

S7 Task Force Report on Main Linac RF

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This Task Force is concerned with Main Linac RF items, i.e. the RF power source (klystron), the pulsed high voltage source (modulator) for the klystron and the RF wave-guide distribution system. The RF power coupler will also be included. Low Level RF control is not included as this will be treated by another task force. As will be seen below, all of the Baseline Configuration Document (BCD) solutions adopted at the Snowmass ILC meeting in August 2005 for these different items correspond to those described in the TESLA Technical Design Report (Vol. II).

Note that this document does not present an “ideal” R&D plan. The initial resources being devoted to RF systems procurement in the U.S. and Japan are driven by the need to have high power RF systems available for the superconducting module test facilities at Fermilab (SMTF) and KEK (STF) respectively and for the test of couplers and passive wave-guide components. The effort in Europe, almost exclusively at DESY, is driven by the needs of the VUV FEL (FLASH) and the relatively short term need to have systems for the future European XFEL. Rather than give an ideal R&D plan, it gives an overview of the R&D which is in progress to consolidate the BCD choices or to offer cheaper, improved alternatives.

Introduction

As will be seen, all Main Linac RF developments are essentially performed in one laboratory of each of the three regions, namely SLAC for the Americas, KEK for Asia and DESY in Europe. The single component exception is the RF power coupler which is being developed in Europe through a LAL-Orsay / DESY collaboration and in the USA through a SLAC/LLNL/FNAL development.

1. Modulator

The Baseline Configuration Document (BCD) choice of modulator, to power the ILC klystrons, is the pulsed transformer type with an LC bouncer circuit for droop compensation. The characteristics of this modulator are as follows:

| | |
|-----------------|-------------------------------|
| Voltage | 120 kV |
| Current | 140 A |
| Pulse length | 1.57 ms (1% voltage flatness) |
| Repetition rate | 10 Hz |

Eleven of these modulators have been built, first by FNAL (three) and then by industry (eight), for the TESLA Test Facility (TTF) at DESY. All of these devices function in a reliable manner (ten years of experience to date) and meet the ILC specification. However, they are physically large, employ heavy oil-filled transformers and are switched at the low voltage / high current end which increase losses.

Three “alternative” designs were evoked at the Snowmass ILC meeting in 2005 by the SLAC group, and these are discussed below.

Alternative modulator developments.

The Americas (SLAC)

The most promising alternative choice is the Marx Generator. This consists of a series of capacitors which are charged in parallel and then switched in series to provide the voltage pulse. This avoids the need for a transformer and allows the switching to be done at low current (130 A). The modulator consists of a series of 12 kV ‘main’ cells with 900 V ‘vernier’ cells for regulation and voltage droop compensation. The modular design should imply high reliability, with extra cells being used to replace faulty ones, and should lend itself to mass production. The principal advantage of the Marx Generator is a potential cost saving of 50% w.r.t. the BCD modulator. A full scale proto-type is under construction. At the time of writing a single cell has been built and operated at full specification and shown to survive being switched into a short circuit. Initial testing of the full proto-type is in progress.

Another alternative is a ‘direct switch’ device being developed by Diversified Technologies Incorporated with funding from the DoE’s Small Business Innovative Research (SBIR) grants. This device will be delivered to SLAC in FY07 for evaluation (2000 hour operation test into a water load).

Finally, the so-called High Voltage Converter Modulator, developed at LANL for the SNS, after modification to allow for droop compensation is a third alternative. One production unit has been loaned to SLAC and installed on their L-band test stand (see below). It may eventually be used for providing HV pulses to test 10 MW klystrons at SLAC.

Europe (DESY)

The pulse transformer type modulator has been adopted by DESY for the European XFEL project. However, some R&D to improve this system is of relevance to the BCD. In a case where the modulator hall is far from the klystron gallery, low loss transmission of the HV pulse is an issue. DESY continue to develop a HV pulse (10 kV, 1.6 kA) cable for use over a distance of 1.5 km (note that this is not the ILC configuration). Improved conduits for these cables are needed and tests are planned on TTF. Electro-magnetic interference issues are also being studied. Improved electromagnetic compatibility cabinets for the modulator are also being studied. The design of the X-FEL version of the RF interlock is now complete and DESY will test this on TTF, on their MBK test stand, on the photo-injector test facility (PITZ) at Zeuthen and on the Module test facility which is being built for X-FEL.

