12. PHOTOCATHODE GUN RF SYSTEMS

The rf power requirements of the 4-1/2 cell normal conducting electron injector are summarized in Table 12-1. The figures refer to a 5 μs rf pulse, i.e. the filling time is included in the power required to achieve gradient (see Chapter 5-RF Photocathode Gun)

Table 12-1 RF power requirements of the electron injector:

Resonator	rf power requirement	
	Peak	Mean
Rf-gun	1.2 MW	60 kW
Accelerating cavity 1	2.5 MW	125 kW
Accelerating cavity 2	2.5 MW	125 kW
Accelerating cavity 3	2.5 MW	125 kW
Total	**8.7 MW**	**435 kW**

To obtain maximum flexibility for the adjustment of the flat beam parameters, the preferred solution is an arrangement of four independent rf chains. This allows full advantage to be taken of fast individual control of each resonator by a digital controller acting directly on a low-power vector modulator, avoiding the use of a high-power rf distribution network with ferrite phase shifters and attenuators.

The structure of each chain is then very similar to the linac rf systems shown in Chapter 5-RF Photocathode Gun with a low power regulating system implemented in digital technology feeding the high-power part consiting of klystron, HV supply or *modulator* and circulator. The high-power part, however, is operating in pulsed rather than CW mode which leads to specific design considerations for the HV power supply (see *Modulator* below).

KLYSTRON REQUIREMENTS

The requirements for the klystrons remain well within reasonable technological limits. Units have been built at much higher and lower frequency bands with substantially higher output powers, in terms of peak as well as average ratings. The choice in L-band is nevertheless rather limited. A klystron that comes close to our requirements is the E3718 from TOSHIBA, described in Table 12-2 [1]. It has been built in small quantities for the Japan Nuclear Cycle Development Institute (JNC), and could be used for our proposed facility after re-tuning from 1249 MHz to the frequency of 1300 MHz. The maximum power output covers the requirement with large reserve, even taking unto account that the useable range is only about 90% of the indicated saturated power limit. The system design considerations are tentatively based on this klystron, pending availability of suitable devices from other manufacturers. This choice may be revised later.

Table 12-2 TOSHIBA klystron E3718

Operation mode	CW	Pulsed
Rf frequency	1.249 GHz	
Rf power	1.2 MW	4.2MW
Efficiency	65%	50%
Beam voltage	90 kV	147 kV
Cathode current	25 A	56.5 A
Drive power	12 W	15 W
Pulse width	-	800 μs
Repetition rate	-	250 Hz

Even though the required power for the rf-gun is less than half of those for the cavities, it is proposed to provide the same rf system in all four chains. This allows overpowering of the resonator of the electron gun to reduce the filling time. It also enhances maintainability and simplifies the logistics.

MODULATOR REQUIREMENTS

Taking the klystron described above as a realistic starting point, the required modulator voltage is 150 kV, together with a peak output power of 5 MW for a klystron efficiency of η=0.5, augmented by 10% reserve. The requirements for a single rf system are given in the Table 12-3.

Table 12-3 Modulator requirements

Parameter	Required values
Modulator voltage	150 kV
Modulator peak power	5.5 MW
Pulse repetition time	100 μs (rep. rate 10 kHz)
Pulse duration	5 - 7 μs
Pulse rise time	500 ns
Duty factor	5 - 7 %
Modulator average power	275 - 385 kW

An adequate design goal for the risetime of the modulator pulse is ~500 ns. This allows consideration of the full range of modulators, based on thyratrons or on semiconductors, where the rate of current rise is a limiting factor. On the other hand, this risetime is still short in comparison with the rf pulse length, and it leads to a reduction of less than 3% in the cavity voltage at the end of the 5 μs pulse for a cavity with Q_0 = 24000 (less reduction for lower Q_0). Alternatively the klystron beam can be switched on 500 ns earlier than the rf pulse to get full rf power capabilities immediately and maximum cavity field, at the expense of a 10% increase in the average power consumption. Either possibility or combination thereof is acceptable, with the best compromise to be found in practical operation.

If the stored energy in the gun cavities is to be removed actively by reversing the drive phase after the bunch has been accelerated, the nominal 5 μs pulse is extended to 7 μs, as shown in Table 12-3.

