DEVELOPMENT OF THE INR LINEAR ACCELERATOR DTL RF SYSTEM

A.V.Feschenko, A.I.Kvasha, V.L.Serov
Institute for Nuclear Research, RAS, Moscow

Abstract

Regular INR DTL RF system operation has started in 1992. By this point three new vacuum tubes, designed especially for INR linear accelerator, have been manufactured at “Svetlana” association in the amount sufficient for RF system operation for 20 years. Among them were two vacuum tubes for final and intermediate RF power amplifiers, GI-54A and GI-51A correspondingly, as well as one vacuum tube for powerful anode modulator – GMI-44A. In the late ‘80s the manufacture of these vacuum tubes was terminated and in 1990 development of new vacuum tube for RF output power amplifier instead of GI-54A has started. The new vacuum tube GI-71A with the output pulse RF power up to 3 MW, plate power dissipation up to 120 kW and power gain about 10 became simpler and less expensive in comparison with GI-54A. The transition to new vacuum tubes started in 1999 and completed in 2014. Successful test of GI-57A for preliminary RF amplifier was fulfilled in 2008 and opened the possibility to replace GI-51A. As for the modulator tube GMI-44A no vacuum tube with the required parameters produced in Russian Federation was found and a decision to use the RF power amplifier tube GI-71A instead of the modulator one has been done.

Below some problems connected with the vacuum tubes replacement and the main results of twenty years DTL RF system operation are described.

INTRODUCTION

Brief reference. *INR linear accelerator is in regular operation since 1993. The accelerator consists of two parts. The low energy part operates at the frequency of 198.2 MHz and includes RFQ, five Alvarez tanks and seven RF amplifier channels including a spare one. The second part operates at 991MHz and includes 28 disk and washer cavities. At present, the accelerator operates with beam pulse length up to 200 µs, repletion rate up to 50Hz and beam pulse current up to 15 mA.*

Each RF channel includes the following units:

- One solid state and four vacuum tube amplifiers;
- Vacuum tube plate modulator (AM) for the first and the second vacuum tube RF amplifiers;
- Powerful vacuum tube plate modulator (PAM) for the two last RF amplifiers;
- Coaxial line between the final RF power amplifier (FPA) and Alvarez tank with the switch enabling to connect any tank with the spare channel instead of a faulty one.
- High voltage power supply for powerful modulator including artificial forming line (AFL) with the impedance of 24 Ohm.

The simplified structure of RF channel is given in fig.1.

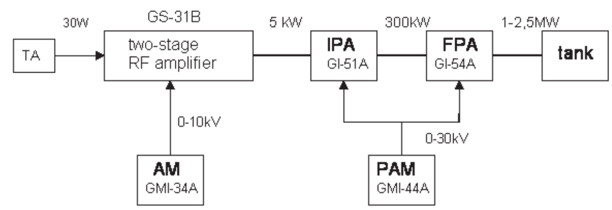

Figure1: Simplified structure of the DTL RF channel (TA – solid state RF amplifier, IPA - intermediate power RF amplifier, FPA - final RF power amplifier).

The pictures of vacuum tube RF amplifiers are shown in figures 2÷4.

Figure 2: Two-stage RF amplifier.

Except for the tubes GS-31B and GMI-34A developed earlier and being manufactured for a long time the following vacuum tubes have been specially developed for INR accelerator:

- Modulator triode GMI-44A with magnetic focusing. Due to the magnetic field the plate-grid characteristics are similar to those of tetrode with small grid current

ISBN 978-3-95450-181-6

and small plate-cathode voltage (*Uak*) of the open vacuum tube. These features enable to decrease the pre-modulator pulse power and plate voltage. Emission current of the tube is up to 500A, plate voltage - up to 60kV and plate power dissipation – up to 150 kW.
- Powerful pulse triode GI-54A for RF final power amplifier (FPA) with the output pulse power up to 4MW and pulse plate voltage up to 40kV. Average power dissipated at the plate is up to 400kW.

Figure 3: Intermediate power RF amplifier.

- Pulse tetrode GI-51A for RF intermediate power amplifier (IPA) with output pulse power up to 400kW and pulse plate voltage up to 40 kV. Average power dissipated at the vacuum tube plate is up to 30kW.

