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Report

Accelerator Beam Centerlines (ABC) and High Energy Sources (HES) Produced at Varex Imaging Corporation

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Abstract

A Salt Lake City (Utah) based Component Division of Varian Medical was spun-off in 2016 and has become an independent public company Varex Imaging Corporation (VREX, NASDAQ) in January 2017. Since the spin-off, we have designed, produced, and tested several Accelerator Beam Centerline (ABC) prototypes to meet or exceed the parameters of the Varian-built predecessors, and some ABC models have been released to production. The primary objective set by the Sunny Sanyal, CEO of Varex, was to develop Varex's own Linac technology that would be a step ahead of current technologies and form the basis of future high energy applications roadmap for Varex; namely, build 3 MeV, 6 MeV, and 9 MeV basic models, in the first place, and eventually, develop advanced products and make Varex an undisputed leader in the field. The fundamental objective has been accomplished and our pilot production line produced 20, 65, and finally, more than twice that much, way exceeding 100, in consecutive fiscal years of 2022, 2023, and 2024, correspondingly. Our LINAC high-power testing was performed only at our Las Vegas facility, but recently, a test cell at our production facility in Salt Lake City was built in May 2024. A LINAC utilizing 6 MeV ABC represents bulk of Varex units shipped in 2024, the LINAC has been fully tested and released to production in a Diode Electron Gun (DEG) and a Triode Electron Gun (TEG) based versions. A LINAC system Mi6SSM-T is designed based on Mi6SSM product, utilizing TEG and TEG High Voltage (HV) Driver (TEGD). Over 100 new LINAC Systems based on our new ABCs have been shipped to Varex customers. The TEGD is composed in a 19" Mi6SSM rack-mounted assembly, but it can be installed in the LINAC X-ray or Electron Beam Head for designs based on the "legacy" LINATRON models. In addition, we are developing new linac models, and some are groundbreaking designs. We have designed and tested MicroBeam LINATRON™ with ABC-6-S-M-X-T-SUBMM, delivering less than 500 μm spot size (estimated 350±150 μm) and only 12.5% maximum dose rate reduction (700 R/min@1m), compared to a standard ABC-6-S-M-X-T (800 R/min@1m). We have bench-tested a new upgraded M9V accelerator, operating at 9 MeV and delivering substantially higher dose rate (maximum over 5000 R/min@1m) of its predecessor M9 (rated at 3000 R/min@1m). Our new K15V, or V15 (under development) will operate at our common frequency 2998 MHz, and it utilizes a patented hybrid standing and traveling wave design. The first 9 MeV section can be a separate machine (V9), that will deliver very high dose rates, while drastically reducing the produced neutron yields, compared to K-15.

Keywords

Electron Beam, Linear Accelerators, LINAC, Microwave, Bremsstrahlung, X-Ray, Varex, Imaging, NDT, Security Screening

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1. Introduction

In January 2017, Varian Medical Systems, Inc. (Varian)[1] completed a spin-off of its imaging components business into a new, stand-alone public company, Varex Imaging Corporation (Varex)[2] (Figure 1).

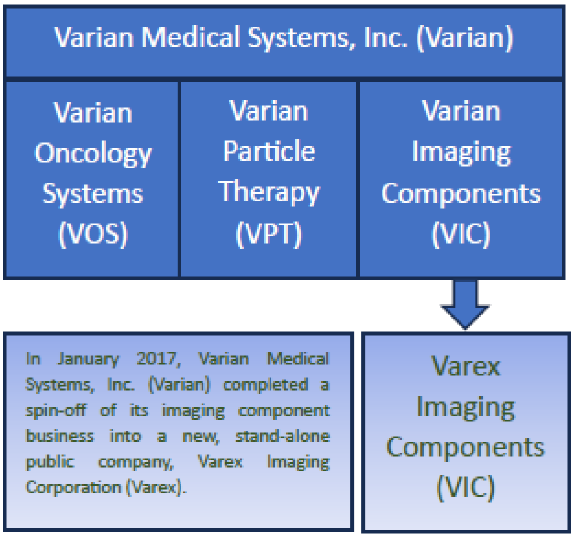

Figure 1. *Formation of Varex Imaging Corporation (VREX).*

Varex is based in Salt Lake City, Utah, and is a leading innovator, developer, and manufacturer of X-ray imaging component solutions. As part of Varex security and industrial business, based in Las Vegas, Nevada, Varex manufactures high-energy linear accelerators (LINACs) (Figure 2). In May 2016, 8 months prior to Varian spinning off the imaging components business, Varian acquired assets of two small companies[3] 1) the distribution of Betatrons and detector arrays and 2) development of linear Accelerator Beam Centerlines (ABC). These assets added to Varex's capabilities. Alongside the acquisition of the two LLCs, Varian Medical offered a Senior Director role to the Author.

The primary objective set for him was to establish the linac beam centerline production at the Imaging Components Division. After closing the acquisition and starting with Varian in 2016, the small production line in Fremont, CA has been maintained and continued to produce an X-Band 12 MeV electron beam ABC equipped with a triode electron gun (ABC-12ER-X-E-T), designed by one of the predecessors (RMX) [1, 2] (Figure 3) for intraoperative radiotherapy system Mobetron by Intraop Medical Corporation in Sunnyvale, California [3, 4] (Figure 4).

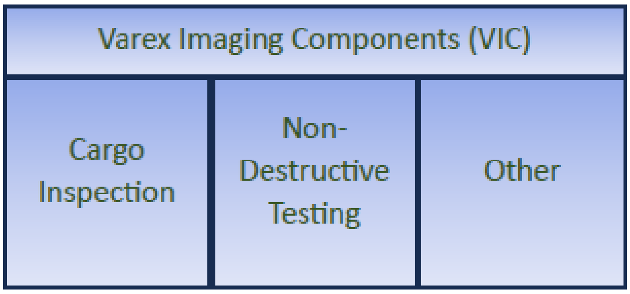

Figure 2. *Security Screening and Non-Destructive Testing (NDT) Industrial Markets and Products remained with Varex Imaging Corporation after the separation from Varian.*

This was necessary to ensure smooth transition of the production, but by the end of 2017, we completely relocated to Varex Headquarters plant in Salt Lake City.

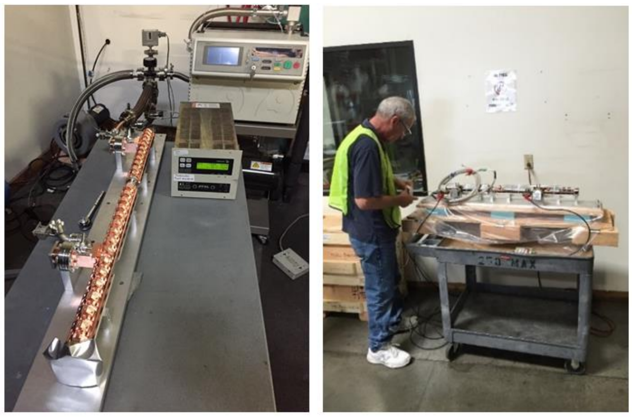

Figure 3. *12 MeV electron beam X-Band ABC equipped with a triode electron gun (ABC-12ER-X-E-T).*

During the past 8 years at Varex Imaging Corporation, we have created a design and production line for Accelerator Beam Centerlines (ABC), built nearly 40 ABC-12ER-X-E-T and replaced supply of Beam Centerlines (BCL) by Varian. In April 2022, the Author was promoted to a position of Vice President in charge of all High Energy Sources R&D and ABC production, combining two groups in Las Vegas (HES or LINAC Systems Development) and Salt Lake City (ABC Development and Production). We were able to build an A+ team of Varex professionals, currently 26 people in HES group, who are responsible for many advances and our overall success. We have completed designs of various ABC prototypes, and now we are shipping most of the models and in process of moving all of them to production.

1 https://www.varian.com/
2 https://www.vareximaging.com/
3 Both Thought One LLC and Radmedex LLC have been dissolved in 2018 upon completion of the transition process.

Figure 4. *ABC-12ER-X-E-T is utilized on Mobetron System for Intraoperative Radiation Therapy built by Intraop Medical Corporation.*

We have reported our progress on ABC and linac systems earlier [5-19]. This manuscript summarizes our work for the past 8 years, the issued patents, and results presented at several professional conferences over the last four years, including the latest IPAC and CAARI in this calendar year of 2024. During Varex Fiscal Year 2024, which ended 30 September 2024, we produced way over 100 ABC, very much meeting goal of the units mix for security, NDT, and other applications. This represents well over 200 percent rate of annual growth during last 3 years (in 2022 and 2023, we produced 20 and 65 ABCs, respectively). We can now claim completion of the original objective, along with many improvements in our ABC performance, which exceeds some features of the predecessor products. The 3 MeV and 9 MeV production units have been designed and passed Verification and Validation (V&V) process. In addition to these accomplishments, we made some advances in our linac systems, over the last two years since the Author's promotion to a Vice President, R&D in April 2022. The Mi6SSM linac model with a Solid-State Modulator (SSM) (the "legacy" LINATRON model used "line" modulators) was designed and built in the early days of Varex, and it utilized a diode electron gun with High Voltage (HV) Power Supply (PS), delivered by one of our OEMs. A triode HVPS (TEGD) was also under development at Varex Imaging, which was planned to be a source for a dual switchable energy linac operation, versus an off-the-shelf triode e-gun PS, available in the industry.

Once the Author was put in charge of all HES R&D, we produced a prototype modification of our SSM system Mi6SSM to Mi6SSM-T, combining inherited design of the Triode Electron Gun Driver (TEGD) (alternatively to a Diode E-gun Supply) with the newly produced ABCs with a Triode Electron Gun (TEG), hence expanding the performance range and adding some features combining "High" and "Low" output linacs. We worked on improving TEGD cooling and ruggedness, driving the prototype to a production ready unit. The "T" system is being finalized and moved to production.

The first round of spot reduction effort in our key models resulted in a record small beam spot we obtained in our TEG-based 6 MeV ABC, measured at 0.8 mm [18] (compared to the common 1.5 mm), which may substantially improve image quality. The next round of efforts resulted in building a specialized 6 MeV ABC with a submillimeter spot size, which FWHM we estimate in 350$\pm$150 µm. The next step will be testing the 3 MeV and 9 MeV similar models to the same or less spot size. Finally, our new 15 MeV K-15 system is being redesigned from an operating frequency of 2856 MHz, used by the predecessor, to a common 2998 MHz used for all our other ABCs. This linac design is patent protected [5] and will have a higher average electron beam power (hence, higher dose rate) capability for high power target testing and operation [16]. It may become our High-Power Platform (HPP) for other systems and applications, including, but not limited to new generation of high-power 9 MeV linac models M9V (upgraded from a legacy Linatron M9) and an ultra-high-power V9, also operating at 9 MeV and delivering a record high dose rate. The V9 may ultimately be considered a replacement to K-15 in many instances, providing the advantage of much less neutron yield, simpler design, and unprecedented dose rate of the generated Bremsstrahlung.

