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Power Efficiency – Comparison between Pulse Forming Network and Solid-State Technology

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Background

The evolution of RF pulse modulators is closely tied to the development of accelerators used in high-energy physics.

Klystrons, which provide high power output and frequency stability, are essential for high-frequency applications and require a modulator to deliver the necessary pulsed power. Historically, Pulse Forming Network (PFN) modulators played a critical role, using a series of capacitors and inductors to shape electrical pulses.

The industry has transitioned to solid-state modulators, a move pioneered by ScandiNova Systems. This transition offered significant advantages like greater reliability, smaller sizes, and improved power efficiency. Modern solid-state systems, such as those from ScandiNova, integrate features like water cooling, adjustable pulse durations, and low insertion loss to reduce power loss and enhance overall efficiency

Results

Experimental and electrical data consistently highlights the superior performance and efficiency of ScandiNova's solid-state modulators when compared to the older PFN modulators. A key finding is the significant difference in the beam power utilized to produce the Radio Frequency (RF) pulse. In tests using an identical klystron, the PFN modulator demonstrated that approximately 55 % of the beam power was converted into RF. In stark contrast, this value increased by 40 %, reaching approximately 78 % for the ScandiNova modulator, which indicates a markedly higher efficiency in power conversion. This, in turn, results in both significant cost savings and reduced environmental impact.

Conclusions

ScandiNova's advances in RF pulse modulation represent a substantial step forward in the field. The transition from conventional PFN modulators to solid-state systems brings measurable improvements across reliability, form factor, and — most notably — energy efficiency.

The experimental data confirms the superior performance of ScandiNova's modulators, which convert electrical power into RF power more effectively and reduce overall power loss. The cost analysis demonstrates that despite potentially higher initial investments, the lower operational and maintenance costs, driven by substantial energy savings, result in a more favorable total cost of ownership over the long term.

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Introduction

The transition to solid-state modulators marked a significant leap forward, offering greater reliability, smaller sizes, and improved efficiency. ScandiNova has been at the forefront of this evolution, developing advanced modulator technologies that integrate features such as water cooling, adjustable pulse durations, and low insertion loss. In addition to the highlighted evolutions, it can also be noted that the modulators include protection for the klystrons (both hardwire and software interlocks), a full featured control system, and more. These modern systems significantly reduce power loss and enhance overall efficiency. Experimental data and case studies, such as those from different scientific laboratories, demonstrate the substantial efficiency improvements achievable with these advanced modulators. For instance, ScandiNova's solid-state modulators have been shown to convert electrical power into RF power more effectively than traditional PFN modulators, achieving higher beam power efficiency. Furthermore, the integration of advanced cooling systems and digital control mechanisms featured in the ScandiNova ScandiCAT™ control system further optimizes performance and reliability. This document, divided into different sections, provides an in-depth analysis of the technical evolution, efficiency improvements, and cost implications of modern RF pulse modulators compared to older technologies. By examining experimental data and case studies, the report highlights the significant strides made in reducing power loss and enhancing system performance. Section one describes the RF pulse evolution, while pulse signal analysis is shown in section two. Finally, a cost analysis as well as potential future improvements are shown in the last two sections.

RF pulse evolution

Historical overview of RF pulse modulators

The development of the RF pulse modulators is closely linked to the development of accelerators used for high-energy physics. Klystrons offer high power output and strong frequency stability, making them a staple of high-frequency applications. A modulator drives the tube by delivering the necessary pulsed power, using one of several available technologies. Magnetrons also require modulators to be driven but will produce much less peak RF power. Different types of vacuum tubes became widely used during the second world war for radar applications. RF pulse modulators were initially just manufactured to drive the pulse, while the integration, stability improvement, repeatability and maintenance free technology became a concern in the early 2000. The efficiency concerns will be addressed approximately 20 years later. In this section we will introduce the two different modulator technologies so called PFN modulators, in section 2.2, and solid state modulators in section 2.3 and finally compare them in the section 2.4.

Historical technology: PFN modulators

Pulse Forming Network (PFN) modulators have played a critical role in the evolution of RF pulse modulation technology. A PFN consists of a series of capacitors and inductors arranged in a specific configuration to create a transmission line that can shape electrical pulses. When a PFN is charged, the capacitors store energy, which is then released through the inductors to form a pulse. The precise arrangement of these components determines the shape and duration of the pulse. PFN modulators operate by charging the capacitors to a high voltage and then discharging them in a controlled sequence. This discharge process generates a pulse with a specific shape, typically characterized by a steep rise time, a flat top, and a rapid fall time. The inductors in the PFN help to control the rate of change of current, ensuring that the pulse shape remains consistent. The Fig. 1 shows the schematic of a PFN modulator that includes the different power supplies and an 18 cell PFN with an impedance of 4 ohm.

