S-Band Relativistic Magnetron Operation With Multichannel Radial Outputs of the Microwave Power

Arkady Sayapin, Uri Dai, and Yakov E. Krasik

***Abstract*— The results of an experimental study of the S-band magnetron operation with a six-vane anode block and multichannel radial outputs for microwave power extraction are presented. The magnetron was driven by a linear induction accelerator (∼350 kV, ∼2.5 kA, and 150 ns). In the case of three outputs for microwave power extraction and another three outputs connected to waveguides short circuited by movable plungers for adjusting the magnetron resonance, frequency-stable generation of the microwaves radiation with a total power of 570 MW from these three outputs was demonstrated. This power was equal to the power obtained when the same magnetron with one output was operated with high efficiency (≥40%). In addition, it was shown that the distribution of the generated microwave power between the three outputs allows wedge insulators to be used in the waveguides vacuum–air interface without electrical breakdown. Finally, microwave radiation, extracted in free space by a cluster of horn antennas connected at the output of the waveguides, was coherently added to each other at the desired distance with a three times larger microwave power density than in the case of 570-MW single output magnetron operation.**

***Index Terms*— Magnetron, microwaves, phased array antenna.**

I. INTRODUCTION

RELATIVISTIC microwave sources driven by high-current electron generators produce microwave radiation with a power $>10^2$ times the power of the microwave radiation generated by nonrelativistic microwave sources. For instance, relativistic magnetrons (RMs) based on explosive emission plasma cathodes generate microwave radiation with a power up to several gigawatts [1]–[3]. However, the practical application of such powerful microwave sources is restricted because of the limited gain of the transmitting antennas and problems related to the concentration of the microwave power at the desired location. In most cases, horn antennas are used at the outputs of relativistic microwave generators. This type of antenna allows one to avoid surface breakdown of the vacuum–air interface insulator located at its output. Indeed, an increase in the antenna output aperture leads to a decrease in the electric field along the dielectric surface. However, the gain of a single horn antenna of reasonable size is ≤25 dB, which does not allow one to direct and concentrate generated microwave power at long distances.

To avoid these disadvantages of a single antenna, a phased array antenna is used. When a single microwave source is applied as a driver for the phased array antenna, an equal distribution of the generated microwave power between the antennas should be achieved. Here, let us mention the recent successful experimental research on the distribution by passive waveguide dividers of the *X*-band microwave power (0.5–1 GW and pulse duration of 30 ns) generated by relativistic backward oscillator [4].

One can use the RM's specific feature related to the radial output of the microwave radiation to solve the problem of directed radiation and its concentration at long distances. Indeed, when the generated microwave power is equally distributed in the anode block resonators, one can extract the power, not from one anode resonator but from several or all the anode resonators. This approach considers the stability of the carrying frequency during microwave generation. In [5], this problem was studied using coupling of two opposite located resonators by ∼2 m in length waveguide. It was shown that this method indeed leads to the stabilization of carrying microwave frequency thus allowing radial output of microwave power to two antennas. However, this stable frequency was obtained with several tens of nanosecond time delay with respect to the beginning of the microwave generation, and during the significant part of the microwave pulse, a drift of 20 MHz/ns in the carrying frequency was obtained.

There are two approaches for applying the multichannel output of the microwave radiation generated by an RM. The first approach considers a high-current generator as a driver for the multiresonator magnetron with microwave radiation extraction from each of the anode block resonators to antennas presenting elementary radiators of the phased array antenna. However, in contrast to non-RMs, RMs with a multiresonator anode block have not been investigated sufficiently. Nevertheless, the research on inverted coaxial magnetron with an anode block having 54 resonators and microwave power output

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from 27 cavities into common coaxial resonator coupled with cylindrical output waveguide [6] did not show restrictions in the number of the resonators. The second approach also considers a high-current generator, but now this generator drives several RMs having anode blocks with only a few resonators [7], [8]. In this case, a part of the resonator's output is used for coupling the magnetrons. This coupling provides frequency stability and phase synchronization of the generated microwaves. The remaining main part of the resonator's outputs serves for driving the phased array antenna.

