High-power feedback systems

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Feedback systems in VLHC

- Several feedback systems will be essential in maintaining beam quality in a VLHC
  - Control of instabilities
    - → Transverse Mode Coupling Instability (TMCI)
    - → Resistive wall coupled-bunch instability
  - Injection errors
  - Control of emittance growth
    - → Ground motion
    - → Magnetic field fluctuations
- Consider only transverse systems here

Parameter	Low-field option	High-field option
Collision energy (TeV)	50	50
Injection energy (TeV)	3	3
Injection error (mm)	0.1	0.1
Revolution frequency (Hz)	577	3156
Bunch spacing (ns)	18.9	18.9
Bunch rate (MHz)	53	53
No. bunches	92000	16800
Bunch intensity (10^{10} protons)	0.82	1.5
Average current (mA)	69	127
Betatron tune	533.235	37.385
Average beta function (m)	246	600
Beam pipe half-aperture (mm)	9	16.5
Beam pipe cut-off TM/TE (GHz)	13 / 9.8	7 / 5.3
rms emittance (10^{-6} m)	1	2.5
rms bunch length/injection (cm)	7.6 / 5.5	5.6 / 7.2

Feedback system	Function	Bandwidth
High-gain, narrowband	Damp strongest modes driven by the resistive wall impedance at low frequencies. High gain to suppress emittance growth.	100 kHz
Broadband, bunch-by-bunch	Damps all transverse modes	26 MHz
High-frequency, broadband	Damps m=1 TMCI mode	26 MHz

Coupled-bunch modes

- **Longitudinal frequency shift**

$$\Delta\omega = j \frac{I f_{rf}}{2\frac{E}{e}} \alpha_p \frac{f_0}{f_s} Z_{eff}^{long.}$$

$$Z_{eff}^{long.} = \sum_{p=-\infty}^{p=+\infty} \frac{\omega_p}{\omega_{rf}} e^{-(\omega_p \sigma_\tau)^2} Z^{long.}$$

$$\omega_p = (pM + n + m\nu_s)\,\omega_0$$

- **Transverse frequency shift**

$$\Delta\omega = -j \frac{I f_0}{2\frac{E}{e}} \beta_{x,y} Z_{eff}^{trans.}$$

$$Z_{eff}^{trans.} = \sum_{p=-\infty}^{p=+\infty} e^{-(\omega_p \sigma_\tau)^2} Z^{trans.}$$

$$\omega_p = (pM + n + \nu_{x,y} + m\nu_s)\,\omega_0$$

$Z^{trans.}$ includes the resonant impedance and the resistive wall impedance

$$Z^{trans.\ res.\ wall} = A\,(1+j)\,\frac{c\,L}{\pi\, b^3} \sqrt{\frac{\mu_0\, \rho}{2}}\, \frac{1}{\sqrt{\omega}}$$

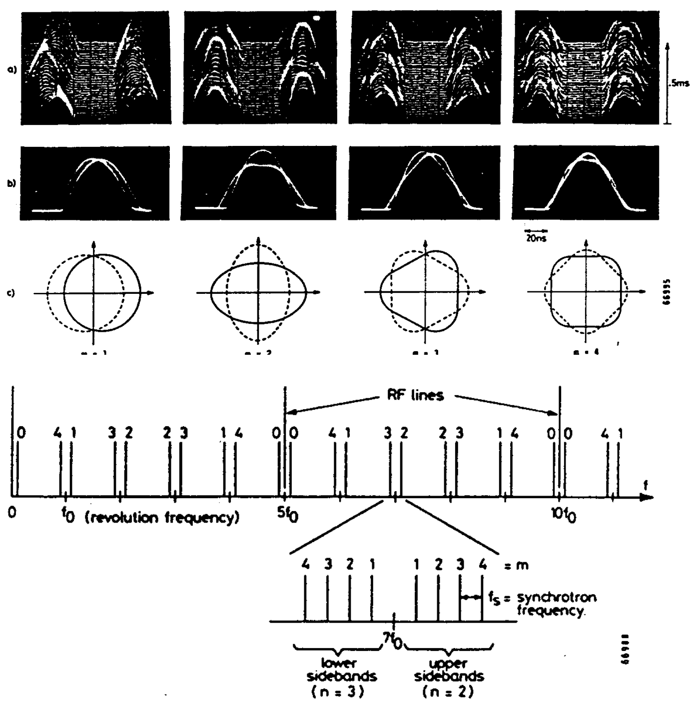
Growth rate $1/\tau = \mathrm{Im}(?\ \omega)$

Coupled-bunch modes

- Longitudinal

$$Z_{eff}^{long.} = \sum_{p=-\infty}^{p=+\infty} \frac{\omega_p}{\omega_{rf}} e^{-(\omega_p \sigma_\tau)^2} Z^{long.}$$

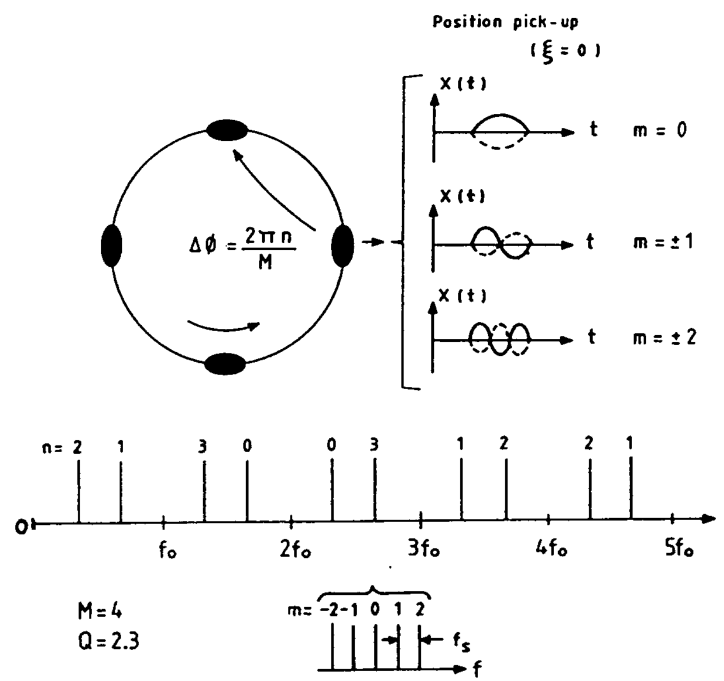
$$\omega_p = (pM + n + m\,\nu_s)\,\omega_0$$



- Transverse

$$Z_{eff}^{trans.} = \sum_{p=-\infty}^{p=+\infty} e^{-(\omega_p \sigma_\tau)^2} Z^{trans.}$$

$$\omega_p = (pM + n + \nu_{x,y} + m\nu_s)\,\omega_0$$



Transverse coupled-bunch modes

- All coupled-bunch modes appear in bands of width half the bunch frequency
    - > 26.45 MHz bands
  - ◊ Modes appear as upper and lower sidebands of orbit harmonics
  - ◊ Strongest driven mode usually dominated by resistive wall
    - → Strongest unstable mode frequency is determined by the fractional tune
    - → $f_{\text{lowest unstable mode}} = (1-?\nu)\ f_o$
      - > ? ν = 0.235 (LF) / 0.385 (HF)
      - > lowest unstable mode frequency 441 Hz (LF) / 1941 Hz (HF)
        - ⇒ tune will be shifted due to reactive impedance

- Growth times from resistive wall impedance are shortest at injection
    - > 4.7 ms (LF) / 57 ms (HF)
    - > 2.7 turns (LF) / 180 turns (HF)

Transverse coupled-bunch modes

- The voltage kick per turn required to match the impedance-driven motion is proportional to the growth rate and the amplitude of the bunch motion

$$V_\perp = \frac{2}{f_0 \tau} \frac{E}{e} \frac{\Delta x}{\beta_\perp}$$

  - ◊ $V_\perp$ = 900 kV (LF) / 5.6 kV (HF)
    - → This is a large voltage in the LF option
    - → HF option is amenable to a "standard" feedback system
      - > PEP-II transverse feedback systems generate 3.4 kV

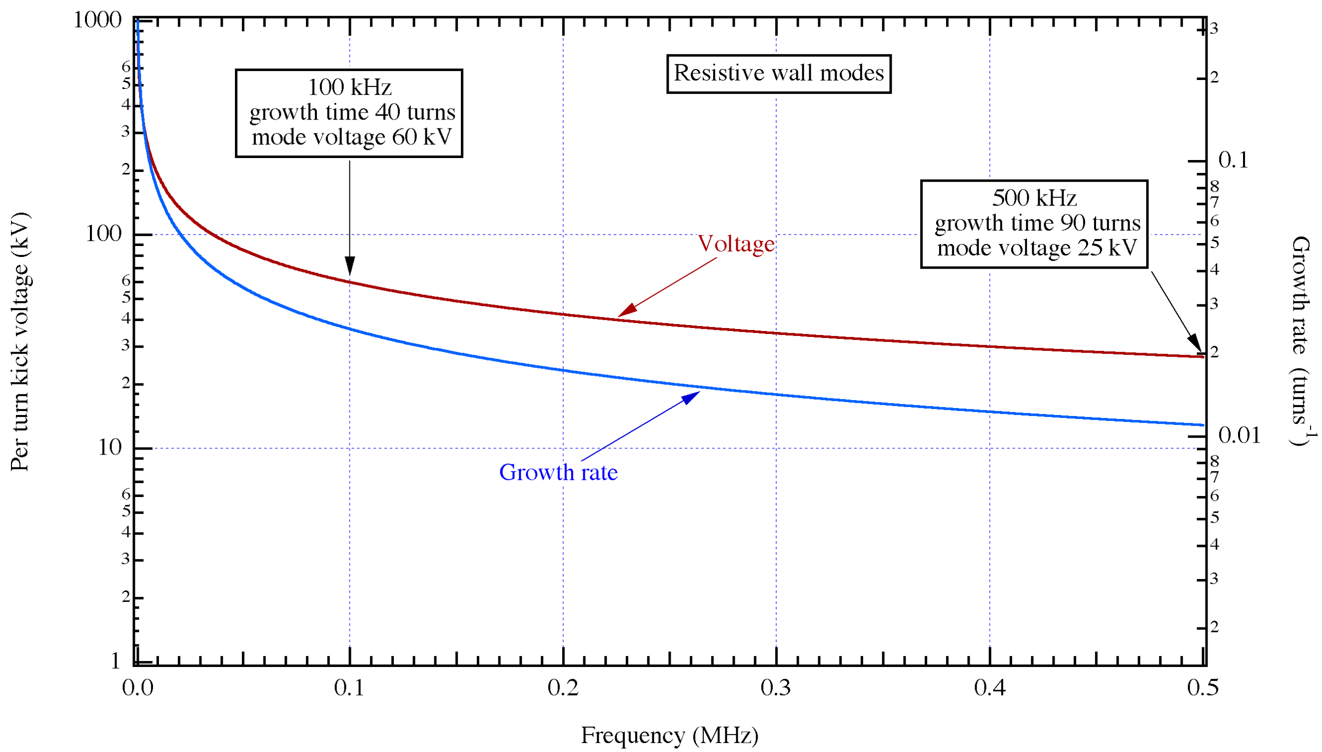
- *e-folding growth in 2.7 turns in LF option cannot be effectively compensated with a single feedback system*
  - ◊ Amplitude of beam motion increases by 45% within a single turn!

