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Comparison of Discrete Klystron Produced RF to Two-Beam Produced RF for Large Accelerator Systems

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Abstract. We compare here some technical aspects, and with it the cost, of constructing a 500 GeV center of mass Linear Collider with either Discrete Klystron or with Two-Beam (relativistic Klystron) technology using X-band for the main linac. A comparison concept is applied to CLIC and NLC technologies, but not to a particular CLIC or NLC design. The methodology created can be extended to higher c.m.s. energies, if the reader so desires.

I INTRODUCTION

One of the critical issues for the success of future electron linear colliders is the efficient and reliable generation of the RF power needed for high-gradient acceleration. Different schemes have been proposed to do that, mainly the use of discrete Klystrons, as already used for SLAC and the SLC, and Two-Beam (relativistic Klystron) technologies as in the CLIC proposal.

This talk is somewhat of a hybrid, because the organizers asked me to talk about the "CLIC concept and its technical details" and "thoughts (or my study) on the advantages and disadvantages of Two-Beam acceleration vs. discrete sources". Up to now research into Two-Beam production (relativistic Klystron) of RF has been mainly geared toward the use of high frequency RF. Research into discrete Klystron technology has been mainly directed toward lower RF frequencies. Since it is the total system difficulties and cost which determine the overall cost of a large accelerator, it is possible to directly compare global ramifications of discrete Klystron (as in NLC X-band at 11.4 GHz) vs. Two-Beam (as in CLIC at 30 GHz) schemes.

The combinations of various possibilities are too numerous to examine all here, so a choice has to be made for meaningful comparison. What do we compare, how do we compare? Are there any rules or models to compare seemingly incomparable

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technical components? And which arbitrary choices do we have to make to be able to compare?

The emphasis here is on technical comparisons, but costs obviously enter the picture. To put things in perspective, Figure 1 shows the reality of costing in R&D. The probability to find that things are easier than anticipated is smaller than the opposite. What is commonly called the contingency can be huge. The lesson to be learned from this figure is that to put a contingency of 25% and more on such estimates is well justified.

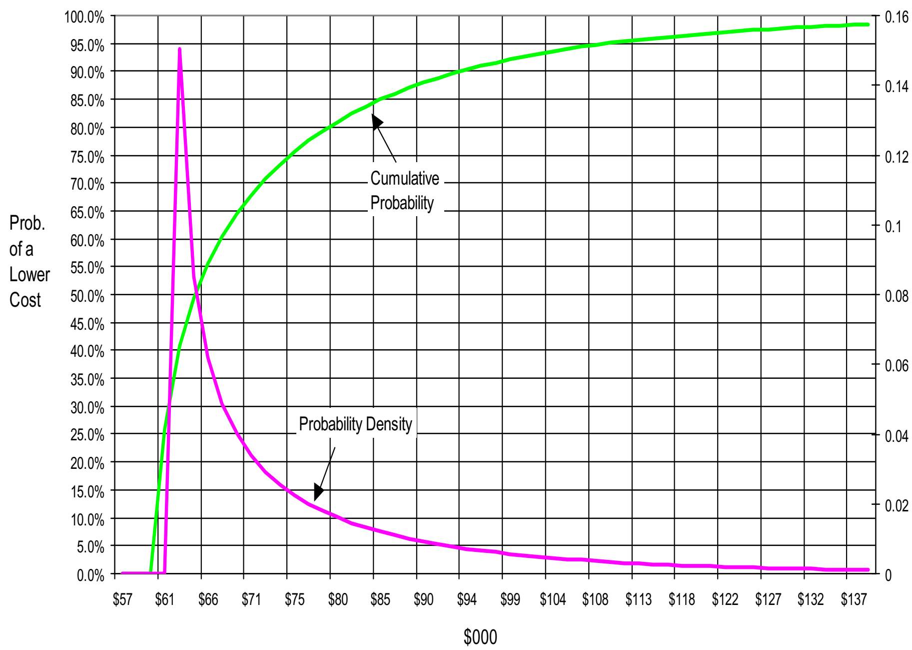

FIGURE 1. An example of a cost contingency for R&D and Hi-Tech items (Figure from of J. Cornuelle, SLAC). The highest probability, what one could naively call the price or the cost, of an item is determined to be $63500. There is a small probability it could be cheaper (easier to produce) and a large probability, with long tails, that it will cost more.

The discrete Klystron reference technology is relatively easy to define: it used to be SLAC S-band, but with 10 years of development at SLAC of X-band Klystrons and acceleration structures [1], and the NLCTA in operation [2], X-band is now the dominant technology, just as the SLAC S-band was before.

The Two-Beam reference technology is more difficult to define. There are many combinations of (low energy, high current) Drive Beam and (high energy, low current) Main Beam RF-wavelengths possible, because the drive beam, when created, can produce in deceleration units any RF frequency desired.