The first research related to multichannel extraction of the microwave radiation from a high-current RM was performed with an A-6 anode block having six resonators [9], [10]. In these experiments, the RM was powered by a low-impedance (2.8 Ω) high-current CAMEL-X generator producing at its output pulses having a voltage amplitude of 1 MV and duration of 64 ns. It was shown that, when a high-current drive is applied, it is possible to achieve efficient (∼30%) RM operation. However, the frequency stability and equality of the microwave power distribution among six resonators were not analyzed in this earlier research. Furthermore, the research on RMs with multichannel extraction of the microwave power is important for RMs driven by a high-impedance (>50 Ω) generator with moderate voltage amplitude (<500 kV).

During the last few years, a significant improvement in the efficiency and duration of microwave generation and amplitude and in the frequency stability of the microwaves generated by RMs was achieved. Currently, an RM powered with a moderate voltage amplitude in the range 250–350 kV generates microwave pulses with a power of ∼500 MW and duration of ∼100 ns, and the efficiency of the microwave generation is comparable with that of non-RMs [11]–[16].

The influence of the additional microwave power outputs on an RM driven by a moderate generator and generating microwaves with high efficiency (≥40%) when it operates with a single output is different from that obtained in earlier research [9], [10]. Indeed, an almost linear increase in the total microwave power extracted from the RM with an increasing number of outputs becomes possible only when the efficiency of the microwave generation is low. In addition, when the microwave pulse duration is ≥100 ns and in the conditions of an almost linear decrease in the anode–cathode accelerating voltage, it is important to avoid frequency drift of microwaves during the microwave pulse. Furthermore, an increase in the number of the magnetron outputs changes the quality factor Q and frequency characteristic of the magnetron resonator. The latter can influence the microwaves' phase and frequency stability and requires careful investigation.

In this paper, the experimental results of the additional radial outputs influence on the operation of the S-band RM, which efficiently (≥50%) generates microwave radiation in the case of single radial output of the microwave power, are presented.

II. Experimental Setup

The chosen design and size of the anode block were similar to those used in the first experiments, where the RM was driven by a high-current generator with a relatively small output impedance [17], [18]. Later, this design was successfully adopted for an RM driven by a high-impedance generator [19], [20]. The main difference in our design of the anode block is that we used a sectional anode block consisting of six vanes radially expanding at an angle of 40° (Fig. 1, item 1). The resonator cavities formed between two azimuthally neighboring vanes radially expanded at an angle of 20°. Both sides of the vanes were short-circuited by endcaps, which also axially limited (Fig. 1, item 2) the resonance cavities. The vanes, connected to each other by these endcaps, were placed tightly inside the external cylinder of the anode block (Fig. 1, item 3). The cylinder had six azimuthally symmetrical windows, each with a cross-sectional area 15×72 mm^2. Thus, the azimuthal rotation of the vane assembly with respect to the cylinder allowed a simultaneous change in the azimuthal size of the windows. The external and internal vane's radii were 42 and 21 mm, respectively, and the vane's height was 72 mm.

The RM was driven by a linear induction accelerator (LIA) [21] with the amplitudes of the voltage and current varied in the range $U = 200$–350 kV and 2–4 kA, respectively, and the pulse duration was ∼150 ns at full width half maximum with the voltage rise time of ∼40 ns at the level of 0.1–0.9 of the its maximal amplitude. The voltage applied to the cathode–anode gap of the RM and the explosive emission plasma cathode current were measured using a capacitive divider and self-integrated Rogowski coil, respectively. The dc magnetic field, varied in the range 0.18–0.4 T, was formed by Helmholtz coils. The vacuum, ∼0.9 mPa, in the system was maintained by three turbo-molecular pumps.

The operation of the RM was investigated with two types of load at its output: 1) with matched waveguide loads placed at the RM's six outputs and 2) with matched loads placed at three azimuthally symmetrically outputs and with three outputs serving as adjustable resonators (see Fig. 2). The resonators of the anode block (Fig. 2, item 1) placed inside the vacuum chamber (see Fig. 2, item 2) were connected to six waveguides (cross-sectional area) (Fig. 2, item 3) through windows made in the vacuum chamber. These waveguides were firmly fixed with respect to the chamber, using sealing rubber and firmness flanges (see Fig. 2, item 4).

