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RF Sources for Electron Accelerators

With a focus on high-duty-factor, low-to-moderate energy architectures

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INTRODUCTION

This document summarizes options for radiofrequency (RF) sources for space applications, specifically for electron accelerators.

Fundamental Concepts and Notation

A charged particle, such as an electron or a proton, is accelerated through its interaction with either a static (DC) or time-varying (RF) electric field. The magnitude of the accelerating field, or gradient, is typically given in units of volts per meter; in charged-particle accelerators, fields are usually expressed as kV/m or MV/m. The energy of the accelerated particle is usually expressed in terms of electron volts, or eV. An electron starting at rest at ground potential, and accelerated to an electrode with a potential of 1 kV, will have an energy of 1 keV.

DC-based accelerators are limited both by the achievable potential difference across the accelerator (e.g. maximum sustainable voltage), and by the resulting field gradients applied to surfaces inside the accelerator. If surface gradients become too large, the structures can "arc" – that is, an electric discharge occurs within the accelerator structure. The largest DC-based accelerators have achieved voltages of ~ 25 MV, but are typically built as multi-story towers. Typical "high-gradient" DC electron beam sources (or guns) operate reliably up to 350 kV; gradients up to 10 MV/m inside the gun body have been achieved. Most DC guns, however, operate at lower voltages and lower gradients. In a space environment, a DC potential difference – whether for an accelerator, or another application – can drive current flows in the background plasma, and thus presents additional constraints. Such currents represent parasitic power loss, and result in damage to components due to ion impact at voltages ranging up to the operating voltage of the beam source.

Most DC-based electron guns require additional equipment, beyond a high-voltage power supply, to generate and control the emission of the electron beam; for instance, a thermionic cathode electron source requires a heater power supply for the cathode, and if the cathode is gridded to gate emission, a power supply to provide the grid control voltage is also needed. Typically such ancillary systems are "floated" on a high-voltage deck at the same potential as the cathode. This increases the overall complexity of the beam source: the additional equipment must be high-voltage isolated, and must be supplied power at the same potential as cathode. For instance, a typical cathode might require 5 W to raise it to operating temperature; if the electron gun is operating at 25 kV, the heater power supply is "floated" at 25 kV, and its operating power (5.5 W, if the heater supply is 90% efficient) must be either supplied by the 25 kV power supply, in addition to any beam power, or via high-voltage isolation transformer.

An RF-based accelerator uses a radiofrequency generator to excite a mode within a resonant structure, or cavity, whose time-varying fields are used to accelerate a charged particle beam. The fields in the cavity are a function of position and time, and can be expressed as a product of a spatially varying field, the spatial "mode pattern," and a sinusoidal time-dependent term, for instance:

$$\vec{E}(x, y, z, t) = E_o \overrightarrow{E_m}(x, y, x) \cos{(2\pi f t + \phi)} \tag{1}$$

where E_o is an overall amplitude term, E_m describes the normalized electric field magnitude and direction as a function of position within the cavity, f is the resonant frequency of the mode, and ϕ is a phase offset.

There is no DC standoff voltage as such within the accelerating structure, and the shell of the accelerator structure is at ground potential, so no current flow is excited in the background plasma external to the accelerator. The oscillating nature of the field within the structure allows much higher gradients to be achieved without arcing. Accelerating gradients well in excess of 100 MV/m have been achieved, and many RF accelerators routinely operate at gradients of 50 MV/m or higher. The upper bound on particle energy is given by the combination of gradient, and length of the accelerator; the SLAC Linear Collider, for instance, routinely generated electrons at energies in excess of 45 GeV. Within the accelerator, any background ions will tend to "quiver" in the RF field, but not experience significant acceleration otherwise[1].

Typical RF-based accelerators are constructed from OFE copper and operated at or near room temperature; or are constructed from niobium and operated at 2-4 K. The former are usually referred to as normal-conducting, or NC, accelerators; the latter are superconducting, or SC. NC accelerators are, typically, simpler to design, build and operate; but can require substantial amounts of RF power to achieve high gradients. SC accelerators are far more efficient in terms of RF power use to obtain a given accelerating gradient, but require complex cryogenic and resonance-control systems. For the purposes of this discussion we will focus on NC structures.

