# EXTENDED INTERACTION KLYSTRON TECHNOLOGY AT MILLIMETER AND SUB-MILLIMETER WAVELENGTHS

**Brian Steer, Albert Roitman, Peter Horoyski, Mark Hyttinen, Richard Dobbs, Dave Berry**
**Contact: brian.steer@cmp.cpii.com. Tel 1-905-702-2225**
*Communications & Power Industries Canada Inc., 45 River Drive, Georgetown, Ontario L7G 2J4*

*Abstract*

This paper reviews the technology and demonstrated capability of mmW and Sub-mmW Extended Interaction Klystrons at CPI Canada. It discusses design and manufacturing concepts stating self-imposed restrictions and design modifications enhancing power capability, bandwidth and extending operating frequency into the THz region.

## I. INTRODUCTION

Many of today's and future applications, such as communications, active denial, atmospheric sensing and near-object analysis, require RF sources producing microwave power of several watts to several kilowatts in the millimeter and sub-millimeter frequency range. The Extended Interaction Klystron (EIK) is one of the few readily available devices capable of providing the required performance.

Since the 1970s CPI has developed and manufactured a series of millimeter-wavelength Extended Interaction Klystron amplifiers and oscillators. These devices are based on vacuum electronics technology, which have consistently produced state-of-the-art performance since their inception.

The EIK has multiple interaction gaps in each cavity, which raises the cavity impedance, offsetting many of the difficulties of scaling VED designs to millimeter-wave frequencies. [1-4]. The EIKs currently operate at frequencies from 18 to 280 GHz. The current state of the art is summarized in the Table below.

**Table 1.** Current State of the Art.

| Achieved EIK Performance | | |
|---|---|---|
| Frequency | Pulsed Power | Average Power |
| 95 GHz | 3000 W | 400 W |
| 140 GHz | 400 W | 50 W |
| 183GHz | 50 W | 10 W |
| 220 GHz | 50 W | 6 W |
| 280 GHz | 30 W | 0.3 W |

Figure 1 presents a photograph of the various EIK models. All EIKs operate with cathode voltages below 21 kV and weight less than 30 lbs (less than 6 lbs for G-band). The lifetime of EIKs in continuous operation is over 60,000 hours at Ka-band and over 10,000 hours in G-band. EIKs are air, liquid or conduction cooled, and many models use depressed collectors.

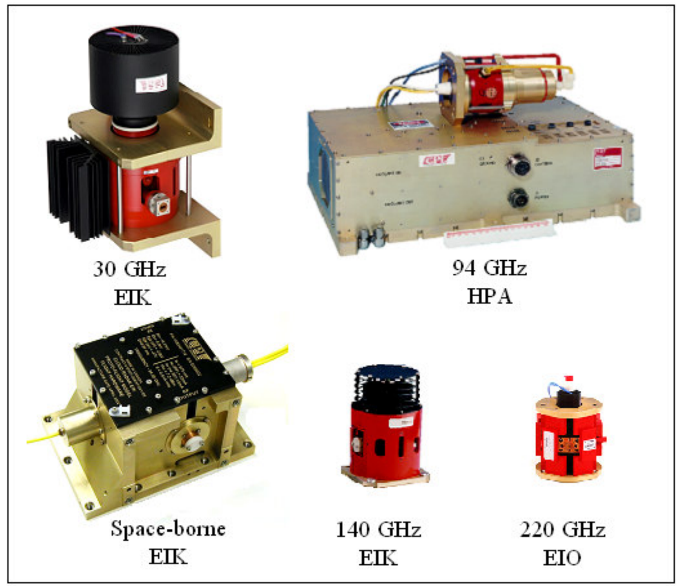


**Figure 1.** EIK Family (not all members are presented)

## II. EIK BACKGROUND

The EIK is an optimum blend between the klystron and coupled-cavity TWT technologies achieving high peak power, efficiency, bandwidth and reliability at millimeter and sub-millimeter frequencies. The multi-gap RF circuit has a simple, rugged geometry and is characterized by high impedance. This supports efficient modulation and energy exchange between the RF field and the electron beam over a broad instantaneous bandwidth.

