Modeling, Simulation and Optimization of Microwave LINACS of the 25 MeV IAC Series

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Microwave Side Coupled Electron Linear Accelerators originally used for medical purposes were completely modified at the Idaho State University's Idaho Accelerator Center (IAC) for its application in nuclear physics research, radiation effect studies and homeland security applications. Modeling of the 25 MeV LINACs, simulation of its behavior and optimization studies were done using different codes, computational methods and experimental techniques. The results of such work are presented in this paper as well as the fundamental ideas behind the possible development of a Cabinet Safe System for this type of electron accelerators.

I. BEAM DYNAMICS STUDIES OF THE IAC MICROWAVE LINACS

The modeling process of the IAC-Varian accelerator series' waveguide was divided in three main parts: RF cavities, confining solenoids and beam characteristics. Each part was then subdivided in smaller ones as follows.

I.A. RF Cavities

The determination of the main accelerating field, which is the TM_{010} mode, was done analytically (*Ref. 1*) and from this solution, a table was generated for its use within the code ASTRA (*Ref. 2*), which calculates the transverse field components from the derivatives of the on axis field.

The metrological part is also an important part of the modeling process because ASTRA allows the inclusion of apertures and material properties for secondary electron emission. Unfortunately, nose-like structures are not allowed. As explained by Floetmann et al. (*Ref. 2 and 3*), when an electron hits an aperture ASTRA generates a random integer number of secondaries according to certain intrinsic model function using a Poisson generator. The secondary electrons are emitted isotropically and the emission position of the secondary electrons is corrected to surface boundaries.

I.B. Confinement Solenoids

The RF cavities that constitute the waveguide are surrounded by two long solenoids to confine the electrons to the waveguide and to minimize multipacting. Like in the case of cavity fields, a table of the axial magnetic field (B_z component) is required for its computation within ASTRA. The table was generated from measurements using an axial magnetic probe, and is in agreement with the information given by the manufacturer (Stangenes Industries).

Both of the solenoids have an external diameter of 25.5 cm and an inner diameter of 21.5 cm. One of the solenoids is longer than the other with lengths of 1.04 m and 0.33 m respectively. The information obtained from the manufacturer established the following operating conditions: 15.7 A at 137 V for the long solenoid and 15.5 A at 42 V for the short one.

I.C. Beam Characteristics

The third point in consideration is the beam itself, a Plateau distribution for the macro-bunch and a Gaussian distribution for the micro-bunch. The efficiency was measured to be of ~10%; roughly 90% of the beam generated in the source is lost, nearly 66% in the injection process in the first half –bunching- cavity (*Ref. 4*).

For the RF waveguide simulation, 8000 macro particles were taken into account in Gaussian distribution with a width $\sigma_{x,y}$ of 0.75 mm and a micro bunch charge of -2nC, being the initial energy of the particles injected in the guide of 50 KeV. The particles were distributed quasi-randomly following the Hammersley sequence, a quasi-Monte Carlo deterministic method. In this way, statistical fluctuations are reduced and artificial correlations are avoided. ASTRA was used for the beam dynamics studies due to its intrinsic algorithm for space charge tracking. ASTRA tracks particles based on a Runge-Kutta integration of 4th order with fixed time step through the user defined external fields taking into consideration the space charge field of the particle cloud (*Ref. 2 and private communications*). A cylindrical grid, consisting of rings (radial direction) and slices (longitudinal direction), was set up over the bunch extension for the space charge calculations. The space charge effect is a principal cause of emittance growth when the beam energy is low.

Figure 1 shows the longitudinal particle position of the lost particles. We see that the majority of the electrons are lost in the first group of cavities and only ~10.89% (-0.2178 nC) of the initial charge reach the exit of the waveguide, which is located at ~1.33 m even though the tracking was done until 1.6 m. The latter is in agreement with what is observed in the control room at the IAC. The secondary electrons that reach the end of the waveguide were estimated to be of 0.0025% of the injected charge, being the total secondary electrons produced inside the waveguide equivalent to 0.0213% of the injected one. The average energy contributed by the TM_{010} mode was estimated in ~14 MeV. These numbers are in very good agreement with the experimental results, as expected.

