SOME PECULIARITIES OF THE INR DTL RF SYSTEM OPERATION AT DOUBLING OF AVERAGE RF POWER LEVEL

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In accordance to the INR linear accelerator project it was foreseen a possibility of the accelerator operation at RF pulse repetition frequencies up to 100 Hz (duty factor 4%). At that repetition frequency accelerator efficiency is noticeably increased, as possibility are appeared of simultaneous acceleration of H^+ and H^- or operation at the isotope complex and physicists. For this reason, in recent years works connected with doubling RF pulse repetition frequency were begun. In the presented paper some additional aspects of INR DTL RF system operation are described, like plate modulator high voltage supply mode of operation; tank frequency control system; series crowbar system; new final and intermediate RF amplifiers.

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INTRODUCTION

DTL RF system consists of sixth RF channels, every of which includes four-cascade RF amplifier, operating at 198.2 MHz frequency with 50 db gain. Plate pulse supply of the first two RF amplifiers valves is realized by means of separate pulse modulator. Plate pulse supply of the intermediate (IPA) and final (FPA) RF power amplifiers vacuum tubes is realized by means of one powerful pulse modulator at vacuum tube GMI-44A. Output pulse amplitude achieves 30 kV at equivalent load 120 Ohm.

As storage device, providing for GMI-44A plate supply, 20-sell artificial forming line (AFL) with characteristic impedance 24 Ohm is used. Since effective resistance of the modulator load (120…150 Ohm) exceeds AFL characteristic impedance the last one operates with partial discharge. At that AFL charge process is aperiodic one with time constant about 20 ms. At RF pulse repetition rate 50 Hz AFL voltage value is 14% lower of maximum voltage value, which takes place at switching off the modulator load. At RF pulse repetition rate 100 Hz the AFL voltage is 37% lower.

In accordance with INR DTL design an overpressure in coaxial anode-grid cavity of the FPA up to 3 bars had been foreseen. The overpressure had to do away with breakdowns in the coaxial cavity. In turn, for powerful IPA and FPA vacuum tube protection from destroying in result of in valve breakdowns, crowbar system was designed. The designed bypass crowbar system has discharged AFL entirely in a case of vacuum tube breakdowns.

Many years experience showed, that FPA efficiency could be achieved without overpressure, if FPA output RF power provides acceleration pulse beam current up to 15…20 mA. At that, the procedure of vacuum tube replace is noticeably simplified. It follows to remind, that at LANSCE DTL (Los Alamos), where until recently FPA had operated under overpressure, vacuum tube replacing was realized for ~ 16 hours [2]. That is why, the last LANSCE DTL FPA modernization supposes operation without overpressure.

Peculiarities of INR DTL FPA anode-grid cavity construction without separating capacity results in impossibility of dividing between breakdowns in the vacuum tube and in the FPA cavity. If quantity breakdowns in vacuum tube are decreased during an operation time, then breakdowns in the anode-grid cavity can appear in any time for a variety of reasons. View of inner steam of the FPA coaxial anode-grid cavity after long-term operation is a strong evidence of the breakdown consequence (Fig. 1). The main reasons of that are: operation at detuning drift tube accelerator cavity (tank) and deterioration of RF contacts in the FPA cavity. The last one results in decreasing of the electrical durability in the coaxial cavity due to appearance of burning materials in the contacts spot. In this connection speed of RF system recovery becomes the deciding factor, interrupting efficiency of the RF system and accelerator operation.

Fig. 1. Traces of breakdowns in the region of FPA output

The bypass crowbar system operation results in full discharge of the AFL with simultaneous switching off plate modulator vacuum tube high voltage supply. Due to long transient in the frequency control system (FCS) accelerator operation can be restored in 15…20 min at RF pulse repetition rate 50 Hz. Five years ago has been tested new series crowbar system (SCS) [3, 4]. In this system modulator output pulse is shortened in 3…4 µs after breakdown. To restore electrical durability of the damaged gap, interruption of RF pulse series for 3…5 s has been added. At the same time, the interrupttion interval value doesn't have to result in noticeable drift tube cavity detuning. Doubling of RF pulse repetition rate inevitably makes to look at SCS operation both from point of view high voltage supply overvoltage and from point of view allowable value of the drift tube cavity detuning.

