

ADVANCES IN X-BAND AND S-BAND LINEAR ACCELERATORS FOR SECURITY, NDT, AND OTHER APPLICATIONS

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Abstract

At AS&E High Energy Systems Division, we designed several new advanced high energy electron beam and X-ray sources. Our primary focus has always been in building the world's most portable commercial X-band accelerators. Today, our X-band systems frequently exceed performance of the similar S-band machines, while they are more portable compared to the latter. The new designs of the X-band accelerators in the most practical energy range from 1 MeV to 6 MeV have been tested delivering outstanding results. More than 100 linacs systems have been produced over HES history and history of its predecessor, SRC. The most compact linac for security is used by AS&E in a self-shielded, Shaped Energy™ cargo screening system. We pioneered using the X-band linear accelerators for CT, producing high quality images of oil pipes and wood logs. An X-band linear accelerator head on a robotic arm has been used for electron beam radiation curing of an odd-shaped graphite composite part. We developed the broad-range 4 MeV to over 10 MeV energy-regulated X-band and S-band systems for medical and NDT applications. The regulated pulse length systems operating in a range from nanoseconds to microseconds have been built both in X-band and in S-band frequency range.

INTRODUCTION

In 2004, we have completed a significant period in our business history of linear accelerators by selling some of the assets of High Energy Systems Division operation, which persuades us to summarize the results of its 6-year activity. Before we start discussing designs and products by the High Energy Systems Division (HESD), we shall review history of its key product - the X-band linear accelerator and of the X-band technology for portable linear accelerators. Development of the X-band accelerators started in late 60-s in USA and in Russia [1, 2]. The first commercial X-band linac produced by Russell Schonberg started its operation 70-s in the United States. Over twenty years of development work Schonberg Research Corporation (SRC) produced miniature linear accelerators MINAC 1.5, 4 and 6 [3], which were distributed and used for non-destructive testing in small quantities. In the 90-s, two accelerator systems were designed based on developed X-band technology and used on medical systems copyrighted by the Schonberg's spin-off companies. In 1998, American Science and Engineering acquired assets of Schonberg Research Corporation and formed High Energy Systems Division. The Division has started to gradually improve performance of the X-band accelerators designs and

generated new designs of the 1-3, 4, and 6 MeV linear accelerators, which produced more than two times the dose rate of their predecessors designed by SRC. Performance of the X-band linacs has become comparable to the similar S-band machines. We have built the world's first energy regulated 4 MeV to 12 MeV X-band linear accelerator used for radiation therapy and for non-destructive testing [4, 6] and produced ultra short pulses in this magnetron-driven X-band system. We expanded applications of the X-band linacs, building these new linear accelerator systems for AS&E's Shaped Shaped Energy™ [7] systems, which are used for screening of dense cargo. The X-band systems permit to minimize necessary shielding of the X-ray source and to avoid using exclusion zones around the scanners. At AS&E, we also pioneered design of the first X-band CT linac for scanning of wood logs [8]. For the two latter systems, we designed a 1 mm (round) to 0.5x4 mm linear) variable beam spot option. In addition to the unique X-band systems, High Energy Systems Division produced a number of S-band systems for a variety of applications. The two most outstanding machines were the 2 MeV, 1 A peak and over 70% efficient 30-cm long traveling wave linac built for E-beam processing [9] and the recently commissioned 7 MeV magnetron-powered standing wave linac with a 10ns to 3 μ s regulated pulse length installed at the University of Pune, India. After 6 years of successful operation, some of the assets of AS&E High Energy Systems Division operation have been sold [10, 11]. As a result of the sale, AS&E retained exclusive rights for the linear accelerator designs for security and non-destructive testing applications.

NEW X-BAND DEVELOPMENTS

Portability of X-Band Linacs

The X-band accelerators operate at three times higher frequency compared to the similar S-band linacs and the accelerator cell cross section area is approximately 10 times less than that of the S-band accelerators (Fig. 1), which permits reduction of any shielding mass along the linac by at least the same factor.



Figure 1: 1 MeV X-Band linear accelerator section (left) next to a single S-Band cavity.

Recognizing the only remaining disadvantage of the AS&E X-band linacs compared to the similar commercial S-band linacs being lower dose rate due to a less powerful X-Band magnetron, we focused on improvements for the linear accelerator structures, which along with improvement of the X-band magnetron performance resulted in reaching parameters, listed in Table 1.

