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NOTES

Simplified radio-frequency generator for driving ion guides, traps, and other capacitive loads

Ronald M. Jones and Scott L. Anderson[a)]
Department of Chemistry, University of Utah, 315 South 1400 E., Room 2020, Salt Lake City, Utah 84112

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We report the design and construction details for a very simple radio-frequency (rf) generator, suitable for driving ion guides, traps, or any capacitive load in the few to few hundred picofarad range. The design is a simple high voltage tube oscillator, and the frequency can be step adjusted by changing capacitors. An optional TTL-triggered keying circuit is provided for applications where the rf needs to be turned off and on under external control. © *2000 American Institute of Physics.* [S0034-6748(00)03511-5]

A few years ago, we published the design for a high voltage radio-frequency (rf) oscillator circuit designed for ion guiding and trapping applications.[1] The design has proven to be popular in the ion community because it is easier to use and more robust than systems based on commercial rf generators. The key feature is that the load (i.e., the ion guide or trap) is directly connected to the rf generator, becoming part of the capacitance of the oscillator circuit. Detailed discussion of the electronics issues relevant to ion applications can be found in the earlier article. The earlier circuit included a number of features (e.g., built-in dc offset power supplies, fast keying circuit with ramp speed control, large variable capacitors for tuning and load balancing) that are not needed in the majority of applications. For typical uses of ion guides for ion transport or integral cross section measurement, the only requirements are: stable rf with amplitude set-able in the 50–500 V range; ability to set the frequency in the 1–15 MHZ range, as appropriate for the ion masses involved; and two out-of-phase rf outputs that oscillate symmetrically about an applied dc potential. For some applications it is also useful to be able to shut off the rf periodically to allow trapped ions to escape.

The circuit described here provides these minimal requirements, while reducing component cost, complexity, and finished size significantly. As in the original design, there is no need for impedance matching or rf-coupling networks. The circuit is quite robust, tolerant of a wide range of load impedances, and is easy to construct and troubleshoot.

The circuit is shown in Fig. 1. As with the original design, it is a high voltage oscillator based around two 6146B tetrode tubes, chosen for being inexpensive and readily available. In our application, small size was a requirement, accomplished by having all dc power supplies external. If size is not an issue, it is straightforward to package the 6.3 V ac filament transformer and high voltage power supplies inside the rf generator case, as we have done for one unit. For our construction, the dimensions of the rf generator are approximately 20×11×16 cm, limited by the size of the main inductor, L_{tank}.

The basic oscillator circuit is enclosed in the dotted rectangle labeled ‘‘oscillator’’ in Fig. 1, and typical component values are given in Table I. To a good approximation, the operating frequency is given by $f=[2\pi(L_{\mathrm{tank}}C_{\mathrm{tot}})^{1/2}]^{-1}$, where $C_{\mathrm{tot}}=C_{\mathrm{tune}}+C_{\mathrm{LOAD}}$. One of the major space and cost savings in the current design is using a fixed, rather than air-variable capacitor for C_{tune}. The frequency range is set by varying the value of C_{tune}. C_{LOAD} is the capacitance of the external capacitive load (e.g., ion guide) plus any stray capacitances from cabling, etc. To minimize stray capacitance, both internal and external wiring should be as short as possible, particularly if high operating frequencies are desired. L_{tank} is a hand-wound coil approximately 5.7 cm in diameter, 18 cm long, with 2.4 turns/cm of heavy (~2 mm) copper wire. To allow additional frequency control, L_{tank} is connected to the circuit by a pair of alligator clips, so that a variable number of turns can be included in the oscillator circuit. In addition, L_{tank} is center tapped and tied to ground by a large capacitor ($C7$). The rf-grounded center tap forces the circuit to oscillate symmetrically, and also provides a place to make the high voltage connection to the tube plates (anodes). The plate high voltage is fed into the oscillator circuit through a filter consisting of $R1$, $L3$, and $C3$. The purpose of $R1$ is to make the rf buildup smoother when the output is externally switched on and off. The alligator clip connections to L_{tank} should be symmetric with respect to the center tap. The feedback required to sustain oscillation is provided by connecting the plate of each tube, via a capacitor, to the control grid of the opposite tube. The capacitor/resistor combination (e.g., $C8/R4$) controls the feedback level. The screen grids of each tube are connected to the high voltage by resistors $R2$ and $R3$.

