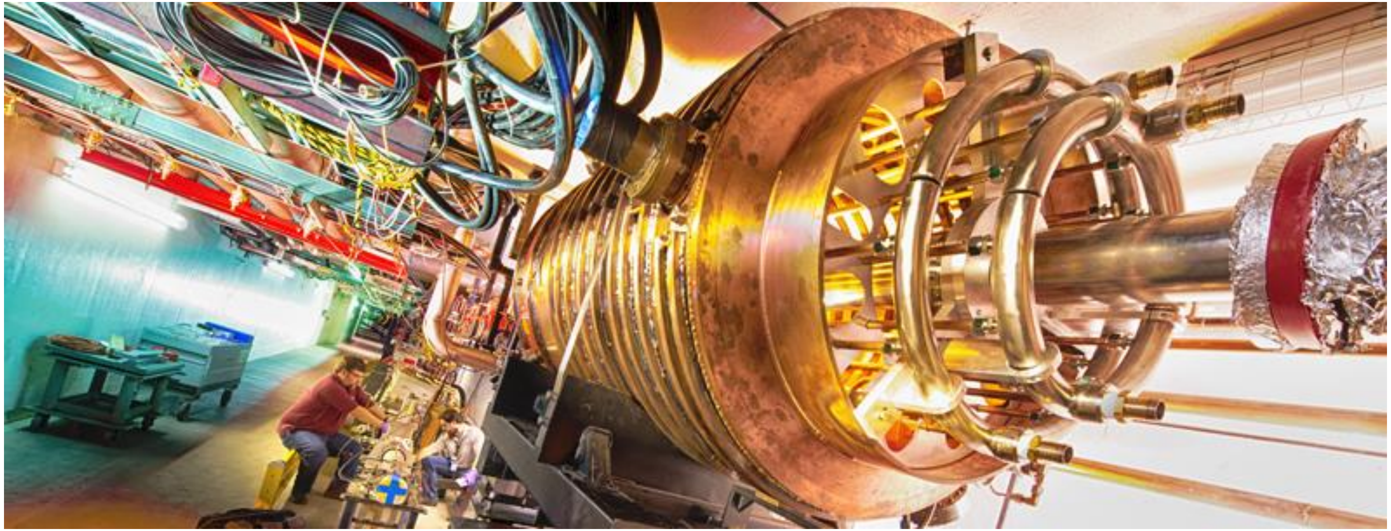

RF and Challenges in Fermilab's Proton Synchrotrons

Paul Derwent
Accelerator Division, RF Department
April 21 2023

About me

- PhD University of Chicago, 1990
  - CDF Collaboration: W and Z cross section measurements
- Post-Doc University of Michigan
  - CDF Silicon Vertex detector: radiation protection, tracking
  - Correlated μ – b quark production cross sections
- Scientist Accelerator Division since 1995
  - Pbar: Stochastic Stacking
  - Run Coordinator, 2001 Run II Collider startup
  - Joined Accelerator Upgrades for NOvA 2006
    - Associate Project for Accelerator and NuMI Upgrades (ANU)
    - Member of the NOvA collaboration
  - PIP-II, Operations
  - Currently in the RF department and Mu2e

Fermi National Accelerator Laboratory

- Fermilab is America's particle physics and accelerator laboratory
  - We bring the world together to solve the mysteries of matter, energy, space and time.
  - As America's particle physics laboratory, Fermilab operates and builds powerful particle accelerators for investigating the smallest things human beings have ever observed.

Fermilab Program Goals

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

- Neutrinos
  - NuMI @700 kW
  - LBNF @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

⇒ ***This requires more protons!***

(and this statement tends to be time invariant)

"Upgrade the Fermilab Proton Accelerator Complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of > 1 MW by the time of the first operation of the new long-baseline neutrino facility" – Recommendation 14, P5 report

Neutrinos have been a focus at Fermilab since the beginning

- The first approved experiment
  - E1A, April 15 1970
    - 1200 hours, with completion of the experiment defined as 20,000 events with $2x10^{17}$ protons on a horn focused beam

HARVARD - PENNSYLVANIA - WISCONSIN COLLABORATION*

NAL NEUTRINO PROPOSAL

ABSTRACT

We propose here an experiment, using neutrinos in the energy range 10 - 100 GeV, that will permit us to: (1) search for an intermediate vector boson W through the reaction $\nu_\mu + Z \rightarrow \mu^- + W^+ + Z$, up to a W mass of $\simeq$ 10 GeV/c^2 at 200 GeV operation of NAL; both the leptonic and hadronic decay modes will be detected; (2) measure the cross section for the diagonal 'point' four-fermion interaction $\nu_\mu + Z \rightarrow \mu^- \mu^+ \nu_\mu Z$; (3) measure $d^2\sigma/dq^2 d(E_\nu - E_\mu)$ in the region $q^2 \rightarrow$ very large, $(E_\nu - E_\mu) \rightarrow$ very large, i.e., the deeply inelastic scattering region; (4) measure $d^2\sigma/dq^2 d(E_\nu - E_\mu)$ and $\sigma_{tot}(E_\nu)$ for the reaction $\nu_\mu + p \rightarrow \mu^- +$ (anything). The device that will be used to accomplish these experiments consists of a large hydrogen target, a heavy metal, fine-grained total absorption calorimeter and a large iron core magnet.

*In alphabetical order: E. W. Beier (P), D. Cline (W), A. K. Mann (P) J. Pilcher (H), D. D. Reeder (W), C. Rubbia (H), plus at least 3 post doctoral people and several graduate students.

- In early 1971, Wilson told the laboratory's Users' Organization that "one of the first aims of experiments on the NAL accelerator system will be the detection of a neutrino. I feel that we then will be in business to do experiments on our accelerator." Later that year experiment E-21, named "Neutrino Physics at Very High Energies" and run by a Caltech group, was the first to detect neutrinos at the new laboratory.

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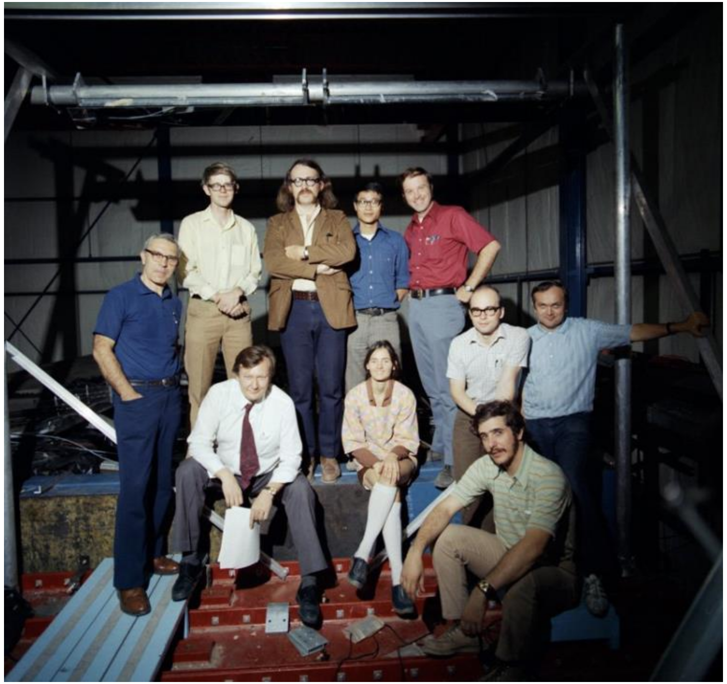

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STATISTICS in Neutrino Experiments

Neutrino Events/Unit Time =

Neutrino Flux x ← **BEAM = Protons/year + Target/horns, Beam Energy**

Neutrino Cross-section/Nucleon x ← PHYSICS!

Number of Nucleons ← **Detector = Mass + Efficiency**

Neutrino Experiments Need : Mass * Power * Time

We want to achieve our physics goals in a timely manner!

DUNE Physics Goals

40kT with 1.2 MW (PIP-II) is a 20 year program

Detector Fiducial Mass (kton)	Proton Beam Power (MW)	YEARS to reach 120kT.MW.yr	YEARS to reach 600kT.MW.yr	YEARS to reach 900kT.MW.yr
10	0.7	17	86	129
20	0.7	9	43	64
30	0.7	6	29	43
40	0.7	4	21	32
10	1.2	10	50	75
20	1.2	5	25	38
40	1.2	3	13	19
20	2.4	3	13	19
40	2.4	1	6	9

1 MW year ~ 1.1e21 protons at 120 GeV : E1A 0.0002e21

DUNE TDR – February 2020 FERMILAB-DESIGN-2020-01

- 1 year = 1.1e21 POT
  - 1.2 MW, 56% uptime
  - If 800 kW: 1.5x longer
  - If 2.4 MW: 0.5x shorter

~~CP~~ Sensitivity	Years (0.8-1.2-2.4 MW)
3σ, 75% δ_{CP}	20 – 13.3 – 6.7
5σ, 50% δ_{CP}	21 – 10.5 – 5.3
5σ, $\delta_{CP}={}^{\pi}/_{2}$	14 – 7 – 3.5

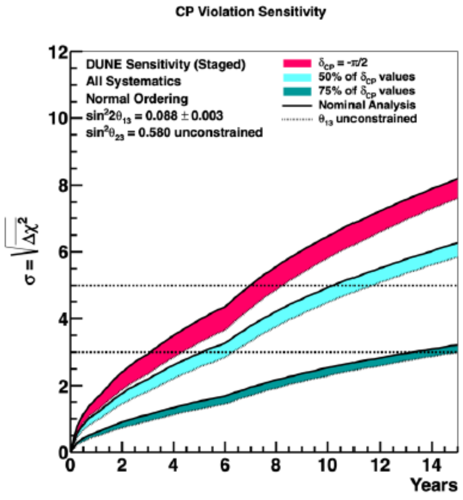


Figure 2.6: Significance of the DUNE determination of CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) for the case when $\delta_{CP} = -\pi/2$, and for 50% and 75% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

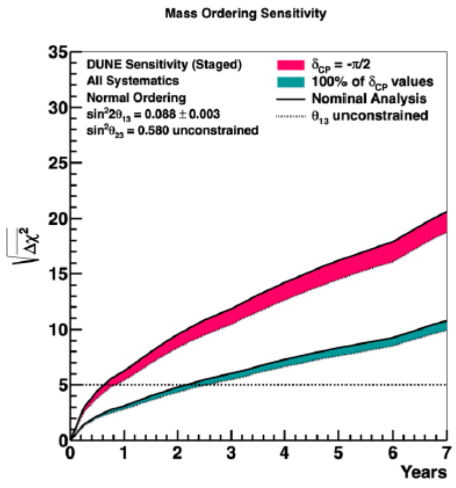
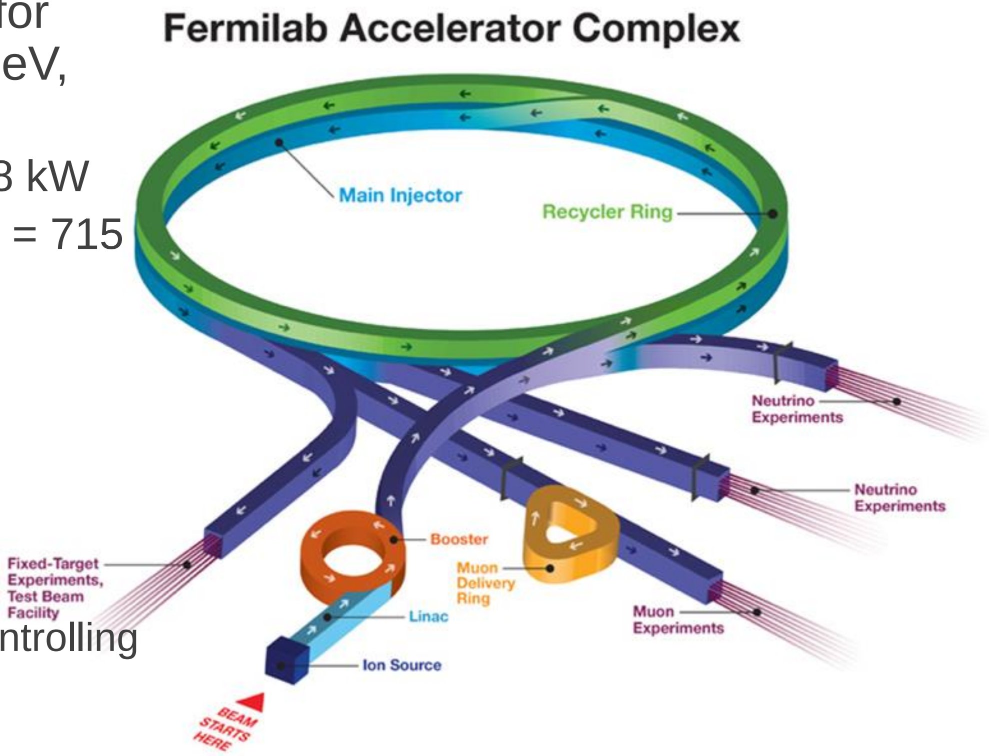


Figure 2.7: Significance of the DUNE determination of the neutrino mass ordering for the case when $\delta_{CP} = -\pi/2$, and for 100% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

The Fermilab Accelerator Complex Today

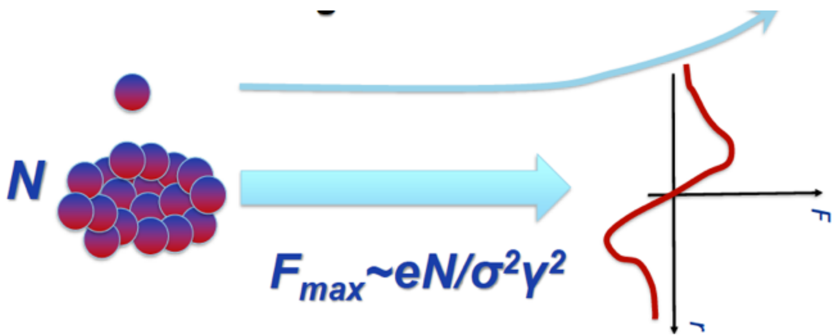
- The Fermilab complex delivers protons for neutrino production at both 8 and 120 GeV, with a present capability:
  - 8 GeV: 4.6×10^{12} protons @ 15 Hz = 88 kW
  - 120 GeV: 5.0×10^{13} protons @ 0.75 Hz = 715 kW
- Present limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
  - Rings Beam Loss
    - Higher Power operation is all about controlling beam loss
  - Target systems capacity
    - Limited to ~900 kW



Increasing Beam Intensity

- High Intensity operations
  - All about beam loss
  - Defocusing force is nonlinear
    - Beam Intensity (N)
    - Beam Size (σ)
    - Beam Energy (γ)
  - Beam Loss:
    - Radiological controls: personnel safety, ground water
    - Radiological activation: maintenance ALARA
    - Radiological activation: component performance / degradation (cables and electronics)

    - Capture in a controlled fashion: collimators
    - Or 'lose' at lower energy
  - Protons – do not have synchroton radiation to control beam size!