Table 1: Parameters of new commercial X-band linacs

Parameter	Units	MINAC1	MINAC4	MINAC6
Energy	MeV	1 to 3	4	6
Current	mA	700	120	100
Linac RF Length	m	0.085	0.4	0.58
Nom.Dose Rate@1m	R/min	50	100	600
Max.DoseRate@1m	R/min	100	200	750

Some of the new results were reported at EPAC-2004, but they were not published in the Proceedings.

New 6 MeV Extended X-Band Section

While we were able to substantially improve performance of the standard X-band accelerator sections [12], the X-band machines still produced output less than the S-band linacs. Therefore, we launched a program to design a new accelerator guide in order to maximize dose rate output at RF power produced by the X-band magnetron. This work has required substantial analysis of both theory and of the extensive experimental results, accumulated over more than a decade. As a result of this development, we produced a design, which delivered a record output comparable to that of the 6 MeV S-band linac. The accelerator guide, which has been fully tested at high RF power is shown in Fig. 2, 3. The experimental results are presented in Fig. 4 - 6.



Figure 2: New 6 MeV accelerator section.

This work has concluded our development of the 6 MeV linear accelerators at AS&E High Energy Systems Division in California. A diagram presenting the improved performance of the linacs over recent years is shown in Fig. 7. We more than doubled output and improved other characteristics of the 6 MeV linear accelerator primarily used for radiation therapy over the considered development and production period and made it comparable to the S-band linac (Table 2).



Figure 3: New 6 MeV accelerator section with shielding designed for less than 0.1% radiation leakage.

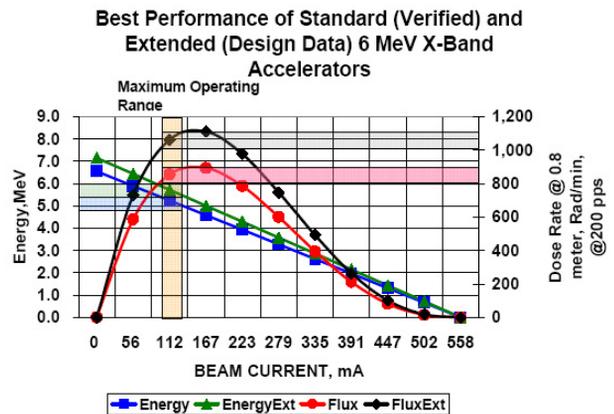


Figure 4: Diagram showing desired operating range and characteristics of new 6 MeV accelerator.

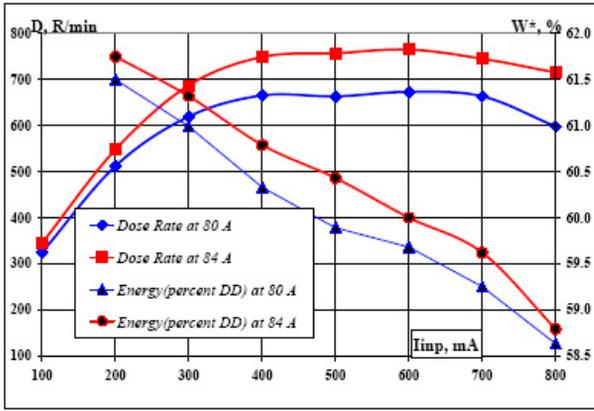


Figure 5: Measured dose rate produced by the new 6 MeV prototype linac.

Table 2: Comparison of Commercially Available X-Band and S-Band 6 MeV Linacs.

	Energy MeV	Dose Rate, Max R/min @ 1 m	Dose Rate, Nominal R/min @ 1 m
S-Band	6	1000	800
X-Band	6	750	600

Demonstrated 6 MeV X-Band Linac Dose Rate R/min @ 80 cm

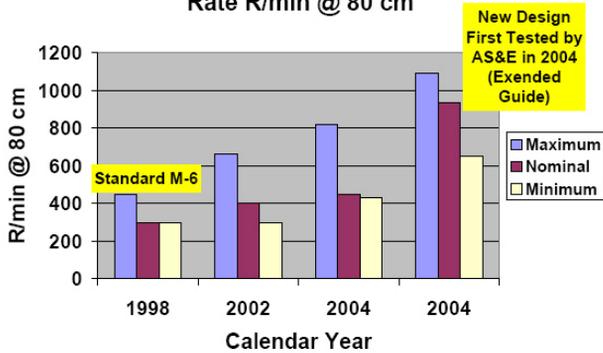


Figure 6: Improvement of X-band linear accelerator performance since establishing of AS&E HESD in 1998.

