Feasibility Study of an All European Klystron for Deep Space Communications

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EXECUTIVE SUMMARY

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Change log

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1.0	12	Initial Version.
1.1	12	Internal changes added.
1.2	14	Changes after Final Review
1.3	14	Internal Update

Contents

1. Introduction

1.1. Scope

The purpose of this document is to present an executive summary on all the activities performed in the frame of ESA contract: "Feasibility Study of an All European Klystron for Deep Space Communications", Contract No. 4000102484/10/F/MOS.

1.2. Applicable Documents

	Reference	Title
[AD01]	AS-TN-1100-KLYSTRON	Requirement Specification for the X Band 25 kW Klystron
[AD02]	AS-TN-1200-KLYSTRON	Requirement Specification for the X Band 100 kW Klystron
[AD03]	AS-TN-2100-KLYSTRON	Description of theoretical aspects relevant to klystron design and manufacturing.
[AD04]	AS-TN-2200-KLYSTRON	Full Design Process Definition
[AD05]	AS-TN-3100-KLYSTRON	Preliminary Design for the X Band 25 kW Klystron Full Design Process Definition
[AD06]	AS-TN-3200-KLYSTRON	Preliminary Design for the X Band 100 kW Klystron Full Design Process Definition
[AD07]	AS-TN-3300-KLYSTRON	Cooling system design
[AD08]	AS-TN-4000-KLYSTRON	Commercial Dossier on Klystron Design and Manufacturing
[AD09]	AS-TN-5000-KLYSTRON	Implementation plan and cost estimation
[AD10]	VKX-7864A-KLYSTRON	250-kW CW Klystron Amplifier for Planetary Radar

2. Executive Summary

Presently communications with Deep Space probes are made mainly using X Band. Future missions will need an improvement of the performances of the Deep Space that in the case of the klystron tubes corresponds to power levels higher than the present 25 kW at X Band. The development of an All European Klystron for Deep Space Communications will secure this availability free of ITAR restrictions.

The objective of this study has been to set the requirements and objectives of the development and define the industrial environment (European manufacturers, non European manufacturers, regulations, patents …) and potential roadmap (cost, schedule …) of the European development.

It is important to note that the intention of this study has been to evaluate the feasibility of creating the know how for design, assembly and testing of Klystrons relying on existing, well established, European manufacturing facilities thereby reducing to the minimum the need for new investments on infrastructures. It has not been the intention of this system study to evaluate the requirements for establishing a new industry or manufacturing centre specifically dedicated to the fabrication of Klystrons.

The results achieved in the frame of this activity can be summarized in four main items:

1. **Requirements:** the requirements for the 25 KW and 100 KW klystron tubes have been established.
2. **Theory & Design Process:** a review of the existing klystron tube theory has been done and a well-defined design process has been described.
3. **Design:** Preliminary design of the 25 W and 100 KW klystron tubes has been performed.
4. **Commercial Evaluation:** a survey of existing companies related to the technological processes involving klystron tubes has been performed. Also, the required investment and the estimated cost of the tubes have been calculated.

In the next sections we expound these four items, summarizing the results achieved.

2.1. Requirements

In the frame of this activity we have established the technical requirements for a 25 KW klystron tube and for a 100 KW klystron tube operating in X-band.

These requirements range from frequency requirements (bandwidth, centre frequency, group delay flatness, etc…) to cooling specifications (flow, temperature, etc…). The main considered requirement topics have been:

- RF: frequency, power level, gain, efficiency, group delay, interfaces…
- Electrical requirements: cathode voltage & current, heater voltage & current, body current, ionization radiation…
- Environmental requirements: temperature, altitude, humidity, size & mass…
- Magnetic system: voltage, current, resistance…
- Cooling system: flow, pressure drop, temperature drop, purity…

2.2. Theory & Design process

The theory of klystron tubes has been compiled in a technical note devoted for such a purpose [AD03]. The main theoretical aspects covered have been:

- Electron gun: the different types of cathodes used have been explained. Mainly, the pierce gun, which is the type of gun typically used in this application, has been described in detail.
- Tube section: in this part we have described the complete theory of klystron modulation. The small signal and the large signal approaches have been explained. The way to calculate the bandwidth and the gain of the tube section has been also expounded. In addition to this, the input and output couplings have been also described. Finally, the tuning mechanism of the cavities has been detailed as well.
- Collector: the basics for collector design have been given with special emphasis in the power deposited which determines the required cooling system.
- Magnetic system: the main beam focusing mechanisms have been described and the parameters to be considered for keeping the body current to a minimum have been considered.

