Proton Intensity for the NuMI Beamline

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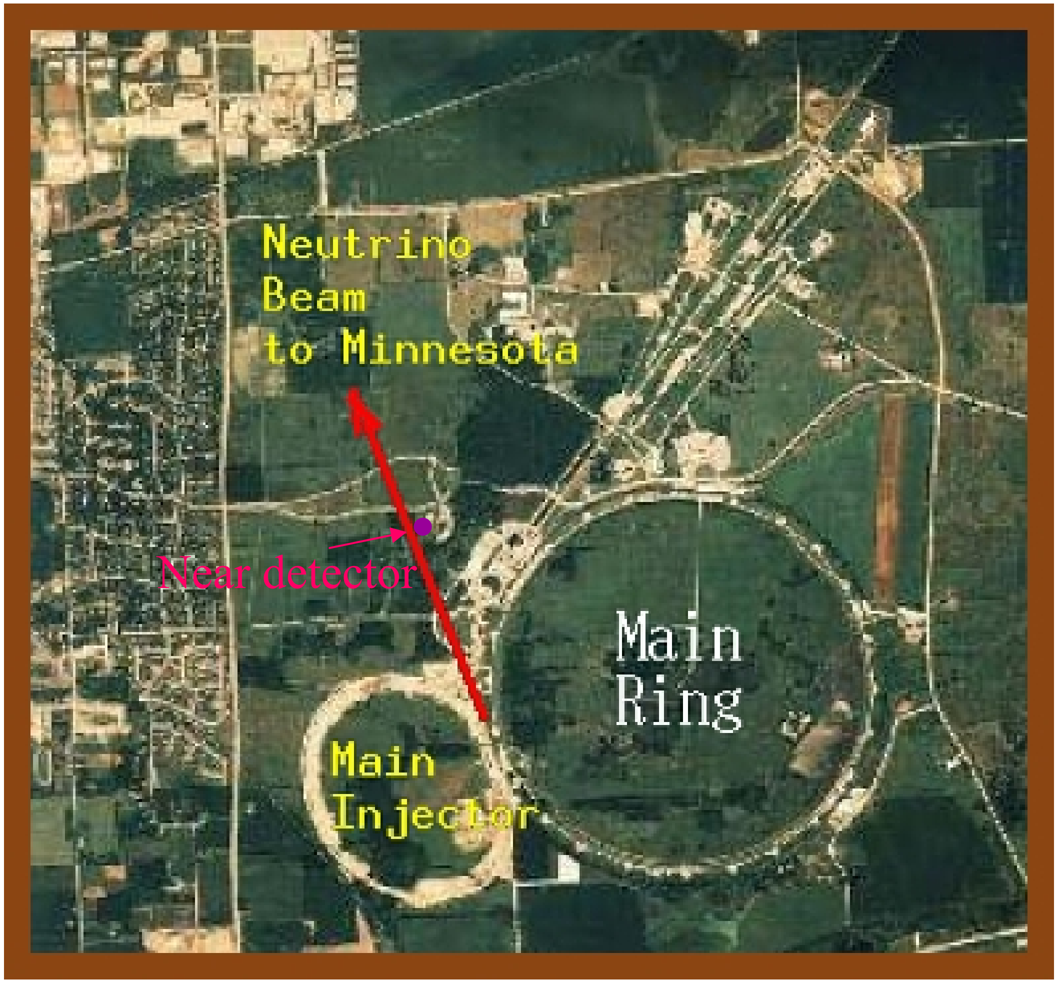
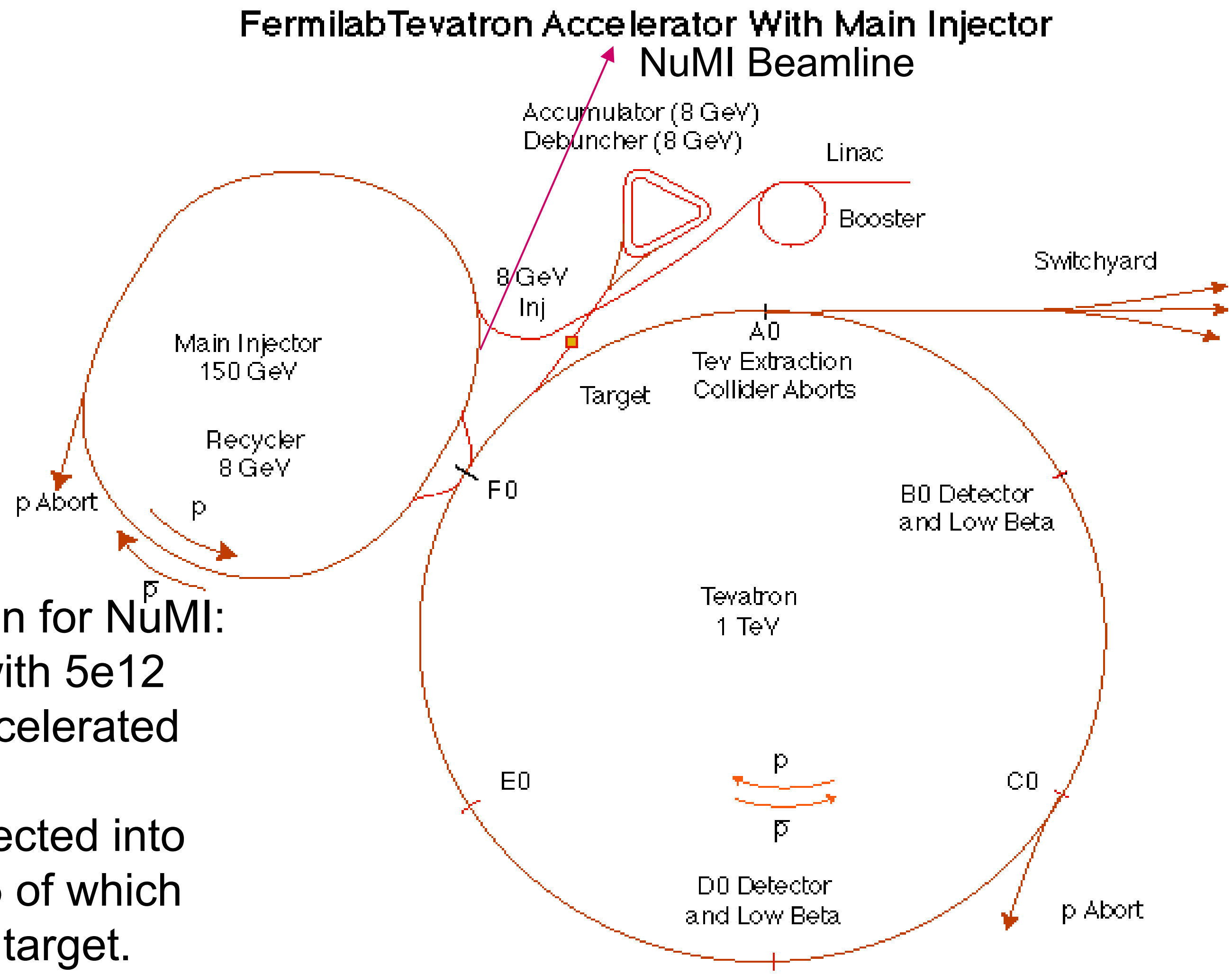
Design Parameters for NuMI



