Beam Emittances and RF structure at Injection into the Main Injector for the Multi-Stage Proton Accumulator

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Concept

- After the collider program concludes, 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

Stages of the Present Proton Plan

- Present - Present Booster -> Main Injector
  - 6.4×10^{16} pph
  - 162kW 120 GeV Beam
  - 1.1×10^{16} pph Collider
  - 2.1×10^{16} pph BNB
- Stage 1 - Proton Plan Booster -> Main Injector
  - 13.5×10^{16} pph
  - 370kW 120 GeV Beam
  - 1.4×10^{16} pph Collider
  - 5.1×10^{16} pph BNB
- Stage 2 - Proton Plan Booster -> Recycler -> Main Injector
  - 13.5×10^{16} pph
  - 705kW 120 GeV Beam

New Stages for the Multi-Stage Proton Accumulator

- Stage 3 - Proton Plan Booster -> Accumulator -> Recycler -> Main Injector
  - 21.6×10^{16} pph
  - 1140kW 120 GeV Beam
- Stage 4 - New Booster -> Accumulator -> Recycler -> Main Injector
  - 43.2×10^{16} pph
  - 2300kW 120 GeV Beam

Booster Throughput Scenarios

Parameter	Present	Stage 1	Stage 2	Stage 3	Stage 4	PD2	
Booster Flux	6.38	13.53	13.54	21.59	43.18	36.36	$x10^{16}$/Hr
Collider Flux	1.09	1.41	0.00	0.00	0.00	0.00	$x10^{16}$/Hr
NUMI Flux	3.21	7.05	13.54	21.59	43.18	36.36	$x10^{16}$/Hr
NUMI Beam Power	162	367	704	1140	2280	1920	kW
MiniBoone Flux	2.08	5.07	0.00	0.00	0.00	0.00	$x10^{16}$/Hr

Parameter	Present	Stage 1	Stage 2	Stage 3	Stage 4	PD2	
Slip Stack Final Intensity	6.9	8	0	0	0	0	$x10^{12}$
NUMI Final Intensity	22	42	55	95	190	150	$x10^{12}$
MI Cycle Time	2.6	2.2	1.5	1.6	1.6	1.5	Sec
Slip Stack Batches	2	2	0	0	0	0	
NUMI Batches	5	9	12	24	24	6	
Slip Stack Efficiency	88	93	100	100	100	100	%
NUMI Efficiency	95	97.5	97.5	99	99	99	%

