POWER SOURCES FOR ACCELERATORS BEYOND X-BAND†

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The availability of power sources suitable for particle acceleration is a key factor determining what acceleration techniques are practical. We examine the fundamental limitations of slow- and fast-wave devices, two beam accelerators, and lasers as power sources for accelerators in the frequency range beyond X-band.

1 Introduction

Sources of coherent radiation operating in the region of the electromagnetic spectrum beyond 12.4 GHz (the upper edge of the 'X-band') are numerous and find broad application in communications, radar, and atmospheric contaminant monitoring at the low end, and in spectroscopy, chemistry, and solid state physics studies in and near the optical portion of the spectrum. These sources are attractive for particle accelerators as they offer the potential for increased accelerating gradient and reduced accelerator size. Additionally, the very short bunches produced by very high frequency acceleration can produce ultrafast radiation pulses if used to drive a free electron laser, improving the temporal resolution of, for example, pump-probe experiments.

Sources used for particle accelerators must provide stable phase and amplitude output, high peak power in short pulses, and be efficient. Where two or more power sources are required to drive the beam to the required energies, the sources must also be phase lockable, that is, they must be power amplifiers amplifying the signal of a common master oscillator. In general, power sources need not be particularly broadband ($\Delta\omega/\omega_o$<1%) or tunable. These requirements narrow the range of currently suitable sources to just two types: vacuum tubes

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(for frequencies up to ~100 GHz) and lasers (for wavelengths shorter than 10 μm).

2 Frequency Scaling of Devices

In general, higher frequencies require that the residual capacitances and inductances in the source be small, which in turn requires the source itself to be small. Most high power sources (vacuum tubes and lasers included) rely on resonant cavities to increase efficiency, but with the introduction of a narrowing of bandwidth comes the need to maintain key dimensions of the device to tighter tolerances, a problem that grows rapidly harder with increasing frequency. With the decrease in size also comes a natural decrease on the available output power that can be generated by the device, owing both to the decreased surface area through which dissipated power can be conducted, and due to the decreased energy that can be stored within the device. Further, Ohmic power losses grow worse as $P_{\Omega} \sim f^{1/2}$ owing to increasing surface resistance.

Vacuum tubes achieve power amplification through the growth of space-charge waves on an electron beam. A small, periodic velocity modulation is imposed on the beam by a drive circuit (typically a resonant cavity). After sufficient drift, the velocity modulation leads to a large density modulation which then permits efficient coupling of the beam's kinetic energy into electromagnetic power via resonant excitation of a mode in the output circuit (also generally a resonant cavity). The amount of current which can be transported through the device is determined by the hole radius through which the beam must pass. As this typically is determined by good design practice for the rf circuits, the radius will scale inversely with the frequency. Consequently, the total transmittable current will scale as $I \sim 1/f^{2}$ causing the output power to also drop as $P \sim 1/f^{2}$ unless other steps are taken.

This argument assumes that the beam current density is fixed which, in fact, is not as poor an assumption as it first appears. The reason is that the source of the electron beam is a hot cathode, the emitted current density from which depends on the cathode temperature and applied voltage. Raising the current density means raising the cathode temperature, which dramatically shortens its usable life. Current cathodes can produce up to 10 A/cm^2 for tens of thousands of hours under favorable conditions, which means current densities of up to 1 kA/cm^2 may be produced from an electron gun with 100:1 compression. Transporting such high current density beams is also challenging, requiring very strong, meticulously designed focussing[1].

Even if the beam current could be appreciably increased to obtain higher output power, efficiency would be compromised. As an example, klystron efficiency approximately follows Symon's Law:[2] $\eta \le 0.9 - 0.2\ k_\mu$, with the electron beam microperveance defined as $k_\mu = 10^{-6} \times I/V^{3/2}$. The increase of microperveance with current, and hence decrease in efficiency with current motivates exploring other means of increasing the output power.