Fermilab

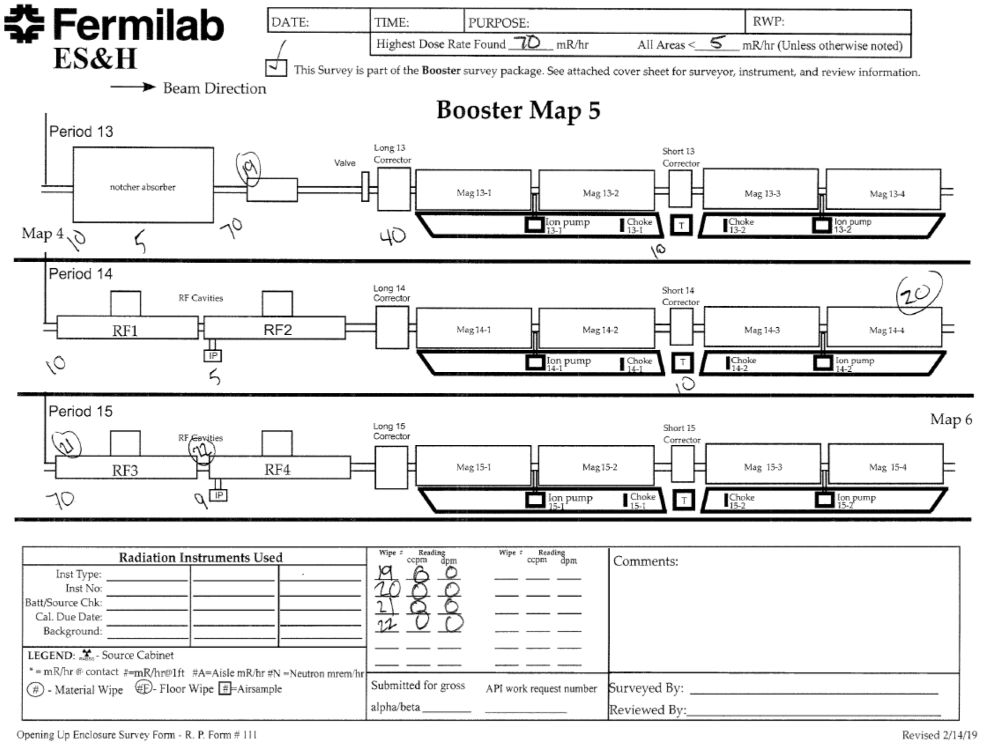
Booster Radiation Survey: July 11 2022 – 2 days after beam off

Numbers : mR/hr at 1'

DOE Limit: 5000 mR/yr

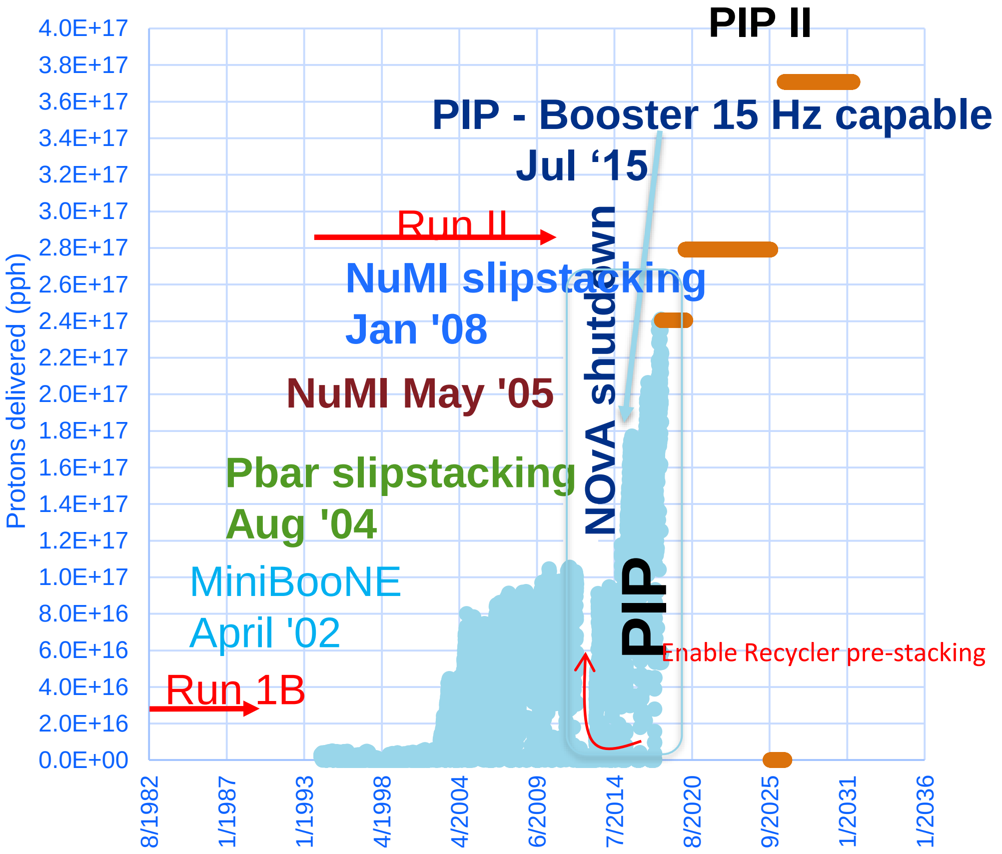
Fermilab Limit: 1500 mR/yr

Largest value here 70 mR/hr, RF Cavity 3



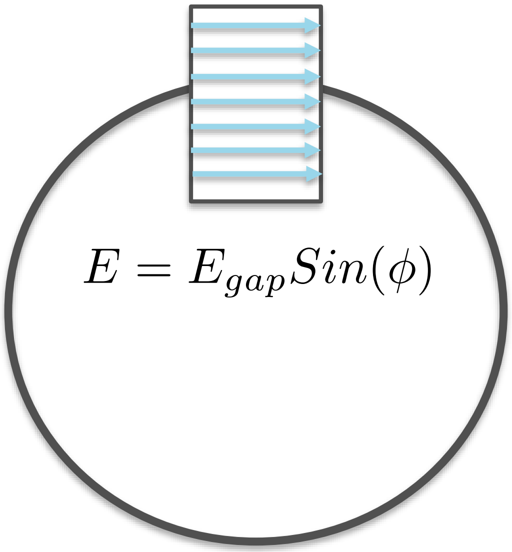
Progress: Beam through Booster

- Collider Era Run 1b
  - 1994-1996
    - 3e15 per hour
- Collider Run II
  - 2001 - 2003
    - 3e15 per hour
- BNB + Collider:
  - 2003-2005
    - 4e16 per hour
- BNB + Collider + NuMI:
  - 2005-2011
    - 7e16 per hour
- BNB + NuMI High Power
  - 2014-now
    - 2.4e17 per hour
- PIP-II era
  - 2028-?
    - 3.7e17 per hour



Beam Acceleration in a synchrotron

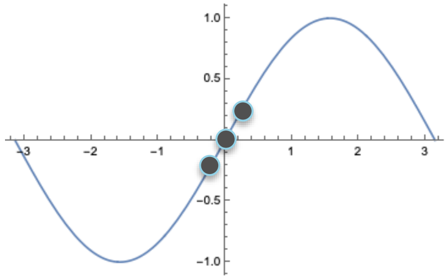
- Constant DC field: would accelerate across gap BUT fringe fields would decelerate particle
- Time varying EM field
- ϕ_s represents phase of synchronous particle
  - Arrive early, - kick
  - Arrive late, + kick
  - Below transition!



- Stationary beam $\phi_s = 0$ (π if above transition)
  - Areas of stable operation and unstable operation

Transition Energy

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$



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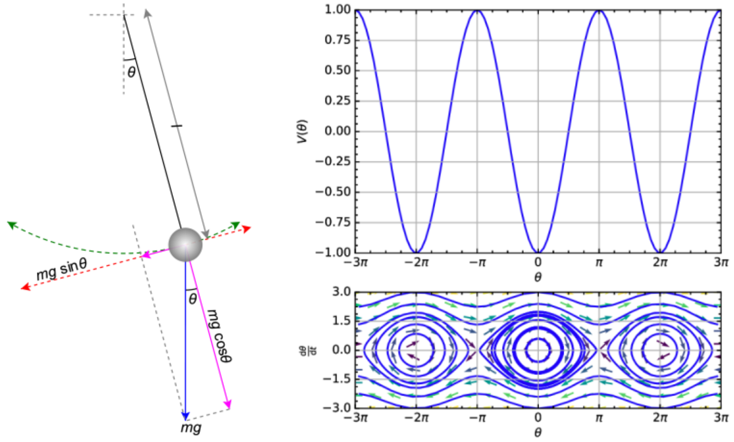
By Krishnavedala - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=24185988



Problem we have all seen: sinusoidal restoring force -> pendulum problem

Beam Acceleration in a synchrotron

$$\Delta E_{n+1} = \Delta E_n + eV(Sin(\phi_n) - Sin(\phi_s))$$

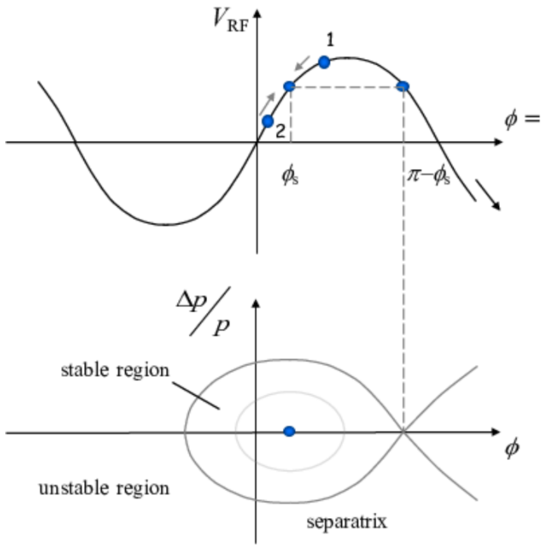
$$\phi_{n+1} = \phi_n + \frac{\omega_{rf}\tau\eta c^2}{v^2 E_s}\Delta E_{n+1}$$

- Energy gain -> ϕ_s as a non zero value
- Difference Equations for energy and phase change for each particle
  - As only have restoring force in the gap, not continuous

