An Alternative Proton Source

Dave McGinnis

April 22, 2005

Motivation

- Develop an alternative plan to provide high intensity proton beams for the neutrino program beyond 2010 should budgets and approvals for the planned projects fail to materialize.
- The proposal needs to have the following important features
  - It must be inexpensive (< $100M or so)
  - It must be completed quickly (before 2012)
  - It should not shutoff the collider complex or the neutrino program for an extended period of time.
- These goals can be accomplished only if:
  - It uses the present Fermilab infrastructure (tunnel enclosures, service buildings, power, utilities, etc.)
  - The project is staged

Concept

- This proposal will only discuss producing 8 GeV protons
  - Acceleration in the Main Injector and MI-RF upgrades are treated in the present Proton Plan
  - Also the present Proton Plan is developing the concept to deal with the vulnerability of RF power tubes in the present Linac

Concept

- The cancellation of the BTeV project eliminates the need to produce antiprotons at Fermilab beyond 2009-2010,
- The present antiproton production complex can be converted into a multi-stage proton accumulator for injection into the Main Injector.
  - Debuncher ->Wide Aperture Booster
  - Accumulator -> Momentum Stacker
  - Recycler -> Box Car Stacker

Project Staging

- Because the concept uses existing infrastructure the performance can be broken into stages
- Project staging has the important benefit of providing
  - a fraction of the total performance
  - at a fraction of the total cost
- The schedule for each stage is driven by physics need and funding availability

Stages of the Present Proton Plan

- Stage 0 - Present Booster -> Main Injector
  - 6.5×10^{16} pph
  - 220kW 120 GeV Beam
  - 1.1×10^{16} pph BNB
- Stage 1 - Proton Plan Booster -> Main Injector (>2008)
  - 13.6×10^{16} pph
  - 370kW 120 GeV Beam
  - 5.1×10^{16} pph BNB
- Stage 2 - Proton Plan Booster -> Recycler -> Main Injector
  - 13.6×10^{16} pph
  - 725kW 120 GeV Beam

New Stages for the Multi-Stage Proton Accumulator

- Stage 3 - Proton Plan Booster -> Present Booster Aperture Upgrade -> Accumulator -> Recycler -> Main Injector
  - 21.6×10^{16} pph
  - 1150kW 120 GeV Beam
- Stage 4 - Proton Plan Booster -> New Booster -> Accumulator -> Recycler -> Main Injector
  - 43.2×10^{16} pph
  - 2300kW 120 GeV Beam
  - Option A
    - 56.8×10^{16} pph
    - 2300kW 120 GeV Beam
    - 13.6×10^{16} pph BNB
  - Option B
    - 64.8×10^{16} pph
    - 2300kW 120 GeV Beam
    - 21.6×10^{16} pph BNB

Multi-stage Proton Accumulator Scheme

- Stages 0-2 are covered in the present Proton Plan
- The rest of this presentation will discuss Stages 3 and 4