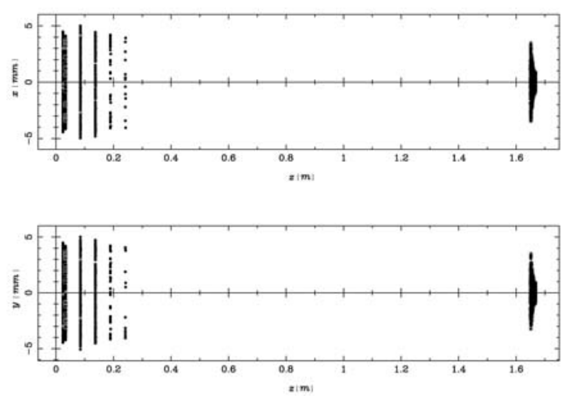

Fig. 1: Longitudinal particle position on IAC-Varian Accelerator Series showing the interaction point of the electrons within the waveguide and with the target. Macro particles: 8000 at origin, 871 at final position. The stars at ~1.6 m represent the normal macro-particles reaching the target; the dark circles represent lost macro-particles and the gray ones are macro-particles traveling backwards. Secondaries generated at the exit window are not shown.

The transverse phase-space distribution at z=1.6 m from the injection point is represented in fig. 2, together with the respective transverse normalized particle density distribution. The beam size $\sigma_{x,y}$ is 1.1 mm and the micro bunch charge ~0.2178 nC.

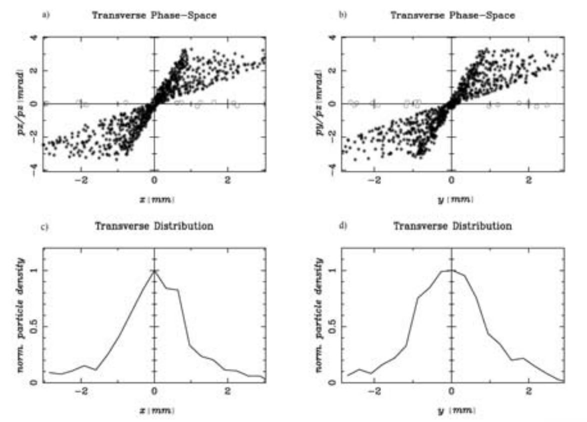

Fig. 2: Transverse phase space and normalized particle distribution for the IAC-Varian Accelerator Series operating at 18 MeV for a point 1.60 m far from the injection point. The RMS beam size was calculated to be $\sigma_{x,y}$ ~ 1.1 mm. The gray circles represent particles traveling backwards.

II. OPTIMIZATION SYSTEM DEVELOPMENT FOR IAC MICROWAVE LINACS

As it is well known, a beam passing thru an RF cavity experiences not only acceleration and longitudinal bunching but also a transverse defocusing. By placing magnetic solenoids in the RF lattice, a transverse focusing can be achieved to counteract this effect. These fringe fields generated by coils extend over long distances and may contain several nonlinearities (*Ref. 5*).

II.A. The Front-End Solenoid Approach.

An approach to consider and study was the use of high field solenoids at the exit of the beam line and perhaps a singlet or doublet at, or close to, the source location (also called bucket solenoid because of the shape of the phase space diagrams produced). The idea behind the Front-End (F.E.) solenoids is to trap and/or confine the secondary particles generated at the exit port reducing in this way the radiation field. In the case of the solenoid(s) at the electron source the goal is to increase the injection efficiency by placing it on the waist position but this topic will not be discussed here.

II.A.1. F.E. Solenoids Influenced by Confinement Ones.

The microwave Linacs of the IAC-Varian Series contains two relatively long solenoids around the waveguide. The goal of these solenoids is to confine the particles and keep them far from the waveguide's walls. The long confinement solenoid interacting with the F.E. solenoids has a measured half aperture of 0.127 m and a length of 1.04 m. Because the solenoid's fringe fields expand far in space, we have to take into account its influence in the F.E. solenoids' generated fields.

Using COSY Infinity's (*Ref. 6*) Differential Algebra based numerical integrator (eighth order Runge Kutta with automatic step size control), the transfer map and tracking (ray tracing) pictures for the F.E. solenoids were generated (*fig. 3*) as well as a file containing the value for the on-axis magnetic field for its inclusion in ASTRA (after statistical cleaning to avoid inversions that could generate numerical instabilities). The output data of the B field and the physical dimensions for the F.E. solenoids, corrected for the confinement solenoid's effect and calculated based on 18 MeV electrons, can be found in table 1.

To conclude this sub section, the beam dynamics studies of the IAC-Varian accelerator waveguide coupled to FE solenoids shows that no important optimizations can be accomplished from the beam dynamics (and Linac performance) point of view, by the use of only F.E. solenoids besides trapping of secondary particles generated in the exit port and a stronger focusing.

TABLE I. Magnetic field and dimensions [m] for the F.E. solenoids based on 18 MeV electrons.