And at last, it is of interest a joint operation of DTL RF system with new vacuum tubes GI-57A (IPA) and GI-71A (FPA) at RF pulse repetition rate 100 Hz.

1. PLATE MODULATOR HIGH VOLTAGE SUPPLY

Model of high voltage storage device is shown at Fig. 2. At the model the source of high voltage rectifier is presented by a battery V2, choke L20 and resistance R22. Time constant of AFL charge aperiodic process is determined by ratio R22/L20 and is equal ~ 20 ms. Switch S1creates pulse series with repetition rate 50/100 Hz and pulse length 400 µs. Switch S2 interrupts operation of switch S1, imitating interruption time of the series crowbar system. Voltage of the battery V2 depends on repetition rate value. Obviously to support an AFL capacities voltage value by the time of S1 switching, it is need to increase V2 voltage with repetition rate rise. Taking this into account AFL capacities voltage is increased till 3 kV – at repetition rate 50 Hz, and till 9 kV – at repetition rate 100 Hz – Figs. 3, 4. As follows from presented transients, operation of series crowbar system results in short-time overvoltage of modulator vacuum tube plate supply.

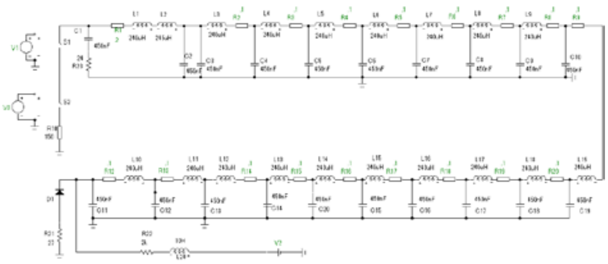

Fig. 2. AFL model

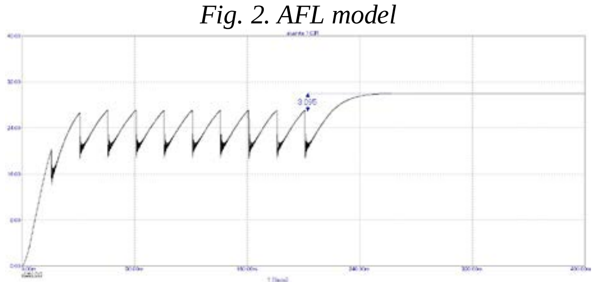

Fig. 3. AFL capacity voltage at repetition rate 50 Hz

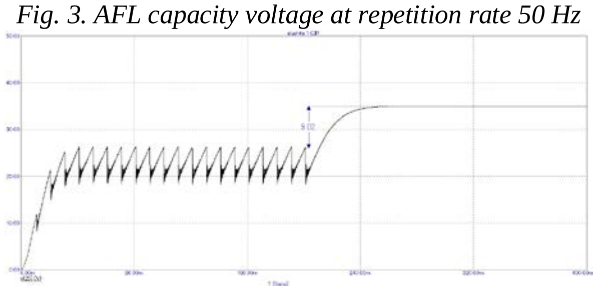

Fig. 4. AFL capacity voltage at repetition rate 100 Hz

At that, due to operation of the amplitude control system overvoltage in drift tube cavity does not appear.

2. TANK FREQUENCY CONTROL SYSTEM

Tank frequency control system (FCS) operation is based on control of water temperature, cooling drift tubes of the tank, depending on level of RF losses in tank inside surface. As measuring device a phase detector, connected with the tank and transmission line, is used. As for tanks body its influence at tank frequency is at order lower than drift tube one. That is why for body cooling the simplest system input water temperature stabilization is used.