Unfortunately the above listed vacuum tubes didn't find application in other Russian accelerators. This circumstance has predetermined the termination of tube production and hence the need to rework the DTL RF system. However, the amount of tubes manufactured in 70s and 80s appeared to be sufficient for twenty years accelerator operation with 2-3 thousand hours annual accelerator run duration.

FINAL POWER AMPLIFIER

The tubes GI-54A appeared to be too expensive especially in case of small scale production (real life time of the tubes was from 5 to 6 thousand hours thus giving the annual need of only 2-3 units).

In early 90s a decision to develop a new tube with lower cost at the expense of acceptable decrease of several parameters was jointly made by INR and JSC "SED-SPb" (former "Svetlana" association). The requirement was to keep electrical and mechanical parameters of the new tube as close as possible to those of the old one with the aim to diminish reworking of the existing equipment of FPA especially the anode-grid cavity.

Figure 4: Final RF power amplifier.

Initially a pirographite grid having important advantages over the metallic one [1] was planned to be used. Unfortunately it was abandoned due to too big expenses for maintenance of pirographite grids production which is of special importance for small market of new tubes. Due to possible deformation of the cathode and the grid the gap between them influencing the gain cannot be smaller than 2-3 mm. That is why even in spite of large cathode surface the gain of new GI-71A tube appeared to be only 10 while for GI-54A this parameter was 25.

The first DTL RF channel has been reworked for the use of new tube in 1999 and the first GI-71A tube started to be used in regular accelerator runs. The process of tubes replacement lasted till 2014 when the stock of GI-54A became completely exhausted.

The biggest modifications were related with cathode-grid cavity and filament circuits. The plate voltage had to be increased by several kV as well to compensate gain reducing.

Generally there are two basic configurations of the RF amplifiers corresponding to one or two-sided arrangement of the anode-grid and cathode-grid cavities with respect to the tube (fig. 5). The one sided configuration is more

ISBN 978-3-95450-181-6

compact and easier to tune but requires special blocking capacitor to supply high voltage to the plate. The RF discharge in the grid-plate cavity does not result in high voltage breakdown between the plate to the ground and hence does not affect the HV modulator.

It is still since times of the proton linear accelerators I-2 (ITEP) and I-100 (IHEP) the second design of FPA has been chosen as the primary one (see fig.5, right). In the last case FPA design is simpler and allows increasing a gap between the inner and outer tubes of coaxial anode-grid cavity. In turn, increasing of the gap reduces the risk of RF breakdowns in plate-grid cavity. Gap size limit is determines by the wave length of the nearest high order mode H_{11} with critical wave length $\lambda_k \sim \pi (R + r)$, where R and r are outer and inner radiuses of the anode-grid coaxial cavity. Supposing equality of wave lengths of H_{11} and operation modes (λ_0) it is easy to determine possible value of the gap (g) between inner and outer tubes of coaxial cavity:

$$g = \frac{\lambda_0}{\pi} - d$$

In the last expression *d* is diameter of inner tube. Thus, as follows from fig.5, two-sided arrangement of the plate-grid cavity really decreases a danger of RF breakdowns due smaller value of *d*. The vacuum tube installation is plate down. High voltage pulse at vacuum tube plate enters at the inner tube in RF electric field node.

Disadvantage of the chosen FPA design is high voltage at the inner tube of coaxial plate-grid cavity. As the result, RF discharge in the grid-plate cavity can result in high voltage breakdown between the coaxial cavity inner tube and the ground and hence affect the HV modulator.

That is why excess pressure was foreseen in the anode-grid cavity, because increasing of outer diameter of the coaxial cavity is impossible due risk of H_{11} mode excitation.

Experience of operation with excessive pressure [3] has shown a possibility to get a pulse power at the FPA output near 4 MW in matched load. But a lack of qualified staff and the situation in the early 90s didn't allow realizing the excessive pressure in all RF channel.

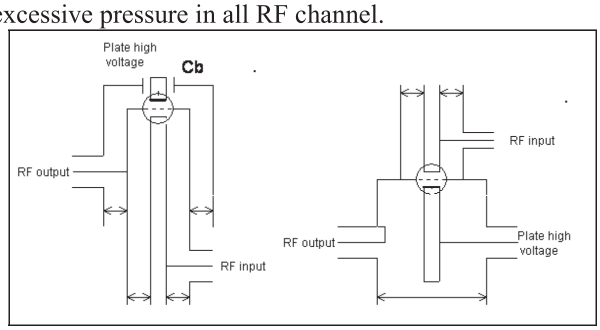

Figure 5: Drawings of two main decisions of FPA design.

