Goals for ACC-to-RR Transfers

- highest transfer efficiency
- lowest emittance dilution
- operational simplicity

Issues for Accumulator-to-RR Transfers

I. Energy offset: 15~20 MeV

II. Circumference (Frequency) offset

III. Event Numbers, Timelines, etc.

IV. 2.5 MHz vs. 53 MHz beam RF Structure

V. Shot vs. Stacking Lattice

Present Procedures for Accumulator-to-Recycler Transfers

1) RF unstack at 2.5 MHz in Accumulator
*2) Bunch at 53 MHz
3) Phase lock Accumulator RF to “fictitious” MI frequency to account for circumference mismatch between Accumulator and the Tevatron/MI/Recycler.
4) Kick the beams out of the Accumulator and down the transfer line to Main Injector
*5) Kick the beams onto the closed orbit in Main Injector. (Closure, dilution…)
*6) Jump the frequency (but keep the phase) to capture the beam at 53 MHz in the MI
*7) Decelerate the beam by 15~20 MeV in the MI to account for the energy mismatch between Recycler and Accumulator (changes to both frequency and bend bus)
*8) Cog the beams from the proper azimuth for transfer to Recycler
*9) Coalesce the 53 MHz bunches back into 2.5 MHz buckets
*10) Kick the beams out of the Main Injector and down the transfer line to Recycler
11) Kick the beam onto the closed orbit in the Recycler
12) Capture the beams at 2.5 MHz in Recycler broadband RF system
13) Debunch and merge into stored beam in RR

*** = potentially may be eliminated**

Original Plan (RR TDR)

1) Phase Lock Accumulator, MI, & RR

2) 2.5 MHz RF structure for Beam Transfers

   – 2.5 MHz RF present in both Accumulator & RR

   – easier than 53 MHz phase match, no coalescing.

3) Go thru ~1/2 Main Injector like a transfer line

   – no MI kickers, closure, RF capture, etc.

4) Adjust Accumulator Energy to match RR

   – Accumulator was assumed to have +/-1% range

   – Appears now not to be the case (?)

   – We need 0.15~ 0.2% energy adjustment, somehow

Why a Standard 8 GeV Energy?

- Fast Acc. → Recycler Transfers

  (and reverse protons from RR→Acc)

- Acceleration of Pbars from Recycler using standard energy ramp

What do we need to know the Energy Offset?

1) The Energy Match between “8 GeV” in MI and the Accumulator.

2) The frequency adjustment in MI “mini-dip”.

3) The delta-B during MI “mini-dip”

4) The frequency offset between MI and RR when the transfer takes place

5) The location of the central orbit in RR & MI

DOMINANT ERRORS ARE 3) AND 5)

Momentum Change with Frequency and Bend field

General Case:

$-\eta \, dP/P = dF/F - \alpha \, dB/B$ *(see derivation on next page)*

If Bend Fields Held Fixed : $(dB/B = 0)$

$dF/F = -\eta \, dP/P$ *(depends on energy & machine optics)*

If Orbit Held Fixed : $(dB/B = dP/P)$

$dF/F = (\alpha - \eta) \, dP/P = 1/\gamma^2 \, (dP/P)$

(just relativistic kinematics -- independent of machine optics)

Derivation of formula on previous page

Circumference is a function of P/B only:

C = C(P/B), so **$dC/C = \alpha\,(dP/P - dB/B) = 1/\gamma_T^2(dP/P - dB/B)$**

From Relativistic Kinematics,

$dV/V = 1/\gamma^2\, dP/P$ (work it out, or just take my word for it)

Frequency = Velocity / Circumference (F = V/C), so

$$
\begin{aligned}
dF/F &= dV/V - dC/C \\
&= 1/\gamma^2\, dP/P - \alpha\,(dP/P - dB/B) \\
&= (1/\gamma^2 - 1/\gamma_T^2)\, dP/P + \alpha\, dB/B \\
&= -\eta\, dP/P + \alpha\, dB/B
\end{aligned}
$$

