THE TESLA RF SYSTEM

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Abstract

The Tesla project proposed by the TESLA collaboration is a 500 to 800GeV e+/e- linear collider with integrated free electron laser facility. The collider is based on superconducting cavity technology. ~20000 superconducting cavities operated at 1.3GHz with a gradient of 23.4MV/m or 35MV/m will be required to achieve the energy of 500GeV or 800GeV respectively. For 500GeV ~600 RF stations each generating 10MW of RF power at 1.3GHz at a pulse duration of 1.37ms and a repetition rate of 5 or 10Hz are required. This paper describes the layout of the entire RF system and gives an overview of its various subsystems and components.

1. INTRODUCTION

The TESLA project proposed by the TESLA collaboration is 33km long 500 to 800GeV e+/e- linear collider with integrated free electron laser facility. It is based on superconducting cavity technology. Details can be found in the TESLA Technical Design Report [1].

In this paper the TESLA RF system with emphasis on its high power part will be described. The RF system consists of a number of RF stations converting AC line to RF power at 1.3GHz for the superconducting cavities of the main linac and for the accelerating structures of the injectors. In the remainder of this paper the RF system layout for the 500GeV collider will be presented. The RF system layout for the 800GeV upgrade differs almost only in twice the number of RF stations.

2. REQUIREMENTS

In order to reduce the cost and to improve the reliability of the entire RF system the total number of RF stations is chosen as small as possible, only limited by the maximum output power which can be generated reliably by a single RF source. The output power of one RF station is then distributed to a number of accelerating cavities.

At a center of mass energy of 500GeV the peak RF power needed for one superconducting cavity at full gradient and maximum beam current, i.e. 23.4MV/m and 9.5mA during the pulse, is 231kW. At TESLA twelve 9-cell cavities will be installed in one 17m long cryo module. The nominal peak power needed for three modules with thirty-six cavities is 8.3MW. Taking into account a regulation reserve of 10% for phase and amplitude control and another 6% for circulator and waveguide losses 9.7MW are required. The particle beam pulse consists of 2820 micropulses with a spacing of 0.337μs resulting in a macropulse duration of 950μs. 420μs are needed to fill the cavity with RF. Hence the RF pulse length is 1.37ms. The repetition rate is 5Hz for the major part of the linac. At the low energy part of the e^--linac the stations will be running at a repetition rate of 10Hz for FEL operation.

3. BASIC RF STATION LAYOUT

Each RF station consists of subsystems required to convert AC line power to RF power and to distribute the RF power to the cavities. A modulator converts AC line power into high voltage pulse power. Its main parts are a high voltage power supply, a high voltage pulser unit and a pulse transformer. A klystron generates pulsed RF power from pulsed high voltage power and a waveguide RF distribution system distributes the RF power to the cavities and also protects the RF source from reflected power. A low level RF system controls the shape, amplitude and phase of the RF. Various auxiliary devices for the klystron and the modulator are also required. A control and interlock system controls each RF station and protects the linac and the station in case of malfunction.

In order to provide RF power for all cavities at an energy of 500GeV, 560 RF stations in the main linac are required. 12 additional stations will be installed in the main linac as spare stations. Another 12 RF stations are required for the injectors. For the 800GeV upgrade the number of stations of the main linac will be doubled to 1144. With the exception of the modulators high voltage power supply and pulser unit, the RF stations will be installed in the tunnel with a separation of 50m (25m for the 800GeV). The modulators high voltage power supplies and the pulsers will be installed in the access halls, which have a separation of about 5km. The connection between the pulser and pulse transformer will be accomplished by high voltage pulse power cables. There will be also additional cable connections for the interlock system between the halls and the tunnel. The number of modulators per hall will be typically 100.

4. THE 10MW MULTIBEAM KLYSTRON

For Tesla a new developed 10MW multibeam klystron was chosen as RF power source. Comparison of different types of klystrons constructed and built so far have shown that a low microperveance p of the klystron electron beam defined as $10^6 \times I/V^{3/2}$ (I=klystron beam current, V=klystron voltage) results in a high efficiency [2, 3]. This is due to lower space charge forces in the beam, which make the bunching easier and more effective. For a single beam klystron at very high output power the demand for high efficiency leads to low microperveance and hence to very high voltage resulting in a reduced reliability. The solution is to use many small low voltage, low microperveance beams in parallel in one vacuum vessel. This principle is utilized in the multibeam klystron. With a multibeam klystron an efficiency of 70% or more seems to be feasible whereas with a single beam 5MW klystron a maximum efficiency of just 45% can be reached.