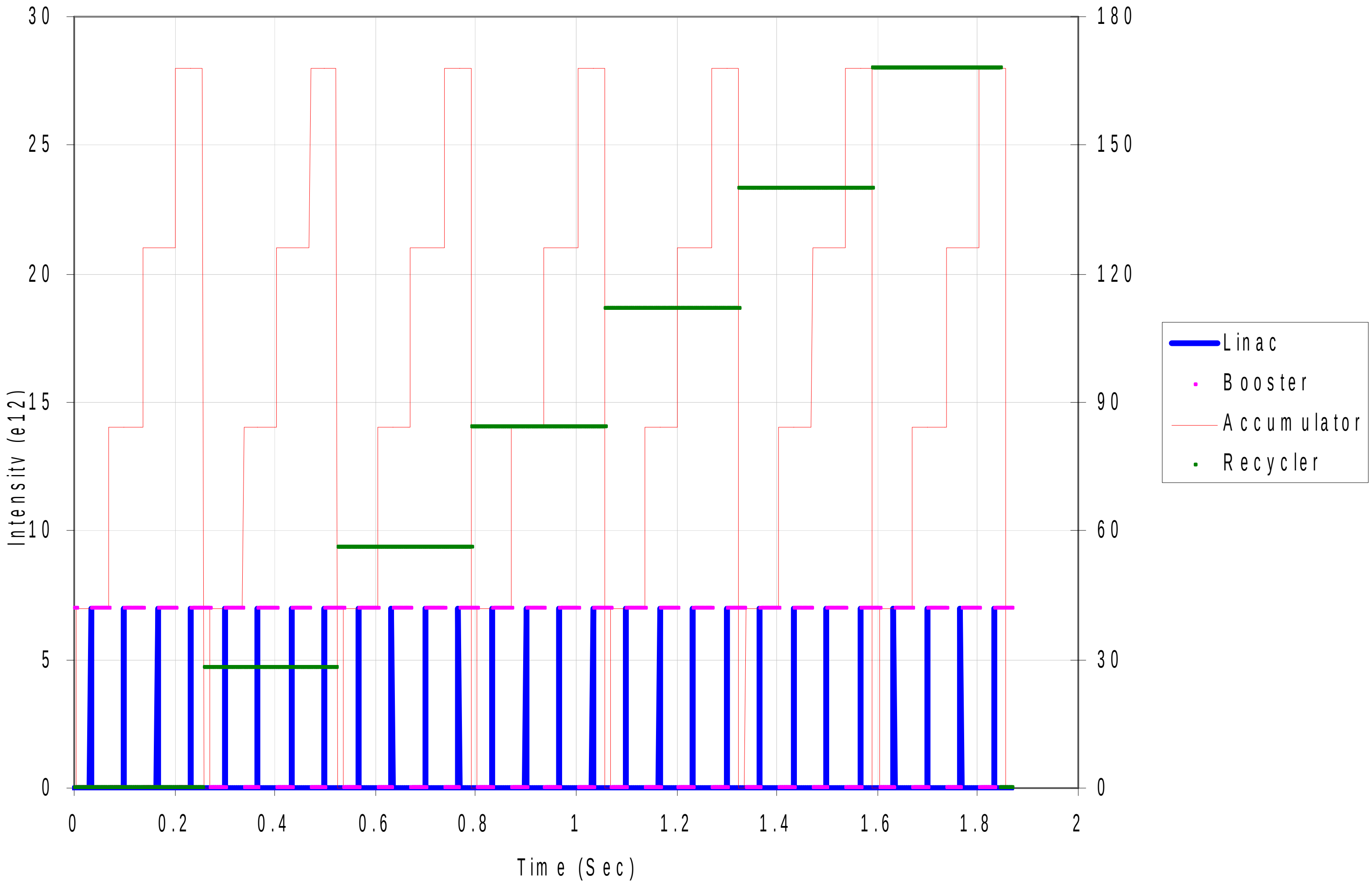
Momentum Stacking in the Accumulator

- 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

Multi-stage Proton Accumulator Scheme

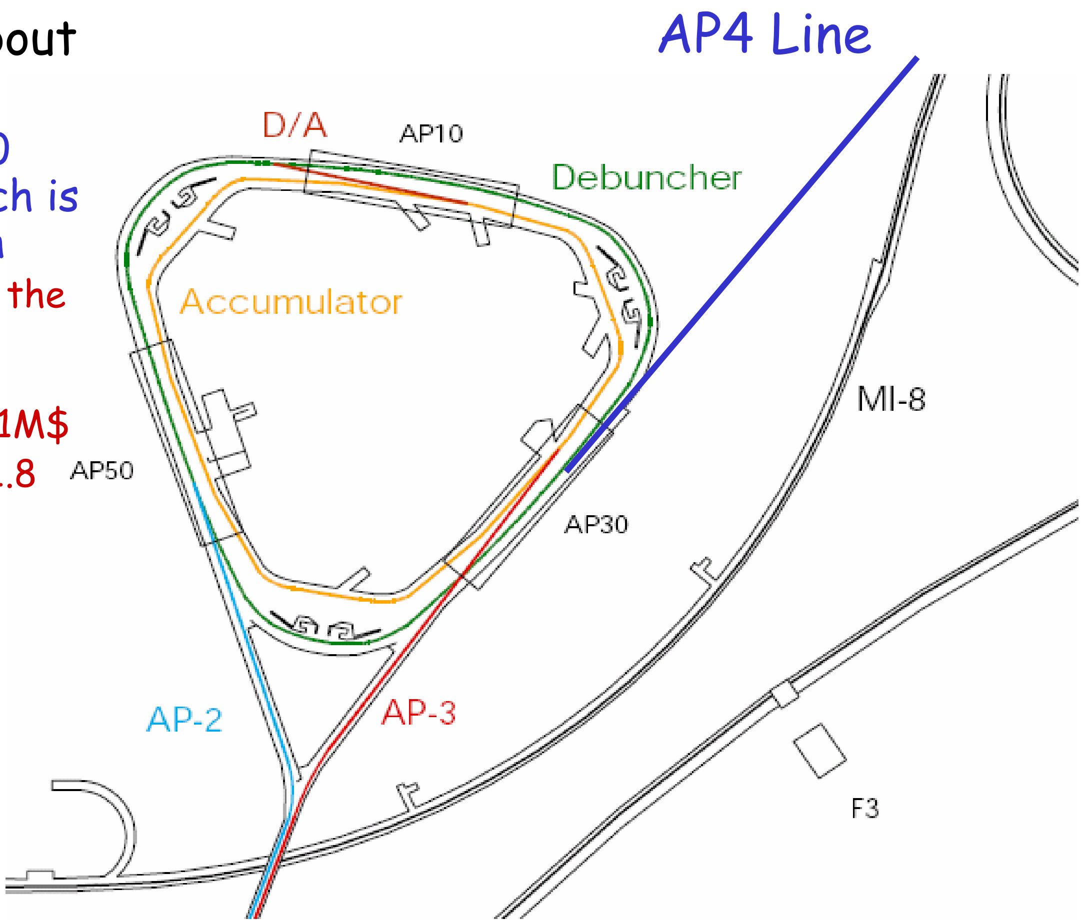
- Momentum stack in the Accumulator
  - Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
  - Decelerate new batch towards core orbit and merge with existing beam
  - Momentum stack 3-4 Booster batches
  - Extract a single Accumulator batch
    - 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



