

# High Efficiency, Low Cost, RF Sources for Accelerators and Colliders

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**ABSTRACT:** Accelerators for High Energy Physics (HEP) are large users of energy, much of it in the form of radiofrequency (RF) power to accelerate particles to very high energies. Proposed HEP projects will require even larger amounts of RF energy. Increasing concerns of the cost and availability of energy will require the HEP community to use energy as efficiently as possible. Successful transfer of HEP technology to the public and private sectors will be most effective if it is highly efficient.

Historically, the HEP community has utilized available RF power sources, mainly in the form of vacuum tube technology, much of which was developed during the cold war or is otherwise used in the private sector. The private sector is moving to solid-state RF sources which do not exhibit the electrical efficiency that is needed for future HEP projects.

Here, we summarize the state of the development of a number of RF sources that promise efficiencies of 80% and above. We also outline future efforts that are needed to fully realize the potential of these sources.

**KEYWORDS:** Accelerator; RF; Efficiency.

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## 1. Introduction

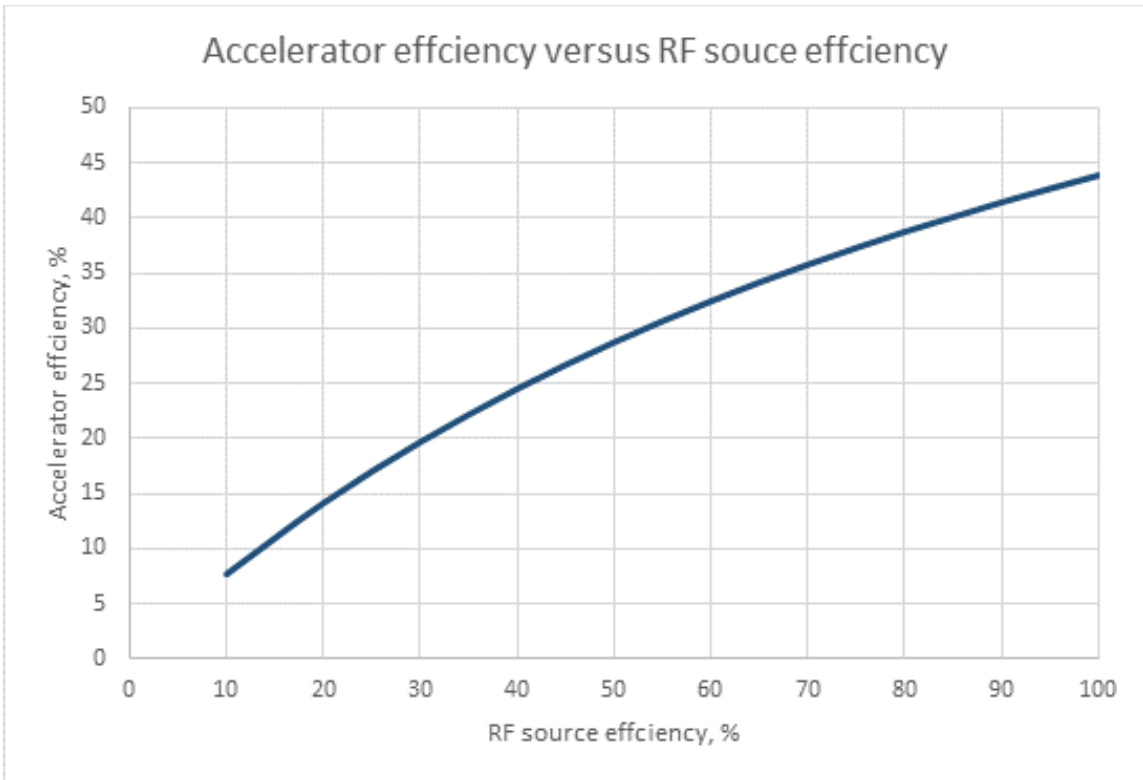
High Energy Physics (HEP) complexes are large users of energy. The HEP community has long been cognizant of this energy usage. In the early development of the Fermilab Tevatron, it was recognized that superconducting magnets could provide a reduction in energy usage, depending on operating parameters, of the Main Ring and Energy Saver from 65 MW to 17 MW [1]. This awareness continues as evidenced by the recent Fermilab PIP-II Sustainability Workshop [2] and the addition of luminosity-per-site-power as a figure-of-merit in the Collider Implementation Task Force Report to Snowmass'21 [3]. In this light, we should continue to exploit all possible developments that can increase the efficiency of the energy that we use.

In any future large-scale, normal conducting RF accelerator facility, the capital and operational costs of the RF power chain – the high-power RF amplifiers (klystrons) and the high voltage modulators for powering them – are substantial [4, 5, 6]. Reasonable budgeting models for a TeV scale collider predict that the high-power RF system alone would cost more than the construction of the accelerator itself and the tunnel required to house it; on the order of \$10B. These estimates assume the use of existing RF amplifier and modulator technologies at a combined ~\$20/peak kW. As was stated in the 2017 DOE Radiofrequency Accelerator R&D Strategy Report:

“When pushing high gradient or intensity limits, RF sources become the leading cost driver for normal conducting accelerators and a significant cost driver for superconducting accelerators. Only with innovative concepts for designing and building RF sources will dramatic reduction in cost and increased efficiency be achieved.”

This same report suggests a target of \$2/peak kW - at least ten times less expensive than what is commercially available today. Whether klystrons, magnetrons, or other existing RF sources are employed, the relative differences in their costs – even considering trade-offs with respect to peak vs. average power, or operational lifetime – are negligible when compared to the order of magnitude reduction in cost that is needed.

While the recent move towards solid state RF power sources exploits its many advantages, they are inherently poor performers with regard to efficiency, with maximum values typically less than 60% in terms of wall plug to RF power. A thorough analysis of the efficiency of accelerator systems has been performed [7]. As an example, this analysis has been used in Figure 1 to illustrate the gains that could be achieved in the Fermilab PIP-II complex by the use of magnetron RF sources. From the figure, one can see that increasing the RF source efficiency from ~50% (present solid-state amplifiers) to 85% (present 75-100 kW magnetron RF sources) would increase the total accelerator system efficiency from 28% to 40%. However, magnetron sources suitable for HEP are not yet ready. Active feedback control of magnetrons is available to adjust the phase and amplitude [8] based on beam loading, but a number of parameters, such as magnetron performance, unit-to-unit central frequency, mean lifetime, and various supporting power supplies and control electronics need to be improved to meet HEP reliability needs. Other potential high-efficiency RF sources require development to meet the needs for future HEP use.



**Figure 1.** Using Fermilab PIP-II as an example, the dependence of accelerator system efficiency on RF source efficiency.

### 1.1 Solid State Amplifiers – Today’s Go-to Device

Historically, vacuum electron tubes that were developed for radar and high-power transmitters have been used for medium and high-power applications with solid state amplifiers used as driver stages. These driver stages had limitations on the maximum frequency at which they could operate. Developments in MOSFET and CMOS technology now covers all frequencies presently of interest to HEP (Figure 2).

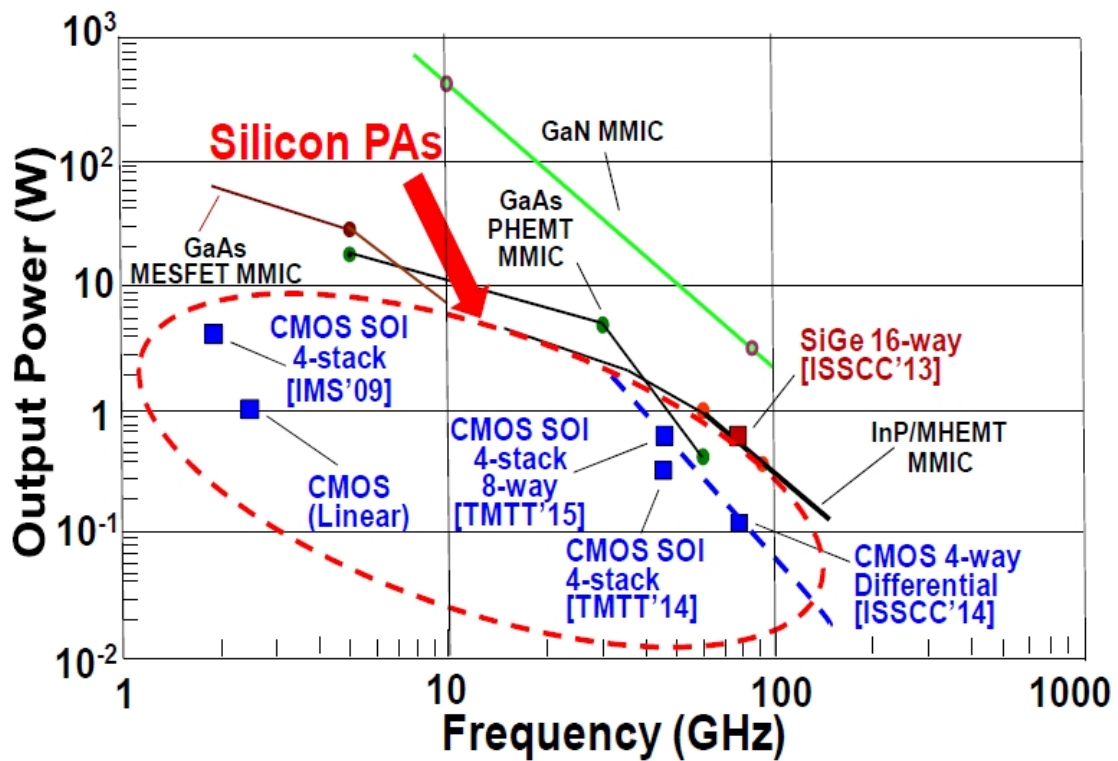


Figure 2. Power range and frequency capabilities of present solid-state RF sources.

Vacuum electron tube technology can produce individual components with peak powers in the 5 – 12 MW range while supporting duty factors up to a few percent. The output of these amplifiers can be fed directly into large accelerating cavities such as drift tube or side-coupled linacs.

Solid state power amplifiers rely on a large number of low power modules whose output must be combined to achieve high power. The individual solid-state modules have efficiencies of approximately 55%. The need for a large number of combiners or circulators further reduces the efficiency of the system. Overall system efficiencies therefore are less than 50%. This large number of contributing components results in large devices as seen in Figure 3 of a 2 MW solid state system. These solid-state systems are also expensive at over \$10/Watt.



**Figure 3.** CERN SPS Thales solid state power amplifiers: 32 towers x 144 kW @ 200 MHz, combined in 2 x 2 MW amplifiers; in operation since 2021.