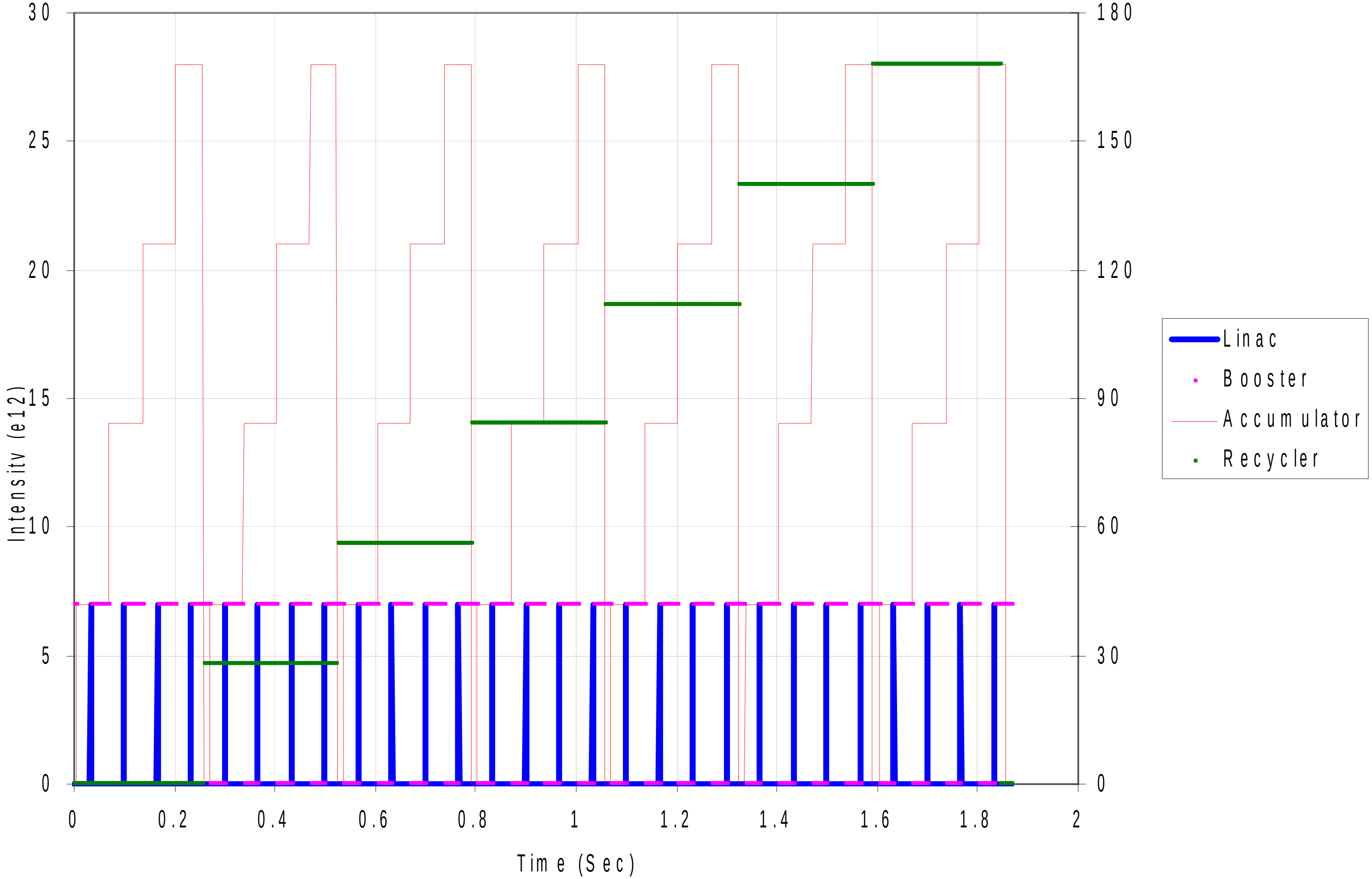
Multi-stage Proton Accumulator Scheme

- Keep the present 400 MeV Linac
- Accelerate in a Wide Aperture Booster
  - Stage 3 - Upgrade the present Booster to run at $6x10^{13}$ protons/sec
    - Low intensity per pulse - $4.0x10^{12}$ protons/pulse
    - Fast repetition rate – 15 Hz
  - Stage 4 - New Booster in place of the Debuncher ring to run at $1.2x10^{14}$ protons/sec
    - High intensity per pulse - $8x10^{12}$ protons/pulse
    - Fast repetition rate – 15 Hz

Multi-stage Proton Accumulator Scheme

- Momentum stack in the Accumulator
  - Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
  - Decelerate new batch towards core orbit and merge with existing beam
  - Momentum stack 3-4 Booster batches
  - Extract a single Accumulator batch
    - Every 200 – 270 mS
    - At an intensity of 3-4x a single Booster batch
- Box Car Stack in the Recycler
  - Load in a new Accumulator batch every 200-270mS
  - Place six Accumulator batches sequentially around the Recycler
- Load the Main Injector in a single turn

Multi-stage Proton Accumulator Production Cycle



Acceleration in a Wide Aperture Booster

- Using the Accumulator as a proton accumulator reduces the peak intensity requirement in the Booster
- Results in a smaller required aperture
  - Smaller space charge tune shift
  - Reduced requirements on acceleration efficiency
- Scaling
  - Use present Booster performance to scale for acceptable beam loss
  - Use PD2 Design report for scaled cost estimate

Scaling Laws

- Compare designs with the same space charge tune shift

$$\varepsilon_n \propto \frac{N_{inj}}{\beta\gamma^2\Delta\nu}$$

- Amount of beam power lost per pulse is inversely proportional to the repetition rate

$$P_L = J_L R$$

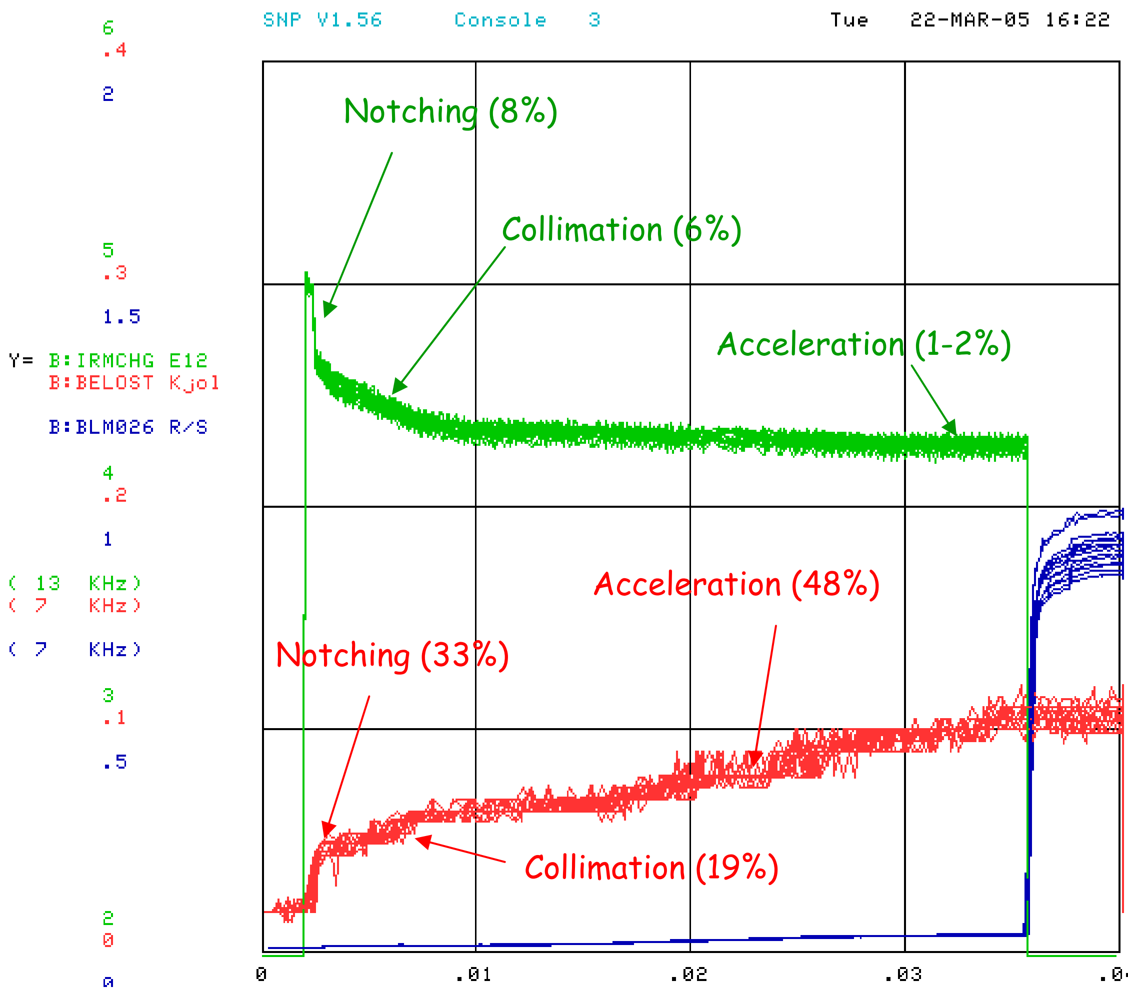
- The transverse acceptance is inversely proportional to the amount of beam loss in the "tails" of the beam

$$A_n \propto -\varepsilon_n \ln\left(\frac{N_{inj} - N_{ext}}{2N_{inj}}\right)$$

