Summary of RF working group

(working group 4)

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1. Introduction

One of the major components of any linear collider, whether normal conducting or superconducting, is the system for generation, distribution and control of the rf power needed to provide the accelerating field and the beam power. A new working group was formed during this workshop with the aim to study the specific problems associated with the rf system of a superconducting linear collider. The main topics defined were : high power generation and distribution , controls, interlocks etc.

The parameters used as a basis are the ones given in the *Baseline design exercise for 0.5 TeV Centre of mass energy* provided by H. Padamsee for this workshop and the ones used for the *Superconducting linear collider test bench* under study at DESY. A selection of the most important parameters is given in the appendix.

2. RF system proposed for the DESY sc linac test facility

At DESY a test bench is under study to test one (perhaps two) full accelerating section consisting of 16 9-cell cavities working at 1.3 GHz. The accelerating gradient should be at least 25 MV/m. One cryostats contains 8 cavities, each cavity has its own RF power coupler feedthrough to room temperature. An electron injector is foreseen to provide a beam with the nominal total charge per pulse. The rf power will be supplied by klystrons and distributed to 16 cavities via waveguides. The power splitting will be done either by a tree structure with magic T's or a linear system with directional couplers which is being used for HERA. Presently the linear system is favoured. A schematic view of the proposed layout is shown in fig 1.

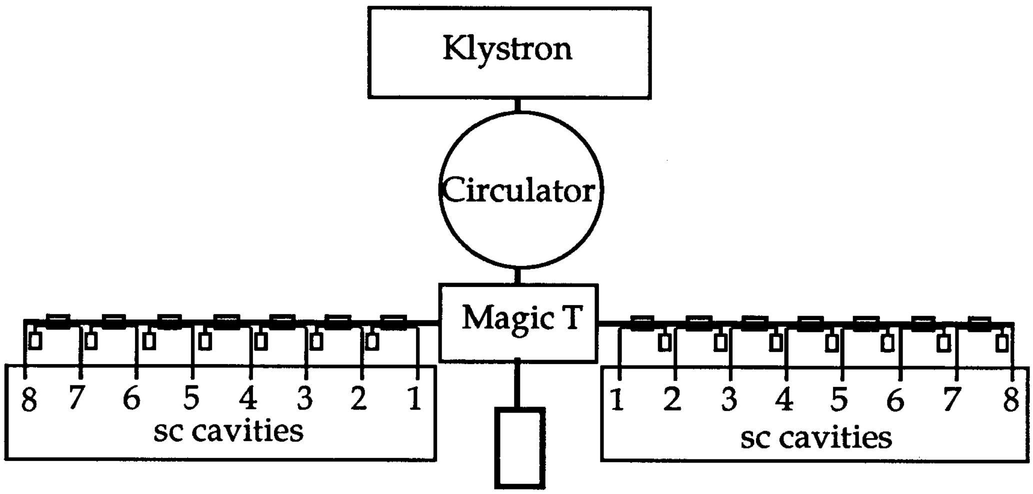

Fig. 1 : RF system proposed for the DESY sc cavity test facility.

This layout was used by the working group as a basis for discussing the various aspects important for a superconducting linear collider.

3. Beam energy spread

A very important parameter of the linac is the energy resolution $\Delta E/E$ of the beam required by physics experiments and by the final focus system. An analysis of beamloading by S. Noguchi, (see appendix) was used to determine the influence of various error sources on the accelerating voltage seen by the particles. Some of these effects are coherent in all cavities and contribute fully to the energy spread, some are reduced by a statistical distribution over all cavities or all RF power sources.

3.1. Error sources

In this section effects contributing to the beam energy spread are reviewed.

Radiation pressure

The detuning of the cavities due to radiation pressure at nominal field is estimated to be 1.8 kHz, corresponding to about 5 bandwidths .This happens at each rf pulse. Trying to keep the cavities in tune during rf switch on looks very difficult, if not impossible. Schemes were considered, where the master oscillator frequency is changed during the fill time, but this requires all cavities to behave exactly in the same way, and was not considered feasible.

The easiest solution for this problem is to stiffen the cavity. However, some flexibility has to be maintained in order to allow deformation tuning. Stiffening the inner cells and tuning by only deforming the end cells, was estimated to reduce the effect to 180 Hz, corresponding to 1/2 bandwidth. This can be taken care of by the tuning system. In any case, for reasons of static stability of the cavities, it was already proposed to stiffen the cavities.

