200 MeV H- Linac RF Amplifier Upgrade Plan

Freddy Severino

Head, RF Systems, Collider-Accelerator Department

C-AD Machine Advisory Committee
December 2025

Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

@BrookhavenLab

Presentation Outline

- Introduction
- Upgrade Justification
- Project Scope
- Upgrade Options Considered - 40-Year Operations View
- Basis of Proposed Upgrade Path (Cost, Risks, and Vendor Estimates)
- Cost and Schedule for Demonstrator Unit
- Summary

Introduction

- The **LINAC (200 MeV Linear Accelerator)** has been in operation since **November 1970**, marking over five decades of continuous use in critical scientific research.

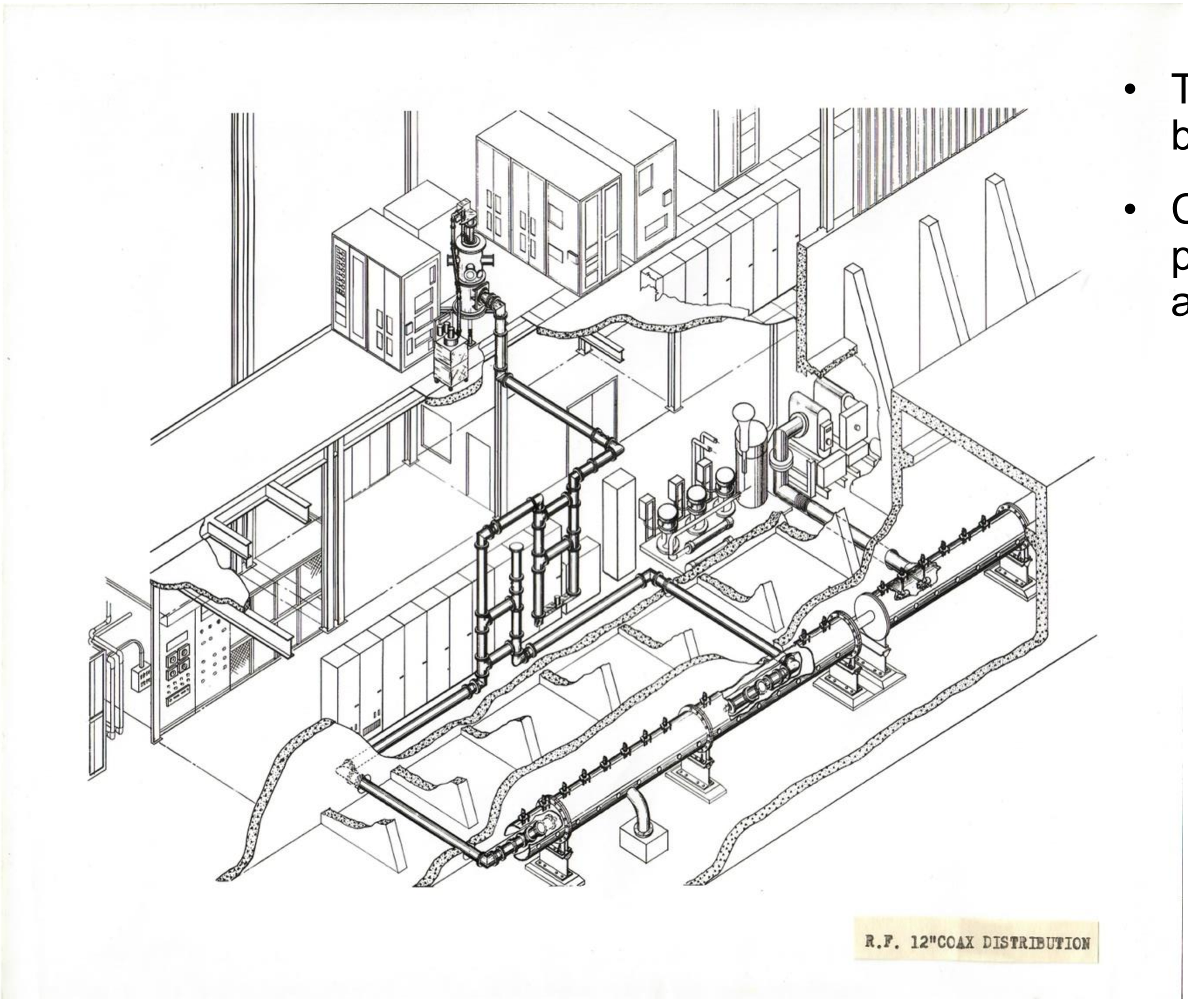
- The **LINAC RF system** consists of **9 RF Tanks**, each powered by a **5 MW pulsed RF power amplifier**, with a **200 kW driver amplifier** and **5 kW pre-driver**.
  - These systems operate at a resonant frequency of **201.25 MHz** and support key operations including **BLIP**, **NSRL**, **RHIC**, and future **EIC** operations for polarized proton beams.