2. Vertical Integration of LINACs using ABC by Varex Imaging

2.1. Objective and Conditions

First and foremost, the objective was to secure production of the base models. Directions received from management were as follows:

1) create our own IP and design all the models ourselves, without any reference to predecessor linacs, except the general specifications and external dimensions,
2) maintain a form-factor that would allow using them as replacement in our standard shielding package,
3) the drop-in model had to operate using the same or other available power sources and power supplies, such as electron gun high voltage, magnetron input power, etc. Fortunately, the transformer used in "legacy" systems permitted use of different e-gun HV – the proprietary Varian electron gun design was unavailable to us.
4) The production line capacity to cover full Varex needs was estimated to be 100-200 units/year, considering new product development and future growth,

2.2. Challenges and Opportunities

We were facing a complex multifold challenge and had to design prototypes of each linac model, ensure they are working to the standard Varian specification or better with a completely different electron gun operating at 3 times lower voltage, available commercially, which redefined requirements to the linac RF structure - part of the serious challenge.

It was clear that under the circumstances, performance of ABC compared to the legacy technology will be different, and our job was to get their specifications to be as close as possible with all the other elements of the system remaining the same or similar.

Another substantial challenge was the expectation that the ABC guides would be a "drop-in" replacement of the predecessor guides, and operate to the same standard, which was, frankly, somewhat contradictory to the requirement of producing Varex's own design and IP, while using a different electron gun.

The Triode Electron Gun Driver, or TEGD, later presented another added-on challenge.

It seems that to some degree, all participants fully realized the complexity and scale of this challenge. Ironically, all we had to do in a few years was to design several key models operating the same or better than contemporary technologies and create a production line for these key models "from scratch", catching up with incumbents in the industry that may have spent many decades in perfecting their production, reaching production rates of many hundreds of Beam Centerlines (BCL) per year.

Indeed, Varex wanted reasonably quick completion of the major task. Our expert estimates for the project duration ranged from 5 to 8 years, while the management hoped for 3-5 years. In the Author's past experience, a full completion and certification of any system prototype would take about 2-5 years, depending on its complexity, and that is only for a single prototype. Now, bringing the product to a complete commercial realization and mass-production could take 8-10 years, and conservatively, in our industry of electron beam linear accelerators for security screening, non-destructive testing, radiation therapy, electron beam processing, it takes 2-5 years for a prototype to become a product ready to mass-produce, and 5-10 years for a production model to fully commercialize and reach top production volume, again, depending on complexity of the product, team maturity, and field of use. Multiple examples can be provided – such as companies and their products, which utilized the linear accelerators the Author participated in developing, such as Mobetron for Intraop, Cyberknife for Accuray, Sentry for AS&E, and a variety of other LINACs [20-40]. A period of 5-8 years seemed reasonable for the multiple developments. Indeed, a staggered schedule helped us to shorten the productization period and, in fact, it is predicted that we will meet the "8-year to 10-year" criteria.

2.3. Vision and Strategy

We did what we had to and accepted the challenge in good faith. Our confidence was based on joint extensive experience and a good production base at Varex, hoping to get it to a full success in reasonable period as noted. To "jump-start", expedite completion, and gain more confidence between the working team and Varex management with every further step at an early phase of the project (during the first couple years), we focused on the most important matters first. The chosen strategy was well-known to the Author; following the proven ways and means, we built working prototypes with a different e-gun, to meet the key specifications, and only then worrying about the form-factor and fit. Having designed the linacs differently than Varian, and using a different, commercially available 15 kV triode electron gun [41, 42] versus Varian proprietary diode electron gun design, which we had no access to and could not use for the Varex IP, presented another, separate challenge. This challenge was brilliantly resolved at low cost, and we managed to have very similar characteristics in our triode and diode e-guns relative to Varian's proprietary electron guns, while securing three suppliers of such e-guns.

Running a bit ahead, in 5-6 years from the cold start we realized that our strategy was working, even with many other challenges that have appeared along the way, we continued to gain confidence and got us to full production of the key 6 MeV linac in 2024, in 8 years. We have also completed V&V process for 3 MeV and 9 MeV during the same year, expecting full production for all three models to continue in 2025. In parallel, we have built linacs with both triode and diode electron gun at 3, 6, and 9 MeV, which provides flexibility in the future. Indeed, as we expected, the units varied in some parameters compared to the existing linacs: some came out superior and some were less impressive than the legacy linacs, but I think we have reached a point where we can confidently state that, for example, 6 MeV linac with ABC technology demonstrates better performance than its predecessor. We continued implementing a policy of continuous improvements for 3 and 9 MeV linacs, which meets the key specifications at these energy values, but have not yet provided exact match at lower energy compared to legacy models. However, we are designing the next generation models, which we believe will exceed Varian specifications in a broad range of electron beam energy. In addition, new initiatives resulting in excellent operational units at various energy values emerged during this journey, and I will be describing them in this monography. The linac vacuum assembly product that was called BCL while delivered by Varian, was now called and trademarked Accelerator Beam Centerline (ABC) to distinct Varex products from Varian products. In the following chapters, we will discuss various ABC models we have put to work at Varex.

2.4. 3 MeV Linacs

While it might seem counterintuitive at the first glance, in 2017 we started with designing an X-Band version of a 1.8 MeV LINAC replacement in NX-1 X-Band LINAC, versus more common S-Band frequency band, the move was proposed by Bob Drubka, a VP and GM of Security and Inspection Products group at Varian/Varex at that time, who thought that we might replace Varian X-Band linac operating with a low-power magnetron in an X-band at that time. Based on extensive experience accumulated by the Author in designing and building X-Band linacs for various applications [1-3, 22, 24, 25, 36] and the inherited 12 MeV X-Band linac design from Radmedex LLC, which performance was highly appreciated by the customer [2], it seemed like a great idea – to give Varex management something in a very short timeframe to boost confidence and prove our competence in the subject. The first built ABC is shown in Figure 5.

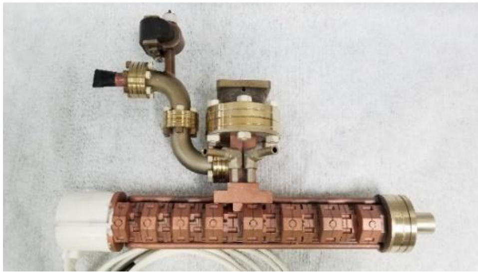

Figure 5. *First ABC built and tested at Varex.*

2.4.1. ABC-1.8-X-X-T and ABC-3.0-X-X-T

The 1.8 MeV section (Figure 5) was designed as a replacement of a Varian produced X-Band guide for an affordable linac system operating at energy of less than 2 MeV, which does not require an export control license. The latter substantially broadens worldwide market for this linac. Three prototypes have been built, and all demonstrated excellent performance, producing the expected parameters: maximum energy of <2 MeV (contingent on RF power input), with loaded nominal energy of 1.8$\pm$0.1 MeV, nominal dose rate of 13$\pm$2 Rad/min. The ABC-1.8-X-X is equipped with a triode electron gun and demonstrated a spot size of 1.0$\pm$0.2 mm.

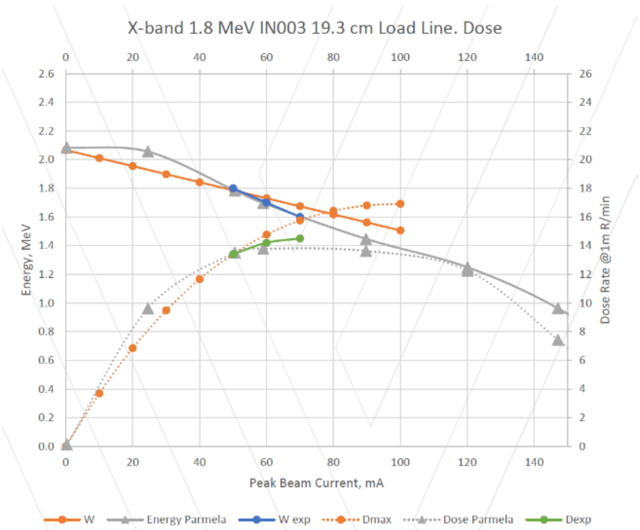

Figure 6. *First ABC Design and Experimental Data using a low power 350 kW magnetron.*

The exceptional match between experimental and theoretical data is presented in Figure 6 and in Table 1. Later, this design was used with higher power 800 kW magnetron, it produced a 2.5 MeV beam [5], Figures 7 and 8. In addition, we have decided to test a technique of two separate sections run through a symmetrical 3 dB splitter was described by Victor Vaguine and Eiji Tanabe of Varian [42, 43], also by Getka in [44], producing a dual section LINAC ABC-2.5-X-X-DI with power input through an approximately 3 dB power splitter (Figure 9), otherwise similar in length and performance to the single section ABC (this happened a year later).

The splitter ultimately can replace a circulator, used for isolation of the magnetron from the reflected power from ABC.

Table 1. *First X-Band Test Results with low-power magnetron.*

Parameter	Units	Value
E-Beam Energy		
Design	MeV	1.9
Experiment	MeV	1.8
Dose Rate		
Design	R/min@1m	14.5
Experiment	R/min@1m	12.7
E-Beam Current		
Peak	mA	48
Average	A	37
Magnetron Power		
Peak	kW	359
Average	W	276

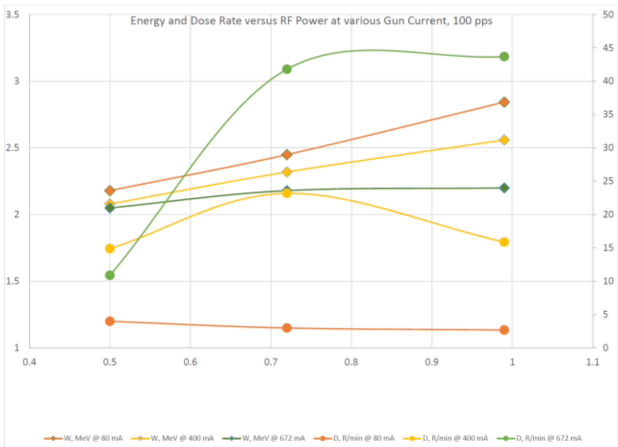

Figure 7. *ABC-2.5-X-X-T Design and Experimental Data using a higher peak power 800 kW magnetron, 100 PPS.*

The symmetrical two-section, dual input through 3 dB coupler design worked very well, and it has a potential for further improvement and cost reduction, or for broad energy and dose regulation, easy low-dose operation, thanks to the triode (gridded) electron gun.