- The half-aperture of the magnets is proportional to
  - The transverse acceptance,
  - The momentum acceptance
  - The closed orbit displacement

$$\Delta x = \sqrt{\frac{A_n}{\beta\gamma}\beta_{max}} + \frac{\Delta p}{p}D_{max} + \text{c.o.d.}$$

Present Booster Performance



Summary for Event 10
From 01-MAR-2005 00:00:00
to 01-APR-2005 00:00:00

Percentage up time:	88.1
Total Events:	13605200
Total Protons:	4.32E+19
Average Events/second:	5.46
Average protons/Event:	3.35E+12
Average protons/hour:	6.58E+16
Maximum protons/hour:	8.33E+16
(protons out)/(protons in):	.828
(Joules lost)/(1e12 prot):	23.7

Wide Aperture Booster - Stage 3

- Upgrade the present Booster to run at 6×10^{13} protons/sec
  - Would be 1.1MW at 120 GeV
  - Low intensity per pulse - 4.0×10^{12} protons/pulse
  - Fast repetition rate – 15 Hz
- Acceptable Losses
  - Present
    - 3.35×10^{12} protons/pulse
    - 5.46Hz
    - 83% efficiency
    - 70 Joules/pulse lost
  - Stage 3
    - 4.0×10^{12} protons/pulse
    - 15Hz
    - 95% efficiency
    - 25 Joules/pulse lost

Wide Aperture Booster Designs

Parameter	Present	Stage 1-2	Stage 3	Stage 4	PD2	
Extraction Intensity	3.4	4.7	4.0	8.0	25.0	$x10^{12}$
Rep. Rate	5.5	8.0	15.0	15.0	15.0	Hz
Average Beam Power Lost	443.0	443.0	443.0	443.0	443.0	Watts
Notch Joule Coef	71.0	35.0	0.0	0.0	0.0	$Joules/10^{12}$
Acceleration Joule Coef	143.0	143.0	143.0	143.0	143.0	$Joules/10^{12}$
Notch loss	8.0	8.0	0.0	0.0	8.0	%
Acceleration loss	9.9	5.2	4.9	2.5	0.8	%
Efficiency	82.1	86.8	95.1	97.5	91.2	%
Injection Intensity	4.1	5.4	4.2	8.2	27.4	$x10^{12}$
Injection Energy	400.0	400.0	400.0	400.0	600.0	MeV
Norm. Emittance at Inj	8.7	11.6	9.0	17.6	40.0	π-mm-mrad
Norm Acceptance at Inj	13.8	22.4	18.1	41.7	119.0	π-mm-mrad
F magnet β_x	33.0	33.0	33.0	15.0	15.0	m
F magnet β_y	14.0	14.0	14.0	20.0	20.0	m
F magnet D_x	3.0	3.0	3.0	2.5	2.5	m
D magnet β_x	14.0	14.0	14.0	15.0	15.0	m
D magnet β_y	22.0	22.0	22.0	20.0	20.0	m
D magnet D_x	2.5	2.5	2.5	2.5	2.5	m
Momentum Acceptance	0.2	0.2	0.2	1.2	2.4	%
Closed Orbit Tolerence	13.0	6.0	10.0	20.0	20.0	mm
F Aperture Width	2.4	2.6	2.5	3.9	6.1	in
F Aperture Height	1.6	1.6	1.6	3.0	4.2	in
D Aperture Width	1.8	1.8	1.8	3.9	6.1	in
D Aperture Height	1.9	2.0	2.0	3.0	4.2	in

Stage 1 Wide Aperture Booster Components

- Move the notcher from the Booster to the front end of the Linac (< $100k)
  - Using momentum stacking in the Accumulator eliminates the need for cogging in the Booster
    - Prior to injection into the Accumulator, the injection orbit of the Accumulator is empty
    - The Accumulator injection system can be phase-locked to the Booster which eliminates the need for cogging in the Booster
    - The Booster notch can be made in the Linac
  - Need to upgrade Linac chopper power supply and controls
  - Saves 24 Joules/pulse at $4.0x10^{12}$ protons/pulse

Stage 3 Wide Aperture Booster Components

- Extraction Septum Upgrades
  - Collimators are presently used to shield small apertures at the extraction septa
  - Remove Long 13 extraction septum (~ $100k)
    - Place a low intensity dump in the MI-8 line for short batches
    - Use the Long 12 kicker for more extraction kick at Long 3
  - Long 3 Pulsed extraction 3 bump (~ $1M)
    - Replace 400 MeV doglegs with pulsed 8 GeV 3 Bump
  - Pull collimators out to larger aperture
  - Saves 13 Joules/pulse at 4.0×10^{12} protons/pulse

Stage 3 Wide Aperture Booster Components

- Aperture Upgrade
  - Booster RF Cavity Upgrade (~ $25M)
    - Build the RF cavities for the new Booster (Stage 2)
      - Install the new cavities in the old Booster
      - Operate the cavities in old Booster until new Booster is ready to be installed and remove and install the new RF cavities in the new Booster
    - Increase the RF cavity aperture by 75% (2.25" -> 3")
    - Cavities incorporate
      - Passive HOM dampers
      - Reliable Power electronics
    - Provide 15 Hz capability
  - Proton Plan (Stage 1)
    - Alignment $0.09M
    - Gamma-t jump $0.1M
    - Ramped correctors $2.1M
    - OR-BUMP $0.7M
      - Also provides 15 Hz capability
    - 30 Hz harmonic $1.8M
  - Need to save 7 Joules/pulse at 4.0×10^{12} protons/pulse

Stage 3 Cost Guess (in k$)

Stage 3		34,900
Linac Notching	100	
MI-8 Dump	100	
Booster Extraction Upgrade	1,000	
Booster RF Cavity Upgrade	25,000	
Booster Proton Plan	4,800	
Booster Proton Plan Credit	-4,800	
AP4 Line 8 GeV Magnets	1,000	
AP4 Line Civil	1,800	
Accumulator RF	500	
Accumulator Extraction Kickers	500	
AP3 Modification	1,900	
Recycler RF	500	
Shielding	2,000	
MI Gamma-t jump	500	

