Simple radio-frequency power source for ion guides and ion traps

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A high power oscillator circuit, designed to power radio-frequency (rf) ion guides and traps, is described. The rf circuit is directly coupled to the guide/trap electrodes, and no frequency or impedance matching is required. The design provides precisely adjustable rf amplitudes from ~50 to 600 V, either under manual or computer control. The operating frequency can be varied from <1 to ~30 MHz to allow best trapping conditions for different ion mass ranges. Provisions are made for balancing the rf amplitude to compensate for small load asymmetries. The rf can be switched off and on under control of a transistor–transistor logic signal, and the rise and fall time for the rf amplitude can be manually controlled from a few rf cycles to milliseconds. Provisions are made for applying both direct current (dc) difference and dc float potentials to the ion guide. The design is easily constructed from readily available parts. *© 1997 American Institute of Physics.* [S0034-6748(97)01809-1]

I. INTRODUCTION

The guided-ion beam technique, originally reported by Teloy and Gerlich[1] over 20 years ago, is becoming a standard method in the ion chemistry and ion physics community. Ion guides are a simply two dimensional ion traps, where low kinetic energy ions are confined by inhomogeneous radio-frequency (rf) fields, in some cases with additional inhomogeneous direct current (dc) fields. Ion traps or guides can be constructed in a wide variety of shapes and sizes for different purposes. The operating principles and construction details have been given by Gerlich,[2] along with a discussion of the historical provenance of the technique, and examples of recent applications.

For the purposes of discussion, we will take the example of the linear octapole,[1] since for historical reasons this has become the most common ion guide geometry. The guide (see inset in Fig. 1) is constructed from eight rod-shaped electrodes (1–3 mm diam) arranged in a circular array. As indicated by the shading, alternate rods are connected together to form two sets of four rods. The two electrode sets are connected to opposite phases of a rf source, so that rf voltages of equal magnitude but opposite signs are applied. In addition to the rf, dc potentials can be applied. In almost all experiments the rf voltages are superimposed on a dc potential applied to both sets of rods. This dc ''float'' potential simply sets the centerline potential of the guide, and this allows the ion kinetic energy in the guide to be set. In some experiments it is also necessary to apply a dc ''difference'' potential (i.e., equal but opposite dc voltages) to the two sets of rods. This dc difference potential leaves the centerline potential, and thus, the kinetic energy of ions moving along the centerline, unchanged. This mode of operation is useful in absolute calibration of the rf guiding/trapping field strength, and also for controlling the focusing behavior of quadrupole guides.

The ideal rf source for ion guide/trap operation depends on the desired operating regime. For high resolution mass selection, as in conventional quadrupole mass spectrometers, a combination of high rf amplitude and dc difference potential create conditions, where only ions with a narrow range mass/charge (m/q) ratios have stable trajectories. The stability is normally described in terms of two dimensionless parameters: $a=8\cdot e\cdot V_{\mathrm{dc}}/(mr^2\omega^2)$ and $Q=4\cdot e\cdot V_{\mathrm{rf}}(mr^2\omega^2)$, where V_{dc} and V_{rf} are the dc difference voltage and rf amplitudes, m is the ion mass, r is the center-to-pole distance, and ω is the rf frequency. By varying the rf:dc ratio, it is possible to adjust the range of masses transmitted. For optimal operation Q is set to 0.7060, and a is set in the range from 0.232 to 0.237 (see the book by Dawson[3] for a detailed discussion). Clearly, for mass-selective operation the rf frequency and rf and dc difference voltages are all quite critical.

For ion guides and many uses of ion traps, the operating conditions are quite different. In most cases it is desirable to trap ions with a wide range of m/q ratios, e.g., reactant and product ions. As discussed by Gerlich,[2] safe operating conditions require lower Q values (<0.3 for a quadrupole), and this is typically achieved by using higher rf frequencies, and/or lower rf amplitudes. For most application, little or no dc difference potential is applied ($a\approx 0$). Under these conditions, the rf and dc voltages are not so critical, and a simple circuit can be used.

