T.1: Indigenous development of high power microwave systems, line type and solid state advanced pulse modulators, microwave amplifiers and associated technologies for self reliance in particle accelerators

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High power microwave systems, for electron accelerators like 20MeV Microtron injector for Booster Synchrotron for Indus 1 and Indus 2, 8 MeV Variable energy microtron for Mangalore University, 10 MeV electron LINAC etc were designed, developed and commissioned with indigenous efforts. Test facilities were developed and supplied to microwave tube R & D lab, CEERI, Pilani, for development, ageing and evaluation of microwave tubes (2 MW S Band pulsed magnetrons and 5MW S Band pulsed klystrons) developed under collaborative efforts. The development of key technologies for advanced accelerators was also taken up. A 1.3 MW pulsed test stand at 352.2 MHz was successfully designed and developed to qualify devices, subsystems and components developed in-house for Indian as well as International collaboration projects. A solid state bouncer modulator operating at 100 kV, 20 A was successfully designed, developed and supplied to CERN under Novel Accelerator Technology, (NAT) collaboration in LINAC 4 project. Development of solid state bouncer modulator for 1 MW 352.2 MHz klystrons to drive 3 MeV RFQ at RRCAT is under progress. Development of RF systems at 1.3 GHz as well as SCRF prototype cavity characterization test set ups at 650 MHz/1.3 GHz are in progress for SCRF technology development. Design and development of 45 MW peak power S-Band test facility is underway. Further efforts on state of the art advanced pulse modulator design and construction for high power klystrons are also underway.

Typical RF/Microwave System

A typical RF/Microwave system consists of microwave generator, microwave driver amplifier, microwave tube (klystron or magnetron), pulse modulator, control/interlock system, waveguide transmission line and microwave vacuum window (Fig. T.1.1).

The characteristics and quality of the beam delivered by a particle accelerator also depends on the characteristics of the high power pulsed RF/Microwave fed to the accelerating cavities for creating the accelerating gradient. Various considerations on the rise time/fall time, flat top, ripple on pulse top, stored energy, as well as reliability and safety are the key factors in designing these high power systems. Faults or failures in the RF/microwave system or any of its constituent components affects the operation of the accelerator and this necessitates careful system design for eliminating or minimising accelerator turn down time

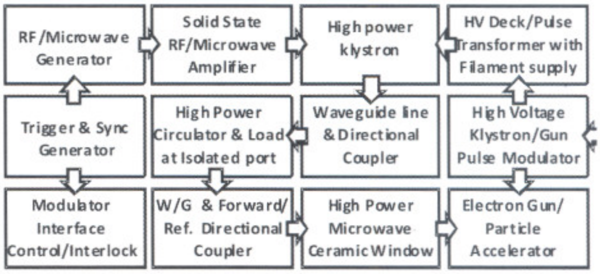

Fig T.1.1 A typical microwave system for accelerators

Self reliance with indigenous development of critical components and devices, efforts towards research, design and development of various high technology items required in the high power microwave systems for various particle accelerator projects was successfully achieved. Various high power RF/microwave systems built with indigenous efforts are listed in Table T.1.1.

Table T.1.1: Pulsed RF/Microwave systems developed for various applications.

Pk Pwr MW	Freq MHz	Pulse Characteristics			Application
		kV/A	PW µs PRR Hz	Device	
5	2856	110/90	3/1	Klystron	20MeV Microtron
5	2856	110/90	5/200	Klystron (CEERI)	Test facility
2	2998	41/100	2.5/200	Magnetron	8MeV Microtron
2.6	2998	41/100	2.5/200	Magnetron (CEERI)	Test facility
6.5	2856	55/280	14/300	Klystron	10MeV LINAC
1.3	352.2	110/24	800/2	Klystron	CERN
1.3	352.2	100/20	600/25	Klystron	3MeV RFQ
45*	2856	300 /335	4.5/10	Klystron	30MeV LINAC*

* under construction.

The pulse modulator generates pulses of specified time duration for operating various microwave vacuum tubes like magnetrons, klystrons etc. The pulse modulator or pulser produces a voltage or current waveform that permits the selected microwave source to operate properly. The microwave tube then converts the electrical energy received from the pulse modulator into the RF/Microwave by first bunching the electron beam inside the vacuum tube by means of buncher cavities and then extracting the RF/Microwave power by means of a resonant cavity at the output of the tube. The pulse modulated RF/Microwave is then applied to the resonant accelerator cavity. The pulse modulator stores the electrical energy, and then discharges a fraction or all of this stored energy into the load. To accomplish this discharge, it is necessary to provide a suitable switch that can be closed for a length of time corresponding to the pulse duration and maintained open during the time required to build up the stored energy again before the next succeeding pulse

The modulators contain some means of storing energy and switch to control discharge of energy into the load (tube). The energy may be stored in a magnetic field or an electric field. This stored energy is delivered to load and hence should be replenished by the power supply (Fig. T.1.2).