There is no risk that under these conditions, radiation pressure could introduce cavity oscillations.

Microphonics

According to experience reported by Schwettman a mechanically stiffened cavity does not have mechanical resonances below 400 Hz. Therefore this topic was not addressed further.

Tuning angle

It was estimated that the tuning angle could be adjusted to within 10 degrees, giving $\Delta E/E = 3 * 10^{-2} / \sqrt{N_{cav}}$.
(Ncav is the number of cavities)

Generator power

Experience shows that it is possible to achieve 0.2 % short term stability, leading to $\Delta E/E = 2 * 10^{-3} / \sqrt{N_{\text{power sources}}}$.

In order to achieve long term stability, feedback with the beam energy is required. It was felt necessary, that the beam energy should be known at one or several points along the linac to within a relative precision of better than 10^{-3}

Bunch charge

The total charge of a pulse has to be very precise. An error of ±0.2 % results in $\Delta E/E$ of ±0.1 % for $\beta = 2\,\beta_b$. (see appendix)

The charge error of an individual bunchlet within a pulse is less critical, an error of ±6 % results in $\Delta E/E = \pm 0.2$ %.

Phase of cavity voltage

The error in the phase of the cavity voltage has several contributions :

a) RF station phase of generators. It was estimated, that by using an actively phase stabilized (perhaps by optical transmission) rf reference distribution, this error could be kept to within ± 1 deg.

b) Microphonics was assumed to be no problem with stiffened cavities. The resultant error was estimated to be ± 1 deg.

c) Slow drifts could be corrected by using beam energy measurements.

A total phase offset of 2.5 deg was calculated to produce $\Delta E / E = 0.2$ %

Statistical effects due to the large number of cavities and power sources which might reduce this effect need further study.

Injection phase

The first bunchlet is injected at time T during the filling time T_f of the cavities. An error in timing $\Delta T/T_f$ of 1 % yields $\Delta E/E=1$ %.

3.2. Summary of arguments concerning energy spread

It was assumed that certain physics experiments on a linear collider in the 0.5 TeV centre of mass energy range can require as much as

$$\frac{\Delta E}{E} \leq 0.1 \ \%$$

This can be achieved with the proposed system, but it is at the limit of what can be done.

If better beam quality is necessary, the consequences are :

- Individual rf power sources will be required for each cavity.
- The rf-control system will become much more sophisticated. Feedback electronics will be required for each klystron. (Experience from CEBAF shows, that the cost for such a system approaches 50 k$ / m) .
- Efficiency will be reduced.

4. Tuning system

As already mentioned, it is proposed to stiffen the cavities such that only the end cells are used for deformation tuning.

It must be possible to detune idling undriven cavities by at least 10 bandwidths; even then the beam induced field is still about 1 MV/m . Each cavity is individually tuned and requires a pick up antenna.

The tuning can be based on the phase of the cavity field with respect to a reference signal obtained from the RF power travelling towards the cavities.

The tuning will only be activated during the RF pulse via gating. The bandwidth required is small. Several Hz are estimated to be enough.

A beam pick up electrode is required for each rf station.

5. RF distribution

Low power

A phase stable reference line is necessary to distribute the RF frequency. The phase stabilization will require active feedback over the length of the accelerator.

High Power

Three alternatives to distribute the rf power to the cavities via waveguides were presented :

a) *Resonant line*. This approach was estimated to be too delicate to use and was not persued.

b) *Tree structure* where the power splitting is done with magic T's. The advantage is, that the waveguide lengths to all cavities are identical, whereby phase shifts due to thermal expansion of waveguides can be controlled easier.

c) *Linear structure* using hybrid directional couplers. This layout has been used for the HERA electron rf system and offers the advantage of requiring minimum space and runs parallel to the accelerator. In addition the number of cavities per power source does not have to be a power of 2.

A circulator for each Klystron is required for several reasons :

- " It makes tuning possible " (quote from KEK). The reference signal for the tuning signal is derived from the forward travelling wave in the waveguide. Due to finite directivity of directional couplers and strongly varying reflections during filling and injection, phase errors are introduced. Therefore it is proposed to derive the reference signal upstream of the circulator at the klystron output.

- It avoids complicated active protection circuits for the power sources.

- " It avoids severe operational headaches " (CEBAF)

6. High power RF generation

For cost reasons, it is clear that the RF generators should have the highest peak power possible.

