ՀՀ ԿՐԹՈՒԹՅԱՆ ԵՎ ԳԻՏՈՒԹՅԱՆ ՆԱԽԱՐԱՐՈՒԹՅՈՒՆ

ԵՐԵՎԱՆԻ ՊԵՏԱԿԱՆ ՀԱՄԱԼՍԱՐԱՆ

Ալի Մոհամմադ Փուրսալեհ

ՄԵԾ ՀԶՈՐՈՒԹՅՈՒՆ ՊԱՀԱՆՋՈՂ ԿԻՐԱՌՈՒԹՅՈՒՆՆԵՐՈՒՄ ՌԱԴԻՈՀԱՃԱԽԱՅԻՆ ՀԱՄԱԿԱՐԳԵՐԻ ՄՇԱԿՈՒՄՆ ՈՒ ՀԵՏԱԶՈՏՈՒՄԸ

Ա.04.03 – “Ռադիոֆիզիկա”մասնագիտությամբ
տեխնիկականգիտություններիթեկնածուի
գիտականաստիճանիհայցմանատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ-2012

МИНИСТЕРСТВО ОБРАЗОВАНИЯ И НАУКИ РА

ЕРЕВАНСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

Али Мохаммад Пурсале

Разработка и исследование радиочастотных систем для высокомощностных применений

АВТОРЕФЕРАТ

Диссертации на соискание ученой степени кандидата

технических наук по специальности

01.04.03 –“Радиофизика”

ЕРЕВАН - 2012

Ատենախոսությանթեմանհաստատվելէ ՀՀԳԱԱՌադիոֆիզիկայիևէլեկտրոնիկայի Ինստիտուտում:

Գիտականղեկավար՝	ֆիզ.-մաթ.գիտ. թեկնածու Ա. Ա. Հախումյան
Պաշտոնականընդիմախոսներ՝	ֆիզ.-մաթ.գիտ. դոկտոր, պրոֆ. Յու.Հ. Ավետիսյան
	ֆիզ.-մաթ. գիտ. դոկտոր, պրոֆ. Է.Դ.Գազազյան
Առաջատարկազմակերպություն՝	«Քենդլ» սինքրոտրոնայինհետազոտություննե րիինստիտուտ» հիմնադրամ

Ատենախոսությանպաշտպանությունըկայանալուէ 2013թհունվարի25-ինժամը 15-ինԵրևանիՊետականՀամալսարանումգործողֆիզիկայի 049 մասնագիտականխորհրդինիստում: Հասցե՝ Երևան, ԱլեքՄանուկյան 1:
ԱտենախոսությանըկարելիէծանոթանալԵՊՀգրադարանում:
Սեղմագիրնառաքվածէ 2012թ.դեկտեմբերի 25-ին:

Մասնագիտականխորհրդիգիտականքարտուղար,
Ֆիզ.-մաթ. գիտ.թեքնածու Վ.Պ.Քալանթարյան

Тема диссертации утверждена в Институте Радиофизики и Электроники НАН РА.

Научный руководитель:	кандидат физ.-мат. наук А.А. Ахумян
Официальные оппоненты:	доктор физ.-мат. наук, проф. Ю.О.Аветисян
	доктор физ.-мат. наук, проф. Э.Д.Газазян
Ведущая организация:	фонд CANDLE- “Институт синхротронных исследований”

Защита диссертации состоится 25 января 2013 г. в 15 часов,на заседании специализированного совета физики 049 при ЕреванскомГосударственном Университете по адресу: Ереван, ул. А. Манукяна 1.
С диссертацией можно ознакомиться в библиотеке ЕГУ.
Автореферат разослан 25декабря 2012г.

Ученый секретарь специализированного совета
кандидат физ.-мат. наук. В.П. Калантарян

THE GENERAL DESCRIPTION OF THE DISSERTATION

Relevance.

High-power radio frequency (RF) systems have been used in many industrial applications. One of the main applications of these systems is in industrial accelerators, which is the objective and the main goal of this dissertation. Main goal of the present study is to design and optimize RF systems of an industrial electron accelerator. Here, we carry out analytical calculations and perform numerical simulations to study design of an RF system for an industrial electron accelerator. First, we introduce and compare different types of industrial accelerators and examine their applications. Then, by considering principles of operations of an RF system in an accelerator, we simulate and evaluate different components of an industrial Rhodotron accelerator.Rhodotrons accelerators are known as one of the most powerful industrial accelerators. One of the issues with the present accelerators is the use of RF vacuum tubes in their RF system. RF vacuum tubes have many disadvantages, for instance, short lifespan which entails frequent replacements in short intervals of time, burdens extra expenses, prevails difficult maintenance, and causes risks associated with high-voltage conditions. Furthermore, manufacturing technology of RF tubes is only available in several industrial countries; therefore, supplying the tubes in many countries is not expedient. Thus, we introduce solid state amplifiers as an alternative technique and review advantages of using them in electron accelerators to overcome problems associated with using RF vacuum tubes. A new RF system for an electron accelerator, particularly for a Rhodotron accelerator using the alternative solid state amplifiers method, is designed and studied based on the numerical simulations. To simulate the RF system of an accelerator and study dynamics of an electron beam in an accelerator, we utilize CST Studio, Ansoft HFSS, ADS, Superfish, and Ansys commercial codes. In addition, math tools such as Matlab and computer aided design packages such as Autocad Electrical, Solid works, Orcad, and circuit analysis code Protel are used in this study. Nonetheless, most of the numerical simulations are carried out using CST Studio 2010. Different environments of this software used in this dissertation to design and analyze new accelerator include: CST Microwave Studio, CST Design Studio, and CST Particle Studio. Finally, a new transistor-based accelerator is proposed and designed by based on the numerical simulations. This accelerator can work with solid state amplifier module and can be connected directly to the acceleration cavity without using either a power combiner and high-power transmission lines or an input coupler.

This design can work with high-power industrial electron accelerators, is small in volume, and has low-manufacturing costs.

Principal aim of this dissertation:

This dissertation aims to design a high power industrial electron accelerator with the main goal of optimizing the RF system.

For this aim different tasks have been studied including:

1 – Assessment and comparison of different types of electron accelerators available for industrial applications,

2 – Studying principles of operations and structure of an industrial RF accelerator, analyzing and performing numerical simulations of its components,

3 – Design and simulation of electron gun as a primary electron generator suitable for a RF industrial electron accelerator,

4 – Analysis and simulation of the RF system in a Rhodotron accelerator,

5 – Design and simulation of a new RF system for an industrial accelerator, and Optimization of a RF system by replacing the RF tube with a solid state amplifier to resolve current problems associated RF tubes in Rhodotron accelerators.

The main goal :

We are looking for design of an industrial RF electron accelerator which is

1 – Easy and inexpensive to maintain and repair,

2 – Safe,

3 – Small in volume,

4 – Economical,

5 – Affordable and suitable to local conditions.

6- high power and high energy

Scientific contribution and novelty of the work is as follows:

1 – According to the studies conducted here, we conclude that a Rhodotron accelerator is one of the most powerful industrial electron accelerators currently available.

2 – From optimizing the performance of the cavity in an electron accelerator, finding effective parameters in the design of a cavity and their effects on the RF parameters, and achieving an optimum configuration for the cylindrical and coaxial cavities based on CST Studio simulations, we conclude that (*i*) cylindrical cavities with rounded corners and nose have better performance

than those without a nose and (*ii*) coaxial cavities with the end-bent-arched walls have the best performance among all the shapes.

3 – To achieve an appropriate design for the electron gun of an RF electron accelerator with abilities to gain impedance match, high current beam, circuit synchronizations, RF field in the acceleration cavity, and the primary generator for the electron beam source, we ascertain that a Triad gun with the thermionic structure and RF modulation is the most suitable electron beam generator for industrial accelerators.

4 – To find the best shape of an input loop coupler which provides RF power for coaxial cavity, we note that an input coupler with a rectangular loop has the best performance.

5 – According to our calculations, we conclude that with an appropriate design and replacement of the coaxial cavity, wavelength of the equivalent coaxial resonance can be changed to the half-wavelength for Rhodotron accelerators, this eventually reduces the return losses.

6 – Investigations on the role of a solid state amplifier to be used instead of an RF tube in an accelerator show many advantages of solid state amplifiers such as modulation, easy to maintain, no need to use high voltage, and no need for a start-up time.

7 – Comparison of resonance of the power combiner in cylindrical and coaxial cavities shows that in low frequencies the coaxial combiners are more suitable than cylindrical combiners.

8 – According to the feasibility study done on feeding power into the cavity using multiple input coupler , we ascertain that due to severe interaction between ports, multiple-port method is not very safe in practice, in this feasibility study, we note that uniform change of impedance in all ports, change in configurations of couplers, change in couplers dimensions, and angles as well as position of coupler within the acceleration cavity do not have positive effects on return power and isolation between ports.

9 – According to the study conducted here, it is found that slitting a cavity and connecting the cavity directly to RF generator excite the cavity to the resonance. With direct connection of the amplifier modules around the slit ,we are to build based solid state accelerators without the need for power combiners, transmission lines, and a input coupler. These accelerators are high in power, small in volume and, quite economical,

10 –we are able to show potential applications of CST for design and analysis of accelerators. We note that this software is comprehensive and quite appropriate for analyzing accelerators.

Main statements for defense

1 – To increase synchronism and concentration of the electric field and the electron beam in a

cylindrical acceleration cavity of a linear accelerator, the cavity should have a nose. Also to increase the quality factor and decrease the losses, the cavity should be spherical.

2 - To increase the shunt impedance in a coaxial cavity, both ends of the coaxial cavity should be bowed. For this case, the height of cavity should be increased to preserve resonance frequency at the half-wavelength.

3 – To have a highly efficient accelerator, the electron gun should be connected to an RF feedback circuit and the RF phase regulator should be connected to the electronic gun.

4 – To have the best amplifier coupled to the coaxial cavity of a RF acceleration, magnetic coupling should be used by means of an input coupler by rectangular loop.

5 – To design an affordable, safe, easy to use, and low cost maintenance accelerators the solid state amplifiers should be used instead of RF vacuum tubes

6 – To reduce the final cost of solid state amplifiers, number of power combiners and transmission lines must be reduced. This can be achieved by designing an acceleration cavity containing a slit and connecting solid state amplifiers directly to the cavity.

7 – To improve s parameter, increase efficiency, and reduce the voltage drop due to presence of a slit in an acceleration cavity containing a slit, a secondary cavity must be used. The secondary cavity is basic and small in size located around the slit such that it surrounds internal amplifiers.

