

## AN EFFICIENT RF SOURCE FOR JLAB\*

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### Abstract

The original CEBAF accelerator at Thomas Jefferson National Accelerator Facility (JLAB) currently uses a system of 340 klystrons with relatively low efficiency, but an MTBF approaching 170,000 hours. Over the lifetime of the project 60% of the tubes have been replaced, giving an MTBF for a single tube of about five to six years. 45% of the klystrons were replaced over the thirteen years of full operation (1995-2007) with an average filament on time of 80% and high voltage on time of 75%, thus a utilization rate of 61% per year or ~4300 high voltage operating hours per year with an overall system efficiency of 35%. This represents 1.6M\$ per year of electricity costs and over 20% of the total electricity usage of the high energy mission specific facilities (HEMSF).

We propose the development of a highly reliable high efficiency RF source for JLAB operating at ~80% efficiency yielding system operating costs of only about 0.7M\$/year for the 6 GeV machine. A number of RF source designs are being evaluated including the concept of two injection locked magnetrons in a novel combining architecture for amplitude modulation. A cost analysis including efficiency and reliability will be performed to determine the optimum system architecture.

### INTRODUCTION

The RF source for the CEBAF machine currently uses 5-8 kW klystrons operating at ~35% efficiency [1]. The annual electricity usage for the HEMS F for the 6 GeV machine is 130,000 MWhrs [2]. As shown in Table 1, the annual savings for the RF source alone would be about 1M\$ per year, neglecting various cooling requirements for the power supply and microwave tube. The savings represent a reduction in the HEMS F usage from 130,000 MWhrs to about 113,000 MWhrs for the 6 GeV machine.

Table 1: Example calculations of the impact of a high efficiency RF source on the operating costs and electricity usage per year.

RF output power	5	5 kW
tube efficiency	35%	80%
DC input power to each station	14.3	6.25 kW
number of stations	340	340
DC Input power for HPRF sources	4857	2125 kW
Power supply conversion rate	95%	95%
Total station input power for HPRF	5113	2237 kW
70% utilization rate	6132	6132 hrs/year
Yearly Electrical Usage	29784	13031 Mwh/year
Cost at 61\$/Mwh	\$1.82	\$0.79 (\$M)
<b>Savings</b>		<b>\$1.02 (\$M) per year</b>

The MTBF of individual tubes in the CEBAF system can be estimated to be 5-6 years or about 37,000 tube

hours with a 75% utilization rate, while the MTBF of the system of 340 tubes is approximately 170,000 system hours (see Figure 1). Magnetrons have a similar MTBF. Varian (now CPII) reported lifetimes of 27,600 MTBF for a 65-80kW X-band coaxial magnetron [3]. In 2006, a study was made at the Naval Post Graduate School in Monterey, of the Total Ownership Cost (TOC) of the Aegis microwave power tubes. In the Aegis system, the MTBF of CFAs was improved from 6000 hours to 45,000 hours from 1983-2002 [4]. Cross-field amplifiers (CFA) are in the same class as magnetrons.

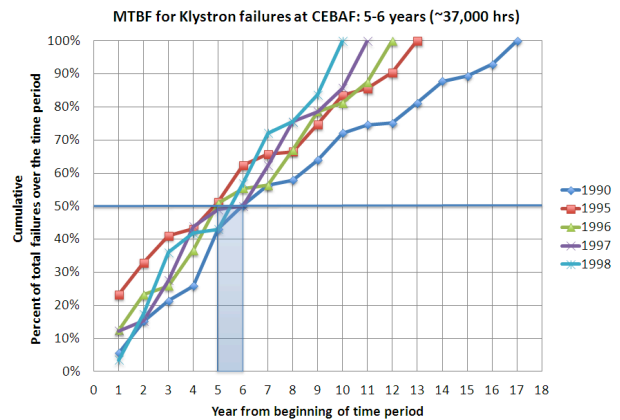


Figure 1: Data Collected from JLAB presentation, “Operating Experience and Reliability Update on the 5 kW CW klystrons at Jefferson Lab,” [5].

Another primary use of magnetrons is in medical linear accelerators where they are operated at high peak powers with low utilization rates. The MTBF of the magnetrons in one linac system architecture was doubled from 20 months to 43 months over a four year period [6].

The point to be made is that, the system design and the interface between the tube(s) and power supplies dominates the MTBF of the RF source. It is reasonable to assume that the MTBF of a magnetron based system can be as good if not better, than the klystron MTBF when the system design is optimized at an early stage of development.

### APPROACH

We have determined two basic designs which will be further analyzed. The first consists of a single RF source (klystron, magnetron, IOT, etc.), and the second would be a dual magnetron source in which the outputs of two injection locked magnetrons would be phased and combined to produce a required output power level and phase.

An initial power balance spreadsheet analysis has shown that a single magnetron would be more efficient than using either a klystron or IOT device. Thus our focus has narrowed to either a single or dual magnetron system.

