

# New IPA Design For 500 MeV TRIUMF Cyclotron

### A. Mitra

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# **Overview**

- Background Information
- Motivation behind IPA Project
- Proposal and Expected Outcomes
- Development
- Calculation of Operating Regime
- Numerical Tube Model
- Output Cavity Design and Simulation Results
- Input Design and Simulation Results
- Discussion

# **Current RF System**



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# Intermediate Power Amplifier and RF Splitter/Phaser

#### IPA

- Self-Contained Unit
- Three stages of amplification: solid state, IPA driver, IPA
- Capable of 100kW RF output
- Stages exhibit complex matching scheme
- Difficult to pinpoint faults





- RF Splitter/Phaser
- 4-way Pi-network splitter
- Outputs are not isolated
- Amplitude and Phase tuning is troublesome

### **Project Proposal**

✤ Replace existing 100kW IPA and RF power/phase splitter with a low level splitter and four 50 Ω, 25kW power amplifiers

### **Expected Outcomes**

- Independent drive adjustment of each IPA
- Amplitude and phase tuning will be accomplished at lower signal levels
- \* 50 Ω design allows for easier troubleshooting

# **New RF System**



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### **Initial Decisions**

- \*  $\lambda/4$  resonating cavity design \*
- 23.06 MHz operating frequency
- ✤ 25 kW maximum output power
- ✤ 4CW25000A grounded cathode tetrode operating in class B \*\*
- Low level RF splitter -> solid state amplifier -> IPA
- Output coupling loop
- Neutralization Capacitor

### Cavity Tuning

- Tuning Plate
- Tuning Loop
- Variable Shortening Capacitance
  - \* Reference design is the 35 MHz S-bend buncher amplifier
  - \*\* Grounded Grid operation is a possibility

### **ISAC I RF AMPLIFIER**



### EIMAC Vacuum Tube Performance Computer

- Works with graph of constant current curves
- Fourier series method
- Points are 15 degrees apart



#### 25kW Operating Line

#### Eimac Tube Performance Computer



### EIMAC Vacuum Tube Performance Computer *cont'd*



**Tube Performance** 

#### General Amplifier Results

<b>RF Input Power</b>	61.4 W
DC Input Power	37.4 kW
RF Output Power	28.4 kW
Efficiency	76%
Gain	26.7 dB

#### Power Dissipation

Anode Power Dissipation	8.95 kW
Grid Power Dissipation	14.6 W
<b>Screen Power Dissipation</b>	250 W

#### ✤ Currents

Peak Anode Current	15.9 A
DC Anode Current	4.15 A
DC Grid Current	140 mA
DC Screen Current	330 mA

#### RF Voltages and Currents

RF Anode Current	7.1 A
RF Anode Voltage	8 kV
<b>RF Grid Current</b>	260 mA
RF Grid Voltage	470 V

Input and Output Impedance

Input Impedance	1.8 kΩ
Output Impedance	1.1 kΩ

Similar calculations have been performed for the grounded grid schematic

SPICE Vacuum Tube Model

### 1<sup>st</sup> Attempt – Analytical Modelling Approach

Attempted to model tube using the mathematical technique presented by Zheng and Keane in [1].

Characteristics of tube made developing a model using their method extremely difficult

# 2<sup>nd</sup> Attempt – Interpolative Modelling

**Approach** Used a lookup table to describe anode, grid, and screen currents curves at different anode and screen voltages

Used linear interpolation between points contained in the table

[1] S. Zheng, J. Keane. *Modelling and Simulation of the Power Amplifier for the RHIC 28 MHz Accelerating Cavity*. Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY

SPICE Vacuum Tube Model *cont'd* 

- Model is a SPICE sub circuit
- Consists of a a number of separate voltage controlled current sources
- Perform linear interpolation between sources

#### For Example:

Consider Vp=1200 V

Anode current is found using the following formula.

 $I_{anode} = (I_2 - I_1) * (1200 - 1000) / 1000 + I_1$ 



#### SPICE sub circuit development



Figure: Column Voltage Source Points of Interest

SPICE Vacuum Tube Model cont'd

The following figure shows the numerical models anode current output

 grid and anode voltage are used to "pick" points off this surface

 Like a 2D matrix indexed by grid and anode voltages

> We will revisit this model when we look at the SPICE schematic of the amplifier



Overview

- \*  $\lambda/4$  resonating cavity design
- 23.06 MHz operating frequency
- Output Coupling Loop
- Tuning Loop
- Variable "Shortening" Capacitance
- ✤ Tuning Plate

#### **Dimensions**:

- ✤ Width = 508 mm (20 inches)
- ✤ Depth = 508 mm (20 inches)
- ✤ Height = 876 mm to 1003 mm (34.5 to 39.5 inches) adjustable



General Design Process

### Cavity Design was a three step process

- Initial Model was developed in HFSS to determine approximate dimensions
- Design was then realized in Solid Works
- Every change in the Solid Works model was validated in the HFSS model