- Over the years, critical upgrades have **enhanced LINAC's reliability**, but the system is still heavily reliant on **legacy RF tube technology**.

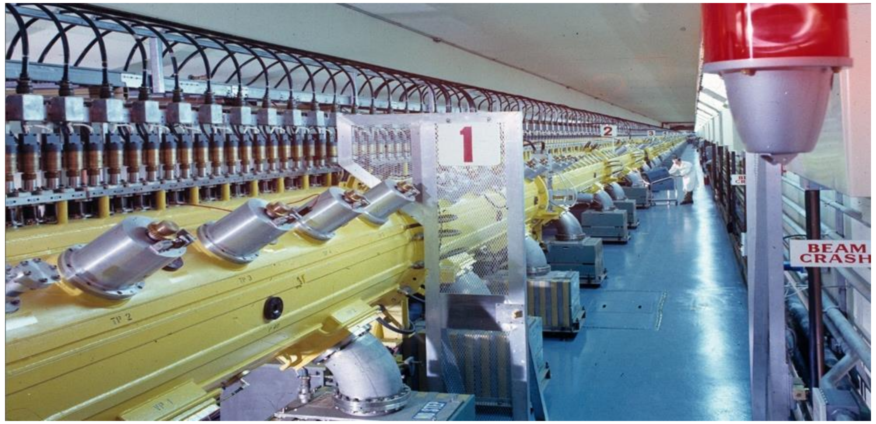
- **Urgency for Upgrade**: The current RF amplifier system, which uses **vacuum tubes**, faces **supply risks** and **decreasing reliability**. As the system ages, there is an **urgent need** to convert to **solid-state technology** to ensure the continued safe, efficient, and reliable operation of the LINAC.

Complete RF System Driver, 5 MW PA, Modulator

RF Systems View



- The **LINAC RF system** consists of **9 RF Tanks**, each powered by a **5 MW pulsed RF power amplifier.**
- Coax run from the PA through the phase shifter, 3 dB hybrid power divider, and feeding two loops in each tank (repeated for all 9 tanks)



Drift Tubes

Upgrade Justification- RF Tube Supply Risk

Aging Technology & Growing Supply Risk

- LINAC relies on two high-power RF tubes (**4616** & **7835**) for beam acceleration
- Originally developed in the 1950s for now-defunct systems, these tubes are now sole-sourced with uncertain long-term availability
- Modulator tubes (**LPT32** & **8618**) are also sole-source, with **rebuilds as the only supply option**

RCA 7835 Power Triode, 7 MW Peak Power

Tube Supply Status & Risks

- **Inventory**: ~6 years (**BLIP** @ 60 mA) / ~10 years (**EIC/NSRL** @ 400 μA))
- **Supply Risk**: Vendors may exit the business in **3–4 years** without large orders. Warranty issues if manufacturer exits the business.
- **Quality concerns**:
    - Shorter lifespans & declining reliability (new/rebuilt tubes)
    - **Skilled labor loss** affecting manufacturing consistency

Conclusion: Without intervention, LINAC operations face **significant risk** due to dwindling tube supply, unreliable rebuilds, and potential obsolescence of critical components.

Project Scope

Scope: This project will initiate the transition of the LINAC RF Power Amplifiers to solid-state technology by upgrading one of nine high-power amplifiers currently utilizing legacy vacuum tubes (types 4616 and 7835). The scope includes developing technical specifications and a Statement of Work (SOW), evaluating vendor proposals, and selecting a solid-state solution based on performance metrics and system compatibility. One amplifier unit will be procured, factory-tested, and installed in LINAC Tank 9 to replace the existing tube-based amplifier. This upgrade will serve as a proof-of-concept, informing the future replacement strategy for the remaining eight RF amplifiers.

