LONGITUDINAL EMITTANCE MEASUREMENTS IN THE FERMILAB RECYCLER RING BARRIER BUCKETS

C.M. Bhat and J.P. Marriner
Fermilab

PAC2003

Acknowledgements

Ming-Jen (Wall Current Monitor data taking program)

A. Cadorna and B. Fellenez (Gated Current Integrator)

Martin Hu and Dan Broemmelsiek (Schottky detectors)

Dave Wildman

Joe Dey (HLRF)

Brian Chase (LLRF)

Jim MacLachlan (simulations)

Cons Gattuso

Motivation

- ➔ The Recycler is a new pbar storage ring for future **ppbar** collider operation
- ➔ The Recycler uses rf barrier buckets extensively for all beam manipulations such as stacking, un-stacking and storage of pbars
  - Need to measure beam emittance in barrier buckets!

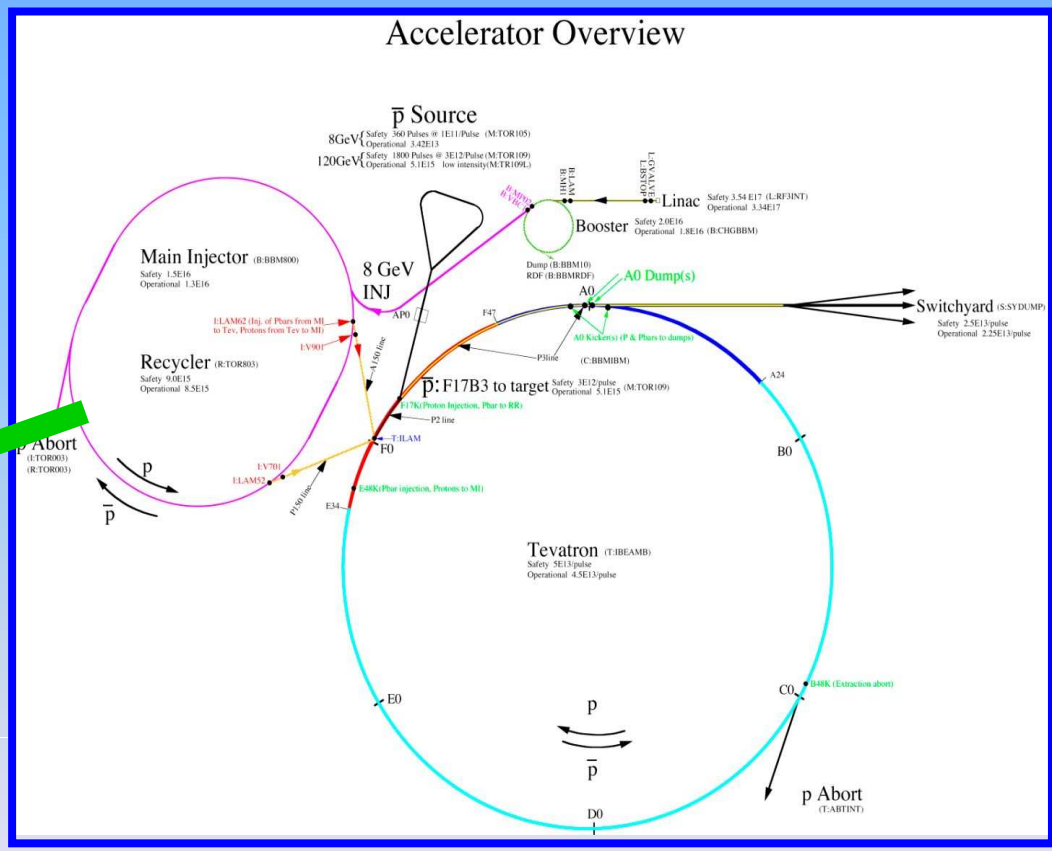
    ← Key to understanding the longitudinal beam dynamics

    ←necessary to achieve improvements for higher luminosity in the ppbar collider

  - We have explored two destructive and two non-destructive methods for longitudinal emittance measurements.

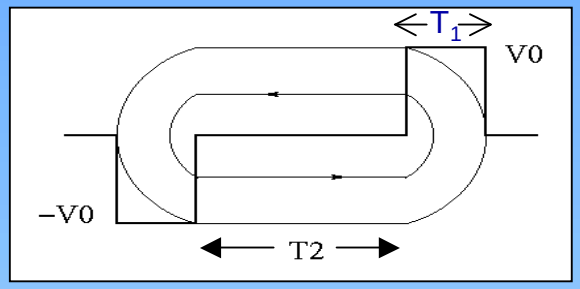
Fermilab Accelerators & Recycler Ring

- **The Recycler is located in the Main Injector tunnel and is directly above the Main Injector.**



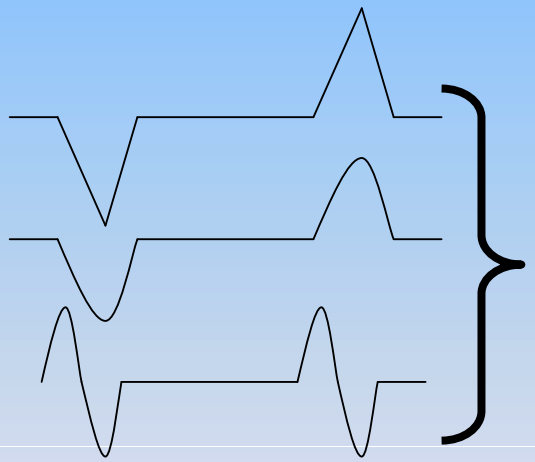
Barrier Buckets in a Nutshell

Choice of Barrier Buckets



RR runs below Transition Energy

V_0=2kV
$(T_1)_{min}$≈100ns



Other standard Barrier forms

Equation of Motion

$$\frac{\Delta T}{T_0} = \eta \frac{\Delta E}{\beta^2 E_0},$$

$$\frac{d(\Delta E)}{dt} = \frac{eV(\tau)}{T_0}.$$

For an Arbitrary Barrier Pulse

$$H = -\frac{\eta}{2\beta^2 E_0}(\Delta E)^2 - \frac{\int_0^\tau eV(\tau)d\tau}{T_0}$$

$$\Delta E_b = \left(\frac{2\beta^2 E_0}{|\eta|}\frac{\left|\int_{T_2/2}^{T_2/2+T_1} eV(\tau)d\tau\right|}{T_0}\right)^{1/2}$$