If tank RF losses are available, drift tube water temperature is decreased. At that, the temperature gradient value is determined by average RF power, dissipated in tank surface, and by quality of heat transfer between drift tube and cooling water. In Table 1 values of water temperatures, cooling drift tubes, in second, third and fifth DTL tanks are presented. In all three tanks RF pulse power was corresponded to rated values but RF pulse repetition frequency was changed from 10 to 100 Hz.

Table 1

Tanks #	Water temperature, °C		
	10 Hz	50 Hz	100 Hz
2	26.4	25.6	24.4
3	23.8	21.5	18.0
5	31.0	25.5	18.5

In case of breakdown in IPA or FPA the series crowbar system interrupts for a few seconds RF pulse sequence. At that, drift tube temperature is decreased as the water temperature is lower than drift tube copper and, correspondingly, tank resonance frequency is increased. Repeated recovery of RF pulse sequence takes place already in detuning tank. Under unfavorable conditions, uncontrollable process of RF power decreasing can be appeared. Such processes are typical for control objects with extreme characteristics, when derivative changes a sign after going over characteristic maximum. Sometimes a positive feedback between tank resonance frequency detuning and FPA output pulse power level can appear (natural feedback).

Situation is improved thanks to amplitude control system operation. The system, on the one hand, reduces influence of destabilizing factors at tank RF voltage and on the other hand provides fund of RF power for beam acceleration. Frequency response of the tank with amplitude feedback looks as it is shown at Fig. 5.

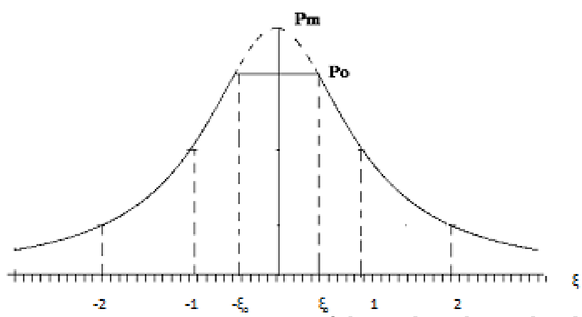

Fig. 5. Frequency response of the tank with amplitude feedback

Here $\xi = \frac{2Q_n}{f_o}\Delta f$ – tank relative detuning, Q_n – loaded quality factor, $P_0 = \frac{P_m}{1+\xi_0^2}$. Heat transfer process between drift tube copper and cooling water are described by well known first order linear differential equation (DE) [5]:

$$C_m M_m \frac{dT_{md}}{dt} = P_0 + (hA)_m (T_{ha} - T_{md}) .$$

Here $C_m M_m$ – is the product of the copper specific heat and drift tube copper mass; T_{md} – metal (copper) temperature; $(hA)_m$ – product of the copper heat transfer coefficient (h), and the heat exchange square in cooling channels (A). DE determines the process of tank metal heating by RF power P_o, dissipated in the drift tubes, relatively to the average water temperature T_{ha}.

As a rule value of $(hA)_m$ can't be calculated theoretically but is determined experimentally in a steady state [6]. For this, at first, water temperature T_{ha} is measured at low level of the average RF power (for example at RF pulse repetition rate 1 Hz). In this a case the temperature is really coincides with drift tube copper temperature. Then water temperature is measured at RF pulse repetition rate 100 Hz. If the average RF power at repetition rate 100 Hz is determined and difference between water temperatures at 1 and 100 Hz is measured, then one can without difficulty calculate $(hA)_m$ value.

