***Omega-P R&D, Inc.***

291 Whitney Avenue, Suite 401

New Haven, CT 06511

**HIGH EFFICIENCY 1 MHz, 2 MW TWO-STAGE KLYSTRON**

Dr. Sergey V. Shchelkunov, Principal Investigator

Tel.: (203) 789-1164, e-mail: [sergey.shchelkunov@gmail.com](mailto:sergey.shchelkunov@gmail.com)

SBIR Phase I proposal submitted in response to DoE SBIR/STTR 2021 Release 2 Solicitation, **Topic 33a**: RADIO FREQUENCY ACCELERATOR TECHNOLOGY, Low-Cost Radio Frequency Power Sources for Accelerator Application

**CONTENTS**

I. IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR

OPPORTUNITY and TECHNICAL APPROACH 2

II. ANTICIPATED PUBLIC BENEFITS xx

III. TECHNICAL OBJECTIVES 1x

IV. WORK PLAN 1x

V. PERFORMANCE SCHEDULE 1x

VI. FACILITIES/EQUIPMENT 1x

VII. RESEARCH INSTITUTION 1x

VIII. OTHER CONSULTANTS AND SUBCONTRACTORS 1x

iX. bibliography and references cited 1x

X. PHASE I or phase II FUNDING COMMITMENT 1x

Work leading to this proposal was carried out by Omega-P R&D scientist Dr. Vladimir E. Teryaev.

The proposal was written by Dr. Sergey V. Shchelkunov (PI) and edited by Dr. Jay L. Hirshfield, Scientific Director.

**I. IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR OPPORTUNITY and technical approach**

**Ia. Identification and Significance of the Problem or Opportunity**

The efficient generation of microwave power has recently gained broad attention in the accelerator community because energy consumption is one of the major concerns for future large-scale high energy accelerator projects. Efforts to achieve high efficiency in high RF power sources for future large-scale accelerators such as the Compact Linear Collider (CLIC), International Linear Collider (ILC), and similar accelerators are centered on multiple beam klystrons (MBK). Two commercial prototypes of the 20 MW, 1.0 GHz klystrons have recently been fabricated and tested in industrial environments, providing nominal RF power with an efficiency of around 70% [1], [2].

Omega-P R&D proposes a new concept of the Two-Stage Multi Beam Klystron (TS MBK) that allows for a remarkably high RF power production efficiency of 90%. It also yields a compact design and delivers a cost-effective electro-mechanical solution. The design for a 1 GHz, 20 MW peak-power klystron was described in an article published by some of us (Teryaev, Shchelkunov, Hirshfield) in IEEE TED [3], [4]. The performance of the tube was validated using particle-in-cell computer simulations and used 12 beams.

In this proposal, we offer to design (Phase 1) and build (Phase 2) a single beam example (furnishing 1/12th the peak power, or about 1.9 - 2MW), to demonstrate the efficacy of the two-stage concept and the predicted efficiency. The frequency for this tube (1000 MHz) aligns with accelerators that we believe are within the purview of DOE-HEP. The power scaling is done by increasing the numbers of beams. The duty factor is 5% correspond to an average power of 100 kW. Moreover, the proposed design can serve as an independent RF-source with long pulses and average RF power up to 100 kW.

This project falls under Topic 33a of the 200 SBIR/STTR Solicitation. The topics reads “…Low cost, highly efficient RF power sources are needed to power accelerators. Achieving power efficiencies of 70% or better, decreasing costs below $2/peak-Watt for short-pulse sources, and below $3/average-Watt for CW sources are essential…” The remarkable performance predicted for our TS-MBK, with its efficiency of about 20% higher than conventional MBK designs, is due to good bunching of its 12, 30-kV, 12-A 2.31 µP hollow beams; followed by 150 kV post-acceleration that results in 0.157 µP beams that drive the output cavity. It is notable that the required modulator for this tube need provide pulses of only 30-kV, since post-acceleration can be achieved using a compact and much lower cost dc power supply. Parameters for this tube meet the criteria required in Topic 33a. These include frequency of 1000 MHz (or 956.2 MHz) as for EIC or the CLIC drive beam; efficiency of 90% that exceeds the 70% requirement; cost of <$2/W that can be met for quantity production; peak power of 20 MW that matches CLIC drive beam requirement (472 tubes!); duty factor of 5% that can be satisfied with a wasted collector power that would be 100 kW (although some applications require duty factor <0.5%); and good phase stability that can be met *via* temperature regulation of the oil bath and good regulation of modulator and dc power. The 1000 MHz frequency for this project is chosen to demonstrate the efficacy and in particular the exceptional efficiency of this novel concept for an RF source, in addition to matching potential future needs, for example for the CLIC drive beam. But if demand intensifies for tubes with similar specifications at other L-band frequencies (1-2 GHz), including 1.3 GHz as specified for ILC, scaling our design to these frequencies will be straightforward.