Fig. 1 The multibeam klystron Thomson TH1801.

Figure 1 shows the multibeam klystron TH1801 produced by Thomson Tubes Electroniques [4]. In this klystron seven beams are produced by the cathode and accelerated by the klystron gun. Each beam has a microperveance of 0.5. The beams share common cavities but have independent drift tube sections. After RF extraction in the output cavity, the spent electron beams are absorbed in the collector. Two output waveguides are required to handle the RF power of 2 x 5MW in the output windows. The total height of the klystron is 2.5m. The multibeam klystron was successfully tested and one klystron is now in use at the TESLA Test Facility (TTF). It achieved an output power of 10MW with an efficiency of 65%. Table 1 summarizes the design parameters and the parameters achieved with the prototype test. More detailed information can be found in [5].

The gain of 48dB means that the drive power is below 160W, and solid state amplifiers can be used. They will be installed near to the klystrons inside the collider tunnel. The klystrons will be mounted in the horizontal position together with the modulators pulse transformer inside a container. The complete assembly will be moved with the tunnels monorail system to its location inside the tunnel and installed below the walk way.

Table 1
Design and measured parameters of the multibeam klystron

	Design	Measurement
Operation Frequency	1300MHz	1300MHz
RF Pulse Duration	1.5ms	1.5ms
Repetition Rate	10Hz	5Hz
Cathode Voltage	110kV	117kV
Beam Current	130A	131A
HV Pulse Duration	1.7ms	1.7ms
No. of Beams	7	7
Microperveance	3.5	3.27
No. of Cavities	6	6
RF Peak Power	10MW	10MW
RF Average Power	150kW	75kW
Efficiency	70% goal	65%
Gain	48dB	48.2dB
Solenoid Power	4kW	6kW

5. MODULATOR

The modulator converts AC line voltage to pulsed high voltage in the 120kV range to be applied to the klystron cathode. The pulse shape must be as rectangular as possible. The flat top ripple should not exceed ±0.5% in order to limit phase and amplitude variations of the klystron RF output. The rise and fall times of the pulse should be as short as possible in order to maximize the total efficiency. The pulse-to-pulse stability must be better than ±0.5%. In case of klystron gun sparking the energy deposited into the spark must be limited to a maximum of 20J. The modulator requirements are summarized in table 2.

Table 2
Modulator requirements

	Typical	Maximum
Klystron Gun Voltage	115kV	120kV
Klystron Gun Current	130A	140A
High Voltage Pulse Duration (70% to 70%)	<1.7ms	1.7ms
High Voltage Rise and Fall Time (0 to 99%)	<0.2ms	0.2ms
High Voltage Flat Top (99% to 99%)	1.37ms	1.5ms
Pulse Flatness during Flat Top	< ±0.5%	±0.5%
Pulse-to-Pulse Voltage fluctuation	< ±0.5%	±0.5%
Energy Deposit in Klystron in Case of Gun Spark	<20J	20J
Pulse Repetition Rate for 90% of the Modulators	5Hz	5Hz
Pulse Repetition Rate for 10% of the Modulators	10Hz	10Hz
Transformer Ratio	1:12	1:12
Filament Voltage	9V	11V
Filament Current	50A	60A

Various types of modulators meeting these requirements are conceivable. It turned out that a bouncer modulator consisting of a DC high voltage power supply, a pulser unit and a pulse transformer seems to be the most promising solution regarding cost and ease of the design and reliability [6].

Several modulators of the bouncer type were built and are in use at the Tesla Test Facility. A very detailed description of the modulator is given in [7, 8, 9, 10].

A modulator based on the SMES (Superconducting Magnetic Energy Storage) principle as a possible alternative will be tested at TTF. Here a superconducting solenoid is used instead of a capacitor bank for the intermediate energy storage [11].