As driver frequencies L-band (937, 952 or 1428 MHz), UHF-band (476 MHz) and induction linacs have been investigated [1]. In the NLC ZDR [1] the Livermore

[1] These frequencies are not always integer multiples of a common frequency because of the slight difference between European and US S-band standard frequency. Also, many of the considerations were never formally published - they are only available in seminar or colloquia notes, and personal

Induction Linac technology was identified as a probable and possible energy upgrade path [3], but see also Ref. [4] for more recent information.

Proposals have been made for the main linac to use X-band (11.4), 2X-band (22.8) and Ka-band (30 GHz). More recently, because of the uncertainty of the validity of the "higher gradients at higher frequency" argument, thinking has again been focused on X-band. Nevertheless, in recent years CLIC made a giant conceptual leap forward, so that now its concept of RF production with a fully-loaded low-frequency linac at room temperature [5], even if not the precise implemention, is also regarded as a valid contender for production of a drive beam.

The inherent flexibility is one of the great conceptual strengths of the Two-Beam approach. This flexibility extends beyond the choice of frequency for the high energy main linac (=30 GHz in the case of CLIC). Once the drive beam exists, it can be used to power RF equipment which otherwise could not be powered. This includes provisions for beam loading compensation (RF ramps) [6], harmonic acceleration (higher mode cavities) [7], RF Quadrupoles for the Final Focus [8], or RF Quadrupoles to do BNS damping while avoiding the introduction of a large energy spread into the beam [9], and other possible applications and refinements.

So as requested, this paper will first describe the CLIC technology but then will focus on an adaptation of the CLIC approach for RF production to an X-band-based main accelerator.

This CLIC scheme, developed over many years at CERN, has indeed some intriguing possibilities as mentioned above. However, its main tenets, namely effective production of a high-current drive beam, deceleration without beam break-up, and the reliable existence of ≈150 MeV/m gradients at 30 GHz, have still to be proven and will not be known until at least until 2005 when the 3rd Clic Test Facility (CTF3) will be fully implemented [10]. But through the continuous test of concepts and material in its Test Facilities (CTF1 and CTF2) it has progressed to a point where it is seriously considered by CERN as a successor to post-LHC time [11].

We want to re-emphasize the main weakness encountered in past comparisons of large accelerator systems: often the focus is on one detail, say RF production, while the overall costs are really dominated by system costs. But the system costs are identical for most parts of a Collider, no matter what the source of the RF, so the relative total cost differences are bound to be not very large.

II PROBLEMS OF PULSED LINEAR ACCELERATORS

A Problem #1: The Gradient

As soon as linear accelerators had been invented, the quest began for higher gradients to get to higher beam energies. It was clear in principle how to get there (apart from just making it longer): higher RF power and/or higher frequency. The SLAC Blue Book ([12], Table 6-2) in the 60's has a very detailed comparison of the relative virtues of different frequency bands (L, S, and X were compared). The advantage of

communications.

going to X-band were clear even then: higher gradients at higher frequencies through higher permissible field strength. But in 1960 there were no power sources available in X-band which were strong enough. The peak power available then for S-band Klystrons was 25MW; 2.5MW was "assumed" to be "possible" at X-band. So the compromise choice for SLAC was S-band [12].

SLAC first increased the beam energy achieved through increasing the peak RF power through the SLED scheme [13]. For the higher frequency path it took SLAC a longer time of concentrated development effort to build an X-band Klystron with 50MW power. The people who designed NLC knew about the (supposed) advantages of even higher frequencies with respect to the achievable gradients. But again, there was no proven power source available.

B Problem #2: The Power Source.

The main thrust behind the CLIC effort [14] is to develop an appropriate power source to reach 30 GHz (Ka-band), and with it the promised higher gradients. The main topic of this paper is to develop a concept for comparison between Discrete Klystron and Two-Beam technology. Since the CLIC Power Source [5] basically is also based on Klystrons (L-band, which here creates the drive beam), the comparison must compare Klystrons in different frequency bands.

CLIC is now optimized for 3 TeV with 30 GHz technology, but the methods are regarded as useful at other frequency bands, for example X-band [15] which for NLC has been optimized to the 1 TeV range.

To summarize, similar to the S-band decision for SLAC in the 60's, X-band for NLC today is a compromise between theoretical expectations at higher frequency and the availability of power sources today. As mentioned above, the high gradients (150 MeV/m) held out at 30GHz may be possible to achieve, but have not been convincingly proven to be usable in long structures.

In the following comparison we choose X-band for the main Linac and compare X-band RF production with discrete Klystrons and Two-Beams. The generic machine we will call P(rototype)LC. It is designed for 500 GeV cms but with conventional facilities costed to allow an upgrade to 1.0 TeV. This upgrade does not assume higher gradients than assumed for the 500 GeV case. Doing so keeps the road open to get to 1.5 TeV in an upgrade, if higher gradients can be achieved at a later date. As nomenclature we use DKPLC (discrete Klystron) and TBPLC (Two-Beam).