In overall, our tube design aligns precisely with the demands for RF power sources as described in [5], on page 14, in Table “RF Source Roadmap”. Our design is but the first step, when addressing the needs for CW RF sources with 100kW/m (of an accelerating structure). The second step is to increase the number of beams to 12 [see our publication [4]. The third step is to reduce the peak current, and increase the duty factor to 100% to be compliant with demand to work in CW. This last step will require collector modification. It is not the purpose of this proposal to develop or elaborate on steps #2, and 3. We talk about them to demonstrate how our tube is aligned with the overall DoE program of building highly efficient sources with low cost per Watt outputs.

To realize this project Omega-P R&D seeks a strategic alliance with a renowned domestic electronic vacuum tube manufacturer, Communication & Power Industries, LLC (CPI). A letter of interest is attached signed by their Business Operation Manager, Mr. Pieter Kolda.

**Ib. Technical Approach**

We structure this section according to the following: 1. General description of the device; 2. Beam Dynamics; 3. Magnetic Field and Coil Configuration; 4. Electron Gun; 5. Cavities; 6. Rejection Filter; 7. Beam collector and 8. Summary of Technical Approach.

***General description of the device*** – In general, klystron efficiency is increased when the beam perveance (K = I/V3/2) is reduced. However, the bunching circuit length is proportional to K-1/2. Thus, the technological challenges and cost limitations associated with the bunching circuit length, may limit efficiency to be below 70% for high power, low frequency klystrons [6]. The novel technique we propose herein — a Two-Stage MBK configuration (hereafter TS-MBK) [3. 4]— provides a compact solution to increase efficiency for tubes that operate at low perveance. In this approach, the two stages are separated by a high-voltage post-accelerating (PA) gap, as depicted in Fig. 1. Because the first stage operates at a relatively low voltage (high perveance), the bunching circuit length can be short as compared to that of a typical klystron. The first stage in TS-MBK functions somewhat as a control electrode in a triode configuration. The post-accelerating (PA) gap provides rapid post acceleration of the bunched beam. This process subjects the bunched beam to rapid cooling in longitudinal phase space. As a result, the bunch length and the normalized bunch velocity spread are reduced. The second stage, comprising the penultimate and output cavities, thus couples with a high voltage (low perveance) beam.

The outline of proposal tube is shown in Fig. 2. The essential design and simulated parameters of the TS klystron with the annular beam are summarized in Table I,

**≈***~*

Source of drive RF power

Input RF coupler

AC power supply of cathode heater

High voltage power supply of 30 kV, 12 A

Post-accelerating high voltage power supply 150 kV, 12A (DC or pulse)

1st stage

2nd stage

Isolating RF transformer

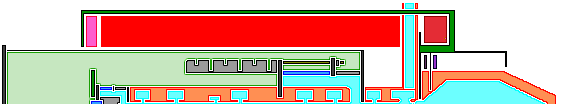
150kV

Rejection filter

Output RF power

**Fig. 1.** Conceptual electric circuit of the Two-Stage Klystron.

PA gap



Magnetic circuit

Band-pass filter

Isolating brace rods

Output WG

Local oil tank

Gun ceramic

30 kV

1st stage

Ceramic 150 kV

2nd stage

Collector coils

1090 mm

Ø800 mm

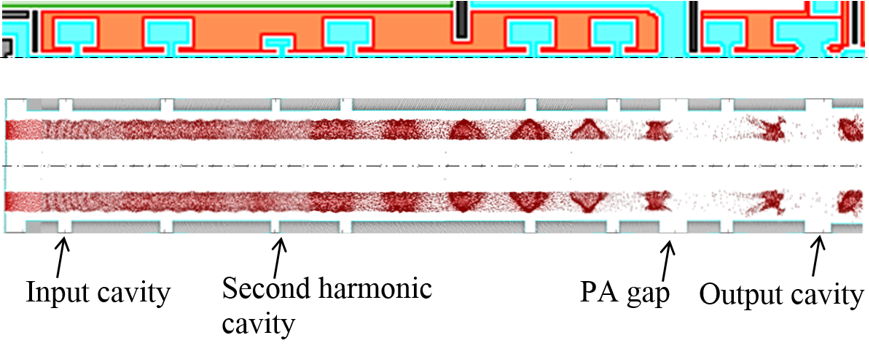
**Fig. 2.** Outline of the Two-Stage Klystron.