RF-driven electron beam sources, in contrast to DC sources, operate at ground potential, so there is no high-voltage isolation required for ancillary equipment such as cathode heater power supplies. While the oscillating nature of the accelerating field can add complexities to the operation of an RF-driven beam source, such sources have been fielded for decades, with generally high reliability.

RF power and field scaling[2]

The field in a resonant cavity is driven by the application of RF power to that cavity from an external RF power source. The shunt impedance, R_s, of an RF-based accelerator describes the relationship between the electric field gradient in the accelerator's cavities (and thus, the voltage to which electrons can be accelerated), and the RF power required to generate those field gradients. Written in terms of the shunt impedance $R_{s,acc}$ of the accelerator viewed as a single structure,

$$P_{wall,mp} = \frac{V_{acc}^2}{R_{s,acc}} \tag{2}$$

where V_{acc} is the output voltage of the electron beam generated by the accelerator, and $P_{wall,mp}$ is the RF power dissipated in the walls of the accelerator. For a given RF-driven accelerator, then, doubling the output voltage will result in quadruple the power dissipated in the walls of the accelerator.

If a beam with a "macropulse" current I_{mp} is being accelerated, then the power delivered to the beam is

$$P_{beam,mp} = I_{mp} V_{acc} \, . \tag{3}$$

This power must also be supplied by the RF system, so the total RF power required when the accelerator is operating, with the accelerator delivering a beam of current I_{mp} at voltage V_{acc}, is:

$$P_{rf,mp} = P_{wall,mp} + P_{beam,mp} = V_{acc}\left(\frac{V_{acc}}{R_{s,acc}} + I_{mp}\right). \tag{4}$$

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[1] A pondermotive force can be defined for ions in high-frequency RF fields, such as would be the case in an electron accelerator; typically, ions would be accelerated to only a few tens of keV, and the direction of acceleration is generally away from high-field regions.

[2] There are several ways the concepts in this section can be formalized; the approach we take is somewhat non-standard but is well suited to accelerators composed of relatively small numbers of independently driven resonant cavities.

RF accelerator duty factor

Most normal-conducting accelerators do not operate continuously, or CW. Rather, they are typically pulsed, providing beam during a “macropulse” that lasts for a given duration, and is repeated periodically. The overall duty factor of the RF source is:

$$DF_{rf} = \tau_{mp} f_{rep} \tag{5}$$

where τ_{mp} is the macropulse duration in seconds, f_{rep} is the macropulse repetition rate in Hz, and DF_{rf} is the net duty factor of the RF source, or fraction of time the source is “on” during a nominal period of time, for instance one second. The duty factor for NC accelerators can be limited by the capabilities of the RF source driving the accelerator, by the ability to remove waste heat from the accelerator structure, or a combination thereof.

The duty factor of the beam, DF_{beam}, will always be less than the duty factor of the RF source. After the RF source begins to provide power, a “fill time” τ_{fill} is required for the RF structure to reach operating gradients. The relationship between RF and beam duty factors can be expressed as

$$DF_{beam} = \left(\tau_{mp} - \tau_{fill}\right) f_{rep} = DF_{rf} - \tau_{fill} f_{rep}. \tag{6}$$

Generally, the fill time is on the order of 2000 - 5000 RF periods for NC structures; so, an S-band structure resonant at 3 GHz, or with a period of 333 ns, would have a fill time on the order of 1-2 μs. The shorter the RF macropulse duration, the larger the reduction in beam duty factor versus RF duty factor. As the RF macropulse duration approaches the fill time, the beam duty factor – and thus beam average power – becomes significantly reduced. So for applications requiring high average power, higher duty factors tend to be preferable.

Multiplying the terms in Eqn. (4) by the beam duty factor, provides the equivalent time-average beam current and power, etc. Note that the average RF power required is higher than implied by Eqn. (4), because RF power must be supplied during the cavity fill time as well as when beam is being generated.