In steady state drift tube temperature T_{md} is equal: $T_{md} = \frac{P_0}{(hA)_m} + T_{ha}$. During RF pulse series interruption for $\Delta\tau$ time by the crowbar system, drift tube copper temperature is decreased exponentially with time constant $T_{DT} = \frac{C_m M_m}{(hA)_m}$. As a rule, the condition $\Delta\tau << T_{DT}$ is fulfilled. Taking into account this inequality, the drift tube temperature changing value in $\Delta\tau$ time is equal:

$$\Delta T_{md} = \frac{P_o \Delta\tau}{(hA)_m T_{DT}} = \frac{P_0 \Delta\tau}{C_m M_m} . \quad (1)$$

Corresponding value of tank relative detuning can be presented as:

$$\xi = 2\pi T_n s \Delta T_{md} . \quad (2)$$

In expression (2) coefficient $s[kHz/d]$ determines, as a linear approximation, connection between drift tube temperature and tank resonance frequency; $T_n = \frac{Q_n}{\pi f_o}$ – time constant of the loaded tank. From the frequency response at Fig. 5 and expressions (1) and (2) one can determine the maximum value of $\Delta\tau_{\max}$, corresponding to tank detuning value ξ_o:

$$\Delta\tau_{\max} = \frac{C_m M_m}{2\pi s P_o T_n} \xi_0 = \frac{C_m M_m}{2\pi s P_o T_n} \sqrt{\frac{P_m}{P_o} - 1} . \quad (3)$$

Just the $\Delta\tau_{\max}$ determines tolerable value of the series crowbar system interruption time that keeps invariable level of RF field amplitude in the tank after breakdown. At that, operation of the final power amplifier with beam can be begun in additional $\Delta\tau_{\max}$, when the tank detuning moves near to zero and RF power supply $\Delta P = P_m - P_o$ is appeared.

So in case of breakdown in IPA or FPA, recovery of accelerator operation occurs in ~ 2 $\Delta\tau_{max}$. It follows to remind that the bypass crowbar system, which had been operated at INR accelerator for near 20 years (up to 2008 year), recovers after breakdown two orders longer [4].

As follows from expression (3) doubling of RF pulse repetition rate results in necessity of twice decreasing of the SCS time interruption due to twice increasing of average RF power P_o, dissipated in the tank. It also follows from this, that a danger of breakdown repetition is increased, as recovery time of the breakdown region also reduces.

3. UP-TO-DATE INR DTL RF SYSTEM

In papers [1, 5, 6] some problems, which appear in connection with ceasing of vacuum tube GI-51A and GI-54A manufacture, were considered. Instead of these vacuum tubes another ones have been installed in IPA (GI-57A) and FPA (GI-71A). In addition to problems, connected with conversion of power amplifiers at new vacuum tubes, there are a few other problems.

The first problem is appeared due to doubling of RF pulse repetition rate, which results in appearance 50 Hz modulation of 100 Hz RF pulse series (that looks as doubling of RF pulse top). As follows from results of modulation study [1] the main reason of the modulation is 50 Hz filament supply of anode modulator vacuum tube GMI-44A and vacuum tubes GI-57A and GI-71A, installed in IPA and FPA, correspondingly.

At the same time, at DTL RF system of accelerator LANSCE, operating at RF pulse repetition rate 120 Hz, there are not problems with 60 Hz modulation. We suppose, that this is connected with d.c. current filament supply of powerful vacuum tubes, used in IPA and FPA of the accelerator [2]. At INR DTL RF system the problem of 50 Hz modulation had been decided by means of making equal phases of powerful vacuum tubes filament 50 Hz supply [1].

Doubling of average RF power causes the next problem, as RF power, dissipated at vacuum tubes electrodes, transmitting lines and power amplifiers cavities, is doubled too. In table 2 some parameters of the former vacuum tubes GI-54A and GI-51A and new generation of vacuum tubes GI-71A and GI-57A are presented. As follows from presented parameters, new generation vacuum tubes parameters are rather lower than former ones. Nevertheless, new vacuum tubes ensure operation of DTL RF system at pulse repetition rate 100 Hz with pulse beam current 15 mA and beam pulse length 400 µs.