New 1 MeV X-Band Linac

This ultra-compact linac (Fig. 7) recently designed and built by our Division deserves special attention. Fitting in one’s palm, it truly demonstrates the advantages presented by using X-band technology and introduces a very compact tool for numerous applications, including but not limited to security applications such as screening of luggage and cargo, replacing isotope sources, NDT, and other applications. The original, less than 10 cm long section has been designed and tested at high power, and the results of the test are presented below. We installed a specially designed X-ray target at the output of this accelerator, so we performed indirect measurements of the electron beam energy using a half-value layer for the produced X-ray beam (Fig.8).

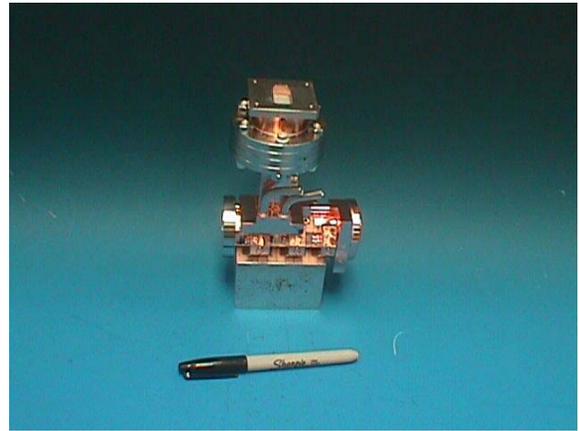


Figure 7: Ultra-compact 1 MeV linear accelerator.

While the measurement error was fairly high for this technique, it permitted to demonstrate the principal characteristics of the 1 MeV linac.

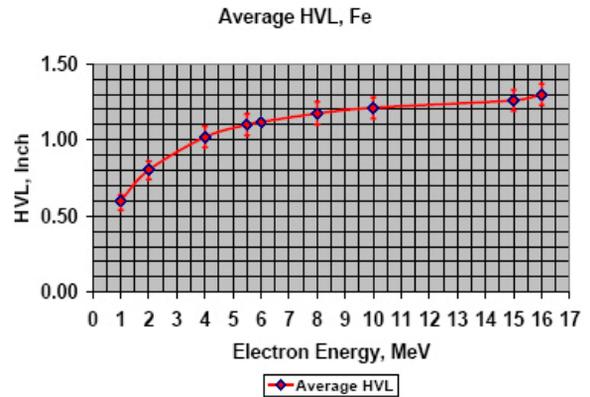


Figure 8: Half Value Layer (HVL) versus electron beam energy.

The Fig. 9 presents estimated electron beam energy in a range of magnetron anode current (RF power). Although the highlighted error is substantial, the section clearly demonstrates a very high RF-to-beam efficiency, which is at least similar or arguably better than that for the S-band machines. It is also interesting that the small linac demonstrated the expected flexibility in a range of the RF power (Fig.10). Two curves at two different injection current levels at 1 A and at 1.4 A lay on a smooth graph, which well matches the design values. The graph essentially presents three load lines with two beam current points at two injected current values of 1 A and 1.4 A, at three different power levels of 1 MW, 1.4 MW, and 1.6 MW.

This smooth electron beam energy regulation feature adds to the qualities of the designed linac. This linac is clearly a candidate to compliment the existing 3.8 MeV linac currently used by AS&E in a Shaped Energy™ system for screening of dense cargo [7].

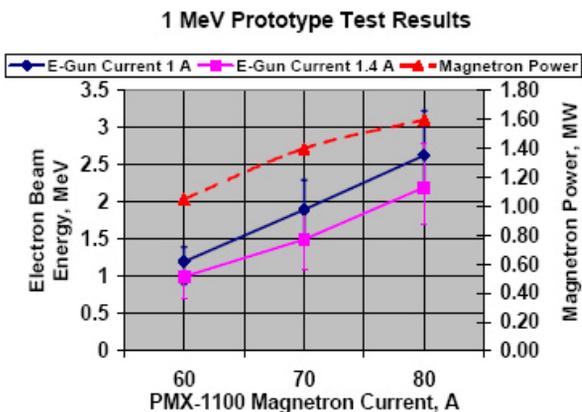


Figure 9: Energy of X-rays based on HVL measurements.