We have experimented with a variety of schemes for applying the requisite rf and dc potentials to ion guides and traps. These have ranged from amateur radio transmitters to various combinations of homemade, and commercial oscillators with tuned and broadband amplifiers. The typical rf system uses a low power tunable oscillator, boosted by several amplifier stages. To allow the rf to oscillate symmetrically

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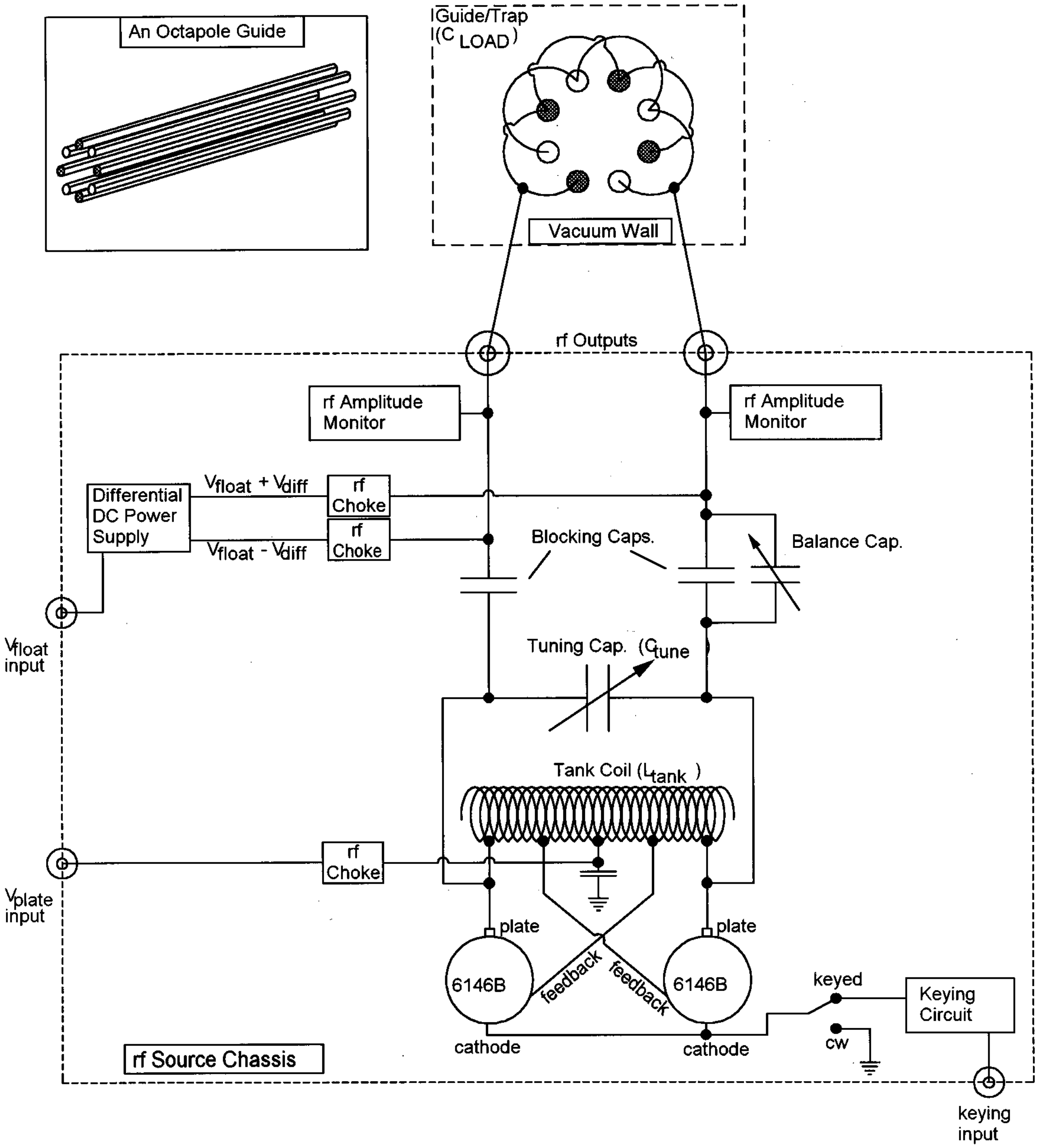

FIG. 1. Block diagram of the rf source.

about the dc float potential, the guide/trap must be decoupled from the amplifier, and this is often done inductively. The guide (electrically a capacitor) is connected to a coil (inductor) to form a (LC)-resonant circuit, driven by an antenna coil attached to the transmitter. Finally, the impedance of the trap/coupling circuit is typically far from the 50Ω load impedance that rf amplifiers are designed to drive. To allow efficient operation and to reduce the chance of amplifier damage from reflected rf power, a tuned impedance matching network (i.e., antenna tuner) is needed (this may also be incorporated into the amplifier or inductive coupling circuit).