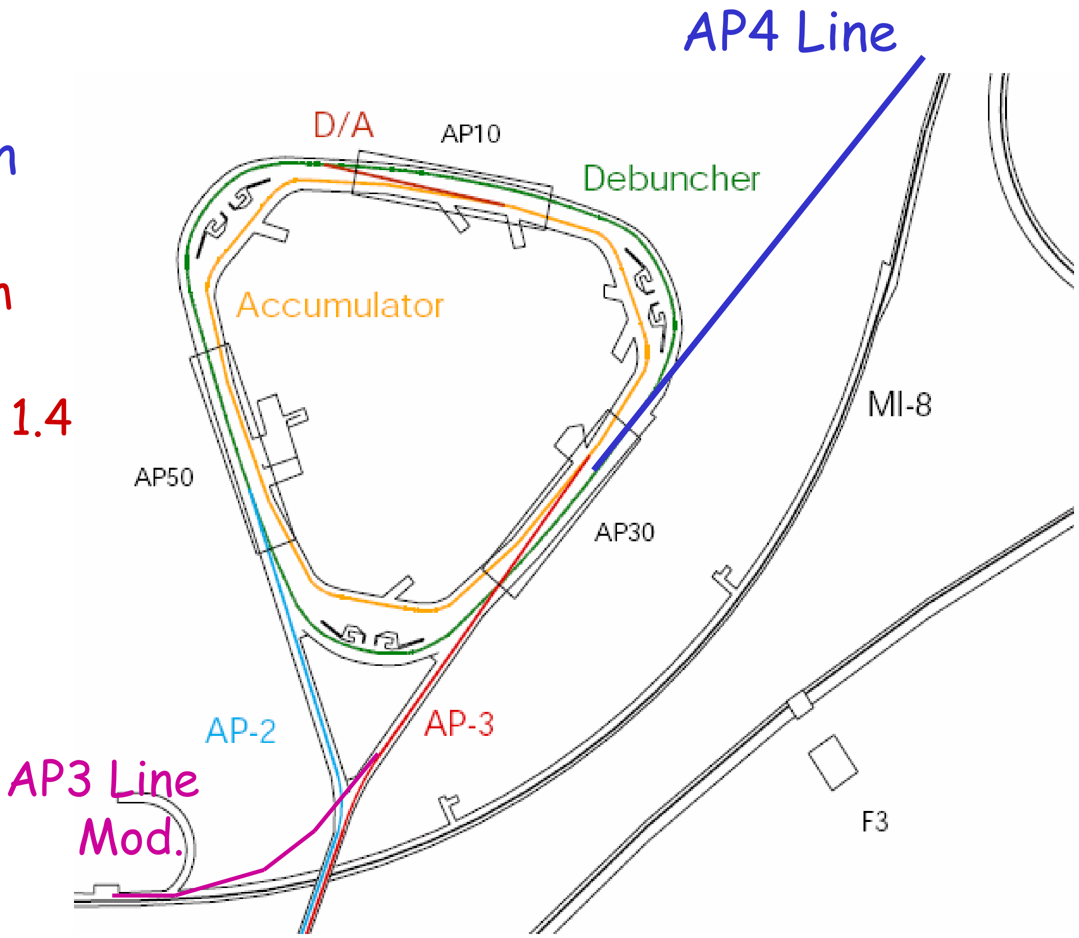
AP-4 Line

- 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
    - Use Magnets from the AP2 line for 8 GeV operation
    - 600 MeV magnets 1M$
    - Civil Construction 1.8 M$