The generated microwave radiation was extracted through the anode cylinder windows and transported in the waveguides toward conical matched loads or was radiated into free space by the horn antennas. In the latter case, three azimuthally symmetrical located waveguides were closed by metal flanges at theirs outputs; in other experiments, these three waveguides were used as external tunable resonance cavities using movable plungers (see Fig. 2, item 5). The microwaves extracted from the other three anode resonance cavities were propagated toward transmitting antennas (Fig. 2, item 7) in bend waveguides (Fig. 2, item 6), a cross-guide directional coupler (Fig. 2, item 11), phase shifter (Fig. 2, item 10), twist (Fig. 2, item 9), and flexible waveguide (Fig. 2, item 8). The receiving antenna or D-dot was placed at a 4-m distance from the output of the central transmitting antenna. For final tuning of the maximum of the radiation diagram directivity, flexible waveguides were used. To achieve parallel electric field components of the electromagnetic fields excited in the antennas, the antennas were turned using twist waveguides.

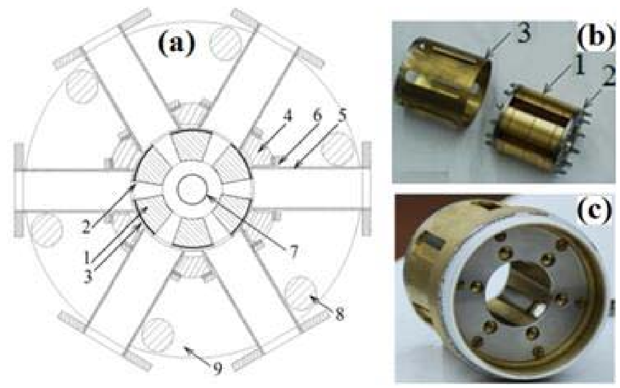

Fig. 1. (a) Design of the RM with six outputs for microwave radiation. (b) and (c) External views of sectional anode block of the RM. 1: vane. 2: axial endcap. 3: external cylinder with slots. 4: vacuum chamber. 5: output waveguide. 6: sealing rubber and firmness flange. 7: Cathode. 8: rod for magnet coil. 9: magnet coil.

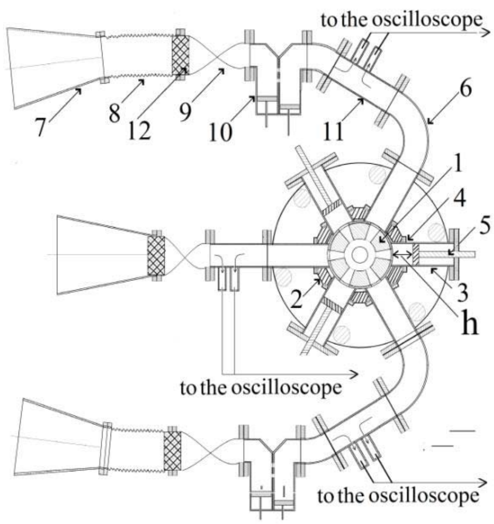

Fig. 2. RMs with three radial outputs connected via waveguides and coupler with horn antennas and three radial outputs connected to waveguides with movable plungers. 1: magnetron. 2: vacuum camera. 3: output waveguide. 4: rubber sealing and firmness flange. 5: movable plunger. 6: bend. 7: horn antenna. 8: flexible waveguide. 9: twist. 10: phase shifter. 11: cross-guide directional coupler. 12: dielectric double sided wedge insert.

The microwave parameters were measured in a cross-guide directional coupler (coupling of −50 dB) and analyzed by a digitizing oscilloscope, Agilent Infiniium DS080404B, with a bandwidth of 4 GHz. For frequency characteristic analysis, when a fast Fourier transform (FFT) was applied, only one channel of the digitizer was used, resulting in a resolution of 40 Gs/s.

When the electromagnetic waves radiating by three antennas were superimposed, phase matching at the location of the receiving free-field D-Dot sensor SFE10G was achieved by using phase shifters (Fig. 2, item 10) and adjusting the phases of the microwaves radiating by the adjacent antennas with respect to the microwave radiation by the central antenna.

A dielectric double-sided wedge insert placed after the waveguide twist (Fig. 2, item 12) was used as a vacuum–air interface insulator. This dielectric insert has a constant size along the wide side of the twist waveguide; the length of the wedge was of ∼20 cm. This design of the insulator results in an electric field tangential component along the insulator surface of ∼17% of the electromagnetic wave electric field. To control the electrical strength of the interface insulator, reflected electromagnetic waves were measured using a directional coupler.