The major headache here is that the various tuning elements in the oscillator/amplifier, matching network, and coupling circuit all interact, and the process of tuning the system can be complex and time consuming. It is particularly a problem if the experiment requires changes in operating frequency or load capacitance, since this requires construction of a new resonant circuit coil, and retuning of the entire system.

The rf source presented here is substantially easier to use than others we have tried. It provides both rf and dc voltages, along with provisions for monitoring and modulating the rf. We have constructed several sources of this design, and examples of their performance in driving an octapole ion guide for both integral and differential cross section measurements can be found elsewhere.[4,5] The design is terribly inelegant by the standards of modern rf electronics, but has many advantages for the purposes of driving ion guides/traps. In addition, it can be constructed from readily available parts by anyone having a passing familiarity with electronics. For

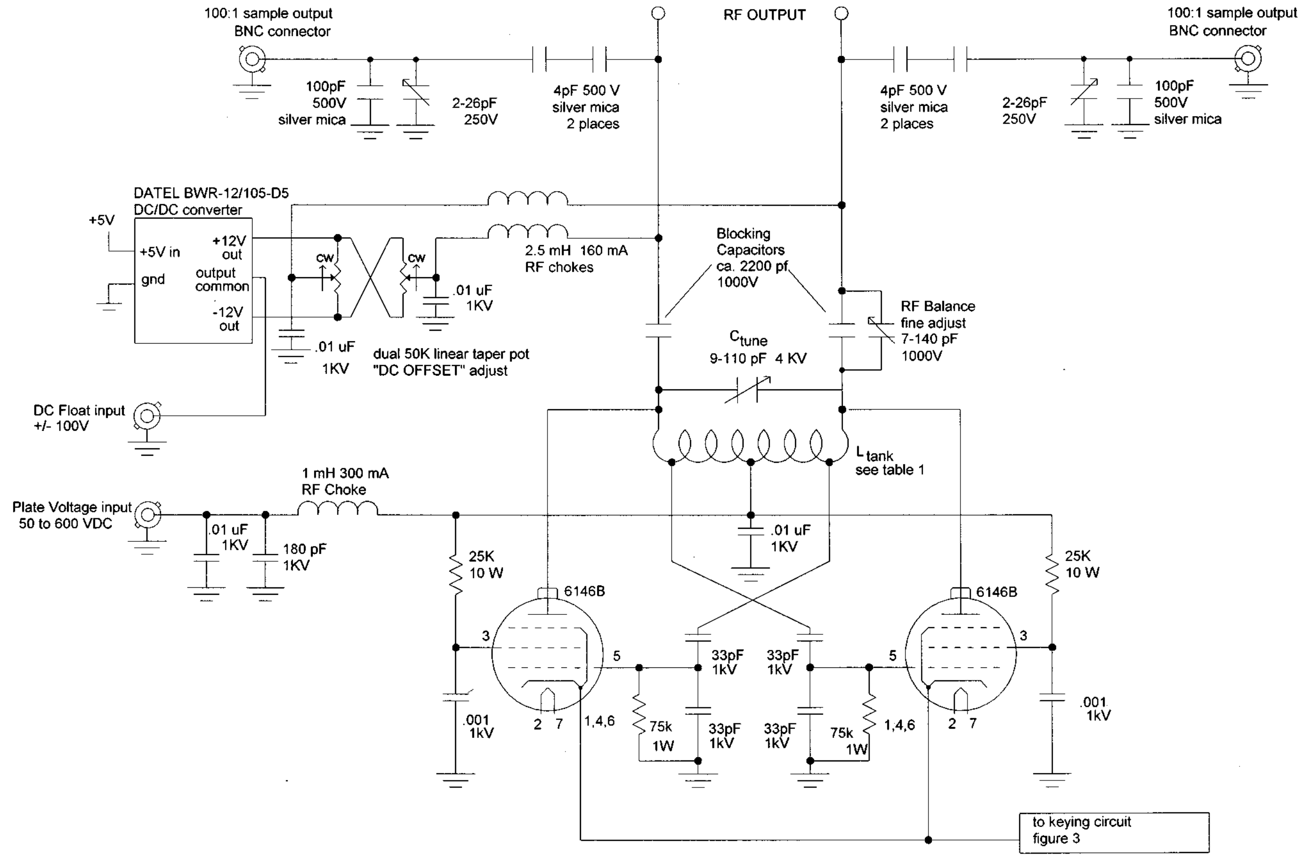

FIG. 2. Schematic of the rf section.

