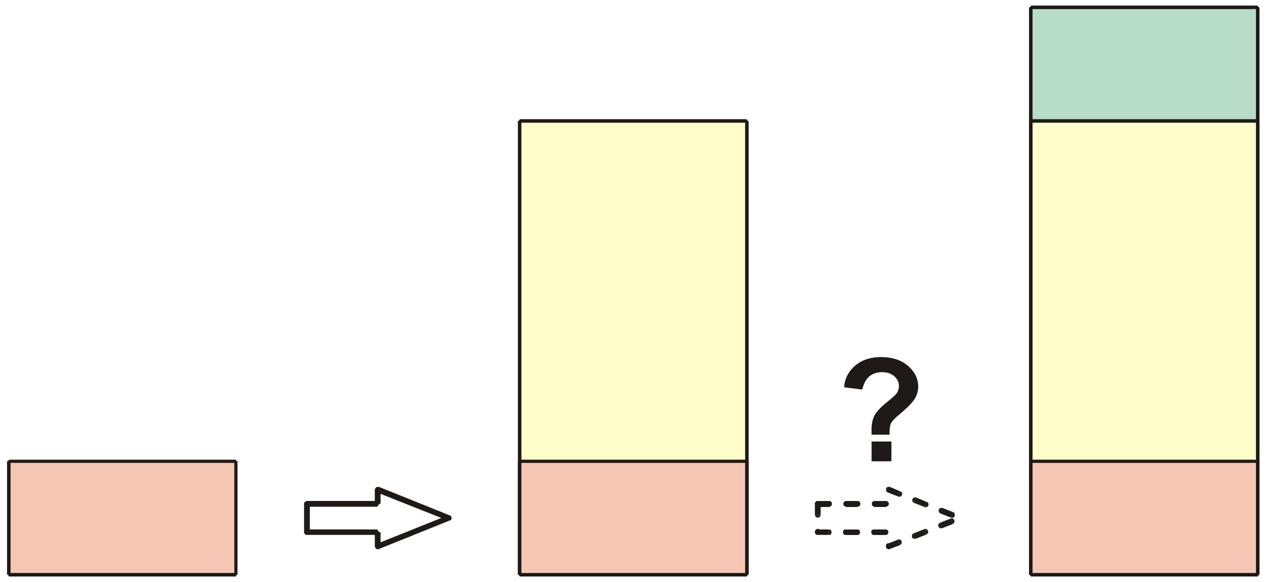
Measures Against Longitudinal Emittance Dilution in HERAp?

Elmar Vogel
November 2002

25% more luminosity – additional to the upgrade!



“old” HERA

HERA after upgrade; β smaller

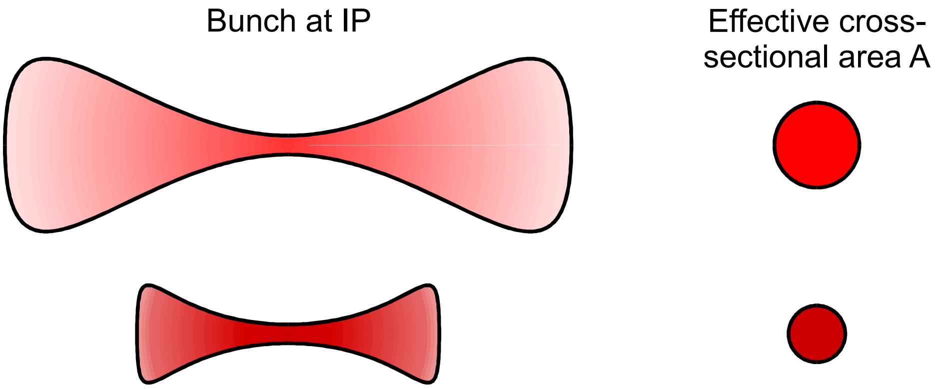
l_{FWHM} smaller and β_y smaller

$\mathscr{L} = 18\,\frac{10^{30}}{\mathrm{cm}^2\,\mathrm{s}}$

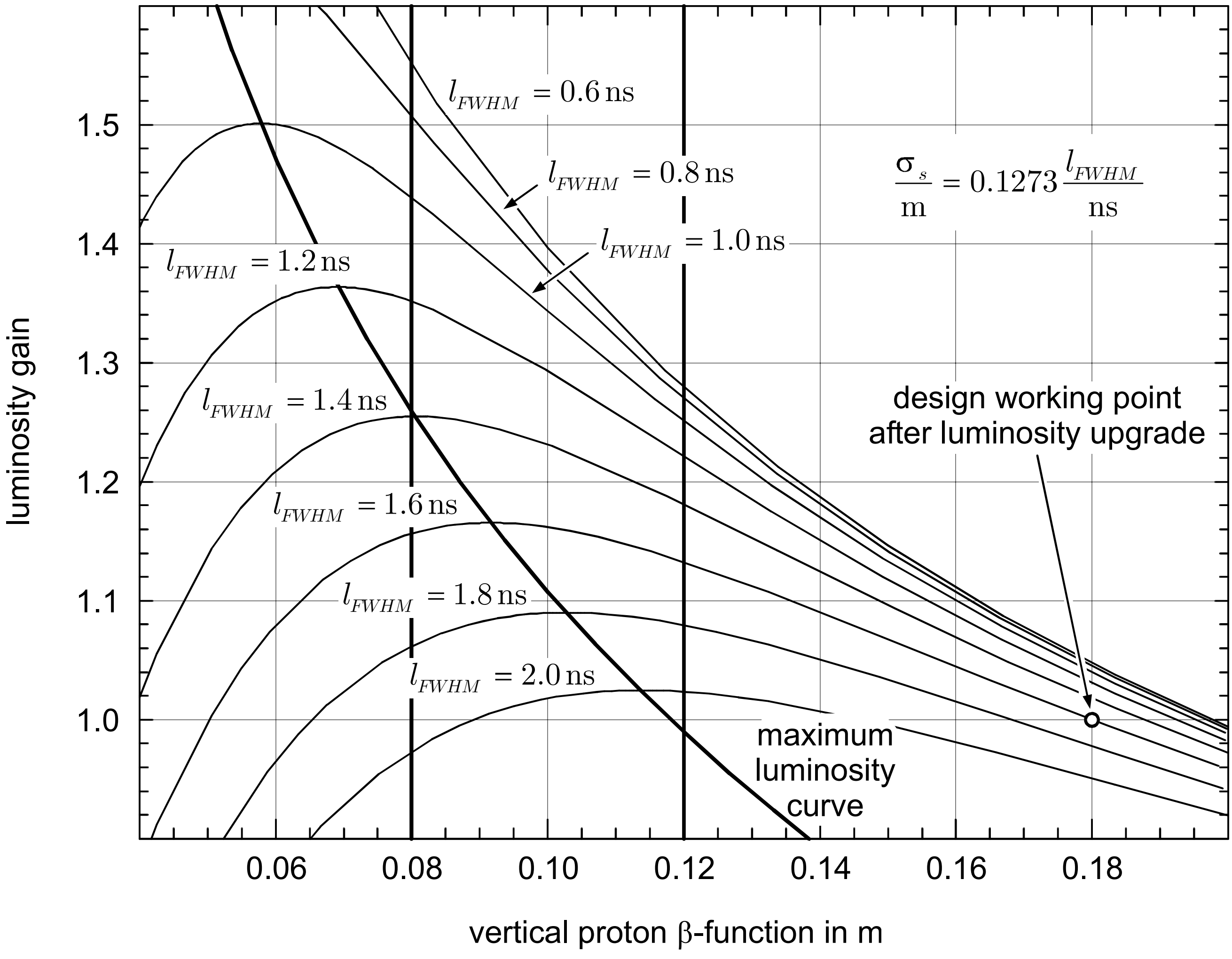
$\mathscr{L} = 70\,\frac{10^{30}}{\mathrm{cm}^2\,\mathrm{s}}$

$\mathscr{L} = 87\,\frac{10^{30}}{\mathrm{cm}^2\,\mathrm{s}}$

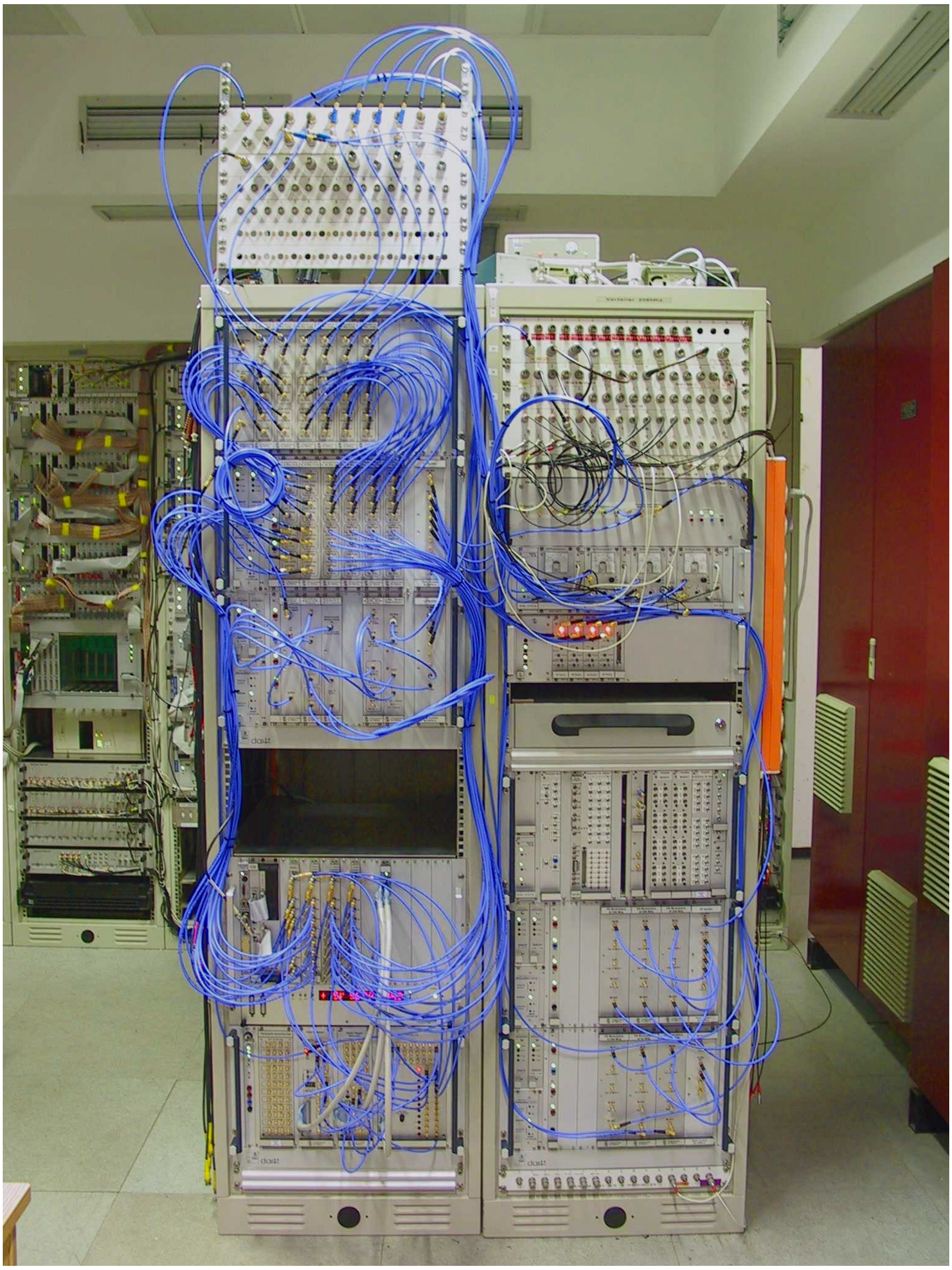
Proton bunch length and luminosity



Gain of luminosity through shorter proton bunches:

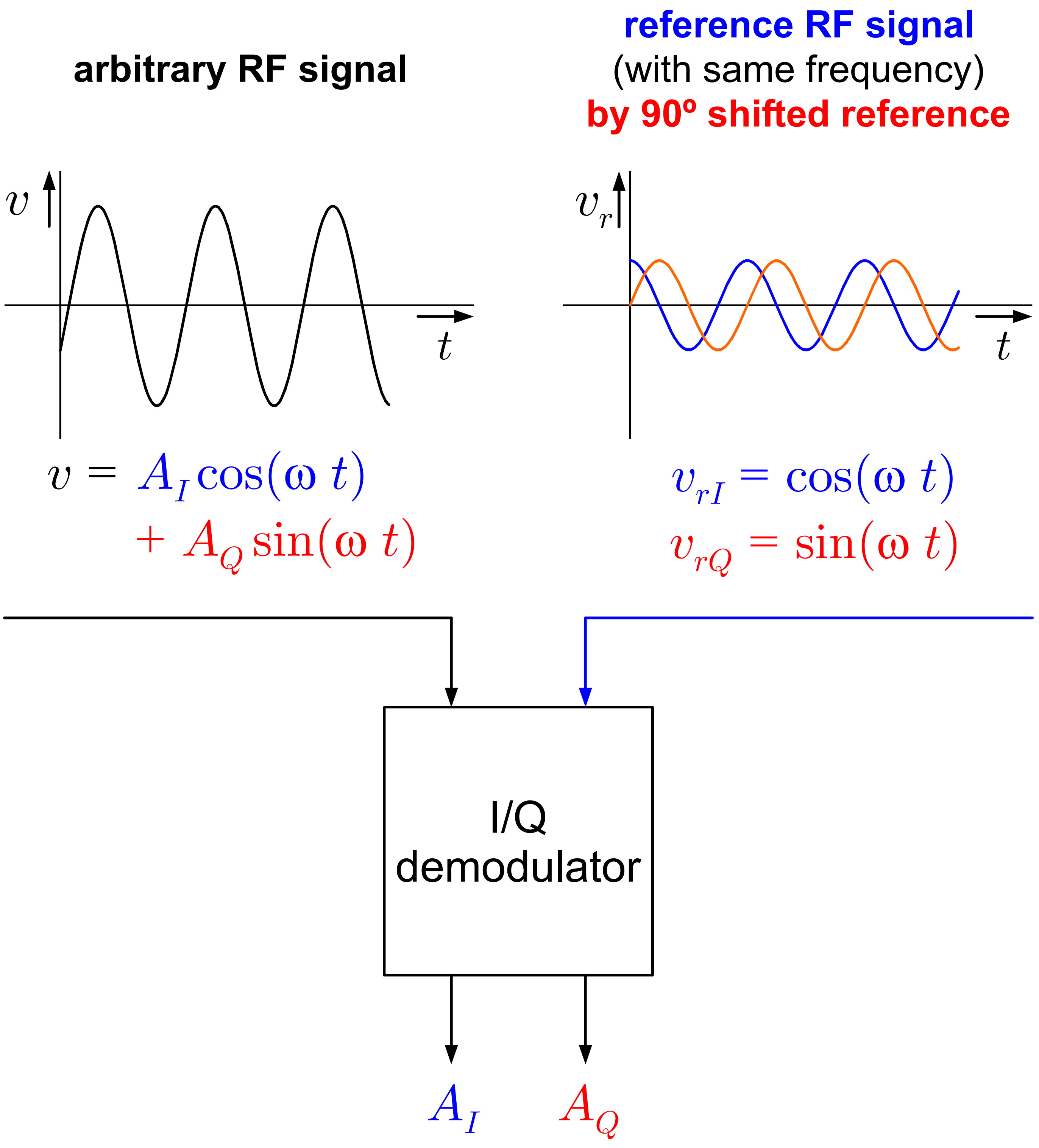


HERAp FLD:
Fast Beam Diagnostics



Racks, containing the fast longitudinal diagnostics.

Measurement of RF-signals with an IQ-demodulator



arbitrary RF signal

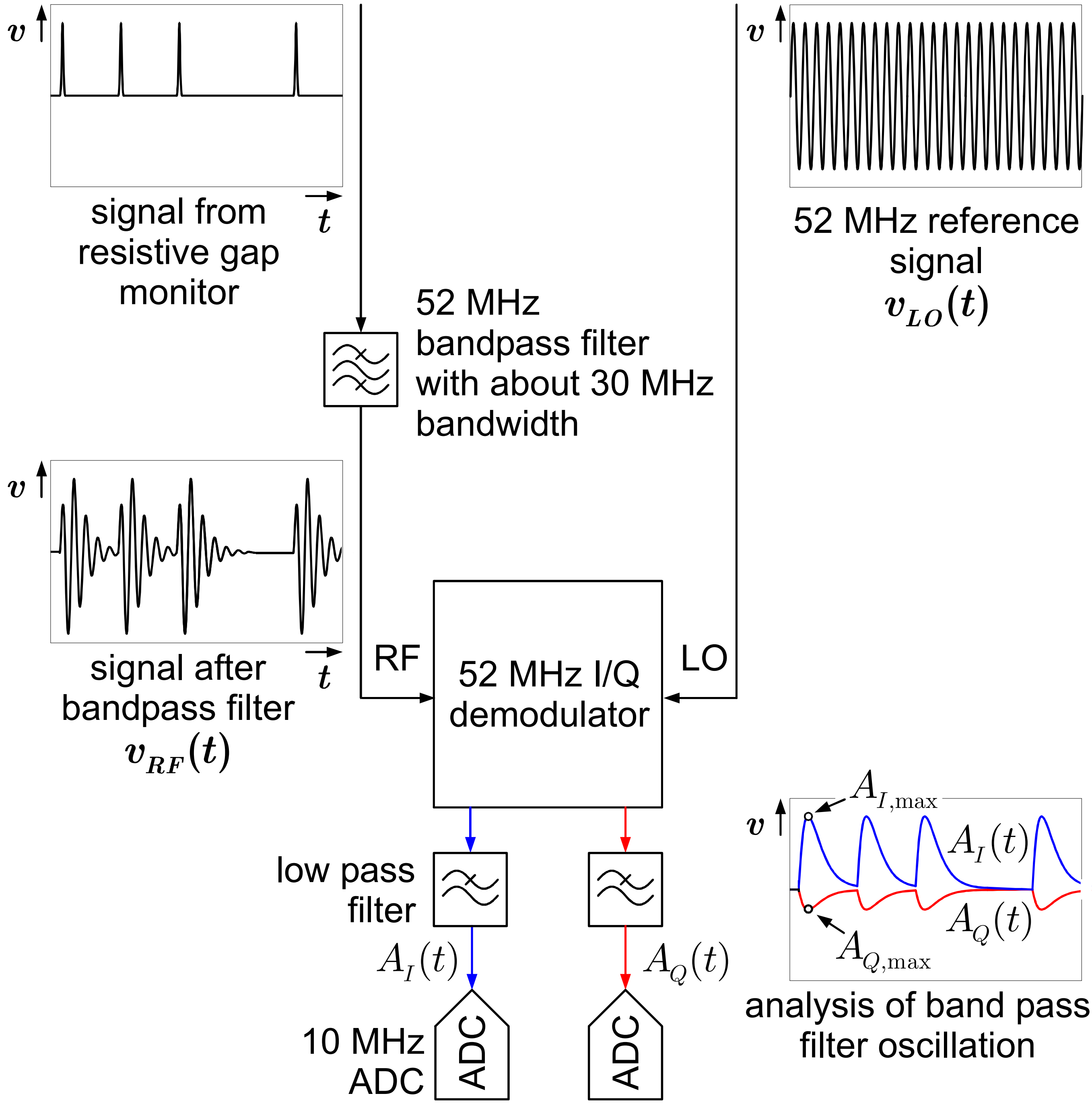
reference RF signal
(with same frequency)
by 90° shifted reference