Transition to Solid-State Modulators

ScandiNova [1, 2] has been at the forefront of this technological revolution, pioneering several advances in modulator technology. ScandiNova's modulators utilize solid-state technology, which offers significant advantages over traditional thyratron-based PFN systems. These modern modulators feature integrated designs, water cooling, adjustable pulse durations, and low insertion loss. The use of water cooling, rather than air cooling, reduces energy consumption and improves overall system efficiency. The flexibility in pulse duration and the low insertion loss further enhance the performance of these modulators. ScandiNova's technological innovations, such as the Splitcore™ Pulse Transformer, Pulse to Pulse Control™, and Parallel Switching™, enable precise control over pulse characteristics, ensuring high efficiency and reliability. These advances address the limitations of older technologies, offering a blend of robustness and flexibility that is essential for modern applications. The Fig. 2, shows an unobstructed view of a K300 from ScandiNova, where the different elements described in the previous chapter are perfectly visible. On the left side of the picture, a klystron tube is shown. The compactness of the system is highly appreciable and clearly understood from the picture

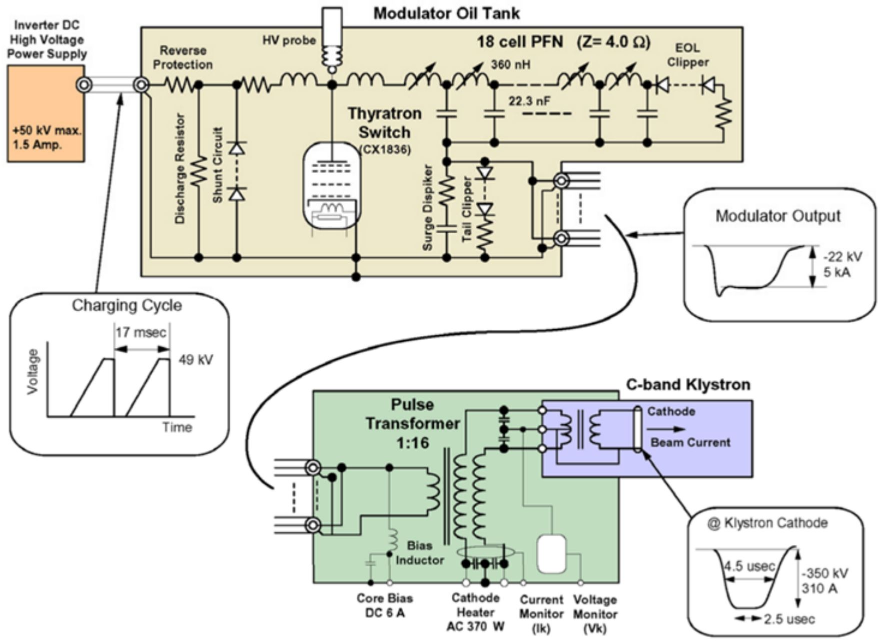

Figure 1: Schematic diagram of a classic Pulse Forming Network (PFN) modulator

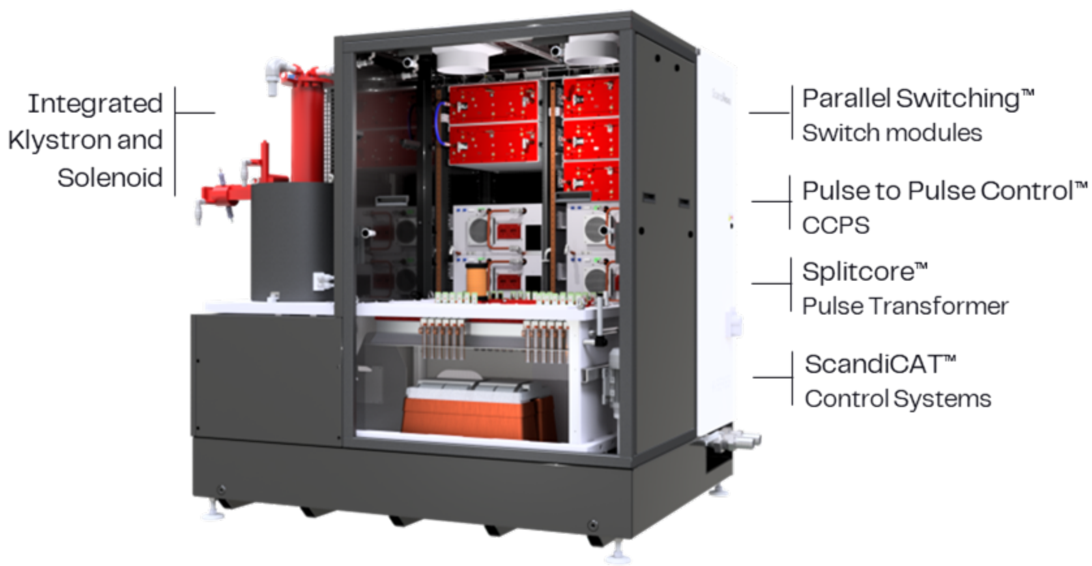

Figure 2: Solid-state pulsed technology. Unobstructed view of a K300 from ScandiNova System

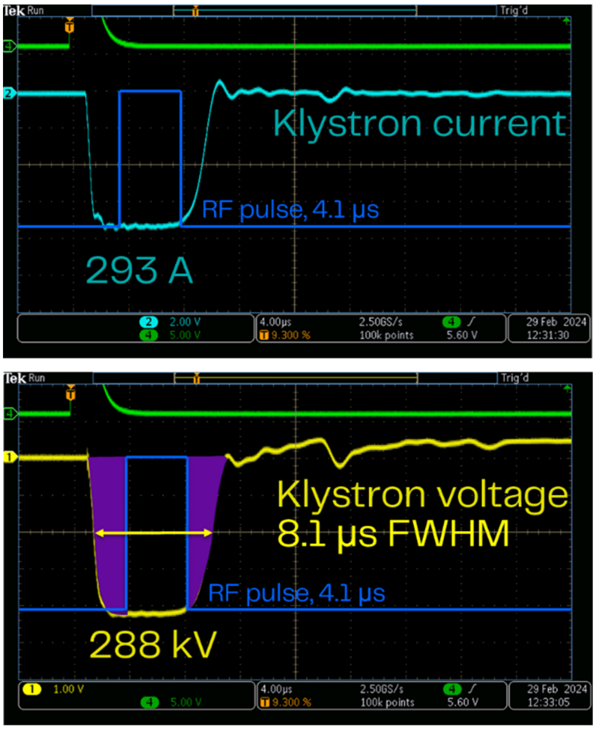

Figure 3: Current (top) and voltage (bottom) to drive a given klystron with a PFN modulator as well as the extracted RF pulse and the beam duration FWHM

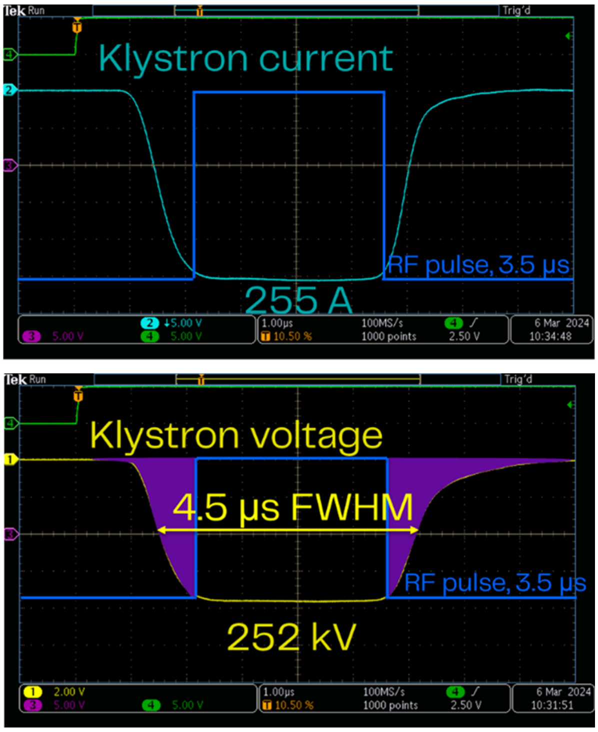

Figure 4: Current (top) and voltage (bottom) to drive a given klystron with a ScandiNova modulator as well as the extracted RF pulse and the beam duration FWHM

Key features of both technologies

Both technologies have advantages and disadvantages. Some of them will be listed in the Table 1.