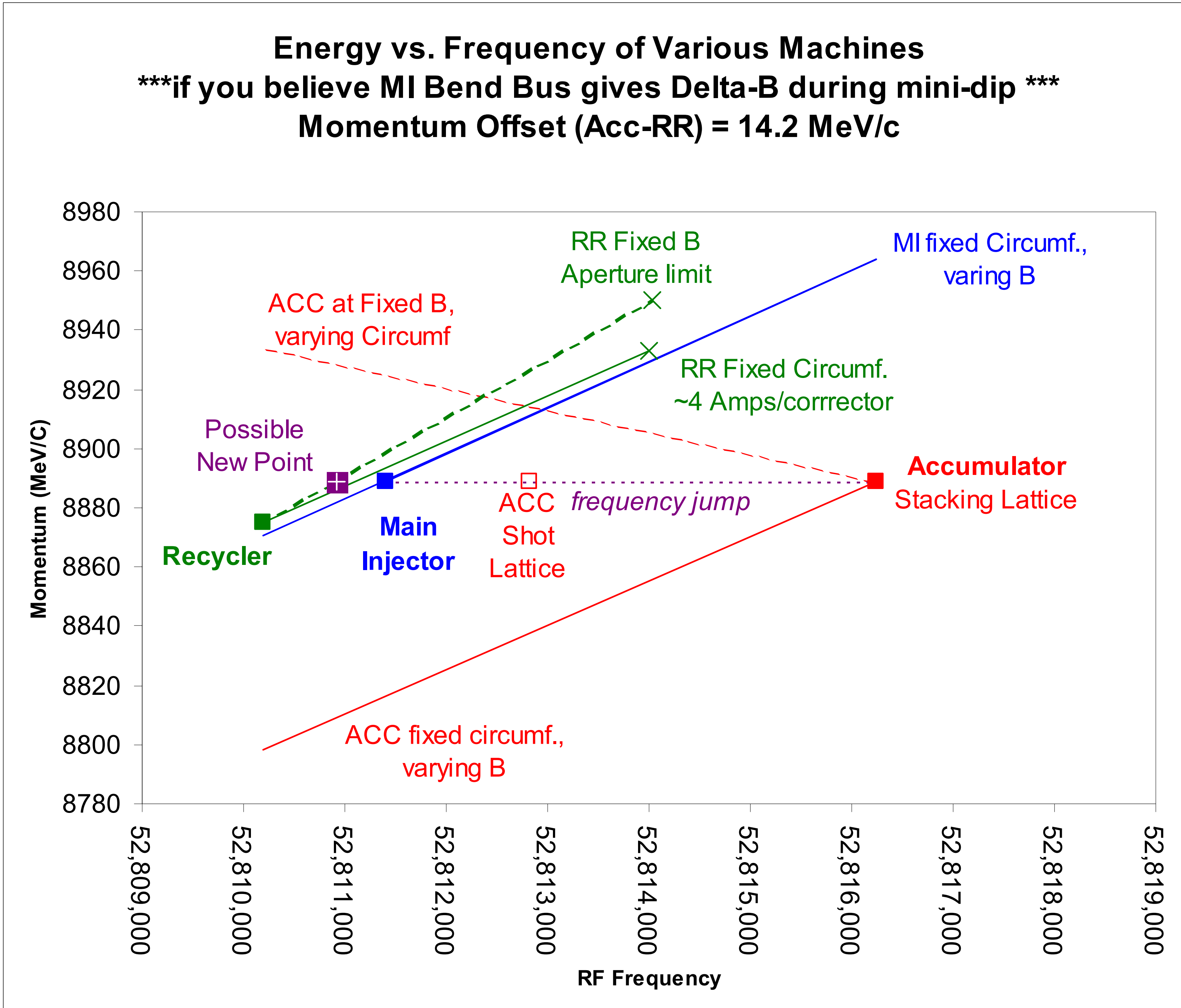
$$-\eta\, dP/P = dF/F - \alpha\, dB/B$$

For MI/RR at 8 GeV,
$\gamma = 9.5$ $\gamma_T \sim 21$
$\alpha = 1/\gamma_T^2 = .0023$
$\eta = 1/\gamma_T^2 - 1/\gamma^2 = -0.0087$

Numbers for MI-RR "Mini-Dip"
if you believe the Bend Bus gives B

	Bend Bus(A)	freq (Hz)
Injection	506.88	52811400
Extraction	505.06	52810200
change	-0.36%	-2.27E-05
dP/P	0.10%	-0.26%
total dP/P	-0.16%	

- This says Recycler is lower by 14 MeV.
- However it also predicts the MI orbit should move by ~3mm during mini-dip (not observed)


Energy vs. Frequency of Various Machines
***if you believe MI Bend Bus gives Delta-B during mini-dip ***
Momentum Offset (Acc-RR) = 14.2 MeV/c
Momentum (MeV/C)
8980
8960
8940
8920
8900
8880
8860
8840
8820
8800
8780
RF Frequency
52,809,000
52,810,000
52,811,000
52,812,000
52,813,000
52,814,000
52,815,000
52,816,000
52,817,000
52,818,000
52,819,000
RR Fixed B
Aperture limit
MI fixed Circumf.,
varing B
ACC at Fixed B,
varying Circumf
RR Fixed Circumf.
~4 Amps/corrrector
Possible
New Point
Accumulator
Stacking Lattice
ACC
Shot
Lattice
frequency jump
Main
Injector
Recycler
ACC fixed circumf.,
varying B

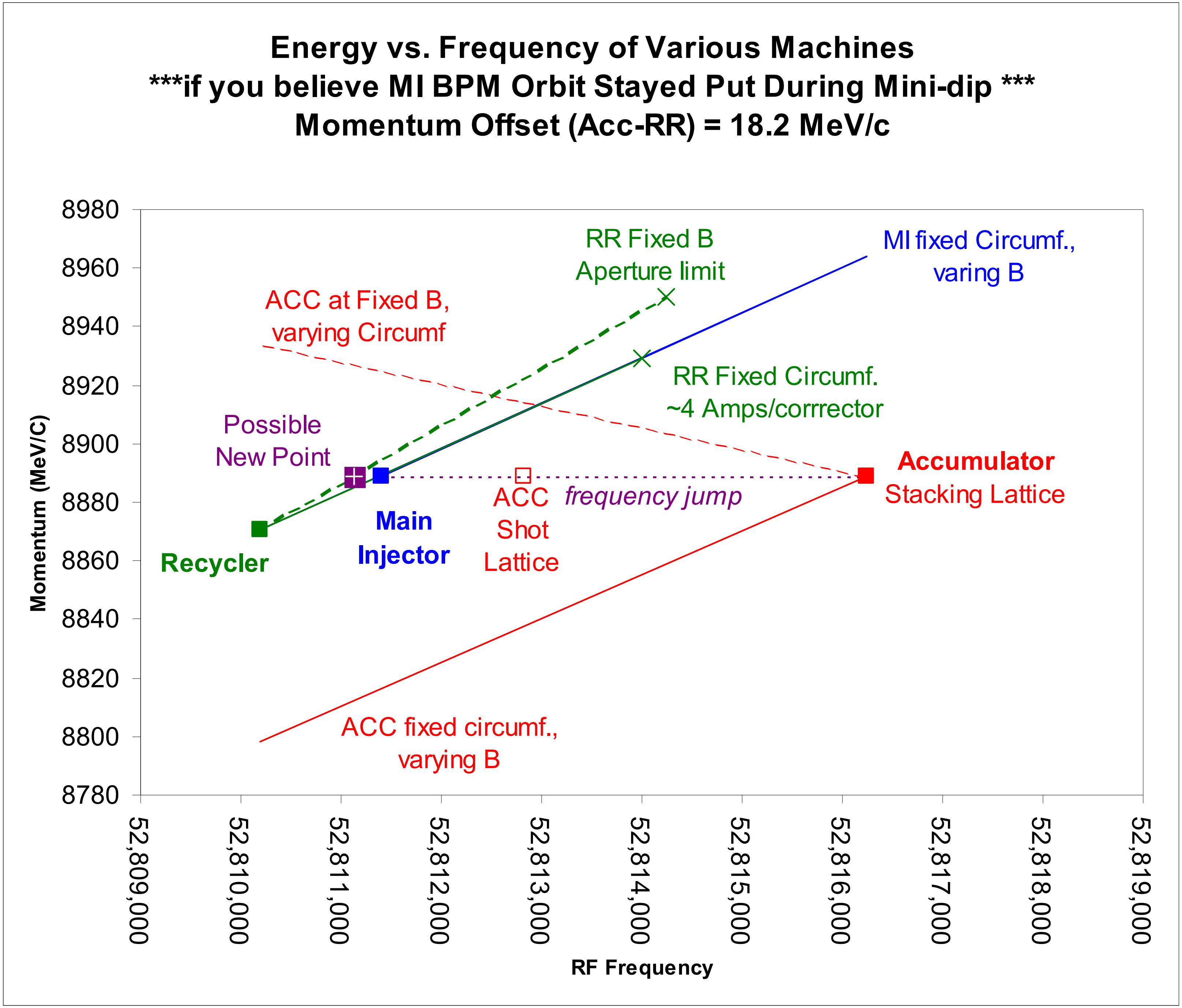
Numbers for MI-RR "Mini-Dip"

if you believe the MI BPMs when they indicated that the orbit was held fixed during the mini-dip

==> $dF/F = 1/\gamma^2 (dP/P)$

Injection Freq (Hz)	52811400
Extraction Freq. (Hz)	52810200
dF/F	-2.27E-05
dP/P	-0.21%
dP (MeV)	-18.2

- This says Recycler is lower by 18.2 MeV.



