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Revision of (sub)nanosecond pulser for IRI Van de Graaff electron accelerator aided by field propagation calculations

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The shorted air line stub used for subnanosecond pulsing of the grounded-grid cathode gun structure of the IRI 3 MV Van de Graaff electron accelerator is revised. Three-dimensional high-frequency field propagation calculations provide better insight into the performance of different geometrical shapes. Effects on rise- and decay time, and ringing on the output pulses are considered. Practical possibilities for improvement are discussed. Comparison with sampling measurements on several device modifications confirms the reliability of the calculations. The calculation method is subsequently used as design aid for the construction of a “1 ns” device using a quartz loaded shorted stub to fit into the geometry of the existing variable pulse length unit. Capabilities for short pulsing of the accelerator are improved and extended by application of the results obtained. © 2005 American Institute of Physics. [DOI: 10.1063/1.1847652]

I. INTRODUCTION

In 1976 our nanosecond pulsed 3 MV Van de Graaff electron accelerator at IRI was equipped with a subnanosecond pulser for the cathode.¹ The modification was obtained by adding a shorted coaxial stub at the exit of the existing nanosecond pulser. The latter was based on the mercury switched coaxial line discharge pulser described by Ramler, Johnson, and Klippert² in 1967. For practical reasons, accuracy of matching to the CP Clare mercury reed switch environment and voltage holding, the unit was made from a typical 50 Ω air line General Radio 874 T connector. The branch perpendicular to the through 50 Ω line was modified as required for 25 Ω characteristic impedance by an increase of the center conductor diameter, and shorted at the end. The length was chosen to determine the desired subnanosecond pulse length by its transmission time. At the time of first realization a correction was made to improve the apparent pulse shape as tested by a tunnel-diode fast rise time pulser (Tektronix S50, t_r 20 ps) and a sampling oscilloscope. The correction was established by a reduction of the diameter of the inner conductor just before and close to the branching point, approximately equivalent to a length of 1 cm with diameter 2.5 mm. In the following years the single prototype unit modeled for a custom designed switch manufactured by Spinner GmbH (München, Germany) able to switch in six steps between 100, 200, 300, 400, 500 ps, and a through 50 Ω line. The latter for using the nanosecond pulse lengths of 2, 5, 10, 20, 50, and 250 ns.³

Experimenters using the pulsed Van de Graaff in various

pulse excitation radiolysis setups have recently developed a wish for a “flattopped” 1 ns duration pulse. They often need the maximum energy obtainable in a commonly available 4 A peak current electron pulse from the accelerator to increase the small signal response of measuring systems which are limited to a 1 ns rise time detection. Because of the far from ideal pulse shape obtained from a direct 1 ns pulse line discharge, particularly in the decay time, it was decided to add a 1 ns pulse length to the existing switchable subnanosecond pulse unit.

Introduction of a “1 ns” air line stub, instead of the seldom used 400 ps, was prohibited by space in the terminal, and the high cost of modification of the complete “Spinner” switching unit. Slowing down the transmission speed of the high frequencies by a factor of about 2 using a low loss dielectric in the stub was found to be the most appropriate solution. A good, and actually the only, dielectric found with a suitable dielectric constant of about 4, constant over the whole frequency range up to several GHz, is quartz or fused silica.⁴ For reasons of saving design cost, and also for optimization and revision of the existing design, collaboration with colleagues from TUE specialized in performing three-dimensional (3D) calculations of electromagnetic wave transmission was initiated.

II. SIGNAL TRANSMISSION IN VARIOUS MODIFICATIONS OF THE SHORT PULSE-FORMING STUB

Electromagnetic pulse propagation calculations were performed using finite-difference time-domain software (CST Microwave Studio, Darmstadt, Germany) for solving truly 3D problems. Different step functions were used as input. For a realistic approach smooth (integrated Gaussian)

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FIG. 1. Schematic representation of the different geometric shapes for the sub-nanosecond stub pulse devices considered for comparison.

step functions without delay of the form $f(t)=\text{erf}(at)$ and Elmore rise time $t_r=1.8/a$ of 20 or 50 ps were chosen.⁵ The Elmore rise time is equal to the 10%–90% signal rise time. For the output signal 100% is defined as the amplitude equal to half the amplitude value of the exciting step, generally equal to the amplitude outside the region of ringing. The high-frequency limit, v_{hc} , of the input signal is given by the relation

$$v_{hc} = a/2\pi. \quad (1)$$

For a 10%–90% rise time t_r this gives the relation

$$v_{hc} = 1.8/2\pi t_r. \quad (2)$$

This results for $t_r=20$ and 50 ps in a high-frequency limit of, respectively, 14.3 and 5.73 GHz.