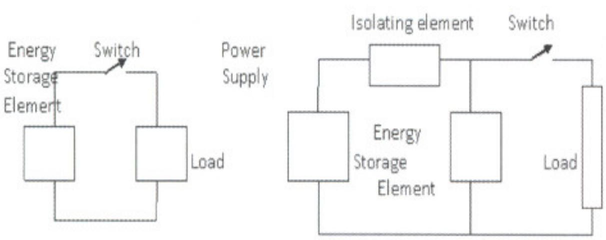

Fig. T.1.2: Basic modulator configurations.

There are three principle types of high voltage pulse modulators:

1) Line type modulator,
2) Hard tube modulator (referred as hard switched modulator in present article)
3) Converter modulator

In the line type-modulator all the energy stored in the storage device is delivered (dissipated) in the load during each pulse, while the hard tube modulator dissipates only some fraction of the stored energy during each pulse. Figure T.1.3 shows a simple line type modulator using a pulse forming line (equivalent to a lumped transmission line). Figure T.1.4 shows a simple configuration for a hard switched modulator in which a part of the energy stored in the storage capacitor is delivered to the load by means of a high voltage tube or a solid state stacked switch to the load. In the first case the duration of the pulse is determined by the pulse forming line components whereas in the second case duration is determined by the ON/OFF duration of the tube or the stacked switch.

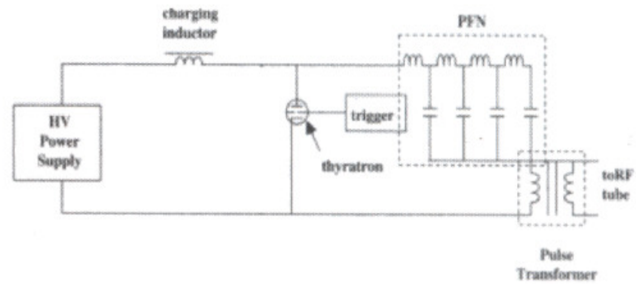

Fig. T.1.3: Line type modulator

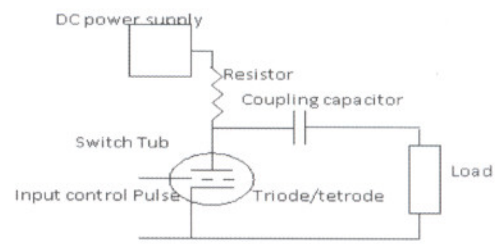

Fig. T.1.4: Hard tube modulator

Line-type/PFN Modulators Vs Hard-tube modulators

Hard-tube pulse modulators produce good rectangular pulse shapes for very long time durations with possibility of changing the pulse duration, can provide higher pulse repetition rates, have low jitter and permit wider load mismatches. The disadvantages of hard-tube modulators are poor efficiency, the need for higher dc supply voltage, greater circuit complexity and greater changes in delivered power for changes in dc voltage. With the advent of the solid state switches now most of these disadvantages are now eliminated and it is possible to make the hard switched modulators particularly for long pulse durations. On the other hand, keeping in mind the advantages of line-type pulse modulators it would not be surprising that these types of modulators are very widely used for producing high power pulsed microwaves using the microwave tubes as these are very simple to construct, the high voltage thyratrons which are used as switches are easily available. The line type modulators are mostly suitable for smaller pulse durations as the size of the PFN becomes limiting for very long pulse durations requiring good pulse shape.

Line Type Modulators

Pulse modulator shown in Fig. T.1.3 is "line-type" modulator because the energy-storage device is essentially a lumped component based transmission line. Since this component of the line type modulator serves not only as the source of electrical energy during the pulse but also as the pulse-shaping element, it is also commonly known as a "pulse-forming network," PFN.

If energy has been stored in the network by charging the capacitance elements, closing the switch will allow the discharge of this energy into the load. When the load impedance is equal to the characteristics impedance of the network, all of the energy stored in the network is transferred to the load, leaving the capacitors in the network completely discharged. Time required for this energy transfer determines the pulse duration and depends on the values of the capacitances and inductances of the network. The important parts of line type modulator are described below:

1) Capacitor charging power supplies

Conventional variac controlled as well as primary SCR controlled high voltage power supplies were used in earlier line type modulators at RRCAT. Subsequently SMPS based power supplies have been incorporated in modulators for 20 MeV Microtron as well as solid state bouncer modulators. Detail description of these power supplies is out of the scope of the present article.