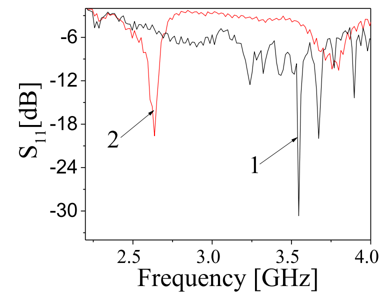

Fig. 3. Frequency response of the magnetron resonator. 1: in the case of the microwave power extraction through six waveguides. 2: in the case of microwave power extraction through the single waveguide. The output window is 72×15 mm^2 and the cathode diameter is 21 mm.

In order to determine the frequency response of the magnetron resonator when it was loaded to antennas and waveguide conical absorbers, one of the absorbers was exchanged with the waveguide/coax adapter used for connecting the network analyzer ROHDE & SCHWARZ—ZVL (9 kHz–6 GHz) to the magnetron resonator. The resonance frequencies of the magnetron resonator were determined according to the minimum values of the reflection coefficient S11 of the electromagnetic wave from the magnetron input.

Experimental Results

A. RM Operation With Six Radial Outputs for Microwave Power Extraction

The results of the measurements of the reflection coefficient S11 are shown in Fig. 3. One can see that, when the microwave power is extracted through six opened windows into the rectangular waveguides, the frequency response of the magnetron significantly changes as compared with the case with the single magnetron output. Namely, one can see that there are no resonance frequencies at $f \leq 3$ GHz for the case of the magnetron with six outputs. Here, let us note that at $f \leq 3$ GHz, efficient microwave generation was obtained in the RM with a single radial microwave power output [17]–[19]. However, in the case of the RM with six fully opened output windows, the lowest resonance frequency is $f \approx 3.65$ GHz. A decrease in the height of the output windows, achieved by azimuthal rotation of the vanes assembly with respect to the anode external cylinder, shows insignificant (∼−9 dB) resonance absorption in the frequency range $f \approx 2.5$–3 GHz.

In addition, comparing frequency response of the RM resonator, one can see in Fig. 3 that at some frequencies, the reflection coefficient S11 can be even smaller in the case of the microwave power extraction through six waveguides than in the case of microwave power extraction through the single waveguide. The latter can be related to larger value of the Q-factor in the case of six outputs, which leads to smaller value of S11 [22], [23]. Thus, it is important to keep large value of the Q-factor in the case of the RM operating with microwave power extraction through six waveguides, which

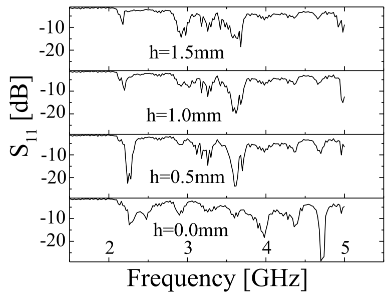

Fig. 4. Frequency response of the magnetron resonators with three radial outputs for microwave power extraction at different positions of the plungers. The anode output window is 72 mm × 15 mm and the cathode diameter is of 21 mm.

also allows one to stabilize the carrying frequency of the electromagnetic waves oscillations.

The application of the driven pulse from the LIA to the RM with six radial outputs results in microwave generation at frequency, close to the resonance frequency of the anode block resonator. The change in the magnetic field in the range $B_z = 0.18$–0.4 T practically does not change the frequency of the microwaves. When the resonators of the anode block are fully opened, thus corresponding to the size of the anode cylinder output windows, the total power extracted from all six outputs is in the range $P_\Sigma \approx 120$–150 MW. A decrease in the size of the windows to 15×50 mm^2 results in a minor increase in the total power $P_\Sigma \approx 150$–200 MW. A further decrease in the size of the output window leads to a significant decrease in the total output power, which becomes <40 MW.

