A Brief Introduction to RF Power Sources

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1 Introduction

In previous discussion of linear acceleration, we have treated the microwave power which is used in the accelerator as a sort of magical substance which is provided upon demand in any quantity and with any time structure required. This is obviously an oversimplification. Indeed, the generation and transportation of RF power is a major industry in its own right, with customers far beyond the pedestrian world of accelerators. In this set of notes, we will briefly describe the role of *klystrons*, *modulators*, and *pulse compression* in the production of RF power.

2 Klystrons

The klystron is the ubiquitous source of RF power in accelerators today; if any lab in the world uses anything but klystrons to produce megawatt levels of RF power, the authors are not aware of it.

The klystron is at heart a narrow-band vacuum-tube amplifier which operates at microwave frequencies. The basic idea of the klystron is shown schematically in figure **??**:

- A continuous electron beam is emitted by the klystron's cathode and accelerated to high voltage (usually non-relativistic) in a DC gun
- The electron beam passes through a resonant cavity (the input cavity) which is excited by an external source of RF power (typically in the kilowatt range) at the resonant frequency of the cavity
- The sinusoidal variation in the cavity voltage causes alternate acceleration and deceleration of electrons in the beam
- The beam passes through a drift tube, in which the accelerated electrons travel faster and the decelerated ones travel slower, resulting in a beam which is bunched at the frequency of the RF drive signal; thus a significant fraction of the beam's power has been moved from DC to the drive frequency
- The beam now passes through a series of output cavities which are resonant at the same frequency as the input cavity; these cavities act like accelerating structures – they become beam-loaded, resulting in a decelerating voltage at the resonant frequency (identical to the beam's bunching frequency) – thus the power is transferred from the beam to the cavities
- The power extracted from the beam travels to an output coupler and exits the klystron body; the spent beam is transported to a collector, which is a water-cooled beam stop.

Let us now go through some of the more interesting steps in greater detail.

2.1 Beam Production

The beam is produced by heating a cathode to release electrons; these electrons are then accelerated by a DC voltage (here V_{klys}). Because the voltage is typically 500 kV or less, the beam is only barely relativistic and is thus subject to longitudinal and transverse forces due to the mutual repulsion of electrons, so-called *space charge* forces.

2.1.1 Space-Charge Limited Emission and Perveance

Imagine a klystron gun with a cathode and anode, each of area A_{gun} and separated by a distance d_{gun}, with an externally-applied constant voltage V_{klys}. If the cathode is heated to release electrons, a current will form between the cathode and anode. What determines how much current will flow through the gun?

To answer this question, we follow the treatment of Isagawa [1]: since the voltage is constant in time and all of the charge flows from the cathode to the anode, we can assume that between the two electrodes there exists a charge density distribution $\rho(x, y, z)$ which is constant in time; for our purposes, we will also assume that the distribution is constant in x and y (ie, along the electrode plates), and can thus be represented by $\rho(z)$, where z is the direction from the cathode to the anode. We can express the relation between voltage and charge density between the two electrodes:

$$\nabla^2 V(z) = \frac{\partial^2 V(z)}{\partial z^2} = \frac{\rho(z)}{\epsilon_0}. \tag{1}$$

Since the cathode is at $V(z = 0) = 0$, an electron at z is at potential $V(z)$ and, in the non-relativistic limit, has $eV = m_e v^2(z)/2$ (note: yes, this is actually a klystron in the antimatter universe, where the beam is made of positrons). Similarly, the current density is given by $J = \rho(z)v(z)$. We can now combine these expressions to find a relationship between the second derivative of the voltage, the voltage, and the current density at any point within the volume:

$$\frac{\partial^2 V(z)}{\partial z^2} = \frac{J}{\epsilon_0}\sqrt{\frac{m_e}{2e}}V(z)^{-1/2}. \tag{2}$$

If we now multiply both sides by $2\partial V/\partial z$, we find:

$$2\frac{\partial V(z)}{\partial z}\frac{\partial^2 V(z)}{\partial z^2} = \frac{2J}{\epsilon_0}\sqrt{\frac{m_e}{2e}}V(z)^{-1/2}\frac{\partial V(z)}{\partial z}. \tag{3}$$