Energy vs. Frequency of Various Machines
***if you believe MI BPM Orbit Stayed Put During Mini-dip ***
Momentum Offset (Acc-RR) = 18.2 MeV/c
Momentum (MeV/C)
8980
8960
8940
8920
8900
8880
8860
8840
8820
8800
8780
RR Fixed B
Aperture limit
MI fixed Circumf.,
varing B
ACC at Fixed B,
varying Circumf
RR Fixed Circumf.
~4 Amps/corrrector
Possible
New Point
Accumulator
Stacking Lattice
ACC
Shot
Lattice
frequency jump
Main
Injector
Recycler
ACC fixed circumf.,
varying B
52,809,000
52,810,000
52,811,000
52,812,000
52,813,000
52,814,000
52,815,000
52,816,000
52,817,000
52,818,000
52,819,000
RF Frequency

I. Possibilities for Dealing with the Energy Mismatch

a) RF Capture & Deceleration in MI (as currently)

b) Move magnets to adjust RR energy

c) Change Recycler Energy with RF frequency only

– orbit moves off center; must steer around Lambertsons

d) Change Recycler Energy with Correctors & RF

– orbit held fixed; energy and tune move **CHOSEN**

Energy shifts can be momentary during shots, or static(chosen).

Ia) : Matching Energy by RF Capture & Deceleration in MI

- current method
- requires kickers, closure, ramping, coalescing, & cogging in Main Injector
- emittance dilution if tuning is imperfect
- adds another beam transfer to maintain

THIS IS MUCH MORE COMPLICATED, AND ULTIMATELY LESS RELIABLE, THAN GOING THRU M.I. LIKE A TRANSFER LINE

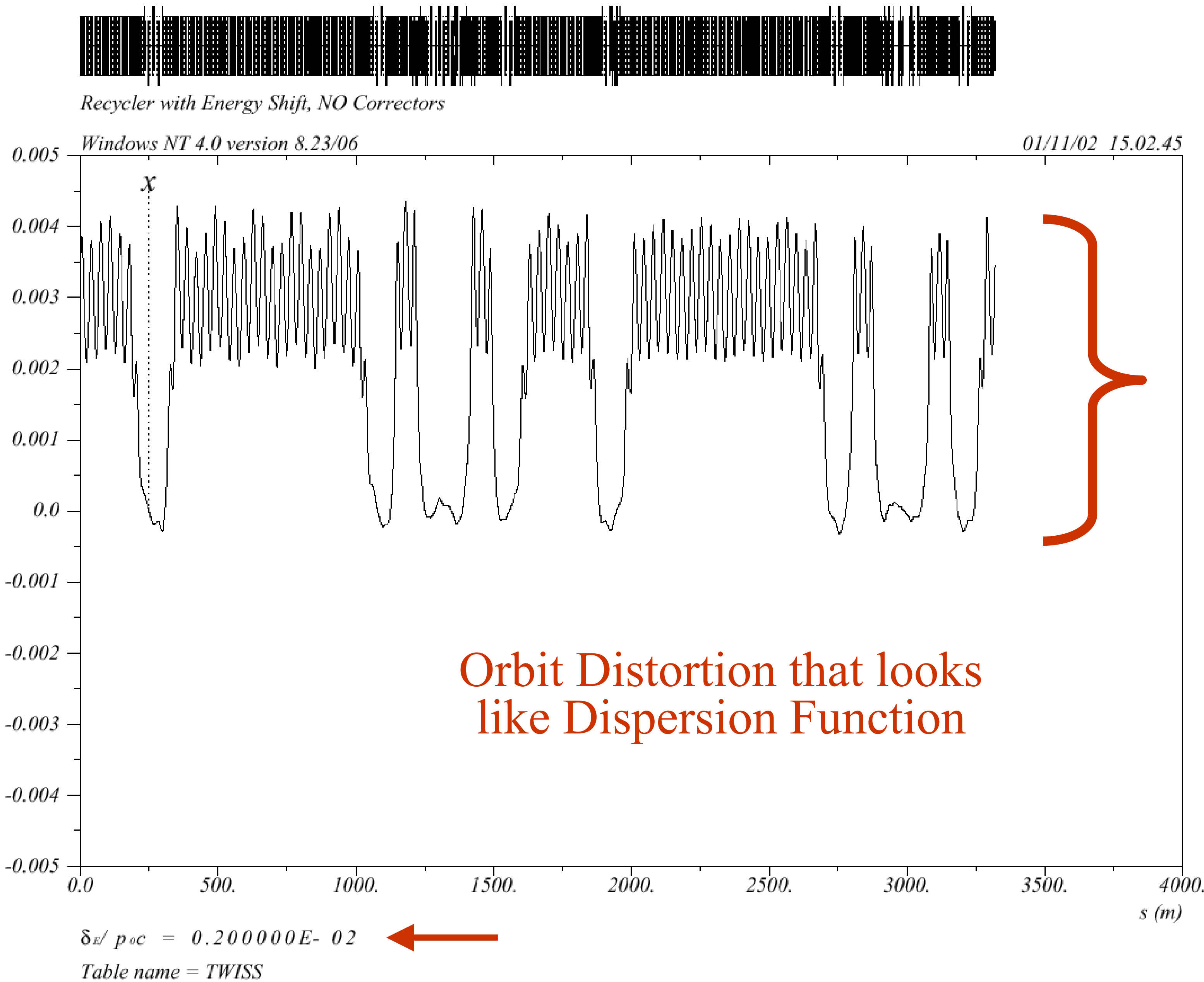
I b) : Matching Energy by Moving Magnets in RR

- Straightforward Procedure:
  - move RGF's outward by +1.5 mm
  - move RGD's inward by -1.5 mm
  - move SGF's and SGD's by +/- 0.7mm
- This could easily have been done during previous RR alignment work,
  if we had known that Accumulator energy was going to be difficult to adjust.
- Now it is probably too late.