High gain per length produces a short interaction circuit and provides the opportunity to use a single permanent magnet for focusing. The result is a well-focused electron beam in a relatively light package. In the case of pulsed operation, a focus electrode aperture grid is used to switch the beam.

A short ladder length minimizes parasitic modes, and various methods for selective mode suppression ensure stable operation with low noise.

Figure 2 presents sketch of an air cooled EIK; electrons are emitted from the thermionic dispenser cathode, a high convergence electron gun (1) accelerates and focuses the cylindrical electron beam through an aperture in the anode. Beyond the anode, the linear beam, confined by the field of the permanent magnets (2), passes through a beam tunnel in the center of a series of cavities (3). Each cavity represents a short piece of the resonant slow-wave structure (SWS) based on ladder geometry.

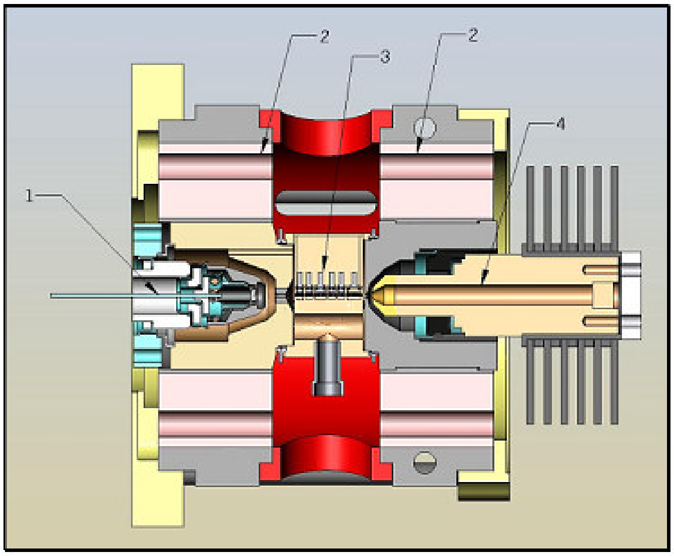


**Figure 2.** Sketch of an air cooled EIK

The number of SWS periods is selected to satisfy the conditions of RF stability and efficient beam modulation. When the electron beam enters the output cavity, the RF current magnitude exceeds the dc beam current by 40%. Approximately 70% of the microwave energy generated in output cavity is coupled to the waveguide. The spent electron beam then leaves the circuit and is recovered in the depressed collector (4).

## III. EIKs FOR SATCOM APPLICATIONS

Ka-band EIKs are traditionally utilized for satellite communication uplink applications. The backbone of this product range is the single-stage collector EIK, available in either liquid or air-cooled configurations. These EIKs have been chosen for systems such as the US Government's GBS system, Spaceways etc. In this application, the Ka-band EIK has demonstrated field life of more than 65,000 hrs, proving the EIK as a rugged and reliable device [5].

CPI continues to develop the Ka-Band EIK, with particular attention being paid to output power, bandwidth and efficiency. The following table summarizes the currently available performance characteristics.

**Table 2**. Performance of the Ka-band CW EIKs

| Ka-Band Operating Range 27-31 GHz | |
|---|---|
| Output Power | Bandwidth |
| 1000 W | 300 MHz |
| 650 W | 550 MHz |
| 300 W | 1000 MHz |