In preparation for X-FEL procurement they have ordered proto-type modulators from two different suppliers (THALES and Imtech-Vonk). The Imtech-Vonk modulator will essentially be, the tried-and-tested bouncer type. The THALES modulator will eliminate the bouncer circuit and will feature the possibility to control the pulse-width and slew rate. It will use a series of 0.5 kV cells (c.f. the Marx generator) which are summed to drive the pulse transformer. Delivery is foreseen for the end of 2007. A new Modulator Test Facility will be installed at DESY-Zeuthen where integration tests of the modulator, HV cable, pulse transformer, klystron, interlocks and controls will be evaluated.

Aisa (KEK)

KEK essentially plans to procure “bouncer” type modulators, i.e. the BCD choice. These are needed for operation of the successive phases of their Superconducting Test Facility (STF) and for testing couplers and wave-guide components. They have already ordered one modulator in 2006 and plan to order a second in 2007. Although this modulator appears not to be very different from the DESY design it will allow Japanese industry to gain experience in this technology and so increase the potential number of suppliers for the ILC units.

2. Klystrons

The BCD choice is the 10 MW, multi-beam klystron (MBK) currently under development by Thales Electron Devices (TED), CPI and Toshiba. The MBK R&D effort is essentially within the industries concerned, but funded by the programmes of those national laboratories (DESY, SLAC, KEK) which have contracts with these suppliers. The MBK uses six (CPI, Toshiba) or seven (TED) beams to allow reduced perveance operation and thus they have a higher efficiency (65%) than more conventional, single-beam, tubes (~ 45%). The nominal specification of the tube is 10 MW, 1.6 ms, 5 Hz.

It is worth noting that such tubes are also planned for use with the European XFEL. About 35 units are needed. However the XFEL requirements, at least in the initial stage, will see the tubes operate well below their nominal peak power capability. For the moment, no plans are foreseen at DESY to perform “life-time” tests of these tubes at their nominal power rating.

MBK Status

Thales have fabricated five MBKs for DESY for use with the TESLA Test Facility (TTF) linac and the Photo-Injector Test facility at Zeuthen (PITZ). These “proto-types” have all shown problems with reliability. Arcing problems have been detected in the gun area and other arcs have been seen when the tube is run beyond 8 MW peak power. The relatively high cathode current density (5.5 A/cm^2) of this tube may be a weakness. The life-time is expected to be 40,000 hours. Toshiba have built one MBK for DESY which has met average and peak power specification. CPI has built an MBK which ran at 10 MW for short pulses. This tube runs with a cathode current density of 2.5 A/cm^2 and has an expected life-time of ~ 100,000 hours. During full pulse-length tests at DESY the tube suffered vacuum problems at 8.3 MW. The efficiency did not meet specification.

Note that all of these tubes are currently designed for vertical mounting. The ILC, however, will require horizontally mounted tubes. This will imply some mechanical re-design.

Alternative klystron developments.

The Americas (SLAC)

As an alternative to the MBK the SLAC Klystron Group is investigating Sheet-Beam Klystrons (SBK). In this approach, a ‘flat’ beam (40:1 aspect ratio) is used to reduce the effects of space-charge forces and thus increase the efficiency of the tube. They have some experience with a 91 GHz design and hope to use this experience to build two ILC L-band proto-types within the next two years. These tubes will be “plug-in” compatible with MBK designs. An advantage of the SBK is that the magnetic focusing is provided by permanent magnets thus reducing ILC power consumption by an estimated 4 MW. The SLAC group claims that these rectangular tubes will be composed of fewer parts, requiring fewer joining operations during fabrication, and thus will have an inherently higher manufacture yield and reduced cost with respect to the MBK. The absence of solenoid focusing will also mean that the tube will be five times lighter. The basic RF design of the SBK is complete and a first proto-type is expected for autumn 2007. At the present time 3-D gun simulations are in progress as are 3-D PIC simulations of the beam-RF interaction.

SLAC will also purchase and perform reliability tests of ‘second generation’ MBKs. These would be purchased from CPI and Toshiba (one of each) in FY07. In 2009 they hope to be able to purchase 3 klystrons from each of two suppliers.