In the calculation program frequencies up to 100 GHz could be taken into account, being safely above these limits. Fields were sampled with ten mesh lines per wavelength. The system was excited in the transverse electric and magnetic (TEM) mode. However, due to the local transitions at the T junction and the size of the GR-874 air line, other modes are generated.⁶ Most probable is the H_{11} mode with the lowest excitation frequency v_{1e} approximated by the relation

$$v_{1e} = 2c/\pi(d+D), \quad (3)$$

where c is the speed of light in vacuum (3×10^8 m/s), d and D , respectively, the (outer) diameter of the inner conductor and the (inner) diameter of the outer conductor of the coaxial transmission line. For the 50 Ω GR-874 air line with d and D of, respectively, 6.2 and 14.4 mm, and for the air line stub with d and D , respectively, 9.5 and 14.4 mm, the lowest excitation frequencies for the H_{11} mode are, respectively, 9.27 and 7.99 GHz. This means that for the 20 ps rise time step excitation the H_{11} mode is excited. For the 50 ps rise time step, which is more realistic in our case since the rise time of the 20 ps excitation pulse is deteriorated by connecting cables, the excitation of the H_{11} mode is less. Because of

FIG. 2. Calculated output pulse responses using a 50 ps Elmore rise time excitation step (long pulse). The different curves refer to the device modifications given in Fig. 1. Curves a1 and a2 are, respectively, for the corrected device excited from the side of the restriction and from the opposite side.

fast damping, and due to its nature the H_{11} mode does not appear as a voltage signal at the (50 Ω) output resistor. The resulting additional high-frequency losses from the TEM mode, however, affect the output signal, in general resulting in an increase in decay time as we shall see.

In an attempt to improve the rise and fall time of the device, several design modifications of the stub device are considered. First the corrected stub as described before, and shown in Fig. 1(a). For comparison the single-sided GR-874 based device without the correction [Fig. 1(b)] is considered. Also the modification with two diametrically placed 50 Ω stubs⁷ using GR-874 dimensions [Fig. 1(c)] and also a smaller diameter air line with $d=1$ mm and $D=2.3$ mm (1c').

For the corrected device 1a the calculations show for all excitation steps exactly the same output pulse independent of the exchange of in- and output of the device. The asymmetry in the geometry (correction respectively nearest to input or output) has no effect as is shown in Fig. 2, curves a1 and a2. This calculation result is confirmed by measurements on a real device shown in Fig. 3, curves a1 and a2. The asymmetry, however, appears in the time structure of the reflected signal, and also in the electric field pulses measured half way up the stub in the plane of the T section, at the input and output side, respectively, E_i and E_o . The 1-cm-long correction (shorter than the 21 and 52 mm wavelengths of the highest excitation frequency for 20 and 50 ps rise time steps, respectively) results only in an overall change of output pulse shape.

The uncorrected device of Fig. 1(b) shows a peak on top of the rise, and a dip after the decay in the calculations in Fig. 2, curve (b). Similar effects are seen in the measurement in Fig. 3, curve (b). In our application for switching the

FIG. 3. Measured output pulse response for the device modifications a1, a2, and b, using a “50 ps” rise time excitation step (Tektronix S50 pulse generator plus cable) and sampling oscilloscope (Tektronix 7834, plug-ins 7T11 and 7S11 plus S4 head).

emission of the biased accelerator cathode for pulsing the electron beam, only the fast rise and decay are functional, provided the average peak voltage is sufficiently high and the modulations on top of the pulse and in the base line are relatively small, not to interfere with, respectively, the “open” or “closed” condition for electron emission from the grounded-grid cathode of the gun. The continuous bias voltage to block unwanted background electron emission is +200 V on the cathode with respect to the grid. For a superposed –500 V short pulse the positive (up) excursions on the “top”, and the negative (down) excursions on the base line should stay well within 20% of the peak value.

