ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И. Будкера СО РАН

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FAST RASTER SCANNING SYSTEM FOR ACTIVE DOSE FIELDS FORMATION

BUDKERINP 94-102

НОВОСИБИРСК

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Abstract

A fast system for raster scanning of a 250 MeV beam is described. The system provides the active formation of a dose field with dimensions up to $40 \times 40\,cm^2$ with a rate of 1000 lines and 10 shots per second. The principal feature of the system is that its construction is based on the key components – thyristors. This removes the limitations on the commutated power, gives a possibility to increase the frequency of the scanning and makes the system more reliable.

1 Introduction

The development of active methods of the dose field formation is one of the most urgent problems for the proton therapy instrumentation. The choice of the dose field formation method and the beam delivery system parameters depend strongly on the type of accelerator – the proton source and on the beam parameters – its time structure and intensity.

In the methods currently developed for the passive formation of dose fields the uniform distribution of a dose in the tumor is achieved by the beam scattering and the limitation of irradiated area with the diaphragms shaped according to the tumor shape providing thereby the conform irradiation. The advantage of this method is its independence of the time structure of a beam. However, in the simplest case with the use of one scatterer, the necessity to have a uniform dose distribution with $\pm 2.5\%$ enables one to use only a small fraction ($\sim 5\%$) of the total intensity cutting it at the maximum of the Gaussian distribution of density. The low efficiency of the beam utilization requires an increased intensity of accelerator and enlarges the radiation background in the place of patient location. There are well developed methods for producing the flat-top on the particle density distribution curves with the double scattering while the second scatterer of special shapes is locating behind the first one. However, with the need to have a large irradiation field ($40 \times 40\,cm^2$) its obtaining with scattering requires quite a long distance from the scatterer to patient. At the same time, with the use in the hospital based dedicated proton facilities of the systems for beam rotation around the patient (*GANTRY*), providing the irradiation from any direction, the distance from *GANTRY* to patient is limited by the distance of $\sim 2\,m$. In addition, in order to provide the conform irradiation the construction of individually matched diaphragms or the use of the complex and expensive dynamic collimator is needed.

The developed methods for active formation of the dose fields allows one (with the two–coordinate scanning of a small size beam over the target area) to use efficiently the beam and promptly form the dose field of any arbitrary shape. With the simultaneous prompt variation of a beam energy there is a chance to avoid the use of the passive components like diaphragms, compensators, Ridge filters, etc., and to provide the *3D*-scanning of a beam over the tumor volume. One of the versions of such a scanning is the raster scanning. It is achieved with the use of two tandem-located magnets with the mutually perpendicular magnetic fields, each supplied with the current of a saw-like form. The period of "saw" for the first magnet – call it magnet of the line scanning – is essentially smaller than that for the second one – magnet of the shot scanning. As a result, the rectangular raster with a large number of lines within one shot is obtained. The third components of the system is the chopper system designed boundary of a field corresponding to the tumor shape inside the rectangular raster. For the time of scanning along one line the chopper system can switch on/off the beam either once or more times forming the region to be irradiated (Fig. 1).

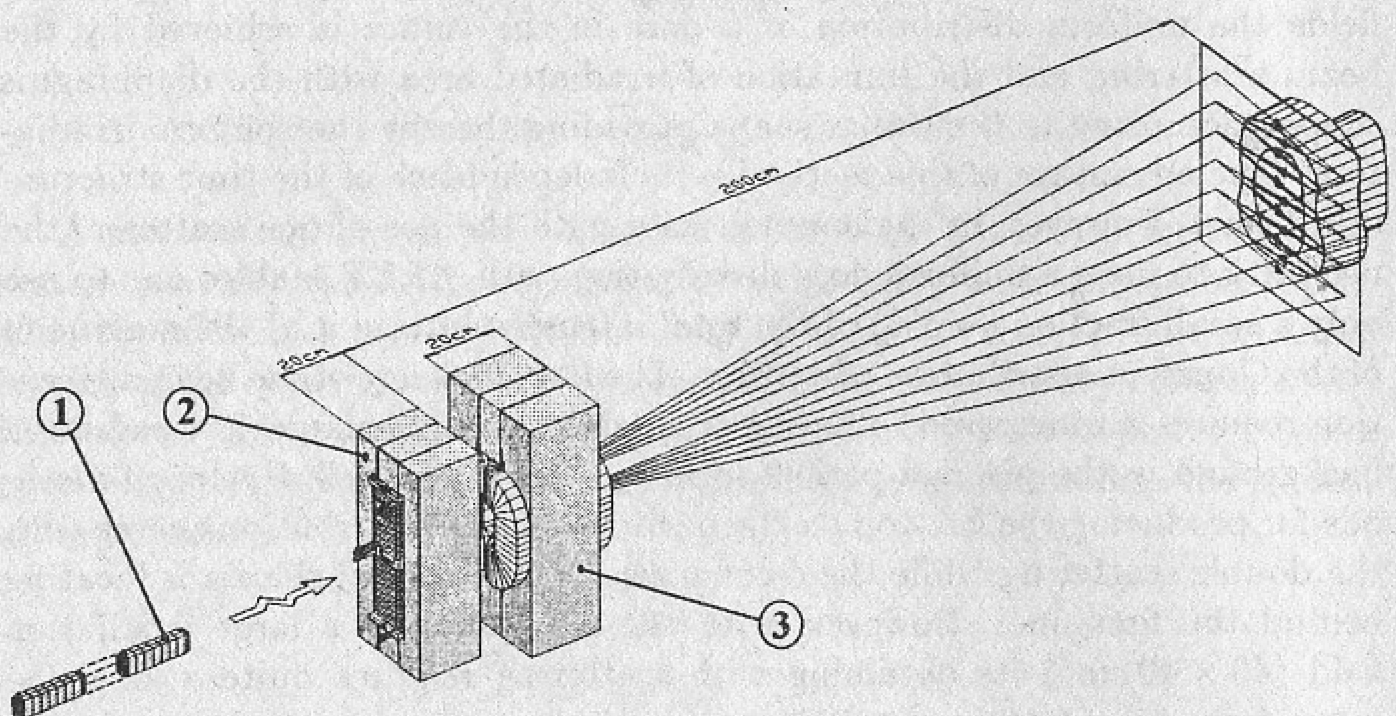

Figure 1: The raster formation of the irradiation field. **1** - chopper magnet; **2** - line scanning magnet; **3** - shot magnet.