The design process of the klystron tube has been defined by splitting the complete design in the different main parts of the tube. For each part, a design process has been provided together with manufacturing processes involved. Also, the klystron tube as a whole has been considered. The main findings of this work can be summarized as the following:

- Electron gun: the software tools available in the market have been identified. The design geometrical process of a Pierce electron gun has been detailed. The electron gun manufacturing basics have been also provided together with the gun processing.
- Buncher section: the software tools available in the market have been identified. The main parameters and how they impact in the design have been described. This includes tube radius, number of cavities, resonant frequencies, cavity shape, etc… A design procedure has been detailed which includes a step to step process ranging from the small signal analysis to the 3D beam analysis. In addition to this, a detailed description on the cavity tuning process has been provided. The processes involving tube manufacturing have been also described in detail emphasizing those techniques that can be used for Oxygen Free High Conductivity Copper.
- Collector: the collector design procedure has been also defined pointing out that the main critical aspect to be considered is the power deposited with the RF off.
- Beam focusing: the magnetic system design process has been also detailed. In particular, the magnetic field required as a function of the tube parameters (radius, current, voltage…) has been provided and the software tools that can be used to design the magnetic system have been enumerated.
- Cooling system: with respect to the cooling system, special emphasis has been provided to the collector since it is the most critical part in the whole klystron tube with respect to temperature issues. The cooling of the cathode has been described as well.

2.3. Design

A preliminary design of both a 25 KW klystron tube and a 100 KW klystron tube operating at X-Band has been performed. Both designs have been kept quite similar in order to reduce costs in future real implementations of these tubes. As input to these designs we have considered ref. [AD10] in which a klystron tube operating at X-Band up to 250 KW has been proposed by the klystron department at SLAC (Stanford Linear Accelerator klystron).

We can divide the work performed into three items: those considering the common aspects in the design for both tubes (which are the major part), the design particularities of the 25 KW tube and the design particularities of the 100 KW klystron tube.

2.3.1. Common design aspects

As mentioned, many aspects of the design have been shared between both designs. In the following we provide a list of common aspects for both designs:

- Small signal code: A MATLAB code has been developed in order to use the theoretical small signal approach. This code allows a first approach for the tubes section design (resonant frequency, quality factor, etc…) and it has been coupled to an optimizer. So, we have been able to optimize the small signal parameters to get the preliminary design of the whole tube section.
- Electron gun shape: the electron gun is a Pierce gun and the shape of the gun is identical in both cases. Of course, the final gun dimensions change because the beam voltage and current changes (although we have kept the perveance unchanged). The typical total length of the designed guns is around 4 cm. Fig. 1 shows the shape of the electron guns designed (left) and how electrons are focused on the tube aperture (right).