The DESY test facility is based on Klystrons with 4.5 MW peak power. These klystrons are already commercially available now. An R+D programme might increase the peak power by a factor 2 and is required in any case to increase reliability and lifetime.

No reason was found to change the RF pulse length, unless a big change is possible.

7. Cost

The question of cost could not be addressed in detail. Experience from accelerators already existing or being built, shows that series production can bring the price for RF power sources and other RF equipment down by a factor of 2 compared to " catalogue prices". It seems that the graph giving klystron cost as a function of peak power shown in the Tesla Calculation Programme (by H. Padamsee) needs revision.

8. Conclusion

The RF layout for the DESY sc linac test facility can be used as a model for future linear colliders. The specifications are not easy to meet, but look possible with techniques available today.

The control system other than the RF controls have not been studied at all, but it should be kept in mind that it presents a major building block of the accelerator.

Because of the complexity and the large numbers of components involved, studies are required to assess reliability and lifetime of the overall system. Some of the questions to be answered are : How many " OFF " cavities and klystrons can one accept ? Does one require access to klystron during operation ?

The presented solution is considered feasible for a beam energy resolution $\Delta E/E \geq 10^{-2}$. If physics requires $\Delta E/E \leq 10^{-3}$, the solutions will have to be drastically different with a corresponding considerable price increase.

Appendix

Parameters relevant for rf system

Energy per linac	250 GeV
Accelerating gradient	25 MV/m
RF frequency	1.3 GHz
Particles per bunch	$5.14 * 10^{10}$
Bunch length σ_z	2 mm
Bunch separation	1 µsec
Nr of bunches per pulse	800
Average beam current	65 µA
Rep. rate of RF pulses	10 Hz
RF pulse length	1.4 msec
Nr of cavities per cryostat	8
Cavity fill time	0.62 msec
Cavity Q_L	$3.65 * 10^6$
Cavity Q_0	$4.8 * 10^9$
Cells per cavity	9
Active cavity length	1.038 m
Peak RF power	200 kW / m

Appendix General consideration for the cavity voltage and so bunch energy gain

The cavity voltage $\tilde{V}$ driven by some generator with $\tilde{V}_g$ and ω is given by

$$\tilde{V} = \tilde{V}_g + (\tilde{V}_0 - \tilde{V}_g)\exp(-\frac{t}{T_F})\exp(j\frac{\tan\varphi}{T_F}t) \quad , \tag{1}$$

where $\tilde{V}_0$ is the cavity voltage at $t = 0$ and

Filling time : $\quad T_F = \dfrac{2Q_L}{\omega_0}$

Detuning angle : $\quad \tan\varphi = T_F(\omega_0 - \omega)$

From this equation, the cavity voltage just before the n-th bunch coming into the cavity $\tilde{V}_n^-$ is expressed using the cavity voltage just after the (n-1)-th bunch going out of the cavity $\tilde{V}_{n-1}^+$ as

$$\tilde{V}_n^- = \tilde{V}_g + (\tilde{V}_{n-1}^+ - \tilde{V}_g)\exp(-\tau)\exp(j\,\tau\tan\varphi) \quad , \tag{2}$$

here τ is a bunch separation divided by the filling time, T_b/T_F. If we take the phase of the bunch induced voltage as the reference,

$$\tilde{V}_n^+ = \tilde{V}_n^- - 2kq_n \quad , \tag{3}$$

where k is a loss parameter and q_n is a charge of the n-th bunch.

Then the equation (2) becomes

$$\tilde{V}_n^- = \tilde{V}_g + (\tilde{V}_{n-1}^- - 2kq_{n-1} - \tilde{V}_g)\exp(-\tau)(j\,\tau\tan\varphi) \quad . \tag{4}$$

And the $\tilde{V}_n^-$, where n is counted from some bunch, is given using the voltage for that reference bunch $\tilde{V}_1^-$ as

$$\tilde{V}_n^- = \tilde{V}_g\{1-\exp(-\tau)\exp(j\,\tau\tan\varphi)\}\sum_{l=0}^{n-2}\exp(-l\,\tau)\exp(j\,l\,\tau\tan\varphi)$$

$$-2k\exp(-\tau)\exp(j\,\tau\tan\varphi)\sum_{l=0}^{n-2} q_{n-l-1}\exp(-l\,\tau)\exp(j\,l\,\tau\tan\varphi)$$

$$+\tilde{V}_1^-\exp\{-(n-1)\tau\}\exp\{j(n-1)\tau\tan\varphi\} \quad . \tag{5}$$