Wide Aperture Booster - Stage 4

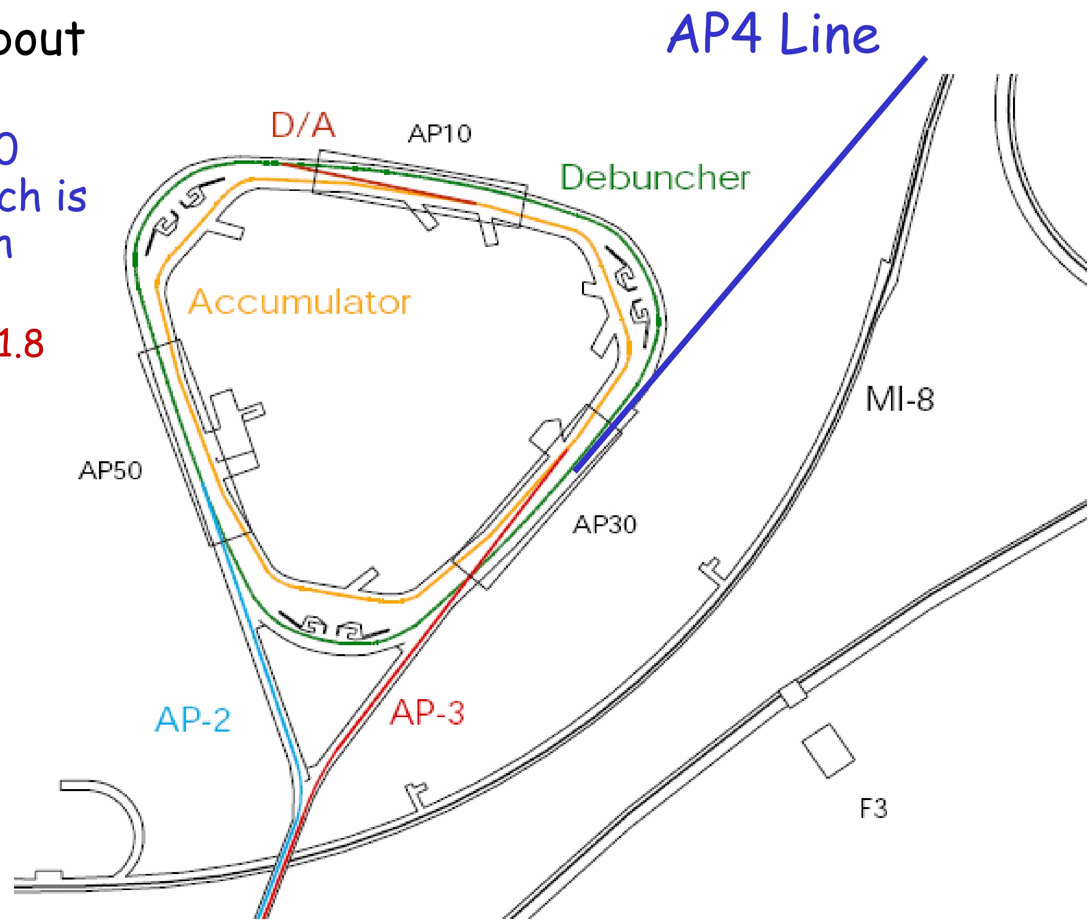
- New Booster in place of the Debuncher ring to run at 1.2×10^{14} protons/sec
  - Would be 2.3MW at 120 GeV
  - High intensity per pulse - 8.0×10^{12} protons/pulse
  - Fast repetition rate – 15 Hz
- Building a new booster in the Debuncher tunnel saves on
  - Tunnel
  - Power & Utilities
  - Service buildings
  - The RF (~25M$) is purchased in Stage 3

Acceleration in a Wide Aperture Booster

Parameter	Present	Stage 1-2	Stage 3	Stage 4	PD2	
Extraction Intensity	3.4	4.7	4.0	8.0	25.0	$x10^{12}$
Rep. Rate	5.5	8.0	15.0	15.0	15.0	Hz
Average Beam Power Lost	443.0	443.0	443.0	443.0	443.0	Watts
Notch Joule Coef	71.0	35.0	0.0	0.0	0.0	$Joules/10^{12}$
Acceleration Joule Coef	143.0	143.0	143.0	143.0	143.0	$Joules/10^{12}$
Notch loss	8.0	8.0	0.0	0.0	8.0	%
Acceleration loss	9.9	5.2	4.9	2.5	0.8	%
Efficiency	82.1	86.8	95.1	97.5	91.2	%
Injection Intensity	4.1	5.4	4.2	8.2	27.4	$x10^{12}$
Injection Energy	400.0	400.0	400.0	400.0	600.0	MeV
Norm. Emittance at Inj	8.7	11.6	9.0	17.6	40.0	π-mm-mrad
Norm Acceptance at Inj	13.8	22.4	18.1	41.7	119.0	π-mm-mrad
F magnet β_x	33.0	33.0	33.0	15.0	15.0	m
F magnet β_y	14.0	14.0	14.0	20.0	20.0	m
F magnet D_x	3.0	3.0	3.0	2.5	2.5	m
D magnet β_x	14.0	14.0	14.0	15.0	15.0	m
D magnet β_y	22.0	22.0	22.0	20.0	20.0	m
D magnet D_x	2.5	2.5	2.5	2.5	2.5	m
Momentum Acceptance	0.2	0.2	0.2	1.2	2.4	%
Closed Orbit Tolerence	13.0	6.0	10.0	20.0	20.0	mm
F Aperture Width	2.4	2.6	2.5	3.9	6.1	in
F Aperture Height	1.6	1.6	1.6	3.0	4.2	in
D Aperture Width	1.8	1.8	1.8	3.9	6.1	in
D Aperture Height	1.9	2.0	2.0	3.0	4.2	in