RF Pulse Analysis

Experimental Analysis

Pulse signal studies provide valuable insight into the performance of different modulator technologies. Experimental data, courtesy of A. Chauchet and S. Curt, highlight the differences in Klystron current and voltage between PFN and ScandiNova modulators. Fig. 3 and Fig. 4 display the current, voltage, beam duration, and RF pulse for a PFN modulator and a ScandiNova Systems modulator, both using the same klystron. The RF pulse is generated when the beam pulse is effective. The PFN modulator demonstrated a Full Width at Half Maximum (FWHM) of 8.1 μs, whereas the ScandiNova modulator exhibited a FWHM of 4.5 μs. This shorter pulse duration highlights the superior control and precision provided by ScandiNova's technology.

The area highlighted in purple represents power losses, which means the portion of power from the beam pulse that does not contribute to RF production. Fig. 5 illustrates the extraction of beam losses and the RF pulse for both PFN and ScandiNova modulators. By calculating the ratio between the RF pulse and the purple area, it is shown that approximately 55% of the beam produces RF in the case of the PFN modulator. In contrast, this value increases by 40%, reaching around 78% for the ScandiNova modulator, indicating significantly higher efficiency.

Electrical analysis

Table 2 illustrates the power distribution and losses in the system, specifically for a ScandiNova K300

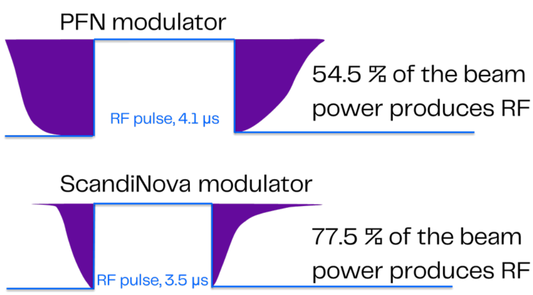

Figure 5: Losses in modulator components: ratio of the beam which is used to produce RF

Table 1: Performance comparison between classic and solid-state modulators

	ScandiNova	PFN
Advantages	Approved technology Robust Compact and fully integrated Water cooling Flexibility (pps, pulse duration) Low insertion loss Low voltage	Approved technology Very robust
Disadvantages	Many parts Need expert to install Need expert to maintain	High voltage Bulky AC cooling Flatness Fixed pulse duration Need impedance matching

driving a 7.5 MW peak power and 38 kW average power S-band klystron. The total power consumption of the modulator was recorded at 113.4 kW, with a power factor of 0.92. The extracted power from the klystron, measured using a calorimeter and a calibrated directional coupler with a power sensor, was 38.0 kW. This average power represents 33.5% of the total power. The beam power lost due to the inefficiency of the klystron was 47.0 kW, or 41.4% of the total power. Additional wasted power, attributed to the rise and fall times (see Fig. 5 bottom plot) and the magnetization of the pulse transformer, was estimated at 14.3% of the total power. Charging losses, mainly from the tuning elements used to fine-tune the beam pulse on the lower power side of the pulse transformer, were about half that amount. Finally, approximately 4% or 4.6 kW of the power consumption was from the various power supplies connected to the three-phase grid.

The analysis in Table 2 is inspired by the work of [3], as shown in Fig. 6. The primary difference lies in wall plug efficiency. While 33.5% of the input power is used to produce RF in the ScandiNova modulator, only 24.3% is achieved in the PFN modulator. Additionally, the wasted pulse power, which does not contribute to the RF pulse, is significantly higher in the PFN modulator, as clearly illustrated in Fig. 5 top plot.

Total Power = 51,371 W		
1. RF Power	12,488	(24.3%)
2. Wasted Beam Power	15,263	(29.7%)
3. Wasted Pulse Power	12,071	(23.5%)
4. Charging Loss	7,072	(13.8%)
5. Aux. Power	4,477	(8.7%)
Wasted Pulse Power		
a. Rise/Fall Time Loss	9,991	(19.45%)
b. Magnetizing Loss	929	(1.81%)
c. Thyratron Loss	416	(0.81%)
d. Eddy Current Loss	463	(0.90%)
e. RC Snubber Loss	272	(0.53%)
Aux. Power		
a. Klystron Magnet	3,000	(5.84%)
b. Thyratron Heater	567	(1.10%)
c. Cooling Fan	450	(0.88%)
d. Klystron Heater	316	(0.62%)
e. Core Bias	100	(0.19%)
f. Thyratron Reservoir	44	(0.09%)

Figure 6: Power distribution on a PFN modulator [3]