- For Stable acceleration

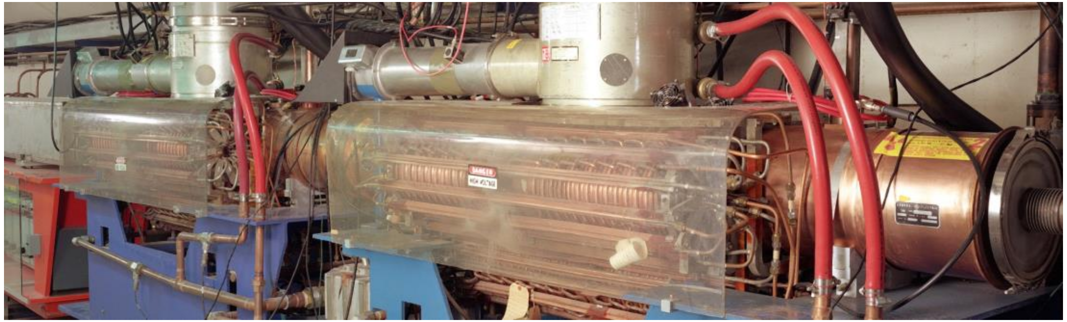
  η Cos (ϕ_s) < 0

  Phase jump at transition



https://cds.cern.ch/record/2674860/plots

Let’s look at the Fermilab Booster

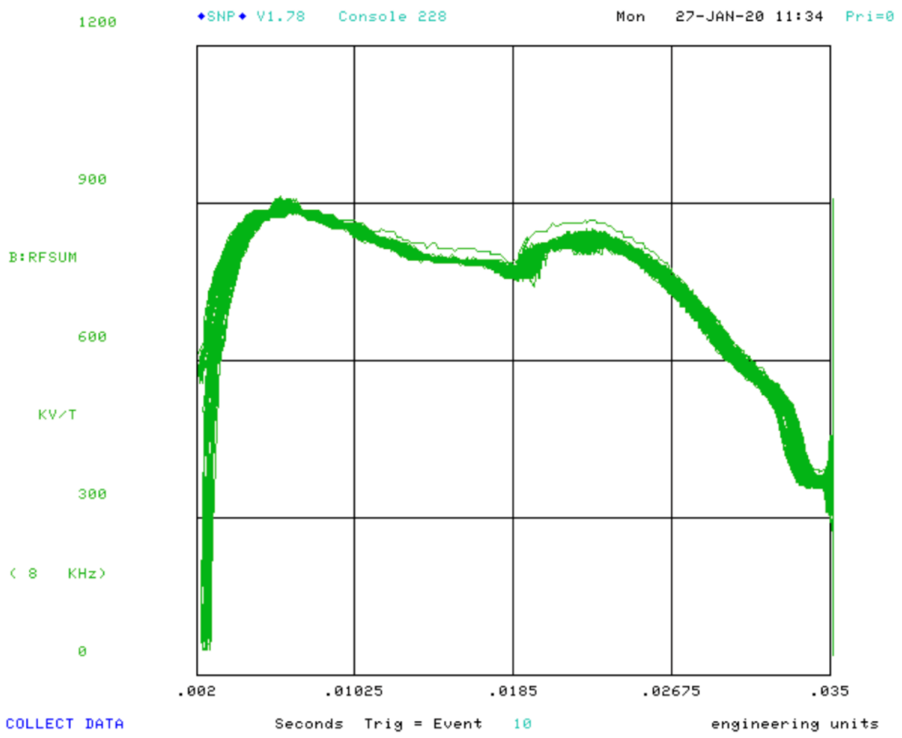


- Rapid Cycling Synchrotron
  - Resonant circuit for the magnet cycle
    - Sinusoid for magnetic field
  - 15 Hz
  - Injection Energy 400 MeV
  - Extraction Energy 8 GeV
  - Transition Energy 5.446 GeV

Booster Ring Parameters	Value	Unit
Circumference	474.20214	m
RF frequency at injection	37.867	MHz
RF Frequency at extraction	52.809	MHz
Harmonic number	84	-
Filled Booster buckets	81	-
Bucket length (injection)	26.408	ns
Bucket length (extraction)	18.935	ns
Maximum power loss (5 min avg)	500	W

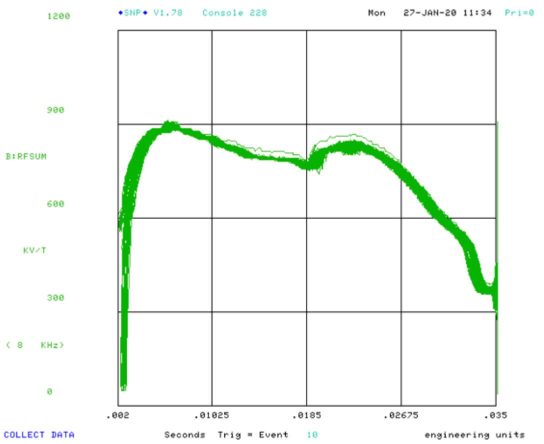
Booster RF Sum

- Why does the RF Sum voltage have this shape?
- What is peak required voltage?
- Booster magnets follow a sinusoid, so momentum does too
  - Would expect energy gain to have similar shape

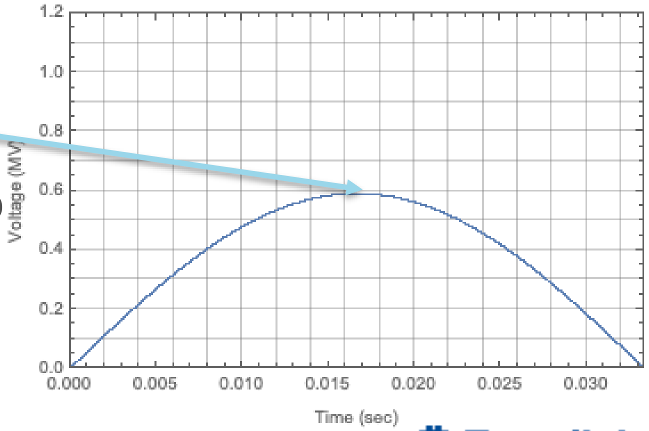


And Why does it have this shape?

- Necessary Energy gain per turn is directly related to pdot, which is directly related to Bdot

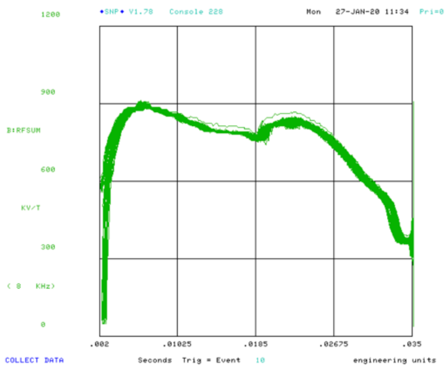


- For this exercise: $p(t) = (p_f - p_i)Cos(2\pi f_{ramp} t) + p_i$
  - p_i = 954.26 MeV/c (E_k = 400 MeV/c^2)
  - p_f = 8888.89 MeV/c (E_k = 8 GeV/c^2)
  - f_{ramp} = 15 Hz
  - Actually want Edot not pdot
    - Peak value is 595 kV at 16.67 msec
  - Accelerating voltage (V_{acc}) shape for a zero intensity zero emittance beam
    - Real bucket need to include the accelerating phase



$$V_{acc} = V_{rfsum} Sin(\phi_S)$$

Real Beams have emittance!



- Accelerating Bucket needs to capture all the beam
  - Bucket area which is a function of
    - Energy
    - V_{rfsum}
    - Accelerating Phase
  - If fix the bucket area, have 2 equation in 2 unknowns (V_{rfsum} and ϕ_s)

$$\text{Bucket Area} = 16\sqrt{\frac{\beta^2 \text{ E } V_{rfsum}}{2\pi\omega_0^2 \text{ h } |\eta|}}\, \alpha(Sin(\phi_S)) \qquad V_{acc} = V_{rfsum} Sin(\phi_S)$$

  - Nonlinear equation, used parameterization

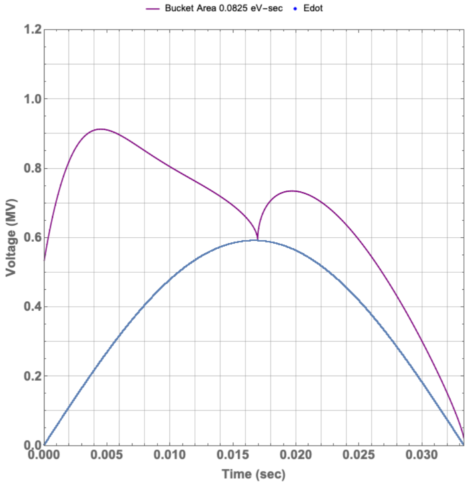
$$\alpha(x) = \frac{1-x}{(1+0.5x)^2}$$

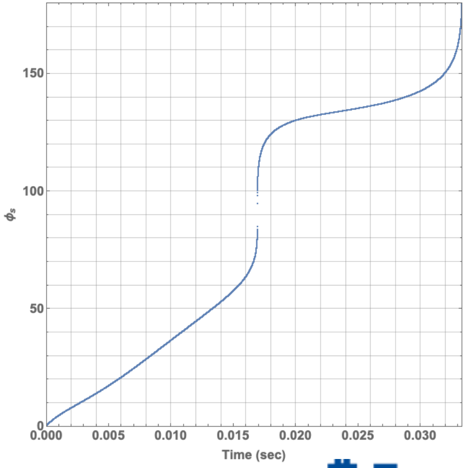
Nota Bene: This idea is not original to me! See S. C. Snowdon, Fermilab-TM-304, May 1971 for an earlier iteration of this same calculation

Including some measurement information

- Set the bucket area below transition
- Following Ostiguy & Lebedev(*), double the bucket area above transition
  - Effectively capture changes due to transition crossing
- Used Mathematica to do the root finding and solve for the accelerating phase and V_{rfsum}
- Getting closer
  - peak around 5 msec
  - Falls off to transition
  - Comes up again above transition

*J.-F. Ostiguy, *et al.*, "Modeling Longitudinal Dynamics in the Fermilab Booster Synchrotron", FERMILAB-CONF-16-162-AD, Proceedings of the 7th International Particle Accelerator Conference (IPAC2016): Busan, Korea May 8-13 2016. http://lss.fnal.gov/archive/2016/conf/fermilab-conf-16-162-ad.pdf





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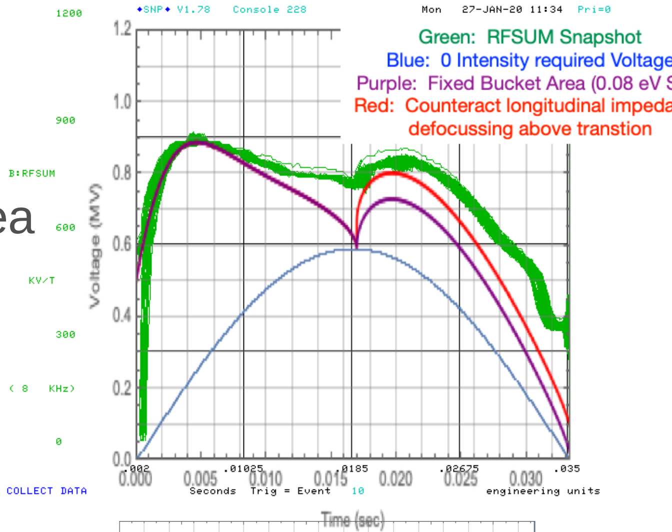

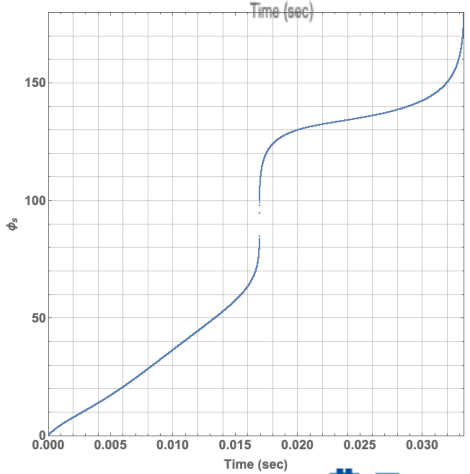

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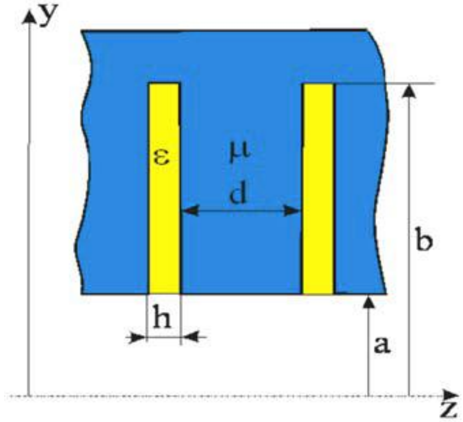
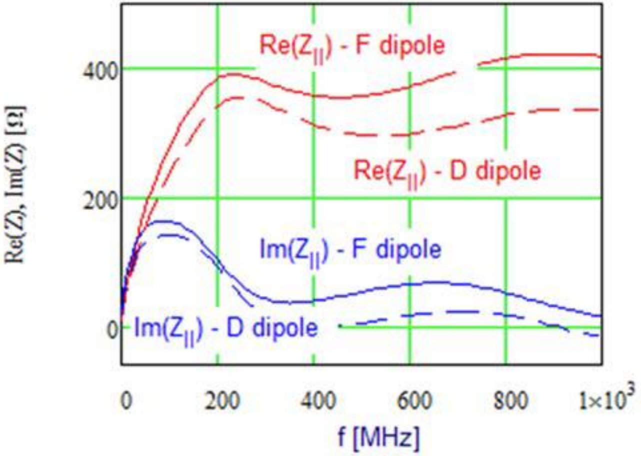
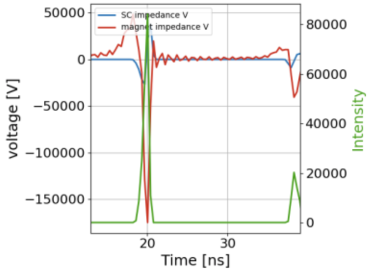
One more term : longitudinal impedance

- Booster magnets do not have a vacuum pipe – beam ‘sees’ the laminations
  - Frequency dependent impedance
  - Convolute the beam frequency spectrum with the impedance spectrum (so need a simulation of the beam!)
    - Generate a voltage – beam loses energy
    - More important as approach transition and time spread gets narrower



