RO & Particles accelerators

Romanian Electron Linear Accelerators
Engineering & Applications

Marian Toma

SUMMARY

- INTRODUCTION
- ALIN-10 AND ALID-7 ELECTRON LINACS
- ALIN-10 AND ALID-7 ELECTRON BEAM CONTROL METHOD
- COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

INTRODUCTION

- The features of industrial electron linear accelerators (linacs) are of critical importance to permit:
  - efficient energy utilization,
  - reliable operation,
  - beam parameters stability,
  - absorbed dose rate determination,
  - measurement and control of beam characteristics.

INTRODUCTION

- Several linac models were designed and built at the Accelerators Laboratory of the National Institute for Lasers, Plasma and Radiation Physics (NILPRP) – Bucharest (Romania) which may be used in conjunction with microwave sources of 2.45 GHz in order:
  - to carry out the research in the radiation processing field,
  - to develop radiation technologies and to provide small-scale commercial irradiation services.

INTRODUCTION

- ALIN-10 and ALID-7, of up to 10 MeV will be presented including their main characteristics and the principal applications that were developed during the past and recent research activities carried out in the laboratory under the framework of national research programs.
- The combined effects of electron beam irradiation and microwave heating in material processing, will be discussed.

INTRODUCTION

- Radiation processing provides many advantages over conventional processes in terms of:
  - product properties,
  - large processing temperature range,
  - environmental protection.

INTRODUCTION

- Linacs are best suited for radiation processing needs due to their:
  - high irradiation power,
  - easy beam deflection,
  - flexible and accurate operation by easy adjustment of the electron beam current,
  - high security in use due to radiation absence when the machine is stopped,
  - no high voltage arching,
  - no pollution from radioactive waste,
  - good conversion factor for X-ray beam production.

INTRODUCTION

- The treatment of important volumes with the required dose, with a convenient speed of passage is now permitted thanks to the several centimeters penetration of the electrons up to 10 MeV.
- Additionally, by combining the ionization effects of accelerated electron beam (EB) and heating effect of microwaves (MW) new promising results in the material-processing field were obtained.

ALIN-10 AND ALID-7 LINACS

- In the Accelerators Laboratory of the National Institute for Lasers, Plasma and Radiation Physics – Bucharest, the first traveling-wave electron linac, AL-3 of 3 MeV, was built in 1965 and has been in operation until 1978.
- Years of research combined with engineering activities have culminated in the development of two electron linacs of higher energy: ALIN-10 in 1977 and ALID-7 in 1982 which have been in successful operation with several improvements until now.

ALIN-10 AND ALID-7 LINACS

- ALIN-10, as a research installation, positioned horizontally inside the irradiation room, is equipped with a post-acceleration beam focusing and bending to direct accelerated EB either on the accelerating structure axis (through a horizontal vacuum window exit port) or at right angles to the accelerator structure (through a vertical vacuum window exit port). ALIN-10 is currently used to develop new technologies in the field of environment remediation, material processing, biomedicine and medical studies.

ALIN-10 AND ALID-7 LINACS

- ALID-7 as industrial equipment, was initially designed and optimized to produce maximum X-ray output for nondestructive testing.

ALIN-10 AND ALID-7 LINACS

- Due to the ever growing ecological problems, this linac was then used for applied radiation research and test installation for:
  - monomer mixture polymerization,
  - rubber mixture vulcanization,
  - acid gases and volatile organic compounds removal,
  - depreciated food, residual water and sludge decontamination,

and small-scale commercial irradiation services like:

  - polyelectrolyte's preparation for waste and potable water treatment,
  - sterilization of plastic plates with agarose gel used for electrophoresis and other applications.

ALIN-10 AND ALID-7 LINACS

- Both ALIN-10 and ALID-7 are of traveling wave type, driven by 2 MW peak power tunable EEV M5125 type magnetrons (English Electric Valve Company Ltd.) operating in S-band (2992 to 3001 MHz). Fig. 1 and Fig. 2 show the schematic drawing of ALIN-10 and ALID-7, respectively. Fig. 3 and Fig. 4 present the photographs of ALIN-10 and ALID-7, respectively.

