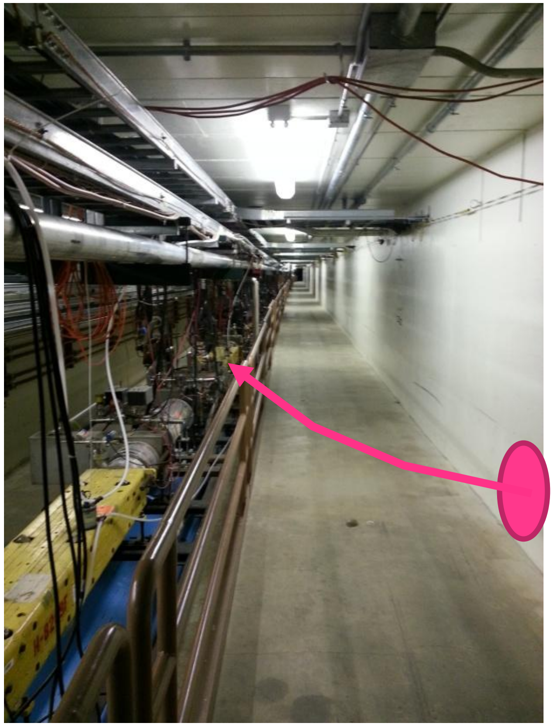
$$f_{RFS} = (n+1/2)162.5MHz$$

with n=2 *f = 406.25 MHz*

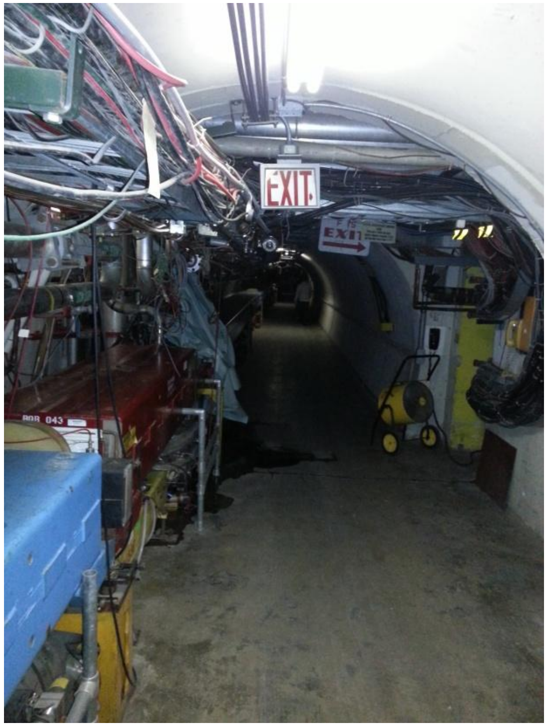
1 GeV: Beam to Booster/ Muon Campus

- Beam to Booster
  - Transport line enters Tev enclosure through a 48^{o} achromatic bend upstream of F0
  - Transport line follows Tev footprint (at Tev elevation) for approximately 800 meters (FODO achromat)
    - Requires same distribution of bending centers (~8 mr/magnet) as P2/P3 line (old Main Ring) and Tevatron
  - A new short enclosure to connect the Tevatron tunnel to the Booster
  - Preliminary optics to confirm feasibility (achromatic half cells)
  - Potential permanent magnet transfer line
- Beam to Muon Campus
  - Share transport line into TeV enclosure
  - Dipole switch at F0 to transfer beam into existing P2 line
  - Trajectory will utilize existing transport line to Muon Campus (i.e P2, AP1, and AP3) used for 8 and 120 GeV beam. Aperture should be OK, new power supplies will probably be needed – needs detailed investigation.