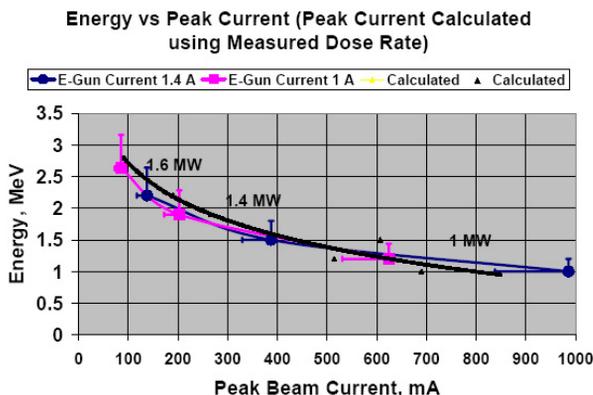


Figure 10: Three two-point load lines at different power levels are combined in a smooth load line for 1 MeV to 3 MeV linac.

Please refer to a poster publication at this conference [13] for more information on this truly unique new linac.

NEW S-BAND DEVELOPMENTS

Following our previous efforts in building a 4 MeV to 10 MeV energy, short pulse programmable X-band linac, we designed a 7 MeV, short variable pulse S-Band linac with fully programmable single pulse, pulse sets, and “continuous” pulsed operation [14]. The accelerator system utilizes an L3 (Litton) M754 grided electron gun combined with an AS&E designed gun drive system that is capable of producing up to 3A at beam energies from 10 kV to 15 kV with pulse lengths of 1.5 uS to 4uS. The beam from the e-gun is focused by magnetic field produced by a lens coil and the first focusing coil, and then it is sent into the electrostatic deflector. The undeflected beam enters an S-band (2998MHz) standing wave side-coupled linear accelerator section with 17 cavities that is 80.8 cm in length. This section is fed by a 2.6 MW magnetron with a circulator providing isolation. The beam is accelerated to 7.5MeV nominal or higher depending on the magnetron power utilized. The beam is confined in the accelerator section using four large Helmholtz coils that surround the linac. After the beam exits the linac it passes through a ceramic break combined

with a Bergoz FCT that provides for beam current monitoring. The end of the ceramic break contains a 0.0006” thick titanium window that allows the electron beam to exit the vacuum system and interact with samples located outside of the vacuum envelope. A 60 l/s MidiVac ion pump that is connected to the linac and deflector and a 0.5 l/s MiniVac ion pump on the gun maintain vacuum for the system.



Figure 11: 7 MeV linac under test at University of Pune, India. Right to left: electron gun, HV deflector, accelerator section with focusing coils, BCM, electron beam window.

In order to produce the desired pulse lengths of 3uS, 400nS, 200nS, 100nS, 50nS, 20ns and 10nS an electrostatic deflector system has been chosen.



Figure 12: 7 MeV linac installed and commissioned at University of Pune, India.

Table 3: Linear accelerator system parameters.

Pulse Length [nS, FWHM]	Peak Current [A]
3000	0.12
400	0.41
200	0.52
100	0.63
40	0.68
18	0.97
8	1.12

This accelerator has been successfully installed and commissioned at the University of Pune early this year.

We have also completed design of a 9/15 MeV, high dose rate S-band linac suitable for NDT, security, and for

some other applications. The latter system design is not included in this paper, and it may be publicized in the near future.

CONCLUSIONS

Over its 6-year history at AS&E High Energy Systems Division, we developed numerous X-Band and S-Band accelerator systems, which usually operated at advanced level. In addition, we established a well-organized and reliable production of the portable X-band accelerators for commercial applications, bringing their performance to a level, comparable with the similar S-band machines. This paper summarizes the last developments at HES before sale of some of the Division assets [10, 11]. AS&E will continue to use the line of the X-band linacs for security and for NDT applications with the previously used brand names MINAC for the X-band linacs, MINATRON and MAGBEAM for the S-band linacs. At AS&E, we will continue pioneering new products and concepts with a focus on security applications. Due to limited space permitted for this publication, it is not possible to present enough details regarding the new developments. Please feel free to contact me at AS&E with any questions or comments you may have.

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