Lecture 5

Special Techniques in Beam Handling

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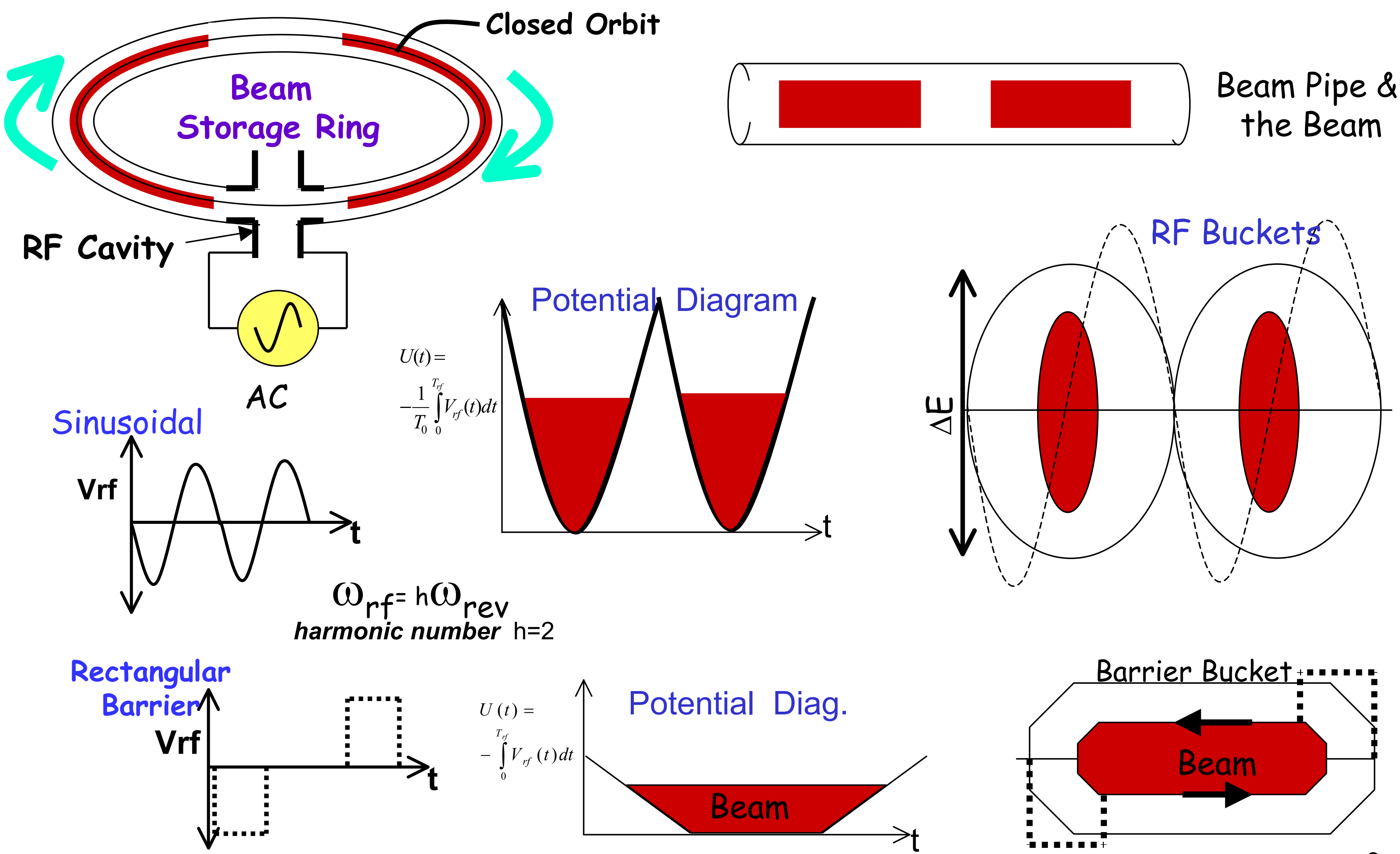
Lectures at RRCAT, Indore, India
http://www-ap.fnal.gov/users/cbhat/

Adiabatic Bunching/Debunching with an RF system

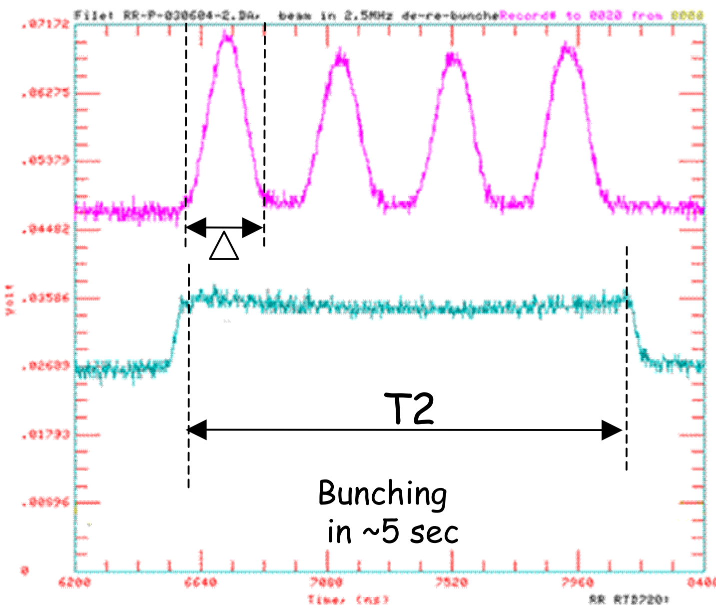
Bunched Beam with Energy $E_0 \pm \Delta E$



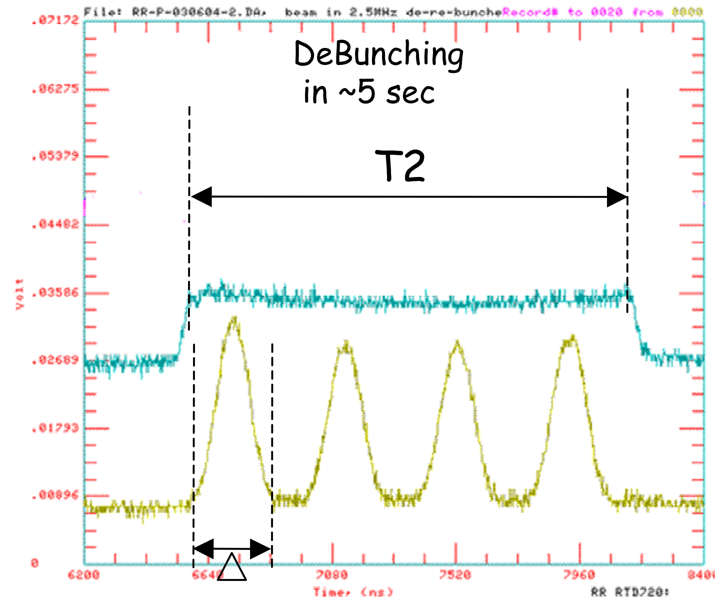
Adiabatic Bunching/Debunching (cont.)

Experimental Data

Beam bunching



Beam debunching



Bunched Beam

$$LE = \sqrt{32}\,\frac{V_0 R_s^{\,2} E_s}{2\pi h^3 c^2 |\eta|}\int_0^{\frac{\Delta}{2}}\sqrt{\cos(x)-\cos\left[\frac{\Delta}{2}\right]}\,dx \text{ and "Half Beam Height, } \hat{\Delta E}_{\frac{1}{2}}\text{"} = \text{Bucket height}\times\sin\left[\frac{\Delta}{4}\right]$$

$$E_s = 8.93GeV,\quad V_0 = 2kV,\quad R_s = 528.67m,$$

$$h = 28,\quad \eta = -0.0089,\quad \Delta = 275\text{ nsec}$$

$$\text{LE} = 2.5\text{ eVs} \Rightarrow \text{Total LE} = 10\pm 2\text{ eVs}$$

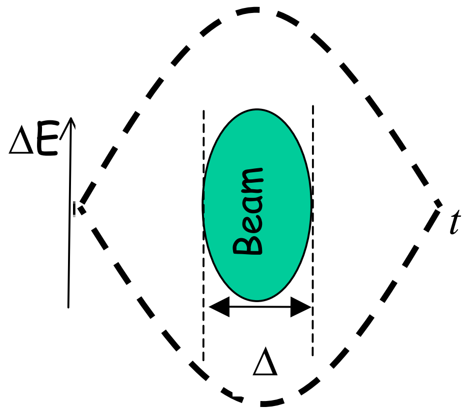
$$\Delta E_{\frac{1}{2}} = 6.0\pm 0.8\text{ MeV},\quad T_s = 0.12\text{ sec}$$

Nearly Coasting Beam

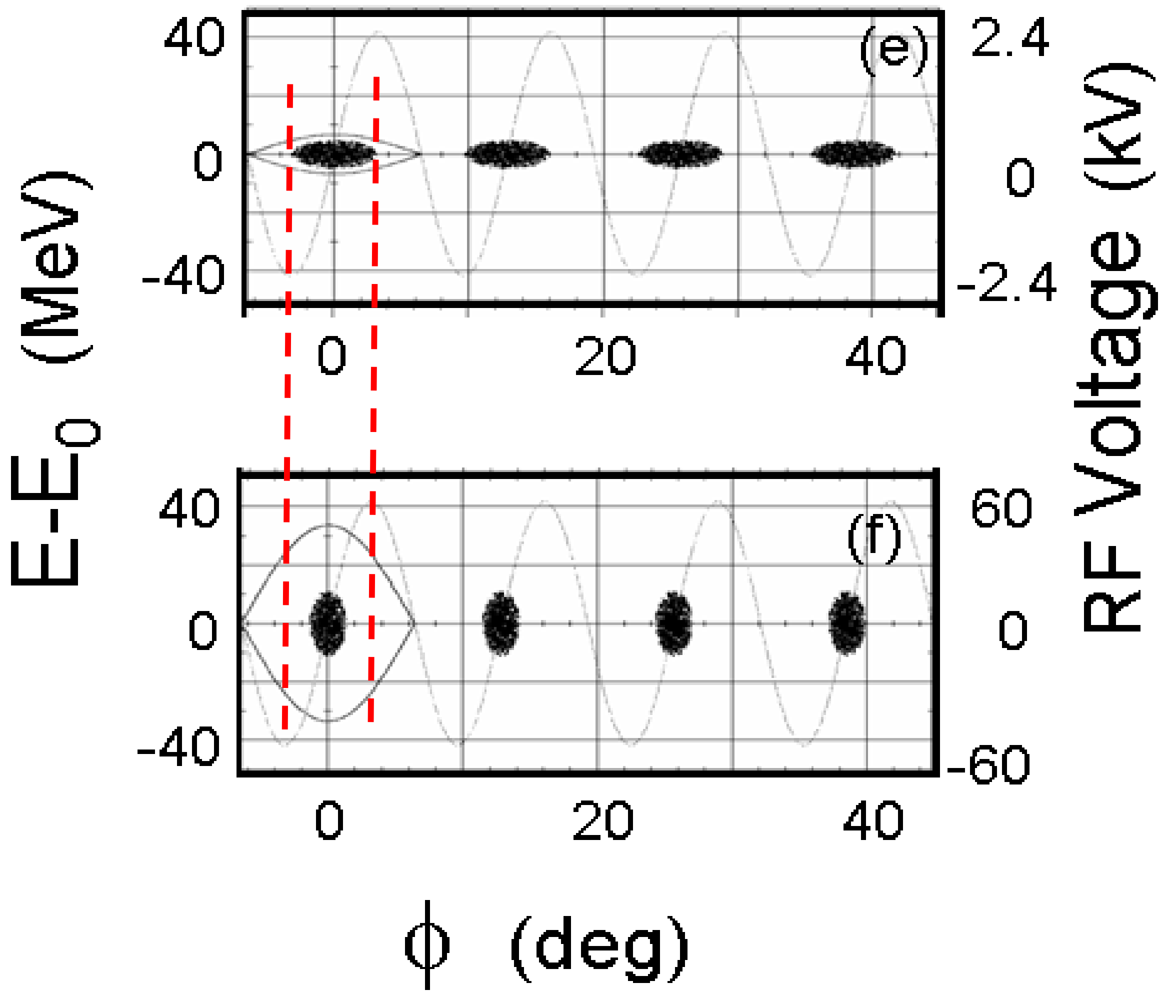
$$T2 = 1590\text{ nsec},\quad \text{T1} = 25\text{ nsec},\quad V_0 = 2\text{ kV}$$

$$\text{LE} = 10\pm 2\text{ eVs},\quad \Delta E_{\frac{1}{2}} = 3.1\pm .6\text{ MeV}$$

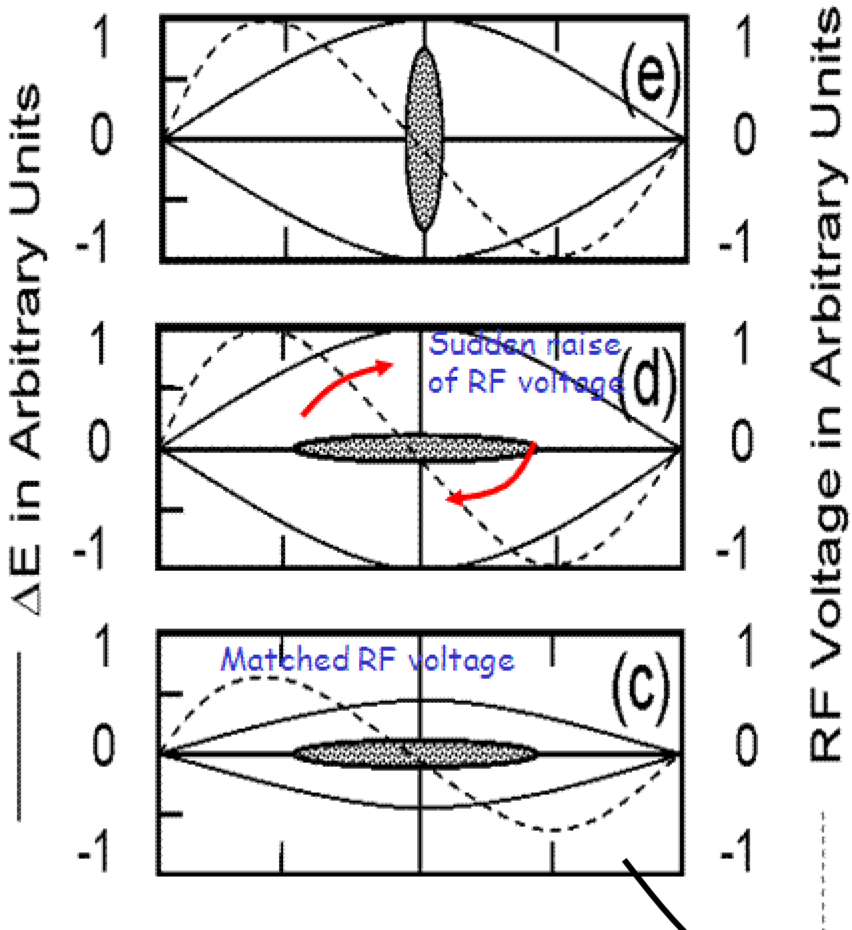
Adiabatic Bunch Compression



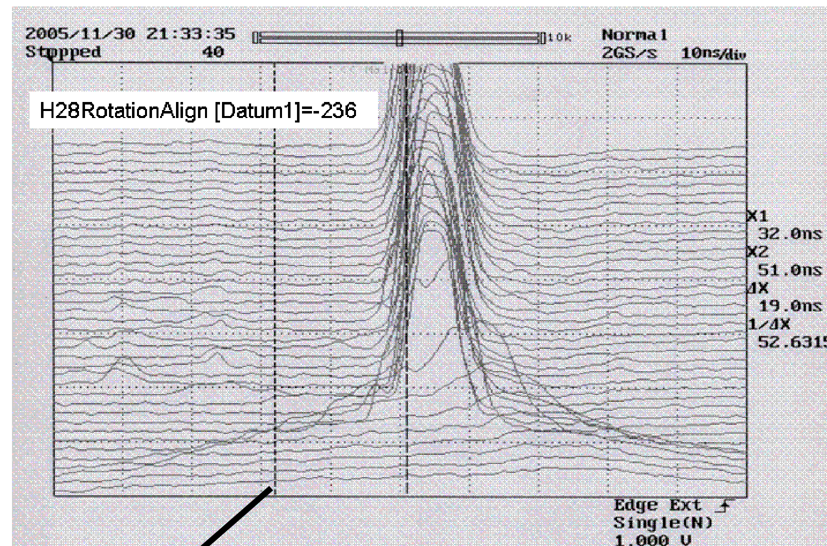
Adiabatically increase the RF voltage (about 6-10 times slower than synchrotron period)



Fast Bunch Rotation



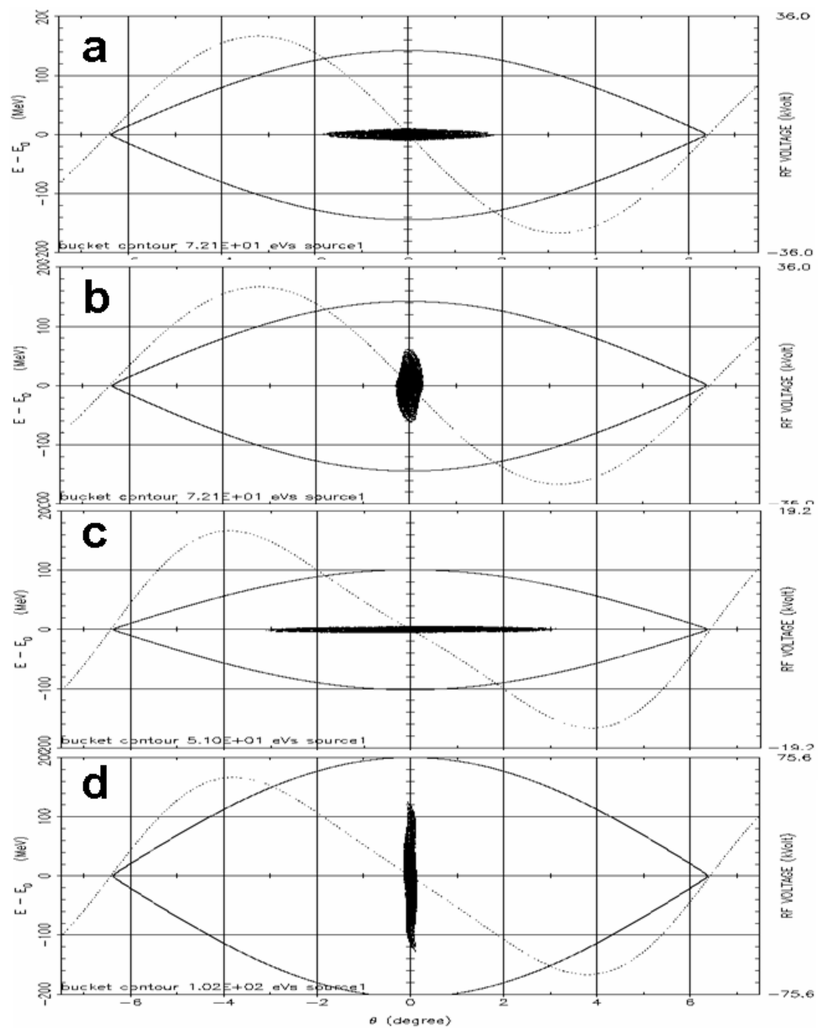
Data on bunch rotation



RF voltage is increased from 10kV to 60kV in about 1 ms

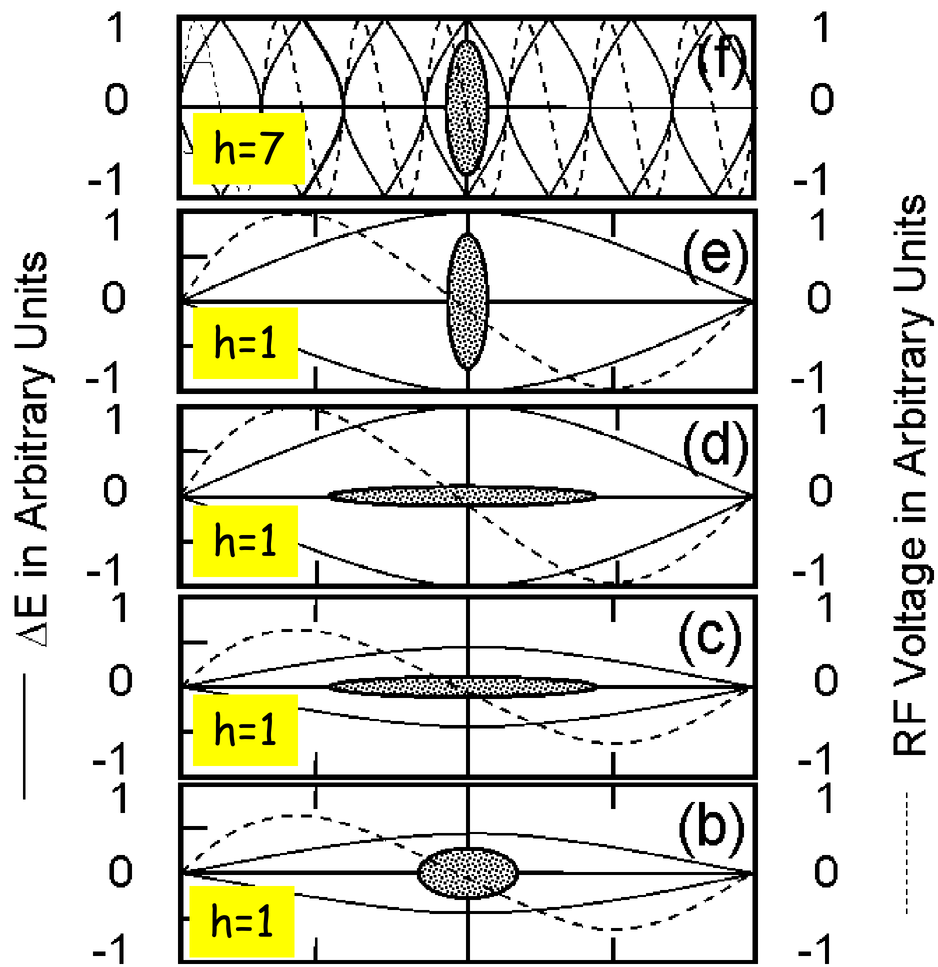
Double Rotation of a Bunch

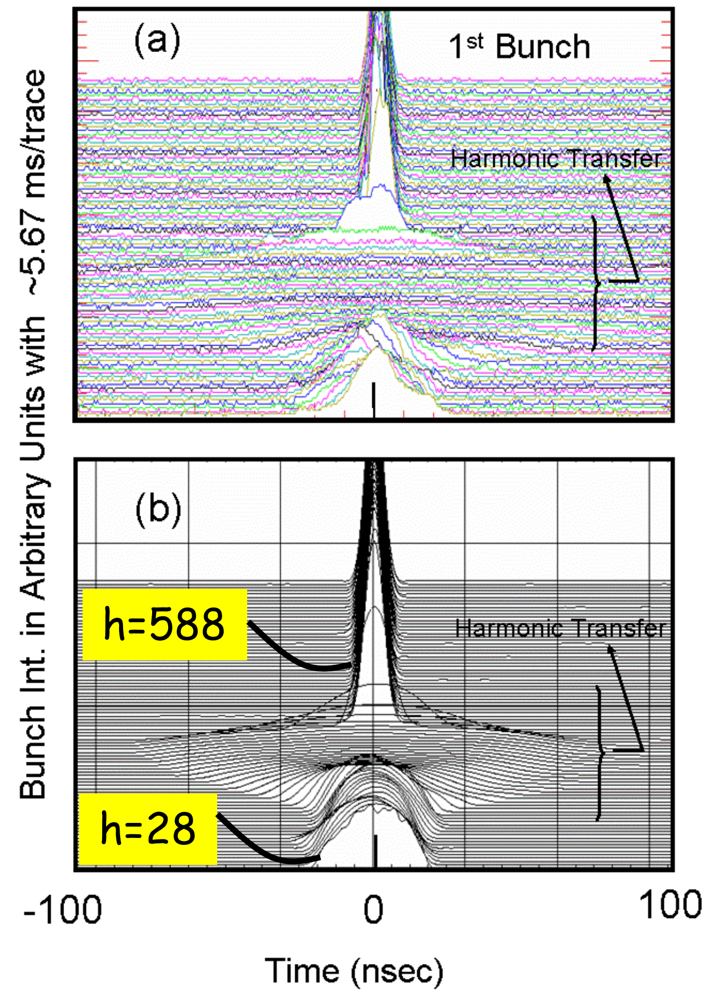
One can narrow the time spread of a bunch significantly. This can be done in two or more rotations.



