RF System
for a High Intensity Superconducting Cyclotron
Demonstration for Active Interrogation
Phase 2A – PED

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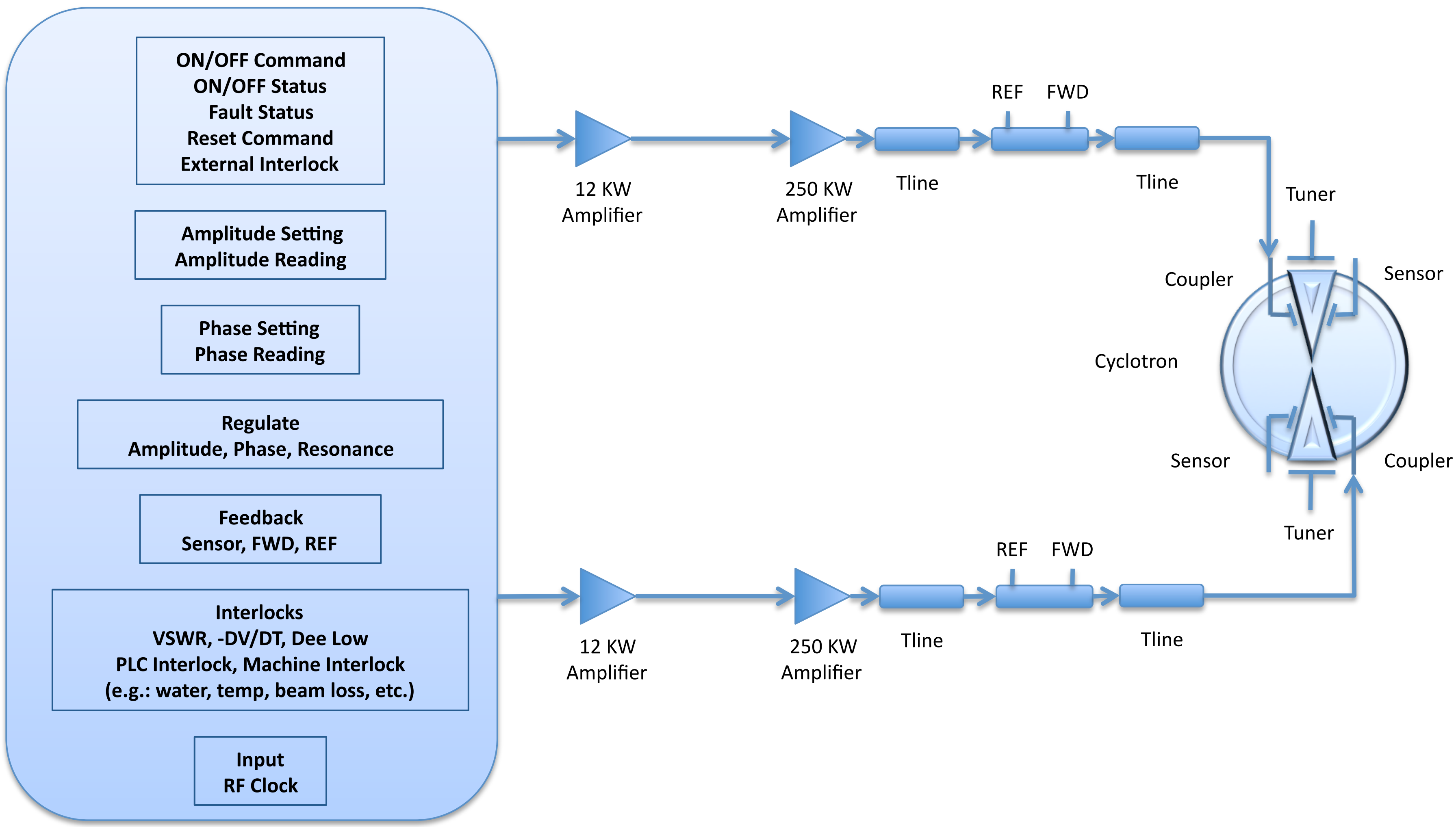
RF Systems Outline

- System Introduction
- System Outline and Parameters
- RF Resonator Electromagnetic Design
- RF System Stability Modeling and Analysis
- Technology
- Estimated Cost
- Summary Comments

RF System Block Diagram



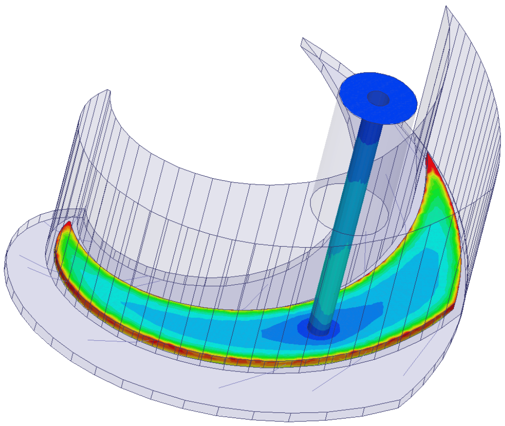
RF Design Parameters

Liner Inner Radius	2.2 cm
Liner Outer Radius	45.24 cm
Dee Inner Radius	4.5 cm
Dee Outer Radius	43.75 cm
Pole-to-Pole Angle	45 degrees
Valley Depth from MP	30 cm
Dee surface to MP	1.25 cm
Dee Plate Thickness	1 cm
Dee to liner minimum gap	1 cm
Number of Turns	2000 turns
Fundamental Frequency	66.99 MHz
Spiral Equation	$\Theta = r/18$, r in cm
Max Energy	250 MeV/u
Effective Transit Time Gap	3.5 cm = 1.0 + 2*1.25
Gap Transit Time Factor (TT)	$\approx 0.99 = \sin(\Phi)/\Phi$
Dee Effective Transit Angle (ψ)	43.00 degrees
Dee acceleration factor	0.726 = 2*TT*sin(ψ/2)
Acceleration Factor per Turn	1.451 = 2* 0.726
Dee Peak Voltage	86.15 KV = (250,000/2000)/(1.451)
Amplitude Regulation	0.5 % RMS
Phase Regulation	0.5 Degrees RMS