For a Rectangular Barrier Pulse

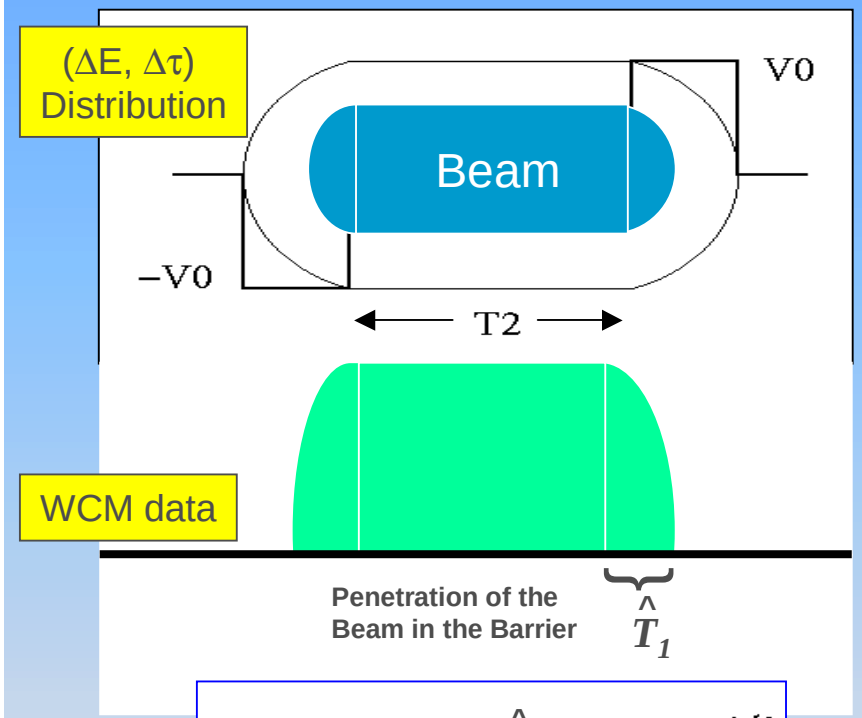
$$A = 2T_2\Delta E_b + \frac{8\pi|\eta|}{3\omega_0\beta^2 E_0 eV_0}(\Delta E)_b^3.$$

$$\Delta E_b = \left(\frac{eV_0T_1}{T_0}\frac{2\beta^2 E_0}{|\eta|}\right)^{1/2}$$

RR Machine Parameters

RR Beam Energy	8 GeV
Slip Factor $\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2}$	-0.0087
Revolution Period T_0	11.126 μs
Barrier Pulse Width T_1	0.908 μs

Longitudinal Emittance



Half Height

$$\Delta\hat{E}_b = \left(\frac{eV_0\hat{T}_1}{T_0}\frac{2\beta^2 E_0}{|\eta|}\right)^{1/2}$$

$$\mathcal{A} = 2T_2\Delta\hat{E}_b + \frac{8\pi|\eta|}{3\omega_0\beta^2 E_0 e V_0}(\Delta\hat{E}_b)^3.$$

Longitudinal Emittance- ε_l, is Phase-space Area occupied by all the beam particles in (ΔE,$\Delta\tau$)-space.

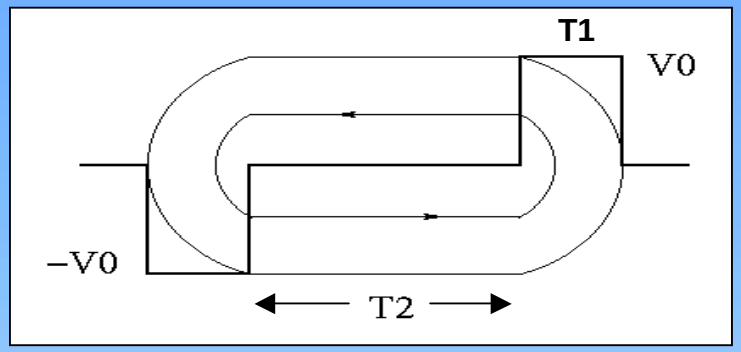
For the beam in a Barrier Buckets shown here the ε_l is sum of two quantities

⇒emittance in linear region where Vrf=0 V

⇒emittance in barrier pulse characterized by beam penetration T_1

Measure the ΔE of the beam and determine the longitudinal emittance.

Destructive Methods



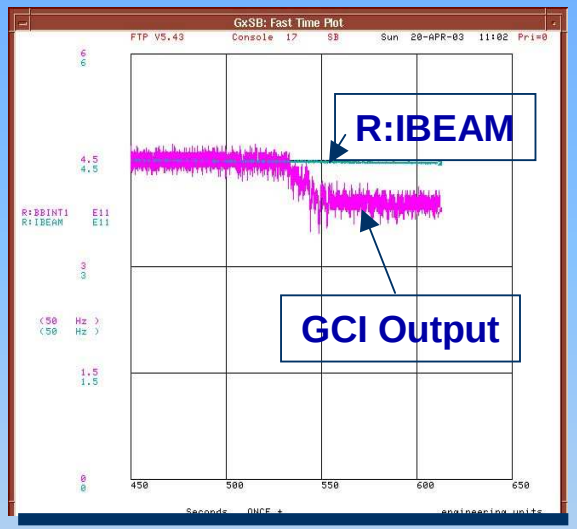
- Two Methods
  - **Matching Beam Area to Bucket Area**
    - *Needs ability to change **Vo** and/or **T1** in a controlled way*
    - *Requires ability to measure the beam intensity in the barrier buckets*

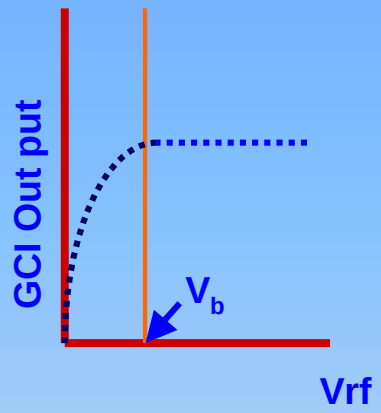
    (A.Cadorna et al, WPPE011)
  - **Fast De-bunching of the Beam**
    - *Turn-off the rf barrier pulse and measure the de-bunching time.*

- Limitations: These are one-time measurements. Hence can be used only for cross calibration and are not useful in routine operation.

Examples of Destructive Methods

Matching Beam Area to Bucket Area





V_b and T_1 give the ΔE

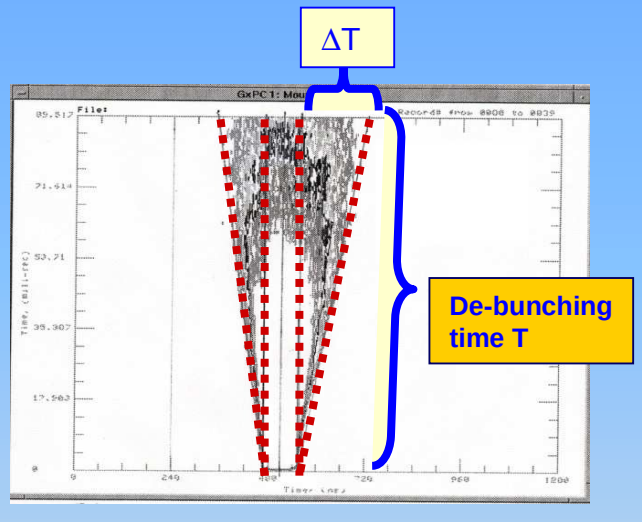
V_b, T_1 and T_1 give **beam area**.