Cavity size and frequency range

For electron accelerators, we consider operating frequencies in roughly the range of 1 – 10 GHz. The diameter of the accelerating structure is inversely proportional to the frequency; a “pillbox” cavity resonant at 1 GHz has an inner diameter of nearly 23 cm and length of 15 cm (for a “speed-of-light” cavity), so is becoming relatively large and heavy, especially if made of copper. At 10 GHz the cavity ID is only ~2.3 cm and length ~ 1.5 cm, or a factor of 10^3 smaller enclosed volume. However, there are disadvantages to increasing the frequency. For instance, the size of the apertures through which electron beams enter and exit the cavity impact the cavity’s shunt impedance, with smaller apertures leading, all else equal, to higher shunt impedance and more efficient cavities. While the relative size of the apertures to the cavity diameter may remain approximately constant – typically on the order of 1/10 to 1/20 the cavity diameter – in absolute terms, as frequency increases the aperture sizes shrink, posing a potential limit to beam current. Machining, surface finish and alignment tolerances scale inversely with frequency, as do the size of ancillary structures such as power couplers, tuners, etc. At higher frequencies, all else equal, the accelerator structure will have thinner walls between adjacent cavities, which can complicate heat removal. We therefore select 10 GHz as a somewhat arbitrary upper limit on frequencies to consider at this time, given the above considerations.

RF POWER SOURCE OPTIONS

The parameter space of available RF power sources, even within the limited frequency band selected, is quite large.

To start narrowing the range, we will focus on RF power sources capable of operating at duty factors of at least 0.1%. Then, for purposes of discussion we will consider three regimes (with soft boundaries) of RF power: low power (up to several kW per individual source); moderate power (between a few kW and ~ several hundred kW per individual source); and high power (greater than several hundred kW per individual source).

Common elements

Regardless of its RF power source, an accelerator will have several critical subsystems. These include the low-level RF and timing system, responsible for monitoring and controlling the performance of the high-power RF system and accelerator; electron beam focusing and diagnostics systems; and the thermal management system.

The design of the low-level RF system will be highly dependent upon the high-power RF amplifier selected, so useful generalizations as far as size, power consumption, etc., are difficult to make. However, in general, the more high-power RF amplifiers there are, the more complex the low-level RF system must be.

The focusing and diagnostics system details will depend on the specifics of the accelerator design, in turn driven by the RF power source chosen. Generally, however, in the energy ranges of probable interest (several MV to several tens of MV), the focusing and diagnostics elements are relatively straightforward to design and implement.

The operation of any RF-driven accelerator results in waste heat generation in two primary locations: power dissipated on the walls of the accelerating structure, as described above; and power dissipated in the high-power RF amplifiers. Beyond simple waste heat removal, the accelerator structure will generally require temperature stabilization to maintain it at its design resonant frequency. Again, the thermal management system must be tailored to the specific design of the accelerator and RF power source, so generalizations are difficult.

Low-power sources

For space-based applications, currently the most attractive low-power sources appear to be solid-state amplifiers[3]. These devices typically operate with input power voltages of 50 – 150 V, in principle allowing them to be run directly from a battery pack without further power conversion needed. Some designs are capable of operating at up to 70-80% efficiency (ratio of output RF power to input DC power), peak output power of 5+ kW, and duty factors of up to 10%. From an accelerator standpoint, these amplifier chips may be considered to be broadband, with bandwidths typically on the order of 10% or more. Most commercial offerings appear to be for frequencies in the range of 0.5 – 1 GHz; however, Cree/Wolfspeed[4] developed a series amplifier chips extending from L-band (~ 1 GHz) to Ku-band (~18 GHz) with substantial power output and high duty factors, and other vendors are following suit. Gain is

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[3] We refer to these sources as “chips” generically; some manufacturers offer miniature palletized systems instead of a standalone discrete component.

[4] Wolfspeed has since sold its RF line to Macom

typically approximately 10-20 dB, so significant preamplifier stages may be required. The output is generally delivered via coaxial 50-ohm cable.

Figure 1 plots peak output power vs. operating frequency for current-catalog RF amplifier chips from Macom, Wolfspeed (now part of Macom) and Integra.