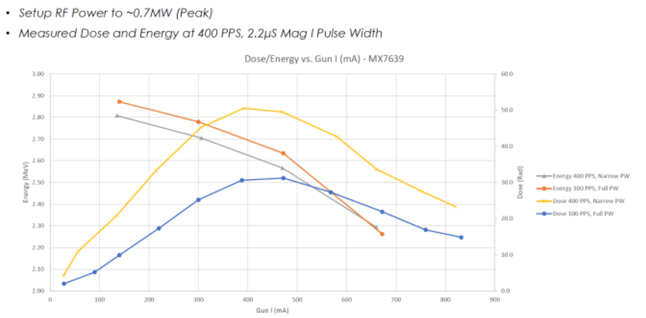

Figure 8. *ABC-2.5-X-X-T Design and Experimental Data using a higher peak power 800 kW magnetron.*

Figure 9. *ABC-2.5-X-X-DI-T "Dual Input" designed for 2.5 MeV and dose rate up to 50 R/min@1 m from target.*

2.4.2. ABC-3-S-X Design Strategy and Challenges

Meanwhile, we were gearing up for designing and building the S-Band prototypes and had some choices here. While we still looked at quite a few years ahead until our deadline, the scale and complexity of the task left no illusions and made us pay attention to every detail in building our future strategy, remembering that we had no time to spare. We have analyzed sales data and were facing some choices in priority of the development - 6 MeV linac represented about 60% sales, 3 MeV linac – 30% of sales, and 9 MeV and other – only 10%. One would think we should have started with a 6 MeV, but at that time, we received a field report of several incidents based on catastrophic target failures, when fast pulsing mode was used, drastically increasing temperature cycling of the target. This urgent need for an alternative solution defined our priorities, and we have focused our efforts on a 3 MeV linac prototype with a different target design.

We found that extensive thermal cycling of the targets at a higher pulse repetition frequency reduces life of X-ray targets substantially. Broad regulation of energies and smaller X-ray focal spots are also among the main points of interest from customers. While working on our new guide ABC-3-S-X, we addressed and had initially, at least, a solution for most or all of the problems mentioned above.

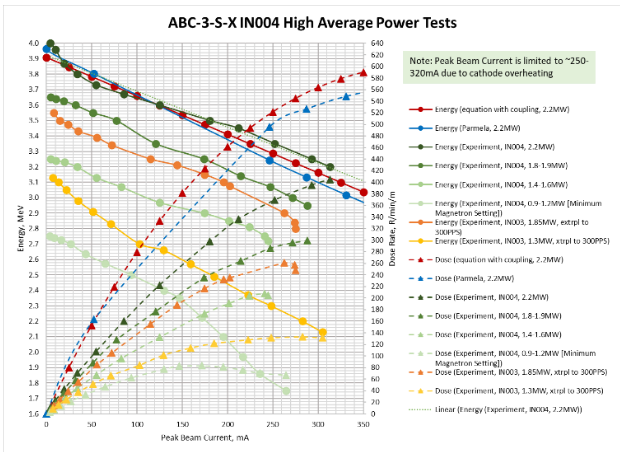

Figure 10. *ABC-3-S-O-X-T performance.*

A proposed different target design with additional cooling has resulted in extended life. Eventually, the prototype ABC has been run continuously at our customer site, for more than 3000 hours up to date without any issues. In a relatively short beam centerline designed to operate at peak beam currents up to 500 mA where fields are high enough, a so-called beam backstreaming issue is one of the output main limitation factors. By utilizing a powerful beam tracking software Opera, we have been able to improve the electron gun beam optics and, at the same time, restrain beam from striking the electron gun cathode. As a result, we have achieved X-ray dose rate of up to 500 R/min at 1 m from the target. The triode gun helps in a continuous regulation between 2 and 4 MeV while regulating input RF power. The SN004 had produced excellent characteristics, shown in Figure 10, the first time. Not many people might realize that this LINAC is the most difficult one in many aspects – a combination of the high RF power losses per unit length and back streaming bombardment of the cathode due to the LINAC short length present a serious challenge.

We struggled a bit, trying triode and diode versions, working on a spot size reduction, and went through several design iterations. Finally, in 2018, we produced a prototype version (SN006) that fully met our internal expectations.

2.4.3. 1st Operational 3 MeV S-Band Prototype Test

This model ABC-3-S-X-D with a diode electron gun marked SN006 has gone through extensive testing at Varex and met the key specification requirements.

Table 2. M3 with our First S-Band ABC-3-S-X-D Test Results.

Parameter	Value
Report Date	3/2/2021
Linac Model	M3
Linac Serial Number	3027
Date of New BCL installation	Week of 10/21/2019
Date Testing begun	10/29/2019
Model Number of BCL installed	ABC-3 IN006
Date Focal Spot was measured on	11/7/2019
Focal Spot as measured	1.9 mm
Beam Hours at time of install	2055
Beam hours as of 3/2/2021 5PM EST	3143
Hours run as of 3/2/2021 5PM EST	1088
Dose Rate @ 400 PPS, at 1 m	0.86 Gray/min

* Notes:
1. Triggered by 1680 Flat Panel Detector Simulator
2. HV Power Supply for Vacion was replaced
3. Thyratron was replaced

Then, it passed life test at VJ technologies [45], the results are presented in Table 2.

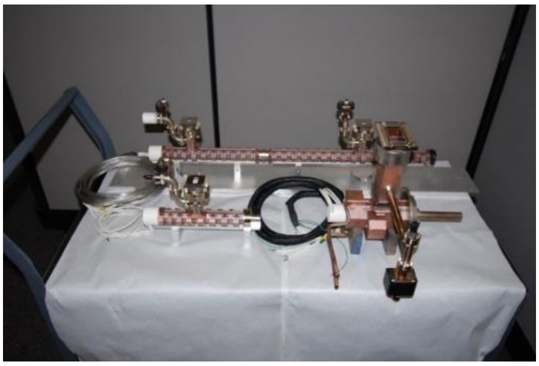

Figure 11. ABC models made available in 2018.

While a few further improvements were due, including, but not limited to redesign of the outer shape and changing the form factor to fit the standard shielding package, the results were very positive (see Table 2) and the physics design was complete. This constituted our first substantial step in designing and building the S-Band replacements.

By the end of 2018, we had a group of 7 people and a few ABC models fully designed ready to produce (Figure 11).

2.4.4. Bringing 3 MeV Design to Production Level

This was our first experience with a diode electron gun, which was a modified version of the standard triode electron gun, and the approach turned out to be a success.

VJ Technologies report stated that "there were no issues" in running the unit, confirmed that the parameters met or exceeded the specification, and, most importantly, that the target ran well - no failures observed under same conditions where we experienced multiple failures with the predecessor guides.

Once the 3 MeV prototype met all the requirements, the interim job was completed but it was already 3 years since we started, and while we were working on the 3 MeV prototype, we made a very important strategic decision to postpone further work on the 3 MeV until we master a 6 MeV design. This strategy served us well and was at the very foundation of our overall success. First, the 6 MeV replacement linac represented most of our sales in Security Screening field, and secondly, we had to come up with a common shape to have form-factors for our linacs to be "drop-in" replacements for the legacy predecessors.

2.4.5. Closing on ABC-3-S-M-X-T and -D and Further V&V and Certification

Some of the test results on these three units are presented in Tables 3 and 4, with TEG and DEG.

Table 3. M3 initial test with ABC-3-S-M-X-T (SN001-003) E-Gun HV at 8 kV, values averaged for 3 units.

PARAMETER	SN001-SN003	
	3.0 MeV	4.5 MeV
Dose Rate, R/min@1m	172	438
Input RF Power Peak, MW	1.4	2.3
Average, kW	2.6	2.7
Pulse Repetition Frequency, Hz	400	261

Table 4. M3 test with ABC-3-S-M-X-D, RF power varied.

Parameter	Units	SN001 Energy, MeV		SN002 Energy, MeV		SN003 Energy, MeV	
Energy	MeV	1.6	3.1	3.0	4.5	3.2	4.5

Parameter	Units	SN001 Energy, MeV		SN002 Energy, MeV		SN003 Energy, MeV	
Dose Rate	R/min@1m	28	278	130*	298*	298	266*
Spot Size							
Hor.	mm	-	-	1.5**	1.0**	-	1.1**
Vert.	mm	-	-	1.4**	1.3**	-	1.3**
RF Power							
Peak	MW	0.85	1.65	1.3*	1.9*	1.9	1.9*
Aver.	kW	1.5	2.68	2.3	2.65	2.7	2.65
PRF	Hz	400	370	400	315	325	315
E-Gun HV	KV	8.0	11.0	10.4	9.4	14.7	9.4

Skipping this break in our work on 3 MeV line of products and going ahead of myself in our recent Varex history, we will describe closure on 3 MeV "standard" linac replacement in 2024. Three guides have been built and tested, based on the geometry proven in CY2019 - CY2021.

Work on productization of this guide was stalled for a couple years until we mastered the 6 MeV, which, as history showed, was a great decision that allowed us to meet the record system shipment volume in Q4FY23 and in FY24 – 150 units built and shipped in FY24, when our 6 MeV shipments represented nearly 100% of the revenue.

The three 3 MeV units as originally designed and tested in 2018-2022 were built, successfully passed V&V test, and shipped as part of M3 units to our customers in FY2024. This happened in a matter of several months, versus a couple years it took us to master the first one to work. We were quite happy with this progress.

2.5. 6 MeV Linacs

As mentioned earlier, we started design work for the 6 MeV early, and this permitted us to build a few prototypes to get a better feel for the "Varian length" 6 MeV ABC operation. It would be appropriate to say that this BCL by Varian was one of the best, if not the best compact linac in the world until we beat the record having a few characteristics better than accomplished by Varian. However, we had to work hard - while our built prototypes worked quite well, we had to make several improvements and solve a few puzzles. We worked on this ABC in parallel with building the 3 MeV, and after three iterations of the 6 MeV geometry, ABC-6-S-O-RS-D-X, still in the old "O" style prototype form-factor, met the specifications.

2.5.1. First Success on ABC-6-S-O-RS-X-T – Preproduction Certification

The third produced guide ABC-6-S-O-RS-D-X (the Triode version also has been tested, see Figure 12), still in the old "O" style prototype form-factor, was the first preproduction ABC certification turned out to be successful. Its testing has been completed in early November 2022 (see Table 5). From the data enclosed in Table 5, one can see that the test results matched the required specification.