I. c) Matching Energy by RF Frequency Adjustment in RR

- Recycler Arcs have > +/-1% momentum aperture
  - magnet good-field aperture > 8 cm horizontally
  - physical aperture ~9 cm nominally (probably ~6cm)
  - D_{MAX} ~2 m ==> dP/P +/-2% w/o betatron or alignment
  - Measured ~ +/- 1%
- Limiting momentum apertures are where D > 0
  1) Lambertsons at 214 and 328
  2) SC tanks on either side of 212
  - *must steer around these as frequency is ramped*

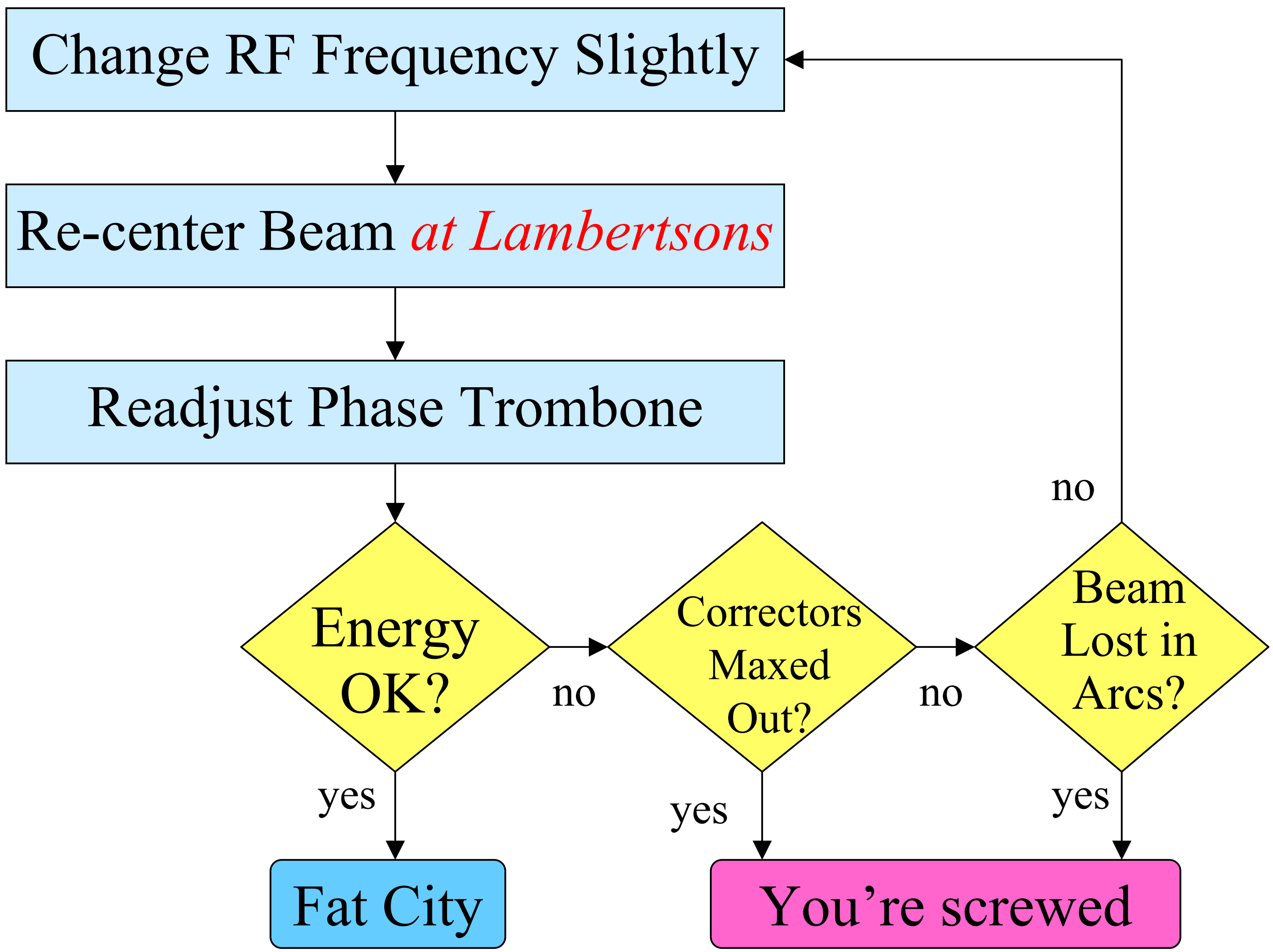
Recycler Orbit With Frequency Shift Only