- 120 GeV protons
- 1.9 second cycle time
- 4×10^{13} protons/pulse
- 0.4 MW!
- Single turn extraction (10μs)
- 4×10^{20} protons/year
- Initial intensity will be less…
  - 2.5×10^{20} protons/year?
- Proton intensity should be considered an integral part of future proposals for use of the NuMI beamline.

The Fermilab Accelerator Complex



- Current nominal plan for NuMI:
  - Booster filled with 5e12 protons and accelerated to 8 GeV.
  - Six batches injected into Main Injector, 5 of which go to the NuMI target.
  - 2.5e13 protons / 1.9 s cycle
  - 2.3e20 protons/ year

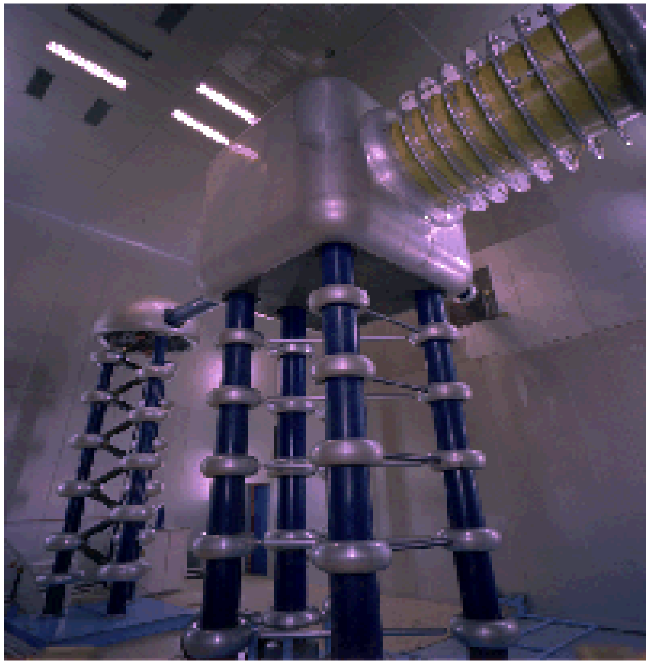
NuMI Proton Intensity Math

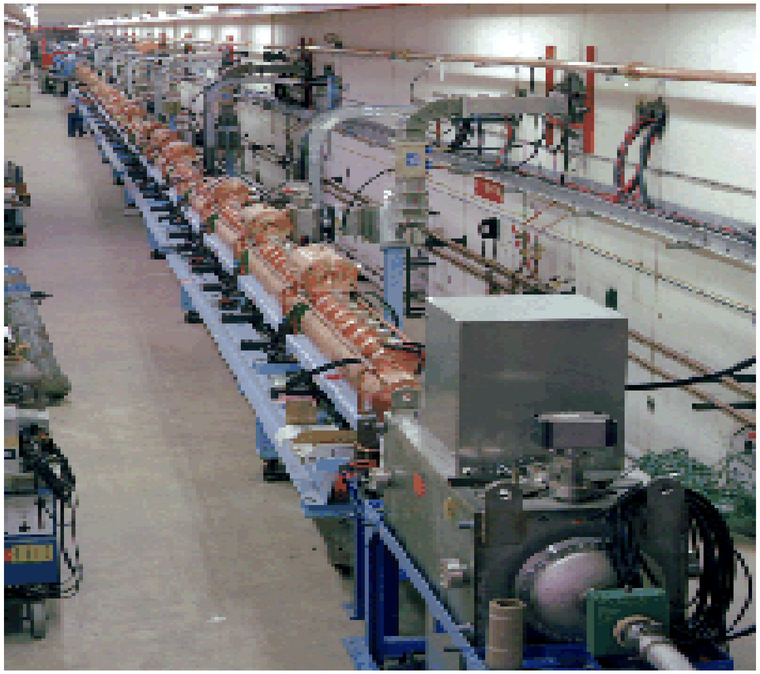
	"Now"	2005	2006	2008	2010	2010+?
			Multi-batch	Faster MI	Recycler	Proton
			Stacking	Cycle	Stacking	Linac
Protons per Booster batch	4.00E+12	5.00E+12	5.50E+12	6.00E+12	6.50E+12	
Batches available for MINOS	5	5	8	10	11	
Relative Efficiency per batch	1	1	0.9	0.9	0.95	
Protons per MI Cycle	2.00E+13	2.50E+13	3.96E+13	5.40E+13	6.79E+13	1.00E+14
MI Cycle Period (seconds)	2.5	2	2.3	1.8	1	1
Beam Power (MW)	0.15	0.24	0.33	0.57	1.29	1.90
NuMI Running time per year (seconds)	1.30E+07	1.80E+07	1.80E+07	2.00E+07	2.00E+07	2.00E+07
Protons per year	1.04E+20	2.25E+20	3.10E+20	6.00E+20	1.36E+21	2.00E+21
Integrated $M Invested		7	15	50	90	400

Notes

- Until a replacement for the Booster is built, or the "Recycler" is used as a MI stacker rather than a pbar stacker, the Booster cycle time will be a dominant effect on proton intensity through the MI.
- Some form of "fast" stacking of Booster batches into the Main Injector during multi-batch operation is crucial for NuMI proton intensity
- Other uses of Main Injector protons and cycles will decrease the proton intensity for NuMI. Test beam running will presumably be kept small enough to keep impact <10%. CKM or other experiments could have larger impacts, possibly around 30-40%.
- Recycler stacking will only be possible if anti-proton production is no longer required. Depends on BTeV. The timescale on which a Booster replacement is "necessary" for an MI neutrino program depends on this. If possible, <$100M for a ~1 MW proton source.