ALIN-10 AND ALID-7 LINACS

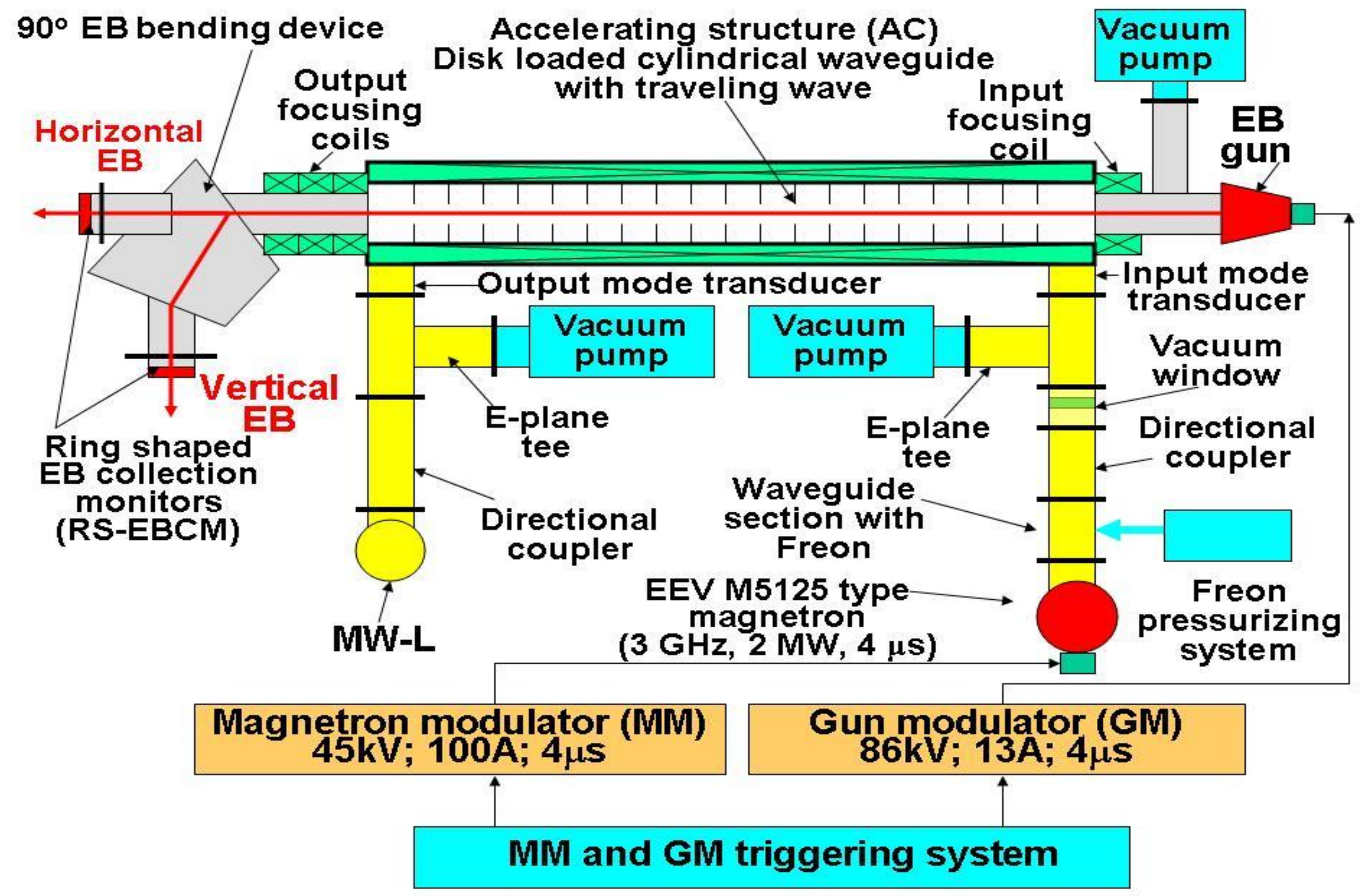


Fig. 1- ALIN-10 schematics

ALIN-10 AND ALID-7 LINACS

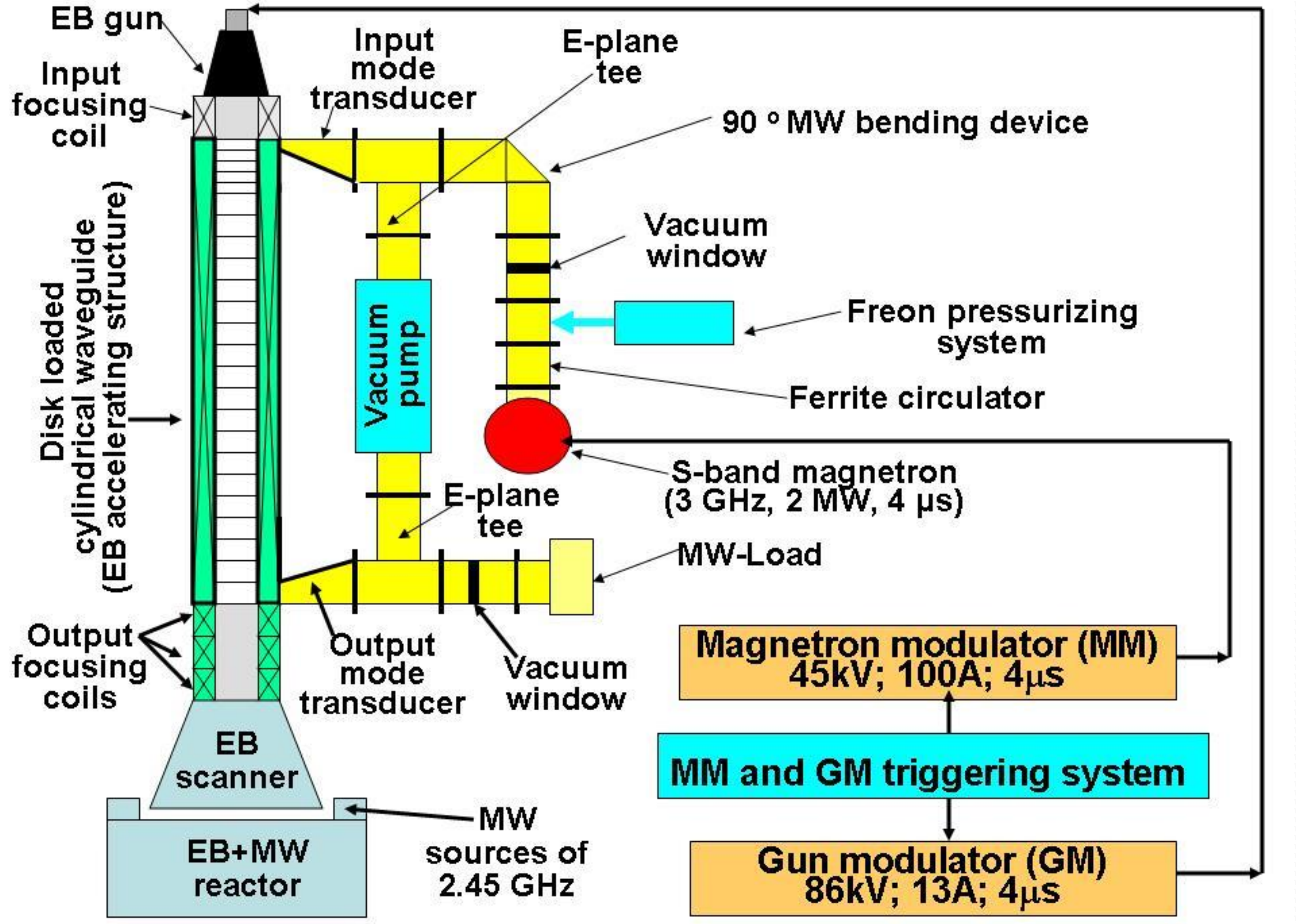


Fig. 2 ALID-7 schematics

ALIN-10 AND ALID-7 LINACS

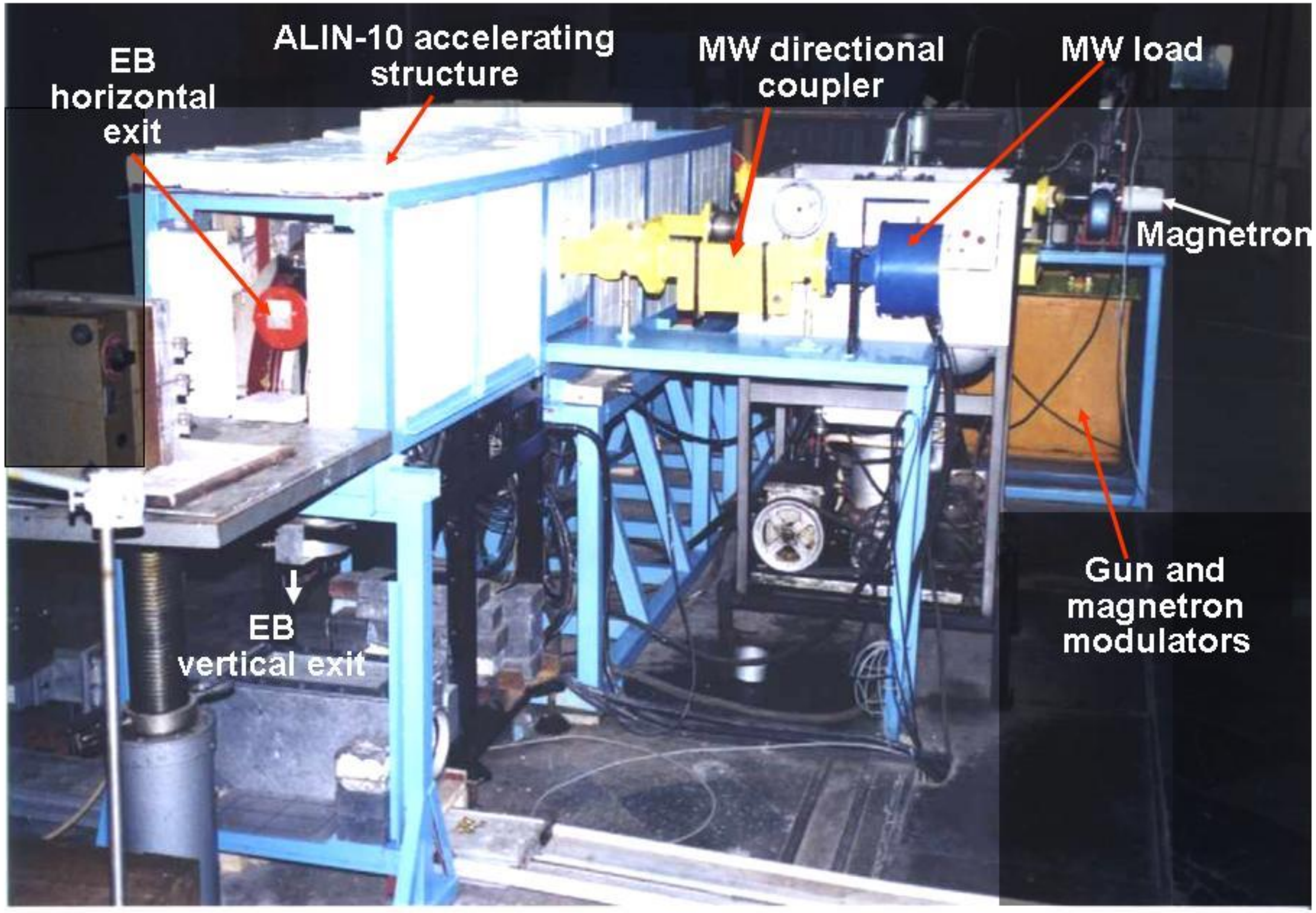


Fig. 3 ALIN-10

ALIN-10 AND ALID-7 LINACS

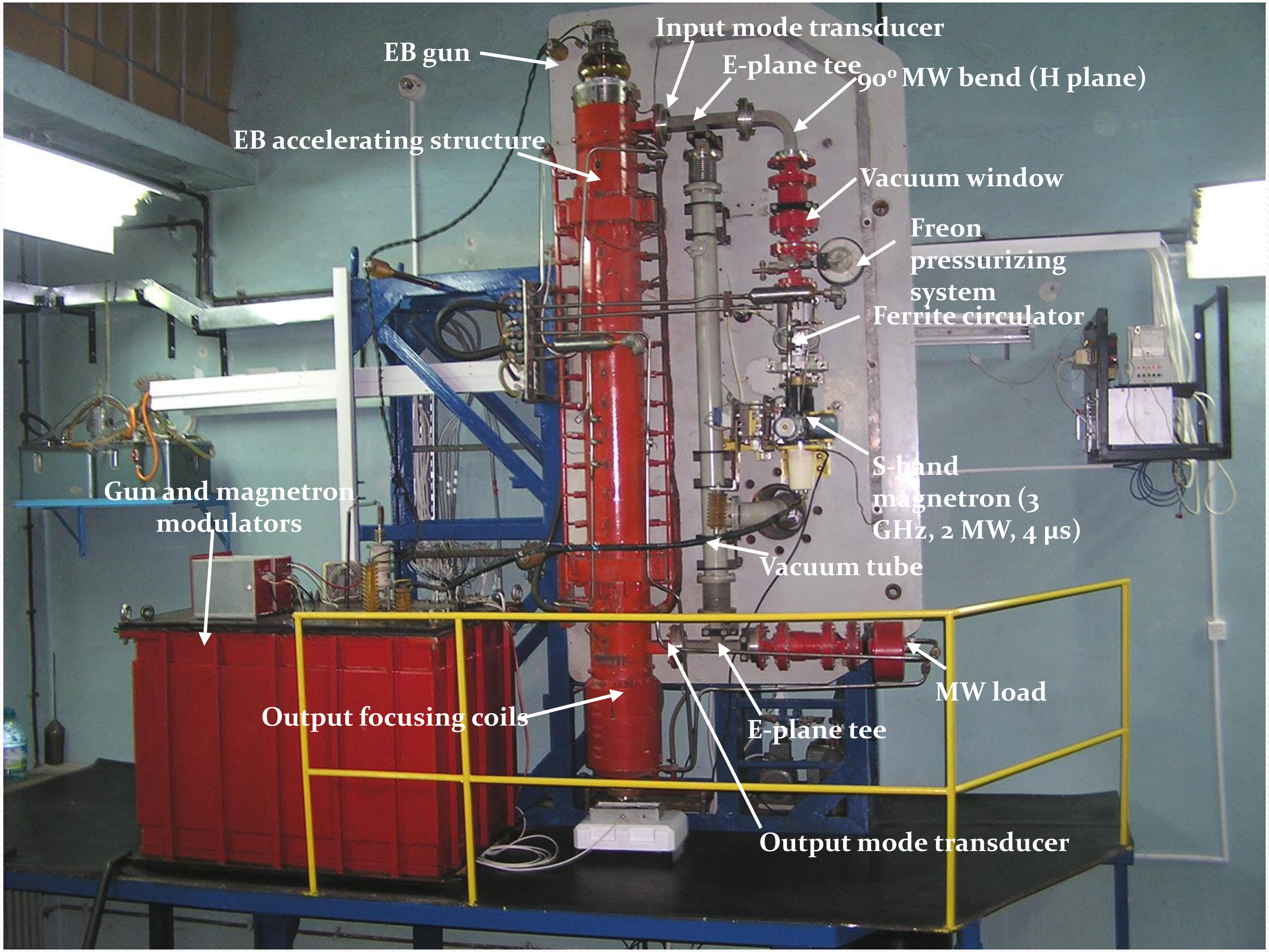


Fig. 4 ALID-7

ALIN-10 AND ALID-7 LINACS

- The electrons are injected from a diode type gun at a voltage of 70 kV and travel through the accelerating structure (AC), a disk-loaded cylindrical waveguide operating in the $\pi/2$ mode.
- The first portion of the accelerating structure is a variable phase velocity buncher and the remainder has a uniform section. The electromagnetic wave energy not absorbed by the beam is dissipated in a high power microwave load.

ALIN-10 AND ALID-7 LINACS

- The input microwave power is introduced in the first cavity of the AC by means of an input mode transducer from TE_{01} mode of the rectangular waveguide (WR284 type) to TM_{01} mode of the iris-loaded circular waveguide. The output power is also extracted from the AC output cavity by an output mode transducer from TM_{01} to TE_{01}.
- The accelerating structures are pumped in the vicinity of 10^{-6} mbar by means of two properly modified E-plane tees. The input and output pressure windows are interposed between these components and those under high pressure.

ALIN-10 AND ALID-7 LINACS

- A rectangular waveguide section is provided with a Freon injection system for pressurizing and cooling of the output magnetron window.
- Two directional couplers are provided (in the ALIN-10 case) for monitoring of the AC input and output microwave power. All microwave units were sealed in order to work under high pressure or high vacuum and thus to avoid voltage breakdown.
- Excepting some special components, like magnetrons and ferrite isolators, all microwave components are built in the laboratory.