Tevatron Enclosure



F0 Enclosure



TeV Enclosure

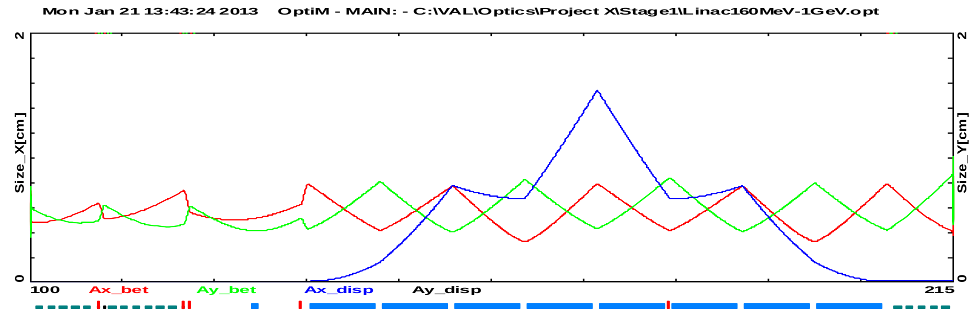
Old TeV ring

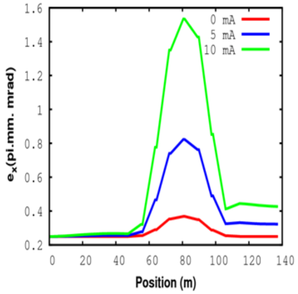
1 GeV: Beam to EA

- One of the goals for Project X is to *'Provide MW- class proton beams at 1 GeV, coupled with novel targets required to support a range of material science and energy applications''*
- Experimental program is in the process of being defined.
  - Detailed beam requirements (emittance & bunch structure) or targeting requirements have not been specified at this point.
  - The expected rms transverse emittance at the end of the 1 GeV linac is on the order of 0.25 π-mm-mr -> shouldn't lead to any targeting issues
- The details of the transport such as lattice type (FODO or doublet), total bending required, collimation, and ultimately targeting will be addressed, but not expected to be technically challenging.

1 GeV: Beam to 3 GeV Linac

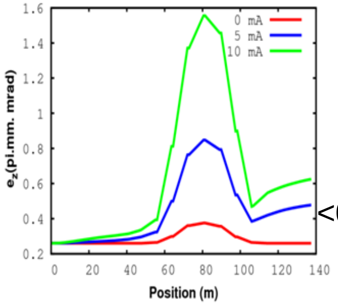
- Consist of arc (with 180º bending angle) which is achromatic and isochronous to suppress horizontal emittance growth and bunch lengthening.
- Initial concept of four 90º FODO cells with 22.5º bending each cell
- Initial simulations show hor/long emittance growth of 20% & 80% for bunch currents of 5 mA.
- Transport line is currently being optimized and these mismatches are expected to be reduced.