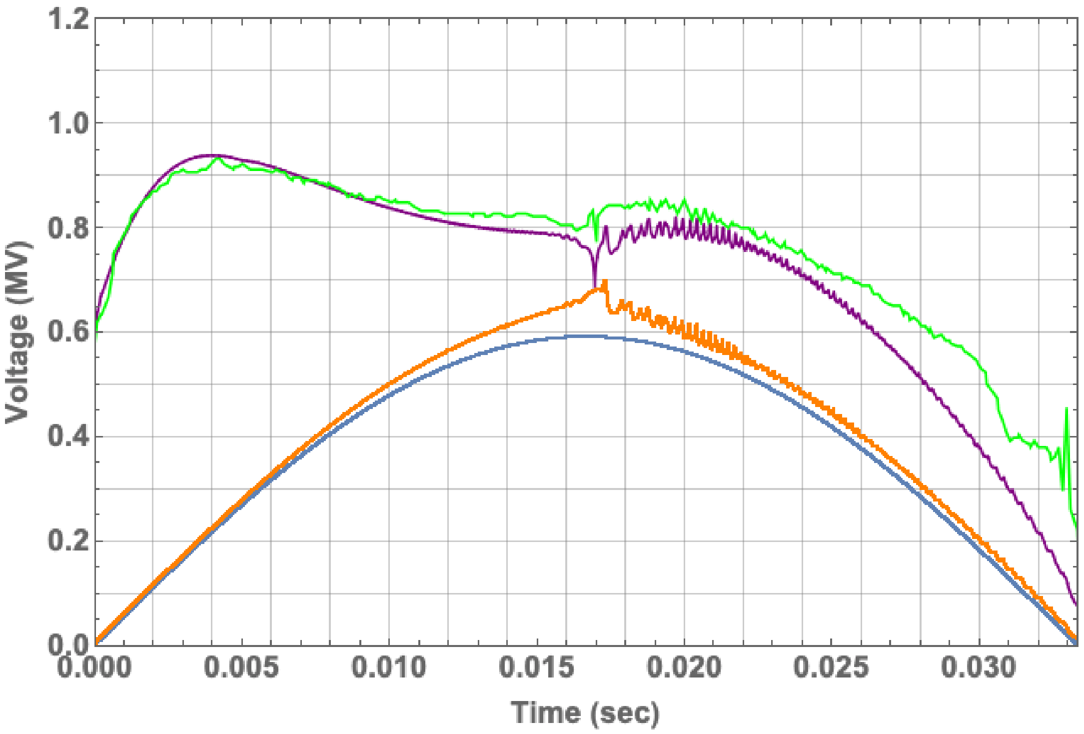




Fermilab

Adding in longitudinal impedance effects

- Green: RFSUM
- Blue: Energy gain/turn
- Orange: Energy gain/turn with impedance effects
- Purple : calculated RF voltage including impedance effects

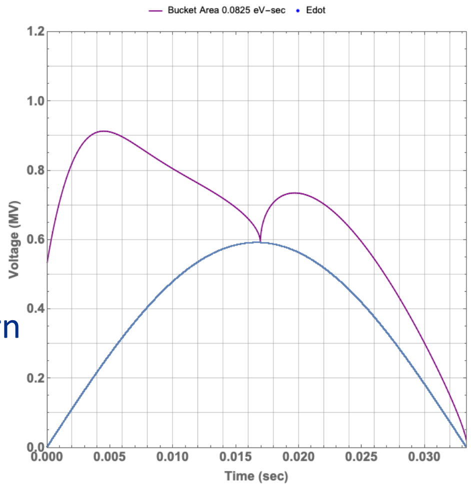


What does it mean operationally?

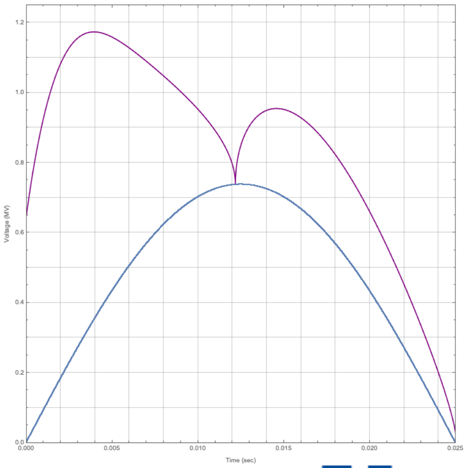
- Peak voltage (and power) requirements
  - Cavity requirements and design
  - Booster has 22 cavities – 20 in use
    - 50-55 kV across the gap

- PIP-II (new SRF Linac) operations
  - New science requirements
    - Change from 15 Hz -> 20 Hz
    - Increase Booster current by 50%
  - Higher voltage and Higher power
  - 6 New Cavities
    - 60-65 kV across the gap

Current Operations:
15 Hz
Peak Edot ~595 kV/turn
~920 kV

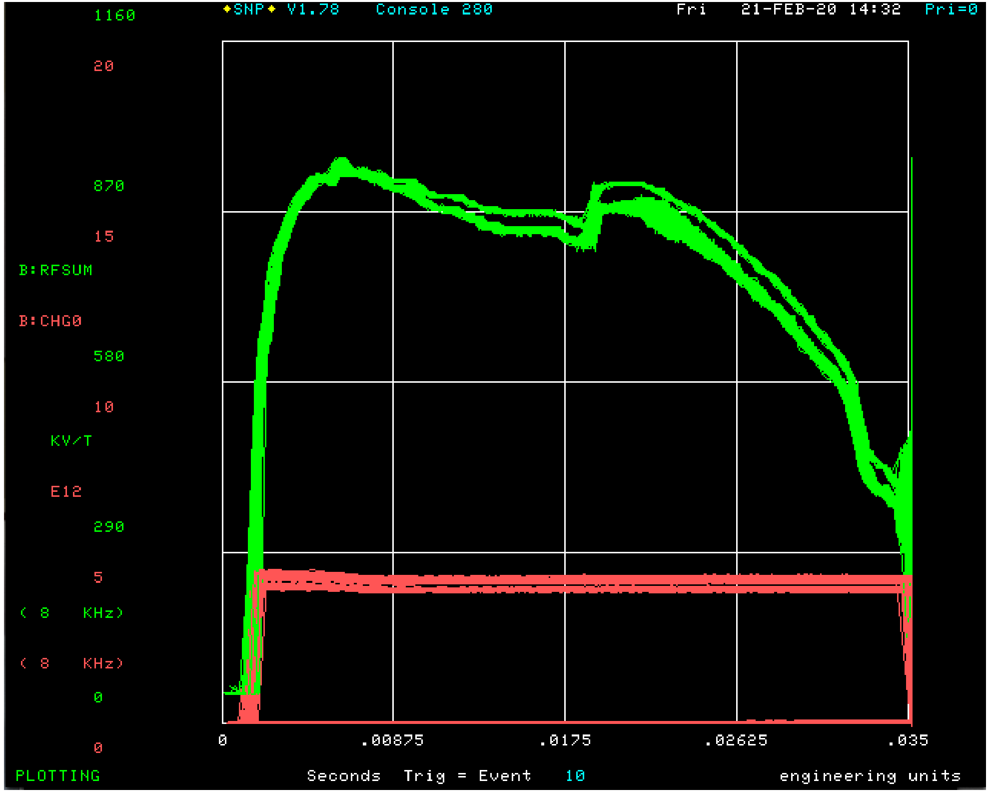


Future Operations:
20 Hz
Peak Edot ~740 kV/turn
~1170 kV



Another interesting phenomena -- Beam loading!

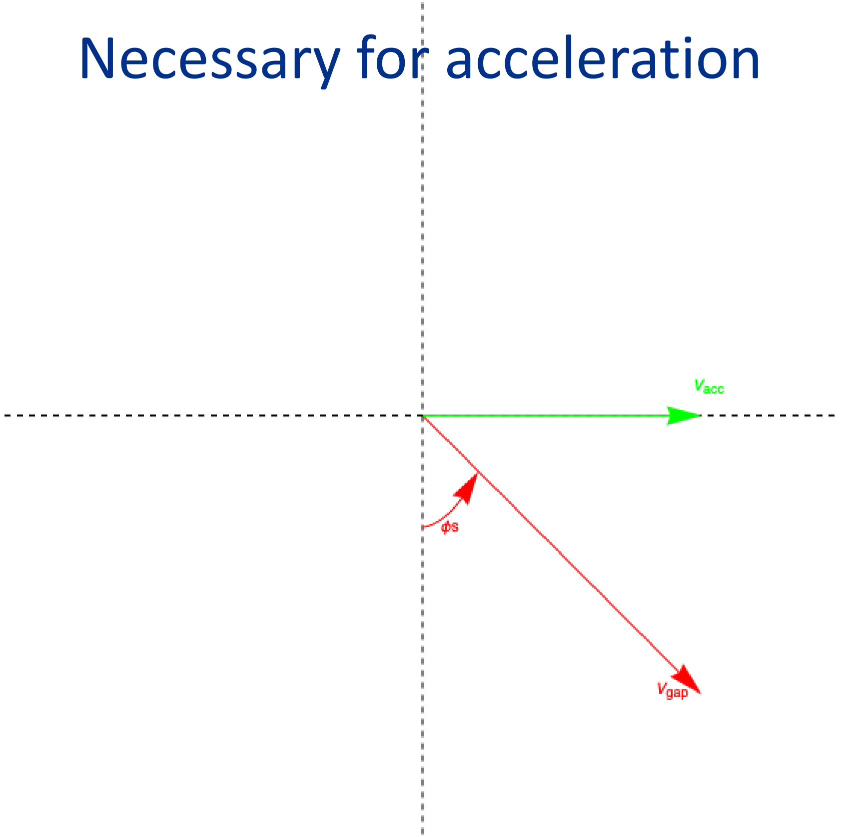
- Outlier traces
- Was on the SY cycle
  - Intensity down by factor of 6
  - Voltage up by 40 kV
- Beam Loading
  - Beam is a current source
  - RF Cavity is also an impedance!
- RFSUM is measured gap voltage
  - up to phase and calibration between the cavities



Phasor Diagram

- Conventions from FNAL TM-1915 for the phasor diagram
  - Accelerating voltage is +x
  - $V_{acc} = V_{gap}\ \mathrm{Sin}(\phi s)$

Necessary for acceleration



- Drawn below transition as $\phi_s < 90$
- Max effect at transition ($\phi_s = 90$)

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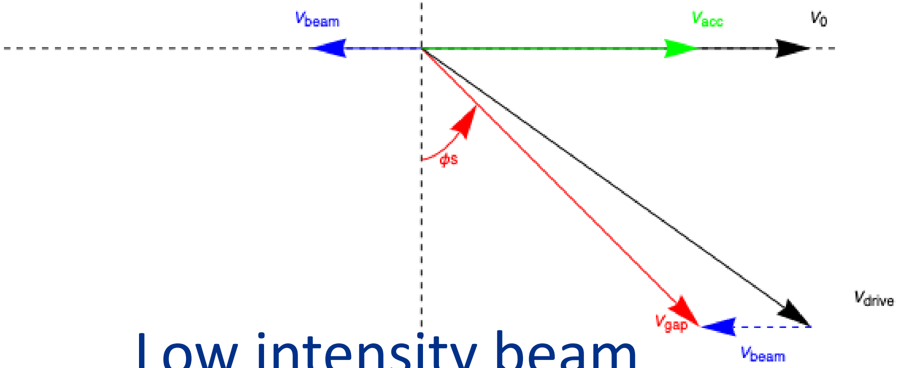
Phasor Diagram

- Conventions from FNAL TM-1915 for the phasor diagram
  - Accelerating voltage is +x
  - $V_{acc} = V_{gap}\ \mathrm{Sin}(\phi s)$
  - Beam loading is –x

  - Beam loading
    - $V_{beam} = i_b R_{shunt}$
    - i_b ~ 2x beam current (Fourier component)
    - $R_{shunt} = 60\ k\Omega$
- Drawn below transition as $\phi_s < 90$
- Max effect at transition ($\phi_s = 90$)

Compensating by increasing the drive voltage

NOT TO SCALE



Low intensity beam case have V_0 not V_{acc}

Phasor Diagram

- Conventions from FNAL TM-1915 for the phasor diagram
  - Accelerating voltage is +x
  - $V_{acc} = V_{gap}$ Sin(ϕs)
  - Beam loading is –x

  - Beam loading
    - $V_{beam} = i_b R_{shunt}$
    - i_b ~ 2x beam current (Fourier component)
    - R_{shunt} = 60 kΩ

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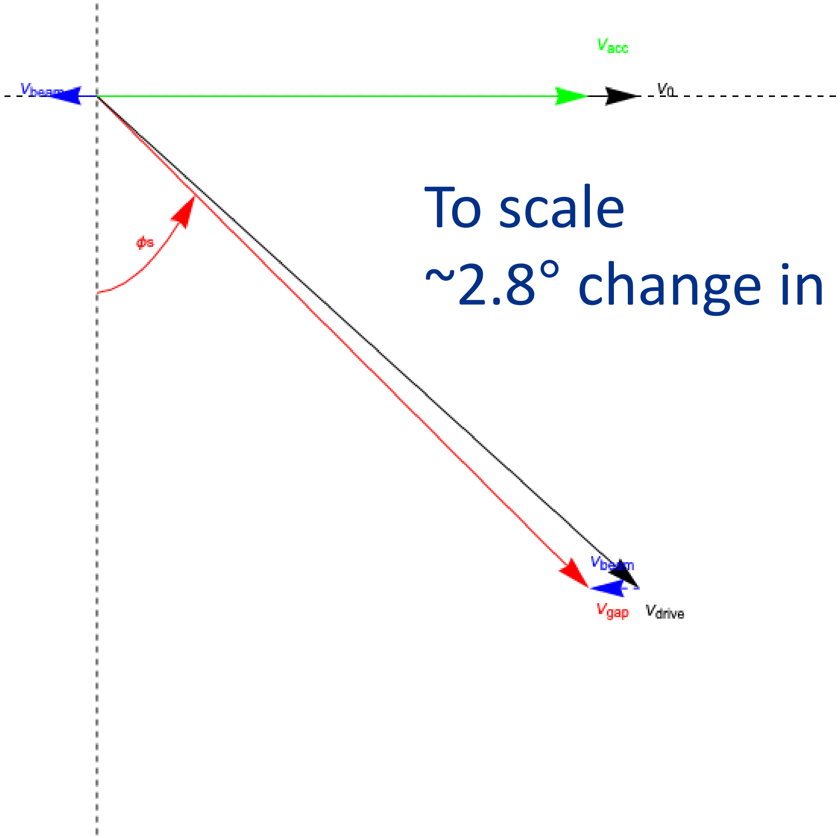
- Max effect at transition ($\phi_s = 90$)