## **2. Research Initiatives for High Efficiency RF Sources**

RF amplifiers are often thought of as “known quantities,” and while there is an abundance of research activity in accelerating structures, R&D in high power RF sources is relatively uncommon. In the past, HEP leveraged RF devices and power amplifier designs developed for radar and high-power transmitters so basic device R&D was not required. Today these other applications no longer exist or at least are not in development. Unfortunately, there are not many commercially viable uses for RF amplifiers in the range of 100 kW and above, and the devices that do exist are usually custom designed for a specific application. It is unreasonable to expect that an industrial supplier will invest their own time and money to reduce cost in anticipation of a single-use system that may (or may not) be assembled decades in the future. In fact, most of the developments described below were funded by various government initiatives. Because of the long-time frame, high technical risk, and undefined initial requirements associated with future machines such as a next generation collider, any reasonable business plan would “price in” the impact of these uncertainties – so when a new facility is proposed, the RF power system will be prohibitively expensive. HEP must now accept this new cost and schedule going forward. Support for high-risk research in RF sources is desperately needed if we are to realize the order of magnitude improvement in cost-capability that is truly required. Such an effort must be led by government labs and academia because these institutions can tolerate the long-term risk of this effort.

An example of a successful lab-led R&D initiative in high power RF sources has been the High Efficiency International Klystron Activity (HEIKA), established by CERN in 2014. This effort has supported worldwide collaboration to understand in detail how to optimize the electrical design of high-power klystrons for maximum DC-to-RF efficiency. As a result of this work, new klystron design methods such as the Core Oscillation Method (COM) and Core Stabilization Method (CSM) were established. New designs for COM-based 8 MW and 50 MW X-band

klystron prototypes have been completed by CERN and industrial partners [9]. In addition, a publicly available 2D klystron simulation code called KlyC was successfully developed, benchmarked, and made available to the RF source community [10]. The tools and design improvements arising from the HEIKA collaboration will be helpful in developing high efficiency (and therefore lower operational cost) prototypes for any future demonstration-scale collider, but more work still must be done to reduce the upfront construction costs of high-power RF sources.

## **2.1 High efficiency RF source options**

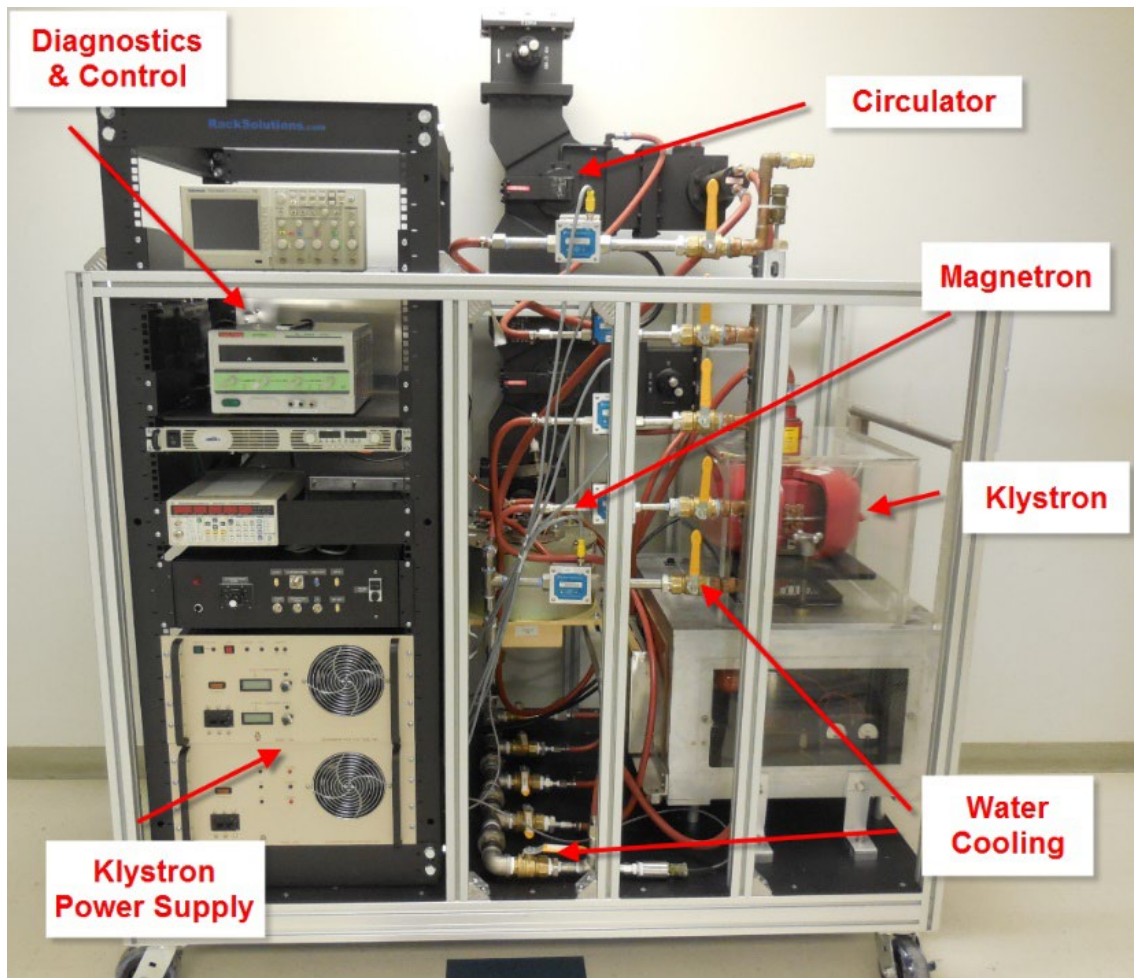
In the following section we examine in more detail four RF technologies that have the potential for improved efficiency at 100s of kilowatt and megawatt scales. These are Magnetrons, Multiple Beam Triodes, High Efficiency Klystrons, and Multiple Beam IOTs.

### **2.1.1 Phase and Amplitude Controlled Magnetrons**

The magnetron is a highly efficient and relatively inexpensive source of RF power. Magnetrons providing 100 kW with efficiencies exceeding 85% are available at 915 MHz and are commonly used in industrial RF heating systems. These are free-running oscillators and not suitable for systems requiring control of the amplitude and phase, including many accelerator systems. While phase locking of magnetrons is well established, amplitude control on a fast time scale is required for many accelerator applications. Calabazas Creek Research, Inc. (CCR), Fermilab, and Communications & Power Industries, LLC (CPI) developed a 1.3 GHz, magnetron- based, RF system for these accelerator applications [11,8].

In this program, CPI scaled a 915 MHz magnetron to produce 100 kW at 10% duty at 1.3 GHz. Amplitude control uses a technique developed at Fermilab that employs phase modulation of the locking signal [12]. Phase modulation shifts RF power to sidebands that are rejected by high Q loads, such as superconducting accelerator cavities. The power in the sidebands represents a reduction in the power delivered to the cavity and provides amplitude control on very fast time scales.

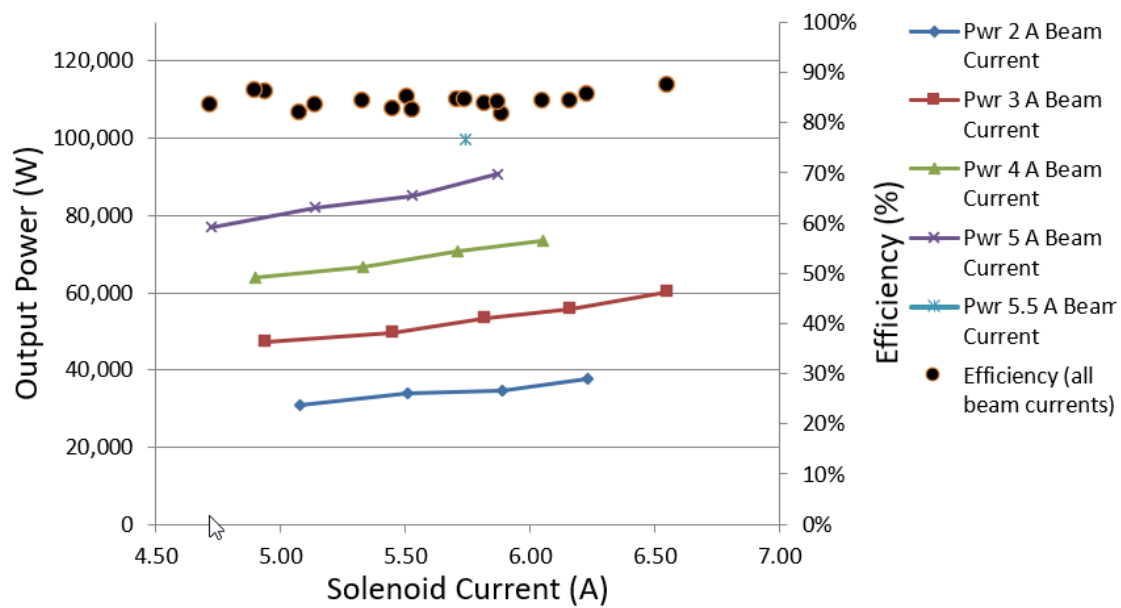
The magnetron was integrated into a transportable system, shown in Figure 4. It included a 5-kW klystron driver for phase locking, circulator, klystron power supply, magnetron solenoid power supply, cooling manifolds, system interlocks, and control and diagnostic electronics. Only the high voltage, pulsed power for the magnetron was external to the system. A solid-state RF source providing approximately 350W can replace the klystron for phase locking.



**Figure 4.** Example magnetron system.

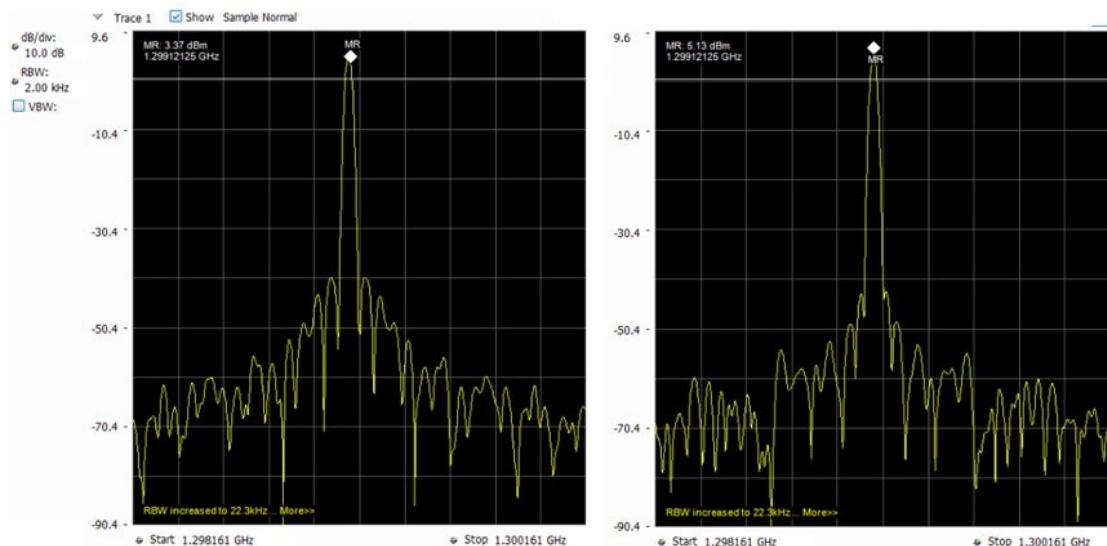
Figure 5 shows the performance as a free running oscillator, which is typical for magnetrons. The magnetron achieved the design output power of 100 kW. The pulse was 1.5 milliseconds at a pulse repetition rate, limited only by availability of processing time, of 2 Hz. The efficiency varied from 80% - 85% over the operating range.