During the operation with the time–continuous beam (from the cyclotron, for example) the frequency of the line and shot scanning is not crucial and it is determined by only the time and intensity of irradiation to be limited desirably by the period within a minutes. With the use of a synchrotron as a source of protons that enables one to promptly vary an energy from cycle to cycle, the necessity appears to produce the slow, elongated beam with a duty factor of the order of ~ 0.5. In this case, one has to get the raster

scanning frequency such as to provide at least one shot for the time of one cycle of the beam extraction and about 50 lines within one shot. The typical operation run for the existing [1] and developed [2] "slow" synchrotrons is the cycle frequency $f_{cycl} = 0.5 \div 1\,Hz$ at a time of extended beam extraction $t_{extr} = 1\,s$. In this case, the system of raster scanning should provide the line scanning frequency of a beam $f_{line} = 50\,Hz$. The arrangement of such a slow extraction from synchrotron cyclotron with small circumference $\sim 20\,m$ with the requirement of high time uniformity of the extracted beam intensity is quite a complex problem from the technical point of view. This problem could be facilitated essentially with the reduction of the beam extraction time. In addition, the intention reduce to the synchrotron pulse intensity retaining the required mean intensity of a beam leads to consideration of possibilities to enlarge the cycles frequency of accelerator operation up to a few *Hz*. So, in the project [3] the cycle frequency $f_{cycl} = 2\,Hz$ at the time of extraction of $t_{extr} = 0.2\,s$ is envisaged; in the project [4] – $f_{cycl} = 5\,Hz$ at $t_{extr} = 0.07\,s$. In this case, the frequency of the line scanning should be of a few hundred *Hz* that is apparently one of the substantial limitations existing for an increase in the cycle frequency of synchrotron.

One should note, that both at a slow extraction and even with continuous beam the raise of the raster scanning frequency (the number of shots per time unit) reduces the spatial nonuniformity of a dose density which is caused by the time nonuniformity of the extracted beam.

In the work presented here the system of a "fast" raster scanning is described. The system provides the frequency of the line scanning of $f_{line} = 1\,kHz$ *(1000 lines per second) and the shot scanning frequency of* $f_{shot} = 10\,Hz$ *(10 shots per second).*

2 Main parameters of the system.

With the distance from the scanning magnets to the patient of $\sim 2\,m$, determined by the radial dimension of a *GANTRY*, the requirement to provide the irradiation field of $40 \times 40\,cm^2$ leads to the necessity to have a beam deflection angle $\alpha = \pm 0.1\,rad$ in both directions. For the deflection of a proton beam with energy of $250\,MeV$ ($730\,MeV/c$) at such an angle the field integral in a magnet should be of $H \cdot l = 2.43 \times 10^5\,Oersted \cdot cm$. The magnet length is also limited by the *GANTRY* radial dimension. So, if one takes it to be of $l = 20\,cm$ the required sweep of a field should be of $H = \pm 1.22 \times 10^4\,Oersted$. If one has the vertical aperture of the first (along the beam path) magnet for the line scanning of $z = 1.6\,cm$, its energy store with such a field will be $W \approx 100\,J$. The second magnet (for the shot scanning) should have larger aperture and energy store will be of $W \approx 1\,kJ$. For the development of the raster scanning system with these parameters one of the main problems is the creation of the pulse generators providing the power supply for the inductive–resistive loads being the magnets with the linearly varying currents of the saw-like shape. Unlike the known methods for solving this problem with the use of the powerful transistors operated in the linear mode [5] *the principal feature of the generators for producing the saw–like currents described below is their construction on the base of the key components - thyristors. This removes the limitations on the commutated power, gives a possibility to increase the frequency of the linear scanning and makes the system more reliable.*

3 Generator of the line "saw".

The basic feature of the generator operation is supplying of the magnet with bipolar meander of voltage with period much smaller than electrical time constant $\tau = L/R$ (where L and R are inductance and resistance of the magnet), avoiding any active correction of voltage on tops of meander.

It's easy to calculate for one slope of "saw" the relative deviation of the current derivative from the constant one will be approximately $\pm\frac{1}{2}T/\tau$ where T is the slope duration (the line duration in other terms). Time constant of fast scanning magnet is $25\,ms$ so to achieve the linearity of $\pm 2\%$ the line duration must to be $\leq 1\,ms$. With the energy store of the line scanning magnet $W \simeq 100\,J$ the required commutation power of a key is $P_{comm} = 4W/T \simeq 400\,kW$ (with account of the transient processes the commutation power of the key is doubled, at least and in this case, $P_{comm} \simeq 1\,MW$).

Fig. 2 shows the schematic diagrams with voltages epures and currents of the generator for the linear "saw". Structurally the generator is a full thyristor's bridge with a special circuits for switching off the thyristors. Here the thyristors marked with the sign "+" serve for the generation of a "saw" of one polarity and "–" - for another polarity. Initial conditions : the load current is equal to zero, capacitor C_1^+ is charged up to $-E_0$ (E_0 is the D.C. feeding voltage). After switching on of the thyristors T_1^+ the load current raises linearly. Simultaneously with T_1^+ the thyristor T_2^+ have been "fired" , and current through it and inductance L_0 charges resonantly the capacitor C_1^+ up to $3E_0$. After the load current has raised to specified value I_{max} the thyristor T_3^+ is turning on, and the capacitor C_1^+ begin to discharge on the load. While the nearly linear discharging of C_1^+ by the current I_{max} the