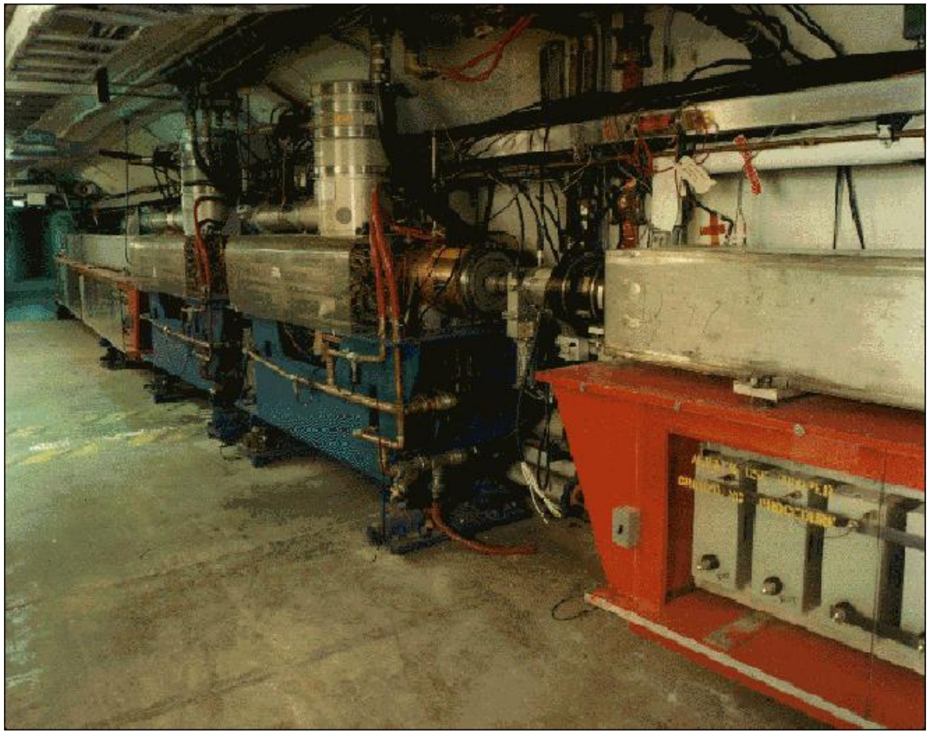
The Proton LINAC





- Accelerates beam to 400 MeV for injection to the Booster.
- Typical operating ability ~45mA of which only a fraction is used.
- No serious issues here for proton intensity with the possible exception of details of injection of the beam into the Booster.
- One can keep filling the Booster with more and more LINAC beam, the problem is keeping it in the Booster once it is there.
- Some of the power tubes have “decayed out of production”. With currently available stock, the LINAC operating lifetime is less than ~2 years. Some solution to this must be identified. This is the potential “Wilson Hall” of the accelerator complex.

The 8 GeV Booster



- 8 GeV Synchrotron with 15 Hz resonant magnet ramps. Slower possible. Faster not possible!
- Currently accelerates ~4-5e12 protons per cycle. Limited by proton losses (~7e12 injected)
  - One cycle every 2.3 s for pbar production with 4.5-5e12 protons per cycle.
  - ~2-3 Hz cycles for Mini-BooNE but at lower proton intensity (~4e12) to stay within proton loss budget.
- For NuMI/MiniBooNE, the Booster must:
  - Increase typical acceleration cycle rate from ~2 Hz capability to ~7-12 Hz
  - Increase protons per cycle from typical 4.5e12 to 5-6e12. (Hopefully!)
  - Increase protons per year from ~3e19 (pre-Mini-BooNE) to ~1.5e21… radiation and activation issues.
  - Decrease longitudinal emittance from ~0.15 eVs to ~ 0.07-0.1 eVs for some types of MI stacking.