Such a comparison is useful. Already the NLC ZDR has investigated the path to higher energy using Two-Beam technology. It is believed from today's point of view that Two-Beam technology is a possible route to follow for energy upgrades of X-band based accelerators, provided that higher gradients can be achieved and tolerated by the structures.

C A way out: Pulse Compression

Despite many differences in technical details, there are common concepts for all linear accelerators: energy storage and pulse compression. The average power is (relatively) low, otherwise the wall plug power could not be provided, but through energy storage and pulse compression one gets (nanoseconds) of high luminosity at high pulse power and high beam energy.

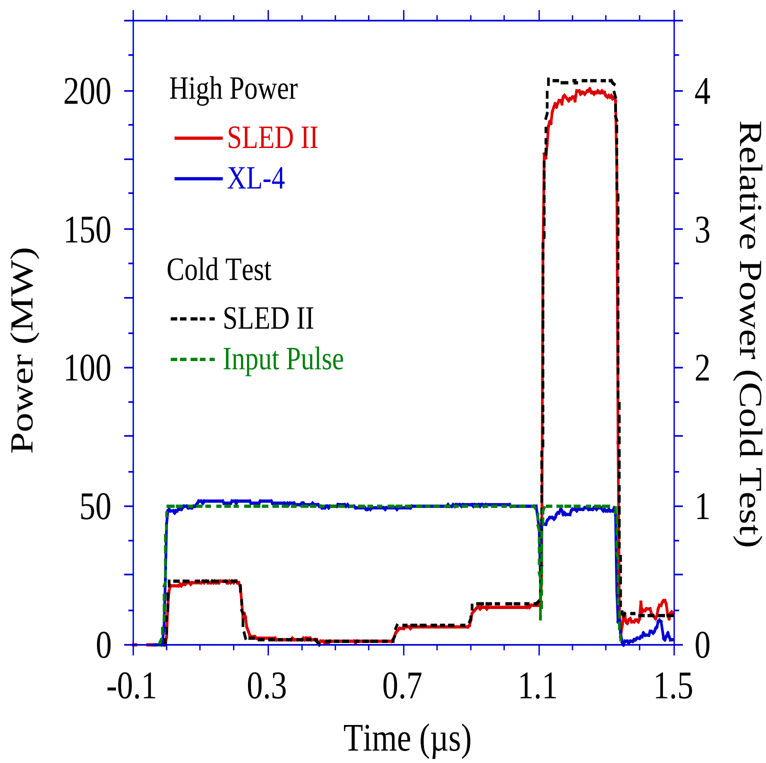

FIGURE 2. Results of pulse compression using the SLED II method for NLCTA, reference [17]. Note, how spectacularly square the pulse stays through the compression process. This is quite an improvement over previous SLED schemes.

Originally SLAC reached 20 GeV maximum beam energy [12] with 3 μsec long RF pulses. The original energy storage was done in capacitors in pulse forming networks (PFN's). Thyratrons were the switches which discharged the capacitors into Klystrons which powered the accelerator's disk loaded waveguide. This compression was done before the pulse reached the Klystron. At low power there is nothing in this scheme which could not be built in anyone's garage: it is the high power which matters.

To reach higher beam energy, shorter pulses with higher peak power are needed. These pulses can not be created efficiently in a direct way, because the rise and fall times of the Modulators become a useless large fraction of the beam. Also, the Klystron peak power would be too large. Consequently pulse compression after the Klystron is used: the front parts of a pulse are delayed and recombined with later parts. This results in a shorter pulse, but with higher peak power.

SLAC used this SLED (SLAC Energy Doubler) idea to store and compress RF pulses [13]. With 800 nsec RF pulses 50 GeV were reached for the SLC [16]. Whether power is stored in superconducting cavities (TESLA), in Delay Lines (NLCTA), or in RF cavities as in the old SLED (or the Japanese C-band), most schemes to store and compress pulses are variation of the original idea. Figure 2 shows a measurement of such compression for NLCTA [17].