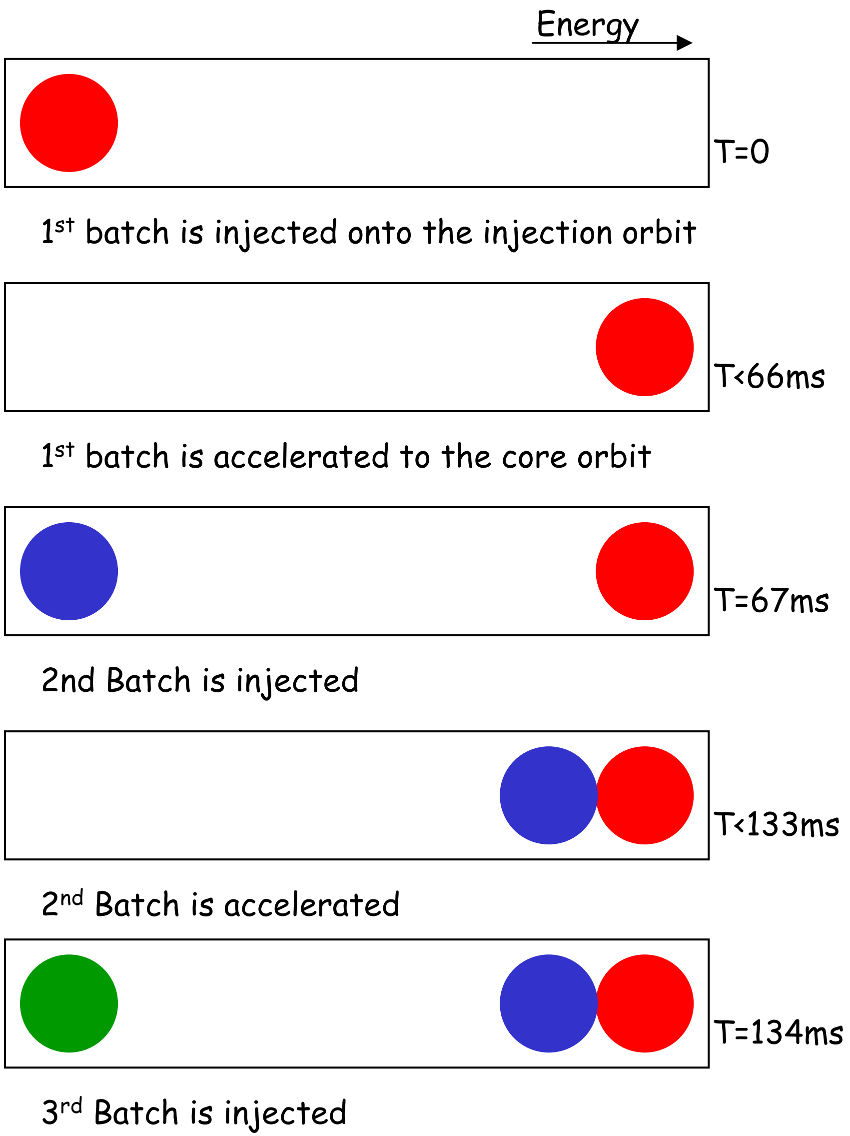
AP-3 Line Modification

- The AP3 line needs to be connected to the MI-8 line
  - The modification is about 100 meters in length
    - Use magnets from the rest of AP3
    - Civil Construction 1.4 M$



Mechanics of Momentum Stacking

- Inject in a newly accelerated Booster batch every 67 mS onto the low momentum orbit of the Accumulator
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-4 Booster batches



Advantages of Momentum Stacking

- Transient Beam Loading
  - Slip stacking or barrier bucket stacking requires manipulating intense beams with 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

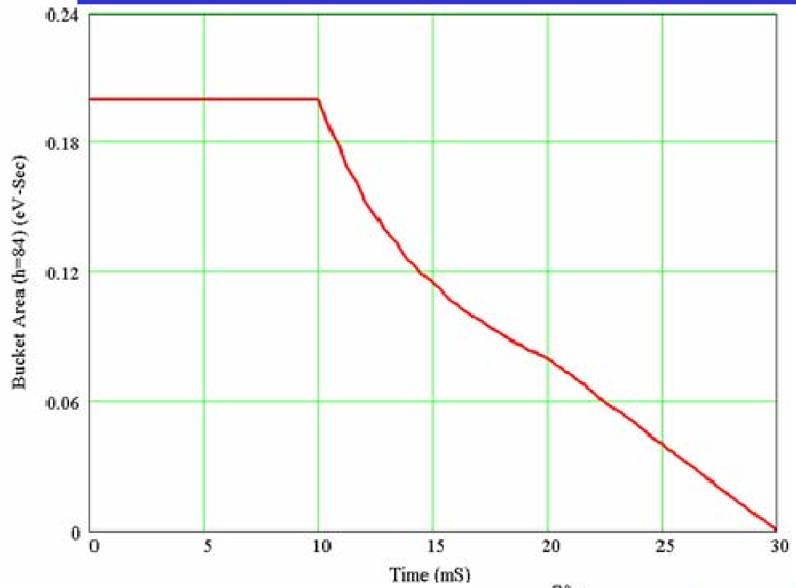
Momentum Stacking in the Accumulator

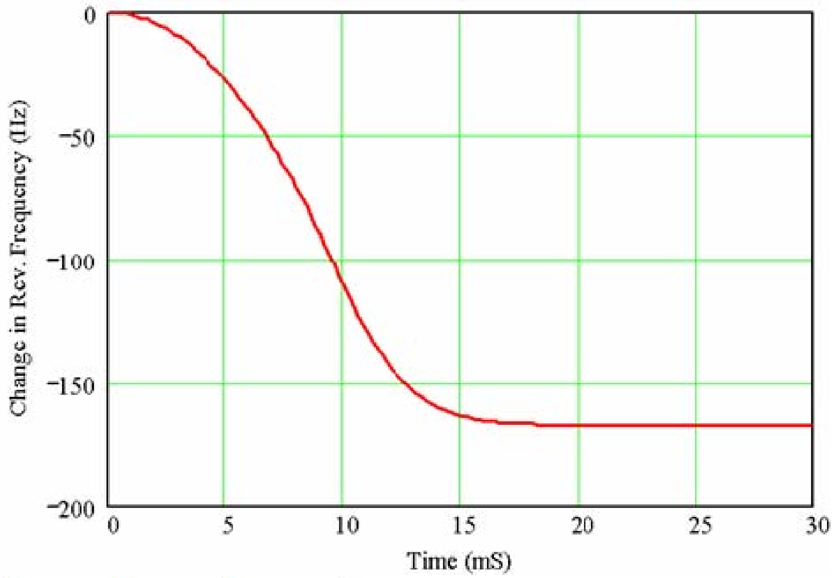
- At injection into the Accumulator, the RF system must provide enough bucket area to hold the injected beam.
  - Presently, the longitudinal emittance per 53 MHz bunch at extraction from the Booster is about 0.08 eV-Sec for a batch intensity of 4.2×10^{12} protons.
  - A reasonable value for the capture bucket in the Accumulator would be 0.2 eV-Sec.
- Once the beam is captured in the Accumulator, the bucket is accelerated towards the high energy side of the momentum aperture with a constant bucket area.
  - Because all the RF manipulations must be done before the next batch is injected, the batch should reach the high energy side of the Accumulator in about 10 mS.