This may not seem like much of an improvement, until we realize that $2\ \partial V(z)/\partial z\ \partial^2 V(z)/\partial z^2 = \partial/\partial z[(\partial V(z)/\partial z)^2]$, thus:

$$\frac{\partial}{\partial z}\left[\left(\frac{\partial V(z)}{\partial z}\right)^2\right] = \frac{2J}{\epsilon_0}\sqrt{\frac{m_e}{2e}}V(z)^{-1/2}\frac{\partial V(z)}{\partial z}. \tag{4}$$

The expression above can be solved to find:

$$\left(\frac{\partial V(z)}{\partial z}\right)^2 = \frac{4J\sqrt{V(z)}}{\epsilon_0\sqrt{e/m_e}} + C_1. \tag{5}$$

In the case where $J \equiv 0$, for example when the cathode heater is switched off so that no free electrons can be formed, Equation 5 shows that the electric field between anode and cathode is constant; this is the familiar result for a parallel-plate capacitor. If, on the other hand, free charges are present in the gun volume, the value of C_1 will be changed from the value it obtains in the capacitor case. In particular, at $z = 0$ where $V(z)$=0, the first term on the RHS goes to zero; since at the space charge limited case $E(z=0) \equiv dV(z)/dz|_{z=z_0} \rightarrow 0$, we therefore find that $C_1 \rightarrow 0$ in the space-charge limited case.

In the case where $C_1 \rightarrow 0$, Equation 5 can be made into a simple differential equation in $V(z)$, which we may solve:

$$V(z)^{-1/4} dV = dz \cdot 2\sqrt{\frac{J}{\epsilon_0}} \frac{1}{(2e/m_e)^{1/4}}. \tag{6}$$

Equation 6 can be solved directly:

$$\frac{4}{3} V(z)^{3/4} = 2\sqrt{\frac{J}{\epsilon_0}} \frac{z}{(2e/m_e)^{1/4}} + C_2. \tag{7}$$

Since $V(z) = 0$ at $z = 0$, C_2 must be zero as well. We can also make use of the fact that $V(z) = V_{\text{klys}}$ at $z = d_{\text{gun}}$, and rearrange Equation 7 to determine the beam current as a function of the voltage and gun length:

$$J = \frac{4\epsilon_0}{9} \sqrt{\frac{2e}{m_e}} \frac{V_{\text{klys}}^{3/2}}{d_{\text{gun}}^2}. \tag{8}$$

For klystrons in the space-charge limit, then, the beam current is proportional to the klystron voltage raised to the three-halves power. The constant of proportionality is known as the *perveance*. Technically, perveance has dimensions of amperes per volt to the three-halves; in general parlance, the units are implicit and perveance is given without any dimensions. Since the perveance of a typical klystron is on the order of 1×10^{-6}, an even more common unit is the *microperveance* with (implicit) dimensions of micro-amperes per volt to the three-halves. The SLAC high-powered klystron for 2856 MHz operation, the Model 5045, operates at a voltage of 350 kV with a beam current of 400 amperes, yielding a microperveance of 1.9. Note that in the space-charge limited regime the power of the klystron rises as the 5/2 power of the voltage and the impedance that the klystron presents to its DC power supply varies as the voltage is adjusted.

2.1.2 Saturation of the Current

The current supplied by the klystron cathode is limited by the availability of electrons supplied by the thermionic emission process (*Edison effect* or *Richardson effect*). The maximum thermionic current density is given by:

$$J_{\text{th}} = K_{\text{RD}} T^2 \exp(-\phi/kT), \tag{9}$$

where T is the Kelvin temperature, k is Boltzmann's constant (1.38×10^{23} joules/Kelvin), ϕ is the work function of the cathode in eV, and K_{RD} is the Richardson-Dushman constant, $K_{\text{RD}} = 1.204 \times 10^6$ A/m^2/K^2 [1].

One practical side effect of thermionic current saturation is that klystron developers engage in continual research to develop a cathode material with a low work function and good tolerance to very high temperatures. Another is that klystrons can run quite stably in the saturation limit: a klystron operating in the space-charge limit will experience a 2.5% variation in power for a 1% variation in voltage (due to the strong variation in the current); a klystron operating in saturation will experience only a linear variation in power, since the current is almost independent of voltage in this limit.

