KLYSTRON CLUSTER SCHEME FOR ILC HIGH POWER RF DISTRIBUTION*

Christopher Nantista and Chris Adolphsen, SLAC, Menlo Park, CA 94025, U.S.A.

Abstract

We present a concept for powering the main linacs of the International Linear Collider (ILC) by delivering high power RF from the surface via overmoded, low-loss waveguides at widely spaced intervals. The baseline design employs a two-tunnel layout, with klystrons and modulators evenly distributed along a service tunnel running parallel to the accelerator tunnel. This new idea eliminates the need for the service tunnel. It also brings most of the warm heat load to the surface, dramatically reducing the tunnel water cooling and HVAC requirements. In the envisioned configuration, groups of 70 klystrons and modulators are clustered in surface buildings every 2.5 km. Their outputs are combined into two half-meter diameter circular TE_{01} mode evacuated waveguides. These are directed via special bends through a deep shaft and along the tunnel, one upstream and one downstream. Each feeds approximately 1.25 km of linac with power tapped off in 10 MW portions at 38 m intervals. The power is extracted through a novel coaxial tap-off (CTO), after which the local distribution is as it would be from a klystron. The tap-off design is also employed in reverse for the initial combining.

INTRODUCTION

The baseline design for the International Linear Collider outlined in the Reference Design Report [1] envisions two parallel tunnels for each main linac, an accelerator tunnel housing the beamline itself and a service tunnel containing the RF sources – power supplies, modulators, and klystrons – that power it through waveguide penetrations. A primary goal of the current Technical Design Phase is to identify and evaluate cost-saving options. To this end, a scheme is proposed in which the power sources are moved to the surface and the service tunnels are eliminated.

There are three ways to plumb the required power down to an underground linac – as AC, as DC, and as RF (for distribution there's also a beam, à la CLIC). The baseline design takes the first approach. The European XFEL project [2] opts for the second, locating modulators in a building on the surface and sending the high voltage pulses down coax cables to klystrons located in the accelerator tunnel. We describe here an implementation of the third method, illustrated in Fig. 1, in which klystrons as well as modulators are clustered in surface buildings.

RF power from groups of thirty five 10 MW klystrons is combined into a single low-loss overmoded waveguide and transported down to the tunnel and along the linac. This is sufficient, allowing for a few percent extra transmission losses to power approximately 1.25 km of ILC linac. At 38 m intervals, partial power is siphoned from this main waveguide in 10 MW decrements through coaxial tap-offs (CTO's) of appropriately increasing coupling. From each tap-off, the RF is distributed to the cavities (26 in three cryomodules) through a WR650 waveguide system, just as it would be from a local klystron.

This approach of sending power down as RF follows the example of the SLAC linac, which served the only previous linear collider, the SLC. The differences arise from having to accommodate a deep tunnel, which makes shafts expensive, and the need to minimize surface impact over what will be a much larger footprint. Thus the idea of clustering is adopted. To further minimize the number of surface buildings and shafts introduced by this scheme, two such klystron clusters can be installed in the same building and share a shaft, with one feeding upstream and the other downstream, covering 2.5 km of linac.

With the RF generating equipment moved to the surface, remaining systems from the service tunnel, such as beam instrumentation and feedback electronics, can be moved into the accelerator tunnel, along with this new main artery waveguide. In addition to the savings in civil construction cost associated with moving to a single tunnel, this scheme brings the heat load associated with RF production to the surface, greatly facilitating cooling.

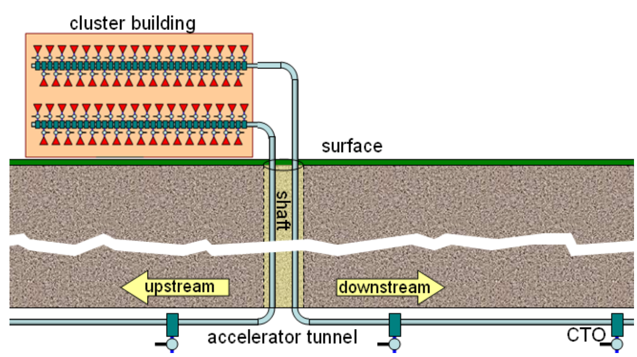

Figure 1: Klystron cluster configuration – RF produced on surface in buildings spaced 2.5 km apart and distributed to 3-cryomodule RF units via overmoded main waveguides.