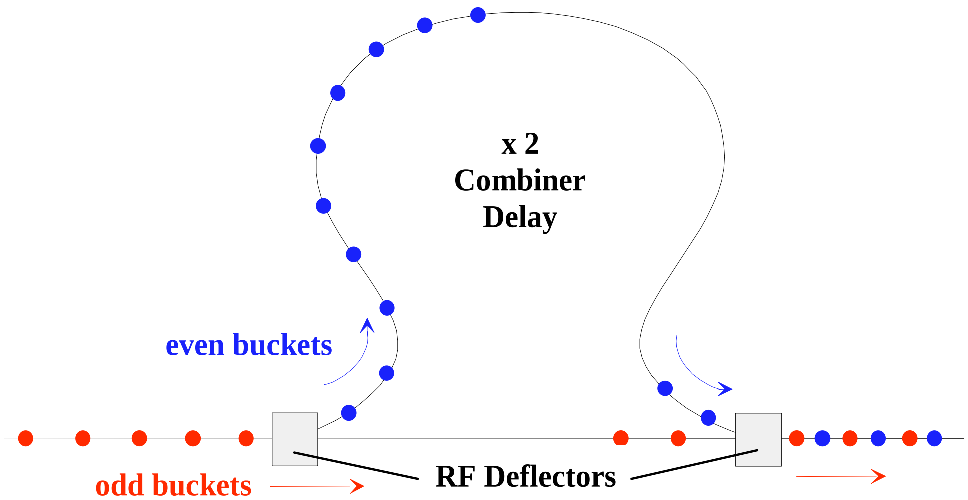

FIGURE 3. The delay loop is the first element in the chain of CLIC combiner rings. The delay loop works without a kicker, because the original 130 nsec bunch trains are alternatively put into odd and even buckets, so that a subharmonic RF deflector can be used. Although the delay loop only increases the current by a factor of 2, it is a very important element of the compression chain, by creating a gap long enough so that in later combiner rings a kicker can kick the accumulated and stacked bunch trains out.

III THE CLIC WAY

CLIC approaches the energy storage and pulse compression task differently, adapted in an innovative manner to the needs of a Two-Beam scheme of RF production. They started originally with a single superconducting RF produced drive beam, which needed to be re-accelerated many times [18]. This has been replaced by a multi-drive-beam scheme, all produced by the same room-temperature linac [14].

The most significant difference is the way CLIC proposes to do compression by frequency multiplication of electron bunches. Figure 3 shows the first element in the chain of 3 rings to get the high current needed for extraction of RF power out of the extraction units. These recent changes have increased the theoretical range of the system to c.m.s. energies of 3 to 5 TeV, based on an assumed high gradient (100 to 200 MeV/m) for acceleration at 30 GHz [5].

We will not describe here the whole scheme with all its details, but in a nutshell, the CLIC approach needs a current of about 250 A in the drive beam trains for each main accelerator. This high current is needed to extract a peak RF power of ≈400-500MW needed for acceleration at 30 GHz. Such a high current can not be created

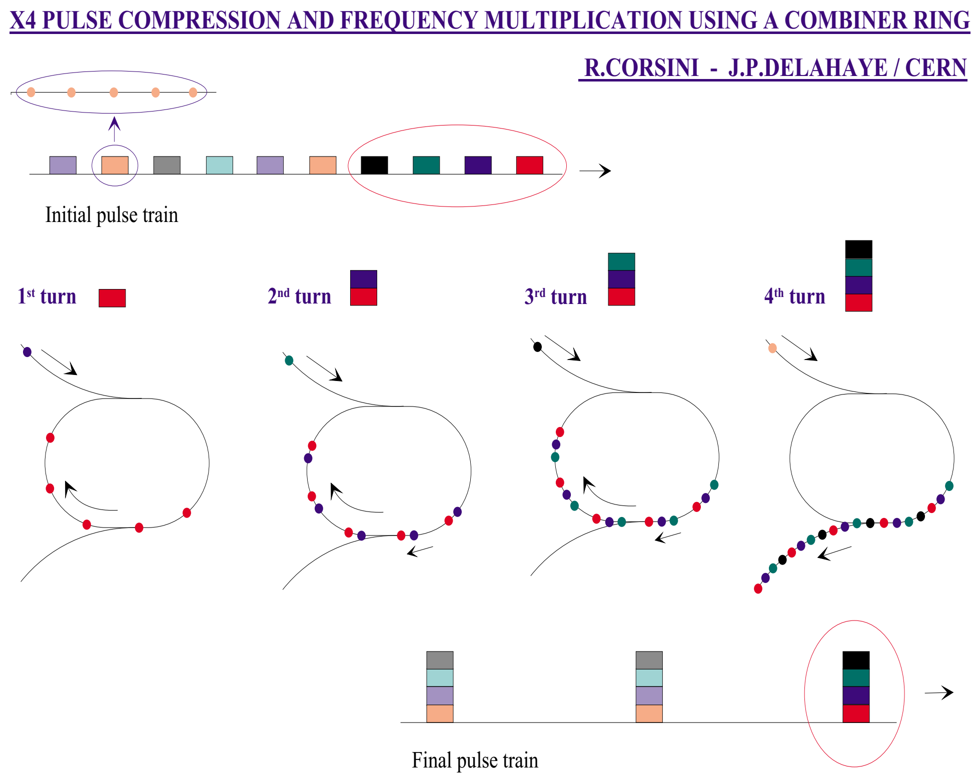

FIGURE 4. A combiner ring increases the density of bunches in a train by a factor of 4 by injecting 4 separate trains (already doubled after the delay loop) and then ejecting the combined new train in the time gap created by the delay loop. In the CLIC case this frequency multiplication by 4 is repeated a second time. For the X-band case, depending if one starts from either 952 or 1428 MHz, multiplication by either 12 or 8, respectively, would be appropriate. Or one could also choose 16 or 24; neither of these multiplication numbers is "magic", but there is a natural limit. This limit is reached when the distance between bunches becomes equal to the wavelength of the RF one wants to extract.

in an existing linac, so it is made by making 32 separate but contiguous 130 nsec long trains (which add up to 4.6 µsec total length) with an 937 MHz RF linac, filling every second bucket and combining them in a delay loop (Figure 3) and 2 combiner rings (Figure 4). The average current in each original train is planned to be 7.6 A.