Booster Improvements

- Hardware upgrades to permit faster cycle time. (Some already planned.)
  - New extraction septum magnet — Success!
  - New extraction power supplies — Success!
  - Upgraded/revamped RF power? — No progress
  - New hardware to help stabilize the beam, reduce proton losses and yield sufficiently small emittance on extracted beam to permit Barrier RF stacking in the Main Injector:
  - Ramped correctors (already planned/installed) — modest success
  - New collimators (already planned) — Semi-disaster
  - Larger diameter RF cavities — Accelerated progress!
  - Inductive inserts, Dampers, pipe liner… — No progress/work
  - Additional acceleration RF harmonic cavities — No work
    - Reduce space-charge at injection time by spreading beam out
    - Reduce longitudinal emittance at extraction
  - Cogging — Getting started
  - Simulations — Substantial new work
  - Other tuning (dog leg problem…) — Progress! Could Booster intensity be >7e12????

The Main Injector

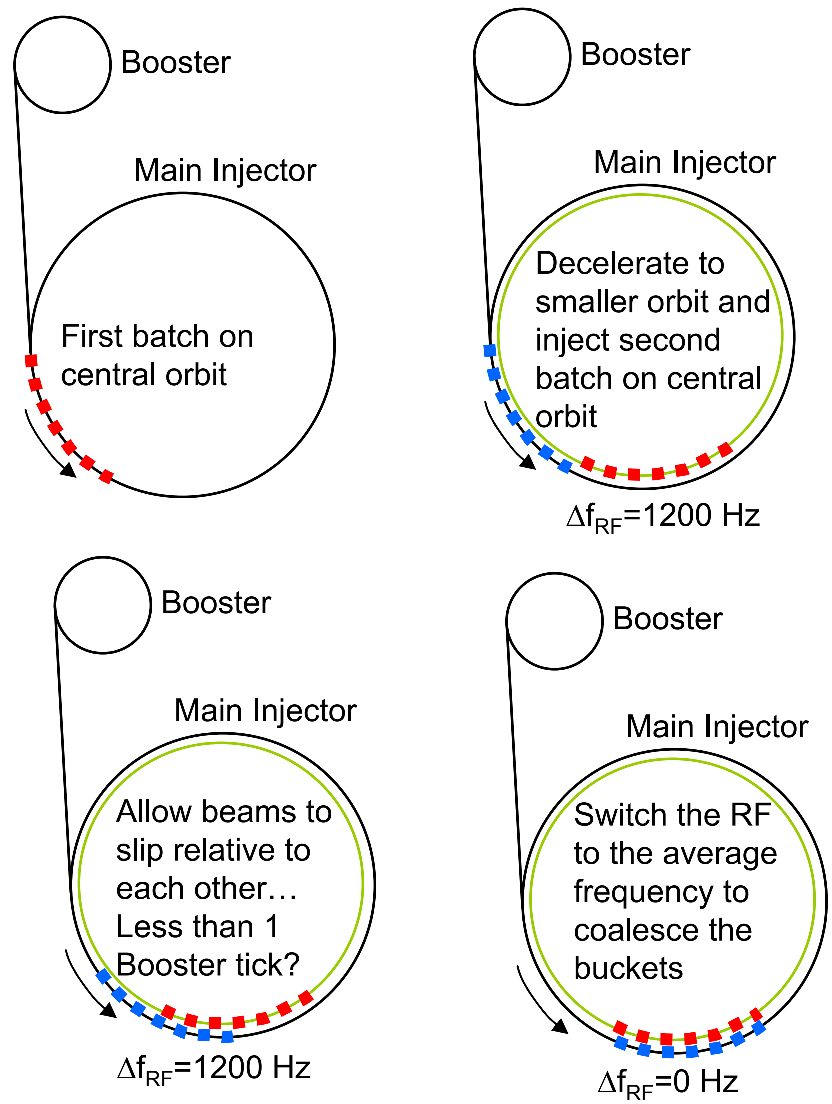
- 150 GeV synchrotron run at 120 GeV (or lower) for NuMI. NuMI cannot run at higher energies.
- Circumference = 7x Booster: Room for 6 Booster batches. Five batches are available for other uses, NuMI being the primary user for the short-term. Slow extraction experiments (E907, test-beams, CKM…) will simply “take cycles”.
- Minimum cycle time at 120 GeV = 1.5 s. Cycle time for multi-batch NuMI operation = 1.9 s due to multiple Booster cycles for filling. When running together with pbar production, the cycle time will vary from 1.8-3.0 s. Operation of the “Recycler” as a pbar stacker is essential to stay near the lower number.
- Nominal design for 2.5e13 protons per cycle. With only small modifications can probably handle up to 5-6e13. The main issue is how to get them there.
- To go higher than ~6e13 protons per cycle, or faster than 1.4 s MI ramp with >2.5e13 protons, additional RF power will be needed as well as additional systems to maintain stability.

