Precision measurements of beam current, position and phase for an e+e- linear collider

R. Corsini on behalf of H. Braun, M. Gasior, S. Livesley, P. Odier, J. Sladen, L. Soby

INTRODUCTION

- Commissioning and operation of a e+ e- linear collider with a beam energy in the TeV range requires the development of very precise diagnostics to measure different beam properties.

- We discuss here the motivations and the requirements for diagnostics whose development has been proposed by CERN in the framework of EUROTeV :

    - a wide-band (~ 20 GHz) current pick-up.
    - a fast beam position monitor (< 100 nm resolution, < 15 ns rise-time),
    - a precision beam phase measurement system (< 15 fs rms),

- The present status and possible R&D scenarios are also presented.

WIDE BAND BEAM CURRENT PICK-UP

Beam current monitor with ≈ 20 GHz bandwidth for measurement of intensity and longitudinal position bunch to bunch.

Signal for machine set-up, equalizing of bunch charge and spacing. Applicable to LC main beams, drive beams and damping rings.

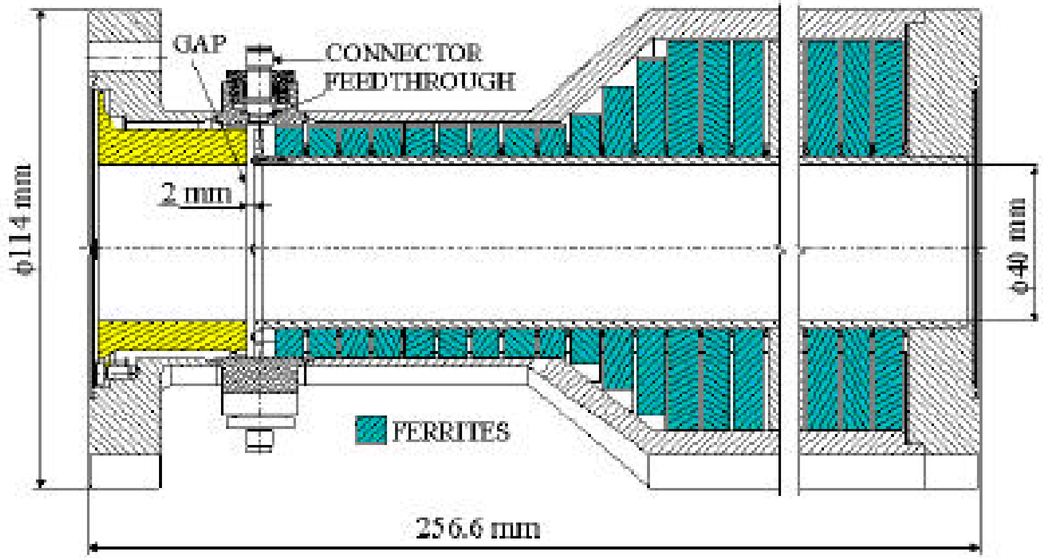
- Tentative CERN participants
  - Patrick Odier
- References:
  - P. Odier, “A New Wide Band Wall Current Monitor,”6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators DIPAC 2003 , Mainz, Germany

WIDE BAND BEAM CURRENT PICK-UP

- Requirements based on the request to resolve single bunch in the main beam for normal conducting LC (e.g., NLC 1.4 –2.8 ns, CLIC 0.67 ns).
- CLIC final drive beam bunch frequency (15 GHz) too high for good bunch resolution, but useful during drive beam acceleration and combination process.
- We propose to develop further an existing working system, tested with beam in CTF3 (wide-band Wall Current Monitor).