Harmonic Transfer in a Machine

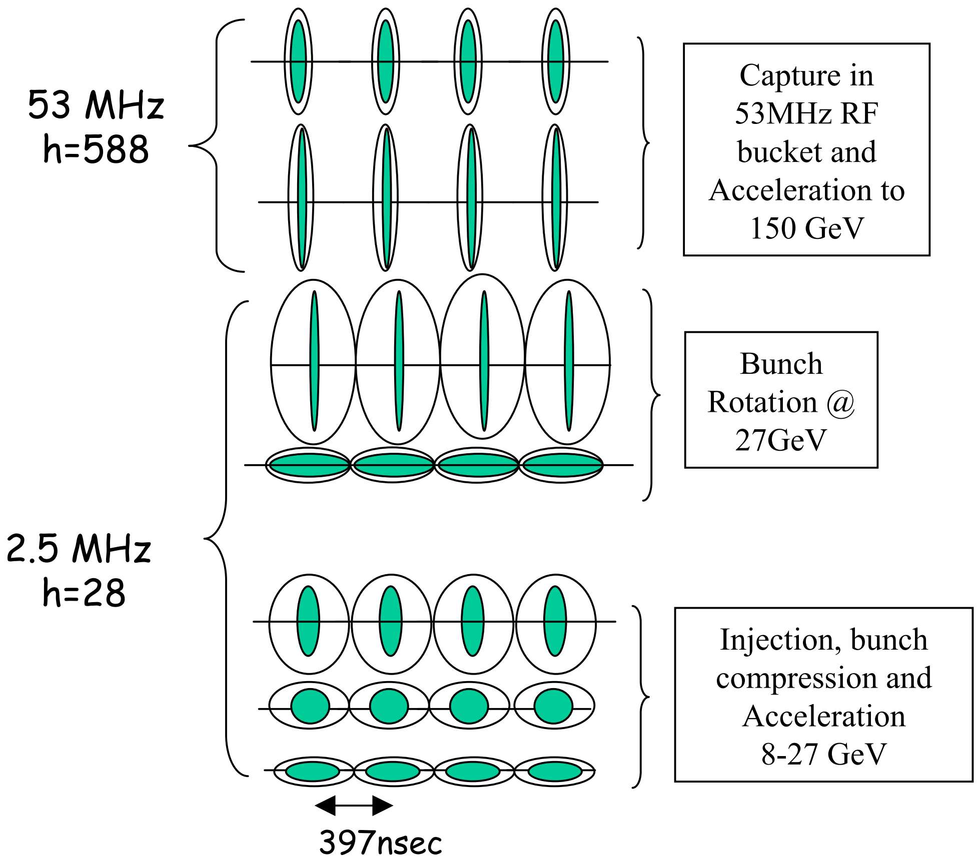
Transfer of a bunch from one bucket to another of different harmonic number.





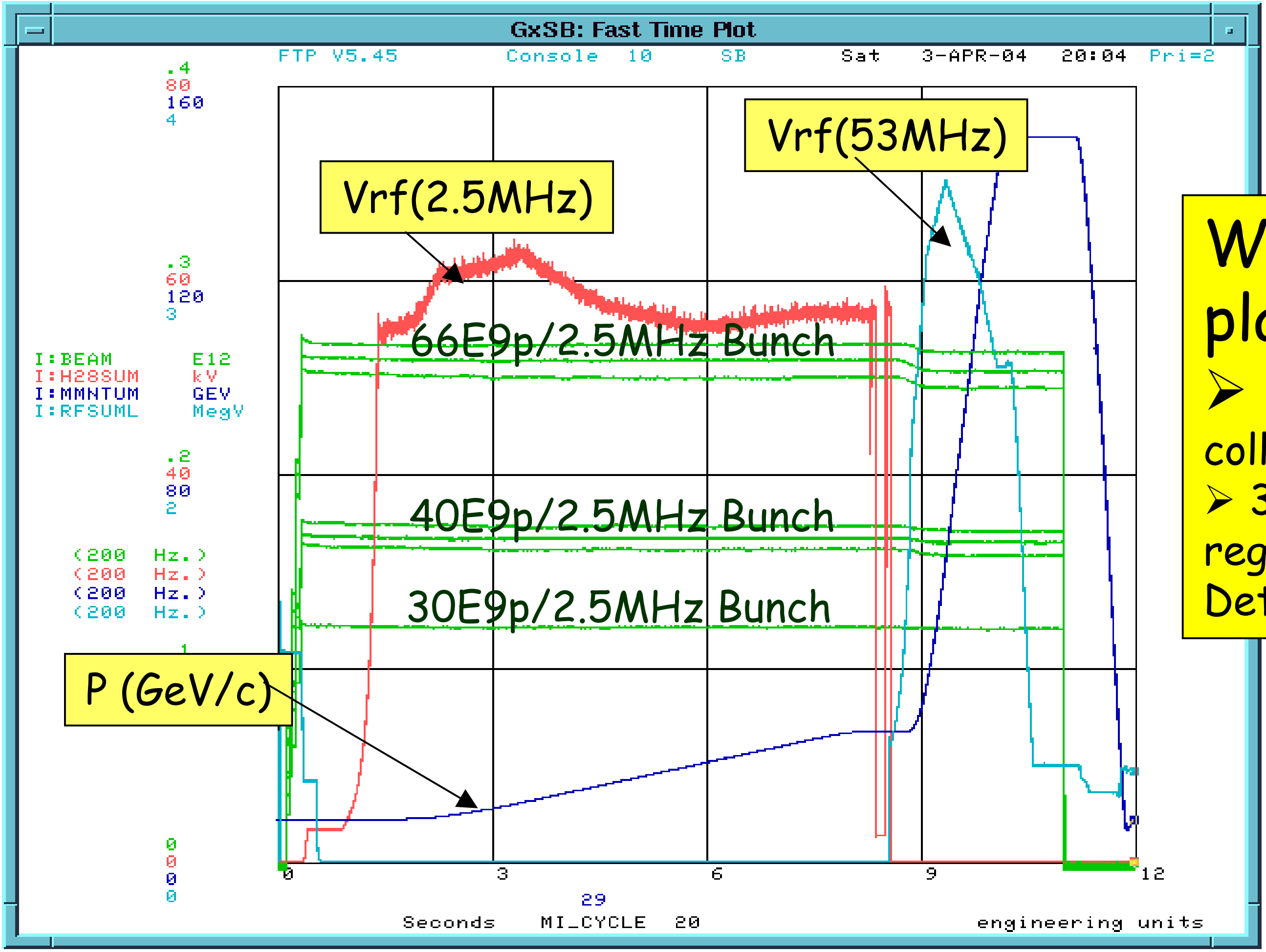
Applications of Harmonic Transfers for Collider Operation

Use of dual RF systems to accelerate pbars
C. M. Bhat, et. al.,Phys. Rev. ST AB V10, (2007),034403



Minimal Longitudinal Emittance Growth and No Beam Loss

2.5MHz Acceleration in the MI (proof of principle)



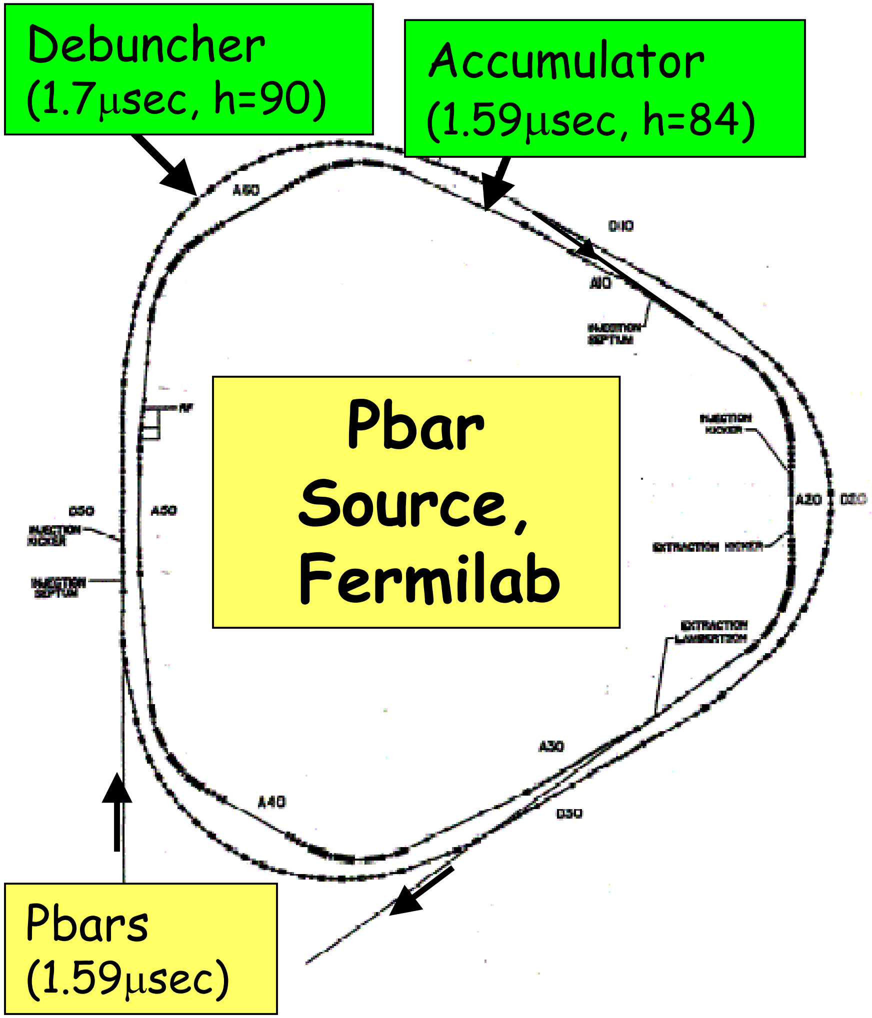
With this scheme in place one expects

- about 17% increase in collider luminosity
- 35% Shorter interaction region for the Collider Detectors

Ref.: PAC2005

History of Barrier RF Systems

A barrier rf system is a broad-band rf system comprising of ferrite loaded rf cavities.



Early stages of antiproton source at Fermilab demanded

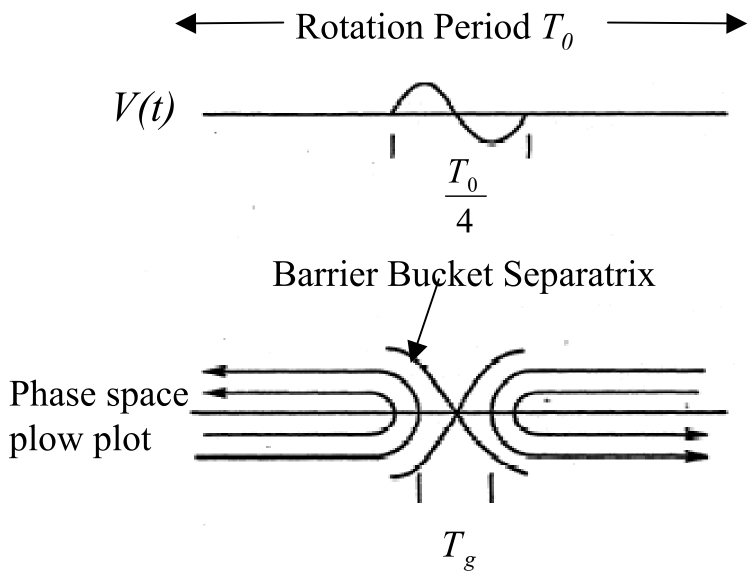
1. The bunch length in the Debuncher and the Accumulator should be the same ← **Gap preservation in the Debuncher beam**
2. Necessity of using "**suppressed rf buckets**" during unstacking pbars from the Accumulator

Invention of Barrier RF system

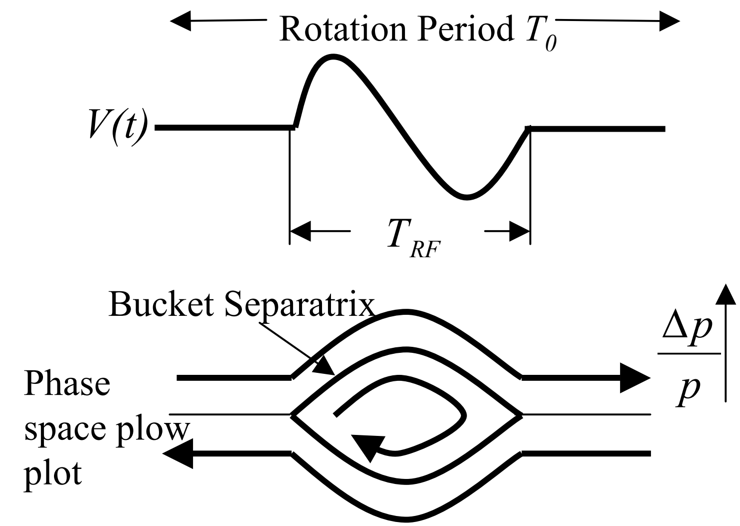
J. Griffin et. al. IEEE Transactions on Nuclear Science, Vol. NS30 No. 4. 3502

Barrier Buckets - Concepts

Gap Preserving barrier buckets



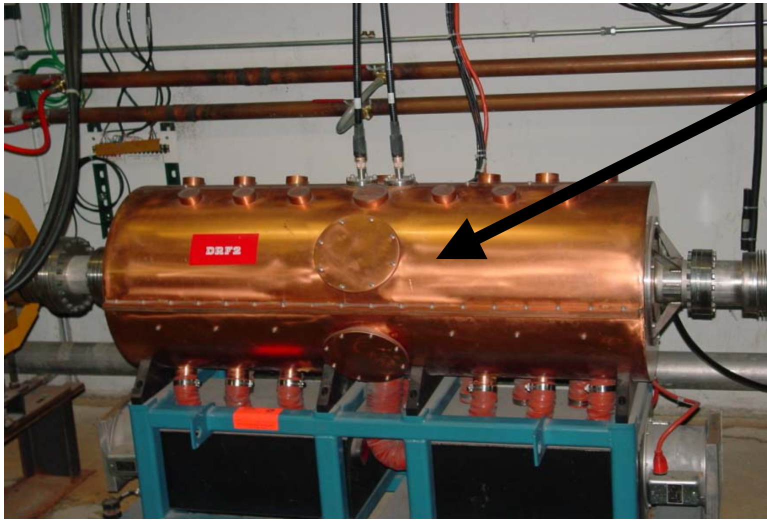
Isolated barrier buckets



$$V(t) = V_0 \frac{2h}{\pi} \sum_{n=0}^{\infty} \frac{Sin(n\pi / h)}{h^2 - n^2} \sin(n\omega t)$$

$$T_0 = h T_{RF}$$

The Earliest Barrier RF System at Fermilab

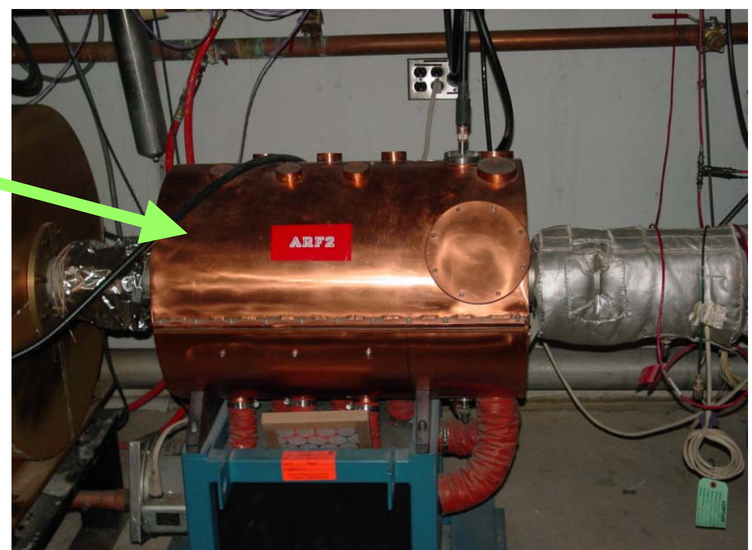


Cavity in the Debuncher

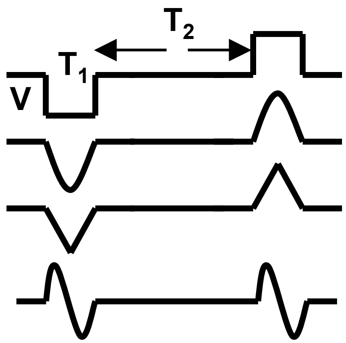
Peak Voltage: 160V (700V) Power: 2.4 kWatts
Type of Ferrite: MnZn+NiZn
Shunt Impedance: 104 Ω /cavity
Band Width : 10kHz -10MHz
Dimension: ~ 1 meters
Amplifier : IFI3100S

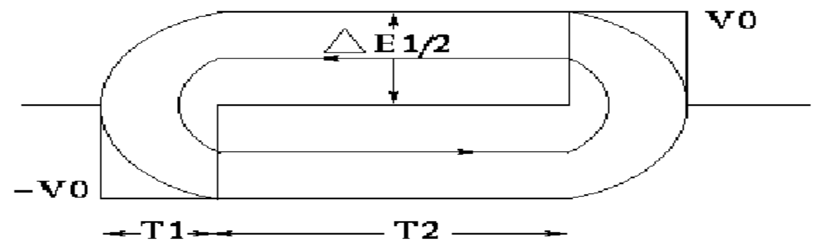
Cavity in the Accumulator

Peak Voltage: 70 V Power: 100W
Type of Ferrite: MnZn+NiZn
Shunt Impedance: 50 Ω /cavity
Band Width : 10kHz -10MHz
Dimension: 1 meter
Amplifier : ENI2100



Properties of Barrier Buckets





Bucket height :

$$\Delta E_b = 2\sqrt{\frac{2\beta^2 E_0}{|\eta|}\frac{\int_0^{T_1} eV_{rf}(t)\,dt}{T_0}}$$

Synchrotron Period :

$$T_s = 2\frac{T_2}{|\eta|}\left[\frac{\beta^2 E_0}{|\Delta \hat{E}|}\right] + 4\frac{|\Delta \hat{E}|}{eV_0}T_0$$

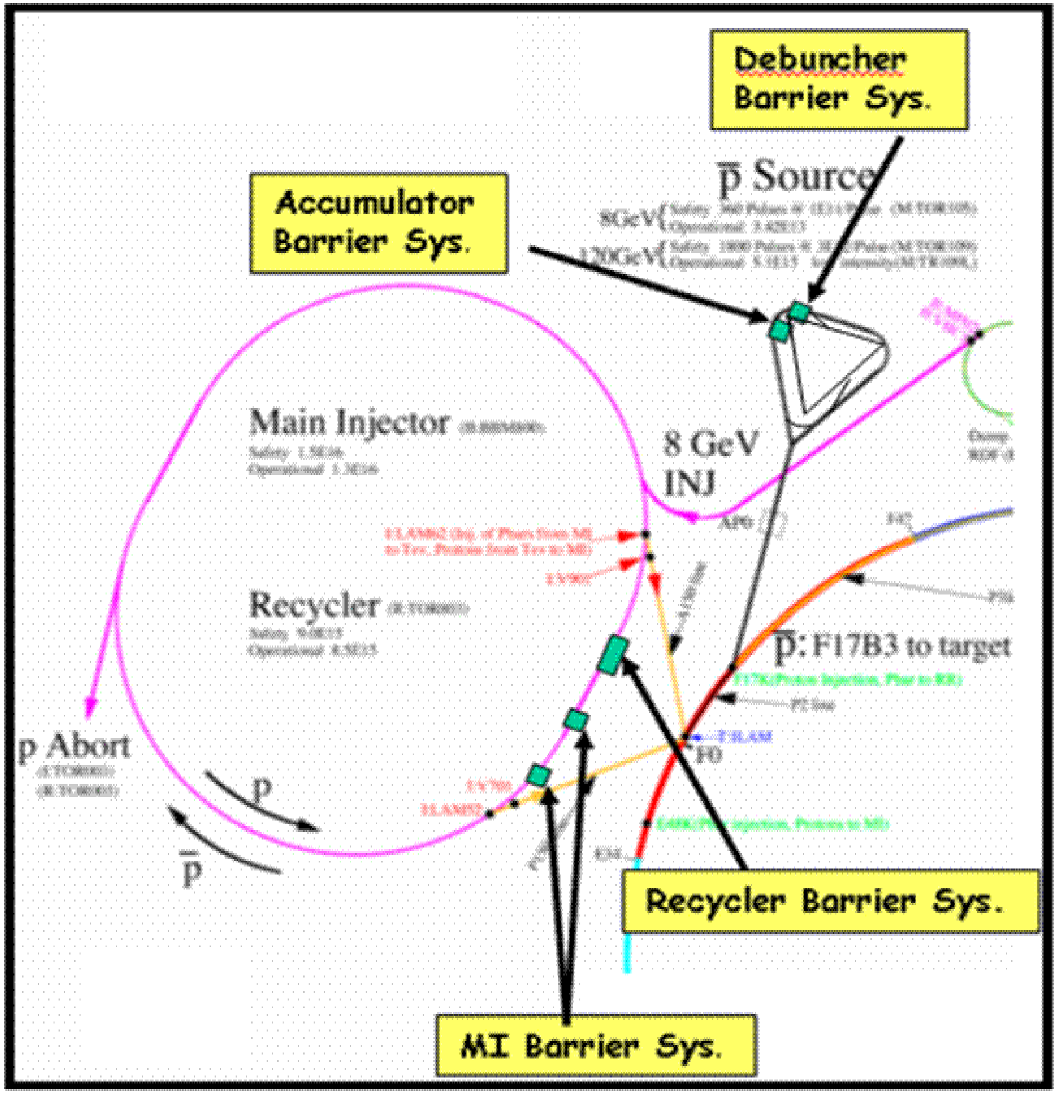
Bucket area :

$$\varepsilon_l = T_2 \Delta E_b + \frac{8\pi|\eta|}{3\omega_o \beta^2 E_o eV_{rf}}\left[\frac{\Delta E_b}{2}\right]^3$$

- η is phase slip factor,
- E_o is synchronous energy,
- ω_o=2p f_{rev} with f_{rev}= beam circulation frequency.