Implementation of the modulator

The key element in the modulator is the high-power switch. One elegant possibility to pulse a hypothetical custom-built klystron is to provide *internal* beam modulation capabilities, such as a modulating anode or a laser-driven photocathode. However for existing klystrons *external* pulsing is necessary. Excluding more exotic possibilities like a hard-tube modulator or a *Hobertron* (Hollow beam valve) there remains a choice between vacuum-tube technology and semiconductor technology. Three feasible designs are presented, namely two *line type* modulators based respectively on a thyratron and on a semiconductor *thyratron replacement* switch, and finally an *induction modulator* with composite semiconductor switch.

A. Line type modulator with thyratron switch. This well-proven technology consists of the following modules [2]:

A1.Thyratron: This is a Turn-ON only switch, based on triggered avalanche conduction in a hydrogen or deuterium-filled tube. Conduction has to be stopped by current reversal in the external circuit which determines the pulse duration. This is performed by a pulse forming network (PFN) that is described below.

For the present application there are two main critical thyratron parameters:

- The time necessary for the de-ionization of the discharge path. This limits the applicable pulse rate in standard units to 400 Hz, respectively to 50 kHz in special units.
- The average current, which determines the average amount of ion bombardment of the cathode. It is usually limited to a few amperes, whereas the requested rating is of the order of 10 A.

Either limitation may be overcome by means such as extensive de-rating or parallel connection of several klystron/PFN assemblies into a common pulse transformer.

Table 12-4 gives the thyratron specifications required, supposing a PFN charged to 40 kV. Parameters of readily available units are shown in columns 3 and 4.

Table 12-4 Thyratron parameters

Parameter	Value		
	Proposed system	CX2412 (Marconi)	CX 1635A (Marconi)
Peak voltage [kV]	40	60	20
Peak current [A]	275	15000	1000
Average current [A]	13.8	15	1
Rate of current rise [kA/μs]	0.7	75	100
Pulse rate [kHz]	10	5	50

It can be seen that all specifications except the pulse rate can be met by the thyratron CX 2412, and that on the other hand a *fast* thyratron such as the CX 1635A falls short in terms of power handling capability (peak voltage and average current). The ratio (average current)/(peak current) of thyratrons is generally of the order of 10^3, whereas the application requires $\geq 5 \times 10^3$. The choice of a thyratron in this case is therefore governed by the available average power, with a large reserve in peak power.

It is possible that a thyratron can be found that meets all the specifications in a single unit, but the use of two thyratrons in parallel has to be envisaged. Investigations with a manufacturer are under way.

A2. Pulse forming network (PFN): The PFN is essentially a low-pass LC network composed of HV capacitors and inductors, optimized to deliver a near to ideal square pulse of a given duration when discharged. The PFN behaves like a transmission line with a characteristic impedance Z and a delay time τ which is half the required pulse duration due to the full pulse reflection at the far end. Here $Z = 20 \times 10^3 / 275 = 72.7\Omega$ and $\tau = 2.5\mu s$.

The load has to be matched to the characteristic impedance Z, the output voltage is then half the charging voltage. The $V * A$ rating of the switch has therefore to be twice the load power.

The capacitors should exhibit low series inductance and use self-healing dielectric. The coils are of the air-core type, mutually coupled and individually adjustable by field displacement plungers.

The ratio between voltage and current of the switch determines the characteristic impedance of the line. It can be varied over a wide range to match all requirements. The number of LC sections determines the quality of the output pulse in terms of risetime and flatness of the pulse top. Variable characteristic impedance along the line may be necessary to compensate for the droop caused by the magnetizing current of the pulse transformer. The PFN may pose some technical problems but is not a critical element.

A3. Pulse transformer A pulse transformer is necessary to bridge the gap between the very high voltage needed by the klystron and the lower voltage that practical switches can sustain. Pulse transformers with step-up ratios 1:3 to 1:25 are in current use. Since klystrons are operated

with the anode at ground potential, the cathode together with the filament connection is at high negative potential with respect to ground. A bifilar or coaxial secondary winding is therefore necessary to carry the filament power to the cathode. The pulse transformer is usually housed in an oil-filled cubicle for reasons of HV insulation, cooling and reduction of acoustic and electromagnetic interference.

For a PFN charging voltage of 40 kV the resulting primary voltage is 20 kV and a transformer ratio of 1:7.5 is necessary to achieve a secondary voltage of 150 kV. A practical design has been devised and described in Reference [2]. It is assembled from three cores, each of outer diameter = 500mm, inner diameter = 200 mm, height =100 mm, wound of METGLAS 2605SA1, 20 micron thick, from Allied-Honeywell. The high permeability of this material leads to a low magnetizing current, and the high saturation limit of 2.5 T allows a low number of turns to be used. This feature is important to minimize the stray inductance, which is further minimized by the winding layout. The primary winding consists of two legs of 3 turns each, connected in parallel and distributed over the circumference; the secondary of 30 turns is arranged with variable spacing according to the increasing voltage from turn to turn.