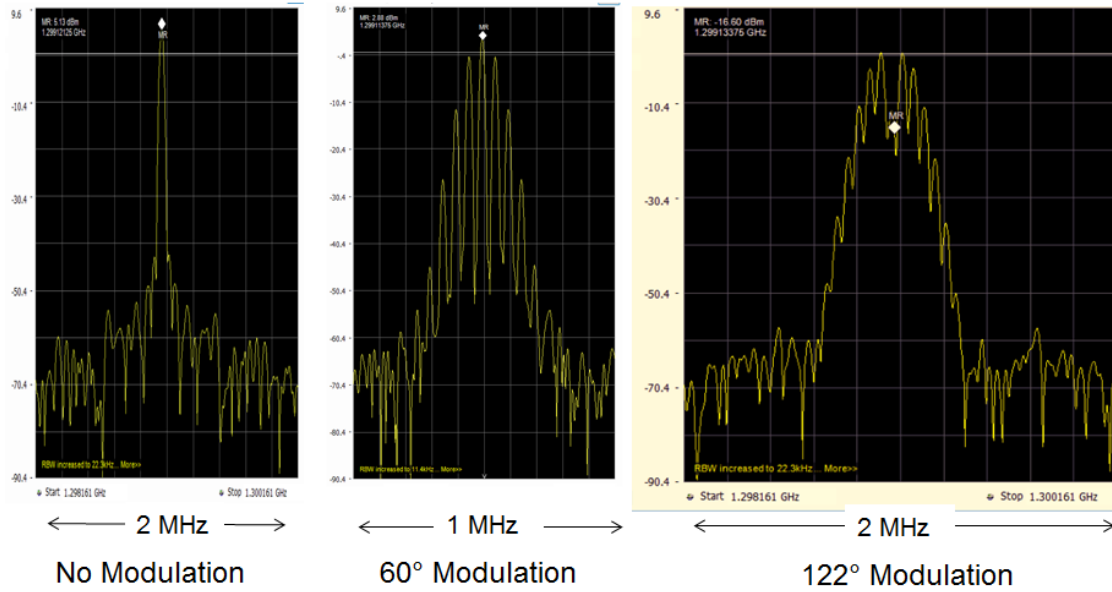
**Figure 5.** Magnetron output power and efficiency as a function of solenoid current. The efficiency is almost constant at 80% - 85% throughout the operating range.

Spectra for the magnetron in free running and phase locked modes are shown in Figure 6. Locking was confirmed by observation of the interference frequency (IF) signal from a balanced mixer. The local oscillator (LO) and RF signals were provided by the klystron driver and the sampled output from the magnetron. When the magnetron was locked, the IF signal was constant during the pulse. The first side lobes were reduced by about 5 dB in the locked mode.



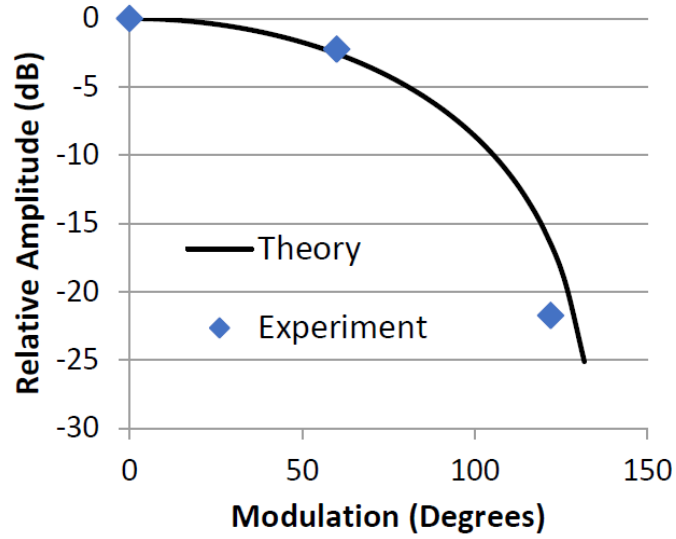
**Figure 6.** Left: Free running magnetron; Right: Driven magnetron at -15 dB down at natural frequency of the magnetron.

Figure 7 shows the effect of phase modulation of the locking signal on the magnetron output. The magnetron operated at essentially the natural (unlocked) frequency when locked with a signal 25 dB below the output power. Phase modulation was introduced via the low-level oscillator driving the klystron at 50 kHz. The figure clearly shows power diverted to the side bands as the phase modulation increases, reducing power at the center frequency. This would result in reduction of power coupled into a high Q cavity on a fast time scale.



**Figure 7.** 50 kHz Phase modulation with 269 W locking power and 66.5 kW magnetron output (-25 dB).

Figure 8 shows the observed power at the center frequency versus the modulation. Also shown is the predicted power,  $1 - S_{ii}(f, M)^2$ , where  $S_{ii}(f, M)$  (see Equation 1) is the amplitude of the side bands and where  $f$  is the frequency,  $f_c$  is the center frequency,  $F_m$  is the modulation frequency, and  $J_0$  and  $J_n$  are Bessel functions.  $M$  is the modulation index, equal to the phase deviation in radians. The measured performance compares well with the predicted values with greater deviation at the highest phase modulation.



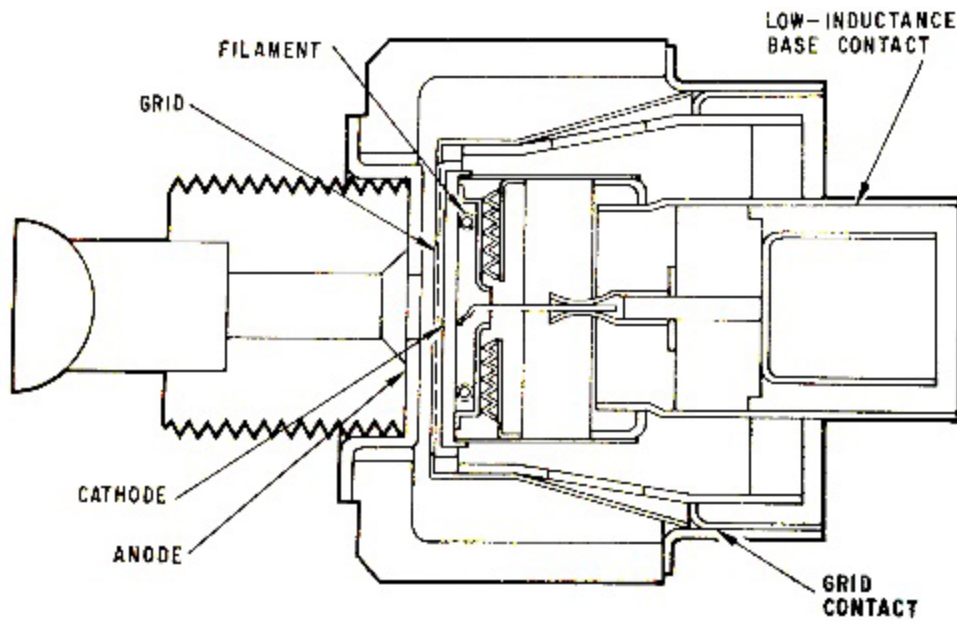
**Figure 8.** Relative power at center frequency as a function of modulation amplitude.

$$S_{ii}(f,M) = \left[ J_0(M) \delta(f, f_c) + \sum_{k=1}^{20} \left[ J_n(k,M) \cdot \delta[f, (f_c + k \cdot F_m)] + (-1)^k \cdot J_n(k,M) \cdot \delta[f, (f_c - k \cdot F_m)] \right] \right] \quad (1)$$

### 2.1.2 Multiple Beam Triodes

Triodes are extremely compact sources of electron beams for RF power generation. Operating in Class C, triode-based RF sources can achieve efficiencies approaching 90%. In addition, the cost is extremely low compared to other sources in this frequency range. Estimated cost is approximately \$0.50/W, which is less than ¼ the cost of klystrons or solid-state sources.

Figure 9 shows a schematic diagram of a planar triode. A potential difference between the cathode and anode plate drives electron flow when an appropriate voltage is applied to the grid. Because of the small grid to cathode displacement, the current between the cathode and anode is controlled by a relatively small voltage difference between grid and cathode.

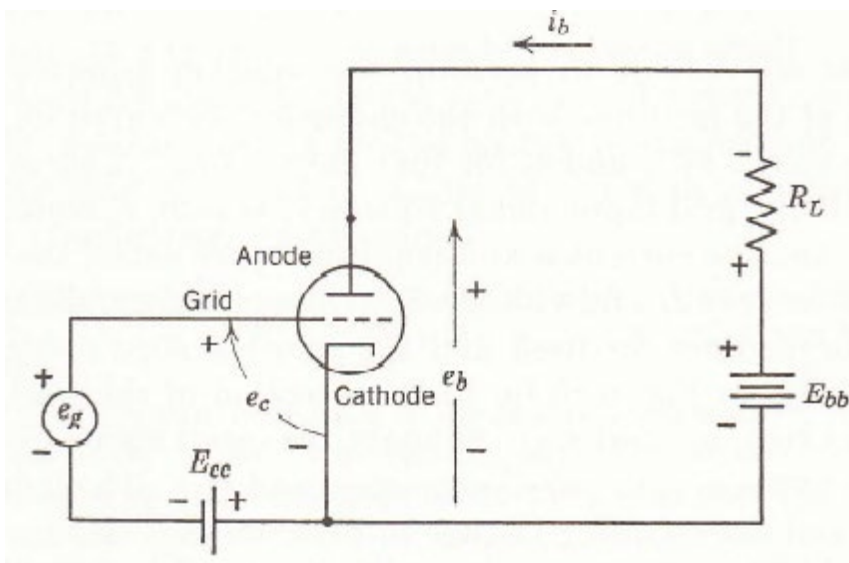


**Figure 9.** Schematic diagram of a planar triode.

Figure 10 shows the basic circuit of a triode amplifier [13,14]. The major components are a generator providing an input RF signal  $e_g$ , a grid bias voltage source  $E_{cc}$ , an anode (high voltage) source  $E_{bb}$ , and a load resistor  $R_L$ . Because of the load resistor  $R_L$ , the potential  $e_b$  between the plate and the cathode depends on the magnitude of the high voltage source  $E_{bb}$  and the magnitude of the anode (beam) current  $i_b$ . The magnitude of  $i_b$  is controlled by the potential between grid and cathode  $e_c$ . The voltage amplification or gain  $K$  is defined as

$$K = \frac{\Delta e_b}{\Delta e_c} = \frac{\Delta i_b}{\Delta e_c} R_L \quad (2)$$

The advantage of a triode is that a large output power can be generated with a small amount of input power because the grid current is usually negligibly small.