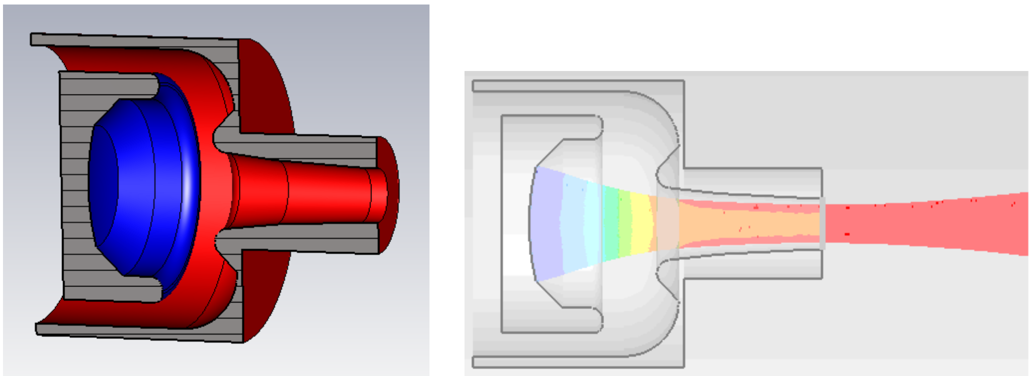

Fig. 1: Electron gun design

- Tube radius: the tube radius for both designs has been kept very similar. This also leads to some similarities in the electron gun design, the cavities and the collector.
- Cavity shape: two cavity shapes (circular and square) have been considered. Both types can be used in the design of the two tubes. Fig. 2 shows the cavities considered in the frame of this activity: cylindrical cavity (left), and squared cavity (right).

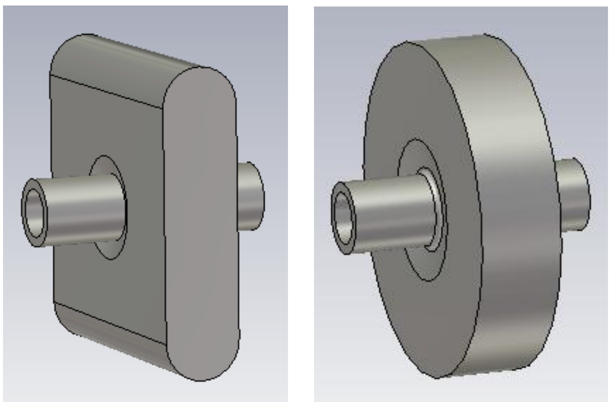

Fig. 2: Cavities designed.

- Tuning: as in the case of the cavities, two tuning mechanisms have been considered. One with a screw exciting the magnetic field (for the circular cavity shape) and another one considering the warp of the cavity wall thus reducing the cavity volume (for the square cavity shape).
- Input/Output coupling: the input and output couplings of the klystron tube have been provided as a first approach. The input is done by means of a coaxial port whereas the output is in waveguide due to the high power levels involved.
- Collector shape: the collector shape has been identical in both cases. Of course, the collector size is different since the 100 KW tube has a large power deposited. Also, the improved cooling modifications are similar: small channels in the outer part of the collector surface in order to improve the cooling and reduce the appearance of vapour bubbles. Fig. 3 shows one of the collectors designed in which the electron trajectories have been displayed.

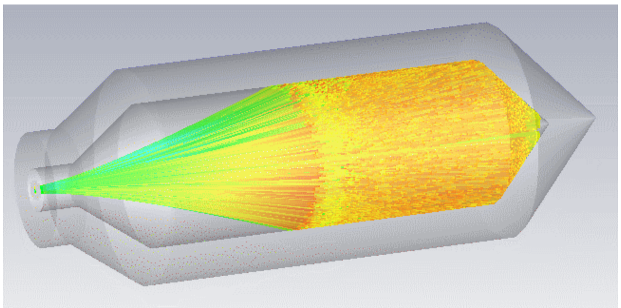

Fig. 3: Collector shape and electron trajectories inside.

- Vacuum dielectric window: an identical output dielectric window has been considered since the output section dimensions are similar (same frequency of operation)
- Magnetic system: the magnetic system considered is similar in both cases. It is based on Helmholtz coils. The difference between both designs is that the magnetic field required for the 100 KW tube is larger than for the 25 KW case.

2.3.2. 25 KW klystron tube design

For the 25 KW klystron tube, the following particularities are relevant:

- Beam voltage and current: 25 KV and 4 A have been considered for the design.
- Tube radius: the tube radius chosen has been 2.5 mm.
- Number of cavities: two designs have been performed. It has been found that the specifications in terms of bandwidth and gain can be met with a 5 cavity klystron tube design. In particular, the bandwidth achieved has been 94.5 GHz, with a maximum gain of 44 dB as shown in Fig. 4.