**Table I.** Design and simulated parameters (MAGIC) of the TS klystron.

|  |  |  |
| --- | --- | --- |
| Operating frequency | 1000 | MHz |
| Beam voltage at the 1st stage | 30 | kV |
| Beam voltage at the 2nd stage | 180 | kV |
| Beam current | 12 | A |
| Beam perveance in the 1st stage | 2.31 | µA/V3/2 |
| Beam perveance in the 2st stage | 0.157 | µA/V3/2 |
| Saturated external output RF power | 1.92 | MW |
| Ohmic loss in wall of output cavity | 15 | kW |
| Beam efficiency | 90 | % |
| Output RF efficiency | 89 | % |
| Saturated power gain | 53 | dB |
| Peak electric field in output cavity | 80 | kV/cm |
| Cathode loading | 2.7 | A/cm2 |
| Focusing magnetic field | 0.14 | T |
| Solenoid power | ~9 | kW |
| Length of RF cavity circuit | 1090 | mm |
| Drift tube diameter | 36 | mm |
| Average collector loading | <150 | W/cm2 |
| Average collector power | 100 | kW |
| Duty factor | 5 | % |

The two-stage solution increases the efficiency to about 84%., while providing for a short RF-cavity section (perhaps 5-10 times shorter, as compared to, e.g., those proposed when one follows the COM method.) To further boost the tube efficiency and simultaneously reduce the total number of beamlets (see, e.g., and compare [3] to [4]), we employ annular (hollow) beamlets instead of solid beamlets. In single beam klystrons, annular beams have already been known (see, e.g., [7]). As it was demonstrated in our article [4] and will be demonstrated in this proposal, utilizing annular beamlets in a multi-beam klystron (configured as TS MBK) allows one to achieve a higher efficiency (the state-of-the-art result is around 90%). The reason for that improvement is simple and can be described as follows. The reason is that interaction of the beam particles with the cavity fields strongly depends on the radius at which a particle moves. The use of annular (hollow) beams allows to greatly reduce this radial dependence, resulting in an improved efficiency of the tube when compared to any tube that uses solid beams.

***Beam Dynamics* –** Modeling and optimizations of this TS klystron is done using MAGIC 2-D and a 2-D model, which fully corresponds to the 2D-geometry of the device. The results of the modeling of beam dynamics in the TS klystron with annular beam is shown in Fig. 3. The corresponding outline of the cavities chain is also shown.



**Fig. 3.** RF cavity chain and the beam dynamics in the Two-stage Klystron.

Result corresponds to beam efficiency of 90 %.

Tube parameters such as the input RF power, diameters of cavities (which determine the resonant frequencies), lengths of drift tubes, and the loading of the output cavity (which defines its loaded Q-factor) result from rigorous numerical optimizations aimed at increasing the output power. As the number of parameters to optimize reaches 18, a suitable method of optimization is the method of Monte Carlo, whereby MAGIC is used as the module to which a set of external optimizing procedures call. The simulation time for one iteration running all the way to a steady state condition for the full geometry of tube having 1 mm mesh size on a PC equipped with 4-cores, 3.3 GHz CPU, takes about one hour. Usually, 20–30 iterations are required to find the tube performance close enough to the optimal for a given parameter. The convergence in power is required within a certain value between iterations, typically <0.1%. After that, other parameters are cycled through. And then, the entire process is repeated. Initial parameters (input RF power, frequencies, and drift tube lengths) are found first by following a set of established procedures following from classical beam dynamics considerations. For instance, the initial cavity positions are specified so the cavities are positioned near those locations where the fundamental harmonic of the beam current has its maximum. Then, optimizations are performed to find the values that deliver the best efficiency.