8 – To connect solid state amplifiers directly to the acceleration cavity containing a slit, amplifier modules must be symmetrically located around the acceleration cavity and output signals from the amplifier should be co-phased and co-amplitude.

Approbation of the results and publications extracted from this dissertation:

Main achieved results of dissertation have been reported to International conference on the technique of microwave and THz waves and its application in biomedical and radar technologies and in remote sensing, Ashtarak-Aghveran (Aremina, 2010) and several seminars in department of radiophysics, Yerevan state university, and Institute of Radiophysics and Electronics, NAN RA, and published in following articles:

1. A. Poursaleh. "Design and simulation of the RF modulated electron gun for high power industrial accelerators". Archives Des Sciences Vol 65, No. 2; pp:10-18, 2012
2. A. Poursaleh, "Numerical Investigation of Input Loop Coupler Configurations for a High Power Industrial Accelerator with a Coaxial Cavity". International Journal of Applied Engineering Research Vol 7, No 3, pp. 321-331, 2012

3. A. Poursaleh, A. Hakhoumian" The effect of acceleration cavity configurations on electron linear accelerator parameters". Information technologies and management, pp.206-216, 2012
4. A. Poursaleh" The effect of Coaxial Cavity Configuration on RF parameter in High Power Electron Accelerator " International Journal of Applied Engineering Research, Vol 7, No10, pp: 1153-1159, 2012
5. A. Poursaleh, A. Hakhoumian. "Scientific and technical investigations of industrial electron accelerators", International Conference "The Technique of Microwave and THz Waves and its Application in Biomedical and Radar Technologies and in Remote Sensing", Ashtarak-Aghveran, Aremina, pp:105-108, 2010
6. A. Poursaleh, A. Hakhoumian, B. Abbasi. "The new design of rf system for high power industrial electron accelerators" International Conference "The Technique of Microwave and THz Waves and its Application in Biomedical and Radar Technologies and in Remote Sensing", Ashtarak-Aghveran, Aremina, pp:109-112, 2010

Structure of the dissertation

This dissertation includes an introduction, five chapters, and conclusion. It includes 170 pages, 170 figures, 18 tables and 120 references.

THE PRINCIPAL SUBSTANCE OF THE DISSERTATION

(A brief overview)

This dissertation is organized into five chapters. **In Chapter1**, principles of operations, classifications of industrial accelerators and their applications are presented. Electron accelerators are categorized into two groups (a) electrostatic (DC) accelerators and (b) radio frequency (RF) accelerators. We describe principles of operations of accelerators and state different components of accelerators in this chapter. We briefly explain the two main industrial electron accelerators including: electrostatic accelerators ELV models and Dynamitron. We also introduce linear RF accelerators with either one-stage acceleration cavity or several acceleration civilities and also multi-stage accelerators with an acceleration cavity. For instance, we have given specifications of different types of accelerators in Table 1. Also in Fig. 1, we have compared well-known industrial accelerators in terms of energy power and power of the beam.

At the end of Chapter one, various applications of industrial electron accelerators have been introduced.

Table 1. Specifications of three different types of accelerators.

Parameter	DC	RF single cavity	RF linear
Electron energy	0.05-5MeV	10 mev	2-10MeV
Average beam current	<1.5A	<100mA	<100mA
Average beam power	400kW	700kW	50kW
Electrical efficiency	60-80%	20-50%	10-20%
Frequency	-	100-200MHz	1.3-9GHz

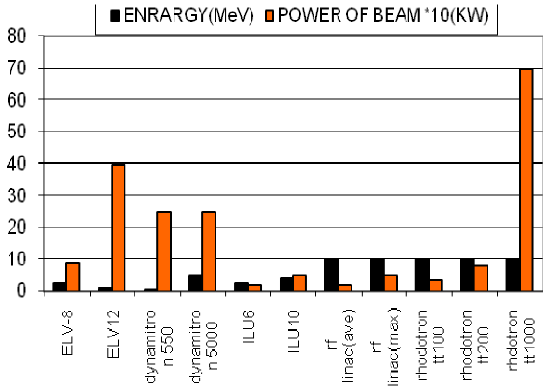
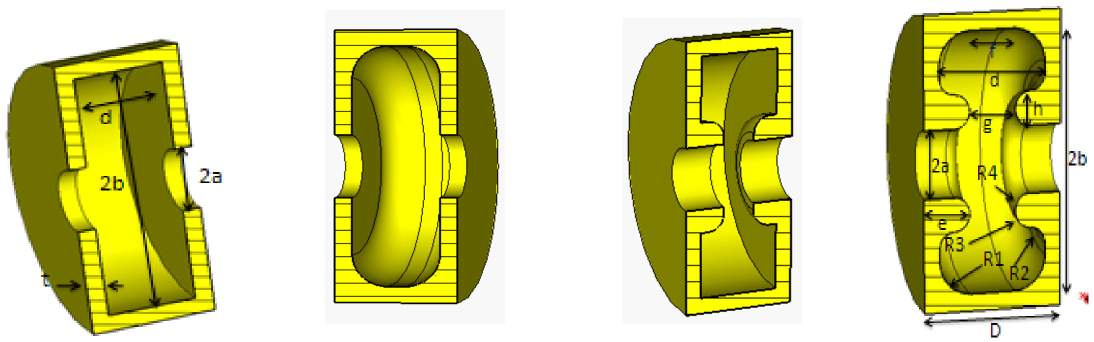


Fig1. Comparison of different industrial accelerators in terms of energy and power of the beam.

In Chapter2, structure and theory of RF accelerators are studied. Based on Maxwell's equations, we obtain design expressions for the resonance cavity of an accelerator. First, we simplify these equations, find important parameters such as resonance frequency of the electric and magnetic fields, stored energy, power loss, quality factor, transit time, shunt impedance , R/Q ratio, and the stress field for a pill box cavity of accelerators. Afterwards, we calculate dimensions of a pill box cavity and design it. Later, we study various shapes of cylindrical cavity of a linear accelerator based on numerical simulations using CST software package. Figure 2 shows various shapes of a pill box cavity.



(a) (b) (c) (d)

Fig2. Various shapes of a pill box cavity, from left to right: (a) simple pill box cavity (b) spherical pill box cavity (c) simple pill box cavity with nose, and (d) spherical pill box cavity with nose

After performing the simulations, for a linear accelerator, the effects of presence of nose and the gap size on various parameters such as quality factor, transit time, shunt impedance, and *R*/*Q* are studied. For instance, Fig. 3 shows the effects of nose gap size on various parameters.

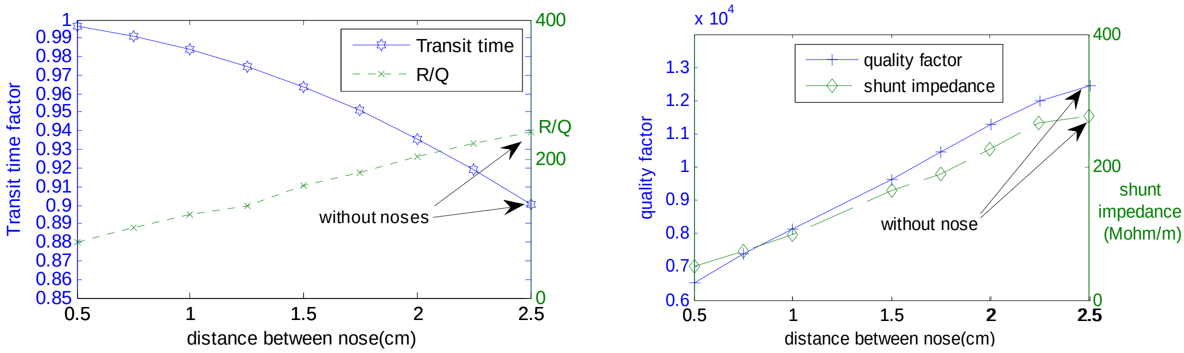


Fig3. Effects of nose gap size on various parameters of a linear accelerator.

From Fig. 3, we understand that increasing nose gap size (or decreasing height of the nose) in the cavity results in higher quality factor and increase the shunt impedance, however; it decreases the transit time and ratio *r*/*q*. Therefore, an optimal point is the mid distance between two walls of the cavity. The effects of changing dimensions of an acceleration cavity on frequency and quality factor are shown in Fig. 4.

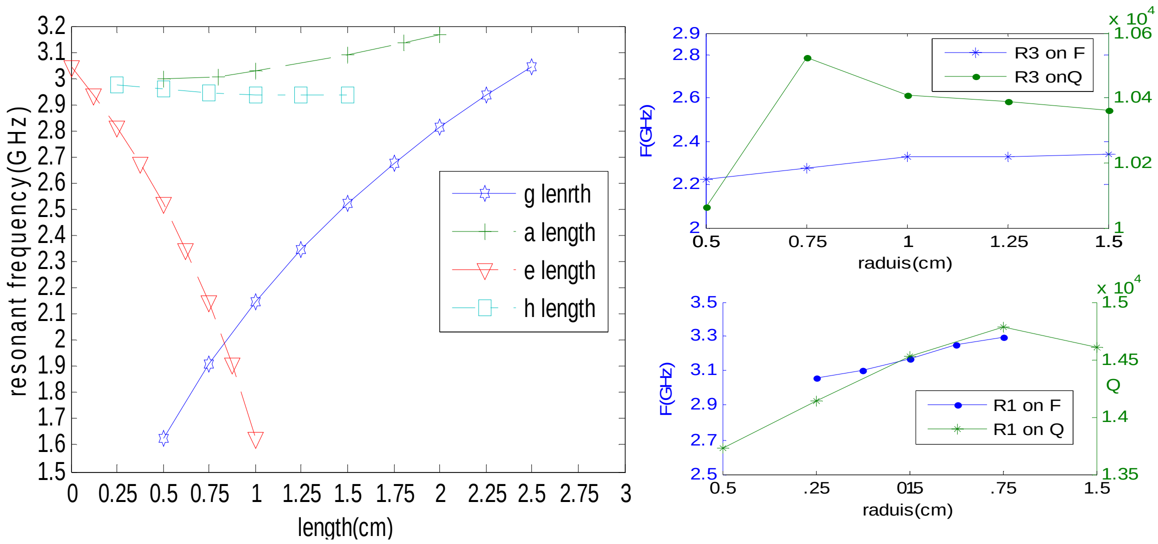


Fig 4. Effects of changing dimensions of cavity on frequency and quality factor.

