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Test Beams for ILC Final Focus

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The International Linear Collider (ILC) will require 250 GeV-500 GeV electron and positron beams to be focused down to a few nanometers in the vertical dimension at the interaction point. This will require unprecedented specifications for the final focus region and related controls. To this end, a set of international test facilities are being planned to address key performance goals of beam delivery sub-systems. These test facilities are described and future plans outlined.

1. INTRODUCTION

The beam delivery system (BDS) is the ILC sub-system that is situated between the main linac and the detector [1]. The BDS has several roles and includes:

- a beam diagnostics section to measure accurately the beam emittance at the exit of the linac,
- a collimation section to reduce beam halo,
- tuning sections so that the beams have the right properties to be focused down to nanometer scales,
- feedback systems to ensure the particle bunches meet at the interaction point (IP),
- crab cavities to ensure that the bunches overlap fully during collision at finite crossing angle,
- upstream (of the IP) beam measurements including polairmetry and high-precision spectrometry,
- the final focus quadrupoles that focus the beams to namometre scales at the interaction point.

These critical components are being tested at international facilities, as described below. These tests, together with a planned integrated test facility by the ATF2 collaboration, will be an important component of the ILC R&D programme over the coming years.

2. TEST FACILITIES

A set of test facilities are in operation (or in advanced planning) with a view to addressing the key technological challenges of the ILC final focus system. These are now outlined in turn.

2.1. End Station A at SLAC

The End Station A (ESA) [2] at SLAC has the parameters listed in Table I. This facility is being used to address:

- Collimator wakefield measurements; the wakefields may perturb beam motion and lead to both emittance dilution and magnification of position jitter at the IP. The aim is to find optimal materials and geometry for the collimating jaws. The principle of the measurement is shown in Fig.1. 8 new collimators have recently been manufactured in the UK and have been shipped to SLAC for tests at ESA in 2006.
- Experiments T-474, T-475 for energy spectrometers. Precision energy measurements to 50-200 parts per million are needed for Higgs boson and top quark mass measurements. Beam Position Monitor (BPM) and synchrotron stripe spectrometers will both be evaluated in a common 4-magnet chicane. Initially, SLAC

Linac BPMs will be used. New electronics based on nano-BPM work at KEK is being developed by UC Berkeley.

Table I: Beam parameters of the SLAC End Station A compared to those at the ILC.

Parameter	SLAC ESA	ILC-500
Repetition Rate	10 (up to 30) Hz	5 Hz
Energy	28.5 GeV	250 GeV
e- Polarization	(85%)	>80%
Train Length	Single bunch; (up to 400 ns possible)	1 ms
Microbunch spacing	20-400 ns	337 ns
Bunches per train	1 (or 2)	2820
Bunch Charge	2.0×10^{10}	2.0×10^{10}
Energy Spread	0.15%	0.1%

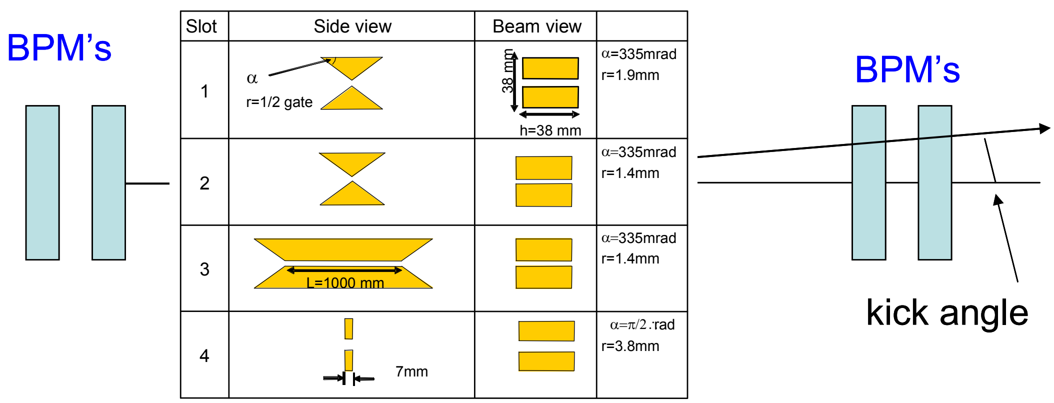

Figure 1: Principle of the collimator wake-field measurement at the SLAC ESA. A variety of collimator geometries will be tested in this way and results compared to simulations for the purposes of optimization.