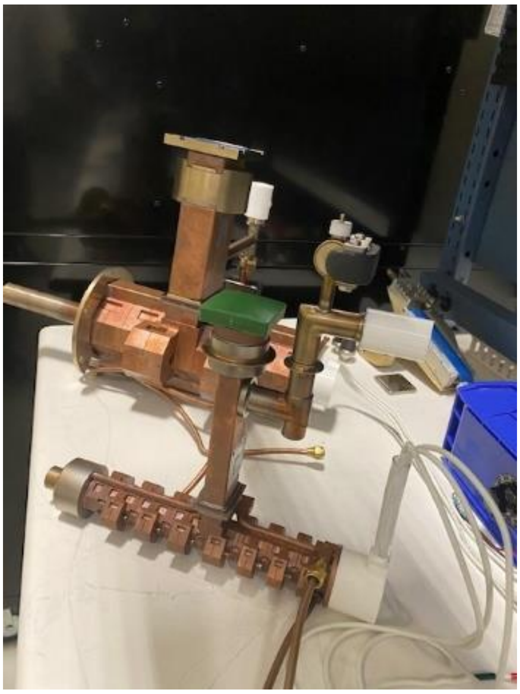

Figure 12. *ABC-6-S-O-X-T next to ABC-3-X-O-X-T.*

Table 5. *Standard Requirements and Test Results for preproduction 6 MeV ABC-6-S-O-RS-X-T.*

Parameter	Units	Value
INPUT DATA		
Magnetron Peak Power		

Parameter	Units	Value
High	MW	2.3
Low	MW	1.4
E-Gun High Voltage	kV	9.0
E-gun Current		1.4
High	mA	629
Low	mA	668
Duty Cycle		
High		0.0012
Low		0.0009
OUTPUT DATA		
E-Beam Energy		
High, Requirement	MeV	6.0
High, Test	MeV	6.1
Low, Requirement	MeV	3.5
Low, Test	MeV	3.5
Dose Rate		
High, Requirement	R/min@1m	800
High, Test	R/min@1m	818
Low, Requirement	R/min@1m	250
Low, Test	R/min@1m	250

Some results exceeded the expectations, such as focal spot size, which was about two times smaller in diameter, than on the BCLs.

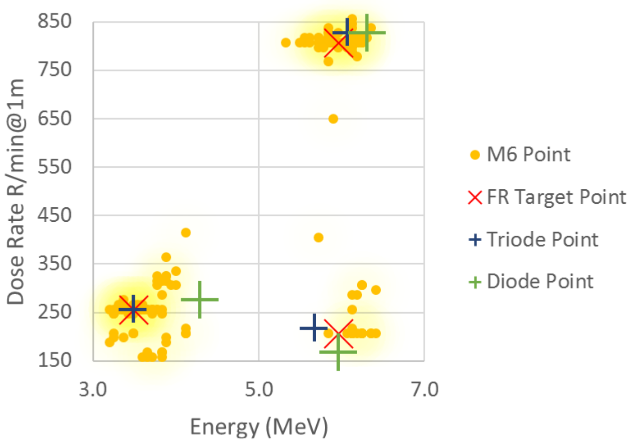

Figure 13. Preproduction and M-style ABC-6-S-M in High Dose Operation in comparison with Varian BCL.

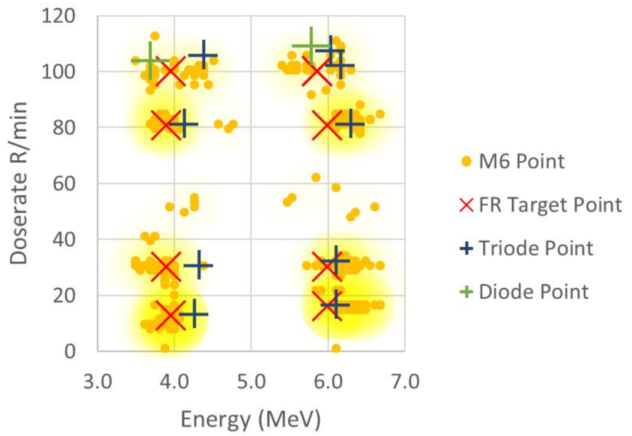

Figure 14. Preproduction and M-style ABC-6-S-M in Low Dose Operation in comparison with Varian BCL.

Figure 15. ABC-6-S-M-X In order as shown: Final Brazed Assembly (1) Vacuum Assembly ready for vacuum processing (2); Completed, ready to ship ABC-6-S-M-X-D (3).

2.5.2. Production-ready "M" Style 6 MeV

A new cell standard cell design called "M" has been introduced, which had an embedded cooling channel as part of the cell design.

After a few iterations of the 6 MeV geometry, we designed first ABC-6-S-M-RS-D-X, where "M" stands for "Modified" - the new common cell type (and RS - for "Reduced Spot", as before). The high-power testing of the first prototype was performed in November 2022, right after completion of the first "O" type ABC guide, described earlier.

While the new "M" worked quite well, we had to make several improvements and solve a few puzzles.

The success was obvious, one can see that by simply looking at the charts, shown in Figure 13 and Figure 14 for the High and Low operation, accordingly, both with a triode and diode e-gun – a comparison of the early design to a statistical data collected on predecessor guides (marked M6).

We had to test both triode and diode e-gun operation of nearly every design, and while our triode design worked right away, we had a few steps to complete with a diode e-gun. I would mention, once again, that we were attracted to using a triode e-gun, because of ease of driving it to a range of currents at the same voltage, in addition, it permitted working both Low and High modes of operation required by the customer using one single and the same guide, while in a diode configuration, we had to use two different designs. A production unit is shown in Figure 15.

2.5.3. Spot Size Reduction in 6 MeV ABCs

In our early designs, we discovered that obtaining a smaller spot requires special attention. The original acceptable beam spots we obtained were on average around FWHM 1.5 mm in diameter, but we substantially improved it in the follow-on units, obtaining spot with FWHM diameter of 1.0$\pm$0.2 mm – without any additional external focusing devices [18]. The beam spot shown in Figure 16 has size of 0.9 mm x 0.7 mm FWHM, which perhaps represents a record in the industry for the common commercial linacs with no focusing, and this result (0.8 mm spot) is indeed superior to the Varian BCL predecessor.

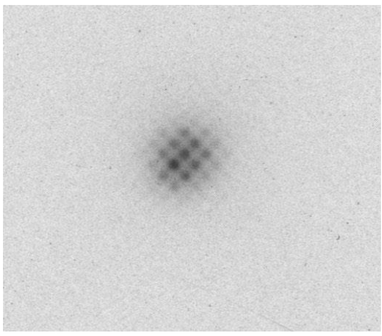

Figure 16. *X-Ray Spot image taken on a radiographic film using spot camera with ABC-6-S-M-X-D.*

We mastered several techniques for beam spot reduction, and eventually, learned how to build ABCs producing the focal spot size of less than 500 μm, establishing a new record in the industry, which is described later in this monography. The latter requires a completely different design of the ABC and a special tuning method that has been developed. The patent is in works and is pending. We called this new line of products MicroBeam LINATRON^{TM} (abbreviated as MBL). In the literature, there are some publications and marketing information stating $\leq$0.5 mm spot achieved in linacs [46], but we have not seen any published proof of that, such as spot profiles as measured and/or other similar results. In addition, in many cases an external magnetic focusing system is present, it seems the case in [47-49], in which energy is only 0.95 MeV.

2.5.4. Full Production Maturity and Certification of the 6 MeV ABCs

In the following two Quarters (Varex Q2-Q3FY23), we completed productization of the 6 MeV linacs for Varex. In Q4FY23, we met Varex production demand, followed by full production cycle implemented in FY24, which ended 30 September 2024 with a total of much more than 100 units, most of them 6 MeV ABCs, both diode and triode, delivered. The formal process of moving the ABC design to production has started in FY24 and will be completed in FY25. Meanwhile, we have made small desired remaining improvements and fixed most if not all issues in the ABC design, which were casing any performance flaws in the 6 MeV ABCs. One might appreciate that was done while the rate of ramp-up is truly unprecedented – from 20 units in 2022 to 65 units in 2023 and to more than double the latter number of units in 2024.

A test cell was built and commissioned in SLC, in addition to the test cells in Las Vegas, which demostrated Varex Management firm commitment to further development of the LINAC business.

By now, our team counted 27 people, the Salt Lake City part of the Team is shown in Figure 17, and Las Vegas part of the Team – in Figure 18.

Figure 17. *Varex Corporate Management congratulating HES on opening new Test Cell in SLC.*

Figure 18. Our HES Las Vegas System Design Group, managed by Rich LaFave (he is waving in the picture).

2.6. 9 MeV

We applied the same strategy to the 9 MeV development process, as we did for the 3 MeV. After building the first prototype, which delivered very promising results at the first try, we postponed further development until the 6 MeV has been completed and productized.

2.6.1. The First Operational ABC-9-S-O-X-T

The first produced "O"- style guide in 2018-2019 (Figure 19) made all very pleased with its performance. We have built the ABC with an e-beam window to perform accurate measurements of its characteristics. The electron beam energy was measured using multi-plate Faraday Cup, at magnetron peak power of 2.2 MW, E-gun High Voltage of 12 kV, Pulse Length was 5 µs, and Pulse Frequency was chosen 50 PPS for this measurement, to keep the average current low and protect the e-beam window from any damage due to extensive heating (Figure 20). We have also produced a few "Beam Trees", a good visual proof of the linac performance, which have quite an artful appearance and enlightened many of the senior management. Another known name for "Beam Tree" is "Frozen Lightening".

Figure 19. ABC-9-S-O-X-T being set in a brazing furnace.

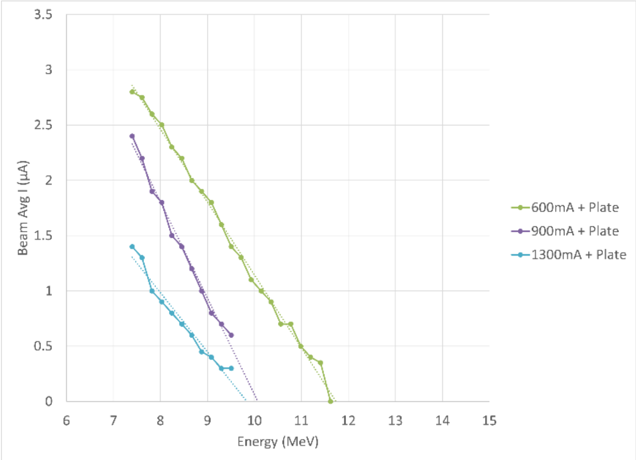

Figure 20. E-Beam Energy Measured for ABC-9-S-O-X-T. SN001 (in 2018) using propagation in Aluminum (Current off plates in FC – tails only), Parameter – E-Gun Peak Current, Penetration is shown in X-Axis and calibrated in MeV.

The process of forming such a Beam Tree in plastic is quite similar to a natural lightening, hence the name. For those who have never seen or heard of this process, it is as follows. First, in a plastic piece one should make a small notch, usually on the side of the plastic piece near the calculated depth of penetration at given energy. This will be a discharge point, which is placed on a grounded surface. The accelerated electron beam, coming from the accelerator output window (spread to an appropriate size) is directed at plastic, and the electrons penetrate the plastic, thus forming a space charge, which discharges into the notch once the breakdown voltage limit is reached, leaving the trace, which looks like a lightening.