After careful examination of an acceleration cavity, we study the effect of a multi-cavity configuration in a linear accelerator. In this section, various resonance modes are studied and the effects of traveling and standing waves in accelerators are compared. Table 2 shows results from comparison of these two waves. Also Fig. 5 shows the simulation of the electric field lines of an acceleration cavity with a five-cell acceleration module and resonance mode of $\pi/2$, that is one of the common modes in linear accelerators.

Table 2. Results from comparison of traveling and standing waves.

Parameter	TW accelerator	SW accelerator
Shunt impedance	Low	High
Isolator or circulator	Not needed	Needed
Maximum accelerating Beam current	High -2A	Low-0.5A
Tuning sensitivity	High	Low
Input coupler design	Complex	Simple
Buncher design	Rather complex	Simple
Spectrum sensitivity on accelerating field	Low	High
Coupler	Dual	Single
Coupler position	First and last	Any

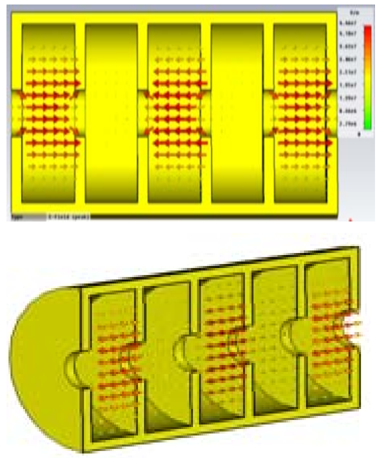


Fig 5. π/2 resonance mode in a five-cell acceleration module.

At the end of this chapter, we investigate various components of an accelerator and study a RF system in a linear accelerator. We describe methods for the RF coupling and present the equivalent circuit diagram and provide the corresponding equations.**In Chapter 3**, we study main components for source of an electron generator in an accelerator. The electron gun is the first component from which generating and accelerating electrons in an accelerator should be studied. In this chapter we analyze and simulate electron guns which are briefly discussed in the first and second chapters. The main objective of this chapter is to design an electron gun suitable for RF accelerators and examine different types of thermionic cathodes and indicate important parameters for designing an electron gun. Then, we design an electron gun with RF modulator compatible for an RF accelerator. Figure 6 shows the electric circuit diagram for the designed electron gun of a high-power industrial RF accelerator

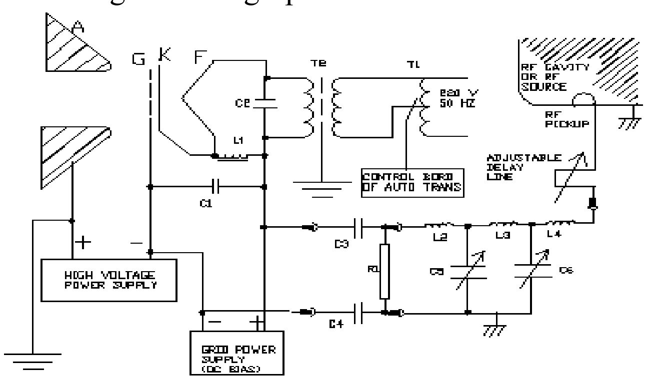


Fig 6. Circuit diagram of an electron gun designed

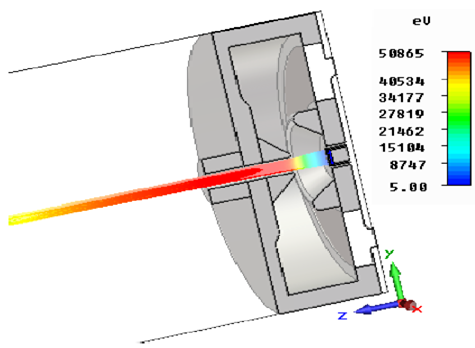
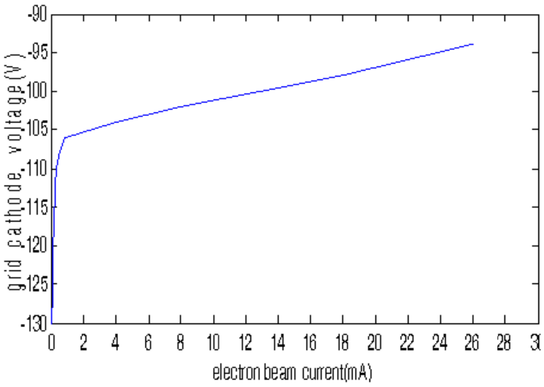
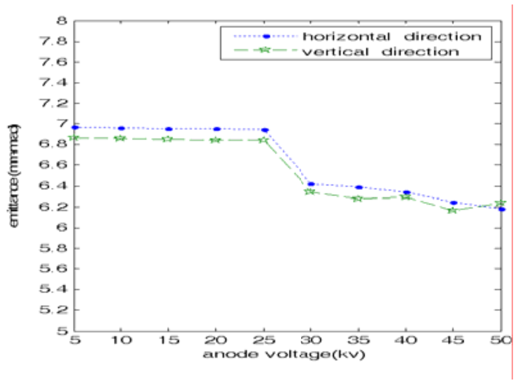


Fig7. Pattern of cathode and anode cavity and the produced beam

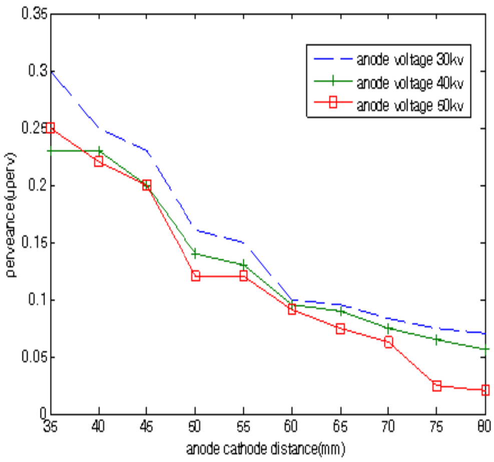
.The designed electron gun is simulated using Particle Studio environment of the CST Studio package. Sketch showing pattern of cathode and anode in the cavity and beam produced is shown in Fig. 7.In this design, the effects of different parameters such as optimum anode-cathode voltage and grid-to-cathode voltage on the beam current are investigated. Also feeding power to excite RF electron guns, perveance, and emittance are studied. Results from the numerical simulations are shown in Fig. 8 (a-d).



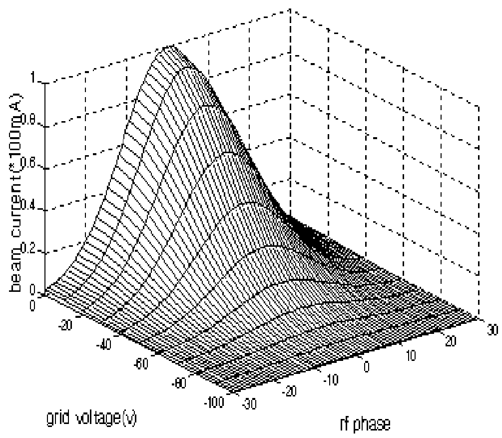
(a)



(b)



(c)



(d)

Fig 8. Results from the numerical simulations: (a) the effect of grid-to-cathode voltage on the electron beam current, (b) relation between anode voltage and emittance, (c) relation between anode-cathode distance and perveance, and (d) relation between RF phase and grid-to-voltage and the beam current.

The results show that the designed electron gun with RF modulation is suitable for a RF electron accelerators.

In Chapter 4, we study the structure of a high-power RF electron accelerator, i.e. a Rhodotron accelerator using a coaxial cavity. Hence, we study RF system of a Rhodotron accelerator. First, coaxial cavity related equations are considered and important parameters such as resonant frequency, electric and magnetic fields, shunt impedance, transit time, stored energy, power losses, and quality factor are calculated. Bases on numerical simulations, exact dimensions of the coaxial cavity of a 107 MHz Rhodotron accelerator are computed.Also to find an optimized acceleration cavity, to maximize the efficiency of the accelerator, several shapes of cavity are considered and simulated. Figure 9-a shows different shapes of an acceleration cavity for which the effects of dimensions on surface flow, shunt impedance, and resonant frequency are plotted in Fig.9.

