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Two-beam Test Stand Experimental Program

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Abstract

We discuss the Two-beam Test Stand experimental program and propose a timing of the different test phases.

1 Introduction

The Two-beam Test Stand (TBTS) has been constructed for the development of PETS and accelerating structures towards CLIC as well as research of physics phenomenons related to the operation of these structures. The commissioning of the first PETS has recently started while the first accelerating structure has been installed and is foreseen to be conditioned during the summer.

CERN is preparing a set of CLIC test modules to be installed into the Two-beam Test Stand. This installation will require a modification of the TBTS and might inhibit some of the experiments possible in the present TBTS layout. It is therefore important to discuss the experiments to be performed at the TBTS and link them to the different construction phases of te TBTS.

To prepare and successfully complete the experimental program, three points are of importance:

- Commissioning and calibration of the instrumentation.
- Focus on the unique capabilities of the two-beam test stand.
- Concentrate on the important questions; scientific and engineering goals.

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The unique capability of the TBTS is the presence of the two beams, drive and probe beam, together with a large amount of instrumentation. RF power is produced by a PETS structure in the drive beam line. This links immediately to the important research topics:

- Fundamental mode behaviour of the structures; acceleration and deceleration, beam kicks.
- RF breakdown, especially in the presence of beam.
- Effect of higher order modes; their influence on the beam (wakefields) and their usefulness for beam based alignment.
- Timing of the two beams, to align the RF phase for optimal acceleration.
- Full system behaviour; step from component prototypes to two-beam acceleration unit prototype. Cross talk between drive and probe beam.
- Intra-girder alignment studies.

The studies linked to these topics can be investigated during different stages of the TBTS build-up and instrumentation.

The different sections of this memo describe the layout of the TBTS and the measurements that can be performed.

2 TBTS Experiment Phases

The TBTS commissioning and experimental program is linked in a set of consequential phases. These phases follow the idea that the experimental investigations have to be performed according to an increasing degree of complexity, building on results from previous investigations:

1. **Component tests.**

   Test of basic RF components;

   - pure RF power tests without beam.
   - investigation of behaviour with beam.

   The RF power tests without beam can be performed at a klystron based test stand.

2. **Two-beam acceleration unit tests.**

   Test of a complete RF unit (FRFU = full RF unit);

   - single PETS powering one or two accelerating structures.
   - complete module with multiple PETS and accelerating structures.

   Uses the probe beam as a diagnostics tool for the module girder alignment by wakefield monitoring.

The layout of the TBTS beam lines and experimental areas is shown in figure 1. The different phases for the TBTS are:

Phase 0 is with beam lines only, before installation of PETS or accelerating structure in the experimental areas.

Phase 1 is with a PETS installed in the drive beam line.

Phase 2 is with a 1 m long PETS in the drive beam line and an accelerating structure in the probe beam line, enabling study of two-beam acceleration. Sub-phases are:

Phase 2.1 one (1) accelerating structure,

Phase 2.2 two (2) accelerating structures. Test of a full RF unit with one PETS powering two accelerating structures. The two accelerating structures will be equipped with wakefield monitors.

After Phase 2 the two-beam test stand will be dissembled and two-beam modules will be installed. At present the following two-beam module phases have been defined:

Phase 3 is with a single CLIC test module installed.

In this phase, a type 0 module will be installed (see section 3).

Phase 4 is with three CLIC test modules installed.

The type 0 module from phase 3 is maintained. A type 1 and type 4 module are added as shown in figure 2.