ALIN-10 AND ALID-7 LINACS

- Several of them, such as high power MW load (MW-L) and MW pressure windows (MW-PW) were of original design at that time (1965). MW-L is a multimode right circular cavity (200 mm diameter and 60 mm length) filled with a high loss dielectric (silicon carbide disk of 200 mm diameter and 25 mm length).
- The WR284 waveguide is directly coupled to the upper end wall of the multimode cavity by an aperture having the same shape and size as the cross-section of the exciting line. The number of excited modes coupled by the loss element is an important factor for less frequency sensitivity of the cavity.
- The matching was obtained by a properly correlation of the geometrical parameters which are present themselves naturally in the dissipative loaded: the cavity diameter D, the cavity length H, the geometrical position of the exciting rectangular aperture on the cavity upper end wall. These loads have a very simple construction, are compact, light, easily to tune over a broad band and, therefore, suitable for service at the end of an accelerating structure.

ALIN-10 AND ALID-7 LINACS

- The MW-PW is made by suitable modification of the output glass metal cylindrical structure retrieved from the depreciated power magnetrons. The broad band matching of this structure was obtained by using short cylindrical rectangular transitions provided with inductive elements (metallic cylinders of 3 mm diameter) symmetrically placed in the rectangular portions.
- An axial magnetic field produced by several separate focusing coils placed around the accelerator tube was used to compensate the radial forces tending to disperse the electrons, which are travelling through the acceleration structure.

ALIN-10 AND ALID-7 LINACS

- After acceleration, electrons are subjected to a succession of electromagnetic devices for beam focusing (quadrupole lens), 90° beam bending (only for ALIN-10), beam scattering in air (with scattering foils or electromagnetic device) for ALIN-10 and beam sweeping in a horn shaped vacuum chamber for ALID-7.
- Scanner geometrical parameters are: 32.2° half angle, 39.7cm height, 4 cm window width and 50 cm window length.
- Direct collection of a part of the accelerated EB is used as a monitoring method by sampling during irradiation process. In the ALIN-10 output arrangement with horizontal and vertical exit ports, the electron beam passes a ring-shaped EB collection monitor (RS-EBCM) shown in Fig. 5.
- In the ALID-7 case is used a block-shaped EB monitor (BS-EBCM) that intercepts only a fraction of the scanned EB field (Fig. 6).

ALIN-10 AND ALID-7 LINACS

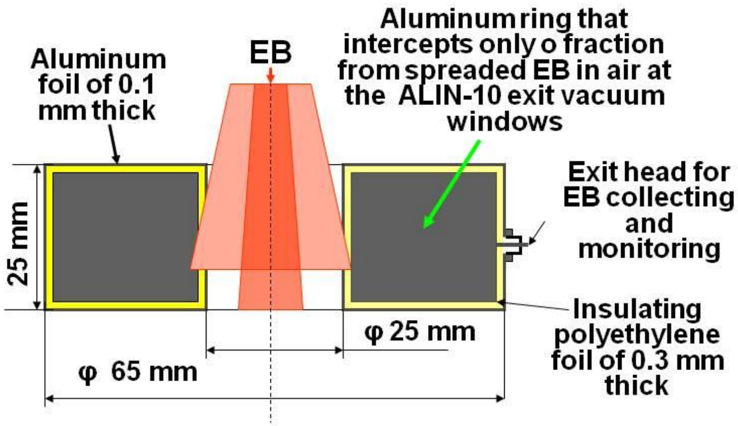


Fig. 5 Ring-shaped EB collection monitor

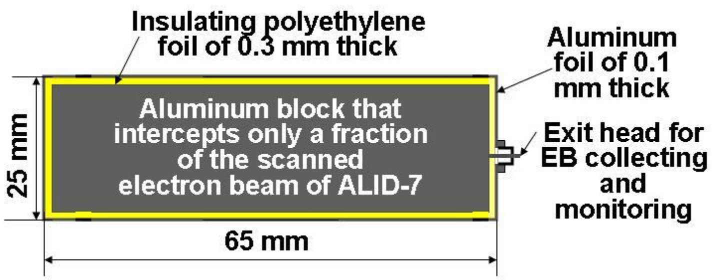


Fig. 6 Block-shaped EB monitor

ALIN-10 AND ALID-7 LINACS

- The EB collection monitors, RS-EBCM and BS-EBM that intercept only a fraction of spread or scanned EB give, together with its associated electronics instrumentation, a relative value of the EB average current (EBAC) and a relative value of EB dose rate (EBDR). The EBAC relative level has been calibrated with a modified Faraday cup (MFC presented in Fig. 7) placed at the EB exit end of the accelerators. Also, the EBDR relative level was calibrated by several dosimeter systems (such as the Chemical Ceric Dosimeter for high dose rates, Chemical Fricke Dosimeter for medium and small dose rate and Advanced Markus Chamber type 3404 used with UNIDOS Universal Dosimeter for very small dose rate used for medical studies) placed at the position where the irradiation is performed.