So in INR FPA from the very beginning the decision was made to refuse from the excess pressure despite of possibilities, laying in design (see fig.4). At that, the procedure of vacuum tube exchange is simplified (In LANSCE FPA with excess pressure it is required about 16 hours to exchange the vacuum tube [4]), but the danger of breakdowns in the anode-grid cavity, surely, grows.

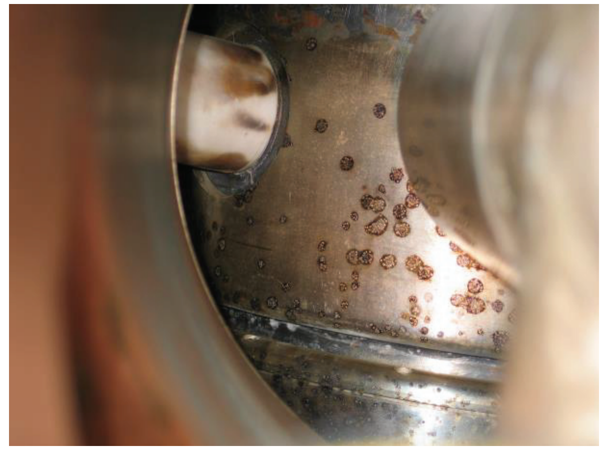

Figure 6: Traces of breakdowns in FPA plate-grid cavity.

At fig.6 picture of the plate-grid cavity inner tube in the region of the loop is shown. Shot has been made in FPA of the first RF channel that operates the longest. Breakdowns in the FPA plate-grid cavity are payment for operation without excessive pressure. At that, if sparking quantity in vacuum tube decreases in process of aging, breakdowns in the cavity, on the contrary, can grow due, for example, pollution of inner surface. The problem can be solved by means of the series crowbar system only [2].

CROWBAR

The series crowbar interrupts beam acceleration for 1-3 second, whereas the traditional crowbar, that entirely discharges the artificial forming line, stops accelerator operation for 10-15 min. The last time determines by peculiarities of the DTL tank frequency control system (FCS). The point is that during operation of the INR Linac with duty cycle value 0.02, RF power, dissipated in the DTL cavity, results in the considerable cavity detuning.

It should be noted, that frequency control system is realized by means of Alvarez cavity drift tubes temperature control. So before input RF power in the cavity drift tubes have to be warmed up to the resonance temperature.

With the rise of RF power in the tank temperature of cooling water has to be decreased so that resonance temperature of the cavity metal was unchangeable. And, on the contrary, after RF channel switching off the water temperature has to be warmed up to the resonance temperature [5]. Really it takes nearly 10-15 min for warming up drift tubes cooling water after RF channel failure. That is why the series crowbar essentially increases efficiency of accelerator operation.

ISBN 978-3-95450-181-6

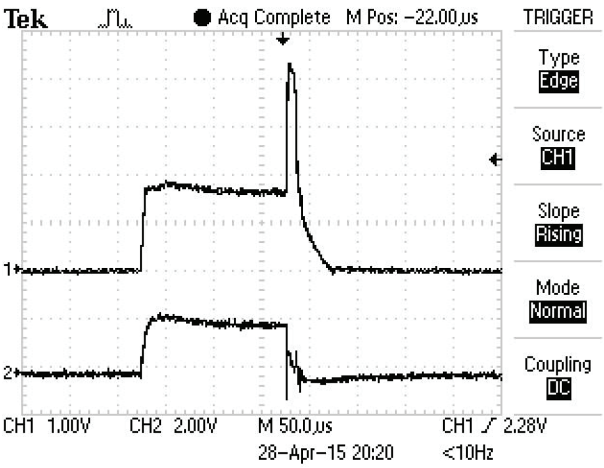

Figure 7: Series crowbar operation. Upper trace is modulator vacuum tube plate current, lower trace is modulator output pulse.