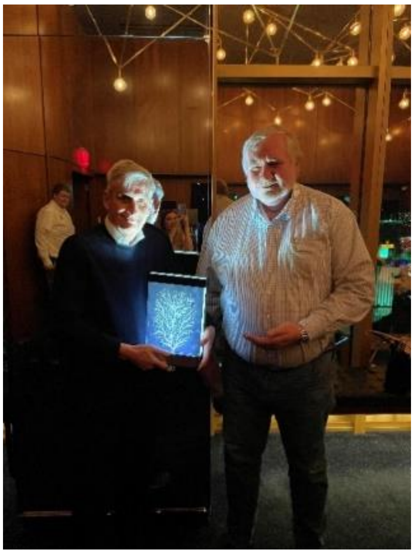

Figure 21. Retirement gift to the Chairman of the Board of Varex Imaging Corporation – a "Beam Tree" created using our first 9 MeV Linac Las Vegas, 9 February 2023.

Some "trial and error" learning is required to produce high-quality "Beam Trees", but the skilled operators can produce very attractive samples. One of these "Beam Trees" created using our first 9 MeV has become a gift to Ruediger Naumann-Etienne when he stepped down from his Chairman of the Board position at Varex Imaging (Figure 21). On a short notice, we did not have one on hand, so the CEO Sunny Sanyal gave up his own in Rudy's favor. We still owe a replacement "Beam Tree" to Sunny, but we have not forgotten!

2.6.2. Preproduction 9 MeV "M" Prototype ABCs Completed in CY2024

While we were closing on productization of the 6 MeV linacs for Varex in Q4FY23, we built and tested a few "M"- style single energy preproduction 9 MeV units. The design was defined earlier by our first model ABC-9-S-O-X-T, which demonstrated good overall performance. Three of the produced units were fully tested with triode and diode electron guns and met the specification requirements. The old design of the LINATRON M9 used a solenoid, so the guides were built with a RF power input closer to the output end of the LINAC, to ensure a "drop-in" feature present. The required key specification parameters were met. In addition, we started to test modifications, which later brought us to a design functioning well without a solenoid, and in addition, delivering higher dose rate (see paragraph 4 "New Developments at Varex").

3. Completion of Standard 3, 6, and 9 MeV ABCs for M3, M6, M9 and Mi6SSM

With successful completion of full high-power testing of the three 9 MeV ABCs, we declared fulfillment of the basic ABC replacements of the Varian BCL predecessors. Production certification of such ABCs will be fully completed in CY2025. Note that in the light of our preference of building the future models with TEG, we have tested and processed to full production certification of both TEG and DEG versions of such linacs. In the course of building the initial models, we have also reviewed their dual energy performance and possibility of using these ABCs for the "A" dual energy legacy linac models, such as M3A, M6A, and M9A. Needless to say, we were driving to meet the specification requirements for single nominal energy values, and our designs were state-of the-art, different from Varian designs, as requested by Varex Senior Management, specifically, we were using a much lower voltage e-gun, different from the e-gun, used by Varian.

Table 6. *Comparison of Statistical Energy and Dose Rate data for Varian single energy BCL and Varex ABC designs.*

	Varian BCL		Varex ABC	
"3 MeV" Energy, MeV	1.5	3.0	2.0	3.0
Dose Rate, R/min@1m	100	300	120	300
"6 MeV" Energy, MeV	3.5	6.0	3.5	6.0
Dose Rate, R/min@1m	250	800	250	800
"9 MeV' Energy, MeV	6.5	9.5	7.0	9.5
Dose Rate, R/min@1m	800	3000	600	3000

Therefore, not all the designed single energy ABCs operated the same as the existing legacy units at lower interim energy values with lower injected magnetron RF power, while the maximum specification requirements were identical.

The relatively small difference in dual energy operation of the Varex and legacy single energy models is described in Table 6, above. Due to difference in design, mostly caused by a different e-gun injection voltage, performance of the Varian BCL and Varex ABC turns out slightly different, in two out of three cases, but it is close enough for ABC to serve as a substitute for the BCL predecessor. This should not come as a surprise to those skilled in the art.

For the cases when customers are adamant to have closer performance between the two linac generations, we drive to build special units for dual energy operations, especially at 3 MeV and 9 MeV. These special units will be described in the following Chapter 4, targeting better performance than their predecessors, operating in broad energy range and delivering higher dose rate, hence "killing two birds with one stone".

Our future development strategy is set – we are following our own road maps, unique for Varex, defining our own future and success, helping the customers to adjust and to be more successful together with us. We have already developed exceptional and at times breakthrough designs, which will be superior to that by our predecessor, and we are hoping that this trend to continue.

4. New Developments at Varex

In the past 8 years, we have developed numerous new ABC designs, working on these in parallel with building and replacing the standard units. A few new units are under development, in FY2025, as we discussed, it was an interesting sign that our journey started from building a new X-Band linac, which operated "from scratch", met the specification delivering an outstanding performance and beam diameter at FWHM of approximately 1 mm, as described in Chapter 2.0. The new X-Band linac flexible design permitted its operation in a broad range of magnetron input power, eventually we built an M3X system based on this ABC. It seems continuing to develop further and produce the X-Band line of products is a low-hanging fruit, but we are quite busy now actively working on S-Band linac developments. We are hoping to eventually get to this X-Band line of products in the next few years, unless we get an inquiry from an interested customer, which might accelerate the X-Band line development.

Below, we present several examples of our new developments, that are currently in process.

We will start with a major success demonstrated in 2018-2019, when we designed a 7 MeV energy-regulated linac, operating in energy range from 3 MeV to 8 MeV, delivering a record dose rate up to 1300 R/min @ 1 m in its maximum [10].

4.1. 3-8 MeV Energy Regulated 7 MeV Linac ABC-7-ER-S-O-X-T

The two versions of ABC-7-S-X have been built – an electron accelerator with a tungsten foil at the output end, and one with an X-ray target. Both have shown outstanding results during high-power testing. Although indirectly measured (with a custom-made Faraday cup in electron case, and via half value level measurement technique in case of X-rays) energy and beam current measurements matched within reasonable margins. ABC-7-S-X has produced up to 1300 R/min maximum dose rate at 6.5 MeV energy. As in the case of ABC-3-S-X, it was measured at 1 m from the target with the 10 x 10 collimator and the ion chamber installed. A triode electron gun helped in establishing smooth energy regulation from 3 to 8 MeV.

Figure 22 illustrates a model of ABC-7-S-X beam centerline and the actual prototype when it was built.

This was major success to have such broad energy range from 3 MeV to 8 MeV, with a record maximum dose rate up to 1300 R/min @ 1 m.

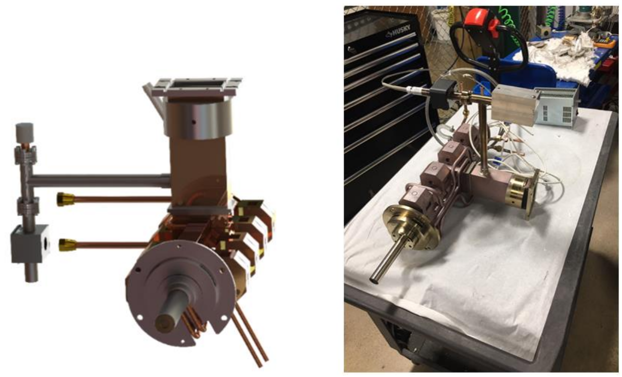

Figure 22. *ABC-7ER-S-O-X-T SolidWorks model (left) and completed prototype (right), ready for high-power testing.*

In Figure 23, we present an image of electron beam spot, measured by exposing tape and measuring discoloration of the tape at full width, half maximum (FWHM) of beam distribution. X-ray focal spot has been measured via a grid camera method in which one should take magnification of an X-ray image into account.

All the obtained beam spot pictures have been analyzed with Varex developed image evaluation software. For both electron beam spot and X-ray focal spot appeared to be less than 2 mm FWHM at within the whole range of electron beam energy values. At that early phase, we have not yet mastered the focal spot reduction, as demonstrated later.

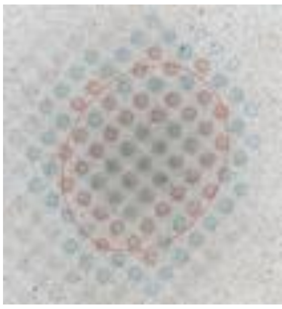

Figure 23. *An example of ABC-7-S-X X-ray focal spot as seen on a film (scaled).*

Figure 24. *M9 LINATRON test assembly with our "drop-in" ABC-9-S-M-X, which demonstrated operation comparable to Varian M9 predecessor at 3000 R/min@1m at its maximum. The upgraded system M9V has been run at a maximum of nearly 5000 R/min@1m.*

4.2. New M9V 9 MeV LINAC Substantially Increased Output of its Predecessor M9

We have completed a bench test for a new product, upgraded M9 that we call M9V, featuring our new ABC-9-S-M-T-RL, test setup is shown in Figure 24.

While operating in the similar energy range, it is capable of much higher dose rate, which reaches nearly 5000 R/min@1m at its very maximum, compared to 3000 R/min@1m for its predecessor.

The complete M9V system will be assembled and fully tested in this FY25 and offered to our customers upon its successful qualification. We are driving for this machine to be based on TEG design for its flexibility and ease of control. Considering that this powerful type of equipment is used for large object inspection, reducing inspection time by 40%-50% will certainly be beneficial to our customers (assuming nominal operating dose rate from 5000 to 6000 R/min@1m).

Standby for our updates.

4.3. New MicroBeam LINATRON™ Line

This work to produce spots less than 0.5 mm in FWHM diameter has been started at Varex a few years ago "in the background" and has been conducted very thoroughly. This design was one of those dreams the Author had for quite some time, as a few other ideas we are trying and bringing to life at Varex. Chuck Stirm, a very experienced Salesman of Varex Imaging and prior to that – of Varian Medical (retired), challenged the Author to produce the linacs with such small spots.

Note that Varex has inspired and funded all these dreams and ideas to materialize. Bravo and Thank You, Varex!

The proposed approach required some fundamental changes in design of ABC RF structure, as well as a different method of tuning, which has been fully developed, tested, and successfully implemented, patent pending. We believe that the proposed approach permits steady delivery of spots in 100 μm to 500 μm range – and that is without any external focusing systems. Once this range is "tamed", we might try going below 100 μm to a nx10 μm range. The importance of this breakthrough event is very difficult to overestimate, as any commercial linac now can routinely deliver such submillimeter spots – in the fields of non-destructive testing, security screening, in radiation therapy – anywhere one needs crisp imaging and/or tights spots for dose delivering accuracy, while not adding any complex, heavy, and expensive elements, such as external magnets: coils, solenoids, or quadrupoles, at least, until certain point. For example, the first prototype we have built at 6 MeV, resembles the standard ABC-6-S-M and can be used in any field system.

