VACUUM ELECTRON DEVICES IN THE 88-INCH CYCLOTRON*

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Abstract

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory is a sector-focused cyclotron that has light- and heavy-ion capabilities and supports a local research program in Nuclear Science and is the home of the Berkeley Accelerator Space Effects Facility, which studies effects of radiation on microelectronics, optics, materials, and cells.

The cyclotron utilizes several vacuum electron devices (VEDs) in different systems, mainly to convey plasma heating, high power RF generation, and high-voltage and current DC power generation.

VEDs have been proven reliable, robust, and radiation resistant. They also have wide range, good response against transients, and stable operation with load mismatch during system tuning, instabilities, or breakdowns.

The paper will describe applications of these devices in the 88-Inch Cyclotron.

INTRODUCTION

The Livingston chart shows the evolution of particle accelerators with the astonishing increase of particle energy by an order of magnitude every 7 years [1], demonstrating a power requirement trend of high-power radiofrequency (RF) sources with frequency from tens of MHz to tens of GHz to match the particle accelerators needs.

At all frequencies, the VEDs surpass the solid-state devices (SSDs) technology in producing higher power [2]. For instance, vacuum tubes can generate RF power outputs up to 1 MW continuous wave (CW) and 150 MW pulsed while a single transistor can generate RF power output in the order of hundreds of Watts CW and up to 1 kW pulsed. Consequently, VEDs are largely used in accelerator systems, otherwise, accelerators would require large numbers of transistors operating in parallel in order to reach the lowest power levels [3].

The comparative evolution of the most important VEDs and the SSDs technologies can be observed by the figure-of-merit $P_{avg}f^2$, Fig. 1. The black solid line shows the figure-of-merit technological trend predicted by the Livingston chart. The physical significance of the figure-of-merit derives from the fact that the maximum beam power that can be transported through the RF structure is directly proportional to the cross-sectional area, which is inversely proportional to the operating frequency [4]. Figure 1 shows that the SSDs technology is currently reaching a figure-of-merit 0.1 MW GHz^2 due to advances in devices based on wide bandgap semiconductor material (GaN).

The reason for the power discrepancy between VED and SSD technologies is that the electron beam flow in a SSD is collision dominated [5]. Thus, it is limited by the capacity to dissipate heat with higher probability of a dielectric breakdown at increased microwave field strengths. Nevertheless, SSD has higher stability and absence of warm-up time.

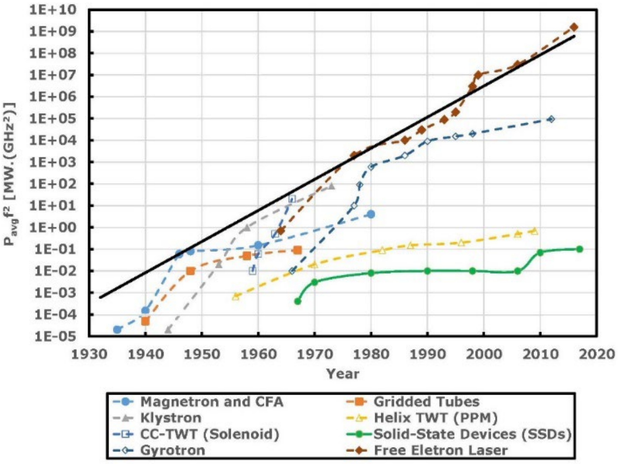

Figure 1: Comparative evolution of major VEDs using the figure-of-merit $P_{avg}f^2$.

Albeit the VED's electron beam flow in vacuum is collisionless, the output power of the VED is limited by the maximum cathode current density available, the maximum anode power density which can be dissipated, the breakdown field strength, the window failure, and the multipactor discharges [3].

VEDs originated in the early 20th century, but they still have a wide variety of commercial and military applications that require high power and efficiency at high frequency, such as commercial satellite communication systems, plasma heating for thermonuclear fusion, radar and electronic warfare systems, medical systems, and accelerators.

The 88-Inch Cyclotron utilizes several VEDs to carry out light- and heavy-ion research that supports a local program in nuclear science. The cyclotron is also the home of the Berkeley Accelerator Space Effects (BASE) Facility. The BASE Facility delivers well-characterized medium energy ion beams to imitate the space environment.