~0.3

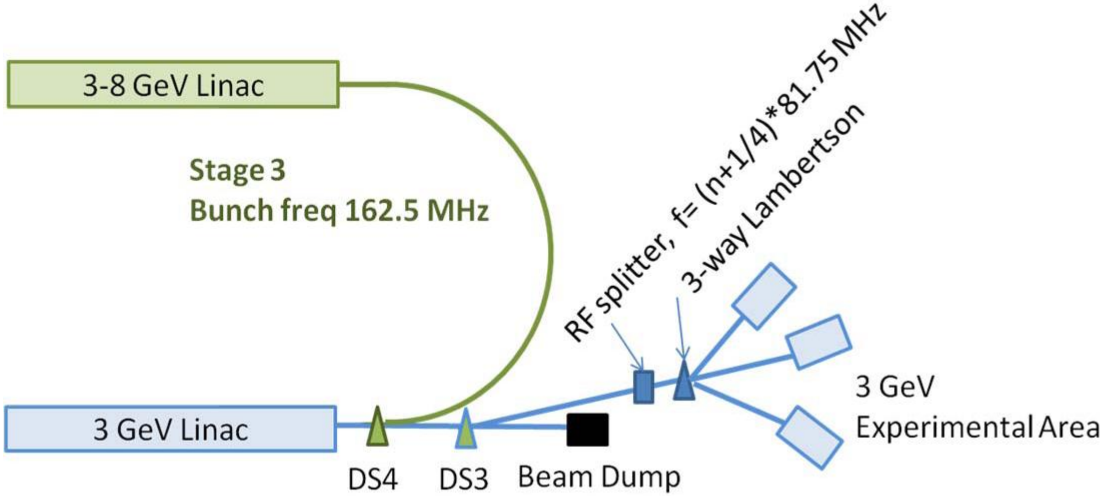
Transverse



<0.5

Longitudinal

3 GeV: Configuration



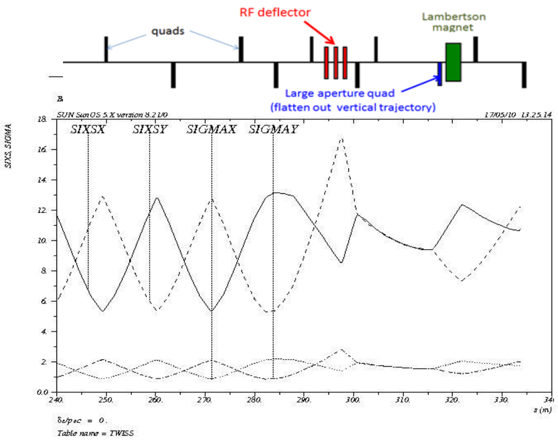
- Pulsed dipole switch immediately after Linac to direct beam toward 3-8 GeV linac
- DC dipole switch to direct beam toward 3 GeV EA
- Both dipoles off beam goes to linac dump
- Transverse RF cavity /Lambertson (similar to 1 GeV) to split bunches to three Experimental Areas

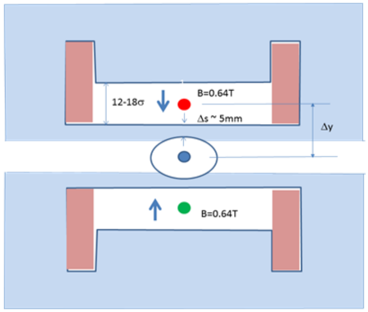
3 GeV: Transport to Experimental Area

- Beam power 3 MW
- Design based on FODO lattice with achromatic bend
- Split off the dump line using a (pair) DC dipole achromat
- Evaluating the requirements for collimation (dependent on level of halo production)
- Utilize a RF splitter/Lambertson to distribute beam to three EA's

$$f_{RFS} = (n + 1/4)81.25MHz$$

With n=5 f_{RFS} = 426.5625 MHz

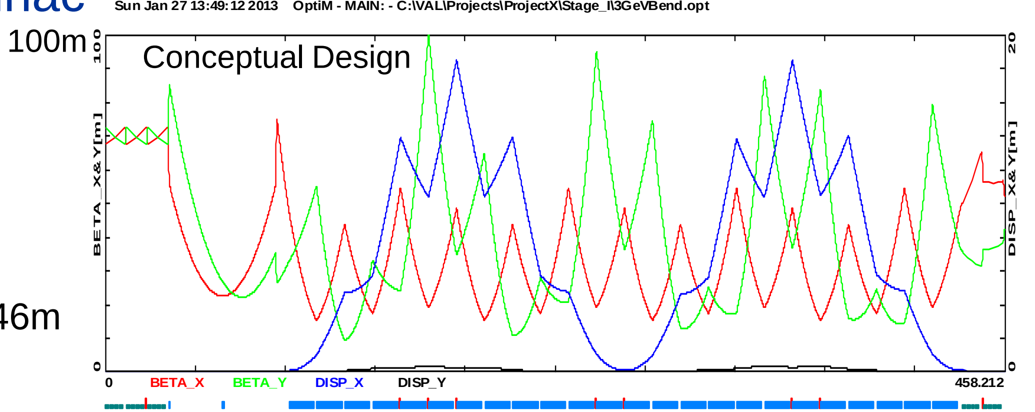




3 GeV: Transfer to Pulsed Linac

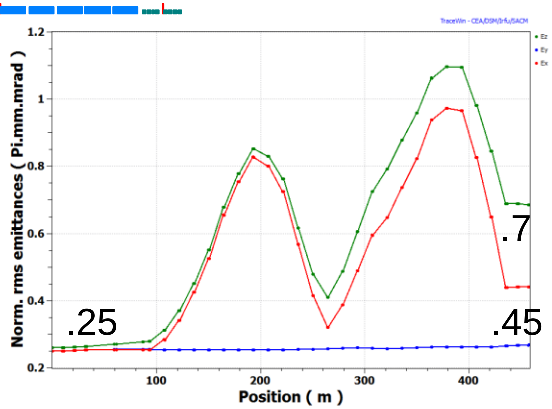
- A pair of dipoles (achromat) split the beam to the 3-8 GeV linac into a 180º achromatic arc (length about 400 m) that will match into the downstream linac