those with no experience with vacuum tubes and rf-circuit layout, handbooks developed for amateur ratio operators provide a practical introduction.[6]

II. DESIGN REQUIREMENTS

The rf generator needs to drive a mostly capacitive load ranging from ~30 to ~300 pF, depending on the size and geometry of the guide electrodes and length and type of cables. The optimal operating frequency depends on the m/q ratio of the trapped ions and thus, needs to be adjustable over a wide range. For light ions typical of ion-scattering experiments ($m/q<100$)frequencies in the 5–30 MHz range are ideal, where frequencies over 15 MHz are only needed if protons are to be trapped. For heavy ions, e.g., from cluster experiments, frequencies in the 0.5–5 MHz range are more typical. The precise frequency value is not important, but once adjusted, the frequency needs to be stable and reproducible to within ~1%. For different experiments, we wanted to be able to vary the frequency easily, and this rules out any sort of tuned amplifier, matching network, or coupling circuit.

The rf amplitude applied to the trap electrodes controls the effective potential[2] confining the ions, and needs to be variable up to ~500 V. For simple guiding experiments, such as integral cross section measurements, the precise amplitude is unimportant as long as it is high enough. For experiments where guides are used to measure ion velocities or for quadrupole trap experiments, where the characteristic ion oscillation frequency is important, the amplitude needs to be controllable with reproducibility of ~1%. To allow automation, it should be possible to set the amplitude by an external voltage, e.g., from a digital to analog converter (DAC).

In some experiments it is desirable to switch off (blank) the rf output periodically, e.g., to empty a trap after some experimental sequence. In addition, we wanted capability to ramp-up the rf with an adjustable time constant after blanking. For convenience, we wanted the rf source to incorporate a bipolar power supply to provide the dc difference voltages, and also provide a connection for the dc ‘‘float’’ voltage. Finally, it sometimes happens that a discharge or short circuit in the guide/trap will suddenly change the load impedance dramatically. This can cause expensive damage to solid state amplifiers, and our tube-based source was designed to be more robust.

III. DESIGN

Our design is outlined in Fig. 1, and details are shown in Figs. 2 (rf section) and 3 (keying and low voltage supplies). In essence, the circuit is a high voltage oscillator powered by a pair of 6146B transmitter tubes connected in push–pull configuration. The oscillation frequency is set by $f=[2\pi(L_{\mathrm{tank}}C_{\mathrm{tot}})^{1/2}]^{-1}$, where L_{tank} is the inductance of the ‘‘tank’’ coil, and $C_{\mathrm{tot}}=C_{\mathrm{tune}}+C_{\mathrm{load}}$. C_{load} is the lumped capacitance of the guide/trap along with strap capacitance of the leads, vacuum feedthrough, etc. C_{tune} is a large air-spaced variable capacitor connected across the tank coil, in parallel with C_{load}, and allows frequency adjustment. The feedback required to sustain oscillation is provided by tap-