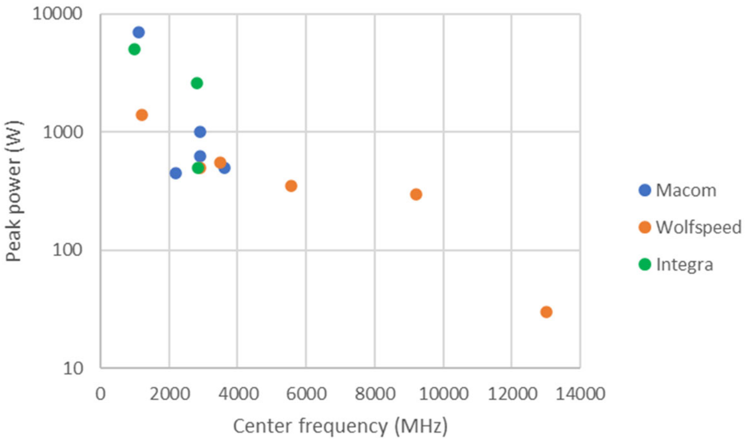

Figure 1: A selection of current-catalog RF amplifier chips.

Cree/Wolfspeed C-band (5 GHz) amplifiers were used in the initial R&D work at LANL on RF electron accelerators for space-based applications, and used for the BeamPIE experiment.

To date, most applications of solid-state amplifiers for driving accelerators, such as the LCLS-II/HE free-electron lasers, have combined the power output of many chips as part of a single RF station. While this is effective at modest powers (the LCLS-II/HE amplifiers, for instance, are 7 kW CW at 1.3 GHz), at higher power the losses associated with many combining stages can lead to net efficiency loss. The accelerator architecture developed for the CONNEX concept addresses this by powering each cavity in the accelerator with a single (or several) RF amplifier chip, each of which is independently phased. The approach takes advantage of the scaling of Eqn (3) by trading per-cavity accelerating voltage for overall accelerator length: modest reductions in accelerating voltage per cavity can result in significantly lowered waste power.

The CONNEX architecture, with a highly distributed high-power RF system, requires a more complex low-level control system, but offers two advantages. By its nature the CONNEX architecture offers high redundancy; with every cell powered by its own high-power amplifier, the failure of a single RF amplifier – with certain notable exceptions – might degrade the accelerator performance slightly but is not likely to result in a complete failure of the accelerator to function. In regions where the loss of a single amplifier could result in a broader failure, such as the start of the accelerator where the initial beam bunching and capture is performed, there are several strategies for adding redundancy and failover capabilities.

The other advantage lies in the very broad-band nature of the amplifiers. Simply, the broad bandwidth of most solid-state amplifier chips should allow, in principle, the accelerator structure temperature to vary far more than allowed by most conventional designs, as the amplifiers could track the resonant frequency of the structure.

Individual chips are relatively lightweight and compact. For instance, the Integra IGNP2931M4000 S-band amplifier pallet is approximately 2” x 5.2” x 0.2” thick. With a peak output power of 4 kW, the pallet provides an areal power density of O(400 W/in^2) and a volume power density of 1.9 kW/in^3.

Travelling wave tubes represent a different low-power RF amplifier alternative for accelerators in space. TWTs have a long history of being used in spaceflight applications. Modern TWTs can operate at fairly high efficiencies, p to 72%, and at powers as high as 300 W[i]. However, they are significantly larger and heavier than SSA-based amplifiers of similar output power, and in general appear to be limited to the few-hundred watt range of output power, as shown in Figure 2.