The moderate level of the total generated microwave power (≤200 MW) can be related to the magnetic field being insufficient, limited by the power supply for the Helmholtz coils. The second reason for the low level of the microwave power can be related to the relatively large impedance of the LIA (∼100 Ω) as compared with the ∼2.8 Ω impedance of the generator used in earlier experiments [9], [10]. In the case of intensive extraction of the microwave power, the electron current can be insufficient for efficient excitation in the magnetron resonator electromagnetic fields, which should be large enough for effective extraction of the energy from the drifting electrons. Indeed, when one of the six output waveguides was closed by a metal flange, the power of the microwave radiation extracted from the adjacent output was almost doubled. The change in the direction of the magnetic field and, respectively, in the direction of the electron azimuthal drift, leads to an increase in the extracted microwave power in the opposite adjacent output of the magnetron. Let us note here that the closing one of the magnetron outputs does not lead to a change in the frequency and power of the microwave radiation extracted from the remaining five magnetron outputs.

The results of this paper show that the system of the anode block resonators with six radial outputs for the extraction of the microwave power retains its property as a sole resonance system that determines the frequency of the generated oscillations. However, in the case of a relatively small electron current, the distributed intense output of the microwave radiation cannot be balanced with the intense energy exchange between the electrons and generated microwave radiation.

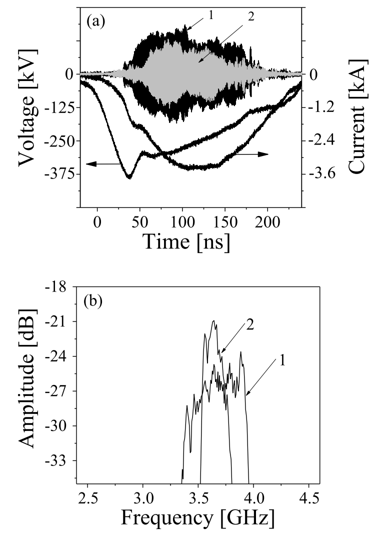

Fig. 5. (a) Waveforms of the voltage and current and microwave pulses (a.u.) at magnetic field: 1−0.39 T and 2−0.28 T. (b) FFT analysis of the microwave pulses for 1 and 2.

B. RM Operation With Three Radial Outputs for Microwave Power Extraction

When three azimuthally symmetrical outputs of the RM are used for extracting the microwave power, the other three outputs can be used as external resonators for tuning the frequency response of the RM resonator. These external resonators were three waveguides short-circuited by movable plungers (Fig. 2, item 5). When three output anode block windows were closed by plungers at $h = 0$ (where h is the distance with respect to the output window of the magnetron anode) and the other three radial outputs were loaded to antennas, no significant changes in the frequency response were obtained as compared with that of the magnetron with six outputs (see Fig. 4, $h = 0$); that is, as with six outputs, there are no well-defined resonance frequencies in the range $f \leq 3$ GHz. The maximal resonance absorption is obtained at $f = 4.75$ GHz. However, operation of the RM at $f = 4.75$ GHz was impossible because of the limitation in the maximal value of the external magnetic field. Here, let us note that a decrease in the size of the anode output windows results in a shift of the lowest resonance frequency from 3.65 to 4.0 GHz.

The frequency response of the RM resonator changed significantly when the plungers were placed at $h = 0.5$ cm. In this case, in addition to resonance, there is a resonance at a lower frequency $f = 2.26$ GHz (see Fig. 4). Let us note that in order to keep equal conditions for all three outputs of the microwave power, all three plungers were moved equal distances.

An increase in the distance h of the plungers to $h \leq 3.5$ cm does not lead to the appearance of well-defined resonance frequencies, which are found only at large distances, namely, at $h = 4.0$ cm and $h = 9.5$ cm. However, at these distances, the external resonator's volume becomes equal or even larger than the anode resonators' volume. Therefore, these external resonators can be considered as loads for the RM where part of the generated power is dissipated.

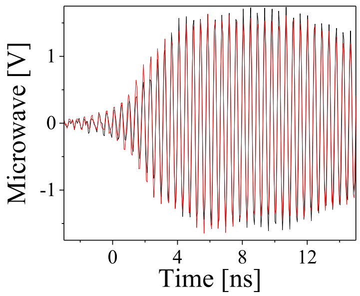

Fig. 6. Fragment of the pulse of the microwave radiation obtained from two arbitrary magnetron outputs.