AP-4 Line

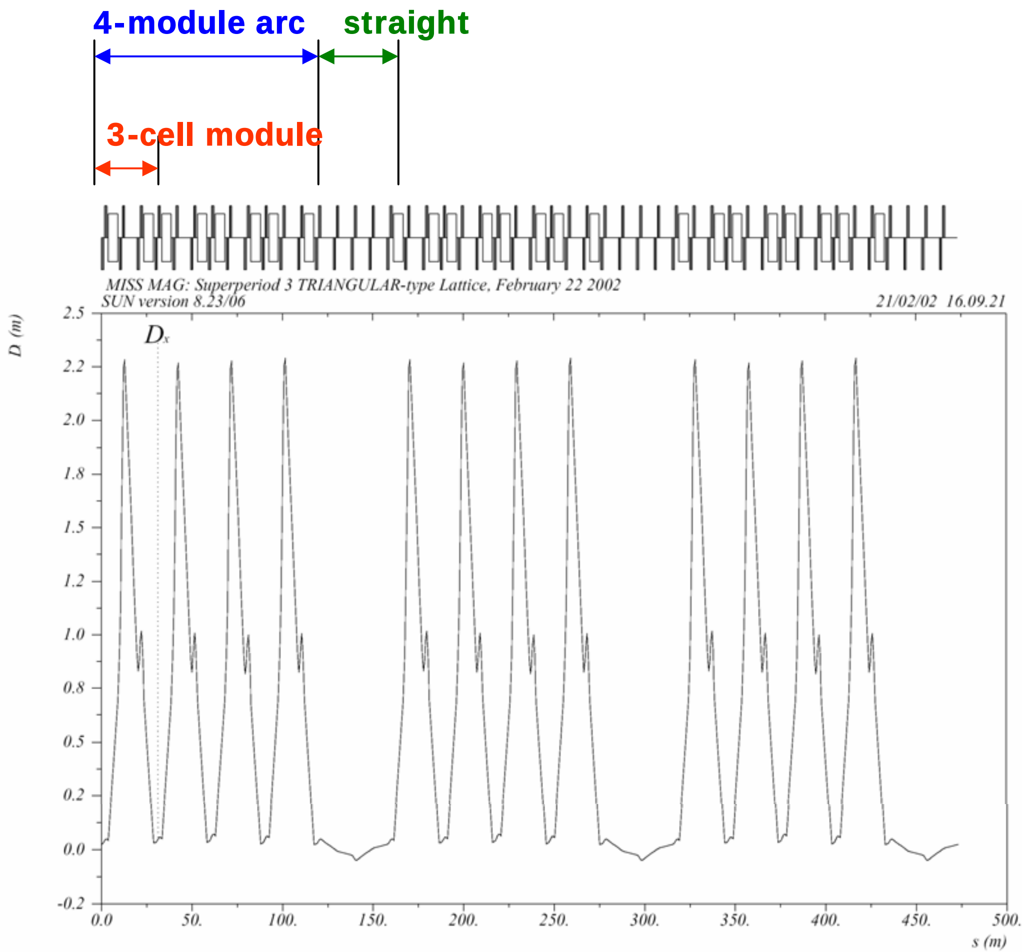
- The old Booster is connected to the new Booster via a re-built AP4 Line
- The new AP4 line is about 240 meters in length
  - Compared to the 600 MeV line of PD2 which is 250 meters in length
    - Magnets 1 M$
    - Civil Construction 1.8 M$

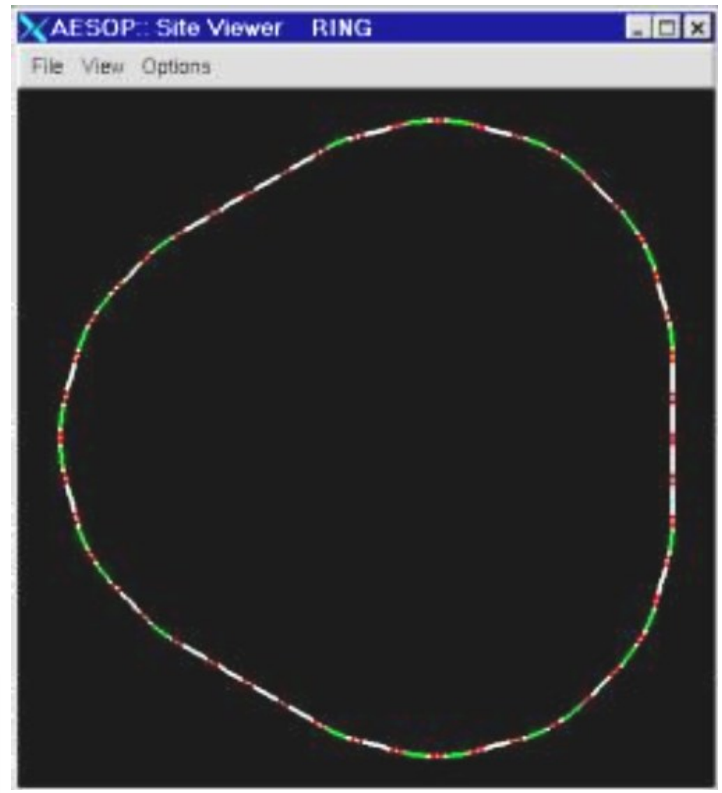


Features of the New Booster

- Ramps from 400 MeV to 8 GeV
- Fast cycling (15 Hz)
- Large aperture
- Separated function magnets.
- Dual harmonic power system for an asymmetric acceleration ramp
- Does not go through transition
- Zero dispersion at the RF cavities
- Modern RF cavity design with higher order mode dampers.
  - Install the new cavities in the old Booster during Stage 3
  - Operate the cavities in old Booster until new Booster is ready to be installed and remove and install the new RF cavities in the new Booster