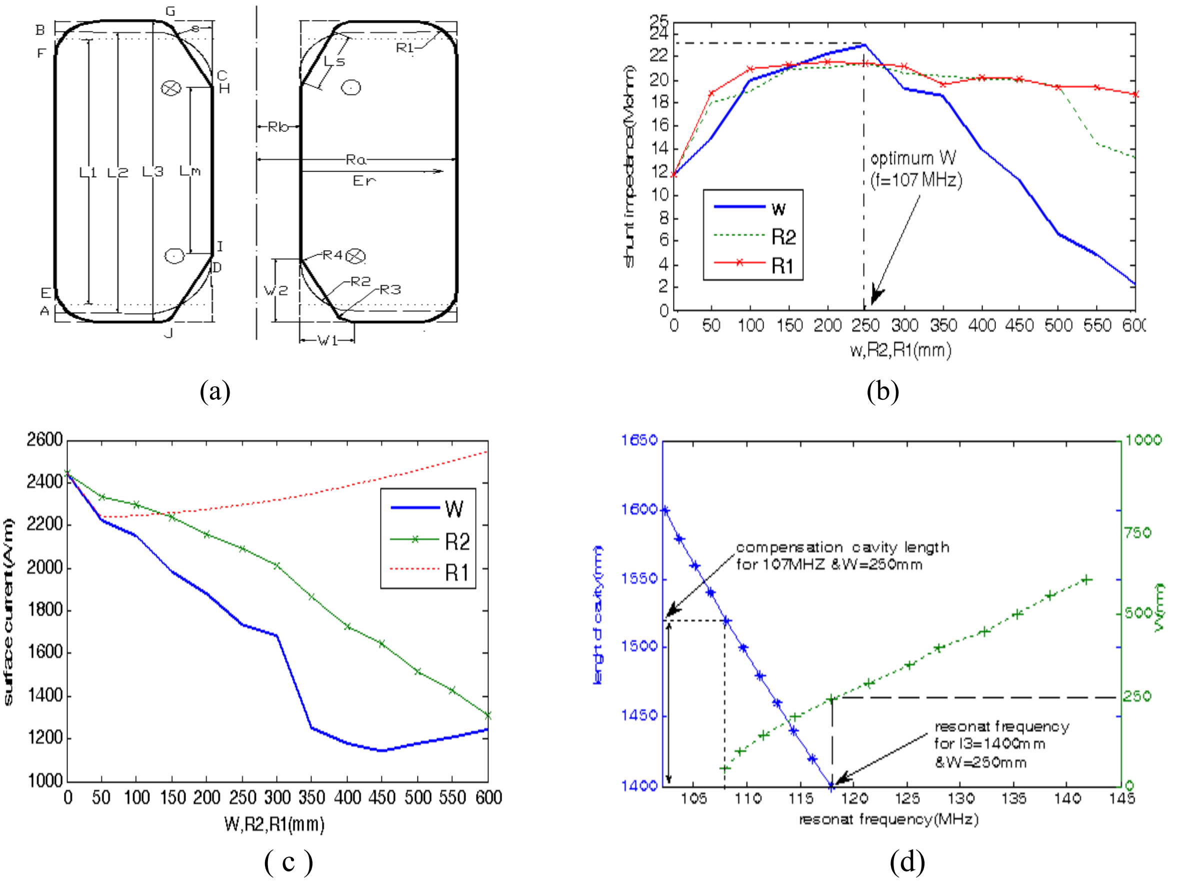
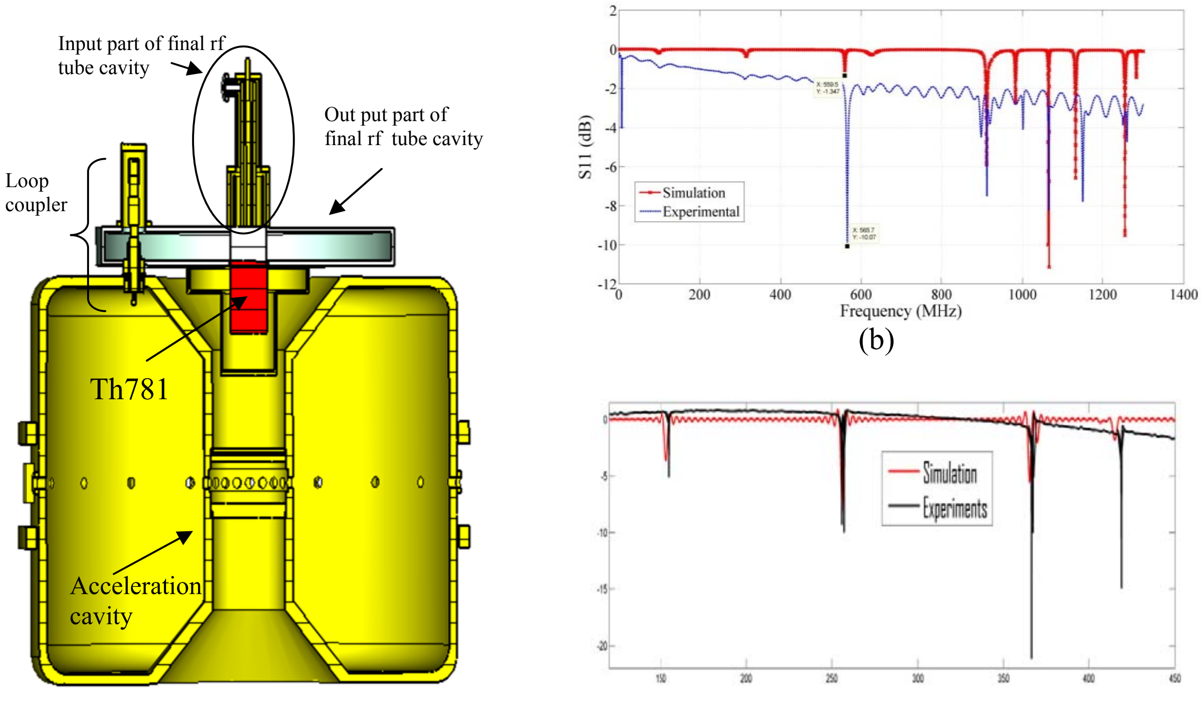


Fig 9. (a)Different shapes of an acceleration cavity.(b) The effects of dimensions on surface flow, (c) shunt impedance, and (d) resonant frequency.

Results from simulations show that the shape of the coaxial cavity, shown in Fig. 9 in bold line, is the optimum option. In a Rhodotron accelerator to achieve the electron beam of 10 mev energy and 100 kW power, it is required to have an RF system with the peak power at 200 kW.

This can be achieved with multi-levels of amplifiers. In Chapter 4, components of an RF system of a Rhodotron accelerator such as low level RF (LLRF**)**, pre-driver amplifiers, driver amplifier, and final amplifier are discussed. Pre-amplifier is a 100 W solid state amplifier which we have designed and tested. However, the driver and final amplifiers have RF vacuum. The driver amplifier uses a TH 341 tube which amplifies RF power to 10 kW and the final amplifier increases the ultimate power to 200 kW. Because of the importance of the final amplifier particularly location of the TH 781 tube in the acceleration cavity, we have analyzed this problem using the CST software. A section-cut view of the cavity and tube located on the upper part of the acceleration cavity is shown in Fig. 10a. We also have compared from the simulations impedance matching and return loss for the input and output ports of tube cavity and compared those with the experiments in Fig.10b,c . The results from simulation are in a good agreement with those obtained from the experiments.



(a) (c)

Fig10. (a)Section cut-view of the acceleration cavity showing location of the tube. (b)Comparison of impedance matching and return loss for the input and (c)output ports of a rf tube cavity .

Moreover, RF coupling with the acceleration cavity is accurately studied. To do so, for exciting the acceleration cavity, three types of input couplers with various shapes are proposed and simulated, Figure 11 shows cross section of the coupler and its location inside the acceleration cavity.

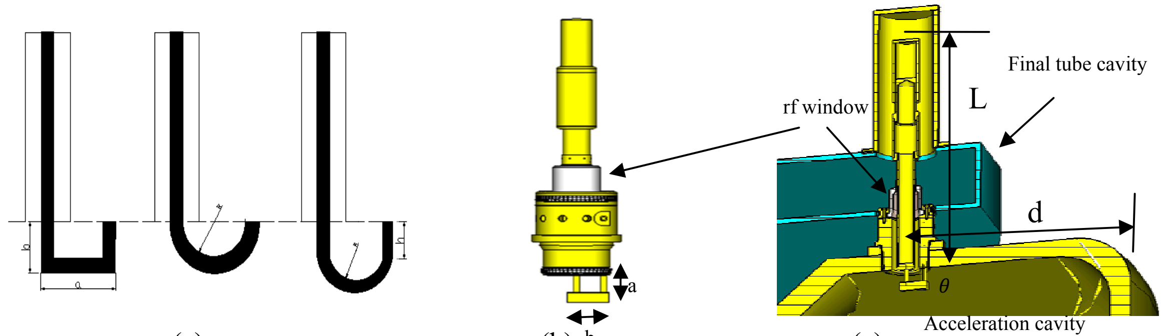


Fig 11.(a) Three types of couplers studied.(b) Cross-section view of the coupler and (b) location of the coupler inside the acceleration cavity

Results from the numerical simulation considering different dimensions of the coupler are shown in Fig. 12. Bases on these results optimum dimensions, location, and angle of a coupler inside the accelerator cavity is determined.

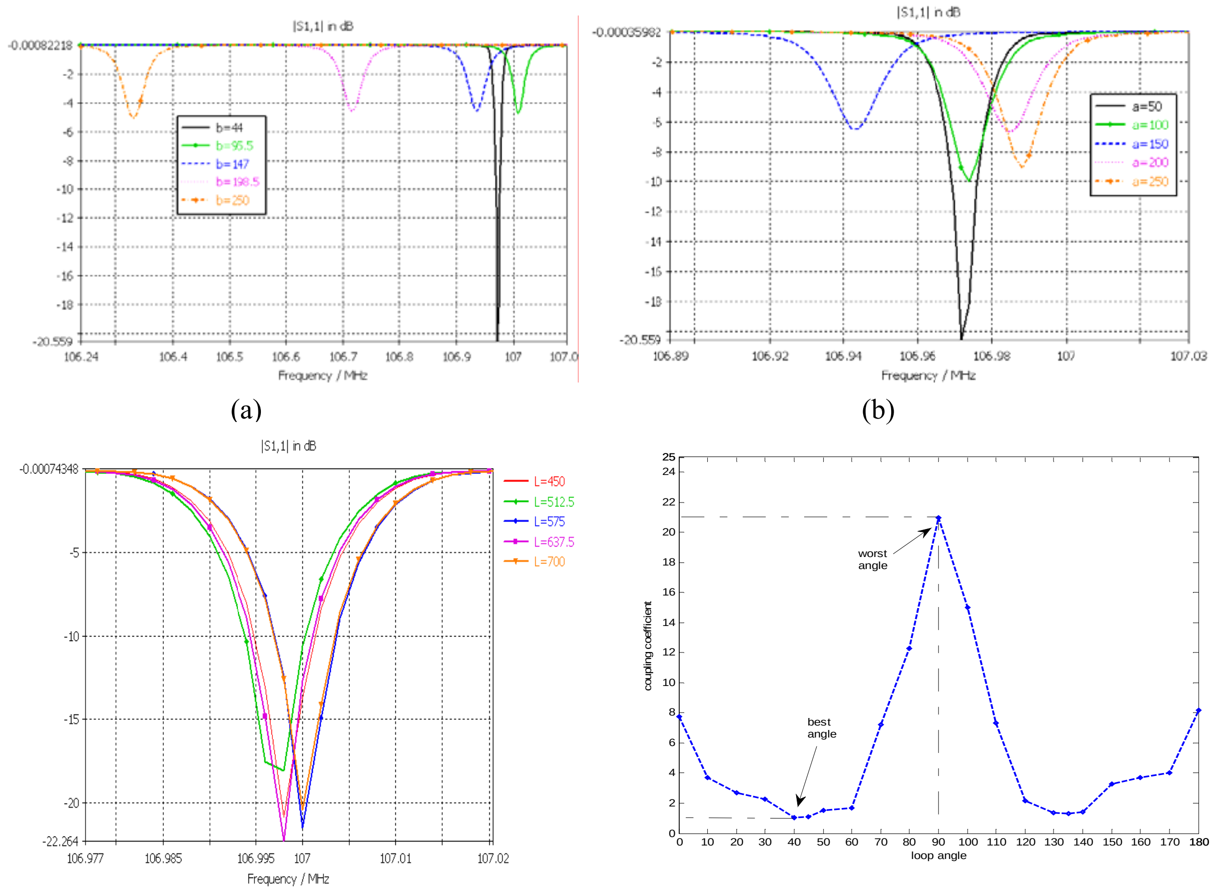


Fig 12. Effects of (a) coupler location on return loss, (b) coupler dimensions on return loss, (c) loop angle on coupling coefficient, and (d) the length of loop on resonance frequency.