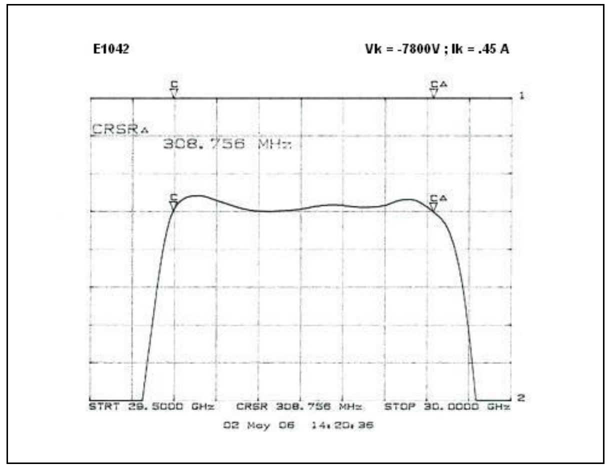


**Figure 3.** 1kW, 300 MHz Ka-Band EIK Bandpass

The single stage collector is capable of running depressed, and in this configuration efficiencies of up to 45% have been demonstrated. To raise the efficiency even further, development work has been started on a Multi Stage Depressed Collector (MSDC) version of the EIK. Initially introduced on UHF klystrons in the 1980's, CPI transferred this technology to the conventional satcom uplink klystron, launching DBS, Ku and C band versions in 2000 now S and C-band Troposcatter in 2007.

Driven by the constantly rising price of energy, as well as space and power constraints placed upon Ka-band systems, CPI has been developing an MSDC version of the Ka-Band EIK[6]. Initial prototype performance is quoted below:

**Table 3.** MSDC Performance

| Ka-Band MSDC EIK Performance | |
|---|---|
| Output Power | 980 W |
| Instantaneous Bandwidth | 300 MHz |
| Efficiency | 48% |

**Figure 4.** The MSDC Ka-Band EIK vacuum assembly

MSDC development continues targeting efficiencies in excess of 50%

Some systems require the EIK to tune beyond the instantaneous bandwidth capability of the EIK. A mechanical tuning mechanism has been developed for the Ka-Band EIK, with the demonstrated results summarized below.

**Table 4.** Tunable EIK

| Tuneable Ka-Band EIK Performance | |
|---|---|
| Maximum Output Power | 1300 W |
| Instantaneous Bandwidth | 300 MHz |
| Mechanical Tuning Range | 900MHz |
| Efficiency | 40 % |

## IV. BROADBAND MULTIMODE EIK

For all other EIKs discussed in this paper, the extended interaction structure of the cavities is used solely to increase the RF impedance of the resonance which interacts with the electron beam. This compensates for the impedance reduction which occurs due to the higher ohmic losses (lower $Q_0$) encountered at millimeter-wave frequencies.

In addition to increasing the RF impedance, having multiple interaction gaps within one cavity also creates multiple cavity eigenmodes. The frequency spacing between these modes and the equivalent slow-wave dispersion can be tailored such that meaningful interaction with the electron beam is achieved simultaneously for more than a single mode.

A recently completed development program [4] has significantly increased the bandwidth of a 95 GHz EIK by coupling to more than one cavity resonance. In this manner, increased amplifier bandwidth is achieved without a proportional loss of peak efficiency.

This design approach was adopted for use with the output cavity of the EIK. While the buncher cavities are also extended interaction circuits, they are physically shorter (fewer gaps) than the output cavity, to ensure electrical stability and to minimize the size and mass of the overall device. The shorter buncher cavities have mode frequency separations, which are too large for use within a single, instantaneous bandwidth. Thus, the design of the EIK consisted of developing a conventional buncher circuit to support over 2% instantaneous bandwidth, and designing a novel output cavity to provide RF impedance across the same bandwidth.

An additional design challenge was the need to provide the required (simultaneous) coupling of the cavity modes to the external waveguide. Improper coupling will lead to excessive gain variation across the band, or even output cavity oscillation.

Two prototype EIKs have been built to-date, and both have met the target performance. A sample plot of RF power versus frequency is shown in Figure 5. The plot shows a peak power of 930 W at 10% duty cycle. The peak power exceeded 1 kW at 1% duty cycle, but as typically occurs, the peak efficiency diminished somewhat with increased duty cycle. A constant RF drive of 140 mW was used, producing a –3dB bandwidth of 2.25 GHz.