THE CTF3 WIDE BAND Wall Current Monitor (WCM)

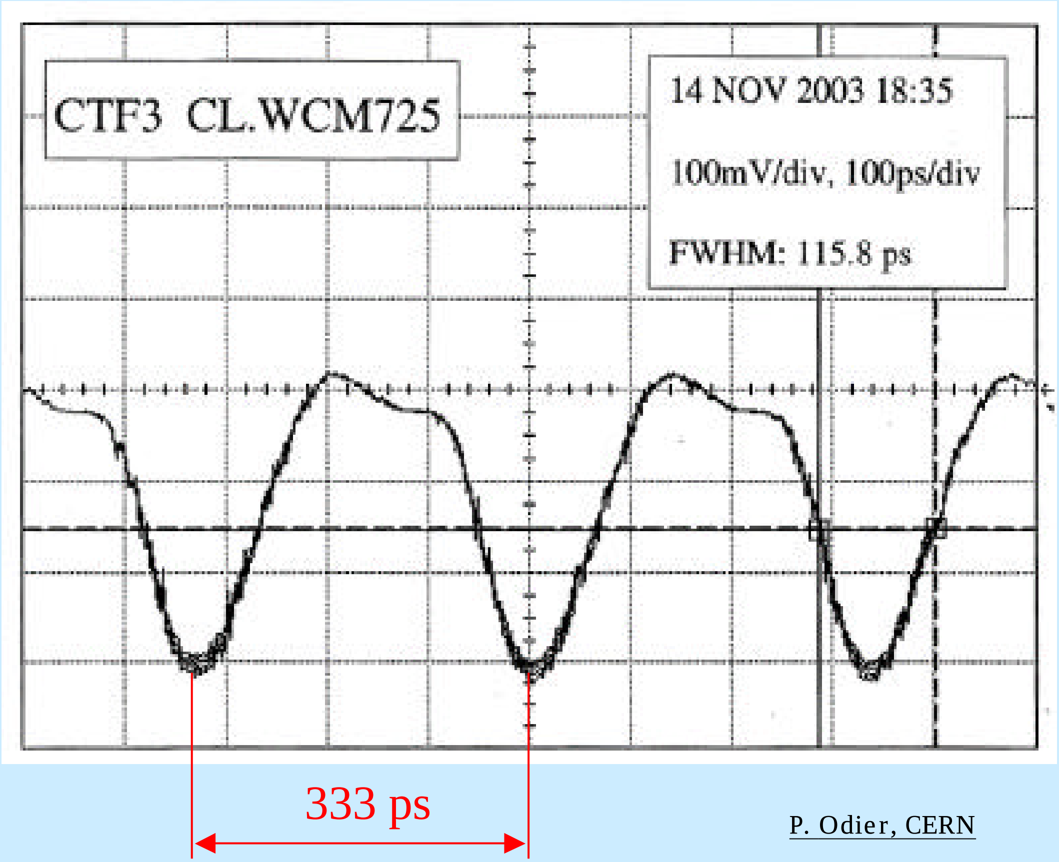
P. Odier,
"A New Wide Band Wall Current Monitor",
6th European Workshop on Beam Diagnostics
and Instrumentation for Particle Accelerators
DIPAC 2003 , Mainz, Germany



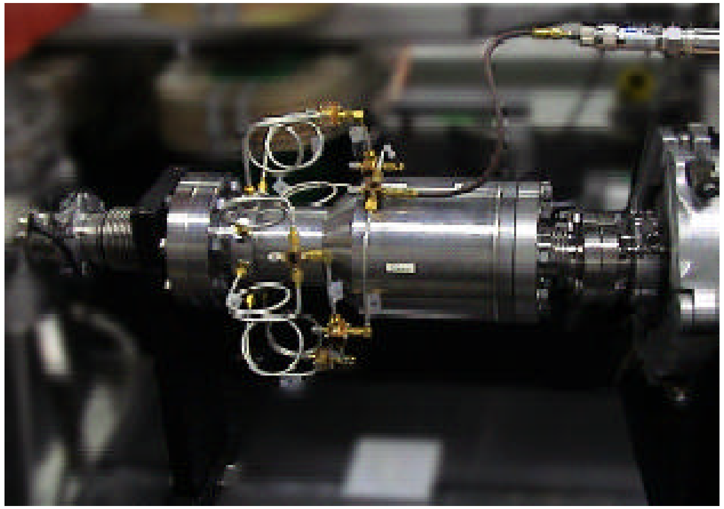
Impedance	0.5 ohms
Resolution	~4mA
Absolute precision	~ 1%
Low frequency cut off	10kHz
High frequency cut off	10GHz
Calibration	No
Number of feed-troughs	8
Gap length	2mm
ID / Length	40mm / 256.6mm
Flange types	DN63CF
Max. bake-out temperature	165 °C