Two feedback systems designs to combat very rapid growth in LF option

- For modes growing in times comparable to the orbit time, we may use several feedback systems distributed around the ring to maintain small amplitude motion
  - Require prompt feedback < 1turn delay
    - $\rightarrow$ Short delay limits bandwidth of system
- For modes growing in more than ~ 40 turns, we may use a "standard" broadband bunch-by-bunch feedback system
- Growth rates in HF option are amenable to "standard" broadband bunch-by-bunch feedback system
  - Growth time ~ 180 turns
  - $V_{\perp} = 5.6$ kV (HF)
- Focus here on LF option systems
  - HF option less demanding on feedback systems

LF option, resistive-wall generated voltage kick and growth rate

- ♦ Resistive wall instability growth rate $\propto f^{-1/2}$
  - ◊ Low-frequency, strongest modes
    - → Narrow-band system will damp modes to ~ 100kHz (see later)
      - > Broad-band system voltage kick requirement 60 kV



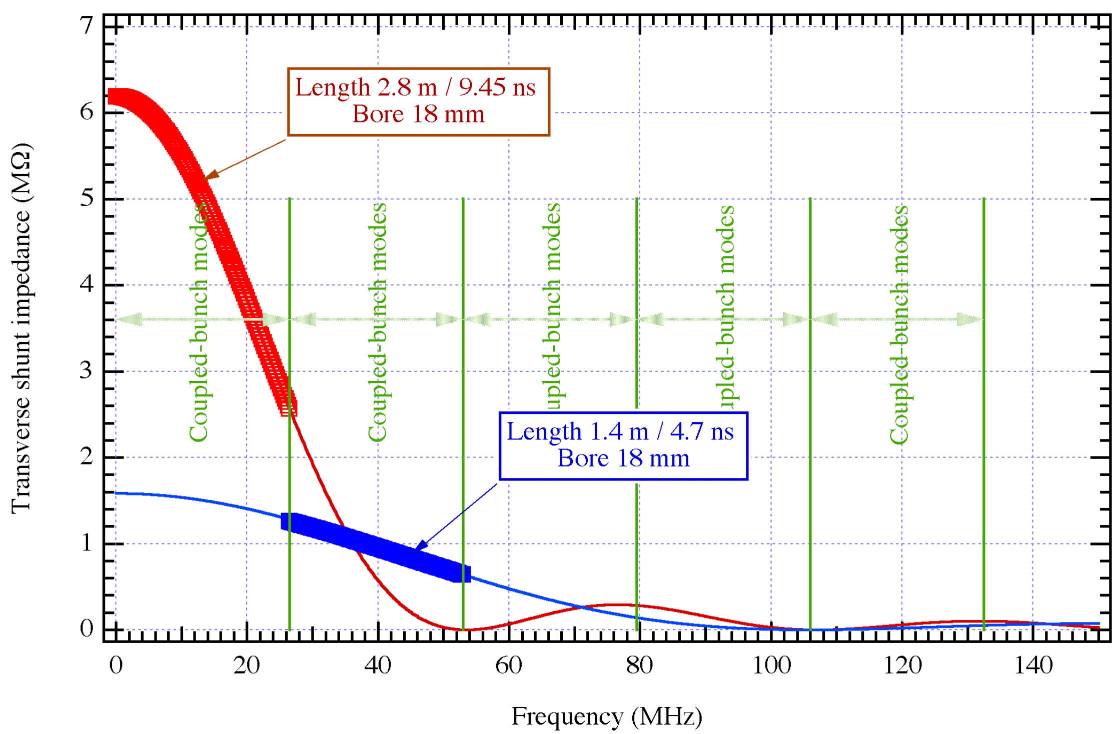
LF option broadband bunch-by-bunch feedback system

- Bunch-by-bunch system to combat modes with growth times > ~ 50 turns
  - $V_{\perp} = 60$ kV
  - 1.4 m stripline kicker
  - 26.5 MHz - 53 MHz band covers all coupled-bunch modes
    - → R = 640 k   (worst case, at 53 MHz)
      - > Use three kickers each providing 20 kV
        - ⇒ Amplifier power $P = (V_{\perp})^2/2R = 312$ W
      - > Buy additional power for safety factor and added damping
        - ⇒ Use 800 W per kicker to obtain a total voltage 96 kV

- Detect and feedback directly in 26.5 MHz - 53 MHz band

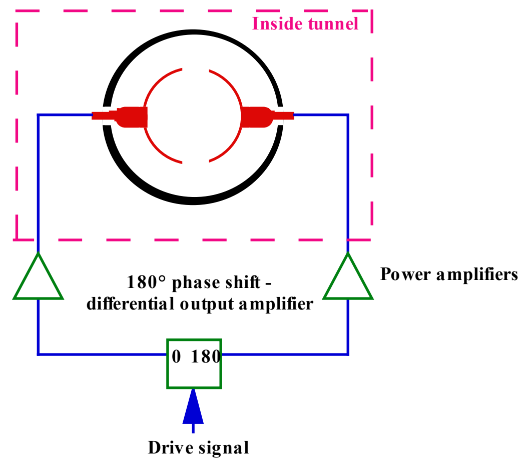
Broadband stripline kicker for transverse feedback

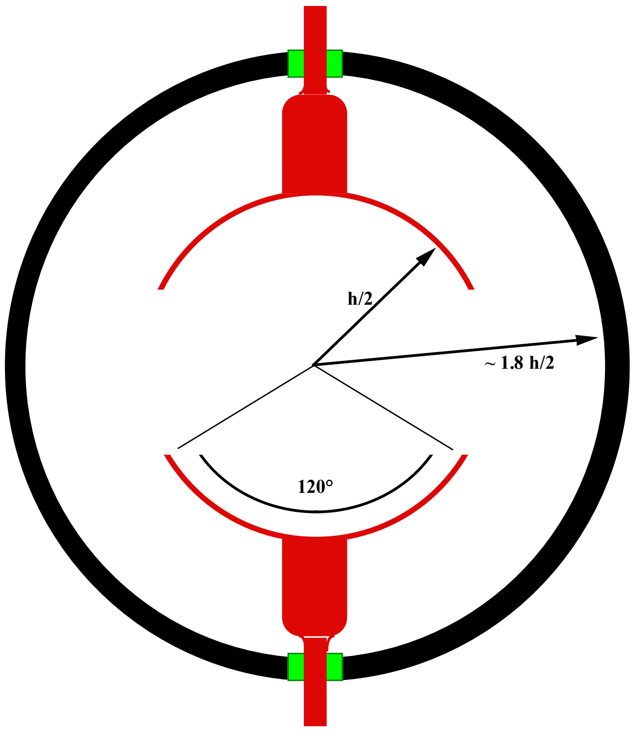
- Transverse shunt impedance $$R_{\perp} = 2\ Z_l \left(\frac{2\ g \sin(kl)}{h\ k} \right)^2$$
  - Kicker length may be optimized for 53 MHz bunch rate
    - → Filling time + bunch passage time = bunch separation time
    - → Length 2.8 m allows bunch-by-bunch action with largest shunt impedance
  - Shorter kicker allows higher frequency bands to be used
    - → Avoid problems attaining lowest frequencies with broadband systems

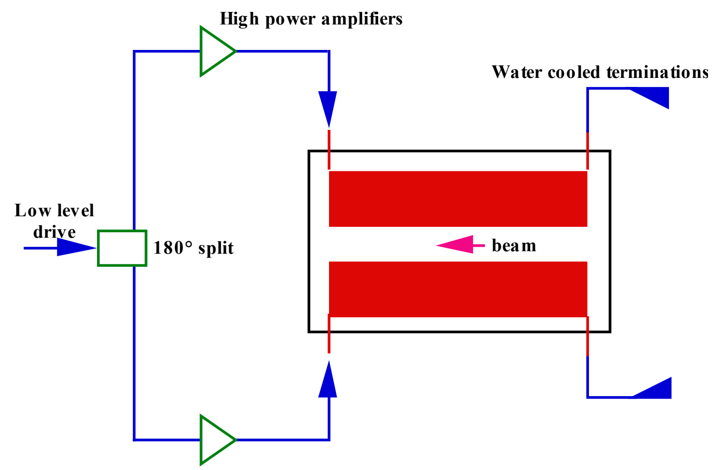


Stripline kickers

- Stripline electromagnetic kickers
  - Beam integrates deflection from both E and H along length of stripline