$$v = A_I \cos(\omega\, t) + A_Q \sin(\omega\, t)$$

$$v_{rI} = \cos(\omega\, t)$$
$$v_{rQ} = \sin(\omega\, t)$$

A_I A_Q

Measurement of phase oscillations of the individual bunches



signal from resistive gap monitor

52 MHz reference signal $v_{LO}(t)$

52 MHz bandpass filter with about 30 MHz bandwidth

signal after bandpass filter $v_{RF}(t)$

52 MHz I/Q demodulator

low pass filter

10 MHz ADC

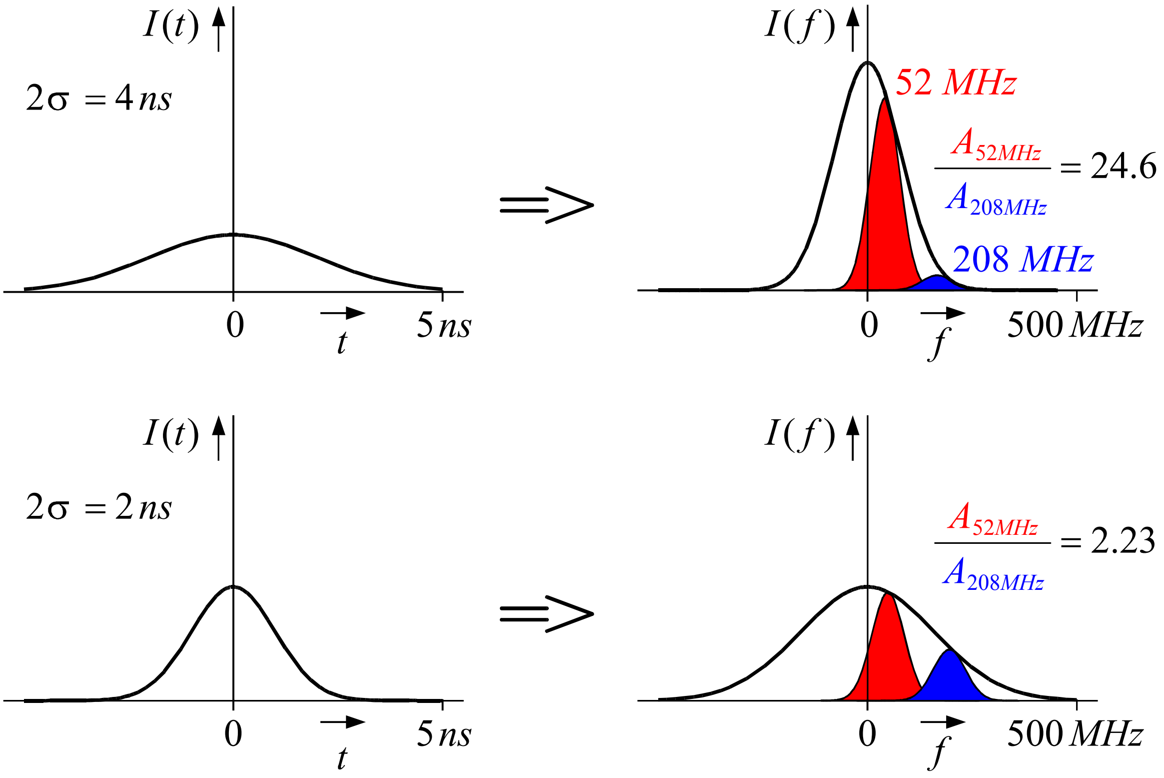
analysis of band pass filter oscillation

⇒ **phase**

⇒ **52 MHz Fourier component**

Fast bunch length measurement

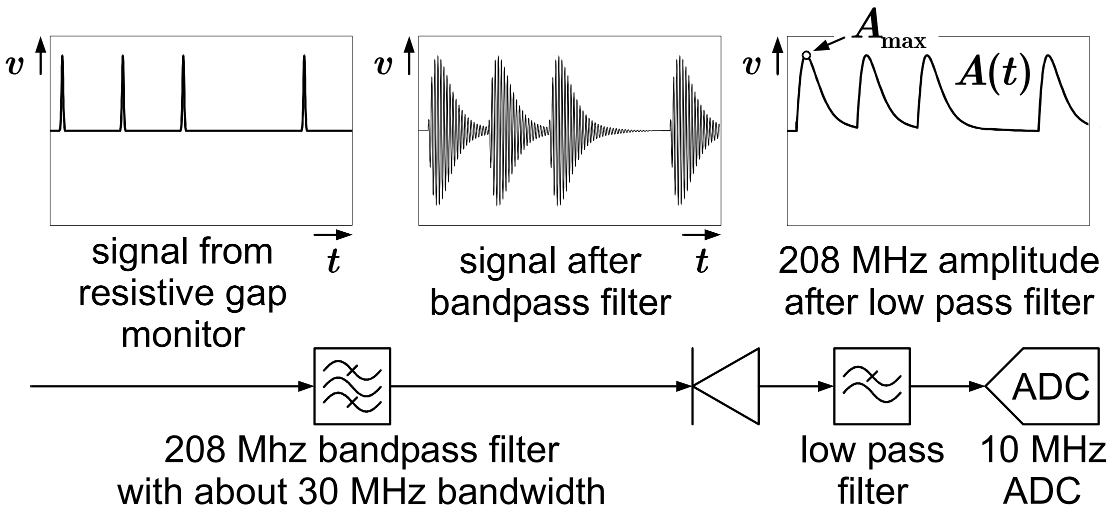
An additional Fourier component of the bunch signal is necessary:



The ratio of both Fourier components supplies the bunch length (for Gaussian bunches):

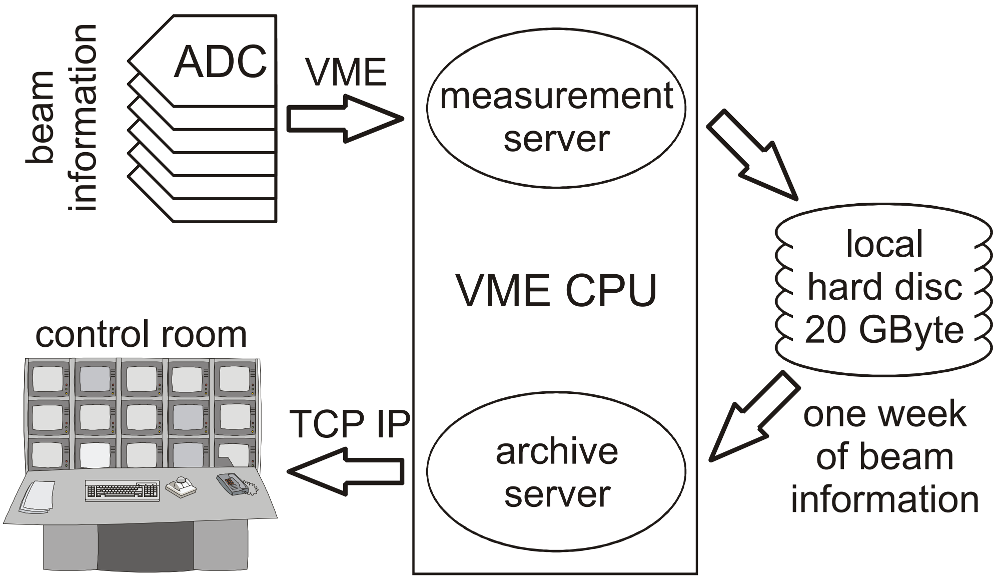
$$\boxed{A_{52\,MHz}/A_{208\,MHz} = \exp\left(0.800622\cdot\sigma^2/ns^2\right)}$$

Considering the characteristic curve of the diode gives: $\boxed{A_{208MHz}}$

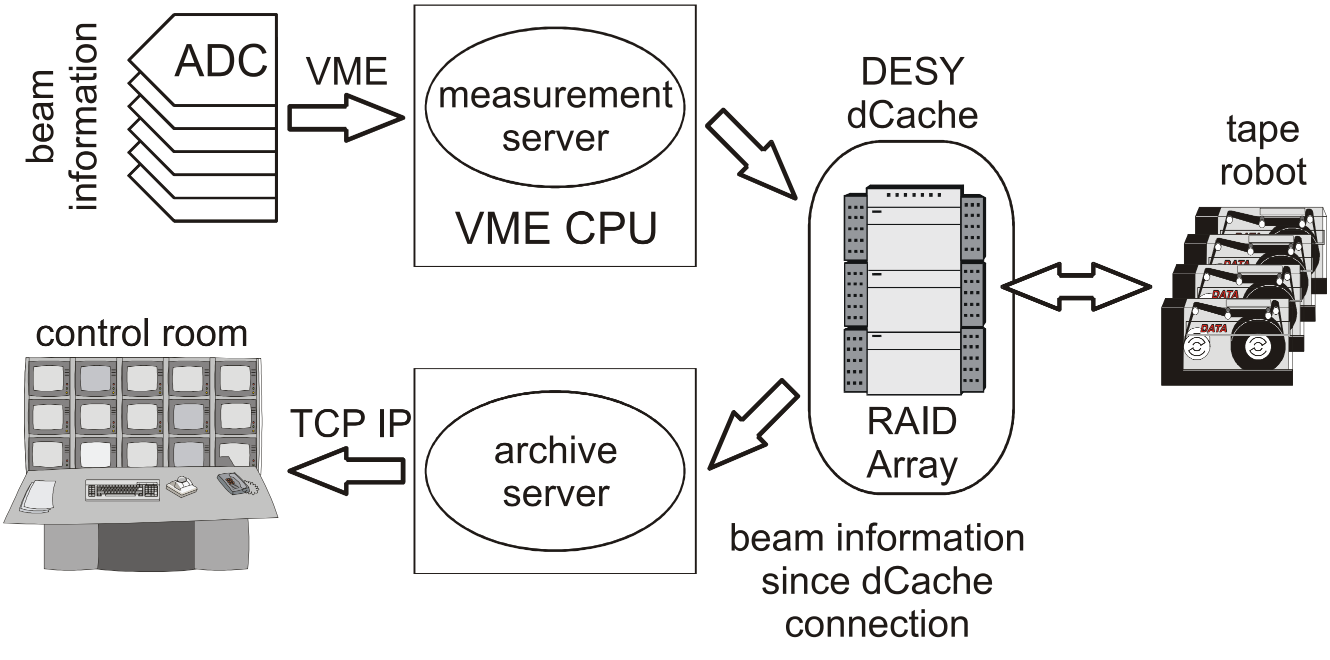


Data acquisition –
a new tool for the control room (BKR)

Actual data flow (in October 2002):



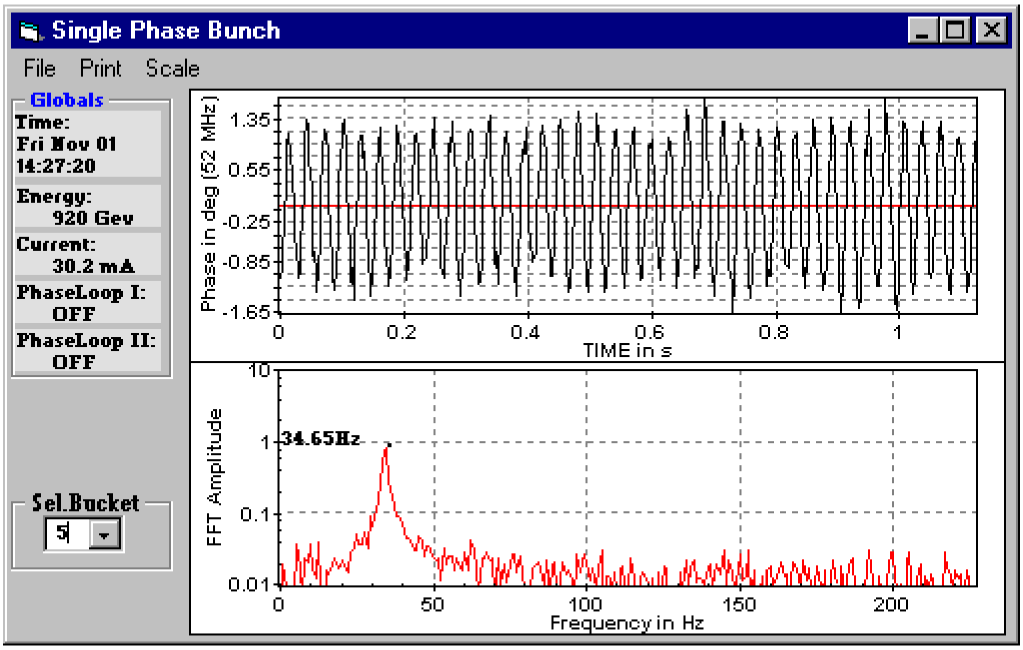
Data flow in future:



Every Day Observable Effects

Please convince yourself in the accelerator control room (BKR), by using the P-Fast Longitudinal Diagnostics, contained in the Diagnostics menu.

A phase oscillation of a proton Bunch



Time:
Fri Nov 01
14:27:20

Energy:
920 Gev

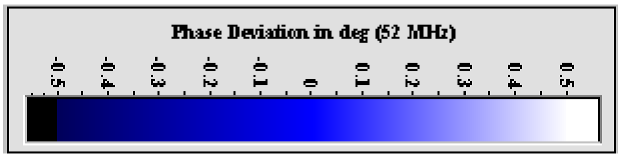
Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

Sel.Bucket: 5

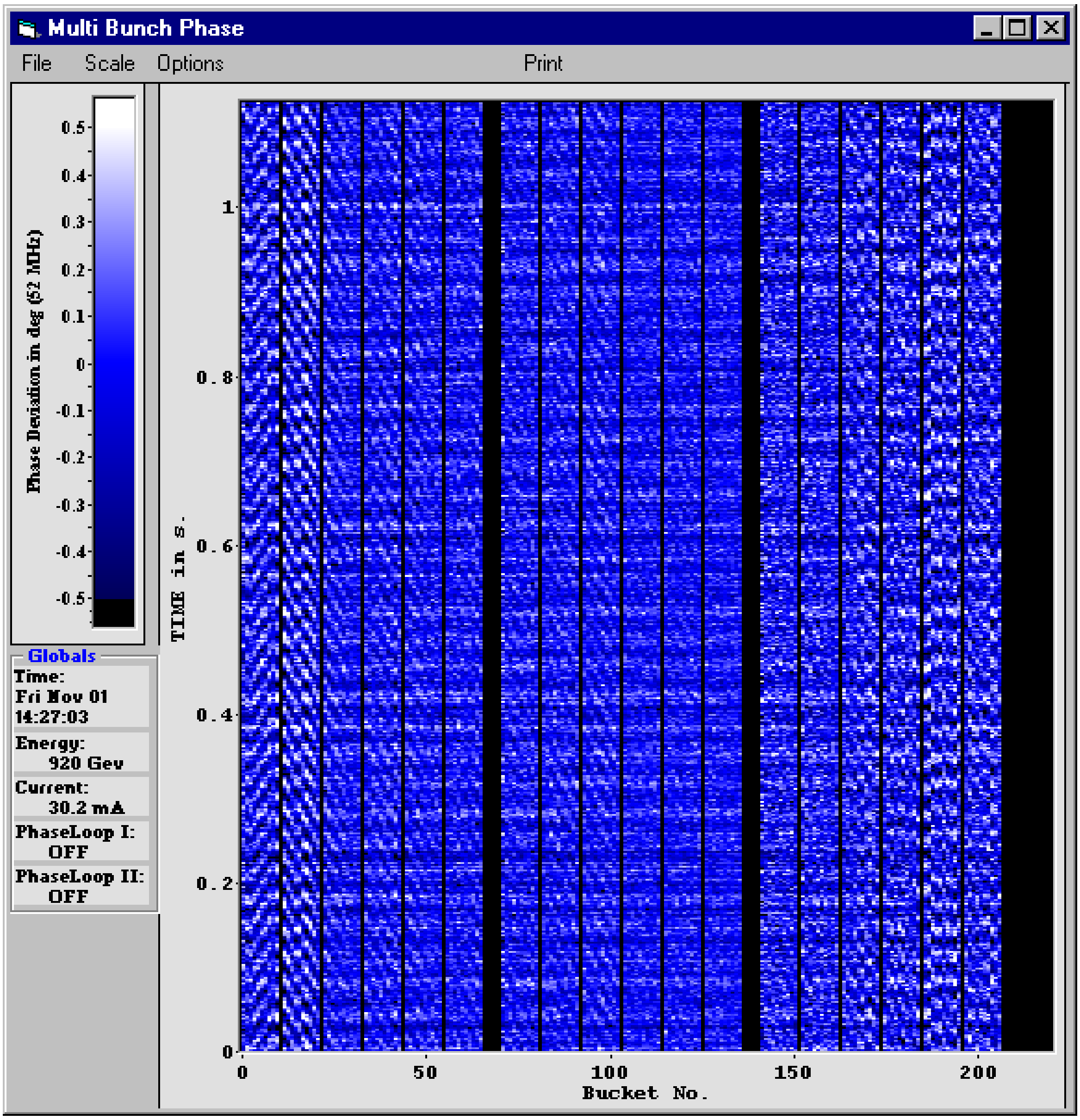
Presentation of the oscillation with a color code.