[a)] Author to whom correspondence should be addressed; electronic mail: anderson@chemistry.utah.edu

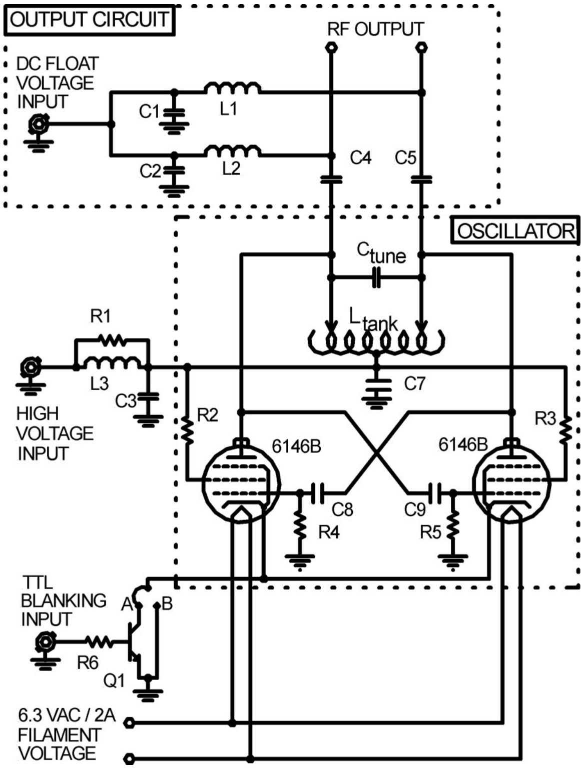

FIG. 1. Schematic of the simplified rf source.

To enable rf output, the cathodes of the tubes are held at ground potential. When the A–B jumper (lower left, Fig. 1) is in the A position, the rf generator is controlled by an external TTL input. When the input is high (5 V), $Q1$ is turned on, holding the cathodes at ground potential, and enabling rf output. When the TTL signal is low (0 V), $Q1$ turns off and allows the cathodes to float, shutting off the rf output. $Q1$ must be a high voltage transistor, because the cathodes float to near the plate voltage when $Q1$ is off. If external control of the rf output is not needed, then the cathodes can be permanently grounded, and the B position of the A–B jumper is provided for this purpose.

TABLE I. Typical component values.

Ref.	Value	Type	Notes
$C1$	0.1 μF at 1 kV	disk ceramic	noncritical rf bypassing
$C2$	0.1 μF at 1 kV	disk ceramic	noncritical rf bypassing
$C3$	0.1 μF at 1 kV	disk ceramic	noncritical rf bypassing
$C4$	1000 pF at 3 kV	disk ceramic	a
$C5$	1000 pF at 3 kV	disk ceramic	a
C_{tune}	44 pF at 2 kV	disk ceramic	for setting frequency
$C7$	0.1 μF at 1 kV	disk ceramic	noncritical rf bypassing
$C8$	10 pF at 500 V	mica	
$C9$	10 pF at 500 V	mica	
$R1$	18 Ω, 1 W	carbon	for ON/OFF keying damping
$R2$	25 K, 10 W	wire wound	screen voltage
$R3$	25 K, 10 W	wire wound	screen voltage
$R4$	36 K, 1/2 W	carbon	grid bias
$R5$	36 K, 1/2 W	carbon	grid bias
$L1$	2.5 mH 60 mA	rf choke	current rating 60 mA or more
$L2$	2.5 mH 60 mA	rf choke	current rating 60 mA or more
$L3$	2.5 mH 250 mA	rf choke	current rating 250 mA or more
L_{tank}	30 μH	hand wound	see the text
$Q1$	Motorola BU208	1500 VCE	must be a high voltage part

[a] $C4$ and $C5$ couple rf to the output. To get the best rf balance, small value 3 kV capacitors can be added in parallel with $C4$ or $C5$ to compensate for variations in capacitor values.

In the oscillator section, the voltage oscillates between ground and the applied plate voltage. For ion guiding/trapping applications, the rf must oscillate symmetrically about an externally provided ‘‘float’’ voltage. The required dc decoupling is provided by the ‘‘output circuit’’ indicated by a second dotted rectangle in Fig. 1. $C4$ and $C5$ provide a low-impedance path for radio frequencies, but block the plate dc voltage. In the current design, the coupling capacitors (C_4 and C_5) are fixed value ceramic capacitors. The value of these capacitors is not critical, as long as they are equal and large compared to C_{LOAD} (typically tens of picofarads). Because capacitors are typically low-precision components, it may be necessary to add small capacitors in parallel to $C4$ or $C5$ to balance rf output (i.e., make the amplitude of the two phases identical). The float voltage is supplied by an external power supply, and is coupled to the rf output connectors through a pair of rf chokes ($L1$ and $L2$). $C1$ and $C2$ protect the float supply by shunting to ground any rf that passes the rf chokes.

In a push–pull oscillator like this, the rf amplitude is approximately equal to the applied plate high voltage, allowing rf amplitude to be simply controlled or programmed by the external high voltage supply. The 6146B tubes are rated at 700 V—sufficient for most ion guiding/trapping purposes. The threshold for oscillation (i.e., the useful lower limit of rf amplitude) is controlled by losses in the circuit and load, and will depend somewhat on construction details. For a typical ion guide system with capacitance in the 100 pF range, the threshold is generally less than 50 V. The maximum power dissipation for the generator is 140 W, and the dissipation is mostly in the form of heating in the tubes, L_{tank}, and other internal components. The unit shown here draws approximately 100 mA from the high voltage supply (positive polarity) when operating at 600 V with no external load, i.e., 60 W dissipation. The additional load from a well constructed ion guide/trap is less than 10 W at 600 V. As a consequence, it is possible to add additional output circuits to allow a single generator to drive several independently floatable ion guide segments. We routinely drive two ion guide segments with a single generator.[2–5] Of course, as additional load capacitance is added, the operating frequency will drop unless C_{tune} is reduced to compensate for it. For the component values given in Table I, the operating frequency with no external load is ~7 MHz, dropping to ~5 MHz when driving a typical octapole ion guide.