To scale

~2.8° change in ϕ_s

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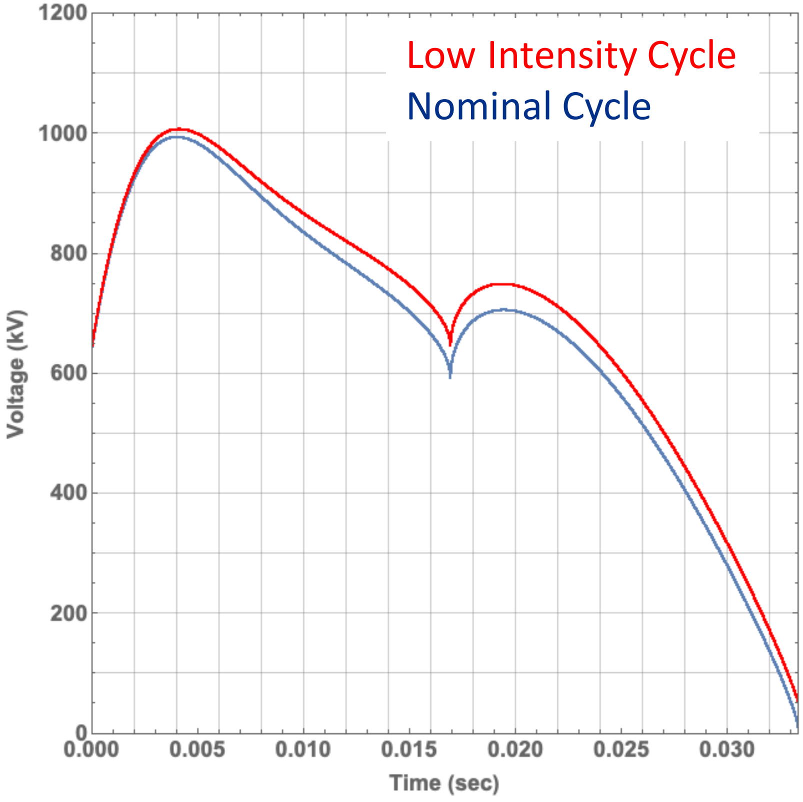
Calculate the effects

- Not doing active compensation
  - Have fixed voltage curve (up to feedback loops)
- Assume that have tuned RF curves for the NuMI and BNB cycles
  - So that energy gain (V_{acc}) matches the Bdot
- SY cycles have lower intensity
  - V_{beam} is smaller, so gap voltage is larger
- Calculated V_{gap} under these assumptions



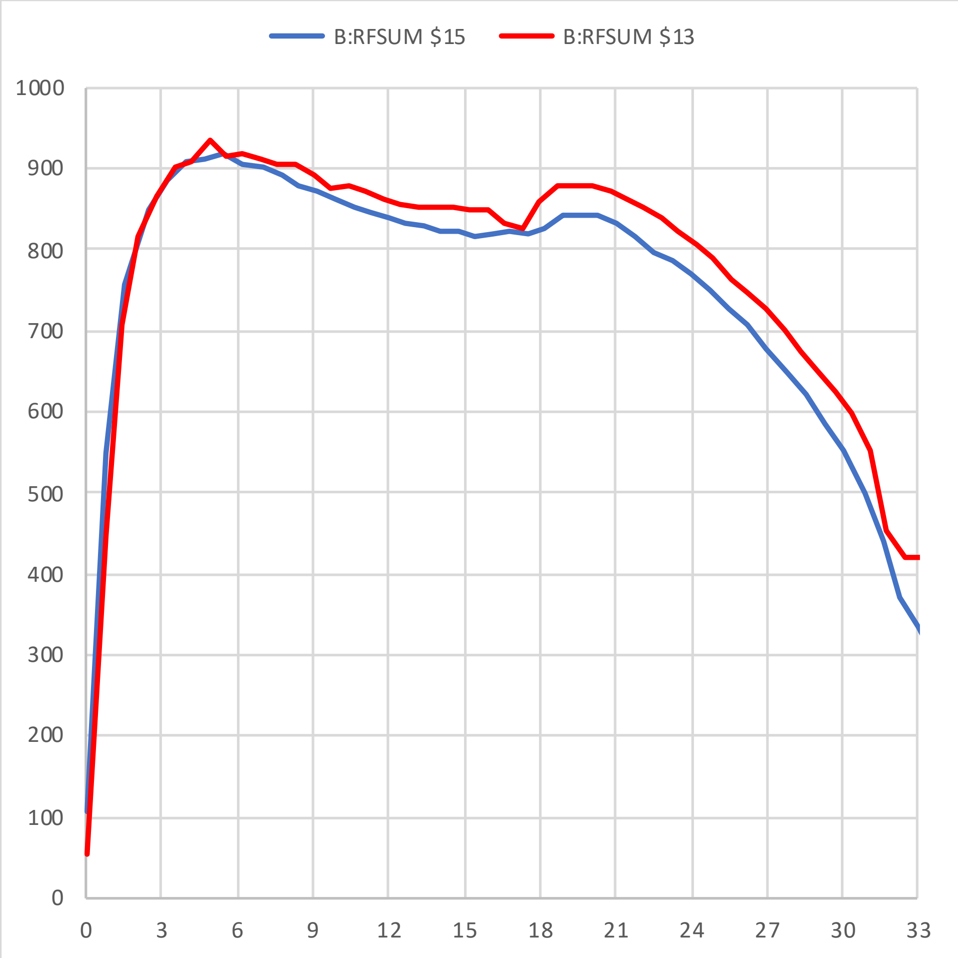
Fermilab

Observations

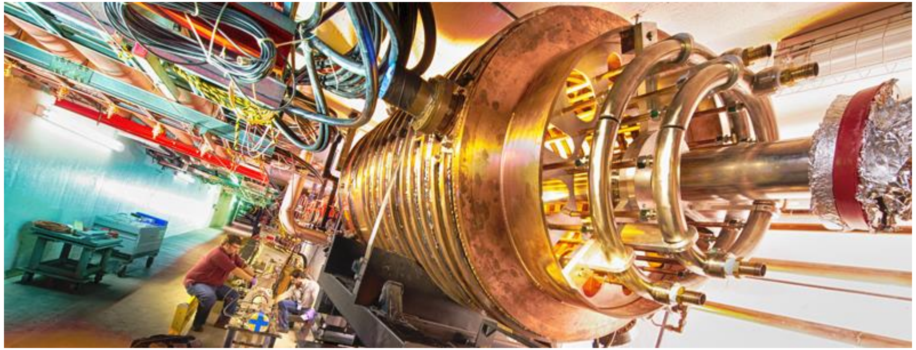
- Averaged over 20 pulses
  - Couple seconds on $15
  - 20 minutes on $13

- Change in shape looks like prediction!

- As in most situations, areas of beam stability
  - Robinson Instability
    - Single bunch dipole mode oscillation
    - Intensity dependent
  - 50% current increase in PIP-II era
    - Need to account

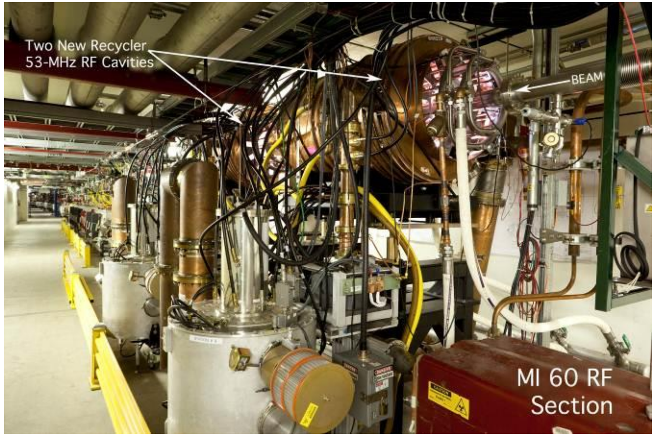


Let's look at the Fermilab Recycler



- Permanent Magnet Synchrotron
  - Fixed field
  - Gradient magnets
  - Energy 8 GeV
  - Transition Energy 21 GeV

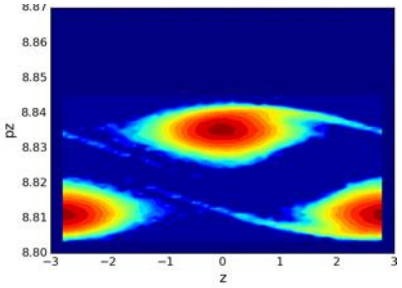
Recycler Ring Parameters	Value	Unit
Circumference	3319.4	m
Center RF frequency	52.809	MHz
ΔRF Frequency	1260	Hz
Harmonic number	588	-

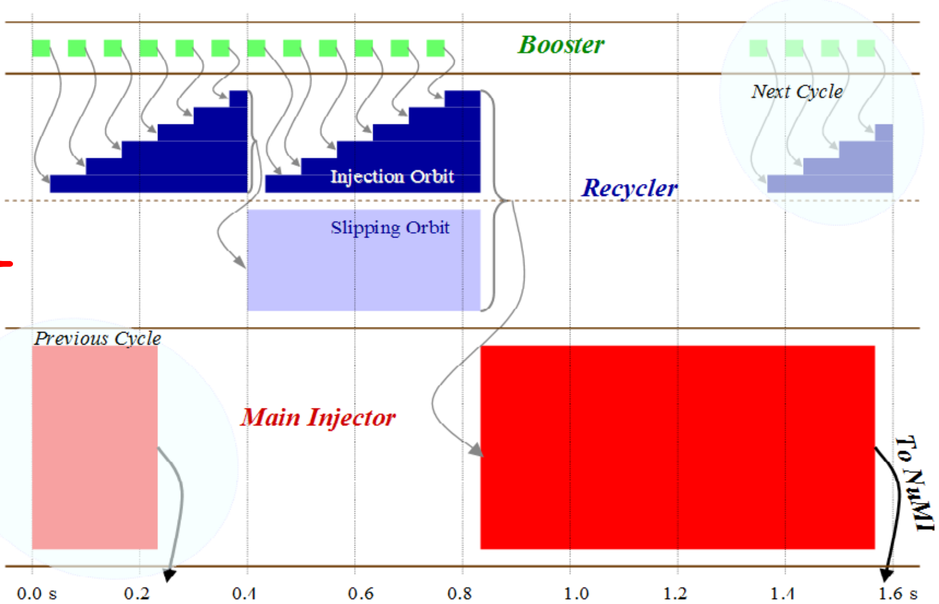


Slip Stacking for Intensity Increases

- The 15 Hz Booster injects 12 “batches” into the Recycler
- These are then transferred to the Main Injector, which accelerates and extracts them them as the loading process repeats in the Recycler
- Inherently a ’lossy’ process
- Clean kicker gaps important to minimize uncontrolled losses

“slip-stacking” cleverly gets around limits on Booster batch size by allowing two batches to “slip” together, doubling the number of protons in each MI cycle





Slip Stacking process

Pictures and simulations from J. Eldred
Slip-stacking Dynamics for High-Power Proton Beams at Fermilab
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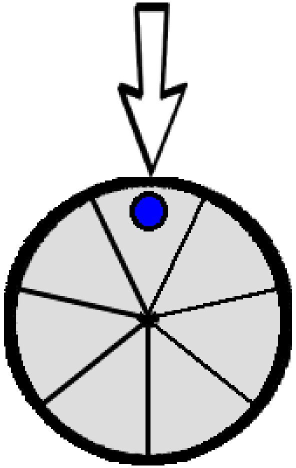
- A batch is injected from the Booster into 1/7 of the Recycler.



Slip Stacking process

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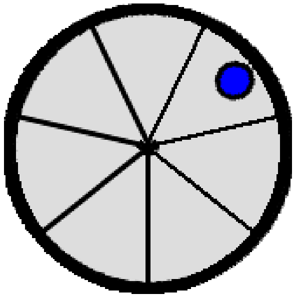
- The first batch is stored in the Recycler while the second batch is prepared in the Booster.



Slip Stacking process

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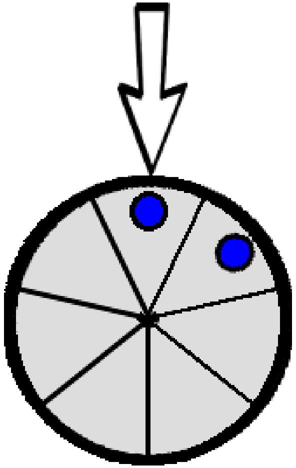
- The timing works out so that the second batch is injected immediately behind the first.
- Called Boxcar Stacking



Slip Stacking process

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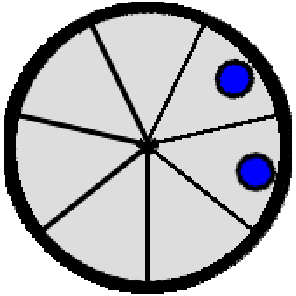
- Now two batches are stored...