2) Pulse Forming Networks

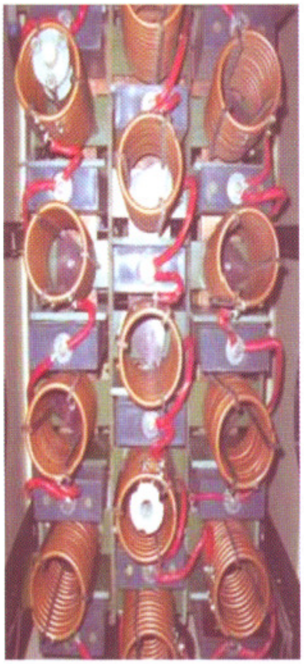

Fig T.1.5: Part of a 15 Section PFN for 55 kV klystron modulator for 10 MeV LINAC.

The pulse-forming network usually consists of inductances and capacitors, which may be put together, in any one of a number of possible configurations. The configuration chosen for the particular purpose at hand depends on the ease with which the network can be fabricated, as well as on the specific modulator characteristic desired. The values of the inductance and capacitance elements in such a network can be calculated to give an arbitrary pulse shape when the configuration, pulse duration, impedance, and load characteristics are specified. In our case we have standardised the PFN impedance to 12.5 ohms and the pulse transformer in each case is designed with proper turns ratio to match the impedance of the microwave tube to that of the PFN. Fig. T.1.5 shows the PFN constructed for klystron modulator 6 MW klystron for 10 MeV LINAC.

1) Hydrogen thyratron switch drives

A very commonly used switch in the line type modulator is hydrogen thyratron. An SCR can also be used for low voltage applications. Both these switches are closed by means of a proper trigger signal and open only when the current flowing through the devices drops down to zero or below a threshold value when all energy stored in the PFN is dissipated. This important property of the circuit makes it possible to take advantage of high current capacity and low voltage drop that are characteristics of gaseous discharge switches. Thyratrons have been extensively used in line type modulators at RRCAT. The main challenges lie in proper design of the triggering, filament and reservoir control and ranging these for long and reliable operation.

4) Pulse Transformers

Pulse transformers are used to isolate the load from the modulator. It is also used to match the impedance of PFN to the load to ensure maximum power transfer to load and avoid reflection.

Pulse transformers are designed specifically to handle square pulses and are precisely constructed to reduce pulse distortion. It is impossible to achieve ideal transforming and some distortion always occurs. In the pulse modulators listed in Table T.1.1, all the pulse transformers were designed and developed indigenously. The pulse transformers for the 5 MW S Band klystrons were developed with 1:10 turns ration and output voltage upto 130 kV. The pulse transformers for 2 MW S Band magnetron were designed with turns ratio of 1:10 and output voltage upto 47 kV. The most challenging task which could be accomplished was the design and development of 1:4 turns ratio, 55 kV, 260 Amp output pulse transformer for a long pulse duration of 16 microsecs and PRR upto 300 Hz which was used to pulse 6 MW S Band klystron for 10 MeV electron LINAC at RRCAT. A typical pulse transformer is shown in Fig. T.1.6.

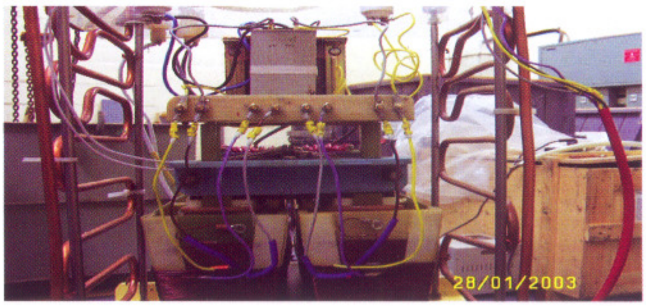

Fig T.1.6: The 55 kV pulse transformer for 6MW Multi-beam Klystron for 10 Mev LINAC constructed in house.

5) Trigger synchronization, control, interlocks

The electronic control and interlocks for the modulators weredesigned and developed and successfully implemented. Also necessary damping circuits for the protection of various high voltage components as well as microwave tubes were incorporated.

Microwave system for 20 MeV Microtron for Booster Synchrotron for Indus 1 and Indus 2

As indicated at Table T.1.1, the 5 MW microwave system for the 20 MeV microtron which is used as a pre-injector for the 450/700 MeV Booster Synchrotron for the Indus 1 and Indus 2 machines has been in successful operation since last 18 years. The 110 kV anode pulse to the 5 MW klystron is supplied through a line type modulator triggered by a hydrogen thyratron. The microwave system and accelerating cavity connected to microtron is shown in Fig T.1.7.

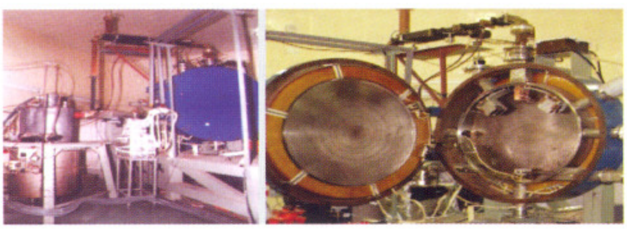

Fig T.1.7: 5 MW Microwave system and microwave cavity installed in 20 MeV Microtron at RRCAT.