The very elegant solution of the bouncer modulator is sketched in Figure 2

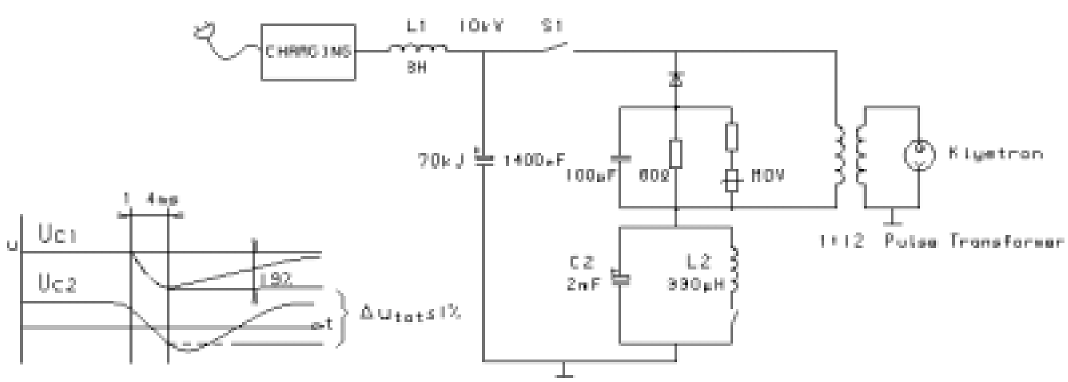

Fig. 2 Circuit diagram of the modulator (schematic).

In operation the DC power supply keeps capacitor C1 charged to the 10kV level. The output pulse is started by closing switch S1 and connecting C1 to the pulse transformer primary. Semiconductor devices like Isolated Gate Bipolar Transistors (IGBT) or Integrated Gate-Commutated Thyristors (IGCT) can be used. The pulse is terminated after 1.57ms (1.37ms flat top +0.2ms rise time) by opening S1. The nominal current switched by S1 is 1.56kA. The primary pulse of 10kV is stepped up to the klystron operating level of up to 120kV by the 1:12 pulse transformer.

During the pulse, capacitor C1 discharges by 19% of its initial voltage, putting an intolerable slope on the output pulse. To correct the slope to the 1% level without resorting to a 29mF capacitor in the C1 location, a bouncer circuit is required. This is a resonant LC circuit, which creates a single sine wave with a period of 5ms and an amplitude at the 1kV level. The bouncer is triggered slightly before the main pulse so that the linear, bipolar portion of the cycle compensates the droop during the main pulse. The size of the pulser units is 2.8m(L) x 1.6m(W) x 2.0m(H). They will be installed in the access halls, typically 100 pieces per hall.

The output pulse of the pulser unit has an amplitude of up to 10kV. Therefore it must be transformed to the 120kV level by means of a pulse transformer disturbing the rectangular pulse shape as little as possible. The rise time of the high voltage pulse is mainly determined by the pulse transformers leakage inductance, which therefore has to be as small as possible. Several transformers with leakage inductances slightly above 300µH have been built and operated at TTF. Some new transformers having even less than 200µH are now available and will be used at TTF. The voltage level of 120kV requires that the transformer will be installed in a tank filled with transformer oil. The klystron socket housing the klystron cathode will be installed in the same tank.

Although the total weight of the pulse transformer tank is 6.5t, its size of 3.2m(L) x 1.2m(W) x 1.4m(H) allows an easy installation inside the tunnel below the walk way together with the klystron. Figure 3 shows a klystron and a pulse transformer during installation in the TESLA tunnel.