Stage 4 Triangular Lattice



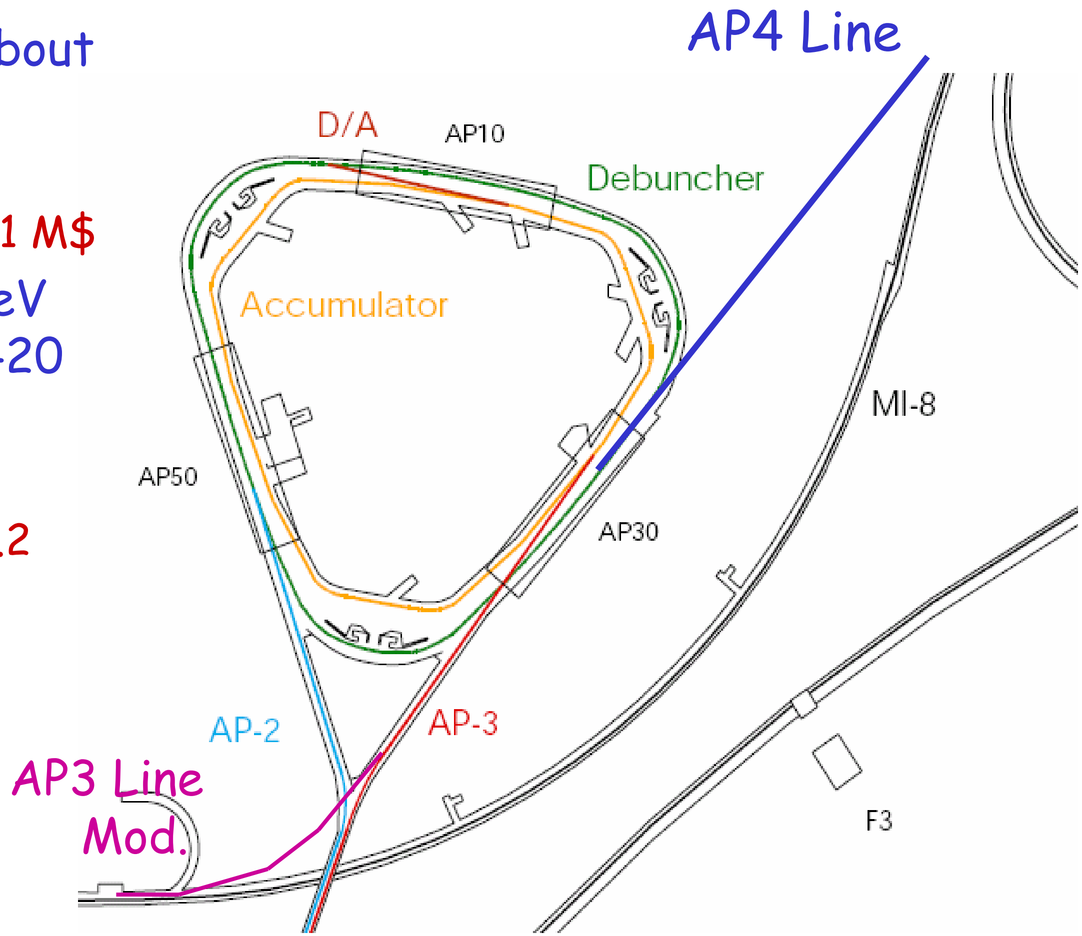


Stage 4 Triangular Lattice

- Triangular shape to fit to the Debuncher footprint
- No transition crossing (γ_t = 18.1)
- Zero dispersion straights
- Simple: 1 type of dipole, 1 type of quad (QF and QD same length)
- Doublet lattice, 90° phase advance per cell
- 3 cells per module, with missing dipole in the mid-cell, 270° phase advance per module
- 4 modules per arc, 6π phase advance per arc
- No need for dispersion suppressor
- Plenty of free space: 24 x 7 m
- Low beta-function (15 m) and dispersion (2.3 m)
- Good optical properties (large dynamic aperture, weak dependence of lattice functions on amplitude and dp/p)

AP-3 Line Modification

- The AP3 line needs to be connected to the MI-8 line
  - The modification is about 100 meters in length
    - Magnets 0.8 M$
    - Civil Construction 1.1 M$
  - Compared to the 8 GeV line of PD2 which is 420 meters in length
    - Magnets 1.9 M$
    - Civil Construction 2.2 M$



Cost Comparison Between Stage 4 and PD2

- Reuse the pbar tunnel
  - Saving $43M in civil
  - However include $3M for radiation shielding
- Reduce magnet aperture from 4" x 6" to 3" x 5"
  - Saving $20M in magnet and power supply cost.
- Use new type of beam pipe
  - Saving $1M in vacuum
- Reuse utilities
  - Existing in Pbar Tunnel
  - Lower beam power.
  - saving $4.4M
- Reuse controls
  - saving $2M
- Do not need foil changer,
  - saving $0.15M.
- The new cost estimate is about $50M,
  - The RF (~25M$) is purchased in Stage 3

Stage 4 Cost Guess (in k$)

Stage 4		50,200
Magnets	17,000	
Power supplies	16,000	
RF Installation	200	
Vacuum	5,000	
Collimators	300	
AP4 Line 400 MeV Magnets	1000	
Injection system	900	
Extraction system	2,100	
Instrumentation	2,400	
Controls	500	
Utilities	500	
Installation	1,300	
Shielding	3,000	

Stage 4 Booster vs BNL AGS Booster

	Stage 4	AGS Booster
Circumference (m)	505	201
Injection (MeV)	400	200
Extraction (GeV)	8	1.5
Rep rate (Hz)	15	7.5
Total dipoles	24×5.2 m = 124.8 m	36×2.4 m = 86.4 m
Total quads	96×1.24 m = 119 m	48×0.5 m = 24 m
Beam pipe aperture	3 in × 5 in	2.8 in × 5.9 in
Max β function (m)	14.8 / 15.2	13.9 / 13.7
Max dispersion (m)	2.3	2.9
Transition γ	18.1	4.79
Beam intensity	7×10^{12}	2×10^{13}
Year constructed	TBD	1991
Construction cost	$75M (estimated)	$32M (1991)
Civil cost included?	No	Yes

- Adjust $32M in 1991 for 14 years of 4% of inflation = $55M
- Scale the cost as the length in magnets = $122M
- Remove civil construction = $122M - $43M = $79M