~4mm orbit shift for dP/P=.002 ~18 MeV

Orbit Distortion that looks like Dispersion Function

Matching Energy using RF Frequency and only Correctors Near Lambertsons



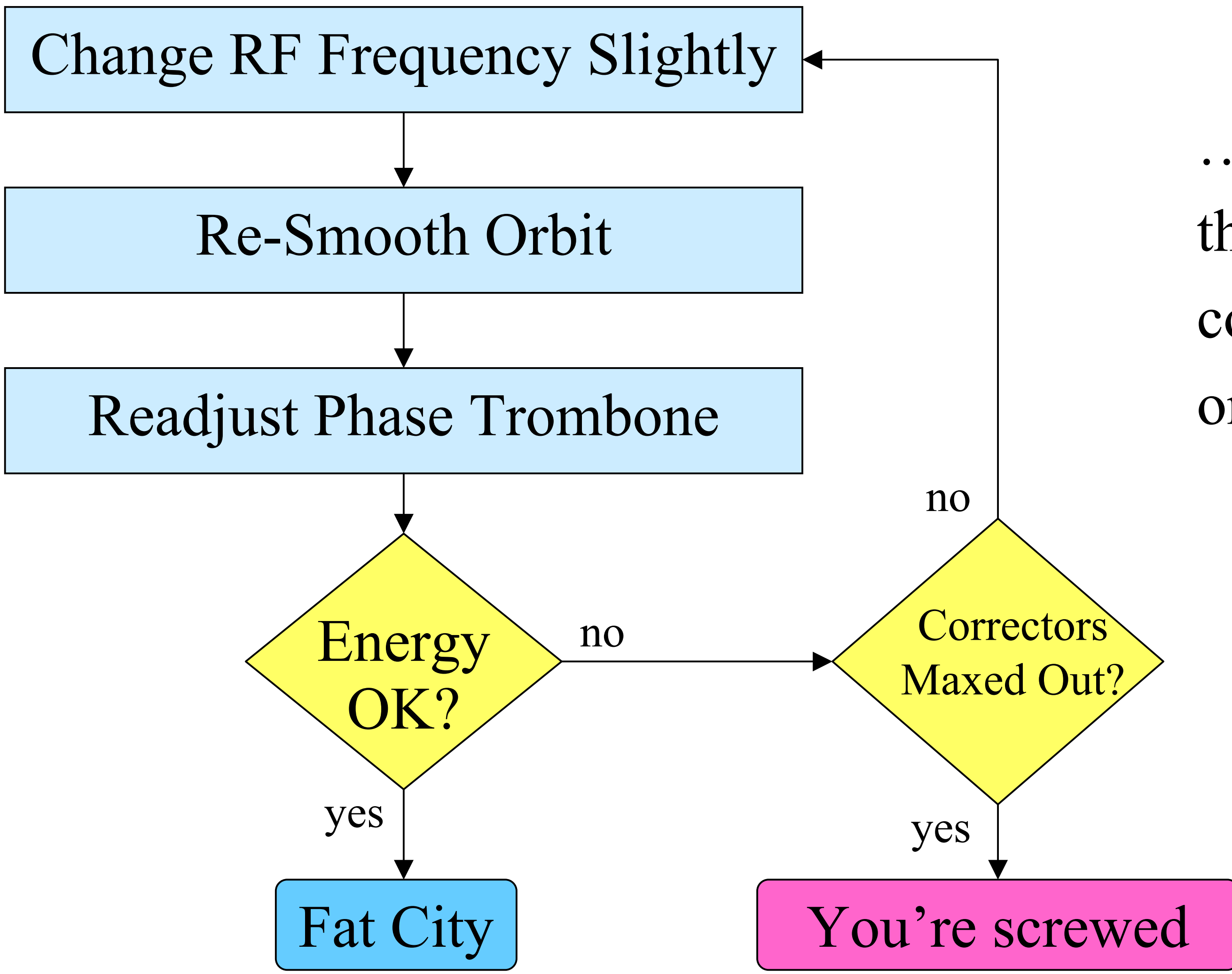
CHOSEN OPTION

I d): Using Correctors to Adjust Energy of RR

1) Keep the orbit fixed as frequency is ramped
   - Moral Equivalent of "changing the bend bus"
   - Requires orbit bump same shape as dispersion
   - Corrector current +1.4A (out of 5A max) for dP/P=0.2%
   - Keeps fixed circumference: $dP/P = \gamma^2 \, df/f$
   - Orbit & tune respond only to momentum change
   - Natural chromaticity (~ -25) gives dQ = -0.05 for dP = +.02% *(~ limit of trombone)*

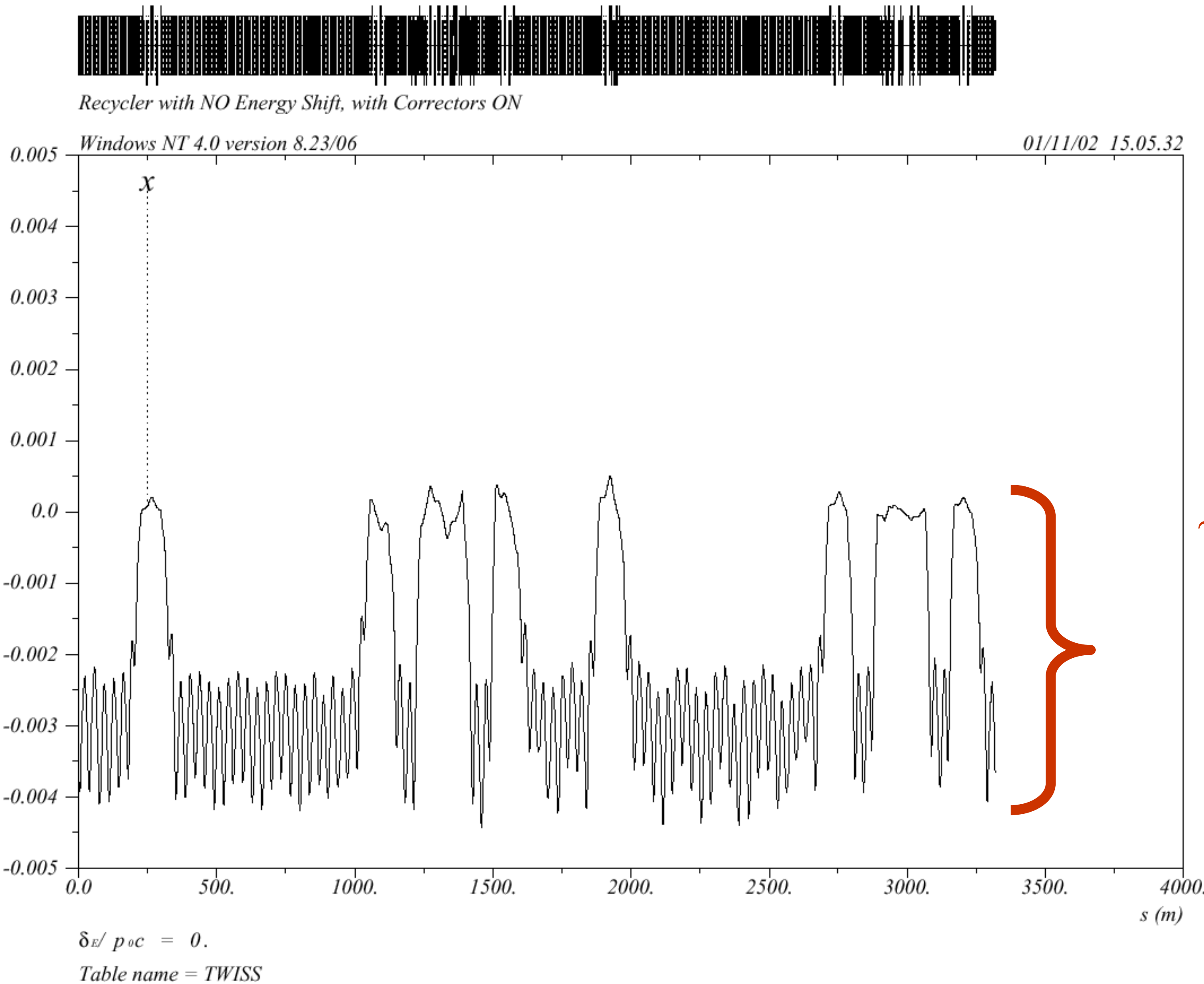
Implementation required raising current limit on phase trombone

Matching Energy Using Correctors and RF Frequency, (orbit held fixed)



…eventually the energy shift combined into one big mult...