Data shown here :

V_b = 80V
T_1 = 908ns
ΔE_b = 3.65MeV
ε_l = 20eVs

First method used to observe the effect of MI HEP Acceleration Cycles on RR stored Beam

Fast De-bunching



V_0 of the Barrier bucket is turned off at a Rate >> de-bunching time T

$$\Rightarrow \quad \frac{\Delta p}{p} = \frac{\beta^2}{\eta}\frac{\Delta T}{T}$$

Data shown here

ΔT~ 50nsec
T~ 90msec
Δp ~ 1.64MeV

Non-destructive Techniques

➔ **W**all **C**urrent **M**onitor Measurements: The "good-old" method –used at almost all laboratories.

- Measures image current of longitudinal profile of the beam
  - ☞ *a broad-band resistive wall current monitor*
  - ☞ *a wave runner or a digitizing scope to collect the beam signals from the **WCM***

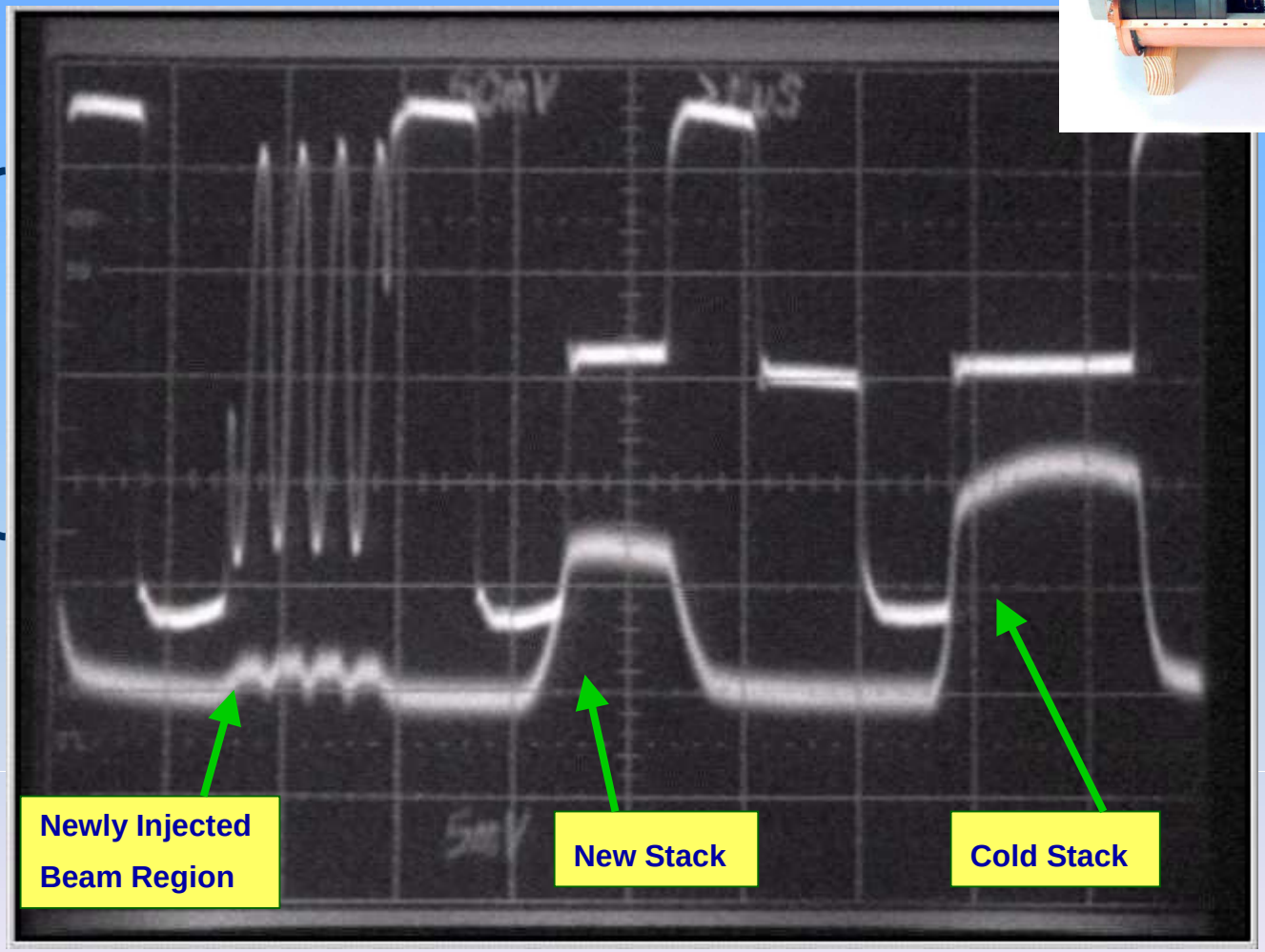
➔ **Schottky** Signal Measurements:

- Measures Schottky spectrum
  - ☞ *high frequency Schottky detector*
  - ☞ *spectrum analyzer to measure the frequency spread of the beam .*