Raising the beam voltage is one obvious way of obtaining more power, but has several important side effects. The formation of bunching of the electron beam occurs on a characteristic time scale determined by the reduced plasma frequency of the beam. For a round beam of voltage V and current density J_o in free space, the distance required for a (small) velocity modulation to become a density modulation is one quarter of the plasma wavelength λ_p :

$$D \sim \frac{\lambda_p}{4} = \frac{\pi c}{2} \gamma^{3/2} \sqrt{\frac{\varepsilon_o m_e \beta c}{e J_o}} \sim \gamma^{3/2} \sim V^{3/2} \tag{1}$$

where the $V^{3/2}$ scaling is exact for relativistic beam voltages ($\gamma >> 1$). Hence, raising the beam voltage rapidly lengthens the separation distance between the drive and output circuits, making beam transport and vacuum pumping more problematic.

A second side effect of raising the beam voltage is that the output circuit voltage must be raised as well. Optimum "electronic efficiency" (rf power output in ratio to electron beam kinetic energy) is obtained when the beam-coupled impedance of the output circuit matches the beam's impedance $Z_b = V/I$. Raising the output circuit voltage requires either larger electric fields or extended interaction circuits to be used (e.g. several resonant cavities in series instead of one), each with its own difficulties.

The beam tube may be enlarged to carry more current by using overmoded circuits for the drive and output. This permits the resonant cavities and accompanying beam holes to be made significantly larger than is practical for the fundamental mode case. The drawback is that for significant increases in circuit size, there will be a very large number of closely spaced resonant modes near the operating mode used for power generation. At their most benign, competing modes will couple power out of the beam and increase circuit heating and lower output efficiency. However, if the adjacent modes include deflecting modes with good coupling, they can lead to beam breakup and rf pulse shortening.

Increasing the current while maintaining the current density constant is another. This has the obvious additional requirement of requiring the circuits to accept a larger beam, and several tricks have been proposed to do this. The annular beam[3], sheet beam[4], and multi-beam[5] klystrons are geometric variations on this idea. For the sheet and annular beam klystrons, the beam transport and interaction circuit designs are quite challenging, with mode competition and field uniformity being difficulties for the circuits, and stable, matched transport being challenges for the focussing. Mode competition in the circuits and beam-to-beam coupling are challenges for the multi-beam klystron.

Taken together, these considerations lead to the conclusion that the power scaling of resonant-circuit based vacuum tubes will remain $P \sim 1/f^2$ with various tricks permitting significant increases in power, but none of which can alter the power scaling law.

Many of these constraints are circumvented by the two-beam accelerator, as will be discussed in section 3.3 below.

Atomic lasers, on the other hand, achieve power amplification through the stimulated transitions of atomic electrons to a lower energy state. Lasers (except fiber lasers) tend to be extremely overmoded and have output frequency characteristics that are determined almost exclusively by the electronic structure of the lasing media itself (by contrast, vacuum tube frequency characteristics are almost exclusively determined by the circuits, and not the gain media [electron beam]). Consequently, lasers will not follow a specific overall scaling law of power with frequency, rather the output power will be determined by the characteristics of the lasing media that are available.

3 Examples of Power Sources Beyond X-band

A rich variety of devices has been built and continue to be designed for the production of power beyond x-band. Included in this section is a representative set of examples drawn from the last decade of research and development. These examples by no means exhaust the many methods of power production being developed today.

3.1 Solid State Devices

The inherent efficiency, robustness, and recent progress in achieving high output powers in the 1-2 GHz range for cellular phone communication make it natural to ask whether solid state devices might at some point meet the requirements for particle accelerators. As with power vacuum tubes, the inverse relationship between device power and device frequency makes this quite problematic. Efforts to develop arrays of amplifiers, which collectively provide higher output powers, have succeeding in developing output powers in the tens of watts cw at 60 GHz using the summed output of 272 solid state power amplifiers[6]. Higher powers are available from pulsed devices, with 20 watts at 92 GHz being produced in 80 ns bursts from a commercially available IMPATT oscillator[7].

3.2 Vacuum Tubes

Power vacuum tubes develop output power through space-charge waves induced on an electron beam by a small drive signal. The waves can represent axial bunching (as in klystrons), azimuthal bunching (as in gyrotrons, helical free electron lasers [FELs], and magnetrons), or periodic transverse deflection (as in planar FELs and magnicons).