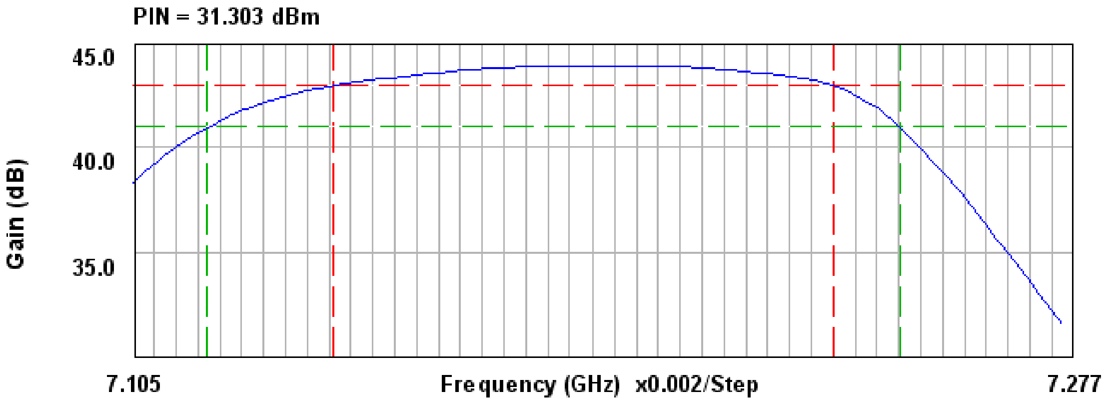

Fig. 4: Gain vs. frequency for the 5 cavity 25 KW klystron tube.

- Magnetic system: A magnetic field of 0.225 Tesla is required for beam focusing. This has been achieved with a current of 5.1 A.
- Collector cooling: The collector has been cooled by using a flow of 13 gallons per meter. This has resulted in a maximum temperature of 273 ºC on the collector surface when using the grooved wall and a wall thickness of 10 mm.
- Length: the total length of the klystron tube is 55.7 cm.
- Radiation: calculations on the expected X-ray radiation on the collector wall disregard the need of special protection measures such as the insertion of a lead layer.

Fig. 5 shows the 3D sketch of the preliminary design of the 25 KW klystron tube.

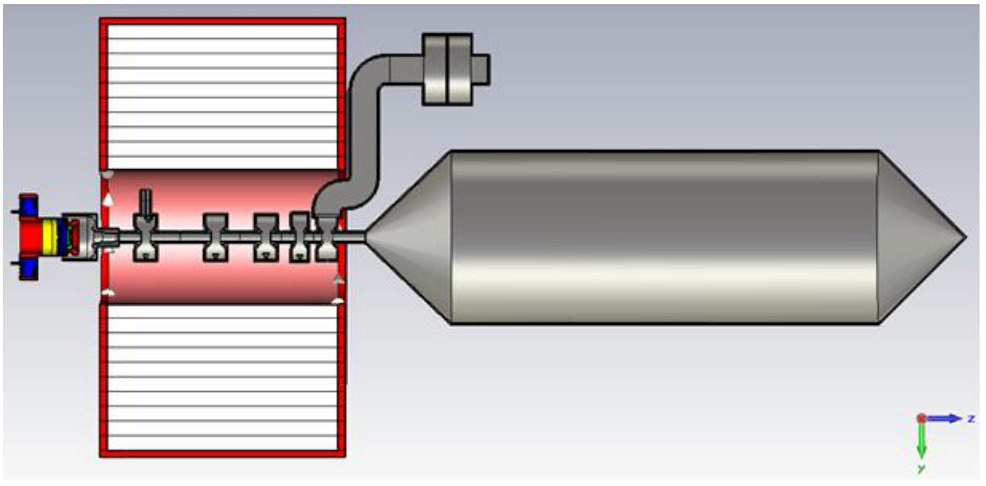

Fig. 5: 25 KW klystron tube preliminary 3D design.

2.3.3. 100 KW klystron tube design

For the 100 KW klystron tube, the following particularities are relevant:

- Beam voltage and current: 40 KV and 8 A have been considered for the design.