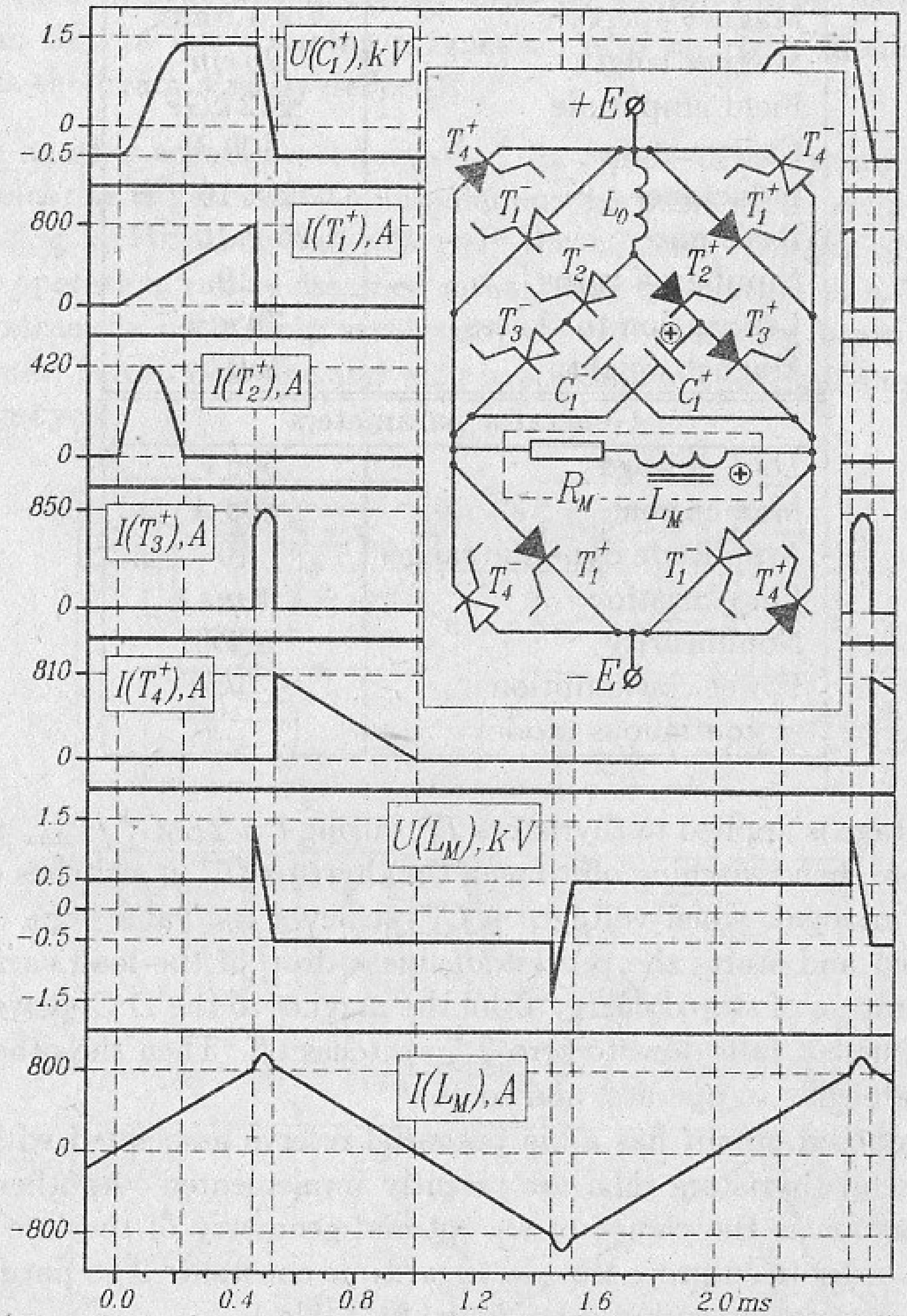

Figure 2: Generator of the line scanning.

Table 1: Parameters of the line scanning system.

Magnet parameters	
Magnet aperture	$4 \times 1.6\, cm^2$
Magnet length	$20\, cm$
Field amplitude	$\pm 12\, kGs$
Energy store	$100\, J$
Inductance	$3.12 \times 10^{-4} H$
Resistance	$1.25 \times 10^{-2} \Omega$
Number of turns	19
Lamination thickness	$70\, \mu m$
Magnet weight	$150\, kg$
Generator parameters	
$D.C.$ voltage	$500\, V$
Max current	$800\, A$
Amplitude dynamic range	10
Line duration	$1\, ms$
Nonlinearity	$\pm 2\%$
Power consumption at continuous mode	$\leq 5 kW$

reverse voltage is applied to thyristors T_1^+ during $t = 2E_0C_1^+/I_{max}$ and while the t is more then switching off time of the thyristor T_1^+ it switches off. A bit earlier the moment when voltage on C_1^+ achieves the value $-E_0$ thyristors T_4^+ are fired and starts the process of linear drop of the load current with the recuperation of stored energy from the magnet to the D.C. power supply. Upon the current falls downto zero T_4^+ switches off. Then the other part of the scheme begins to operate, and so on.

The proposed circuit has a big potential reserve associated with using a more powerful thyristors then are recently implemented. Another field for an optimization is the choice of an optimal geometry of the line scanning magnet in order to improve the electrical time constant. The parameters of prototype is recently produced are listed in Table 1.

4 Generator of shot "saw".

It's impossible to use for the construction of the shot "saw" generator the same scheme as that used for the line generator since :

- with the required duration of the shot scanning of dozens milliseconds and more the construction of a magnet with such a time constant seems to be unreal from technical point of view.
- the shot magnet has an energy store by an order of magnitude higher than that of line scanning magnet since its aperture should allows to pass the beam already deflected.

So an another scheme was developed. It consist of two symmetric parts, each enables one to generate the unipolar current pulse with the linear leading edge is using for scanning and relatively short "dead" trailing edge. Therefore, the operation run is assumed either with irradiation of a "half-shot" for one extraction cycle from accelerator or with switching beam off for the time of pulse polarity change and with irradiation of two "half-shots" for one extraction cycle.