Bz [T]	Length	Aperture	Drift length
0.74509	0.13702	0.10153	0.11471

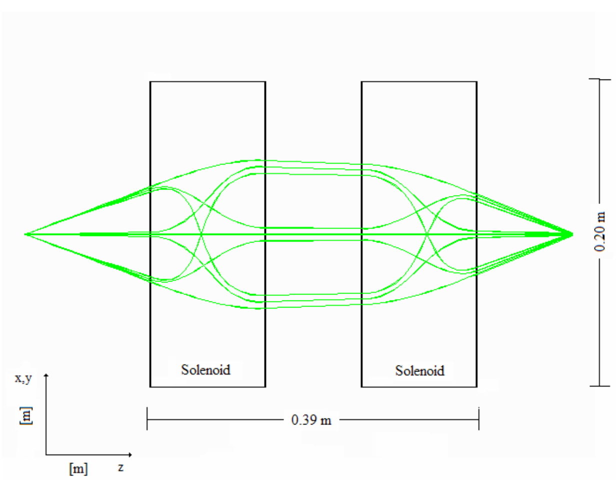

Fig. 3: Projection figure showing the trapping and focusing effect of solenoids over electrons, taken into consideration the effect provided by the relatively thick solenoids existent over the waveguide, and once their parameters were calculated using the fitting algorithms provided by COSY Infinity.

II.B. Effect of a Single Thin Solenoid on the Accelerator Waveguide Coupled to F.E. Solenoids

It was shown in the last section that the utilization of only F.E. solenoids have small effect in the optimization of the beam dynamics and only trapping of secondaries outside the waveguide could be accomplished; it is clear that the addition of other optical elements to the system had to be studied. The first step was to investigate the effect of a solenoidal element located close to the bunching (half) cavity, where many particles are lost. It turned out that the effect of a thin solenoid (2.5 cm length; ~14 cm radius) with a magnetic field of around 0.087 T located over the first full-cavity at 7.1 cm would change the beam dynamics of the system in a promising way for our goal of optimizing the accelerator and for the development a Cabinet-Safe System.

The same particle distribution was used: 8000 macro particles in a Gaussian distribution distributed quasi-randomly following the Hammersley sequence, with a width $\sigma_{x,y}$ of 0.75 mm, a micro bunch charge of -2nC and an initial energy of 50 keV for the particles injected in the waveguide/RF system. The first results can be seen in figure 4, which shows the longitudinal particle position. This initial solenoid clearly displaces the particle-cavity interaction points. The total micro-bunch charge increased ~100%, from ~0.214 nC to ~0.396 nC, which means an increased in the efficiency of the RF system. Unfortunately, the single solenoid cause higher energy particle loss, causing an increase in unintended radiation. Using these results, the idea of Multiple Solenoidal System become stronger and the doors to further studies were opened.

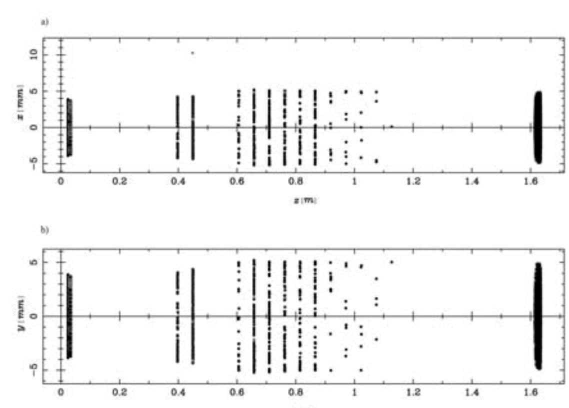

Fig. 4: Longitudinal particle distribution (interaction points with matter) for IAC-Varian Accelerator coupled to FE solenoids and a thin 0.087 T solenoid over the first full cavity (total energy of 18 MeV with 14 MeV due to TM_{010} mode). The circles close to the horizontal axis represents some few particles lost traveling backwards.

II.C. Development of a Multiple Solenoidal System

Based on the models developed in sections II.A and II.B a multiple solenoidal system was designed, as seen in figure 5, with the following characteristics.