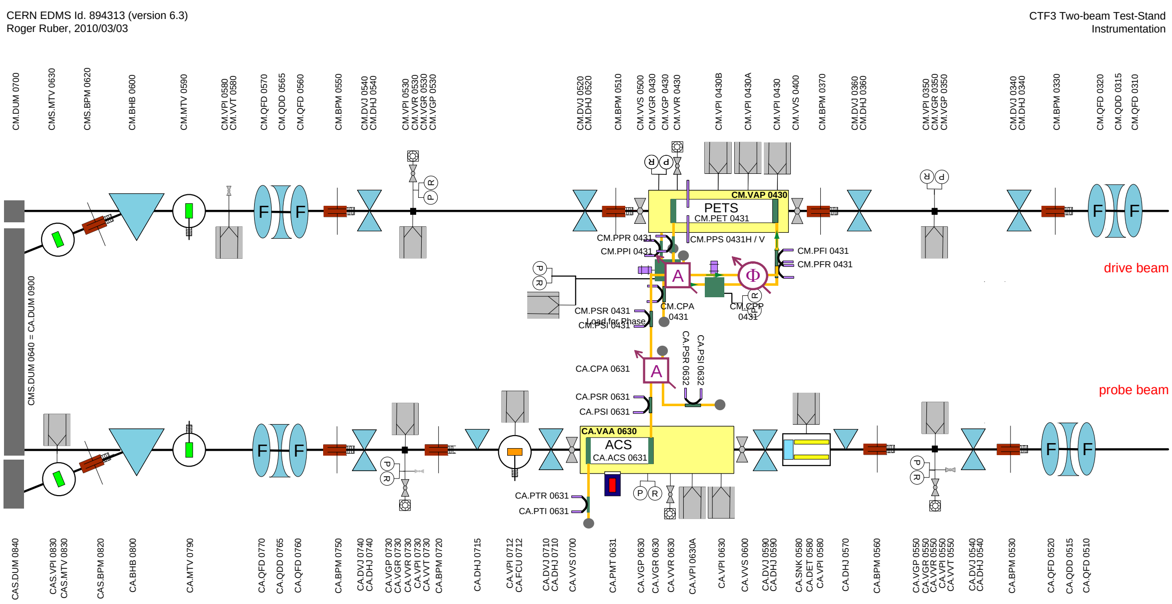

Figure 1: Layout of the TBTS phase 2.1.

3 Two-beam Test Modules

The two-beam modules in the TBTS will be as close as possible to the planned CLIC final modules, while adapting to the test infrastructure. Double length PETS structures will be used, each feeding two accelerating structures.

The layout of the two-beam test modules is:

Type 0 contains eight (8) accelerating structures in the probe beam line and two (2) double length PETS, two (2) quadrupoles and two (2) BPMs in the drive beam line.

Type 1 contains six (6) accelerating structures, one short quadrupole and one BPM in the probe beam line. The drive beam line contains two double length PETS, two quadrupoles and two BPMs.

Type 4 contains one full length quadrupole and one BPM in the probe beam line and two quadrupoles with two BPMs in the drive beam line. No accelerating structures and no PETS are present.

Several accelerating structures have a build-in wakefield monitor. The drive beam quadrupoles are identical along the module types while the probe beam quadrupoles have different lengths. The final CLIC two-beam modules will have a layout type 2 and 3 with a probe beam quadrupole of increased length replacing four and six accelerating structures respectively. Each PETS in the drive beam line powers two accelerating structures in the probe beam line. The PETS structures used in the test modules have the double length compared to the CLIC type PETS. This is to compensate for the lower drive beam current and power in CTF3 compared to CLIC. Therefore, in the test modules only half of the available accelerating structures can be powered. The integration of the two-beam modules is being studied and few configurations exist.