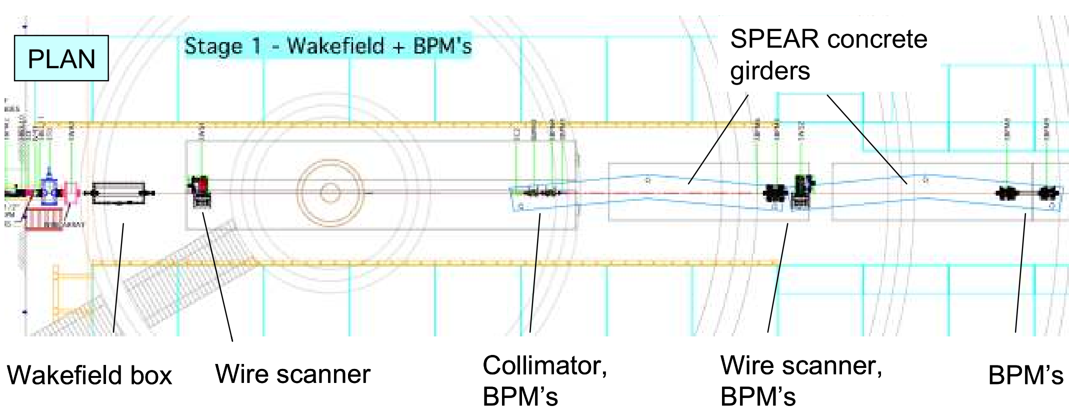

Figure 2: Plan view of the ESA layout for spectrometry and collimator wake-field experiments.

New BPMs, optimized for energy spectrometry, are being designed at University College London in collaboration with BPM experts at SLAC and KEK. A plan view of the ESA area is shown in Fig.2. Other ESA plans and/or possibilities include:

- BPM test stations.
- IP BPMs/kickers (necessary for fast inter-train and intra-train feedbacks), studies of sensitivity to backgrounds and RF pickup. Possibilities for installing a feedback system are also under investigation.
- Electromagnetic interference (EMI) impact on beam instrumentation or detector electronics, with plans to characterize EMI along ESA beam-line using antennas and fast scopes.
- Bunch length and longitudinal profile measurements; in particular: electro-optic, Smith-Purcell, coherent transition radiation, and possibly others.
- Spray beam or fixed target to mimic pairs, beamsstrahlung, disrupted beam for testing a synchrotron stripe energy spectrometer, IP BPMs, and BEAMCAL (the very low angle calorimeter).
- Interaction region mockup of the beam-line geometry at the IP within ±5 meters in *z* and ±20 cm radially.
- Single particles (electrons, photons, pions) with energies 1-25 GeV and 1 or fewer particles/bunch at 10Hz for ILC Detector tests.

2.2. PETRA

PETRA is an electron (and positron) storage ring with the beam properties listed in Table II.

Table II: Beam parameters of PETRA.

Energy (GeV)	4.5 to 12
Bunch Length σ_z (ps)	~ 100
Charge per bunch (nC)	1 to 3
Horizontal beam size σ_x (μm)	100 to 500
Vertical beam size σ_y (μm)	~ 100

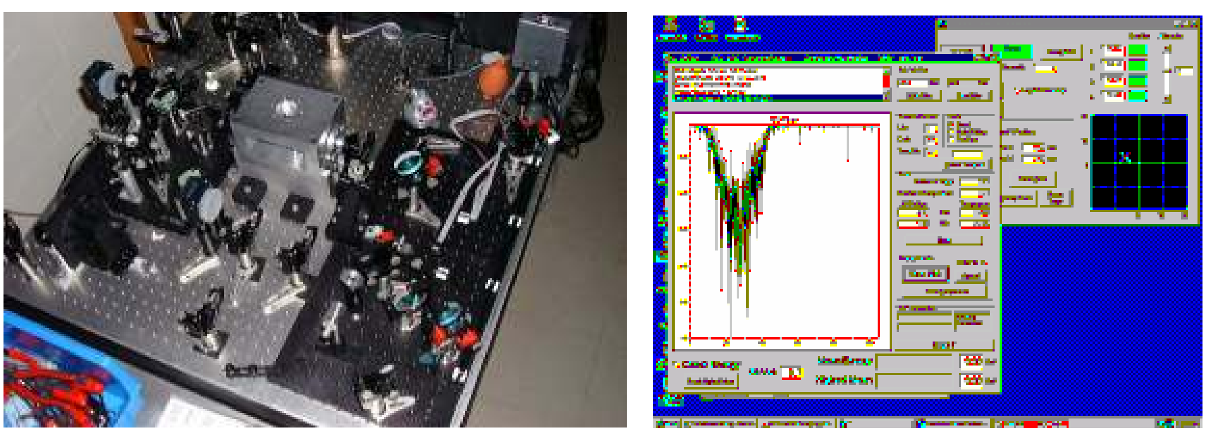

Figure 3. Left: layout of PETRA laser-wire hardware under test in the lab at RHUL before shipment to DESY. Right: a screenshot from a run in February 2005 that shows the laser-wire scan (forward) and BMP reading (rear).