Cost analysis

The use of RF pulse modulators can be costly, making it essential to analyze their economic viability and long-term benefits. This chapter focuses on the cost analysis of traditional PFN modulators compared to ScandiNova modulators, covering operational costs, maintenance expenses, and overall cost efficiency. Operational costs include expenses associated with running the modulators, such as electricity, cooling, and other utilities. As highlighted

Table 2: Power distribution on a K300 with a 7.5 MW peak power and 38 kW average power klystron

Contributor	Detail	Total	Percentage
Total input power	400 Vac, 178 A, $\cos\phi = 0.92$	**113.4 kW**	100 %
RF power	7.5 MW, 10 μs, 500 Hz	38.0 kW	33.5 %
Wasted beam power *Power dumped in the collector*	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power (*Power which does not contribute to the RF pulse*)	Magnetization: 900 W Rise/Fall Time: 15300 W	16.2 kW	14.3%
Charging losses (*Losses in the transformer and tuning elements*)	1250 V × 2 cores × 64 turns RF power − Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies [1]	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1%

in the previous chapter, traditional PFN modulators, with their bulkier design and higher cooling requirements, tend to consume more power. Their lower efficiency results in a larger portion of the input power being wasted as heat, necessitating more robust and expensive cooling systems. This not only increases electricity bills but also adds to the overall operational costs. For example, consider a klystron producing 40 MW, 4 μs RF pulses, operating at 100 Hz. The RF average power is 16 kW. Assuming the klystron has an efficiency of 45% and operates 10 hours per day, 5 days a week, the annual consumption would be 64,500 kWh. Based on Fig. 5, a PFN modulator would consume 93,500 kWh per year, whereas a ScandiNova modulator would consume 79,000 kWh per year. Another key factor is cooling. Due to operating in the tens of kV range, PFN modulators cannot be water-cooled and dissipate heat into the experimental hall. Table 3 compares the average heat generated by each modulator and the method of heat extraction, using air conditioning and water cooling, measured in tons (the amount of heat required to melt a ton of ice). Under the same operating conditions, a PFN modulator would consume 90,500 kWh per year for cooling, while a ScandiNova modulator would consume only 22,300 kWh per year.

Table 3: Cooling of the modulator by air conditioning and water

	ScandiNova	PFN
Average modulator heat	6.1 kW	24.8 kW
Air conditioning	0.3 tons	9 tons
Water cooling	1.7 tons	0

Table 4 provides a summary of the energy consumption required to operate and cool down the systems. The difference in energy consumption between a PFN and a ScandiNova modulator is approximately 46%, translating to an annual cost difference of €18,000. This calculation assumes an operation of 10 hours per day, 5 days a week, with an average electricity price of €0.21 per kWh.

Maintenance expenses are another critical aspect of cost analysis. Traditional PFN modulators, with their reliance on vacuum tube technology, require regular maintenance to replace worn-out tubes and other components. The high cooling requirements also mean that cooling systems need frequent servicing to ensure optimal performance. These maintenance activities can lead to significant downtime and additional costs.

ScandiNova modulators benefit from the robustness and reliability of solid-state technology, which typically requires less maintenance compared to vacuum tube-based systems. The absence of vacuum tubes reduces the need for regular replacements, and the advanced design of ScandiNova modulators minimizes the wear and tear on components. This results in lower maintenance costs and less downtime, contributing to overall cost savings. Long-term cost efficiency is a key considera-

[1] The losses from non-pulsed sources are shown to be less in percentage due to the fact that the solid state modulator is operating at a much higher average power compared to the PFN.

Table 4: Total consumption of the modulators

	ScandiNova	PFN
Energy consumption to produce the RF pulse	79 000 kWh/year	93 500 kWh/year
Energy consumption to cool down the system [2]	22 300 kWh/year	90 500 kWh/year
Total consumption	101 300 kWh/year	184 000 kWh/year
Price	21 300 €/year	39 000 €/year
Saving	46 %	

tion when evaluating different modulator technologies. While the initial investment in ScandiNova modulators may be higher, their superior efficiency, lower operational costs, and reduced maintenance expenses contribute to a more favorable total cost of ownership over time. The improved efficiency of ScandiNova modulators means that more of the input power is converted into useful RF power, reducing wasted energy and associated costs. This is particularly important in applications where energy consumption is a sizable portion of the operating budget. For example, in large-scale scientific research facilities or industrial processes, the savings on electricity can be substantial over the life of the modulator.

Future improvements

Each kilowatt saved on the system can contribute to reducing the electricity bill. Based on the previously mentioned operating time, every kilowatt saved can lead to savings of 550€ per year. The primary improvements fall into four categories, detailed in the following subsections.