A Strategy for Main Injector Improvements

- **Step 1: By 2005 establish 2 batch slip-stacking for pbar and simultaneous 5 batch operation for NuMI with ~2.0 s cycle time.**
  - New damper electronics and components.
    - Now starting to be commissioned for transverse modes.
    - Essential for all future multi-batch and high intensity p-bar operation.
  - New beam-loading compensation
  - Small amount of additional 53 MHz RF power?
  - Lots and lots of practical operation issues for both accelerators and MI/NuMI beamline.
- **Step 2: 2006+, Establish Multi-Batch stacking with cycle time ~2.3 s. Improve stacking efficiency and speed over a 3 year period.**
  - "Fast" Multi-Batch Stacking:
    - "Fast" simply means that more total protons are accelerated through the MI per "macro-unit" of running time (a week say) than would be accelerated without such stacking. There are three current candidates:
    - Slip Stacking
      - Currently *the* option being pursued for stacking two batches (8e12 protons) for Run II.
      - Slipping time may be fast enough for Multi-Batch?
      - Main sticking point for any number of protons will be beam loading of RF cavities.
    - Barrier RF stacking:
      - Appears promising for increasing protons accelerated to 120 GeV by 60%. Compared to single batch slip stacking for pbar production will increase the protons to NuMI by as much as a factor of 2.4!
      - Requires well-behaved Booster
      - Requires new barrier RF systems in Main Injector. Reduces concerns with beam loading.
    - Fast "Recycler" stacking:
      - Uses barriers and an RF ramp to stack. Very similar to barrier stacking but possibly with less longitudinal emittance blow-up.
  - Additional RF power?
  - Additional beam loading compensation
  - Additional damper controls/systems/power
- **Step 3: 2008, Reduce MI Cycle Time to 1.8 s with multi-batch stacking.**
  - MI120 GeV ramp time is reduced from 1.45 to 1.0 s
  - Additional RF with modified RF cavities (~$10M)
  - Additional magnet power supplies (~$15M)
  - Additional damper controls/systems/power
- **Step 4: 2010+, Remove Booster Cycle time from MI cycle time, MI cycle time = 1.0 s**
  - Recycler stacker (~$30M)
  - Replacement for Booster (~$300M)
- **Step 5: 2011+, "Adiabatic" increase in power capabilities towards 2.0 MW with new proton source**