VED amplifiers utilized in the cyclotron convert electromagnetic radiation into coherent radiation through a beam-wave interaction. The coherent radiation requires a bunched electron beam that maintains synchronism with the electromagnetic field. The basic mechanisms for the electromagnetic radiation are [6]:

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- Cerenkov radiation - when an electromagnetic wave propagates with a phase velocity slower than the speed of the electrons (TWT),
- Transition radiation - when electrons pass through an inhomogeneous medium (Klystron), and
- Bremsstrahlung radiation – when the electrons are subject to a periodic force created by electric and/or magnetic fields (Gyrotron).

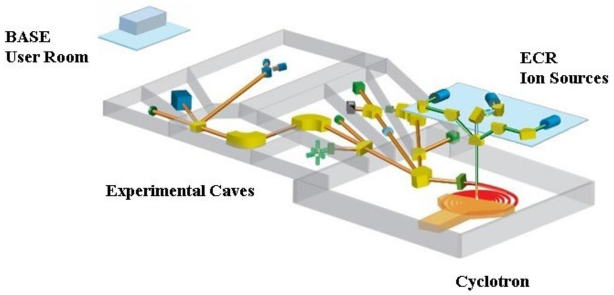

Figure 2: 88-Inch Cyclotron Facility Layout. Ions are produced by ECR ion sources and injected in the cyclotron, where they are accelerated and transported to experimental caves. The BASE user room is used to collect and analyze the experimental data.

88-INCH CYCLOTRON

Figure 2 shows that the ions produced by electron cyclotron resonance (ECR) ion sources are transported to the 88-Inch Cyclotron. After the ions are inflected at the middle of the cyclotron, they are accelerated and bunched by a radiofrequency (RF) electric field and maintained in a spiral trajectory by a static magnetic field. The orbit increases with radius as the ions gain energy until they are extracted with the deflectors. The cyclotron magnetic field and RF frequency can be tuned to produce ion beams with energies up to 55 MeV/u.

A mixture of near-identical charge-to-mass ratio ions, called “cocktail”, can be produced by the ion sources, injected simultaneously, and selected within a minute with small adjustments of RF system frequency.

The heavy ion cocktails of 4.5, 10, 16, 20, and 30 MeV/u are currently available. They offer different ion species and charge states that can be accelerated to various energies, consequently the users of the Berkeley Accelerator Space Effects (BASE) Facility can use these ions to probe the components under examination at different depths [7].

ECR System

The cyclotron ion sources evolved over time to produce higher charge states and intensities of heavier ions, which allows the cyclotron to produce higher beam energy and power, respectively.

The first ECR ion source was commissioned in the 1980s. It has a plasma primary heating frequency of 6.4 GHz, which is delivered by a 2.5 kW CW Klystron, and a magnetic confinement field of 0.4 T.

The ECR sources produce plasma through a resonant heating process where the microwave radiation couples and gives energy to electrons that further ionizes the plasma by collisional processes. The density of the plasma is directly proportional to the RF frequency squared [8], so an increase of the VED’s frequency with consequent rise of the magnetic confinement field is required to improve the ECR performance.

The second ECR generation, the advanced ECR or AECR, was commissioned in the 1990s. It has a plasma primary heating frequency of 14 GHz, which is delivered by a 2.5 kW CW Klystron, and a secondary heating frequency of 10.75 to 12.75 GHz, which is generated by a 400W CW traveling wave tube (TWT) amplifier. The AECR plasma requires a magnetic confinement field of 1.7 T.

The AECR broadband TWT optimizes the source performance [9] by producing a secondary resonance surface that heats and improves the stability of the plasma.

The third ECR generation, the versatile ECR ion source for nuclear science or VENUS, was commissioned in the 2000s. It has a plasma primary heating frequency of 28 GHz, which is delivered by a 10 kW CW Gyratron, and a secondary heating frequency of 18 GHz, which is generated by a 2.5 kW CW Klystron amplifier. The VENUS plasma requires a magnetic confinement field of 4 T.

The sources use VEDs to heat the plasma and produce high-current and high-charge state or low-current and ultra-high charge state ions for the variable energy experiments. The VEDs are very efficient, rugged, and extremely reliable devices that have a large figure-of-merit.

RF System

The RF system has a frequency synthesizer that generates the RF signal that will be modulated by a series FET RF transistor to regulate the RF amplitude and amplified by a 10W wideband amplifier.

Two solid state linear amplifiers, located outside of the vault, further amplify the signal to the maximum power to 2 kW CW, before the RF signal is sent into the vault to drive the final power amplifier.