Out of Scope:

- Replacement of the remaining LINAC RF amplifier units.
  (Future phases will convert **6 of 8 tanks**; **2 low-power tanks remain tube-based**.)

Assumptions:

- Existing infrastructure can support solid-state amplifier integration with minor adjustments.
- Technical experts are available for reviews and vendor evaluations.
- The selected vendor will meet all contractual technical and delivery requirements.

Upgrade Options - 40-years of Operations

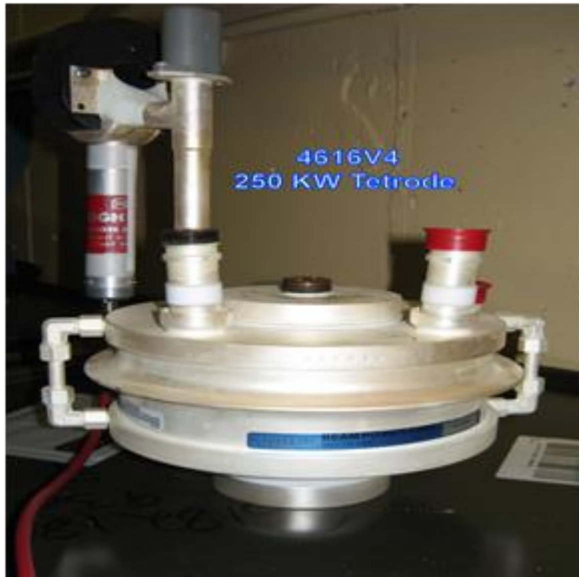
Four options were evaluated for projected 40-years of operations for BLIP/NSRL & EIC:

Option 1: Keeping the same tube but stock for critical component for next 40 years.

- Present stockpiling of RF and modulator tubes is **not sustainable**
- Sole-source manufacturers of RF tubes is likely to exit the business
- **Large tube order for 40 years within the next 3 to 4 years**
- **Critical material for tube manufacturing may not be available**
- **Large tube storage facility needed at BNL**
- **Large number of tubes to validate and test at BNL**
- **Warranty issues when manufacturer exits the business**
- Estimated material cost 40 Years (9 Tanks): **$96 M**

(C/o: Vinnie LoDestro)

7835 Triode ($487,945.00)



4616 Tetrode ($152,360.00)

LINAC TUBE	LINAC AVERAGE TUBE LIFE (Hrs)	AVERAGE FAILURE-RATE PER YR FY-2006 to FY 2024	TUBE UNIT PRICE FY-2025	Operating Years Available Inventory and in process (# Years)	TUBE COST (FY 2025 US DOLLARs) 1 YEAR	40 YEARS MINUS CURRENT INVENTORY
4CW2500	23285.53	2.05	$ 9,000.00	4.39	$ 18,450.00	$ 657,004.50
8618	17782.252	8.42	$ 24,000.00	4.87	$ 202,080.00	$ 7,099,070.40
LPT32	17575.486	2.74	$ 15,000.00	10.2	$ 41,100.00	$ 1,224,780.00
4616	9910.75	4.63	$ 152,360.00	7.99	$ 705,426.80	$ 22,580,711.87
7835	13971.1	3.95	$ 487,945.00	6.32	$ 1,927,382.75	$ 64,914,251.02
				Total Material Cost	$ 2,894,439.55	$ 96,475,817.79

Upgrade Options - 40-years of Operations

Four options evaluated for projected 40-years operations (BLIP/NSRL & EIC):

Option 2: Low power Diacrode tubes (Los Alamos) (Cost ~81 M + facility upgrades**)**

- **Description**: This option involves combining two **Diacrode tubes** to achieve **4 MW** of RF power
- **Required Modifications**:
  - **Major Facility Modifications**: The dual-amplifier design requires significant changes to the existing setup, including modifications to infrastructure and support systems.
  - **Installation Time**: Expected to result in **18 months** of interruption to LINAC operations, impacting critical research schedules.
- **Material Cost Estimate**:
  - Estimated 40-year cost for 9 Tanks: ~**$81 M**
  - Additional **facility upgrades** cost.