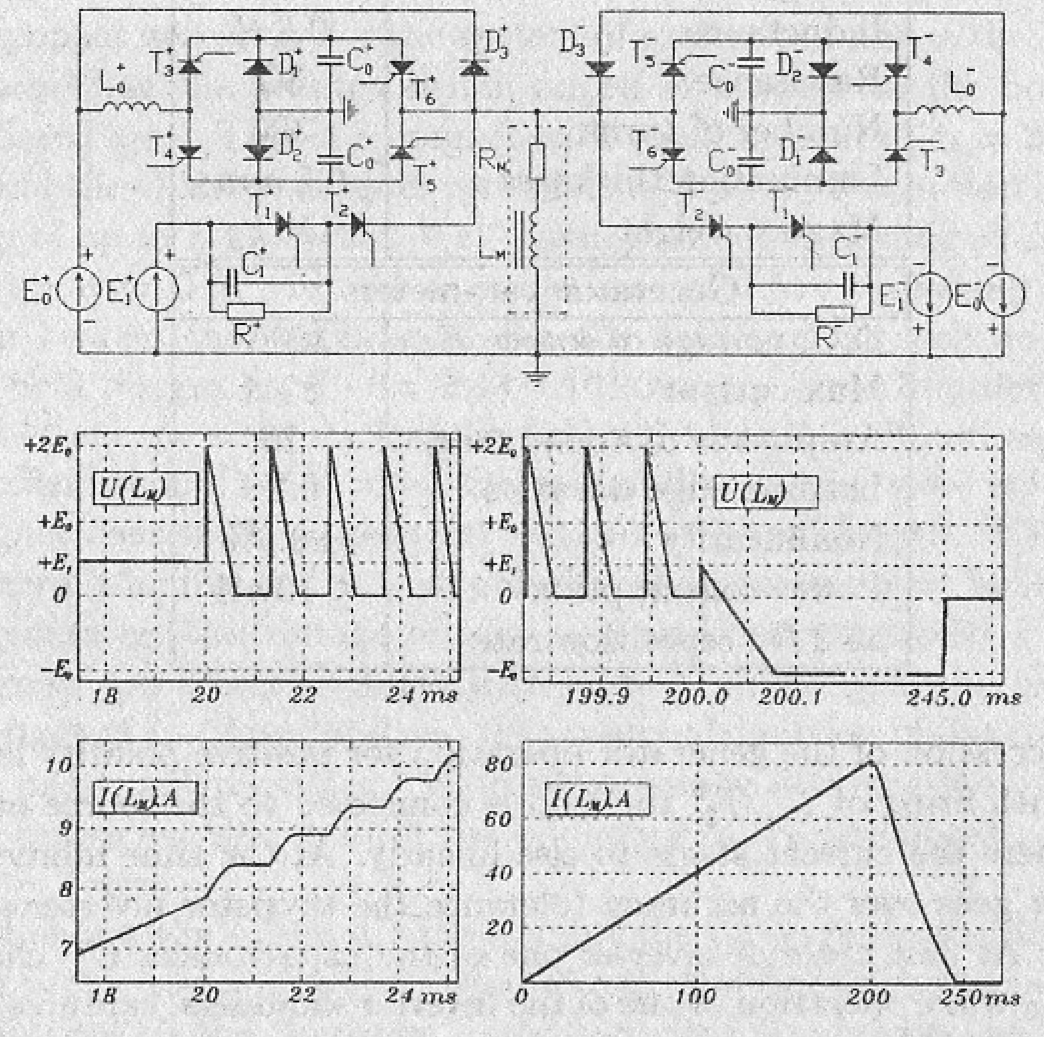

Figure 3: Generator of the shot scanning.

For the generation of a shot "saw" the thyristor inverter is used which transmits into a load a precise portion of energy each cycle [6]. The linear growth of a current in the shot magnet has been achieved by manipulation of the inverter operation frequency according to a certain law. Nevertheless, in the initial part of a "saw" the inverter can't provides the required accuracy. Therefore, for the formation of this initial part a way similar to that for the line scanning is used.

The shot "saw" generator scheme and plots of its currents and voltages are shown in Fig. 3.

Table 2: Parameters of the shot scanning system.

Magnet parameters	
Magnet aperture	$6 \times 8 cm^2$
Magnet length	$20\,cm$
Field amplitude	$10\,kGs$
Energy store	$1\,kJ$
Inductance	$0.3\,H$
Resistance	3Ω
Number of turns	390
Lamination thickness	$0.5\,mm$
Magnet weight	$150\,kg$
Generator parameters	
D.C. voltage of source E_0	$300\,V$
Max current	$82\,A$
Amplitude dynamic range	10
Leading edge duration	$0.2\,s$
Nonlinearity	$\pm 0.5\%$
Power consumption at $2\,Hz$ repetition rate	$\leq 10\,kW$

The succession of the generator operation for positive polarity is the following : with firing of T_1^+, T_2^+ the load is connected to the source of voltage E_1^+ and there the current starts to rise linearly. At the time moment when the current goes over the accuracy tolerance the thyristor inverter starts its operation. At first cycle of inverter one of the capacitances C_0^+ charged to voltage $2E_0$ while operation of one of the inverter shoulders, captures the load current by switching on another shoulder and the thyristors T_1^+, T_2^+ are off with the inverse voltage equal to $2E_0 - E_1$. The inverter continues operation, transmitting to load portion of energy $W_0 = 2C_0E_0^2$ each cycle.

When the load current achieves its maximum value, the inverter stops the generation and at the moment of voltage drop on C_0^+ down to zero the

thyristor T_2^+ is switched on. In this case, the inverse voltage of E_1^+ occurs on T_5^+ and T_6^+, they are switched off and the load current is captured by the circuit E_1^+, C_1^+. During the charge of capacitor C_1^+ with the load current up to a voltage $E_1 + E_0$ the diode D_3^- is opened and the generation process of the "saw" drop starts and also energy recuperation from the shot magnet into the source E_0^-. The inverse voltage occurs on thyristor T_2^+ and it is switched off. The generation of a "saw" of another sign proceeds in symmetric way.

According to this scheme there is a possibility to generate the shot "saws" with the duration ranging from tens milliseconds to a few seconds. The test results of the prototype for the shot magnet and generator in the mode of "saw" generation of $0.2\,s$ duration are represented in Table 2.