Momentum Stacking in the Accumulator

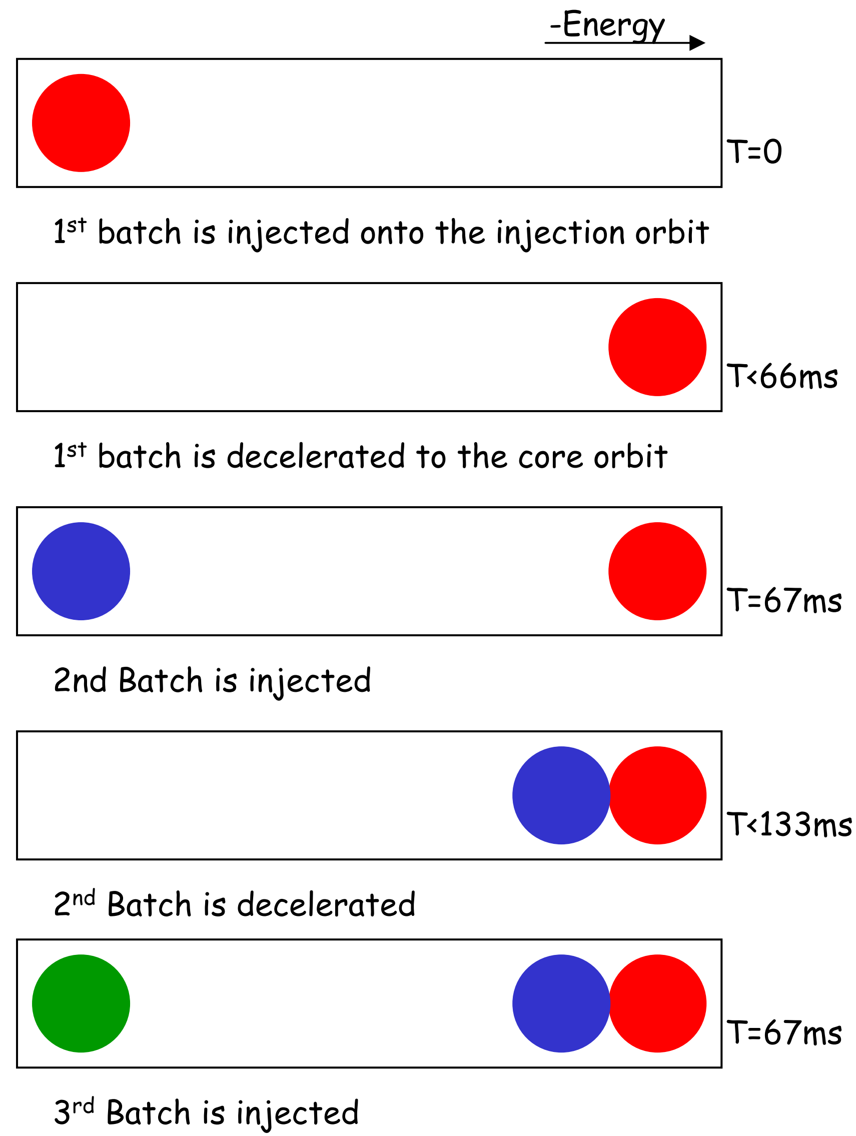
- After acceleration in the Booster the beam will be transferred to the Accumulator ring.
- Using the Accumulator as a proton accumulator reduces the peak intensity requirement in the Booster
- Results in a smaller required aperture for the Booster
  - Smaller space charge tune shift
  - Reduced requirements on acceleration efficiency
- The Accumulator was designed for momentum stacking
  - Large momentum aperture ~ 84 x 2.8 eV-Sec
  - Injection kickers are located in 9m of dispersion
  - Injection kickers do not affect core beam

Advantages of Momentum Stacking

- Transient Beam Loading
  - Slip stacking or barrier bucket stacking requires manipulating intense beams wit low RF voltages in a mostly empty circumference
  - In momentum stacking, the circumference is always uniformly loaded
- Speed of process
  - Injected beam can be decelerated quickly towards the core beam
- Longitudinal emittance dilution
  - The core beam can be debunched during stacking process reducing the amount of "white spaces"
- Cogging in the Booster
  - Prior to injection into the Accumulator, the injection orbit of the Accumulator is empty
  - The Accumulator injection system can be phase-locked to the Booster which eliminates the need for cogging in the Booster
  - The Booster notch can be made in the Linac

Mechanics of Momentum Stacking

- Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
- The freshly injected batch is decelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-4 Booster batches
  - The longitudinal emittance of a batch at 8 GeV from the present Booster is 84x0.1eV-sec
  - The present momentum aperture of the Main Injector is 0.5 eV-Sec for a 53 MHz bunch
  - Will need at γ_t jump system in the Main Injector (~ $0.5M)



Extraction From the Accumulator

- After 3-4 batches have been stacked begin preparing to extract all the beam from the Accumulator to the Recycler
- Re-bunch the entire stacked beam at h=4 in the Accumulator (2.5 MHz)
  - 2.5 MHz would provide a large gap between buckets which could accommodate kicker rise time
  - Could consider higher harmonic bunching (h=21, RF frequency = 13.2MHz)
    - Keep the momentum spread low
    - Keep synchrotron frequency high
- Other Schemes
  - Re-bunching at 53 MHz would require at gap placed in the beam for kicker rise time
    - Speed and voltage of a barrier bucket is a concern
  - Preserve gap from injection by never debunching the Booster batches and slip stacking the gaps
    - Revolution frequencies are close so slipping would be slow
    - Emittance dilution is a concern

Extraction From the Accumulator

- Accelerate the beam to the extraction orbit
  - Phase lock to the Recycler
    - If the accumulator is at η=0.023, the revolution frequency of the Recycler is harmonically related to the revolution frequency of the extraction orbit of the Accumulator
  - Kick the beam into the AP3 line using the Accumulator high dispersion extraction kickers
    - Might have to extend the momentum range of the extraction kicker
      - Place an extra kicker where the present 4-8 GHz momentum cooling system is presently located

Box Car Stacking in the Recycler

- After 3-4 booster batches have been momentum stacked in the Accumulator, the beam would be transferred to the Recycler.
  - 2.5 MHz synchronous transfer
  - Accumulator phase locked to the Recycler
- The Accumulator is 1/7 of the Recycler's circumference
- Boxcar stack six of the Accumulator batches (which contain 3-4 of the Booster batches), leaving 1/7 of the Recycler ring for an abort gap.
- After 6 Accumulator batches have been stacked into the Recycler do a 2.5 MHz synchronous transfer to the Main Injector
- In the Main Injector
  - perform a 2.5 MHz bunch rotation to reduce the momentum spread
  - Re-capture in 53 MHz buckets for acceleration.

Stage 3-4 Cost Guess (in k$)

APS				85,100
Stage 3			34,900	
	Linac Notching	100		
	MI-8 Dump	100		
	Booster Extraction Upgrade	1,000		
	Booster RF Cavity Upgrade	25,000		
	Booster Proton Plan	4,800		
	Booster Proton Plan Credit	-4,800		
	AP4 Line 8 GeV Magnets	1,000		
	AP4 Line Civil	1,800		
	Accumulator RF	500		
	Accumulator Extraction Kickers	500		
	AP3 Modification	1,900		
	Recycler RF	500		
	Shielding	2,000		
	MI Gamma-t jump	500		
Stage 4			50,200	
	Magnets	17,000		
	Power supplies	16,000		
	RF Installation	200		
	Vacuum	5,000		
	Collimators	300		
	AP4 Line 400 MeV Magnets	1000		
	Injection system	900		
	Extraction system	2,100		
	Instrumentation	2,400		
	Controls	500		
	Utilities	500		
	Installation	1,300		
	Shielding	3,000		

Booster Neutrino Beamline (BNB) Option

- After Stage 4 is complete, the old Booster is abandoned
- The present Linac can support pulse lengths in excess of 50 μS
  - A 40mA Linac beam pulse for 50 μS has 12.4×10^{12} particles
- From a single Linac pulse, a chopper placed in the 400 MeV line would be able to send
  - 8.2×10^{12} protons to the new booster
  - 4.2×10^{12} protons to the old booster.
- This would require an RF acceleration system in both Boosters.