**Figure 10.** Basic circuit of a triode amplifier.

The high frequency performance of a triode is limited, in part, by the capacitance between grid and anode. This results in a gain dependent change in the input capacitance known as the Miller effect. This can be avoided by inserting a coarse mesh, referred to as a screen grid, between the control grid and anode. The screen grid shields the control grid from capacitance between the grid and anode. This device is referred to as a tetrode.

For high power gridded tubes with significant beam current, the shielding can partially be achieved by space charge in the electron beam. This research program focused exclusively on the triode.

When integrated with input and output cavities, the combination can provide an extremely compact, low cost, high efficiency source of RF power. Figure 11 shows a 425 MHz RF source at CPI used for testing triodes. It produces 25 kW of RF power at an efficiency of 90% and cost approximately \$30K. The size can be determined by comparison with the pencil shown in the photo.

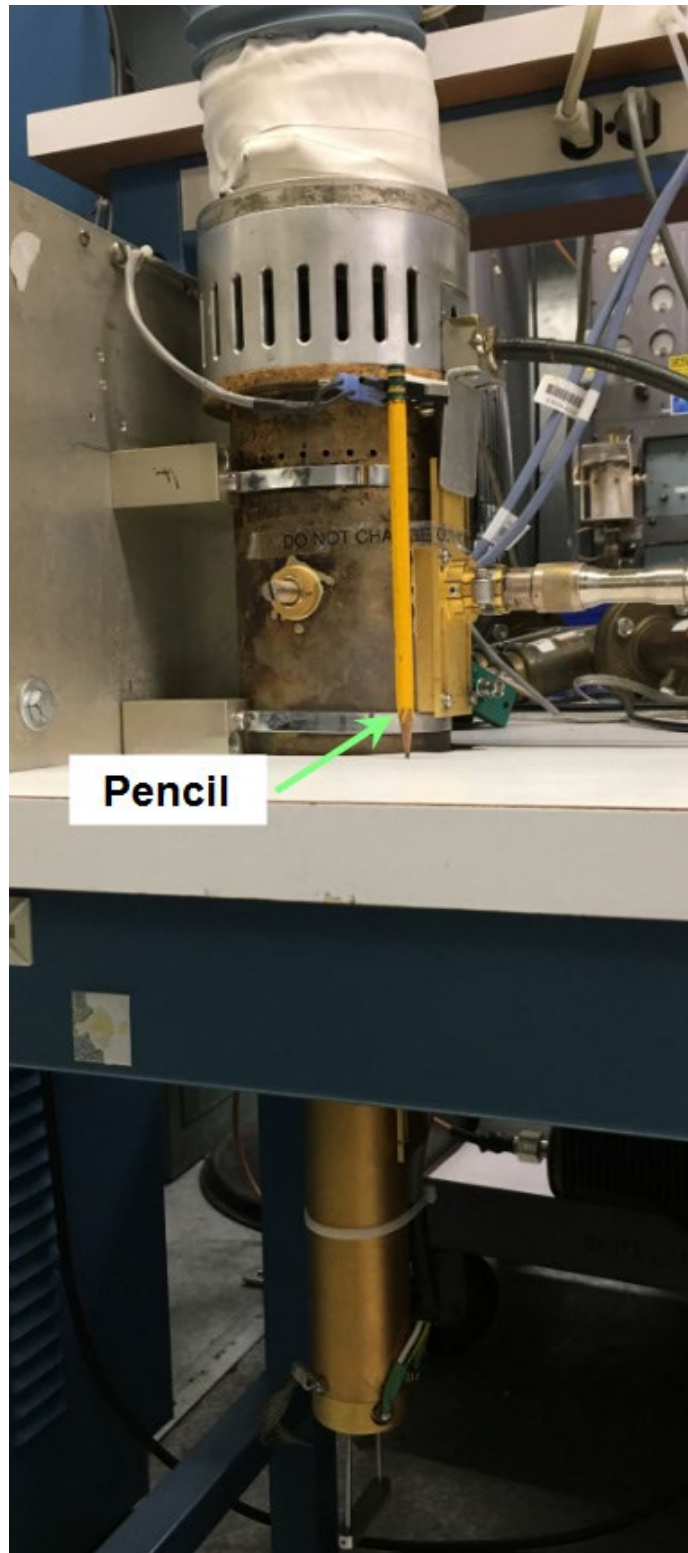
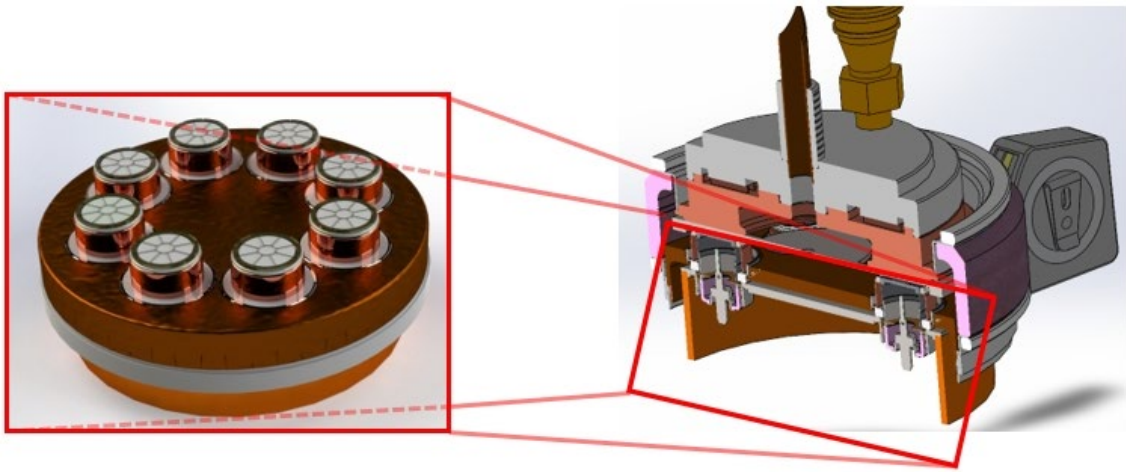


Figure 11. 425 MHz RF source.

This program is developing a multiple beam version of this device to produce 200 kW at 352 MHz [15]. Triode based RF sources consist of a triode that provides the pulsed RF beam, an input cavity that drives the gun grid in Class C, and an output cavity that converts electron beam power into RF power. Consequently, these sources only consist of two coaxial cavities. While efficiencies of 90% can be achieved, they exhibit relatively low gain, with 14 dB being typical. This program is tasked with producing approximately 200 kW of RF power. Consequently, approximately 6 kW of drive power will be required.



**Figure 12.** Elements of multiple beam triode.

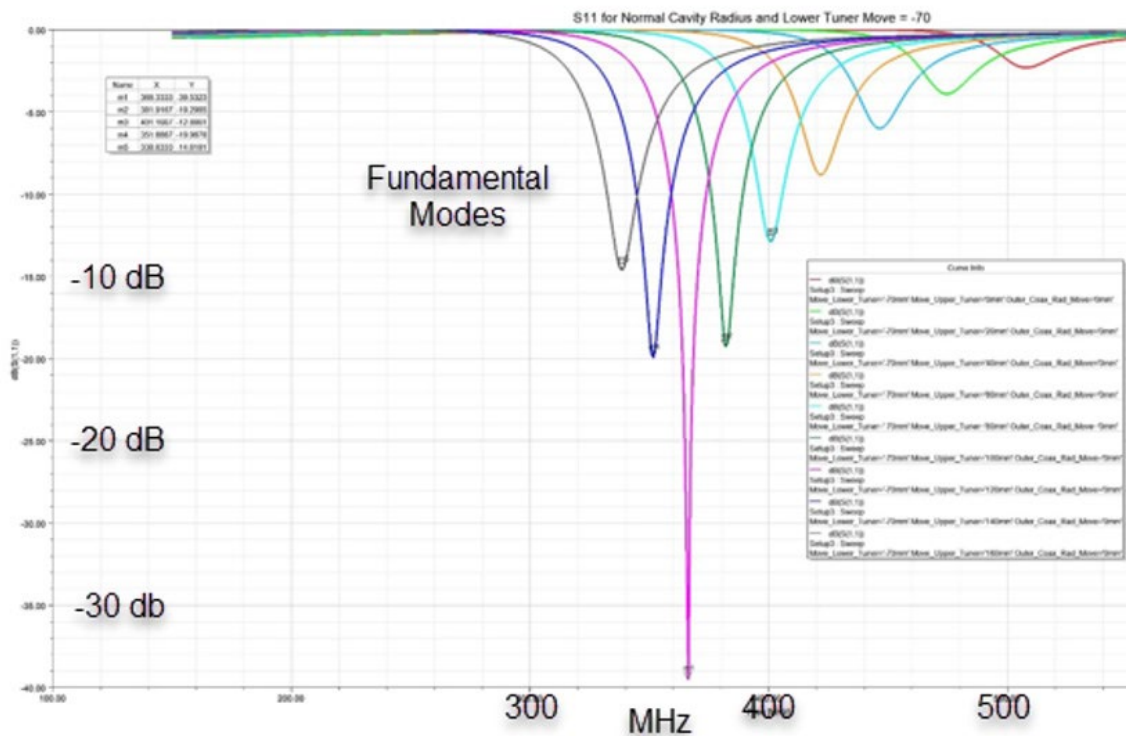


Figure 13. HFSS simulation showing tuning range.

The multiple beam triode consists of eight grid-cathode assemblies from a production triode mounted in a circular pattern on the copper support plate. These are driven in parallel by a common input cavity to produce eight electron beams across the grid – anode gap inside a vacuum tube. Figure 12 shows a solid model of the tube. This is the only component in the RF source that is under vacuum.