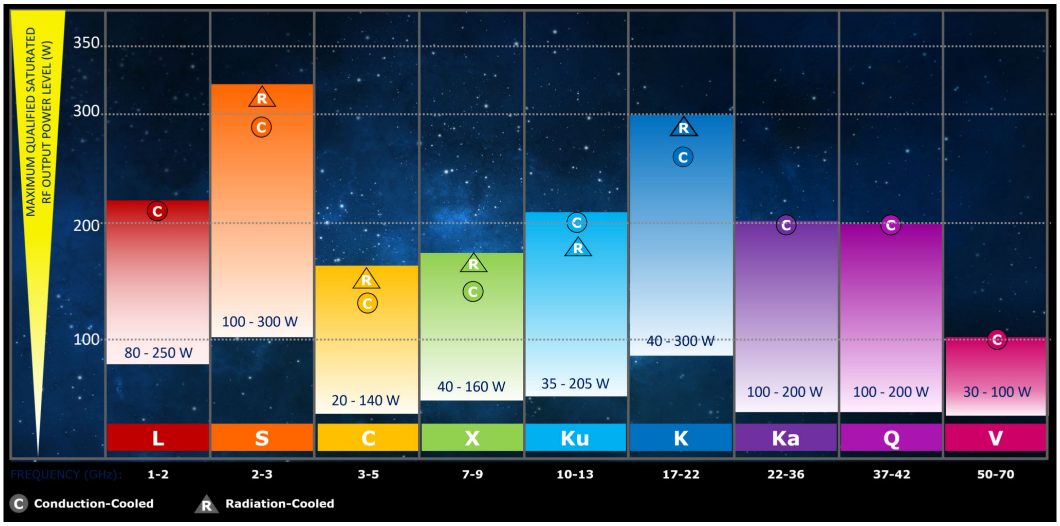

Figure 2: Space-rated TWT output power. Image courtesy Stellant Systems[ii].

Moderate-Power RF Sources

Moderate-power sources are, for purposes of this discussion, those producing from a few tens of kW peak output power, up to several hundred kW. These, as well as higher-power sources, are almost exclusively vacuum electronic devices. That is, they generate RF power by accelerating, modulating and extracting power from an electron beam. Examples of such devices include cavity-coupled travelling wave tubes; crossed-field amplifiers; inductive output tubes; klystrons; and magnetrons. Manufacturers include Stellantis, CPI (several divisions), Teledyne e2v, and Canon.

Common features include the requirement for a high-voltage power supply, typically on the order of 10 – 50 kV depending on the unit. Duty factors can range from a fraction of a percent to CW. Cooling is usually via liquid (e.g. water), especially for higher average power systems. A magnetic focusing system is also often required, and can be either permanent-magnet or electromagnet based, depending on the particulars of the system.

As an exemplar device, consider a cavity-coupled TWT from CPI: the VTS-5754A. This device can produce 150 kW of RF power at a 6% duty factor, is water cooled, and uses a permanent magnet focusing array to confine its internal electron beam. The tube is driven by a 46-kV, 19-A power supply; a cathode heater and cathode grid bias supply are also required. Weight, exclusive of power supplies, cooling system, etc., is 150 lbs.

Output of such such systems is generally via waveguide, in this case WR-284, versus coaxial line. This, combined with the power levels generated, make such systems well-matched to short, higher-gradient accelerators fabricated as a single multicell resonant structure, instead of multiple independently powered cavities. This is a traditional, and highly successful, design approach used on the great majority of normal-conducting RF-driven accelerators. The use of several such RF power sources to drive a single accelerator would likely facilitate higher voltage operation in the same physical length, compared to solid-state driven, but with significantly less redundancy than offered by an SSA-based accelerator. To the best of our knowledge at the time of this writing, moderate-power tubes have not been flown nor tested in space-relevant environments.

High-Power (MW-Class) Sources

As mentioned above, tube-based devices represent a continuum of capability, in terms of peak output power and duty factor, not a series of discrete stages. The highest peak and average power devices, in the frequency range of interest, are magnetrons and klystrons. Single accelerator structures driven by single magnetrons are a demonstrated path towards generating beams with voltages in the 5-MV range, and kW-class average beam power. Magnetrons are nominally simpler devices to operate than klystrons, but historically have been problematic to operate in parallel to either increase net output power or to drive multiple sections of a single larger accelerator, due to issues in synchronizing the phase of output power across multiple devices. Also, magnetron output power is generally limited to 5-7 MW[iii], but klystrons with output power of up to 100 MW are commercially available[iv].