As a part of continuous upgrade the microwave system was upgraded with command charging scheme as well as the driver klystron was replaced with a solid state S Band driver amplifier. Also features were included in the microwave system for short pulse operation to inject upto 60 nsec electron beam pulse into the Booster Synchrotron for single bunch operation for detailed studies.

Microtron Accelerating cavity optimisation and tuning

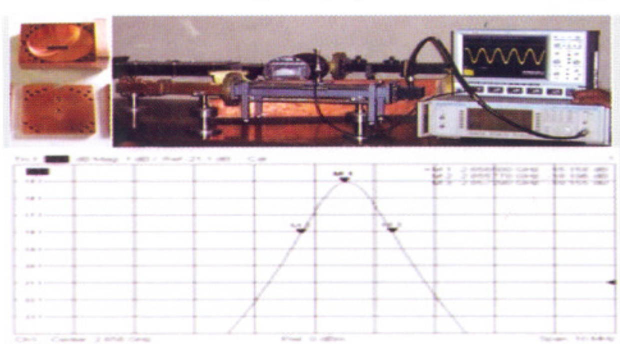

Fig T.1.8: Microwave accelerating cavity for 20 MeV Microtron during tests of resonant frequency and coupling factor. installed in 20 MeV Microtron at RRCAT.

The microwave accelerating cavities are tuned close to 2856 MHz and coupling coefficient of 2.63. This is done by means of stage wise measurements and machining of the cavity dimensions and coupling iris. The microwave accelerating cavities for the 8MeV microtron installed at Mangalore University are tuned at 2998 MHz.

6 MW peak power klystron based microwave system for 10 MeV, 10 kW LINAC

LINAC needs 6 MW peak power and 25 kW average power microwave system at 2856 MHz to achieve the rated specifications. For this a 6 MW peak power and 25 kW average power multi beam klystron was selected. A line type modulator for 15 MW peak and 90 kW average power capability was developed indigenously and is in operation.

The microwave system for LINAC consists of a stabilized signal generator, circulator, 200 W driver amplifier, circulator, directional coupler, and 6 MW klystron amplifier and waveguide system. The power from the signal generator is amplified up to 200 W by the driver amplifier, which in turn is fed to a 6 MW klystron. The power from the klystron is fed to the accelerator by means of a dual directional coupler, flexible waveguide, circulator, dual directional coupler and vacuum ceramic window. The klystron needs 55 kV, 270 Amp beam voltage pulse to achieve the rated output power. The specifications of the klystron are listed in Table T.1.2. The klystron modulator has been designed to give output pulse voltage of 14 microsecond duration see Fig. T.1.9. The specifications of the klystron modulator are listed in Table T.1.3.

The klystron modulator and pulse transformer are designed to supply also the gun voltage up to 55kV. The rise time, pulse top flatness, fall time and droop are achieved better than the specs. The rise time of the output pulse for the klystron modulator is <1s.

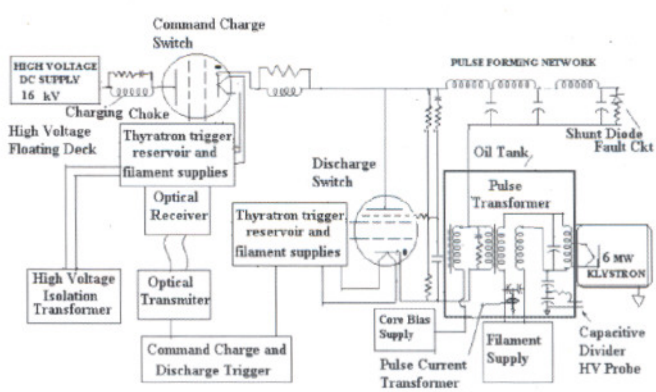

Fig. T.1.9: Schematic of 15 MW klystron modulator for 6 MW MBK for 10 MeV LINAC.

Optimization of the modulator component values yielded desired flat top response. Droop correction methods have been incorporated to achieve the low droop response. Subsequently the charging diode was replaced with a command charging thyratron isolated by means of optical circuits.

Table T.1.2 Microwave system specs.		
Peak o/p power	MW	6
Average o/p power	kW	25
Op. frequency	MHz	2856
Pulse duration	μs	12.5
Pulse repetition rate	Hz	280
Pulse top variation	%	±1
Pulse rise time	μs	<1
Pulse-pulse stability	%	<1
Table T.1.3 Modulator Specifications		
Pulse output power	MW	15
Pulse voltage output	kV	55
Output impedance	Ω	200
Pulse duration	μs	15
Rise time	μs	<1
Fall time	μs	<2
Flat top variation	%	< ±1
Mean output power	kW	90

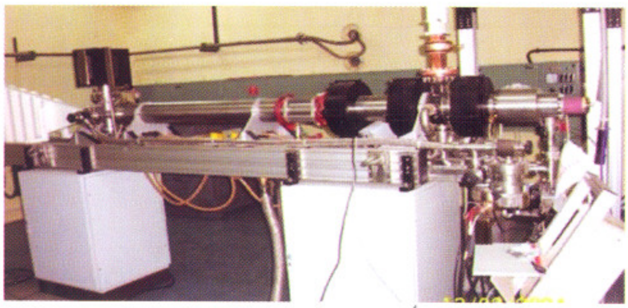

Fig. T.1.10: WR 284 waveguide line connected to the 10 MeV LINAC input power coupler.