2.2 Beam Transport

As the beam coasts along the "beam stick" between the input cavity and the output cavities, the beam density modulation results in regions of very intense space charge. This can result in transverse growth of the beam to the point where the walls of the beam stick begin to intercept the beam. This is obviously an outcome to avoid, especially when operating at currents of hundreds of amperes. For this reason klystron beam sticks always have transverse focusing magnets. Conventional modern klystrons use electromagnet solenoids to achieve their focusing, while older klystrons used permanent magnet focusing. In very new klystrons permanent magnet focusing is making a comeback – permanent magnets do not consume power (which can be a significant source of net inefficiency in klystrons), and such klystrons do not rely on the vagaries of their focusing power supplies to remain operational.

3 Modulators

The modulator is the DC power supply for the klystron; it supplies the voltage and current in the klystron gun. The name comes from ancient radar applications: the klystron's input AC signal would be continually present, and the modulator would be switched on and off, thus "modulating" the resulting high-power klystron output signal.

Klystrons require voltages in the range of several hundred kilovolts. In general it has not proved practical to build modulators which generate such voltages directly (for one thing, it becomes extremely hard to find a switch that can hold off such a large voltage). Thus, modulators typically operate in the tens of kV regime (with correspondingly immense currents – kiloamperes are not uncommon), and a step-up transformer (with 10:1 or 20:1 ratios typical) are used to generate the klystron voltages.

4 Pulse Compression

The modulator switch, the pulse transformer between the modulator and the klystron, and the filling time of the klystron output cavity all limit the speed with which the klystron can "switch on" (ie, go from zero to full power output). This results in a reduction in the system efficiency similar to the filling time of the RF structure – the energy transferred from the modulator to the klystron during the switch-on time is irretrievably lost. In order to minimize this efficiency, long klystron pulses are optimal. Since, however, the average power of the klystron is limited (typically by its water cooling capacity), a long klystron pulse is necessarily a low-power pulse.

RF structures, by contrast, typically are designed for short, high-power pulses. The time structure of the klystron pulse is matched to that of the RF structure by a pulse compression system. Over the years several such systems have been devised and tested; in a couple of cases, the systems have seen considerable use. We describe a few of the most popular ones below, following the treatment of Nantista [2]. First, however, we must describe a piece of RF technology which is indispensable to all high-power RF pulse compression technologies.

4.1 The 3-db Directional Coupler

A 3-db directional coupler is a passive shaped-copper device which can accommodate microwaves in any of four ports. In schematics it is represented with the symbol in Figure **??**.

The key feature of such a device is that if microwave power is introduced into port 1, then exactly half of that power propagates from port 1 to port 2, and exactly half from port 1 to port

3; none of the power propagates from port 1 to port 4. Similarly, power introduced at port 4 is split evenly between ports 2 and 3, and similar relationships hold in the opposite direction. Most generally, each line in Figure **??** is an allowed direction of power propagation.

A key feature of the directional coupler is that power which propagates along one of the diagonal lines follows a longer path than power along a horizontal line. To be exact, the path length difference is equal to 90° of the frequency of interest (which implies that a 3-db coupler only works right for a particular frequency of interest).

We can see why this is interesting by considering a 3-db coupler with two power sources of equal amplitude, which are introduced at ports 1 and 2, and which have a 90° phase difference between them already. At a given moment in time the power from port 1 to port 2 can be represented by $\sin(\omega t)/\sqrt{2}$ and that at port 3 by $\cos(\omega t)/\sqrt{2}$. The power from port 4 to port 3 can be represented by $\sin(\omega t + \pi/2)/\sqrt{2}$, and that from 4 to 2 by $\cos(\omega t + \pi/2)/\sqrt{2}$. The amplitude of the RF at each port can thus be computed through use of trigonometric identities:

$$\begin{aligned} A_2 &= \frac{1}{\sqrt{2}}\left[\sin(\omega t) + \cos(\omega t + \pi/2)\right] \\ &= \frac{1}{\sqrt{2}}\left[\sin(\omega t) - \sin(\omega t)\right] \\ &= 0, \\ A_3 &= \frac{1}{\sqrt{2}}\left[\cos(\omega t) + \sin(\omega t + \pi/2)\right] \\ &= \frac{1}{\sqrt{2}}\left[\cos(\omega t) + \cos(\omega t)\right] \\ &= \frac{2}{\sqrt{2}}\cos(\omega t). \end{aligned} \tag{10}$$

Thus, we see that in this case all of the power from both sources exits the device at port 3, and none of it reaches port 2. If we were to change the phase of either source by 180°, the opposite would be true – all of the power would exit at port 2, none at port 3. Thus a 3-db coupler can be used to split the power from 1 source between 2 outputs (with a phase difference between them), or to combine 2 inputs with a phase difference at a single output.