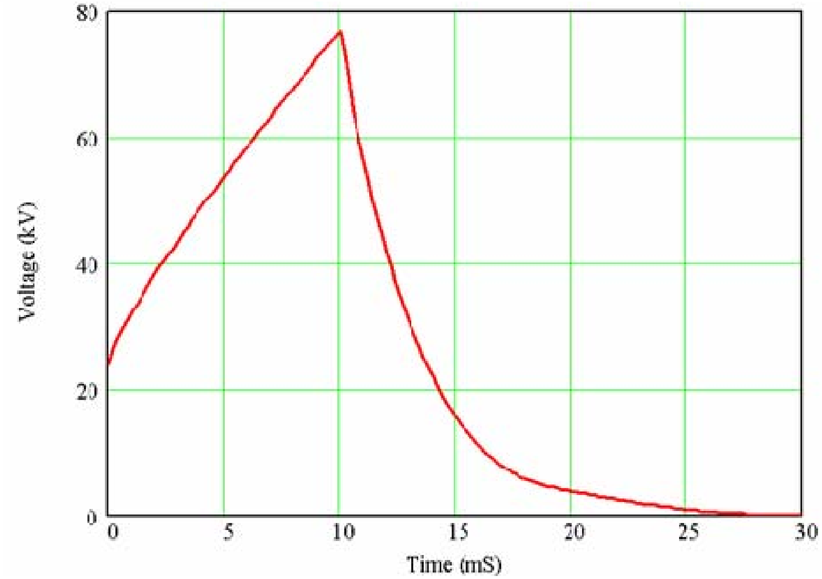
Momentum Stacking in the Accumulator

- When the high energy edge of the bucket reaches the target energy, the bucket area is shrunk while keeping the high energy edge of the bucket fixed at the target energy.
  - This period while the bucket is shrinking with the high energy edge fixed should take an additional 10 mS.
- When the bucket area has shrunk to the beam area, the bucket stops accelerating and de-bunches.
  - The de-bunching process will take another 10 mS.
- The whole process requires 30 mS which leaves 37 mS before another batch is injected.
- The extra 37 mS will be used to recapture the batches for extraction from the Accumulator.
- The maximum 53 MHz voltage required for the accelerating 0.2 eV-Sec bucket is 80 kV.
  - The present Accumulator RF system has two cavities that could provide 35 kV of RF each.
  - In comparison, a 0.14 eV-Sec accelerating bucket requires 60 kV.
  - A third RF cavity is probably necessary.