Slip Stacking

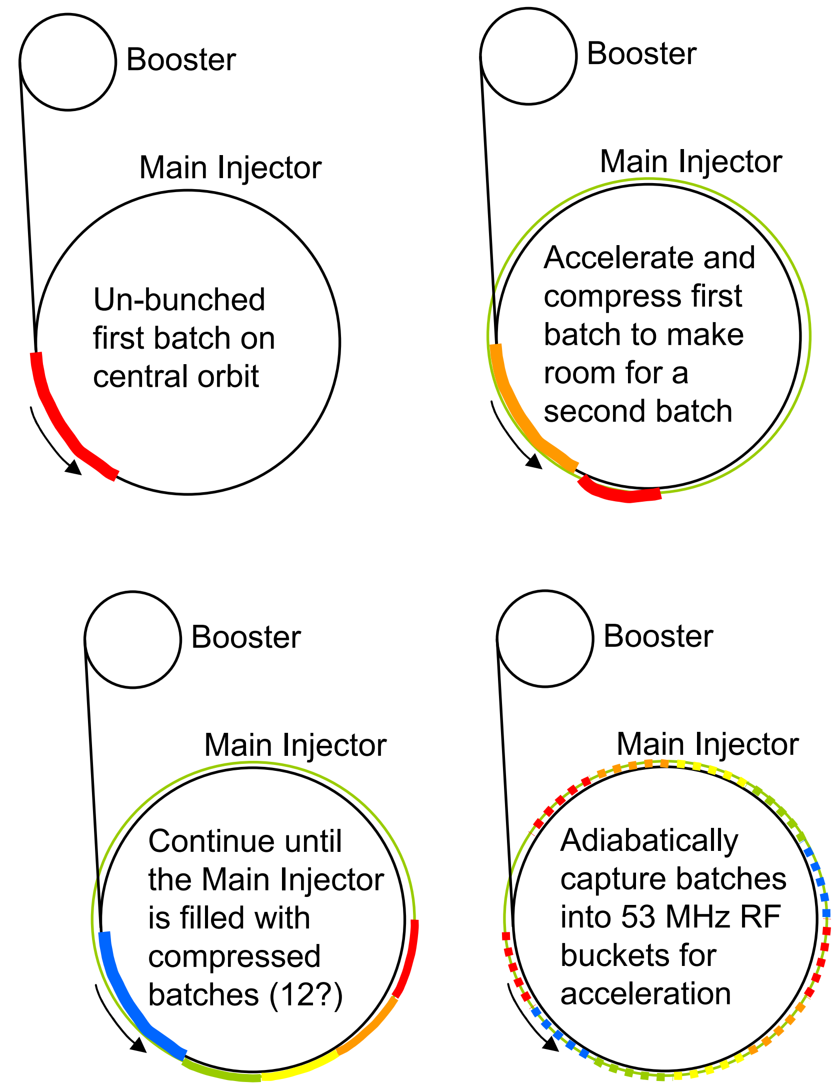
- Slip stacking is a means of combining two Booster batches of protons into a “single” batch in the Main Injector while keeping the protons in the 53 MHz RF buckets.
- To accomplish this, the MI RF cavities are separated into two groups at slightly different frequency.
- Slip Stacking Steps:
  - Inject first batch, capture in 53 MHz buckets using ½ of RF cavities and decelerate by ~50 MeV.
  - Inject second batch and capture in slightly different frequency ~53 MHz buckets using the other half of RF cavities.
  - Allow higher momentum protons to catch up to the first batch until they are completely overlapping in space.
  - Switch all RF cavities to the average frequency from two halves and allow the beam to coalesce into the same buckets, but with 2-3 times the longitudinal emittance of either batch alone.
  - Accelerate to 120 GeV.
- The biggest technical problem with this technique is beam-loading of the RF cavities, which is further complicated by having two beams and frequencies as the entire stacking process is occurring.
- There are also issues in bringing the larger emittance, higher intensity beam through transition. This is similar for all stacking techniques, but maybe a bit worse for SS.
- Fermilab’s immediate goal is to slip-stack two batches for pbar production and then inject 5 additional batches for NuMI
- Can this be used for multi-batch stacking?



Thus far, tested only at low intensity, ~1e12 protons total
Run II goal is 8-10e12 protons per stacked batch

Barrier Stacking

- Barrier stacking manipulates and compresses batches of protons which have been unbunched (no 53 MHz buckets). It uses barrier RF cavities to accomplish this.
- There are two main advantages that this approach may have compared to Slip Stacking:
  - No beam loading problems during the stacking process. This means that higher intensity batches can be stacked and that multiple batches can be stacked.
  - Almost certainly possible to stack as fast as the Booster can cycle… if it works at all!
- Barrier Stacking Steps:
  - Inject first de-bunched batch… Should come from Booster de-bunched.
  - Accelerate and compress first batch using a travelling barrier. Contain all batches using a fixed barrier.
  - Inject subsequent batches right where they would have gone without stacking (like 6 batch operation)
  - Add up to 12 batches, fewer if joint NuMI/pbar operation.
  - Turn on 53 MHz RF to adiabatically capture in buckets.
  - Accelerate to 120 GeV.
- There are three main technical challenges for this technique:
  - Recapture of the unbunched beam in 53 MHz buckets for acceleration.
  - Sufficiently small momentum spread from the Booster
  - Barrier RF cavities with adequate voltage and repetition rate capabilities.
- There are also issues in bringing the larger emittance, higher intensity beam through transition. This is similar for all stacking techniques, but maybe a bit worse for SS.
- Significant simulations have been performed and work is progressing to machine studies and development of the necessary hardware.
- On this view, “Fast Recycler Stacking” looks the same as “Barrier Stacking”.
  - Makes use of the coming-into-existence wide-band RF damping system.
  - Can be used very soon to test high intensity MI operation?
  - Eventually may need similar voltage barriers as “Barrier Stacking” for real operations.