The PETRA laser-wire hardware, shown in Figure 3 (left) has now been running for approximately 2 years and is routinely providing useful results as shown in Figure 3 (right). A scan takes about 30s, limited by the laser repetition frequency of 30Hz. The hardware has recently (Dec. 2005) been upgraded to enable scans in both *x* and *y* and the original Q-switched laser is being replaced with an injection-seeded system that should improve the longitudinal mode quality. Data taking with the new system is planned for spring 2006. Further details are provided in [3,4,5]

2.3. ATF

The ATF ring at KEK has the properties listed in Table III.

Table III: ATF beam parameters

Maximum energy		1.28 GeV (γ=2500)
Beam emittance	Vertical	$(1.5 \pm 0.25) \times 10^{-11}$ m rad
	Horizontal	$(1.4 \pm 0.3) \times 10^{-9}$ m rad
Bunch Length		~ 8mm (26 ps)
Single bunch population		1.2×10^{10}
Energy Spread		0.08%

The mission of the ATF/ ATF2 collaboration [6,7] is:

- ATF, to establish the technologies associated with producing the electron beams with the quality required for ILC and to provide such beams to ATF2 in a stable and reliable manner.
- ATF2, to use the beams extracted from ATF at a test final focus beam-line which is similar to that envisaged for the ILC. The goal is to demonstrate the beam focusing technologies that are consistent with ILC requirements. For this purpose, ATF2 aims to focus the beam down to a few tens of nm (rms) with a beam centroid stability within a few nm for a prolonged period of time.
- Both the ATF and ATF2, to serve the mission of providing young scientists and engineers with training opportunities of participating in R&D programs for advanced accelerator technologies.

Current ATF projects include:

- polarised positron generation R&D at the ATF extraction line (ended June 2005),
- laser wire R&D in the damping ring (Kyoto University); see below,
- high quality electron beam generation by photo-cathode RF Gun (Waseda University),
- X-Synchrotron Radiation monitor R&D (University of Tokyo),
- Optical diffraction radiation R&D (Tomusk University); see below,
- beam based alignment R&D,
- nano-BPM project of SLAC, LLNL and LBNL; see below,
- nano-BPM project of KEK; see below,

- FONT project (UK Institutes); see below,
- laser wire project at extraction line (UK Institutes); see below,
- fast kicker development project (DESY, SLAC, LLNL),
- fast ion instability research,
- multi-bunch instability study.

Some examples of these projects are now reviewed briefly.

The ATF has been host for many years to a very successful laser-wire project [8,9] located in the damping ring. This system uses a continuous wave (CW) laser combined with an high Q-factor optical cavity to increase the laser power at the IP; a cavity is required for each of the vertical and horizontal dimensions as shown in Figure 4 (Left) together with a photograph of the system in Figure 4 (right). The entire optical table is moved with high precision actuators, to provide the scanning mechanism.