5 Chopper-system.

The component necessary for the system of raster scanning is the "chopper" system providing the prompt switch on/off of a beam on the boundary of the irradiated area. This is a magnet with small aperture ($A_r = 2\,cm$, $A_z = 1.5\,cm$) and the O-shape magnet core made of ferrite. The proton beam with an energy of up to $E_{max} = 250\,MeV$ passing through the magnet is deflected at an angle $\alpha = 0.01\,rad$ and at a distance of $1.5\,m$ displacing by $1.5\,cm$ is thrown beyond the diaphragm. For the deflection at such an angle the required field integral is $H \cdot l = 2.43 \times 10^4\,Oersted \cdot cm$. In order to reduce the magnet energy store its length is chosen to be $l = 70\,cm$, so, that the magnetic field should be $H = 340\,Oersted$ and an energy store is $W = 0.1\,J$. The magnet consists of 5 identical sections of $14\,cm$ length. Each section has a 8-turn winding and it is supplied with a current $I = 50\,A$ from the special generator; the voltage of each magnet does not exceed $V = 500\,V$. The magnets are power supplied with current pulses with the leading and trailing edges of $1 \div 3\,\mu s$ duration. The minimal duration of flat top is $30\,\mu s$, maximal one is not restricted. With the scanning line length of $40\,cm$ such fronts of pulses enables to form the boundary of the irradiated region with accuracy $\sim 1\,mm$.

Fig. 4 shows the schematic diagram of the pulse generator designed for the "chopper" system. The succession of generator operation is the following: upon switching on the thyristor T_1 the capacitor C_1 charging up to voltage E_1 discharged to magnet. In this case, the leading front of a pulse with a time $\tau = \pi/2\sqrt{L_mC}$ is formed. At the moment when the current reaches its amplitude value I_m, by switching on the transistor V_2 on the load the voltage of source E_2 with subtraction the voltage drop on the open diode D_1

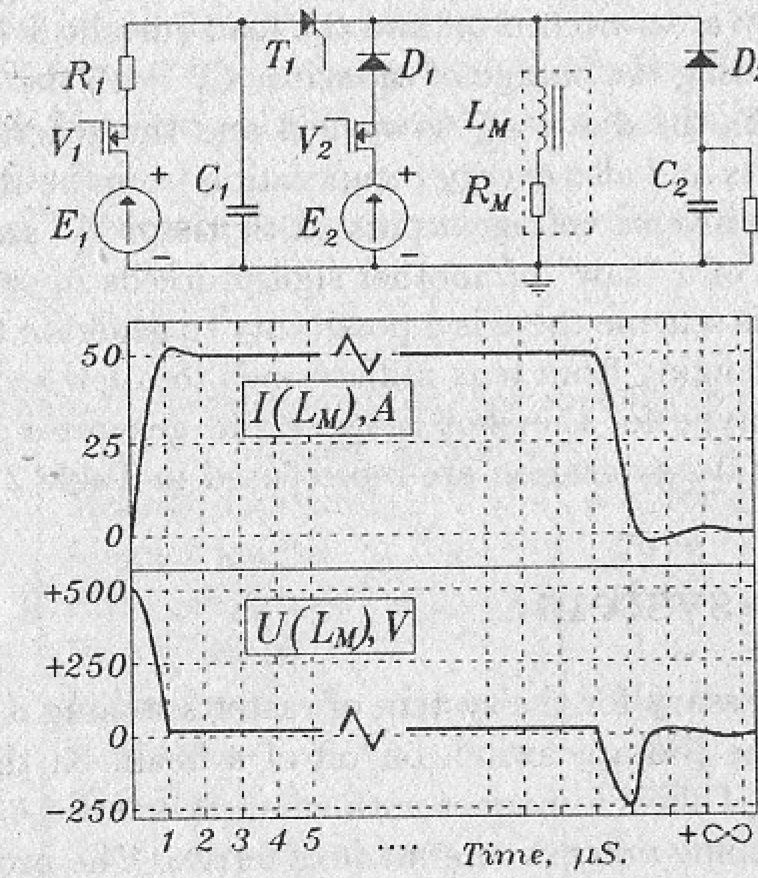

Figure 4: Chopper generator.

is fixed. It freeze current in chopper because the value of E_2 is chosen to obey equation $E_2 = I_m R_m$ where R_m is an active resistance of the magnet winding. In this case, the thyristor T_1 is switched off. The pulse trailing edge is generated during the switching off the transistor V_2, in this case the stored energy from magnet transmits through the opened diode D_2 to capacitance C_3, whose nominal is equal to C_1, and further dissipates in the resistance R_2. Simultaneously with switching off the transistor V_2 the transistor V_1 is switched on and the capacitance C_1 is charged from the source E_1. The generator is ready for the next cycle.

At present the testing of the chopper prototype is fully completed.

The generators of all magnets are located in the same electrotechnical cabinet of the size $1 \times 1 \times 2\, m^3$.

The total weight of the scanning magnets is $\approx 300\, kg$. *The magnets are assembled at rigid frame and could be placed at the GANTRY exit (Fig. 5).*