3.2.1 Axial Bunching Devices

Klystron development beyond X-band has yielded a number of devices and designs. The Budker Institute and Protvino jointly developed[8] a 14 GHz relativistic klystron for the Russia linear collider VLEPP that was experimentally tested to give 90 dB saturated gain and 50 MW peak output power in 250 ns pulses at 30% efficiency[9]. The extraordinary saturated gain of this tube meant that very weak drive signals would yield full output power, a property that made self-oscillation more probable. Although the tube was designed to produce 150 MW, oscillations ultimately limited the stable operating power to less than half that value.

Haimson Research and NRL collaborated[10] to produce a 17.136 GHz klystron that was tested to give a saturated gain of 67 dB, an output power of 26 MW in 150 ns pulses, and a 49% efficiency. This klystron is the centerpiece of a high gradient accelerator R&D program at MIT.

SLAC has designs for 94 GHz klystrons of both round[11] and sheet beam[11,12] construction, and has been pursuing fabrication efforts. The primary challenges of working at this frequency come from the small structure dimensions (e.g. a beam hole diameter of 800 μm) and very tight tolerances on critical dimensions (typically a few μm). Deep x-ray lithography and electroforming techniques are being explored for constructing the drive and output circuits.

3.2.2 Azimuthal Bunching Devices

The gyroklystron, traveling-wave tube (TWT), helical FEL, and magnetron are examples of devices in this category. An annular beam is generally used and is focused in a solenoid field. Since the EM interaction is primarily azimuthal, however, this implies that the cyclotron motion of the beam in the focussing channel plays a critical role in the interaction process. In particular, a synchronism condition between the rf frequency ω, the axial field variation $k_{||}$, and electron beam cyclotron frequency $\Omega_c=qB/\gamma m$ must be satisfied:

$$\omega - k_{\|} v_{\|} = n\Omega_c \qquad (2)$$

where the harmonic number n is a nonzero integer, and the axial beam velocity is $v_{||}$. Since the cyclotron frequency is proportional to B, this implies the focussing field strength must increase for increasing rf frequency. As a rough rule of thumb, 1 Tesla field strength increase is required for each 14 GHz increase in operating frequency[13], assuming a 500 kV electron beam is used.

A collaboration of the University of Maryland, NRL, and Communications & Power Industries (CPI) has produced and measured several gyroklystrons working at 34.9 GHZ and 94 GHz. The 34.9 GHz tube produced 225 kW in 2 μs pulses with a saturated gain of 30 dB and 31% efficiency. The highest output power 94 GHZ tube (one of five measured) produced an output power of 84 kW in 2 μs pulses with a saturated gain of 42 dB, and 34% efficiency[14].

U.C. Davis, UCLA, and Micramics Incorporated are collaborating on the design of a 35 GHz harmonic gyro-TWT. They have designed for 400 kW output power, 35 dB saturated gain, and an efficiency of 20%[15]. This tube operates on the TE_{31} mode, and will incorporate special cuts in the circuit to suppress competing modes.

An IAP Nizhny Novgorod/GYCOM Company collaboration constructed and tested[16] a 93.5 GHz gyroklystron that produced 210 kW at 30% efficiency and 20 dB saturated gain.

The highest power w-band (75-110 GHz) tube proposed to date has been designed by the UMD/Calabazas Creek Research collaboration. Their gyroklystron design achieves 10 MW output power at 91 GHz with a saturated gain of 55 dB and electronic efficiency of 37.4%[17]. The guide field required for this high frequency is 2.76 T, and will be supplied by a superconducting solenoid.

Finally, as an example of what output power is possible from gyro-devices, the gyrotron has received considerable development as a power source for electron cyclotron resonance heating (ECRH) of plasmas for fusion research. The gyrotron is an oscillator, making it unsuitable for all but low-energy, single-power source accelerators, but working tubes produce powers of 1.7 MW at 165 GHz with an efficiency of 35.2%[18]. This high power is possible through the use of very highly overmoded circuits, with the present example using the $TE_{31,17}$ mode for the output circuit.

3.2.3 Deflection-based Devices

The magnicon and planar FEL (or ubitron) are the primary members of this category. A pencil beam is generally used, and interaction is either with $TM_{n,m}$ deflecting modes of the interaction circuits (as with the magnicon) or with pure TEM modes (as with the FEL) in a transversely oriented, axially periodic magnetic field.