The results of optimization are found in Fig. 4, which shows the evolution of the bunch shape, particle energies, and harmonics of the RF current. One observes that, that at the end of the first stage, the current’s first harmonic becomes I1/I0=1.8 (at perveance of 2.31 µA/V3/2). In the second stage, before the output cavity, the first harmonic rises further, up to I1/I0=1.9. The decisive factor in obtaining high efficiency is the post-accelerating (PA) gap, where the bunch is accelerated. Because the phase space (as induced after the passage through the first stage) is preserved, the relative energy spread of the bunch is reduced significantly. Herein, the relative energy spread is reduced by about V0/VGun=6 times. In other words, one may say that the bunch is cooled. Other examples of this cooling have been already presented by us in [3].

A close up of a map

Description automatically generated

**Fig. 4.** The particles dynamic (top), energy distribution (middle), RF current modulation depth (bottom) in the output part of the RF cavities chain. The distance along horizontal axes are of the same scale. Observe that the bunch occupies less than 60o of the phase space, which is a straightforward indication of excellent bunching needed to gain high efficiency.

The loaded quality of the output cavity that is optimal for achieving high efficiency is modelled in MAGIC by using a material (damper) with Ohmic losses. We define it as the beam efficiency, , of a circuit that is equivalent to the output cavity. To determine the output RF efficiency, , it is necessary to exclude the power losses in walls of the output cavity, as determined by its intrinsic quality-factor, Q0. Thus, the results of MAGIC simulations suggest that and . High effective deceleration of the beam can be easily seen in Fig. 4, where the change of energy of particles in the output cavity is presented.

***Magnetic Field and Coil Configuration*** **–** The magnetic circuit of the proposed Two-Stage klystron is shown in Fig. 8. The magnetic circuit includes a solenoid and additional compensating and matching coils located in the region of the electron gun and in the vicinity of output waveguide. These coils minimize magnetic field deviations from a homogeneous profile in areas occupied by the tube cavities and drift pipes. A dedicated collector coil generates the magnetic field to control the thermal loading of the collector caused by electrons.

The magnetic field in the TS klystron is chosen to be high (i.e., 0.14 T) to provide sufficient focusing of the beam in the 2nd high-voltage (180 kV) stage; though for the 1st low-voltage (30 kV) stage, such a strong field (about 10 × Brillouin field) is rather superfluous. Detailed maps of the field in the gun and collector region are depicted in Figs. 5, 6.



**Fig. 5.** Outline of the magnetic system of Two-Stage Klystron, and (**bottom**) axial magnetic field along beam axis.

|  |  |
| --- | --- |
| **Fig. 6a.** Magnetic field map in gun region. | Diagram  Description automatically generated  **Fig. 6b.** Field map in collector region. |

***Electron Gun*** **–** Because the electron beam in the gun are totally immersed in a strong uniform axial magnetic field, the beam optics is simple, which in turn considerably simplifies the design of the electron gun (Fig. 7). In the full 20MW, twelve beamlets are positioned around a common circle with a radius of 90 mm [4]. In the described prototype, we are proposing to design and build, there is one beam centered at the tube axis. The outer diameter of a beam cathode is 30 mm. This configuration allows for a very modest cathode loading of 2.7 A/cm2, thus guaranteeing a long cathode life. The perveance of an individual beamlet in the gun is 2.31 µA/V1.5. The electron gun performance is carried out using code DGUN [8].

****

**Fig. 7**. Electron gun geometry (D = 36mm) and its performance; **(right)** cathode loading (A/cm2) as function of cathode radius (mm) is shown.

***Cavities*** **–** The 1st stage of the TS klystron with annular beams consists of six cavities. The third cavity is a secondharmonic cavity. The design of the first stage allows one to achieve high values for the beam current harmonics at the entrance of the post-accelerating gap. Similar structures for RF cavity chains and similar cavity sequencing is described in [9] and [10] and has become rather traditional for achieving high efficiency in klystrons. The topology of the klystron RF cavities is shown in Figs. 8 -11.

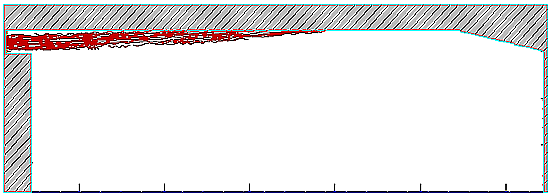


Fig. 6. Result of MAGIC simulation of a dynamics of the RF modulated beam in collector. Trajectories of particles are shown.