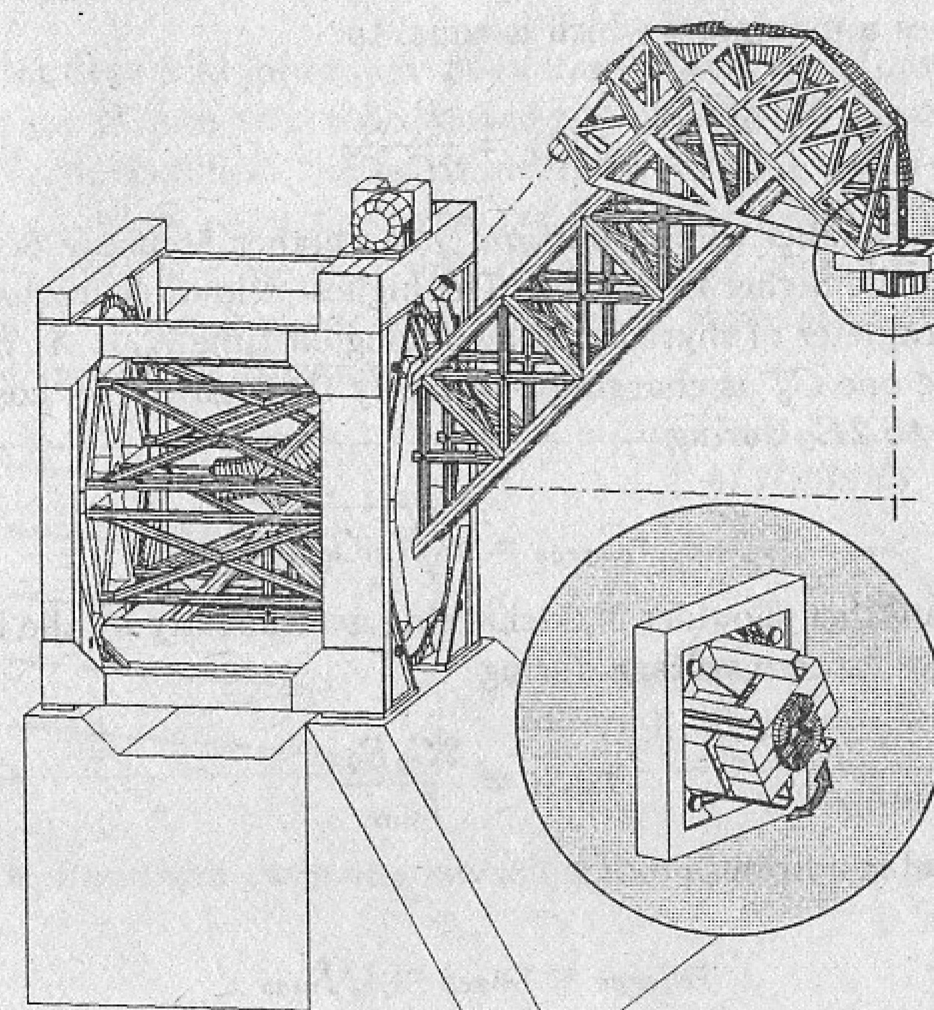

Figure 5: Displacement of magnets on *GANTRY*.

Appendix

A Basic relations for the slow saw generator.

While current in magnet with inductance L_M and resistance R_M rises linearly from zero to I_{max} during time T the consumed power obey to equation

$$P(t) = \left(\frac{I_{max}}{T}\right)^2 \cdot (L_M \cdot t + R_M \cdot t^2) \qquad (1)$$

The maximal value has been reached at $t = T$:

$$P_{max} = R_M \cdot I_{max}^2 \cdot \left(1 + \frac{L_M/R_M}{T}\right) \qquad (2)$$

Inverter transmits into load the portion of energy $Q = 2C_0E_0^2$ each cycle so the frequency of inverter f_{inv} must growth by low which is similar to (1) and at $t = T$ riches a maximum which is equal to

$$f_{max} = \frac{P_{max}}{2C_0E_0^2} \tag{3}$$

Evidently, the smaller energy portion Q the higher accuracy of "saw". But the smaller Q the higher frequency. The highest allowable frequency depend on such a parameter of thyristor as switching off time τ_{off}. At each cycle of inverter while one C_0^+ is charging resonantly through L_0^+ by cosine-like law from zero up to $2E_0$ during

$$\tau_{charge} = \pi\sqrt{L_0C_0^+} \tag{4}$$

capacitor in another shoulder is discharging near linearly by the load current from $2E_0$ down to zero voltage during

$$\tau_{disch} = \frac{2C_0E_0}{I_{max}} \tag{5}$$

At the optimal condition, i.e. if

$$\tau_{charge} = \tau_{disch} = 1/f_{max} \tag{6}$$

the time during which the reverse voltage is applied to thyristors of one shoulder is equal to $1/(2f_{max})$. Thus

$$f_{max} = 1/(2\tau_{off}) \tag{7}$$

and combining (3), (4), (5), (6) and (7) other parameters can be obtained:

$$E_0 = \frac{P_{max}}{I_{max}} \tag{8}$$

$$C_0 = \frac{\tau_{off} I_{max}^2}{P_{max}} \tag{9}$$

$$L_0 = \frac{4\tau_{off} P_{max}}{\pi^2 I_{max}^2} \tag{10}$$

B Estimations of the dose error.

With the raster dose field formation the center of beam spot (haven gaussian-like distribution of intensity with meansquare radius σ) moves on zigzag trajectory. Whole dose field can be considered as superposition of two "subfields", each formed by parallel segments of the trajectory with the line spacing S (Fig. 6). Let one use σ as unit of length and choose the coordinate system origin at midpoint of one of the trajectory segment, x-axis is aligning with the spot trajectory direction.

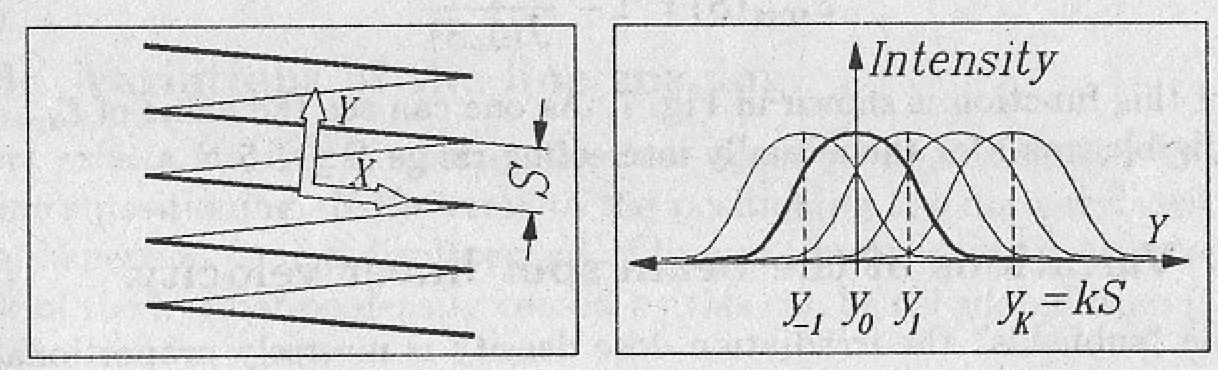

Figure 6: Beam spot trajectory and pill-up of lines from one subfield.

B.1 Space dose variation with precise line positioning.