- Tube radius: the tube radius chosen has been 2.75 mm.
- Number of cavities: It has been found that the specifications in terms of bandwidth and gain can be only met with a 6 cavity klystron tube design. In particular, the bandwidth achieved has been 94.7 GHz, with a maximum gain of almost 56 dB as shown in Fig. 6.

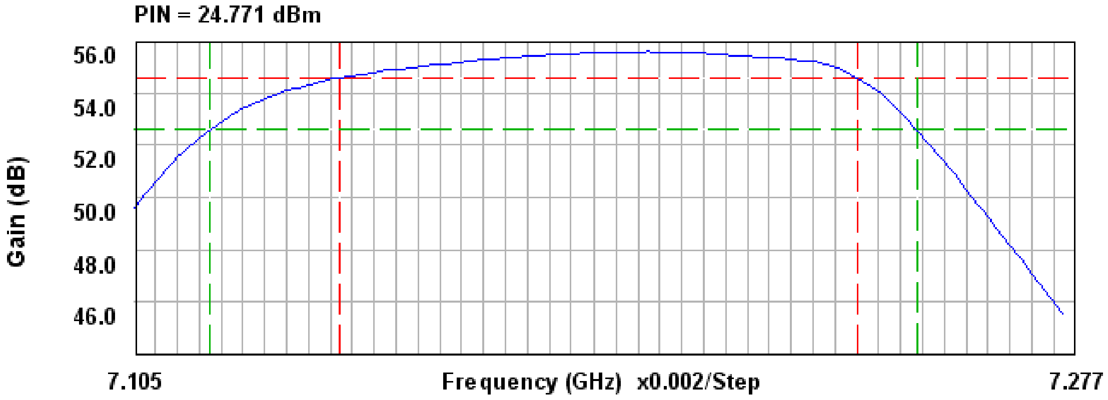

Fig. 6: Gain vs. frequency for the 6 cavity 100 KW klystron tube.

- Magnetic system: A magnetic field of 0.3 Tesla is required for beam focusing. This has been achieved with a current of 6.8 A.
- Collector cooling: The collector has been cooled by using a flow of 65 gallons per meter. This has resulted in a maximum temperature of 300 ºC on the collector surface when using the grooved wall and a wall thickness of 7 mm.
- Length: the total length of this klystron tube is 84.3 cm.
- Radiation: calculations on the expected X-ray radiation on the collector wall indicate that additional isolation could be required. This can be achieved by the use of a thing lead layer.

Fig. 7 shows the 3D sketch of the preliminary design of the 100 KW klystron tube.

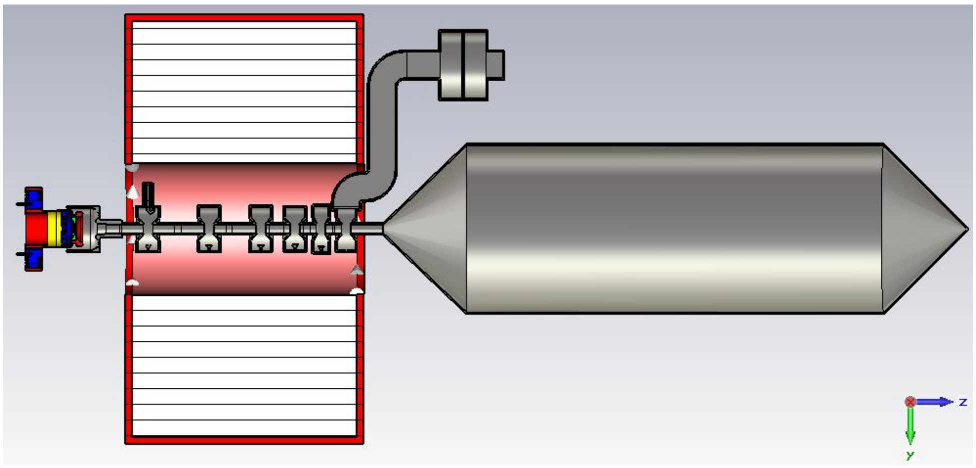

Fig. 7: 100 KW klystron tube preliminary 3D design.