WCM data
RR Beam Scenario

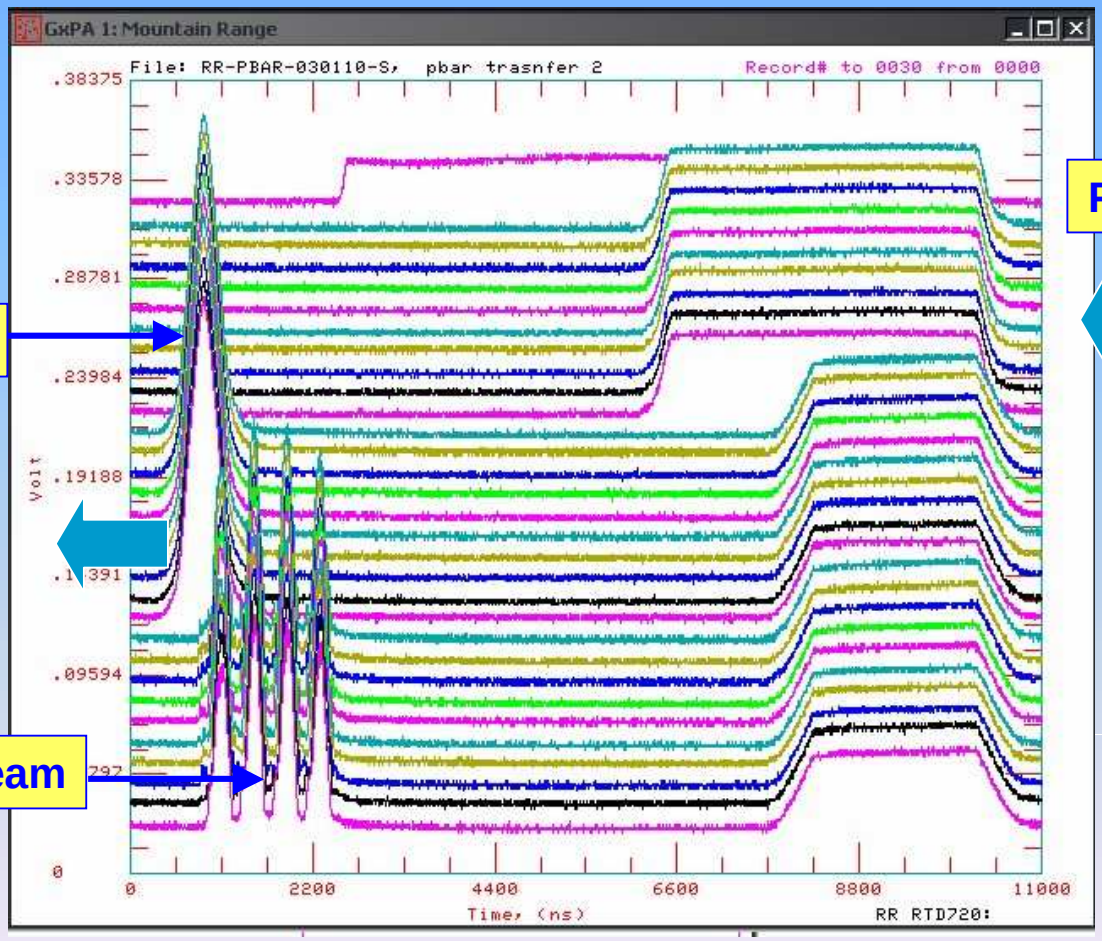
RF Fanout signal

WMC signal



WCM Data for pbar stacking

RTD720 – A digitizing scope data



Final Stack Beam

Squeezed Beam

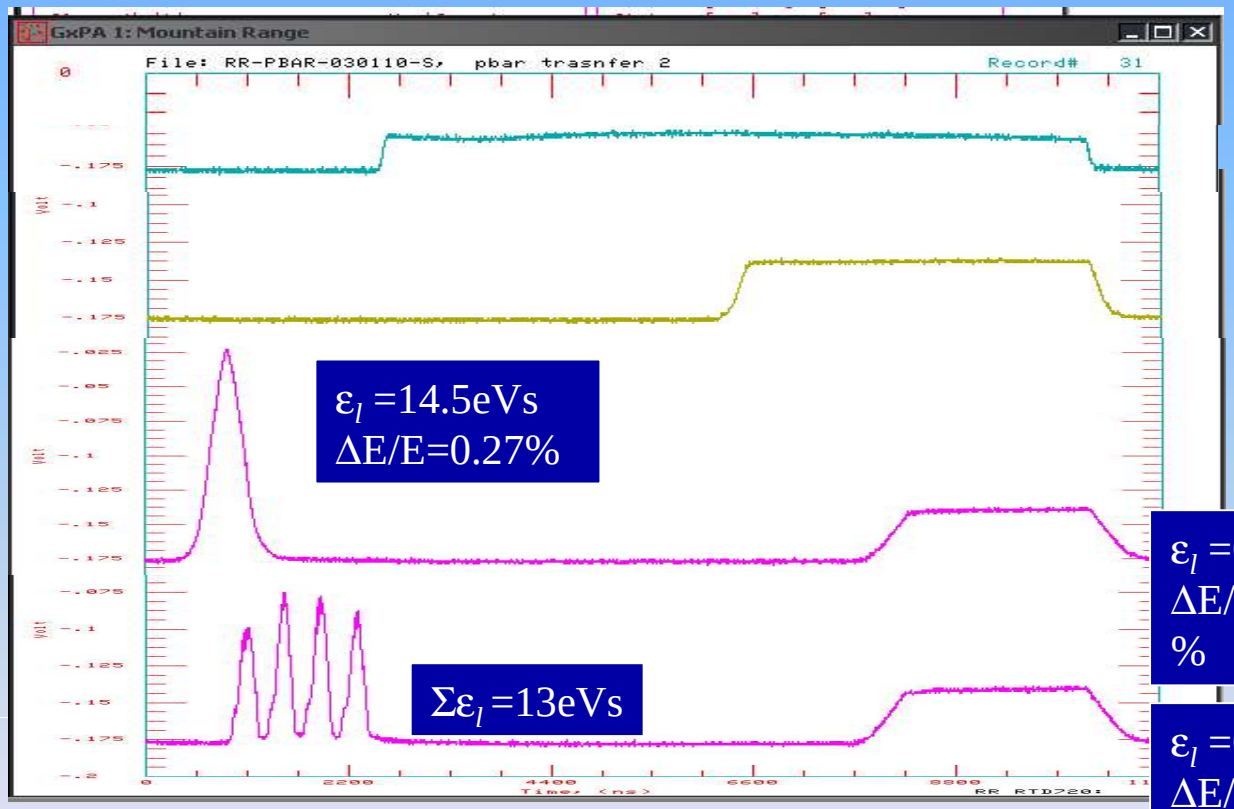
Beam cogging direction after squeeze

Newly arrived Beam

Stacked Beam

WMC Emittance at Different Timings during Stacking

RTD720 – A digitizing scope data



Sum Emittance

ε_l =88eVs
$\Delta E/E$=0.13%

ε_l =81eVs
$\Delta E/E$=0.23%

ε_l =14.5eVs
$\Delta E/E$=0.27%

ε_l =64eVs
$\Delta E/E$=0.29 %

$\Sigma\varepsilon_l$ =78.5eVs

$\Sigma\varepsilon_l$ =13eVs

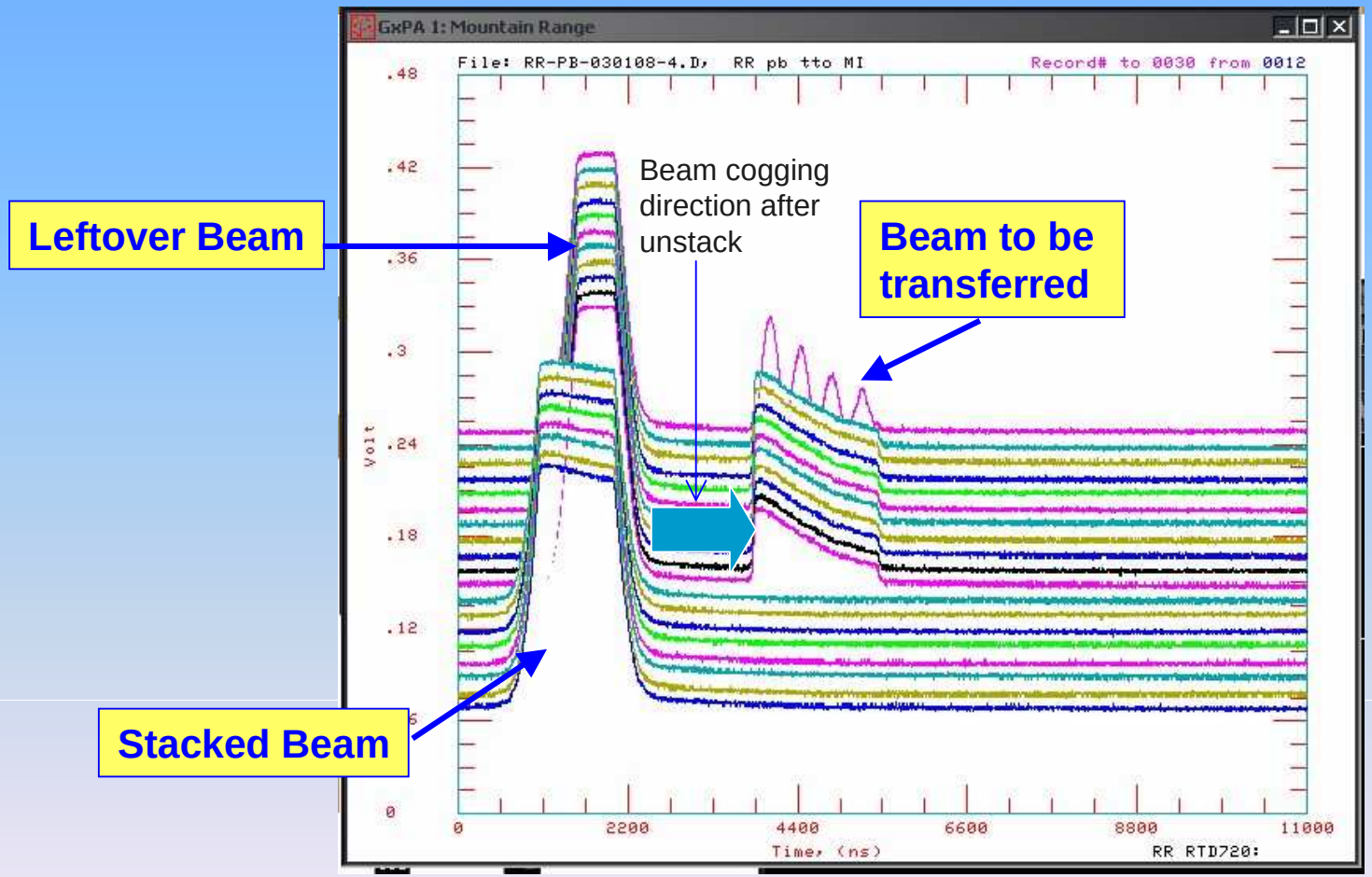
ε_l =64eVs
$\Delta E/E$=0.29%

$\Sigma\varepsilon_l$ =77eVs

The error in the measured longitudinal emittance ≅ 20%

WCM Data for pbar un-stacking

RTD720 – A digitizing scope data



Schottky Signals & Longitudinal Emittance