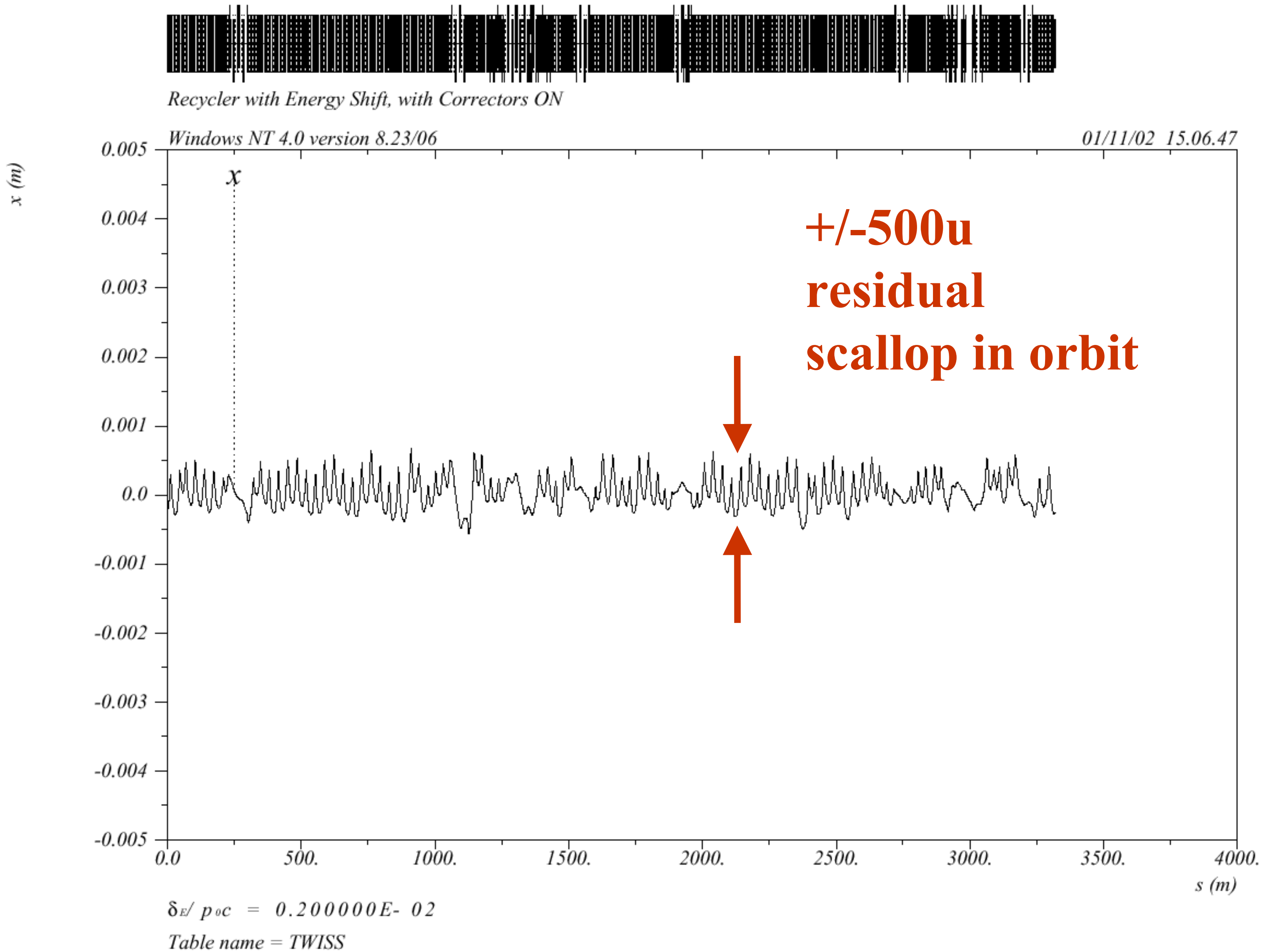
Corrector Mult Making Orbit Bump which Looks like Negative of Dispersion Function



~4mm orbit shift for

1.5A max corrector current

Residual Orbit Distortion after Frequency + Corrector Shift



Status of Energy Offset Correction

- The energies of the Accumulator & Recycler have been matched by adjusting the Recycler Correctors and Frequency
- Some teething pains:
  - ramp card programming bugs
  - Steering around tanks & Lambertsons (BPMs!)
- We have re-established ~140 Hour Pbar lifetimes at small stacks
- Circulating aperture has to be re-optimized via aperture scan (since“desired position files” require working BPMs)

II . Circumference (frequency) Mismatch

- Currently there is a ~5 kHz (out of 53 MHz) frequency shift (circumference error) between Accumulator and MI/RR/Tevatron.
- From the shot lattice, the circumference error is smaller (1-2 KHz?) but nonzero.
- The “frequency jump” trick will not work when there is already stored beam in target machine.

Therefore we should try to develop a fix for this on the Recycler end.

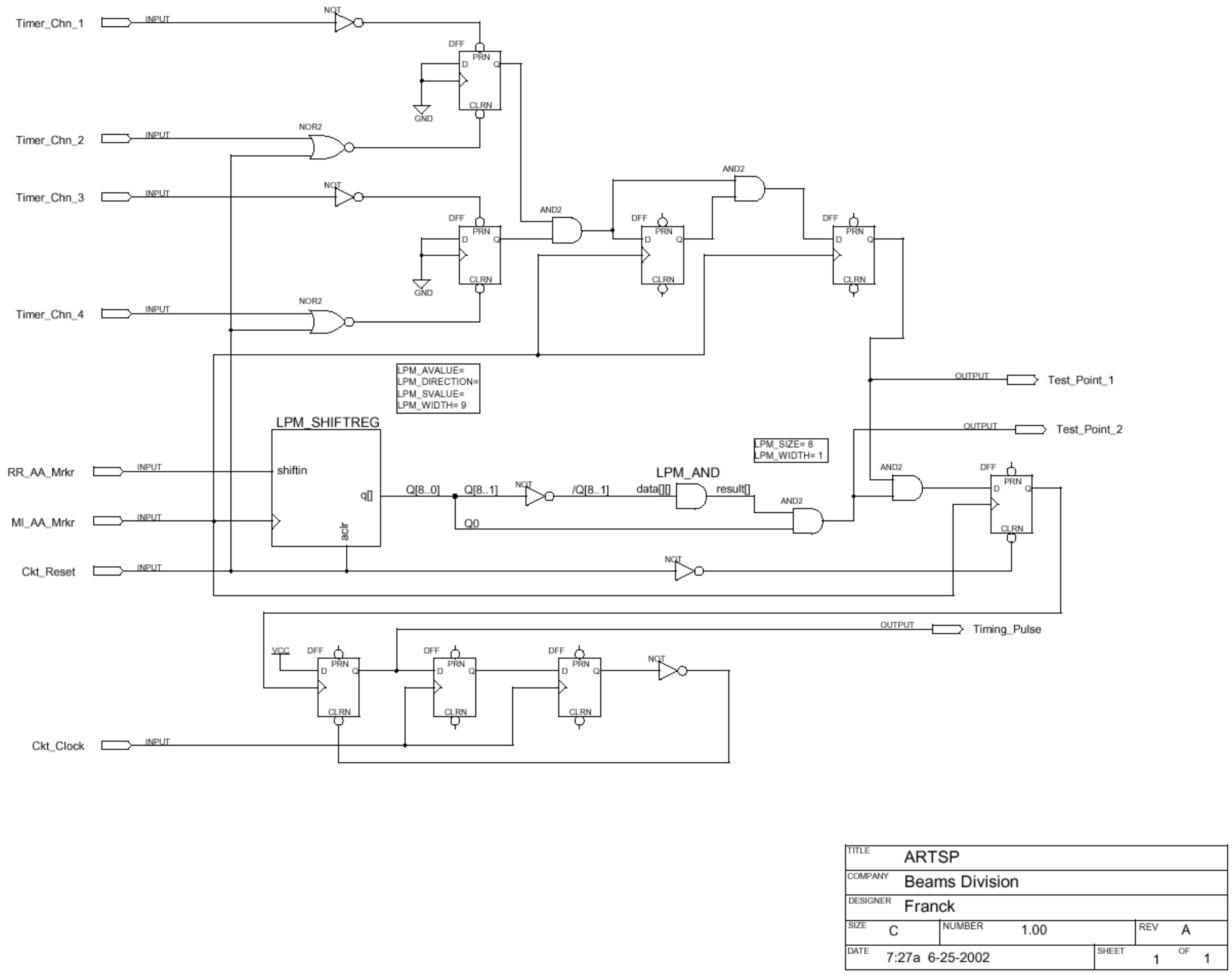
Why the Frequency-Jump Trick won't work for Acc-to-RR transfers