At the end of Chapter four, we provide details of design of a new accelerator. To reduce power losses in an accelerator with dimensions similar to those of a Rhodotron accelerator, we show, based on the numerical calculations, that the length of cavity must be equal to the wave length. Figure 13 illustrates a section-cut view of the new designed accelerator.

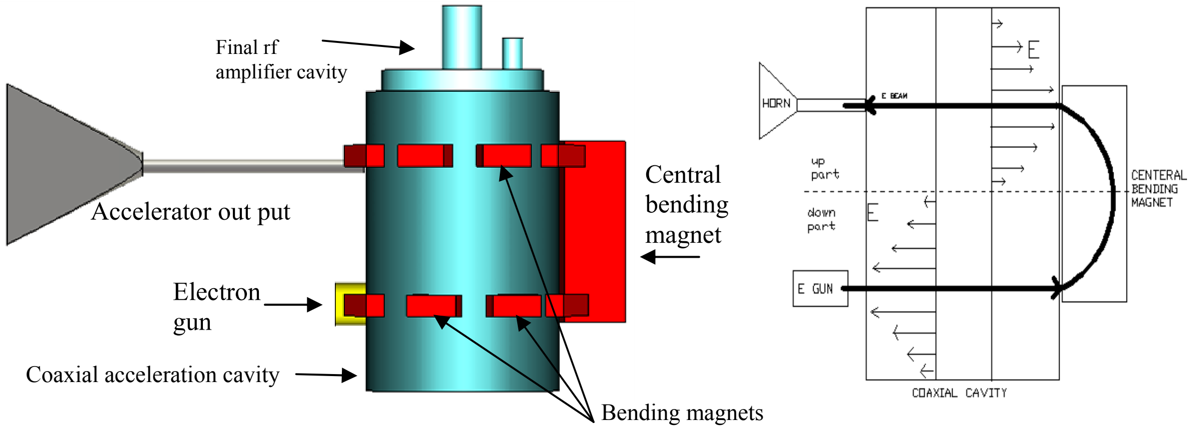


Fig 13. Section-cut view of the conceptual designed accelerator.

In Chapter 5, high power RF systems including a solid state amplifier is studied. The main objective of this chapter is to investigate feasibility of replacing an RF vacuum tube with a solid state amplifier in the industrial accelerators. First, we review solid state amplifier technology, assess high power transistors, and learn about benefits of solid state amplifiers over an RF vacuum systems. We evaluate some of the high power RF transistors such as BLF574 and MRF 6VP41KH. Furthermore, we look into the various high power combiners to be used for the solid state amplifier and determine important design criteria and finally simulate a Wilkinson combiner. Then, we study SOLEIL synchrotron facility in France, in which the solid state amplifier technology being used. Afterward, we focus on design of a new RF system for the high power Rhodotron accelerator. Figure 14 shows the schematic sketch of a 200 kW RF system with a solid state amplifier. This amplifier includes 20 × 10 kW amplifiers. Subsequently, design and manufacturing a 10 kW continuous-wave (CW) amplifier are explained. Different components of this amplifier are shown in Fig. 18.In the design of this amplifier, based on the calculated loss power twelve modules of 1 kW are used. Each module consists of two BLF 574 push-pull transistors biased in the AB class, a power supply, control and measuring circuits, and a circulator.According to the block diagram shown in Fig. 15, this amplifier consists of three groups of quaternary amplifiers. There is a 1/3 micro-strip splitter at the input of this amplifier which divides the 100 W input power into three and supplies it to the amplifier modules using an 1/4 splitter.

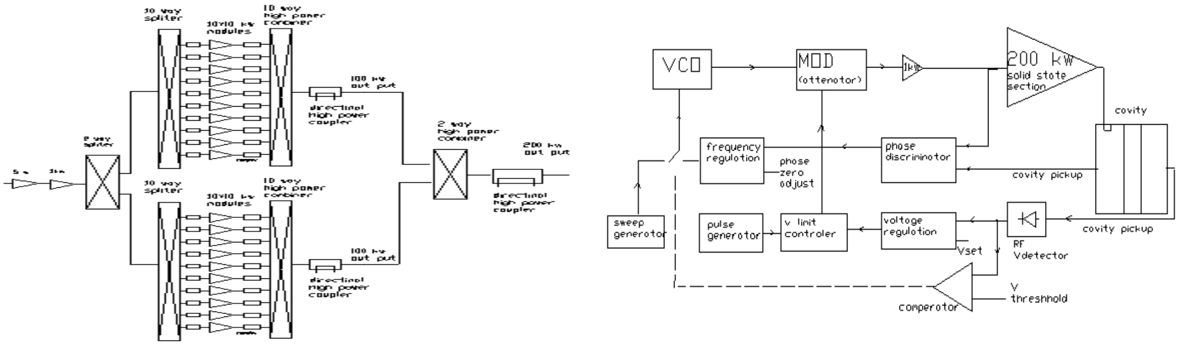


Fig14. Schematic sketch of a 200 kW RF system with a transistor amplifier for a Rhodotron accelerator.

In a similar manner but in the reverse order, the output power from the amplifier modules is combined. All the components of this amplifier are designed and simulated using ADS and CST Studio software. Results from the simulations are compared with those from the experiments, results are in a reasonable agreement.

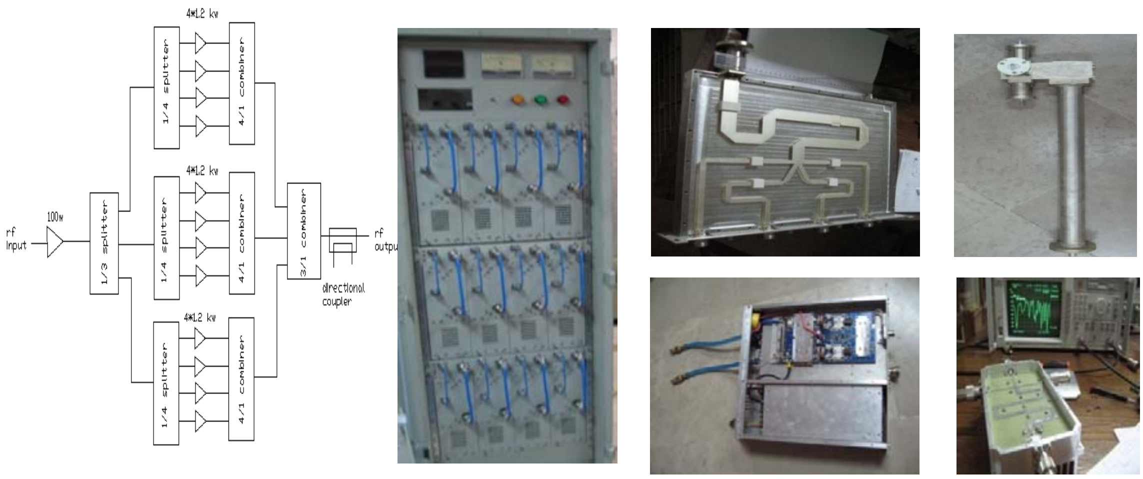


Fig15. the block diagram and some components of our 10 kW solid state amplifier .

To transfer power from a high power solid state amplifier, it is required to have an appropriate transmission line and the proper coupler. Here, we have designed an adjustable coupler which able to transfer 200 kW power from the transistor amplifier, see Fig. 16.

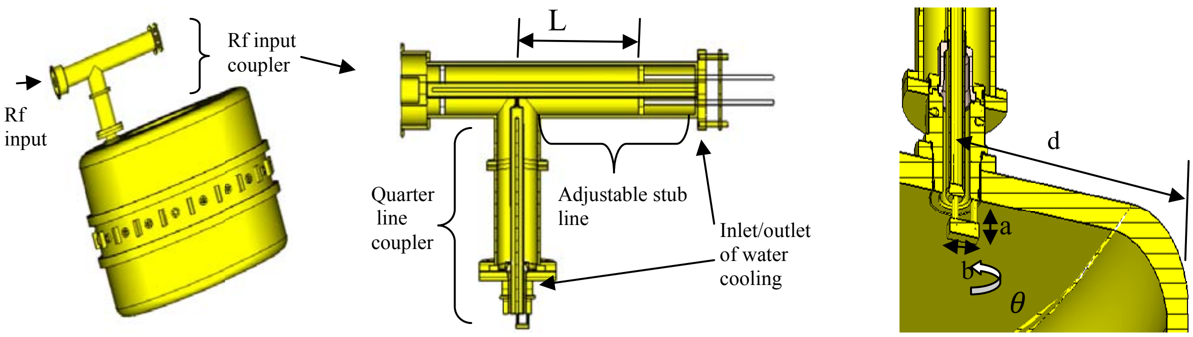


Fig 16. Section-cut view of the designed high power coupler and its position on the acceleration cavity

Shown in Fig.17, based on the numerical simulations the effects of different dimensional parameters of this coupler on the return loss and impedance matching at input are studied. Optimum length and width, step length, angle, and position of the coupler in the acceleration cavity are obtained from these results.

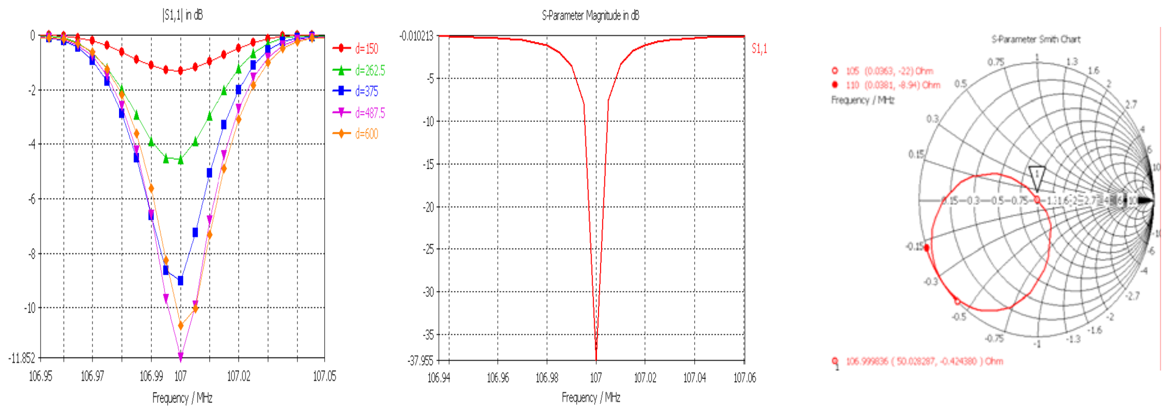


Fig17. The effects of different dimensional parameters of the designed coupler on (a) return loss and (b) impedance matching.