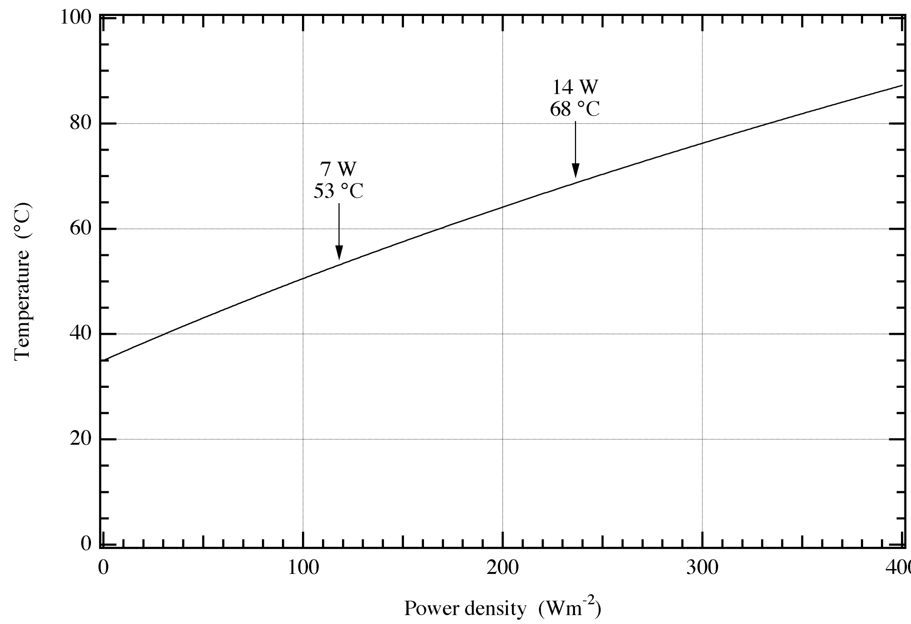






Stripline electrode heating - broadband system

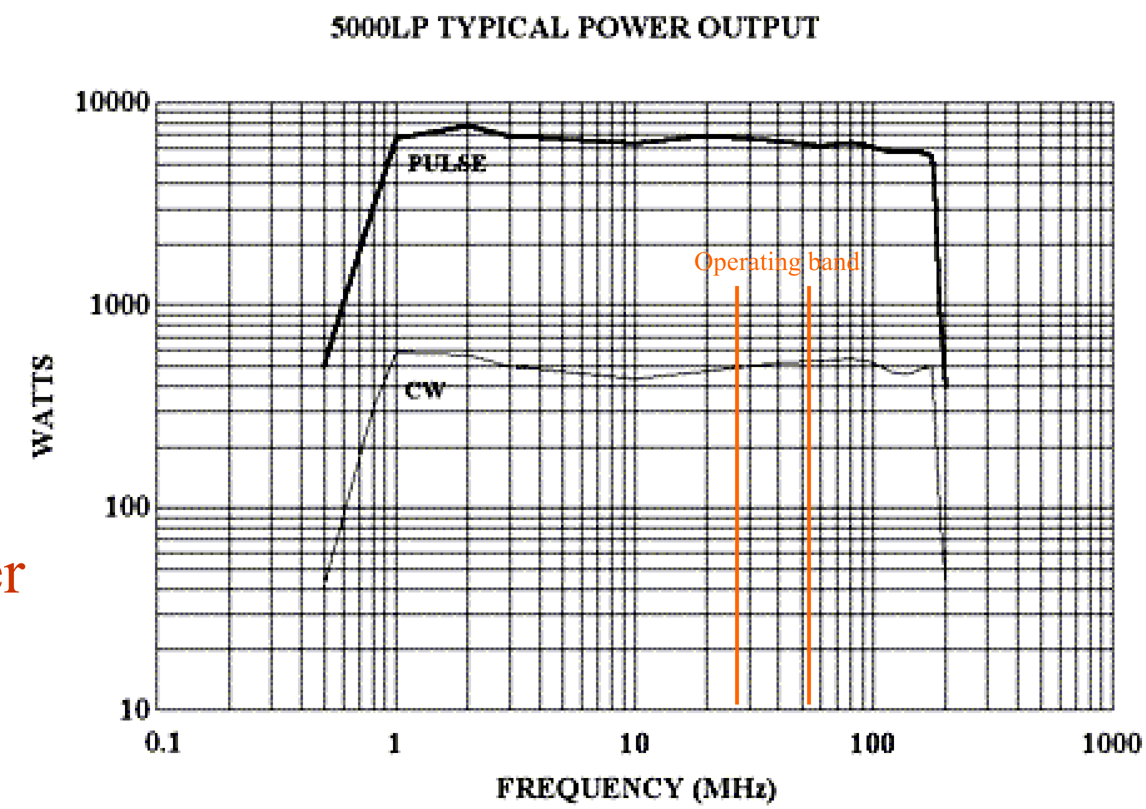
- Heating from 400 W RF drive ¡ 0.5 W
- Beam induced heating (69 mA) on electrodes 0.01 W
- Power density ~ 20 Wm^{-2}
  - Small thermal conduction through feedthroughs
  - Radiative cooling
    - → blacken surfaces
      - > Successful at ALS and PEP-II



Broadband power amplifier - AR 5000LP

- Use one 400 W amplifier per stripline plate
  - ± 1.5 dB
  - 67 dB gain
  - 175 MHz instantaneous bandwidth
  - 10 ns rise/fall time

- Narrower-band units also available from other vendors

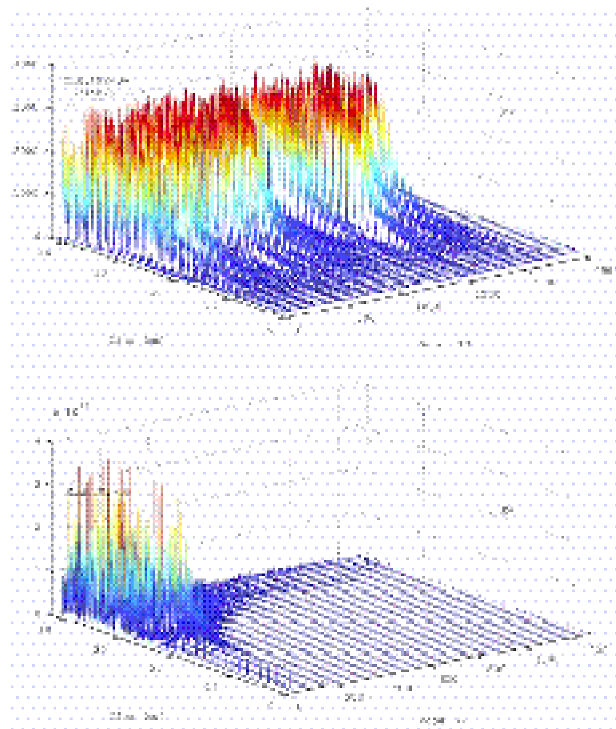


LF option broadband feedback system

- Detect bunch-by-bunch beam position using striplines
  - Pickup signal is at bunch rate, 53 MHz
- Use hybrid to take difference between stripline signals
- Filter to reject out-of -band signals
- Reject orbit offset
  - Orbit offset can be very large and may saturate digitizer
    - → Steer beam, or subtract sum signal
- Digitize bunch-by-bunch moment (I? x) @ 53 MHz
- Digital delay by ~ 1 turn
- Generate differential signal (digitizer may have differential output)
- Amplify signal to each stripline of kicker
  - Amplifier linear over bandwidth $1/(2\tau_b)$
- Stripline kicker
  - Bandwidth $1/(2\tau_b)$

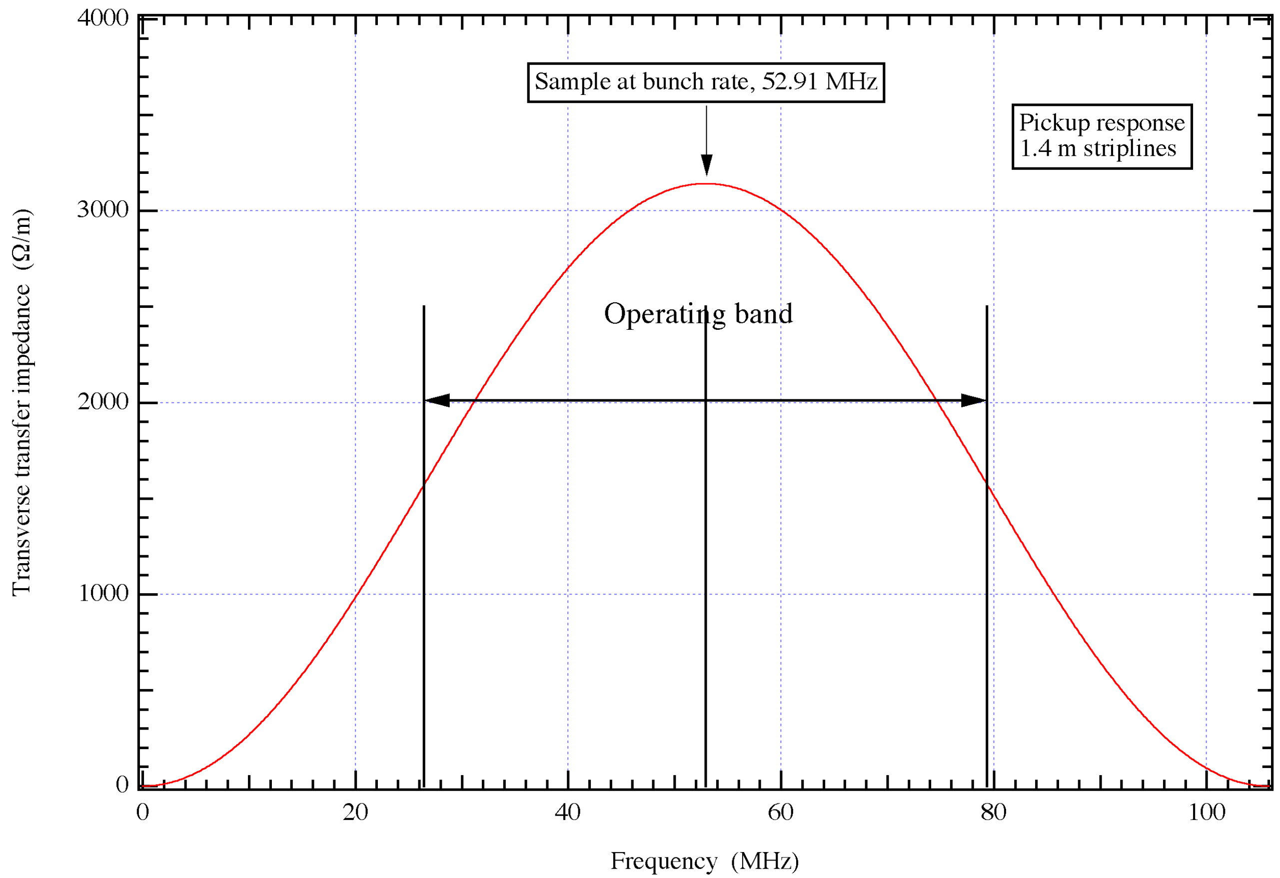
Digital delay

- 10-bit sampling at 100 MSPS available
- System dynamic range limited by ADC
  - Dynamic range 54 dB
- Digital system allows useful beam measurements
  - Growth and damping rate measurements
    - → individual bunch amplitudes
    - → modal analysis
  - Transfer function measurements
    - > Allows effective beam impedance to be determined



Broadband stripline pickup

$$Z_{\perp}^{\text{pick-up}} = \sqrt{\frac{Z_c Z_l}{2}}\,\frac{2\,g}{h}\left[\cos\left(\frac{\pi}{2} - kl\right)\sin(kl)\right]$$