The oscillation looks like

⇒ All bunches can be presented together

Picture gallery of a coupled bunch oscillation in the HERA proton ring …



Globals

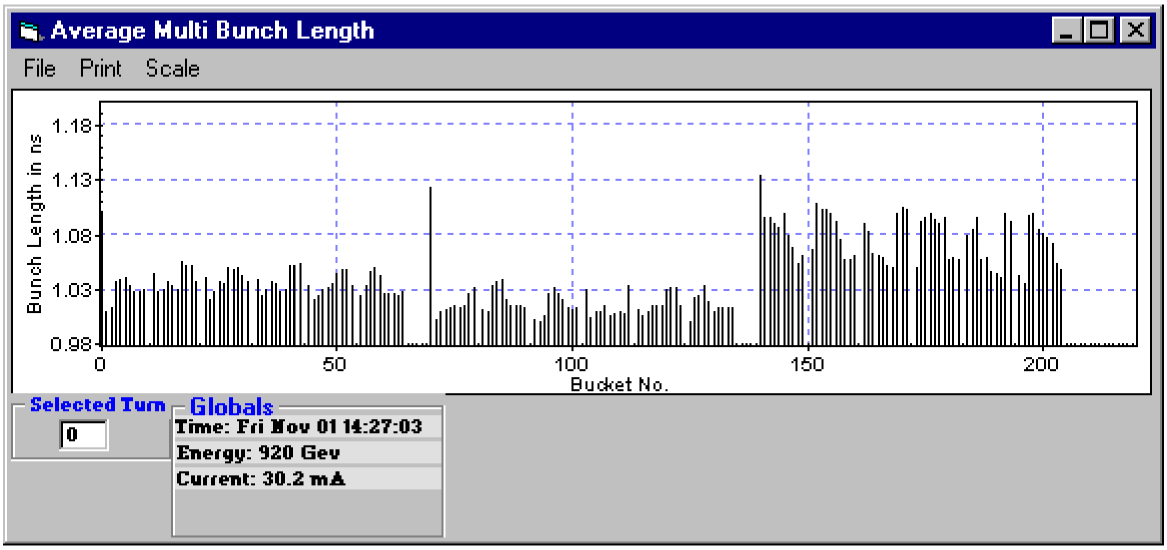
Time:
Fri Nov 01
14:27:03

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF



Selected Turn

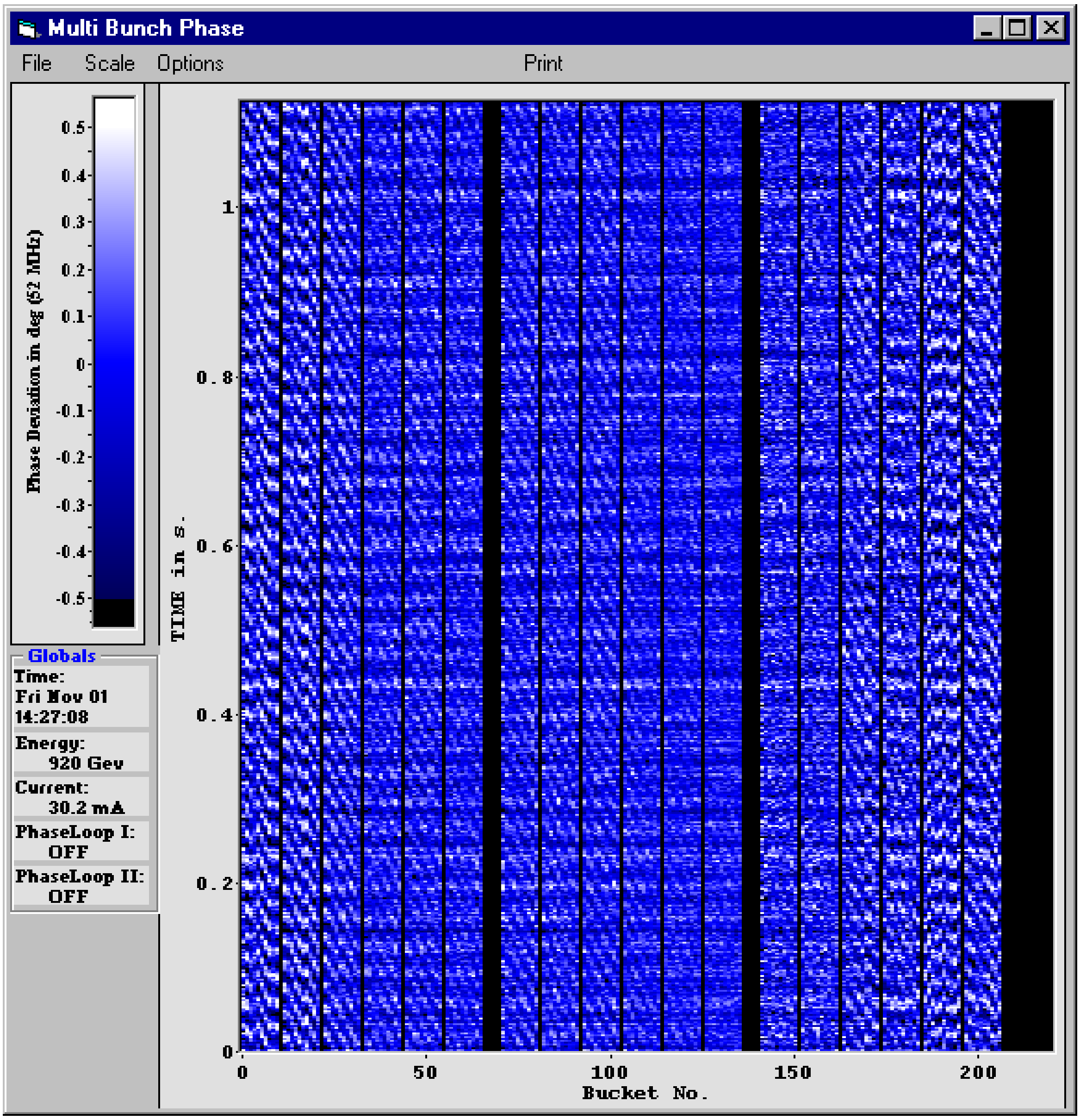
0

Globals

Time: Fri Nov 01 14:27:03

Energy: 920 Gev

Current: 30.2 mA



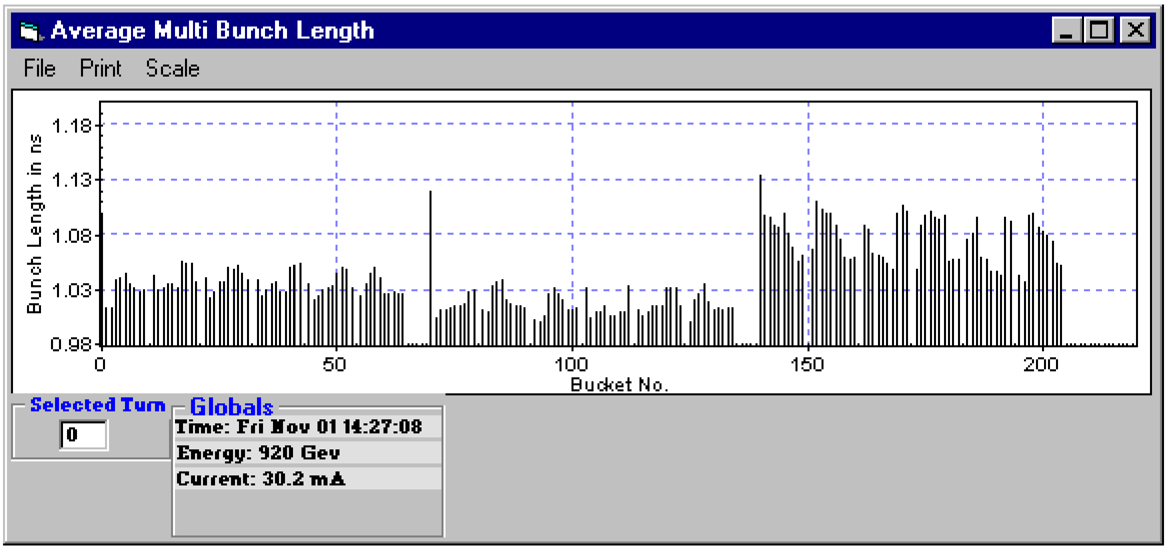
Time:
Fri Nov 01
14:27:08

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

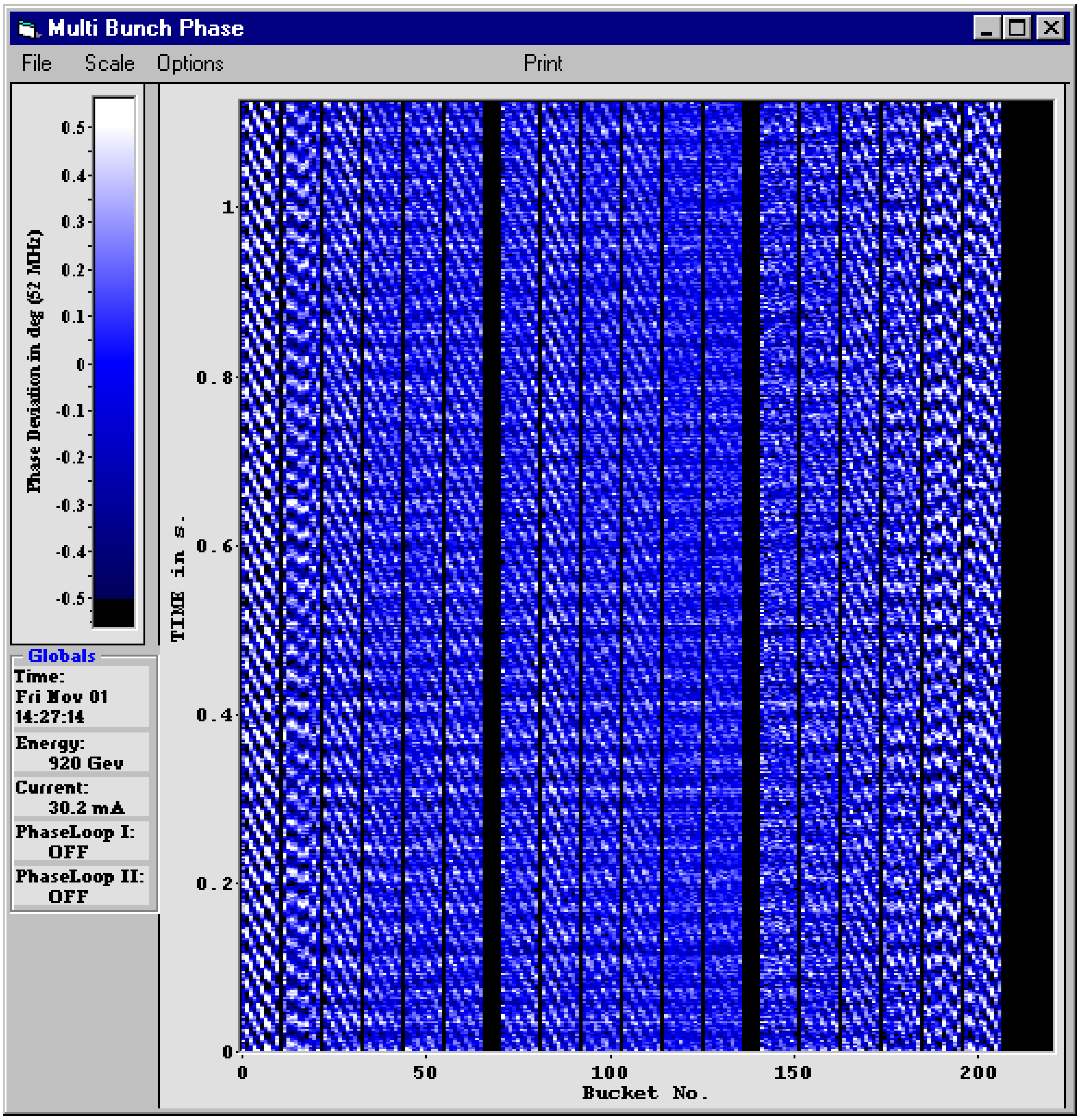


0

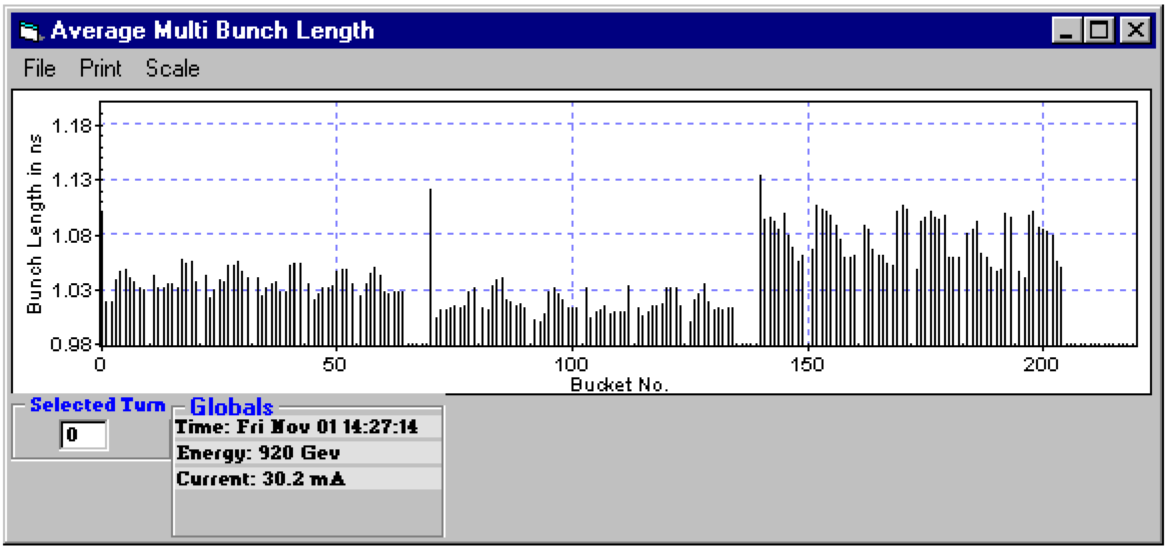
Time: Fri Nov 01 14:27:08

Energy: 920 Gev

Current: 30.2 mA

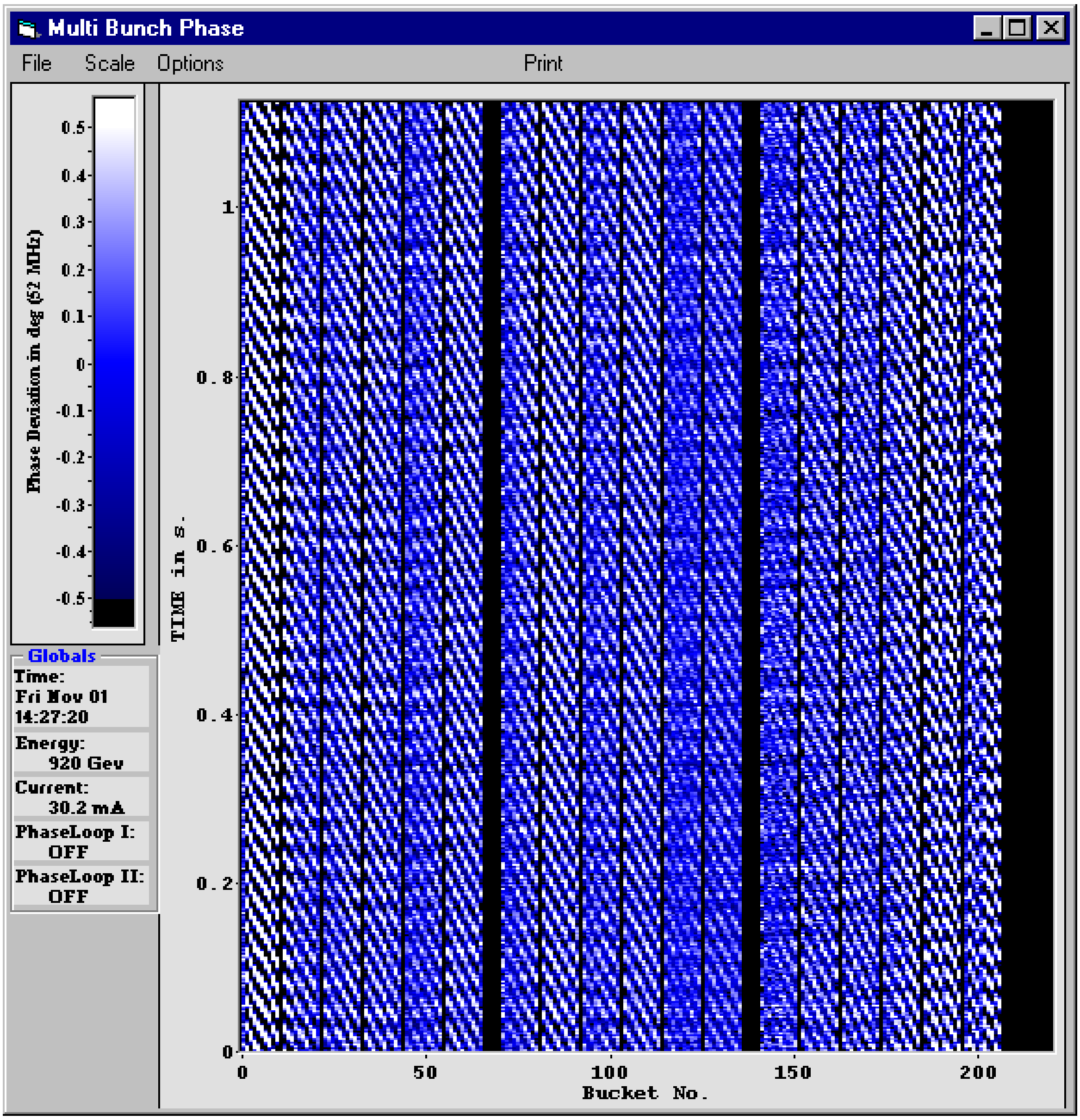


Time:
Fri Nov 01
14:27:14
Energy:
920 Gev
Current:
30.2 mA
PhaseLoop I:
OFF
PhaseLoop II:
OFF