ALIN-10 AND ALID-7 LINACS

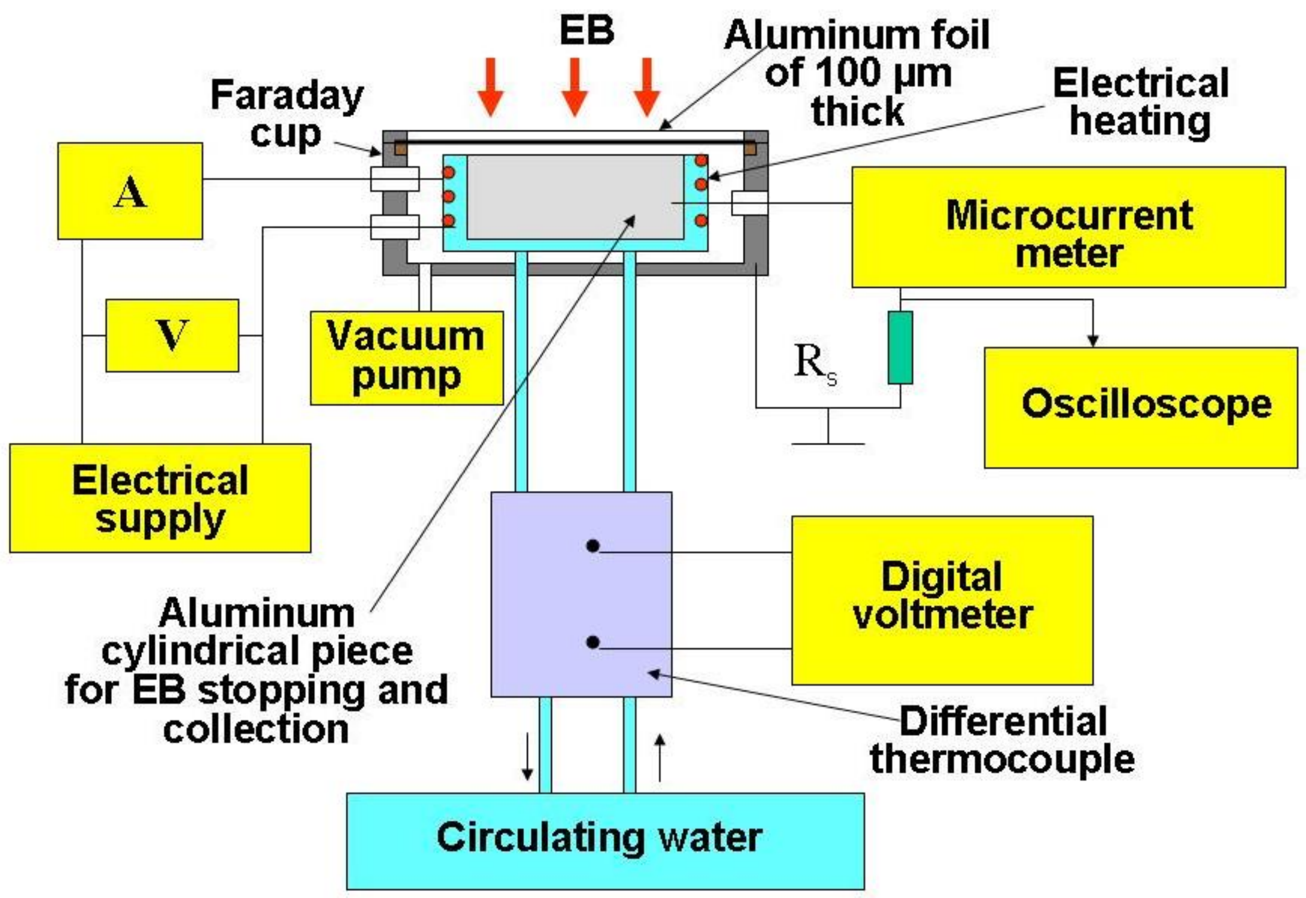


Fig. 7 Drawing of the modified Faraday cup (MFC) for simultaneous measurement of EB peak current, EB average current and EB power

ALIN-10 AND ALID-7 LINACS

- It is important to note that MFC permits simultaneous measurement of EB peak current, EB average current and EB average power by calorimetric method. The advantages claimed for the calorimetric method applied for beam loading characteristic include rapidity and simplicity of the procedure. Thus, such a method is very suitable for EB power maximization as a function of the accelerator parameters: gun voltage (U_{Gun}), magnetron voltage ($U_{Mag.}$) and magnetron frequency ($f_{Mag.}$). Figures 8 and 9 show the beam loading characteristic and beam power characteristic for ALIN-10 and ALID-7 linacs, respectively, determined by applying calorimetric method with MFC.

ALIN-10 AND ALID-7 LINACS

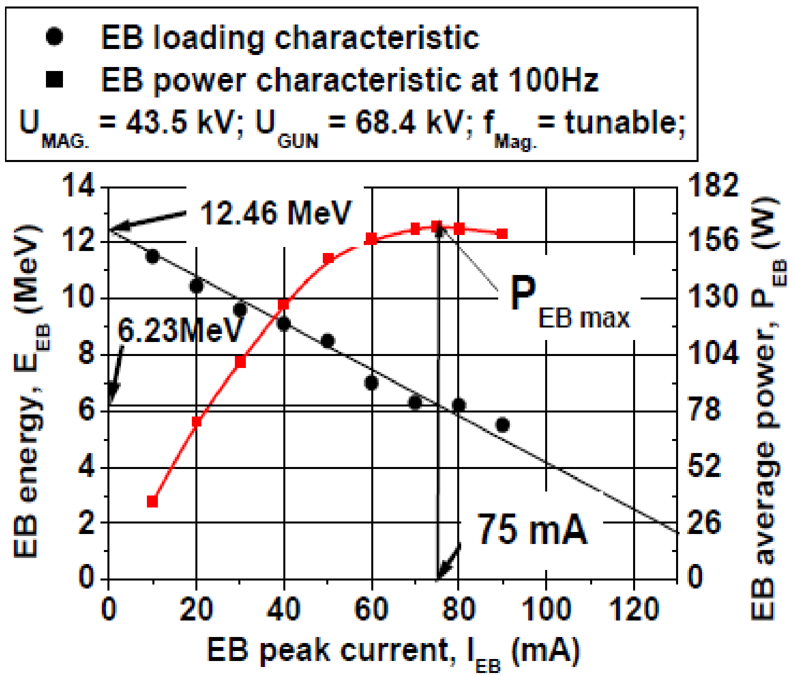


Fig. 8.Electron beam energy (E_{EB}) and electron beam power (P_{EB}) versus peak beam current for ALIN-10 accelerator

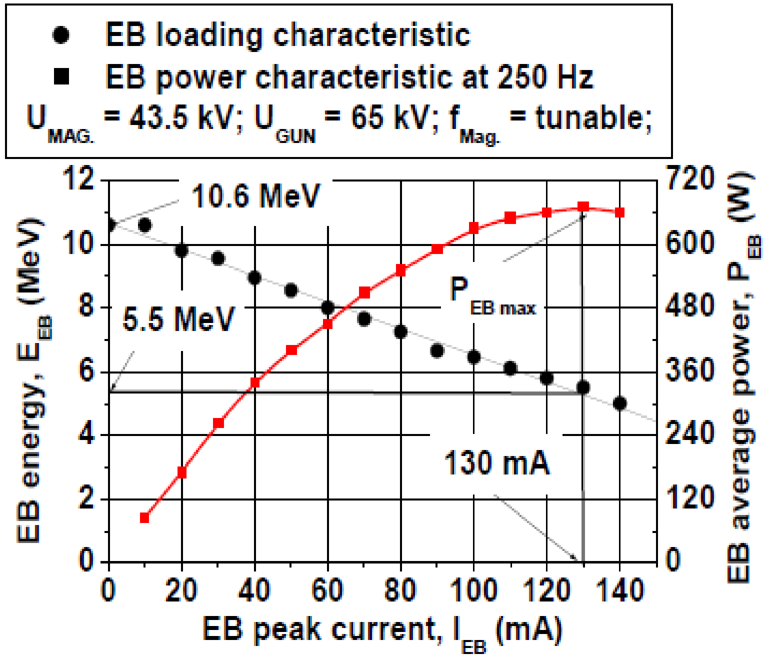


Fig. 9. Electron beam energy (E_{EB}) and electron beam power (P_{EB}) versus peak beam current for ALID-7 accelerator

ALIN-10 AND ALID-7 LINACS

- Some important physical characteristics of the beam are of great interest at the end of the accelerating process. The first is the available output power of the electron beam (P_{EB}), which represents the basic processing capability of a given electron source for a "required dose". The second characteristic is related to the energy of the accelerated EB (E_{EB}), which determines the depth to which EB will penetrate the product. Figs. 8 and 9 demonstrate that the optimum values of the EB peak current I_{EB} and EB energy E_{EB} to produce maximum output power P_{EB} for a fixed pulse duration τ_{EB} and repetition frequency f_{EB} are as follows:
- ALIN-10: E_{EB} = 6.23 MeV; I_{EB} =75 mA; P_{EB} = 164 W (f_{EB} = 100 Hz, τ_{EB} = 3.5 μs)
- ALID-7: E_{EB} = 5.5 MeV; I_{EB} =130 mA; P_{EB} = 670 W (f_{EB} = 250 Hz, τ_{EB} = 3.75 μs)

ALIN-10 AND ALID-7 BEAM CONTROL METHOD

- In order to permit reliable operation, flexibility and stability of EB parameters, features of critical importance for research and semi-pilot scale level application of the separate and combined EB and MW irradiation, the ALIN-10 and ALID-7 linacs were equipped with a special designed EB control system (EB-CS) for obtaining programmed single electron beam shots and pulse trains, with desired pulse number, pulse repetition frequency and pulse duration by discrete pulse temporal position modulation of the gun electron pulses and magnetron microwave pulses.