Booster Neutrino Beamline (BNB) Option Option

- An RF acceleration system in both Boosters.
  - Option A:
    - Move the RF system built for Stage 3 into the new booster
    - Re-install the old RF system into old Booster
    - Comments
      - Inexpensive
      - Keeps BNB at 13.6×10^{16} protons/hour
  - Option B:
    - Keep the RF system built for Stage 3 in the old Booster
    - Build a new set of cavities for the new Booster.
    - Comments
      - Expensive ~ $25M
      - Gets BNB to 21.6×10^{16} protons/hour
      - Keeping the old Booster running while installing the new Booster makes the transition between Stage 3 to Stage 4 easier

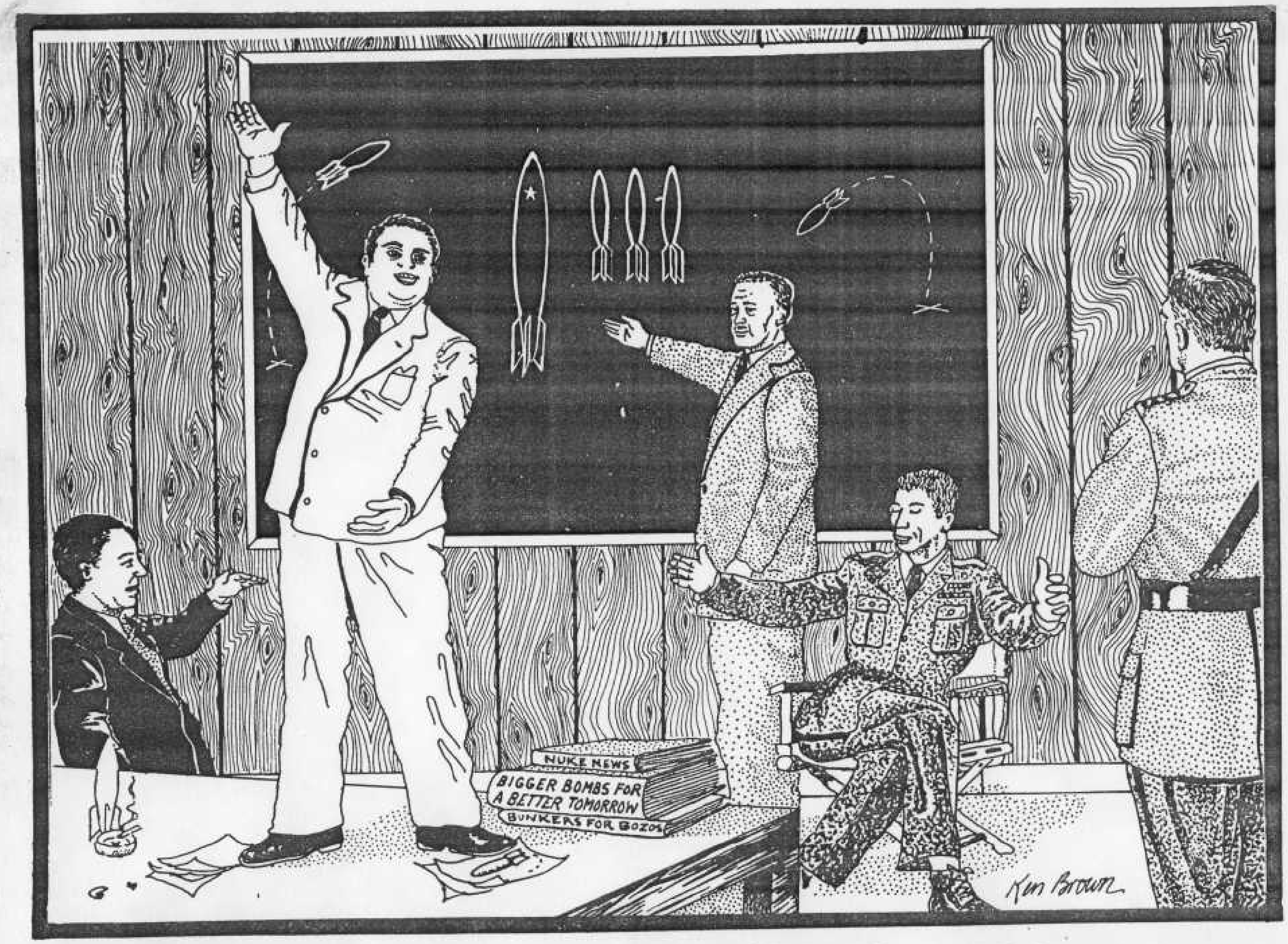
Summary

- The present antiproton production complex can be converted into a multi-stage proton accumulator
  - That supplies enough protons for a 1.1 MW 120 GeV beam for a cost of about $40M ($5M of which is already funded in the present Proton Plan)
  - That can be upgraded to provide enough protons for a 2.3 MW 120 GeV beam for an additional cost of about $50M
- Because the concept uses existing infrastructure the performance can be broken into stages
  - Project staging has the important benefit of providing
    - a fraction of the total performance
    - at a fraction of the total cost
  - The schedule for each stage is driven by physics need and funding availability
- Integrating the present Booster into this scheme could in addition provide 8 GeV protons in 1.6 μS bursts at a rate of 14-21x10^{16} protons/hour for a Booster Neutrino Beam (BNB)

Things To Do

- Get cost estimate for Booster RF upgrade
- Lattice design for the new Booster
- Layout of AP3 modification andAP4 line
- Simulate momentum stacking
- Simulate extraction from the Accumulator

Acknowledgements



WHITE MEN IN TIES DISCUSSING MISSILE SIZE