One of the important issues in design of couplers is the cooling of the system. In this design, this issue is solved by designing a suitable cooling system including pipeline and paths for the input and output ports.Some of the advantages of this RF system comparing to the vacuum tube system include: (*i*) system modulation which enhances easiness for upgrading, repairing and maintaining the system. However, in a vacuum tube system when a single vacuum tube is broken, entire system has to be shut down for maintenance; (*ii*) the designed system does not need high voltage power supplies, while a system with the vacuum tube deals with high voltage which entitles physical risks; (*iii*) the designed system, unlike vacuum tube systems, does not need start-up time and does not suffer from issues related to installation; (*iv*) lifetime of the system is higher than that of a RF vacuum tube, (*v*) solid state systems can be built locally. Thus, with reference to the design, we are able to build a transistor-based RF system for an industrial electron accelerator such as Rhodotron. However, building this system for a Rhodotron accelerator is expensive, where most expenses are due to the need for power combiners. To solve this issue, we therefore intend to design an accelerator in which the acceleration cavity can also act as power combiners. In other words, RF amplifiers are connected independently to the cavity. Figure 18 is displaying schematic sketch of this design. Our main goal in this section is to perform feasibility studies of using this method in the accelerators.

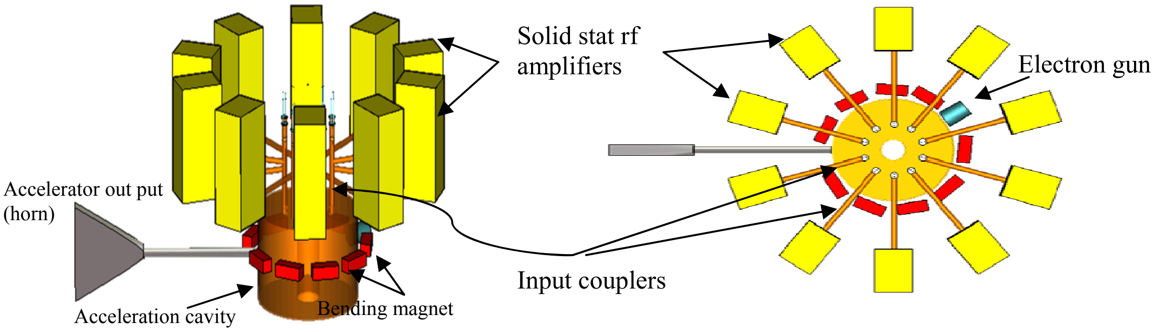


Fig18. Schematic sketch of design of the multiple input couplers to acceleration cavity.

To provide exact details of this design, we initially evaluate and investigate several cavity type power combiners and select the suitable one for the case study to perform experiments. Here, several examples of pill box cavity and the coaxial cavity in TM and TEM resonance modes are studied. A power combiner is then designed based on analytical calculations and numerical simulations. Afterwards, the combiner is built and tested. Results of the simulations and those of experiments are in a good agreement. The designed combiner is shown in Fig.19.

Fig19. Example of the power combiners designed and built.

Based on the results of the simulations and those of the experiments, we find out that in a particular frequency, coaxial cavity combiners are performing better than pill box cavities. The most important characteristics of these combiners include: smaller volume, higher quality factor, and also easiness in adjustment. Therefore, we have chosen the coaxial cavity and performed feasibility studies and carried out experiments. Based on the dimensions calculated for an acceleration cavity of a Rhodotron accelerator that calculated in Chapter four, we then study the effect of number of ports on performance the coaxial cavity. For an example, we consider the cavity with four inputs and one output, see Fig. 20, and find out that the results from the simulations are satisfactory. For this example, the return loss of main port is about -23 db, coupling losses is about -0.09 db, and isolation between ports is approximately -11 db.

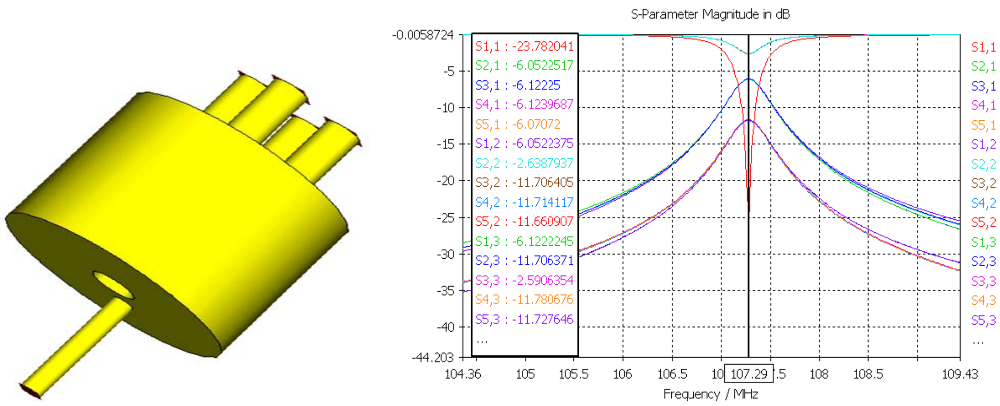


Fig 20. Power combiner with four inputs and one output with dimensions equal to those of a Rhodotron acceleration cavity.

Now if we remove the output port and activate input ports, e.g. shown in Fig. 21, power return loss and isolation between ports increase to -6 db for the best case.

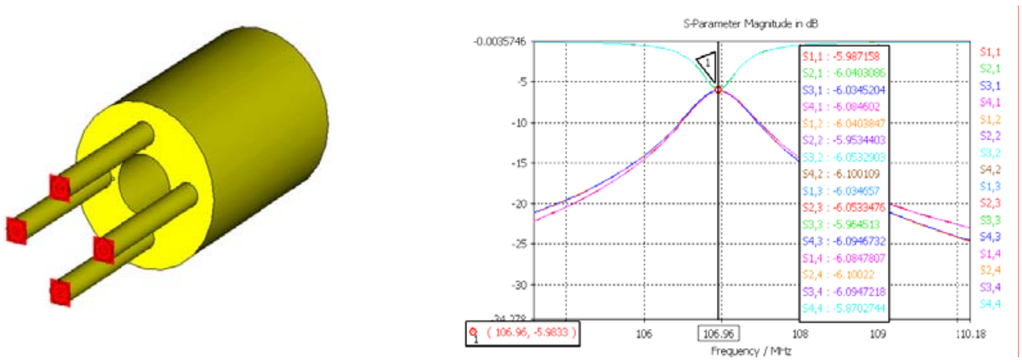


Fig 21. Response of the S parameters obtained from the simulation for a cavity with four input ports.

To improve response of the system and find the optimum state, parametric studies are performed to determine the effect of varying different parameters on the S parameters, that is:

1-The effect of varying angle of the input coupler

2-The effect of varying impedance of the input ports

3-The effect of varying the size of the coupler loop

4-The effect of coupler position on the acceleration cavity

5-The effect of shape and frequency of acceleration cavity

6-The effect of varying phase of the ports with respect to each other

7-The effect of varying materials and absorbers inside the acceleration cavity

8-The effect of varying shape of the input coupler loop

9-The effect of input ports on the electric field inside the acceleration cavity

10-The effect of increasing number of input ports on S parameters

Thus, based on all of variables and the efforts studied, the best configuration for the four input port is -6 db. We should note that the results become worse with the increasing number of the ports. This design is simulated using CST Studio, Ansoft HFSS, and ADS. Results from these three simulations are almost the same. That is, increasing number of the ports has positive effect on the energy of the electron beam. This effect was studied by the Particle Studio software and results of simulation are shown in Fig. 22.

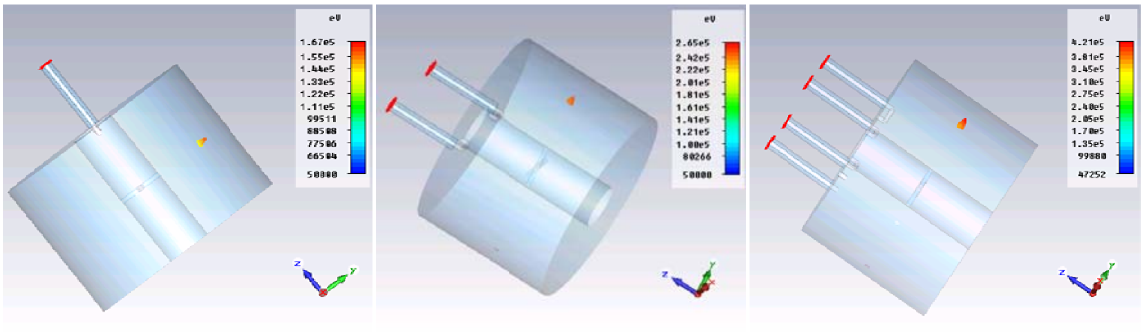


Fig 22. The effect of increasing number of ports on the electron beam energy in an accelerator cavity.

As it can be seen from this figure, the electron beam energy increases by increasing number of the input ports, e.g. the beam energy for one port is 140 kev, for two port is 260 kev, and for four port is 420 kev. As it can be seen, increasing number of ports is directly proportional to the electron beam energy, however, if the entire energy is absorbed, this method is useful otherwise it is not.To make sure that results of the simulations are reliable, we validate the concept and design by various experimental tests. First, we need to perform experiments on the accelerator. However, considering the required time for the test and unavailability of the accelerator due to daily schedule, we have built several small coaxial cavities made of copper and aluminum, as shown in Fig. 23, to perform the tests.

Fig 23. Several coaxial cavities built to perform tests.

Important note in this design is that the synchronization of RF amplitude and phase signal. According to tests conducted and numerical simulations performed, we find that if phase difference is not considered for the applied signal at the input ports of the cavity, not only it is impossible to improve return losses at the port, but also the overall results on the S parameters deteriorate. Also lack of phase difference has detrimental effects on both the electric field inside the cavity and the electron beam energy. Therefore, to set phases of the input ports in practice, we use the delay lines (or trombone), as shown in Fig. 24. To ensure that all phases are synchronized, we use an oscilloscope and plot Lissajous curves.