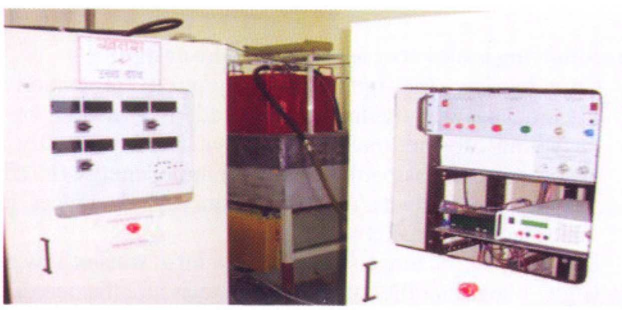

Fig. T.1.11: Microwave system installed in equipment room of 10 MeV LINAC.

WR 284 waveguide components

WR 284 waveguide components were designed and fabricated in-house for use in the microtron, electron LINAC at RRCAT as well as test facilities for the microwave tube development. We have developed straight as well as bent waveguide sections, dual directional couplers, high power microwave loads. In-house set ups were prepared and used to qualify the waveguide components to rated high power microwave input. Some of the WR 284 waveguide components developed at RRCAT are shown in Fig. T.1.12 and Fig. T.1.13.

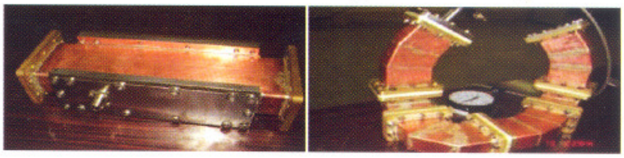

Fig. T.1.12: Left side wall type directional coupler, right various bends under high pressure tests.

Fig. T.1.13: Left ,loop type dual directional coupler undergoing lower power tests, right SiC load under high power tests on test stand.

WR 2300 waveguide components

For the development of pulsed high power RF systems for 3 MeV RFQ in-house development of WR 2300 waveguide components was launched. This was also necessary to prepare necessary test set ups and test facilities to test the high power klystrons received from CERN under NAT collaboration project. The waveguide components were designed using CST MWS and fabricated in RRCAT workshop using aluminium allow 6061 T6. Dual directional couplers, full height to half height transitions, waveguide to coaxial transitions, straight sections and bends were developed and tested. Prototype power coupling WR 2300 waveguide structures have been developed for the LINAC 4 project of CERN.

Fig. T.1.14: (Left) 352.2 MHz circulator under tests in WR 2300 test set up. (Right) WR 2300 waveguide Full height to half height transitions, Coaxial to waveguide adapter and straight sections developed at RRCAT.

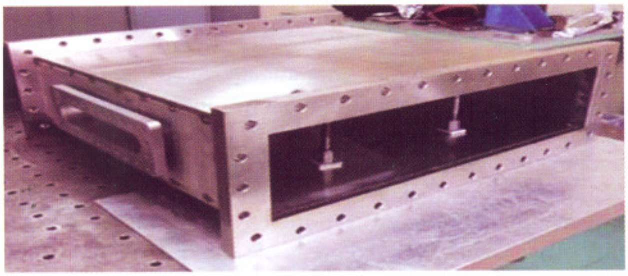

Fig. T.1.15: WR 2300 half height prototype power coupling waveguide developed at RRCAT for LINAC 4 project of CERN.

Prototype SCRF cavity characterization test set ups

For tests on the prototype half cell, dumbbell as well as single cell, cavity characterization and test set ups were designed and fabricated at 1.3 GHz. After qualifying the initial prototypes made in aluminium and copper, finally two niobium single cell cavities were constructed by RRCAT and tested, as shown in Fig.T.1.12. These were sent to FNAL for tests at Vertical Test Stand where the one of the cavity stood 23 MV/m accelerating gradient.

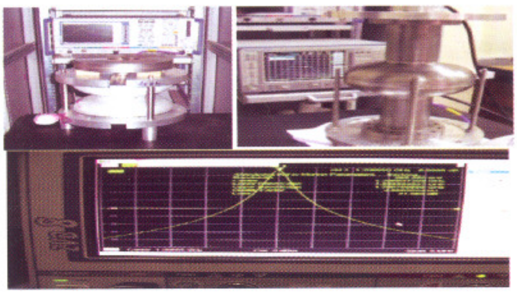

Fig T.1.16: From upper left modified dumb bell prototype test set up. Upper right niobium single cell cavity with resonant frequency trace shown beneath.