\*Work supported by DE-SC0009693

Figures 2 & 3 show the system diagrams for each of those two options.

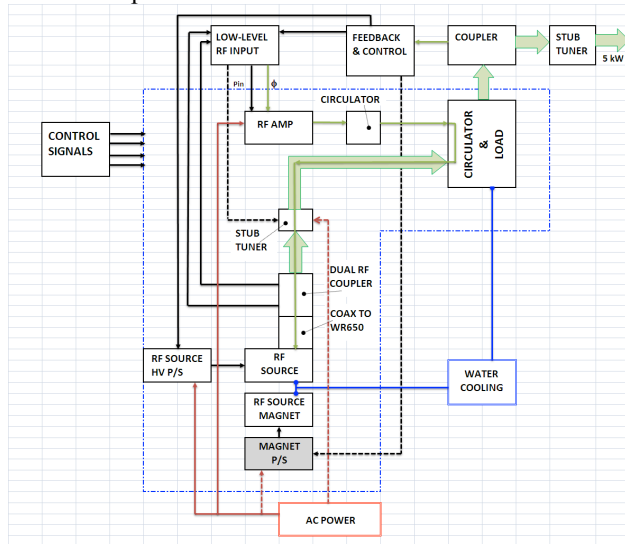


Figure 2: Single RF source system diagram.

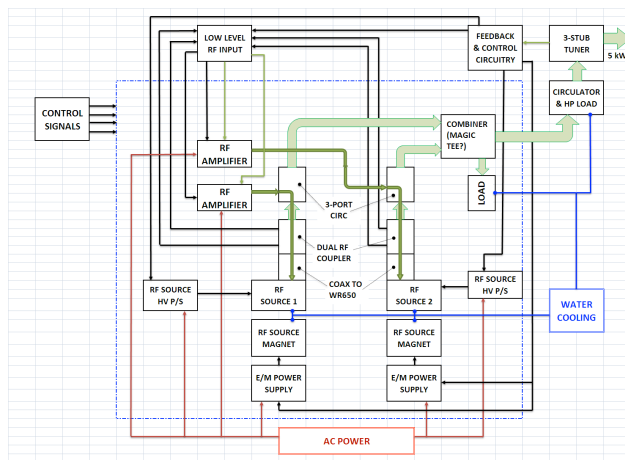


Figure 3: Dual Magnetron source system diagram.

Figure 2 is similar to the current CEBAF system using a single klystron. Figure 3 however shows an injection signal fed through a circulator into a combining network which may be as simple as a magic TEE. Both magnetrons are fed with this signal, injection locked, and deliver their output to combine in the fourth leg of the magic TEE. To adjust the output amplitude, the amplitude and phase of one magnetron is adjusted relative to the other (via the Feedback & Control system). The sum is sent to the output, and the difference is sent back through the circulator to a load. This is a straightforward system, just like the others, but the devil is in the details.

The first of those details is controlling the output phase of one magnetron relative to the other. In the work already done by JLAB, 0.8° phase stability was achieved, limited by noise from the digital power supply used.

Additional details being analyzed and optimized are:

- 1) What design elements or improvements are required to meet the AM requirements of the combined system?

- 2) What is the most cost effective combining system?
- 3) Will an electro magnet be used for the magnetron focusing to optimize efficiency?
- 4) Will the design of the 1497 MHz magnetron include a side coupling for improved locking?
- 5) Will phase shifters be required in addition to magnetron pushing by the beam voltage to achieve the required amplitude modulation?
- 6) What is the overall efficiency of the system under realistic operating conditions? How does it impact TOC?
- 7) Can a low gain cross-field amplifier (CFA) be used in addition to the phase locked magnetrons to meet the 12 GeV upgrade requirements?

### System Efficiency and TOC

The system efficiency of various system architectures is being studied to determine the optimum design. The methodology is shown in Figure 4 (shown on the next page). Each element of the system architecture will be analyzed in terms of input power, efficiency, and heat loss. The TOC is a summation of acquisition cost and operating costs. The payback of the acquisition cost, in terms of cost savings from operating costs, is being determined.

New components will need to be designed, such as the 1497 MHz magnetron, and the methodology to determine the design effort (cost) as well as the TOC without knowing exactly which elements will be involved will utilize a scoring method similar to that shown in Figure 5. In this method, various elements of the designs are “scored” for cost, ease of design, complexity, etc. (1 being easy / low cost, and 3 being difficult / high cost).