Option 3: Replacing high power tubes with CPI Klystron (Fermi Lab) (Cost ~88 M + facility upgrades**)**

- **Description**: This option involves replacing the current high-power RF tubes with **CPI Klystron** technology.
- **Required Modifications**:
  - **Major Facility Modifications**: (Larger size of the **CPI Klystron** amplifiers)
  - **Radiation Safety**: The CPI Klystron system is a **radiation-generating device**, which adds complexity to safety measures and regulatory requirements.
  - **Operational Impact**: (**24 Months of Disruption**)
- **Material Cost Estimate**:
  - Estimated 40-year cost for 9 Tanks: ~**$88 M**
  - **Additional facility upgrade costs** required for the larger amplifiers and safety modifications

Upgrade Options - 40-years of Operations

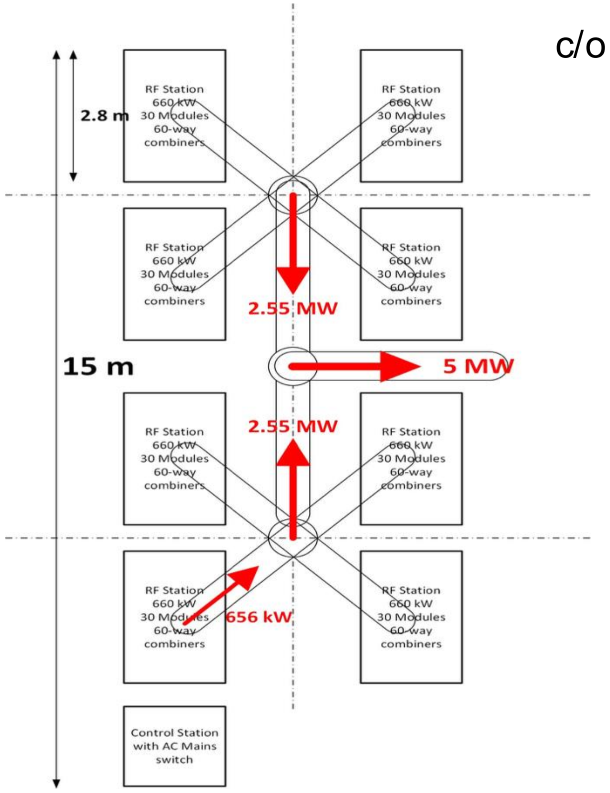
Option 4: Phase conversion to Solid-State RF Amplifier

Key Advantages:

- **Eliminates single-source risk** – transition from aging tubes
- Proven, modern SSA technology
- **Major cost savings** – power cut from 2.5–3 MW → ~800 kW
- **Enhanced safety** – 50/100 V vs. 50 kV systems
- **No civil construction** required
- **Non-disruptive rollout** – install during shutdowns
- **Scalable & phased** upgrade path
- **Improved performance** – longer pulse length (1.2 ms)
- Better diagnostics & remote control

Fits into existing building, No modification needed

c/o Alex Zaltsman



5 MW Solid-State Amplifier to replace Complete RF System(Driver, RF PA, Modulator)

Estimated Material Costs:

- Estimated 40-year cost for 9 Tanks (Phase 1 & 2): **~$80 M**

SSA CRE-3201A 201MHz, 5 MW, pulse, 1.2 ms, 1% duty cycle: 7.500.000 € per piece

(Alex Zaltsman)

FY2024 Budgetary Quote

5 MW RF PA Unit Cost ~$8.1 M

Benchmarking

- SSA pulsed systems: **~$1.62/Watt**
- CW systems (e.g., EIC CW PA): **~$7/Watt**

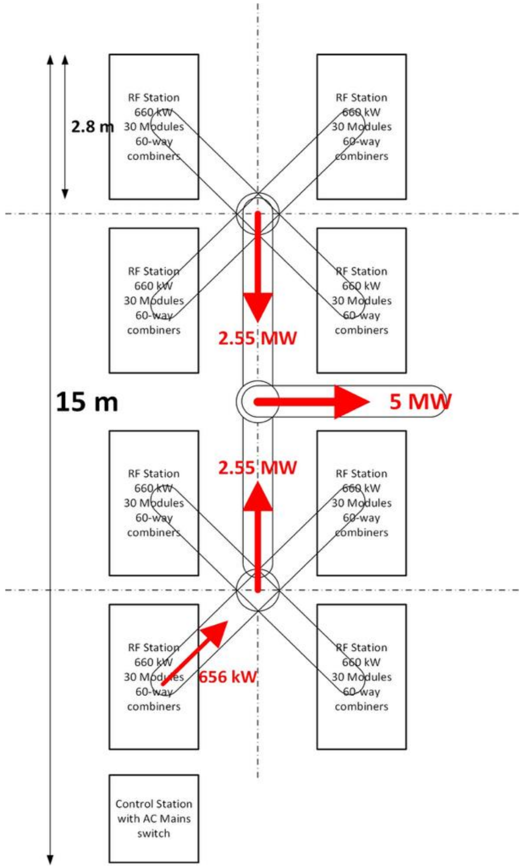
This comparison demonstrates that the proposed SSA solution is highly cost-effective, delivering required performance at the fraction of $/W of continuous-wave systems.