WCM BEAM TESTS IN CTF3

Beam current signal (3 GHz bunched beam) observed with a sampling scope



P. Odier, CERN



The WCM installed in CTF3

Measurement conditions:

- 20GHz sampling scope in KG
- External trigger, from the streak camera
- Cable length: 17m
- Record length: 450pts
- Averaging on 8 records

WIDE BAND WCM – TENTATIVE SCHEDULE

DELIVERABLES

2005	2006	2007
Study of band-width limitations of existing CTF3 10 GHz WCM. Identify sources of high frequency resonances limiting the bandwidth.	Design of improved version. Construction of improved WCM.	Test in CTF3 and/or TTF to determine performance.

PRECISION BEAM POSITION MONITOR

BPM with < 100 nm resolution, < 10 μm precision, < 15 ns rise-time, aperture > 4 mm

Beam position monitoring in LC main beam and beam delivery with performance as required from beam dynamics studies.

- Tentative CERN participants
  - Lars Soby
  - Marek Gasior
- References:

  - M. Gasior, “An Inductive Pick-Up for Beam Position and Current Measurements,” 6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators DIPAC 2003 , Mainz, Germany
  - J. P. H. Sladen, I. Wilson, W. Wuensch, “CLIC Beam Position Monitor Tests,” Fifth European Particle Accelerator Conference, Sitges (Barcelona), 1996

PRECISION BEAM POSITION MONITOR

- Precision and resolution based on CLIC requirements but consistent with other LC project, taking into account a scaling in aperture. N.B.: the goal of 100 nm is not an "hard" limit (D. Schulte).

- Rise time of 15 ns required for intra-pulse resolution in main beam. Typically must be smaller than accelerating structure fill-time.

- Technology choice still open (button or stripline pick-up, RF resonant pick up with low external Q, inductive pick-up)

- Requirements seems reachable with an evolution of an existing design, working and tested with beam (CTF3 inductive pick-up).

- Past experience with beam testing of resonant pick-ups in CTF II have shown that experimental measurement of resolution is often limited by beam jitter and beam losses. Good beam quality and the use of several pick-ups to exclude correlated jitter is therefore needed.

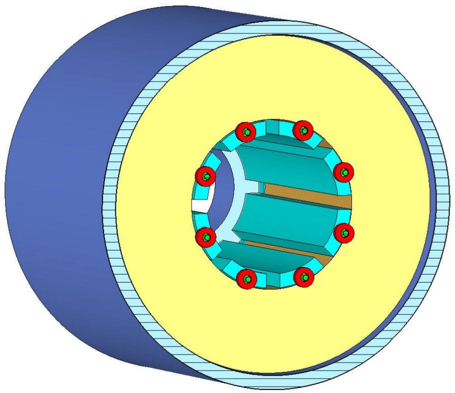
THE CTF3 BPM (INDUCTIVE PICK-UP)

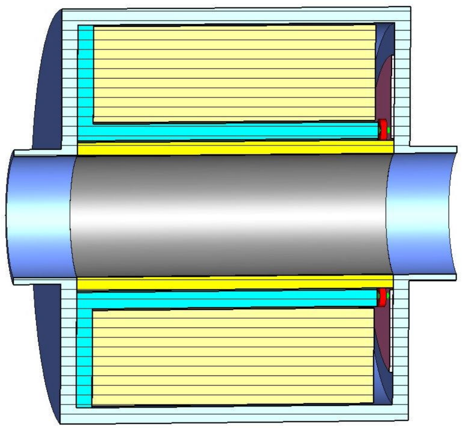
An Inductive Pick-Up (IPU) senses the azimuthal distribution of the beam image current.