The output cavity has a relatively large gap size (40mm). That allows one to have a modest operating peak value of the surface electric filed (about 80 kV/cm). The output circuit consisting of a cavity and an output waveguides will be fully developed in the course of Phase 1 work.

It is envisioned that the first stage of TS klystron is to be housed in an oil tank, in a manner similar to that described in [11].

|  |  |
| --- | --- |
| Diagram, engineering drawing  Description automatically generated  **Fig. 8a.** Output cavity. R/Q1=123.5. | Chart, diagram, line chart  Description automatically generated  **Fig. 8b.** Field profile in the output cavity |

|  |  |
| --- | --- |
| **Fig. 9a.** Gain (intermediate) cavity R/Q1=89.4 | Chart  Description automatically generated  **Fig. 9b.** Field profile in the gain cavity |

|  |  |
| --- | --- |
| **Fig. 10a.** Second harmonic cavity (SHC) with R/Q1=63.8. | Chart  Description automatically generated  **Fig. 10b.** Field profile in the second harmonic cavity |

***Rejection Filter*** **–** A pre-bunched beamlet radiates when it passes through the post-accelerating (PA) gap. To evaluate this, radiation simulations using MAGIC 2-D [12] have been undertaken [3], [4]. The radiated RF power is evaluated by quantifying ohmic power losses occurring in a power-absorbing matched load. Two models have been investigated – with and without a rejection filter. In a configuration without a rejection filter (the smooth surface of the coaxial cylinder), the peak radiated RF power was found to be 4 kW, which is about 0.2% of beam power. The spectra of the radiated RF electric field in a PA gap is shown in Fig. 11. Obviously, in the spectrum of the field, the operating and the second harmonic frequencies considerably prevail.

To attenuate the radiated (into the oil tank) RF power, a coaxial rejection filter is employed to reject at two frequencies (Fig. 11). The stopbands of the filter are tuned to the operating frequency and at its second harmonic. The filter consists of coaxial cavities having a radial depth close to λ/4 and λ/8, where λ is the wavelength in oil corresponding to the operating frequency. The results are shown in Fig. 15 (bottom). The peak RF power radiation is reduced from 4 kW down to 0.3 W. Equivalently, the filter attenuation is -41 dB. Numerical modeling also shows a presence of RF voltage harmonics induced by the beam current in the PA gap. These values are practically unaffected by the presence or absence of the rejection filter. We note that the harmonics of the voltage induced by the beam are automatically considered during beam dynamics MAGIC simulations.

|  |  |
| --- | --- |
| Shape  Description automatically generated  **Fig. 11.** The spectra of the radiated RF electric field in the PA gap without a rejection filter. | Chart  Description automatically generated  **Fig. 12.** The rejection filter (with 6 coaxial cavities) and matched load (top), and the attenuation of RF electric field across the filter (bottom). The peak RF power radiation is reduced from 4 kW (0.2% of beam power) down to 0.3 W (-41 dB). Note that the two plots have the same horizontal scaling. |

***Beam Collector –*** During Phase I, it is planned to develop and design the collector by performing a thorough cycle of optimizations to minimize the heat loading. This will be done by selecting the collector sizes, and the configuration of magnetic system around it. The criterion is what we showed in Table I already, namely the loading less than 150 W/cm2. An example of the collector field has been already given in Fig .6b, and will be optimized further.

***Isolating RF Transformer*** **–** In Phase I, we are to develop only the physical and technical concepts to build the TS klystron. However, it will need an isolation transformer. We plan to design such a transformer during Phase II. The isolation transformer is shown in Fig. 2. Its location is in the oil tank, and it is an independent device. In Fig. 13, we show a possible design. As of the present, this information is given to merely demonstrate our awareness of the need for the isolation transformer.

|  |  |
| --- | --- |
| Diagram  Description automatically generated  **Fig 13a.** Example of design of isolating RF transformer. | Diagram  Description automatically generated  **Fig 13b.** Performance of isolating RF transformer. |

***Summary of Technical Approach*** **–** In conclusion of this technical section, we summarize that the concept of the 90% Efficiency Two-Stage Klystron with annular beams has been presented and explained in detail. PIC computer simulations (MAGIC 2-D) of the tube confirmed that a new record of efficiency of 90% can be achieved in a cost-efficient way. The success of the given concept is caused by three factors: 1) Post-acceleration of the pre-bunched beam is deciding contribution and adds about 15% to the efficiency of the klystron; 2) Annular configurations of the beam further helps to boost the efficiency by about 3%. The use of the second harmonic cavity improves the efficiency by approximately 3%.