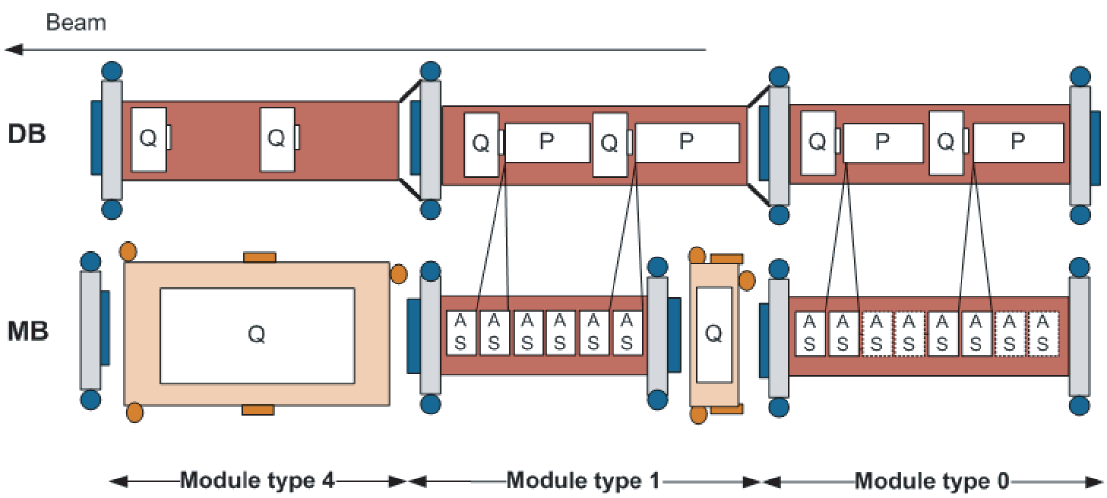

Figure 2: Layout of the three two-beam test modules for phase 4.

4 Commissioning

The commissioning is intended to understand the beam lines' response matrices and to debug and calibrate the instrumentation. Especially BPM and MTV calibration is indispensable for reliable beam kick and beam energy measurements.

Measuring the response coefficients in the TL2', CALIFES and both TBTS lines both in the horizontal and vertical plane will give a comprehensive view of BPM and steerer scale errors and quadrupole gradient errors. Even though the latter will be difficult to determine, because the quadrupoles in the triplets are rather close and it is difficult to disentangle. These measurements should be done in the context of the kick meaurements, because the interpretation of the BPM signals and converting them to physically relevant quantities such as kick angles depend on the optics.

- beam orbit and optics
  - BPM resolution and timing
  - MTV resolution
  - steering knobs for alignment and H/V offset (R_{12} response matrix)
  - waist knobs to shift the β-function
  - incoming drive beam with zero dispersion (use TL2/TL2 quads)

  There are 4 BPMs in a row with just drifts. BPM resolution studies can be done by taking two magnets, predicting the third (and fourth) and making a histogram of (predicted-measured). The width of the histogram is the BPM resolution and the DC offset tells you something about alignment. This should be done for the 'average position' in a pulse and see whether it varies along the pulse.

  Need to time the BPM such that the average is measured at the proper time window and then we need to see the shift of one versus another BPM to be able to analyze the kick data

  Commission steering knobs in both drive and probe beam.

  Wiggle steerers and observe the change on the BPM. This will tell us a lot about optics and calibration errors of the BPM and steerers (R12 response matrix).

  Observe and quantify the incoming jitter of the beam. In the probe beam this means the full-blown fit, but without active PETS. In the drive beam we just measure the 5 TBTS BPM and fit incoming orbit and energy to it.

- beam loss monitoring
  - to monitor beam transport if possible w/o losses
  - to distinguish losses in drive and main beam (CLIC study)

5 Fundamental Mode Behaviour

These studies are intended to understand the effects of acceleration and deceleration on the respective beams. The effects on the beam can be dependent on the bunch train structure, the beam current and the RF power.

- beam behaviour as function of RF power: PETS RF power production
  - as function of drive beam parameters ("knob" test)

  Study how the RF power production in the PETS varies depending upon drive beam parameters (beam current, bunch length, bunch frequency, ...)

- beam behaviour as function of RF power: beam loading
  - how predictable is the energy spectrum
  - phase advance as function of the beam loading

  In an unloaded structure the gradient of the RF field increases along the length of the structure (depending upon the structure design). Note that beam loading also shifts the working point on the breakdown rate versus gradient graph (see section 7.

  Measurement options:
  - single pulse in the main beam
  - scan over a range of input power

- beam energy (acceleration and deceleration)
  - drive/probe beam energy incoming beam
  - drive beam energy loss (deceleration) as function of RF output power and beam parameters [1]
  - probe beam energy gain (acceleration or deceleration) as function of RF power and beam parameters
  - average energy spread
  - time resolution (to check for trapped modes in the PETS)

  Beam energy and energy loss/gain can be measured with the downstream BPM in the spectrometer line.