With the 3-db coupler in hand, we can now explore the original high-powered RF pulse compressor: SLED.

4.2 SLED Pulse Compression

SLED stands for Stanford Linac Energy Doubler, and is shown schematically in Figure **??**: a klystron is connected to a pair of resonant cavities (in this case utilizing the TE_{015} mode) by a 3-db coupler; each cavity has an input iris with coupling coefficient β_{SLED}, and each cavity has a wall Q of Q_{SLED}. The fourth port on the 3-db coupler goes to the accelerator structures.

To understand the SLED system, we can use some of the formalism developed for standing-wave accelerator structures. The incoming power is split between the two cavities (and a net phase shift is introduced in the two arms). The output electric field amplitude from each resonant cavity, relative to the klystron amplitude, is given by:

$$E_{\text{out,SLEDcav}} = \frac{E_{\text{klys}}}{\sqrt{2}}\left[\frac{2\beta_{\text{SLED}}}{1+\beta_{\text{SLED}}}\left(1 - e^{-t/t_c}\right) - 1\right], \tag{11}$$

where t_c is the SLED-cavity time constant, $t_c \equiv 2Q_{\text{SLED}}/\omega(1+\beta_{\text{SLED}})$. Note that the output power from the two cavities goes to the fourth port (leading to the accelerator), and not to the klystron port. To see why this is, recall that the arms from the klystron port to the cavity ports have a path length difference of 90°. The power which goes from the klystron to the second SLED cavity and is reflected thus has a total phase difference of 180° relative to the power reflected from the first cavity (since the power to the second cavity has to travel the 90° path length difference twice). By a similar logic, one can show that the path length difference for power which goes from the klystron port to the cavity coupler and is reflected to the accelerator port is zero. Thus, all of the power which exits the SLED system goes to the accelerator rather than back to the klystron (this, indeed, is why two cavities are needed).

While all of this is happening, the portion of the RF pulse which is not reflected or emitted from the cavities is being stored therein, the stored energy in each cavity $U_{\rm SLED}$ given by:

$$U_{\rm SLED} = t_c \frac{P_{\rm klys}}{2} \frac{2\beta_{\rm SLED}}{1+\beta_{\rm SLED}} \left(1 - e^{-t/t_c}\right)^2. \tag{12}$$

As we can see, both the output power to the structure and the stored energy in the SLED cavity are reaching a steady state in the limit of infinite time.

The second term on the RHS of Equation 11 is due to the reflection of the input power of the klystron. If the klystron is suddenly switched off, then the RF amplitude out of the SLED cavity is suddenly larger than the amplitude available from the klystron by a factor of $2\beta_{\rm SLED}/(1+\beta_{\rm SLED})$, which is a factor of 2 for large values of $\beta_{\rm SLED}$. Even more effective is to leave the klystron on and suddenly change its phase by 180°. In this case the sign of the klystron amplitude, and the reflected klystron pulse, change; rather than having emitted and reflected RF signals that cancel one another, the emitted and reflected signals add:

$$E_{\rm out,SLEDcav} = \frac{E_{\rm klys}}{\sqrt{2}} \left[\frac{2\beta_{\rm SLED}}{1+\beta_{\rm SLED}} \left(1 - e^{-t_{\rm flip}/t_c}\right) + 1\right]. \tag{13}$$