Thus, design of the FPA, quality of the FCS, and choice of crowbar system are interdependent. At fig.7 snapshots of the modulator output voltage and plate current are presented. Short time (about 10µs) between times of breakdown and interruption of FPA plate pulse is useful from the point of view FPA vacuum tube aging.

INTERMEDIATE POWER AMPLIFIER

As mentioned above, manufacture of vacuum tubes, designed especially for INR Linac, has been terminated 25 years ago. Among them was tetrode GI-51A designed for operation with common cathode and used in intermediate RF power amplifier IPA. Similarly to FPA the blocking capacitor was not foreseen in IPA and the plate high voltage was applied to the inner electrode of the coaxial cavity. The view of IPA is shown in fig. 3.

The search of a new tube for IPA has started near ten years ago. The main requirements were the capability to provide the pulse output RF power 300-400 kW and the possibility to mechanically fit with the existing equipment. The only choice was RF triode GI-57A, designed and manufactured in JSC "SED-SPb" for radar stations. Unlike GI-51A the tube GI-57A was designed to operate with the common grid. The parameters of the tubes GI-51A and GI-57A are given in table 1. One should note that the dimensions of input and output cavities of the amplifier are essentially determined by the inter-electrode capacitances grid-cathode Cgc and grid-plate Cga respectively for common grid circuit and by the capacitances grid-cathode Cgc and plate cathode Cac for common cathode circuit. The difference of the capacitances resulted in a need to fully change the dimensions of both input and output cavities. However the most complicated unit - the tank of the anode-grid cavity was succeeded to keep unchanged (fig. 8).

Generally replacement a tetrode by triode decreases a gain of RF amplifier. However in our case we succeed to keep it due two reasons. Firstly, the plate voltage was increased as IPA and FPA are powered in parallel (fig. 1).

Figure 8: Intermediate power amplifier after revision.

and increasing of plate voltage is also needed for FPA with GI-71A tube. Secondly, better matching between IPA output and FPA input has been achieved.

Table 1: Parameters of the tubes

Parameters	GI-51A	GI-57A
Pulse plate voltage, kV	40	28
Output RF power, kW	400	300
Operating life, hours	1000	3000
C_{ga}, pF	0,1	30
C_{ac}, pF	17	0,5
C_{gc}, pF	470	270

At present, two IPA with GI-57A tubes are installed and operate in RF channels and the third one is assembled, tested and is ready for installation.

MODULATOR VACUUM TUBE

All the GMI-44A vacuum tubes were manufactured in 70s-80s. Unfortunately, in the early years of RF system operation low-resistance water was used for modulator vacuum tubes cooling. Scale formation resulted in overheating of the tube elements and the lifetime of the tubes was only 1.5-2 thousand hours. After upgrading of the cooling system the lifetime increased up to 6-7 thousand hours, but significant amount of tubes has been lost by that time.

Since 2000 INR contacted "SED-SPb" several times and proposed to resume manufacture of the modulator tubes.

However due to several reasons, with the main being absence of consumers except for INR, the resumption of the manufacture was impossible. Fife years ago "SED-

ISBN 978-3-95450-181-6

SPb" agreed to start restoration procedure of the old vacuum tubes. Unfortunately, only seven tubes were restored of the whole amount about 24 vacuum tubes delivered for restoration. The quality of the restored tubes appeared to be lower than expected. For example pumping time increased from 20-30 minutes for new tubes up to several days for the restored ones. The life time of the restored tubes was less than 1000 hours. Only one of the restored tubes operated for 4000 hours.

The restoration program appeared to be unsuccessful and it was necessary to urgently find a replacement for GMI-44A. Similarly to the RF tubes the requirement to keep the existing equipment as unchangeable as possible was of importance. First of all this requirement was related to the filament power transformer and the transformer for negative grid bias. Due to series connection of modulator and FPA vacuum tubes [5] the secondary windings of the transformers are under high output pulse voltage and require HV isolation. The transformers have been produced about 30 years ago and their reproducing now is hardly possible.

After careful analysis and the consultations with "SED-SPb" a conclusion about a possibility to use RF triode GI-71A as powerful anode modulator vacuum tube has been done.