Slip Stacking process

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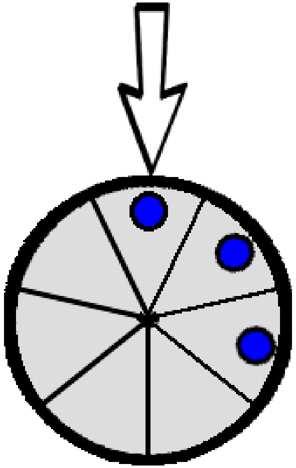
- And a third batch is injected…



Slip Stacking process

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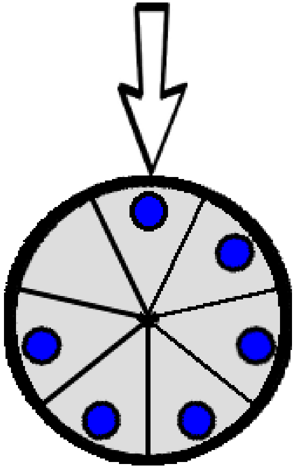
- This process repeats until 6/7 of the Recycler is filled.



Slip Stacking process

Pictures and simulations from J. Eldred
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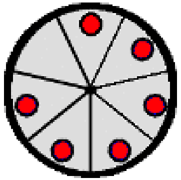
- The RF cavity is gradually lowered in frequency so that these 6 batches are now in a lower momentum orbit.



Slip Stacking process

Pictures and simulations from J. Eldred
Slip-stacking Dynamics for High-Power Proton Beams at Fermilab
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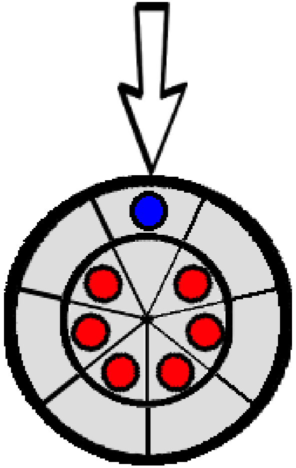
- The seventh batch can be injected in that 1/7 gap without kicking out any beam.
- Two RF cavities at different frequencies: Slip-stacking



Slip Stacking process

Pictures and simulations from J. Eldred
Slip-stacking Dynamics for High-Power Proton Beams at Fermilab
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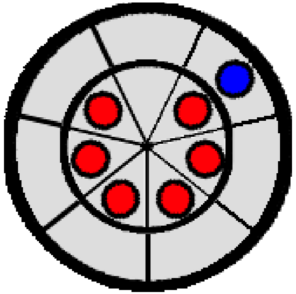
- The batches slip past each other and can occupy the same azimuthal space.
- Because the shifted batch is slower, the gap lines up again for the next injection.



Slip Stacking process

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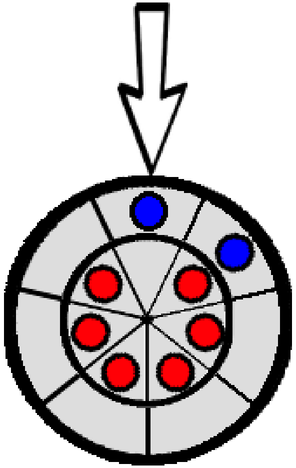
- The eighth batch is injected immediately behind the seventh batch without kicking out the first six.



Slip Stacking process

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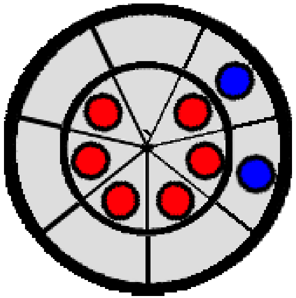
- Those batches can be stored and slipped as well.



Slip Stacking process

Pictures and simulations from J. Eldred
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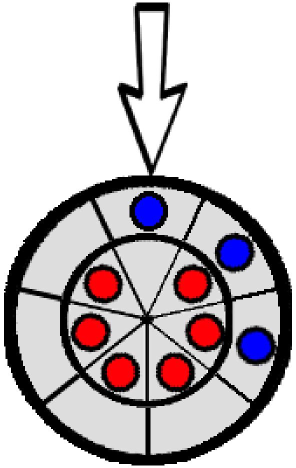
- And the ninth injection can proceed smoothly.



Slip Stacking process

Pictures and simulations from J. Eldred
Slip-stacking Dynamics for High-Power Proton Beams at Fermilab
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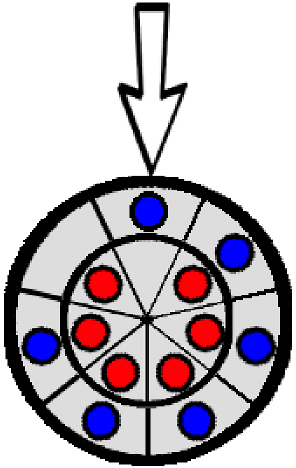
Indiana University 2015

- The process continues until there are a total of twelve batches, six in each momentum orbit.



Slip Stacking process

Pictures and simulations from J. Eldred
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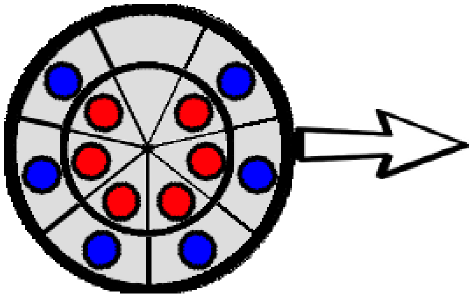
- All batches are ejected to the Main Injector.
- The Recycler can begin to fill again while the MI ramps.
- The extra 1/7 azimuthal space is used for the kicker.



Single-RF Dynamics:

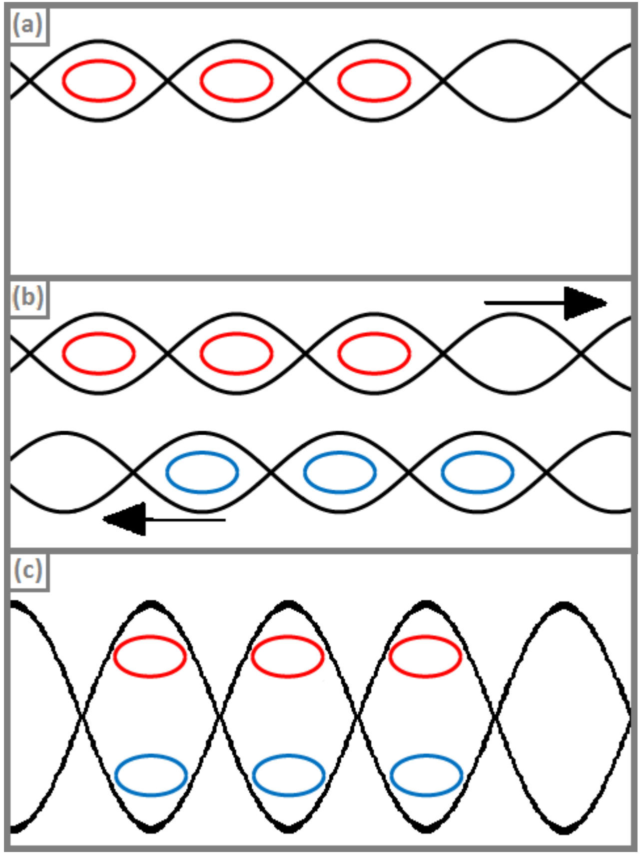
$$\ddot{\phi} = -\omega_s^2 \sin\phi$$

Slip-stacking Beams:

$$\ddot{\phi} = -\omega_s^2[\sin\phi + \sin(\phi + \omega_\phi t)]$$

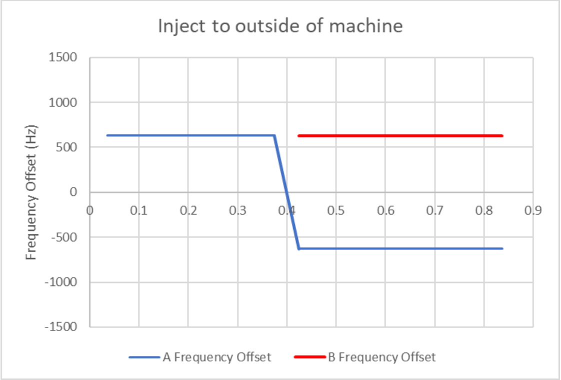
Captured Beams:

$$\ddot{\phi} = -6\omega_s^2 \sin\left(\phi + \frac{\omega_\phi}{2}t\right)$$

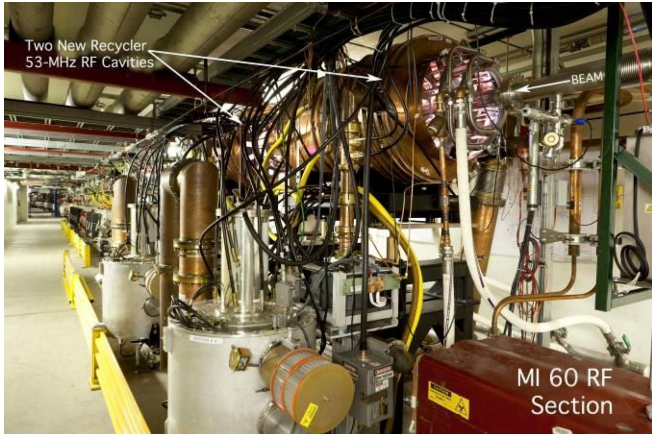


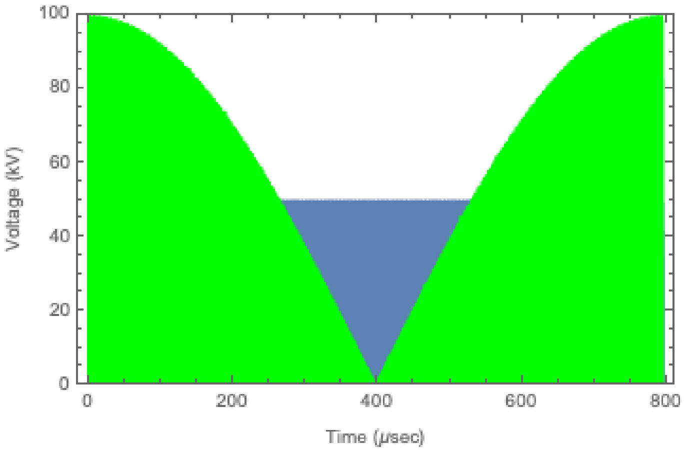
Think of them as independent kicks and frequency

- But they are really not
  - Beam sees the superposition of the two frequencies
  - Beat against each other @1260 Hz
  - Leads to complicated phase space results



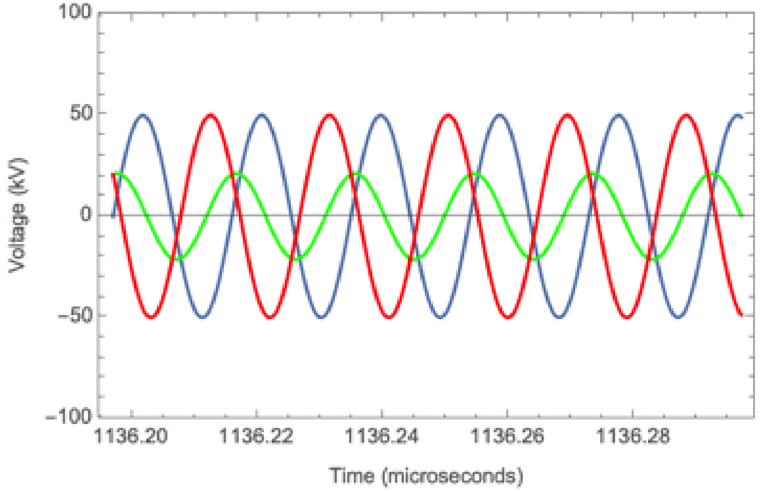
$$V(t) = V_1 \sin(2\pi(f_0 + A_{offset})t) + V_2 \sin(2\pi(f_0 + B_{offset})t)$$

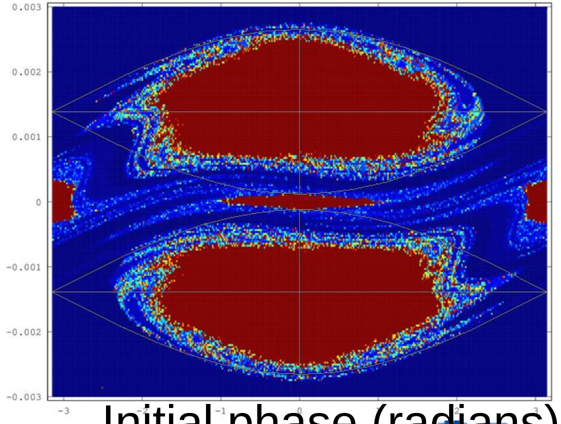




Frequency Beat in Slip Stacking

- Frequency + A_offset
  - 52.809 MHz – 1260 Hz
- Frequency 2 + B_offset
  - 52.809 MHz
- Sum Frequency 1 + 2
  - Beat Frequency
  - 1260 Hz around 52.809
- Leads to complicated phase space results
  - Beam slipping out of the ‘buckets’
  - Some captured, some not when transferred to Main Injector
    - Not captured -> Beam Loss