Now, in the limit of large $\beta_{\rm SLED}$ values, the RF amplitude going to the accelerator structure can be as large as 3 times the amplitude of the klystron pulse (for a total of 9 times the power). If we turn the klystron on at $t = 0$, flip its phase at $t = 1$, and turn it off at $t = 2$, then we find an output pulse from the klystron which is given by:

$$\begin{aligned} E_{\rm out,SLEDcav} &= \frac{E_{\rm klys}}{\sqrt{2}} \frac{2\beta_{\rm SLED}}{1+\beta_{\rm SLED}} (1 - e^{-t/t_c}) - 1,\ t \le t_1, \\ &= \frac{E_{\rm klys}}{\sqrt{2}} \frac{2\beta_{\rm SLED}}{1+\beta_{\rm SLED}} \left[\left(2 - e^{-t1/t_c}\right) e^{-(t-t_1)/t_c} - 1\right] + 1,\ t1 < t \le t_2, \\ &= \frac{E_{\rm klys}}{\sqrt{2}} \frac{2\beta_{\rm SLED}}{1+\beta_{\rm SLED}} \left[\left(2 - e^{-t1/t_c}\right) e^{-(t_2-t_1)/t_c} - 1\right] e^{-(t-t_2)/t_c},\ t > t_2. \end{aligned} \tag{14}$$

By the rules of the 3-db coupler discussed above, we can see that the total amplitude going to the accelerator is $\sqrt{2}$ larger than the output pulse from each SLED cavity.

4.2.1 Limitations of SLED

The most obvious limitation of the SLED system is that the maximum amplification factor, achieved in the limit of large $\beta_{\rm SLED}$, is a factor of 3 over the amplitude of the klystron amplitude. Although this corresponds to a factor of 9 increase in power, the fact remains that if you need a factor of 10 you can't get it from SLED under any circumstances.

A related limitation is the efficiency of the SLED system. In the limit of large $\beta_{\rm SLED}$ and long times, the maximum stored energy in a SLED system is $2t_cP_{\rm klys}$, even though in this same limit the energy output of the klystron is infinite. This is because of the combination of wall losses in the storage system and the fact that, early in the klystron pulse, all or nearly all of the klystron power is reflected to the accelerating structure rather than being captured in the SLED cavities.

A final limitation is that the SLED output pulse after $t = t_1$ varies quite a lot – Equation 14 shows an exponential decrease in the output amplitude. When combined with the finite filling-time of an accelerating structure, this can lead to a structure energy gain which varies substantially over the length of the SLED pulse. In practice this can be overcome by repeatedly flipping the klystron phase between the phase which stores energy and the phase which extracts energy, but this in turn reduces the efficiency of the SLED system even further.

4.3 SLED-II

The SLED-II pulse compression system is an extension (literally!) of the SLED design. It was designed to allow a compressed RF pulse which is more constant in time than what was available in the original SLED configuration.

The canonical SLED-II system is shown schematically in Figure **??**. Like SLED, SLED-II begins with a klystron which is connected to two resonant cavities through a 3-db coupler. In this case, however, the resonant cavities are extremely long compared to the RF wavelength being stored. In this limit, we can treat the cavities as travelling-wave elements rather than standing-wave cavities.

Let us consider what happens when RF power from the klystron first reaches the travelling-wave cavities. The RF signal with amplitude E_{SLED2} encounters the coupling iris, which in this case has a reflection coefficient significantly different from 1. The incident signal splits into a reflected signal and a transmitted signal: the reflected signal is given by $E_{\mathrm{ref}} = sE_{\mathrm{SLED2}}e^{i\theta_{\mathrm{SLED2}}}$, while the transmitted signal is given by $E_{\mathrm{trans}} = \sqrt{1-s^2}E_{\mathrm{SLED2}}e^{i(\theta_{\mathrm{SLED2}}-\pi/2)}$, where s is real, positive, and smaller than 1, and $\theta_{\mathrm{SLED2}} > 90°$. The transmitted power travels down the travelling wave cavity; since the cavity is long, it does not begin to re-emit stored energy until that energy has had time to travel to the far end of the cavity, reflect off the short at the end, and travel back to the iris. Let us call this round-trip time t_{SLED2}. As a result of the combination of the SLED-II total path length and the reflection off the short at the end, the phase of the stored RF pulse as it reaches the coupling iris is θ_{store}.