Ref: S. Y. Lee, *Accelerator Physics*, (World Scientific, Singapore, 1999)

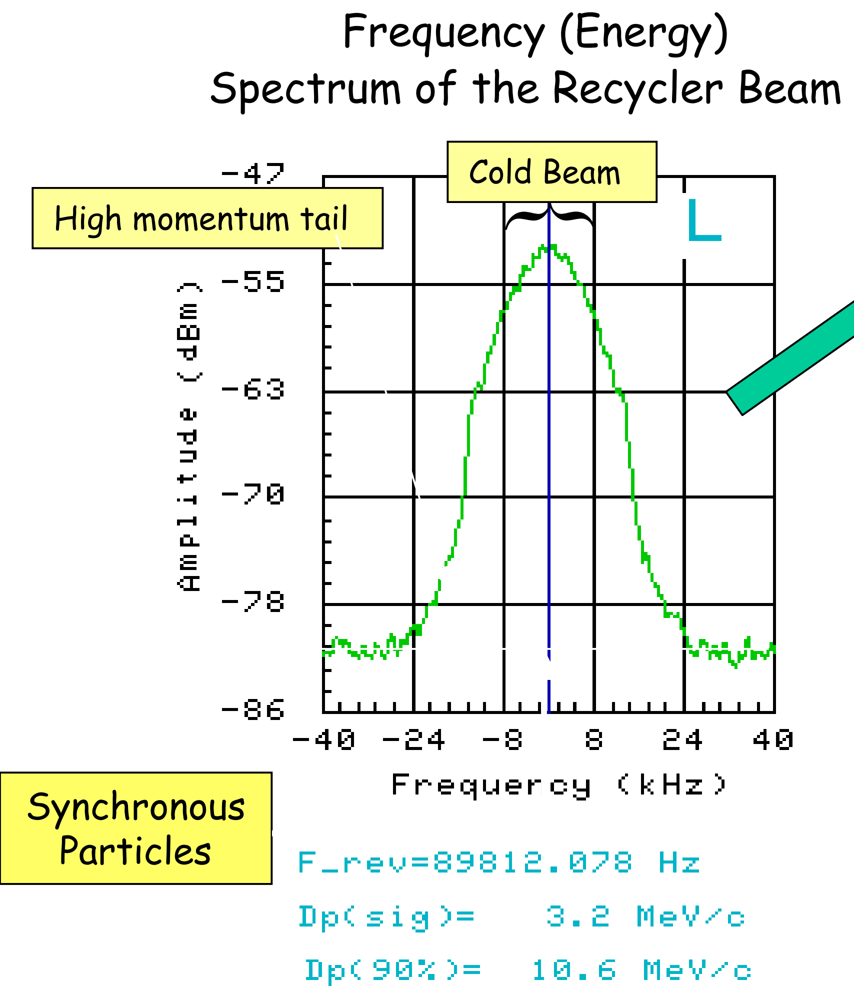
Barrier RF Systems at Fermilab Accelerators

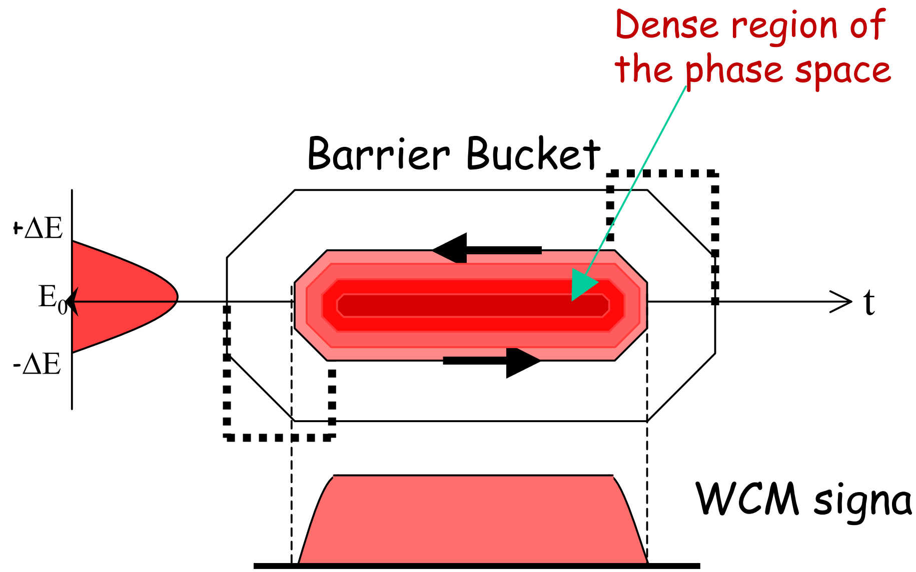


Applications of Barrier RF Systems at Fermilab

- **Longitudinal Momentum Mining**
- New Schemes to **produce intense beam** in accelerators← Barrier Stacking
- **Phase space Coating**

What is Momentum Mining on a Cold Beam?

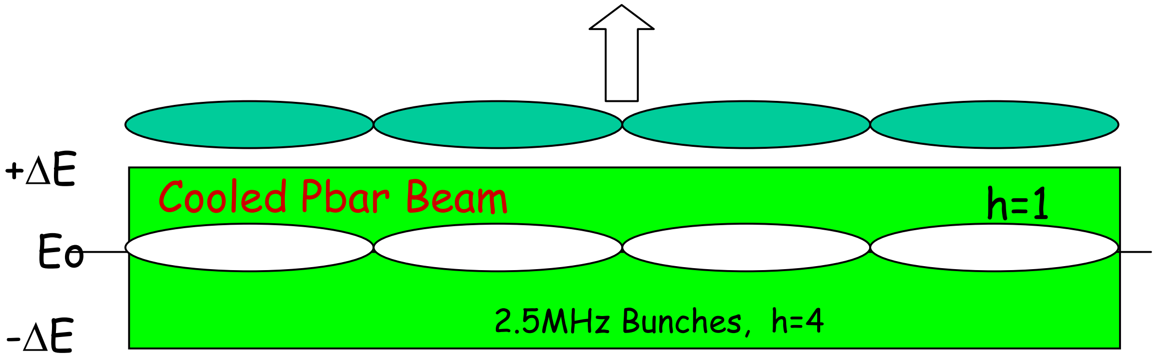


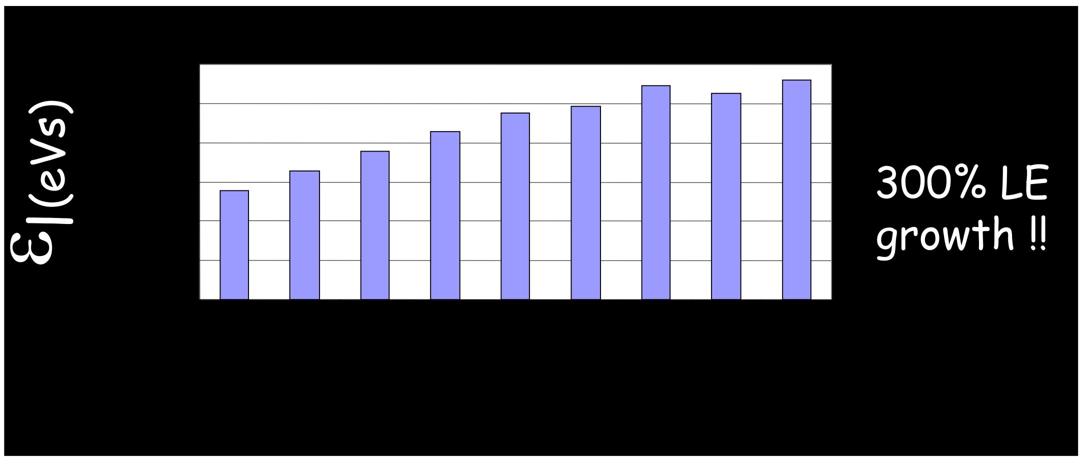


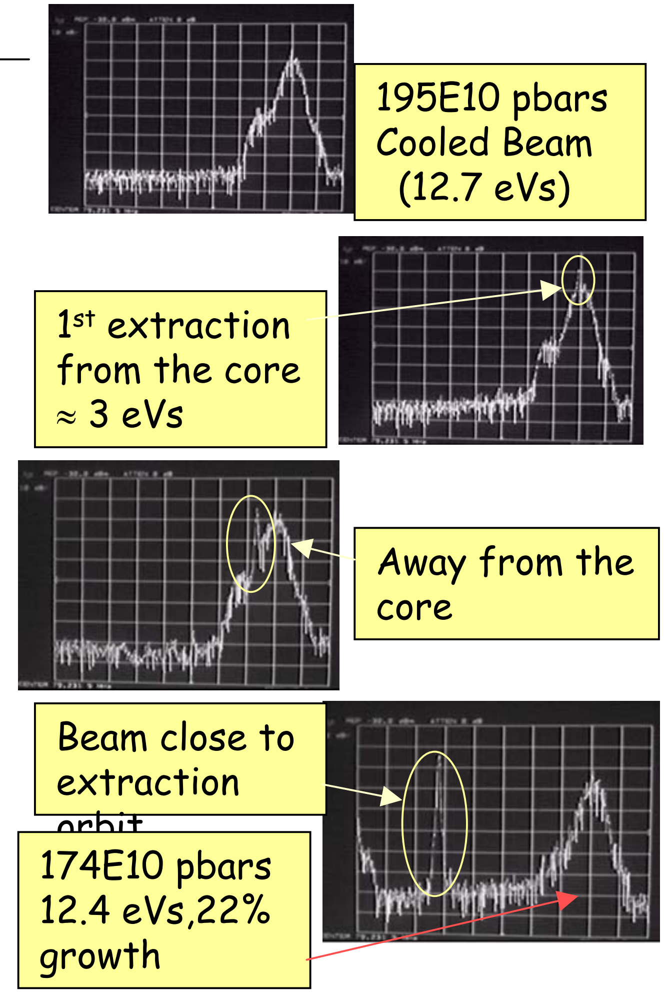
Is it possible to isolate the cold beam from the high momentum tail of a beam distribution without emittance growth and use only the cold beam and use the leftover hot beam after further cooling?

Transverse Momentum Mining

(Current Mining Scheme at the Fermilab Accumulator)







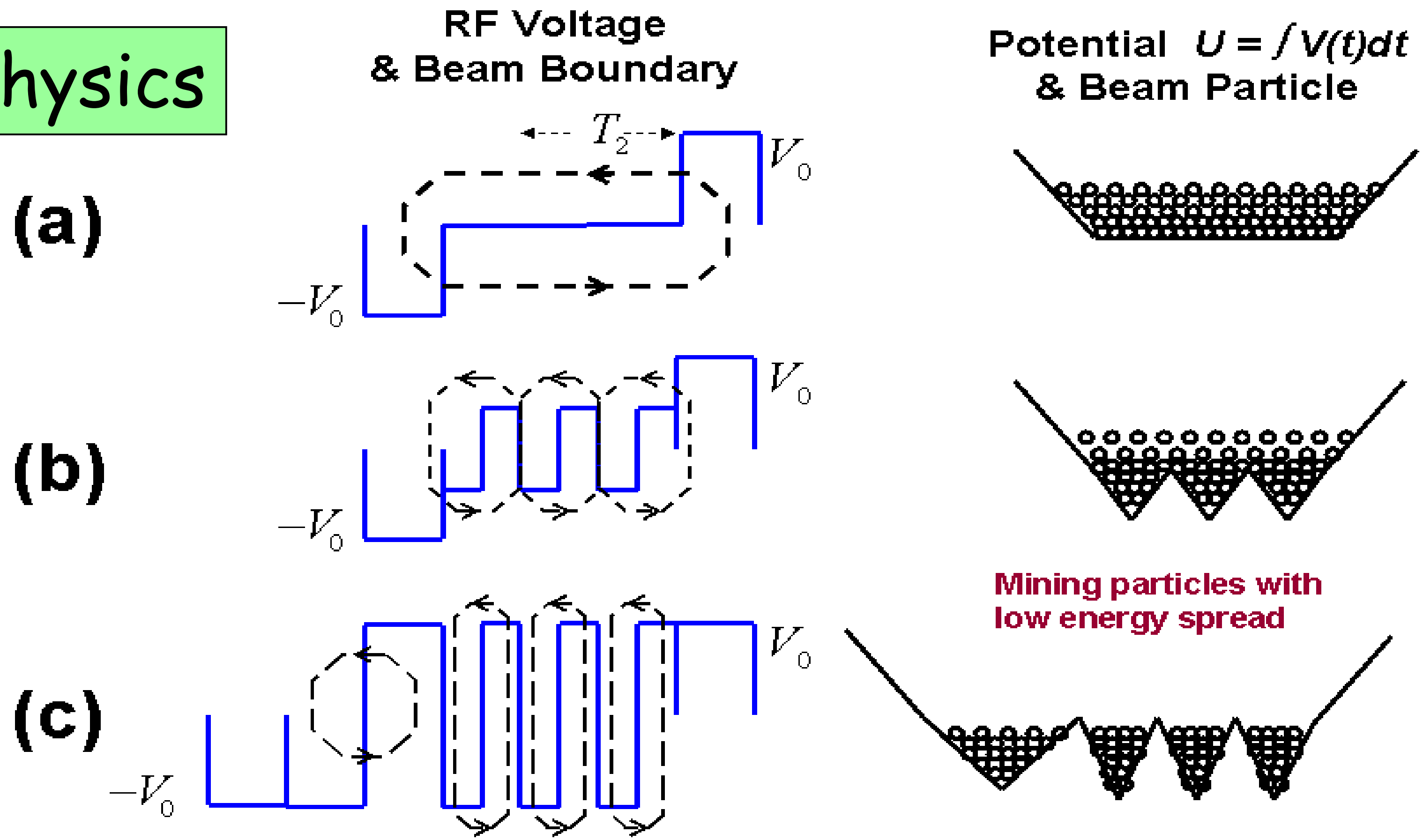
- This is the method used in all hadron storage rings so far.

Longitudinal Momentum Mining in a Synchrotron

Ref: C. M. Bhat, Phys. Lett. A 330 (2004) 481

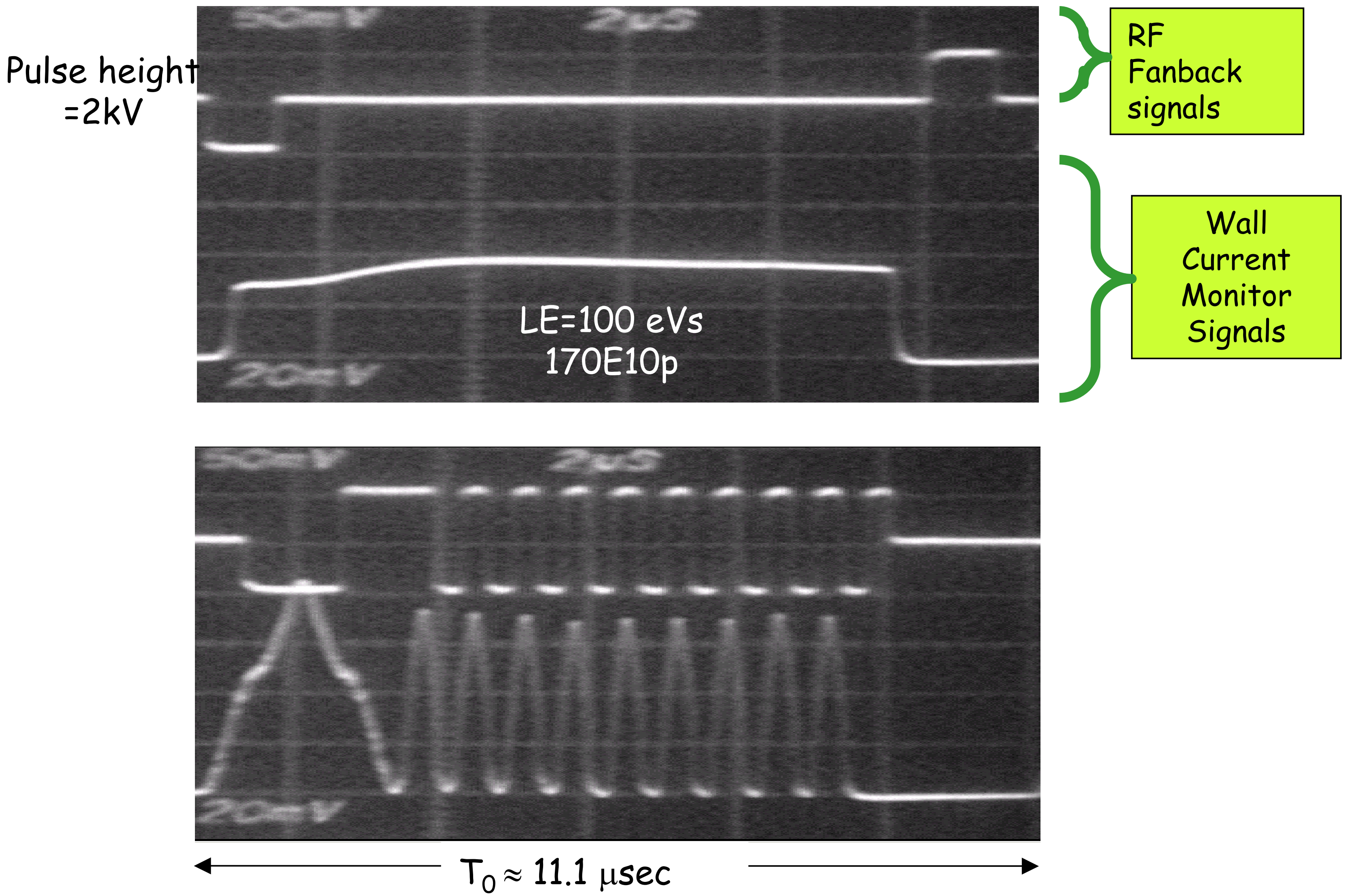
New Technique

Physics

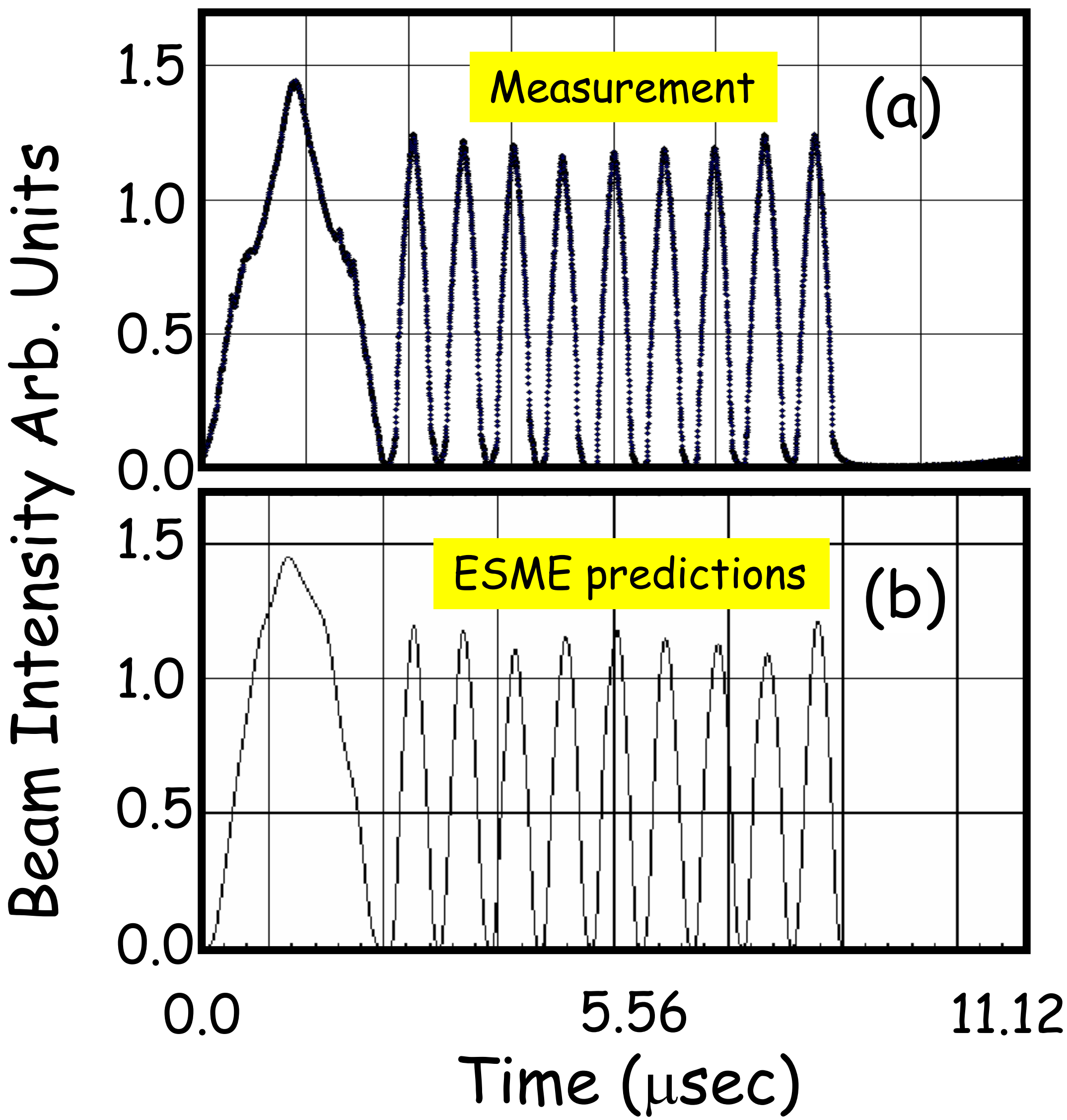


Technique is applicable to any storage ring for beam mining

Proof of Principle Experiment on Proton Beam in the Recycler (2004)



A Comparison between Measurements and Predictions



Initial Beam Intensity = 170E10p
LE= 100 eVs
Goal: Mine 54 eVs of the cold region of the phase-space and divide into 9-equal parts. Rest in a large bucket.

Measurements:
75% beam is mined. LE=9x 5.5eVs
Do not care about others. But, no loss.

Predictions:
65% beam is expected to be mined. LE=9x 6eVs
Do not care about others.

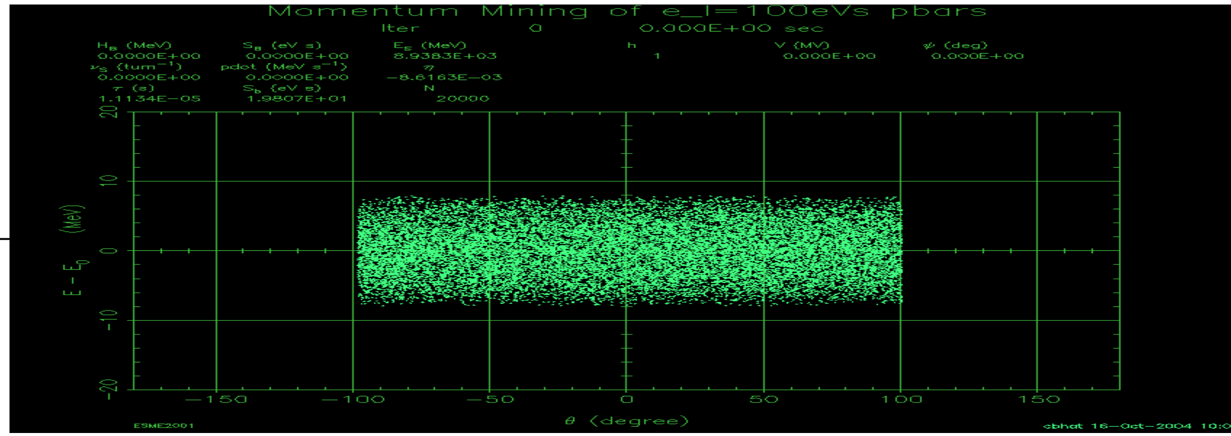
Why? Calculations assumed Gaussian distribution for the beam before mining!!!