Loaded Quality Factor

Unloaded Quality Factor:

$$Q_o = 2\pi f_o \frac{U_e}{P_o}$$
$$Q_o \cong 3000$$

 $V_{Sh} = \int E \cdot dl$ 

TT

Shunt Voltage:



Loaded Quality Factor:

$$R_{Sh} = \frac{V_{Sh}^2}{2P_0} \cong 90k\Omega$$
$$Q_L = Q_o \frac{R_A}{R_{Sh}}$$
$$R_A = 1.1k\Omega$$

 $Q_L = 37$ 

Note:

$$U_{e} = \frac{\varepsilon_{o}}{2} \iiint E \cdot \overline{E} dV$$
$$P_{o} = \frac{R_{s}}{2} \iint J \cdot \overline{J} dS$$
$$R_{s} = \sqrt{\frac{\mu_{o} \pi f_{o}}{\sigma}}$$

Design - Coupling Loop

- The coupling loop is needed to connect the amplifier to the output transmission line
- The loop can be rotated to match quality factor of external load

#### **Effect of Loop Rotation**

Angle	Frequency (Mhz)	<b>Quality Factor</b>
0	23.68	25
22.5	23.68	33
45	23.57	73

 For loop angles greater than 45 degrees altering loop area should be considered



Design - Coupling Loop *cont'd* 

#### **Loop Power Dissipation**

$$P_{loop} = \frac{1}{2} \cdot \sqrt{\frac{\pi \cdot \mu_0 \cdot f}{\sigma_{copper}}} \int_S \Re(J_{surf} \cdot J_{surf}^*) dS = 11.5 W$$

$$\frac{P_{loop}}{A_{loop}} = \frac{11.5W}{1437.12cm^2} = 8 \ mW/cm^2$$



#### **Loop Inductance**

Calculations in HFSS indicate an inductance of approximately **0.3 uH** 

Natural air cooling is adequate

Design - Tuning Plate

Resonant frequency of the cavity can be changed by raising or lowering the tuning plate

Tuning plate has a total of 127 mm or 5" of travel.

The Maier-Slater Theorem and HFSS was used to quantify frequency shift of changing plate height

### **Maier-Slater Formula for Frequency Shift**

$$\Delta f = f_0 \cdot \frac{\Delta U_{Electrical} - \Delta U_{Magnetic}}{2 \cdot U_{Total}}$$



#### High cost due to mechanical chain and drive mechanism

Design - Tuning Plate cont'd

\*\*

 Resonant frequency shift was recorded as the plate was raised and lowered by 10 mm for tuning loop angles of 0, 22.5 and 45 degrees

Below are the results obtained from using Maier and Slater's formula

	Loop Angle	Frequency Shift per 10 mm	
	0 deg	159 kHz	
	22.5 deg	152 kHz	×
	45 deg	146 kHz	
HF	SS results *		These results indicate tuning plate sensitivity of approximately
	Loop Angle	Frequency Shift per 10 mm	150 KHZ per 10 mm
	0 deg	163 kHz	
	22.5 deg	167 kHz	
	45 deg	147 kHz	

Total tunable frequency window is approximately **1.9 MHz** centred around **23.4 MHz** 

\* Solutions vary slightly based on mesh construction

Design - Tuning Loop

 Another loop in addition to the coupling loop to increase the tuning range

 By by rotating the passive loop one can change the resonant frequency of the cavity

#### **Simulation Results**

<b>Loop Orientation</b>	Frequency
Horizontal	23.4 Mhz
Vertical	24.4 Mhz

Tuning Range of  $\sim \! \mathbf{1} \ \mathbf{MHz}$ 



This tuning mechanism is extremely desirable due to its simplicity and low cost

Design – Variable Shortening Capacitance

- Shortening capacitance of 100 pF
- Decreases the required cavity size
- With no shortening capacitance the required cavity height would be 2.5 m
- Originally four parallel 25 pF capacitors
- Now a fixed 75 pF and variable 3-30
   pF vacuum capacitor in parallel
- More economical

#### Simulation Results

Capacitance	Frequency	<b>Quality Factor</b>
78 pF	24.21 MHz	23.3
105 pF	22.51 Mhz	24

Tuning Range of ~1.7 MHz

This tuning mechanism is simple but the variable capacitors are expensive (~\$2800)

3 – 30 pF Vacuum Capacitor



#### 75 pF Vacuum Capacitor

Design – Variable Shortening Capacitance *cont'd* 

#### The capacitor mismatch causes a current imbalance on the capacitor plate

#### Doesn't affect performance



- Total of 8.3 W of power dissipated on capacitor plate
- ✤ 83 % of total power dissipated is on the 75 pF side (17.9 mW/cm<sup>2</sup>)
- ✤ Air cooling is still adequate

Summary

### **Cavity Tuning Summary**

Component	Frequency Range
Tuning Plate	1.9 Mhz
Tuning Loop	1 Mhz
Variable Capacitor	1.7 Mhz

\* Output Coupling Loop quality factor 25 - 73



### **Electric Field Magnitude**



Dimensions: Width = 508 mm (20") Depth = 508 mm (20") Height = 876 mm to 1003 mm (34.5" to 39.5")