F.E. solenoids:

- B_z field at the center of each solenoid, 0.745 T
- Magnetic fields of opposite signs
- Drift length between solenoids, 0.1147 m
- Drift between first solenoid and Linac, 0.05 m
- Aperture (radius), 0.1015 m
- Length, 0.1370 m

Thin solenoids:

- B_z field at the center of each solenoid, 0.08718 T
- Aperture (radius), 0.14 m
- Length, 0.025 m
- Aperture (radius), 0.1015 m
- Length, 0.1370 m
- Located at 0.0005 m (0), 0.071 m (1), 0.228 m (4), 0.65 m (12) (cavity)

The computation was made by dividing the beam line in 1000 segments for the calculation of the statistical bunch parameters. The bunch length was divided in a grid of 25 (+2) longitudinal slices and 25 radial rings with automatic scaling for the space charge field calculation. The field at any point between the grid center points was calculated by means of a cubic spline interpolation. Why splines and not polynomials? One might expect the quality of interpolation to increase with increasing degree n of the polynomials used but unfortunately this is not generally the case. Indeed, the corresponding interpolation polynomials may tend to oscillate more between nodes as n increases leading to possible numerical instabilities. Such oscillations are avoided by the method of splines.

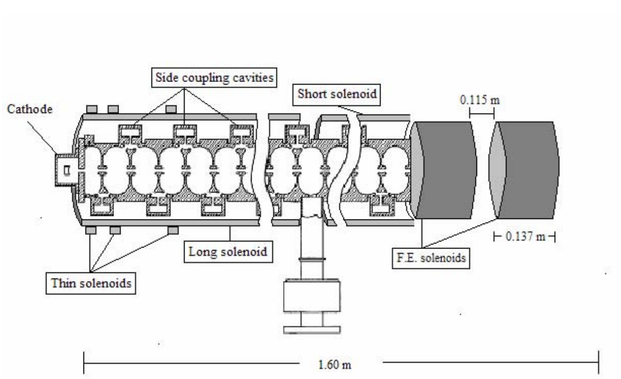

Fig. 5: Longitudinal cross section diagram of the IAC-Varian microwave Linac with the implemented Multiple Solenoidal System.

The longitudinal particle positions over the waveguide, through the FE solenoids and up to a distance of 1.6 m from the injection point, are represented in Fig. 6. From the 8000 macro-particles injected, 7992 macro-particles reached the final position at 1.60 m. The number of active secondary electrons was greatly reduced as well as the energy spread (0.47 MeV).

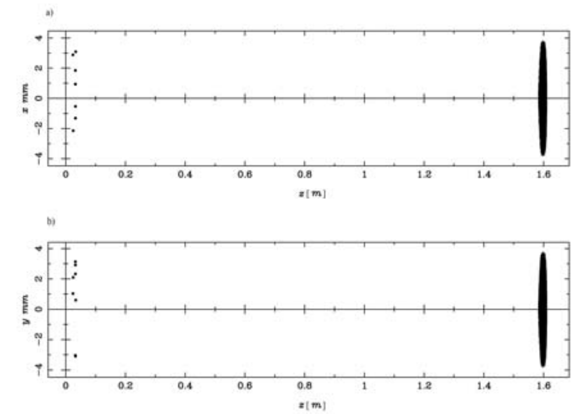

Fig. 6: Longitudinal particle positions (interaction points) for the Multiple Solenoidal System on IAC-Varian Accelerator's waveguides at 18 MeV (14.2 MeV due to TM_{010}). The plot shows very few macro-particles lost at the beginning of the waveguide (cavity 0) and more than 89% ($\pm$10%) of the injected ones reaching the final tracking position at z=1.60 m. The secondaries generated, and the particles lost, on the exit port/window are not considered here and represent a source of uncertainties to take into consideration.

Figure 7 shows the transverse phase space particle density distribution with a micro-bunch charge of ~1.99 nC (99% of the original charge). The estimated beam size is $\sigma_{x,y}$ ~1.9 mm. The divergence of the beam within the waveguide is also shown on Fig. 8 where one can see how the magnetic fields minimize the original divergence estimated in 5+ mrads at the exit of gun. The trajectories of 5 probe particles are shown in Fig. 9. Comparing the trajectory plots of the IAC-Varian accelerator's waveguide with and without (*Ref. 1*) the Multiple Solenoidal System, one notice how the problem of particle loss over the first group of cavities is solved. We also notice the helical trajectory followed by the particles generated by the multiple magnetic fields. The average energy deposition due to particle loss (and calculated in 1 m steps) was estimated to be ~5.1 10-7 J m^{-1} per micro-bunch.