Selected Turn: 0

Time: Fri Nov 01 14:27:14
Energy: 920 Gev
Current: 30.2 mA



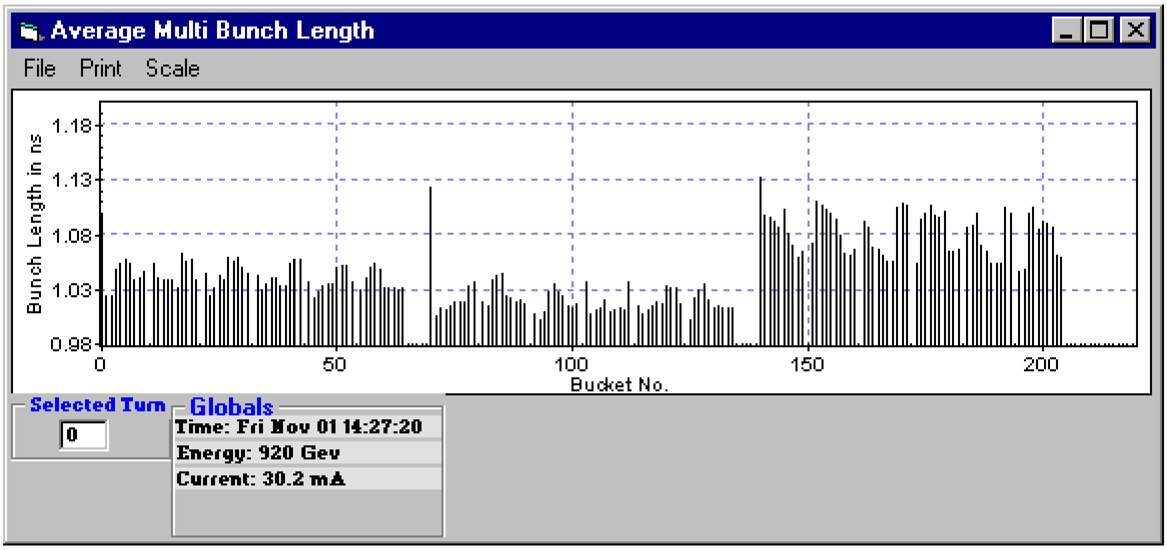
Time:
Fri Nov 01
14:27:20

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

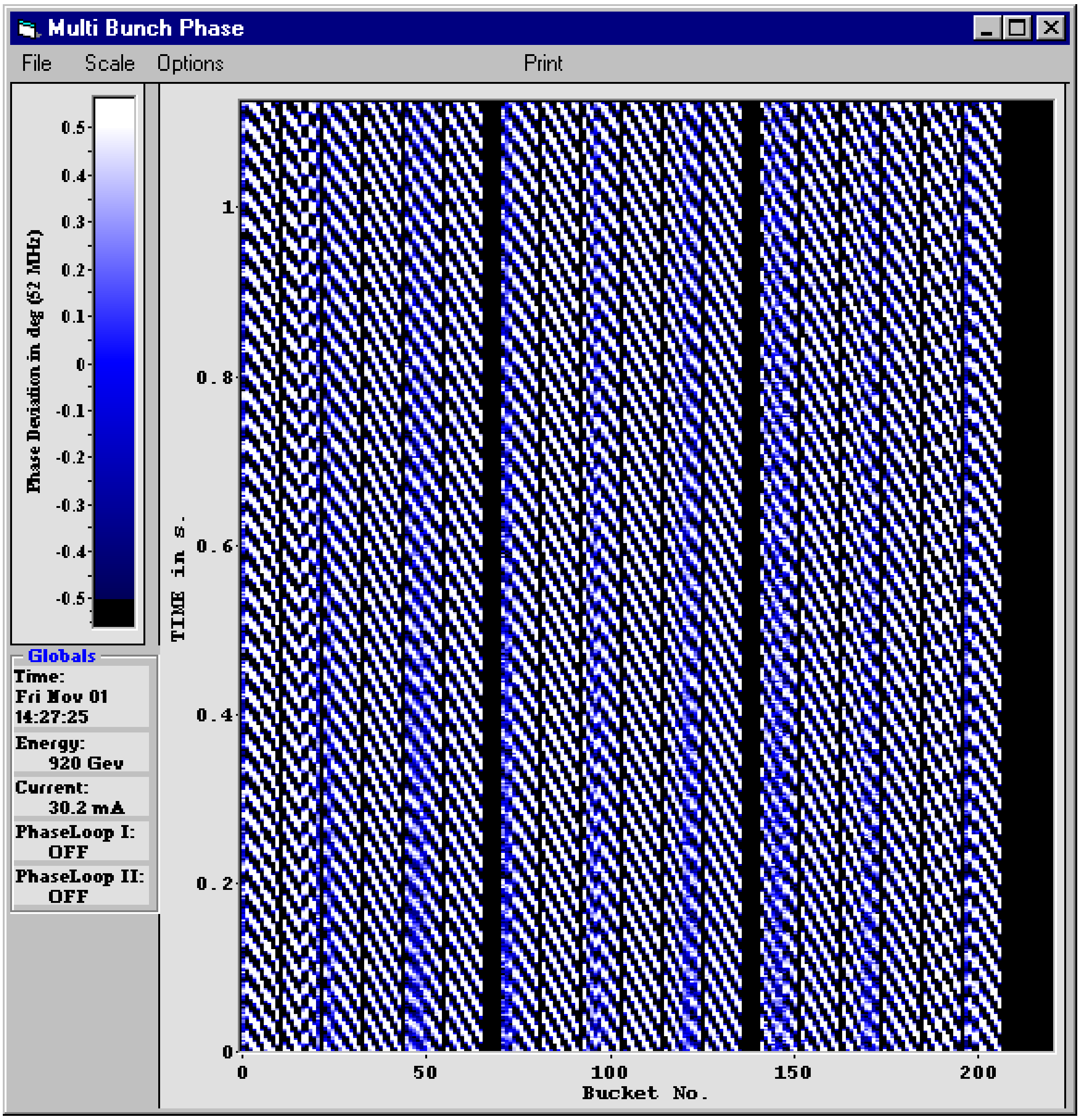


Selected Turn: 0

Time: Fri Nov 01 14:27:20

Energy: 920 Gev

Current: 30.2 mA



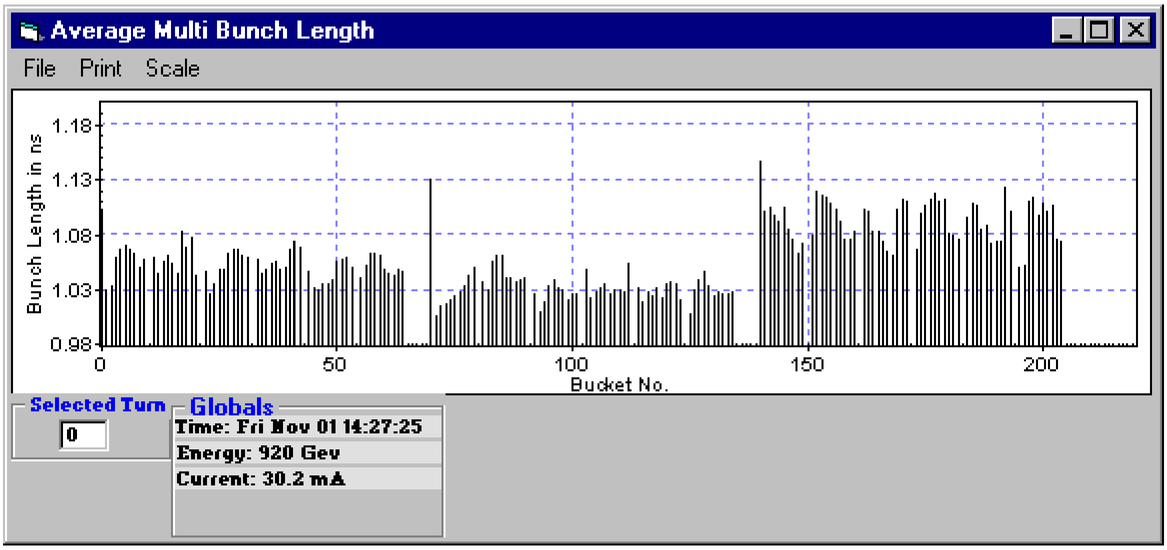
Time:
Fri Nov 01
14:27:25

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

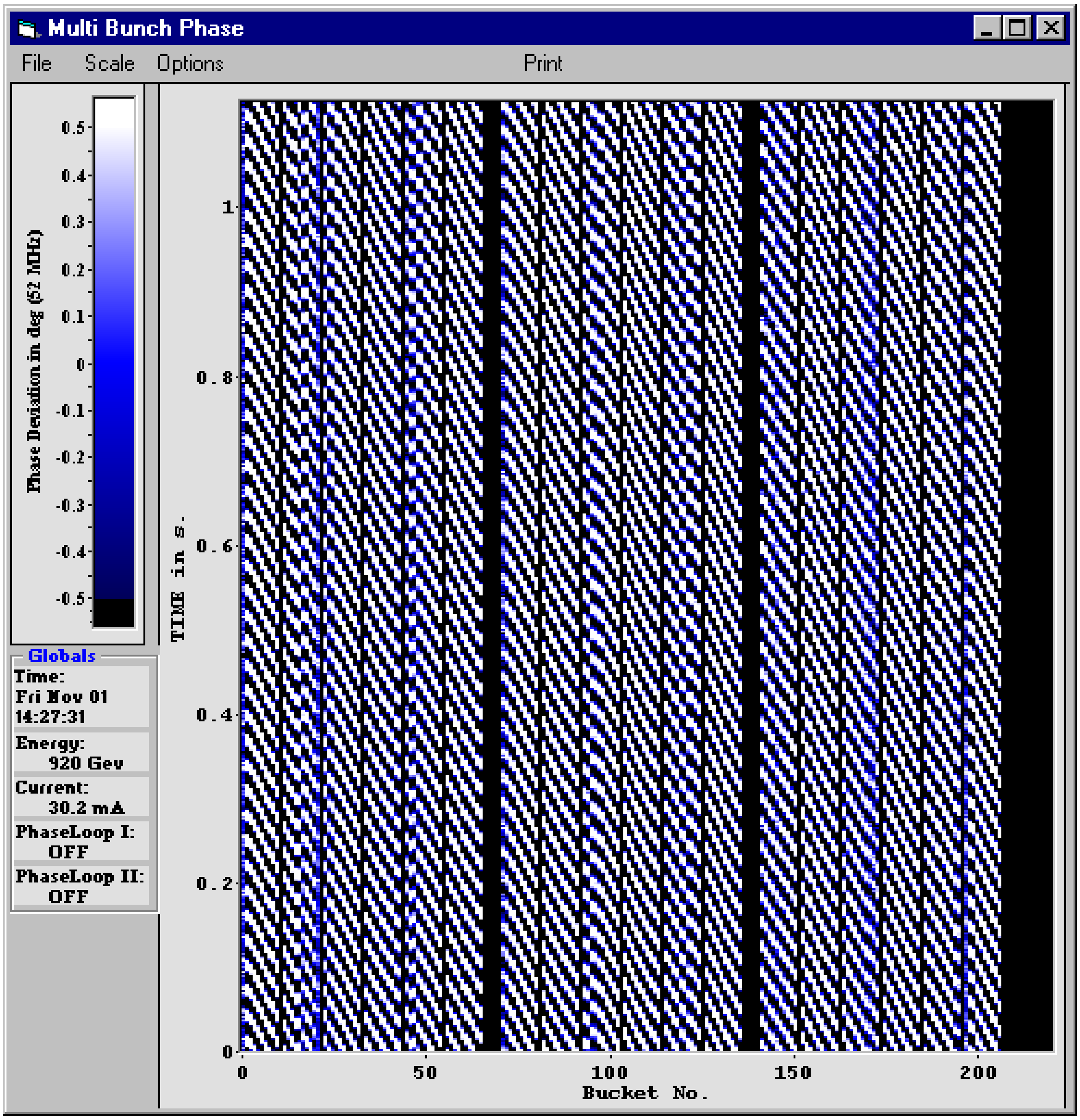


Selected Turn: 0

Time: Fri Nov 01 14:27:25

Energy: 920 Gev

Current: 30.2 mA



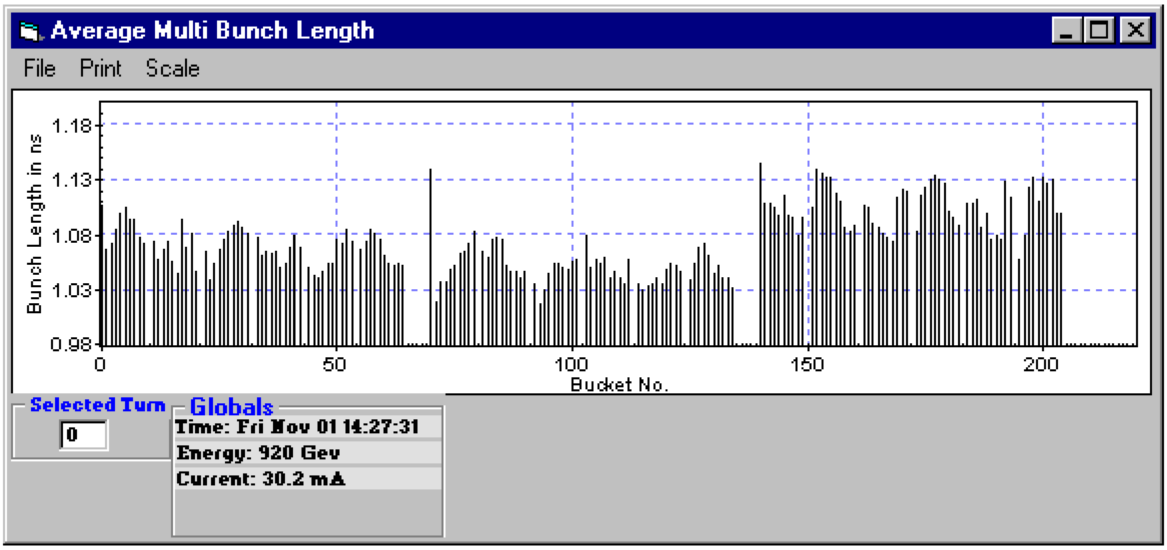
Time:
Fri Nov 01
14:27:31

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

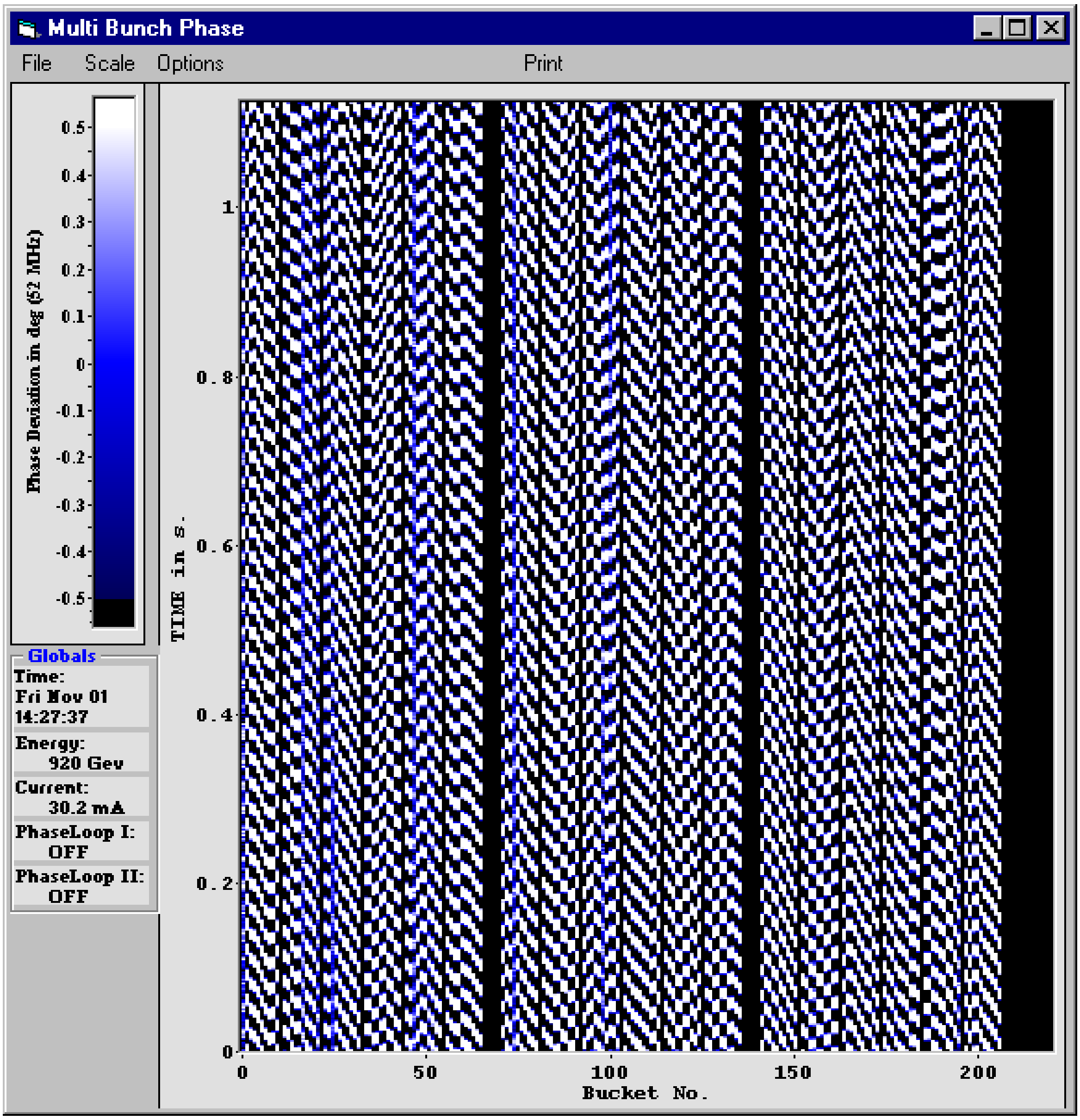


Selected Turn: 0

Time: Fri Nov 01 14:27:31

Energy: 920 Gev

Current: 30.2 mA



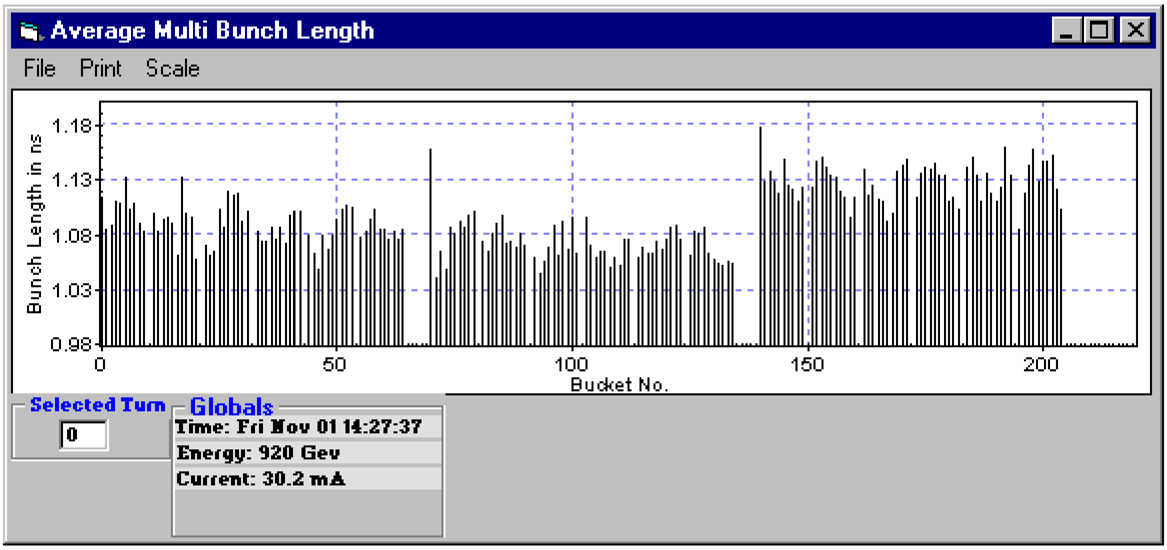
Time:
Fri Nov 01
14:27:37

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