For 3 TeV cms CLIC needs drive trains with a total duration of 92 µsec. For a lower c.m.s. energy, in the CLIC scheme, one uses simply a smaller number of 4.6 µsec trains. Although the total number of L-band Klystrons is not reduced, the pulse width of each one is. Consequently energy costs, and the Klystron and Modulator costs, will scale linearly with the cms energy, see Equation (1), below.

The bunches in these original 32 trains have a distance of 64 cm between each other. (In an X-band equivalent scheme starting from 1428 MHz (1/2 of S-band frequency) [15] they would start with 43 cm distance from each other.) These 32 trains in the CLIC case are stacked in a series of delay loops and combiner rings such that one drive train of 130 nsec length results, which has 32 times the original current.

In other words, the bunches have now a distance from each other of 2 cm, well

Parameter	Name	Initial	After Delay	After 1st Ring	After 2nd Ring	Unit
Pulse Length	τ_P	~ 92	~ 92	~ 92	~ 92	µs
Trains/Pulse	N_T	1	352	88	22	
Train Length	τ_T	92	0.130	0.130	0.130	µs
Bunch Separation	Δ_B	64	32	8	2	cm
Train Periodicity	Δ_T	-	0.26	1.04	4.16	µs
Pulse Current	I_P	7.6	15.2	61	244	A

FIGURE 5. Development of the bunch characteristics as they progress along the compression system for the 30GHz case, taken from reference [17]. The final compression is 32. For the X-band case at 952 MHz drive beam frequency, the frequency we will use below for costing, the final compression was chosen to go up to 24.

matched in time structure to the 30 GHz extraction units. Conceptually the reduction in bunch spacing, called frequency multiplication, is equivalent to pulse compression in as much as the bunch train intensity (current) is increased. In the X-band case, if starting from 952 or 1428 MHz L-band, the compression has to be optimized in a way that high enough final currents are achieved, in order to make the RF extraction from the deceleration units efficient. The development of bunch characteristics for the CLIC case is collected in the table in Figure 5 [19].

One of the advantages of bunch compression via frequency multiplication is the efficiency. Direct RF pulse compression always has some losses; frequency multiplication does not, at least in theory.

One requirement for successful frequency multiplication is that the rings are isochronous, i.e., that the bunches preserve their separation. As a first step toward showing the validity of frequency multiplication CLIC recently has shown [20] that isochronicity is preserved in the LEP electron-positron accumulator ring EPA with simple modification of the strength of the Quadrupoles, without any hardware modification. In 50 turns no lengthening of the bunches could be observed.

After creation in the combiner rings, the combined, high current (250A), 130 nsec drive beam trains are now being sent separately to the main linac in a counter flow pattern. With the correct timing they are bent around in 180^{Θ} achromats in the tunnel and sent through deceleration units immediately next to the main linac acceleration structures (Figure 6). The 30 GHz RF is extracted in the decelerators and is being used to accelerate the main beam. At the end of each sector, the energy depleted drive train (at about 100 MeV) is kicked into a local dump, and a new drive train takes over.

One of the interesting advantages of this system is that all high power installation can be centralized. There are no Klystrons to be supplied and cooled in a long tunnel.