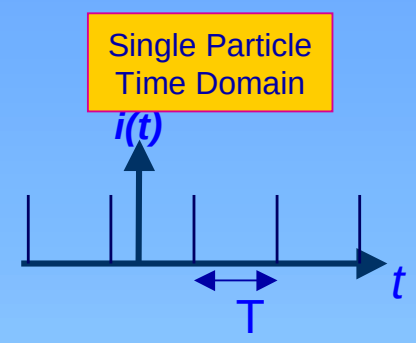
(D. Boussard –CERN Report 95-06, 749-782)

The Schottky noise in a Particle Beam (De-bunched Beam):

The time domain response of a **single particle** with charge *e* in a storage ring is δ–function repeated with a time interval T. Then the current is given by

$$i(t) = ef_0 \sum_{n=-\infty}^{\infty} \delta(t - nT)$$

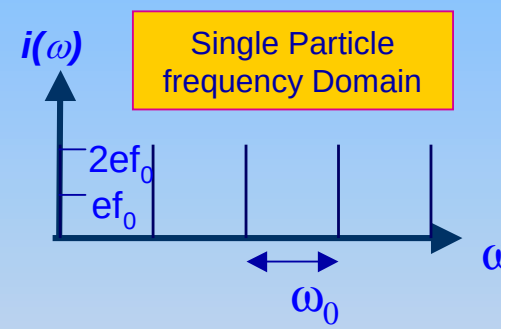
f_0= revolution frequency



The frequency response, $i(\omega)$, as seen in a spectrum analyzer is,

$$i(t) = \sum_{n=1}^{\infty} i(\omega)\cos(n\omega_0 t)$$

for +ve frequencies



with $i(\omega)=e\,f_0$ for n=0, $i(\omega)=2e\,f_0$ for $\omega=n\omega_0$ and $i(\omega)=0$ everywhere else.

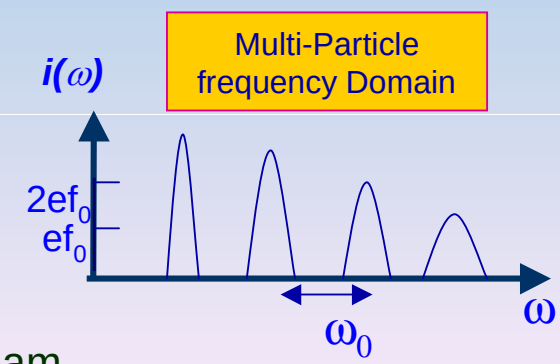
Thus **the frequency response**

= A DC part + successive harmonics corresponding to revolution frequency.