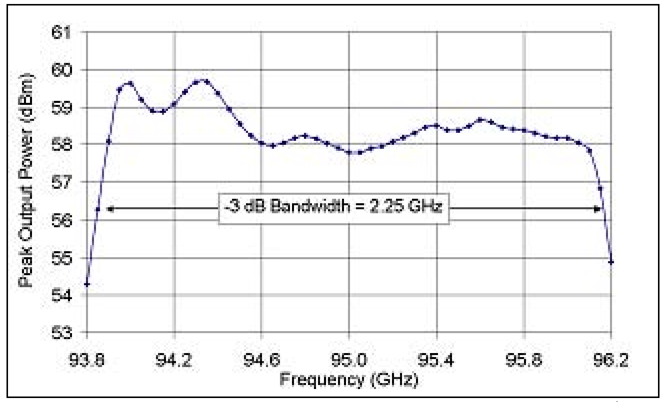


**Figure 5.** Peak RF output power vs. frequency for 1st prototype build of a broadband multi-mode EIK

The electron beam focusing system used on the two prototypes was a design iteration of that used on the standard narrow-band 95 GHz EIKs. The resultant beam transmission was 99% with saturated RF output and 40% depression of the single stage collector. The EIK was water-cooled, but could easily be adapted to air- or conduction-cooling.

The results clearly show that good electrical efficiency has been achieved across greater than 2% bandwidth, while maintaining the excellent beam transmission necessary for long and reliable operation.

## V. HIGH POWER EIKS AT 95 GHZ

A core area of interest for CPI Canada has been the development of high power sources at W-band (95 GHz), which is a frequency band of interest to the commercial, scientific, and military communities.

For narrow-band applications, the standard EIK offers 2kW of peak power and 150W of average power, in a package weighing less than 5 kg. A recent development program has extended the average power capability of this device to 400W, while maintaining the small size and high efficiency of the baseline product. In order to achieve this greater average RF power, a redesign of the RF circuit and collector was required for greater thermal margins. An improved RF window design was also implemented.

The thermal performance of the circuit is critical given that the electron beam has a peak power density in excess of 20 $MW/cm^2$. It is essential to keep the electron beam physically close to the RF circuit for good electrical efficiency, and so high thermal margin in the RF circuit is needed to cope with the small but inevitable amount of electron beam interception, which occurs on the circuit. The design of the collector required an optimization of the thermal performance over a broad range in ambient temperature while maintaining a compact EIK size and mass.

Multiple prototypes have been built and tested, and all have achieved the targeted performance of 400W average power. A typical power-versus-frequency plot is shown in Figure 6.

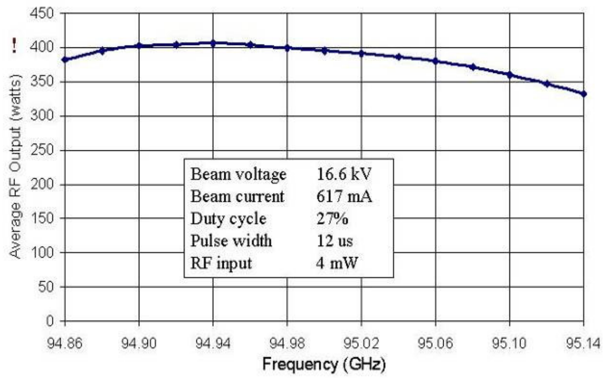


**Figure 6.** Test results from 1st prototype of 400W EIK

A follow-on development program is currently underway with the goal of 1000 W CW at 95 GHz. The analytical design and large signal modeling have been completed, and a first hardware prototype is currently under construction. This design is not derivative of an existing EIK, but rather is a new circuit design utilizing a lower beam voltage and higher beam perveance. Hardware testing is expected to be completed in the autumn of 2007.

## V. SPACE-BORNE EIKS

Since 1990 CPI Canada has developed flight EIKs for various space missions. The first W-band space qualified EIK was developed for NASA's CloudSat mission [1]. The CloudSat mission provides cross-sectional view of clouds with information on their thickness, altitude, optical properties, water and ice content. The payload comprises the first space-borne 94 GHz cloud profiling radar that is 1000 times more sensitive than current weather radars. The satellite was launched in April 2006, and the EIK based radar is in continuous service since June 2, 2006. Over 10,000 hours of CPR operation is accumulated at the time of this paper submission. The EIK generates pulsed power of 1.9 kW with the peak cathode loading of 10 A/cm$^2$. From life-test results it is expected that the cathode current will drop by 10% after approximately 20,000 hours of operation with consequent reduction in gain by ~3 dB and output power by ~2 dB. To optimize lifetime performance, the EIK was overdriven at the beginning of operation by 1.8 dB. Initial on-orbit performance is in a good agreement with the design predictions. CloudSat carries two EIKs on the board - one operational and one spare. After 1 year of flawless operation and significance of the cloud data the CloudSat mission was extended from 2 to 5 years.