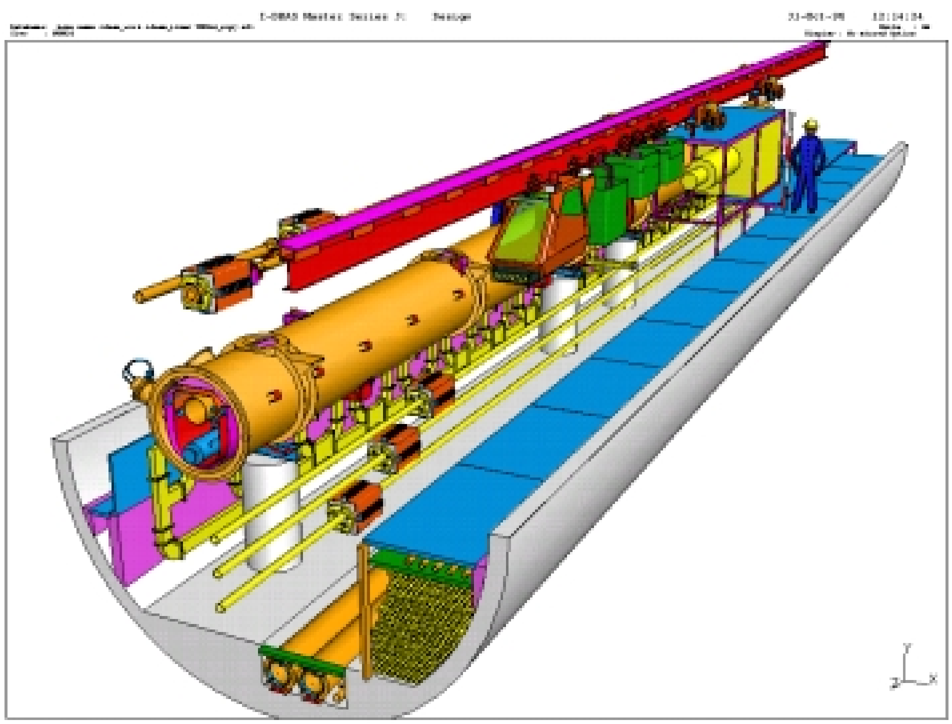

Fig. 3 Klystron and pulse transformer during installation in the TESLA tunnel

The energy transport from the modulator to the transformer will be done via pulse cables. The distance between the different service halls and the location of the pulse transformers inside the tunnel is up to 2.8km. The required cross section of the copper current lead is 300mm^2 per conductor. In order to transmit the high voltage pulse without significantly distorting the pulse shape, especially at the leading edge of the pulse, the cable impedance must be matched to the klystron impedance, and the skin effect must be minimized. Therefore four cables will be installed, each with a cross section of 75mm^2 and an outer diameter of 30mm. The cable impedance Z_0 of the four cables equals 6.45Ω. The cables are of coaxial construction to prevent electromagnetic noise, which might be generated by the cables, from spreading inside the tunnel. The inner lead is at high potential (12kV). The outer lead is at the potential of the bouncer circuit (±2kV). There is an additional shield of overall 16mm^2. As insulation material VPE will be used. Additional line matching to the pulse transformer will be done via a RC network. The power losses on the cable will be 2% on average. Simulation results and further information on the cable are given in [12].

The high voltage power supply, which charges the pulsers main capacitor, has to meet two requirements. The capacitor has to be charged to an accurate value of voltage in order to obtain the same voltage at the klystron from pulse to pulse. The low repetition frequency of 5Hz and 10Hz respectively has to be suppressed in order not to produce disturbances of the mains.

Each modulator will have a separate switch mode power supply. The input voltage will be three phase low voltage grid. The voltage output is 12kV, the nominal power of each power supply is 150kW for 5Hz and 300kW for 10Hz repetition rate respectively. The power supply is built in modules, which ensure a high reliability. As switch mode units buck converters will be used. Series resonant converters are a possible alternative.

The power supply regulation is a digital self-learning regulation of the input power, made possible by the high regulation dynamic of the switch mode supply. In addition the voltage at the capacitor bank at the firing time of the pulse will be regulated within 0.5% accuracy.

The size of a high voltage power supply is 1.2m(L) x 1.6m(W) x 2.0m(H). Further information about the power supplies can be found in [13].

In addition to the main high voltage power supply auxiliary power supplies are required for the operation of the klystron and the modulator. These are a power supply for the klystrons focusing solenoid, a power supply for the klystron filament, vacuum pump power supplies for the klystron and a core bias power supply for the pulse transformer. Since the klystron will be installed together with the pulse transformer in the collider tunnel, the auxiliary power supplies will be installed together in a rack near to the klystron below the walk way in the tunnel.

6. EFFICIENCY AND POWER REQUIREMENTS

The klystrons must deliver a RF power of 9.7MW when required. This takes into account the regulation reserve of 10% for phase and amplitude control and 6% for losses in the waveguide distribution. To allow for the regulation, the klystron must be run slightly below saturation, and the efficiency drops from the design (saturation) value of 70% by a few percent. Taking this into account, we assume a klystron efficiency of 65%; a corresponding klystron voltage of 117kV is then required. The high voltage pulse of the modulator meets this requirement during the flat top but not during the rise and fall times. The pulse rise time is of the order of 200µs, however the average rise time of the HV pulse at the klystrons will be above 200µs because of the long cables between the pulse forming units in the service buildings and the pulse transformer-klystron units in the tunnel.