  The energy spread (including the average variation of the energy gain/loss) along the bunch train can also be measured with the downstream BPM in the spectrometer line (or with a segmented beam dump)? Energy spread can be measured with the OTR in the spectrometer line.

- beam emittance

  - along the bunch train, (might vary when a RF breakdown happens, but almost impossible to measure)

  Emittance measurement along the bunch train needs a screen in the straight line. It will be difficult to measure in a single shot and extremely difficult in a single break down. Need to compare emittance measurements from consecutive OTRs and see whether it is the same. Often saturation on screens is a problem. For luminescence screens the internal diffusion of light may influence the emittance measurements.

- beam phase variation along pulse

  The arrival time variation along the drive beam pulse will be measureable by analyzing the RF signals in the recirculation system for the PETS structure. The analysis is similar to the one described in CTF3-Note-094 [2], but requires some additional work on reworking the algorithm to extract the arrival time, or, equivalently the phase, from the data. This analysis will be useful to set the phases in the drive beam linac. Any energy variation along the pulse will be translated into an arrival time (or phase) variation along the pulse due to the various contributions to the R_{56} along the beam line. Measuring the phase will provide an observable to tune on.

  Furthermore, the phase measurement will be useful for trimming the beam optics in the TL2 line and the recirculator, especially adjusting the kickers and determining the constancy of the kicker field along the flat top. Any variations will result in different kick angles given to different parts of the beam which will affect the arrival time through the R_{52} which is equal to the R_{16} – the dispersion – between the kick and the observation point. In turn, this might provide a method to tune the dispersion, but the accuracy to which this is possible needs to be worked out.

6 Higher Order Modes

- higher order modes (pick-up in damping slots)

  Can be measured indirectly with the PETS antenna signals and on the accelerating structures with build-in wakefield monitors.

  - check for RF power dependent coupling into wakefield signal

  While the RF amplitude and probe beam are set to nominal values yielding maximum acceleration we should transversely move the beam in the structures using the steering knobs and simultaneously observe the signals on the PETS antennas and the HOM monitors in the acceleration structures.

  If a clear correlation between HOM power and position is visible the HOM monitors can be used to center the beam. We can suspect that only the HOM power is detectable and therefore there will be no information encoded in the signal whether the beam is too far on one side or the other (a reference phase signal would be required). If we assume that the HOM power in transverse modes is proportional to the electic field of the mode which in turn is linear in the position, we could expect to observe a parabola when plotting the power as a function of the position. From a fit, the minimum of the parabola can be easily determined. This would then correspond to the center of the structure.

- beam kicks
  - beam kicks due to dipole modes, as function of incoming beam offset.
  - beam kicks due to misalignment between structure and beam

  Note: need to understand alignment between structure and beam.

  If the beam is not centered in the structure it will generate transverse wakefields that will affect sections of the bunch train that arrive later. A beam kick would therefore depend on the transverse position of the beam in the structures. Basically the earlier parts of a bunch train will kick a later part, just as a kick due to a breakdown will affect earlier and later parts of the bunch train – before and after the breakdown – of the bunch train, differently. In the case of transverse wakefields one could expect an exponentially growing kick along the bunch train. Such a measurement within one bunch train is in a way self-calibrating in the sense that no absolute positions from the BPMs are used, but only the changes of the BPM positions along the bunch train.

  Doing an absolute measurement at different transverse positions in the structure is very difficult, because the absolute position change due to the wakefield kick would be indistinguishable from a non closure of the bump and changing the bumnp might lead to different closures. This would be impossible to disntangle. By focussing on the relative variations along the bunch, the absolute changes due to non-closure of the bump are cancelled out.

- beam based alignment

  The probe beam is used as a diagnostics tool for the alignment of a single accelerating structure or a complete girder of a test module. This requires a progressive step wise approache in which first the wakefield monitor of a single structure has to be understood, then used as a tool to align a single structure. Only then it can be investigated as a tool for beam based alignment of a complete girder of accelerating structures in the test module.