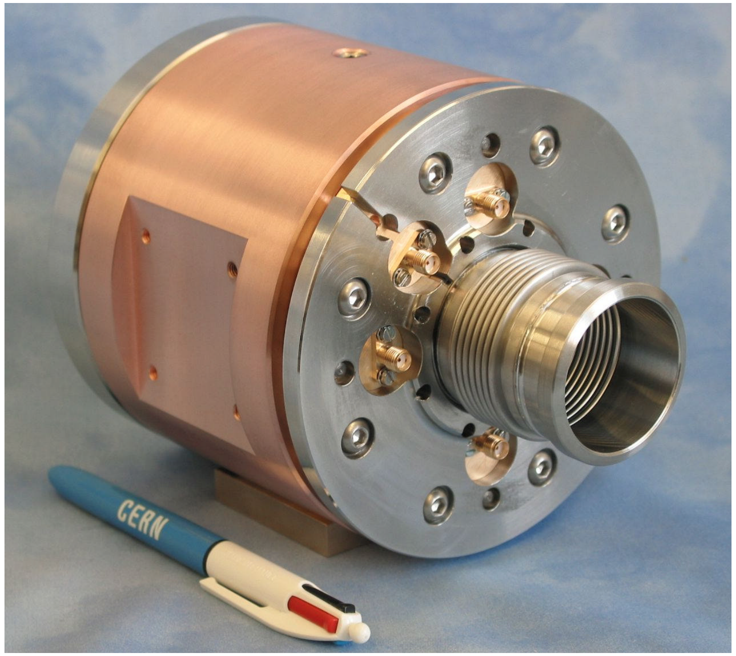
Its construction is similar to a wall current monitor, but the pick-up inner wall is divided into electrodes, each of which forms the primary winding of a toroidal transformer.

The beam image current component flowing along each electrode is transformed to a secondary winding, connected to a pick-up output.

Four pick-up output signals drive an active hybrid circuit (AHC), producing one sum (_) signal, proportional to the beam current, and two difference (Δ) signals proportional also to the horizontal and vertical beam positions.