Europe (DESY)

DESY is the laboratory which has the most experience with procurement and testing of MBKs. This development was initiated by DESY in the context of the TESLA project. These tubes will be used for the European XFEL and DESY are currently ordering klystrons from all three manufacturers. They are working with industry on a klystron/transformer-tank interface to allow horizontal mounting. They plan to receive the first horizontally mounted klystron in spring of 2008. They will perform basic tests of tube perveance stability and of phase and amplitude stability of their MBKs at the Zeuthen facility mentioned above.

Asia (KEK)

For FY07 KEK proposes to purchase an MBK from Toshiba in 2007. This klystron will be needed for use with STF-phase II. As SLAC will also purchase a Toshiba MBK the KEK and SLAC groups will collaborate together to evaluate the suitability of the Toshiba tube for the ILC. The KEK klystron will be of the vertical type.

As an “alternative” device KEK will work on a super-MBK (24 beams) design, from 2008, along with Russian collaborators. This design would allow a strong reduction in the modulator voltage and, consequently, in the cost of the charging supply.

3. RF Wave-guide Distribution

The BCD choice for the RF wave-guide (WG) distribution corresponds to the layout found in the TESLA Technical Design Report (Vol. II). This system includes a number of standard WG components;

WG bends (E and H plane),
directional couplers,
3-stub tuners,
3 port ferrite circulators,
high-power WG loads.

The wave-guide distribution system, as well as distributing power to the cavities, must protect the klystron against reflected power and allow the control of RF phase and external Q factor of the cavities. The BCD system uses a rectilinear distribution system with equal amounts of RF power being fed to each cavity through directional couplers. The circulators, along with the high power loads, protect the klystron from reflected power during the cavity filling time. The 3-stub tuners allow independent phase matching ($\pm 50^\circ$) of the cavities and adjustment of their external Q factors (impedance matching).

This system is by now a mature design which requires essentially no further R&D. As it is based on mainly commercial WG pieces it has been reliably costed for the TESLA TDR. The main drawbacks are that it uses a large number of expensive standard parts and that, in its present configuration, it has some redundancy in terms of the parameters to be controlled (phase, Q_{ext}).

Alternative wave-guide distribution developments

The Americas (SLAC)

The SLAC group suggests four modifications to the BCD choice:

- (i) Suppression of the circulators. These are a major cost item among the WG components ($\sim 1/3$ of total). Therefore the SLAC group proposes to use a tree-like system of power distribution, powering the cavities in pairs using 3-dB hybrid couplers. This would still isolate the cavities but would allow 1% of the reflected power to return to the klystron in the event of a cavity or coupler incident.
- (ii) A variable “tap-off” system to feed the cavity pairs – such as rotate-able polarised TE_{11} circular WG sections whose orientation would be adjusted once only after the cavity performance was measured.
- (iii) Replacement of the 3-stub tuners with phase-shifters, which, again would be adjusted once only after the RF system was installed.
- (iv) Considering the large number of WG flanges concerned a system for welding of the flanges to reduce cost and improve reliability.
- (v) Use WR770 wave-guide in place of the WR650 wave-guide for long wave-guide runs, thus reducing WG power losses.

The BCD choice has already gained much experience at DESY on the TTF linac. The SLAC group proposes to test and evaluate an eight-cavity feed system, incorporating these modifications, to be used on the first FNAL cryo-module. They hope to provide one such distribution system to FNAL each year from 2007 to 2009, inclusive.

Europe (DESY)

Studies are in progress at DESY on an alternative WG distribution system which would use what they call “shunted-tees”. In this scheme the 3-stub tuner is replaced by a phase-shifter. These would allow the string of cavities to be powered in pairs, with each pair having its own, optimised, specific gradient. The advantages of such a system is that it would be physically smaller, lighter, would use fewer flanges (faster assembly, better reliability) and fewer types of WG components. Despite this improved performance, the savings with respect to the BCD choice are estimated at only $\sim 10\%$. This alternative system has not yet been tested at high power but there are plans to do so using module ACC6 on the FLASH linac at DESY.

Asia (KEK)

4. The Power Coupler

Strictly speaking, the power coupler is not really part of the RF waveguide distribution system. However, to be consistent with the activities included in items 3.8 and 5.8 of the U.S. Work Breakdown Structure, it is included here. The “cold” part of the coupler is actually an integral part of the cavity as it plays the role of sealing the cavity vacuum, whereas the “warm” part of the coupler could be said to be the “last” component of the WG distribution.