Parasitic Modes

Shown below are the parasitic modes of output cavity with the tuning loop in horizontal and vertical positions

#### **Modes with Horizontal Tuning Loop**

Mode	Frequency	Qext	Rsh	Qo
1	24.5	31	70900	2400
2	64.9	1.40E+05	28350	2000
3	91.7	8.29E+04	88100	1600
4	131.7	41	2040	1450
5	166.7	8.4	155	1260
6	237.8	16.6	880	1650
7	302.7	8.7	17	600

#### **Modes with Vertical Tuning Loop**

Mode	Frequency	Qext	Rsh	Qo
1	23.4	26	89400	3025
2	48.9	7.15E+07	0.59	2150
3	64.7	1.91E+06	27700	1870
4	92.1	87700	82800	1550
5	138.7	19	2660	1830
6	177.6	11.6	50	860
7	231.5	20.5	420	950



# **Topological Amplifier Schematic**



### Schematic Overview



### Interpolative SPICE Tube Model Results vs. EIMAC Computer Results

✤ Before any simulation can proceed the numerical tube model should be compared to the results obtained from the EIMAC Tube Performance Computer

Simplified schematic is shown below



- Plate voltage source now in series with load
- Series resistances added to ideal voltage sources
- Neutralization bridge removed
- Input is now a 470 V sine wave with -340 V DC offset

### Interpolative SPICE Tube Model Results vs. EIMAC Computer Results *cont'd*

#### General grounded Cathode Amplifier Results Comparison

	EIMAC	Model
RF Input Power	61.4 W	81.7 W
DC Input Power	37.4 kW	38.8 kW
<b>RF Output Power</b>	28.4 kW	28.4 kW
Efficiency	76%	73%
Gain	26.6 dB	25.4 dB

#### Power Dissipation Comparison

	EIMAC	Model
<b>Anode Power Dissipation</b>	8.95 kW	10.4 kW
<b>Grid Power Dissipation</b>	14.6 W	19.1 W
<b>Screen Power Dissipation</b>	250 W	208 W

#### ✤ RF Current Comparison

	EIMAC	Model
<b>RF Anode Current</b>	7.1 A	7.6 A
<b>RF Grid Current</b>	260 mA	285 mA

#### Current Comparison

	EIMAC	Model
Peak Anode Current	15.9 A	17 A
DC Anode Current	4.15 A	4.4 A
DC Grid Current	140 mA	152 mA
DC Screen Current	330 mA	277 mA

Input and Output Impedance

	EIMAC	Model
Output Impedance	1.10 kΩ	1.00 kΩ
Input Impedance	1.80 kΩ	1.75 kΩ

### Interpolative SPICE Tube Model Results vs. EIMAC Computer Results *cont'd*

The performance characteristics of the tube in a grounded grid configuration were also calculated using the EIMAC Tube Performance Computer

The table below summarises the results obtained from the computer and the SPICE tube model

	EIMAC	Model
Input Impedance	67.2 Ω	62.2 Ω
Output Impedance	1114 Ω	1000 Ω
RF Input Power	1340 W	2 kW
RF Output Power	28.6 kW	28.2 kW
Gain	13.3 dB	11.5 dB

٠.	General	Grounded	Grid Amplifier	Results	Comparison
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Variable Inductance Design *cont'd* 

The variable inductor design is based off an a similar design on another tube socket

 $\checkmark$  To obtain the required 0.33  $\mu\text{H}\text{,}$  a fixed coil and variable length strip will be used

The strip length can be anywhere
between 2.5 cm to 7 cm, with a width of
1 cm and a thickness of 3 mm

\* This leads to a variable strip inductance of  $0.013~\mu H$  to  $0.051~\mu H$ 

Centering this around 0.33 μH we obtain a total variable inductance between
 0.31 μH and 0.35 μH

 $\clubsuit$  Based of these calculations, the fixed inductance must be  $0.30~\mu H$ 



### Variable Length Strip

### Input Schematic Testing

✤ A physical model of the amplifier input was constructed and tested

Attempted to determine the maximum tuning range of the variable inductor and matching of the variable capacitor



- Measurements performed on the circuit showed a tuning range of 700 kHz
- The S11 parameter remained fairly constant at -9.5 dB over this window

### **Amplifier Neutralization**

The neutralization capacitor (Cn) was added to the amplifier to provide negative feedback

 Improves the stability of the amplifier

Forms a bridge with the grid to plate, grid to cathode, and plate to cathode capacitances of the tube





The Bridge should be be balanced when:

$$C_n/C_4 = C_6/C_3$$

# SUMMARY

Most of the components have been procured including the power tube and the ceramic capacitor.

Other parts are being fabricated in the machine shop.

Prototype will be assembled and tested as soon as manpower is available.

Decision to be taken to produce 4 IPA and priority to be settled.

Careful planning is required to replace existing IPA with new IPA.

This can be done only during long shutdown.

# THANK YOU FOR YOUR ATTENTION