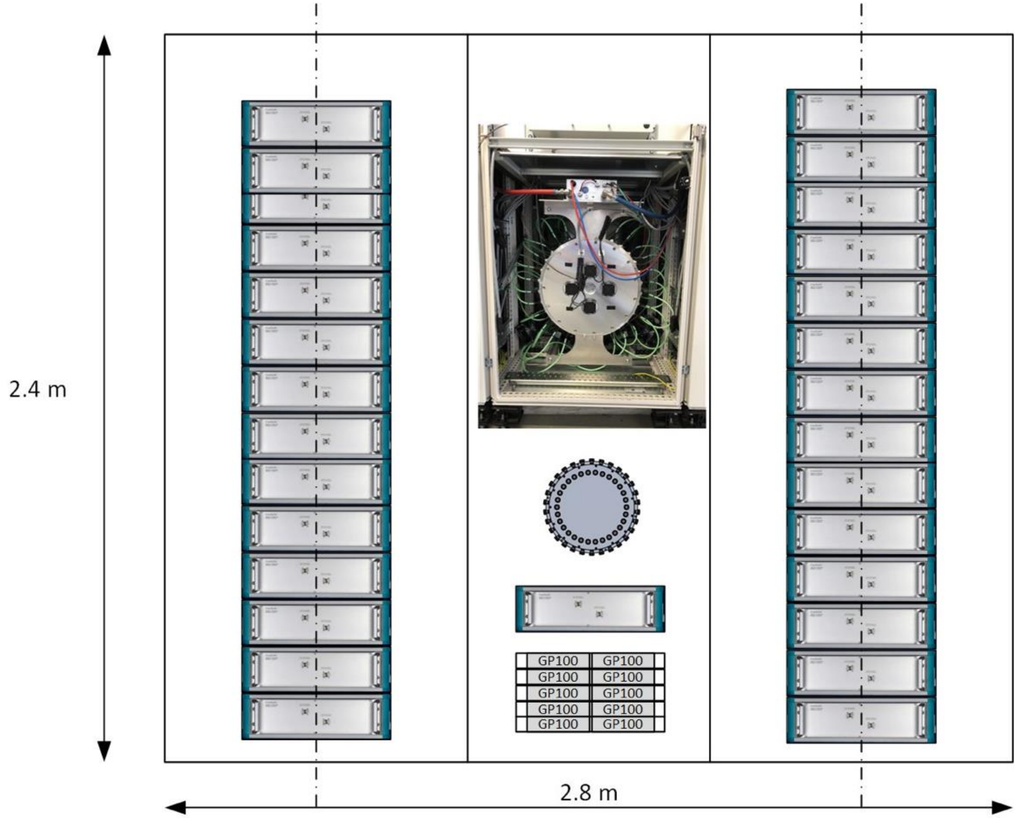
Wall-plug power consumption will be around 80-120 kW

RF output power, peak	[W]	5 000 000
DC/RF efficiency		69%
DC power during pulse	[W]	7 246 377
RF pulse lenght	[ms]	1.2
Switch on bias current before pulse starts	[ms]	1
Bias current	[A]	1
Drain voltage	[V]	65
Bias power for 1 ms before pulse starts	[W]	65
Qty of transistors		768
Bias power loss before each pulse	[W]	49 920
Repetion rate (1.2 ms, 1% duty cycle)	[Hz]	8.3
Total DC energy in pulse	[J]	8 696
Total DC energy before pulse	[J]	50
Total DC Energy in one second	[J]	72 880
Total DC power average	[W]	72 880
ACDC efficiency		92%
Total AC consumption	[W]	79 217
Additional consumption for Driver and Control	[W]	5 000
Total verage AC consumption		84 217