Characterization set ups for measurement of R/Q of single cell and multi-cell prototype 1.3 GHz SCRF cavities were designed and developed in-house.

Fig. T.1.17: A multi cell characterization set up for R/Q measurements on prototype 1.3 GHz SCRF cavities.

Solid state pulse modulators development

The simplest solution for a pulsed converter is a circuit where the voltage source is directly connected to the load through a switch as shown in Fig. T.1.10.

The challenge with running such a circuit at 100 kV is to obtain a switch that can handle the voltage level. Today there are still no existing solid-state modules that can singly operate anywhere near 100 kV. Currently the maximum available voltage rating of IGBT modules are about 6500 V. Switches that shall handle higher voltages therefore have to be based on arrays of several serial connected switches. Based on this technique, voltage levels up to 200 kV have been reached, but the technology is complicated and expensive. One way to avoid the high switching voltage is to insert a transformer between the switch and the load. For instance, a ten time reduction of the voltage will completely change the situation and allow for a wider range of available switches. However, to keep a satisfactory square shape of the pulse, a specially designed pulse transformer is required. The common power source for such applications is a capacitor bank connected to a standardized capacitor charger. However, a challenge with the capacitor bank is the voltage droop that will occur as the pulse energy is quickly extracted. This problem can easily be solved by adding capacitors until the droop is within the accepted range. Alternatively, some means of compensation system can be used. A bouncer circuit can be used for droop compensation.

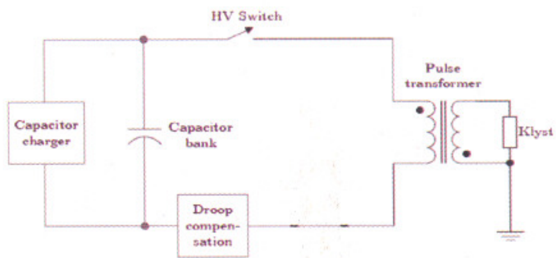

Fig. T.1.18: Solid state bouncer compensated Klystron modulator configuration.

Design considerations

The following issues are considered in the design:

- Crow-bar-less (no ignitron or thyratron) protection of klystron against arcing. The protection is assured by a) switching-off the main series switch very swiftly b) absorbing and dissipating the maximum of energy stored in the parasitic elements (stray capacitances, inductances, etc) inside the damping networks
- Low rise and fall time to limit the amount of wasted power
- High voltage stability of the flat top to assure the necessary phase stability of the RF output
- High reliability, minimum maintenance efforts and high lifetime due to solid-state construction

A effort was launched to start development of solid state modulators in the country. Initially an all solid state modulator was developed using series stacked MOSFET switches for output of 5 kV at 10microsecs, 10 Hz. Later a bigger switch upto 5 kV was developed and with the help of a 1:10 pulse transformer it reliably produced output upto 55 kV, 15 μsec with PRR upto 200 Hz. This is in used as an electron gun modulator for testing the indigenous electron guns, Fig. T.1.19.

Fig. T.1.19: 55 kV solid state modulator on (left) and high voltage electron gun test set up (right).

A solid state bouncer modulator with output 110 kV was successfully designed and developed. This has been supplied to CERN and commissioned there by RRCAT engineers under NAT Collaboration in LINAC4. See Fig. T.1.20.

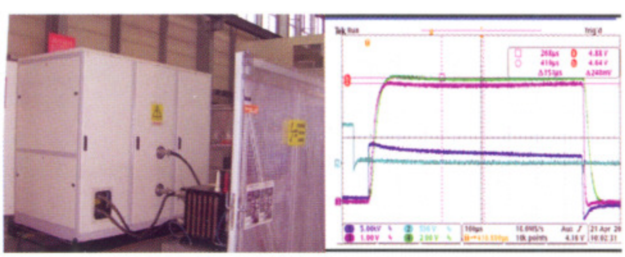

Fig. T.1.20: Bouncer modulator delivered to CERN and commissioned. Waveforms from top indicate output voltage 104 kV@20 kV/div, output current@5 A/div, primary voltage referred to ground, and bouncer switch voltage respectively.

Efforts are under way to design and develop advanced modulators based on Marx Modulator as well as Inverter Modulator designs keeping in view the future requirements of upto 1.3 ms, 50 Hz requirements for proton accelerator projects. A 1.3 MW 352.2 MHz test stand was developed to test and qualify high power klystrons, circulators and waveguide components under DAE CERN Collaboration. Two klystrons received from CERN under NAT collaboration were successfully tested up to 1.3 MW pulsed operation at 800 μs/2 Hz operation on these tests stands. Figure T.1.21 shows the photograph of the test stand at RRCAT and Fig. T.1.22 shows the results of these tests

Fig. T.1.21: (Left) 1.3 MW 352.2 MHz Test Stand at RRCAT, (right) the solid state modulator with PC based control system with touch screen GUI.