The multiple beam RF source incorporates an input cavity below the cathodes and an output cavity that extends above and below the grid-anode gap. Because RF power densities are so low, cooling is only required for the vacuum tube anode and grid support plate. The surrounding cavities are primarily fabricated from aluminum. These upper and lower output cavity sections incorporate sliding shorts which determine the inductance of the coaxial sections. The tuners can be adjusted to achieve resonance at the operating frequency using the tube’s internal capacitance and circuit stray capacitance. Typical tuning range exceeds 150 MHz, as shown in the HFSS simulation in Figure 13. Consequently, a single design can be used for a multiplicity of applications. Figure 14 shows a solid model of the 200 kW RF source with a six-foot human figure, which demonstrates the compactness of the device.





**Figure 14.** Rendering of a 200 kW, 350 MHz multiple beam triode RF source model.

One issue with triode base RF sources is the inherent low gain, typically 14 dB. Consequently, a 6 kW RF source will be required to drive the multiple beam tube. This program will use a single beam triode-based RF source provided by JP Accelerator Works as the RF driver. They are a key collaborator in this research program.

#### **2.1.2.1 Development Issues**

The program encountered two fabrication issues, one electrical and one mechanical. The mechanical issue relates to brazing eight grid-cathode assemblies to a single support structure and ensuring that they are vacuum tight. The program initially encountered materials issues, then design issues, that delayed successful completion of the assembly; however, the tube was eventually sealed and baked. It is clear that any further development must address the fabrication and assembly issues to reduce the cost, improve yield, and increase reliability. This is the most complex and intricate assembly in the device, as eight grid cathode assemblies must be properly integrated into a single, vacuum tight structure.

The electrical issue relates to coupling of the RF fields to the pulsed electron beam in the grid – anode gap. Significant effort was made to model this structure using HFSS; however, the results were not consistent with experimental results for single beam devices. HFSS predicts

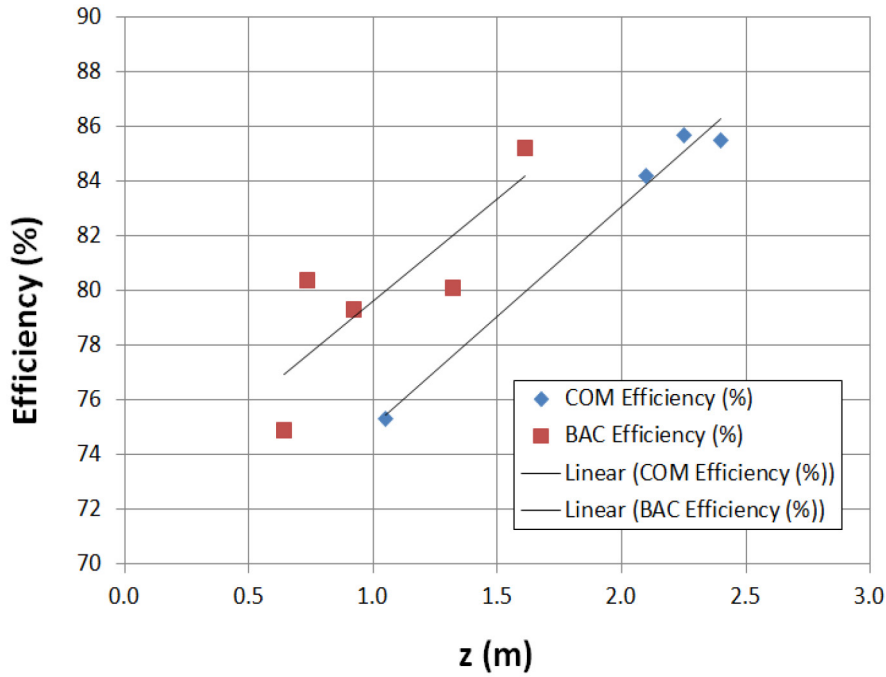
lower beam impedance than is consistent with high efficiency. The variation from experience implies that the complex HFSS model is not accurately capturing the configuration, leading to erroneous results.

Because of the simplicity of the mechanical construction. The plan was to iterate on the mechanical design during high power testing to experimentally investigate and optimize the performance. The cavities include tuners and are assembled with fasteners, so modifying the geometry becomes a relatively simple and inexpensive process. This allows rapid variation of the mechanical configuration without the uncertainties associated with computer modeling. It also would have been significantly faster than analyzing with HFSS.

While testing the tube to obtain current characteristic curves, an intermittent short developed between the grid and anode when anode voltage was increase to approximately 350 V. Hi-potting appeared to clear the grid to anode short but an arc caused a grid to cathode short. Since the cathode and grid are tied among all the guns, it was not possible to distinguish which gun or guns are shorted. This could not be resolved using a Tesla coil, and it now appears that the tube will have to be rebuilt before the development can continue.

### **2.1.3 High Efficiency Klystron**

The U.S. Department of Energy is funding CCR to investigate new approaches to increase the efficiency of klystrons [16]. Specifically, CCR is developing a 100 kW CW, 1.3 GHz klystron with a targeted efficiency exceeding 80%. During the initial research, the program investigated the “Bunch, Align, and Collect” (BAC) method proposed by Gusilov [17] and the “Core Oscillation Method” (COM) proposed by Bajkov [18]. Following extensive analysis of both techniques using AJDISK with optimization and TESLA, it was determined that both approaches could achieve the targeted efficiency, as shown in Figure 15. CCR elected to down select the approach based on mechanical complexity. The BAC approach required fifteen cavities, while the COM approach required eight. As shown in Figure 15, the COM approach requires a circuit approximately 0.5 m longer. After consulting potential users, it was determined that most all facilities could accommodate a longer klystron; consequently, CCR selected the COM design.



**Figure 15.** Circuit efficiency as a function of circuit length for both BAC and COM designs. The klystron was simulated using AJDISK. The voltage was 52 kV and the current, 2.3 A for all designs.

The design was simulated using four codes: TESLA [19], from the Naval Research Laboratory; AJDISK from A. Jensen [20], KLYC from CERN [10], and MAGIC-2D [21, 22]. The results are shown in Table 1. The simulated efficiency agreed within 3%.

**Table 1.** Results for simulations of the klystron.

CODE	Power [kW]	Efficiency [%]
TESLA	104.5	79.5
AJDISK	106	81
KLYC	103.5	79
MAGIC	102	78

Table 2 provides the operating parameters, Figure 16 shows the cross section of the klystron, and Figure 17 shows a klystron assembly without the solenoid. The tube was successfully assembled and baked in January 2023 and is now being prepared for high power testing during March and April 2023.

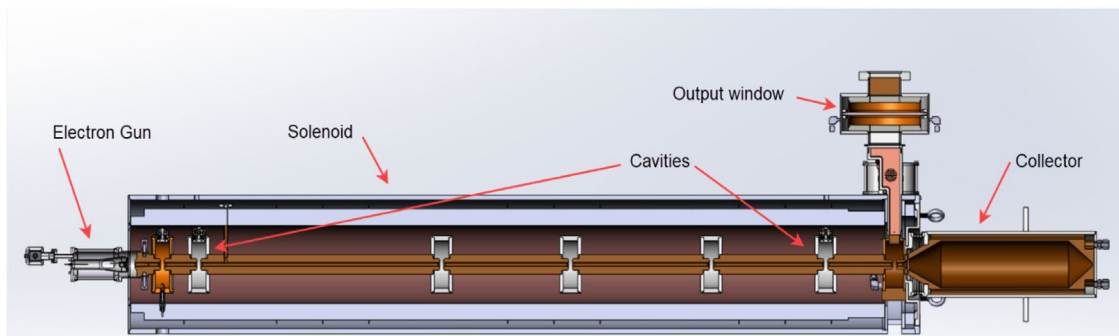
**Table 2.** Operating parameters for 1.3 GHz klystron [23].

Parameter	Value
Power	104.4 kW
Frequency	1.3 GHz
Voltage	53.5 kV
Current	2.46 A
Efficiency	79.4%

Number of cavities	7
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There are two significant challenges related to tube assembly. The first is associated with the cavity frequencies and  $Q_s$ . Simulations define the tolerances associated with these parameters, which are quite specific. Tuners were incorporated into cavities where the frequency must be particularly precise. Each cavity is cold tested and modified as required to achieve the required performance. As cavities are completed, the computer models are updated with the measured parameters to ensure the target efficiency can be achieved.

**Figure 16.** Cross section of the klystron. The length is 2.8 meters.



The second challenge is ensuring the tube remains straight during bakeout, transport, and installation into the test set. The copper beam tunnels are quite long, so the circuit is enclosed within a stainless-steel cage. This cage must accommodate the differential expansion that will occur between the cage and the copper drift tubes. Following bakeout, the tube must be moved horizontally from the assembly building to the test building, a distance of 500 meters.



**Figure 17.** High efficiency 1.3 GHz klystron assembly without the surrounding solenoid.

#### **2.1.4 Multiple Beam IOT**

A major goal at DOE is development of high efficiency, MW-class, high duty RF sources for several potential applications for RF power. Recent demonstration of 1.2MW multiple beam IOTs (MBIOTs) by CPI-Thales and L3 Electron Devices (L3) demonstrated that these sources can provide this level of power, at least at low duties [24,25]. These devices, though achieving the power and efficiency specifications, were quite complex and expensive. The goal of the CCR program is to investigate techniques for increasing efficiency and reducing the cost. Consequently, the program is focused on three innovations.



**Figure 18.** Input coupler for CPI MBIOT for the European Spallation Source.

These include:

- Adding 3<sup>rd</sup> harmonic drive power to improve electron bunching,
- Employing a power splitter approach to simplify the input coupler,
- Replacing pyrolytic graphite grids with moly grids to reduce cost and risk.

The operating parameters are provided in Table 3.