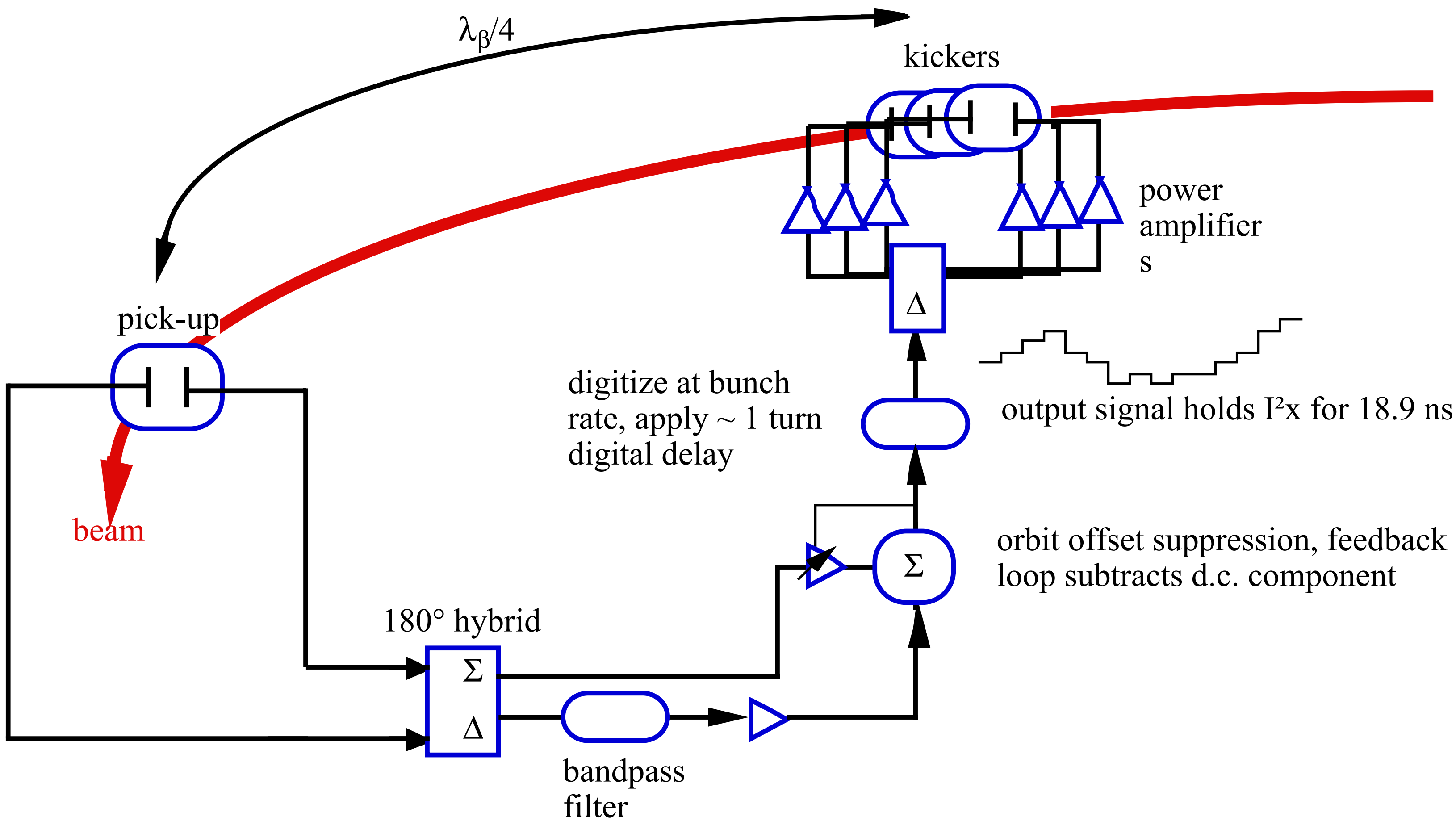
System noise

- rms beam displacement driven by noise in the feedback system

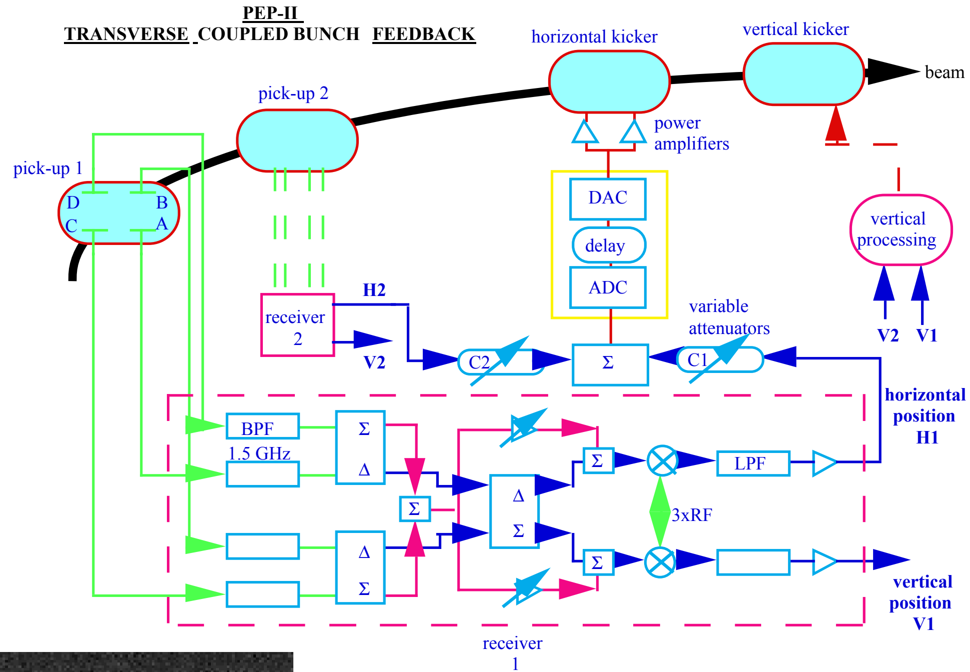
$$\Delta X_{rms} = \frac{\sqrt{Z_c\, k\; 10^{NF/10}\; T\; \Delta f}}{Z_\perp\, I}$$

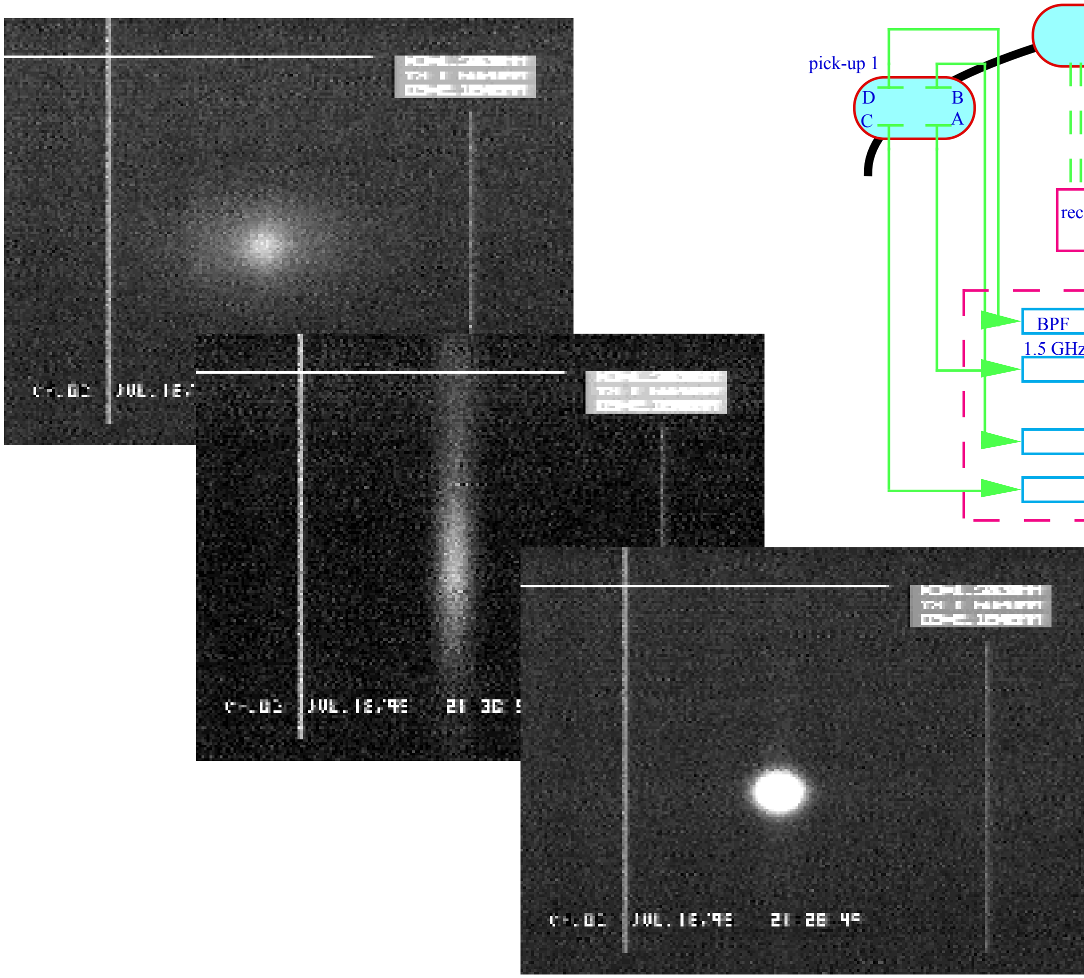
- ΔX_{rms} = 0.026 μm (LF) / 0.014 μm (HF)
  - Small effect

LF option broadband feedback system



PEP-II and ALS - example high-power broadband bunch-by-bunch transverse feedback systems