A single line will be replaced by a band of frequencies (**Schottky Band**) for **randomly distributed N particles**, each with slightly different ω_i, Then the $\Delta\omega$ and Δp are related by,

$$\frac{\Delta\omega}{\omega_0} = \frac{\Delta f}{f_0} = n\,\eta\,\frac{\Delta p}{p}$$

where Δp is the **momentum spread** of the beam



Schottky Signals & Longitudinal Emittance

The Schottky noise in a Particle Beam (Bunched Beam):

The particles in the bunched beam execute **synchrotron oscillations** at the frequency $\Omega/2\pi$. The time of passage of a particle in front of the detector is modulated according to

$$t \rightarrow t + \tau \sin(\Omega t + \varphi)$$

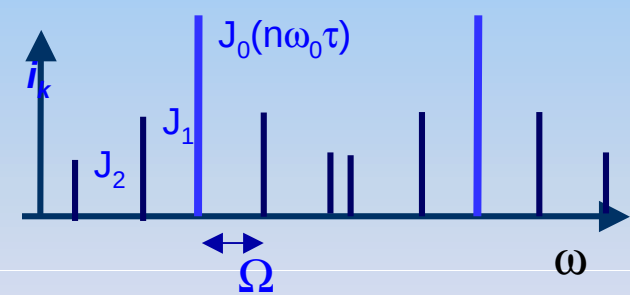
$\tau, \Omega, \varphi =$ Synchrotron amplitude, frequency and phase

The beam current for a single particle in frequency domain will become

$$i(t) = ef_0 + 2ef_0 \sum_{n=1}^{\infty} \sum_{k=-\infty}^{\infty} J_k(n\omega_0\tau) \cos[(n\omega_0 + k\Omega)t + k\varphi]$$

where J_k is the Bessel function of order k. Thus, each revolution frequency line, nf_0, now splits into an infinite number of synchrotron satellites, spaced by $\Omega/2\pi$.

Single Particle frequency Domain



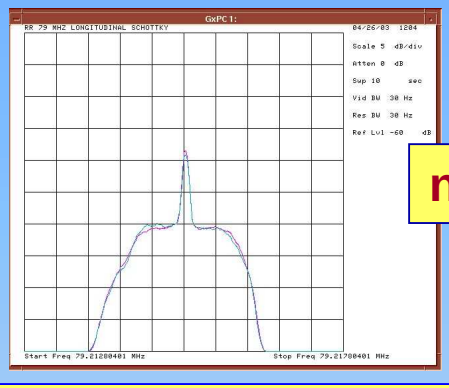
Amplitude of Satellite $\propto$ Bessel function of the argument

For Schottky bands with same value of ***k***, but, different ***n***'s are correlated. This leads to **coherence**

However, for **LARGE** n ?

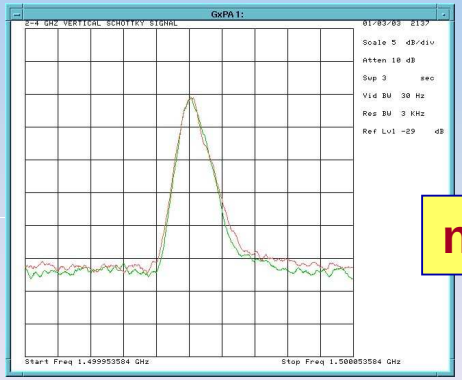
$$\frac{\Delta f}{f_0} = n\,\eta\,\frac{\Delta p}{p}$$