**Table 3.** MBIOT operating parameters.

<b>Parameter</b>	<b>Value</b>
Frequency	700 MHz
Output power	170 kW cw
Beam voltage	30 kV
Average current	6.67 A
Number of beams	8
Gain	23 dB
Target efficiency	85%

The MBIOTs developed by CPI-Thales and L3 employed separate drives and input cavities for each electron gun. For CPI-Thales, this required ten input cavities with drive lines. Consequently, the IOT input section, shown in Figure 18, dominated the device in terms of size and complexity. This complexity was driven by uncertainties concerning the level of amplitude and phase variation that could be present and still provide high power at high efficiency. The separate input couplers allowed variation of drive amplitude and phase for each gun. In the end,

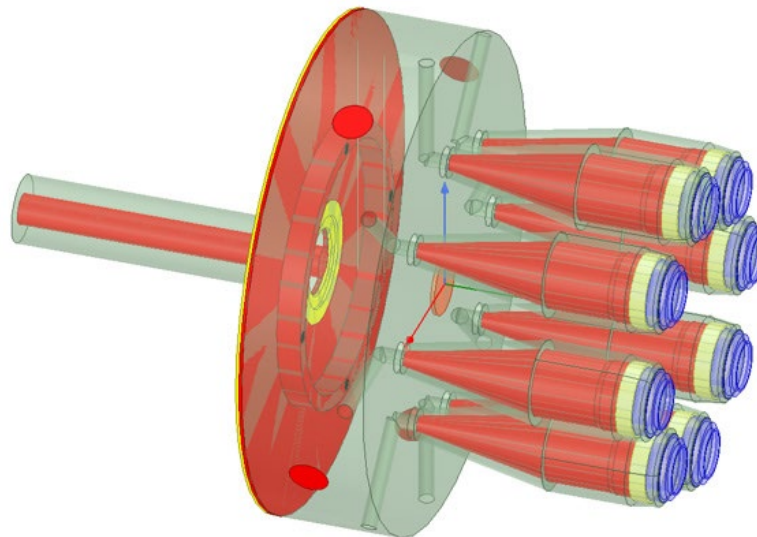
experimental measurements determined that the IOT could handle significant variations in amplitude and phase without significant performance degradation. This was confirmed with tests of the L3 MBIOT. This allowed CCR to pursue a simpler input coupler without the complexity of individual gun amplitude and phase controls [26].

Because multiple guns will provide the beam power, CCR investigated replacing traditional pyrolytic graphite (PG) grids with molybdenum grids. Thermal analysis, including consideration of beam loading in Class C operation, confirmed that moly grids could handle the anticipate heating.

It was anticipated that transitioning from PG to moly grids would be relatively straight forward; however, existing grid manufacturers were not willing to fabricate large grids for the IOT guns because of the engineering and tooling costs. This was coupled by the requirement for only eight grids, plus two spares, for the CCR program. A vendor was finally identified that has an interest in fabricating grids for IOTS and other vacuum electron devices. CCR is assisting this company develop grid fabrication capabilities, and prototype grid fabrication is currently in progress.

The final innovation is the addition of 3rd harmonic power to the drive signal. Analysis with the advanced simulation code NEMISIS predicts a 2 – 4 % increase in efficiency with the addition of 3rd harmonic drive [27]. Optimum performance is predicted when the 3rd harmonic is approximately 40% of the fundamental and phase shifted by  $\pi$  radians. This primarily impacts electrons outside the main bunch created by the fundamental drive.

Significant effort was required to develop an input coupler that provided adequate transmission of both the fundamental and the 3rd harmonic. While the 3rd harmonic match is not optimum, it should be adequate to evaluate the impact on MBIOT performance. Figure 19 shows the input coupler geometry interfaced to the eight-gun assemblies. CCR will use a commercial combiner to input the fundamental and 3rd harmonic signals into the input, coaxial transmission line.



**Figure 19.** Input coupler geometry.

A key question is whether or not the increased cost and complexity for the 3rd harmonic drive is justified by the efficiency increase achieved. One must consider the cost for an additional driver, combiner, and control system in comparison to the reduced operating cost from higher efficiency.

Performance of the moly grids was simulated using CCR’s Beam Optics Analyzer (BOA), which includes 3D, finite element, time domain analysis of the electron beam with complete thermal analysis of the grids. The thermal analysis incorporated the pulsed heating from beam interception and continuous radiant heating from the cathode.

Heating of PG grids is dominated by radiant heating from the cathode due to its emissivity. The simulated PG temperature is approximately 600°C, while the moly grid temperature is approximately 470°C. When RF is initiated, the temperature increase for the PG is significantly less than for moly, as is the thermal displacement. The PG grid displacement is approximately 7 μm, while that for moly is approximately 54 μm. The electron gun design compensates for this increased displacement. In all cases, the moly grid remains well below stress limits and temperatures that could result in grid emission.

### 3. Status and Estimated Costs

#### 3.1 Magnetron

##### 3.1.1 Estimated cost

The principal components of the system include the magnetron, solid state locking amplifier, 4-port circulator, power supplies, and control electronics. The system shown in Figure 4 included a klystron and its power supplies, which experiments confirmed could be replaced with a solid-state amplifier. The estimated cost for the upgraded system is provided in Table 4. The estimate is for a single system, without the magnetron power supply/modulator. The modulator should cost less than that for an equivalent klystron, since the voltage will be lower. There would be a considerable cost reduction if multiple systems were purchased. For example, for twenty magnetron-based systems, the cost for each would be less than \$84,000. This is less than \$1/W of delivered RF power.

**Table 4.** Estimated cost of a 100 kW 1300 MHz magnetron system with amplitude and phase control.

<b>Component</b>	<b>Cost</b>
Magnetron	\$72,000
500 W SS amplifier for locking	\$17,000
Circulators w/waveguide	\$20,000
Controls	\$10,000
Package	\$10,000
<b>TOTAL</b>	<b>\$129,000</b>

##### 3.1.2 Applications to accelerators

The interface between the magnetron system and an accelerator will vary with configuration, but some general observations can be made. The primary difference between magnetron and klystron driven systems is the technique for controlling the frequency, phase, and amplitude. For the magnetron driven system, the frequency and phase are controlled by a locking signal as shown in



Figure 7. The CCR system includes a high-power amplifier requiring a control signal of approximately 1 W. This can be generated with a standard signal generator, such as the SG380 RF Signal Generator from Stanford Research Systems [28] and a low cost, low noise amplifier. Slow control of the magnetron amplitude can be accomplished by adjusting the voltage or solenoid current. The magnetron voltage and the solenoid current must be adjusted simultaneously to achieve a specified combination of power and frequency.

When driving a superconducting cavity, the amplitude can be rapidly adjusted using phase modulation. Power in the sidebands, outside of the narrow acceptance band of the cavity, will be reflected into the circulator load. As shown in Figure 8, the power in the center frequency is a monotonic function of the phase modulation amplitude. This can be controlled with the SRS signal source through a 0 -1 V DC input signal.

Control of accelerator cavity input power based on beam loading can be accomplished using a feedback loop. Chase et al. presented the details of such a loop in a low power demonstration of the technology using a 2450 MHz magnetron at Fermilab [12].

Since the magnetron's efficiency is almost constant from 30% - 100% of the design power, the power can be tuned close to that required for a particular accelerator cavity, with phase modulation producing fast corrections in the amplitude. This differs from a klystron, where operation at significantly less than the optimum power results in decreased efficiency.

### **3.1.3 Summary of magnetron system development**

This research program demonstrated a high efficiency, magnetron system with phase and amplitude control for driving high Q accelerator cavities. The system produced 100 kW at 1.3 GHz with 1.5 ms pulses. A locking bandwidth of 0.9 MHz was obtained with a drive signal 25 dB below the magnetron output power. Consequently, the system can be controlled at full power with a 316 W locking signal, readily available from commercial, solid-state sources.

The demonstrated average power was about 300 W, which was limited only by the available test time. The design was scaled from a 100 kW, 915 MHz device, and it has been reported that 30 kW of average power was achieved.

### **3.1.4 Further development of magnetrons**

Magnetron tubes are inexpensive, so the cost of replacement is not a concern for the process heating industry (drying wallboard and lumber) which is a major user of magnetrons. For HEP, the concern would be process interruption on a frequent or irregular basis. Longer lifetime and a more dependable mean-time-to-failure is necessary for adoption of this power source. Two significant reasons for the present state of tube lifetime are:

- Anode sputtering of the cathode material.
- Cathode bombardment by backward electrons

General measures which may be taken to address these issues are:

- Active vacuum pumping of the magnetron
- Electron dynamics optimization

Attention to electron dynamics may also improve the magnetron efficiency. Recent investigations show [29, 30, 31] that magnetron efficiency may be improved together with lifetime extension by operating in a sub-critical operation regime with a larger locking signal.

IARC at Fermilab is developing of a compact, super conducting RF (SRF) electron accelerator. This effort is exploiting Fermilab's expertise in conduction cooled, superconducting, Nb<sub>3</sub>Sn coated cavities. The economic and efficiency (see Figure 1) advantage of the SRF accelerator will not be realized until more efficient RF sources are available. With these thoughts in mind, IARC at Fermilab has outlined a program to address these issues of magnetron lifetime and efficiency. The program details are:

1. Use the 3D simulation code, MICHELLE [32], to understand in detail the beam dynamics of a magnetron. The emission model will need to be modified to take into account tangential DC magnetic fields on the cathode as they have been developed and tested for high-power electron guns for electron cooling [33]. The simulation code should be modified also to simulate the transient processes of tube excitation and operation regimes – like it has been done for IOT modeling [34].
2. Next, the code will need to be benchmarked with the collaboration of a company with experience in high-power magnetron development.
3. Finally, it would be possible to optimize the magnetron design to improve its longevity and efficiency and optimize various operation regimes. Different options could be explored, like 2D harmonic cavities, different types of cathodes including the newly developed Nanocomposite Scandate Tungsten cathodes [35].

The goal would be to achieve an efficiency of more than 85% with tube lifetime of ~50,000-80,000 hours.

### **3.1.5 System development**

As noted in Section 3.1.1, the magnetron is but one component in the RF source system. In addition to the development of better performing magnetrons themselves, further work on complete RF systems is needed. As noted in Reference 8, a 100-kW system has been assembled and operated at full power but at a low duty factor. Appropriate funding and focus is needed to better characterize this or similar systems. Other elements of the RF system also need development to support magnetron operation. For instance, DC power supplies are a large part of the ancillary components but have stringent regulation requirements.

## **3.2 Multiple Beam Triodes**

### **3.2.1 Estimated cost**

CCR and CPI began investigating the potential to dramatically increase triode power using multiple beams in 2016. A triode consists of a flat cathode, flat grid, and a flat anode/collector surrounded by a ceramic insulator. There is no magnetic field or focusing optics. The multiple beam device uses the grid cathode assembly from CPI's YU-176 triode. The assembly consists of a nickel cylinder with a barium oxide coating (the cathode), a grid cut with scissors from a tungsten screen, and the appropriate support rings and ceramics. Figure 20 shows a photograph on one assembly. These are in production at CPI and cost less than \$1,800 each.



**Figure 20.** Grid-cathode assembly

Oxide cathodes are extremely simple and inexpensive; however, they are limited to an average current emission density of 0.25 A/cm<sup>2</sup> for CW operation. Even though triodes operate in Class C, the RMS average current emission density of the YU-176 cathode is 1.45 A/cm<sup>2</sup> for 25 kW operation. Consequently, the duty is limited to less than 18%. A dispenser cathode for the YU-176 costs approximately \$2,800 in quantities of ten or more. One still must add the grid assembly, which can be the same as used with the oxide cathodes.