Layout of the system

Fits into existing building, No modification needed





RF Circulator 201MHz, 5 MW, pulse, 1.2 ms, 1% duty cycle: $280,000.00 per piece

FY2024 Budgetary Quote
Single Unit

AFT microwave | Specification 1-0020120100-206 | Circulator 201MHz 5MWp Cx 9 3/16"

Author C. Weil
Revision 00
Release 30.03.2022
Page 1 of 4

Parameter	Value	Unit	Remark
Footprint Drawing No.	t.b.d.		
Product Type	Circulator		
Configuration	3-Port		
Type of Transmission Line	Coaxial		
Set Up	3-Port T-Junction		
Orientation of Rotation	clockwise		
Center Frequency f_0	201	MHz	
Bandwidth BW	± 1	MHz	
Forward Peak Power	5000	kW	max.
Forward Average Power	50	kW	max.
Reverse Peak Power	5000	kW	max., at any phase
Reverse Average Power	50	kW	max.
Pulse Width	1	ms	
Duty Cycle	1	%	
Insertion Loss (all ports matched)	≤ 0.15	dB	at f_0
	≤ 0.2	dB	in BW
Return Loss (all ports matched)	≥ 26	dB	at f_0
	≥ 20	dB	in BW
Isolation (all ports matched)	≥ 26	dB	at f_0
	≥ 20	dB	in BW
RF Waveguide (Size)	Coaxial 9 3/16", 50 Ω		
RF Flange / Connector	3x 9 3/16", male connector, 50 Ω, gas-pressure sealed		
Cooling System			

Cost Estimate : Equipment Cost

- $8.8M Equipment Cost (Tank 9 Solid-State Conversion)
  - Based on FY24 budgetary quotes for one unit

Material Cost	Estimated Cost
SOLID-STATE RF AMPLIFIER 201MHz, 5 MW, pulse, 1.2 ms, 1% duty cycle	$8,100,000
RF Circulator 201MHz, 5 MW, pulse, 1.2 ms, 1% duty cycle	$280,000
RF Load, 201 MHz, 5 MW, Pulse, 1% duty cycle	$100,000
RF Components (Directional Couplers, Cables, Adapter)	$20,000
Critical Spares (Estimated)	$300,000
Equipment Total Cost	$8,800,000

Key Technical Specifications

Parameter	Nominal	Units	Range
Frequency	201.25	MHz	
Output Power	> 5	MW	@ 1.0 dB compression
Bandwidth	> 2	MHz	@ 1 dB
RF Pulse Width	1.2	ms	
Duty Cycle	1.0	%	
Pulse Rise/Fall Time	< 1	us	
Efficiency	> 60	%	From AC to RF
Group Delay	< 250	ns	
DC Level	50 - 100	V	

Technical Specifications & SOW

We have begun collecting the technical specifications and are consolidating all system requirements. To support the design effort, we will host a seminar with experts from the high-power RF community to review lessons learned, evaluate solid-state amplifier technology options, and obtain guidance on long-term reliability considerations.

TECHNICAL SPECIFICATI

for the

201.25 MHz RF Amplifier Sys

Quality Classification: A-3

Prepared By:

Date: _

M. Sowinski, High Power RF Engineer

Reviewed By:

Date: _

M. Hoffmann Wallner, High Power RF Engineer

Date: _

A. Zaltsman, High Power RF Engineer

Date: _

J. Zipper, Quality Assurance

Date: _

C. Schaefer, ESH

Date: _

C. Galdamez, Procurement Liaison Engineer

Approved By:

Date: _

F. Severino, RF Group Leader

Table of Contents

IEC 61000-6-2	Immunity Testing of Industrial Equipment
IEC 61000-6-4	Emission Standard for Industrial Environments
29 CFR 1910 Subpart S	Occupational Safety and Health Standards 1910 Subpart S - Electrical
NFPA 70E-2021	Standard for Electrical Safety in the Workplace Articles 340, 350, 360
UL 508	Standard for Industrial Control Equipment

3 REQUIREMENTS

3.1 Technical/Performance Characteristics

All requirements shall be met across the entire bandwidth of the RF amplifier system.

3.1.1 RF Amplifier System Characteristics

The RF amplifier system shall be constructed with solid state devices. Its mode of operation shall be Pulsed. The operating class shall be AB.