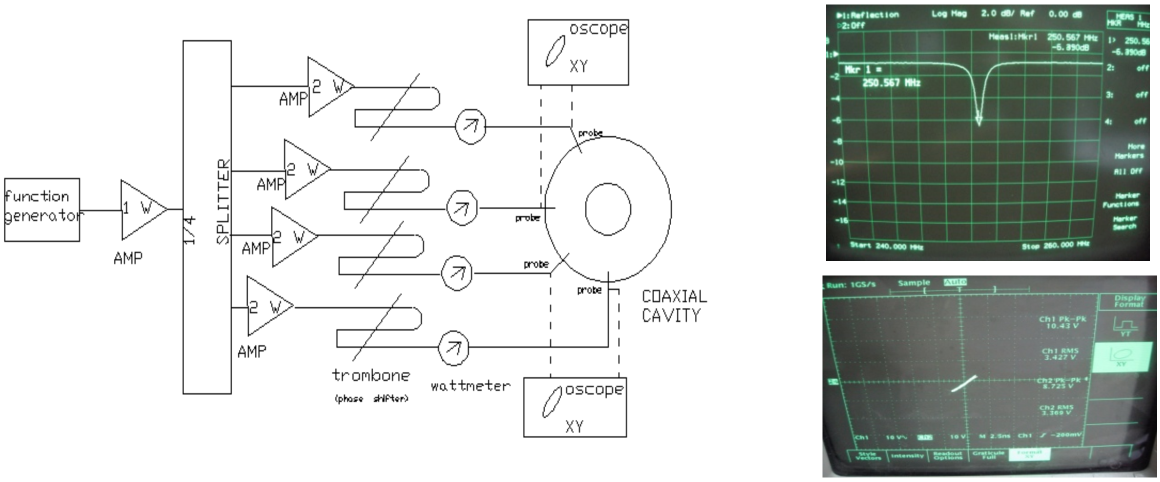


Fig 24. Schematic of the circuit with four input ports (left) and some measuring result (right).

Based on Fig. 24, at zero phase results from the experiments, i.e. S parameters, forward and return powers are in good agreement with those from the simulations. For example, Table 3 shows comparison of the experimental and the simulations result for the small copper cavity.

Table 3. Comparison of S parameters determined by simulation and experimental tests for the small copper cavity.

Parameter	Simulation (db)	Experiment (db)
S_{11}	-6	-5.9
S_{22}	-6	-6
S_{33}	-6	-5.9
S_{44}	-6	-6.1
S_{12}	-6.1	-6.2
S_{13}	-6.11	-6.13
S14	-6	*-6.15*
S_{23}	-6	-6.17
S_{34}	-6	-6.1 1

The results from experiments show that if the feeding power is not absorbed into the cavity, it will return to the source through either the port itself or the other ports. Therefore, it is possible to adjust the required feeding power by means of a control circuit. However, due to safety issues, this method is not recommended. We also have tried to improve the results by considering different conditions and various shapes of an acceleration cavity, and finally find out that one of the methods to improve the results is slitting the acceleration cavity and directly connecting the solid state amplifier modules to the cavity. Hence, we excite several slit cavities to resonance modes by directly connecting the ports to the cavity as shown in Fig. 25.

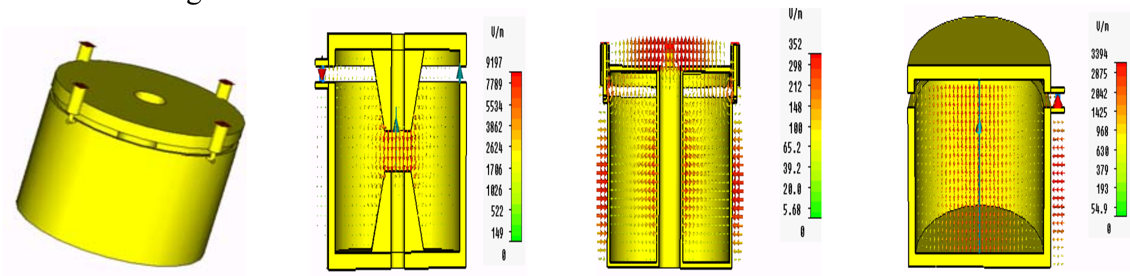


Fig 25. Several cavities with slit excited

Although, we have excited the cavity to resonance modes, there are some problems including: voltage induced in the slit, the emission waves, and surface currents. The solution for these problems is to build a secondary cavity around the slit. Building this cavity is very simple because this cavity does not need to be very sensitive and does not require a high quality factor, but it has very important roles. Some of the important roles of the secondary cavity include:

1.Reducing the voltage between the slit and the acceleration cavity
2.Improving the current on surface of the acceleration cavity
3.Increasing the electric field inside the acceleration cavity
4.Isolating the acceleration cavity with respect to the voltage shock and leakage of the electromagnetic waves
5.Improving the return loss on each port
6.Improving the isolation between ports
7.Improving the resonant frequency and avoiding the shifting
8.Reducing additional harmonics

In a nutshell, it can be noted that using the secondary cavity improves the results. In additions, several amplifier modules can be connected to the acceleration cavity using this method. The structure of the secondary cavity is such that it surrounds the amplifier modules. In this case amplifier modules should be arranged symmetrically and both the phase and the amplitude of the outputs of these modules should be synchronized. This method is tested for cylindrical and coaxial cavities with a quarter- and half-wavelength. For example for a coaxial cavity with four input ports, results of simulations on the return loss and electrical field in the acceleration cavity are shown in Fig. 26.

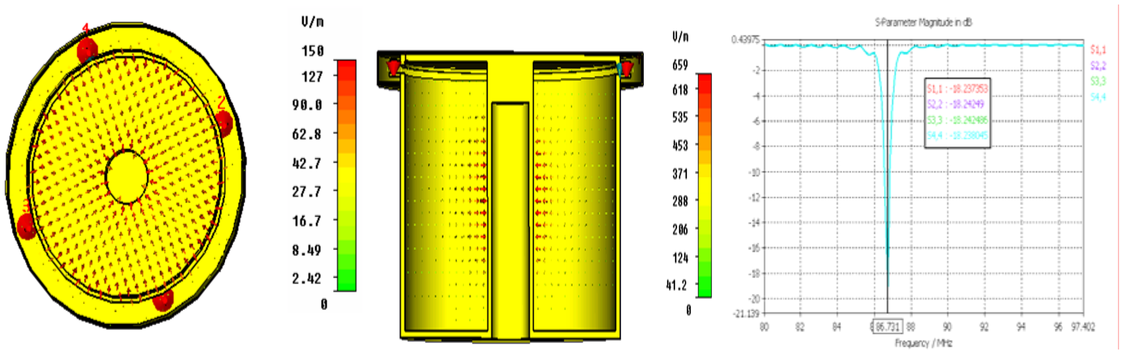
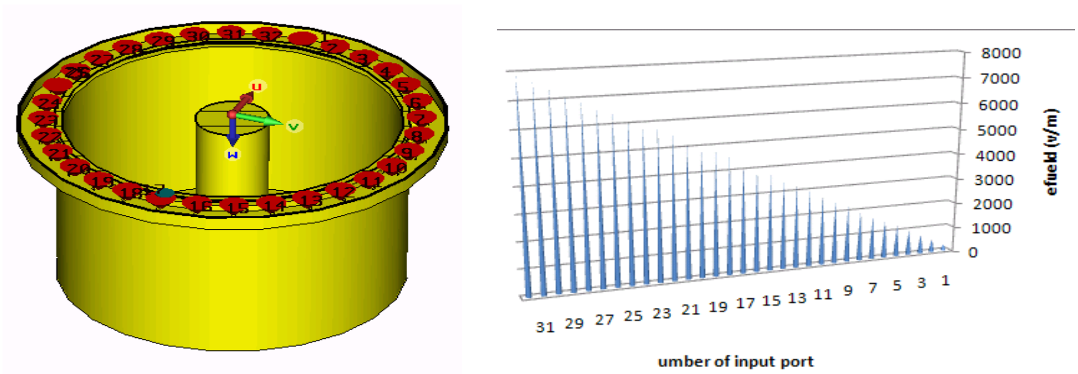


Fig 26. Return loss and electrical field calculated from numerical simulations for a coaxial acceleration cavity with direct connection of ports and using the secondary cavity.

By increasing amplifier modules, the electric field inside the acceleration cavity is increasing. We have tested an acceleration cavity with up to 180 modulus around of acceleration cavity. We should note that the effects of short (or open) circuit in the amplifier modules is also investigated. We find out that although short (or open) circuit occurs in some of the modules, especially when the number of modules are too high, it cause little or no change on impedance and power, it does not cause damage, shut down, or does not effect the overall performance of the structure. For instance, we have shown in Fig.27 an acceleration cavity with 32 one-Watt amplifier modules and also distribution of the electric field inside the cavity.



Fige 27. An acceleration cavity with 32 amplifier modules and the effect of number of modules on distribution of the electric field inside the acceleration cavity.

According to the investigation carried out for the design of a slit acceleration cavity, we summarize from the results that a slit cavity can be used to design and build new accelerators. For instance, Fig. 28 shows a new designed accelerator using this concept and the solid state amplifier with a structure similar to that of a Rhodotron accelerator.

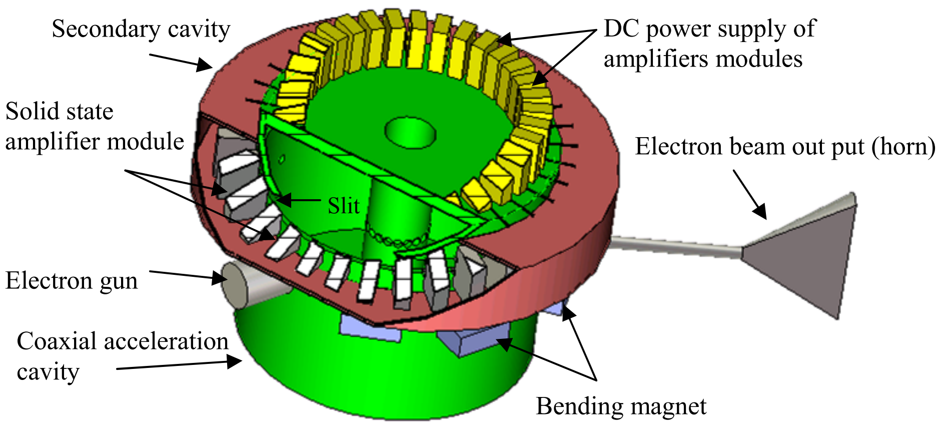


Fig 28. The new designed accelerator designed including solid state amplifier and slit cavity concepts.

The new designed accelerator has many advantages including:

1.This design is a transistor-based accelerator and has a modular structure which is easy to maintain.

2.This accelerator is built considering native technology and available facilities.

3.The structure of this accelerator is such that the acceleration cavity also plays the role of a power combiner.