The calculated stray inductance of this winding layout is only ~ 45 μH, supposing that the entire core cross-section is free of magnetic flux when the primary winding is short-circuited. The real conditions depend critically on the layout of the primary winding and are therefore difficult to take into account. Even if the real stray inductance is twice as large the resulting transformer risetime of ~ 67 ns is still small compared to the permissible overall risetime of 500 ns. This large margin can either be used to reduce the rate of current rise in the switching element by slowing down the input pulse, or the number of transformer turns can be increased to reduce the core losses and the magnetizing current. The best compromise has to be found by practical tests.

The cores are operated at 0.025 volt-seconds, which together with an effective core cross-section of 31 * 10^{-3} m^2 leads to a magnetic induction swing of 0.806 T. The core loss at this modest induction is estimated at about 100 J/m^3 for the pulse duration of 5 μs, the total dissipation in the effective core volume of 34.7×10^{-3} m^3 is then about 3.5 J per pulse or about 4 J per pulse together with the copper losses. At a pulse repetition rate of 10 kHz, the transformer losses amount to 40kW.

If better performing but more expensive core material such as 2714, 2705M or Finemet is chosen, then the core losses could be reduced to less than 2 Joules per pulse for an efficiency of about 95%.

Could a single pulse transformer feed all four klystrons in parallel? The core losses remain the same, but the copper losses would increase by an order of magnitude, and the risetime by a factor of four. A detailed technical study is needed to ponder this possibility. The same applies for an increase of the pulse length to 6 μs to allow one additional microsecond for phase reversal at the end of the rf pulse.

Going to a significantly higher repetition rate, however, would necessitate a complete rethinking of the pulse transformer to raise the efficiency and master the cooling problems.

A4. Resonant charger: essentially a switched inductor that transmits charge from a storage capacitor to the pulse forming network (PFN), doubling the voltage in the process. The value of the inductor is chosen such that the resulting resonant charging current resets the core of the pulse transformer.

A5. Charging supply: A regulated AC/DC converter, which rectifies the 60 Hz supply voltage and charges a storage capacitor to 20 kV. The precision of this DC voltage determines the precision of the pulsed output voltage of the modulator. The charging supply with average AC input power of about 350 kVA is at the same time the major cost element.

B. Line-type modulator with solid-state "thyratron replacement" switch.

The tendency to replace thyratrons in existing systems by solid-state devices is in full swing. Switch modules containing 3 to 6 thyristors or SCR's together with drive electronics and rated 10 to 12 kV are available from at least two manufacturers [3,4]. The switches are of the *Turn-ON* only type therefore a PFN is needed as before, the topology of the modulator remains unchanged.

Table 12-5 shows the relevant parameters for the two available semiconductor modules in columns 3 and 4, column 2 giving again the project requirements. In both cases the series connection of three modules is assumed to comply with a PFN charging voltage of 27 kV. With these devices the rms current has to be taken as a yardstick of multipulse performance (contrary to thyratrons where the *average* current is the limit).

Table 12-5 Parameters of available "Thyratron replacement" solid-state switches

Parameter	Value		
	Proposed system	"10 kV module" (Applied Pulse Power)	EFM-SPR 08F4500-6-WC (Asea Brown Boveri)
Peak voltage [kV]	27	3x10	3x12
Peak current [A]	407	8000	1500
RMS current [A]	91.1	>35 (not tested)	94.8
Rate of current rise [kA/μs]	1.02	30	1.5
Pulse rate [kHz]	10	> 0.06 (not tested)	> 0.4 (not tested)

The *10 kV module* from Applied Pulse Power has an impressive margin in peak power capability. Maximum rms current and maximum pulse rate are neither tested nor specified. According to the manufacturer, the given data represent the limits of the test power supply rather than the device. Successful tests with the series connection of three modules are reported, in normal mode and under fault conditions.

The module *EFM-SPR 08F4500-6-WC* from Asea Brown Boveri meets all requirements except pulse rate. Again it is not clear whether the latter represents a limit of the device or the test facilities. The possibility of series connection is explicitly mentioned in the device description.

Both devices show promise for the present application. In general, the ratio of mean power/ peak power is considerably larger than in thyratrons, hence these devices are more suitable for high duty factor. It is conceivable that the apparent pulse-rate limit is the result of the test setup restraints but does not reflect the inherent capabilities of these devices. According to catalog data the circuit-commuted turn-off time of similar devices is of the order of ~50 μs therefore operation at 10 kHz and higher should be possible, but the maximum obtainable pulse rate remains a critical parameter.