Half-cell length ~46m



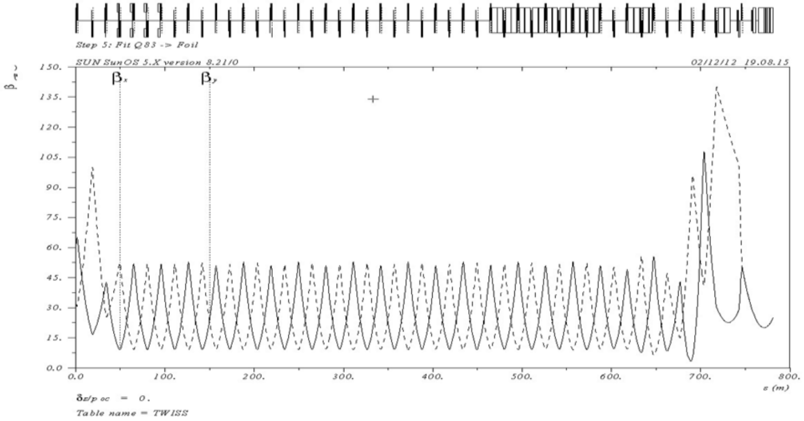
R11=R12=0
R51=r52=R56=0

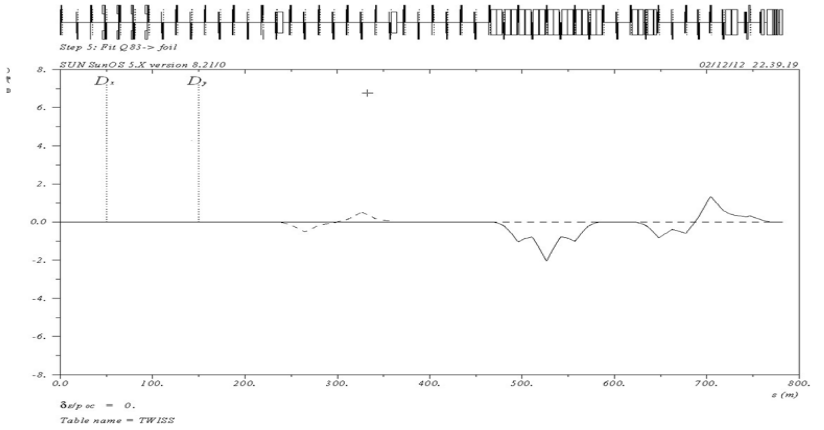
- This arc should minimize emittance growth in both transverse and longitudinal planes.
  - An initial concept is shown (not optimized)
  - A cryo module at the center point could reduce emittance growth
  - Optimization of this arc is underway



8 GeV: Transport to Recycler

- Single achromatic bend to avoid MI-65 building
- 90^o FODO , vertical bend to match Recycler elevation
- Transverse H^- collimation
- Flexible optics control for matching into symmetric injection straight
- Permanent magnet design (currently envisioned as c-magnet)
- Based upon previous designs for Proton Driver/early Project X
- Beam power 345 kW – dominant loss from BBR expected at 0.3 W/m with warm beam pipe. When beam power increases can convert to 150^o shield