When the RF pulse reaches the iris, a portion of the pulse will be transmitted through the iris with phase shift $\theta_{\mathrm{SLED2}} - \pi/2$, and a portion will be reflected with phase shift θ_{SLED2}. The energy storage capacity of the total system is maximized when the transmitted stored energy interferes destructively with the reflected klystron energy and the reflected stored energy interferes constructively with the transmitted klystron energy. If we define the klystron pulse to be the reference phase (the "zero phase") for the system then our requirements translate to the following:

$$\begin{aligned} \theta_{\mathrm{store}} + \theta_{\mathrm{SLED2}} &= \theta_{\mathrm{SLED2}} - \frac{\pi}{2} \\ \theta_{\mathrm{store}} + \theta_{\mathrm{SLED2}} - \frac{\pi}{2} &= \theta_{\mathrm{SLED2}} \pm \pi. \end{aligned} \tag{15}$$

Fortunately, both conditions can be accommodated simultaneously if $\theta_{\mathrm{store}} = -\pi/2$. Thus, the length of the SLED-II travelling wave cavity must be adjusted such that the phase of the returning wave at the iris differs from the simultaneous klystron power phase at the iris by $-\pi/2$.

With the phase adjusted in this manner, the relationship between the emitted field amplitude and the incoming field amplitude is

$$E_e = (1-s^2)E_{\mathrm{SLED2}}, \tag{16}$$

while the amplitude of the trapped field becomes

$$E_{\mathrm{store}} = s\sqrt{1-s^2}E_{\mathrm{SLED2}}. \tag{17}$$

More generally, as the trapped energy interferes constructively with the incoming RF power, the emitted amplitude can be represented as:

$$E_e(n_{\rm trip}) = \frac{1-s^2}{1-s}(1-s^{n_{\rm trip}-1})E_{\rm SLED2}, \tag{18}$$

where $n_{\rm trip}$ is one larger than the number of complete round trips which have been completed so far (ie, $n = 1$ for $t < t_{\rm SLED2}$, $n = 2$ for $t_{\rm SLED2} \leq t < 2t_{\rm SLED2}$, etc. – $n_{\rm trip}$ is the counter which tells "which cycle" of the system it's presently executing). The pleasant feature of E_e is that it varies in steps, rather than continuously, and is constant at each value for a period of $t_{\rm SLED2}$.

At this point, life with SLED-II is quite similar to life with SLED. After some number of RF power round-trips in the travelling wave cavity the klystron phase is reversed so that the reflected klystron power combines constructively, rather than destructively, with the emitted power. Let us assume that the klystron pulse is longer than $t_{\rm SLED2}$ by an integer factor $n_{\rm max}$, and that the klystron phase is flipped only in the last SLED-II cycle of its pulse. In this case,

$$\begin{aligned} E_{\rm out} &= E_e(n_{\rm max}) + sE_{\rm SLED2} \\ &= E_{\rm SLED2}\left[\frac{1-s^2}{1-s}(1-s^{n_{\rm max}-1}) + s\right]. \end{aligned} \tag{19}$$

Note that the output amplitude cannot exceed 3 times the input amplitude in a SLED-II system. We can simplify this expression:

$$\frac{E_{\rm out}}{E_{\rm klys}} = 1 + 2s - s^{n_{\rm max}-1} - s^{n_{\rm max}}. \tag{20}$$

For a given value of $n_{\rm max}$ which is greater than or equal to 3, the value of s which maximizes the ratio of output amplitude to input amplitude is approximately given by:

$$s_{\rm opt} \approx \left[\frac{1}{n_{\rm max} - 1/2}\right]^{\frac{1}{n_{\rm max}-3/2}}. \tag{21}$$

As an example, consider a system where $n_{\rm max}$=6, so the SLED-II system is filled for 5 round-trip times and the stored energy is extracted during the sixth. The optimum reflection coefficient is equal to 0.685, and the amplitude gain factor is 2.12, meaning that during round-trip 6 the output power is larger than the klystron power by a factor of 4.48. The output amplitude and power as a function of time are shown in Figure **??**.

Note that, like SLED, the SLED-II pulse compressor has a significant inherent inefficiency: some RF power is sent to the structure during round-trips 1 through 5, rather than being stored. This can be seen as well in the fact that, in the example above, during round trip 6 the pulse energy is 4.48 times the klystron pulse energy while in total the klystron output is 6 times the klystron output during round-trip 6.

The principal advantage of SLED-II over its predecessor is that a flat output pulse can be achieved. The principal disadvantage is that it requires a pair of SLED-II travelling-wave cavities which are each half as long as the desired length of the output pulse. For this reason, SLED-II is only really acceptable for systems in which the desired output pulse is short.