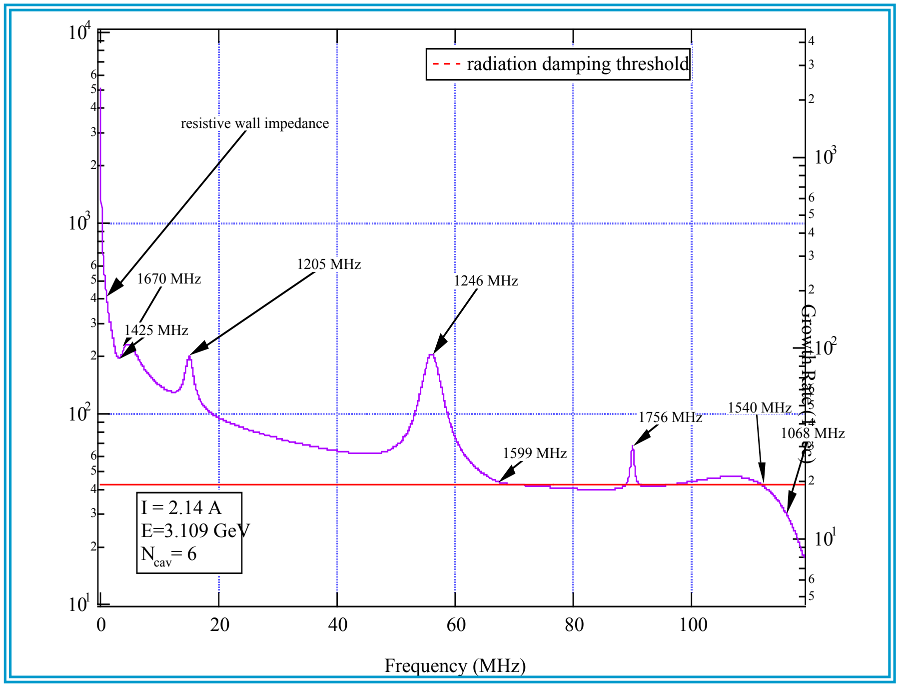




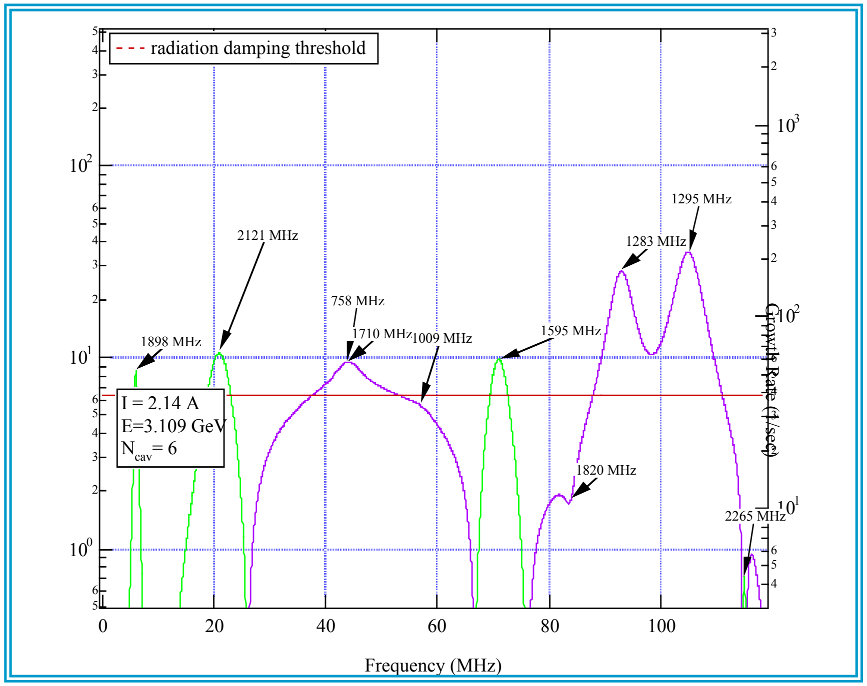
- Button pick-ups
- Analog processing to baseband
- Eliminate orbit offset
- Digital delay
- Stripline kickers

Coupled-bunch growth rates in PEP-II

- PEP-II LER transverse



- PEP-II LER longitudinal

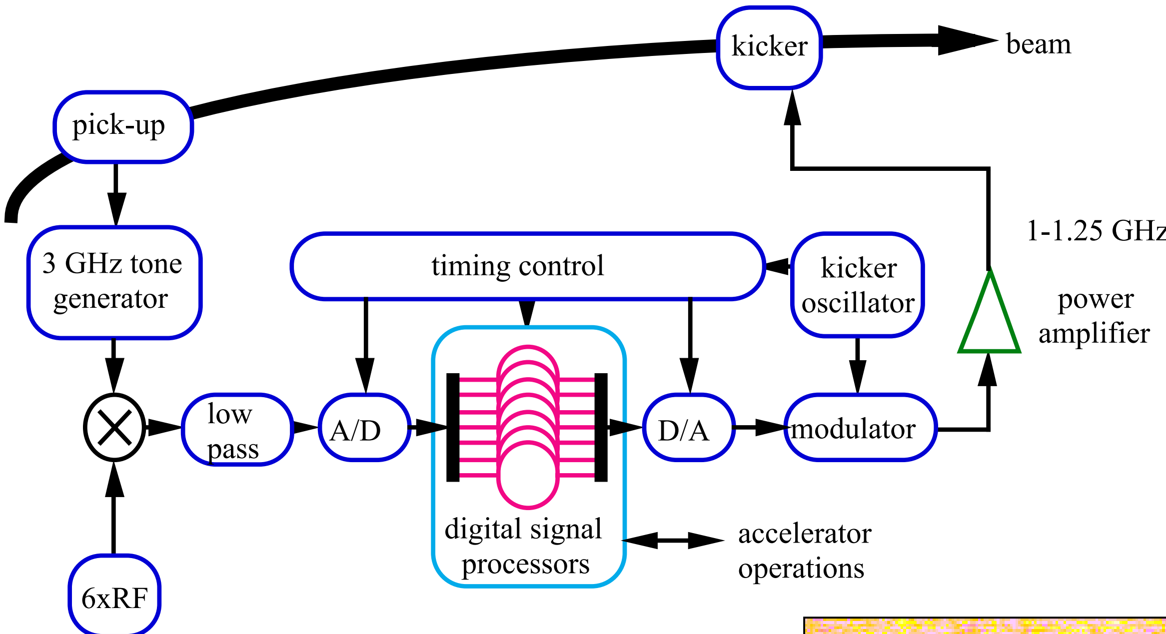


PEP-II transverse feedback systems

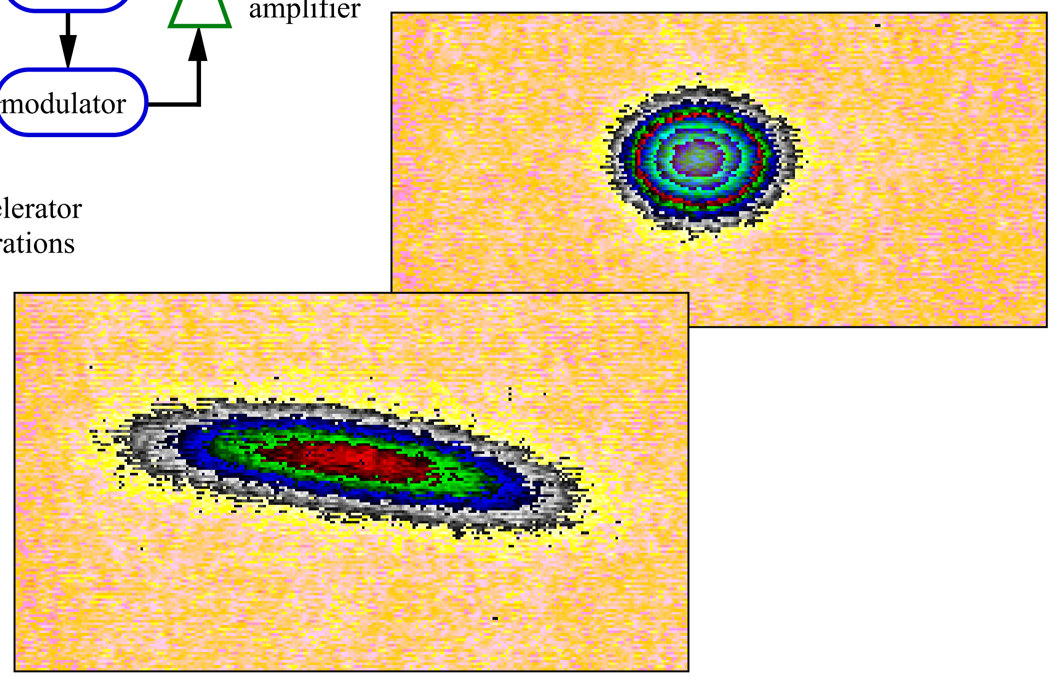
- Strongest mode driven by resistive wall
  - 13.6 kHz lowest mode
- Growth time 300 μs
  - 42 turns
- Feedback system may apply up to 3.4 kV per turn
- Damping times of < 100 μs observed
  - Gain ~ 0.07
- Sample bunch position at 476 MHz
- Bandwidth 238 MHz
- 240 W RF power to kickers

Parameter	Description	Value
E	Beam energy	3.1 GeV
f_{rf}	RF frequency	476 MHz
I_b	Average current	3.0 A
f_0	Orbit frequency	136.3 kHz
β_{av}	Average β	10 m
ν_f	Fractional tune	0.9
τ_b	Bunch spacing	4.2 ns
Z_{rw}	R-wall impedance	4.85 MΩ/m
α_0	Growth rate of m = 0 mode	3200 sec^{-1}
ŽV/Žx	Req'd feedback gain	14.6 kV/mm
R_s	Kicker shunt impedance	24 kΩ
P_k	Available kicker power	240 W
V_{max}	Max. available kick	3.4 kV
y_{max}	Max. mode amplitude	0.23 mm
V_{mode}	Voltage to excite y_{max}	71.3 kV-turn
Δf_{min}	Req'd bandpass	13.6 kHz-119 MHz
–	Electronics bandpass	10 kHz-250 MHz
–	Kicker bandpass	DC - 119 MHz
σ_y	Vert. beam size	0.16 mm
-	Req'd dynamic range	23 dB
-	Actual dynamic range	42 dB
y_{os}	Allowable effective orbit offset	1.8 mm