WAVEGUIDE

For low transmission loss and robustness against RF breakdown, overmoded waveguide must be used for the main high power RF conduit. The obvious mode choice for this is circular TE_{01}, whose attenuation constant drops faster with radius than most others and which has no electric fields terminating on the wall. Aiming for a transmission efficiency of ~90% over a kilometer, we find a good diameter choice would be 0.480 m, midway between the TE_{51} and TE_{22} cutoffs and 6.8% below that of

*Work supported by the U.S. Department of Energy under contract DE-AC02-76SF00515.

TE_{02}, by which point TE_{01} has become the lowest loss mode. With a 100 m depth and 1.25 km run, the average added ohmic transmission loss to 33 RF units, not considering the combining circuit tap-offs and bends, would be about 6–8%, depending on whether the waveguides are copper-plated stainless or aluminum.

With such high power levels, the main transmission waveguide would likely be evacuated and thus need sufficient wall thickness, about 1 cm. Rubber o-ring seals should suffice for the flange joints. There are twelve propagating modes at the chosen diameter (21 counting cross-polarizations), so preserving the mode integrity places fairly tight tolerances on the pipe. A preliminary consideration of losses due to discreet discontinuities at joints only suggests radius, roundness, and alignment tolerances on the order of a millimeter and a straightness tolerance of half a degree. In general, long range variations are more benign, as long as they are not resonant with the beat wavelength of different mode couplings, which range from 0.37–5.24 m. Fabrication possibilities are being explored.

Each main waveguide, or "big pipe", will need to undergo two 90° bends, downward into the shaft and horizontal along the tunnel. These both occur at maximum power, between the last tap-in and the first tap-off, so the design will be a challenge. They must have excellent mode preservation and high power handling (low surface fields) without being excessively bulky. One possibility is to use corrugated waveguide with a profiled curvature, as was done by General Atomics for the BPC experiment at SLAC [3].

COAXIAL TAP-OFFS

With power levels up to 350 MW, it would be best to avoid converting the main power to non-azimuthally-symmetric and creating surface electric fields. An approach ideally suited for this situation is the coaxial tap-off [4], originally conceived for X-band application.

The basic idea of this device involves stepping up the diameter of a TE_{01} mode circular waveguide from below to above the TE_{02} cutoff, creating a mixture of the two modes. The distribution with radius of electric field will vary as these modes beat due to their different guide wavelengths. A wall at the original radius is reintroduced at an appropriate distance separating the inner volume from a coaxial outer volume and dividing the power between the two in circular and coaxial TE_{01} modes. To then extract the stripped power, the coaxial guide is shorted and a coaxial wraparound mode converter is used. Like a standard circular TE_{01} mode wraparound [5], this feature couples power from the coaxial region, via several short radial waveguides or apertures, through the broad wall of a rectangular waveguide wrapped around it. From the standing wave resonant in the latter, power exits through one or more radial waveguides in its outer wall.

The coupling of the tap-off is a function of the gap between the diameter step and the start of the inner wall. Nearly full range is achievable if the diameter step ratio is the ratio the TE_{01} and TE_{02} cutoffs; the inner wall is then at the TE_{02} field null. A small mismatch from this coaxial extraction section is matched by a ridge in the input waveguide. The gap length and ridge are the only features that will vary in the many designs needed for coupling ratios ranging from -15.4 dB to -3.0 dB. Fig. 2 shows the coupling in percent as a function of the gap length and a matched example for a design which steps in diameter from 34.925 cm to 63.9445 cm (35.56–65.10 cm for the former).