2.4. Commercial Evaluation

In the frame of this activity, several actions have been taken with respect to the commercial aspects for the development/manufacturing of the two klystron tubes proposed.

With respect to management aspects, the following actions have been taken:

- A list of klystron tube companies has been provided: the main manufacturers of klystron tubes worldwide have been identified and listed.
- A database of companies has been created: basically, companies in Europe with the technology required to manufacture/develop any part of the klystron tube have been identified. This ranges from companies devoted to the manufacturing of microwave components to companies able to perform vacuum brazing.
- Companies have been contacted: some companies have been contacted to evaluate their interest in participating in this initiative. When possible, they have provided rough order of magnitude quotations of the items they could develop in the supplier chain to be set up
- Klystron companies have been contacted: some European klystron companies have been contacted in order to know their interest in participating in this initiative.
- A database of relevant patents has been generated: patents affecting the different parts of the tube have been identified and selected.

In addition to this, we have also presented an implementation plan and cost estimation. The main outcomes of such items have been:

- The required facilities and the manufacturing processes required have been established.
- A very preliminary implementation schedule has been given, proposing the main work packages required for the klystron tube developments.
- The required investment for the klystron tube development has been established. Two possibilities have been analysed: a scenario in which a non-klystron manufacturer takes care of managing the supplier chain (including integration) and testing and the case in which, keeping the manufacturing supplier chain, a klystron company takes care of the integration, design and test. In the second case, a smaller investment is expected since many facilities shall be available (such as the cooling system) and others shall be shared with other klystron business lines of the company. Also, the investment in personnel is expected to be lower since the personnel can be devoted to provide support to more than one klystron manufacturing line.

Table 1: Investment in facilities, design items and personnel in 10 years.

Type of company	Investment (Euro)	Personnel (Euro)
Non-manufacturer	**1.155.000**	**896.000**
Manufacturer	**550.000**	**523.000**

- The main items to be considered in this investment are the testing facilities and the man power required. No investments have been associated to manufacturing capabilities assuming that they are available in Europe.
- The expected cost per klystron tube has been calculated assuming three possible scenarios in which different number of units is manufactured in a period of 10 years. This is shown in Table 2.

Table 2: The three scenarios analysed for the cost estimation.

Scenario	Number of 25 KW tube units	Number of 100 KW tube units
Conservative	10	3
Realistic	15	6
Optimistic	20	10

Based on this, the estimated the price per unit has been determined for the types of companies involved as shown in Tables 3 and 4. All the prices provided are estimations. Deviations of around 30-40 % are feasible.

Table 3: Estimated price per unit (in Euro) for the 25 KW klystron tube.

Type of company	Conservative	Realistic	Optimistic
Non-manufacturer	**281.375**	**212.937**	**179.434**
Manufacturer	**209.973**	**167.300**	**146.358**

Table 4: Estimated price per unit (in Euro) for the 100 KW klystron tube.

Type of company	Conservative	Realistic	Optimistic
Non-manufacturer	**426.957**	**299.947**	**244.126**
Manufacturer	**355.554**	**254.310**	**211.051**

2.4.1. Main Conclusions of the commercial evaluation

The main conclusions with respect to the feasibility of the production of the requested klystron tubes at European level are the following:

- The technology required to develop the tubes is available in Europe.
- The market is small since these tubes are basically used by space agencies exclusively. The price has a strong dependence on the number of units manufactured.

- The cost of the 25 KW tube is quite high due to the fact that the investment costs are shared between the two types of tubes. This is also leads to a more competitive price for the 100 KW tube.
- After 10 years, the total profit for the company is rather low (in the range of 300 to 400 KEuro).
- The break even point occurs rather late (around the 9th year). This implies a high risk to the involved company due to the long time needed to recover the whole investment.
- The cost per unit in the case of a non-manufacturer klystron company is higher due to the higher investment required in such a case.