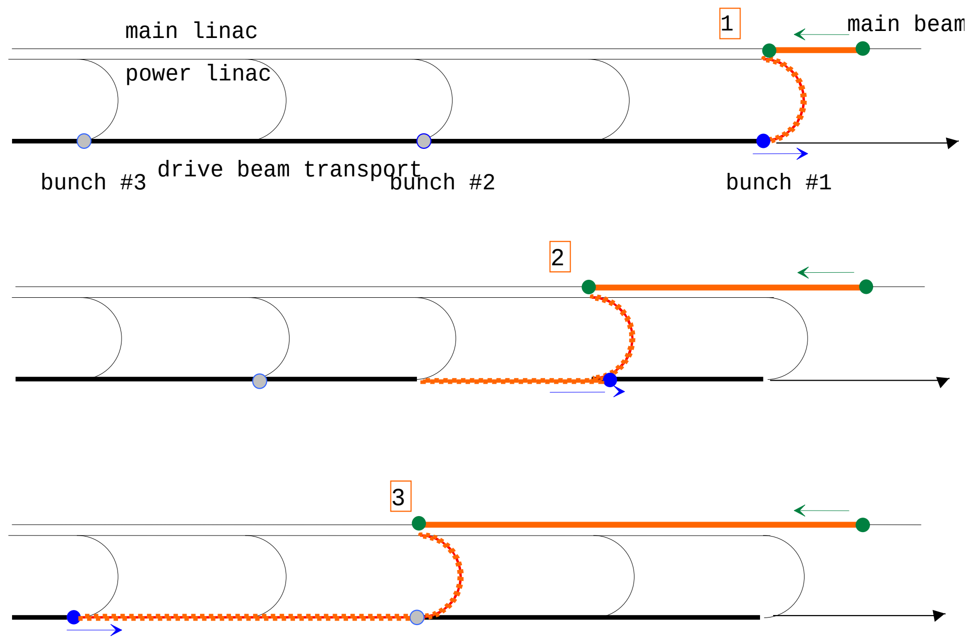

FIGURE 6. A snapshot of three 130 nsec drive trains as they move along the drive beam transport line (bottom line) at an energy of approx GeV. They are kicked into an 180^0 achromat which brings them around to the "power linac" (deceleration units), where the RF is extracted. The RF is fed to the main linac where it accelerates the main beam. At the end of each sector the energy depleted drive train (at about 100 MeV) is kicked into a local dump, and a new drive train takes over.

IV COMPARISON

A Identical Systems

Let us first identify the elements of any Collider which are the same and will cost the same. Then we will pick a model to compare the RF system for both the cases described above.

- The tunnels. [1]
- Other civil engineering, like electricity distribution, water and waste.
- The cooling and power systems.
- The injectors, positron production, and damping rings.
- The main beam line systems of the main linac and its alignment and control system.
- The beam delivery, collimation, and the final focus.

[1] The TBPLC tunnels are slightly longer because of the combiner rings. This expense has been proposed to be partly off-set in the TBPLC, by parasitically using the drive linac for Injector purposes [15]. On the other hand, this is not completely parasitically because then the drive linac needs to have a longer pulse then is otherwise would need. So we just leave it at the actual length.

B How to Compare the RF Producing System?

This leaves a comparison of the RF production. While here we only look at the initial cost, there is an important difference in the cost of a main beam energy upgrade, depending on how it is done.

- If the upgrade is done by extending the active length of the linac, starting from existing systems and keeping the gradient constant, the TBPLC needs just longer pulses in the (existing) L-band Modulators and Klystrons, but DKPLC needs more additional Modulators and Klystrons. This naturally raises the question, can the L-band Klystrons (and Modulators) be upgraded at a fraction of the new cost, or at great savings, or does one need completely new ones, at great cost?
- If the energy upgrade is done by raising the gradient in the X-band acceleration structure, the DKPLC needs to upgrade the (square of the) voltage by upgrading every modulator-klystron package. The TBPLC can upgrade by a combination of more current, more Klystron power on the existing structures, and/or additional Klystrons and accelerating structures. This can be tricky and the original optimization of the drive linac has to be done with great care to save as much as possible from the fully loaded condition in the upgrade.

Inverse learning curve @ 90%

avg. power/kW 39 100
freq/MHz 2856 952
data: $150k for the last one of many

Lot Size	cumulative	S-band (39kW) cost	S-band diff. cost	S-band avg cost	L-band (100 kW) cost	L-band diff. cost	L-band avg cost
256	512	150	38400	150	43	10940	43
128	256	167	21333	167	47	6078	47
64	128	185	11852	185	53	3377	53
32	64	206	6584	206	59	1876	59
16	32	229	3658	229	65	1042	65
8	16	254	2032	254	72	579	72
4	8	282	1129	282	80	322	81
2	4	314	627	314	89	179	90
1	2	348	348	348	99	99	99
1	1	387	387		110	110	
	total		86400			24600	
	average cost		169			48	

remember: power x frequency ^{2}
cost factor: 100/39/9 = 0.28

FIGURE 7. Normalized cost estimate (for a 100kW L-band average power) Klystron derived from the SLAC data of the actual design and purchasing experience of many 39kW S-band Klystrons. Equation (1) is used as a model.

The elements one has to compare are the Klystrons. They are used in a different way for RF production in the main linac (X-band) and in the drive linac (L-band)

Inverse learning curve @ 90%

avg. power/kW	1200		100	
freq/MHz	476		952	
data:	$270k for #2-8 from Bfactory *			

band		UHF (1200kW)			L-band (100kW)		
Lot Size	cumu-lative	cost	diff. cost	avg cost	cost	diff. cost	avg cost
256	512	143	36733	143	48	12244	48
128	256	159	20407	159	53	6802	53
64	128	177	11337	177	59	3779	59
32	64	197	6299	197	66	2100	66
16	32	219	3499	219	73	1166	73
8	16	243	1944	243	81	648	81
4	8	270	1080	270	90	360	90
2	4	300	600	300	100	200	100
1	2	333	333	333	111	111	111
1	1	370	370		123	123	
	total		82600			27500	
	average cost		161			54	

remember: power x frequency ^{2}

cost factor: 100/1200*4 = 0.33

* Note however: $470k for #10,11 from B-factory

FIGURE 8. Normalized cost estimate (for a 100kW average power L-band Klystron) derived from the actual design and purchasing experience of a modest number of 1200kW UHF Klystrons. The note on the bottom is a reminder that prices in the bidding process can easily be different up to a factor of two. This should put a damper on expecting too accurate a number from the fortuitous agreement between Figures 7 and 8. A range of two for bids in non-standard hi-tech or R&D items is also the experience of CERN. A consistency check between UHF and S-band Klystrons gives agreement within 16%.