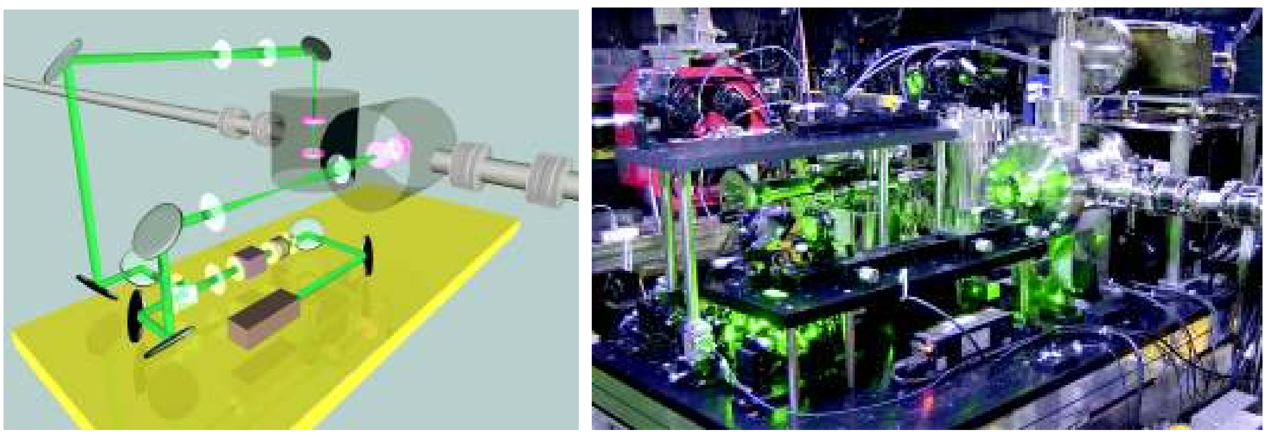

Figure 4. Left: schematic of the ATF damping ring laser-wire showing the horizontal and vertical optical cavities. Right: a photograph of the system showing the optical table that is moved by high precision actuators during a scan.

The laser used at the ATF to provide light to the optical cavities is a 300 mW 532 nm solid-state CW system and the optics is set up to provide a waist of 14.7 μm in x and 5.7 μm in y. A scan takes about 15 minutes for x and 6 minutes for y. The system has been used to show the damping mechanism taking place in the ring, using the Compton detector timing to isolate the relevant timing period from several separate scans [9].

Another laser-wire experiment has recently (Dec. 05) been installed at the ATF extraction line [4]. This aims at a single-pass device to measure micron-scale electron spot sizes, such as will be needed at the BDS (and linac) of the ILC. For such a system a high-power pulsed laser system is required, which supplies of order 10 MW (or higher) pulsed power. The technical challenges for such a system centre on the design of f/1 optics for the laser final focus system (to obtain micron-scale electron spot-sizes) and on maintaining the high-power laser [5]. It is planned to learn from the experience at the ATF extraction line laser-wire system to construct a laser-wire based emittance measurement station for the ATF2 programme.

The ATF Nano-BPM project has two 600 mm triplets of cavity BPMs. The KEK triplet is shown in Figure 5 (left) and the SLAC/LLNL triplet shown on the right. The triplets are spaced apart by about 5m in the ATF extraction line.

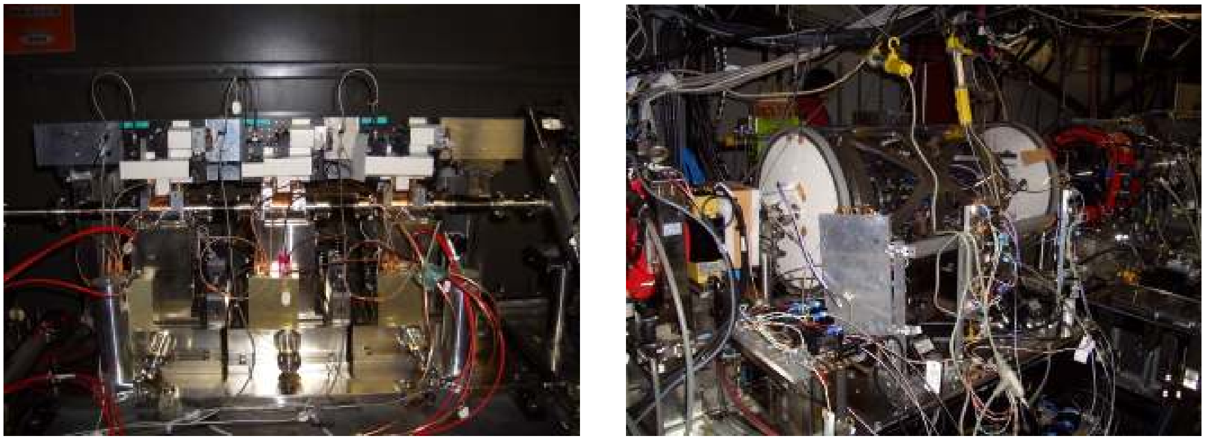

Figure 5. Left: the KEK triplet of BPMs. Right the SLAC/LLNL triplet, including the LLNL support frame.

The LLNL frame (shown in Figure 5, right) contains three BPMs made at BINP with approximately 2 cm dipole mode selective couplers. In addition the setup contains high precision movers that allow one BPM at a time to be moved. In this way the BPM phase, scale and offset as well as beam motion can be extracted by linear regression of BPM readings against mover position, together with all the other BPM readings. With one minute of data-taking using 100 pulses a rms resolution of 17 nm has been obtained. Details are described elsewhere in these proceedings.