The rise and decay of the uncorrected device are faster than for the corrected device. Therefore we have decided to revise the construction and use the shape as given in Fig. 1(b). The modification 1(c), with the two opposing 50 Ω stubs⁷ as a cross shape, gives in the calculation, curve 2(c), more equal rise and decay and less damped oscillations after rise and fall. This “cross” modification 1(c′) with the smaller diameter for *D* and *d* of, respectively, 2.3 and 1 mm, gives in the calculations a perfect pulse with hardly any or no ringing after rise and fall for, respectively, the step with 20 and 50 ps rise time. For the 50 ps rise time step the result is shown in curve 2(c′). The construction 1(c) with the larger GR874 size gives more ringing, particularly at decay, for the 50 ps rise time excitation. For the 20 ps rise time excitation the ringing increases (not shown in proof). This is in agreement with more (*H*₁₁) mode conversion. The 10%–90% rise time, where 0% and 100% is the level without the ringing, may occasionally be shorter than the rise time of the excitation pulse, due to a high overshoot. See Table I for a survey of calculated rise and decay times, *t_r* and *t_d*, for the different modifications, for 20 and 50 ps rise time excitation steps. For the thin cross construction 1(c′) rise and decay times are

TABLE I. A 10%–90% rise time *t_r* and decay time *t_d* in ps calculated for the different modifications of the stub device as shown in Fig. 1. The value of (48.8) for the corrected device a excited by the 50 ps rise time step was calculated from the 10%–80% rise.

Modification (see Fig. 1)	20 ps rise time excitation step		50 ps rise time excitation step	
	<i>t_r</i>	<i>t_d</i> (ps)	<i>t_r</i>	<i>t_d</i> (ps)
a	22.3	66.9	(48.8)43.4*	76.3
b	15.7	58.5	40.5	69.9
c	20.1	38.2	48.9	54.7
c′	19.8	20.2	50.0	50.0

close to each other and also to the rise time of the respective excitation step. The interesting qualities of modifications (c) and (c′) concerning *t_r* and *t_d* are obvious. For reasons mentioned before and simplicity of construction we are practically restricted to the GR874 sized *T* devices. However, as a result of the present analysis, the former correction for pulse rise overshoot as in modification 1(a)³ is no longer considered an improvement.

Due to the “overcorrection” for rise time ringing in modification 1(a) the 100% value after a 50 ps rise time step is only reached after about 150 ps (Fig. 2.1a). Therefore we have obtained here the 10%–80% rise of 43.4* ps, where the asterisk is added to distinguish this value from the usual 10%–90% value. For comparison of relative slope a virtual 10%–90% *t_r* of 9/8 × 43.4 = 48.8 ps is calculated, and given between brackets in Table I.

For the 1 ns device with quartz dielectric the design shown in Fig. 4 is calculated and made. The results of the 3D calculation with *t_r*=42.3 ps and *t_d*=70.5 ps, and the measurement of the real device with *t_r*=46.6 ps and *t_d*=74.2 ps are shown in Fig. 5, curves (a) and (b), respectively. Regarding the technical problems in the practical realization the agreement of the calculated and measured response is very good. The difference in pulse length of 27.6 ps between calculated and measured pulse is probably due to the difference between the relative dielectric constant used for quartz in the calculations (3.86) and the real value. The practical result is

FIG. 4. Simplified construction drawing of 1 ns stub device with quartz (fused silica) loaded side arm. (Replacing former 400 ps stub in Spinner switch.)

FIG. 5. Output response of quartz loaded 1 ns stub device to “50 ps” rise time excitation step. (a): Solid line, calculated using 3D program; (b): dotted line, measured by electronic sampling as described under Fig. 3.

found to satisfy the requirements, and has been incorporated into the modified version of the switch and subsequently into the accelerator terminal.

III. DISCUSSION

As a result from 3D simulation calculations of our sub-nanosecond stub pulser, confirmed by measurements, we find that the performance of the design can be improved in sev-

eral ways. Omitting the formerly applied rise time overshoot correction gives an improvement of rise and decay time. The decay time is still considerably longer than the rise time of the exciting step. This becomes even more dramatic for a shorter rise time of the step, due to increased mode conversion losses. Further improvement may be obtained by the construction of a symmetric cross device, and even more by reduction of the diameter. This, however, complicates the mechanical construction, increases the size of the device, requires a very high accuracy and contact quality of the mechanical switching system, and decreases the voltage holding capacity for pulse voltages to 1.5 kV. In our practical situation with about 50 ps rise time, the results for the GR874 *T* device are, however, acceptable.

The 3D field propagation calculations are an efficient tool to save design cost for (future) new developments, as is demonstrated in the case of the quartz loaded stubdevice for generation of flattopped 1 ns pulses.

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