Losses

- Many facilities use the metric of 1 W/m as a limit for beam loss (for hands on maintenance of equipment)
- ALARA considerations for residual activation we would like to keep average residual activation to < 20 mrem/hr
- Average beam loss under normal operating conditions is estimated to be on the order of 0.1 W/m
- Single particle loss mechanisms
  - Lorentz Stripping
    - ➢ Gives upper limit on fields in transport line - dependent on energy
    - For a loss rate of 5×10^{-8}/m we have: 1 GeV B ~ 2.9 kG 3 GeV B ~ 1.3 kG and 8 GeV B ~ 550 kG
  - Residual gas stripping
    - Dependant on molecular composition and loosely on energy. The fractional loss rate ≈ 1.6 * vacuum level.
    - Routine vacuum levels achieved in FNAL transport lines is in the "low 10^{-8}'s" to "high" 10^{-9}'s.
    - ➢ With reasonable care this should not be a major contributor to loss levels.
  - Blackbody radiation
    - Not an issue at 1 GeV loss rate ~3×10^{-9} /m
    - ➢ Could be an issue at 3 GeV and 8 GeV dependent on beam power
    - ➢ Can be mitigated through reducing beam pipe temperature
    - At 300°K loss rate at 3 GeV ~ 3×10^{-7} /m (dominant for 3MW) and 8 GeV ~ 8×10^{-7} /m

Losses (con't)

- Intra-beam stripping
  - Loss rate proportional to bunch intensity, normalized angular spread, and intra-beam stripping cross section
  - Inversely with beam size and gamma squared
  - Preliminary estimates for the CW linac show losses below 0.1W/m in the first GeV falling to below 0.05 W/m at higher energy
  - Preliminary estimates for 8 GeV show this should not be a problem
  - For a given range of Linac currents can be mitigated by optics design (will verify with simulation)

- Collimation
  - Collimation systems for the 1 GeV EA, 3 GeV EA, and 8 GeV transport lines to remove halo are considered (more details in section IV.2.1 of the RDR
- Beam dumps / Injection absorber
  - Without going into detailed design, it is expected that each Linac will have a dedicated beam dump for tune up purposes, The dump capacity will be approximately 10% of the ultimate beam power delivered by each of the Linacs. Additionally, the absorbers should "survive" a small number of full intensity hits. (more on Recycler injection absorber in section IV.2.2 of the RDR)

Hardware Requirements

- Based upon the initial conceptual designs of the transport lines estimate the number and strength of the dipoles and quads for each line. All field strengths are kept below the level which Lorentz stripping becomes important.
- 1 GeV switchyard
  - Transverse RF deflecting cavity kick approx +/-1.5 to +/-3 mr
  - 3 way Lambertson 2 kG 1 meter long gives 35 mr bend
- 1 GeV to Booster (3 sections: linac to TeV tunnel, TeV tunnel transport, transport from TeV tunnel to Booster)
  - Dipoles approximately 52 with fields of 870 Gauss and 1.5 kG
  - Quads approximately 140 with gradients of 21 kG/m
- 1 GeV to Muon Campus (shares first section with Booster transport)
  - Remaining transport utilize existing transport lines
- 1 GeV to EA Spallation target
  - Detailed magnet counts and strengths TBD
- 1 GeV Arc
  - Dipoles 16 - 4 meter dipoles with 2.7 kG
  - Quads 10 - Currently 20 cm length with gradient ~38 kG/m
- 3 GeV to EA
  - Dipoles – 16 to 18 depending on final site of EA length ~ 3.8 m and field of 1.15 kG
  - Quads - ~30 depending on final site of EA length 1 meter and gradient ~ 33 kG/m
  - Transverse RF deflecting cavity kick approx +/- 1.3 mr (+/- 27mm) 3 way Lambertson (5 m @1.2 kG)
- 3 GeV arc
  - Dipoles – 24 dipoles each with 7.5 degree bend (16.7 kG-m)
  - Quads – 24 quads with a gradient of 28.97 kG/m + 6 matching quads
- 8 GeV to Recycler
  - Dipoles - 16 arc dipoles , 4 vertical bend dipoles , and 8 injection dipoles with lengths 4 to 6 meters and fields ~ 500G
  - Quads – 30 to 40 1.3 meter quads with gradients ranging from 10 to 30 kG/m
- For all beam lines a full complement of instrumentation (BPM, LM, profile monitors, torroids, etc) , orbit correctors, and trim quads where needed.
- All transport lines still to be optimized