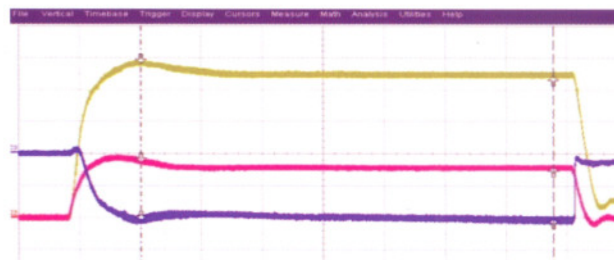

Fig. T.1.22: Klystron beam voltage96 kV , beam current 21 A and output RF power @1.25 MW, 352.2 MHz

.Solid State amplifier development

Solid State amplifiers are fast replacing the tube based devices in low and medium high power levels (Up to hundreds of kW) in the RF system of particle accelerators these are smaller, have very longer life, require less maintenance and are free of high voltages. PHPMS had been engaged in indigenous developing the technology for use in electron and proton accelerators as driver amplifiers for the high power klystrons and has acquired expertise in design and development of L-Band and S-Band solid state power amplifiers.

Amplifier development at L-Band

A 200 W, 1300 MHz pulsed amplifier system has been developed to be used as a driver stage for high power klystrons and for test and measurement of RF cavities and other L-Band accelerator components under pulsed conditions. The salient features of this amplifier are mentioned in Table T.1.4

Table T.1.4 Specifications of L -Band Amplifiers

Parameters	Value
Operating Frequency	1300 MHz ± 50 MHz
Output Pulsed Power	200W
Gain	≥50 dB
Pulse width	1.8 ms
PRR	10 Hz

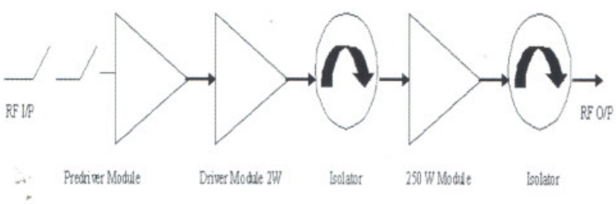

Fig. T.1.23: Simplified Block Diagram of Three stage 200 W Pulsed SSPA

The amplifier is designed as a three stage amplifier consisting of pre-driver, driver and high power stages. This modular design enables us to test each module separately and provides scope for further enhancement/modifications in case the need arises. All the three stages have been developed in house and fabricated using low loss RF Substrate.

The amplifier system is protected from any reflected power (which is common during testing of accelerator components) by use of isolator at the output. Protection mechanism to prevent amplifier damage due to overheat or overvoltage has also been incorporated.

L-Band LDMOS transistors were selected for driver and high power stages. The high power stage is developed using 50 V Dual LDMOS transistor operating in balanced configuration.

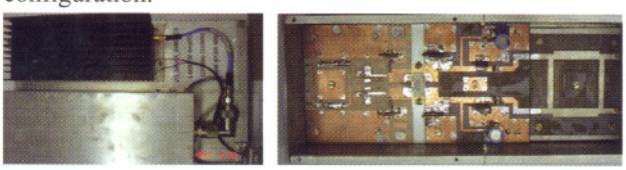

Fig.T.1.24. L Band 50 W and 250 W High power amplifier modules.

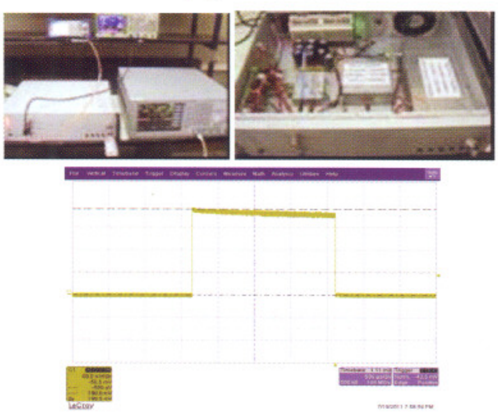

Fig. T.1.25: The 200 W Amplifier system at 1.3 GHz for SCRF cavity tests assembled in a 3U enclosure and output waveform as seen using a microwave diode.

The development of a 500 W CW amplifier at L-Band which will be used as source of RF power for the Vertical Test Stand (VTS) being developed in collaboration with FNAL USA is in the advanced stage of completion. The test stand will be used for characterization of SCRF 1.3 GHz cavities. The amplifier is realized by combining two 250 W stages using hybrid combiners and dividers. For driving high power stage a 50 W CW amplifier is developed driven by a broad band 1 W predriver amplifier. The driver amplifier is developed as an air cooled pallet which can be independently used to provide RF power required for testing of single cell cavities. The 500 W amplifier is a water cooled version to achieve higher efficiency and increased ruggedness.