However, the lower RF power output and plate voltage limits of vacuum tubes GI-57A and GI-71A results in necessity of more accurate tuning of IPA and FPA. To a great extent the last statement has to do with tuning of IPA, because GI-57A (triode) parameters differ from GI-51A (tetrode) ones. As for vacuum tube GI-71A it had been designed so that installation GI-71A instead of GI-54A did not result in changing of FPA coaxial anode-grid cavity dimensions.

Situation with installation GI-57A is more complicated. That is why additional numerical simulation had been fulfilled [6]. The reasoning behind this simulation was real dimensions of IPA anode-grid cavity and vacuum tube GI-57A. Due to desire to keep unchangeable the main dimensions of the IPA anode-grid coaxial cavity, coupling between cavity tuning and changing of shorted coaxial line length, placed in parallel with the loop coupler, is increased.

Table 2

Parameters		GI-51A	GI-57A	GI-54A	GI-71A
RF pulse power		300 kW	300 kW	5 MW	3 MW
Plate dissipated power		30 kW	16 kW	300 kW	140 kW
Pulse plate voltage		40 kV	28 kV	40 kV	35 kV
Power gain		25	20	25	10
Vacuum tube capacities	C_{ag}, pF	17	29	100	85
	C_{gk}, pF	480	270	900	200
Filament parameters		~1.7 V, 2000 A	~1.7 V, 2100 A	d.c. 5 V, 4600 A	~ 16 V, 1100 A

The shorted coaxial line length regulation results in changing of current value in the loop coupler, i.e. in changing of output RF power. Results of simulation presented in paper [6] in detail. As an example, distribution of RF magnetic field in anode-grid coaxial cavity of IPA is shown in Fig. 6. At that, real dimensions of the coaxial cavity and vacuum tube GI-57A were taken into consideration. As can be seen from Fig. 6, magnetic field intensity in the region of HV input is nearly the same as in the coaxial anode-grid cavity. At the same time the loop coupler is displaced relatively maximum value of magnetic field.

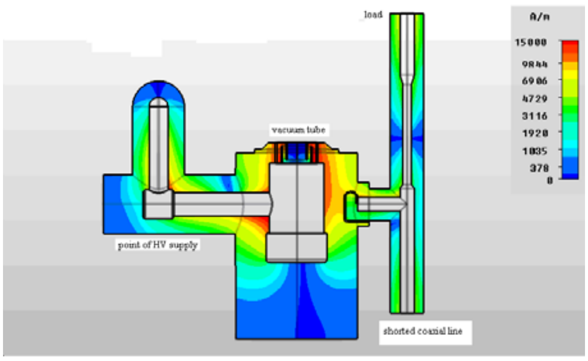

Fig. 6. RF magnetic field distribution in IPA anode-grid cavity

All this is a consequence of installation of vacuum tube GI-57A in the coaxial cavity, designed under vacuum tube GI-51A, with minimum conversions. Result of this is a necessity of contact pressure increasing in the region of high voltage input. Moreover, couple between cavity tuning and regulation of output RF power evidently grows.

In Fig. 7 frequency response function of IPA coaxial anode-grid cavity as a function of shorted coaxial line length is presented. From the frequency response function follows that changing of output power level by means of shorted coaxial line length regulation results in both cavity quality and resonance frequency changes. Thus, the optimal tuning of IPA at maximum output RF power supposes to have two degrees of freedom, as it is impossible to divide frequency and RF output power value control.