The final amplifier boosts the power up to 150 KW CW and feeds a quarter-wave cantilever type resonating structure with movable panels around it.

Coarse frequency tunings are produced by adjusting the panel position and the anode trimmer capacitor, which vary the inductance and capacitance of the RF vacuum tank circuit.

After resonance, a lock-in amplifier samples the Dee voltage with a capacitive probe and maintains the phase relationship to the signal from the synthesizer by automatically adjusting the Dee trimmer capacitor, preventing the RF tank circuit from running out of resonance mainly due to thermal effects, similarly to other cyclotrons.

The RF system is resonant from 5.5 MHz to 16.5 MHz and is driven by the final power amplifier.

Final Power Amplifier

The final power amplifier uses the 4CW150,000E tetrode in a grounded-cathode configuration that operates as a class AB amplifier and has a feedback neutralization circuit to avoid oscillations [10]. The tube must be located inside of the vault and as close as possible to the RF tank to decrease losses and avoid the generation of parasitic components that may interfere with the RF tank resonance. The tube has unmatched radiation resistance for the application because beam losses in the vault can produce large radiation fields that would damage sensitive electronics.

The final power amplifier converts the DC power from the anode power supply in RF power that is fed to the RF vacuum tank circuit that works as a resonator.

Anode Power Supply

The anode power supply has a ML7560 grid-controlled triode that operates as a hard-tube modulator [11]. It can handle 440 kW and feeds the 4CW150,000E tube from the final power amplifier.

A crowbar circuit detects breakdown events and triggers the 672A thyratron tube, which applies a negative voltage to the ML7560 grid, placing the tube in the non-conducting state and protecting the 4CW150,000E tube in the final power amplifier. The thyratron has the advantage of being highly reliable and having a large dynamic voltage range.

The anode power supply has two functions. First, it is a device used to regulate the 4CW150,000E plate voltage, removing perturbations of rectifier ripple and changes in beam loading. Second, it functions as a high speed disconnect to protect the 4CW150,000E tetrode during breakdowns inside the RF tank, primarily caused by multipacting.

VEDs are used in the anode power supply because they provide excellent fault-protection of the RF final power amplifier, good voltage regulation, and are extremely reliable. They also have low internal noise, good response against transients, and stable operation with load mismatch during the system tuning [11].

CONCLUSIONS

The 88-Inch Cyclotron can produce light- and heavy-ion beams to carry out a local research program in nuclear science and support the BASE facility, which employs well-characterized beams to simulate space environment.

The cyclotron utilizes several VEDs in different systems. The three ECR ion sources utilize microwave power from Klystrons, a TWT, and a Gyrotron to heat the plasma and produce ions with high intensities and charge states. The density of the plasma is directly proportional to the RF frequency squared, so the increase in the VED's operating frequency and power is required in next ECR generations. The demanding figure-of-merit, occasional mismatches caused by plasma instabilities, and ruggedness requirements entail the unsurpassed use of VEDs in the ECR sources.

The cyclotron RF system is a broadband resonant system that is driven by the final power amplifier, which uses the 4CW150,000E tetrode in a grounded-cathode configuration that operates in class AB mode. The final power amplifier has high efficiency, high gain, and low harmonic output content. It converts the DC power from the anode power supply into maximum RF output power of 150 kW CW in the frequency range of 5.5 to 16.5 MHz, which excites the resonating structure and produces a maximum Dee peak voltage of 75 kV. The final amplifier must be located next to the RF tank to decrease losses and avoid the creation of parasitic components that may interfere with the RF tank resonance. Since the final power amplifier is located in a region of high radiation fields, the VEDs are an unmatched choice because of their inherent radiation resistance.

The anode supply voltage utilizes several VEDs and operates as a hard-tube modulator. The supply is used to regulate the 4CW150,000E plate voltage from 0 to 25 KV with currents up to 10 amps, but it has a secondary function of protecting the 4CW150,000E tetrode during breakdowns inside the RF tank, mainly during the RF tank conditioning. The VEDs constitute a well-established solution to drive and protect the final power amplifier from demanding transients observed during the RF tank conditioning.

In summary, VEDs are largely used in the cyclotron because they have been proven reliable and can reach higher RF power than SSDs, besides being tolerant to overloads, voltage spikes, and radiation. They also have wide range, good response against transients, and stable operation with load mismatch during system tuning or breakdowns.

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