J. Eldred, Slip-stacking Dynamics for High-Power Proton Beams at Fermilab
FERMILAB-THESIS-2015-31
Indiana University 2015

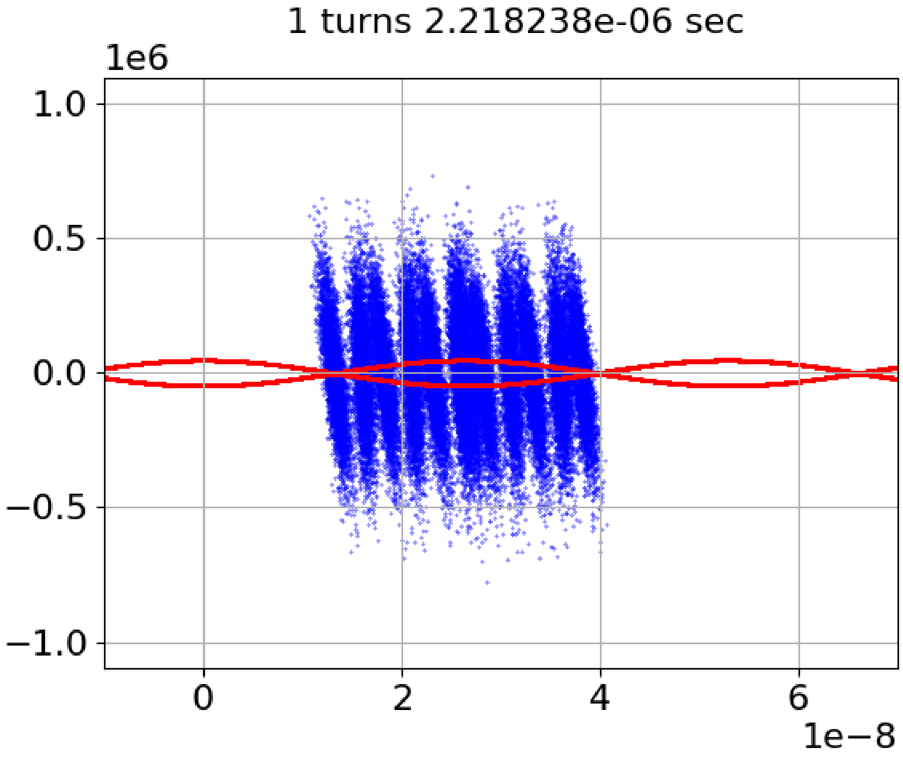
Summary

- RF Dynamics in synchrotrons are lots of fun
  - While known problems
    - Transition crossing
    - Beam Loading
    - Single and Multi bunch instabilities
  - Every machine is unique and has its own manifestation of the problems
- Spoke today to some of the things we see in the Fermilab Booster and Recycler
  - Lots more of interest coming
    - PIP-II Linac 50% more intensity
    - Different injection scheme

Injection Model

Adjustable parameter in model

- 201.25 MHz Linac beam
  - Bigaussian
    - σ(dE) = 0.4e6 eV
    - σ(dt) = 530 psec
    - from Chandra's PSP presentation July 2 2020
  - Multi-turn injection
    - 15 turns
    - PPB = 4.5e12/81/15 = 3.7e9
    - 1-81 bunches



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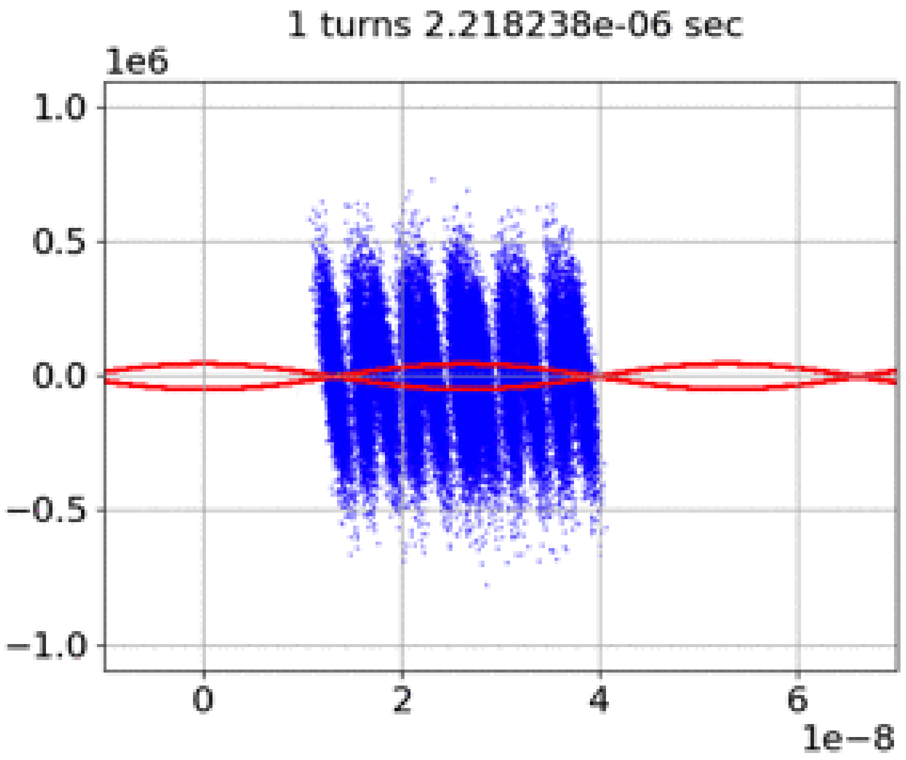
- 75 turns capture in 500 kV



Fermilab

Injection Model

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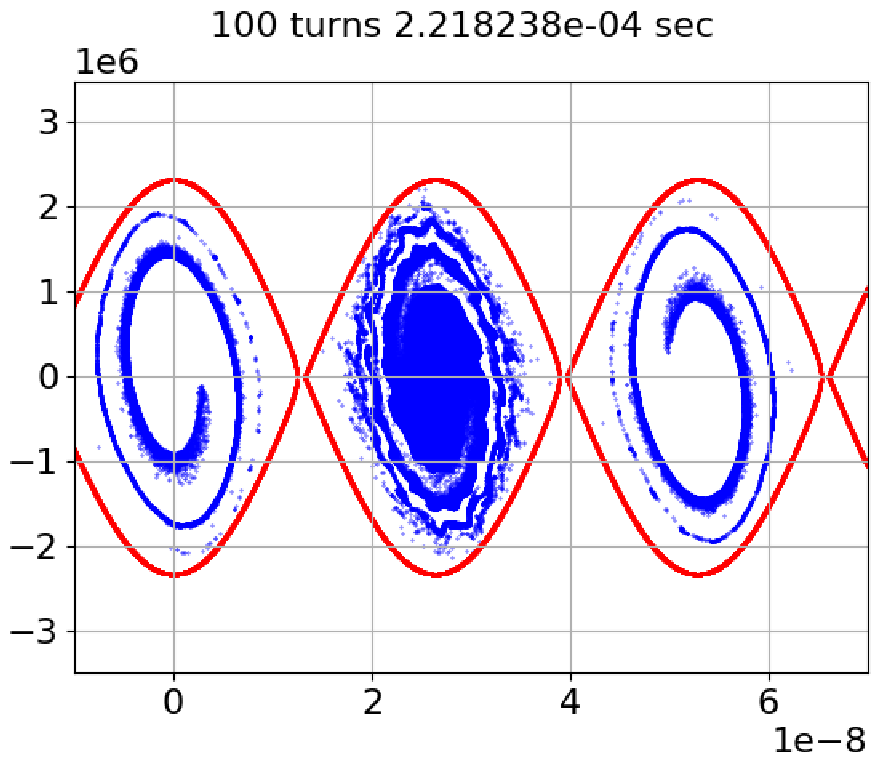
    - 15 turns
    - PPB = 4.5e12/81/15 = 3.7e9
    - 1-81 bunches
- 75 turns capture in 500 kV
- RMS Longitudinal emittance in B1 after 100 turns: 0.006 eV-sec



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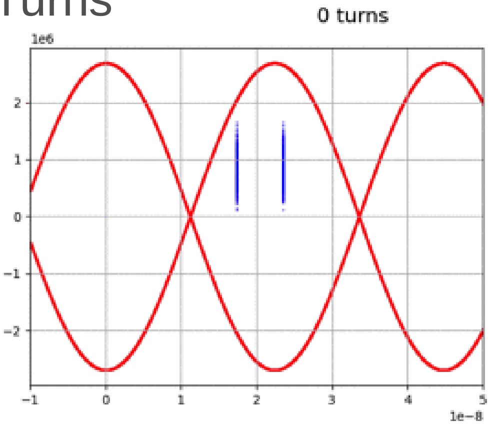
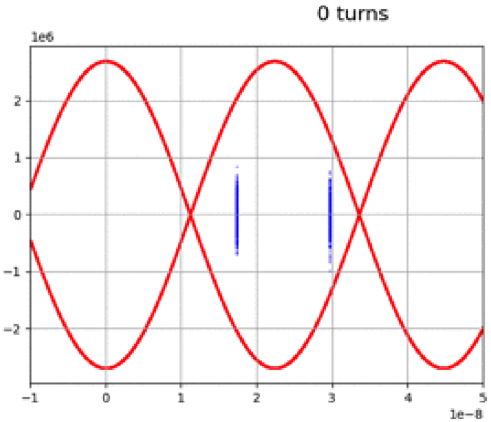
PIP-II Injection

Injection Model

- 162.5 MHz Linac 44.7 MHz Booster
  - Align them at T=0
  - Select Linac buckets that fit in Booster Bucket
    - Off Energy: $0 < |\phi| < 0.55\pi$
    - On Energy: $0.15\pi < |\phi| < 0.7\pi$
    - Variables: Energy Width, Energy Jitter, Extinction Fraction
- 292 Turns
- Space Charge based on circular beam pipe
  - Changes were within statistical variations
- Remaining simulations no SC



Red : Separatrix
Blue: Injected beam
No RF tracking to show where full buckets land



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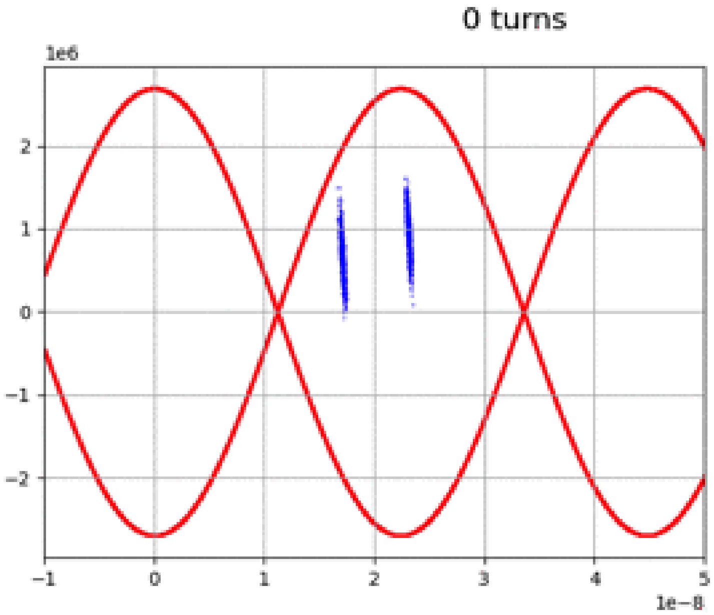
Injection Parameters

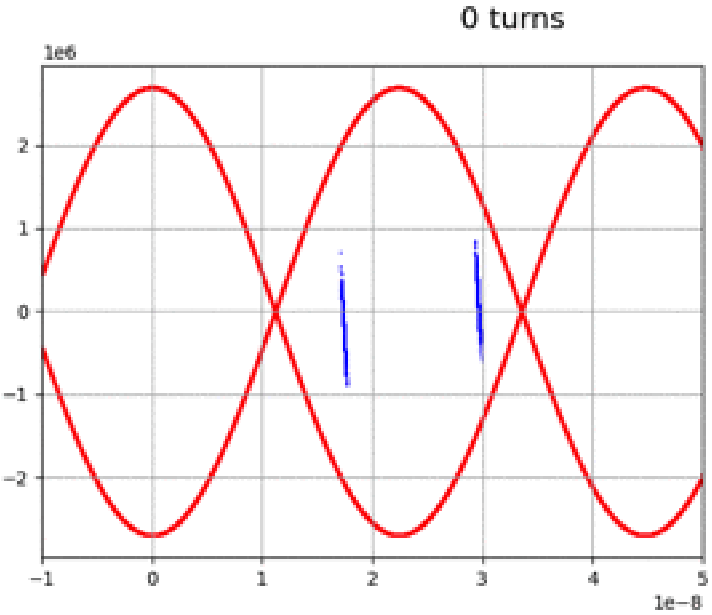
- From various project requirement documents:

Variable	Value	Unit	Reference
Linac Energy (kinetic)	800	MeV	PIP-II Parameters PRD [6]
Energy Spread (σ)	0.24	MeV	PIP-II Parameters PRD [6]
Time Width (σ)	76.9	psec	PIP-II Parameters PRD [6]
Linac Momentum $\frac{dp}{p}$ Jitter	1×10^{-4}		PIP-II Booster PRD [7]
Booster GMPS stability $\frac{dp}{p}$ Jitter	2.5×10^{-4}		PIP-II Booster PRD [7]
Linac Phase Jitter (σ)	0.073	psec	PIP-II Linac RF PRD [8]
Linac Bunch Population	1.4×10^{8}	ppb	PIP-II Booster PRD [7]
Booster - Linac Energy Offset	0	MeV	PIP-II Booster PRD [7]
ϕ range in Booster Bucket	$[-0.55\pi, 0.55\pi]$	radians	On Axis Scheme [9]
Extinction Fraction	1×10^{-3}		PIP-II Booster PRD [7]
Booster Bucket Area	0.077	eV-sec	PIP-IIBooster PRD [1]