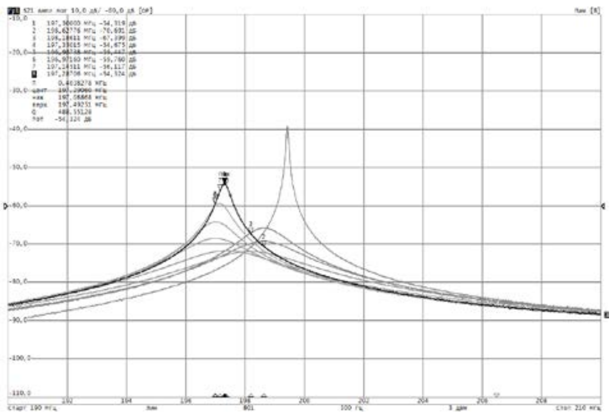

Fig. 7. Frequency response functions of IPA coaxial anode-grid cavity

CONCLUSIONS

1. INR DTL RF system modernization, made last years and connected, in the main, with installation in IPA and FPA new series of vacuum tubes GI-57A and GI-71A allows operating at doubling beam pulse repetition rate with pulse beam current 15…20 mA.
2. For increasing of DTL RF system operation efficiency at RF pulse repetition rate 100 Hz it follows very carefully to do tuning of anode-grid cavities both IPA and FPI and optimize operation of the crowbar and frequency control systems.
3. To this time duration of DTL RF system continues operation at doubling frequency repetition rate is about a few ten hours only. The final results of the RF system operation will be known after a few hundred running hours at frequency repetition rate 100 Hz.

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ОСОБЕННОСТИ РАБОТЫ СИСТЕМЫ ВЧ-ПИТАНИЯ НАЧАЛЬНОЙ ЧАСТИ УСКОРИТЕЛЯ ИЯИ РАН ПРИ УДВОЕНИИ СРЕДНЕЙ ВЧ-МОЩНОСТИ

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Хотя проектом ускорителя и предусмотрена возможность работы на частотах повторения импульсов тока пучка вплоть до 100 Гц, из-за трудностей реализации такого режима до последнего времени ускоритель работал с частотой повторения до 50 Гц. В то же время, реализация режима 100 Гц позволяет существенно расширить возможности ускорительного комплекса: возможность одновременного ускорения ионов H^+ и H^- и возможность одновременной работы на экспериментальный и изотопный комплексы с использованием системы импульсного разделения пучка. По этой причине в последние годы начат комплекс работ по удвоению частоты следования импульсов тока пучка. В настоящей работе более детально рассмотрены такие аспекты, как изменение режимов системы высоковольтного питания модулятора, последовательной системы защиты ВЧ-каскадов при пробоях, системы автоматической стабилизации собственной частоты резонатора и модернизированных ВЧ-каскадов на лампах ГИ-71А (оконечный каскад) и ГИ-57А (предоконечный каскад).

ОСОБЛИВОСТІ РОБОТИ СИСТЕМИ ВЧ-ЖИВЛЕННЯ ПОЧАТКОВОЇ ЧАСТИНИ ПРИСКОРЮВАЧА ІЯД РАН ПРИ ПОДВОЄННІ СЕРЕДНЬОЇ ВЧ-ПОТУЖНОСТІ

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Хоча проектом прискорювача і передбачена можливість роботи на частотах повторення імпульсів струму пучка аж до 100 Гц, із-за труднощів реалізації такого режиму до останнього часу прискорювач працював з частотою повторення до 50 Гц. В той же час, реалізація режиму 100 Гц дозволяє істотно розширити можливості прискорювального комплексу: можливість одночасного прискорення іонів H^+ і H^- і можливість одночасної роботи на експериментальний та ізотопний комплекси з використанням системи імпульсного розділення пучка. З цієї причини останніми роками розпочатий комплекс робіт з подвоєння частоти дотримання імпульсів струму пучка. У цій роботі детальніше розглянуті такі аспекти, як зміна режимів системи високовольтного живлення модулятора, послідовної системи захисту ВЧ-каскадів при пробоях, системи автоматичної стабілізації власної частоти резонатора і модернізованих ВЧ-каскадів на лампах ГИ-71А (кінцевий каскад) і ГИ-57А (передкінцевий каскад).