PEP-II and ALS longitudinal feedback systems

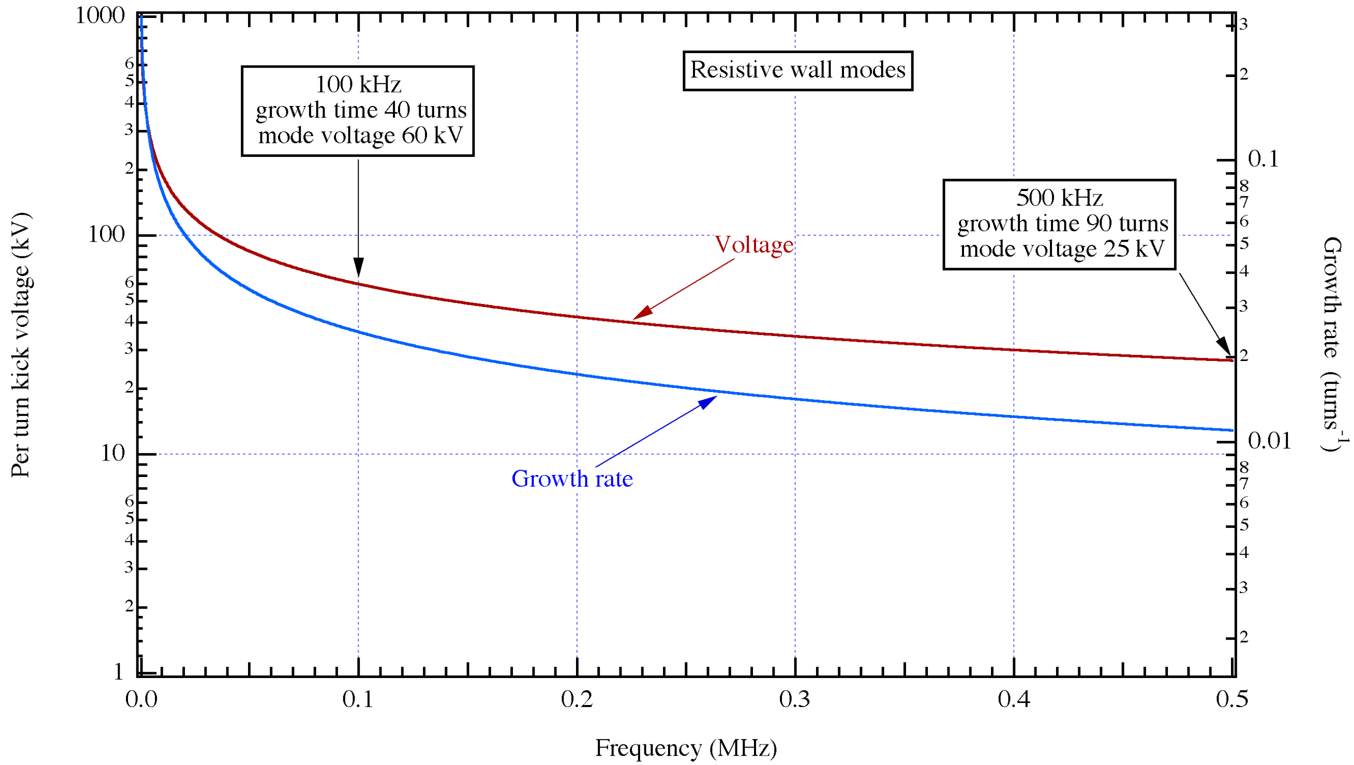


- Button pick-ups
- Tone-burst phase measurement
- Digital processing
- Drift-tube kickers



LF option, resistive-wall generated voltage kick and growth rate

- ♦ Resistive wall instability growth rate ∝ $f^{-1/2}$
  - ◊ Low-frequency, strongest modes
    - → Narrow-band system to control fastest-growing modes

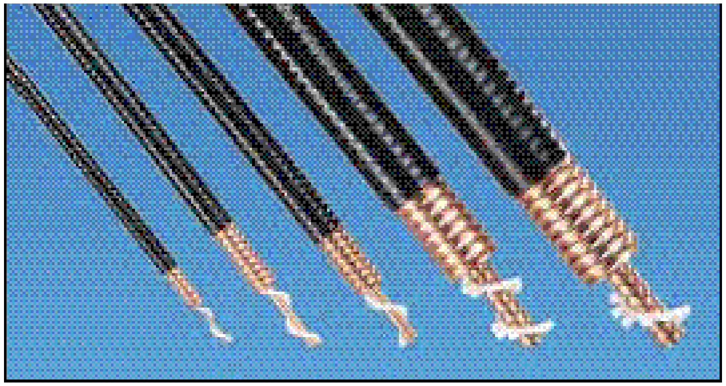


LF option distributed, narrowband feedback systems

- Narrowband system to combat modes with rapid growth times
  - Strongest resistive wall modes driven at low frequencies
- Feedback must be prompt to maintain beam control in the face of strong resistive wall wakefields
- Place kicker downstream from pickup by $\lambda_\beta/4 \sim 500$ m
  - Coaxial signal cable propagation β ¡ 0.9
    - → Cable delay = (1-β) 500 = 50 m
    - → Additional ~ 50 ns delay from electronics components
    - → Delay must be small compared to wavelengths of modes to be damped
  - Limit delay to ~ 10°
    - → Highest frequency ¡ 128 kHz (λ = 2.3 km)
      - > Bandwidth ~ 100 Hz to ~ 100 kHz
        - ⇒ Remaining modes damped by broadband system

Low-loss, high-speed coaxial cables

- Air-core, 7/8 inch
- $\beta = v/c > 0.9$
- Attenuation = 0.65 dB/100 m (at 30 MHz)
- Power rating 14 kW



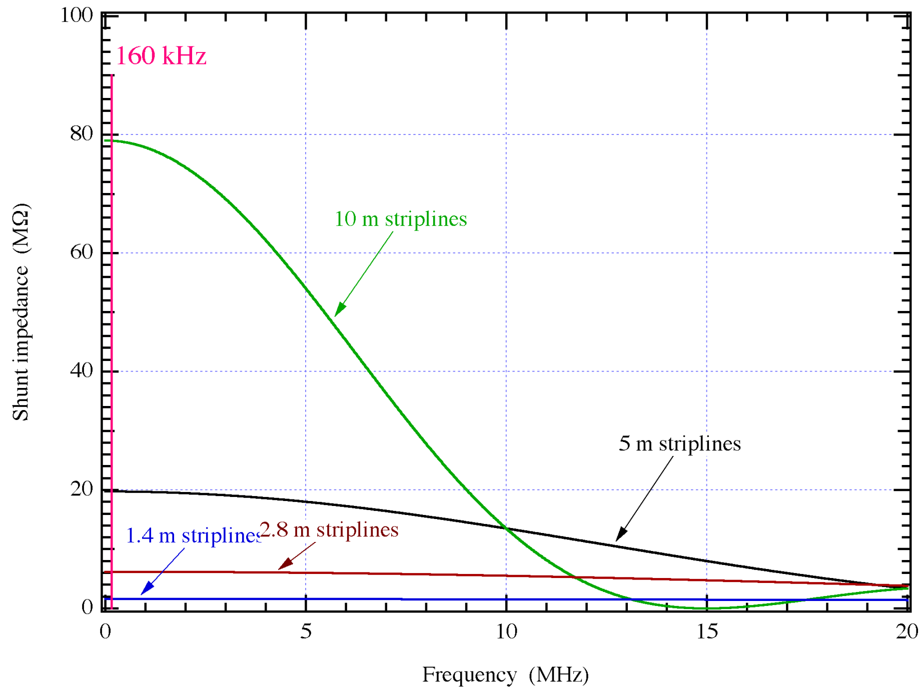
LF option distributed, narrowband feedback systems

- Using 10 equally spaced narrowband feedback systems to combat the strongest resistive-wall driven modes requires high gain
  - Growth over n turns ~ $e^{n/2.7}$
  - Growth per station ~ $e^{1/(10*2.7)} \sim e^{0.037} = 4\%$
- If we stipulate an attenuation factor of 0.9 (damping of 10%) per station
  - Gain = 0.248
  - Voltage per station = 300 kV

$$G = 1 - \left(D\, e^{-0.037}\right)^2$$

LF option narrowband feedback system kickers

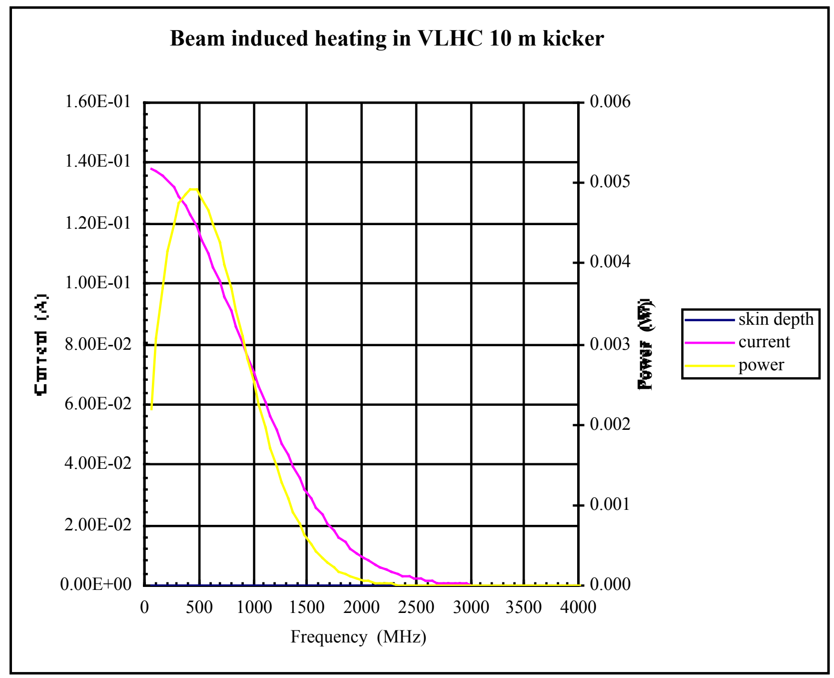
- Use long striplines to increase shunt impedance
  - ◊ 10 m stripline kicker
    - $\rightarrow$ R = 79 M   over 100 Hz - 100 kHz
      - $\Rightarrow$ Amplifier power $P = (V_{\perp})^2/2R = 570$ W
- Kickers add to beam impedance



Stripline electrode heating - narrowband system

- Heating from ~ 600 W RF drive ¡ 0.2 W (up to 100 kHz)
- Beam induced heating (69 mA) on electrodes only 0.1 W
  - Prompt image current on inside electrode surfaces
  - TEM mode currents on outer electrode and inner vacuum chamber surfaces

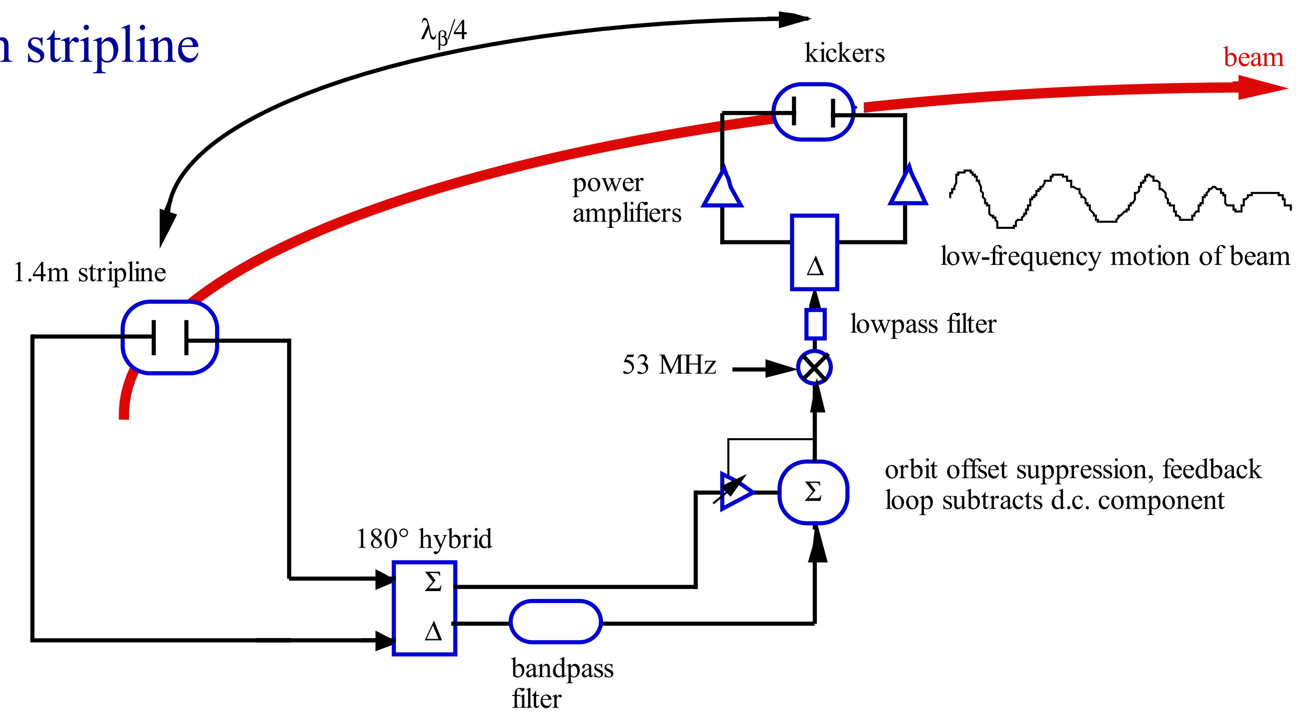
    → TEM mode propagates in both directions