Regardless of the RF output power requirement, the RF amplifier systems shall fulfill the following specific requirements. These characteristics are shown in Table 1:

Table 1: RF Amplifier System Characteristics

Parameter	Min	Nominal	Max	Unit
Operating frequency	200.25	201.25	202.25	MHz
Input power (for Rated Output Power)	-1.5	0	+1.5	dBm
Linear Pulse Power	5			MW
Gain (over 60 dB Dynamic Range)[1]	95.5	97	98.5	
RF on/off ratio[2]	97			
Phase Linearity (60dB Dynamic Range)			30	°
RF Pulse Width	0.01	1.2	2	ms
RF Duty Cycle	0.1	1.0	2.0	%
Rise Time			0.5	µs
Fall Time			0.5	µs
Pulse Droop (@ max pulse width)			0.5	dB
Phase Error Over Pulse (@ max pulse width)			2.5	°
Input / Output Impedance		50		Ω
Input VSWR			1.5:1	---

Key Design Requirements

System Overview

- ➢ Replace existing amplifier chain (pre-driver → 200 kW driver → HP tube PA) with a 5 MW solid-state system.
- ➢ Focus on high efficiency and high operational reliability.

Modular Architecture

- ➢ ≥20% power overhead; full rated output with up to 20% modules offline.
- ➢ Fail-safe behavior: no cascading failures; continued operation until scheduled maintenance.

Protection & Fault Tolerance

- ➢ No damage under RF short, open, arc, or high-reflection conditions
- ➢ Defined VSWR tolerance; robust arc/reflection protection.
- ➢ Redundant critical power supplies—no single-point failure.

Maintainability

- ➢ Plug-in, field-replaceable RF modules.
- ➢ Clear fault indication (front-panel LED + control-system reporting).

Diagnostics & Integration

- ➢ Comprehensive temperature and health monitoring.
- ➢ Full monitoring interface to facility control system.

Proposed Project Schedule

Project Scope: Tank 9 Solid-State Conversion

Immediate Decision Needed → To enable order placement by **May 2027**

- Preparation Phase *(May 2026 – May 2027)*
  - Technical specifications and SOW development
  - ~1 year procurement preparation effort
- Procurement & Delivery:
  - Complete order package/ place SSA order by **May 2027**
  - Delivery expected **Aug 2029** (24-month lead time)
- Integration Timeline:
  - **Removal/Installation in Tank 9:** June – December 2029
  - **System Level Test & Validation** : January – June 2030

Future Scope: Phased Rollout for 6 of Remaining 8 Tanks

- Maintain tube inventory through **June 2030** (8–10 years coverage)
- Order 6 SSA units by **December 2030**
- Install during summer shutdowns: **2 tanks/year (2030–2034)**
- Use leftover tube inventory to support 40-year operation of **Tanks 1 & 2** (low-power systems)

LINAC RF Amplifier Upgrade – Summary

Objective: Modernize the LINAC RF system using solid-state amplifiers to mitigate long-term supply risk associated with obsolete, sole-source RF vacuum tubes.

Mission & Urgency: The LINAC RF system is mission-critical for RHIC/EIC, BLIP, and NASA NSRL, but depends on 5 MW vacuum tubes with credible production loss in ~3–4 years and limited remaining inventory.

Technology Selection: Multiple upgrade paths were evaluated (including continued tube procurement and alternative tube technologies); **solid-state RF was selected** as the lowest-risk, most sustainable option based on reliability, safety, vendor diversity, and lifecycle cost.

Phase 1 – Tank 9 Only (Demonstration):

- Convert **Tank 9** from tube-based RF to a **5 MW, 201 MHz solid-state system** to validate performance, integration, reliability, and lifecycle cost.
- Duration: ~4 years (decision ~2026; install/validate 2029–2030)
- Cost Estimate: $12.9 M (fully burdened, includes contingency)
- Installed during scheduled shutdowns; no impact to operations

Phase 2 – Follow-On Upgrade (Post-Demonstration):

- Following successful Phase 1, begin a phased conversion of **six additional LINAC RF systems**, starting ~2030 and completing over ~4 years.
- Estimated additional cost: **~$80 M**

MAC Input Requested:

- Review the technology selection and phased approach; assess technical, schedule, and supply-chain risk; and advise on Phase 1 initiation and funding, approval pathway, procurement strategy, and the proposed plan for a phased upgrade.

Thank You