Let use use a Canon E3729 klystron as an exemplar. This device is characterized as a “medium pulse” device, with a peak output power of 34 MW, and average power of 12.8 kW. A 312-kV, 328-A beam is produced inside the tube to generate this output power. The tube itself is 1.9 m long. To provide focusing for the beam inside the tube, a solenoid coil weighing 1000 lbs is required; the coil requires a 24A, 250V (6 kW) DC power supply to provide the focusing. An oil tank weighing an additional 1270 lbs is required for high voltage isolation of the klystron socket.

Such a structure could power a relatively short accelerator (on the order of 1-2 m in length) capable of delivering an ampere-class beam at several tens of MV; however, the duty factor would be on the order of 0.4%.

Tube-Based Device Performance Comparisons

This section provides a series of plots showing aspects of relative performance for tube-based devices, including both mid- and high-power devices, from a number of manufacturers. As mentioned there is considerable overlap in performance space between device types, so this section provides general comments and trends on tube-based devices in general. Often, more than one type of device may provide a solution to requirements for peak and average power, frequency, etc.

While these plots extend up to several tens of MW, there are significant number of tubes – specifically, klystrons – that are especially well-suited to driving accelerators intended to operate at high gradients, e.g. research machines, Compton backscatter X-ray sources, etc. The plots below exclude most of these on the supposition that they will generally be poorly matched to the currently envisioned mission requirements.

Figure 3 illustrates the frequency coverage vs. peak power for various device types. Generally, the entire range from 1 – 10 GHz is well covered at peak powers up to 1 MW; in the 1-10 MW range, coverage tends to constrict to focus around S-band, or 3 GHz. This is likely due to the prevalence of medical and industrial devices, such as X-ray radiation therapy machines, that operate at this frequency band.

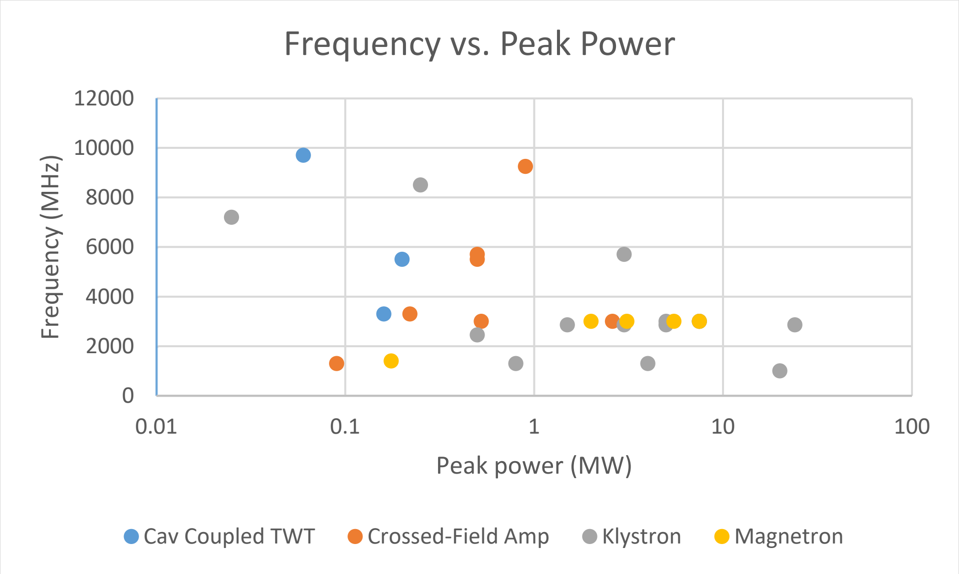

Figure 3: Operating frequency vs. peak output power for various device types.

Figure 4 compares peak to average power output across a variety of devices. Klystrons, generally, provide a broader range of peak power output, as well as generally higher average power output. Magnetrons, crossed-field amplifiers and cavity-coupled TWTs tend to cluster with average power outputs around 5 – 10 kW, regardless of peak power output.