- Power density ~ 2 Wm^{-2}

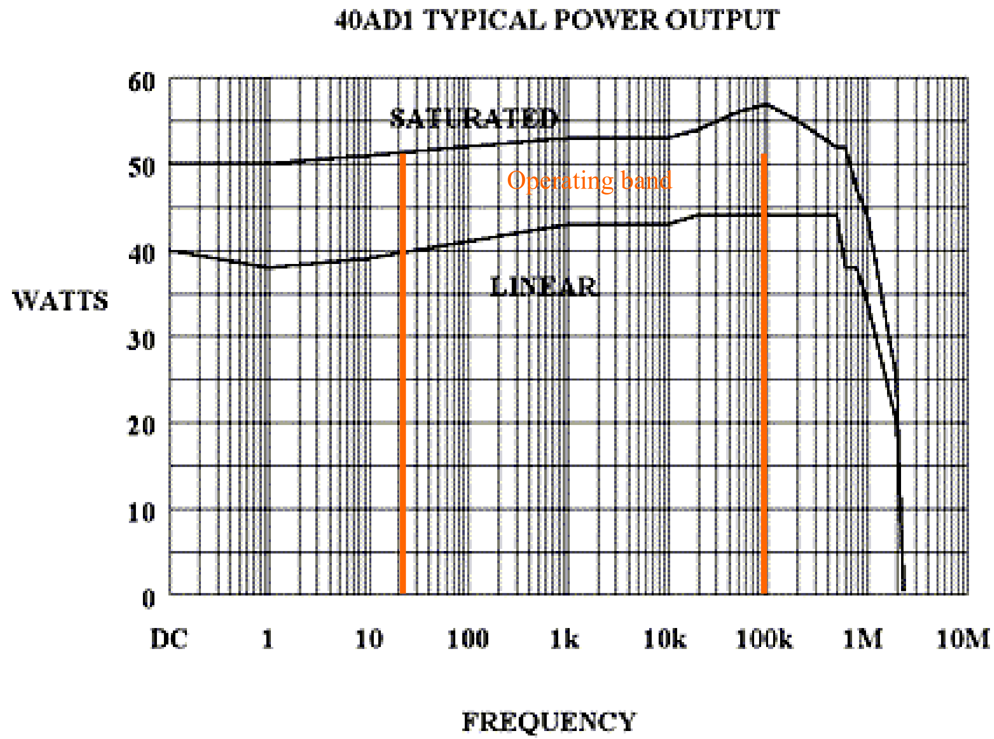
LF option narrowband feedback system

- Pickup at 53 MHz
  - Pickups insensitive at low frequency
- Mix down to baseband
  - Lowpass filter 100 kHz
  - Kick with 10 m stripline



Low-band power amplifier - AR40AD

- 100 Hz - 100 kHz required

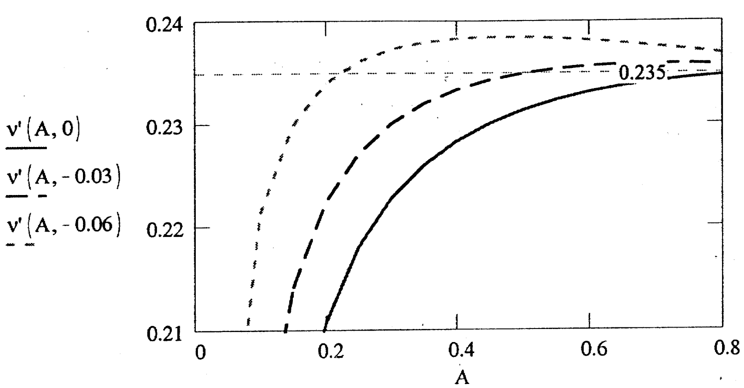


- Audio power amplifiers
  - Few Hz to >150 kHz
  - kW output power available

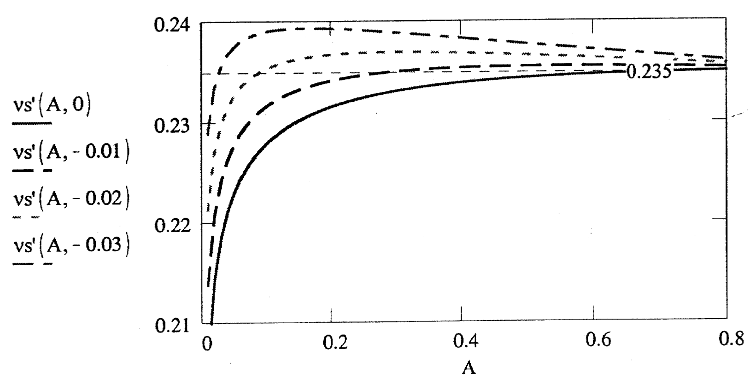
High-gain systems for suppression of emittance growth

- High-gain systems control coherent beam motion
  - Correct for motion induced by magnet movements and field fluctuations
    - → Low-frequency
- Use narrowband system previously described
- Pickup-kicker phase advance □π/2 may reduce tune shift from feedback system

G = 0.99 for single system



G = 0.68 for 10 systems



High-gain systems for suppression of emittance growth

- For distributed system with gain 0.68
  - Transverse kick voltage per station = 820 kV
  - Power per kicker = 4 kW
  - Kicker heating increased to 1.3 W
    - → ~ 7 Wm^{-2} power density
    - → Radiatively cool electrodes

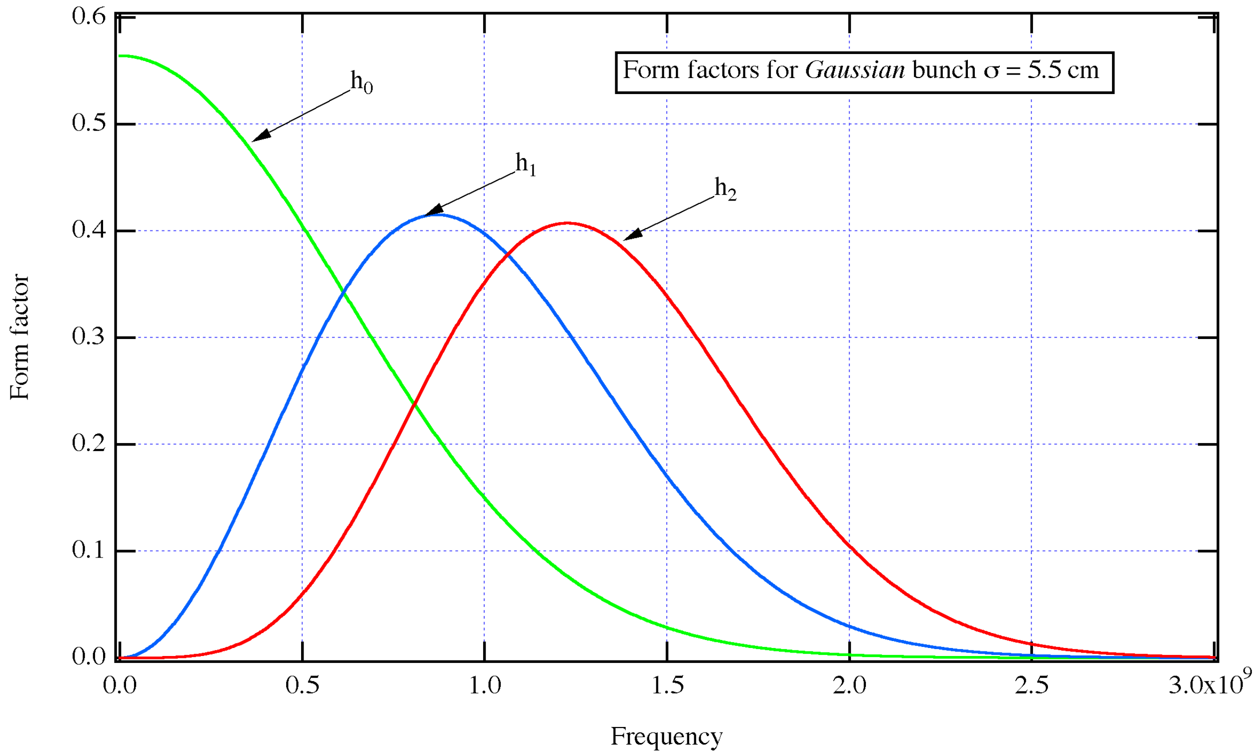
- Rate narrowband system for high-gain requirements
- Single system for resistive wall and emittance growth suppression