First let consider an ideal case: the beam intensity is time–independent, the beam spot velocity and line spacing is constant, size of irradiation region is very large in comparison with other values of length's dimension (i.e. here and below we consider points which is far enough from the borders of the irradiation region). Then for one subfield the irradiation dose (we will use "dose" as synonym of "dose density") $J(\tilde{y}, S)$ at point with y-coordinate $\tilde{y}$ is given by the expression:

$$J(\tilde{y}, S) = \left. \frac{\sum_{k=-\infty}^{\infty} e^{-\frac{(\tilde{y}-y_k)^2}{2}}}{\sum_{k=-\infty}^{\infty} e^{-\frac{y_k^2}{2}}} \right|_{y_k=kS} \tag{11}$$

Denominator in (11) is chosen to have the unit dose at $\tilde{y} = 0$. Evidently $J(\tilde{y}, S)$ is periodic by $\tilde{y}$ with period S reaching minimums with $\tilde{y} = \left(k + \frac{1}{2}\right) S$. So there is a systematic error which can be written as:

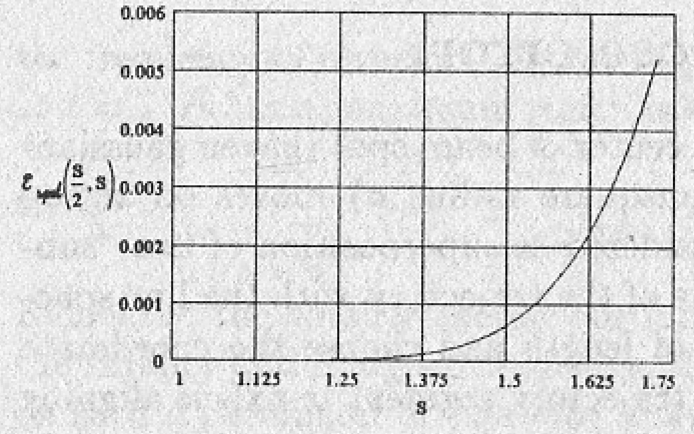

Figure 7: Maximal systematic space variation of dose density dependly on the line spacing. Line spacing is measuring in units of the σ - meansquare radius of the beam, space variation - in relative units.

$$\mathcal{E}_{spot}(S) = 1 - \frac{J(\frac{S}{2}, S)}{J(0, S)} \tag{12}$$

Plot of this function is shown in Fig. 7. As one can see the value of $\mathcal{E}_{spot}(S)$ is negligible small for the actually interesting range $S \leq 1.5$

B.2 Variations of the beam spot linear velocity.

For one "subfields" the irradiation dose density is inversely proportional to linear velocity of the beam spot $v_s(x)$. The total dose is forming by superposition of two "subfields", mirrorly symmetrical relatively $x = 0$. Total intensity J as function of x is proportional to :

$$J(x) \propto \frac{1}{v_s(x)} + \frac{1}{v_s(-x)} \tag{13}$$

The beam spot velocity as function time is proportional to the field derivative in scanning magnet [1]:

$$v_s(t) \propto D_{fast}(t) = \frac{dB}{dt}(t) \tag{14}$$

which is easy measurable. Since the dose density as function of x-coordinate is symmetrical it reaches one extremum at ends of interval an another one just at middle. So with the empiric suggestion that there exist only one extremum inside the interval the following estimation for the relative error of dose associated with inconstancy of the beam spot velocity can be written:

[1] it is valid for small deflection angle. If one take into account first changing of the effective magnet length, second non-perpendicular projection then the relative increasing of the beam spot velocity with deflection angle α can be estimated as $\frac{d}{d\alpha}\tan(\frac{\alpha^2}{\sin\alpha}) - 1 \simeq \frac{3}{2}\alpha^2 + \frac{115}{72}\alpha^4$

$$\mathcal{E}_{line} \simeq \frac{1}{2}\left|1 - \frac{D_{fast}(\frac{T}{2})}{2}\left(\frac{1}{D_{fast}(0)} + \frac{1}{D_{fast}(T)}\right)\right| \tag{15}$$

It is accepted that the beam spot is at $x = -x_{max}$ at the time moment $t = 0$ and reaches $x = x_{max}$ at moment $t = T$ (i.e T is line duration). Of course it's necessary to understand that "middle of T" isn't the same as "middle of x" but near the middle by x the $J(x)$ is near flat and such a substitution is legal enough.

B.3 Variations of the line spacing.

There exist a statistical error in the dose density which is caused by errors in line's positioning. If the error of the positioning has normal distribution with dispersion δy and displacement of lines is independent then the relative error of the irradiation density caused by this can be calculated from (11) as:

$$\frac{\delta J}{J} = \delta y \cdot \mathcal{E}_{snap}(\tilde{y}, S) ;$$

$$\mathcal{E}_{snap}(\tilde{y}, S) = \frac{\sqrt{\sum_{k=-\infty}^{\infty}\left(\frac{d}{dy_k}e^{-\frac{(y_k-\tilde{y})^2}{2}}\right)^2}}{\sum_{k=-\infty}^{\infty} e^{-\frac{y_k^2}{2}}}$$

$$\approx \frac{\sqrt{\frac{1}{S}\int_{-\infty}^{\infty}(y-\tilde{y})^2 e^{-(y-\tilde{y})^2} dy}}{\frac{1}{S}\int_{-\infty}^{\infty} e^{-\frac{y_k^2}{2}} dy}$$

$$= \frac{\sqrt{S}}{2\pi^{\frac{1}{4}}} \tag{16}$$

$\tilde{y}$ disappears from (16). Of course it's result of changing sums for integrals which was made in assumption $S \ll 1$. But comparison with numerical estimation (Fig. 8) which is made from "pure" sums, which depend on $\tilde{y}$ shows that (16) has precision of $\sim 10\%$ up to $S = 1.5$.

Equation (16) gives estimation of the dose error for one of two "subfields". It can be accepted that the second one has independent random shift of lines

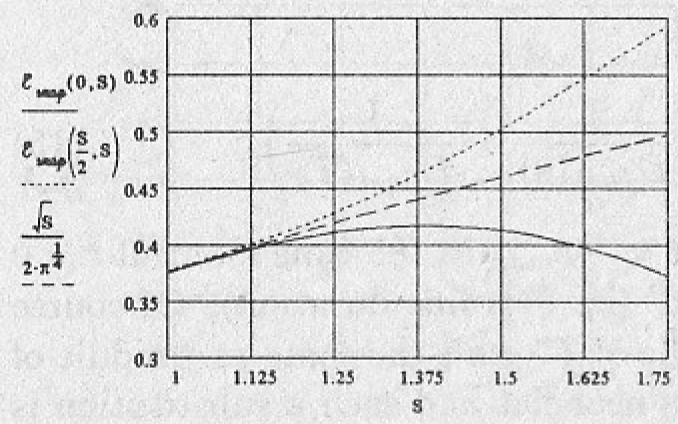

Figure 8: Error of the dose density occasioned by the error of the line positioning. Function $\mathcal{E}_{snap}(\tilde{y}, S)$ is the coefficient of proportionality between meansquare error of the line positioning and error of dose in point with y-coordinate $\tilde{y}$.

if one looking far enough from vertexes of whole trajectory of the beam spot. In such a case the relative error of the irradiation density for the subfields superposition is $\sqrt{2}$ times smaller.