4.4 Binary Pulse Compression

A more energy-efficient pulse compression scheme which also permits generation of a flat output pulse is Binary Pulse Compression. Consider the system sketched in Figure **??**: two klystrons are combined through a 3-db coupler. Depending on the relative phase of the two klystrons, their combined power output will be sent to one or the other of the output ports; the phase of the output power is determined by the absolute phase of the two klystrons.

If each klystron has a pulse length of t_{klys} and and output power of P_{klys}, then we can direct the first half of their combined pulse to the upper output and the second half to the lower output by exchanging the phase of one klystron halfway through their pulse. Thus there will be a pulse of RF power $2P_{\text{klys}}$ at the upper output from $t = 0$ to $t = t_{\text{klys}}/2$, and an equal pulse at the lower output from $t = t_{\text{klys}}/2$ to $t = t_{\text{klys}}$.

We can combine these two RF pulses into a single pulse of RF power $4P_{\text{klys}}$ which lasts for a period $t = t\text{klys}/2$ if we delay the power from the first port by a time $t_{\text{klys}}/2$ (using a length of waveguide, for example), then combine it with the later pulse in another 3-db coupler.

By combining successive stages of this system, the pulse length can be reduced by successive factors of 2, and the peak power increased by the same factors. For this reason the system is called *binary pulse compression* (BPC).

The principal disadvantage of BPC is the large length of RF "plumbing" required for compression. Consider, for example, a BPC system and a SLED-II system which are each required to compress a pulse with length t_{klys} by a factor of $2^{n_{\max}}$. The SLED-II system requires 2 waveguides with length $0.5t_{\text{klys}}/2^{n_{\max}}$, or a total of $t_{\text{klys}}/2^{n_{\max}}$ worth of waveguide. For BPC, on the other hand: a factor of 2 requires a delay line of length $t_{\text{klys}}/2$ (identical to a comparable SLED-II system); a factor of 4 requires 2 delay lines of length $t_{\text{klys}}/2$ and one of length $t_{\text{klys}}/4$ (total of 1 1/4 t_{klys}; a factor of 8 requires 4 delay lines of length $t_{\text{klys}}/2$, 2 delay lines of length $t_{\text{klys}}/4$, and one of length $t_{\text{klys}}/8$ (total 2 5/8 t_{klys}.

4.5 Delay Line Distribution System

Observant readers may have noticed that, in the previous Section, the RF power from 2 klystrons was combined into 2 pulses, each of length $t_{\text{klys}}/2$, by the simple expedient of the first 3-db coupler; all of the subsequent gymnastics involving the second coupler and the long delay line was required because the resulting pulses were not synchronized in time.

We can capitalize on this phenomenon in the manner shown in Figure **??**: we produce 2 pulses of RF power, each of length $t_{\text{klys}}/2$, with a relative delay of $t_{\text{klys}}/2$ between the "early" pulse and the "late" pulse. The "early" pulse is sent *upstream* (that is, in the direction opposite that of the beam) for a time t_{delay}, at which point it is injected into an accelerator structure for use by the beam. The "late" pulse is sent directly to the nearest accelerator structure. The system will work if the beam enters the upstream structure at the same instant that the "early" pulse arrives, and enters the downstream structure at the same instant the "late" pulse arrives. The "early" pulse and the beam both reach the upstream structure at $t = t_{\text{delay}}$, while the beam reaches the downstream structure at $t = 2t_{\text{delay}}$ and the "late" pulse reaches the structure at $t = t_{\text{klys}}/2$. Thus, we find that $t_{\text{delay}} = t_{\text{klys}}/4$ for this system.

This method of RF pulse combination is known as a *Delay Line Distribution System* (DLDS), and in a formal sense it isn't a pulse compressor at all: that is, the energy from the early and late portions of the klystron pulse are not combined with one another. Instead, the RF power from two (or more) klystrons can be combined and distributed in time by a network of 3-db combiners.

We have already seen that DLDS can produce pulses with a total length of $t_{\text{klys}}/2$ in a delay line length of $t_{\text{klys}}/4$. Similarly, one can combine 4 or 8 klystrons and generate pulses which are 1/4 or 1/8 as long in time as the original pulse, with 4 or 8 times the original power.

References

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