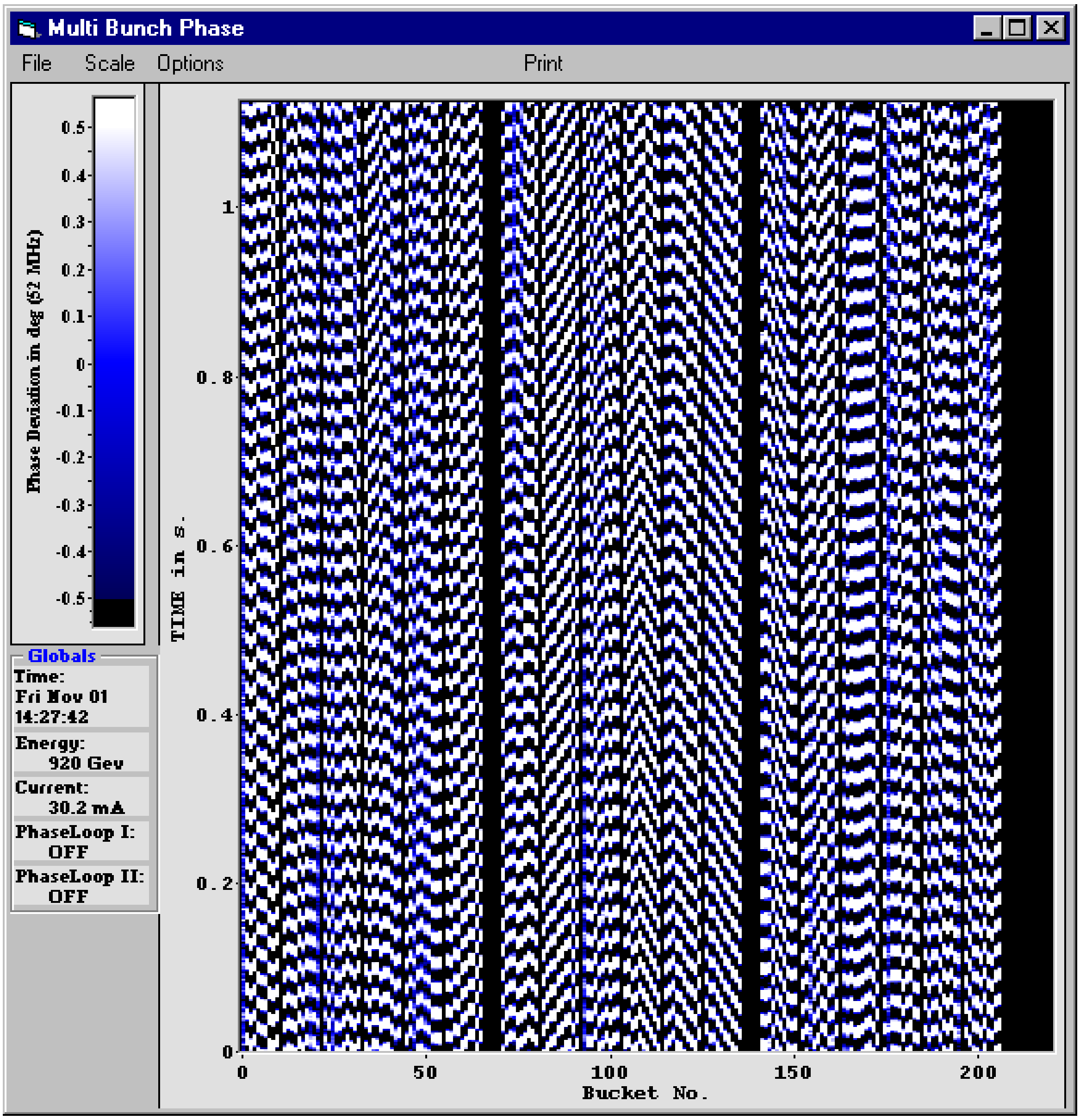


0

Time: Fri Nov 01 14:27:37

Energy: 920 Gev

Current: 30.2 mA



Globals

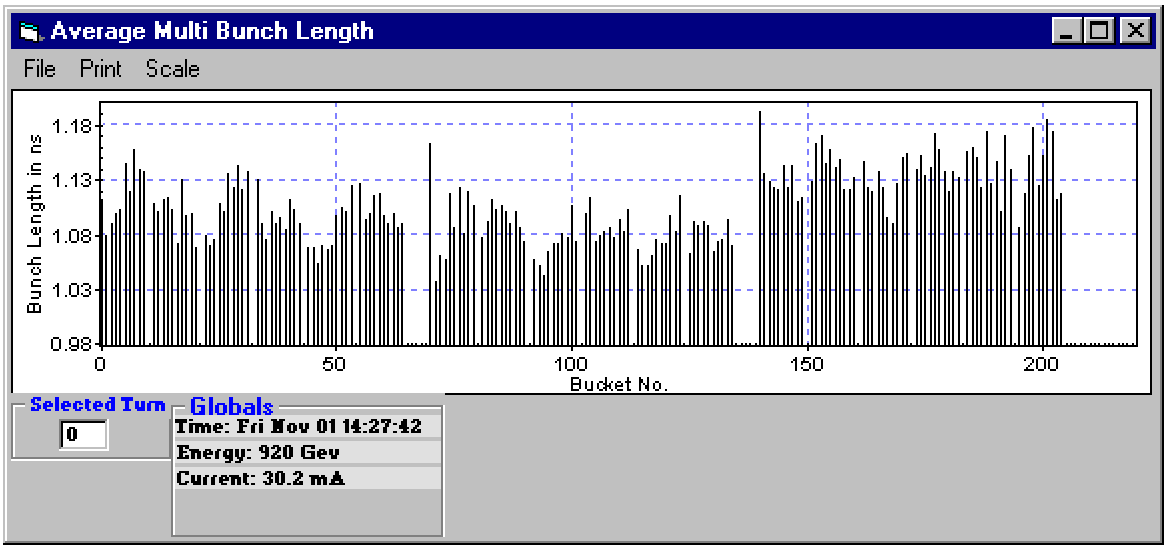
Time:
Fri Nov 01
14:27:42

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF



Selected Turn

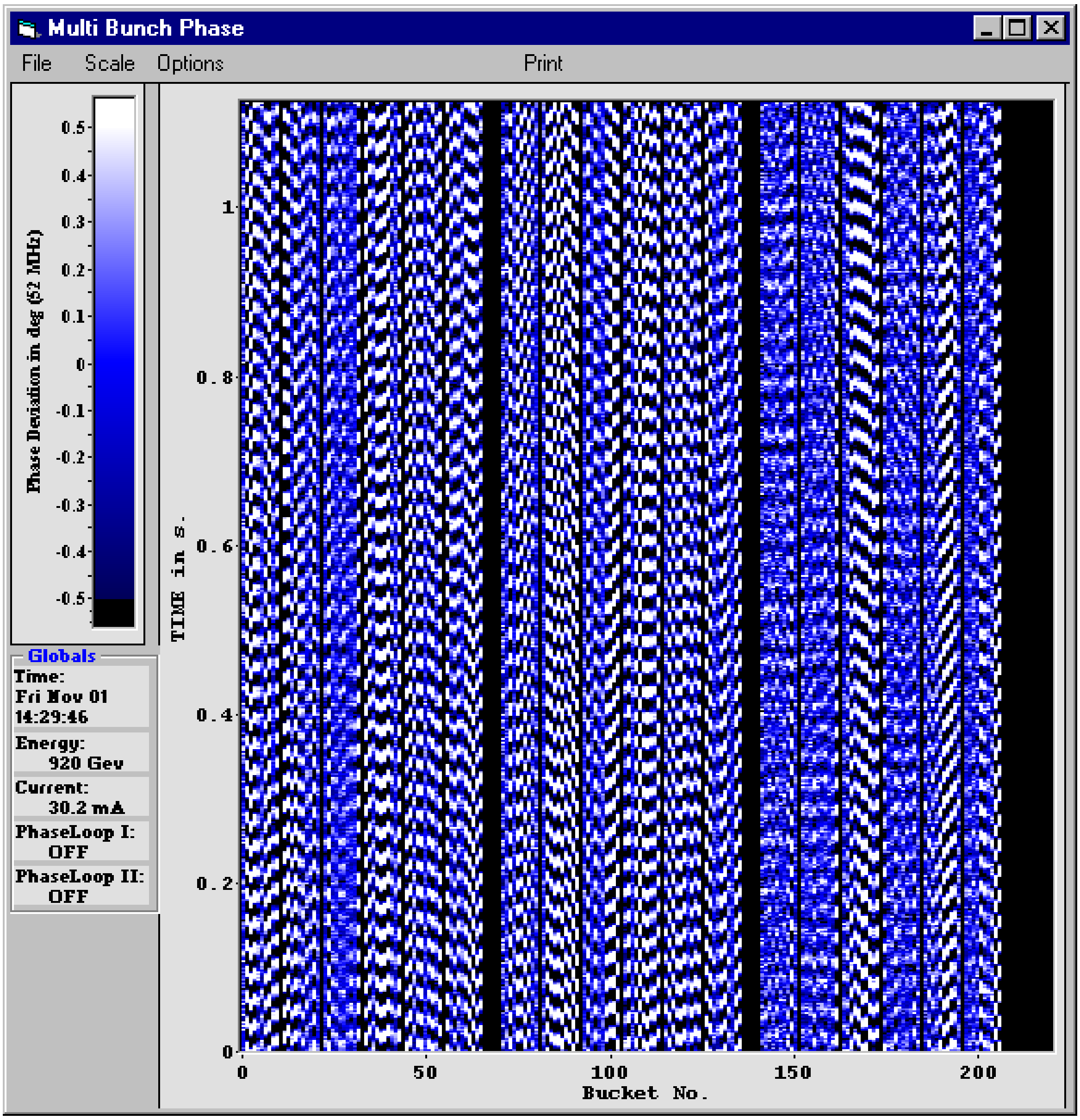
0

Globals

Time: Fri Nov 01 14:27:42

Energy: 920 Gev

Current: 30.2 mA



Globals

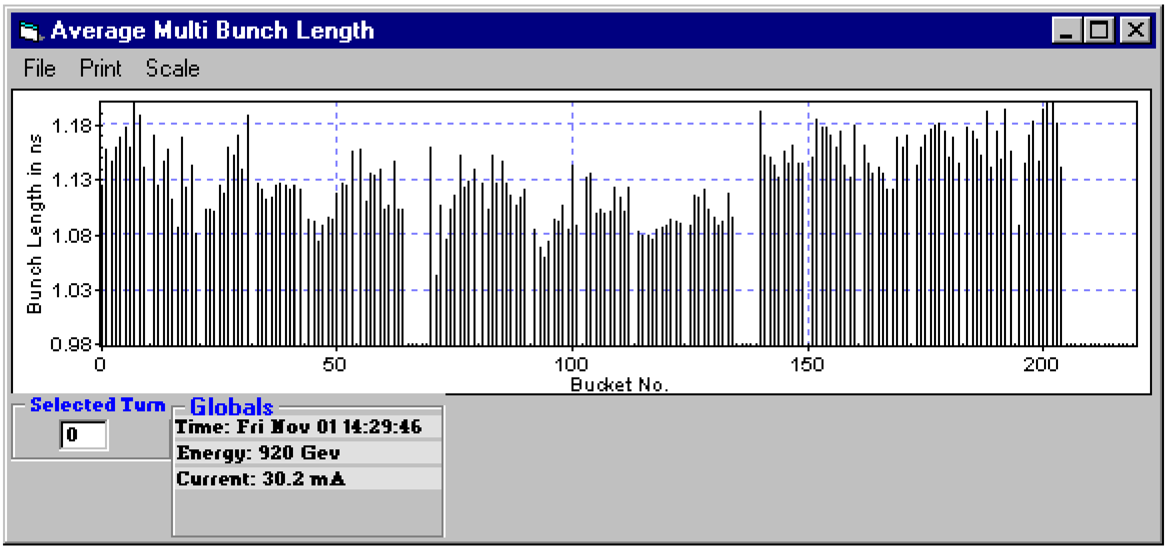
Time:
Fri Nov 01
14:29:46

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF



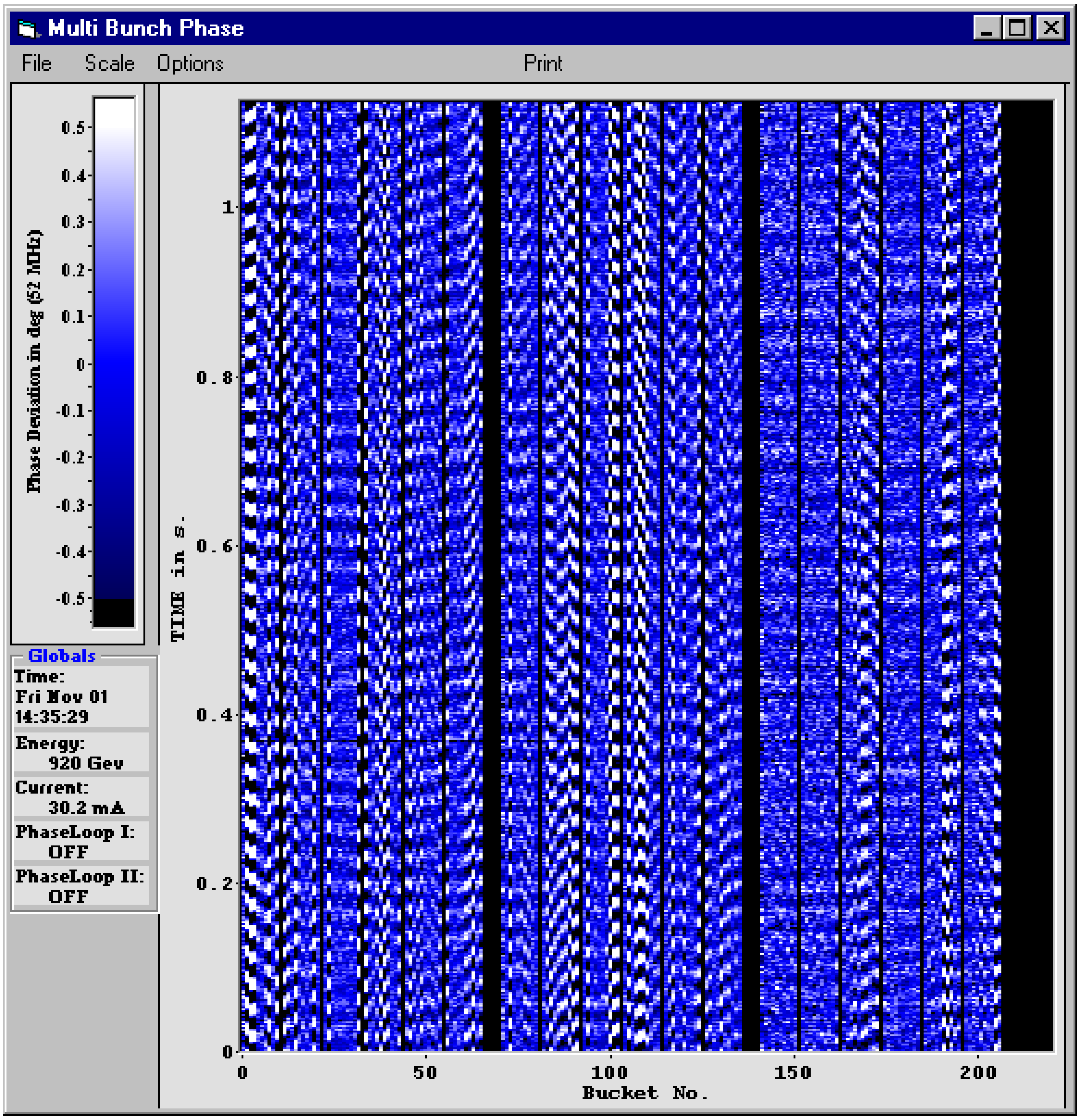
Selected Turn
0

Globals

Time: Fri Nov 01 14:29:46

Energy: 920 Gev

Current: 30.2 mA



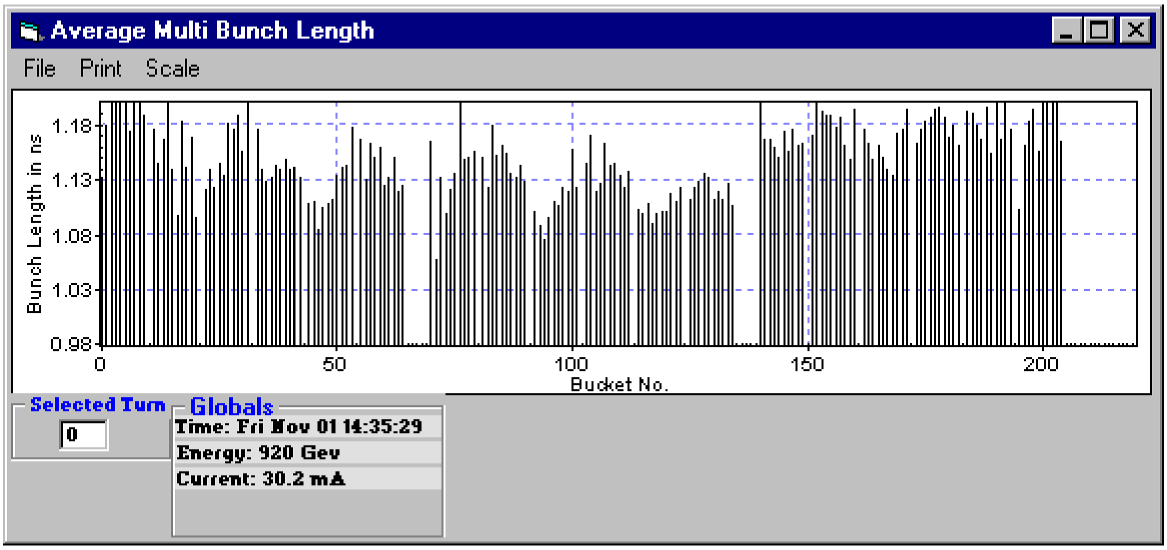
Time:
Fri Nov 01
14:35:29

Energy:
920 Gev

Current:
30.2 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF



Selected Turn: 0

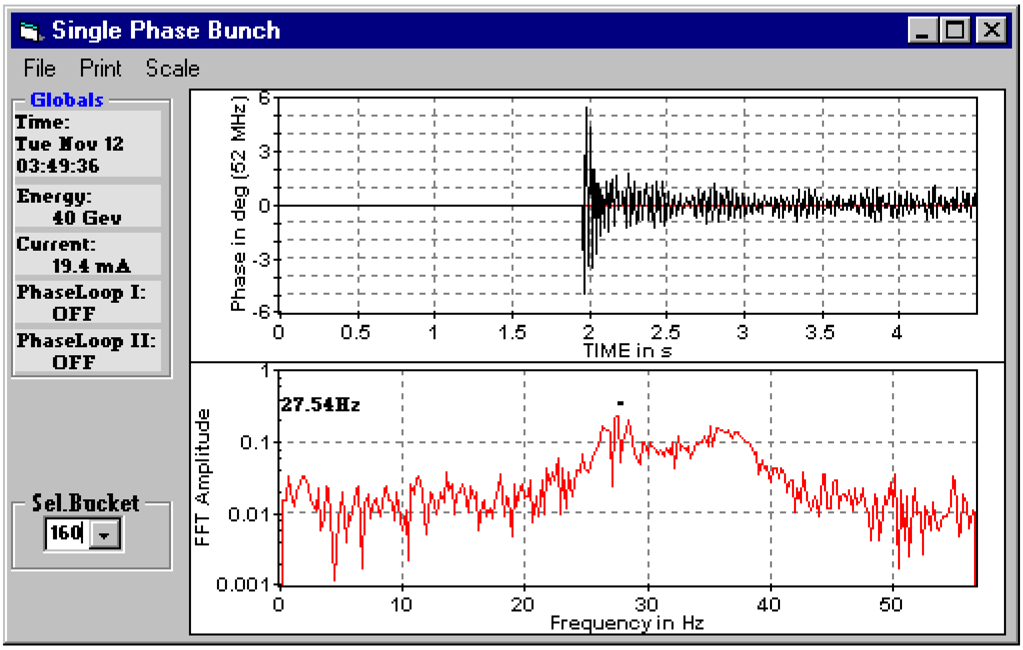
Time: Fri Nov 01 14:35:29

Energy: 920 Gev

Current: 30.2 mA

Emittance dilution due to injection?