C. Induction modulator with semiconductor ON-OFF switch

This approach is based on *Turn-OFF* switches such as IGBTs (Isolated Gate Bipolar Transistor) or MOSFETS (Metal Oxide Semiconductor Field Effect Transistor). They allow full control of current flow, into the conducting as well as non-conducting state. The pulse length is no longer determined by a pulse forming network, but by the drive pulse to the switches which can be adjusted by computer control. These devices work at peak voltages up to 3 kV.

The operating principle of the induction modulator or inductive adder is similar to an induction linac. It permits a high voltage transformation ratio to be obtained with low stray inductance, resulting in short pulse risetime. A secondary winding passes through a number of induction cores which are driven individually, enclosing their total rate of change of magnetic flux, hence adding the output voltages. An arrangement of n individual cores is also said to consist of n (or $1/n$) *fractional turns* with respect to the common secondary. While the initial concept is based on a single turn in primary and secondary windings, the method is also applicable to an arbitrary number of either turns, to accommodate electromagnetic and dimensional constraints.

Table 12-6 gives in columns 3 and 4 the characteristics of induction modulators of existing and proposed systems. Column 3 shows the parameters of the *CLW* modulator (named after its inventors, Crewson, Lindholm and Woodburn) that is used in a commercial cancer treatment system from Scanditronix and in the Japan National Cancer Center [5]. The power is controlled by eight 1-kV modules equipped with IGBT switches, which take the required energy from a common storage capacitor. A sophisticated winding scheme for the primary turns is used to assure that at least two independent switches feed each fractional core, to assure that the core is always energized and to prevent overvoltages in case of trigger malfunction.

Column 4 shows the data of a replacement project for the conventional SLAC 5045 klystron modulator [6]. The huge peak output power is needed as a common source for eight klystrons. Each core is driven by two PC boards with one 3.3 kV IGBT per board that can be easily exchanged for maintenance. Freewheeling reverse diodes protect the semiconductor switches.

Table 12-6 Parameters of induction modulators

Parameter	Values		
	Proposed system	CLW modulator (operating)	SLAC 5045 Replacement (Project)
Peak output voltage	-150 kV	-140 kV	-500 kV
Peak output current	36.7 A	95 A	2120 A
Peak output power	5.5 MW	13.3 MW	1060 MW
Duty factor	$50 * 10^{-3}$	$3 * 10^{-3}$	$0.36 * 10^{-3}$
Average power	275 kW	40 kW	382 kW
Pulse width	5 μs	3..10 μs, variable	3 μs
Pulse risetime	0.5 μs	0.4 μs	0.4 μs
Pulse repetition rate	10 kHz	0.3 kHz	0.12 kHz
Number of secondary turns	30	70	3
Number of "fractional" turns	3	2	80
Switches / fractional turn	2	4	2
Peak voltage at switch	1.67 kV	1 kV	2.1 kV
Peak current at switch	0.55 kA	1.6625 kA	3.18 kA
Peak power at switch	0.917 MW	1.6625 MW	6.67 MW
Average power at switch	45.85 kW	5 kW	2.4 kW
RMS current at switch	123.1 A	91.1 A	60.3 A

Column 2 shows a possible design for the proposed femtosecond Xray source based on the same pulse transformer as described above. Compared to the other two examples its ratings are very conservative except for the average power together with the pulse repetition rate. The IGBT proposed for the SLAC project, part FZ80033KF1 from EUPEC, is rated for an RMS current of 800 A and should be able to provide the required 123 A with large reserve, supposing adequate cooling. Again the turn-off time with respect to the maximum obtainable pulse rate needs clarification with the manufacturer.

Summary of pulsed rf gun systems

The rf system for the photocathode rf gun is entirely feasible for 10 kHz repetition rate and can be implemented with very small development risk. All three modulator concepts appear to be feasible by reasonable extrapolation of similar existing equipment. The maximum obtainable pulse rate is a critical parameter in all designs. A technical study is required to investigate the different possibilities in close contact with component manufacturers.

The most attractive concept is Variant C, the induction modulator. It provides the reliability of low-voltage ground-referenced components, the flexibility of pulse length control and the convenience of a uniform modular structure. The superiority of semiconductor solutions may make the thyratron technology obsolete and lead to procurement problems in the long run.

Last but not least the cost may be a factor in the final decision.

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