Emittance Measured with Schottky Detectors in RR



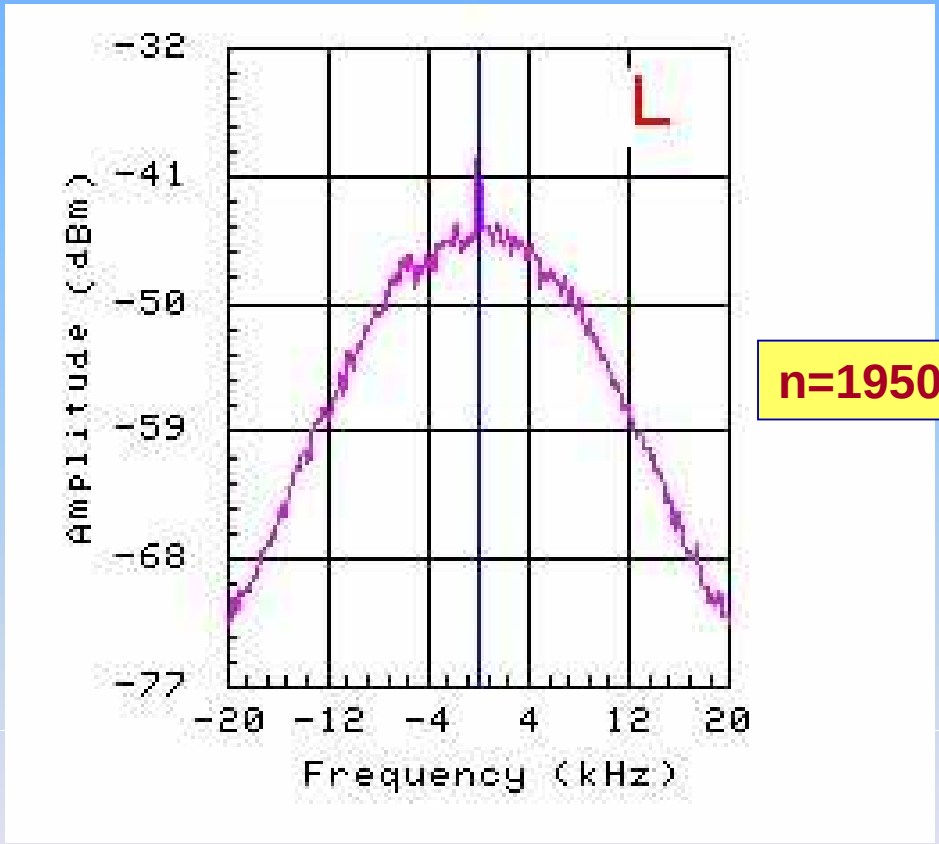
n=882

79MHz Detector Data



n=16700

1.5GHz Detector Data

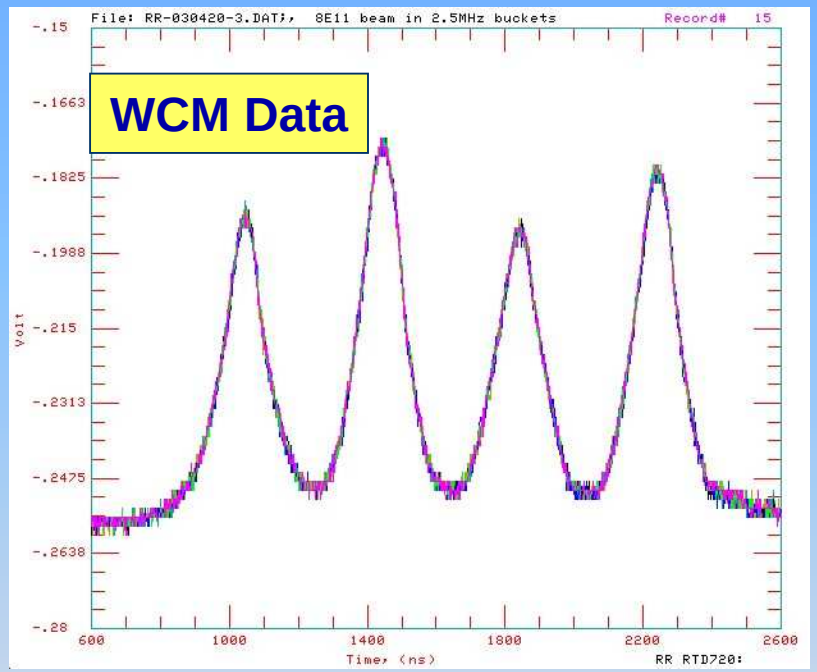


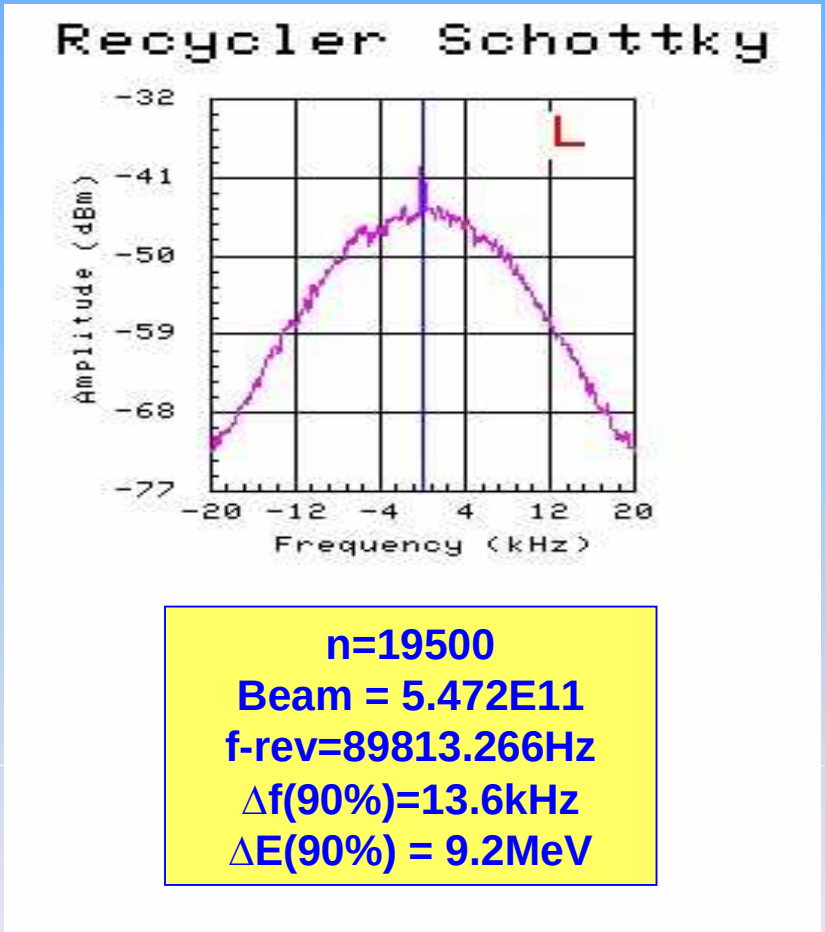
n=19500

1.75GHz Detector Data

Comparison Between Different Techniques

RR 2.5MHz Bunches



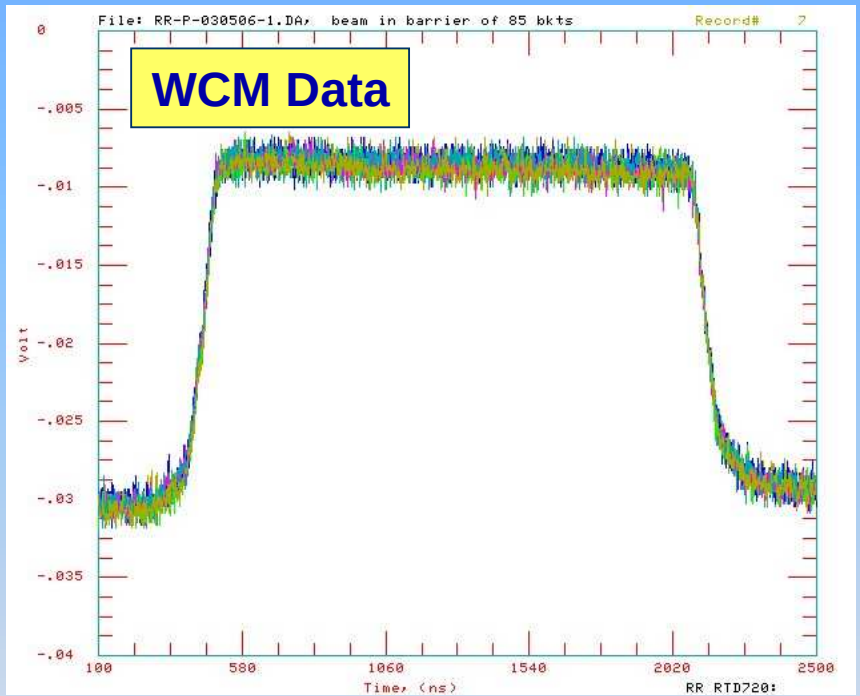


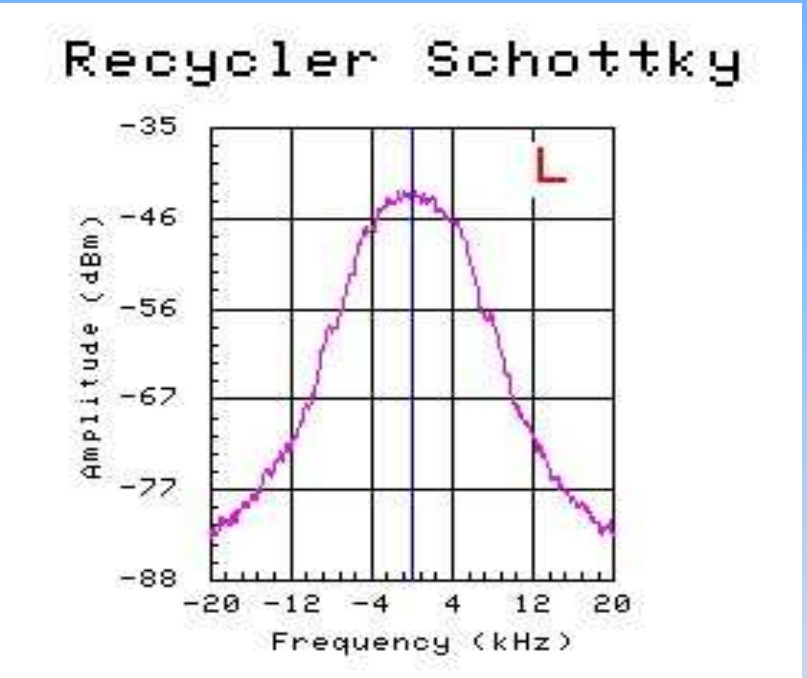
BL (90% by area)=260ns
Vrf(2.5MHz) = 2kV
ε_l(90%) = 2.3eVs
ΔE(90%) = 11.6MeV (20%)

n=19500
Beam = 5.472E11
f-rev=89813.266Hz
Δf(90%)=13.6kHz
ΔE(90%) = 9.2MeV

Comparison Between Different Techniques (Cont.)