7 RF Breakdown

These studies are intended to understand the effect of RF breakdown on the traversing beams. Some of the RF breakdown studies might be easier at a klystron except for transverse kick effects and possible correlation effects between PETS and accelerating structure.

- RF power production
  - recirculation parameters [2, 3]
  - beam dynamics effects of recirculation

  - transverse effects, check wakefield on antennas
  - power output and beam deceleration as function of beam current
    Note: damped PETS always produced less power than expected
  - power output and beam deceleration in response to the bucket filling order in the beam train (i.e. 1.5 GHz × 0, 2, 4 or 8 recombination)
  - PETS on/off mechanism by internal recirculation (active reflector)

- RF breakdown in the PETS
  - rate
  - beam kick effects, see above
  - correlation between PETS and accelerating structure
    Note: requires correct pulse-to-pulse correlation

- RF breakdown in the accelerating structure
  - dark current and ion current profile
    * magnitude (upstream BPM at opposite polarity)
    * time structure (chicane with Faraday cup or flashbox)
    * does it vary from shot to shot?
    * is there a precursor of breakdown? (compare with pulses before/after RF breakdown)
  - rate
  - dependency on pulse length, instantaneous power
  - early indicators of breakdown
  - where in the pulse train does it happen?
  - location inside the structure

- beam dynamics

  If there is a discharge in the drive beam, there is obviously no power flowing to the probe beam and part of th probe beam will not be accelerated, leading to a mismatch of the beam energy to the quadrupole lattice in the probe beam, that may lead to an increased emittance due to filamentation of the beta mismatch. A second effect could be that an RF pulse with the wrong phase will be injected into the accelerating structure, potentially leading even to a deceleration of the probe beam. Experimentally observing this is very difficult, but we might see a variation of the energy along the pulse that will be visible as a position variation along the bunch train on the dispersive BPM CAS.BPM0820.

- beam kick, transverse

  The study and understanding of the beam kicks is extremely important for prediction of the CLIC drive and main beam behaviour. Transverse kick of the beam can be measured by the combination of all five BPMs in the TBTS [4].

  - due to RF breakdown

    The RF breakdown will change the electric field amplitude and direction thus possibly causing a transversal acceleration or beam kick.

  - correlation with breakdown current (electrons and ions)

    A Flashbox is being developed for inline electron and ion current measurements (with the probe beam on). The intention is to bend electrons and ions in the horizontal plane to individual detector plates by an electro-magnetic field to determine both current and energy distribution.

- breakdown rate variation with beam loading

  When the structure is loaded (beam passing through) the RF gradient decreases compared to the unloaded case and the gradient in the first cell will be the highest. Thus full beam loading decreases the RF gradient in the structure and hence it shifts the working point on the break-down-rate versus gradient graph.

- multipactoring (travelling electron resonance)

  - need electron trajectory analysis and identify hot-spots for emission and hitting

8 Timing

For optimal acceleration of the probe beam it is necessary to achieve accurate timing of the probe beam arrival to the phase of the RF power produced in the PETS by the drive beam.

- coarse timing drive and probe beam

  As a first step, a coarse timing has to be achieved between drive and probe beam to ensure that they reach the experimental table simultaneously, at least on a nanosecond time scale. The pulse of the probe beam needs to be within the time window given by the drive beam pulse. This can be verified by timing the BPM and RF signals.

  - compare relative timing BPM and RF signals (use same ADC types?)
  - check for temperature effects

- fine timing and phase adjustment

  The probe beam pulse (and buckets) have to be shifted on the same time scale as the phase shift of the 12 GHz RF pulse, i.e. sub-ps timing adjustment. The effect of this shift can be monitored by observing the energy gain of the probe beam in the accelerating structure with the spectrometer line.

  The CALIFES probe beam laser system has a phase shifter based on a 1.5 GHz reference signal.

  - scan along PETS 12 GHz RF phase (sub-ps timing adjustment, 1o = 0.23 ps) by modifying the laser phase to adjust bunches to PETS phase

- monitor the energy gain in the probe beam to demonstrate acceleration (spectrometer position signal is proportional to the probe beam energy). We should be able to observe a sinusoidal position variation when scanning the phase. The amplitude of the position variation is proportional to the maximum energy gain in the acceleration structure.
- **Note:** acceleration by 15% requires adjustment of downstream optics
- **Note:** how to do with multiple structures? Need to modify relative phase change!