Yale and Omega-P Incorporated have collaborated to design and produce a 34 GHz magnicon that uses a TM_{110} drive circuit mode, and TM_{310} output circuit mode, giving harmonic multiplication of frequency. Since the drive frequency is one-third the output frequency, the tube is more stable against oscillation (backward waves in the tube have the wrong frequency to drive the input circuit) and the input source is more straightforward. The prototype tube is nearly complete as of this writing, with tests planned presently. The design calls for 48 MW in 1.5 μs pulses, 45% efficiency, and 54 dB of saturated gain at 34 GHz[19].

The record holder to date in the generation of high power high frequency rf is the Lawrence Livermore FEL. Designed as a source for microwave absorption measurements for a fusion experiment (the MTX tokamak), the FEL provided 140 GHz, 1-2 GW pulses of 20 ns duration, a gain of 76 dB, and an efficiency of 14%[20].

3.3 Two-beam Accelerators

Although the two-beam accelerator is in essence a distributed relativistic klystron, it deserves special treatment because it has special flexibilities in frequency, pulse length, output power, and power distribution that are impractical to realize with discrete klystrons.

Like a klystron-powered accelerator, in which a low energy, high current electron beam is used to produce rf power to accelerate a higher energy, low current electron beam, the two-beam accelerator has a high current beam (the “drive” beam) used strictly as the energy source for making rf to accelerate the good beam. The differences are, however, that the low-quality beam is of high enough energy that it can be used to generate power for many structures, and that the output circuits used to do so are distributed close to the accelerating structures.

For a tube-powered accelerator, one has hundreds of drive beams—one for each power tube supplying the accelerator—and hence the sources must be simple and inexpensive to be practical. Since just one source is needed to produce the drive beam for the two beam accelerator, it can be very complicated, permitting substantial flexibility.

The Compact Linear Collider (CLIC) is designed on the two-beam principle, and uses a single main drive linac (operating at 937 MHz) to produce a 92 μs long pulse train of 1.16 GeV electrons averaging 8.2 Amperes. This pulse train is then folded back on itself 32 times by interleaved injection into a series of three combiner storage rings to produce a 2.9 μs long pulse train of 1.16 GeV electrons averaging 262 Amperes. The pulse train produced not only has 32 times the peak current, but the fundamental Fourier harmonic frequency is also 32 times higher, permitting efficient generation of 32x937 MHz=29.984 GHz. The pulse duration has also been shortened by a factor of 32, a benefit in decreasing the effects of surface heating in the accelerator structures due to the rf power. This pulse train is subdivided into 20 smaller pulse trains, which are fed to groups of transfer structures which generate 29.984 GHz rf power for portions of the accelerator (viz. output circuit). The entire process from AC power to rf power is expected to reach efficiencies of 47%[21], and result in the production of ~27 MW from each of the 11,000 transfer structures. Since the transfer structures can be located quite close to the accelerator structures, power transmission losses are minimized.

Power generation from a drive beam has been demonstrated by the CLIC Test Facility II (CTF II), which extracted 120 MW of power in 16 ns pulses[22]. CTF III is commissioning at present, and will provide the first demonstration of pulse combining in a pair of storage rings[23,24].

For generation of rf power for high energy colliders, the two-beam accelerator is a very promising concept. The need for very high peak power in short pulses becomes increasing difficult to meet at high frequencies for conventional power tubes, but is potentially achievable with a two-beam accelerator.

3.4 Lasers

The laser has often been considered as a potential power source for particle accelerators owing to the extreme peak powers that are possible, but only recently has achieved the power efficiency and phase stability required for accelerator applications.

Two key developments have enabled significant gains in laser efficiency. Solid-state diode lasers can produce radiation in the near infrared to red with wall-plug to light-output efficiencies that are excellent, with commercially available products already passing 30% efficiency[25], and laboratory diode lasers having achieved 54% at low power (0.25 W)[26] more than a decade ago. Very high power diode bars (1 kW/cm^2) with wall-plug to optical efficiencies of 45% are under development now[27].