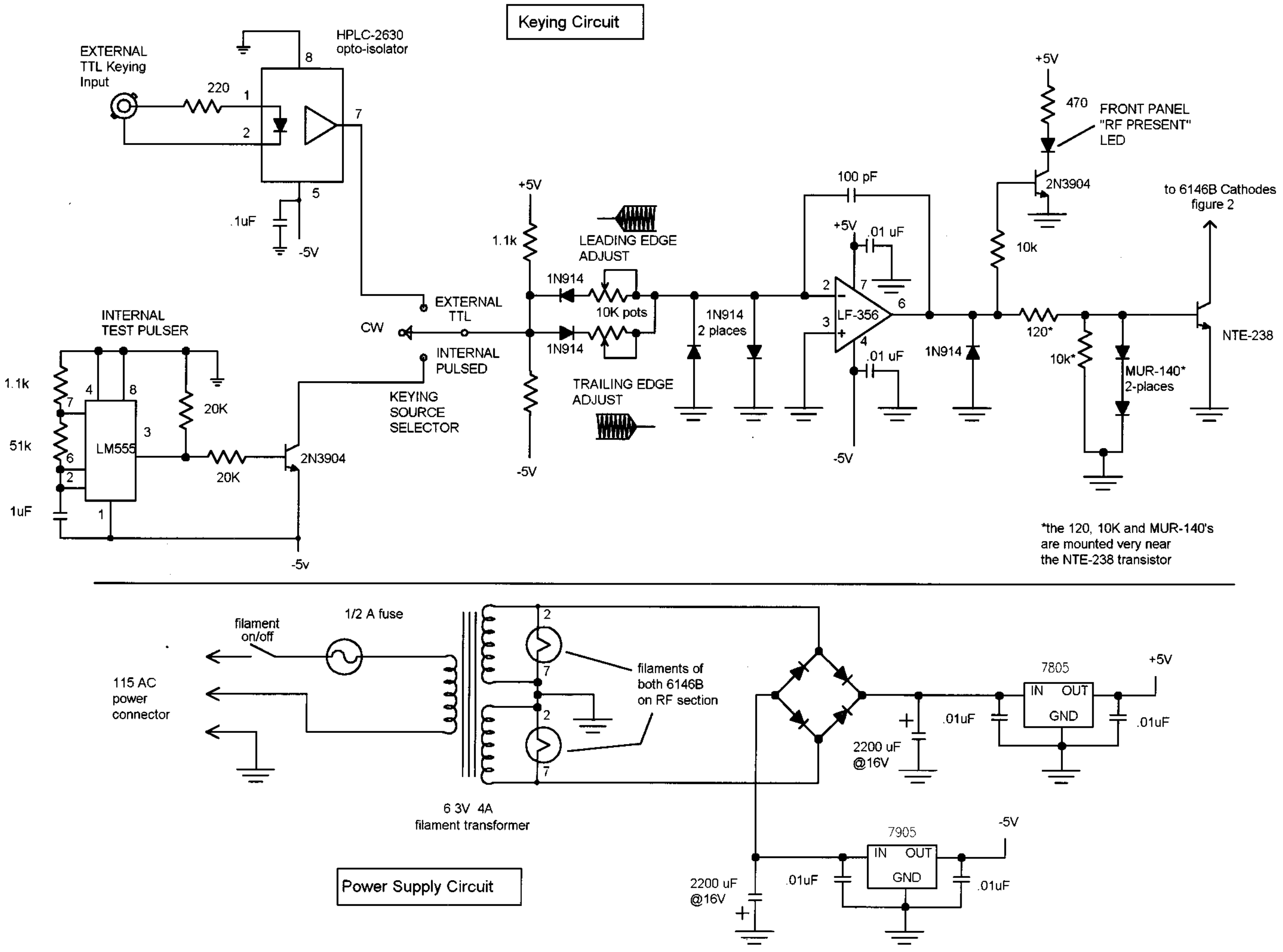

FIG. 3. Schematic of keying circuit and power supply.

ping the tank coil ~1–2 turns from each end and feeding the resulting rf voltage to the control grid of the opposite tube, as shown. The tap position is not critical, but the two sides of the coil should be trapped symmetrically. Additionally, the tank coil is center-tapped and tied to ground via two large capacitors. The rf-grounded center tap forces the circuit to oscillate symmetrically, and provides a place to make the high voltage (HV) dc connection to the tube plates (anodes).

Since the coil inductance (L_{tank})is one of the frequency-determining elements, we have built some of our rf sources so that several different coils can be interchanged. This is done by supporting the center of the coil on a high voltage stand-off, that also makes the center tap electrical connection. The plate and grid connections (taps) are simply made by attaching wires at the appropriate points along the coil using alligator clips. The output frequency is continuously adjustable by varying C_{tune}, small changes in frequency range are made by moving the plate and grid taps on the coil, and large range changes are made by changing coils.

The tank coils are constructed of ~2.5 mm diam copper wire, wound on plastic coil forms, with coil diameters ranging from ~2.5 to 5 cm, and pitch of 1–4 turns/cm. Coil forms are not strictly necessary, however, unsupported coils may change shape with temperature, and this will cause frequency drift. Table I describes two typical coils, the plate and grid tap positions, and the resulting frequency ranges. The plate and grid taps are made symmetrically about the center tap position. Since the actual frequency depends on the load/cable/feedthrough capacitance, these values should be taken as an approximate guide to coil construction.