The two independent nano-BPM systems will be coupled to an optical geodetic structure, employing a two-dimensional grid of Michelson interferometers, to explore the possibility of using active stabilization at the ILC. This project is now being set up at the ATF extraction line [10].

The development of non-invasive micron beam size diagnostics using optical diffraction radiation (ODR) has been achieved at the ATF [11]. The results for a multi-shot measurement are shown in Figure 6 (left); the periodic behavior of the ODR pattern as a function of the target position was confirmed. As shown in Figure 6 (right), single shot ODR measurements with an ICCD have been performed and the electron beam size was estimated and compared with measurements using a wire scanner

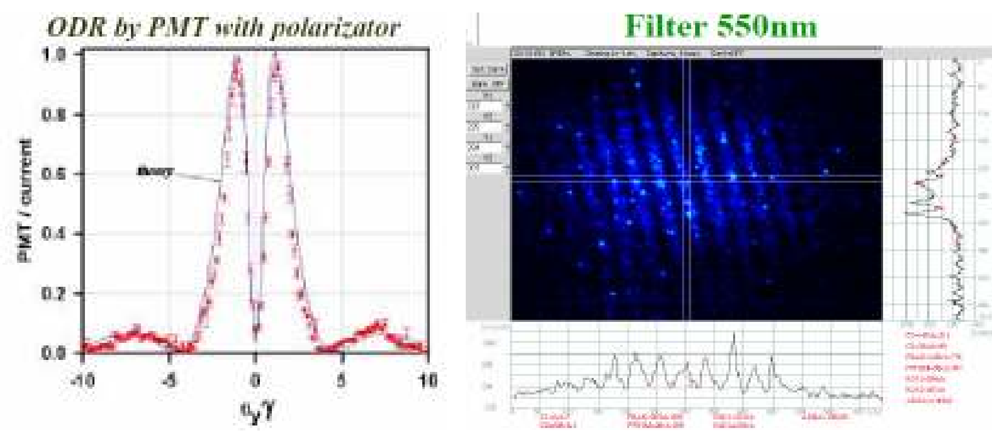

Figure 6. Left: ODR multi-shot measurement. Right: ODR interference as captured on CCD [11]

A set of projects performed within the Feedback On Nanosecond Timescales (FONT) collaboration has been based for several years at the ATF [12]. The system, shown in Figure 7 (left) has demonstrated feedback with a delay loop, using an ultra-fast system with a total latency of 23 ns. During this project the main gain, delay loop length, and delay loop gain were varied; the system behaved as expected as shown in Figure 7 (right).

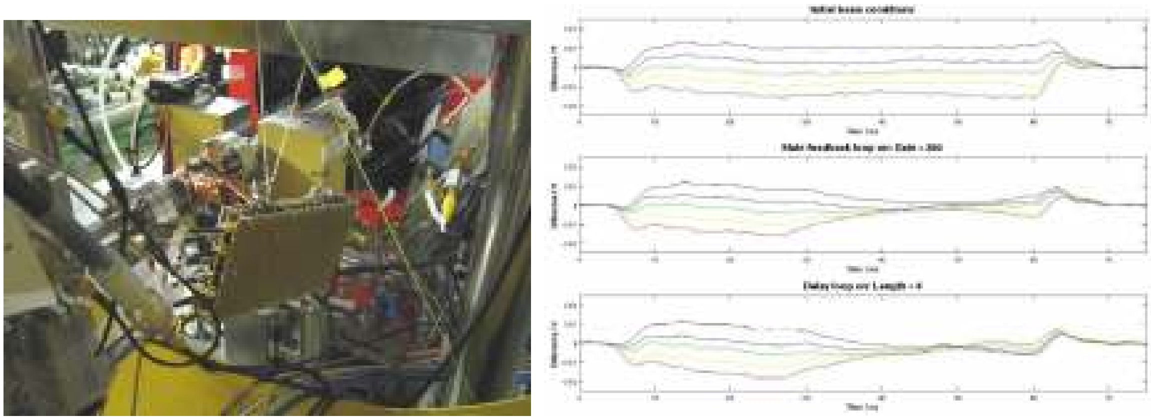

Figure 7. Left: FONT3 amplifier installed at the ATF extraction line. Right: results from FONT3 run showing the effects of feedback on the beam position.