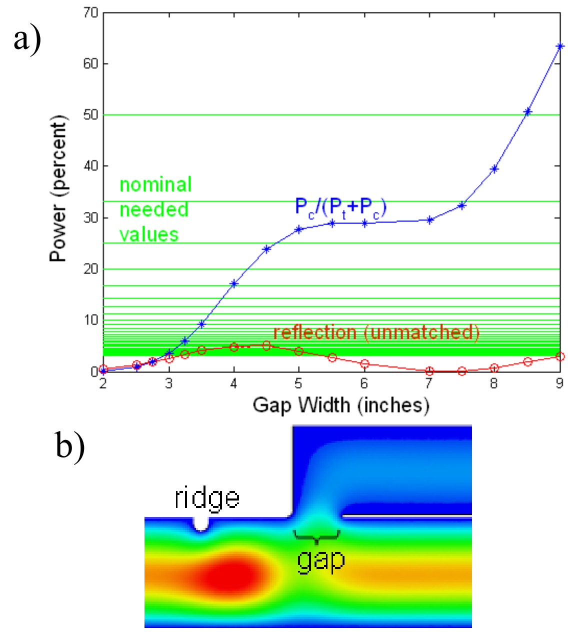

Figure 2: a) Coupling ratio as a function of gap length and the reflection amplitude to be matched by a ridge; b) Half cross-section with electric field plot for a 7.9375 cm gap, tapping off about 6.6% or 1/15 of the power.

The highest azimuthal propagating mode in the coaxial region is TE_{70}, so the wraparound needs eight slots to avoid parasitic mode coupling. To optimize coupling to the coaxial TE_{10} mode, the wrap guide width was expanded to 20.1422 cm. To keep power at the 5 MW level in the output waveguides and their RF windows and since power needs to be divided anyway, the wraparound was given two outputs, just like the klystron. By adjusting the slot widths, match of -38 dB was achieved.

Fig. 3 shows the two sections integrated in a complete CTO RF design with a field plot. Also shown are the scattering matrix amplitudes. A short double step taper will match each 34.925 cm port to the 48 cm transmission waveguide, and a similar taper or an asymmetric mitered bend will convert each output to WR650.

The CTO can also be used for combining power in the klystron cluster building simply by reversing its orientation. In this case, the match and efficient combining in the forward direction depends on having power already flowing in the waveguide with the correct relative amplitude and feeding in with the proper phase. For the first tap-in and last tap-off, or launcher and extractor, a standard wraparound design can be developed.

Alternatively, one can use a CTO as follows. The scattering matrix for a 3-port tap-off with coupling C is:

$$\mathbf{S} = \begin{pmatrix} 0 & \sqrt{C} & \sqrt{1-C} \\ \sqrt{C} & (1-C) & -\sqrt{C(1-C)} \\ \sqrt{1-C} & -\sqrt{C(1-C)} & C \end{pmatrix}$$

Turning it around and shorting port 1 at distance l turns it into a 2-port with (2→1', 3→2')

$$\mathbf{S}' = \begin{pmatrix} 1-C\left(1+e^{-i2\beta l}\right) & -\sqrt{C(1-C)}\left(1+e^{-i2\beta l}\right) \\ -\sqrt{C(1-C)}\left(1+e^{-i2\beta l}\right) & C\left(1+e^{-i2\beta l}\right)-e^{-i2\beta l} \end{pmatrix}$$

If C = ½ (-3 dB) and l=0 or π/β, the result is a matched mode transducer.