The original Freiburg/Chemnitz design used a 5894 dual tetrode tube as the active element. In the updated Utah design we switched to the pair of 6146B tubes, because they are more readily available, more powerful, and a pair of them cost less than the 5894 with its special socket. In addition, we added the rf amplitude keying (blanking/ramping) and monitor circuits.

In this push–pull oscillator design the rf amplitude on the guide electrodes is approximately equal to the plate voltage applied to the tubes. For the 6146B the maximum amplitude is 700 V, which is more than adequate for most purposes. Indeed, the resulting 1400 V between adjacent guide electrodes approaches the limit where discharges become a real problem. The maximum power dissipation of the rf

TABLE I. Tank coil construction and approximate frequency ranges.

Approx. freq. range in MHz	Turns from center tap to each grid tap	Turns from center tap to each plate tap
Coil one—1.2–15 MHz 5 cm diam, 4 turns/cm, 60 turns total, 15-cm-length		
1.9–2.7	15	29.5
2.2–3.2	13	20.5
2.9–4.2	8	13.5
3.3–4.8	6	10.5
4.6–6.6	5	8.5
5.5–7.8	4	6.5
7.0–9.5	3	3.5
8.7–11.8	2	2.5
11.8–15.5	1	1.5
Coil two—10–30 MHz 2.5 cm diam, 1 turn/cm, 11 turns total, 11-cm-length		
10–17	3	5.5
13–18	2	4.5
16–24	2	3.5
22–30	2	2.5

source is ~140 W, however, for a typical guide/trap only 5–10 W are required to produce the full output amplitude.

The plate voltage (V_{plate})controls the rf amplitude; indeed, the amplitude is quite linear with plate voltage once the oscillator is well above threshold (~50 V). V_{plate} is input from an external power supply chosen to suit the experimental requirements. For simple trapping/guiding applications where amplitude stability is not at all critical, any well-filtered dc supply with voltage adjustable up to ~400 V and output current of at least 100 mA is suitable. Simple unregulated homemade supplies are adequate as long as they are well filtered. For applications where the amplitude is critical and/or needs to be varied under computer control, we have used a variety of commercial supplies. Particularly convenient is the Bertan Inc. model 210-01R (0–1000 V, 250 mA), because it can be programmed by a 0–10 V input from a DAC. To prevent rf from interfering with the power supply, the plate voltage is connected through a LC filter. In addition to feeding the plates via the center tap on the tank coil, V_{plate} is fed to the screen grids on both tubes through 25 kΩ resistors. The voltage drop across these resistors sets the screen grid voltage.

The rf peak-to-peak voltage appearing across C_{tune} and the tank coil oscillates approximately between ground and $2 \cdot V_{\mathrm{plate}}$. The rf applied to the guide/trap must oscillate between $V_{\mathrm{float}}+V_{\mathrm{plate}}$ and $V_{\mathrm{float}}-V_{\mathrm{plate}}$, where V_{float} is the desired dc ''float'' potential for the guide/trap. To decouple the oscillator stage from the output stage, each phase of the rf output is passed through a large value ceramic blocking capacitor. To compensate for small imbalances in the load capacitance, one phase has a variable air-spaced capacitor in parallel with the fixed ceramic capacitor. This allows fine control of the rf balance (i.e., symmetry of the two output phases) by varying the net impedance of the blocking capacitor set. The net capacitance of the fixed+variable capacitors on phase B should be approximately equal to that of the fixed capacitor on phase A, such that $C^{B}_{(\mathrm{fixed+variable})}$ can be varied in the range $C^{A}_{\mathrm{fixed}} \pm 10\%$. Since capacitor values are typically rather imprecise, this requires some trial and error. C^{A}_{fixed} is ~2200 pF.