Injection Example   Nominal Bunch Parameters

Perfect match   Perfect extinction





Bucket is full almost to edge

Bunching Factor = Peak / Average

Energy: 1.8

Time: 2.7 (off), 2.5 (on)

Efficiency Calculation and Power loss

- Injection Efficiency is defined as:

$$\frac{\text{Number of MacroParticles within the separatrix}}{\text{Number of MacroParticles injected}}$$

- Power loss is defined as:

  Power loss = (1-Injection Efficiency) * 17.6 kW

  2 mA * 800 MeV * 20 Hz * 550 μsec = 17.6 kW

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Energy Jitter

- Vary Energy match of Linac to Booster
  - Pulse to pulse variation

Model	Energy Jitter (10^{-4})	Beam Loss (10^{-4})	Power Loss (W)
Off Axis	0	0.2106 ± 0.0065	0.37
Off Axis	0.5	0.2396 ± 0.0178	0.42
Off Axis	1	0.3315 ± 0.0421	0.58
Off Axis	1.5	0.9764 ± 0.3231	1.72
Off Axis	2	1.2348 ± 0.2824	2.17
Off Axis	2.5	3.6176 ± 0.9957	6.37
Off Axis	3	4.4711 ± 1.4385	7.87

Off axis -> Central Linac momentum offset by 7×10^{-4} $^{dp}/_{p}$ from Central Booster Momentum

On axis -> Central Linac momentum equal to Central Booster Momentum

Model	Energy Jitter (10^{-4})	Beam Loss (10^{-4})	Power Loss (W)
On Axis	0	0.0014 ± 0.0005	0.00
On Axis	0.5	0.0017 ± 0.0005	0.00
On Axis	1	0.0055 ± 0.0025	0.01
On Axis	1.5	0.0050 ± 0.0010	0.01
On Axis	2	0.0297 ± 0.0098	0.05
On Axis	2.5	0.0679 ± 0.0235	0.12
On Axis	3	0.4163 ± 0.2064	0.73

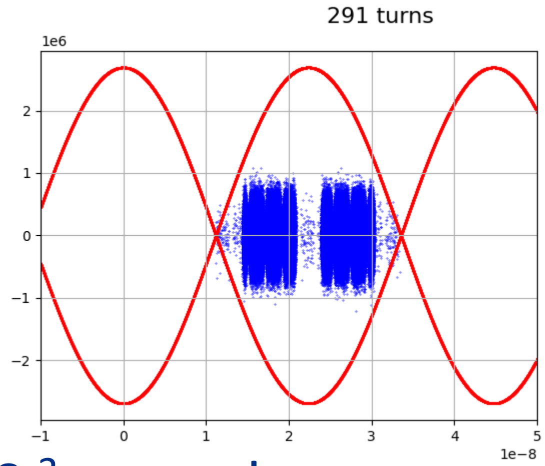
Extinction Fraction

- Extinction fraction defined as

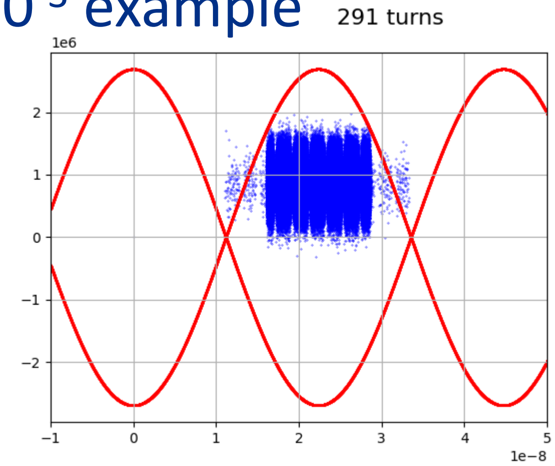
$$\frac{\text{Population chopped bunch}}{\text{Population normal bunch}}$$

Model	Extinction (10^{-3})	Beam Loss (10^{-4})	Power Loss (W)
On Axis	1	1.1573 ± 0.0086	2.04
On Axis	3	3.4916 ± 0.0173	6.15
On Axis	5	5.7350 ± 0.0221	10.09
On Axis	7	8.0758 ± 0.0250	14.21
On Axis	9	10.4096 ± 0.0253	18.32
Off Axis	1	4.0420 ± 0.0122	7.11
Off Axis	3	11.7249 ± 0.0217	20.64
Off Axis	5	19.4137 ± 0.0297	34.17
Off Axis	7	27.1148 ± 0.0333	47.72
Off Axis	9	34.6260 ± 0.0345	60.94

- PIP2IT (pip2-docdb #5373)
  - 0 + 3 x 10^{-3} for Booster mode (RMS?)

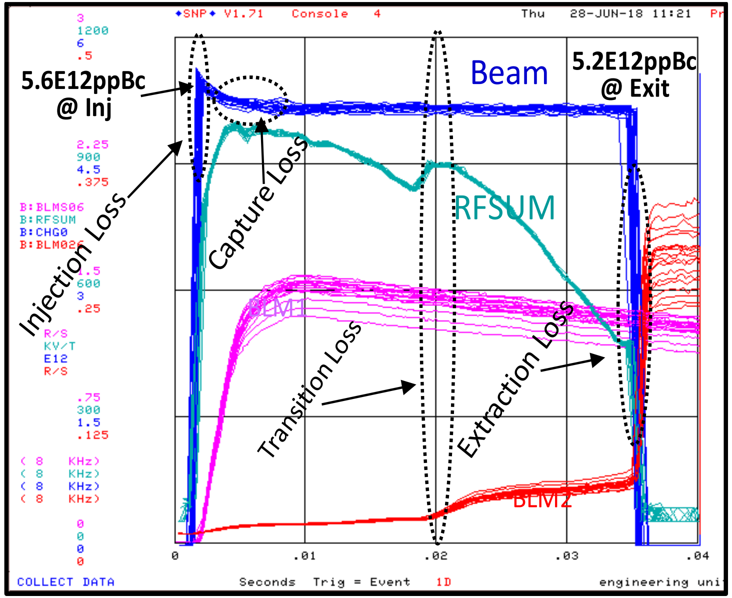


10^{-3} example



Booster Challenges – remember I said it was all about losses

- Losses in Booster
  - During transition crossing (gamma = 5.45)
    - Implementing Q-jump or γt-jump system
    - LLRF improvements for transition crossing
- Beam loading compensation is required
  - Beam current increases by 50% from PIP to PIPII.
    - Calculations show beam will be Robinson unstable above 2 GeV.
    - In-house developed LLRF ARRIA board to be used.



Present: Beam in Booster for 33 ms.
PIPII: Beam in Booster for 25 ms

Note:legacy RF cavities operate at a maximum voltage of 50 kV aperture 2.25”. Wide bore RF cavities operate at voltage of 60 kV (tested), aperture 3.25”.

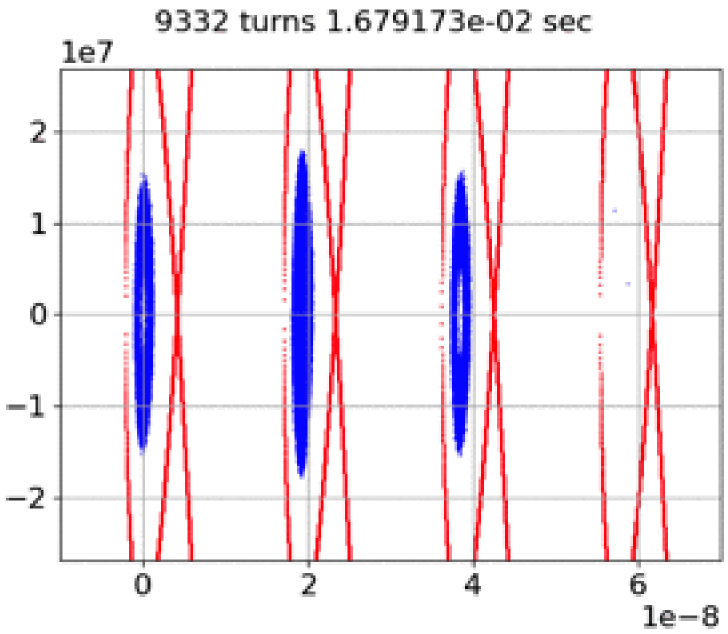
Transition Crossing

- γ_t = ?
  - Valeri has used 5.446 (FERMILAB-CONF-16-162-AD)
  - Chandra has used 5.4782
  - For this exercise, matched in ramp to ESME values

- Single turn ϕ jump (ϕ_s -> $\pi - \phi_s$)
  - Turn 9581

- No dampers

±250 turns around transition



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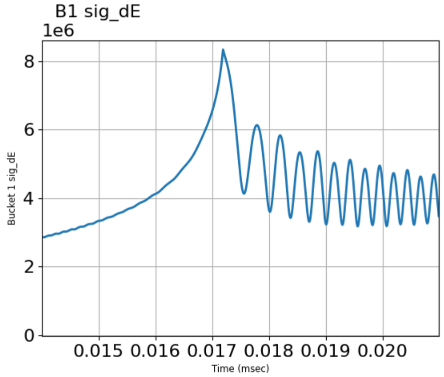
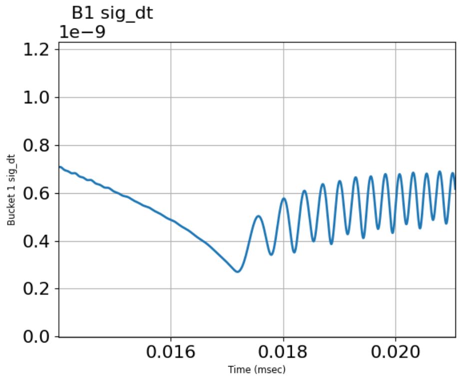
  - For this exercise, matched in ramp to ESME values

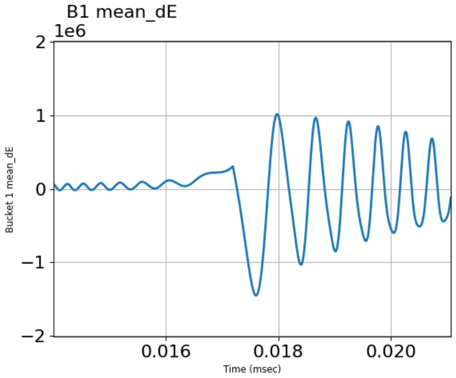


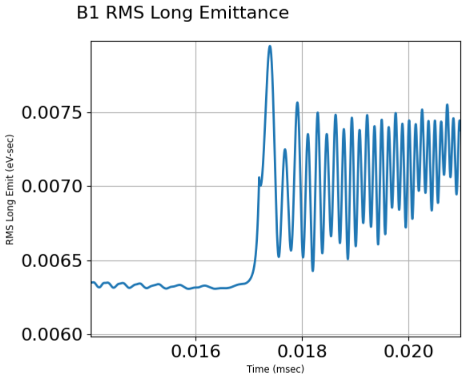


- Single turn ϕ jump (ϕ_s -> $\pi - \phi_s$)
  - Turn 9581

- No dampers

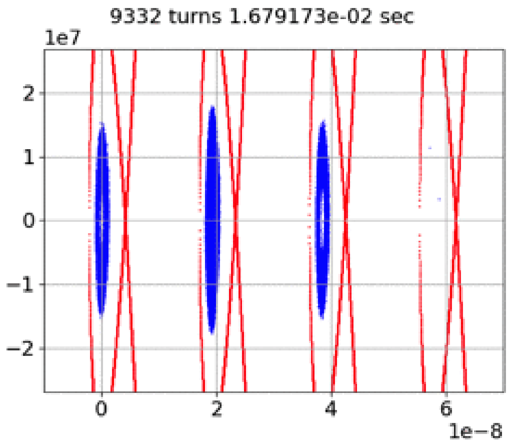
- RMS Long Emittance increases ~15%

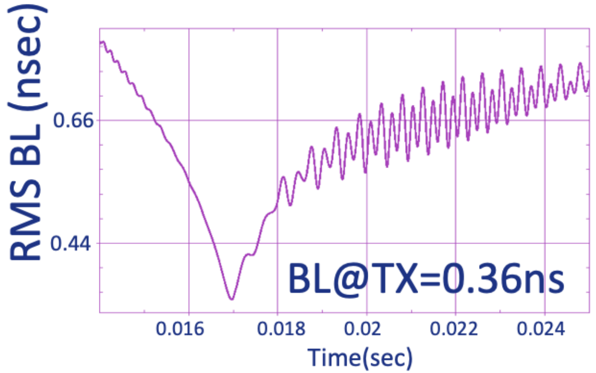




Transition crossing simulation

- At turn 9580
- Phase jump from ϕ_s to $\pi - \phi_s$
  - Stability $\eta \cos \phi_s < 0$!
  - Energy spread means beam crosses transition on different turns
  - If not matched . . . Quadrupole oscillations
  - Booster at 5.4 GeV, MI at 21 GeV
    - Higher energy more impact on total power loss





Fermilab