In this context the arrival time jitter of the probe-beam is also important. The relative phase/timing between probe and drive beam is addressed in the next section, but it is equally relevant to address the arrival time variation of the probe beam itself. This would require an absolute timing reference with sub-ps accuracy to compare to. A potential candidate is a streak camera signal that uses synchrotron light from the spectrometer dipole. In this case the streak camera needs to be triggered by some 'absolute' timing signal. The trigger for the drive beam gun might be a suitable candidate.

- jitter due to amplitude and phase fluctuations

If the intensity or the arrival phase of the drive beam fluctuates, the amplitude and phase of the RF pulse in the drive beam will affect the energy gain of the probe beam. The amplitude jitter could be investigated by timing drive- and probe-beam for maximum energy gain and observing the energy jitter, which would be dominantly due to amplitude variation in the power generated by the drive-beam. Note that this measurement of the amplitude jitter is rather insensitive to phase errors of both drive- and probe-beam, because the probe-beam is located at the crest (maximum) of the RF and there the dependence of the energy gain on phase is quadratic in the phase offset.

Adjusting the arrival phase of the probe beam to the zero crossing of the RF wave, where the acceleration gradient has its maximum dependence on the arrival time, leads to maximum effect on the arrival time Δt. The energy gain ΔE is then given by

$$\Delta E = 2\pi f \Delta t \hat{V} \tag{1}$$

where f is the frequency of the RF and $\hat{V}$ is the maximum energy gain. The position variation Δx on the downstream spectrometer line BPM (CAS.BPM0820) will be $\Delta x = D\Delta E/E$ where E is the beam energy and D is the dispersion at the BPM.

In the described way we could quantify the amplitude and phase jitter of the drive beam.

9 Full System Behaviour (Test Module)

This study is intended to understand the behaviour of a complete two-beam acceleration module (as opposed to the individual component studies) and validate the design and integration of all technical systems. For example, this study includes the inter-module correlation effects between PETS and accelerating structure. The two-beam module tests will allow for the validation of the technical systems in an integrated approach. some of the technical systems have to demonstrate feasibility as a single component. This is the case for stabilization. Another question to be answered is how the RF breakdown rate of the full system is linked to the RF breakdown rate of the individual components.

- full system RF breakdown rate and dependence on components RF breakdown rate

  In the test module, the interconnections and waveguides are different from the set-up with a single PETS to accelerating structure connection. Does this influence the RF behaviour and RF breakdown rates?

- how to detect breakdown

  In future CLIC modules there will be no instrumentation for breakdown detection. Some RF and vacuum measurements will however be available. The breakdown detection knowledge thus has to be expanded from the component and full module testing with extensive instrumentation to the CLIC module with limited instrumentation.

  The question remains of how to distinguish a breakdown in the PETS from one in the accelerating structures, but that is probably solvable in the TBTS testing because we will have ejected electrons and ions in the Flashbox if there is a breakdown in the accelerating structures and, moreover, there will be reflected power visible (on CA.PSR 0631). In the absence of reflected power there we can interpret the event as one having a breakdown in the PETS.

  If there is a substatial amount of reflected power from the accelerating structure, it might even travel all the way back to the PETS. It might be interesting if we can see an enhanced reflected power signal level on some of the directional couplers in the vicinity of the PETS structure.

- RF waveguides network

  RF losses and RF phase stability, especially with independent alignment of the two beam lines.

- CLIC oriented beam instrumentation

  CLIC prototype beam instrumentation can be tested in a realistic environment (space considerations etc).

- wakefield monitor

  Wakefield monitor performance in low and high power conditions, and after a breakdown.

- beam based alignment of complete CLIC module

  Accelerating structure alignment on its girder using the probe beam.

  The intended type 0 test module contains eight (8) accelerating structures with integrated wakefield monitors. Only four of the accelerating structures will be powered (due to the lower drive beam power of CTF3 compared to CLIC).