The float voltage, generated by an external supply, is applied to the rf output section through a pair of 2.5 mH rf-blocking chokes. Because many of our experiments require an applied dc difference voltage (V_{diff}), the float voltage is passed through a pair of adjustable supplies such that the dc voltages applied to the rf chokes are $V^{+}=V_{\mathrm{float}}+V_{\mathrm{diff}}$ and $V^{-}=V_{\mathrm{float}}-V_{\mathrm{diff}}$. As a simple floatable adjustable bipolar supply we use a dc/dc converter to supply floating ±12 V dc, with a dual linear potentiometer to adjust the voltage symmetrically. A pair of batteries can be substituted for the dc/dc converter, if dc difference potentials are only needed occasionally. For the dc/dc converter, we have chosen a part with 1000 V isolation. This is far more isolation than needed normally, but provides a measure of safety in case the one of the blocking/balance capacitor fails, thus putting the full plate voltage on the output stage.

Accurate measurement of the rf amplitude is needed for differential scattering experiments[2] or where the characteristic ion oscillation frequency in a trap must be determined. The problem is that typical rf oscilloscope probes have capacitance of 2–10 pF, and thus disturb the rf one is trying to measure. Lower capacitance probes can be constructed, but quantitative amplitude measurements are difficult because the probes pickup rf from any electrodes or leads in near proximity. We solve this problem by building a pair of matched rf probes into the output stage. These have relatively high capacitance (~2 pF), but since they are a permanent part of the circuit, there is no disturbance when the probe is monitored. The probe circuits are designed to give 100:1 rf amplitude reduction, when attached to standard 1 MΩ impedance oscilloscope input via a 1 m length of RG-58 coax cable. A small air-variable trimmer capacitor is provided for calibration purposes.

Keying the rf output is accomplished by controlling the cathode voltage of the tubes, using the keying circuit shown at the top of Fig. 3. Keying is controlled by a transistor–transistor logic (TTL) waveform, passed through a fast HP-2630 opto-isolator. The rf is switched on and off by TTL HI and LO, respectively. The two diode/potentiometer sets, together with the integrating capacitors connected across the op-amp, allow manual adjustment of the rise and fall times of the rf. The MUR-140 ultrafast Schottke diode needs to be positioned as close to the NTE-238 HV transistor as possible. If keying is not required, the cathodes can simply be connected to ground by a manual switch.

Also shown in Fig. 3 is a ac/dc power supply that provides the 6.3 V ac filament voltage for the tubes and ~9 V dc to power the keying circuit.

As with any rf device, it is good practice to lay out the circuit so as to minimize the lengths of leads and connections. Parasitic oscillations (i.e., oscillations at undesired frequencies sustained by resonances from stray capacitances and inductances) are the major nuisance with rf-circuit construction, but these are only a significant problem in the higher frequency ranges ($f \geqslant 10$ MHz). The circuit is housed in a 23 cm×23 cm×30 cm ($w \times h \times d$) aluminum chassis, with the top and sides covered by perforated aluminum sheet to allow convective cooling. The chassis has a lower compartment ~8-cm-high. The tube sockets and supports for the tank coil are mounted on the ''deck'' separating the lower and upper compartments. All high-rf parts of the circuit (tube plate connections, C_{tune}, L_{tank}, and the output stage) are housed in the upper section of the chassis, to isolate them from the keying circuit and other low rf components housed in the lower compartment. Low voltage inputs and outputs are via BNC connectors, V_{plate} is input via a MHV connector, and the rf output is via UHF connectors. Best results are obtained by locating the rf source within 20 cm of the vacuum wall, and using unshielded wire (AWG 14) for the external connection. If the device must be mounted at a longer distance (<1 m!) from the vacuum feedthrough, R/G8 coax can be used for the connection, but this limits high frequency operation due to the high capacitance of the cable. The capacitors used in the rf part of the circuit are either fixed ceramic type or air-spaced variable capacitors. Chokes are standard high voltage rf chokes with π-section windings. The choke for the plate voltage input should be rated for at least 300 mA currents, and the rest should be 10 mA or better.

It is important to remember that the tubes, tank coil, tuning capacitor, and associated leads and hardware are floating at the full dc plate voltage. The output section of the source floats at V_{float}, which can also be dangerously high. It is crucial that all power supplies be disconnected, and the voltage on the oscillator and output circuits discharged to ground, before the housing is opened or any work on the circuit is attempted. Be aware that air-spaced variable capacitors can short circuit if the plates are bent or dirty. Failure of the variable blocking capacitor will put high voltage on the output stage, so this capacitor should be conservatively rated, clean, and in good condition.

ACKNOWLEDGMENT

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