Improvement on the klystron's efficiency

ScandiNova Systems is not a klystron manufacturer, but klystrons currently operate at around 45% efficiency. Improving klystron efficiency would have multiple positive effects. It would allow for either extracting more power with the same modulator or achieving the same power with a smaller modulator. This would help to reduce the modulator's price, carbon impact, and footprint. With a more efficient klystron delivering the same peak power, there would be fewer modulator ohmic losses, less power dissipated in the beam dump, and fewer power supplies or switch units needed. Consequently, the energy required to cool down the system and the power drawn from the grid would decrease. Increasing klystron efficiency from approximately 45% to 70% could improve wall plug efficiency by 50%.

Improvement on the solenoid

The solenoids consume a significant amount of energy in DC mode. Although ScandiNova Systems does not manufacture this equipment, the potential gains from improvements are substantial. Some klystrons need a 20 kW DC power supply to drive the solenoid. However, using permanent magnets or high-temperature superconducting magnets could reduce this power requirement by a factor of 10 or more. This would have a major impact on wall plug efficiency and significantly lower the electricity bill.

Improvement on the wasted pulse power

ScandiNova is actively working on reducing wasted pulse power. As illustrated in Fig. 5, a huge portion of the beam is not utilized for RF production. By improving transformer size to reduce leakage inductance and making enhancements to the primary side inductance of the transformer, it is possible to achieve sharper rise and fall times. The main challenge with this approach is the overshoot, which disrupts beam flatness and the phase of the produced RF pulse. A solution has been found to mitigate this issue by using a large capacitor bank. These improvements, already implemented in some of the magnetron modulators, demonstrate excellent performance and help to reduce power loss.

Improvement on the charging losses

Part of the power is lost in the tuning elements, which consist of series and parallel inductances and resistances at the transformer's primary side. To address this, innovative ideas are being developed to eliminate the need for these tuning elements by digitally controlling ScandiNova's key technologies, the Splitcore™ Pulse Transformer and Parallel Switching™. This innovation will maintain the same beam flatness without losing energy in passive components.

Conclusions

In conclusion, the advances in RF pulse modulation technology from ScandiNova Systems mark a significant leap forward in the pursuit of efficiency and sustainability. The transition from traditional PFN modulators to modern solid-state systems has brought about notable improvements in

[2]Estimated considering the cooling media (air or water), the average modulator heat, the use of the air conditioning and the use of the water chiller.

reliability, size, and energy efficiency. Experimental data and case studies consistently demonstrate the superior performance of ScandiNova's modulators, which convert electrical power into RF power more effectively, reduce power loss, and enhance overall system efficiency. The cost analysis highlights the long-term economic benefits of adopting ScandiNova's technology. Despite higher initial investments, the reduced operational and maintenance costs, coupled with the significant energy savings, contribute to a more favorable total cost of ownership. The detailed breakdown of power distribution and losses highlights the substantial efficiency gains that can be achieved with modern modulators. Looking ahead, the potential for further improvements in klystron efficiency, solenoid energy consumption, and reduction of wasted pulse power presents exciting opportunities for continued advancements. ScandiNova's commitment to innovation and excellence positions it as a leader in the field, driving the industry towards greater efficiency and sustainability. The ongoing efforts to refine and enhance RF pulse modulator technology will not only meet the growing demands of scientific and commercial applications but also contribute to a more sustainable and cost-effective future. By systematically addressing the challenges and working on innovative technologies, ScandiNova Systems continues to open the way for the next generation of RF pulse modulators, moving ever closer to the ideal of near-perfect efficiency.

References

[1] W. Crewson, M. Lindholm, and K. Elmquist, "Green pulsed power achieved by efficient solid state pulsed power technology", in Proc. 18th IEEE Pulsed Power Conf. (PPC'11), Chicago, USA, June 2011, pp. 1471–1473, 2011. doi:10.1109/PPC.2011.6191665

[2] K. Elmquist, M. Lindholm, and W. Crewson, "Pulse quality", in Proc. 18th IEEE Pulsed Power Conf.PPC'11), Chicago, USA, June 2011, pp. 1598–1601, 2011. doi:10.1109/PPC.2011.6191689

[3] S. Oh, M.H. Cho, W. Namkung, T. Shintake, H. Matsumoto, K. Watanabe, and H. Baba, presented in the "Efficiency issue in C-band klystron-modulator system for linear collider" at the 1997 Particle Accelerator Conference.