The proposed TS klystron are most practical when the generation of low frequency (UHF and L-band) and high-power microwave signals is required and can be very beneficial for the RF power systems of high-energy accelerators.

**II. ANTICIPATED PUBLIC BENEFITS**

The remarkable performance predicted for our TS-MBK, with its efficiency of about 20% higher than conventional MBK designs, is due to good bunching of its 12, 30-kV, 12-A 2.31 µP hollow beams; followed by 150 kV post-acceleration that results in 0.157 µP beams that drive the output cavity. It is notable that the required modulator for this tube need provide pulses of only 30-kV, since post-acceleration can be achieved using a compact and much lower cost dc power supply.

Parameters for this tube meet the criteria required in Topic 33a. These include frequency of 1000 MHz (or 956.2 MHz) as for EIC or the CLIC drive beam; efficiency of 90% that exceeds the 70% requirement; cost of <$2/W that can be met for quantity production; peak power of 20 MW that matches CLIC drive beam requirement (472 tubes!); duty factor of 5% that can be satisfied with a wasted collector power that would be 100 kW (although some applications require duty factor <0.5%); and good phase stability that can be met *via* temperature regulation of the oil bath and good regulation of modulator and dc power.

The 1000 MHz frequency for this project is chosen to demonstrate the efficacy and in particular the exceptional efficiency of this novel concept for an RF source, in addition to matching potential future needs, for example for the CLIC drive beam. But if demand intensifies for tubes with similar specifications at other L-band frequencies (1-2 GHz), including 1.3 GHz as specified for ILC, scaling our design to these frequencies will be straightforward.

In overall, our tube design aligns precisely with the demands for RF power sources as described in [5], on page 14, in Table “RF Source Roadmap”. Our design is but the first step, when addressing the needs for CW RF sources with 100kW/m (of an accelerating structure). The second step is to increase the number of beams to 12 [see our publication [4]. The third step is to reduce the peak current, and increase the duty factor to 100% to be compliant with demand to work in CW. This last step will require collector modification. It is not the purpose of this proposal to develop or elaborate on steps #2, and 3. We talk about them to demonstrate how our tube is aligned with the overall DoE program of building highly efficient sources with low cost per Watt outputs.

~~The proposed tube should find applications in a wide variety of projects aimed to use high average power accelerators. This RF-source can be used for applications such as treatment of water and wastewater, treatment of flue gas, treatment of sewage sludge, hazardous waste environmental remediation, environmental remediation of contaminated soil, sterilization and asphalt treatment [2], [3] as a part of larger, accelerator-irradiator facilities. Our proposed klystron is highly-efficient and cost-effective, thus, its introduction to the market should remove one biggest and major impediment to the progress of waste-treatment accelerator-based irradiation facilities at a large, nation-wide scales, namely their presently low efficiency arising from a low efficiency of their respective RF-sources Our novel RF-source is expected to be, thus, of interest primarily to vendors and customers looking to build and/or use accelerator machines for waste treatment. We also anticipate that we will capture about 40% of the market as vendors of 1300MHz RF-sources for many future projects proposing accelerator machines for waste treatment and sterilization. Since this also overlaps with the TV broadcast band there should be potential for sales into that market.~~

**III. TECHNICAL OBJECTIVES**

The overall goal of this project is to develop and demonstrate a novel two-stage multi-beam klystron (TS-MBK) for use in accelerator, medical, national security, medical, and environmental cleanup applications. The novelties embodied in the TS-MBK design include use of hollow beams to obtain strong coupling to cavities, and post acceleration after bunching to reduce the beam’s energy spread to allow an exceptional electronic efficiency that we predict can reach 90%.