The application of the driven pulse from the LIA to the RM with three radial outputs for microwave power extraction and three external resonators with the plungers at $h = 0$ results in maximal total microwave radiation power $P_\Sigma \approx 300$ MW and pulse duration $\tau \approx 130$ ns at maximal magnetic field of $B \sim 0.39$ T. Typical waveforms of the voltage and current and the microwave pulses generated under these conditions are shown in Fig. 5. However, the FFT of the generated electromagnetic pulse [see Fig. 5(b)] has bandwidth $\Delta f \geq 500$ MHz. Furthermore, the FFT of different time intervals of the microwave pulse showed a linear decrease in the frequency of microwave oscillations with a rate of 4.5 MHz/ns.

In addition, it was found that a decrease in the external magnetic field results also in a decrease in the power and duration of the generated microwave pulse. The waveform of the microwave pulse at $B = 0.28$ T is shown in Fig. 5. The total power of microwave radiation in this case does exceed $P_\Sigma \approx 200$ MW. However, at this value of the magnetic field, the decrease in the rate of the frequency drift becomes almost twice slower, and the FFT of the microwave pulse [see Fig. 5(b)] has bandwidth $\Delta f \approx 250$ MHz with a better defined carrying frequency $f \approx 3.65$ GHz.

When the plunger's position is $h = 0.5$ cm, when one obtains resonance frequencies in the RM frequency response dependence (see Fig. 4, $h = 0.5$ cm), the RM operation changes significantly. Namely, at $B \leq 0.28$ T, the generation of the microwave radiation was almost absent. An increase in the magnetic field results in the appearance of microwave generation at a high level of the total microwave power, i.e., $P_\Sigma \geq 300$ MW. The maximum of the microwave radiation, with frequency $f \approx 2.260$ GHz, which is close to the lowest resonance frequency of the RM, was obtained within the first 50 ns of the microwave generation. Later in the duration of the microwave pulse, a sharp change in the frequency to $f \approx 3.75$ GHz was obtained, accompanied by a decrease in the power of the microwave radiation.

An increase in the magnetic field to $B \approx 0.4$ T results in a decrease in the duration of the microwave radiation generation to $\sim$20 ns at $f \approx 2.260$ GHz, with an accompanying increase in the power to $P_\Sigma \approx 190$ MW in each of the three RM outputs, with a total power $P_\Sigma \approx 570$ MW. The waveform of the microwave radiation and its power coincide with those obtained in earlier research for this RM with a single radial output [16].

Now let us compare the microwave signals generated at $f \approx 2.260$ GHz obtained at different outputs of the RM (see Fig. 6). On the screen of the Agilent Infiniium DS080404B digitizing oscilloscope, the signals from two cross-guide directional couplers (see Fig. 2, item 11) were synchronized using the time delay unit of the digitizer. One can see almost the same amplitudes, while the frequency is stable and the microwaves are phase synchronized.

Finally, for superposition of the electromagnetic waves radiating by three antennas with phase synchronization at the location of the receiving D-dot, the waveguide phase shifters were used. Coherent summing of the electric fields of these three sources allows us to obtain the density of the power flux at that location of $\sim$55 kW/cm^2, which would require a microwave source radiating in free space through one antenna three times more power, i.e., $\sim$ 1.7 GW.

III. Conclusion

The experimental results show that the sequence of the anode block resonators with six radial outputs for generated microwave power retains its property as a common resonance system that determines the frequency of generated oscillations. However, when the impedance of the pulse generator is relatively large, the distributed intense extraction of the microwave radiation cannot be balanced with the intensity of the energy exchange between the electrons and microwave radiation.

When the microwaves are extracted through three azimuthally symmetrical distributed radial outputs and in the condition when the voltage on the anode–cathode gap decreases $\geq$2 times, the long generation of the microwave radiation in the RM can be supported by the drift of the carrying frequency when the resonance frequencies of the magnetron resonator are absent in the band of the generated frequencies.

With the application of three waveguide outputs for microwave power extraction and three waveguide outputs short-circuited by the plungers for tuning the magnetron resonators, the generation of the microwaves with a stable frequency and phase was achieved. The obtained total power of the microwaves, $P_\Sigma \approx 570$ MW, was comparable with the power of microwaves obtained in the earlier research with the same RM operating with high efficiency ($\eta \geq 40\%$) and one radial output for the microwave extraction.

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Uri Dai, photograph and biography not available at the time of publication.

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