Dividing q_n into some constant and a fraction, $q_n = \bar{q} + \Delta q_n$, eq. (5) becomes

$$\tilde{V}_n^- = \tilde{V}_g - 2k\,\bar{q}\,\tilde{F}$$

$$+(\tilde{V}_1^- - \tilde{V}_g + 2k\,\bar{q}\,\tilde{F})\exp\{-(n-1)\tau\}\exp\{j(n-1)\tau\tan\varphi\}$$

$$-2k\,\bar{q}\exp(-\tau)\exp(j\,\tau\tan\varphi)\sum_{l=0}^{n-2}\frac{\Delta q_{n-l-1}}{\bar{q}}\exp(-l\,\tau)\exp(j\,l\,\tau\tan\varphi) \tag{6}$$

and $$\tilde{F} = \frac{\exp(-\tau)\exp(j\,\tau\tan\varphi)}{1-\exp(-\tau)\exp(j\,\tau\tan\varphi)} \quad . \tag{7}$$

From this equation (6) we can find that if the third term is negligible the cavity voltage converges into

$$\tilde{V}_c = \tilde{V}_g - 2k\bar{q}\tilde{F} = \tilde{V}_{gr}\cos\varphi\exp(j\varphi) - 2k\bar{q}\tilde{F} \quad , \tag{8}$$

and $\tilde{V}_n^-$ is equal to $\tilde{V}_c$ independently on n if $\tilde{V}_1^- = \tilde{V}_c$.

In the case of pulse operation like for TESLA application, 4 parameters , $\bar{q}$, T_b, number of bunches N_b and an energy gain per cavity V_0 are given firstly.

From eq. (8),

$$V_0 = \mathrm{Re}(\tilde{V}_c) = V_{gr}\cos\varphi\cos(\theta+\varphi) - 2k\bar{q}\mathrm{Re}(\tilde{F}) \quad , \tag{9}$$

where $$V_{gr} = 2\sqrt{P_g\left(\frac{R}{Q}\right)\frac{Q^2_L}{Q_{in}}}$$

and P_g : Generator power

θ : the phase of $\tilde{V}_{gr}$.

To get the maximum energy gain, we want to set θ and $\varphi = 0$, and in this case eq. (9) becomes

$$V_0 = 2\sqrt{P_g \left(\frac{R}{Q}\right) \frac{Q^2_L}{Q_{in}}} - 2k\bar{q}\frac{\exp(-\tau)}{1 - \exp(-\tau)} \quad . \tag{10}$$

At the coasting beam limit, $\tau << 1$, and using $\bar{q}/T_b = I_b$,

$$V_0 = 2\sqrt{P_g \left(\frac{R}{Q}\right) \frac{Q^2_L}{Q_{in}}} - \left(\frac{R}{Q}\right) Q_L I_b \quad . \tag{11}$$

So to get V_0, P_g must be set as

$$P_g = \frac{\omega W_0 Q_{in}}{4Q^2_L}\left(1 + \frac{P_b}{\omega W_0} Q_L\right)^2 \quad , \tag{12}$$

where Stored Energy : $W_0 = \dfrac{V^2_0}{\omega\left(\frac{R}{Q}\right)} = \dfrac{P_0 Q_0}{\omega}$

Beam Power : $P_b = V_0 I_b$.

Using coupling constant,

$$\beta = Q_0/Q_{in} \quad \text{and} \quad \beta_b = P_b/P_0 \quad ,$$

$$P_g = \frac{P_0}{4\beta}(1 + \beta + \beta_b)^2 \quad . \tag{13}$$

If τ, $\tau\tan\varphi << 1$

$$\tilde{F} = \frac{\cos\varphi}{\tau}\exp(j\varphi) \quad . \tag{14}$$

So the cavity voltage at $n = \infty$, eq. (8), is expressed as

$$\tilde{V}_c = V_0\left\{\left(1 + \frac{P_b Q_L}{\omega W_0}\right)\exp(j\theta) - \frac{P_b Q_L}{\omega W_0}\right\}\cos\varphi\exp(j\varphi) \quad , \tag{15}$$

$$= V_0\{(1 + \frac{\beta_b}{1+\beta})\exp(j\theta) - \frac{\beta_b}{1+\beta}\}\cos\varphi\exp(j\varphi) \quad . \tag{16}$$

In the next place, we discuss the second term of eq. (6).