It may to be interesting to rewrite (16) in more practical form, when all physical values aren't dimensionless. Let Y_{max} is half-size of raster by y. This y-position of beam spot is reaching with I_{max} – a maximal value of current in the spot scanning magnet. Let one sign $N = Y_{max}/S$ (it is number of lines of one direction in "half-raster"). Then the relation between the relative error of intensity $\delta J/J$ and relative error of the magnet current $\delta I/I_{max}$ is:

$$\frac{\delta J}{J} = \frac{1}{2^{\frac{3}{2}}\pi^{\frac{1}{4}}}\left(\frac{Y_{max}}{\sigma}\right)^{\frac{3}{2}} N^{-\frac{1}{2}} \cdot \left(\frac{\delta I}{I_{max}}\right) \qquad (17)$$

Here σ is the meansquare radius of the beam spot.

B.4 Variations of the extracted beam intensity.

If space profile of the beam spot is gaussian, the beam intensity is time–independent, then for an observation point which laying on the beam spot trajectory the time dependence of irradiation intensity is gaussian too with meansquare duration τ:

$$J_{ideal}(t, \tilde{t}) = \frac{1}{\sqrt{2\pi}\tau} e^{-\frac{(t-\tilde{t})^2}{2\tau^2}} \qquad (18)$$

Here t is the clock time, $\tilde{t}$ is moment when spot passes the observation point.

But there always exist time variations of the beam intensity during extraction. Let us to consider it's contribution into the irradiation nonuniformity at semi–quality level, accepting average value of the beam intensity as unit, and calling all deviation from average value as "noise". Let the beam noise $J_{noise}(t)$ in frequency domain has a spectrum $\mathcal{F}_{noise}(f)$. Then from the convolution theorem the meansquare error of the integral of the beam intensity from one passing the observation point by beam is equal to:

$$\mathcal{E}_{cross}(\mathcal{F}_{noise}, \tau) = \sqrt{\int_{-\infty}^{\infty} |\mathcal{F}_{noise}(f)|^2 \, e^{-(2\pi f \tau)^2} df} \qquad (19)$$

But the observation point is irradiating not only when the beam spot moves along the selected line of raster. Accounting all lines from both "subfields" leads to multiplication of (19) by factor $P(S) < 1$:

$$P(S) = \frac{1}{\sqrt{2}} \cdot \frac{\sqrt{\sum_{k=-\infty}^{\infty} e^{-(kS)^2}}}{\sum_{k=-\infty}^{\infty} e^{-\frac{(kS)^2}{2}}} \simeq \frac{\sqrt{S}}{2\pi^{\frac{1}{4}}} \qquad (20)$$

There S, the same as above, is line spacing measured in units of the meansquare beam radius.

And finally the relative error of the irradiation intensity arising from the time variation of the beam intensity can be written as:

$$\mathcal{E}_{time}(\mathcal{F}_{noise}, \tau, S) = \mathcal{E}_{cross}(\mathcal{F}_{noise}, \tau) \cdot P(S) \qquad (21)$$

B.5 Total error of the irradiation density.

Since all factor have been considered above (the extracted beam intensity, the line spacing, the beam spot velocity) comes into irradiation density by the multiplicative way then total relative error $\mathcal{E}_{total}$ is the sum of all partial relative errors:

$$\mathcal{E}_{total} = \mathcal{E}_{time} + \mathcal{E}_{snap} \cdot \delta y + \mathcal{E}_{line} \qquad (22)$$

Here δy is the meansquare error of the line positioning and it is measured in units of the meansquare radius of the beam spot - the same as in text above.

References

[1] R. Little, Nucl.Instr.Methods Phys.Rev., B56/57, pp.1192–1196 (1991)

[2] S. Fukumoti, K. Endo et al. "Tsukuba Medical Proton Synchrotron", Proc. of the Int. Heavy Particle Therapy Workshop, PSI, September 1989, PSI-Bericht (1990) «69 pp. 70-74.

[3] A.P. Trippe, R.C. Sah "A Proton Therapy System", Maxwell Laboratories, Inc., Brobeck Division, Proc. of the Int. Symposium on Hadron Therapy, Como, Italy, Oct.18–21 1989, to be publishied at NIM.

[4] V.S. Khoroshkov and K.K. Onossovsky "H^- Synchrotron for Proton Therapy Facility", Proc. of the NIRS Int. Workshop on Heavy Charged Particle Therapy, July 1989, Chiba, Japan

[5] G. Stover, M. Nyman et al. "A Raster Scanning Power Supply System for Controlling Relativistic Heavy Ion Beams at the Bevalac Biomedical Facility", Proc. of IEEE Part. Conference March 16–19 1987, Washington, D.C. v.3, pp. 1410–1412.
John E. Milburn, Jack T. Tanabe et al. "Raster Scanning Magnets for Relativistic Heavy Ions", the same Proc., pp. 2000–2002.

[6] A.D. Chernyakin, G.I. Silvestrov, V.G. Volokhov, "Device for Charging Capacitive Storage by Constant Power", Proc. of the 8 All-Union Conf. on the Charged Particle Accelerators, Dubna, USSR, 1983, v.2, p.135.

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Ответственный за выпуск С.Г. Попов
Работа поступила 29 ноября 1994 г.

Сдано в набор 22 декабря 1994 г.
Подписано в печать 28 декабря 1994 г.
Формат бумаги 60×90 1/16 Объем 0.8 печ.л., 0.7 уч.-изд.л.
Тираж 200 экз. Бесплатно. Заказ N° 102

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН,
Новосибирск, 630090, пр. академика Лаврентьева, 11.