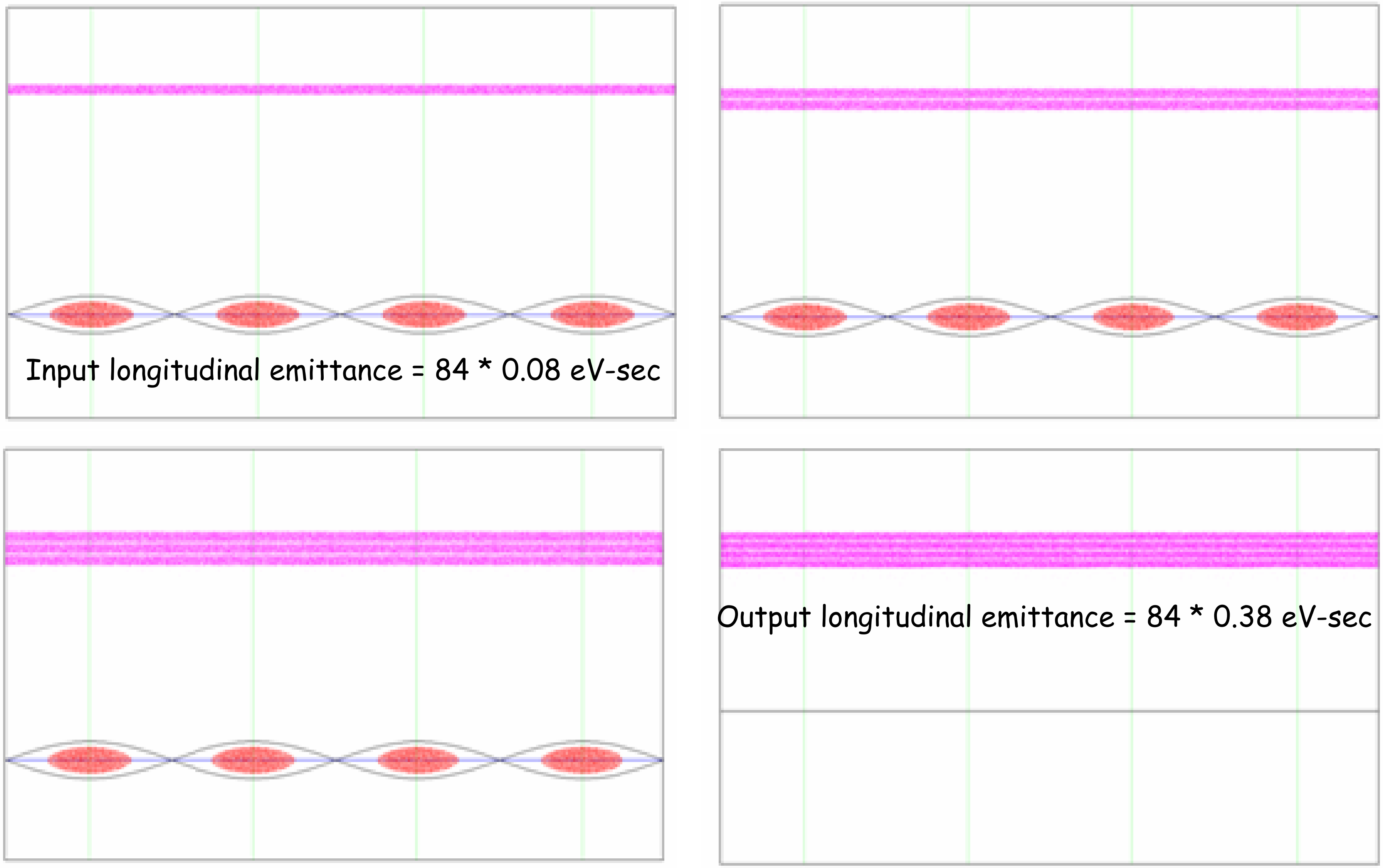
Momentum Stacking RF Curves





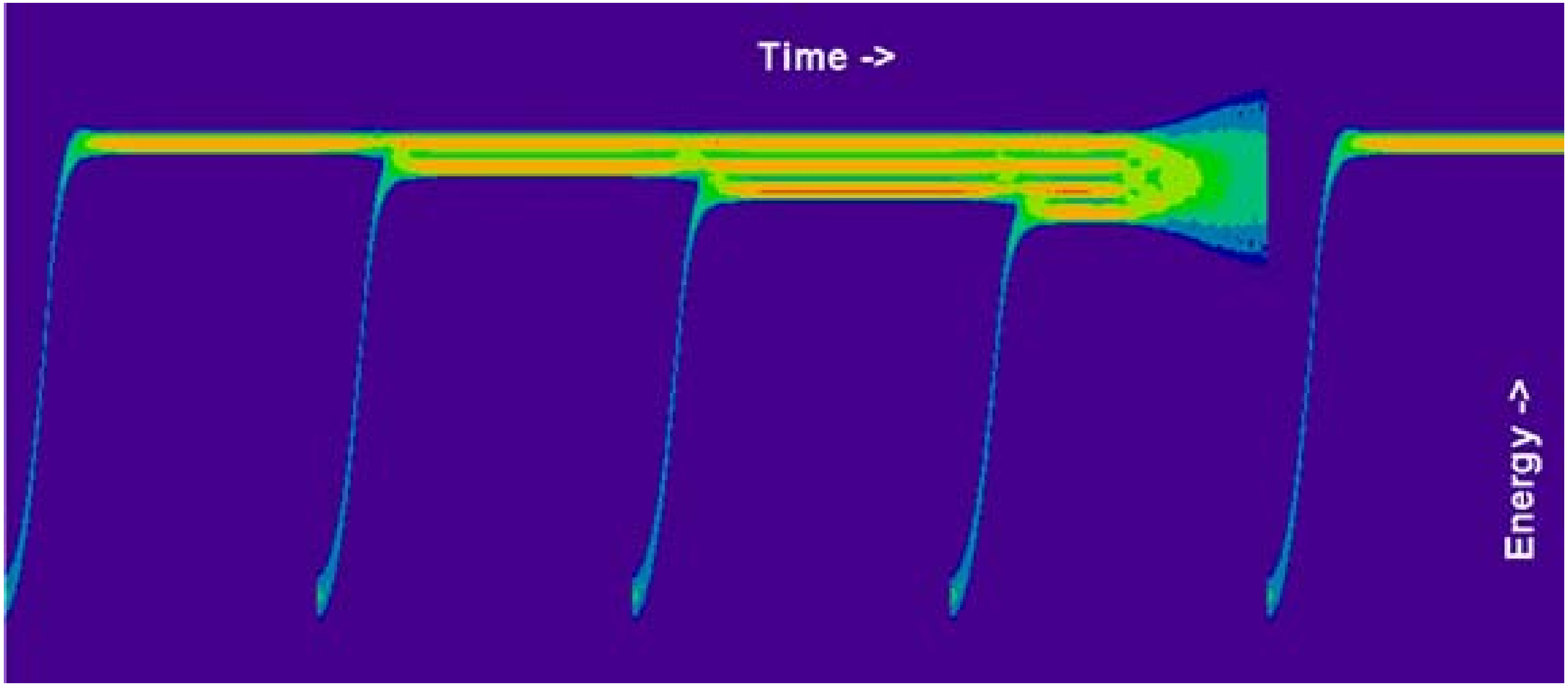


Momentum Stacking Phase Space



Momentum Stacking

Output longitudinal emittance = 84 * 0.38 eV-sec



Input longitudinal emittance = 84 * 0.08 eV-sec

Momentum Stacking Simulation Results

- The longitudinal emittance of the Booster batch used in these simulations is 0.08 eV-sec per 53 MHz bucket.
- The total longitudinal emittance for the coasting beam at the end of the process is 84 x 0.38 eV-Sec.
  - This corresponds to an emittance dilution of 19%.
  - A simulation using an initial emittance of 0.10 eV-sec was performed and the resulting coasting beam emittance was 84 x 0.47 eV-Sec which corresponds to a dilution of 18%.
  - For simulation using an initial emittance of 0.12 eV-sec, only three batches were momentum stacked to give a coasting beam emittance of 84 x 0.43 eV-Sec.
    - Three batch momentum stacking would require a faster Main Injector cycle time of 1.2 seconds to deliver the same 120 GeV beam power as four batch stacking.
- There has been significant work on decreasing the Booster longitudinal emittance for slip-stacking.
  - Without using the gamma-t jump in Booster, the longitudinal emittance per 53 MHz bunch at extraction from the Booster is about 0.08 eV-Sec for a batch intensity of 4.2x1012 protons.
  - Most of the longitudinal emittance growth occurs at transition in the Booster.