4.3.1. The First "drop-in" 6 MeV SUBMM ABC

The best developed and productized linac model in house – our ABC-6-S-M-X-T has become a natural candidate for the first try of our new approach. Our design group under Dr. Stanislav Proskin's supervision made the proposed necessary changes, creating ABC-6-S-M-X-T-SUBMM.

We maintained the form-factor of the guide to make sure we can install it in any standard shielding in our LINAC systems and made the appropriate changes to its RF structure design.

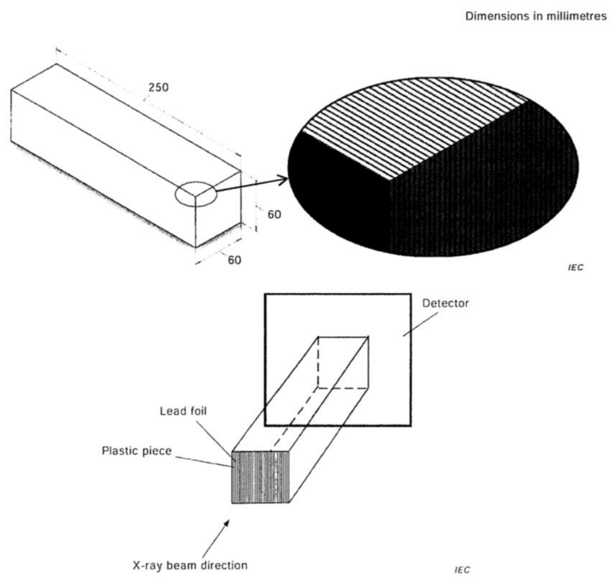

Figure 25. *Planar Camera or multilayered "Sandwich" first used to make the measurements of Submillimeter beam spots. This technique is well-known and published.*

Upon design completion, assembling, tuning and standard processing of the guide, we performed a high-power test. The first results were obtained using a "planar camera", or multilayered plastic/tungsten (or lead) sandwich, where a step between the centers of the tungsten plates or centers of plastic plates equals 0.009" or 0.23 mm, which largely defines resolution of this device, used as is shown in Figure 25.

The obtained images are shown in Figure 26 (left), in comparison with a standard 1.5 mm spot image (right).

Later, we created overexposed images, shown in Figure 27. Based on the measurements, we concluded that the spot size is approximately (350±150) μm at its FWHM diameter. Indeed, resolution of the method was not enough to make more accurate measurement.

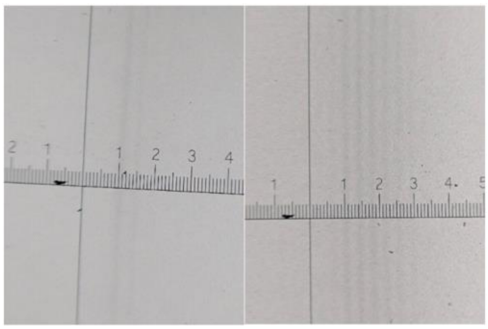

Figure 26. *Comparison of MicroBeam Spot (left, 2 visible lines, 1 gap) to a Standard 1.5 mm Spot (right, 7 lines, 6 gaps). Visual estimates suggest spot size of 200-300μm FWHM.*

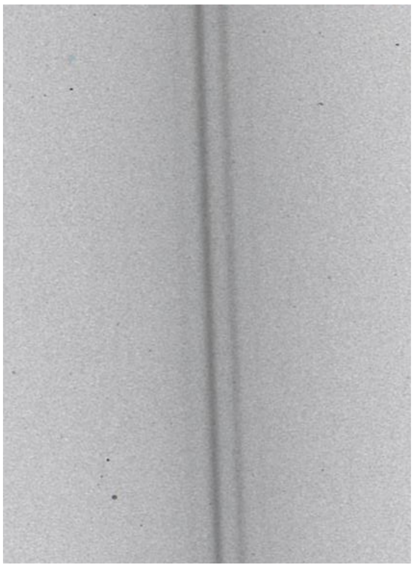

Figure 27. Planar Camera overexposed image of the submm spot, 4 lines 3 gaps are visible, which would suggest possible maximum size of the spot of 400-500μm FWHM.

Dr. Martin Hue, who resides in Chicago area and works at Varex Imaging Franklin Park facility is the lead expert in measuring the spot sizes at Varex Imaging Corporation, and we invited him together with Rich LaFave, head of Las Vegas LINAC System Design group (part of my HES group), report who also has extensive experience in this field of science, to make the measurements in our test cell in Salt Lake City using Dr. Hue's technique. The results are shown in Figure 28 and Figure 29.

Dr. Hue and Mr. LaFave have concluded that the spot resembles perfect Gaussian distribution, strongly focused (no "tails"), and its measurement resulted in 530x 482 μm^2 spot dimensions, followed by double wire test, which suggested D8 image quality with geo magnification 1.91, *which is phenomenal*, and provides resolution of 184 μm horizontally and 171 μm vertically. Indeed, we anticipated some measurement error.

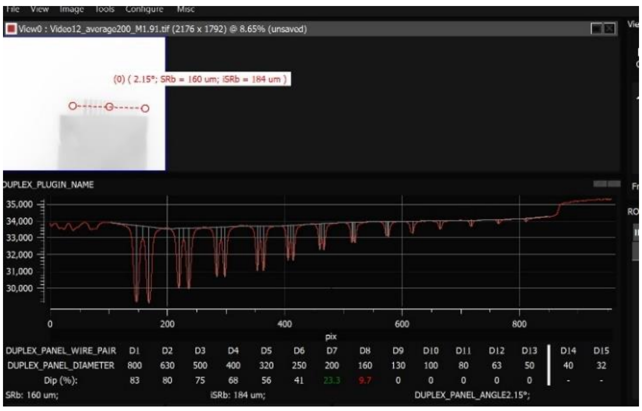

Figure 28. ABC-6-S-M-X-T-SUBMM "double wire" test results obtained at the second round of measurements.

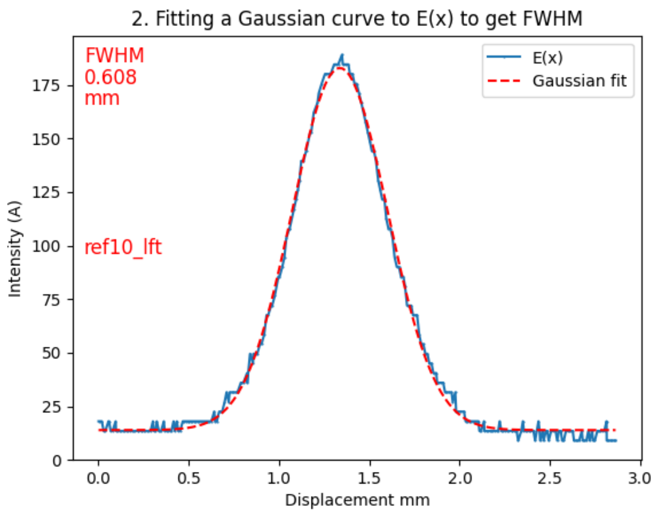

Figure 29. One of the ABC-6-S-M-X-T-SUBMM spot scan test results obtained at the second round of measurements.

Operation of the ABC was found to be very steady, although it took about 30 seconds to get fully stabilized at some grid voltages, which we defined later to be a result of some magnetic instabilities combined with specific grid voltage values. We mitigated the problem by using magnetic shield and grid voltages, which ensured steady operation.

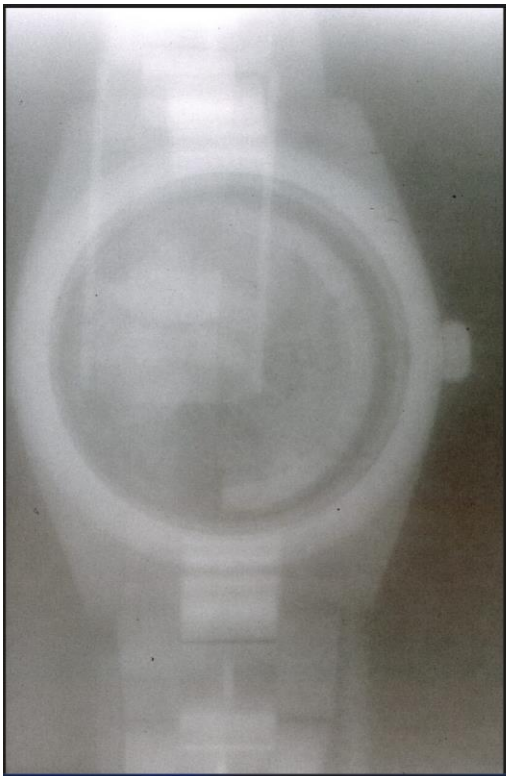

Figure 30. A film image of a watch with a metal wrist band behind one-inch-thick steel plate. One can clearly see a thin plate of watch band behind the watch.

One quick imaging attempt using film is shown in Figure 30. Imaging of the watch was performed behind a 1”-inch thick plate. Note that both the front of the watch and the metal strap behind it are visible and present sharp image.

Now that we were convinced the proposed design and method worked, we performed detailed measurements of the E-Beam Energy and produced Dose Rate versus E-beam current and Input Peak RF Power, which is presented in Figure 31.

Currently, we are building a full M6M system prototype and will perform full scale testing of this system, with appropriate imaging tests and looking for ways to further reduce the beam spot. Completion of this work is planned in this FY25. Standby for our updates.

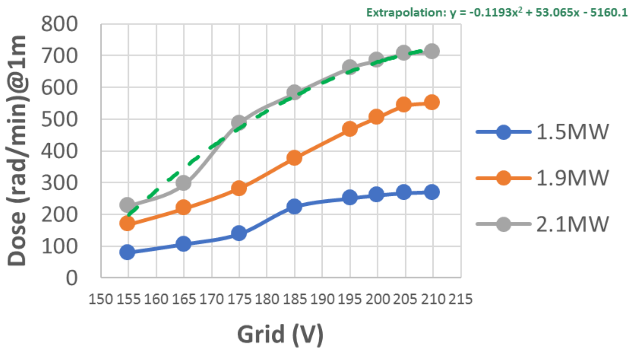

Figure 31. *Bremsstrahlung Dose Rate produced by 6 MeV MicroBeam LINATRON™ on a tungsten target. Note that at its maximum, it is only 12.5% less than standard specification requirement of 800 R/min@1m, yet the magnetron peak power is 2.1 MW, remains below nominal of 2.3 MW.*

4.3.2. The 3 MeV and 9 MeV SUBMM ABC

Currently, we are building 3 MeV and 9 MeV ABC prototypes, using the same technique as we used on the first 6 MeV submillimeter ABC-6-S-M-X-T-SUBMM.