Beam Momentum Mining

(ESME simulations)

http://www-ap.fnal.gov/ESME/

Phase-space Distribution of pbars

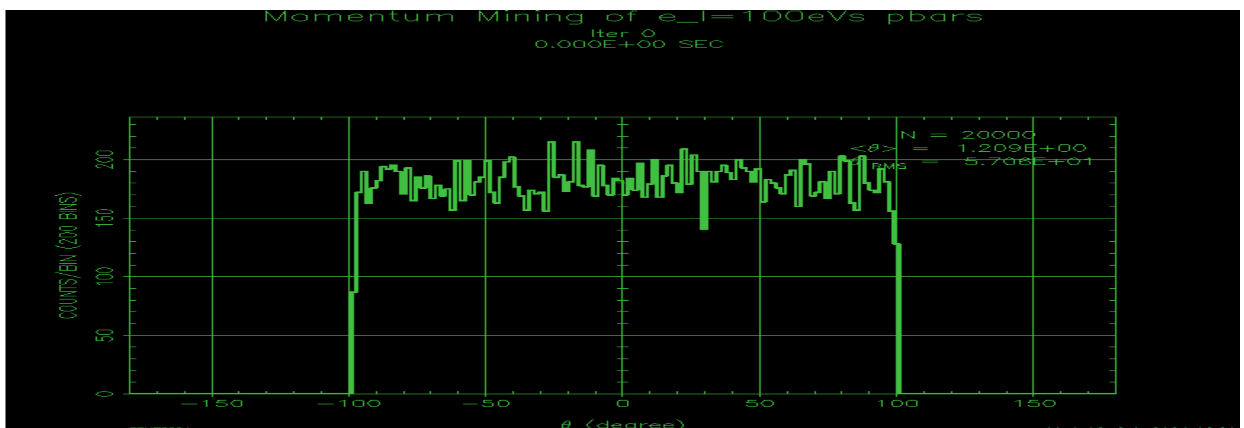


+ΔE

0

-ΔE

WCM data (predictions)



Intensity

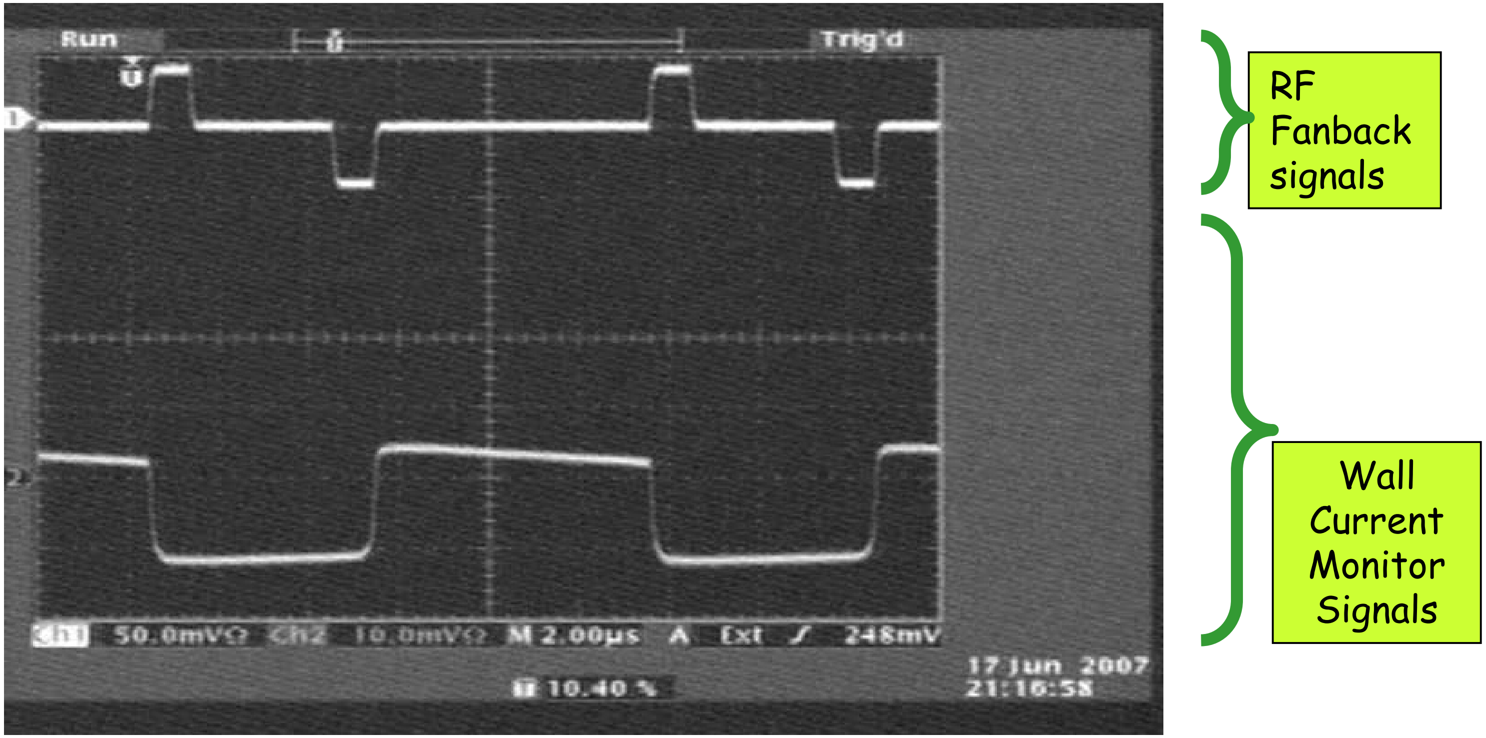
$\Delta\theta$ (or Time)

360^0 (or 11.12 μsec)

Longitudinal Momentum Mining

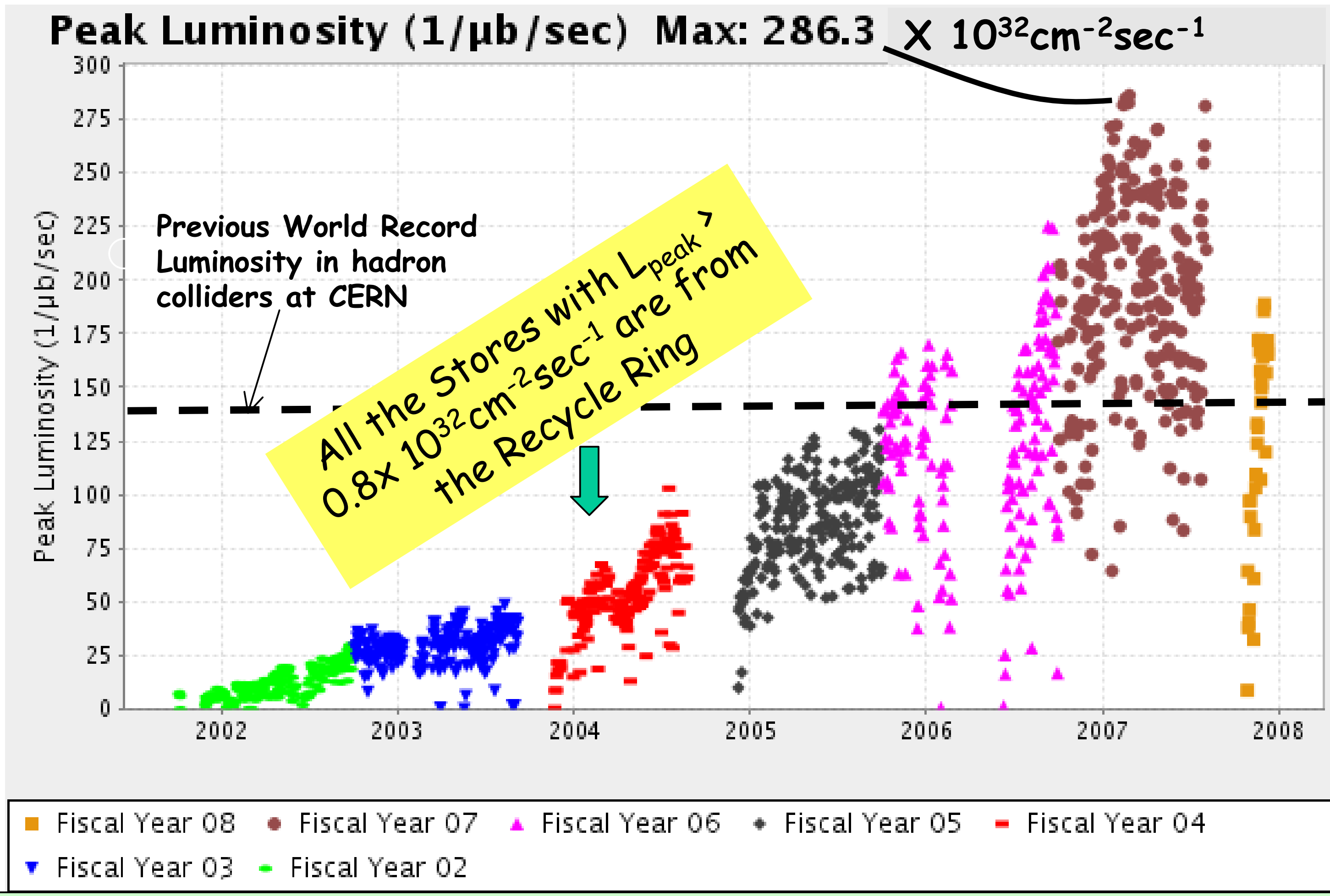
Recent Operational Status

Beam Intensity = 310E10pbars; LE(initial) ≈ 65 eVs



We are using this scheme since early 2004.

RESULTS
World ppbar record Luminosity at the Tevatron

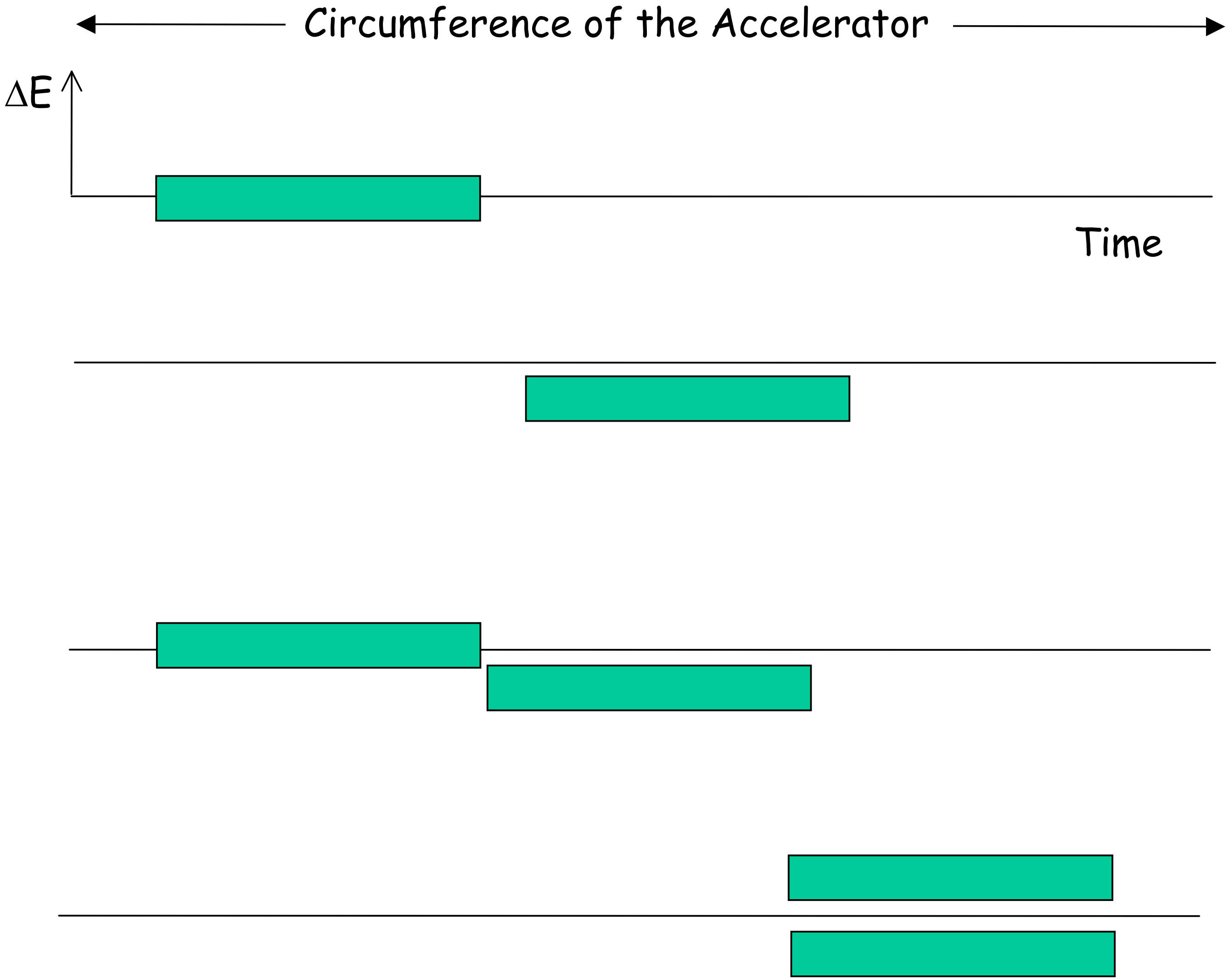


Outcome –All the ppbar collider stores in the Tevatron with initial L > 0.8 x10^{32}cm^{-2}sec^{-1} came from longitudinal momentum mining in the Recycler.

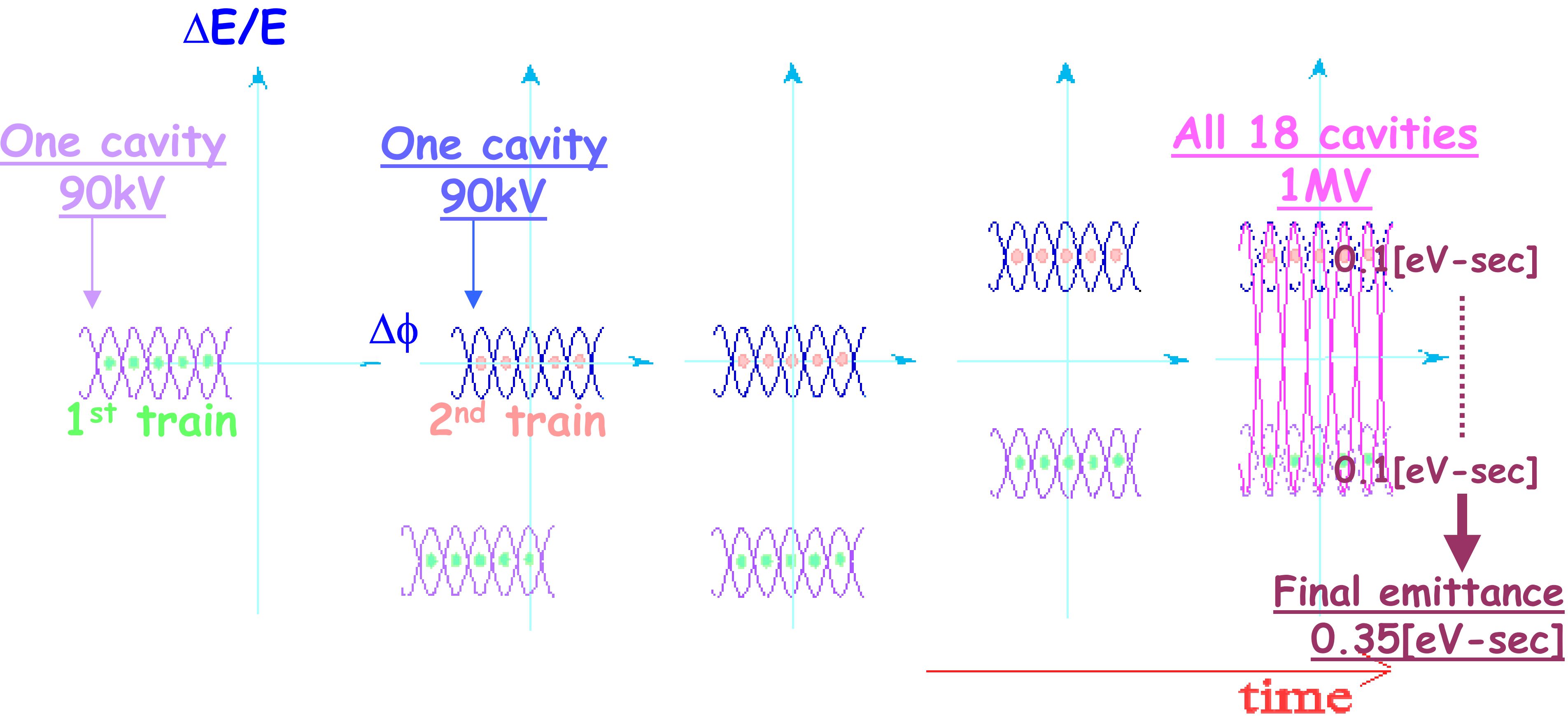
Doubling the Beam Intensity by Slip Stacking

Physics of

Slip stacking process in phase space

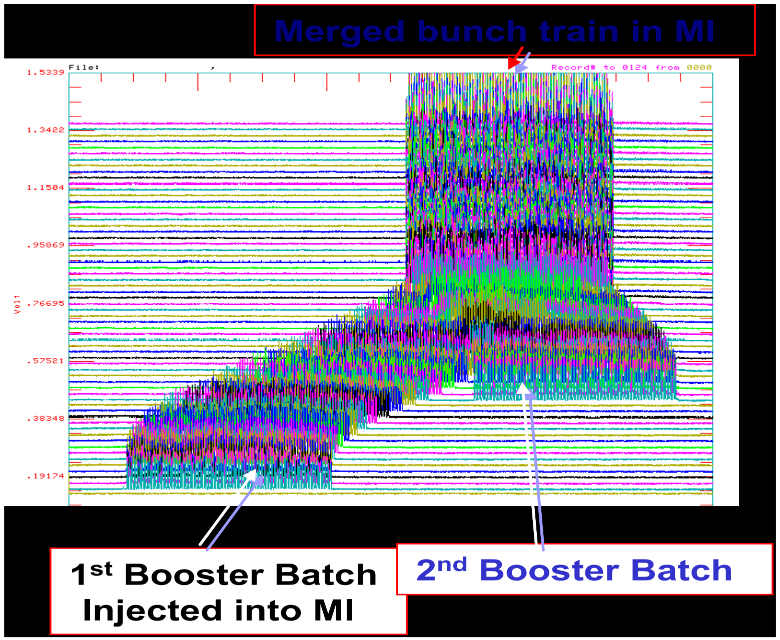


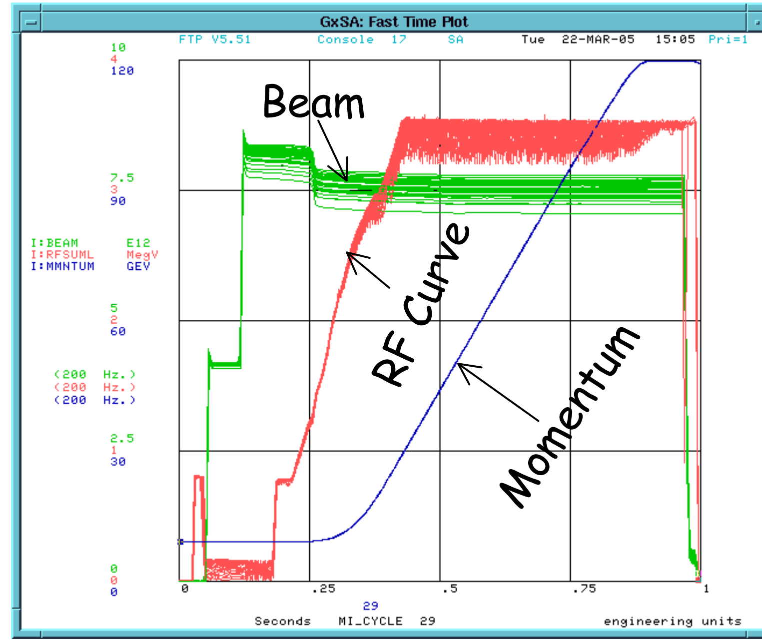
Physics (cont.)

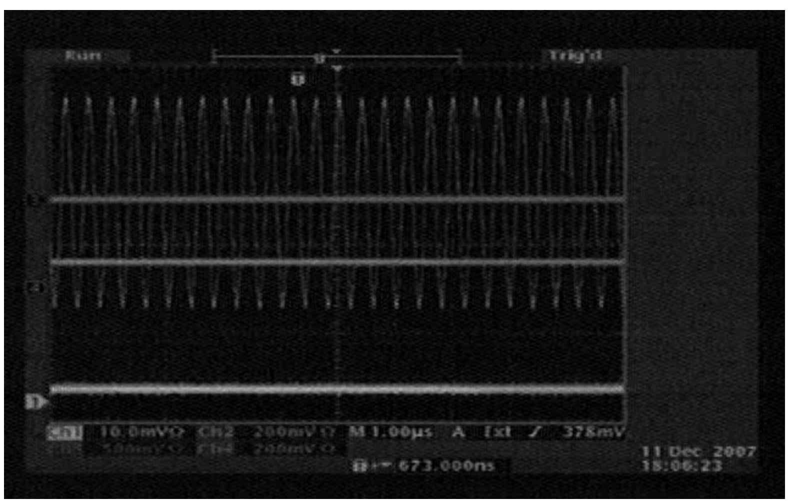


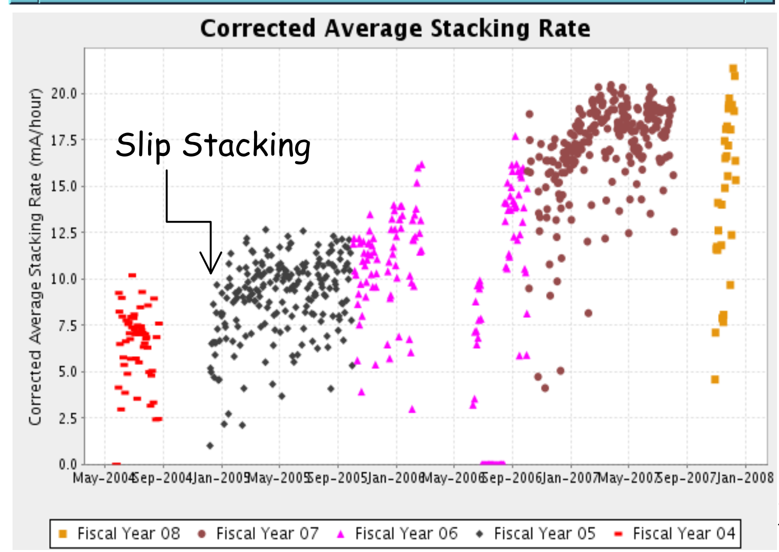
(From Kiyomi S)