    - The Booster gamma-t jump is not currently used because it interferes with cogging.
    - Currently an RF step at transition is under consideration to decrease the longitudinal emittance.
    - Since cogging in the Booster is not required in Stage 3, another reduction in longitudinal emittance might be possible if the Booster gamma-t jump is re-commissioned.

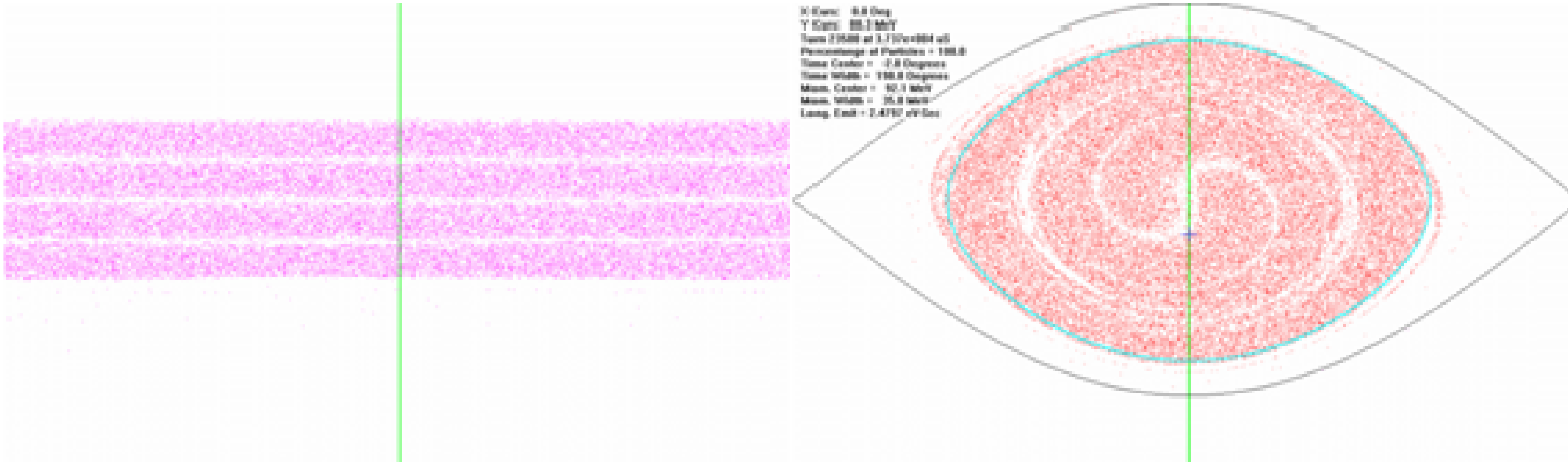
Extraction From the Accumulator

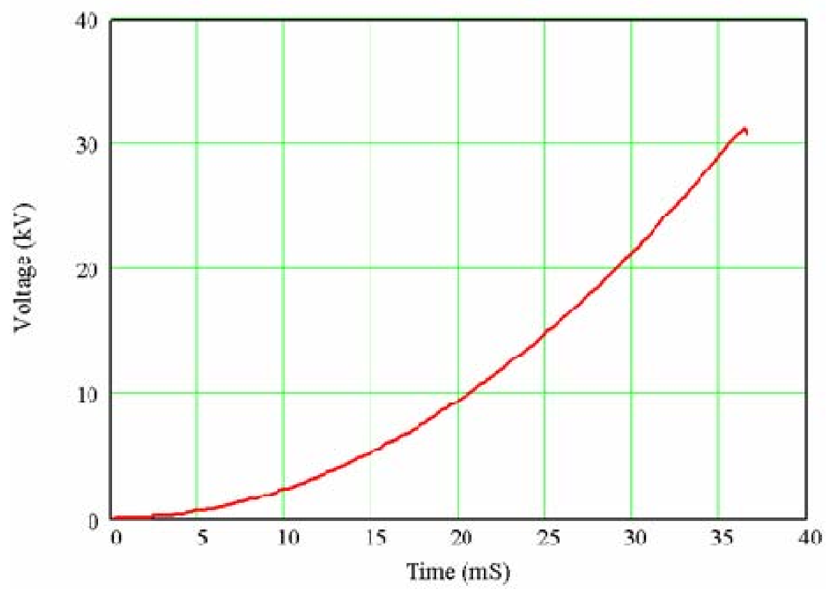
- The low emittance dilution of the momentum stacking process is a result of de-bunching the batches into coasting beam.
- Because of kicker rise time, a gap must be placed in the coasting beam so that no beam is lost while the extraction trajectory is swept across the face of the extraction magnet.
- With the large amount of proton flux, small transfer inefficiencies can result in a substantial amount of tunnel activation.
  - **With 4.0×10^{12} 8 GeV protons per batch transferring at a 15 Hz rate, a beam loss of 0.7% is equivalent to a beam power of 500W.**
- The beam gap could be formed with a barrier bucket.
  - A 10 kV barrier that is 120 nS wide would be required to form a barrier in the coasting beam distribution
  - The wideband RF power supply to generate a 10 kV barrier would be substantial.
  - More importantly, the synchrotron frequency for a 10 kV barrier is slower than the Booster repetition rate.
  - Forming a barrier faster than the Booster repetition rate would result in substantial emittance dilution.