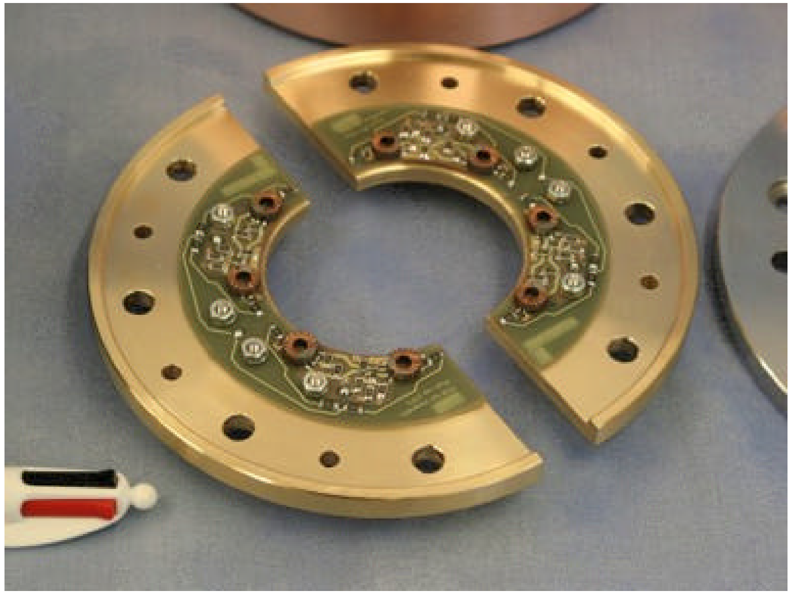


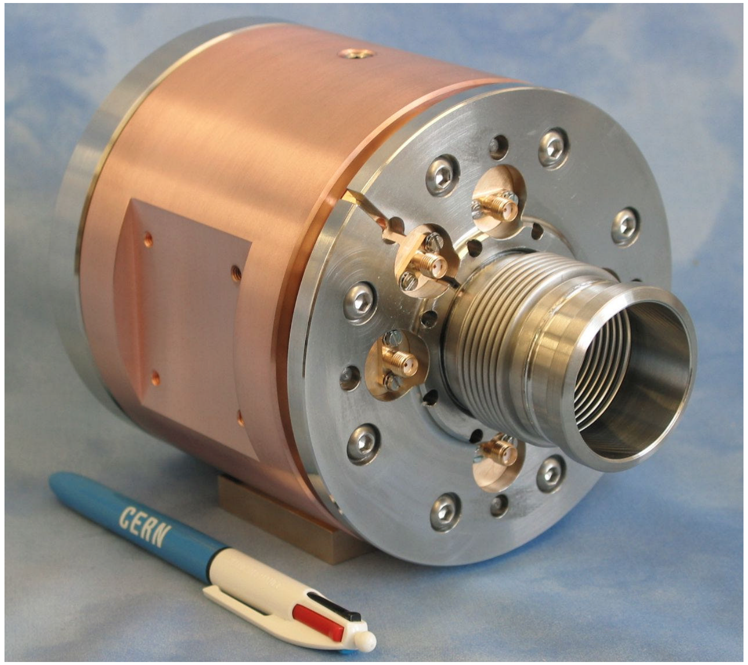
Aperture 40 mm

Resolution < 10 μm

Rise time ~ 2 ns

THE CTF3 BPM (INDUCTIVE PICK-UP)



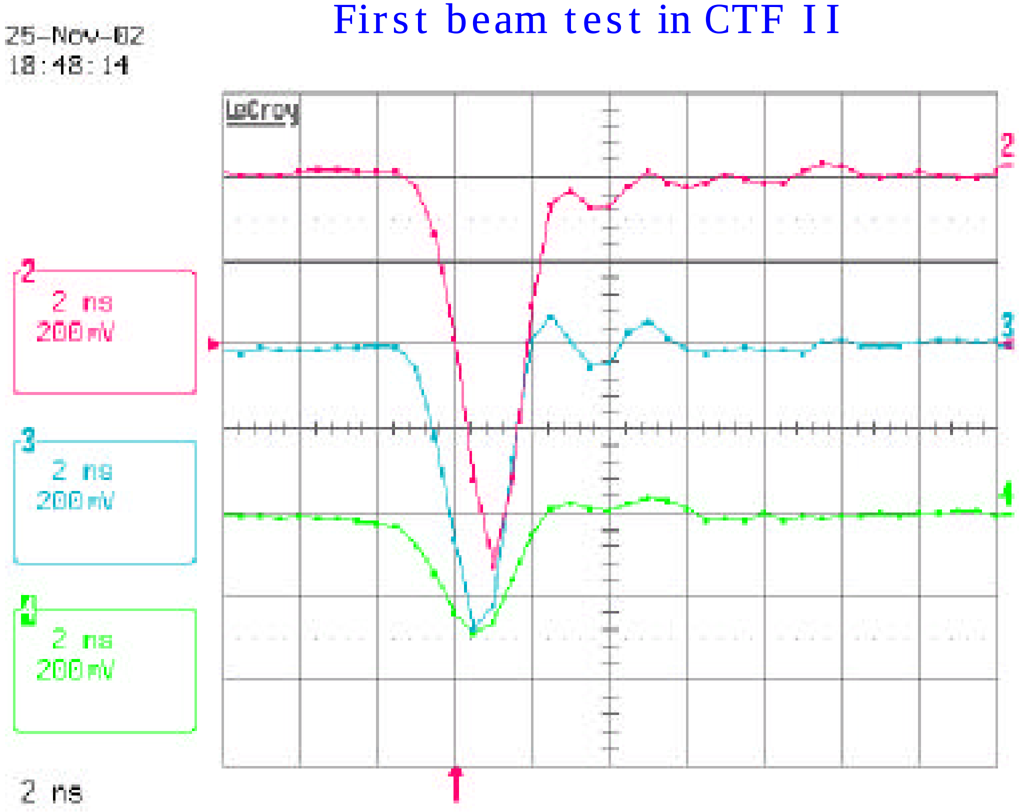


THE CTF3 BPM - PERFORMANCES

Rise time ~ 2 ns

(Beam tests)