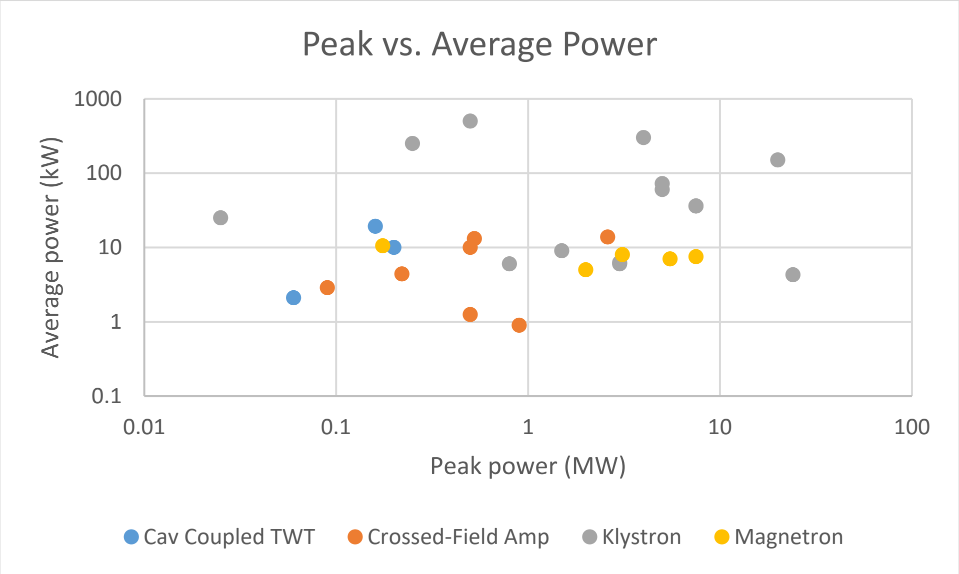

Figure 4: Peak vs. average output power for various device types.

Figure 5 illustrates the trend of duty factor versus peak power for various devices. Again, klystrons tend to define the overall boundary towards higher performance; but there is a general trend that higher peak powers correspond to lower duty factors; the three dots along the top of the plot are CW-capable klystrons. This is consistent with the previous plot.

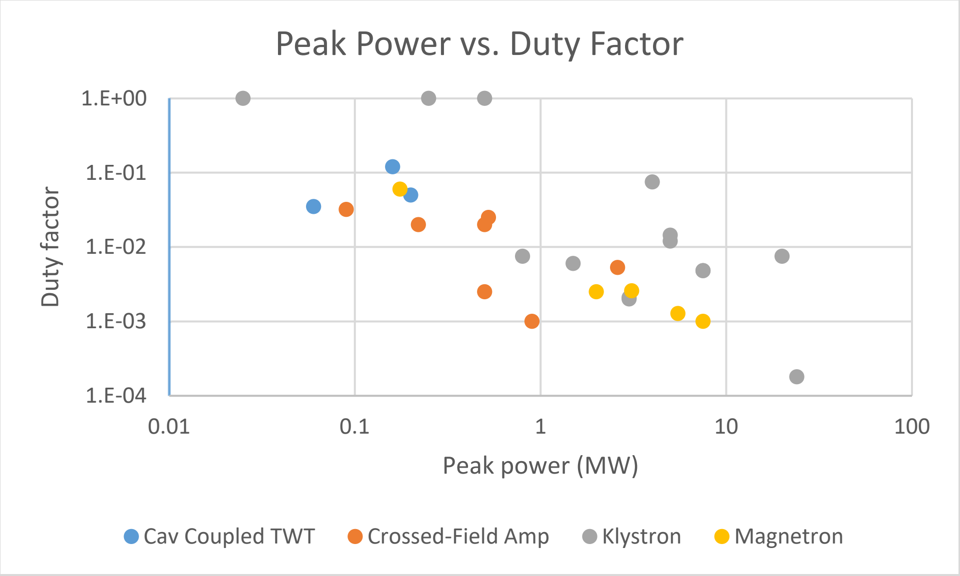

Figure 5: Peak power vs. duty factor for various device types.