Extraction From the Accumulator

- Another choice for forming this gap would be to bunch the beam with a sinusoidal RF.
  - For a 53 MHz bunch structure, the kicker rise time would have to be faster than 10 nS which would be extremely difficult to achieve at 8 GeV.
- Larger gaps can be made with lower frequency RF.
  - Because the bunching process should not result in significant emittance dilution, the synchrotron frequency must be much higher than the Booster repetition rate.
    - For example, the synchrotron frequency needed to bunch the beam at 2.5 MHz (h=4) is only 60 Hz
    - The synchrotron frequency for the beam bunched at 7.5 MHz (h=12) is over 180 Hz.
      - The gap that can be created in the beam with 7.5 MHz RF bucket that is 70% full is over of 45 nS.
      - The present Accumulator injection and extraction kickers would have to be re-built to have a rise time smaller than this gap.
- The extraction curves can span up to 37 mS before the next Booster batch is injected into the Accumulator.
- For an h=12 RF system (7.5 MHz), the bucket area needed to capture the coasting beam distribution is 2.75 eV-Sec.
  - The RF voltage is ramped up to 32 kV to provide a 4.2 eV-Sec bucket at extraction.
  - A 4.2 eV-Sec bucket will leave a gap between bunches of about 45 nS.
    - For this example, the bucket area is linear time ramp which will result in a small amount of longitudinal emittance growth.
    - The h=12 emittance that contains 100% of the particles before extraction is 2.75 eV-sec. The 95% emittance after extraction is 2.5 eV-Sec.

Extraction Phase Space





Box Car Stacking in the Recycler

- After 4 booster batches have been momentum stacked in the Accumulator, the beam would be transferred to the Recycler.
  - 7.5 MHz MHz synchronous transfer
    - New system
    - Need 80kV/Turn for a 4.2 eV-sec bucket
  - Accumulator phase ALIGNED to the Recycler
- The Accumulator is 1/7 of the Recycler's circumference
- Boxcar stack six of the Accumulator batches leaving 1/7 of the Recycler ring for an abort gap.
- After 6 Accumulator batches have been stacked into the Recycler debunch 7.5 MHz beam in >80mS
- Re-capture in 53 MHz buckets for acceleration.
  - Need 500 kV for 0.6 eV-sec
  - Use three Tevatron RF cavities

RF Manipulations in the Recycler

- The Recycler will also require a 7.5 MHz (h=84) RF system for synchronous bucket to bucket transfers from the Accumulator.
  - To match to a 4.2 eV-Sec bucket, the Recycler RF system will require 80 kV at 7.5 MHz.
  - Because the magnets and the frequency of the 7.5 MHz RF systems in both the Accumulator and Recycler do not ramp, a phase alignment and frequency jump system instead of a phase lock system for synchronizing transfers should suffice.
  - Using a phase alignment system would permit the entire 37 mS period left for extracting the beam from the Accumulator to be used for bunching the beam.
- Once the 7.5 MHz bunches have been transferred to the Recycler,
  - The beam must be debunched out of the 7.5 MHz buckets
  - Recaptured into 53 MHz buckets for transfers to the Main Injector.
  - There will be 266 mS for this process while the Accumulator is momentum stacking another four Booster batches.
  - Because the synchrotron period for the 7.5 MHz bunches is approximately twice as long in the Recycler as it is in the Accumulator, the 7.5 MHz de-bunching process in the Recycler should take over 75 mS.

RF Manipulations in the Recycler

- About 500 kV of 53 MHz RF (h=588) is needed in the Recycler to provide 0.6 eV-Sec of bucket area
  - which should be enough to re-capture and extract the 0.4 eV-Sec longitudinal emittance of the 53 MHz bunches.
- Three of the Tevatron cavities along with the power amplifiers could be installed into the Recycler to provide the necessary RF voltage.
  - Because the current Tevatron RF system can provide over 2.0 MV of 53 MHz RF with eight cavities
  - The Recycler 53 MHz frequency does not need to ramp,
- The remaining 190 mS should more than adequate to re-bunch the beam at 53 MHz in the Recycler.
  - Because the fill time of the Tevatron cavities is about 0.2 mS.
  - The synchrotron frequency for 500kV of 53 MHz RF in the Recycler is 550 Hz.,