When the cavity is driven by Pg, eq. (12) and (13), at t = 0, the cavity voltage builds up according to the following equation.

$$\tilde{V}(t) = V_0\frac{1+\beta+\beta_b}{1+\beta}\{1 - \exp(-\frac{t}{T_F})\exp(j\frac{\tan\varphi}{T_F}t)\}\cos\varphi\exp\{j(\theta+\varphi)\} \quad . \tag{17}$$

If θ and $\varphi = 0$, ideal case, the first bunch must come into the cavity at $t = T_e$.

$$T_e = T_F\, l_n\frac{1+\beta+\beta_b}{\beta_b} \quad . \tag{18}$$

Then the $\tilde{V}_1^- = V_0$ and the second term of eq. (6) becomes 0 when $\theta = \varphi = 0$ and $\tau << 1$.

<u>Energy gain spread due to errors of various parameters</u>

Using above equations, we can estimate the error of energy gain. For simplicity we assume

τ and $\tau\tan\varphi << 1$

β and $\beta_b >> 1$

and discuss 3 terms of eq. (6) separately, of course the reference is an ideal case

$$\theta = \varphi = 0 \quad .$$

A. First Term

From real part of eq. (16)

Error Source	Error	Energy Gain Error
Pg	± 10 %	± 10 % ($\beta = \beta_b$), ± 8 % ($\beta = 2\beta_b$)
θ	± 5°	– 0.76 % ($\beta = \beta_b$), – 0.57 % ($\beta = 2\beta_b$)
φ	± 20°	– 11.7 %
$I_b(\bar{q})$	± 1 %	∓ 1 % ($\beta = \beta_b$), ∓ 0.5 % ($\beta = 2\beta_b$)

B. Second Term

From eq. (17) and (18)

Pg	± 10 %	± 10 %
T_e/T_F	± 0.01	± 1.0 %
θ	± 5°	– 0.4 %
φ	± 20°	– 0.88 % ($\beta = \beta_b$), – 1.96 % ($\beta = 2\beta_b$)

C. Third Term

Since this term is statistical, we examine two special cases, two missing bunches and ten + or – 20 % bunches.

Using $$\frac{2k\bar{q}}{\tau} = \frac{\beta_b}{1+\beta} V_0$$

and assuming $\tau = 0.005$, $\varphi = 0°$ and $\beta = \beta_b$,

Two missing	+ 1.0 %
ten ± 20 %	∓ 0.98 %

If $\beta = 2\beta_b$, $\tau = 0.01$

Two missing	+ 0.99 %
ten ± 20 %	∓ 0.95 %

Finally we discuss about the optimum coupling β.

In the case of CW operation, the optimum coupling condition is given by $\beta = \beta_b + 1$. In the case of pulsed operation, however, the integrated wall plug power should be minimised.

The total operating power is a sum of following 5 contributions.

1. RF power during build up

$$P_g T_e = \frac{W_0}{2} \frac{(1+\beta+\beta_b)^2}{\beta(1+\beta)} \ln \frac{1+\beta+\beta_b}{\beta_b} \quad . \tag{19}$$

2. RF power during acceleration

$$P_g N_b T_b = \frac{(1 + \beta + \beta_b)^2}{4\beta\beta_b} N_b \bar{q} V_0 \quad . \tag{20}$$

N_b : Number of bunches in a pulse

3. Cavity wall loss during build up

$$2W_0 \frac{(1 + \beta + \beta_b)^2}{(1 + \beta)^3} \ln \frac{1 + \beta + \beta_b}{\beta_b} - W_0 \frac{3 + 3\beta + 2\beta_b}{(1 + \beta)^2} \quad . \tag{21}$$

4. Cavity wall loss during acceleration

$$P_0 N_b T_b = \frac{\omega W_0}{Q_0} N_b T_b \quad . \tag{22}$$

5. Cavity wall loss during decay

$$\int_0^\infty P_0 \exp(-\frac{\omega}{Q_L} t) dt = \frac{W_0}{1 + \beta} \quad . \tag{23}$$

The optimization should be done by taking the efficiency of RF power source and refrigerator, static heat load and pulse length into account.

In the TESLA application, the optimum coupling β will be ~ $2\beta_b$, and this choice relaxes the serious constraint on $I_b(\bar{q})$ and microphonics with moderate reflection power of 12.5 %.