Summary

- We have presented a conceptual plan on how to provide beam to simultaneous experiments at multiple energies as well as providing beam for multi-turn injection into the Booster and ultimately into the Recycler.
- The optics design for arcs connecting the three linacs is demanding and requires special attention to minimize emittance growth and bunch spreading
  - This is currently being addressed.
- Many details of the transport lines remain to be worked out, but it is not expected to be a major technological challenge.
- Due to the beam power requirement of many of the transport lines careful attention must and will be paid to beam loss

Back-up Slides

Emittance Evolution thru 3 GeV Linac

Parameters	Unit	Beginning of SC CW linac (2.1 MeV)	End of 1 GeV Linac	End of 1 GeV Bend	End of 3 GeV Linac
ε_z	π.mm.mrad	0.28	0.288	0.36	0.354
ε_y	π.mm.mrad	0.21	0.247	0.247	0.25
ε_x	π.mm.mrad	0.21	0.23	0.316	0.332
					Arun Saini

3 & 8 GeV Loss Summary

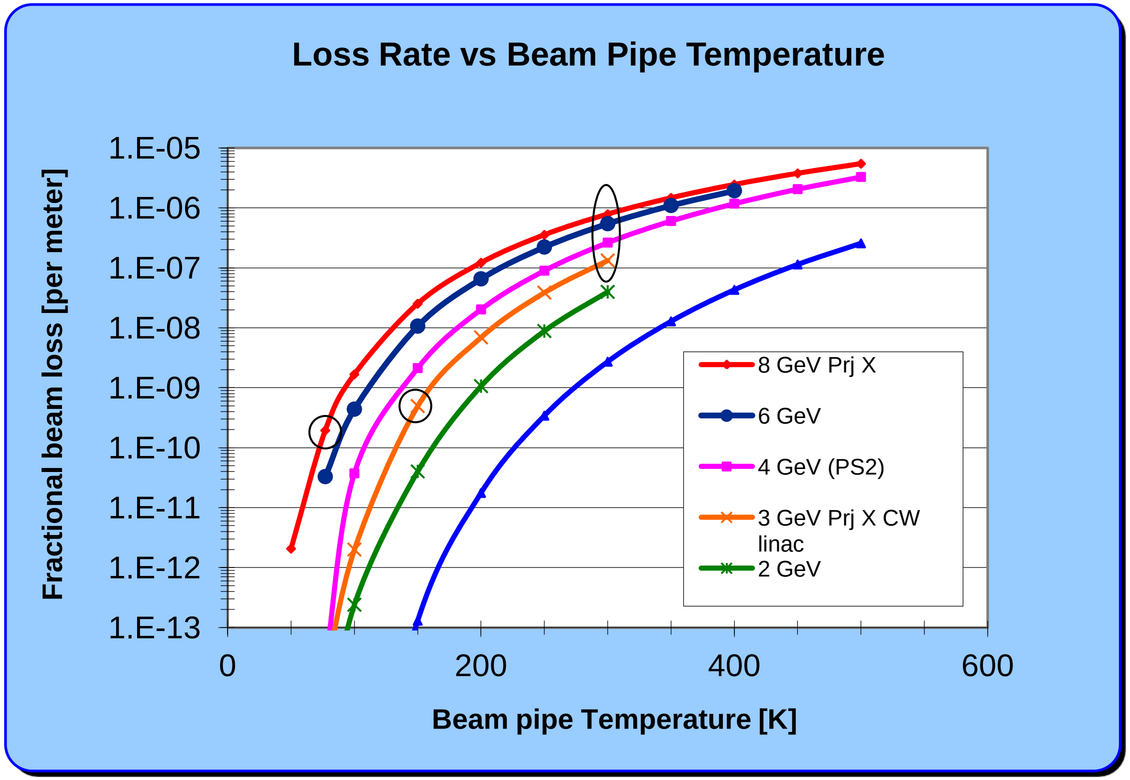
3 GeV loss summary

Loss Mechanism	CW to P Linac 125 kW			Experimentsl 3MW w/o shield			Experimental 3MW w/ shield		
	Value	loss/m	W/m	Value	loss/m	W/m	Value	loss/m	W/m
Vacuum	$1x10^{-8}$	1.30E-08	0.002	$1x10^{-8}$	1.30E-08	0.039	$5x10^{-9}$	6.90E-09	0.021
Lorentz	1.4 kG	2.90E-07	0.037	1.2 kG	3.40E-09	0.01	1.2 kG	3.40E-09	0.01
Black body	300^{0}K	1.30E-07	0.017	300^{0}K	1.30E-07	0.387	150^{0}K	5.00E-10	0.001
Intra-beam	NA	NA	0.001	NA	NA	0.03	NA	NA	0.03
Total		4.33E-07	0.057		1.464E-07	0.466		1.08E-08	0.062
Residual activation bare beam pipe [mrem/hr]			8.50			69.49			9.25

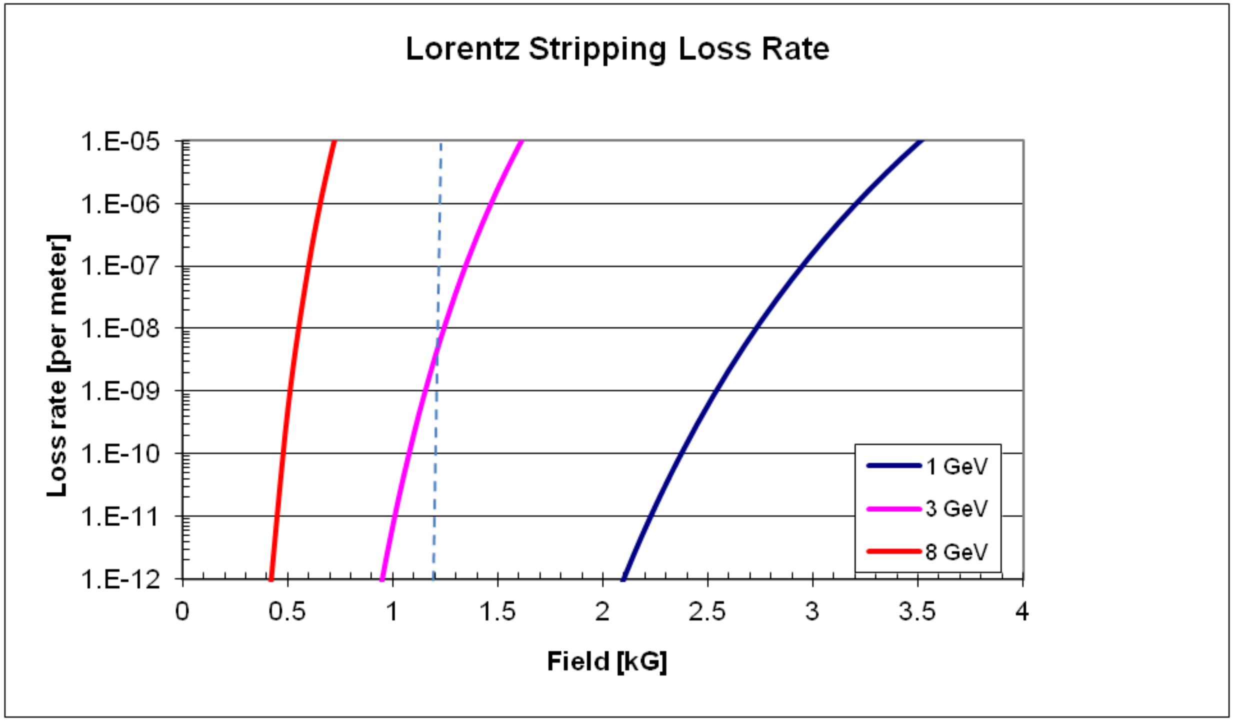
8 GeV loss summary

Loss Mechanism	8 GeV: 345 kW		
	Value	Loss/m	W/m
Blackbody	300 K	8×10^{-7}	0.3
Lorentz	500 G	5×10^{-10}	0.0002
Vacuum	1×10^{-8} Torr	1×10^{-8}	0.004
Total		8×10^{-7}	0.3
Residual activation bare beam pipe (mrem/hr)			15

Blackbody Radiation



Lorentz loss rate



1 Gev Transport to Booster