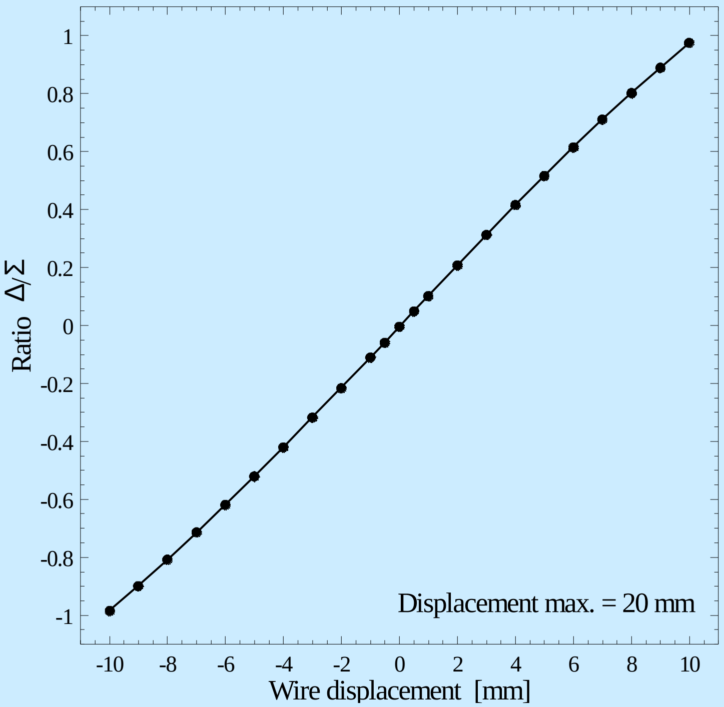
First beam test in CTF II



Σ - CH2 ΔH - CH3 ΔV - CH4

Resolution < 10 μm

(Lab tests – wire method)



- Electron beam of one 1 nC , 5 ps_{RMS} bunch
- The signals have the rise time of about 2 ns

THE CTF3 BPM – HOW TO IMPROVE PERFORMANCES

- Need a factor ~ 100 in resolution.
- A factor ~ 10 hopefully can be obtained scaling the aperture from 40 mm to 4 mm.
- A further gain in resolution expected increasing the rise time from 2 ns to the 15 ns range.
- Need to improve noise from electronics (active hybrids), at present not optimized for that.
- First step: assess precisely the actual resolution limit of the system with beam tests in CTF3 (present measurements limited by initial ADC resolution). Planned for next CTF3 run, starting in June 2004.

PRECISION BPM – TENTATIVE SCHEDULE

DELIVERABLES

2005	2006	2007
Design of BPM pick-up and readout electronics. Specification of all required components. Ordering/start of fabrication of all components for two BPM prototypes.	Assembly and test of functionality with antenna.	Measurement of both BPM prototypes simultaneously in CTF3 or TTF to determine achieved performance.

PRECISION BEAM PHASE MEASUREMENT

Phase reference with stability better 15 fs rms over long distances (km).

Needed for timing of LC collider beams to fulfil stability requirements on phasing and IP collision timing.

- Tentative CERN participants
  - Jonathan Sladen
  - Steven Livesley

- References:
  - L. De Jonge, J. P. H. Sladen, "RF Reference Distribution for the LEP Energy Upgrade," 4th European Particle Accelerator Conference EPAC '94 , London, UK, 1994

PRECISION BEAM PHASE MEASUREMENT

- Phase stability of the main beam with respect to the accelerating RF is required for all LC. Typical values are in the 1° range. Main limitations come from the momentum bandwidth effects in the main linac and the BDS.
- The requirements in CLIC are probably the tightest, due to the higher frequency, and the possibility of coherent phase errors between the main and the drive beam used to generate the RF power. Such coherent phase error must be smaller than 0.16° rms (15 fs at 30 GHz) for a 2% peak luminosity loss.
- Several stabilization strategies are possible, in any case, one needs a stable phase comparison system (electronics, local oscillators, signal transport, beam phase pick-ups, etc...)
- The proposal is mainly aimed at the development of precise electronics. The development of a stable oscillator and a beam phase measurement system are possible extensions of the program.
- Technology choices are open.