	Sum	Total Tube Cost	# of tubes	Eff	Tube Cost (each)	Gun	Interaction Region	Collector	Total System Cost	RF Driver	waveguide system	Feedback System	Power Supply
Klystron	19	15	1	0.4	6	1	3	2	4	1	1	1	1
IOT	14	8.57	1	0.7	6	2	2	2	5	2	1	1	1
2 Magnetrons													
master slave	19	8	2	0.5	2	1	1		11	3	3	3	2
peer to peer	19	8	2	0.5	2	1	1		11	3	3	3	2
2 CFAs	16	8	2	0.5	2	1	1		8	3	2	1	2
1 Magnetron													
Anode V Modulated	12	2.5	1	0.8	2	1	1		9	2	1	3	3
B-Field Modulated	11	2.5	1	0.8	2	1	1		8	2	1	3	2
Gridded	9.8	3.75	1	0.8	3	2	1		6	1	1	1	3

Figure 5: Example of a risk assessment used to determine the optimum architecture for the RF source in this project.

For example, since 340 units are anticipated in the full replacement of the klystrons, there will be learning curve applied to the unit cost of the RF source designed in this Phase I program. This will include a risk assessment and median pricing for the most probable cost of 680 magnetrons. The MTBF of the RF source will be applied to arrive at a total quantity of magnetrons needed, which may exceed 1000 magnetrons over ten years. Cost estimates from various suppliers will also be used where applicable. With this methodology in place, the most cost effective system architecture will be determined.

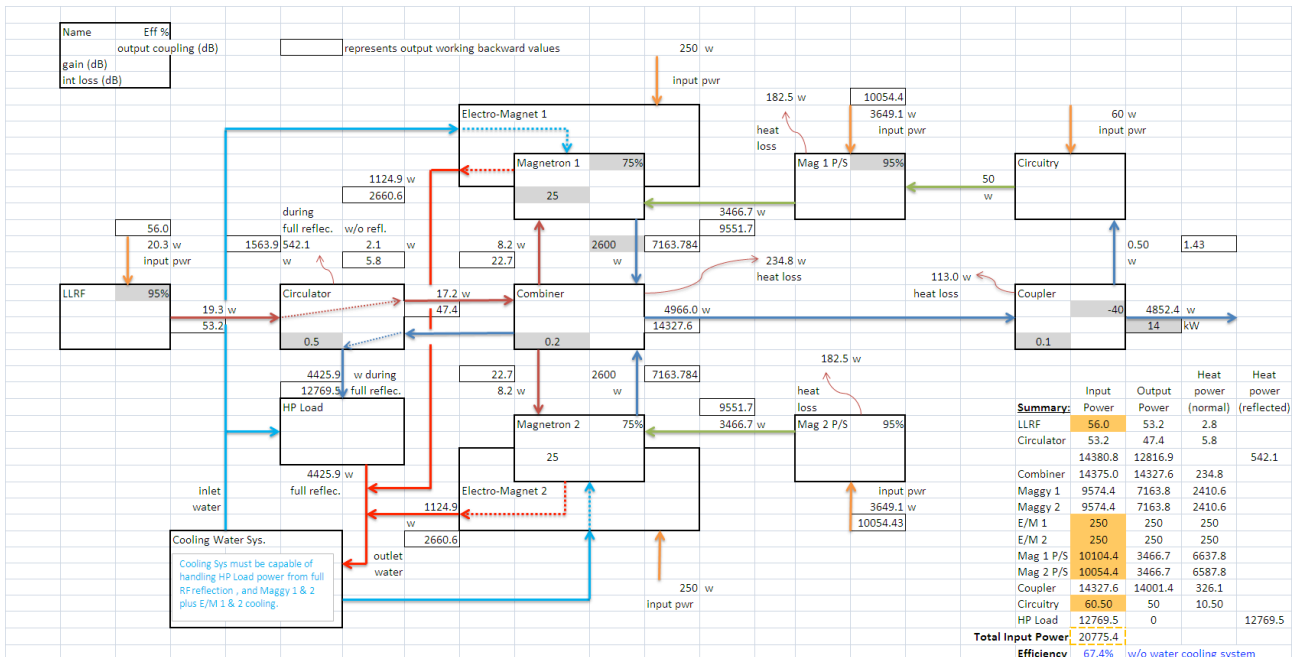


Figure 4: An example analysis for the system of Figure 3, showing elements of the analysis for total operating efficiency including the cooling system.

### 1497 MHz Magnetron

The RF source will be based upon a modest scaling of the common water-cooled industrial cooker magnetron: a 3 kW 2450 MHz magnetron [7]. The efficiency of this magnetron is about 70%. The efficiency of the similar 915 MHz water cooled magnetron is over 90%, so it is reasonable to assume a 1497 MHz magnetron can be designed to operate at ~ 80% efficiency. A paper design of a 1497 MHz magnetron is part of our program. Details of the anode structure can be designed in Comsol or CST. The details of the heater package, coupling, cooling, and other mechanical elements of the design will be made in sufficient detail so that bids for a total quantity of 1000 tubes can be obtained.

### CONCLUSION

Initial work has shown that design of a more efficient CEBAF RF source system is reasonable, and should save JLAB 1M\$+ in electricity costs per year. Technical performance and reliability equivalent to or better than the existing sources needs to be demonstrated. Total cost of ownership and time to recoup the initial investment will be calculated.

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