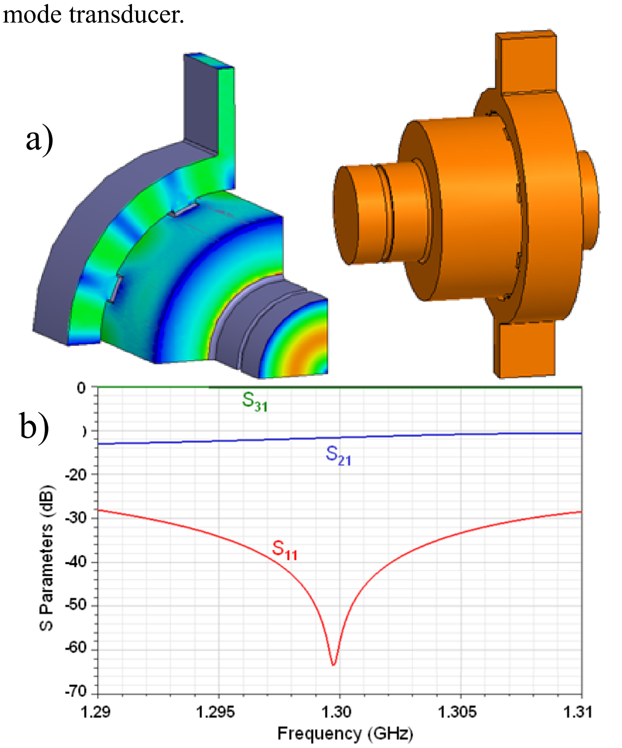

Figure 3: a) Quarter geometry of a CTO design with field patterns (magnetic on outer cylinder) and full model; b) Simulation S matrix plots showing an excellent match and a -11.63 dB coupling.

IMPACT

Adopting the klystron cluster layout would affect the ILC in various ways. The effect of a klystron failure would be greatly spread out, rather than producing a localized effect in the energy profile, which may be easier for the lattice to accommodate. An RF unit's worth of cavities would not have to be detuned due to lack of power. On the other hand, due to combining circuit, the available RF power will go as the square of the fraction of klystrons operating; loss of one out of 35 would result in 33 klystrons worth of power in the line, with another klystron's worth being misdirected into input isolator loads. (Similar degradation occurs in the baseline if cavities are not detuned, due to beam loading.)

The low level RF control would have less granularity. The vector sum manipulation by which the acceleration profile across the bunch train must be kept flat must deal with ~858 signals, rather than 26. The time response of feedback is also limited by the delays introduced, only 0.98 μs for the downstream line, but 9.32 μs (0.8% of fill time) for the upstream line. The gradient variation caused by the latter may cancel out; otherwise the cavity fill times can be adjusted to the RF arrival time by manipulating the Q_L's. Overall, however, timing is lost as an adjustable parameter for optimizing each RF unit. More study is needed of the ramifications of this scheme. Since the beam pulse current is known before it enters the linac and since FLASH results suggest small and uncorrelated local cavity errors, the coarser time and location control may well be acceptable.

Another concern is the energy available for an RF breakdown. The maximum of the product of power flow at a given location, linearly decreasing along the waveguide, and the shutoff time delay for a reflection trip from that location is about 4.1 μs × P_0, or up to 1.4 kJ. R&D plans call for storing perhaps 1/5 of this energy, at the design power level, in a resonant ring. Hopefully our mode choice will simply prevent breakdown. The bends may be a bottleneck, but at least they're close to the sources, where power can be quickly cut. It will also be a challenge to effectively combine power from so many sources and achieve the desired distribution; there will be some loss in efficiency and loss of local power control.

BENEFITS

Despite some technical concerns and added risk that require further attention, the klystron cluster concept has much to offer. The elimination of the linac service tunnels would represent a major cost reduction. The tunnel (non-cryogenic) cooling requirements are greatly reduced, as is the AC power distribution. RF power amplitude can be controlled by manipulating a common phasing difference between one half of the klystrons and the other half, which is easier than running slightly below saturation. Maintenance will also be facilitated by moving equipment to the surface. With a potential for ILC savings on the order of 5%, R&D on this concept is worth pursuing.

REFERENCES

[1] ILC Reference Design Report (http://www.linearcollider.org/cms/?pid=1000437).

[2] The Technical Design Report of the European XFEL (http://xfel.desy.de/tdr/tdr/).

[3] T.L. Lavine, *et al.*, "Binary RF Pulse Compression Experiment at SLAC," EPAC '90, Nice, France, June 12-15, 1990; SLAC-PUB-5277.

[4] Christopher D. Nantista, "Overmoded Waveguide Components for High-Power RF," proceedings of the 6th Workshop on High Energy Density and High Power RF, Berkeley Springs, WV, June 22-26, 2003; SLAC-PUB-10218.

[5] Sami G. Tantawi, *et al.*, "The Generation of 400-MW RF Pulses at X-Band Using Resonant Delay Lines," IEEE Trans. MT&T vol. 47, No. 12, December 1999; SLAC-PUB-8074.