During Phase I of this project, Omega-P R&D will refine its conceptual design of the 1.0 GHz TS-MBK, perform mechanical tolerance analysis, and collector design and cooling requirements for several levels of average power output. In parallel, CPI will perform preliminary engineering design, cost estimates for fabrication and testing of a prototype to be carried out during Phase II, and preliminary market research. If it turns out that estimated costs for fabrication and testing of a full 12-beam TS-MBK prototype will exceed available Phase II funding, our Plan-B will be adopted. In it, a single-beam version will be designed and built, with all specifications identical to the 12-beam version, except that he peak and average power levels will be reduced by a factor of about 12. This one-beam version will still allow evaluation of the efficacy of our design concept for implementing two stages (including prevention of radiation loss at the HV gap), and for demonstrating the predicted 90% electronic efficiency.

This project will be directed by Omega-P R&D’s senior scientist Dr. Sergey V. Shchelkunov, assisted by Dr. Jay L. Hirshfield. CPI’s technical POC will be…, and business POC will be…

**IV. WORK PLAN**

**Task 1**: Optimize the cavity chain (optimize further both the first, bunching stage, and the second, output-cavity stage). The goal is to attain as much in efficiency as possible and to have the beam dynamics delivering minimal beam interception. This task involves also optimization of the magnetic system around the cavity chain, and optimization the PA-gap.

**Task 2:** Based on the results of Task 1, optimize further the gun and its magnetic system; and study the beam distribution. The goal is to minimize beam ripple and to match it for injections to the RF cavity-chain with the diameter that is optimal for high efficiency. Another goal is to minimize further, if possible, the cathode current loading (to promote an increase in the cathode life time)

**Task 3:** Following Tasks 1 and 2, optimize further the collector and the magnetic system around it. The goal is to minimize the peak thermal loading on its surface, and selection of geometry/parameters to allow for a compact, light-weight collector.

**Task 4:** Work in parallel with CPI on preliminary engineering design, cost estimates for fabrication and testing of a prototype to be carried out during Phase II, and preliminary market research

**Task 5:** Prepare reports for submission to DoE as required. Prepare and publish relevant articles in conference proceedings, and/or reviewed journals.

**Task 6:** Prepare material and compose the project final report.

V. PERFORMANCE SCHEDULE

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Task | month 1 | month 2 | month 3 | month 4 | month 5 | month 6 | month 7 | month 8 | month 9 |
| 1 | x | x | x | x | x |  |  |  |  |
| 2 |  |  | x | x | x | x | x |  |  |
| 3 |  |  |  |  | x | x | x | x | x |
| 4 |  | x | x |  | x | x | x | x |  |
| 5 |  |  |  |  |  |  |  | x | x |
| 6 |  |  |  |  |  |  |  |  | x |

**VI. FACILITIES/EQUIPMENT**

Omega-P R&D has facilities at 291 Whitney Avenue, New Haven, CT with up-to-date computer work terminals wherein commercial and custom-written software and simulation programs are available for analysis such as that shown in this proposal, and as will be used during the Phase I activity. Our consultants and part-time employees have permission to use their own computers, software and related resources to produce new results as applicable to the scope of this project and/or to confirm and check the results of analysis conducted by Omega-P R&D, Inc.

Principal simulation software to accomplish the Phase I tasks is listed below:

* MAGIC: will be used for the analysis and optimization of the dynamics of electron beams;
* CST Microwave Studio with different solvers’ licenses: can be used to simulate the fields, and multipacting;
* HFSS: this software will be used to simulate the electromagnetic fields and optimize the cavity geometries, and to find many associated electromagnetic properties (e.g. S-coefficients, VSWR, etc);
* Ansoft Multi Physics: this suite can allow one to do simulations directed to perform combined RF, thermal and stress analysis;
* Solid-Works and/or AutoCAD: these packages allow for creation of engineering drawings and 3D models;
* Mathcad (Mathsoft, PTC), Mathematica (by Wolfram), FORTRAN and C#: these software packages are to assist in summarizing and reversing data dependences, utilizing data interpolation, matrix operations and similar mathematic tools and algorithms to assist in data analysis, interpretation, understanding and presentation.

**VII. RESEARCH INSTITUTION**

During Phase I, no collaboration with a Research Institution will occur.

**VIII. CONSULTANTS AND SUBCONTRACTORS**

Dr. , a highly qualified accelerator scientist and RF engineer, who is presently working at Yale University, will be engaged as a consultant in this project during its Phase I. Dr. , among other things, originated the concept underlying... Preliminary engineering input by vendor XYZ, Inc/LLc. will be obtained via a purchase order.