- alignment and stabilization

  In a dynamic accelerator environment. Note experiences of CTF2 where the alignment and stabilization electronics had to be switched of during the passage of a beam pulse due to induced noise. Alignment corrections could be implemented only after the passage of a beam pulse to be ready for the next pulse.

- module integration

  Interconnection of the different components and their behaviour under nominal and transient conditions. Two-beam acceleration in compact modules integrating all technical systems for RF production, beam measurement and acceleration including alignment, stabilisation and vacuum at their nominal parameters. Including module interconnection.

- engineering experience on a full two-beam module

  The thermo-mechanical behaviour of the two-beam module has to be understood in detail, thus allowing to improve and optimize the design as well as fabrication, assembly and installation procedures.

  Validation of assembly, transport, activation and maintenance procedures.

- vacuum system performance

  Both static and dynamic with beams and RF on.

- cooling systems

  Especially dynamic performance due to beam loss and power flow changes.

10 Discussion and Conclusions

Some studies, like the beam kick, are difficult or impossible when more than a single accelerating structure is installed. These studies must therefore be completed before progressing to the next TBTS phase with complete RF units (phase 2.2 and onwards). This implies that it might be advantageous to extend phase 2.1 by testing also a single accelerating structure with wakefield monitor and a HOM antenna in the damping slots, before progressing to two structures in phase 2.2. For the study of the RF power production with the PETS on/off mechanism the present PETS installation has to be modified. This should be done before progressing to phase 3.

To summarize, the different TBTS phases should focus their studies as follows:

Phase 2.1 (Summer 2010 – Summer 2011)

- Acceleration and deceleration.
- RF breakdown and beam kicks.
- Wakefields and higher order mode fields, their influence on possible beam kicks and their usefulness for beam based alignment.

- Timing of the two beams, to align the RF phase for optimal acceleration.
- Characterization of individual structures.

Phase 2.2 (Summer 2011 – Winter 2011)

- Wakefields and higher order mode fields, and their usefulness for beam based alignment.
- PETS on/off mechanism

Phase 3 (Spring 2012 – Winter 2012)

- Wakefields and higher order mode fields, and their usefulness for beam based alignment.
- Cross talk between drive and probe beam.
- Full system behaviour.

Phase 4 (Spring 2013 –)

- Integration of multiple modules.
- Full system behaviour.

A klystron based 12 GHz stand-alone test stand is being prepared, which intends to focus on accelerating structure studies: conditioning, accelerating gradient and RF breakdown. Some of the studies can be moved from the TBTS to the klystron. Alternatively the 12 GHz stand-alone test stand can be used to

- condition RF structures and waveguide parts before installation into the TBTS.
- power accelerating structures in the TBTS.

The timing of phase 0, 1 and 2 is such that the CTF3 12 GHz stand-alone klystron based test stand will become available for experiments only during phase 2 of the TBTS experimental program, i.e. during end 2010 to begin 2011.

Note that the switch from phase 2 towards phases 3 and 4 requires modification of the TBTS beam lines, girders and cabling in order to free the space required for the module installation. Single component testing will then no longer be possible. An alternative is to construct the instrumentation test beam line (ITB) for which space has been reserved next to the TBTS probe beam line. It could be used for accelerating structure studies with beam using RF power produced by the 12 GHz klystron of the stand-alone test stand.

References

[1] E. Adli, “Techniques for estimation of beam energy loss in the Two-beam Test Stand PETS, applied to the first 12 GHz PETS tests with beam”, CERN CTF3-Note-097 (2009).

[2] V. Ziemann, “Data Analysis for PETS Recirculation”, CERN CTF3-Note-094 (2009).

[3] E. Adli, "Analysis of the first 12 GHz PETS tests with beam using a constant parameter recirculation model", CERN CTF3-Note-096 (2009).

[4] M. Johnson, "Beam-based Diagnostics of RF-breakdown in the Two-beam Test Stand in CTF3", CERN OPEN-2007-022, CLIC Note 710 (2007).