FONT4 will use the new 1.3 GeV ATF extraction line beam that consists of 3 bunches with spacing of approximately 150ns. The project will use a modified FONT3 BPM front-end signal processor, a digital feedback system together with a modified FONT2 solid-state amplifier providing a 300 ns long output pulse, and the FEATHER adjustable-gap kicker. FONT4 is aiming for a first demonstration of feedback with ILC-like bunches with an electronics latency goal of 100 ns and the stabilisation of the 3rd bunch at the micron level. First results are expected early in 2006. An additional possibility currently under investigation is to use μm feed-forward system using BPM measurements in the damping ring to reduce the beam jitter in the ATF extraction line via a new strip line kicker.

2.4. ATF2

The main aim of ATF2 [6] is to demonstrate that nm scale electron spot-sizes can be obtained reliably and to improve on the results obtained at the FFTB [13]. This will require:

- achievement of ~37 nm electron beam size,
- demonstration of a compact final focus system based on local chromaticity correction,
- maintenance of the small beam size over extended running periods,
- control of beam position,
- demonstration of beam orbit stabilization with nm precision at the IP,
- establishment of beam jitter controlling techniques at nm level with ILC-like beam,
- development of a successful commissioning and tuning process, of relevance also to the ILC.

The ATF has achieved the necessary pm emittance and so provides the ideal source to achieve the ATF2 goals. The ATF2 proposed optics IP parameters are presented in Table IV. The ATF2 beams are therefore similar to those for the ILC in chromaticity, energy spread and aspect ratio; but differ in geometric emittance and bunch length [7]. The ATF2 goals are to have extracted beam position jitter of less than 1/3 σ_y in the first stage, decreasing to 1/20 σ_y in the final stage. The bunch structure will be 3 bunches with 150 ns spacing in the first stage, with many bunches with a few ns spacing for the final stage. The preferred ATF2 schedule aims at commissioning in February 2008.

Table IV: ATF2 proposed optics parameters in comparison with those for the ILC.

	ATF2	ILC
Beam Energy [GeV]	1.3	250
L* [m]	1	3.5 - 4.2
$\gamma\varepsilon_x$ [m-rad]	3.10^{-6}	$1.\ 10^{-5}$
$\gamma\varepsilon_y$ [m-rad]	3.10^{-8}	4.10^{-8}
β_x^* [mm]	4.0	21
β_y^* [mm]	0.1	0.4
η' [rad]	0.14	0.094
σ_E [%]	~0.1	~0.1
Chromaticity W_y	$\sim 10^4$	$\sim 10^4$
σ_z [mm]	8	0.3

2.5. TTF

Possibilities exist for installing beam diagnostics projects at the Tesla Test Facility (TTF) at DESY, although no candidate projects exist yet for final focus studies because the main efforts have been concentrating on developing the superconducting linac. There is a bypass line on top of the TTF undulator that could be used for new projects and a modification of the beam-line in order to use a dedicated bunch structure for experiments would be possible. There might be some restrictions arising from scheduling issues and from the beam losses (radiation protection) in that area.

2.6. CTF3

The CLIC Test Facility CTF3 aims at demonstrating the CLIC drive beam generation scheme, generating 30 GHz power for testing of the 30 GHz structures, and acting as a test bed for CLIC technology. As a part of this programme, a CLIC Experimental Area (CLEX) is planned, with construction of a new building in 2006. In this area there will be a Probe Beam Injector linac, providing beam to a two-beam test stand and to a Test Beam Line (TBL) for studies of drive beam decelerator dynamics, stability and losses.

Table V: Properties of the CTF3 Probe Beam Injector

Energy [MeV]	~ 200
Normalised rms emittance [mm mrad]	< 20π
Energy spread [%]	< ± 2
Bunch Charge [nC]	0.5 nC
Bunch spacing [ns]	0.333
Number of bunches	1 - 64
rms bunchlength [ps]	< 0.75

The TBL will not be used all the time and so the Probe Beam Injector will in principle be available to provide beam for other studies; the properties of this beam are presented in Table V. The current CTF3 schedule shows the probe beam in full use during 2006-7, so from 2008 onwards the TBL could be a new facility for beam diagnostics tests.

3. SUMMARY

Several test facilities exist world wide for ILC final focus projects, including dedicated projects at ESA at SLAC, PETRA (and possibly TTF in the future) at DESY, ATF/ATF2 at KEK and also plans at CTF3. Projects include diagnostics, feedback and nano-BPM R&D, among others. The ATF2 is an international project, ideally suited for R&D in the key final focus issues for the ILC.

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