Thus, this accelerator does not require the transmission lines, power combiners, or a loop coupler. Considering that this accelerator is a transistor-based accelerator, therefore it does not require high voltage and does not deal with risks associated with high voltage. Regardless of its small volume, it provides high power and is quite economical.

Conclusion

In this dissertation, we have reviewed various accelerators and found out that industrial electron accelerators have been used extensively in modern industry in which RF systems have an important role. Among industrial electron accelerators, Rhodotron accelerator as one of the most powerful accelerators is considered in this dissertation. Here, we have studied principles of performance of RF accelerators and have analyzed and simulation their different components.

The Rhodotron accelerators work with RF vacuum tubes which have many problems associated with the tube-based systems. Considering many advantages of solid state amplifiers, we have proposed methods and studied the methodology to replace RF vacuum tube systems with transistor systems. Finally, we have designed a new high power industrial accelerator based the solid state and slit cavity technology. The new design is compatible with the native technology and is feasible with the available and local facilities. Additionally, it is small in volume, has low manufacturing costs, and easy to maintenance.

ԱՄՓՈՓԱԳԻՐ

Մեծ հզորություն ունեցող ռադիոհաճախականային (ՌՀ) համակարգերը լայն կիրառում են ստացել տարբեր արդյունաբերա-արտադրական տեխնոլոգիաներում, ինչպիսիք են նյութերի չորացումը, սինթեզումը, սթերիլիզացումը, պլազմային մշակումը և այլն: Այս կիրառումների շարքում առանձնահատուկ տեղ են կազմում արդյունաբերական արագացուցիչները, որոնք խիստ անհրաժեշտ են թե' արտադրություններում, թե' բժշկության ոլորտում:

Արդյունաբերական արագացուցիչների լայն կիրառման համար պետք է ապահովվեն նրանց բարձր տեխնիկա-տնտեսական բնութագրերը՝ անվտանգությունը, խելամիտ և մատչելի գինը, փոքր չափսերը, սպասարկման պարզությունը և տնտեսական նպատակահարմարությունը: Նշված պահանջների ապահովման գործընթացում գլխավոր դերը պատկանում է հզոր ՌՀ համակարգին, որի բնութագրերը գլխավորապես որոշում են արագացուցչի հնարավորությունները: Ուստի խիստ արդիական է դառնում արդյունաբերական արագացուցիչների ՌՀ համակարգերի, ինչպես նաև նրանց բաղադրամասերի, օպտիմալացումը և կառուցման նոր ուղիների որոնումն ու հետազոտումը:

Ատենախոսությունում մանրամասն ուսումնասիրվել են Rhodotron տիպի արդյունաբերական արագացուցիչների ՌՀ համակարգերը: Հետազոտվել են էլեկտրոնային թնդանոթի, ՌՀ ռեզոնատորի և գրգռիչների օպտիմալացման ուղիները, մշակվել են նրանց կառուցվածքները:

Կատարվել են խորը հետազոտություններ, ուղղված ՌՀ համակարգերը ամբողջությամբ կիսահաղորդչային բաղադրամասերով իրականացնելու հնարավորությանը և առաջարկվել է սկզբունքորեն նոր՝ էլեկտրավակուումային լամպերից զերծ համակարգ: Ստացվել են հետևյալ նոր գիտական արդյունքները

1. Ցույց է տրվել, որ բարձր բարորակությանը և բեռնված իմպեդանսի հասնելու համար, անհրաժեշտ է արագացուցիչներում կատարել՝ լայն կիրառություն գտած կոաքսիալ ռեզոնատորների ձևափոխություն, տալով նրանց «թիթեռնիկի» տեսք: Գտնված են օպտիմալ ձևափոխության հարաբերությունները:
2. Առաջին անգամ առաջարկվել է Rhodotron արագացուցիչներում կիսալիք երկարությամբ կոաքսիալ ռեզոնատորը փոխարինել լիալիքային ռեզոնատորով: Ցույց է տրվել, որ համապատասխան ձևափոխությունների արդյունքում ապահովվում է հետադարձ կորուստների ավելի ցածր մակարդակ: Նաև, ցույց է տրվել, որ աղբյուրի և ռեզոնատորի միջև լավագույն կապը ապահովվում է դաշտի մագնիսական բաղադրիչի միջոցով, և, որ կապի էլեմենտի օպտիմալ տեսքը՝ ուղղանկյունն է:

3. Հաստատվել է, որ էֆեկտիվությունը բարձրացնելու համար անհրաժեշտ է, որպեսզի էլեկտրոնային թնդանոթը լինի հետադարձ կապով միացված ՌՀ փուլակառավարման շղթային:
4. Առաջարկվել և հետազոտվել է Rhodotron արդյունաբերական արագացուցչի ռեզոնատորի սկզբունքորեն նոր կառուցվածք, որը թույլ է տալիս էֆեկտիվորեն գումարել բազում համափուլ աղբյուրների դաշտերը: Ռեզոնատորը իրենից ներկայացնում է մոդիֆիկացված կոաքսիալ կառուցվածք, որում արտաքին գլանի և ռեզոնատորի կողաճակատի միացման մասում կազմավորված է օղակաձև ճեղք: Ռադիացիոն կորուստների կանխարգելման նպատակով ճեղքը բեռնված է կարճ միացում իրականացնող օղակաձև շլեյֆով, որի միջով անցնում են յուրաքանչյուր աղբյուրից եկող կապի տարրերը:

Ստացված արդյունքների կիրառական նշանակությունը՝
1. Արդյունաբերական Rhodotron տիպի արագացուցիչների ՌՀ համակարգի բաղադրամասերի՝ էլեկտրոնային թնդանոթի, ռեզոնատորային կառուցվածքի և նրա սնուցման օպտիմալացման համար առաջարկված եղանակների կիրառումը թույլ է տալիս էականապես բարձրացնել արագացուցիչների էֆեկտիվությունը և բարելավել տեխնիկական բնութագրերը:
2. Մշակված էլեկտրադինամիկական նոր կառուցվածքը ապահովում է աղբյուրների բարձրակարգ կապազերծումը, բացառում է բարձր հզորության արտաքին գումարիչների անհրաժեշտությունը և, որպես արդյունք, թույլ է տալիս Rhodotron տիպի արագացուցչի իրականացումը լիովին պինդմարմնային ուժեղարարների վրա բացառելով ՌՀ հզոր էլեկտրավակուումային աղբյուրների անհրաժեշտությունը:
3. Առաջարկված՝ երկրորդ լրացուցիչ օղակաձև ռեզոնատորով կոաքսիալ ռեզոնատորի ճեղքի շրջապատման եղանակը հանգեցնում է մի շարք կարևոր կիրառական նշանակության արդյունքների.
    - Նվազեցվում է լարման անկումը ճեղքի մեջ բացառելով էլեկտրական ծակման վտանգը
    - Բարձրացնում է ռեզոնատորի էլեկտրական դաշտի լարվածությունը, լավացնելով էլեկտրոն-դաշտ փոխազդեցությունը
    - Ռեզոնատորում ճնշվում են խանգարող բարձր մոդերը
    - Բարելավվում են անդրադարձման կորուստները և կապազերծումը յուրաքանչյուր մուտքից:

АННОТАЦИЯ

Радиочастотные (РЧ) системы высокой мощноости нашли широкое применение в различных промышленных технологических процессах, таких как сушка и синтез материалов, плазменных обработках и т.д. В ряду таких систем особое место занимают промышленные ускорители, которые крайне необходимы как в производствах и обработках, так и в медицинских областях.

Для широкого применения промышленных ускорителей необходимо обеспечить их высокие технико-экономические характеристики: безопасность, разумная стоимость, небольшие габариты, несложное обслуживание и экономическая целесообразность. Главную роль в деле обеспечения указанных требований принадлежит мощным РЧ системам, параметры которых, в основном, обуславливают возможности ускорителя. Следовательно, актуальной является задача оптимизации РЧ систем в целом и его составных частей, а также поиск и исследование принципиально новых путей их построения.

В диссертационной работе подробно исследована РЧ система промышленного ускорителя типа Rhodotron. Исследованы пути оптимизации электронной пушки, РЧ резонаторов, элементов связи и разработаны их конструкции.

Проведены глубокие исследования, направленные на поиск возможности построения РЧ системы целиком на полупроводниковых компонентах, и предложена принципиально новая структура, исключающая необходимость электровакуумных мощных ламп.

Получены следующие научные результаты:

1. Показано, что для достижения высокой добротности шунтирующего импеданса необходимо видоизменить геометрию нашедшего широкое применение в ускорителях коаксиального резонатора, придав ему форму “бабочки”. Найдены оптимальные соотношения преобразования.
2. Впервые для ускорителей типа Rhodotron предложено заменить полуволновый коаксиальный резонатор на целоволновой резонатор. Показано, что в результате соответствующих изменений увеличивается эффективность взаимодействия РЧ поле – электронный пучок и уменьшаются потери на отражение. Определено, что оптимальную связь с резонатором обеспечивает элемент связи на магнитной компоненте в виде прямоугольной петли.

3. Найдено, что для увеличения эффективности необходимо, чтобы электронная пушка имела обратную свяязь с системой фазовой подстройки.
4. Предложена и исследована принципиально новая структура резонатора промышленного ускорителя типа Rhodotron, которая позволяет эффективно суммировать поля множества синфазных источников. Резонатор представляет собой модифицированный коаксиальный резонатор, разрезанный в области соединения внешнего цилиндра с торцом. Для предотвращения радиационных потерь образованная щель нагружена на кольцевой шлейф, через который проходят элементы связи от каждого источника.

Прикладное значение полученных результатов следующее:

1. Применение предложенных методов оптимизации РЧ системы промышленных ускорителей типы Rhodotron и таких его составных частей как электронная пушка, резонаторная структура и элементы связи, позволяют значительно повысить эффективность ускорителей и улучшить их характеристики.
2. Разработанная новая электродинамическая структура обеспечивает высокую развязку между источниками, исключает необходимость в внешних сумматорах высокой мощности и, как следствие, позволяет построение ускорителей типа Rhodotron целиком на транзисторных усилителях, тем самым исключая необходимость в мощных вакуумных лампах.
3. Предложенный метод покрытия щели в коаксиальном резонаторе вторичным кольцевым резонатором приводит к ряду практически важных результатов:

- Уменьшается падение напряжения в щели, тем самым исключается опасность пробоя.
- Увеличивается напряженность электрического поля в основном резонаторе, улучшая взаимодействие с электронным пучком.
- Подавляются паразитные высшие моды резонатора.
- Улучшаются развязка и потери на отражение от каждого из источников.

FOR NOTES

FOR NOTES