Since the first 420µs of the RF pulse will only be used to fill the superconducting cavities with RF power the RF pulse can be started already during the rise time of the high voltage pulse. Although the klystron RF output power during the rise time will be lower than during the flat top it can already be used to fill the cavities. When the klystron voltage reaches 80% of the flat top voltage, ca. 100µs after the beginning of the high voltage pulse, the RF pulse can already be started. The klystron output power at this voltage is about 4MW. As a result of the changing klystron voltage the RF phase shifts by ca. 320^o until the flattop is reached. This phase shift can be compensated by the low level RF.

With this method the rise time efficiency of the modulator, defined as the ratio of the energy per high voltage pulse used for RF generation to the total energy per high voltage pulse, can be increased to 96%. The electronic efficiency of the modulator is 90%. We also take into account ohmic losses of 2% in the pulse cables. This results in a total modulator efficiency of 85%.

In order to generate 9.7MW in a 1.37ms long RF pulse at 5Hz repetition rate an average AC power from the wall plug of 120kW per RF station is required. In addition 14kW for the auxiliary power supplies must be added. The total average AC power required for 560 active RF stations is therefore 75MW. Table 3 summarizes the power requirements for RF generation in the main linac. For FEL operation 6.7MW AC power must be added to these numbers.

Table 3
Efficiency and power requirements of the RF system

RF peak power per RF station	9.7MW
Duty cycle	0.685%
Average RF power available per RF station	66kW
Klystron efficiency	65%
Modulator efficiency	85%
Total efficiency	55%
AC power per RF station	120kW
Auxiliary power per RF station incl. LLRF and waveguide tuner	14kW
Total wall plug power per station	134kW
Number of active stations	560
Total wall plug power	75MW

7. MODULATOR AND KLYSTRON PROTECTION AND CONTROL

For the reliable and save operation of the RF system a comprehensive interlock system is necessary. In the event of a klystron gun spark the energy deposited in the spark must be kept below 20J to avoid damage of the klystron gun. The response to a spark will be an immediate opening of the concerned IG(B)CT switch to disconnect the capacitor bank from the sparking klystron. The energy stored in the transformer leakage inductance and in the power transmission cable is dissipated in two networks, one at the cable end near the IG(B)CT consisting essentially of a reverse diode and a resistor. The second one is made up by an 80Ω resistor across the transformer primary and by a 100μF capacitor which limits the peak inverse voltage at the primary to 800V when the IG(B)CT is opened. In addition a crowbar is fired. Other important interlocks are control of cooling water flow and temperature, of the focusing solenoid current, and a vacuum interlock. Other interlock conditions result from sparks in the RF distribution system, reflected power, RF leaks, power couplers and from cryogenics.

In order to meet the different safety requirements, different interlock techniques will be used. The interlock, which inhibits RF operation during tunnel access, is accomplished by a hard-wired system. This will be made by two separate and independent systems, which switch off the klystron RF drive power and the modulators high voltage power supply.

The technical interlock, which protects the linac and the RF station in case of malfunction, will be realized with programmable logic controller (PLC) and system-on-programmable-chip (SOPC) techniques. Today these systems are industrial standard techniques. Therefore knowledge in planning, structure and programming is well known. Hardware for almost all applications is available from different manufactures.

Besides system protection and providing start up and shut down procedures for the RF stations, the control and interlock system will offer a comprehensive diagnostics of the RF systems. It will allow to measure and to diagnose actual parameters as well as to adjust set points within certain limits for each RF station and its subsystems and to react to different fault conditions in a flexible manner. Communication with the accelerators main control will be accomplished by VME bus.

The interlock system will be divided in two units, one installed in an electronic rack in the tunnel near to the klystron and another installed near to the pulser and the high voltage power supply unit in the access hall. Connection and communication between these two units are accomplished by glass fiber cables, which allows fast transfer of the interlock signals. The interlocks of each unit are summarized into categories. Only these sum interlocks will be exchanged between the units and therefore the number of fibers connecting both units is limited to ten. Each unit is connected via its own VME bus to main control.