DELIVERABLES

2005	2006	2007
Survey of technologies, selection of most appropriate technology and optimisation.	Specification and ordering of components for test set-up. Assembly of set-up.	Commissioning of test set-up and determination of performance.

ITEM	SPECIFICATION	ACHIEVED	IMPROVEMENT NEEDED
Quadrupole BPMs	0.3 µm resolution	1 µm resolution (FFTB striplines) [1] 0.025 µm resolution (FFTB cavities) [2]	Factor of 3 None
Rf structure BPMs	5.0 µm resolution	2 µm resolution (NLC structure prototypes DDS3 and RDDS1) [3]	None
Magnet Movers	0.05 µm step size	0.3 µm step size (FFTB magnet movers) [4]	Factor of 6
Rf Girder Movers	1 µm step size	0.3 µm step size (FFTB magnet movers) [4]	None
Laser Profile Monitor	Measure 1 µm rms beam size	Measure 1 µm rms beam size (SLC laser wire) [5] Measure 0.06 µm rms beam size (FFTB laser interferometer profile monitor) [6]	None None
Magnet/Girder Supports	Add < ~3 nm vibration wrt tunnel floor	Add ~2 nm vibration wrt tunnel floor (FFTB quadrupole supports) [7]	None

The low-level rf drive system [21] in the main linacs generates the rf that is amplified by the klystrons to power the accelerator structures. Rf amplitude and phase are modulated at the milliwatt level for each klystron in the linacs. The low-level rf reference signal used for this purpose is generated by frequency multiplication of the master timing signal (714 MHz) sent to each sector through fiber-optic links. After modulation, the rf power is increased to the 1-kW level by a traveling-wave-tube (TWT) amplifier driving each PPM klystron. Both the TWT amplifier and klystron are operated near saturation to improve stability and efficiency.

During each pulse, the relative phase of the rf input going to each klystron is modulated as required for the DLDS (Section 4.4) to route the combined power of eight klystrons to the accelerator structures in the proper sequence, synchronous with the beam. Modulation of the phases of pairs of klystrons, in quadrature, compensates for the beam loading by creating a 120-ns initial ramp on the pulse that accelerates the beam. This shape 'preloads' the structures so the field profile witnessed by the first bunch is the same as that in steady-state loading.

Rf detectors on the structure outputs will be used to monitor the rf-to-beam phase. To improve sensitivity, the phase of the beam-induced rf will be measured on dedicated pulses where the klystron power is absent. This information will be used to phase optimally the rf going to each of the eight DLDS feeds. Any steady-state phase variations during the pulses can also be compensated, in particular, those resulting from voltage ripple on the modulator pulse. The goal is to achieve a 1° rf-to-bunch setting accuracy and a 1° pulse-to-pulse stability. The rf amplitude stability is expected to be better than 1%. The bandwidth of the system will allow the power routing to be changed in about 10 ns. This switching time, which represents a loss in efficiency, has been taken into account in the design parameters.

For rf modulation and demodulation, a programmable digital IF solution is planned, rather than an I/Q approach currently being used at NLCTA. Prototype studies have begun using a Direct Digital Synthesizer, a new commercial component that promises 12-bit vertical resolution, 300-MHz update rate, 100-MHz bandwidth, and low cost. The system would use an 89.75-MHz sub-IF that would be frequency multiplied by a factor of 8 and mixed up to 11.424 GHz.

The 1-kW amplifier needed for each klystron has such low average power (a few watts), that it can be designed to maximize lifetime without causing unacceptable thermal problems. The TWT amplifier portion of this system is being developed through the use of High Energy Physics SBIR funding from the Department of Energy. Prototype units have been made available to SLAC and integrated with traditional power supplies. These units are in operation but do not yet contain the desired long-life features. A prototype of an inexpensive Marx-style power supply is being developed and will be tested soon.

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