Slip stacking in the Main Injector to improve the Pbar Stacking Rate

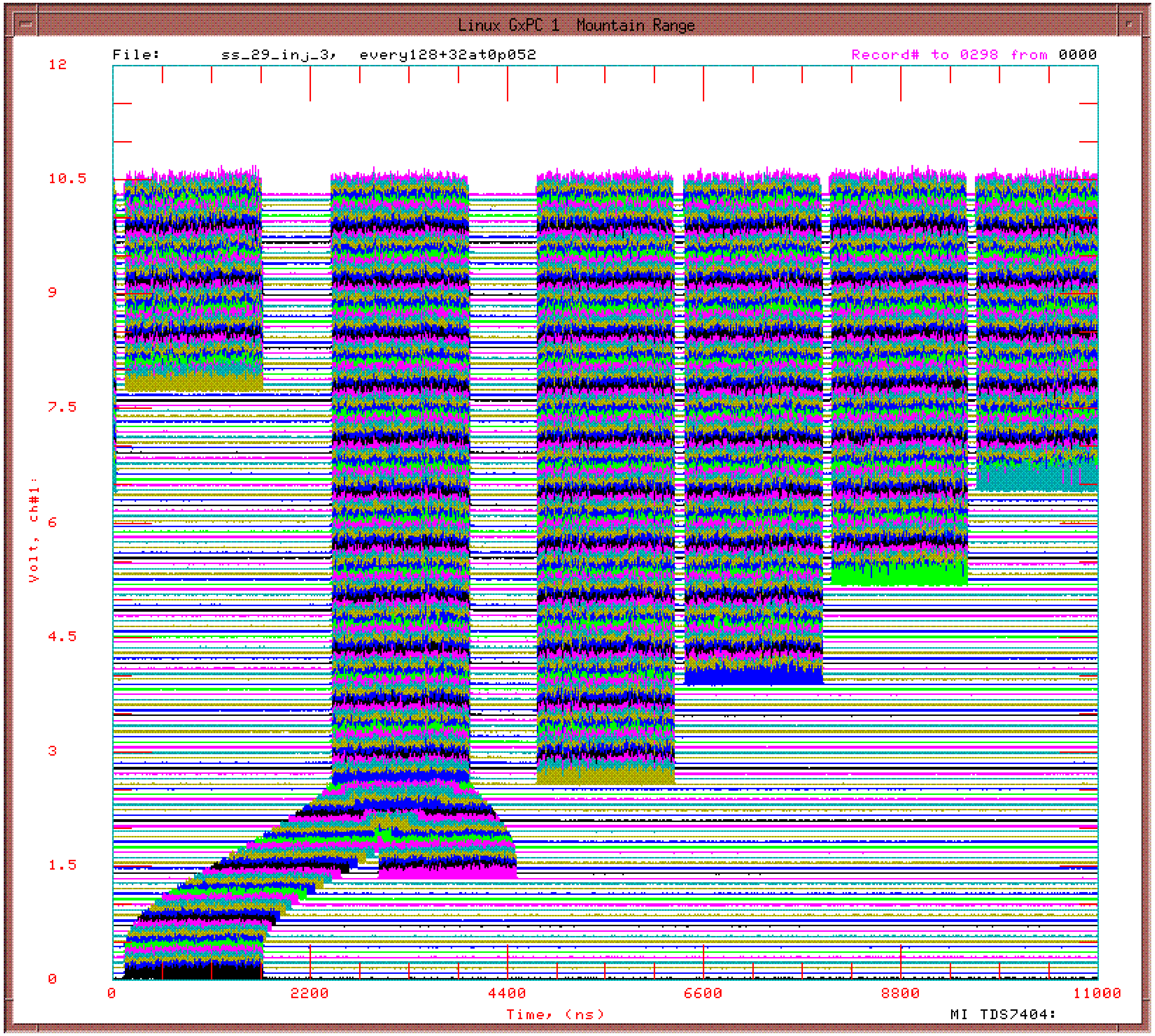




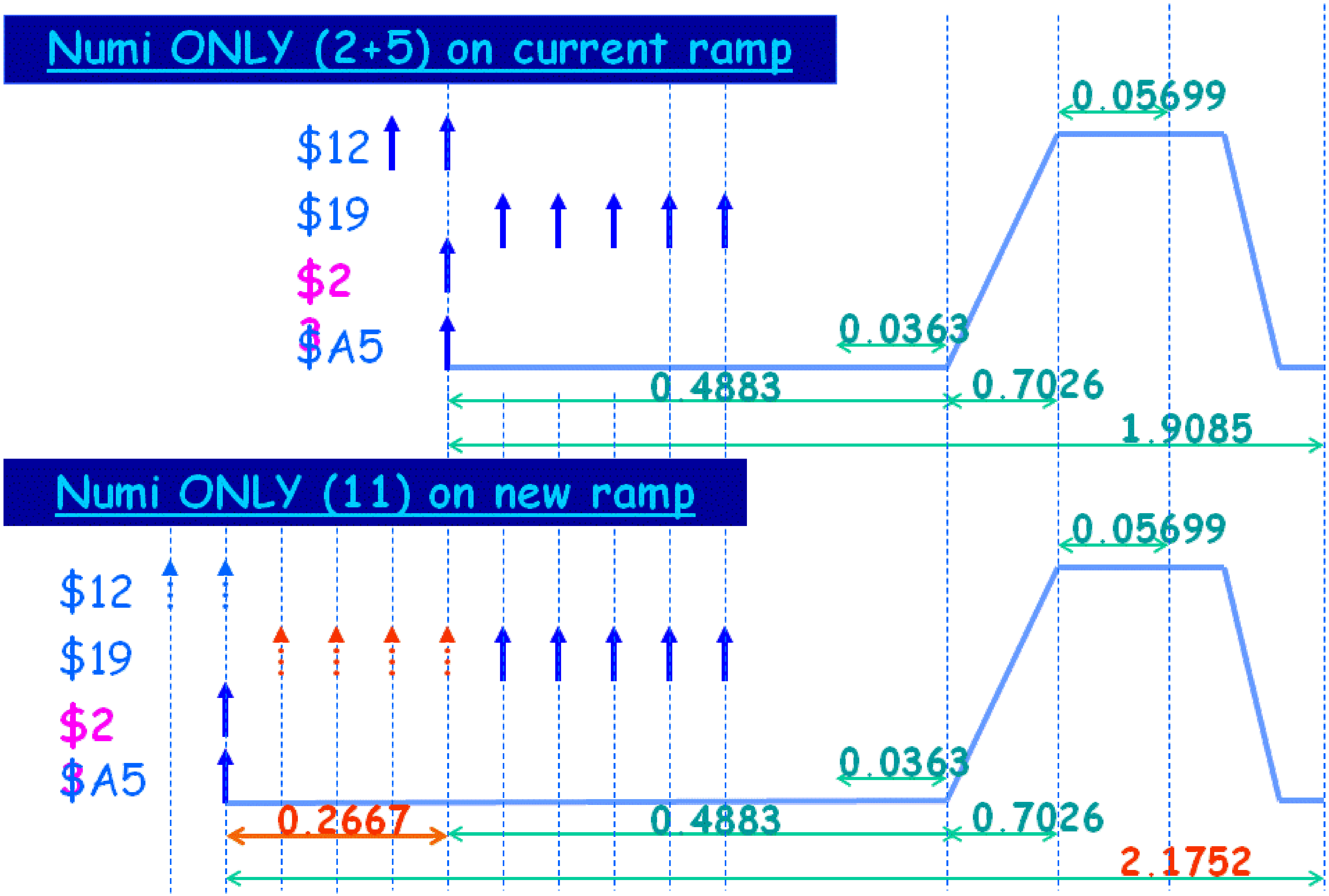




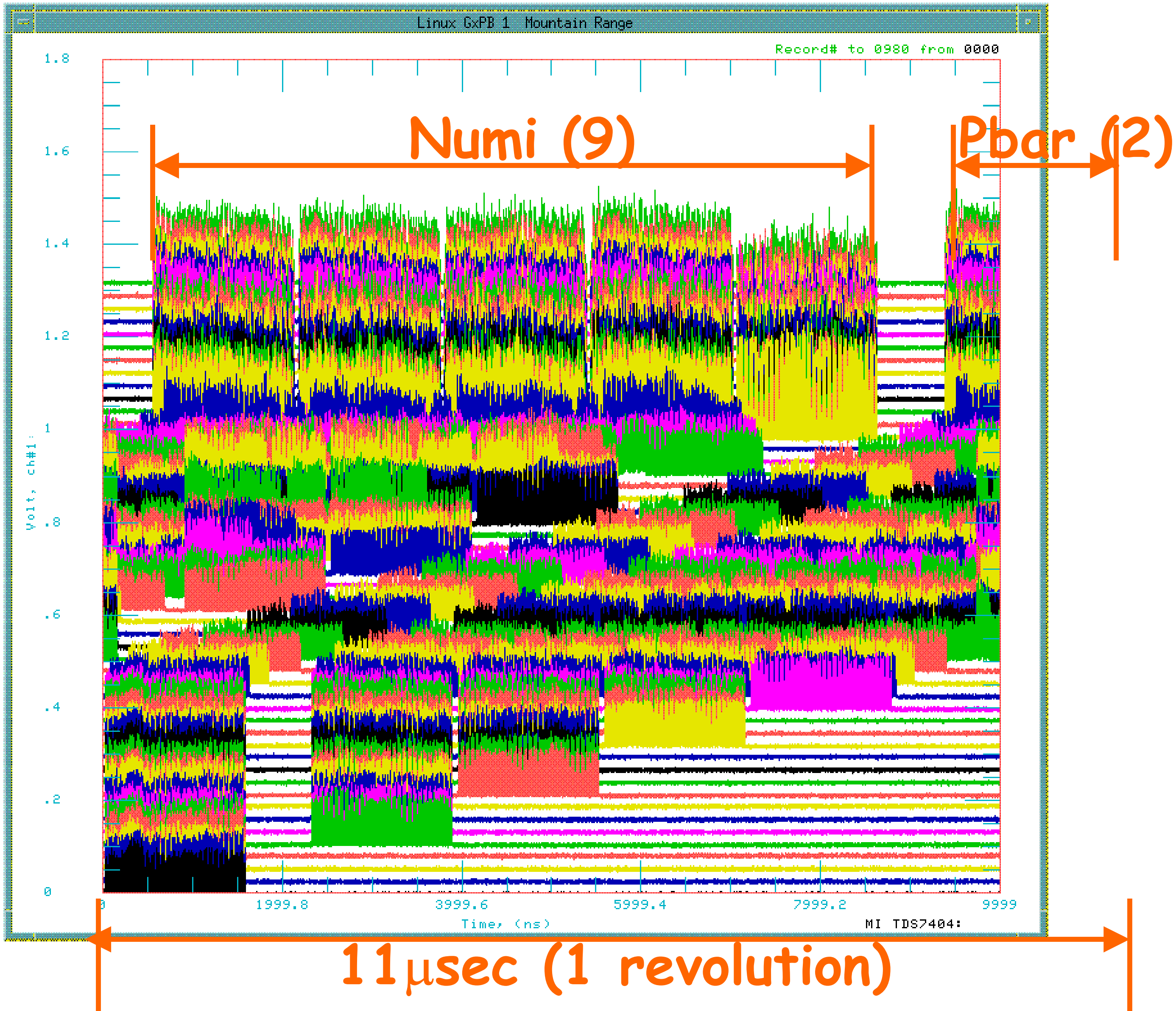
Slip Stacking + Box-cart stacking



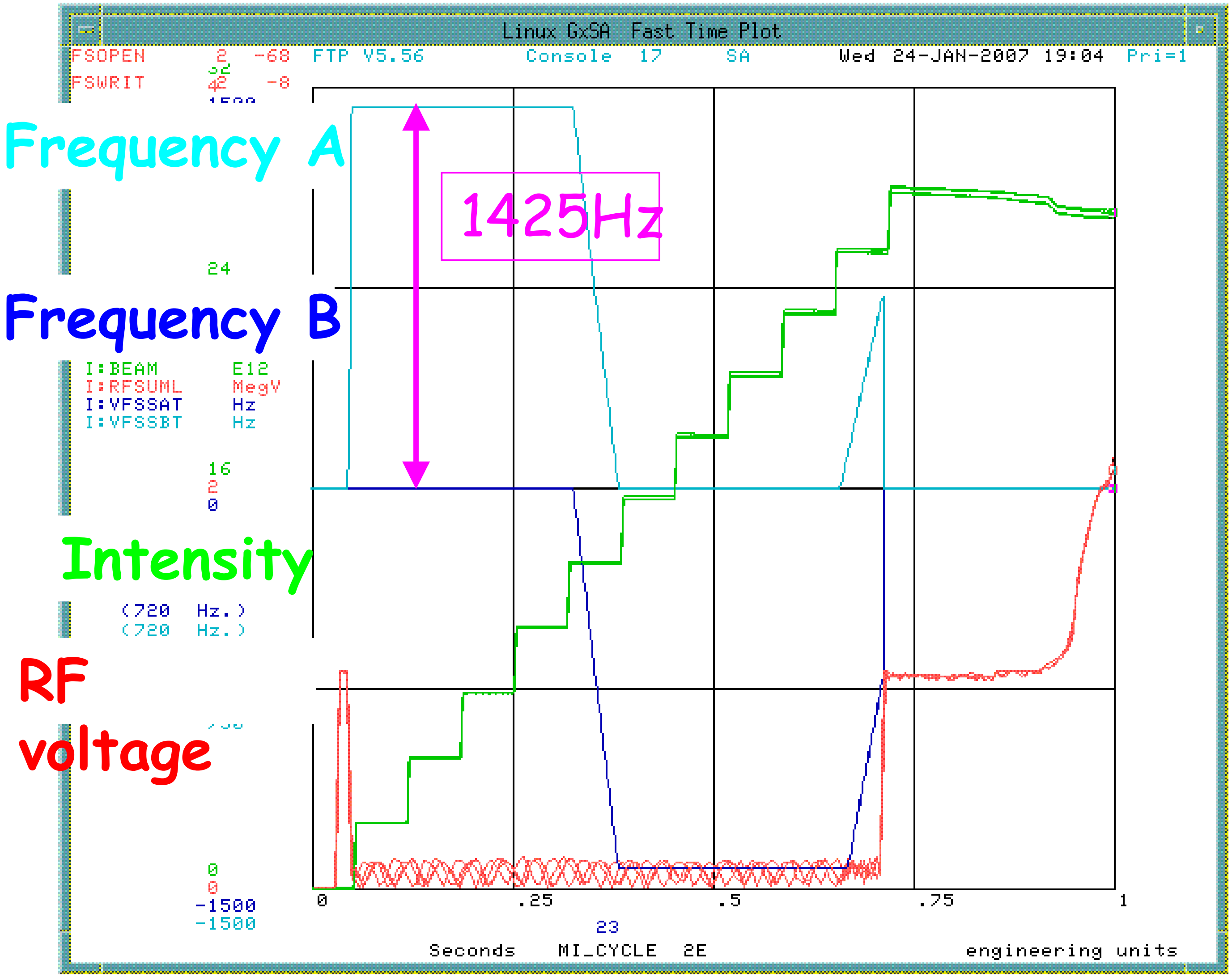
Main Injector Ramps



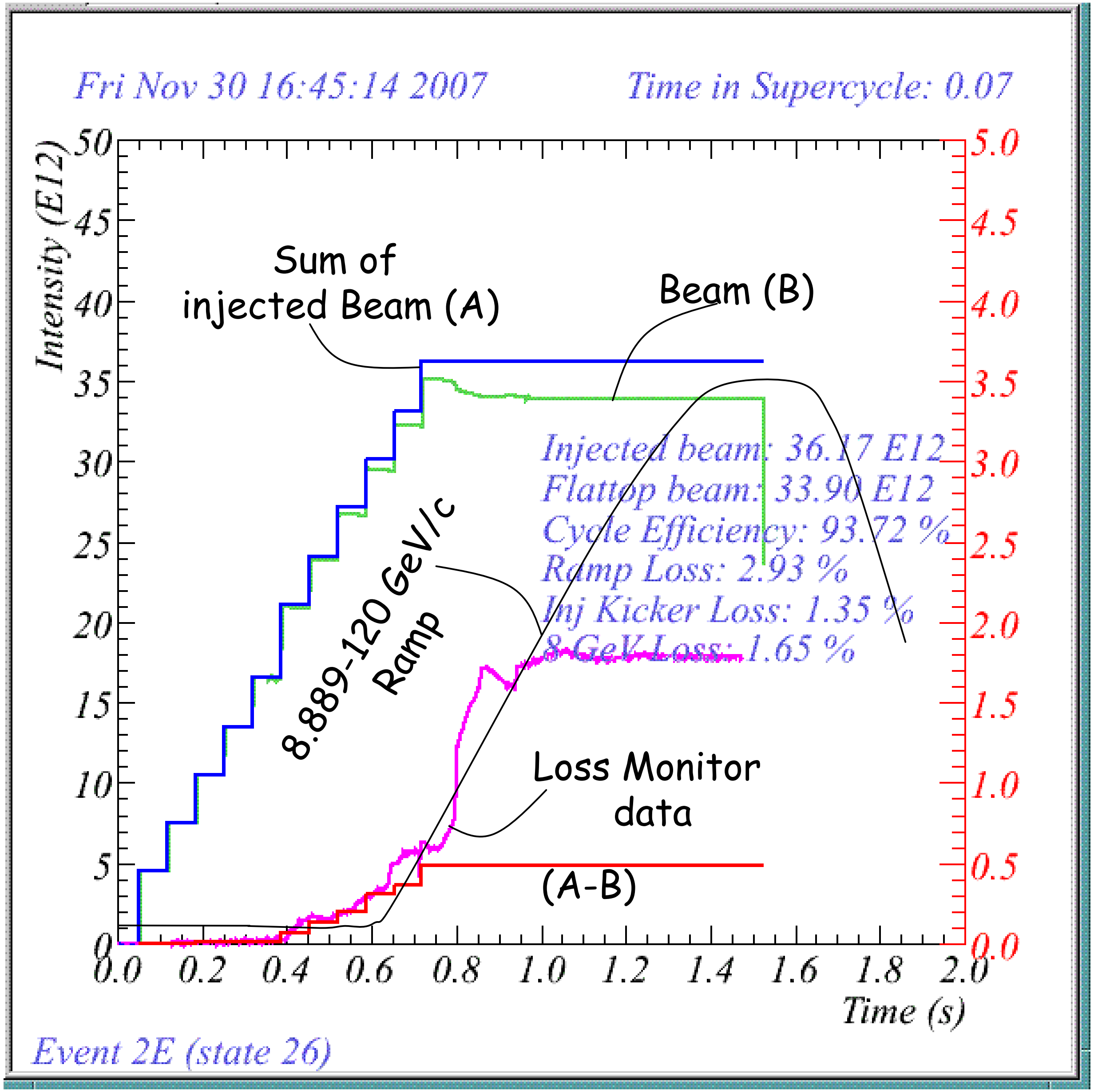
11 Batch Slip-stacking



Intensity and frequency curves

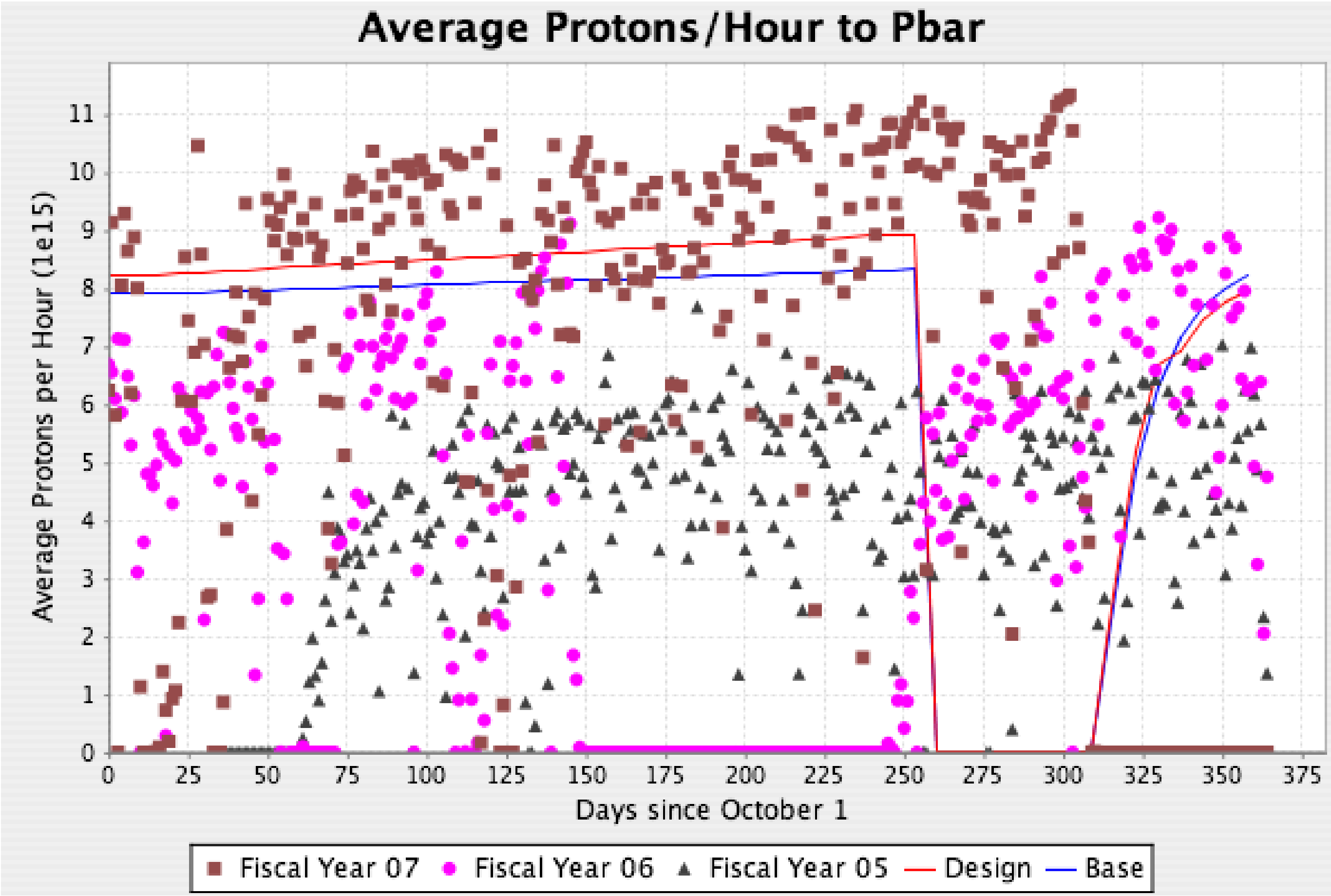


Multiple Batch Beam Acceleration



MI is originally designed for 3E13/protons batch. Current record operation has exceeded limit.

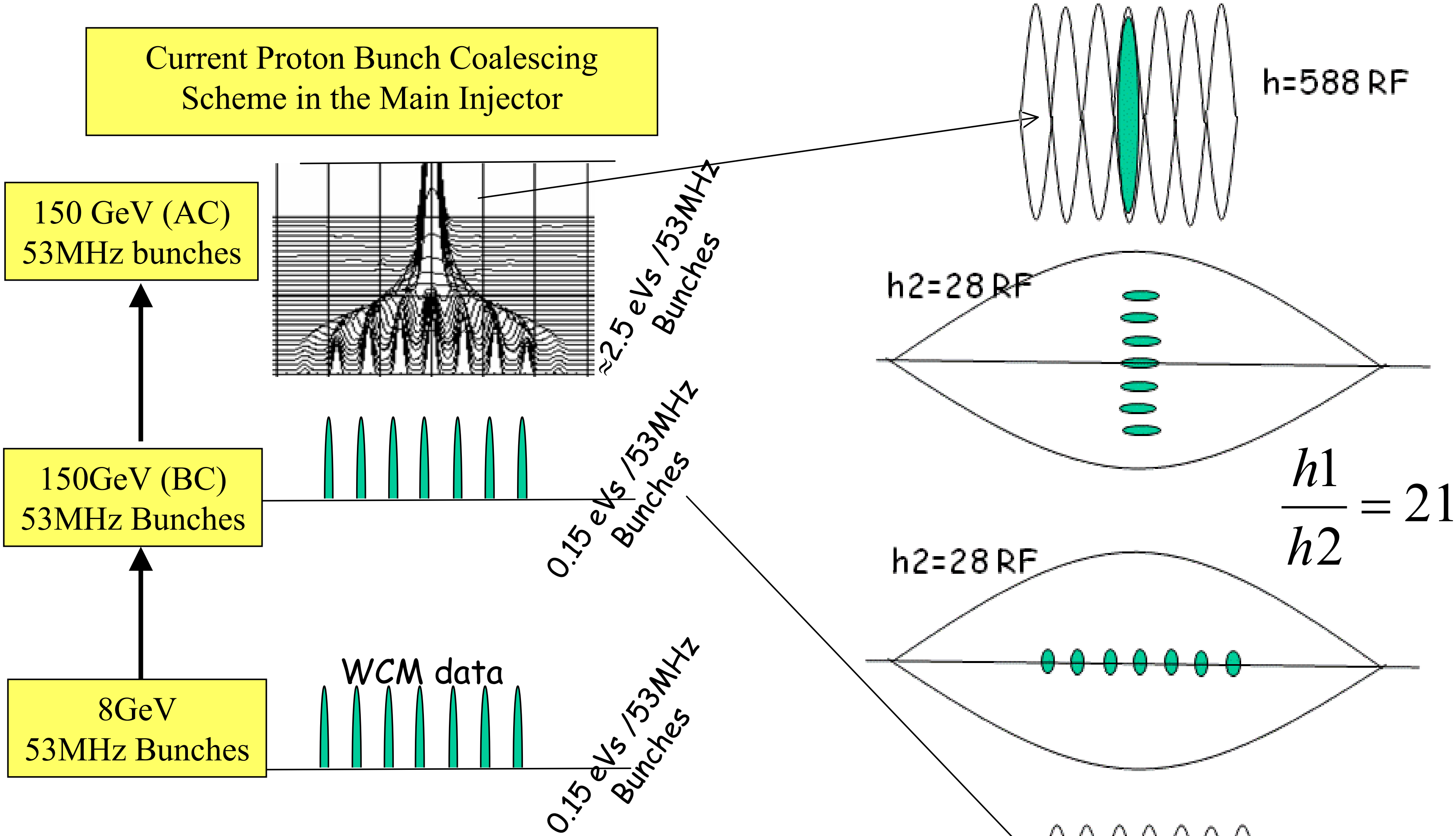
Results
Protons on Pbar Target at Fermilab

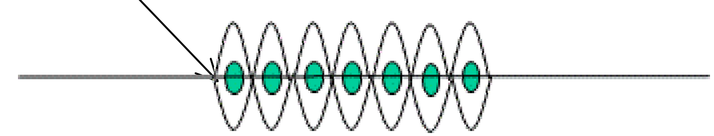


As a result of slip stacking the proton intensity went up by about 70%.