**IX. bibliography and references cited**

1. M. Aoyama, K. Tetsuka, K. Hayashi, Y. Okubo, “Development of a 20-MW, 1- GHz Multi Beam Klystron for CLIC Project”, in Proc. 13th Annual Meeting of Particle Accel. Soc. Of Japan, Chiba, Japan, Aug. 2016, pp. 156-160, and refs. therein. [Online]. Available: <https://www.pasj.jp/web_publish/pasj2016/proceedings/PDF/TUOM/TUOM09.pdf>
2. S. Doebert, "High efficiency L-band Klystron development for CLIC Drive beam", presented at CLIC Workshop 2018, CERN, Geneva, Switzerland, Jan. 22-26, 2018, and refs. therein. [Online]. Available: <https://indico.cern.ch/event/656356/contributions/2848528/attachments/1587065/2511880/LbandKlystronDevelop2018b.pdf>
3. “Innovative Two-stage Multi-Beam Klystron: Concept and Modeling”, Vladimir E. Teryaev, Sergey V. Shchelkunov, Jay L. Hirshfield, IEEE Trans. Electron Devices, vol.67, no.7, July 2020; pp. 2896-2899. DOI: 10.1109/TED.2020.2991681 [Online]. Available: https://doi.org/10.1109/TED.2020.2991681
4. “90% Efficient Two-stage Multi-Beam Klystron: Modeling and Design Study”, Vladimir E. Teryaev, Sergey V. Shchelkunov, Jay L. Hirshfield, IEEE Trans. Electron Devices, vol.67, no.12, December 2020; pp. 5777-5782. DOI: 10.1109/TED.2020.3033267 [Online]. Available: <https://doi.org/10.1109/TED.2020.3033267>
5. Blazey, G. “Radiofrequency Accelerator R&D Strategy Report.” DOE HEP General Accelerator R&D RF Research Roadmap Workshop, March 8-9, 2017, <https://science.osti.gov/-/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf>
6. R. B. Miller, W.F. McCullough, K.T. Lancaster and C.A. Muehlenweg “Super-Reltron Theory and Experiments”, IEEE Trans. Plasma Science, vol.20, no.3, pp.332-343, June 1992. DOI: 10.1109/27.142834
7. M. Read, R. Jackson, P. Ferguson, G. Nusinovich, and R. L. Ives, “Design of a 10 MW, L-Band, Annular Beam Klystron,” in IEEE Trans. Electron Devices, vol. 61, no. 6, June 2014; pp. 1836-1841. DOI: 10.1109/TED.2014.2299519
8. A. Larionov, and K. Ouglekov. "DGUN-code for simulation of intense axial-symmetric electron beams", Proc. of 6th Inter. Comp. Accel. Physics Conf., p. 172, 2000.
9. A. Yano, S. Miyake, S. Kazakov, A. Larionov, V. E. Teryaev, Y. H. Chin. “The Toshiba E3736 Multi-Beam Klystron”. Proc. LINAC 2004, Lubeck, Germany, pp. 706-708, August 2004. [Online]. Available: <http://accelconf.web.cern.ch/AccelConf/l04/PAPERS/THP45.PDF>
10. V. E. Teryaev, S. V. Shchelkunov, S. Yu. Kazakov, J. L. Hirshfield, R. L. Ives, D. Marsden, G. Collins, R. Karimov, R. Jensen. "Compact Low-Voltage, High-Power, Multi-beam Klystron for ILC: Initial Test Results". Proc. Div. Particles and Fields, Aug 4-8, 2015, Ann Arbor, MI, USA. [Online]. Available: <http://arxiv.org/abs/1510.06065>
11. V. Vogel, A. Cherepenko, S. Choroba, J. Hartung, P. Bak, A. Korepanov. “Connection module for the European X-ray FEL 10MW horizontal Multi-beam klystron”, Proc. IPAC 2010, pp. 3978-3980, Aug 2010, Kyoto, Japan.
12. B. Goplen et. al. “User-configurable MAGIC for electromagnetic PIC calculations”. Comp. Phys. Comm., Vo. 87, No. 1, 54, 1995.

**X. PHASE I OR PHASE II FUNDING COMMITMENTS**

No commitment exists for Phase I funding for this project from the private sector or from non-SBIR/STTR sources. The matters of Phase II are being discussed with CPI.