Table T.1.5: Salient features of the 500W CW amplifier.

S.No.	Parameters	Value
1.	Saturated O/P Power	500 W
2.	Frequency Bandwidth	1270 MHz-1310 MHz
3.	Efficiency(overall)	40%

S-Band Amplifier development

S-Band amplifiers of up to 300 W of pulsed power have been developed for driving high power klystrons used in RF Systems of 10 MeV electron LINAC and 20 MeV pre-injector microtron in INDUS-II complex. Figure T.1.26 shows the 300 W S-Band pulsed module developed using NPN transistors combined via Wilkinson divider/combiners.

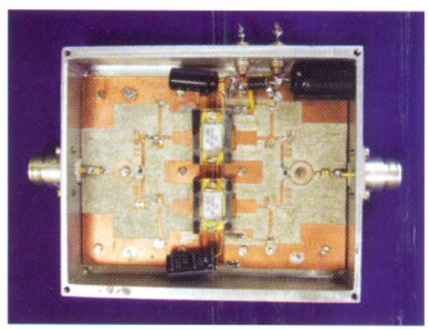

Fig. T.1. 26: 300 W S-Band amplifier module.

In order to drive 45 MW peak power klystrons required in RF system of proposed S-Band accelerator component test facility, the development of 1 kW S-Band pulsed amplifier was initiated and is under advanced stage of completion. Fig. T.1.27 provides the details of the amplifier design. The amplifier consists of four 300 W S-Band pulsed power transistors independently matched to 50 Ohms at the Input and the Output stage. These are then combined together using Wilkinson combiner and divider to attain 1 kW.

Among different combining approaches we have selected a two stage Wilkinson divider/combiner, Wilkinson design is simple and easier to realize on a planar circuit. Table T.1.6. presents the design specifications for the amplifier.

Table T.1.6: Amplifier Design Specifications

Parameter	Value
Operating Frequency	2856 MHz
Bandwidth	± 5 MHz
Output Power (Pulsed)	1 kW
Pulse width	10 μs (max)
PRR	100 Hz (max)
Gain	8.5 dB

The Wilkinson Divider and combiners have been designed and tested, these are fabricated on a 60 mil thick, 2.2 dielectric constant low loss substrate. Fig. T.1.28 shows the Wilkinson divider modules

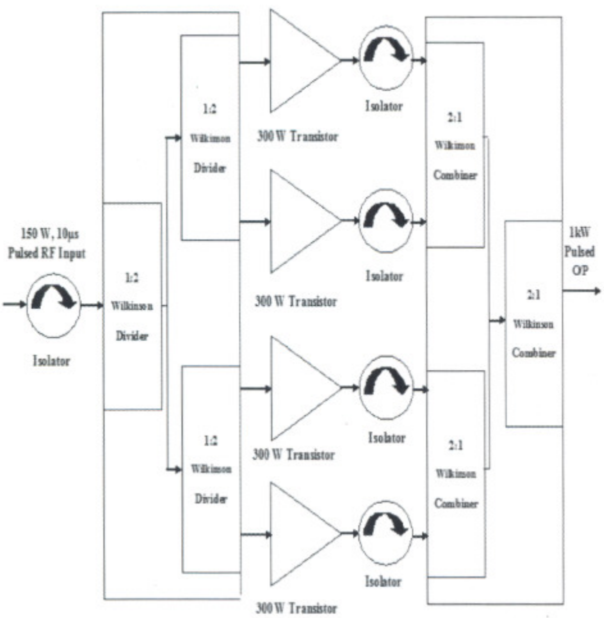

Fig. T.1.27: 1 kW S-Band Amplifier configuration

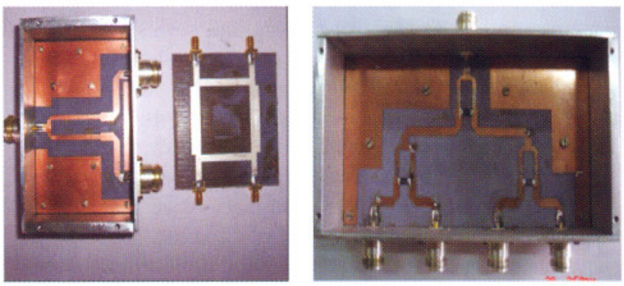

Fig. T.1.28: S-Band 2-way and 4-way power Dividers

Conclusion

Indigenous development of various technologies required for constructing the high power microwave systems, solid state modulators and solid state microwave amplifiers was achieved successfully. The RF/Microwave systems have been realised and used in the particle accelerators developed at RRCAT. The advanced technology components and subsystems have been developed and supplied to CERN LINAC 4 programme. Further developments are launched with collaborative efforts with CERN and FNAL.

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