ALIN-10 AND ALID-7 BEAM CONTROL METHOD

- The accelerated EB existence at the accelerator exit window is determined by the electron gun and magnetron pulses overlapping. The method consists in controlling gun and magnetron pulses overlapping in order to deliver the accelerated EB in the desired sequences. A schematic diagram of this kind of modulation applied to the gun pulses and some temporal distributions of the electron beam is presented in Fig. 10.

ALIN-10 AND ALID-7 BEAM CONTROL METHOD

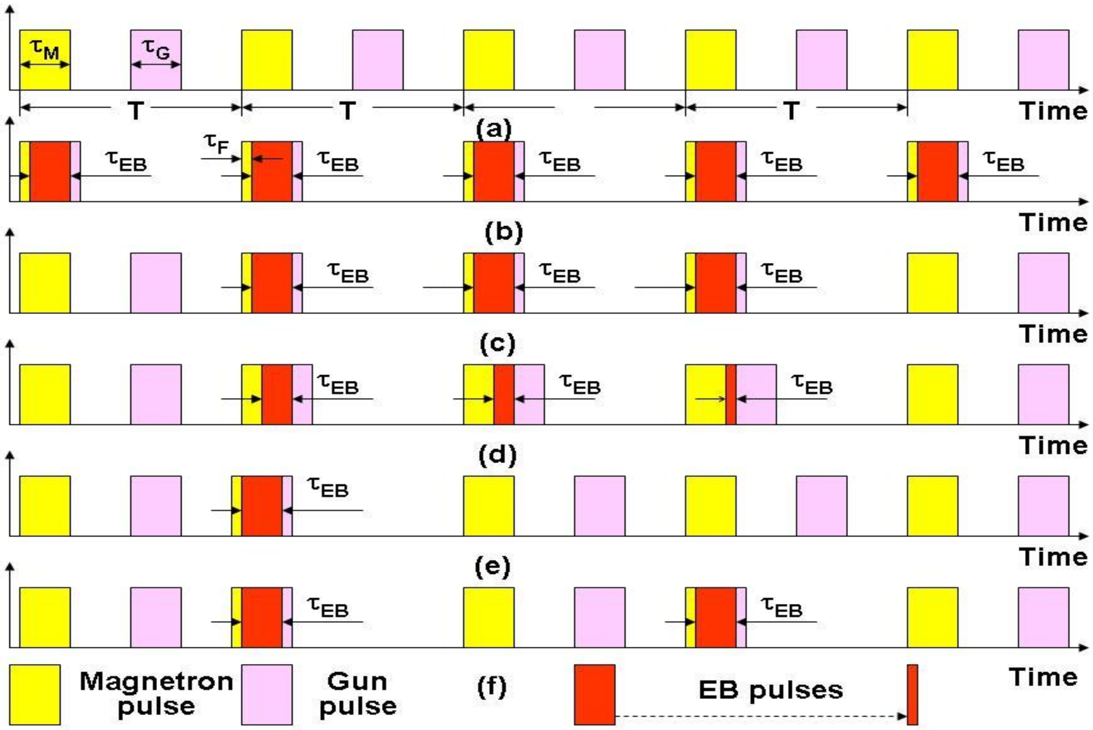


Fig. 4: Schematic diagram of the discrete pulse temporal position modulation method applied to the gun pulses and some temporal distributions of EB pulses
(a) magnetron and gun pulses are shifted (no accelerated EB); (b) M and G pulses are overlapped (accelerated EB start); (c) 2nd, 3rd an 4th G pulses are shifted to overlap with the corresponding M pulses (three accelerated EB are delivered); (d) 2nd, 3rd an 4th G pulses are partially shifted to overlap with corresponding M pulses (three accelerated EB with different duration are delivered); (e) 2nd G pulses is shifted to overlap a single M pulse (single accelerated EB pulse is delivered); (f) 2nd, 4th, 6th, etc. G pulses are shifted to overlap the corresponding M pulses (EB repetition period is 2T)

ALIN-10 AND ALID-7 BEAM CONTROL METHOD

- To implement the above mentioned method, two separate modulators are provided: a gun modulator (GM) and a magnetron modulator (MM) as shown in Figs, 1 and 2. The EB-CS, which synchronizes all the system units, delivers trigger pulses at a programmed repetition rate (up to 100 Hz for ALIN-10 and up to 250 Hz for ALID-7) to the GM and MM. For no gun and magnetron pulses overlapping, no accelerated electron beam results at the output (Fig. 10a). The instabilities of the gun and magnetron transitory regimes are avoided by operating the accelerator with no accelerated beam for a certain time. At the operator "beam start” command, EB-CS controls electron gun and magnetron pulses overlapping and the accelerated EB is generated (Fig. 10 b). The pulse-to-pulse absorbed dose variation is thus considerably reduced.

ALIN-10 AND ALID-7 BEAM CONTROL METHOD

- The proportion of filling-time electrons and thus electrons energy dispersion, may be reduced to some extend by arranging the electron gun to trigger at some optimum time (accelerating structure filling time τ_F) after the beginning of each magnetron pulse (Fig. 10b). Thus, gun modulator pulses are shifted by τ_F with respect to the leading edge of the magnetron modulator pulses. Also, an EB with a controlled number of pulses (three in Fig. 10c and single pulse in Fig. 10e) or with a controlled repetition period (2T in Fig. 10f) may easily be obtained by this electron gun and magnetron triggering method.