Completion of this work is also planned in this FY25. Standby for our updates.

4.4. LINAC System Evolution and Mi6SSM

The Figure 32 and Figure 33 provide vision of Mr. Lawrence Miller, our Software Engineer, who happens to be the most experiences fellow in electronics at Varex, and in the HES group he reports to Rich LaFave, operating in Las Vegas. Lawrence leads Control System and System architecture development, acting Lead Electronic Engineer. His views are reflecting the development phases for our modulators (Figure 32) and controls (Figure 33).

This vision and the system Mi6SSM (Figure 34), equipped with a Solid-State Modulator (SSM) have been developed before I took charge of the office. Mi6SSM has been designed to operate with Varian guides, which use Diode Electron Gun (DEG). For this DEG, a 3rd party High Voltage Power Supply (HVPS) is used, which is produced by the same vendor as our SSM. We have designed and built DEG-based ABC-6-S-M-X-D, which is drop-in replacement for the 6 MeV predecessor (while operating at HV of 8-15 kV, much lower than the predecessor), as described earlier.

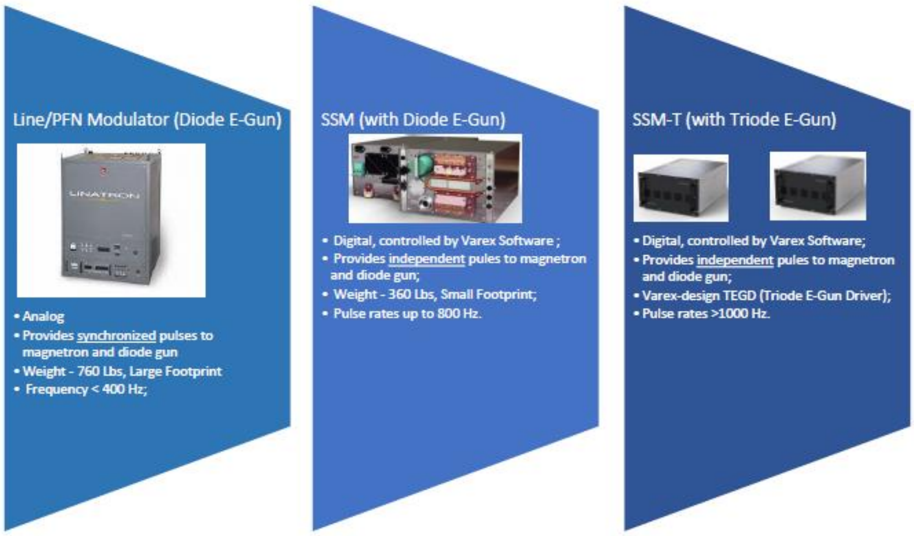

Figure 32. *Modulator and E-Gun HVPS Evolution.*

Figure 33. *System Controls Evolution.*

Thus, production of the Mi6SSM has been now fully transitioned to Varex base, and Varian guides were no longer needed.

Figure 34. *A single block, SSM based Mi6SSM (Tower) LINAC system primarily used for Security Screening. Temperature-Regulated Water Chiller and Operator Console come separately and not shown.*

We have inherited the Triode E-Gun (TEG) Driver (TEGD). The first design was completed and tested by the Senior EE Mr. John Turner, also prior to me taking the VP job. It worked well in the laboratory environment, but it had to go through several phases of improvements for the field operation, as it was not rugged enough. We are currently completing the third round of such improvements and expect it to be fully production ready in this FY25. In parallel, we are working on several improvements to the original Mi6SSM design.

We intend to drive our TEG design to prevail for the existing and new products, due to better control over the e-beam current in TEG versus DEG.

4.5. High Power Platform for 15 MeV V15 – successor of K-15

As one of the last efforts in this LINAC replacement program, we are considering changing design of our Linatron® K15, the only standard production unit in the world capable of delivering bremsstrahlung at 12000 R/min at 1 meter by striking a stopping target with a high energy Electron Beam (EB) at 15 MeV. We plan on changing the operating frequency from 2856 MHz, used in the legacy predecessor, to 2998 MHz, establishing one common frequency for all our S-Band linear accelerator RF sources. Various designs are being investigated for the new 15 MeV ABC, including but not limited to two collinear standing wave (SW) sections and a Varex patented combination of SW and traveling wave (TW) sections with reverse feeding of RF power [5], see Figure 35. The results of the preliminary analysis have been presented and published at IPAC 2024 [17]. The platform can be used for running guides at various energy levels from 1 to 20 MeV continuously or selectively changing energy and upgrading the platform to higher average beam power levels. Indeed, operating at high average beam power above 1-2 kW level may require new advanced target development and in the case of e-beam applications, a scan horn will be required for extracting e-beam from vacuum to air.

The new 15 MeV LINAC will be called V15. The 1st SW section is based on any of the available standard Varex ABCs, in EB energy range from 1 MeV to 9 MeV. The TW section length will be varied, correspondingly. Overall accelerator length can vary from 1 m to 2 m, depending on the chosen injector and TW section parameters. The RF source power input can vary from 3 MW to 7 MW depending on the optimal length and depending on a chosen RF source.

The first part of this LINAC uses the standing wave section, designed for higher peak and average power and it can be a separate system called V9, shown in Figure 36.

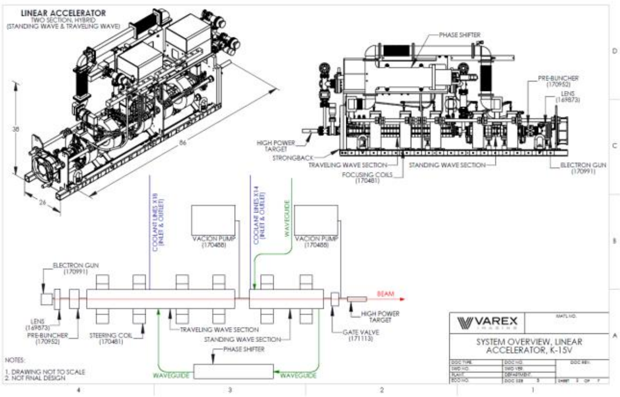

Figure 35. Proposed V15 LINAC with hybrid SW and TW structure and reverse feed protected by Varex patent.

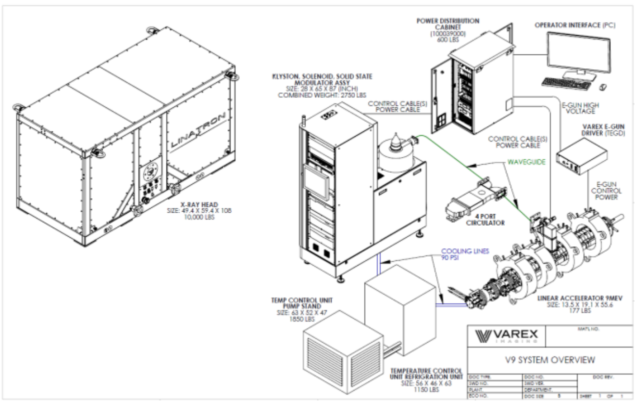

Figure 36. First 9 MeV part of V15 - presents a complete V9 linac system, with its own advantages compared to V15.

The Author has presented this concept at CAARI 2024 in Fort Worth, Texas. The V9 machine may have advantages to V15, such as substantial reduction of the neutron yield and activation of the materials, while maintaining high dose rate.

We intend to use all our advances to produce a small beam spot in V9 system and investigate target behavior at extremely high dose rates of nx10,000 R/min@1m.

5. The Best Results

1) As discussed in Paragraph 2.1, the first and foremost objective was to secure production of the base models and build ABC production line, which was met.
2) As we all observed a "deal of the century", the largest US company in producing equipment for radiation therapy and linear accelerators Varian Medical has been sold to Siemens Healthineers in CY 2020 [50], 3 years after separation of the component division and the industrial part and spinning off Varex Imaging in 2017. Siemens Healthineers is Headquartered in Erlangen, and it remains a German company. The created new ABC design and production line, which strengthened and broadened capability of Varex Imaging Corporation, which remains a US-based public company on US soil, positioned Varex to become the largest domestic LINAC manufacturer, now with unique capability of designing and producing ABC and advanced LINAC systems in-house. It creates a potential for Varex's substantial growth in the existing and several other High Energy Sources markets, beyond security screening and NDT:
   a) We created our own IP and designed all the LINAC models ourselves, without any reference to Varian linacs, except the general specifications and outline dimensions,
   b) We maintained form-factor that would allow using them as replacement in our standard shielding package,
   c) To the extent possible, the "drop-in" model operation was very similar to the predecessors and met all specification requirements using the same or other available power sources and power supplies, the exception in the design was the electron gun, available off-the-shelf, that was used in our linacs, but the transformer used in "legacy" systems or HVPS used in Mi6SSM permitted use of different (lower HV) e-gun, which was commercially available versus proprietary Varian e-gun design.
   d) The production line capacity in 2024 was shown to cover full Varex needs exceeding 100 units/year, this number includes new product development.
3) We have mastered several novel techniques to substantially improve performance of our predecessor BCLs and created or creating prototypes with some outstanding characteristics protected by Varex Patents, Patent Applications, Trademarks, etc., as follows:
   a) Designed and bench tested M9V Linatron, a successor of M9, which can produce much higher dose rate, reaching 5000 R/min@1m (versus 3000 R/min@1m for M9), the operational prototype is under construction and will be tested in this FY25,
   b) Upgraded Mi6SSM based on DEG ABC to Mi6SSM-T based on TEG based ABC with increased flexibility,

c) Created new unique dual energy designs, superior to the predecessor's models, patents pending.
d) Designed protection from backstreaming currents for high power LINACs, patent pending.
e) We have created a unique, groundbreaking technique and design, tuning technique to reduce beam spot size, fully tested the first 6 MeV prototype, delivering outstanding results of perfect beam spot of less or equal to 500 µm and now working on a full line of MicroBeam LINATRON^{TM} products in a broad EB energy range, patent pending.

6. Discussion

The very nature of this monography is based on replacing the legacy technology by Varex ABCs, and their comparison is presented throughout the manuscript. However, we can summarize the analysis here over larger classes of the devices, such as "Single Energy ABC", firstly.

6.1. Single Energy ABC Models

As a starter, here we can reference Table 6 presented earlier in Paragraph 3.0, which provides comparison of the "single" energy linac sections, designed to operate at nominal energy W_{nom}, MeV and defining a nominal or maximum dose rate P_{nom} R/min@1m at this energy value.

