Chapter 2
Industrial Microwave Sources at ISM Frequencies

At Forschungszentrum Karlsruhe, Germany, the properties of using millimetre waves for a possible industrial use have been investigated as a spin-off project of the magnetic fusion program and gyrotron development since 1993 [8]. Primarily, the interests have been focused first on processing structural and functional ceramics (like low lossy alumina), where unique advantages of millimetre-wave heating and processing where shown as well as novel system design technologies and hybrid heating. To investigate other industrial applications, e.g. heating or processing organic based materials with microwaves a detailed feasibility study on microwave sources [9], their size and efficiency was performed first. In addition, to understand and predict the material dynamics, hot spot formation, thermal runaway phenomenon etc., several computational codes (MiRa, THESIS, DELFI) developed by the author have been used to clear the choice of internationally licensed ISM (**I**ndustrial, **S**cientific, **M**edical) frequencies for specific technological applications. Comparing e.g. computationally the properties for applicator design of mm-wave and 2.45 GHz microwave systems, significant differences are noticed as a result of their physical appearance.

Figure 2.1 shows the competition for micro- and mm-wave technology depending on system costs (consisting of source, applicator, waveguide components, etc.) and R&D-efforts for developing an industrial solution. Mm-wave system components for industrial applications have to be individually designed and developed implying much higher investment and development costs as well efforts for electromagnetic compability compared to standard microwave and conventional technologies on the market. In general, the physical advantages of microwaves compared to conventional heating are very well known:

- Volumetric heating of materials
- Selective heating
- High heating rates
- Reduction of processing time
- Increased product quality
- Processing of new materials
- Savings on energy consumption
- “Clean” technology etc.

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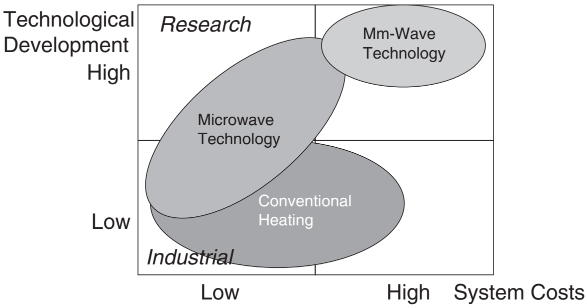

Fig. 2.1 Costs/R&D-efforts overview on heating technologies

From the point of view of standard microwave technology at ISM frequencies (as 915 MHz and 2.45 GHz), the need for using higher frequencies like 24.15 GHz (additional SM frequency) for industrial applications has to be carefully verified with respect to special physical/engineering advantages or to limits the standard microwave technology meets for the specific application problem [10]. Costs evaluation of industrial mm-wave systems have to be competitive, not only to conventional heating, but also to standard microwave solutions. An important point is in addition the availability of appropriate sources in power, size and efficiency. The following comparison of mm-wave system technology and standard microwave technology at 2.45 GHz has been performed for industrial processing and heating of materials.

Possible 24.15 GHz Sources and Their Properties

Several specific advantages have been proposed originally for using higher frequency microwaves than standard 2.45 GHz. These are

- Enhanced coupling of the materials to the electromagnetic field
- Potential of increased field homogeneity within smaller volumes
- More compact and smaller components/applicators
- Overmoded waveguides for low loss transmission applicable
- Focusing and targeting of generated beams
- Optical transmission techniques and mirror systems applicable

A crucial point for new industrial systems is the availability of a set of appropriate sources in power, size and efficiency, as well as components. For research purposes, a 30 GHz gyrotron source has been used at FZK for detailed heating and processing considerations. For industrial use, different types of devices have to be compared first (Fig. 2.2).

Anyway, the most common microwave source is the magnetron (e.g. kitchen microwave oven) and the klystron (e.g. radar applications). At very high

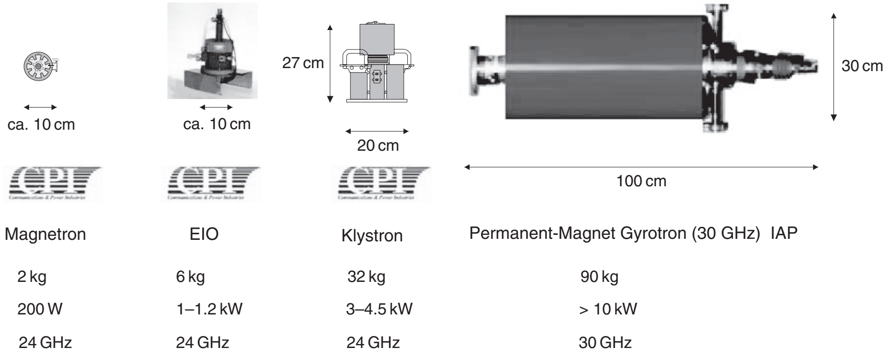

Fig. 2.2 Design overview of 24 GHz vacuum electronic devices

frequencies, only the gyrotron and EIO (Extended Interaction Oscillator) attract due to their unique high power properties.