8. RF WAVEGUIDE DISTRIBUTION SYSTEM

The 10MW multibeam klystron has two RF output windows and has to supply thirty-six 9-cell cavities, which are installed in three modules. Therefore the RF distribution is based on two symmetrical systems, each supplying eighteen cavities. For the RF distribution a linear system branching off identical amounts of power for each cavity from a single line by means of directional couplers will be used. It matches the linear tunnel geometry best and leads to lower waveguide losses than a tree-like distribution system, because long parallel waveguide lines can be avoided. Such a system is already in use for the HERA superconducting RF system and has also been successfully tested in TTF.

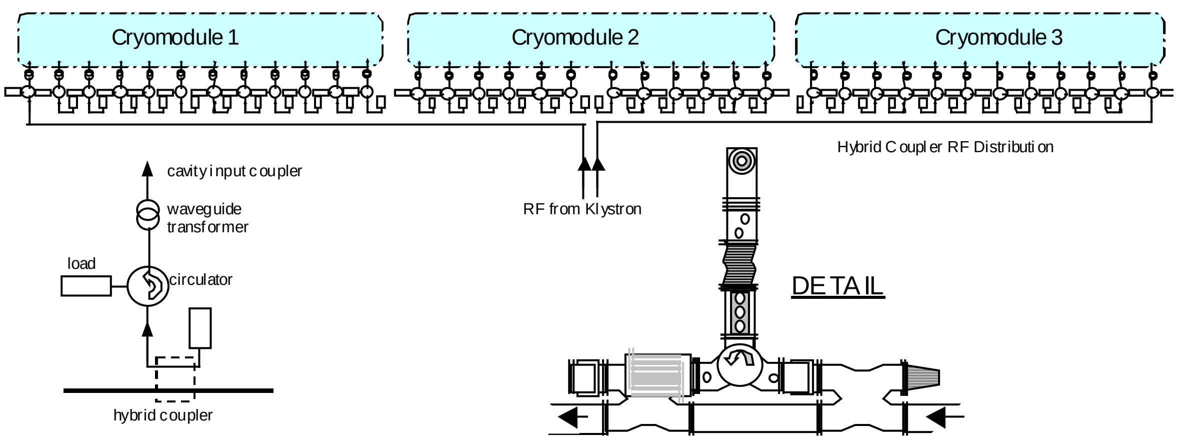

Fig. 4 RF waveguide distribution of one RF station

Circulators are indispensable. They have to protect the klystron against reflected power at the start of the RF pulse during filling time of the cavity and at the end of the pulse. In conjunction with load resistors and the power input coupler, they define the loaded cavity impedance as seen by the beam.

Only 4% of the average power generated by one klystron will be lost in the waveguides, additional 2% in the circulators. Thermal expansion will result in a RF phase shift of 6^{o} and 12^{o} for operation at full power and pulse duration at 5Hz and 10Hz respectively. This can be compensated easily by the waveguide transformers (three-stub waveguide transformer) installed between the circulators and each cavity. The waveguide transformers provide an impedance matching range from $1/3Z_W$ to $3.0Z_W$ and the possibility of $\pm 50^o$ phase adjustment. Each stub will be equipped with a motor, which will be controlled by the low level RF system.

The RF distribution system will be equipped with several interlock sensors, for instance for reflected power, sparking and RF leakage. Similar systems meeting these demands are in use at TTF. Additional information on the design criteria of the waveguide distribution system can be found in [14].

9. LOW LEVEL RF

The low level RF system controls amplitude and phase in the superconducting cavities of the linac. Fluctuations must be kept small in order to keep the energy spread below a maximum tolerable level of $5x10^{-4}$. The main source for perturbations are fluctuations of the beam current and fluctuations of the cavity resonance frequency due to mechanical vibrations and due to Lorentz force detuning. The amplitude and phase errors to be controlled are of the order of 5% and 20^o respectively as a result of the Lorentz force detuning and mechanical vibrations. These errors must be suppressed by a factor of at least 10. Long term variations (on the timescale minutes or longer) are counteracted by the use of cavity frequency tuners while fast variations are counteracted by a fast amplitude and phase modulation of the incident RF power. Since most of theses perturbations are of a repetitive nature, a fast feed forward system can be used. For non-repetitive pulse-to-pulse and intra-pulse variations a feed back system is required. The RF modulator for the incident wave is designed as an I/Q modulator to control the in-phase (I) and quadrature (Q) component of the cavity field. Each RF station has one RF modulator. Therefore only the vector sum of thirty-six cavities can be controlled. More detailed information of the LLRF system can be found in [15, 16, 17, 18, 19].

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