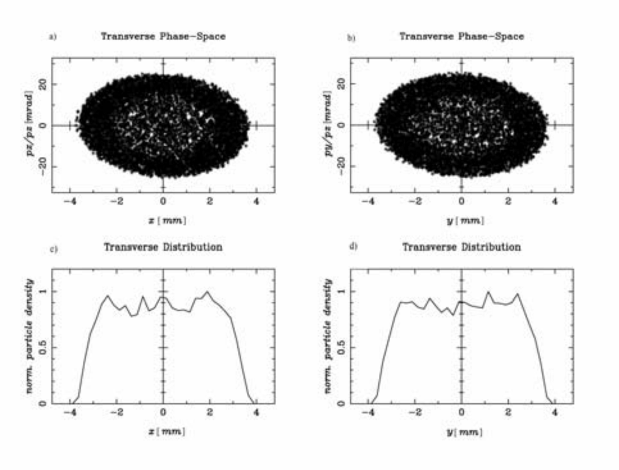

Figure 7: Transverse phase space and particle density distributions, at z=1.6 m, for the Multiple Solenoidal System on the accelerator's waveguide at 18 MeV (14.2 MeV due to TM_{010}). The estimated beam size is $\sigma_{x,y}$ ~1.9 mm.

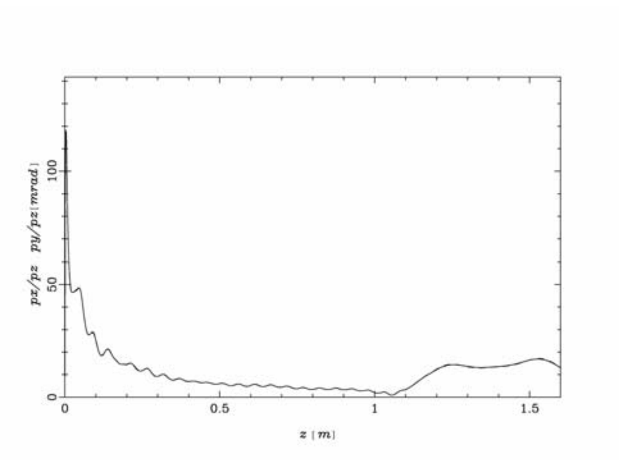

Figure 8: Beam divergence over the Multiple Solenoidal System on the IAC-Varian accelerator's waveguide working at 18 MeV (14.2 MeV due to TM_{010}). The plot shows how the divergence is well controlled after the initial critical points (injection into the half cavity for bunching).

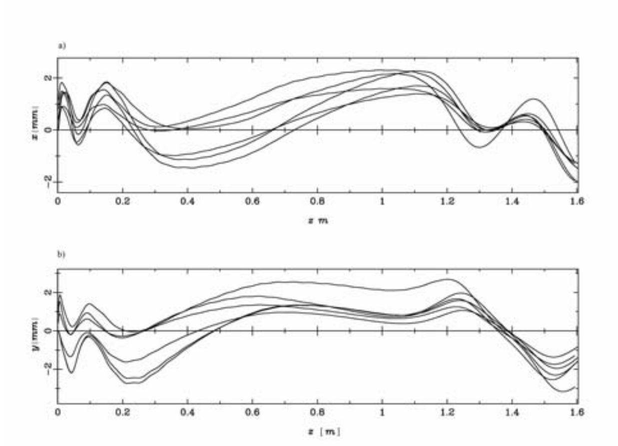

Figure 9: Probe particle trajectories along the z axis on Cartesian coordinates for the Multiple Solenoidal System coupled to the IAC-Varian accelerator's waveguide. All the probe particles reach the end of the waveguide while in the original model (no Multiple Solenoidal System implemented) only one of such probe particles was able to reach the target position.

As it can be seen at first sight, huge improvements can be accomplished by the use of a Multiple Solenoidal System. The uncertainties in these models and simulation are given mainly by:

- Model and simulation of the bunching system is difficult without precise phase information.
- Maximum acceptance for a bunching system is ~80% (being this last only accomplished in RFQ systems).
- Wakefields modify the way that a cavity interacts with the beam and its calculations are still a topic of research.
- Dipole mode could have some influence but it is the thought of these authors that its influence would be limited for this particular type of accelerator. As we know, dipole modes are transverse fields deflecting the particles if it is strong enough but it is our belief that the beam loading will avoid reaching the point of instabilities (i.e. TM_{110} generates dipole modes).

III. CONCLUSIONS

The Multiple Solenoidal System turns out to be a very good way to improve the efficiency of the accelerator waveguide, minimizing the particle loss and minimizing the radiation generated; implying at the same time an ease in the shielding requirements. The latter, with an optimization of the injection system by modifying the electron gun and a possible addition of an extra bunching system, would produce huge improvements in this type of accelerators. These constitute not only an optimization method but it also provides the ground for the development of a cabinet safe system for microwave linear accelerators of intermediate-low energy by optimization of the beam optics in a relatively easy and straight forward way.

ACKNOWLEDGMENTS

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