- Currently we phase-lock the Accumulator & MI at an un-physical frequency (MI beam would not circulate), then jump the frequency at the moment of transfer.
- Beam is captured, decelerated, coalesced, and cogged in MI before transfer to RR
- This trick only works when there is no previously circulating beam in target machine
- Therefore it will not work for the Recycler

Synchronization Logic

- Best alternative is to copy MI-to-TeV transfers:
  - Continue to phase-lock the Accumulator to MI at the same un-physical frequency.
  - At this frequency, the MI and RR markers will slide past each other at ~1 nsec per turn (they never miss)
  - Pull the trigger when revolution markers line up in RR and MI. This happens about 10 times/sec.
  - Both machines will think they saw a synchronous transfer
  - Beam will land in the right part of RR (no cogging)

Accumulator -to- Recycler Synchronization Logic



720 Hz Synchronization to Avoid Power Supply Ripple Effects

- *Perhaps* we need to fix 720 Hz phase for transfers, to reduce power supply ripple effects in the long transfer line
- Brian Chase has conceptual scheme to implicitly phase lock the transfer to 720 Hz
- Will need study of beamline looking at closure as a function of 720 Hz (and potentially 60 Hz) phase.
- Eventual solution in injection dampers in RR, so that small closure errors are not a big deal.

Schedule for Test of Transfer Synchronization Logic

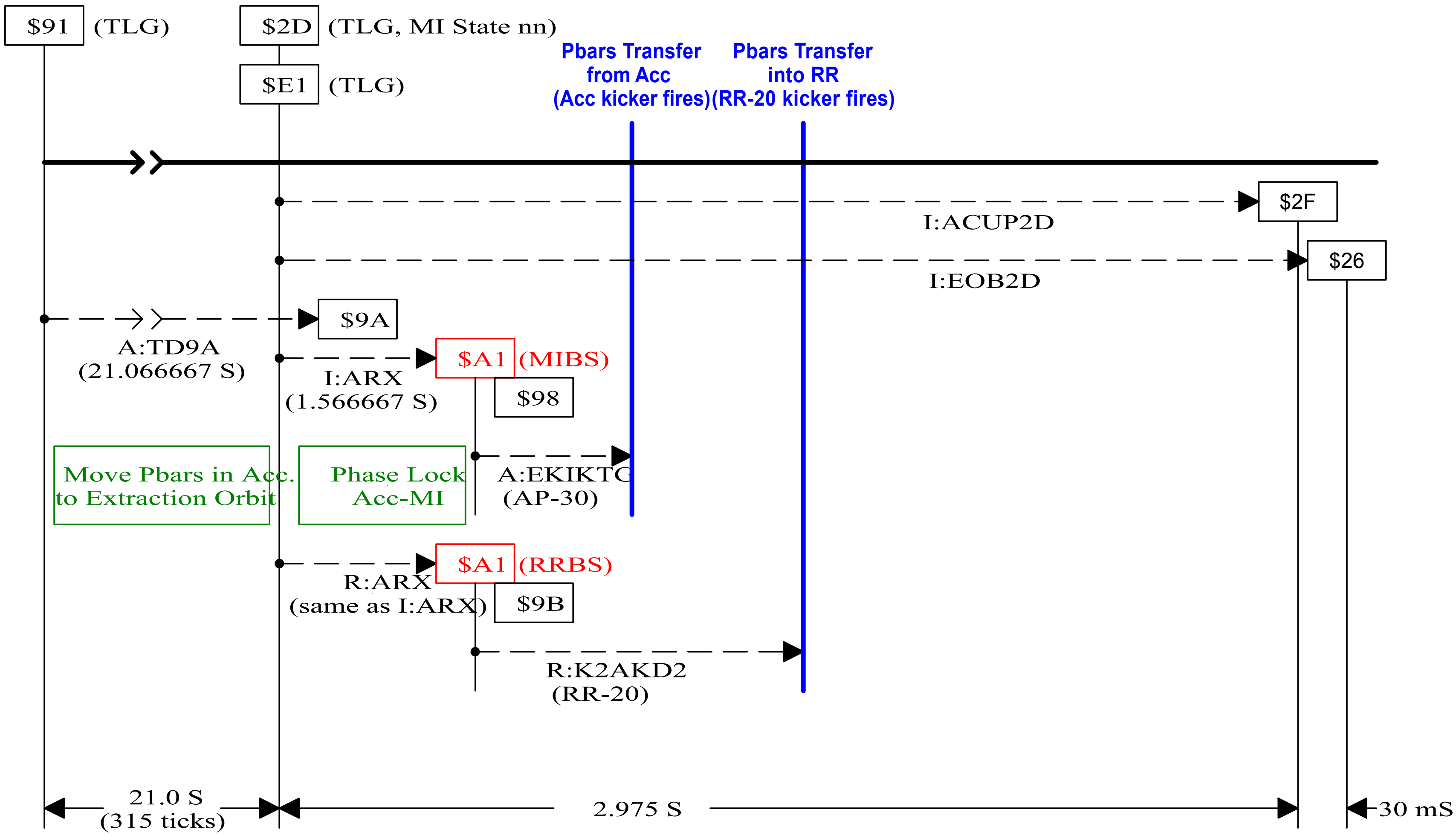
- The synchronizaton logic has been built
- Will require some MI-60 down time for Vogel et. al. to install & test new event generation logic.
- The logic can be debugged with MI-to-RR transfers (the frequency jump is smaller but everything else is the same).
- Then Reverse Protons, then real Transfers

III. Event Numbers, Timelines, etc.

- The event numbers for direct Acc-RR transfers were all reserved during MI construction, *and miraculously* they have not yet been swiped for other uses.
- Greg Vogel believes the Recycler is probably already set up to listen to these events.
- A handful of devices in Pbar will have to be programmed to respond to the new events, identically to the current events.