The parts cost for the multiple beam tube prototype with oxide cathodes was approximately \$38K. The addition parts cost for the cavities and other components was approximately \$35K. Most labor and assembly cost are associated with the vacuum tube. There's only one braze for the outer cavities, and everything else is welded or attached with fasteners. It's anticipated that the complete 200 kW multiple beam RF source will cost approximately \$100K. Adding \$35K for the single beam, triode-based driver brings the total cost to approximately \$150K, for a cost per Watt of 75 cents. Cost could be significantly less for production quantities.

### **3.3 High Efficiency Klystron**

#### **3.3.1 Estimated cost**

It is premature to provide an accurate estimate of the cost, since the klystron is fairly complex and expenditures to date include considerable non-recurring engineering costs. The parts costs for the prototype klystron were approximately \$115K, and the solenoid cost approximately \$64K. The labor hours expended on the prototype klystron are quite high, exceeding 1000 hours, as is typical for any first-time build, and these should drop significantly for future builds. Bakeout, processing,

and testing cost will also add to the total. It would not be unreasonable for the total cost to exceed \$400K, or \$4/Watt for the klystron and magnet.

One task for high power testing will be looking for opportunities to simplify the design or flexibility in parameters, such as cavity tunings, that could lower the cost. In the end, there will probably be a tradeoff between acquisition cost and operating cost. If the klystron efficiency exceeds the goal of 80%, the acquisition cost might be justified by the long-term operating cost, particularly for a CW device.

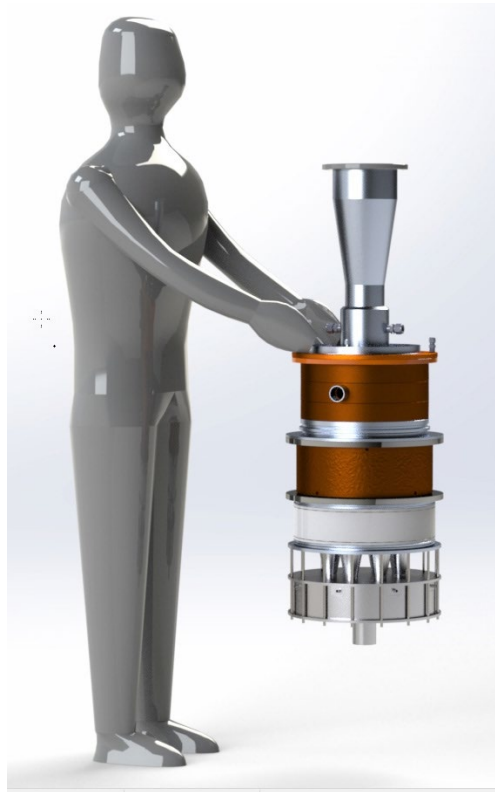
### **3.3.2 Summary of high efficiency klystron development**

The goal of this program is to determine the efficiency that can be achieved using advanced circuit design approaches and quantifying the additional fabrication cost, specifically for the COM approach. For applications where a longer tube is acceptable, successful demonstration of high efficiency in the prototype klystron may provide a roadmap for future klystron development. This research program is focused on precisely fabricating the klystron according to the design parameters identified by extensive computer analysis and optimization. The goal is to provide the best opportunity for demonstrating high efficiency operation in a high-power klystron.

## **3.4 MBIOT**

### **3.4.1 Program status**

Design of the electron gun, input coupler, output cavity, output window, and collector are complete. The MBIOT will use a common, cylindrical collector for all eight beams. Figure 21 shows a solid model of the MBIOT. Drawing are in progress and parts procurement will begin as drawings are finalized and released. The program has been plagued by major supply chain issues. Cathodes for the eight guns were initially due in fall 2022 and are now scheduled for delivery in spring 2023. The high voltage ceramics were due in November 2022 and are now forecast for March 2023. The solenoid, scheduled for delivery in January 2023, is also forecast for delivery in March 2023. As previously described, a qualified vendor for the moly grids is still not available. The program is currently focused on fabricating and demonstrating functionality of the simplified input coupler using low power RF testing.



**Figure 21.** Solid model of 700 MHz, 200 kW MBIOT

### 3.4.2 Estimated cost

Since few parts have been procured, estimating the MBIOT cost is only speculative, at best. The electron gun is based on the K2 gun used in production tubes at CPI. Previous cost was approximately \$15K each, suggesting the eight guns for the 700 MHz tube will cost approximately \$120K. The high voltage ceramic assembly cost is approximately \$20K, and the coaxial output window cost is estimated to be \$20K. The remaining metal parts are fabricated primarily from copper and stainless steel, and none appear to be problematic. Estimated cost for the remaining parts is \$50K. The MBIOT requires a solenoid for beam transmission with a cost of \$20K. This brings the total parts cost to approximately \$230K. The MBIOT should be somewhat easier to assemble, manage, and transport than the klystron, since it's more compact and mechanically robust. A reasonable estimate for the total cost of a tube and magnet would be \$350K. For a 200 kW source, this is \$1.75/Watt.

### 3.4.3 Summary of MBIOT development

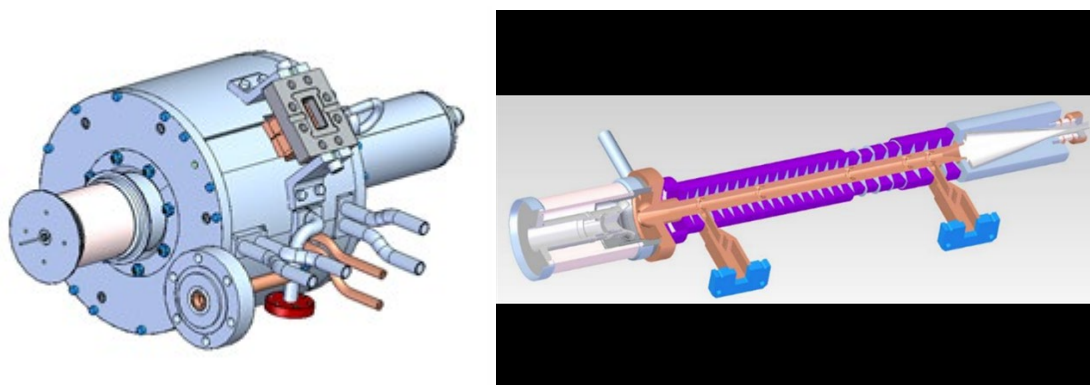
Recent experimental results demonstrated that MBIOTs can provide MW levels of RF power at high efficiency. Fabricating reasonable cost MBIOTs at MW-relevant power levels and high duty remains to be demonstrated and is the principal thrust of this program. Significant cost reduction will be demonstrated if the input coupler design is successfully implemented. The program could also determine the potential impact of 3rd harmonic drive on RF performance. Computational design is complete and drawing generation is underway. Parts procurement began in summer 2022 and is still in progress. Given on-going supply chain issues the earliest the tube could be tested

would be fall 2023, and it is anticipated that additional funding will be required to complete the development.

#### 4. Basic research needs to improve cost/capability

##### 4.1 Near-term R&D: Multi-use RF source technologies

In the near term, research institutions should identify and aggressively pursue new applications of RF sources and accelerator systems in the commercial, defense, and medical sectors; and to the degree possible, develop broadly useful RF source topologies that could have a need in high volume production. As one example, compact low-voltage klystron amplifiers are being developed for use in multiple linac-based radiography systems (see Figure 22). If such a “building block” RF source can be optimized for use in small and large accelerator systems alike, and standardized as much as possible, then commercial opportunities and real competition between suppliers would drive significant cost reductions. Compare this to the approach of using custom-designed RF sources for a single facility, and the path to improved cost/capability is clear.



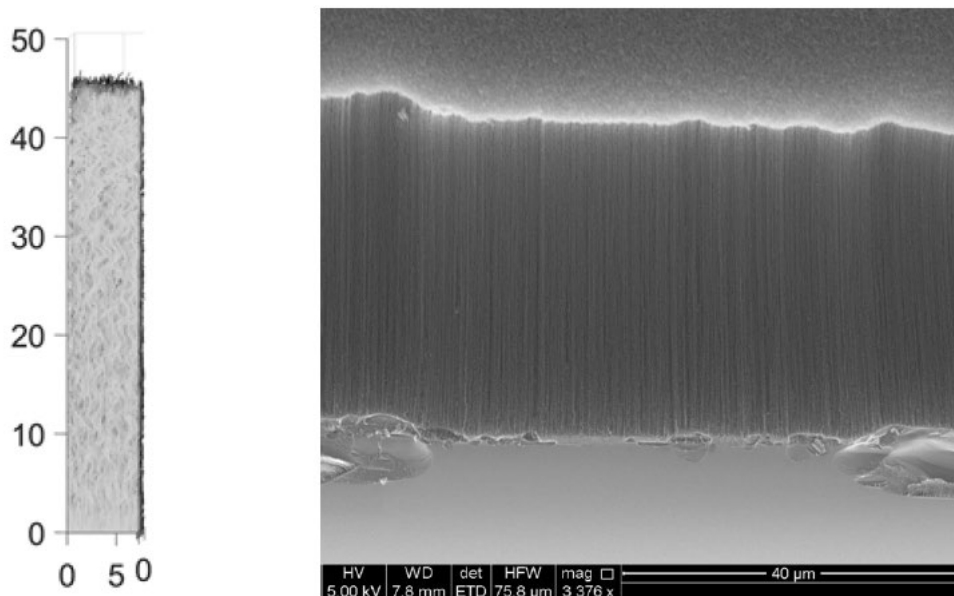
**Figure 22.** Examples of compact, low-voltage klystron designs for commercially compact accelerator systems, which could be standardized and produced at large volume [36].

In the longer term, investment in fundamental research on RF sources – complete prototypes, components, and the underlying physics of devices and components – is essential for the order-of-magnitude cost and efficiency improvement demanded by a future collider. The major cost drivers of many RF sources tend to be the same: the electron source, focusing magnet, and complexity of assembly and handling (i.e., multiple brazing steps, cleanliness, and vacuum compatibility). These pain points should all be attacked in parallel because a breakthrough in any one area will create new opportunities in the others. For example, if a high current density electron source can be generated that is less sensitive to impurities than thermionic cathodes, then perhaps the source can operate with a lower quality vacuum, and the assembly process can be simplified. Similarly, advances in microfabrication or additive manufacturing could enable new field emitters or focusing magnet topologies, respectively.