ALIN-10 AND ALID-7 BEAM CONTROL METHOD

- Programmed absorbed dose, irradiation time, beam pulse number or other external events may interrupt the coincidence between the gun and magnetron pulses and the irradiation regime. The beam pulse duration may be continuously adjusted from 0.25 μs to τ_M-τ_F, where τ_M is the magnetron pulse length and τ_F is the acceleration structure filling time (Fig. 10d). The short pulses duration is limited only by the values of the gun pulse leading edge and of the magnetron pulse trailing edge. Slow absorbed dose variation is compensated by the control of the triggering pulse repetition frequency as well as by magnetron and gun pulses overlapping.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- From the results obtained by basic studies and pilot plant tests, irradiation with EB was put forth as a very effective method for material processing because can induce chemical reactions at any temperature in the solid, liquid and gas phase without using catalyst.
- The feature of inducing chemical reactions at room temperature brings unique advantages of ionizing radiation processing for industries but the radiation doses required are generally too high.
- Low irradiation doses are required for the process efficiency and a high dose rate must be used to give large production capacities. Thus, for industrial scale processing, the problem of reducing the electrical energy consumption as well as the electron beam cost is especially important.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The MW processing of materials is a relatively new technology that provides new approaches to improve the physical properties of materials and to produce new materials and microstructures that cannot be achieved by other methods. The frequency range of microwave (300 MHz - 300 GHz) corresponds to quantum energy ($W=h\nu$, where h is Planck's constant and ν is radiation frequency) which are small (1.2 $\mu eV \leq W \leq 1.2$ meV) as compared to the ionizing radiation. Hence MW cannot interact with atoms by transition between principal energy levels, e.g. between a base state and an excited state.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The application of microwave in a wide range of areas, including chemical processing, utilizes classical interaction of electromagnetic radiation with matter such as dielectric heating in solids and liquids. The advantages of the use of MW and MW systems can be summarized as follows:
  - rapid energy transfer;
  - volumetric and selective heating;
  - very high heating rate;
  - convenient and clean heating;
  - fast switch on and off;
  - clean environment, free from products of combustion;
  - compact equipment;
  - the microwave system cools very rapidly when the field is switched off.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The comparative analysis of the application of the EB irradiation and MW heating to the material-processing field led to the following main conclusions:
  - The EB processing uses the Coulomb interaction of the accelerated electrons with atoms or molecules of the gases, liquids or solids. By this interaction ions, thermal electrons, excited states and radicals are formed and thereby the chemical reactions are driven;
  - The MW processing (dielectric heating) uses the ability of some liquids and solids to transform electromagnetic energy into heat and thereby the chemical reactions are driven. The magnitude of electromagnetic energy conversion depends on the properties of molecules. This allows some control of the material's properties and may lead to reaction selectivity.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The general conclusion of reported results is that both EB processing and MW processing are based on the electromagnetic radiation ability to alter the physical and chemical properties of a material. Thus, effects of interaction of nonionizing and ionizing electromagnetic radiation with matter are of widespread interest and have broad commercial applications.
- The final comparison is between the two heating methods: conventional and microwave. Here, the use of conventional heating requires a significantly longer time than microwave heating. Also, with microwave heating and its concurrent deep penetration, superior results can be obtained.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The main goal of this work was to combine the advantages of both, EB and MW, i.e. the very high efficiency of EB processing with MW high selectivity and volumetric heating, in order to reduce the required absorbed dose level and irradiation time, and thus to decrease the material processing costs. This idea was suggested by the observation that both, accelerated electron beams and microwaves, in their separate passage through matter, produce by different physical action principles, the same final effects, such as: polymerization of monomer/oligomer systems, cross linking, grafting and degradation of polymers, degradation of pollutants in air or water, food preservation, sterilization of medical supplies, decontamination of sewage sludge, the extraction of sulfur and nitrogen oxides from combustion gases by induced non-thermal plasma processes, etc.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- However, there is a fundamental difference between the EB (ionizing radiation) and MW (nonionizing radiation) in their interaction with matter: EB interacts with matter by the same physical mechanisms (basically, Coulomb interaction with electrons in inorganic and organic materials generating excitation and ionization) at any matter state (solid, liquid and gas phase) and matter temperature while MW interacts with matter by different physical action principles as a function of matter state and temperature, MW frequency and polarization, environmental factors (temperature, humidity), samples volume and geometry, MW applicator types etc.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The presented aspects suggest that by combining the ionization effects of accelerated EB and heating effect of MW it could be possible to obtain new and promising results in the material-processing field. The first expected and obtained result was the decrease of the required EB absorbed dose. Thus, the ionizing radiation costs could be decreased and the application of low intensity EB sources, which are less expensive, will become economically attractive in the material-processing field.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- Also, it was expected that by combined EB and MW treatment to decrease the average microwave power level while keeping the material temperature increasing as low as possible. The last expected and obtained result was the improvement of material properties. The effects of combined EB and MW irradiation were investigated for the following material processes: polymerization of monomer mixtures in aqueous solutions, vulcanization of rubber mixtures, removal of nitrogen oxide, sulfur dioxide and volatile organic compounds from flue gases, biological decontamination of waste water, sludge, depreciated food, and more.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- Many experimental models of combined electron beam and microwave irradiation facilities (CEBMIF) were built in our laboratory. Here will be presented as representative example a semi-pilot installation, named SPI-EB+MW, that was built for the comparative studies of material processing (monomers mixture polymerization, depreciated food decontamination, etc.) using separate and combined (successive and simultaneous) EB irradiation and MW heating (Figs. 11 and 12). The SPI-EB+MW consists mainly of the following units:
- An EB source (ALID-7 electron linear accelerator of 5.5 MeV and 670 W maximum output power);
- A multimode rectangular cavity, MRC, of 0.612 m x 0.612 m x 0.367 m inner dimensions, in which are injected both EB and MW;
- A conveyor which moves the vessels with samples through MRC.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