Speaking of the FWHM spot size, the predecessor linacs are usually rated at "less than 2 mm" and practically, they deliver 1.2 mm to 1.8 mm spot sizes, while ABCs are rated from 0.8 mm to 1.2 mm, in most cases; some operate at less than 1.5 mm FWHM size.

All these models will be production certified in FY25.

6.2. Dual Energy ABC Models

The Table 6 also shows correlation between the lower energy in the "single energy" guides when input RF power is reduced, and EB current is adjusted accordingly or optimized. These numbers are slightly different for the two OEMs, the reason being different design and IP.

The primary factor is the electron gun design is different between the two, and the operating HV is more than two times lower for ABC, compared to BCL.

The conclusion is that the single energy guides can run in a dual energy mode, but for some units, the lower energy and dose point will be slightly different than in the legacy units.

To improve operation in broad energy range, Varex created state-of-the art designs, which we believe will operate better than BCLs.

For example, our design values for broad energy 1-3 MeV. 3-8 MeV[4], and 4-9 MeV ABCs are enclosed in a Table 7.

4 This 7 MeV model prototype has been built and tested, the 3 MeV and 9 MeV broad energy range prototypes are under construction.

Table 7. *Comparison of Statistical Energy and Dose Rate data for Varian dual energy BCL and Varex ABC designs (calculated and rounded data except for measured "7 MeV").*

	Varian BCL		Varex ABC		
"3 MeV" Energy, MeV	1.5	3.0	1.0	2.0	3.0
Dose Rate, R/min@1m	100	300	50	150	450
"7 MeV" Energy, MeV	3.5	6.0	4.0	6.5	8.0
Dose Rate, R/min@1m	300	800	350	1300	300
"9 MeV' Energy, MeV	6.5	9.5	4.0	6.0	9.2
Dose Rate, R/min@1m	800	3000	400	1700	3300

6.3. New ABC Models

We are working on improvements of the low-to-medium power linacs and in this manuscript, we described several accomplishments in this area.

We were able to reduce focal spot size in our standard Mi6SSM linac to 0.8 mm, which is one of the best if not the best result in our industry.

We described our new upgraded M9V system, which doubles dose rate compared to its M9 predecessor. This is significant for low power class of such devices.

The most significant accomplishment in terms of its scale certainly was creation of a new design for the MicroBeam LINATRON^{TM}, which was an industry scale event and permitted Varex launching off a new unique product line in broad energy range with spot sizes reliably under 500 µm. As discussed earlier, linacs having spots less than 1.0 mm are rather rare and unique: a single design linacs with spot less than 1.0 mm likely used external magnetic focusing system, such as 950 keV X-Band LINAC [46, 47] and/or the Hextron series advertised by GRANPECT did not have any supporting published evidence [45], at least, the Author could not find any. It seems the company removed these "Small Spot Linacs" from their website. At Varex, we developed a new design, which required new tuning method, that can reliably produce small spots of less than 500 µm without any external magnetics and working on further reduction of such focal spot FWHM diameter.

The above results are summarized in Table 8, showing LINACs after various improvements as implemented. Abbreviation MBL6 is used for MicroBeam LINATRON^{TM} prototype designed for 6 MeV.

The MicroBeam LINATRON^{TM} Series are shown in Table 9 could be compared with key Hextron Small Spot parameters, as advertised in their marketing brochure. However, we do not have information if focusing system is used on such or any data confirming the small spot as advertised. For Varex MBLs, please note that while 6 MeV has been tested, we are still working on 3 MeV and 9 MeV prototypes, and the presented data are design only. While we have high confidence in our success, please wait patiently until the performance can be demonstrated.

Table 8. Comparison of older Varian LINAC models and Varex new LINAC models in low-to-medium power range.

OEM	Units	Varian	Varex	Varex	Varex	Varex
Model	N/A	M9	M9V	Mi6SSM	Mi7SSM	MBL6
Energy	MeV	9.5	9.5	6.0	7.0	6.0
Dose Rate	R/min @1m	3000	5000	800	1000	700
Spot Size	mm	1.2+0.4	1.2+0.4	<1.5	1.0+0.2	<0.5
Solenoid	N/A	Yes	No	No	No	No

We are also working on improvements of the medium-to-high power linacs and described several accomplishments in this area. While there is still a lot of work to be done, we would like to share our goals within our community for their information and planning purposes (Table 10). We welcome the interested customers to send inquiries and discuss their needs early, and we might consider taking the orders sooner rather than later.

Standby for our future updates.

Table 9. Varex New MicroBeam LINATRON™ Line.

OEM	Units	Varex	Varex	Varex
Model	N/A	MBL3	MBL6	MBL9
Energy	MeV	3 (1-4)	6 (4-7)	9 (6-9)
Dose Rate	R/min@1m	200	700	2000
Spot Size	m	350+150	350+150	350+150
Solenoid	N/A	No	No	No

Table 10. Comparison of older Varian LINAC models and Varex new LINAC models in medium-to-high power range.

OEM	Units	Varian	Varex	Varex	Varex
Model	N/A	K15	V15	V9	V9MBL
Energy	MeV	15 (9-20)	15 (2-20)	9 (6-9)	9 (6-9)
Dose Rate	R/min @1m	12000	40000	20000	12000
Spot Size	mm	<2.0	1.2+0.4	1.2+0.4	0.35+0.15
Solenoid	N/A	Yes	Yes	Yes	Yes

7. Prospects and Industry Trends

As readers might have noticed, at Varex, we are following the industry trends and current customer demands in the relevant markets of Security Screening, NDT, Electron Beam and X-Ray Processing, such as Sterilization, Pasteurization, Radiation Therapy.

Some requirements are common for all markets, and some are specific to an application.

Reduction of the Focal Spot Size – this requirement benefits mostly Imaging and Radiation Therapy applications. Penumbra prevents creating sharp images in all applications when imaging is required and accurate dose delivery in case of medical applications. For the E-beam and X-ray high power applications, the spot size must be enlarged and, in addition, scanned across the E-beam window or X-ray target in order to reduce power, dissipated per unit area or volume for very high-power beams.

For the Imaging and Radiation Therapy applications, increase of the Bremsstrahlung Dose Rate, produced by the electron beam striking a target is a contradictory requirement to reduction of the focal spot on such target, limited simply by the target temperature, which, in turn, is defined by beam power, dissipated in the target volume, material of the target, its design, etc. Reaching an appropriate balance between the focal spot size and produced dose rate and maximizing the ratio is an art and very difficult to improve for fixed targets. A rotating or simply a ”moveable” target for better beam dissipation is an appropriate tool for further improvement.

Improvement of RF-to-Electron Beam efficiency is important across the board for all applications, but it is most important for Processing applications, when power reaches tens and hundreds of kilowatts.

Reduction of size and mass of the irradiators and whole systems is important in any applications, especially those that require any portability and used on gantries and cranes. In addition, mass and size of the machines is directly related to cost reduction, in most cases.

Finally, cost reduction has always been a requirement for the industry to maintain competitiveness. However, the following factors must be considered:

In current markets, cost increase is substantial, for some assemblies, subcomponents, raw materials, cost has nearly doubled.

“We get what we pay for” – usually, considering reasonable approach costs and prices are very similar between producers. As usual, too low and too high costs raise concerns, and defining a reasonable price for current market is a challenge. For a groundbreaking, reliable machine, which has a good life span, premiums are quite appropriate.

OEM qualifications and reputation will define and mitigate many of the unknowns.

The challenge, as always, is that natural increase in cost is ahead of customers' expectations based on the "last year deliveries", but I guess is a common challenge in any markets.

8. Conclusions

This paper summarizes the 8-year history of establishing a completely new for Varex ABC design and production line and describes new designs, some have already resulted in prototypes that are superior to the predecessor's models, and some are truly groundbreaking.

In conclusion, the Author would like to emphasize, once again, that we have improved and strengthened Varex LINAC production by establishing ABC design and production line, also took Varex to a completely new level of a new leader in linac design and production in the United States and worldwide. Before birth of Varex, Varian has always been a leader, a well-known US company, the largest LINAC manufacturer with a long multi-decade history, with products that were hard to match and replace.

We have matched and replaced legacy models at Varex Imaging, and at times, we have exceeded performance of some predecessor LINACs. While Varex remains an undisputed leader in production of the tubes, panels, imaging technology, it is our intent to continue our improvement and growth, support our customers and become a true and undisputable world leader in the industry of High Energy Sources – Linear Accelerators for a variety of applications, which include, but not limited to Security Screening, Non-Destructive Testing, Electron and X-Ray Radiation processing – sterilization, pasteurization, Radiation Therapy.

We take this duty very seriously, so please do contact us with your needs and we will work with you to our best creating solutions to your requirements.

In addition, we request the scientific and engineering community: please do contact us with any feedback and questions.

We are hoping that our customers and interested parties will follow our publications at many professional conferences – we are hoping to gain your interest in our existing and new products.

Abbreviations

HES	High Energy Sources
BCL	Beam Centerline (used on Varian LINACs)
SW	Standing Wave
TW	Traveling Wave
ABC	Accelerator Beam Centerline (Varex product)
LINAC	Linear Accelerator
HV	High Voltage
HVPS	High Voltage Power Supply
DEG	Diode Electron Gun
TEG	Triode (Gridded) Electron Gun
TEGD	Triode (Gridded) Electron Gun Driver
FWHM	Full Width at Half Maximum
EB	Electron Beam
IP	Intellectual Property
MBL	MicroBeam LINATRON™

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Andrey Valentinovich Mishin is the sole author. The author read and approved the final manuscript.

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript and provided references.

Conflicts of Interest

The author declares no conflicts of interest.

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Biography

Andrey Valentinovich Mishin is a Vice President, High Energy Systems (HES) at Varex Imaging Corporation, Headquartered in Salt Lake City, UT, USA. He graduated from National Research Nuclear University (MEPhI) in 1985 and completed his PhD equivalent in Charged Particle Accelerator Physics in 1992. Dr. Mishin has been in senior leadership positions with private and public companies in USA since 1995. He has completed Management of High-Technology Companies course with AeA Stanford Executive Institute in 2002. In 2024, Dr. Mishin was included in directory of top managers and professionals by Marquis Who's Who, "for his pioneering work in microwave devices and linear accelerators". Dr. Mishin is a member of the esteemed IEEE and of ASNT. Throughout his 42-year career, he has spearheaded multiple major domestic and international projects, was an Invited Speaker, Session Co-Chair at international conferences. He was Chairman of a Sister City Committee with Santa Clara Government.

Research Field

Andrey Mishin: Electron Beam Sources, X-Ray Sources, Linear Accelerators, Microwave Devices, Security Screening, Non-Destructive Testing, Electron Beam Processing, Radiation Oncology Systems, Intraoperative Radiation Oncology Systems