The BCD choice of coupler for the ILC at Snowmass was the so-called TTF-III coupler which was designed at DESY for TESLA. More than 60 such couplers have been built by industry between two industrial companies (CPI and ACCEL). At the time of the Snowmass meeting they had already seen $\sim 40,000$ coupler-hours of operation on TTF. Although originally designed for 25 MV/m and 210 kW of peak power, this coupler has been tested with cavities

to 35 MV/m in a horizontal test cryostat and with 1 MW of travelling wave power into a matched load. Its performance clearly meets the specification of the ILC.

Two problems were identified for this coupler at the time of the release of the BCD; (i) the unit cost of the coupler was too high; (ii) the “conditioning” times of the coupler were too long (typically ~ 60 to 120 hours).

Alternative coupler developments.

The Americas (SLAC, LLNL, FNAL)

In order to investigate performance limitations in the coupler, SLAC are building a Coupler Component Test Stand in collaboration with LLNL. This test stand will allow sub-components of couplers to be tested individually between two wave-guide to co-axial transition pieces. This is in contrast to the tests at DESY, Orsay and KEK where a complete pair of couplers must be tested. On this bench one can determine the gas load from the “device under test” and evaluate which parts of the coupler are contributing to multipactor or long conditioning. They plan to build a class 10 clean room to gain experience in cleaning, baking and assembly of couplers. They will also do high power tests of a series of 12 TTF-III couplers procured by FNAL in FY07. First high power tests have already begun. In 2008-09 they hope to supply ~ 48 couplers to FNAL for use on SMTF and to study dimensional tolerances with a view to producing lower cost versions of TTF-III.

FNAL have commissioned an industrialisation study of large series coupler production with CPI.

Europe (DESY and LAL-Orsay)

DESY have adopted the TTF-III coupler for use with the European X-FEL. This machine will require ~ 1000 such couplers. For some years DESY and LAL have been collaborating on coupler development for TESLA and the X-FEL. In the context of this collaboration LAL have performed conditioning studies of the TTF-III couplers. These studies have resulted in alternative conditioning procedures which have shown, albeit for a small series of couplers, that conditioning times of < 20 hours can be achieved at room temperature on a test bench. The conditioned couplers, after being shipped to DESY were then mounted onto cavities at 2 K where they rapidly allowed the cavities to reach gradients of 35 MV/m. Another 60 TTF-III couplers have been purchased by DESY for the TTF VUV-FEL (FLASH), X-FEL and ILC test modules. At least 30 of these will be conditioned at Orsay before the end of 2008.

In addition to these conditioning studies, LAL have undertaken Industrialisation studies of TTF-III coupler production. That is to say, they have signed agreements with three industrial suppliers to investigate alternative production methods aimed at producing a large series (500 ~ 1000) couplers in a cost effective manor. The companies who obtained contracts are geographically spread over the three regions; CPI (Americas), ACCEL (Europe) and TOSHIBA (Asia). Although the results of these studies will not be known before the spring of 2008, there is every reason to believe that the unit price of the coupler will be greatly reduced.

In principle these conditioning studies and industrialisation studies should answer the basic criticisms of the TTF-III coupler as an ILC candidate. In addition to the TTF-III couplers, Orsay are developing alternative proto-types of two other couplers (so-called TTF-V and TW60 respectively). Funding from the European Union’s FP6 project, CARE, has allowed

phase-1 proto-types of each of these couplers to be built. However, the high power tests are progressing slowly and, as the Orsay test bench is increasingly used for conditioning X-FEL couplers, it is unlikely that either of these proto-types will be sufficiently developed early enough to be considered as an alternative to the TTF-III coupler.

Asia (KEK)

The KEK laboratory is developing, in parallel, two alternative coupler designs to the baseline choice. These couplers are designed to power the “low-loss” (LL) cavities foreseen for the KEK Superconducting Test facility (STF). The first is based on the window design used for the TRISTAN coupler and will be used with the KEK STF cavities. The second, so-called capacitive coupling window coupler is a novel modular design where the coupler is fabricated from four basic parts aimed at cost reduction. Preliminary results from both of these couplers were presented at the last TESLA Technology Collaboration meeting in September 2006 and both have demonstrated power handling capability beyond that which is needed for ILC. The KEK group are also developing a number of technologies for use in coupler production (brazing alloys, anti-multipactor coatings, flanges).