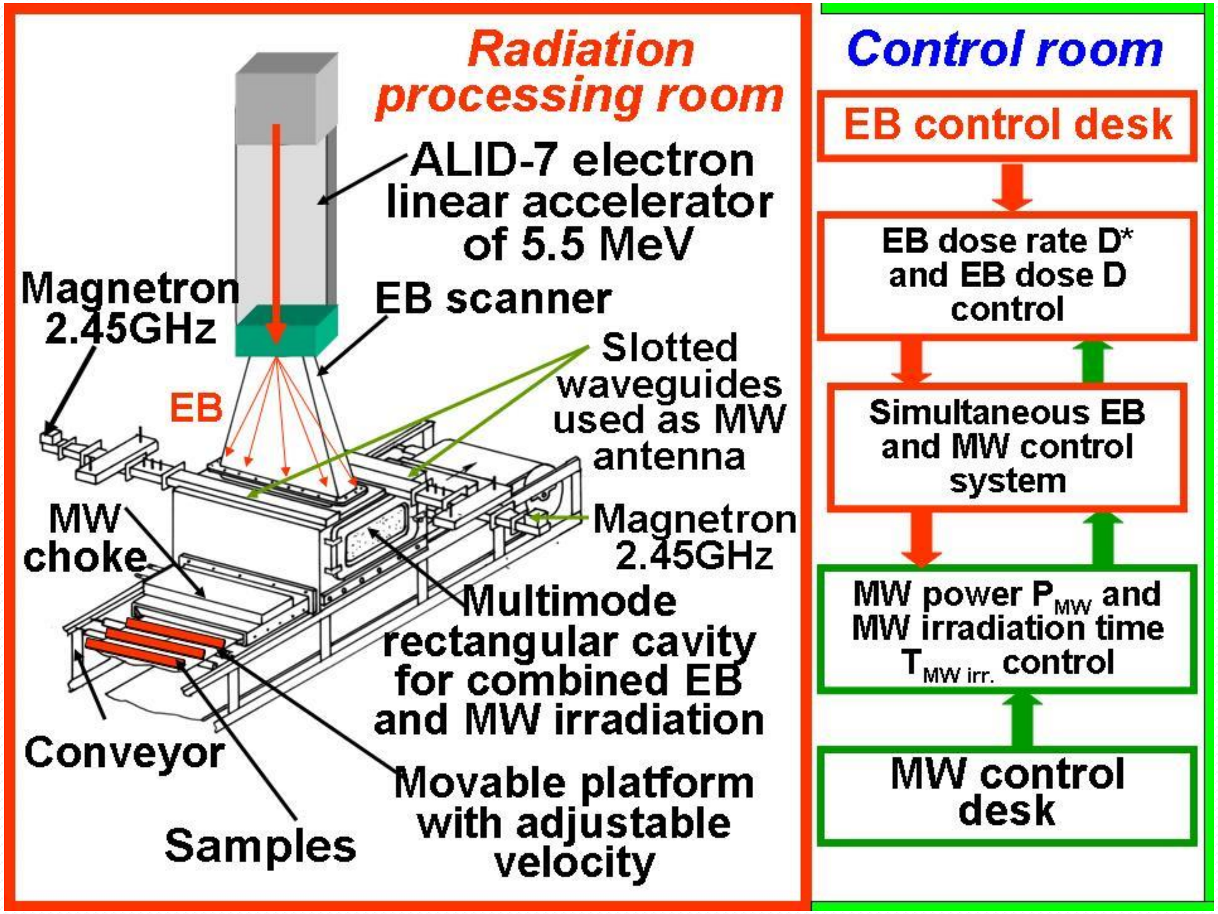
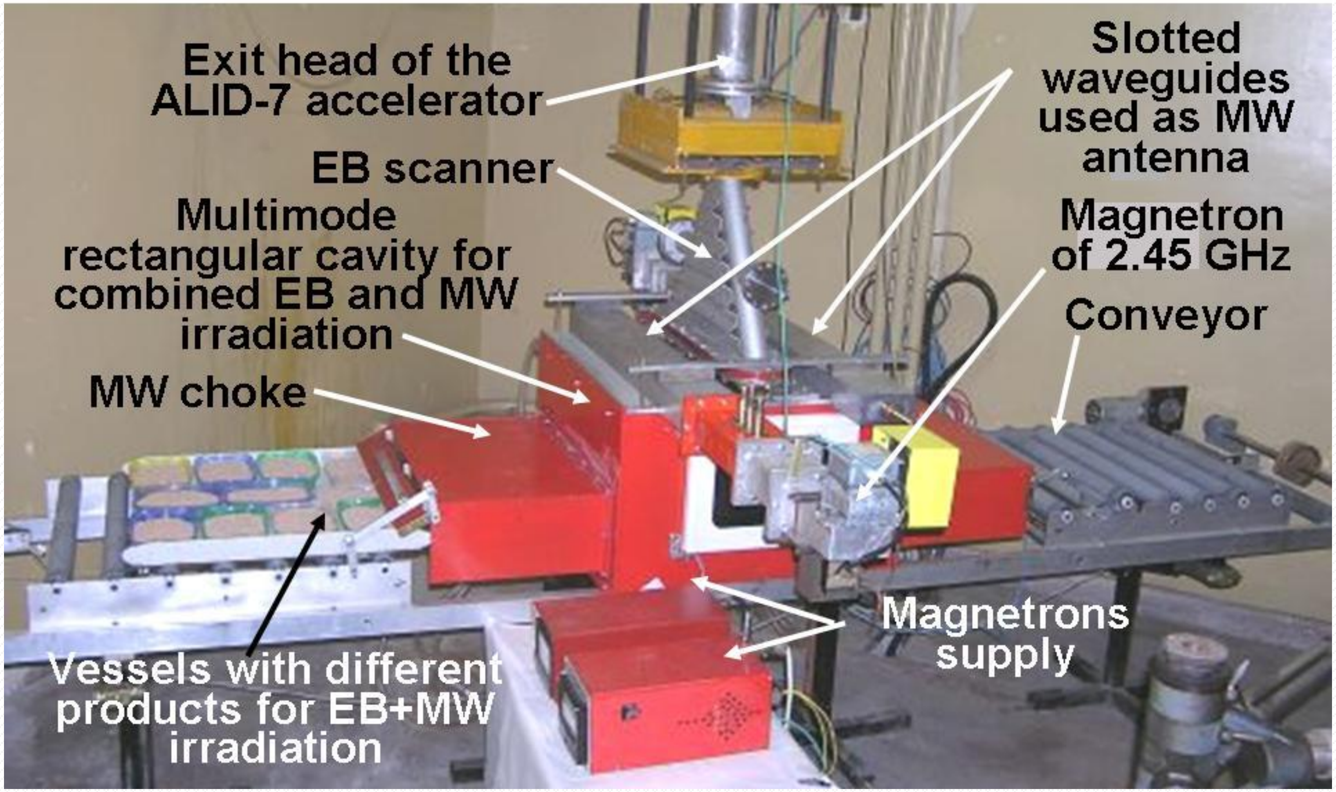


Fig. 11 The SPI-EB+MW schematic drawing

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

Fig. 12 The SPI-EB+MW photo



COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The scanned EB is introduced perpendicularly to the MRC upper end plate through a 100 μm thick aluminum foil while MW power is coupled through the same MRC upper end plate by two slotted waveguides used as MW radiating antennas. The slotted waveguide system provides good microwave energy transfer and uniformity over a large area. Each slotted waveguide, consisting of several inclined series slots cut in the broad wall of a WR430 standard rectangular waveguide propagating the dominant mode, has the advantage of simplicity of structure, manufacturing ease and adaptability of configuration to meet radiation pattern requirements .

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The WR430 waveguide was selected because it has shortest guide wavelength (λ_g) at the used frequency (2.45 GHz) which provides that the radiating slots to be placed as close as possible. All slots are spaced $\lambda_g/2$ away from adjacent slots in the same waveguide. The MW power of 2.45GHz is fed into one end of the slotted waveguide and the other slotted waveguide end is connected to a movable short circuit for impedance matching. The conventional operation of 2.45 GHz oven magnetron supplied by an L.C. single-phase-half-wave doubler (LHCHWD) was properly modified in order to permit the use of a manually-controlled or PC-controlled electronic variator for the MW power adjustment from zero to 850 W for each slotted waveguide.

COMBINED ELECTRON BEAM AND MICROWAVE IRRADIATION FACILITY

- The following types of irradiation modes were performed: Separate EB irradiation; Separate MW irradiation; Successive irradiation (EB irradiation followed by MW heating) named EB+MW; Successive irradiation (MW heating followed by EB irradiation) MW+EB; Simultaneous irradiation with EB and MW named S(EB+MW).

THANK YOU FOR YOUR ATTENTION!

No questions, right?