To illustrate our component layout, Figs. 2 and 3 show front and bottom views of the rf generator. The generator is constructed around a small aluminum chassis ($20\,\mathrm{cm} \times 11\,\mathrm{cm} \times 4\,\mathrm{cm}$), with tubes and L_{tank} on top, and most other components in the bottom. Not shown are covers, constructed of perforated aluminum sheet, that completely surround the unit. Note that dangerously high dc and rf voltages are present in the generator in operation. For safety and to reduce rf emissions, it is important that the unit be enclosed.

Figure 2 shows L_{tank}, hand wound on a plastic coil form, the two tubes, $Q1$ (mounted on the base at rear), and a small

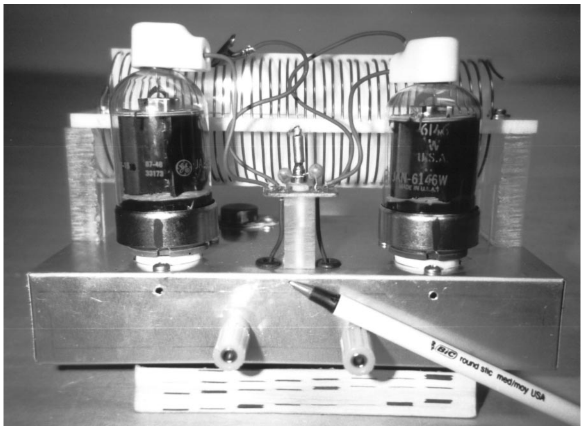

FIG. 2. Front view of rf source.

piece of copper-clad circuit board mounted on an insulating plastic block. This circuit board is etched to provide two isolated copper pads that are used to make the connections to the coil, to the tube anodes, and to C_{tune}. To make use of components on hand, our generator has C_{tune} made up from two capacitors in series. C_{tune} should be mounted so as to be easily accessible, because changing its value is the main frequency tuning method. Leads connecting one tube plate to $C8/C5$ and the other plate to $C9/C4$ can be seen running from the circuit board pads, down through insulating bushings into the lower section of the generator. There is also the connection (not visible) from the center tap of L_{tank} through an insulating bushing into the lower section of the generator. For our unit, banana jacks (visible at the bottom of Fig. 2) were used for the rf output because the generator is mounted only a few cm from the load (i.e., from the vacuum feedthrough leading to the ion guide). Because the leads are short, rf shielding is achieved by enclosing the gap between the generator and feedthrough with a metal tube. If the generator cannot be mounted close to the load or feedthrough, then RG-8 coaxial cable should be used for leads, and the banana jacks should be replaced by suitable shielded connectors (e.g., UHF). Note, however, that coaxial cabling adds substantially to the capacitance of the load (~80 pF/m), lowering the operating frequency and the quality factor of the total circuit. For best performance, the rf leads should be kept as short as possible.

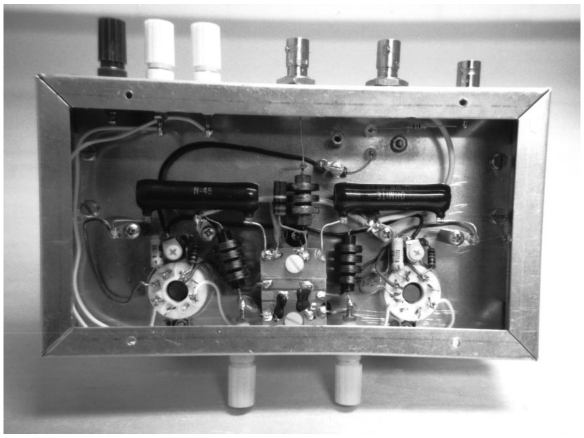

FIG. 3. Bottom view of rf source showing contents of the lower section.

Figure 3 shows the lower section of the generator. Most connections are made directly to the tube sockets or on insulated standoffs, added where needed to support components or provide connection points. Again, a piece of copper-clad circuit board has been etched to make mounting pads for $C4$ and $C5$ and $C8$ and $C9$. The mounting pads make it easy to add small capacitors in parallel with $C4$ or $C5$ to balance the rf output. From left to right at the top of Fig. 3, connectors are provided for ground and filament connections (three banana jacks), the high voltage and bias voltage inputs (MHV connectors), and the TTL control signal (BNC connector).

No special construction techniques are needed, other than normal precautions taken in building or using high voltage circuits. In general, both internal and external leads should be as short as possible. Because the design has no provisions for balancing the rf output in operation, it is important that both the generator and load/cabling be arranged so that the stray capacitances associated with the two phases are identical. In practice, constructing the circuit and load as symmetrically as possible eliminates balance problems.

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