The maximum beam intensity seen is about 9E12protons/batch.
Design value was 5E12protons/batch

High Intensity Bunches by Coalescing



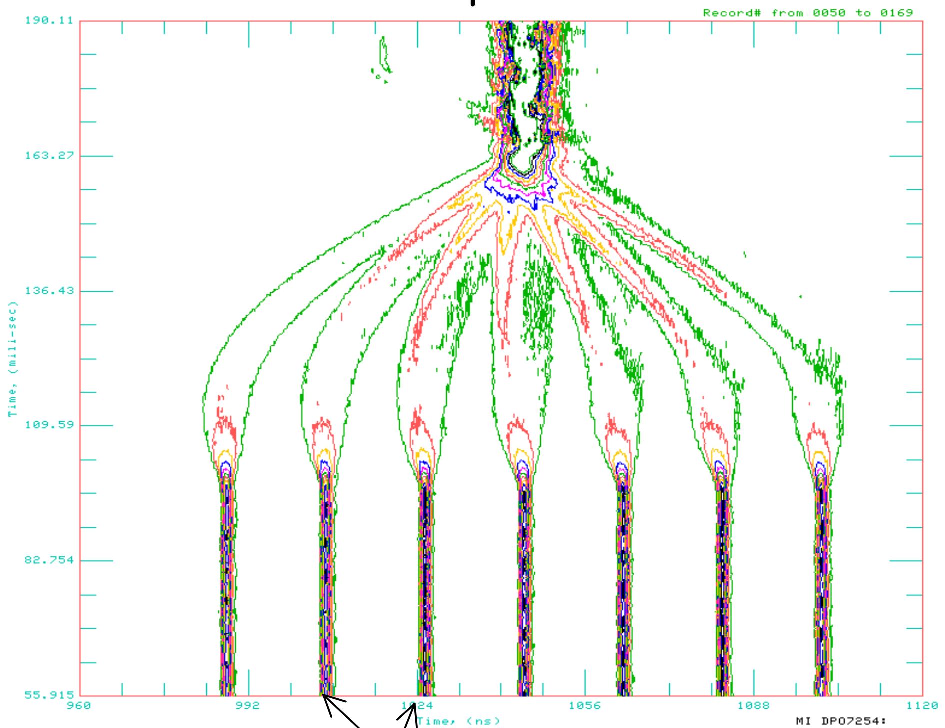


In principle there is at least 27% longitudinal emittance growth.

High Intensity Bunches by Coalescing (cont.)

Experimental Data

300E9 protons/bunch



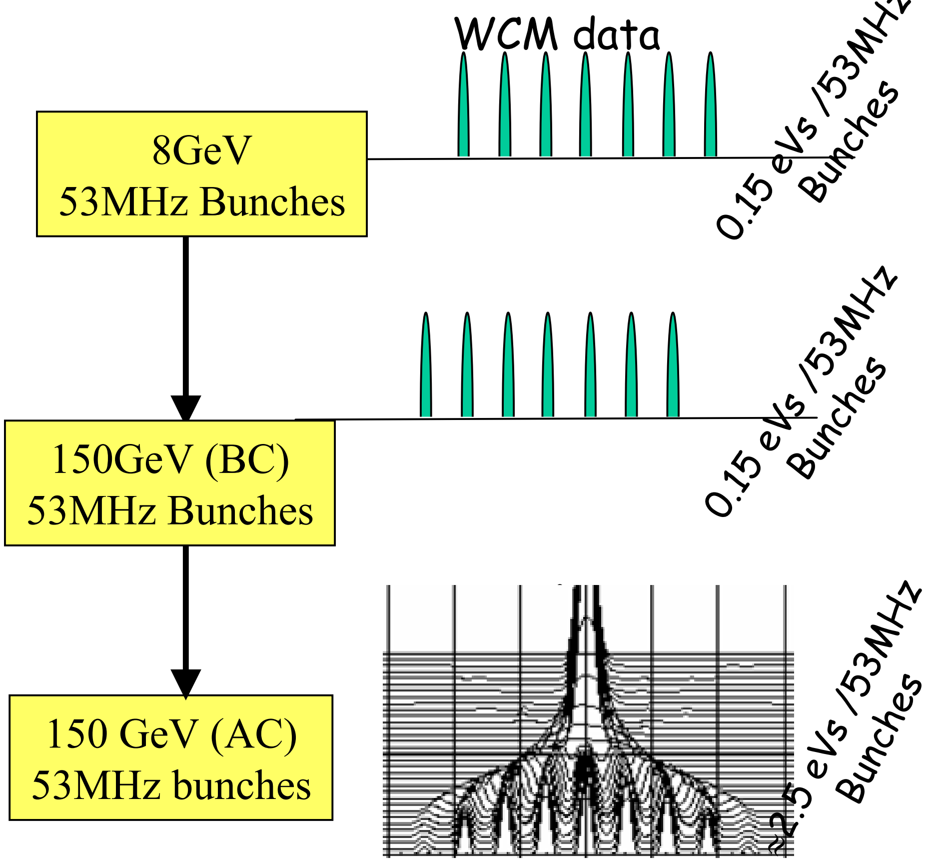
50E9 protons/bunch

<u>Results</u>

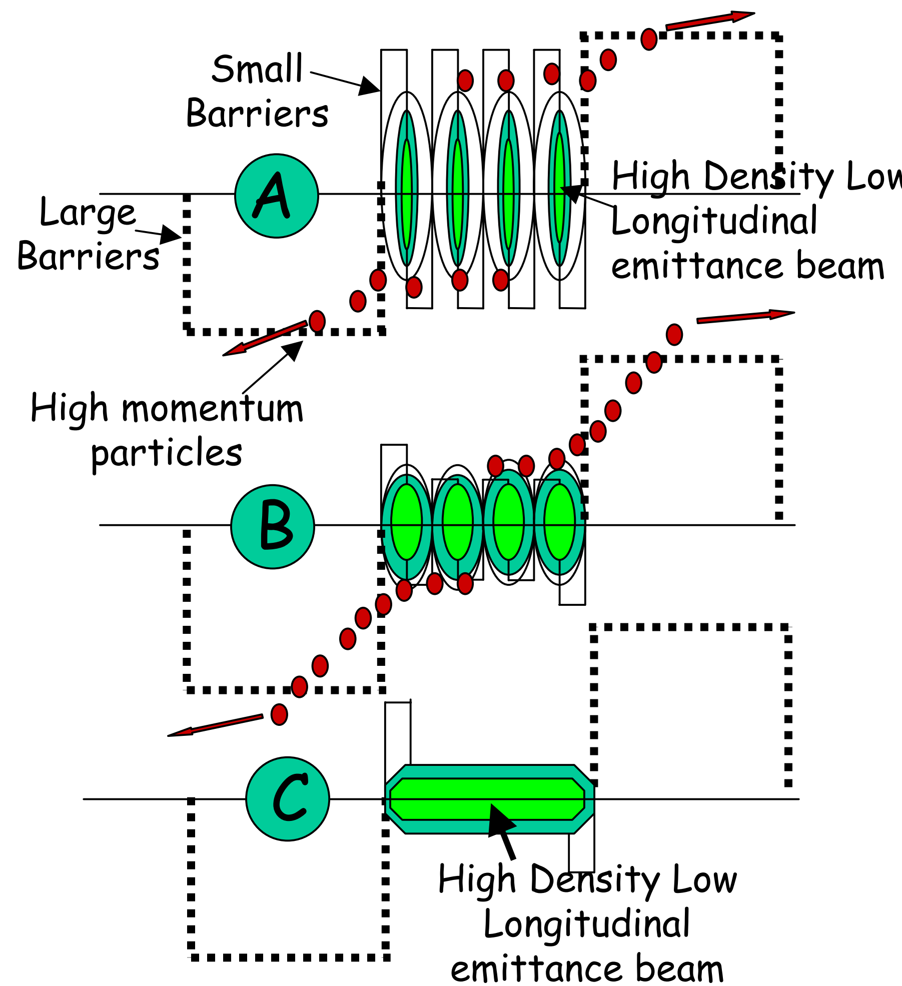
1.>200% longitudinal Emittance Growth from 8-150 GeV
2.Intensity /bunch went up by about 7 times
3.85% efficiency

Bright Proton Bunches for Future

Current Proton Bunch Coalescing Scheme in the Main Injector

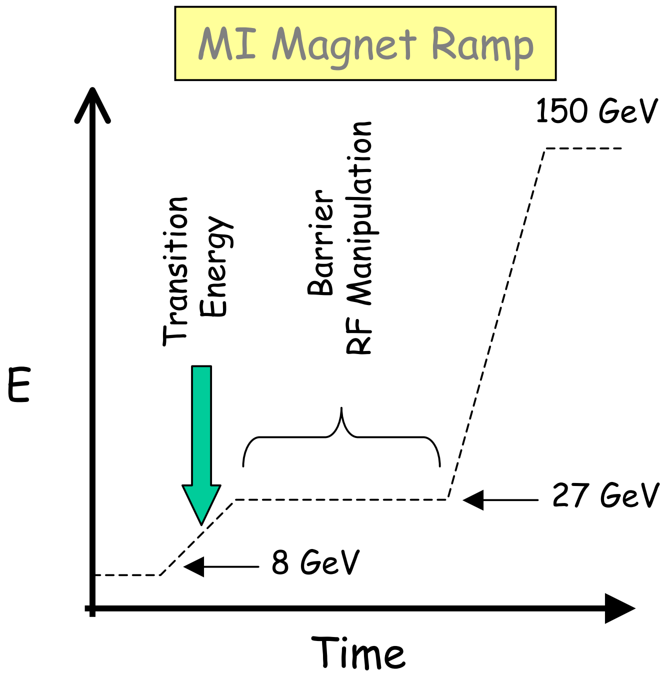


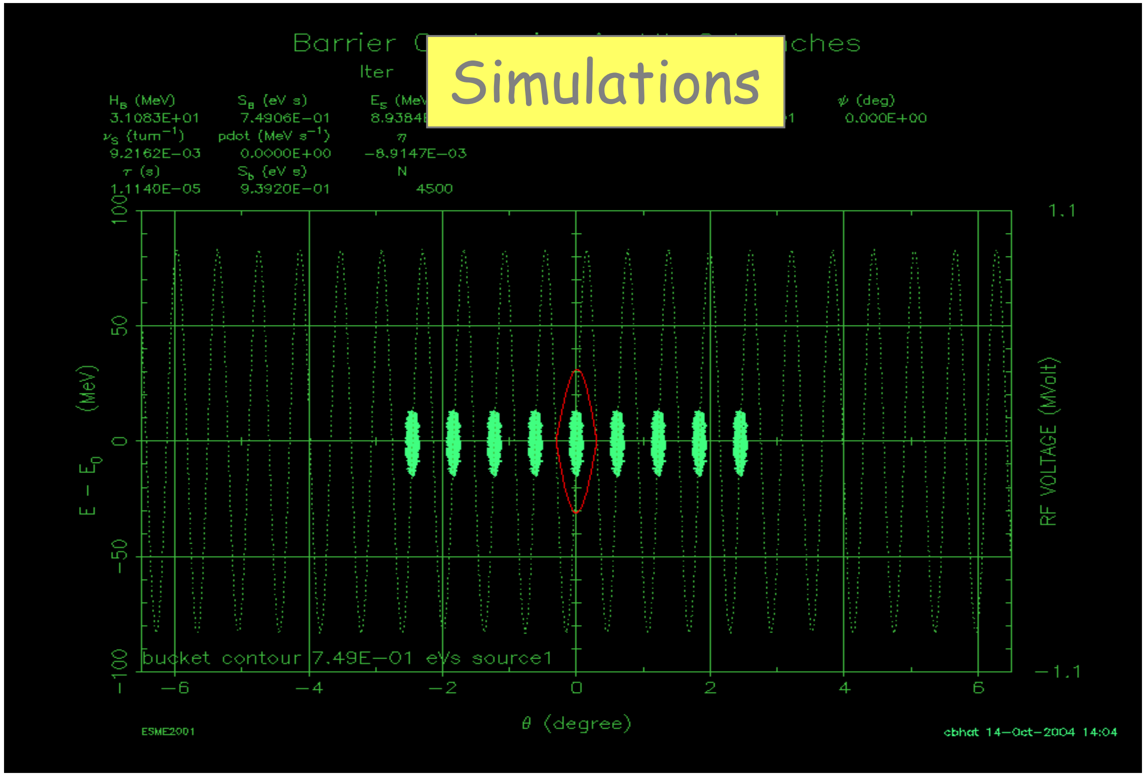
Proposed Barrier Proton Coalescing
(C. M. Bhat.FERMILAB-FN-0761-AD (October 2004))



Bright Proton Bunches for Collider Shots

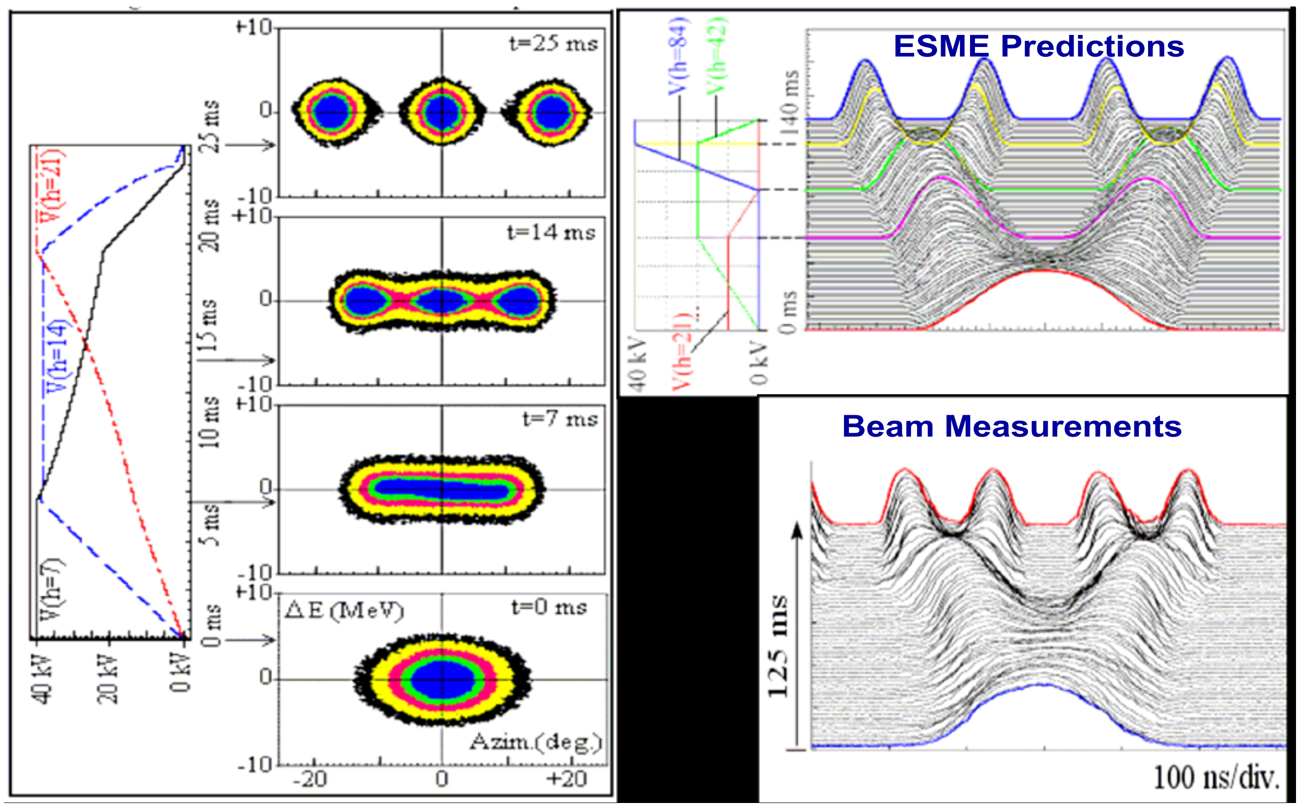
MI Barrier Coalescing





By this scheme one anticipates
- 50-100% lower longitudinal emittance proton bunches
- Better matching between p and pbar bunches
- Consequently,
  >25% increase in the collider luminosity

Bright Proton Bunches for LHC



Bunch Splitting in the CERN PS

Each bunch is split into 3-bunches at Injection
Further bunch double split is done at 25 GeV
6x3x2x2 = 72 bunches/injection to SPS
# of Injection from PS to SPS = 3
# of Injection from SPS to LHC = 13

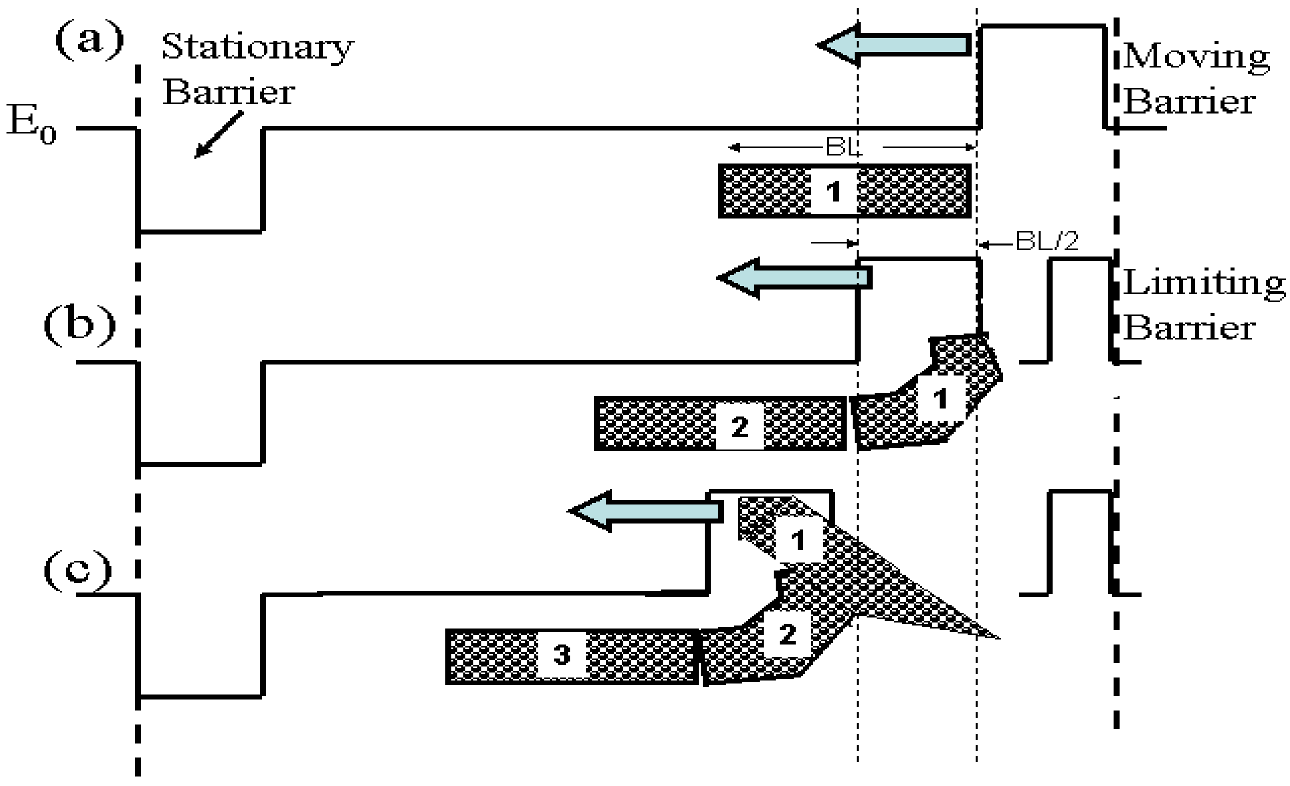
Parameters:

Number of Bunches = 2808
# of protons/bunch = 1.15-1.7x10^{11}
Transverse Emit. = 3.75pi-mm-mr
LE = 2.5 eVs

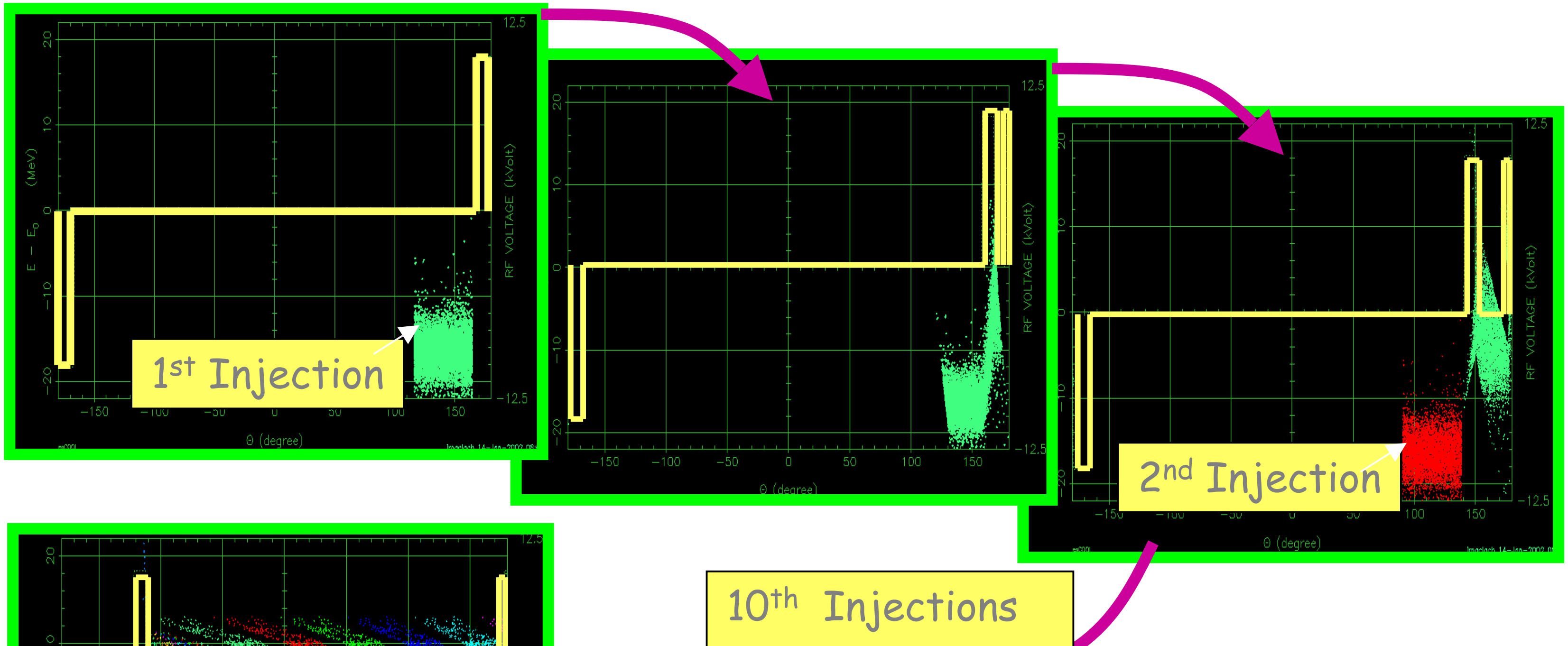
Momentum Stacking

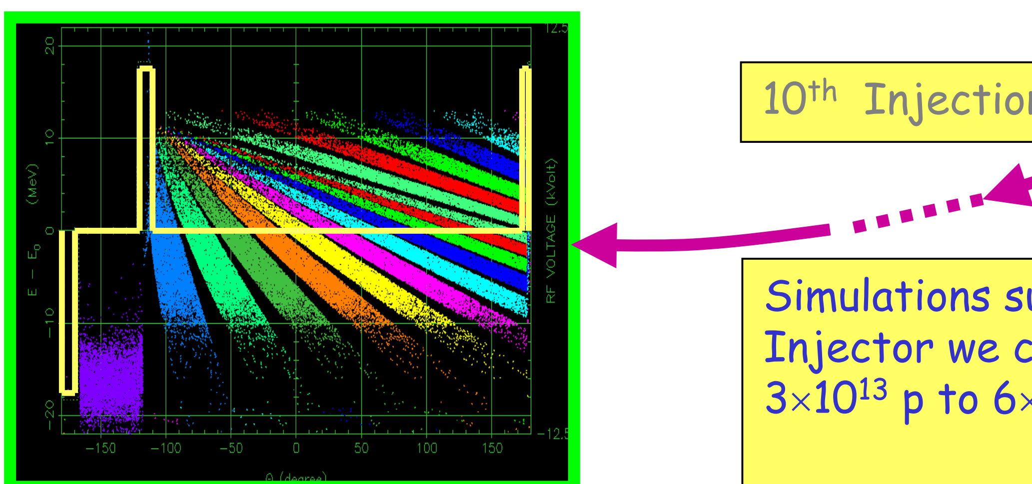
(J. Griffin-Private Communications)

Concept: Inject a batch of beam particles slightly below the synchronous energy of a circular Accelerator between a stationary and a moving barrier pulse. Confine the beam batches in a limiting barrier. And so on.