The following overview compares the standard vacuumelectron tubes (single component) at the "near millimetre" ISM frequency of 24.15 GHz with typical power levels < 10 kW in terms of the tube's size, weight and efficiency [11].

The design study for the magnetron, EIO and klystron has been performed together with the company of CPI in Palo Alto, U.S.A. on considerations for airborne use of higher frequency devices. Due to this, only a permanent magnet gyroton can be taken into account because of its compact size – these technological sources are built by GYCOM/IAP in Nizhny Novgorod, Russia.

Due to their physical interaction principles, the EIO and the magnetron are most efficient for compact applications, where the component size is strictly limited. If one considers the component's weight related to its microwave power, the EIO concept as well turns out to be the most lightweight source at 24.15 GHz (see Figs. 2.3 and 2.4) [12].

In terms of generated mm-wave power, the gyrotron is the most efficient source at 24 GHz. With a single stage depressed collector efficiencies of 50%-60% can be

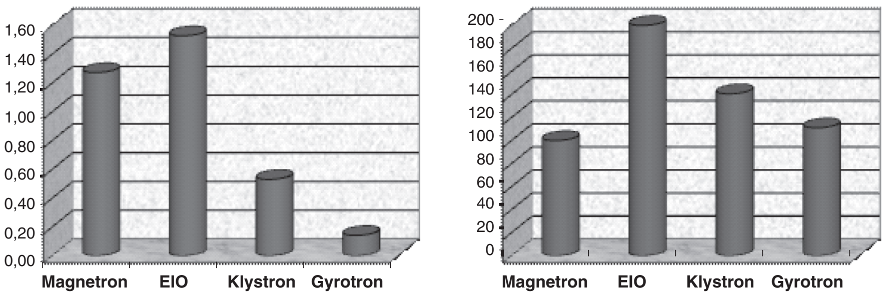

Fig. 2.3 *Left*: power vs. size [W/cm^3], *right*: power vs. weight [W/kg]

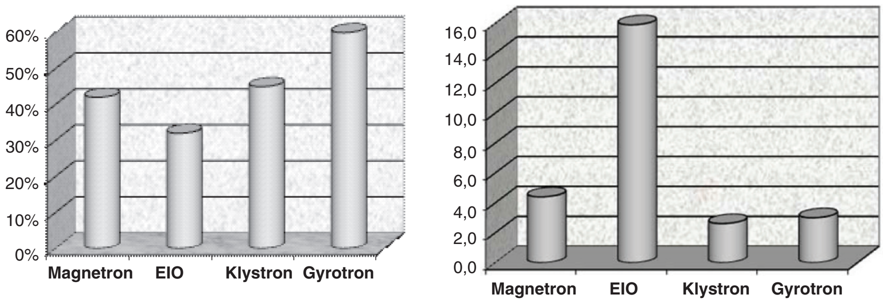

Fig. 2.4 *Left*: 24.15 GHz tubes and their efficiency, *right*: accelerating voltage over output power [kV/kW]

achieved. The EIO shows here the lowest performance. Another clear disadvantage of the EIO is obvious on the necessity of high accelerating voltage per power. The gain in compact dimensions and weight is reduced by the need of oversized power supplies and related costs [13].

As a result of this work, current technical parameters of the proposed components at higher frequencies unfortunately do not satisfy industrial requirements for commercial heating also with respect to energy efficiency or special avionic applications–furthermore, detailed comparisons on the electrothermal heating using mm-waves did not show any significant temperature homogeneity advantages for processed materials to microwaves (p. 79–81).The frequency choice is reduced in terms of costs, power availability and need, as well as the geometrical dimensions of the application. Applicable frequencies to be used are proposed for 915–927 MHz, 2.45 and 5.85 GHz.

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