##### 4.2 Alternatives to thermionic electron sources

Novel alternatives to thermionic cathodes are needed, especially if they are suitable for massively parallel systems. Plasma cathode electron sources can deliver up to hundreds of Amperes of electron current at hundreds of Volts, and can operate at substantial pressures, partially mitigating

the need for pristine vacuum environments. Advances in the control of carbon nanotube growth and patterning processes (Figure 23), along with their high resilience to ion bombardment, present another possibility, as do microfabricated field emitter arrays.



**Figure 23.** Growth simulation (left) and SEM images (right) of carbon nanotube forest samples for field emitter characterization studies. [36].

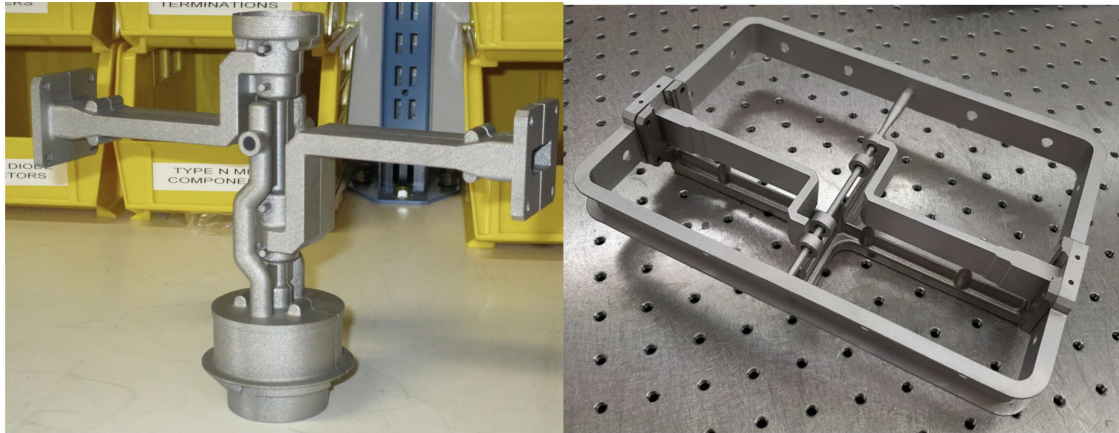
#### 4.3 Simplified focusing / transport of high current beams

Beam focusing in RF sources is another major challenge – with magnets for a single klystron costing tens of \$k themselves, alternative focusing approaches for low voltage beams should be investigated. With recent advances in the capabilities of magnet manufacturers, there should be an effort to develop high efficiency RF sources that only use inexpensive mass-produced magnets designed for larger-scale commercial applications. Potential areas of higher-risk exploration could include multiple stage electrostatic focusing of low voltage beams, self-focusing of high current beams in a plasma background, and hybrid approaches of combined electrostatic and magnetic focusing. These efforts would require significant computational and experimental work but raise many interesting basic physics questions, and in some cases, could be synergistic with R&D efforts in the plasma wakefield accelerator community.

#### 4.4 Advanced manufacturing techniques for RF sources

Additive manufacturing is a promising development for minimizing the touch labor required to assemble an RF source, and the availability of commercial additive processes is growing rapidly. Developing inexpensive additive processes specifically for the niche of vacuum devices is a difficult undertaking. However, widely available additive manufacturing processes are constantly evolving, and many could be suitable for RF source fabrication, but they have not been fully characterized with respect to RF losses, high vacuum, high voltage, etc. In certain subsystems of an RF amplifier, particularly in klystrons where RF ohmic losses are only appreciable near the tube output, or in low-duty operation, additive manufacturing could be feasible (see Figure 24).

When existing additive processes are not suitable, fundamental research in novel additive manufacturing processes should be supported as well.



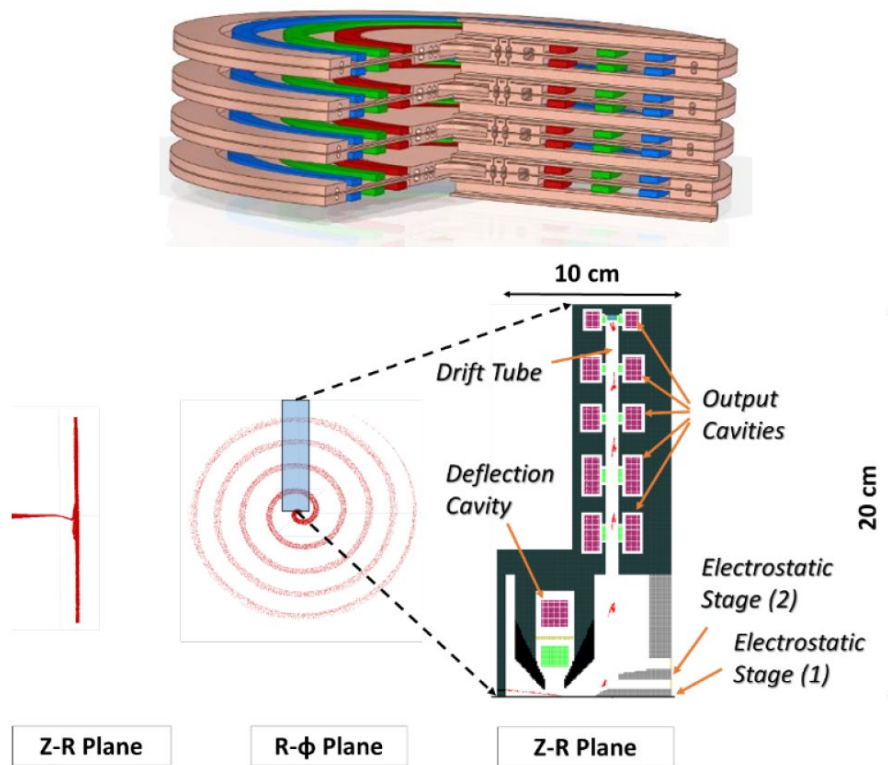
**Figure 24.** Klystron body produced by direct metal laser sintering (left); Mandrel (negative space) of klystron RF circuit (right). [36]

#### 4.5 Unique RF source topologies

Fundamental and exploratory research dedicated to RF sources and their components is essential for more than incremental improvements. One approach to minimizing system-wide costs of RF power involves optimizing the complete RF power chain, which naturally leads to using lower voltage modulators made from mass-produced commercially available components, which are simpler and require less infrastructure and maintenance. Then, new RF sources are needed which can operate efficiently at low voltage and high current. Multiple-beam amplifiers leverage this concept, but this scaling approach can add complexity and does not really solve the fundamental problem - breaking the tradeoff between efficiency and the space charge effects of high current densities that is inherent in conventional linear-beam devices. Reconsidering RF sources in this way raises several interesting fundamental physics and engineering challenges.

As noted above, using multi-dimensional electron beams allows for higher current densities at a given voltage. Another example is shown in Figure 25. This relaxes requirements on the beam focusing magnets and could potentially minimize the impact of space charge on RF efficiency. In another approach, the trajectory of a monoenergetic beam is modulated and interacts with a higher order mode in the output cavity; this could be promising for high efficiency amplification or frequency multiplication.





**Figure 25.** RF source topologies utilizing multi-dimensional beams. Radial klystron array (top); Deflected beam amplifier (bottom) [36]

## 5. Summary

High Energy Physics will always continue to grow in the energy, intensity, and the variety of its accelerator systems. The RF power required will grow proportionally. While a number of facilities are turning to solid state RF power sources, the size and cost of these systems are burdensome. The inefficiency of solid-state sources should make them unacceptable in light of growing climate concerns.

A number of traditional RF sources can provide highly efficient, compact, high-power devices. Currently available RF sources are summarized in Table 5. Active development efforts for improved sources and their projected cost in production are summarized in Table 6. By providing large amounts of power per device, they reduce losses due to combiners and circulators. A development program to further develop devices to match the performance parameters needed for HEP will have great benefit in the long run.

**Table 5.** Comparison of presently available RF sources.

Source	Projected Unit Cost	Efficiency	Average Power	Cost of Average Power in Quantity	Peak Power	Cost of Peak Power in Quantity	Status
Current State of the Art							
Pulsed S-band Klystron	~\$1M	45%	41 kW	~\$24/W	65 MW	~\$15/kW	SLAC 5045
Pulsed X-band Klystron	~\$1M	40%	9 kW	~\$110/W	50 MW	~\$20/kW	SLAC XL4/XL5
CW UHF Klystron	~\$1M	60%	1 MW	~\$1/W	1 MW	~\$1000/kW	SLAC BFK
COTS medical klystron		45%	36 kW		5 MW		
UHF Multi-beam IOT	~\$880k	70%	1.2 MW	\$1.40/W	1.2 MW	~\$730/kW	L-6200 (rough estimate)

**Table 6.** Comparison of projected cost, performance, and status of future RF sources.

Source	Power	Efficiency	Projected Unit Cost	Cost per delivered Power in quantity	Status
Active Prototype Development Efforts					
Magnetron	100 kW +	>85%	\$84k	< \$1/W	Phase and amplitude control successfully demonstrated. Available for scaling to other frequencies and power levels. Electronics for feedback control requires additional design and testing.
Multiple Beam Triode	200 kW	90%	\$150k	< \$0.75/W	Additional funding required for rebuild and test of prototype
High Efficiency Klystron	100 kW	80%	\$400k	\$ 4/W	In preparation for high power tests in March 2023
Multiple Beam IOT	170 kW	85%	\$350k	\$ 1.75/W	Improved input coupler being fabricated for low power testing. Moly grids being fabricated. Will require additional funding to build and test a prototype MBIOT to confirm performance
Solid State	<200 kW	55%		> \$ 10/W	Established, becoming industry standard

The Snowmass community can create more reliable and more energy efficient accelerators. We believe we should embark on this endeavor now, before we are requested to do so by the circumstances. A goal of more reliable accelerators for science and industry is within Snowmass community goals, mission, and capabilities.

## 6. Conclusion

In summary, the high cost of RF power can be a major budgetary constraint for any new high energy physics facility. Although it is often assumed that RF sources are “established,” the truth is the current state of the art is nowhere near what the high energy physics community needs regarding cost/capability. Solving this enormous physics and engineering problem will require significant support for both computational and experimental R&D efforts in RF sources [37]. A real solution demands that we fundamentally re-imagine RF source topologies and rigorously attack the many exciting basic questions that arise from this challenge.

Improving the performance of high-power RF sources will allow us to be responsible environmental stewards in our pursuit of discovery science. A frequently cited benefit of basic science is spin-offs of technology. These improved RF sources will then be available as efficient sources for many industrial accelerator systems that presently rely on less efficient sources. For instance, two recent design studies of industrial high-power SRF e-beam industrial accelerators have shown their cost and energy efficiency to be limited by the RF source [38,39]. These would greatly benefit from the availability of high-efficiency RF sources.

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