RR Beam in Barrier Bucket



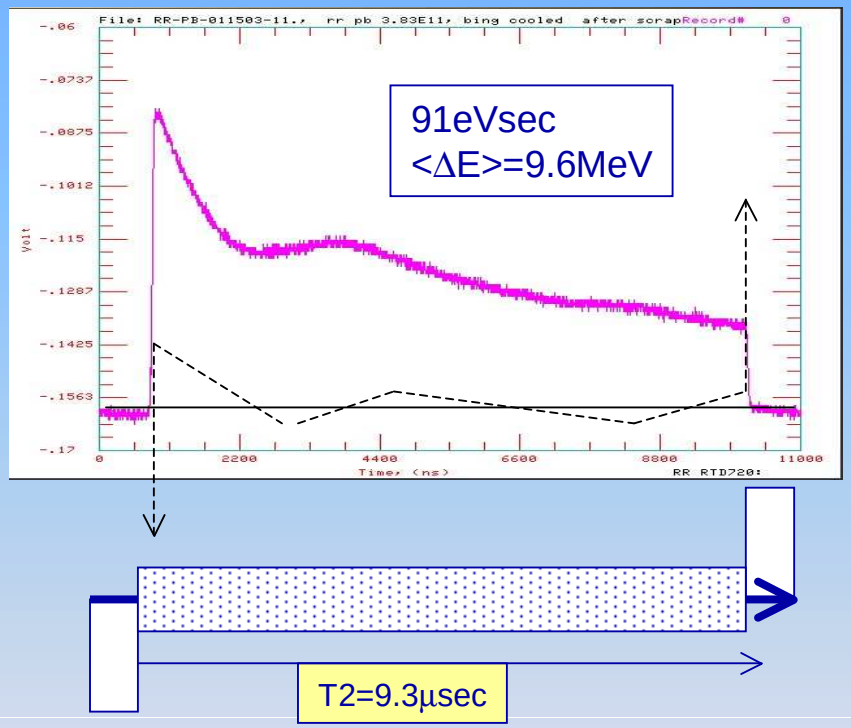


Barrier Pulse Width = 905ns
Barrier Gap = 1.6μs
Vrf(Barrier) = 1kV
ΔE(90%) = 7.8MeV (~20%)
ε_l(90%) = 13.6eVs

Beam = 4.2E11
f-rev=89813.266Hz
Δf(90%)=9.7kHz
n=19500
ΔE(90%) = 5.6MeV
ε_l (90%) = 9.3eVs

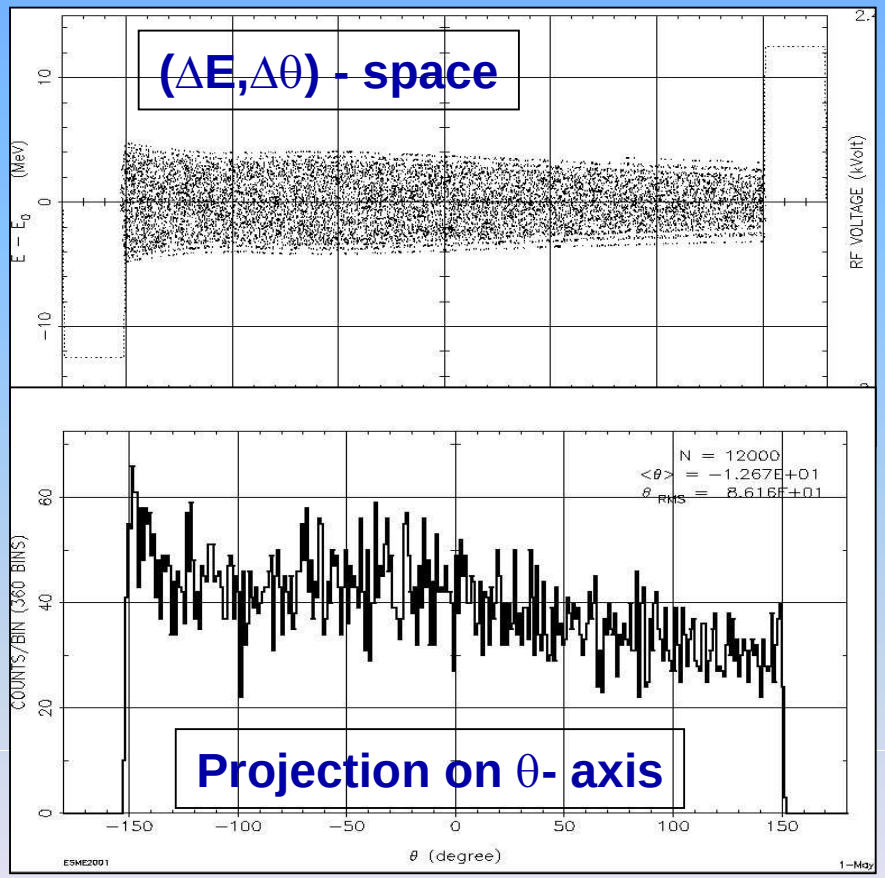
Some Exceptional Cases: Longitudinal Beam Dynamics Simulations

WCM data for pbar



Schottky Det. : ΔE_{max} = 6.4MeV

ESME Simulation Result



Simulations suggest that ~2.5% overshoot related baseline oscillations gives rises to ~20% larger emittance for beam in a barrier bucket

Summary and Conclusions

- ➔ Measuring the Longitudinal Emittance of the beam in the Recycler at different stages of rf manipulations is important.
- ➔ We have explored four methods to measure the ΔE & ε_l of the beam.
- ➔ WCM measures ΔE and ε_l in multiple barrier buckets
- ➔ The Schottky detector method is very promising. Measures ΔE_{max} independent of barrier pulse-shape.
  - Use of this device to measure ΔE_{max} in multiple barrier buckets is under development at Fermilab
- ➔ Errors in measurements need to be addressed