Klystrons. In order to remove as much arbitrariness from the process as possible, we need a formalized model to estimate cost between different wavelength Klystrons.

A Klystron Figure of Merit (f.o.m. = cost, or difficulty) scaling law, widely used in the Klystron Industry, is:

$$\mathtt{cost} = \mathtt{averagepower\ x\ frequency}^2 \qquad (1)$$

We will use this model in the following.

Looking at Modulator costs it is found that they track closely the cost of the associated Klystrons. For this study we assume they are identical.

Some argument has been made of better energy efficiency of one design vs. another. We find that the total power needed for RF Production and cooling is nearly identical for the same center-of-mass energies. The efficiencies for wall plug to beam power are typically just below the 10% level. Consequently, much of the wall plug power related infrastructure needed is the same.

On the next level of scrutiny, we find that all finesse of using different L-band starting frequencies, different combiner ratios, and different pre-acceleration schemes, does not make much difference in parameters and cost.

One question which has to be re-addressed by both the TB-community and the DK-community is the number of Klystrons needed as stand-by (see Reference [21]). These "spare" Klystrons are needed when a Klystron fails, to ensure that the energy of the drive linacs (TBPLC) and the main linacs (DKPLC) can be kept constant to the 10^{-3} level as needed. For SLC this overhead was about 6%; LEP needed 10% and more [22]; the NLC ZDR [1] assumed 3%. [1].

This stand-by Klystron power needs to be mechanically connected to the accelerator sections all the time, to be available to go on-line in seconds. This creates problems with the present schemes of coupling together 2, 4, or even 8 Klystrons. This topic needs more research and thought, but we could take 6% as a usable number in the final cost summary for the DKPLC in analogy to the SLC experience. This number would double to 12% for the TBPLC because of the fully loaded condition of the drive linac and even 24% if 2 Klystrons are coupled together.

To compare appropriate items we will focus now on an X-band main linac and develop parametric differences between Two-Beam and Discrete Klystron RF production. Because of continuous progress this is a moving target. For NLC, e.g., the number of Klystrons needed has gone down by a large factor in recent years with the advent of more powerful Klystrons with a longer pulse length [23]. While a few years ago it was many thousands, it is now only in the many 100s.

We know that buying large quantities of anything reduces the unit price. But there is no experience with R&D in, and procurement of, a large number of L-band Klystrons. For estimating their cost we use the methodology of the DOE Cost Estimating Guide [24], "Effects of Doubling Production". Instead of the learning curve described in Ref. [24] we use a reverse learning curve.

The use of the reverse learning curve is appropriate here, because good data for large quantities, including past bids, exist from SLAC's 5045 S-band Klystron. In addition we can estimate the cost from below in frequency using the SLAC B-factory Klystron experience, although from a smaller number of units.

Figures 7 and 8 show the cost of L-band Klystrons derived from the classical SLAC S-band Klystron and from the B-factory UHF Klystron. For our further considerations we use the average, $51k for a L-band Klystron normalized to 100kW.

V SUMMARY

The cost have been estimated for a 500 GeV cms X-band Collider using Discrete Klystron and Two-Beam RF production technology. The summary from TB simulations using 952 MHz Klystrons for the drive beam is shown in Figure 9 [2].

The Klystron cost have been given above in US$, but in Figure 10 the cost are in **€** (Euro). The original cost research at CERN [21] , which was used to create Figure 10, was done in Swiss Francs (CHF) and Euros (**€**). For conversion into US$

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1) One should realize that unlike SLC, the LEP Klystrons were not accessible during operation. On the other hand, global corrections in RF power are easier with CW Klystrons when one Klystron fails. So probably any number between 5 and 10% is realistic.

2) I am thanking Roberto Corsini for the use of his "magic" spread sheet.