Barrier Stacking: Simulations

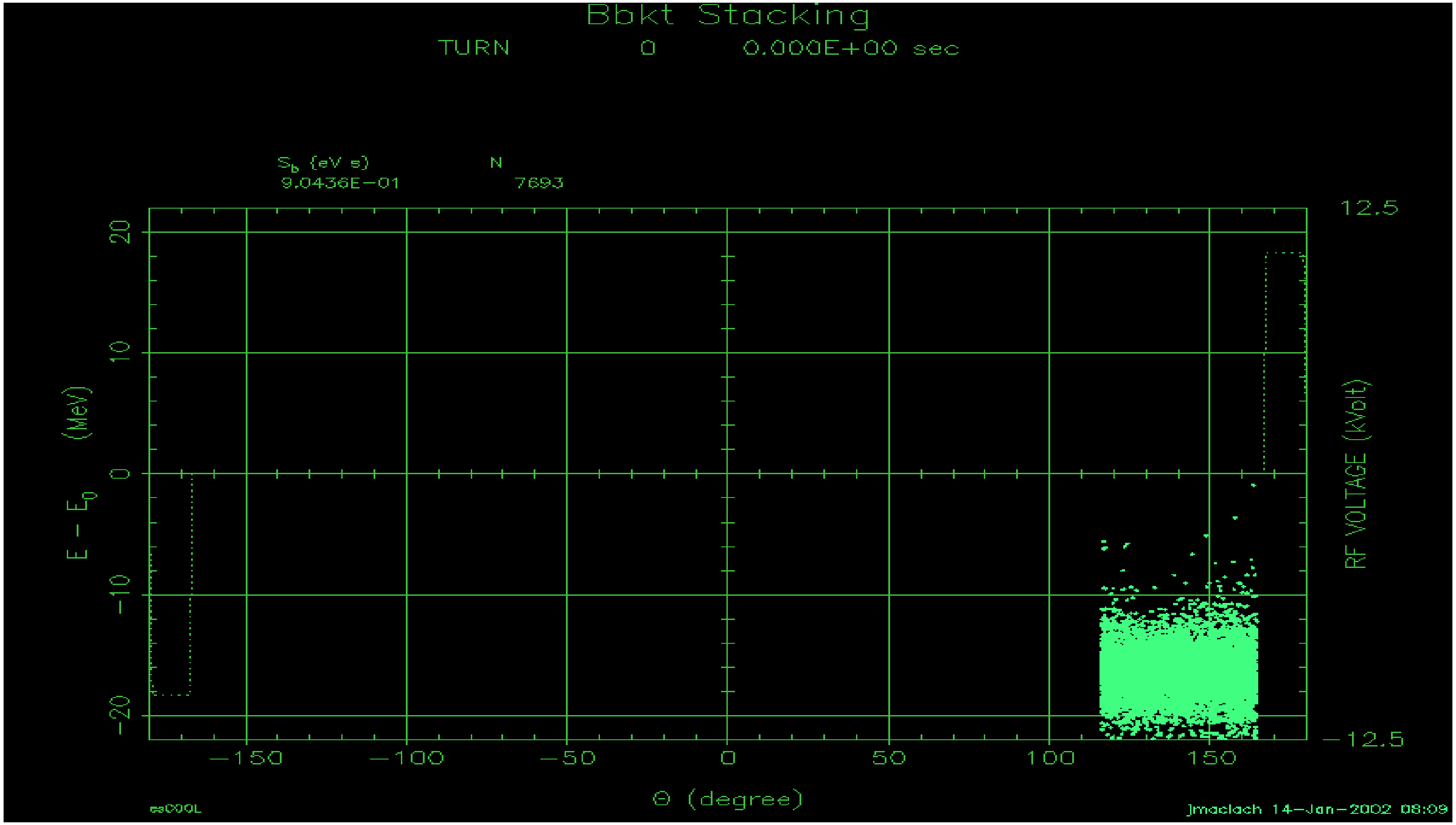




Simulations by J. MacLachlan

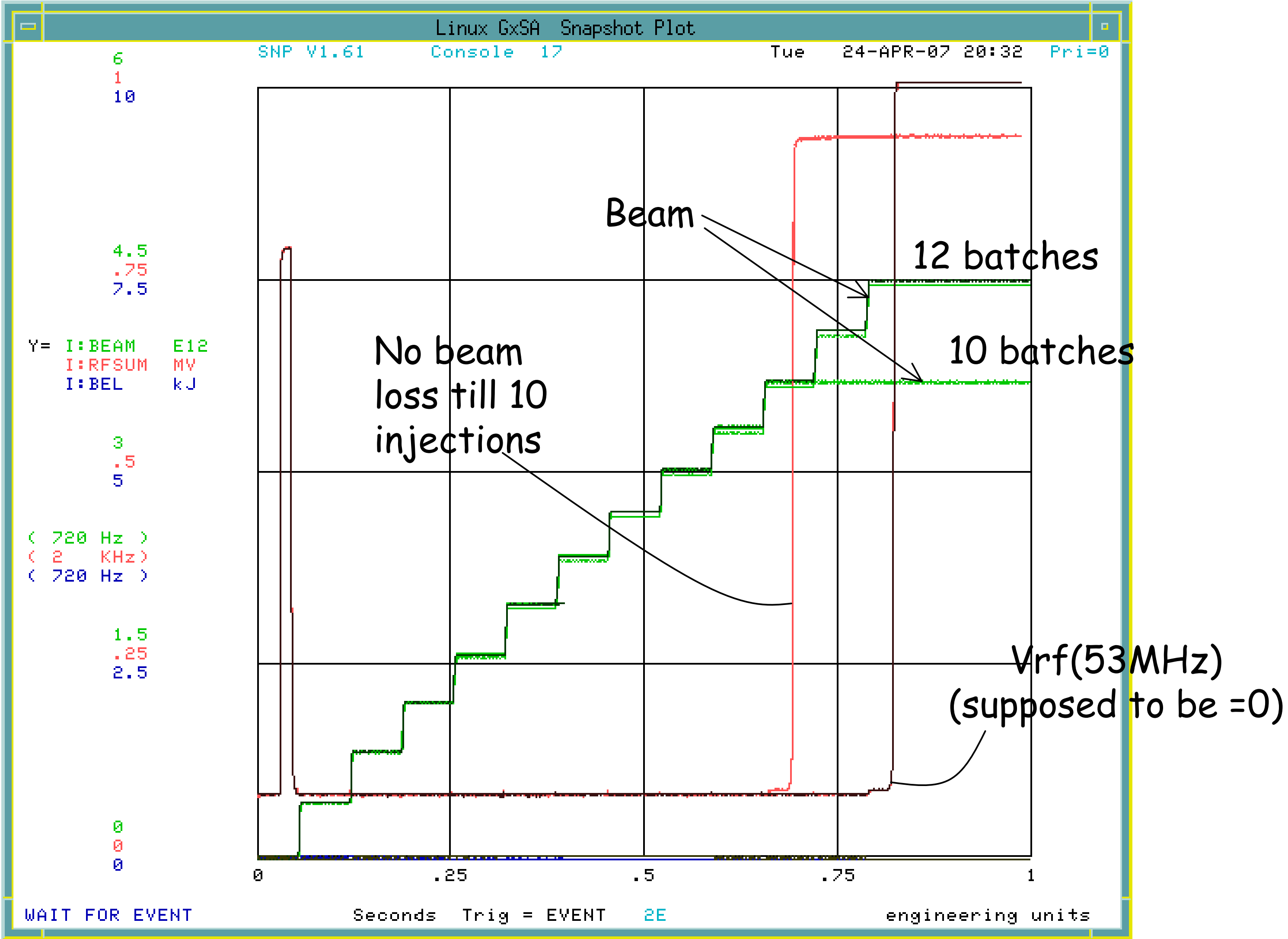
Simulations suggest that at the Fermilab Main Injector we can increase beam intensity from 3×10^{13} p to 6×10^{13} p per acceleration cycle.

Barrier Stacking, ESME Simulations
(J. MacLachlan, 2003)



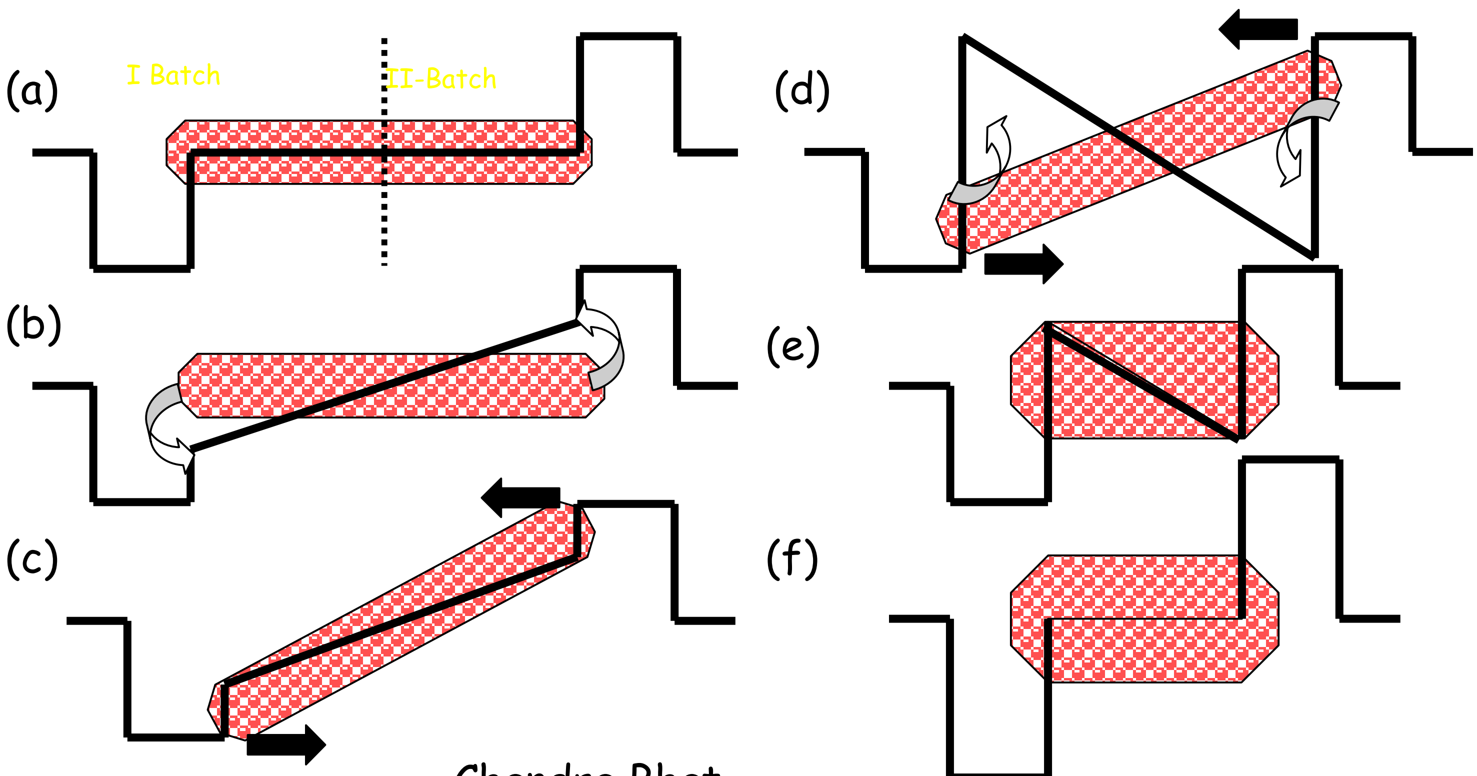
Barrier Stacking Beam Experiment

(Dave Wildman, W. Chou, J. Griffin)

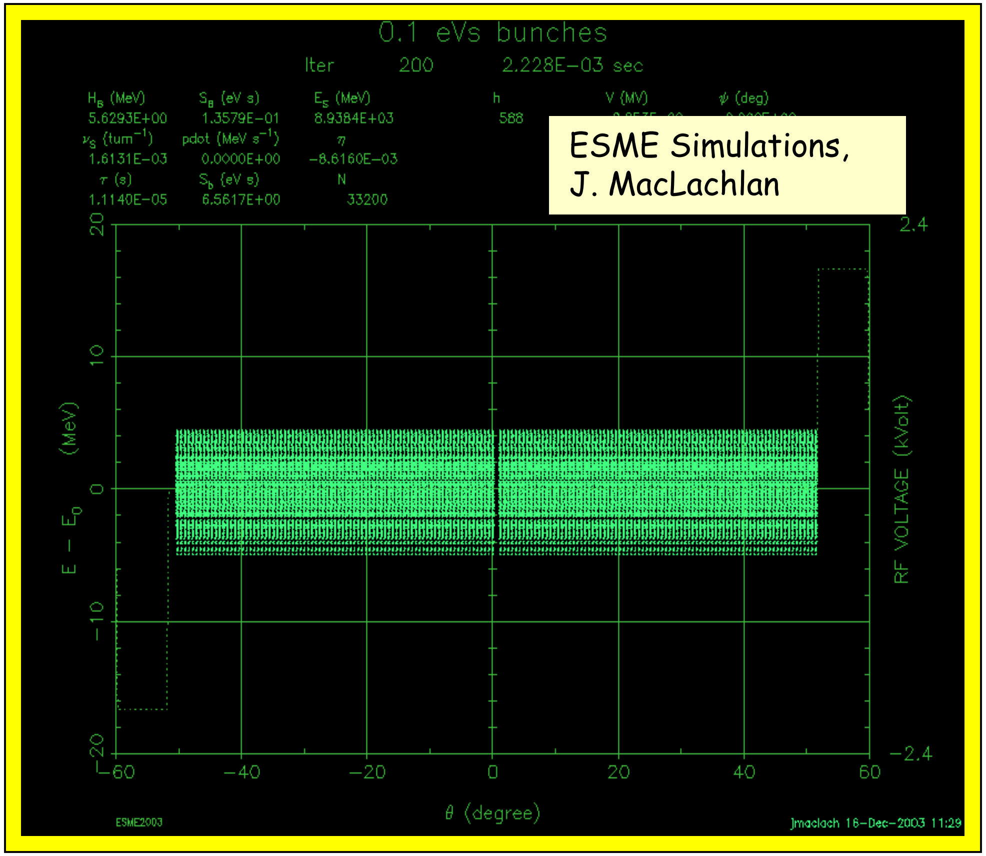


Fast Bunch Compression
(W. Foster, et. al., EPAC2004, page 1479)

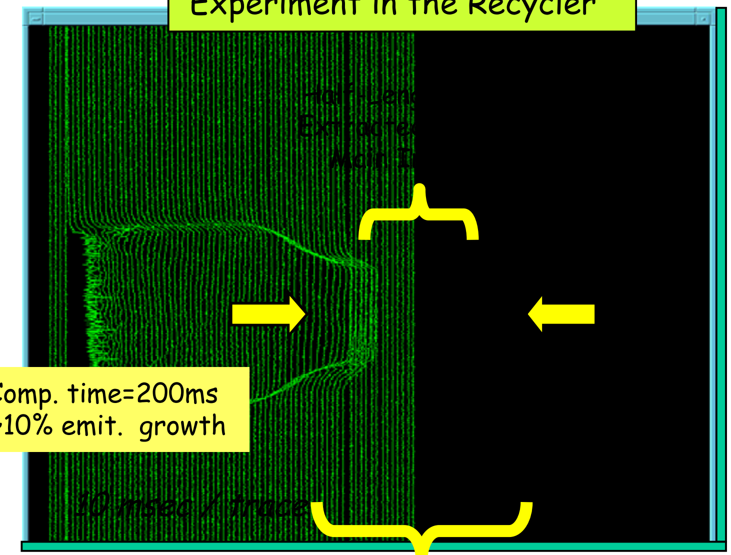
Concept: Fast rotation of a bunch about rf stable and unstable points.



Flip-flop Technique: Simulations and Demonstration



Experiment in the Recycler



Injected Batch from Main Injector,
Bunch Length=1.59 μsec

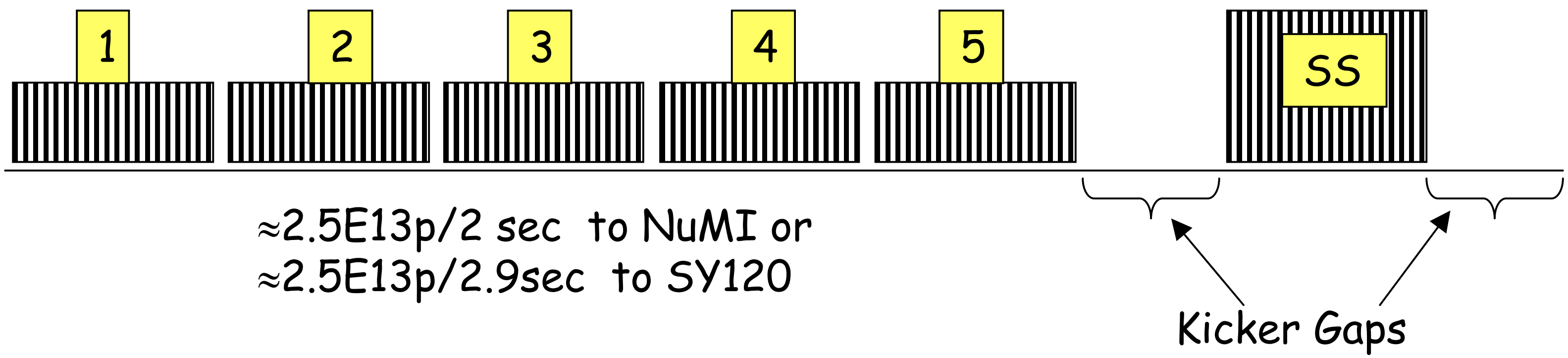
- Longitudinal emittance is preserved to 10-15% here as compared with 100% growth in slip-stacking
- However is an alternative to the present slip stacking.
- Potential scheme for high intensity for neutrino program.