The second key development that has markedly improved laser efficiency is the discovery of diode-pumped laser media that efficiently use the pump power. For all lasing media, the pumping transition requires more energy than the radiative transition emits. This difference is expressed as a ratio of the emitted photon wavelength λ_e to the pump photon wavelength λ_p, known as the quantum defect $D=\lambda_e/\lambda_p$. For lasing media like Ti:Sapphire, the pumping absorption band peaks at λ_p=490 nm, while the lasing transition peaks at around λ_e=790 nm, which means that the pump-power-to-output-power efficiency will be *at most* D=0.62 or 62%, and in practice will be somewhat lower. A host of materials have been developed with small quantum defects, including Yb:KGd$(WO_4)_2$ (commonly called just Yb:KGW) with D=0.96 and a measured slope efficiency (optical power out versus optical power in) of η_o=57%[28], Yb:KY$(WO_4)_2$ (called Yb:KYW) with D=0.957, η_o=86.9%[29], and Cr^{++}:ZnSe, with D=0.70, η_o=0.52%[30]. The ytterbium-ion media lase in the 1 μm range, while chromium-doped zinc selenide lases near 2 μm, both conveniently in a window where silicon is transparent and may be used for accelerator structures.

Phase-locking of lasers at the optical time scale to an external microwave reference is a key step to synchronizing two or more lasers to power an accelerator. Laser pulse shape is simply amplitude modulation of the underlying optical “carrier” wave, and in modern lasers the carrier is not locked in phase to the pulse envelope. Locking the carrier phase to an external reference is a critical step in synchronizing lasers, and has been recently demonstrated[31,32].

4 High Frequency Power Transmission and Compression

Steadily increasing Ohmic losses on conducting surfaces makes handling high power at very high frequency challenging. Fundamental-mode waveguide becomes extremely lossy (e.g. rectangular copper waveguide in TE_{10} mode used for 90 GHz transmission attenuates at approximately 3 dB/meter) requiring that other methods of power transmission be used. Overmoded waveguide and quasioptical transmission are the alternatives.

Overmoded waveguide achieves lower loss by decreasing the induced surface currents on the guide, but with the added complication that scattering from the desired transmission mode into other guided modes is no longer forbidden. Maintaining mode purity is essential for efficient power coupling to the accelerator structure, and hence great care must be taken to ensure the guide is free from geometric defects that would scatter power out of the desired mode. Waveguide losses may be further reduced by switching to an HE_{11} mode and corrugating the surfaces of the guide. Corrugations with a depth of $\lambda/4$ will transform the impedance of the conducting wall (essentially a short circuit) into very high impedance, further reducing wall currents and hence loss. The machining complication of corrugated guide makes this a costly option, however.

Quasioptical transmission uses free-space TEM modes directed and focused by mirrors, lenses, and gratings, much as is done with light in the optical range, but in a domain where diffraction effects dominate[33]. The Rayleigh quarter wavelength rule for surface accuracy[34] which applies to optical mirrors applies here as well, but in the millimeter-wave range is trivial to achieve. The main drawback of quasioptical power transmission is that diffraction effects require the components to be very much larger than their guided-wave counterparts, typically by two orders of magnitude.

5 Conclusion

The potentially higher accelerating gradients and decrease in the size of accelerator components that are possible at higher frequencies makes the development of sources beyond x-band attractive. The naturally shorter electron bunches produced by high frequency acceleration are also of interest in their own right.

The two-beam accelerator concept is an excellent solution to the power requirements of a linear collider, where the high cost of producing and manipulating the drive beam becomes comparable to the cost of thousands of discrete power sources.

Where smaller accelerator systems are desired, discrete sources remain the practical solution. Significant research and development has taken place and will continue in this area, offering the promise of more potent sources. Point-to-point communication and radar will continue to motivate development of sources in the various atmospheric transparency bands (30-40 GHz, 75-95 GHz) and in the peak absorption band near 60 GHz for secure communications between satellites. ECRH of plasma for fusion research will continue to motivate very high power sources in the range beyond 100 GHz. Continued progress in the efficiency and stability of lasers will also continue, driven by the materials processing and telecommunications industries, with commercial solid-state diode-pumped lasers with good efficiency becoming available in the not too distant future.

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