Clock	Event#	Source	Notes
TCLK	$91	TLG	Pbar Reset to unstack Pbars for Extraction
	$2D	TLG	MI Reset for 8 GeV Beam
	$E1	TLG	RR Reset for Pbar Inj from Acc via MI Partial Turn
	$9A	A:TD9AAcc Reset Extract Pbars to MI (21.066667s)($91)	
	$98	MIBS	TCLK reflection of MIBS $A1
	$9B	RRBS	TCLK reflection of RRBS $A1
MIBS	$A1	ARTSP 8 GeV pbar transfer Acc. to RR	
RRBS	$A1	ARTSP 8 GeV pbar transfer Acc. to RR	

DRAFT Timeline for Accumulator to Recycler Transfers (MI Partial Turn)



Notes:
1. R:K2SKD2 requires TCLK $E1 to arm and RRBS $A1 to trigger. (Kicker also requires R:K2SKD2 enabled to fire)
2. A:EKIKTG requires MIBS $A1 to trigger

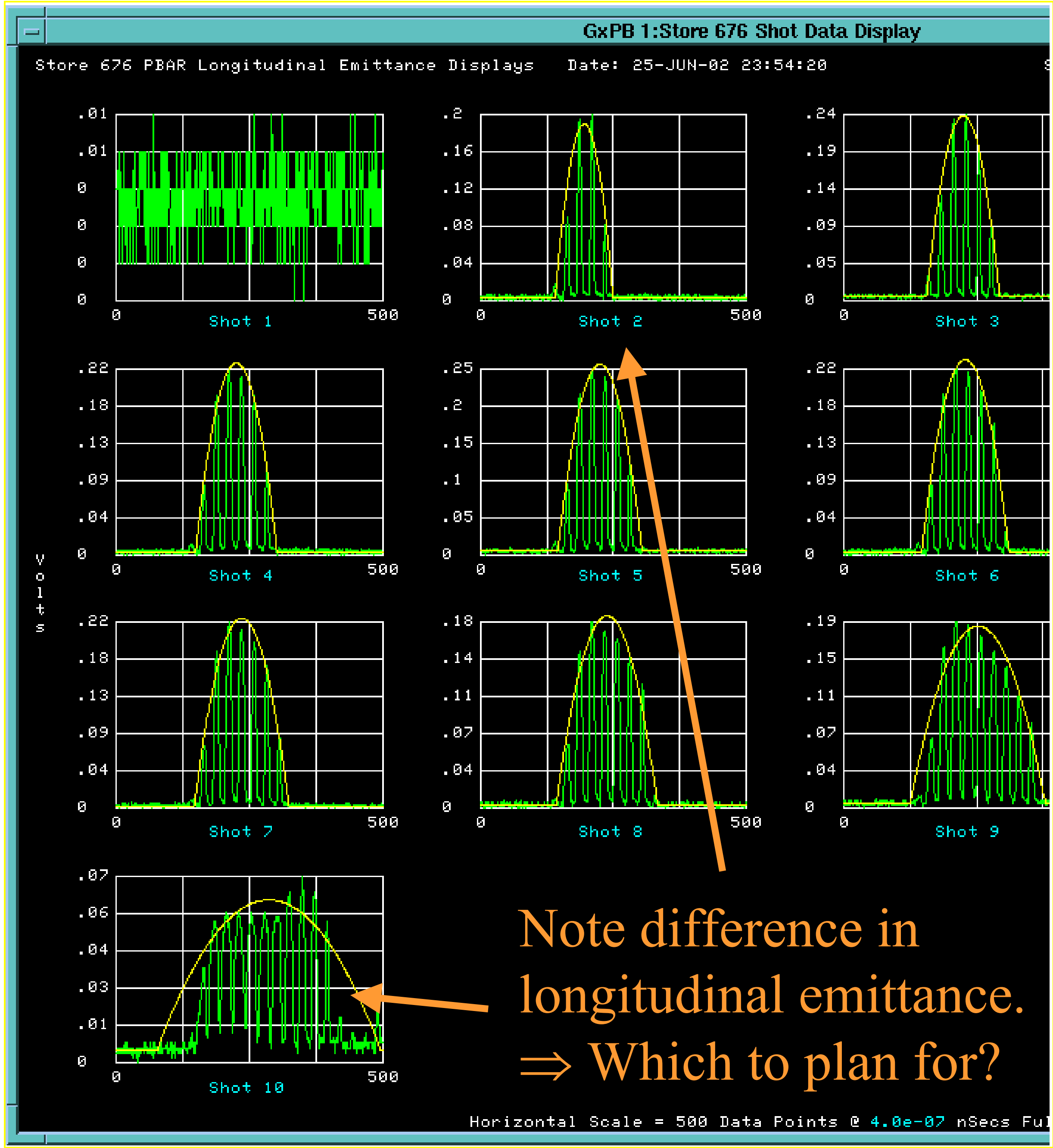
G. Vogel 6-12-02

IV. 2.5 MHz vs. 53 MHz Bunches

- Currently transfers use 53 MHz + 2.5 MHz RF
  1) RF unstacking with 2.5 MHz buckets
  2) 2.5 MHz bunches split into variable number of 53 MHz buckets before extraction from Acc.
  3) 53 MHz bunches must be recoalesced in MI before being received in 2.5 MHz buckets in Recycler
- ==> Emittance Dilution
  – increases load on RR stochastic cooling system
  – more momentum aperture required for transfers

Waveforms from a recent shot

- 2.5 MHz & 53 MHz RF
- Less Emittance Dilution if 2.5 MHz only



Other Issues with 2.5 MHz vs. 53 MHz Bunches

- BPM’s currently only respond to 53 MHz
- Injection dampers in RR must work at whatever bunch spacing is chosen.