Slip-stacking and proton Beam for the Fixed Target Experiments

For the Last One Year: (Mixed Mode Operation)

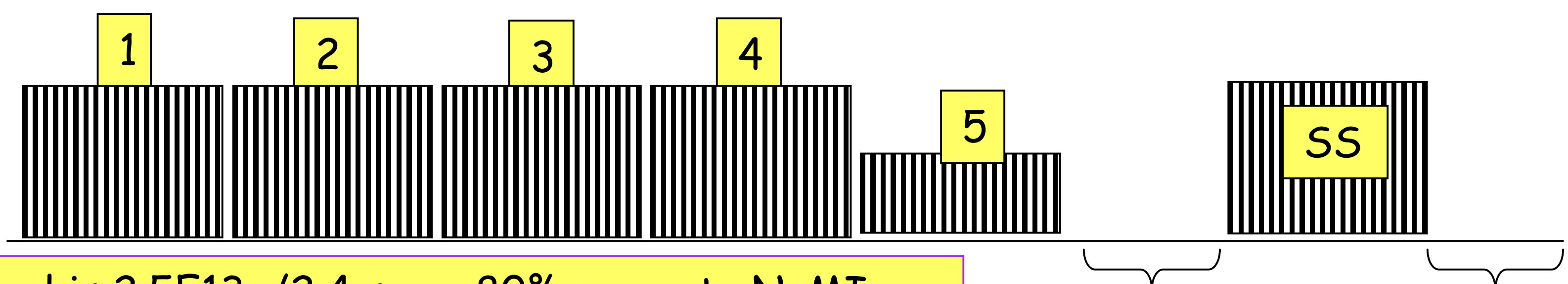
Beam to Fixed Target Experiments (NuMI and SY120)

Beam to pbar-target



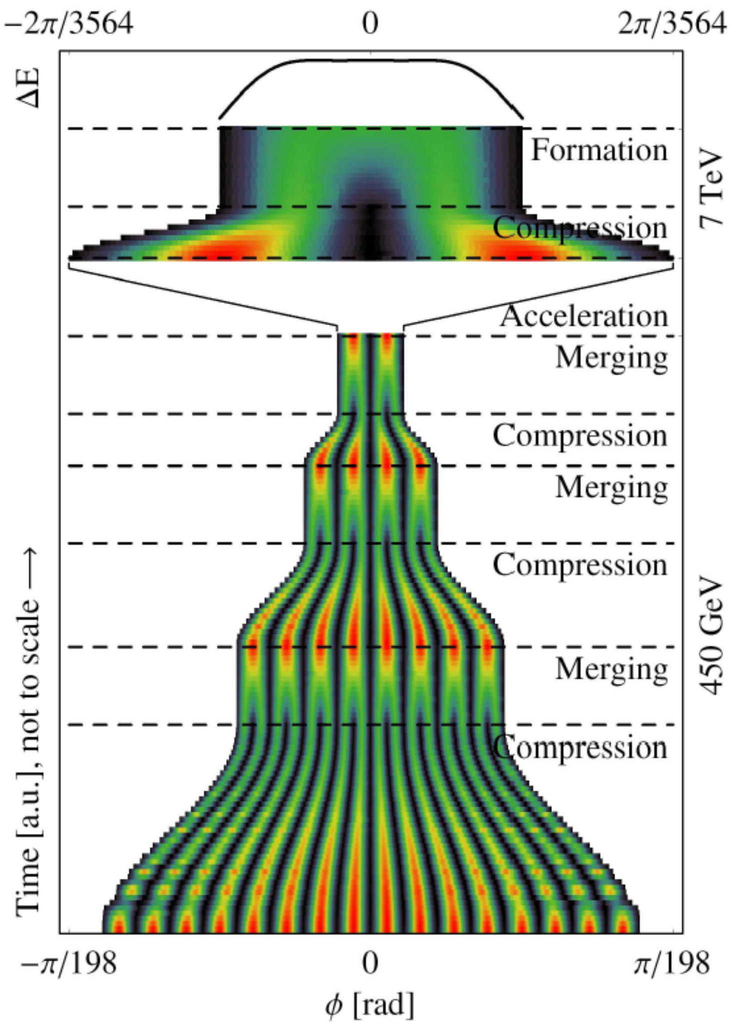
≈2.5E13p/2 sec to NuMI or
≈2.5E13p/2.9sec to SY120

Future Possibility: (Demonstrated)



Goal is 2.5E13p/2.4 sec + 80% more to NuMI or
and 2.5E13p/3.3 sec + 80% **more** to SY120

Bright Proton Bunches for LHC

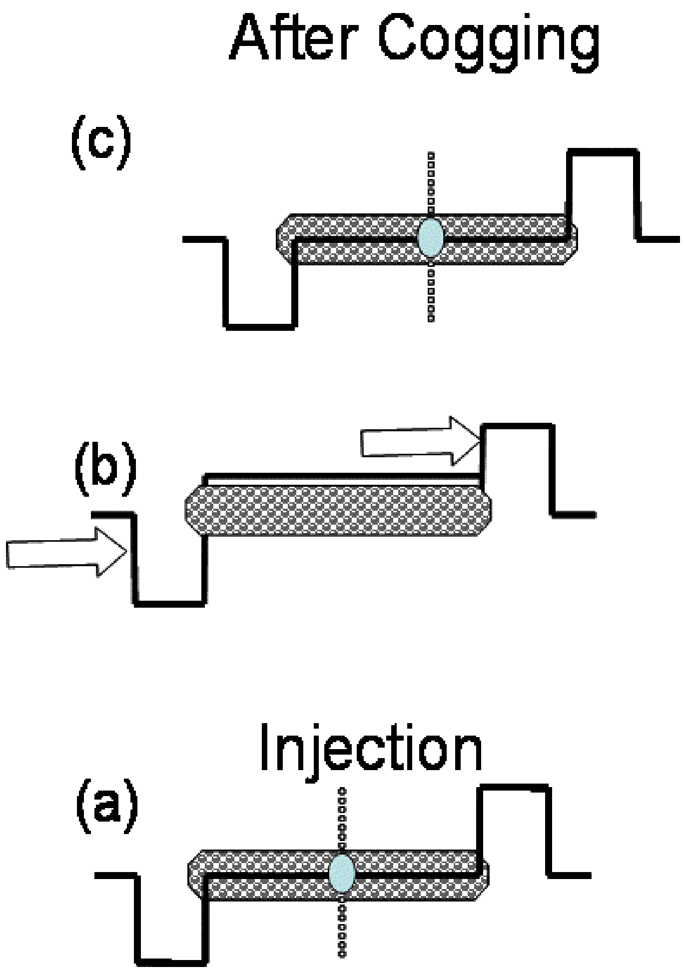


H. Damerau and R. Garoby, EPAC2004 (2004) p1852

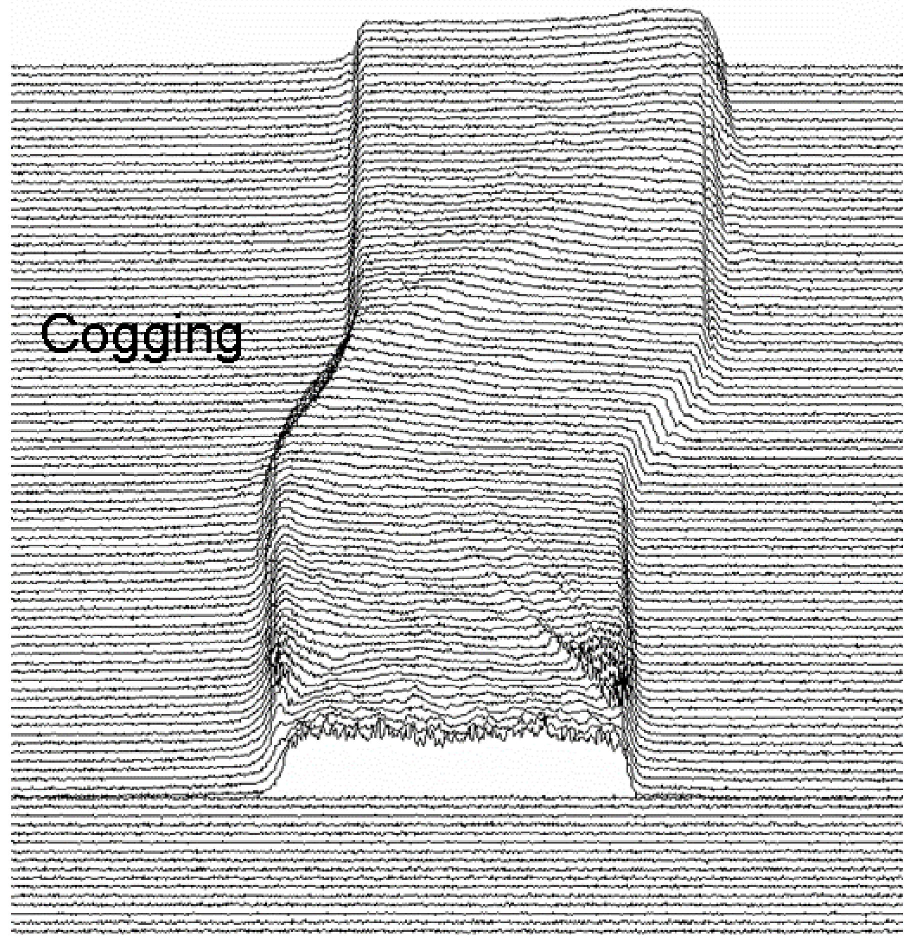
- Uses several RF systems of sub-harmonic
- Bright bunches are produced by bringing several bunches together slowly

Beam Cogging and some Gymnastics

Schematic View

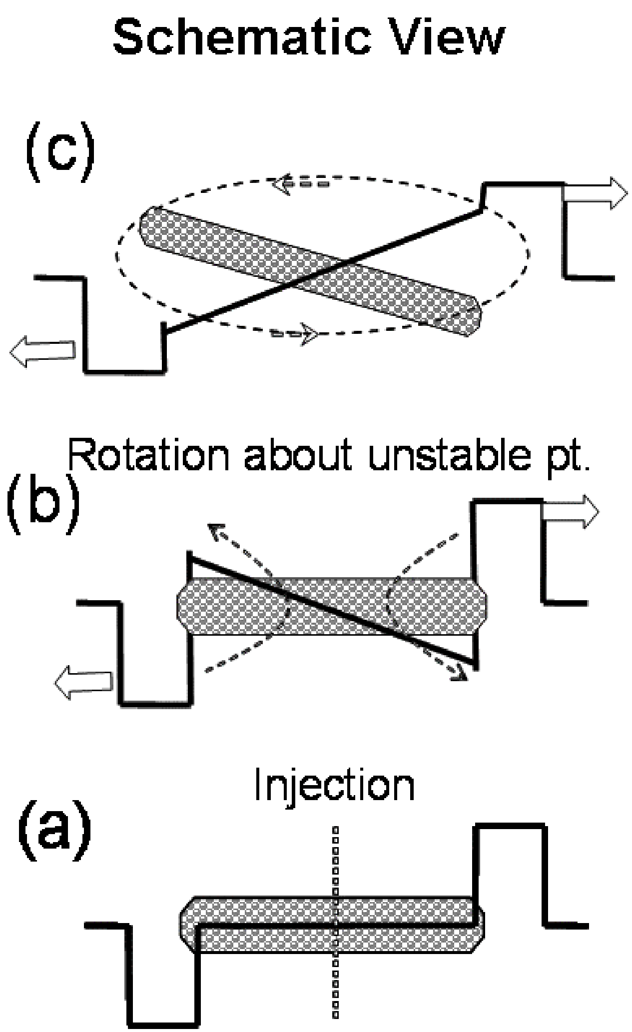


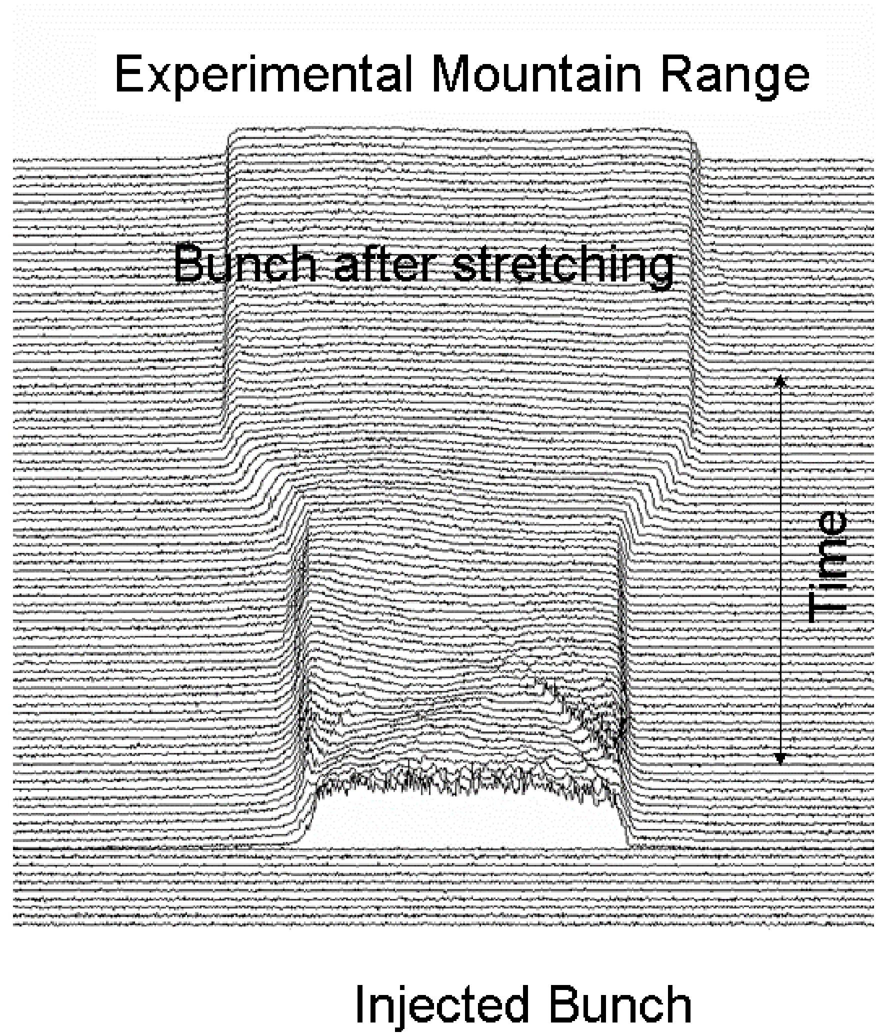
Experimental Mountain Range



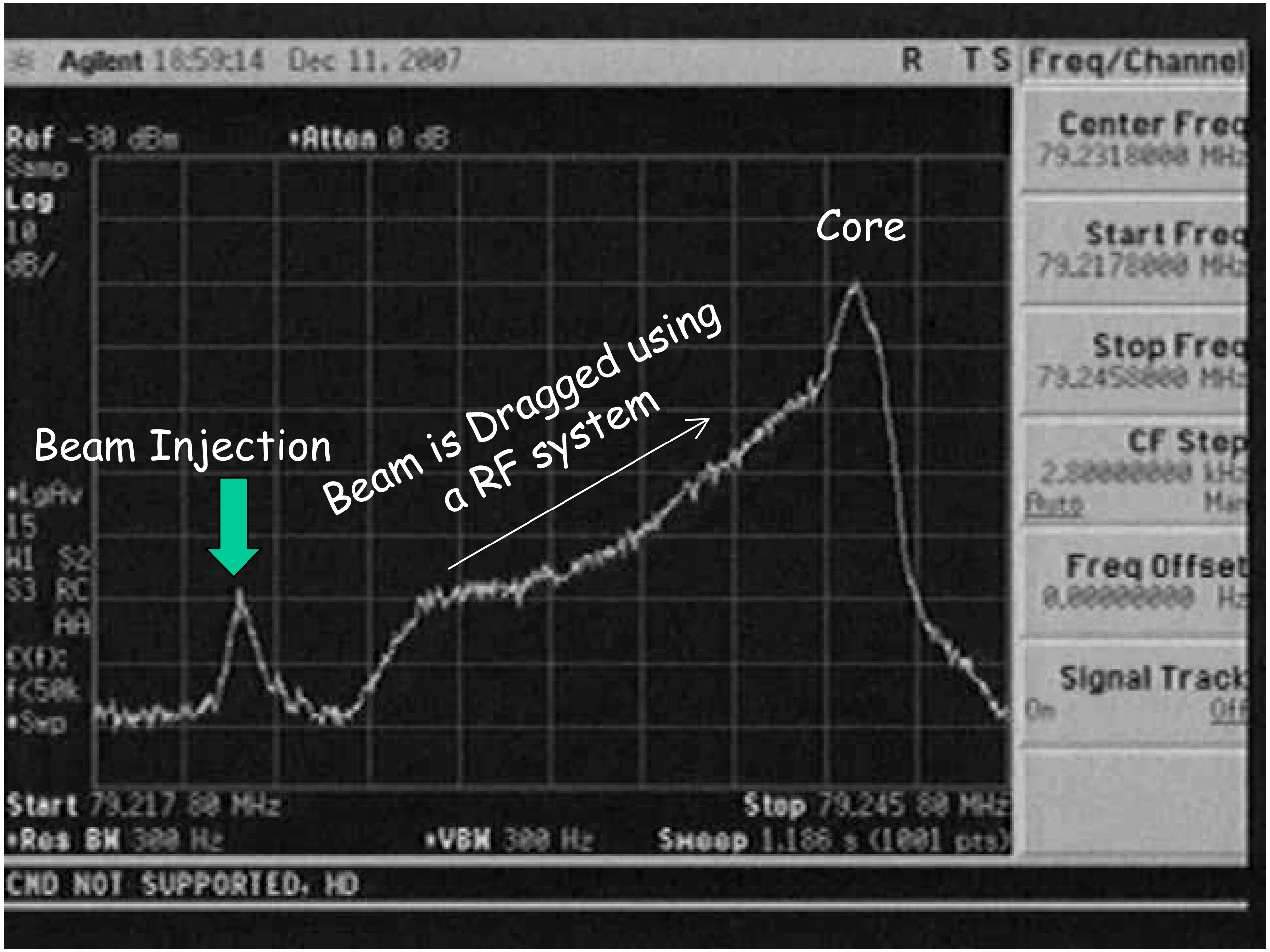
Injected Bunch

Beam Cogging and some Gymnastics



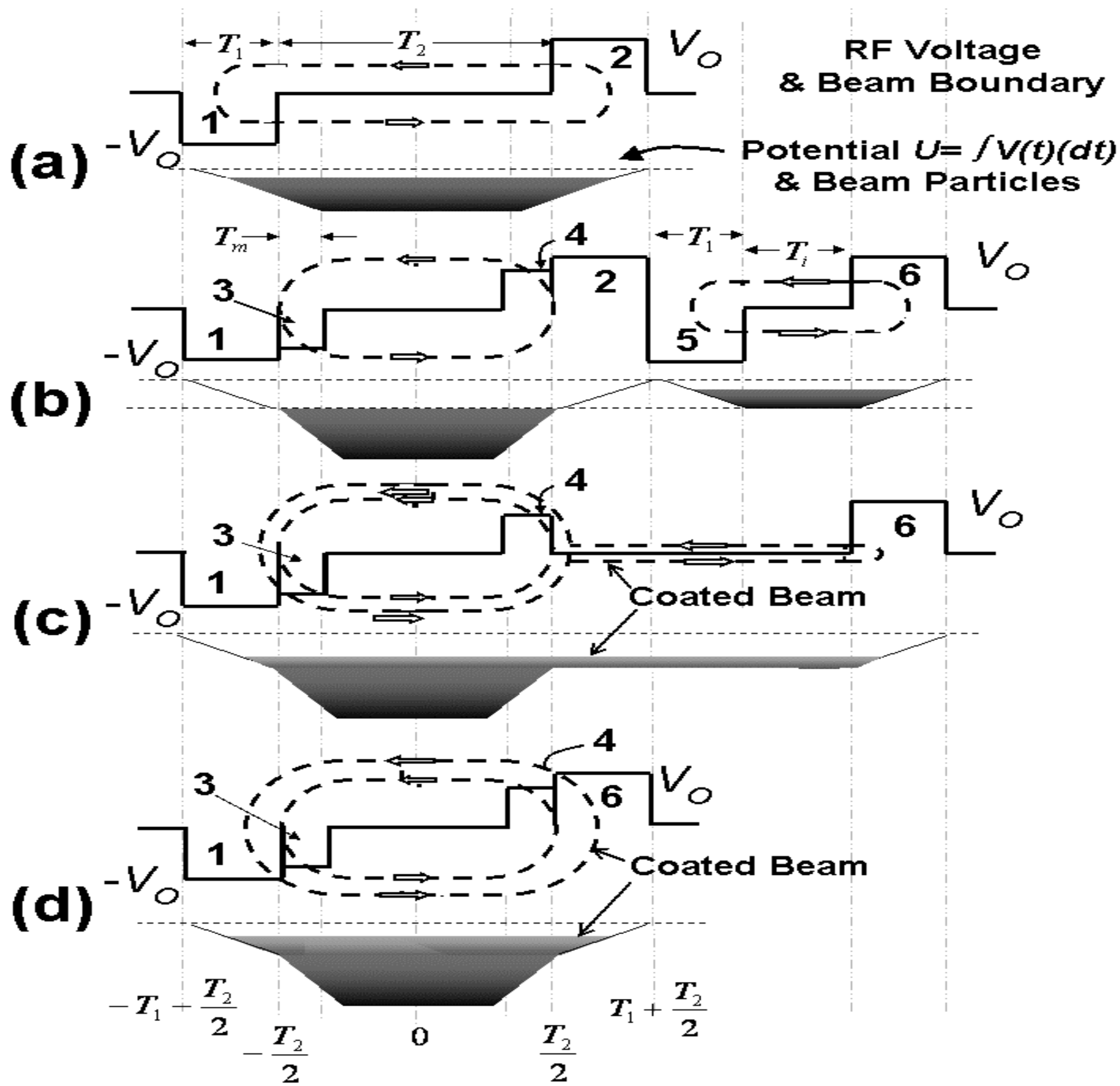


Van der Meijer stacking



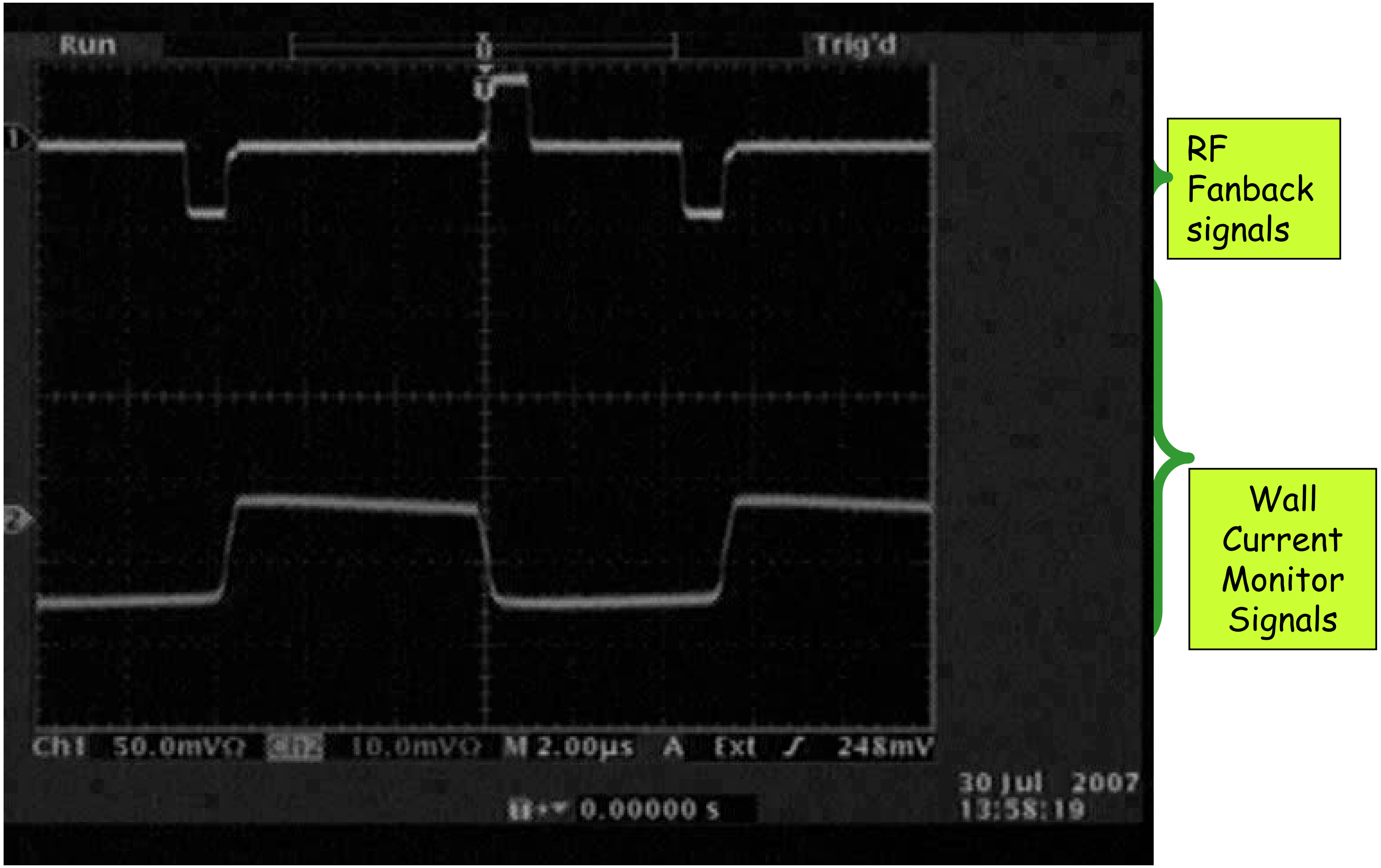
Longitudinal Phase-Space Coating

C. M. Bhat (2005, unpublished)



Longitudinal Phase-Space Coating

C. M. Bhat (2005, unpublished)



By this scheme we anticipate that the total beam stacked would be in excess of 600E10 antiprotons in the Recycler which can be used for the Tevatron collider operation.

Final Remarks

Hope that I was able to convey

1. Basics of accelerator physics
2. Practical aspects and
3. Recent developments

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