Finally, as mentioned above, the rf pulse duration is important when attempting to obtain high average beam power; the longer the rf pulse duration relative to the fill time, the higher the beam duty factor can be relative to the rf source's duty factor. Figure 6 plots rf pulse durations vs. peak RF power. The three dots at the top of the plot are, as before, for CW klystrons.

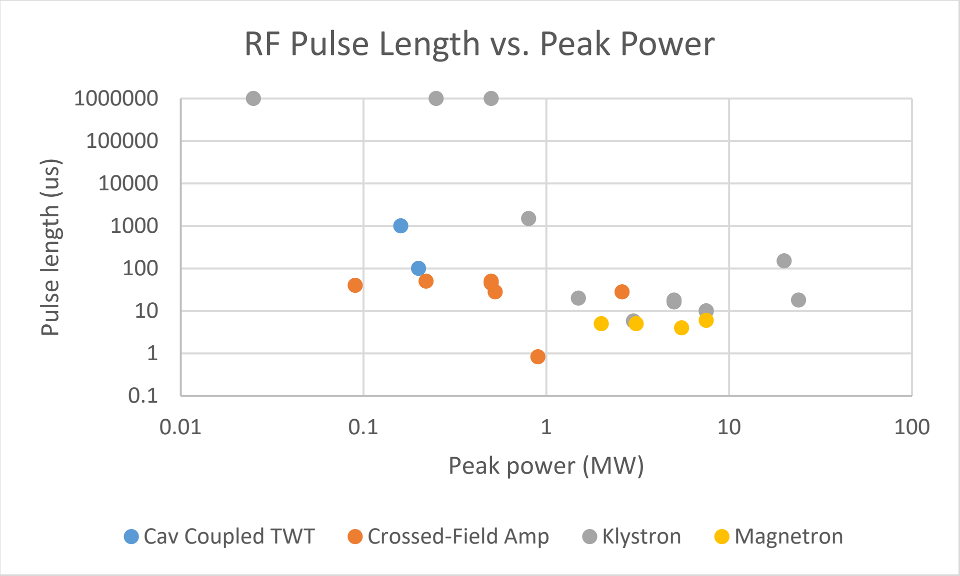

Figure 6: RF pulse length vs. peak power for various device types.

CONCLUDING THOUGHTS AND COMMENTS

The capabilities of individual RF amplifier chips has reached the point where a single or few chips can drive a single accelerator cavity at useful accelerating gradients. This represents a breakpoint in accelerator architecture design space.

As of this writing, development of RF amplifier chips in frequency ranges of interest, appears to be occurring at a fairly rapid pace, and the performance regimes discussed above can be expected to expand in the future. In contrast, tube-based RF sources, at all power levels, are based on very mature and stable technology. While incremental improvements, e.g. in efficiency and small-signal gain, continue to occur, order-of-magnitude increases in performance are not seen as likely.

Two important factors, for the design of an RF-driven accelerator, are the efficiency and gain of the high-power RF source. The former has a significant impact on the overall power budget and wallplug efficiency (output beam power to total system input power). The latter impacts the design of the low-level RF system. These factors are not addressed above. In the case of RF amplifier chips performance, in terms of both efficiency and gain, appears to be improving along with overall power output. In the case of tube-based systems, both efficiency and small-signal gain can vary widely based on type of device, vendor, and operating regime.

Finally, of the many considerations to design of an accelerator, overall system complexity can become a driving factor for cost, robustness and maintainability. Designing amplifiers based on single RF amplifier chips will increase complexity versus driving a monolithic structure with a higher-power monolithic source; however, complexity is accompanied by the potential for increases in robustness, redundancy and modularity.

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[i] S. K. Ghosh, "Travelling-Wave Tubes for Space Application: Present and Future," 2020 URSI Regional Conference on Radio Science (URSI-RCRS), Varanasi, India, 2020, pp. 1-3, doi: 10.23919/URSIRCRS49211.2020.9113591.

[ii] https://stellantsystems.com/traveling-wave-tubes-space/

[iii] https://www.teledyne-e2v.com/en-us/solutions/rf-power/rf-devices/magnetrons

[iv] https://etd.canon/en/product/category/microwave/klystron.html