Inject new batches on every Booster cycle?

Very Rough Costs

Item	2002	2003	2004	2005	2006	2007	Total
Extraction septum power supply	20						20
Extraction septum magnet	20						20
Other duty factor upgrades		100	200	800	800	400	2300
ramped correctors	20						20
Collimators	20	20					40
Cogging and notching		20	20				40
Larger aperture RF cavities	20	200	500	2000	2000		4720
Inductive Inserts		60	100	100			260
RF for space-charge reduction		60	200	400	200	50	910
Total	100	460	1020	3300	3000	450	8330
Additional RF power		100	500	500	500	200	1800
Additional Magnet power		500	1000	4500	4500	4500	15000
Cycle time reduction with tuning		20	20				40
Dampers	40	100					140
Collimators			100	100	100		300
Barrier RF stacking components	30	300	300	300	100		1030
Total	70	1020	1920	5400	5200	4700	18310
Total Spending Profile	170	1480	2940	8700	8200	5150	26640

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Director's Proton Committee

- Charge from Witherell: Among other things…"Define an investment of few x $10M over a 7 year period"…
- …Booster replacement, etc are beyond scope.
- Draft report by May 1, Final report June 1.
  - Much faster than ideal…
  - …Essential to get going next year.
- Members:
  - Finley (Chair, former head of Beams Division)
  - Stefanski (Secretary)
  - Conrad (Mini-BooNE)
  - Prebys (Booster)
  - Kasper (Mini-BooNE)
  - Michael (MINOS)
  - Mishra (Main Injector)
  - Marchionni (MINOS)
  - Ankenbrandt ("Independent", general accelerator expert)
- It is clear that this committee will not be the final word for investments in proton intensity on the timescale of an off axis experiment. But it can be a start!

The Longer Term Future

- Use the recycler ring as a stacker for Booster protons and injector to the MI.
  - MI can spend its entire time ramping. (Hopefully with as little as 1.0 s ramp cycle time for the MI.)
  - Only possible if the Collider isn't running for CDF, D0 and/or BTeV.
  - Beam power approaching 1 MW should be possible
- Build a new 8 GeV proton driver to replace the current LINAC/Booster.
  - Synchrotron Option
    - Initial MI beam power of 1 MW, upgradable to 2 MW
    - ~$200M first phase + $?M second phase
  - LINAC Option
    - Build ala TESLA… Acts as a prototype?
    - Good for electrons and protons
    - Straight to 2 MW capability?
    - $300M?
  - Either option needs additional MI RF and stability improvements. ~$25M.
  - http://www-bd.fnal.gov/pdriver/8GeV for Study II report.

A Very Important Message for Off-Axis

- Technical means for the Main Injector to deliver the nominally expected protons per year (4×10^{20}) for Off-Axis NuMI have been identified. Technical options for more have also been identified.
- Given Fermilab's plans for other experiments, it is not clear to me at this time that the investment required to deliver this number of protons will be undertaken.
- It is likely that investment at any of the higher levels that I discuss here will require the approval of a beyond-MINOS experimental program in the NuMI Beamline.
- I strongly suggest that this point be turned around. Specifically:
  - An Off-Axis proposal should not simply assume that the expected proton intensity will be available but should explicitly include a plan for investment necessary to achieve the intensity.
  - Probably it will make sense to scale/stage the total investment along with the detector construction investment.
  - Achieving these intensities should be considered an integral part of the Off-Axis experiment and its collaboration with Fermilab.

Conclusions

- It is possible to make investments in the existing accelerator complex at Fermilab to make major increases in the proton intensity for the NuMI beamline.
  - 0.3 MW by 2005 $10M
  - 0.6 MW by 2008 $50M
  - 1.0 MW by 2010 $90M
  - Physics motivations for the investment are essential.
- A new proton driver (replacing the current 8 GeV Booster) can bring the proton power up to ~2 MW.
- The NuMI Off-Axis experiment can provide an important part of the motivation for new proton intensity investment… I believe this should be an explicit part of the proposal.
- Just like the detector construction, it takes years to plan and carry out proton intensity projects. Now is the time to start the work.