More Ka-band and W-band models are currently under development for the ESA/JAXA EarthCARE mission and for a variety of space-borne weather and Topographical-mapping radars. The EarthCARE EIK specification is similar to CloudSat with the exception of longer operational life and higher duty cycle. To ensure over 30,000 hours of reliable on-orbit operation, the EIK design was updated to reduce cathode loading and electrical stresses [7].

Various space missions require 35 GHz High Power pulse amplifiers. Specification requirements range from 800 W at 0.5% duty cycle for a rain radar to 3 kW, 30% duty cycle for a deep space Topo-mapping radar mission. For these applications CPI developed a highly efficient and compact Ka-band EIK on the platform of the W-band space-qualified model [8]. These EIKs share common beam-optics and packaging, and operate with the same Power Supply (Fig. 7).

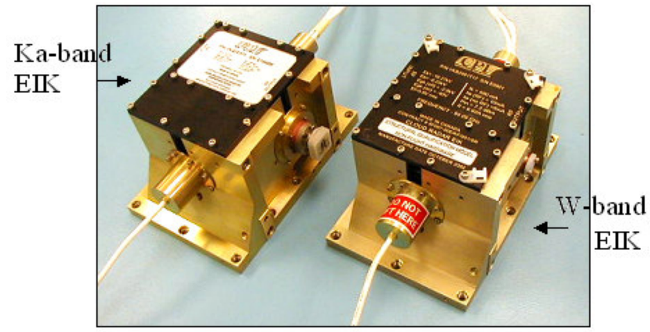


**Figure 7**. Ka- and W-band EIKs for Space-borne Applications

Demonstrated performance is summarized in Table 2. Recently, CPI completed development of a high power compact collector, which was tested at duty cycles up to 30%. This collector will be mated to the space-borne EIK.

**Table 5**. Performance of EIKs for space-borne applications

| Parameter | 94 GHz EIK | 35.5 GHz EIK |
|---|---|---|
| Peak Power | 2000 W | 3000 W |
| Bandwidth | 250 MHz | 200 MHz |
| Duty Cycle | 3-10% | 10% |
| Gain | 55 dB | 46 dB |
| Efficiency | 33% | 40% |
| Weight | 6.2 kg | <7 kg |
| Lifetime | 50,000 hours | >35,000 hours |

## VI. SUBMILLIMETER EIK'S

Extended Interaction Klystron technology is capable of providing sub-millimeter radiation in a compact package, at low operating voltages, and with high efficiency.

Figure 8 presents a photograph of the recently developed 220 GHz Extended Interaction Oscillator that demonstrates a 2% mechanical tuning range. This EIO operates in CW-mode with 11 kV cathode voltage and 105 mA cathode current. The EIO produces 6 W of power and weighs less than 3 kg.

Using existing manufacturing technologies such as EDM and dispenser cathodes, EIKs may be fabricated and reliably reproduced to 700GHz. The EIK therefore represents a high potential and a rapid avenue for Terahertz technology development.

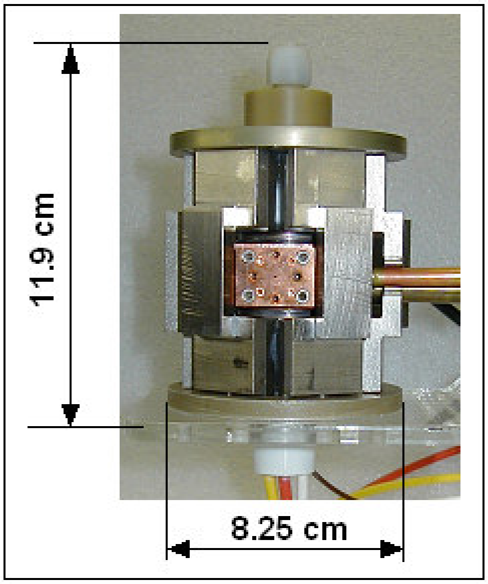


**Figure 8.** G-band 2% tunable EIO

Within CPI's self imposed design constraints for low voltage, compact dimensions using room temperature high-energy magnets, the typical bi-periodic ladder EIK is capable of operating in the frequency range of 30-300 GHz. Operation up to 450GHz can be achieved by operating at a higher order ladder mode. Preliminary analysis indicates that EIK operation at 700 GHz could be achieved by interaction with both higher order cavity and ladder modes (Table 3).