This choice simplifies several problems:

- Bias and filament transformers can be used without revision.
- GI-71A can be installed in the existing modulator rack.
- The assortment of vacuum tubes manufactured by SED-SPb for INR linear accelerator can be decreased to two items – GI-57A and GI-71A. In turn, manufacturing of GI-71A will doubled and a quality of the tubes could be improved.

The experience and the results of the studies connected with the replacement of the modulator tubes by the RF tubes are described in [6]. Several problems have been met:

- Pre-modulator power has to be clearly increased more than order of magnitude due much higher grid current of GI-71A than that of GMI-44A.
- The gain in the feedback loop of the accelerating field amplitude control decreases due to smaller GI-71A tube gain as compared with that of GMI-44A.
- Malfunctioning of the series crowbar system. Though in case of the breakdown the pre-modulator pulse is interrupted, the modulator tube GI-71A remains open.

Fig.9 demonstrates the processes which observed during breakdown in the final power amplifier, operating at pulse plate voltage 25 kV and output RF power near two MW.

From snapshot at fig.9 follows that in spite of modulator pulse interruption (middle trace) by the series crowbar system the modulator tube current (upper trace) continues up to full discharge of the artificial forming line.

At that breakdowns take place namely in the FPA plate-grid cavity, because they accompanies by sound. It means that an energy of artificial forming line discharges in the cavity but not in the FPA vacuum tube.

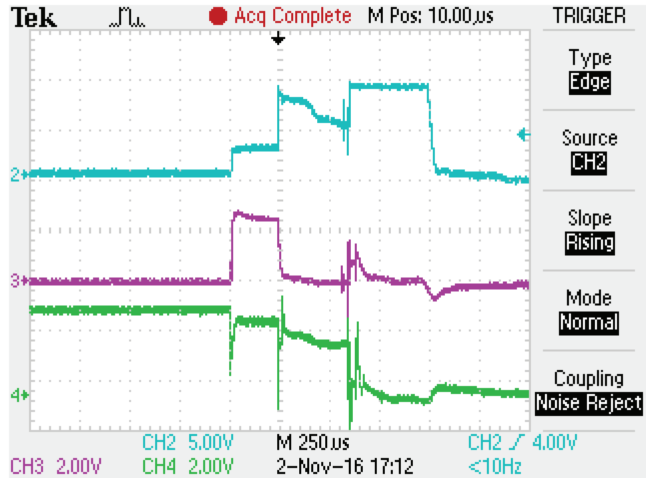

Figure 9: Processes in the PAM during FPA breakdown.

We consider several ways to overcome the problem. Among them are installation of solid-state opening switch [7] in GI-71A plate circuit and right choice of correcting circuits to limit grid-cathode gap overvoltage.

We don’t also eliminate a possibility of GI-71A design changing. In particular there is agreement with SED-SPb about placing magnetic discharge vacuum pump at grid electrode of GI-71A.

REFERENCES

[1] A.I.Kvasha, etc. "A new 200MHz Powerful Pulse Triode for the Output Power Amplifier of DTL RF System", Proc. PAC2001, Chicago, p.1222.

[2] A.I.Kvasha. V.L.Serov "Development of the INR DTL RF System Crowbar Operation", Proc. of RUPAC2008, p.218.

[3] S.K. Esin, etc. “Stendovie ispitanija canala usilenija visokochastotnoy moschnosti nachal’noy chasti uskoritelja nezonnoy fabriki INR AN USSR. Trudi 3-go Vsesoyuznogo seminara "Programmaexperimentalnih issledovaniy na mezonnoy fabrike INR AN USSR", 23-27 April 1983, Moskva 1984,pp.23-30.

[4] John T.M. Lyles etc. “Progress on the new high power 200 MHz RF system for the LANSCE DTL”, Proceedings of the 2001 PAC, Chicago, pp.996-998.

[5] Yu.Kiselev, A.Kovalishin, A.Kvasha, D.Hlustin "Simulation of the INR RAS DTL frequency stabilization system", Proc. of RUPAC 2006, pp.258-260.

[6] A.I.Kvasha, V.L.Serov “Powerful RF triode as anode modulator vacuum tube”, these proceedings.

[7] Ian S. Roth etc. “A solid-state opening switch for crowbar replacement”, Proc. of the PAC2001, Chicago, pp. 1459-1461.

ISBN 978-3-95450-181-6