High-frequency system for TMCI

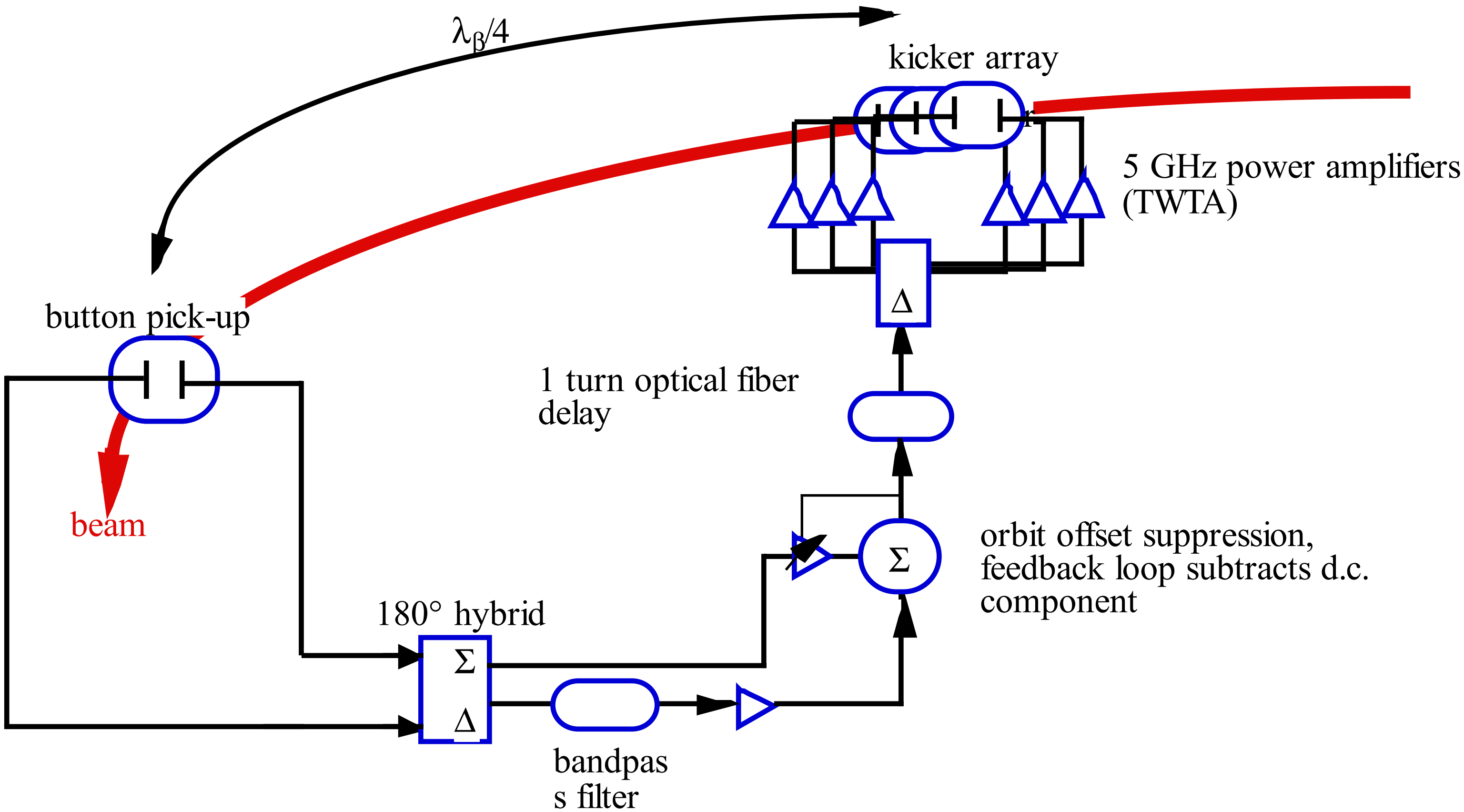
- m 1 modes observed as synchrotron sidebands about the m=0 (tune) dipole-motion signal
  - Broadband system acts on m = 0 mode
- "head-tail" motion
  - Within-bunch typical frequencies ~ $1/\sigma_t$ ¡ 3 GHz
- Pick-up and kick at this frequency
  - Stay below beampipe cut-off frequency 9.8 GHz
- Delay with optical fiber
  - Digital system possible for m=1
- Travelling wave tube amplifiers operate in GHz region with octave bandwidths

Coupled-bunch modes

- Mode spectra envelopes

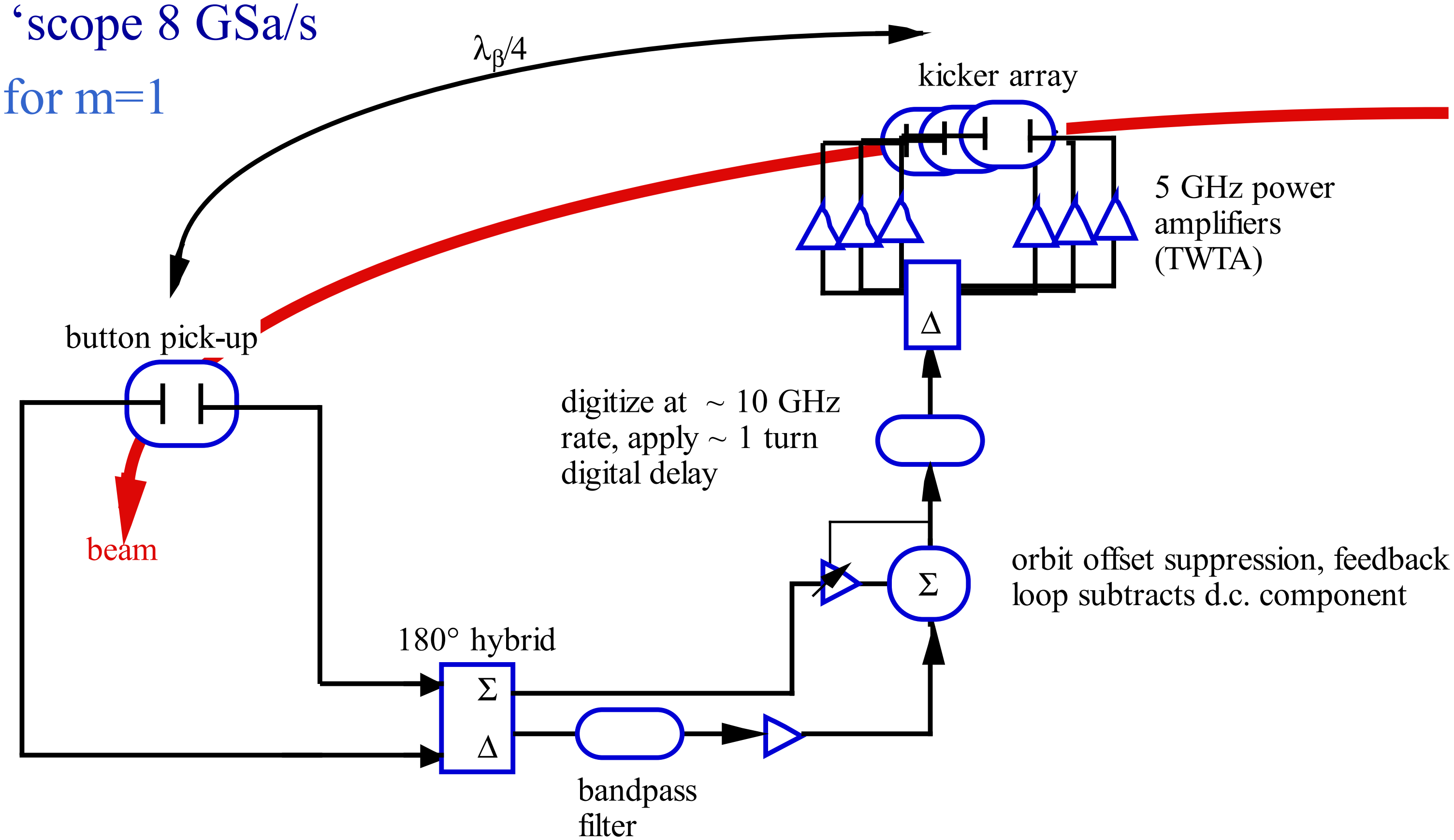


High-frequency system to damp TMCI



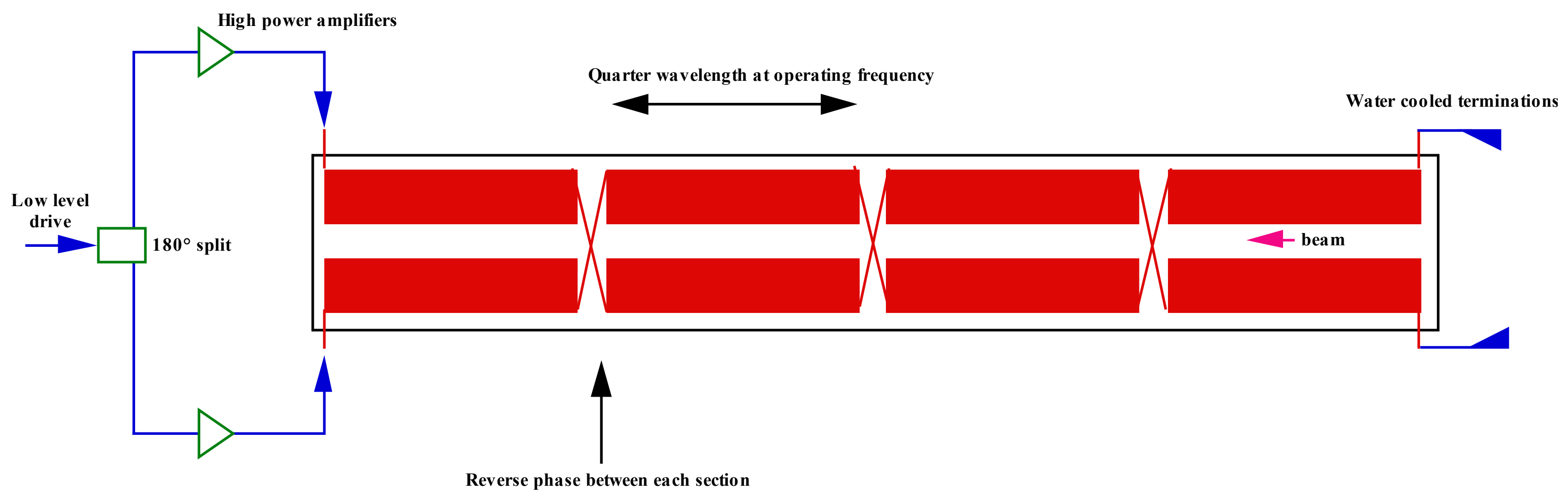
High-frequency system to damp TMCI

- Available digitizers may allow a digital system
  - Infinium 'scope 8 GSa/s
    - → OK for m=1



High-frequency kickers

- ♦ Transverse kickers less efficient at high frequency
  - ◊ Use stochastic cooling type arrays or array of kickers with π phase-shift between electrodes



Summary

- Propose three transverse feedback systems for VLHC

Feedback system	Function	Bandwidth
High-gain, narrowband	Damp strongest modes driven by the resistive wall impedance at low frequencies. High gain to suppress emittance growth.	100 kHz
Broadband, bunch-by-bunch	Damps all transverse modes	26 MHz
High-frequency, broadband	Damps m=1 TMCI mode	26 MHz

- Most demanding systems would be in the LF option
- TMCI suppression high-frequency feedback systems need development
  - ◊ m=0 systems have been successfully used to increase TMCI thresholds by factors of a few on several machines
- Longitudinal requirements not addressed