Main Beam		
	CM Energy (TeV)	0.54
	Maximum Gradient (MeV/m)	68
	Actual Gradient (MeV/m)	62
	2 Linac Length (km)	10.9
	Repetition Frequency (Hz)	120
	Pulse Length (nsec)	263
	Number of Bunches	95
	Charge per Bunch (10^9)	9
	HE Beam Total Energy (KJ)	37
Drive Beam		
	Number of Drive Beams per Linac	4
	Rf Pulse Total Energy (KJ)	122
	Rf Pulse Length (nsec)	375
	Deceleration Section Length (m)	1350
	DriveBeam Pulse Length (Microsec)	36
	Total Drive Beam Energy (KJ)	175
	Drive Beam Energy (GeV)	0.98
	Drive Beam Current (A)	4.9
	Frequency of DBA (MHz)	952
	Active Length of DBA (m)	296
	Structure Length (m)	2.97
	Klystron Power per Structure (MW)	49.4
	Delay Line Length (m) x2	112.5
	1st Combiner Length (m) x3	225
	2nd Combiner Length (m) x4	675
	Frequency Multiplication (2x3x4)	24
Total		
	Number of 50 MW Klystrons (for 2 Linacs)	200
	Wall Plug Power (MW)	82
	Total RF Efficiency (%)	39
	Wall to Beam Efficiency (%)	9.7

FIGURE 9. Summary of technical parameters for a TBPLC based on 952 MHz for the L-band frequency. The optimization was done for a gradient of 62 MeV/m in the X-band linac, and to always keep the power needed for the drive linac Klystrons below 50 MW. If the TB-RF system is optimized in a way to match the planned NLC RF power per 1.8 m section (170MW corresponding to ≈68 MeV/m), the L-band Klystron count goes up to 226.

we used a rate which is believed to reflect the purchasing power, that is 1€ ≈ 1US$ ≈ 1.5CHF.

The cost of X-band RF equipment has been calculated as if only half the main linac tunnel would be filled for 0.5 TeV cms. But all infrastructure needed to reach 1.0 TeV has been costed, assuming a main linac tunnel length of 22 km. It was also assumed that a total wall plug power capability of 200 MW was installed.

With this length of 22 km a full complement of acceleration structures and Klystrons could reach 1.0 TeV at a gradient of 62 MeV/m. This gradient seems to be within reach from the NLCTA experience. Also, with this tunnel length and a gradient of 93 MeV/m a cms energy of 1.5 TeV could be reached. All calculations assume a fill factor of 80% and an energy overhead for BNS and other items of 8%.

A PLC built strictly only to reach 0.5 GeV, without the infrastructure in tunnel, power, water, and some other minor items, to get to 1.0 TeV, would be

System	TBPLC	DKPLC	Remarks	f(E)
				c = constant
Conventional Facilities				E = proportional
Tunnels (incl. IR's)	850	800	25k€ / m	c+E
Power, Cooling, Water, Waste etc.	300	300		c+E
	1150	**1100**		
Injector Systems				
Damping Rings	200	200		c
pre-linacs(L,S,C,X)	100	100		c
other Systems	200	200		c
	500	**500**		
Main Linac				
RF	**0**	**500**	1M€ / GeV, no standby	E
BL Systems	300	300	Structures,Quads, Movers, ...	E
other Systems	200	200	Installation, Integration	c+E
	500	**1000**		
Drive Beam				
L-band Linacs	**220**	0	100x2 Kly, no standby	E
Frequency Multiplication	**70**	0	delay line + 2 combiner rings	c
Transports, Turnarounds, Dumps	**30**	0	10% of Linac BL Systems	E
decelerators	**80**	0	25% of Linac BL Systems	E
	400	**0**		
Control System	**200**	**200**		c+E
Beam Delivery	**200**	**200**	incl. IRs, no Detector	c+E
Services @ 20%	**590**	**600**	Tech. Support, Pre-ops	c+E
	3540	**3600**	**in M€**	

FIGURE 10. Summary of costs with the assumptions as described in the text. It is clear that this estimate is crude. It is also clear that items which have never been built and operated, like fully loaded linacs, combiner rings and decelerators, carry a larger contingencies than standard equipment. No contingency is assigned here.

≈ 500M€ cheaper.

The L-band Modulators and Klystrons for TBPLC have been costed with a 36 μsec pulse and 216 kW average power to be able to reach 0.5 TeV with 11 km of main linacs. These numbers would double to 72 μsec pulse and 432 kW to double the main linacs lengths to 22 km for 1 TeV.

It is clear from Figure 10 and the text that the raw cost of producing RF using a Two-Beam scheme could be lower than the direct Discrete Klystron scheme. But the major component cost in both systems go up proportional to energy. For the same (low) gradient of 62 MeV/m, there is no clear advantage of one vs. the other.

However, there are some conceptual advantages (and also a whole host of as of yet unproven assumptions). We mentioned already the possibility to have the high power installation at a central place and not distributed in the tunnel. So even if Two-Beam would be more expensive (which it is not), it has certain advantages in flexibility, which should give pause for thought.

One concrete example is the CLIC simulation [6] which shows that with a staggered RF ramp an energy spread of only $\Delta E/E = 5\ 10^{-4}$ can be reached. The energy spread produced in linear colliders operated in a classical way is large, $\Delta E/E = \approx 10^{-2}$. This large value creates a whole range of beam dynamics problems one could easily do without.

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