**Table 3**. Expected Performance of the future EIK models

| Future EIK Performance | | |
|---|---|---|
| Frequency | Pulsed Power | Average Power |
| 95 GHz | 3000 W | 1000 W |
| 220 GHz | 100 W | 10 W |
| 350GHz | 20 W | 1 W |
| 450 GHz | 10 W | 0.5 W |
| 700 GHz | 2 W | 0.1 W |

## VII. FURTHER DEVELOPMENTS

In order to increase the RF output power and to enhance the lifetime of the EIK, CPI is investigating alternative configurations of the electro-dynamic structure. The optimum structure should provide sufficient coupling impedance for the electron beam with the diameter of ~λ/2. This will permit operation with high electron current and also improve circuit thermal performance and sensitivity to assembly tolerances.

Success with novel technologies such as multiple or sheet electron beams, cold cathodes, lithographic manufacturing and MEMS technology will further expand EIK performance higher power and frequencies.

## VIII. CONCLUSION

The Extended Interaction Klystron is one of the few available devices that are capable of providing high output power in millimeter and sub-millimeter frequency ranges.

EIK technology preserves the ruggedness and high power capability of the conventional Klystron. It achieves enhanced power, bandwidth and efficiency at millimeter frequencies through the introduction of cavities with multiple coupled gaps. A Ladder-type RF circuit supports high efficiency and thermal stability at millimeter and sub-millimeter frequencies, while operating with moderate electron beam voltages.

CPI Canada's experienced team continues to lead the way in providing reliable sub-millimeter wave medium power sources.

## IX. REFERENCES

[1] Albert Roitman, Dave Berry, Brian Steer. "State-of-the-Art W-band Extended Interaction Klystron for the CloudSat Program", IEEE Transactions on Electron Devices, Vol. 52, No. 5, May 2005, pp. 895-898

[2] Albert Roitman, Peter Horoyski, Mark Hyttinen, Brian Steer. "Wide bandwidth, high average power EIKs drive new radar concepts", 1st IEEE International Vacuum Electronics Conference 2000, May 2-6, 2000, Monterey, p. 3.5

[3] Albert Roitman, Peter Horoyski, Mark Hyttinen, Dave Berry, Brian Steer. "Extended Interaction Klystrons for Sub-millimeter Applications", 7th IEEE International Vacuum Electronics Conference 2006, Monterey, April 25-27, p. 191

[4] Peter Horoyski, Dave Berry and Brian Steer. "A 2 GHz Bandwidth, High Power W-band Extended Interaction Klystron ", 8th IEEE International Vacuum Electronics Conference 2007, Kitakyushu, Japan, May 15-17, pp. 151-152

[5] Dobbs et al., "Rugged and Efficient Ka-Band Extended Interaction Klystrons for Satellite Communication Systems", 8th IEEE International Vacuum Electronics Conference 2007, Kitakyushu, Japan, May 15-17, pp. 107-108

[6] Dobbs et al., "Current Development Programs for the Satcom Ka-band EIK", 7th IEEE International Vacuum Electronics Conference 2006, Monterey, California, 25-27 April 2006, pp. 213-214

[7] Albert Roitman *et al.,* "Extended Interaction Klystrons for Space-borne Applications", 6th IEEE International Vacuum Electronics Conference 2005, Noordwijk, The Netherlands, 20-22 April 2005, pp. 217-218

[8] Albert Roitman *et al.,* "Compact High Power Ka-band Extended Interaction Klystrons for Terrestrial and Space Applications", 7th IEEE International Vacuum Electronics Conference 2006, Monterey, California, 25-27 April 2006, pp. 205-206