Injection of third bunch train:



Time: Tue Nov 12 03:49:36

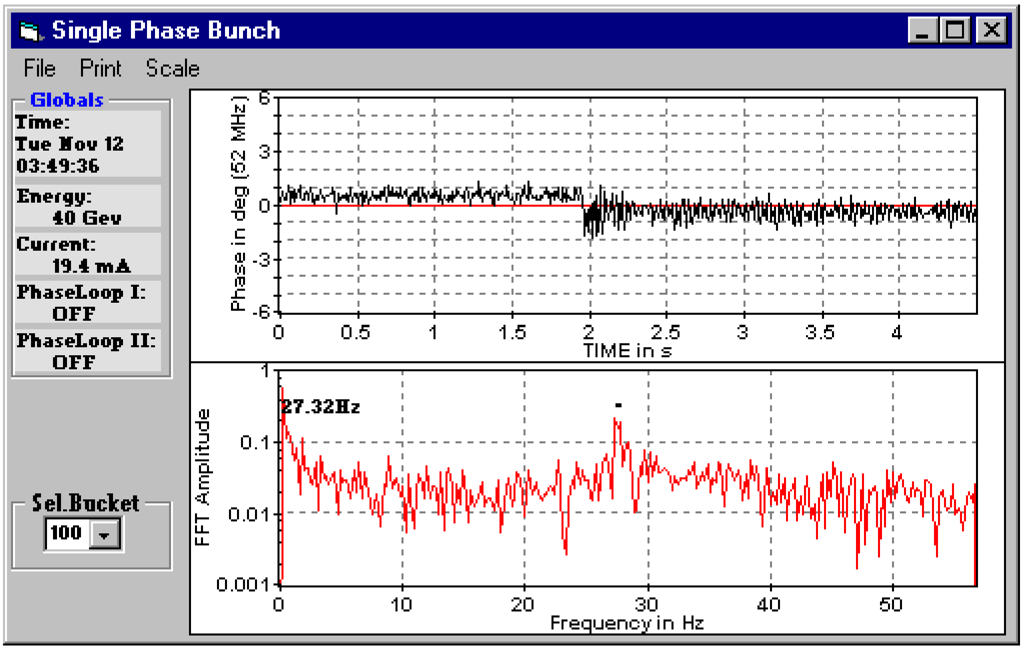
Energy: 40 Gev

Current: 19.4 mA

PhaseLoop I: OFF

PhaseLoop II: OFF

Sel.Bucket: 160



Time: Tue Nov 12 03:49:36

Energy: 40 Gev

Current: 19.4 mA

PhaseLoop I: OFF

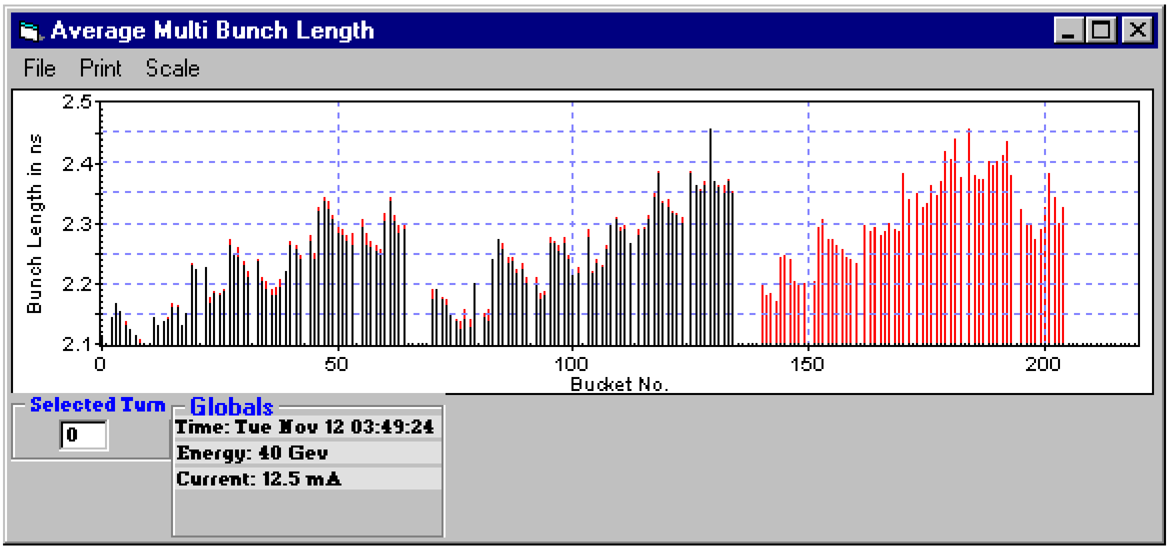
PhaseLoop II: OFF

Sel.Bucket: 100

Effect on the bunch lengths (emittance) …

Bunch lengths before and after injection

Before (black) and after (red) injection:

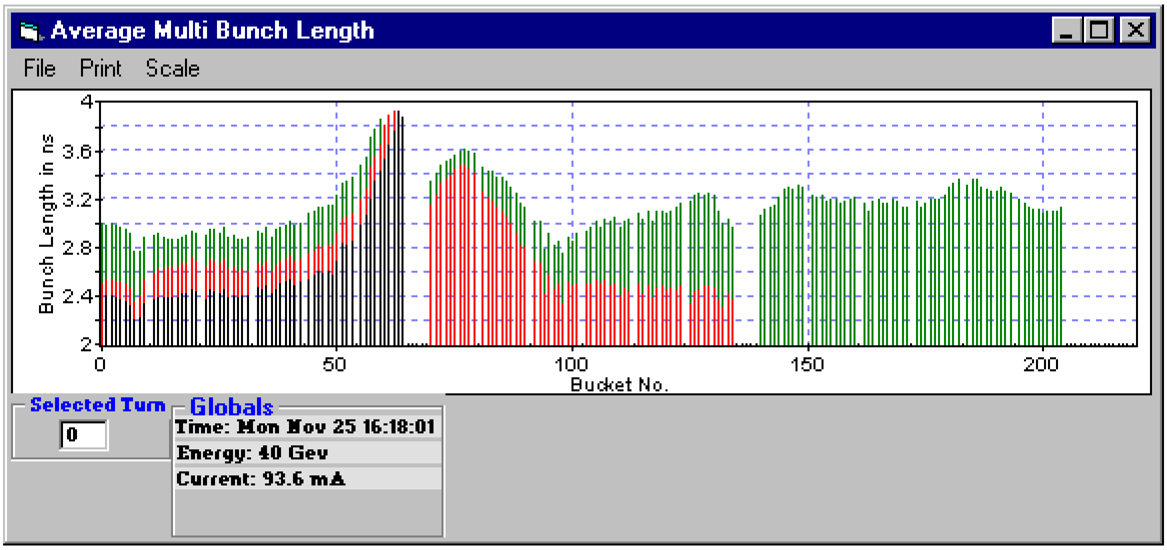


0

Time: Tue Nov 12 03:49:24
Energy: 40 Gev
Current: 12.5 mA

⇒ Low intense bunches suffers no emittance dilution during injection

⇒But: this is not the case for high intensities!

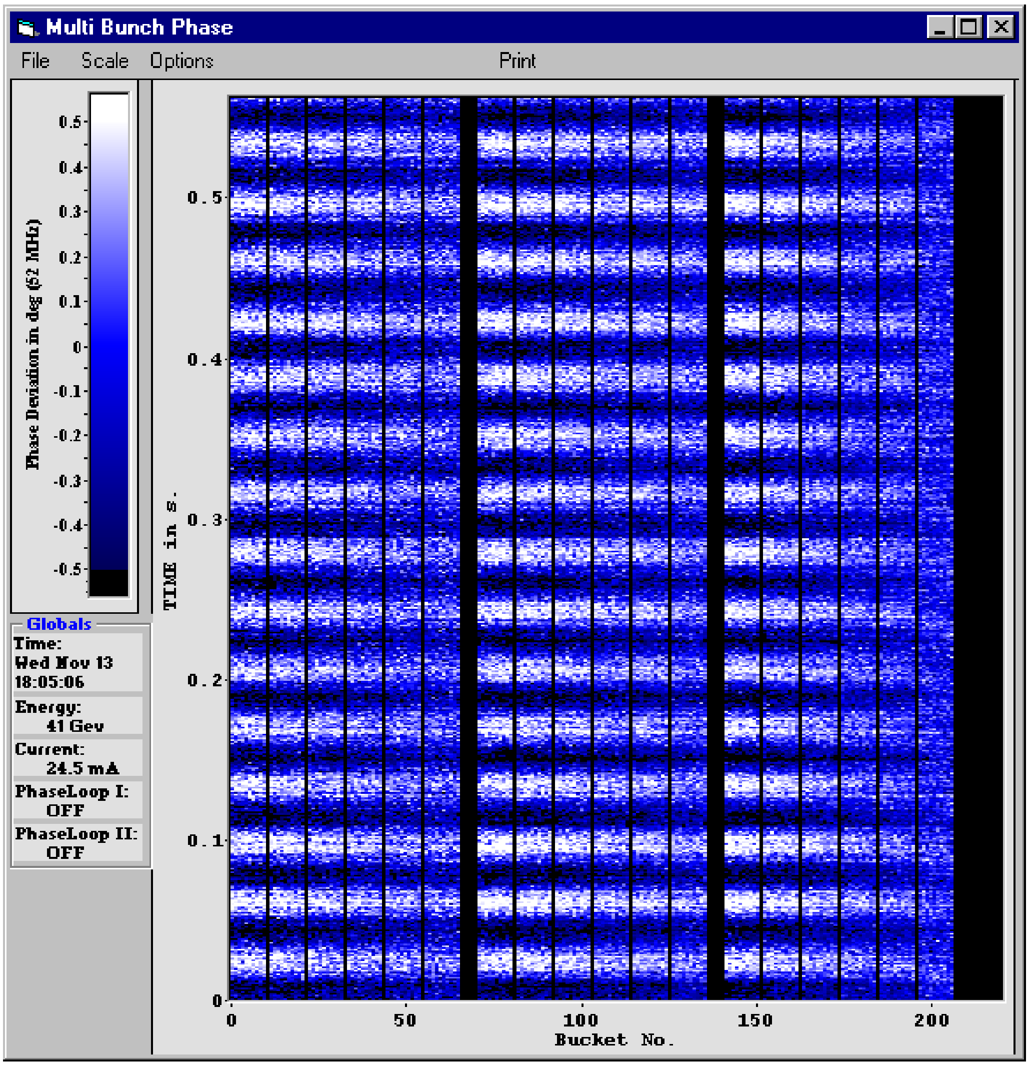


0

Time: Mon Nov 25 16:18:01
Energy: 40 Gev
Current: 93.6 mA

The ramp between injection and 70 GeV

At low energies, the coupled bunch mode $l = 0$ is visible:



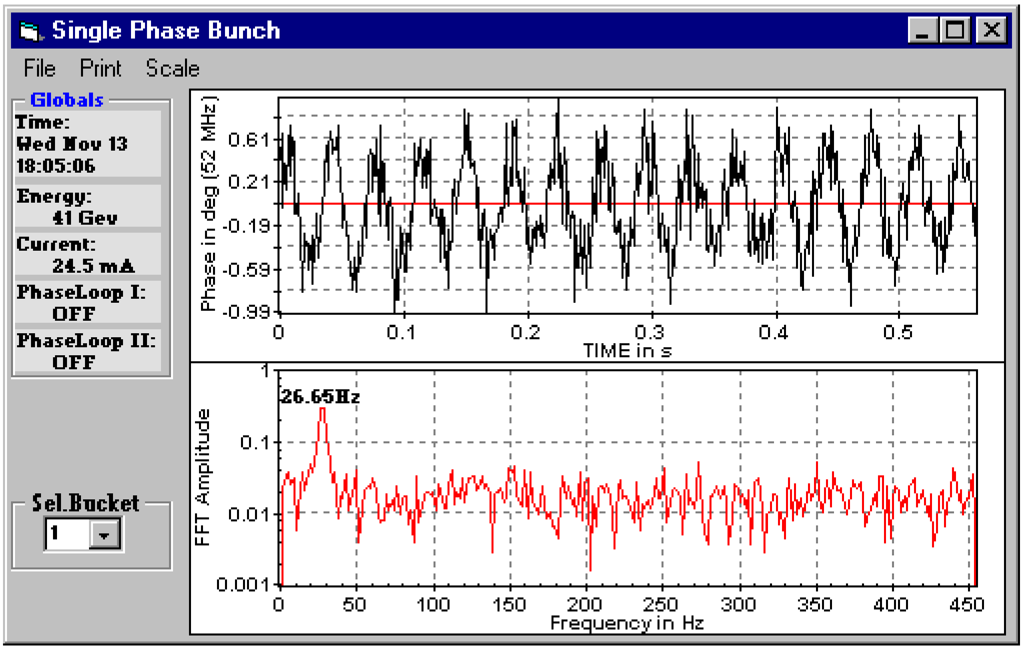
Time:
Wed Nov 13
18:05:06

Energy:
41 Gev

Current:
24.5 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF



Time:
Wed Nov 13
18:05:06

Energy:
41 Gev

Current:
24.5 mA

PhaseLoop I:
OFF

PhaseLoop II:
OFF

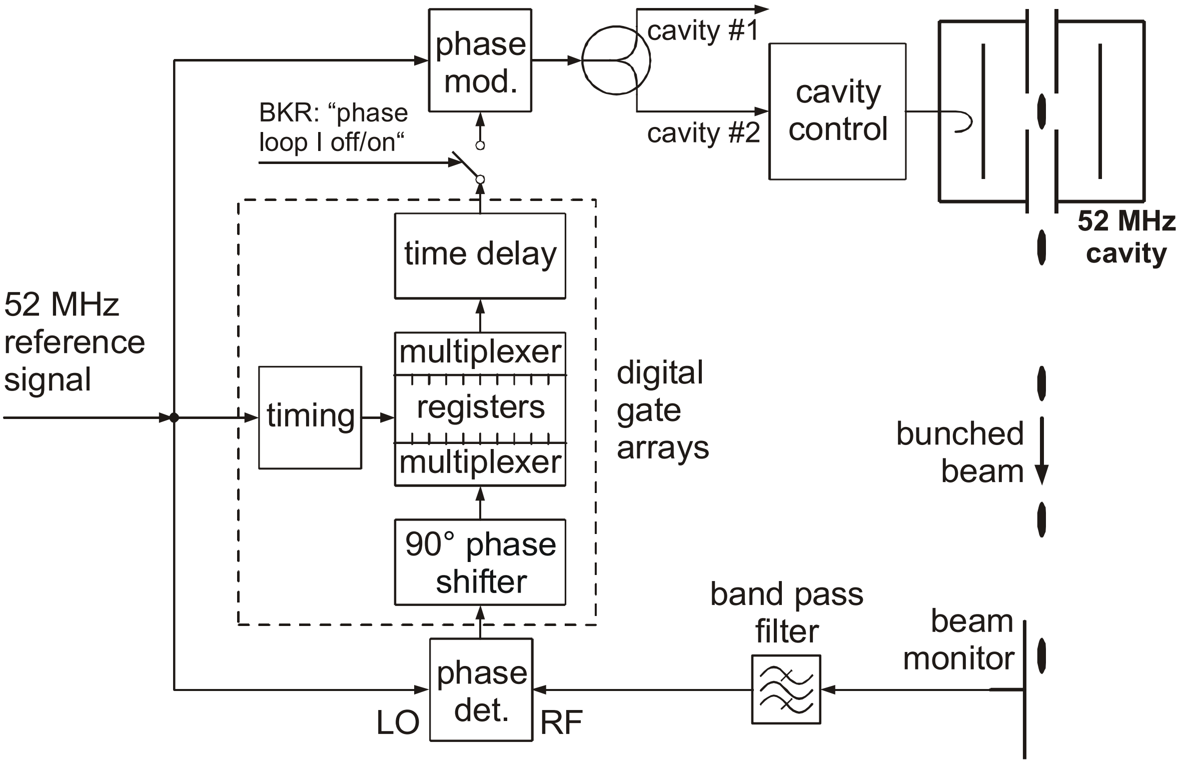
Sel.Bucket: 1

Measures Against Longitudinal Emittance Dilution

Emittance preservation at injection – Phase Loop I and/or Feed-forward

For low beam intensities not necessary, otherwise Phase Loop I (from MHF-p) or a Feed-forward preserves the emittance:

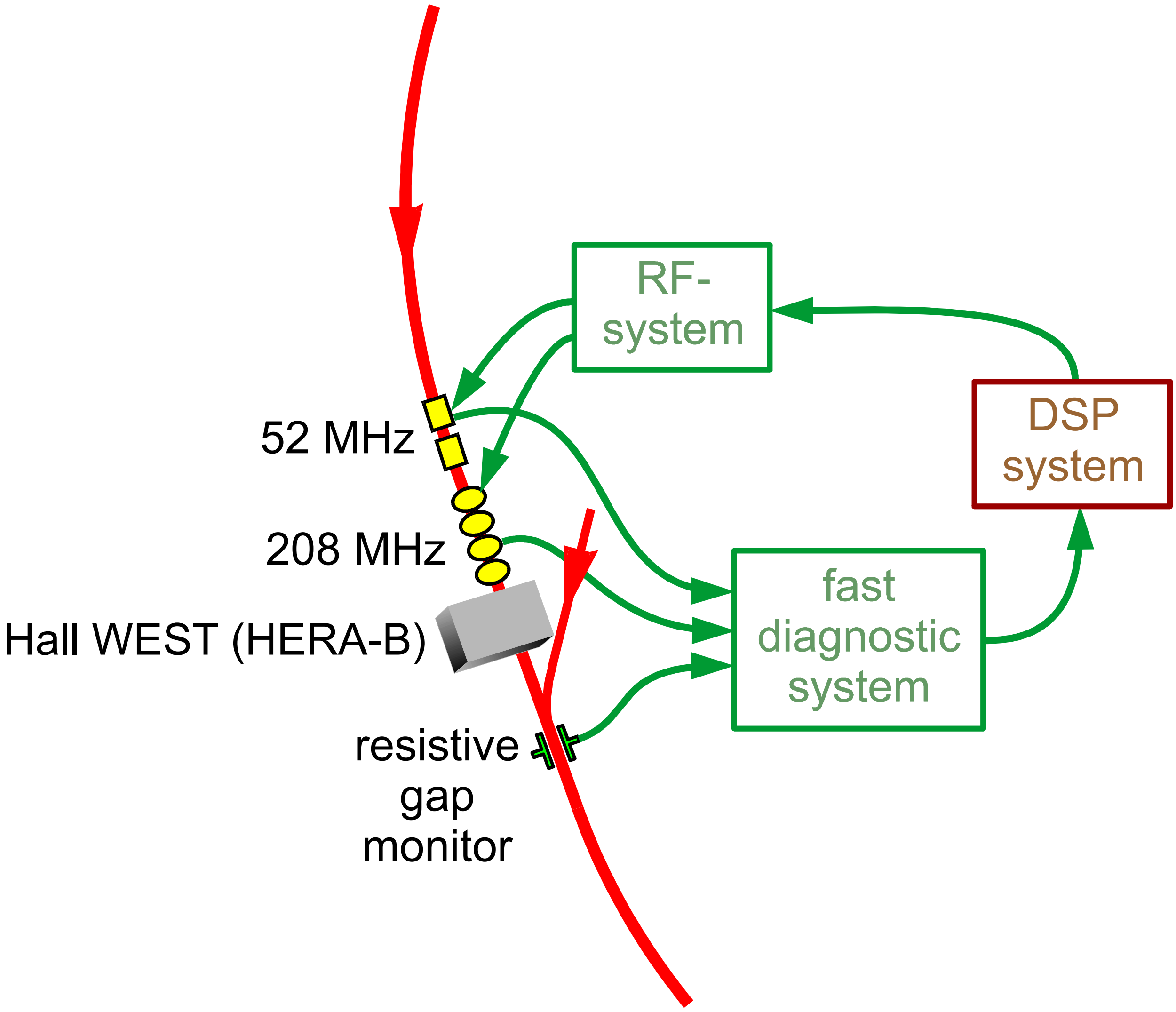
Phase Loop I



Actual problems:

- the loop works only for phase oscillations larger than 5°
- the 90° phase shift is fixed to a value matching 30 Hz
- switching the loop on and off causes RF phase jumps

Feed-forward

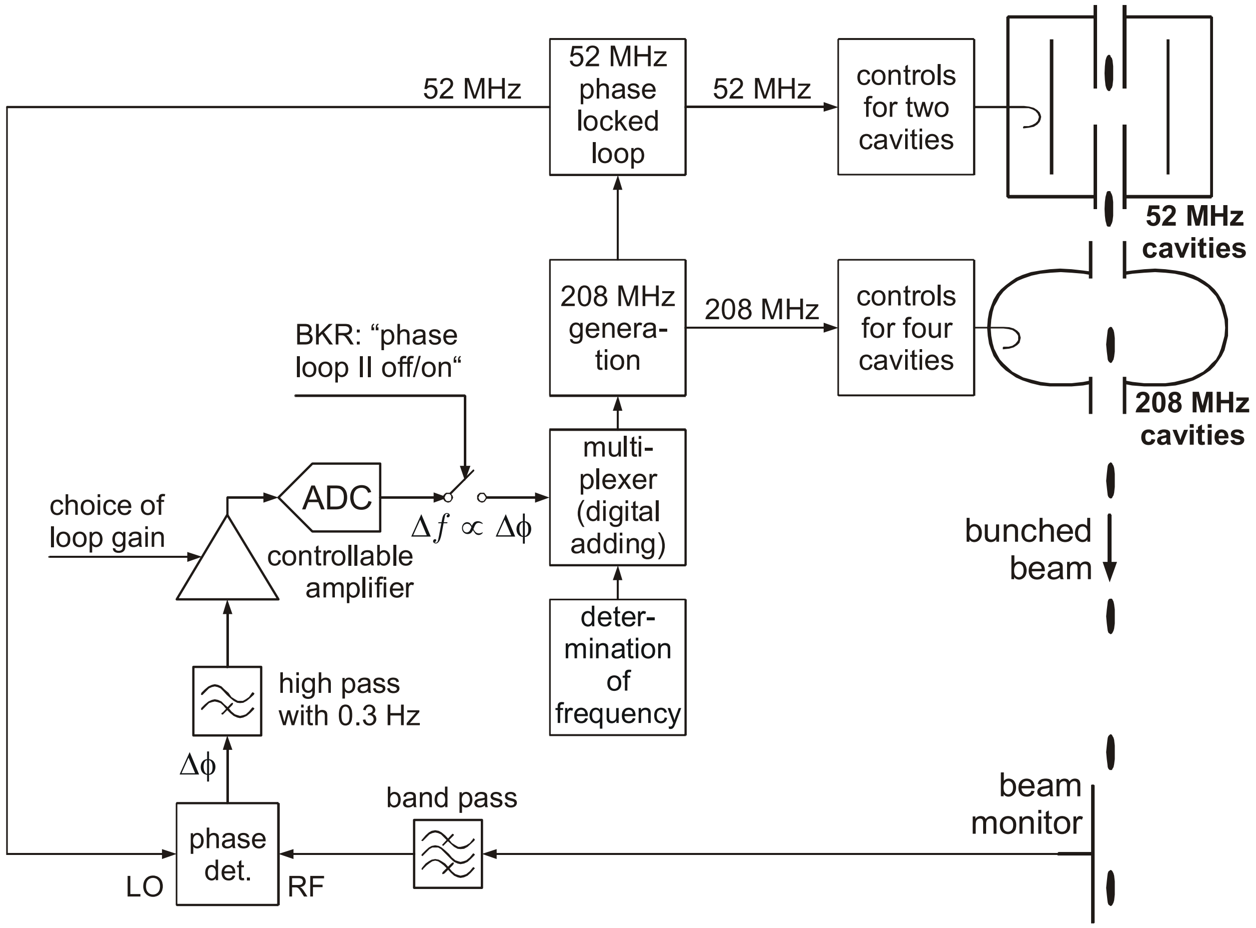


Everything operable, except for the DSP-system

Additional effect: Reduction of the effective machine impedance!

Emittance preservation between 40 GeV and 70 GeV – Phase Loop II

The coupled bunch mode $l = 0$ should be ideally damped by the Phase Loop II (from MSK):



Actual problems:

- the loop confuses the frequency generation – there is a strong suspicion that the confusion is produced in the multiplexer

⇒ This problem is solved since yesterday!

Emittance preservation at high energy – fighting coupled bunch mode $l \approx 165$

Preliminary remark: Phase Loop I and Phase Loop II can not achieve this, because of their limited bandwidths!

1. **Elimination of the source of the instability?**

2. **Reduction of effective impedance**
   - Feed-forward
   - One-turn-delay feedback – 47 kHz notch filter in RF fast-feedback loops (see SPS at CERN)

3. **Active measures**
   - Increase of coherent synchrotron frequency spread with h + 1 harmonic RF or 47 kHz RF amplitude modulation
   - Increase of incoherent synchrotron frequency spread with Landau damping cavity (see SPS at CERN)
   - Modal feed-back fighting direct coupled bunch mode $l \approx 165$
   - Coupled bunch feed-back (with overloaded reserve 52 MHz Cavity?)

Elimination of the source of the instabilities?

How large is the impedance of HERAp?

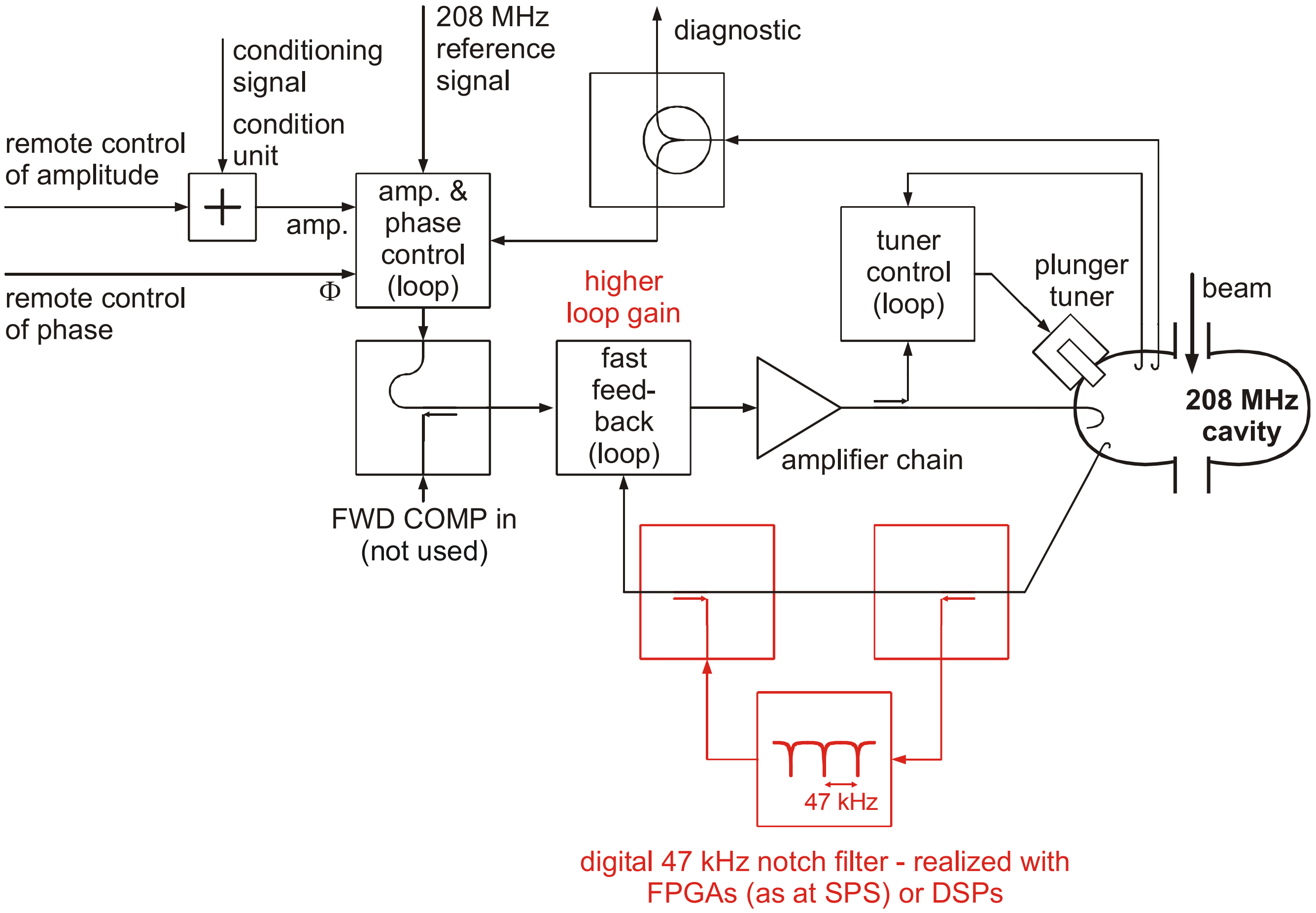
- design goal already was small impedance
- theoretically estimated value: 1 Ω
- from measured rise times (before Upgrade) obtained value: 1 Ω

What does this mean?

In HERA, no prominent troublemaker exist, which can be removed for conserving the longitudinal emittance!

One-turn-delay feedback – 47 kHz notch filter in RF fast-feedback loops

By filtering out the revolution frequency and its harmonics, one can increase the gain of the fast-feedback loop over the ‘Nyquist limit’. At HERA this is a gain larger than 120.



⇒ from beam 'seen' cavity-impedance will become smaller

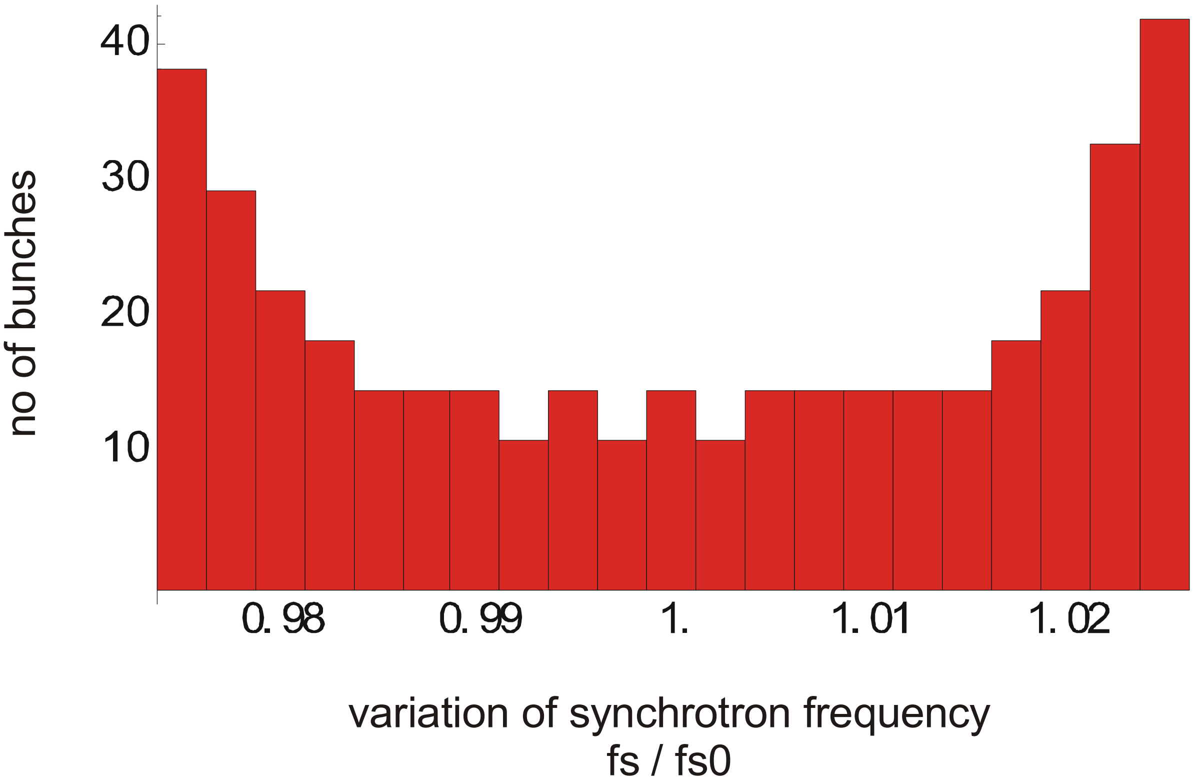
Active measures …

Increase of coherent synchrotron frequency spread

For the suppression of the observed instabilities we need at least a coherent spread of:

$$\boxed{S_\omega > 1\,\mathrm{s}^{-1}}$$

This can be achieved by a RF amplitude modulation of about 5 % (30 kV) causing the following frequency distribution:



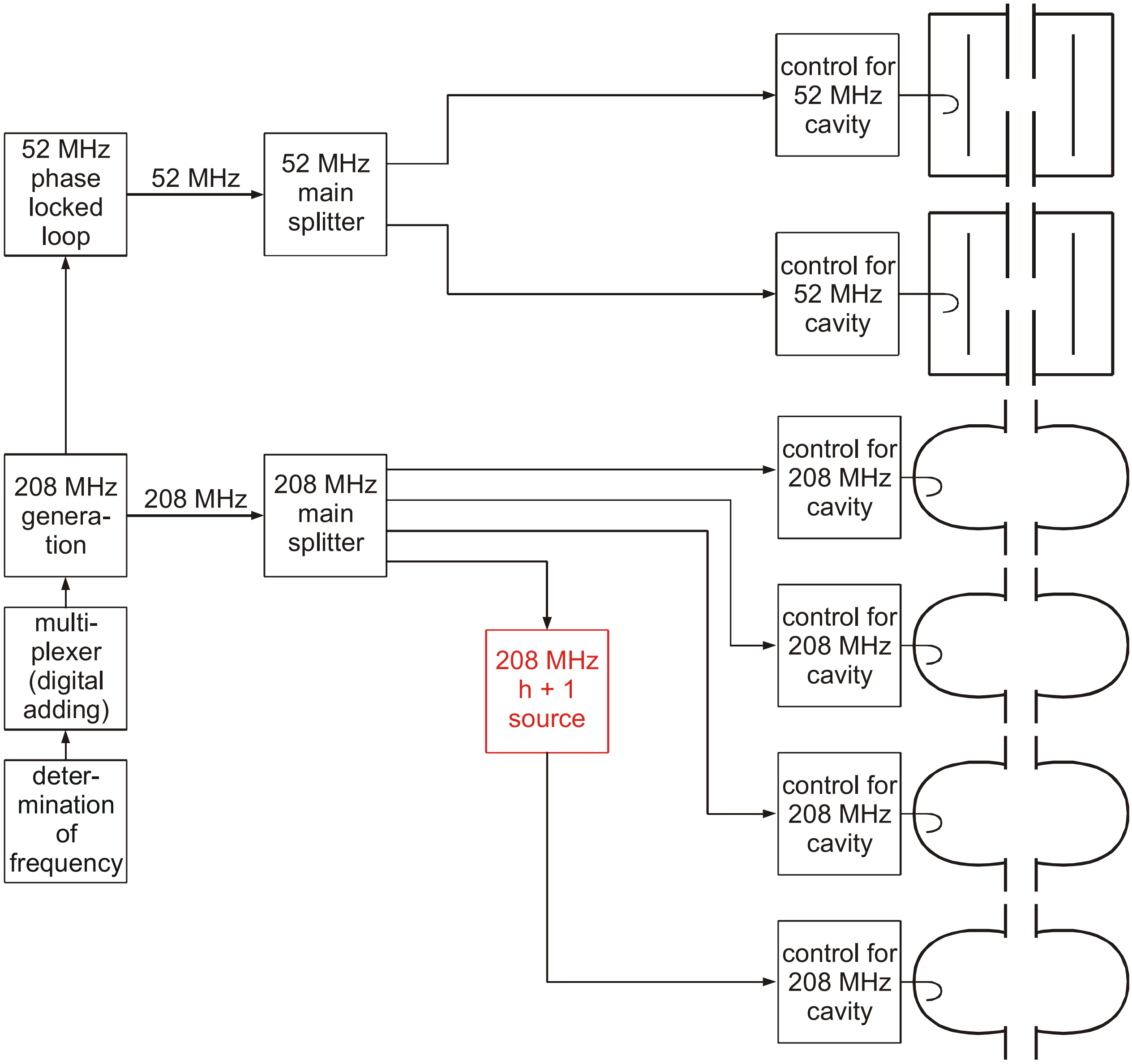
h + 1 harmonic cavity

One 208 MHz Cavity operated with

$$f_{RF,h+1} = \frac{4400+1}{4400} f_{RF} = 208\,\mathrm{MHz} + 47\,\mathrm{kHz}$$

$$\text{with} \quad \text{RF amplitude} \geq 30\,\mathrm{kV}$$

provides this spread. The technical realization:



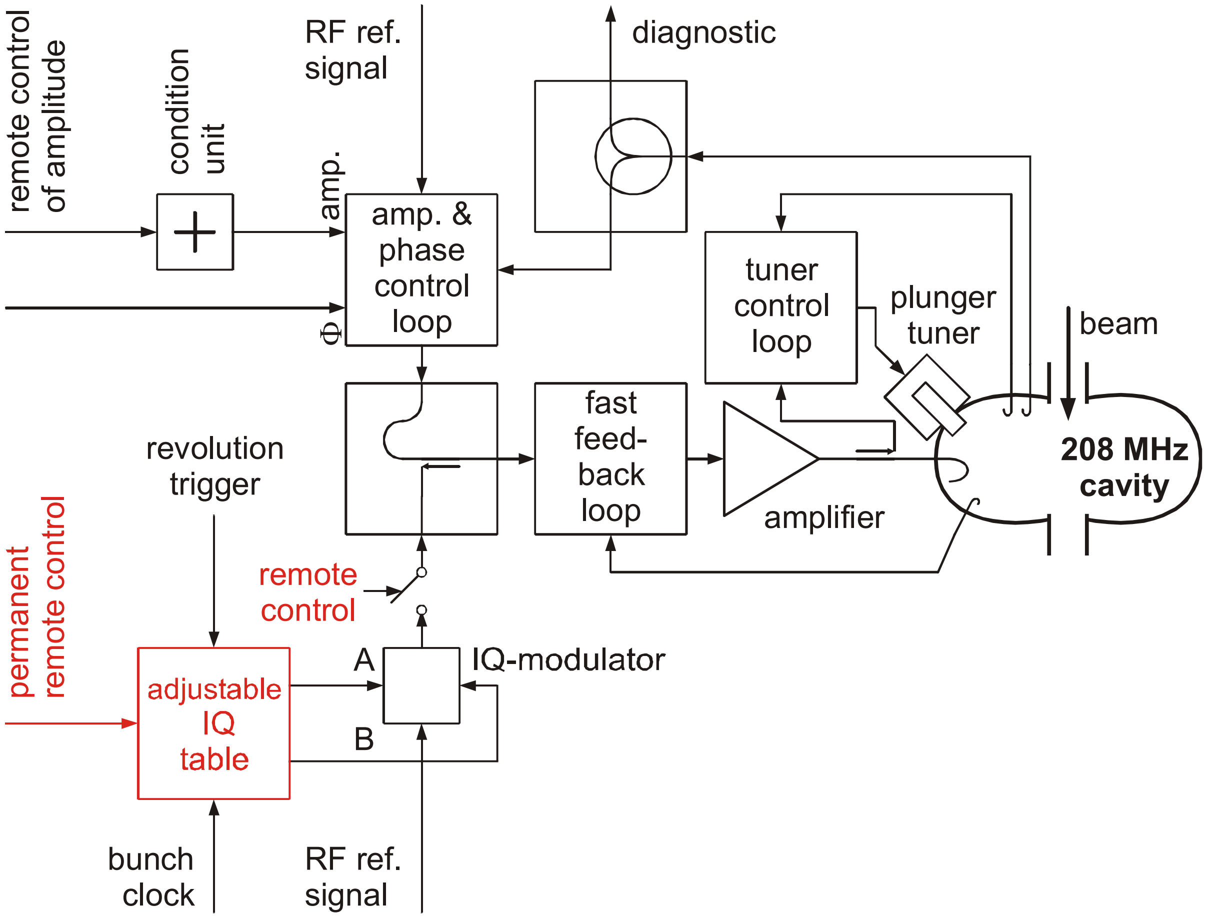
Disadvantages:	bunch to bunch phase shift lowers luminosity
	problems at injection (bucket matching)
Advantage:	fast realization

RF amplitude modulation

We may also modulate the RF amplitude of one 208 MHz cavity to increase the coherent spread:

$$\text{RF amplitude modulation} \geq 30\,\text{kV}$$

Technical realization:



Advantages: no bunch to bunch phase shift lowers luminosity

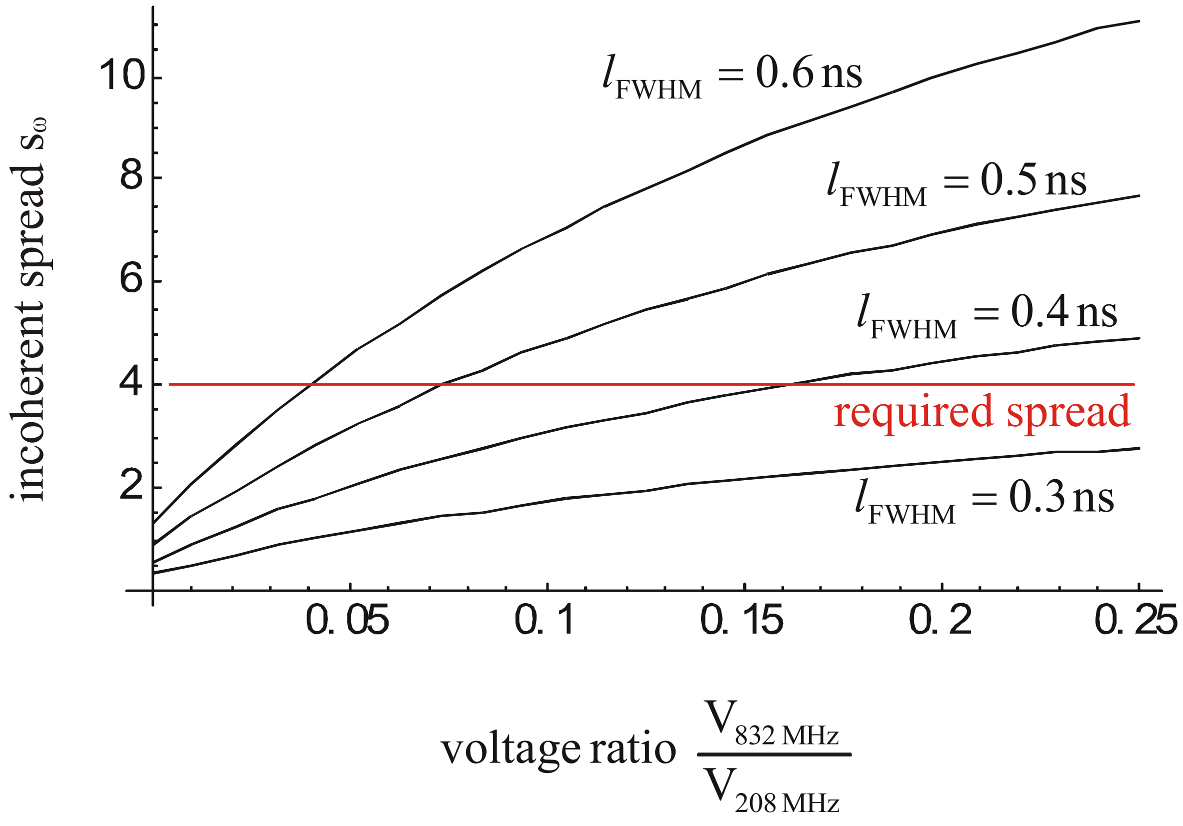
no problems at injection by decreasing the modulation

it can be completely switched off

Disadvantage: needs more time for realization as compared to the h + 1 solution

Increase of incoherent synchrotron frequency spread

We deform the bucket potential and increase the incoherent frequency spread (BS case) by implementing an additional RF system with a four times higher harmonic number:



actual 208 MHz voltage: 3 x 190 kV - 30 kV = 540 kV

maximum possible: 4 x 800 kV = 3200 kV

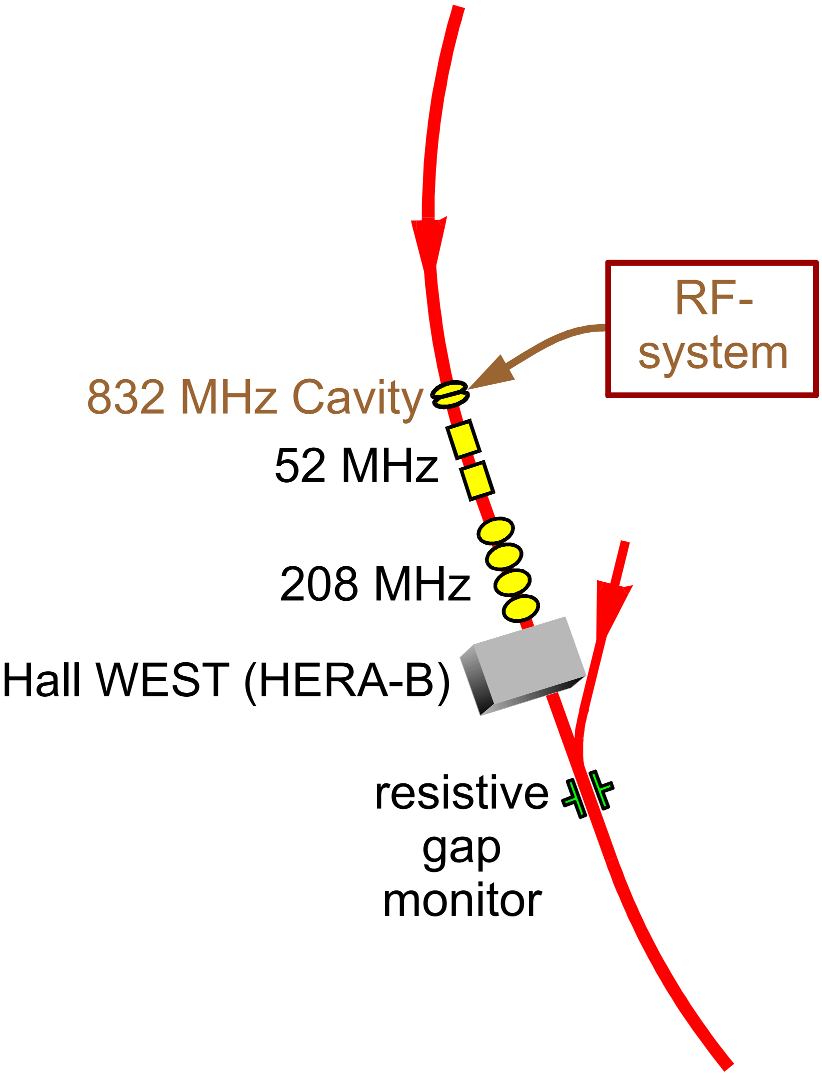
minimal required 832 MHz Voltage: 0.05 x 540 kV = 27 kV

recommended 832 MHz Voltage: 0.15 x 3200 kV ≈ 500 kV

This is called a ‘Landau-damping cavity’ ...

Landau-damping cavity

- 40 GeV: 208 MHz cavities
- 920 GeV: 832 MHz cavity (as at SPS)



Advantages: no bunch to bunch phase shift lowers luminosity
no problems at injection by decreasing the modulation
no systematic bunch length modulation

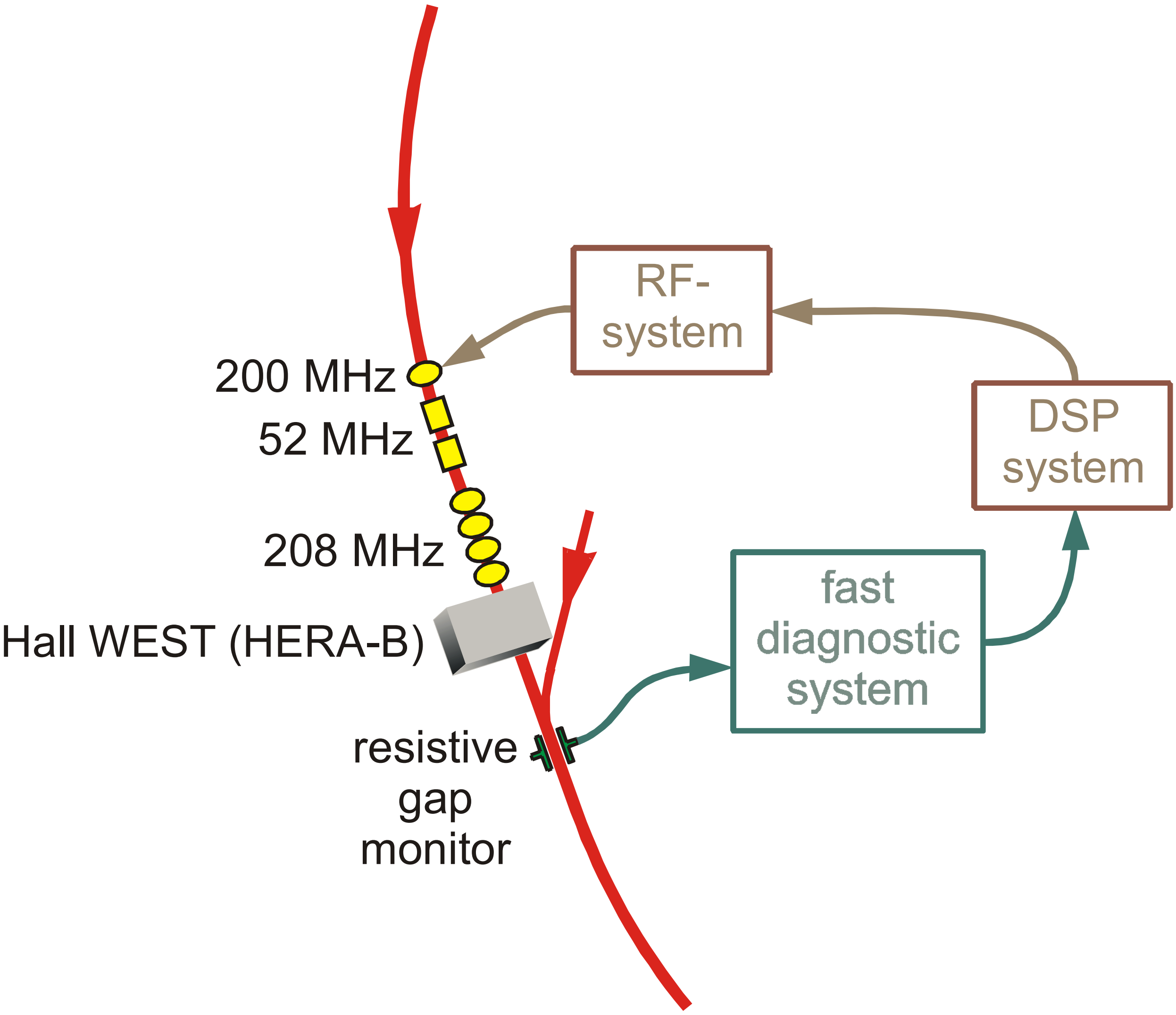
Disadvantages: manpower requirement
costs

Modal feed-back - fighting coupled bunch mode $l \approx 165$

The modulation of the RF phase with

$$f_{\mathrm{mod},l=165} = \frac{f_{208\,\mathrm{MHz},}}{4400} 165 = 7.8\,\mathrm{MHz}$$

may be achieved by a 200 MHz cavity (for example a old LEP cavity). A voltage of 3 kV should be sufficient for damping mode $l \approx$ 165.



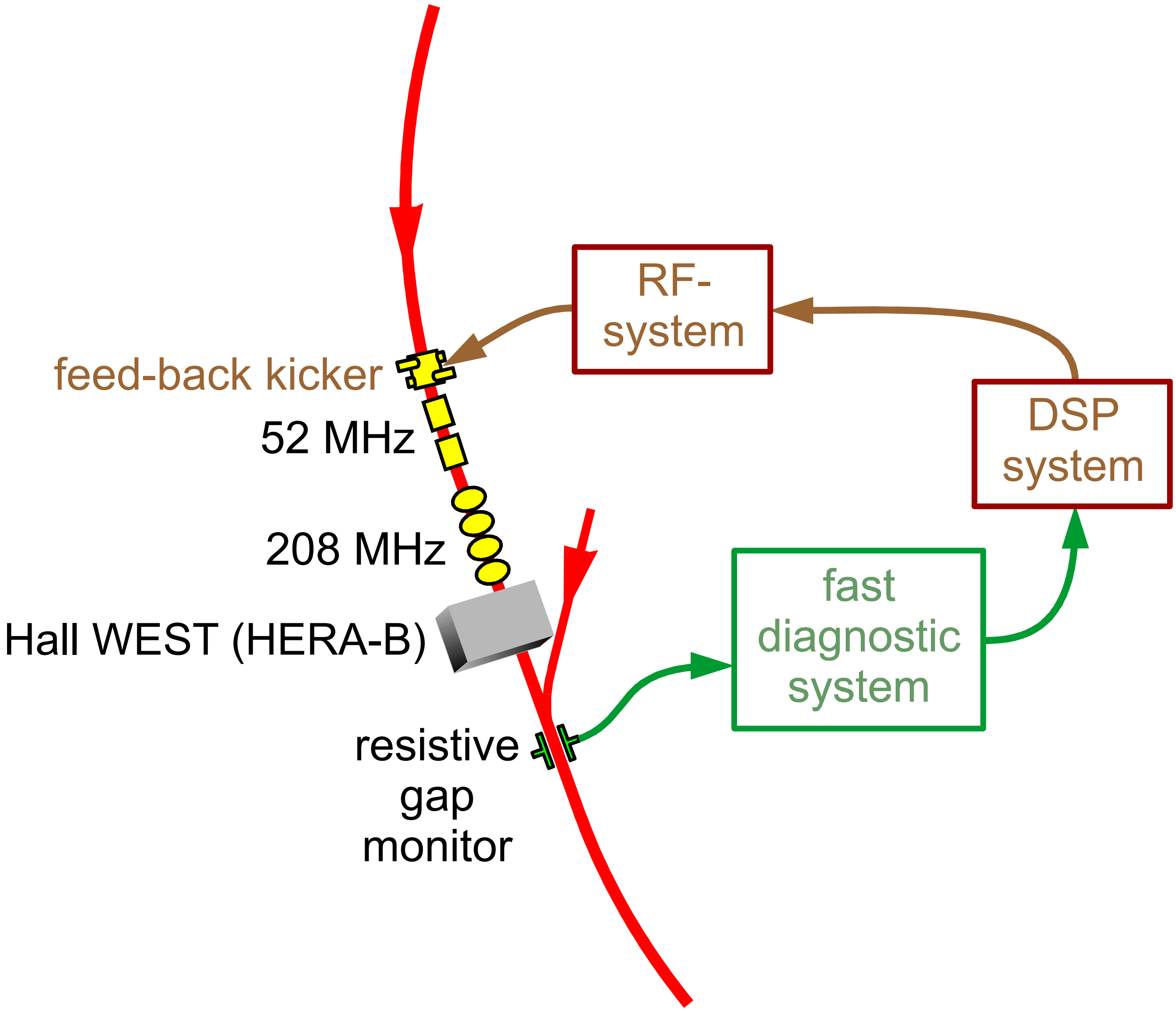
Advantage: maybe cheaper as a coupled bunch feed-back

Disadvantages: only effective when mode $l \approx 165$ is present!

what to do with beam loading?

Coupled bunch feed-back

One may use the reserve 52 MHz cavity as feed-back kicker. The required band width may be achieved by overloading the cavity. A kicker voltage of about 2 kV is necessary.



Advantages: no bunch to bunch phase shift lowers luminosity
no problems at injection by decreasing the modulation
no systematic bunch length modulation
single bunch excitations for permanent determinations are possible (measurements of f_s, decoherence, etc.)

Disadvantages: manpower requirement
costs

Summary

More luminosity due to shorter proton bunches

Every day observable effects

- at injection
- between 40 GeV and 70 GeV: mode $l = 0$
- at high energy: mode $l = 0$
- longitudinal, coherent oscillations make bunches longer

Measures against emittance dilution

- debugging Phase Loop I and Phase Loop II
- Feed-forward
- 47 kHz notch filter in RF fast-feedback loops
- h + 1 harmonic RF
- 47 kHz RF amplitude modulation
- Landau damping cavity
- Modal feed-back
- Coupled bunch feed-back