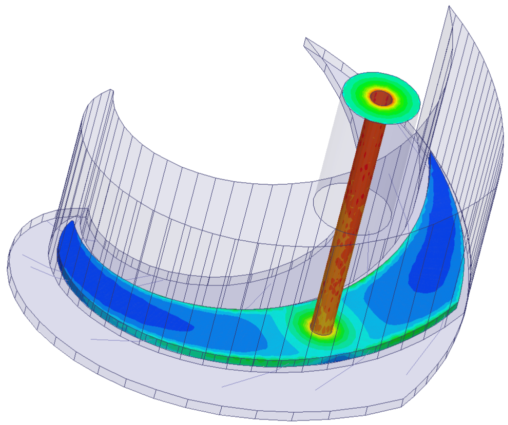
RF Resonator Analysis

- The RF resonator is analyzed using Ansoft HFSS software.
  - Models are based on the MIT defined spiral equation.
  - A classic single stem design is compared against a flat-topping design.
  - The stem(s) radial position(s) are chosen to balance the voltage distribution along the Dee.

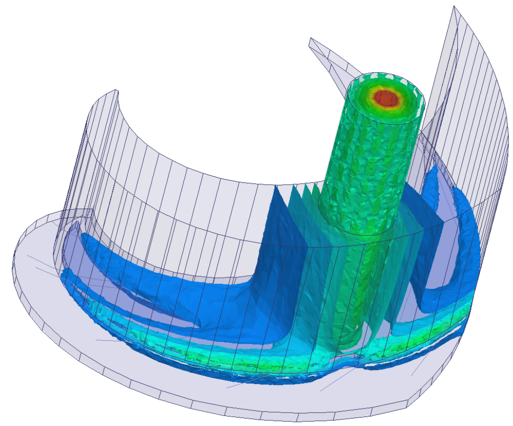
HFSS Single Stem Case



Surface E Field



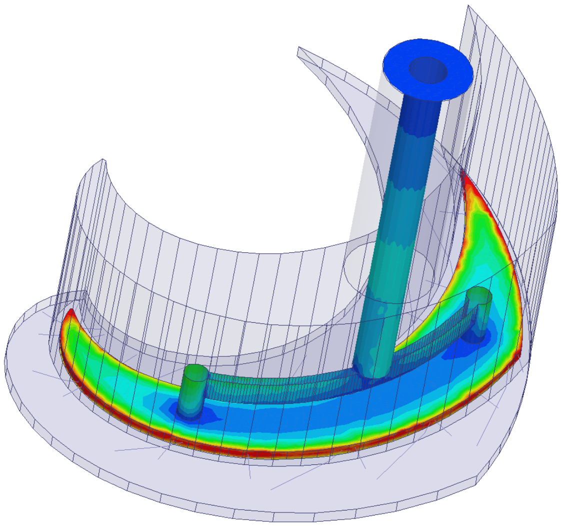
Surface H Field



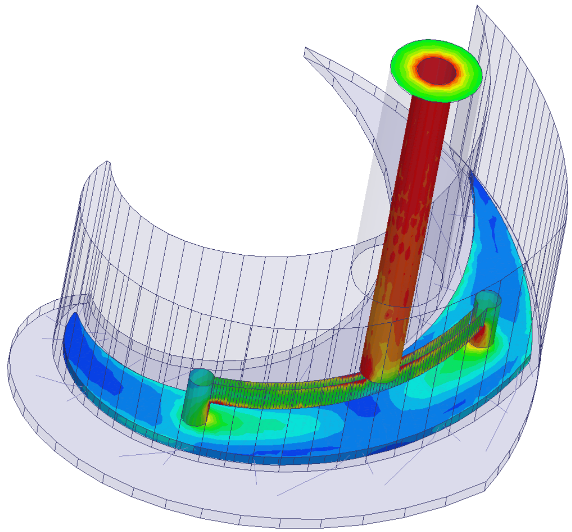
Volume H Field

Results	Operating Values	Mechanical
F = 69.3 MHz	Tip Peak Voltage = 100 KV	Valley Depth = 20 cm
Qu = 3120	Driver Power = 65.9 KW	Stem Radial Position = 31 cm
	Stem Current = 1478 Arms	Stem Length = 16.5 cm

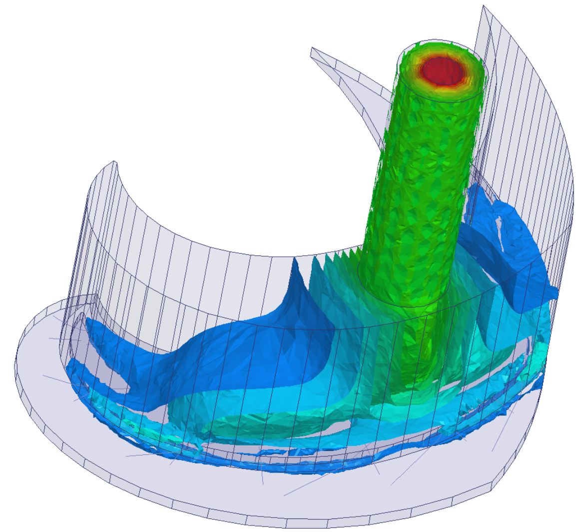
HFSS "Flat-Top" Case



Surface E Field



Surface H Field



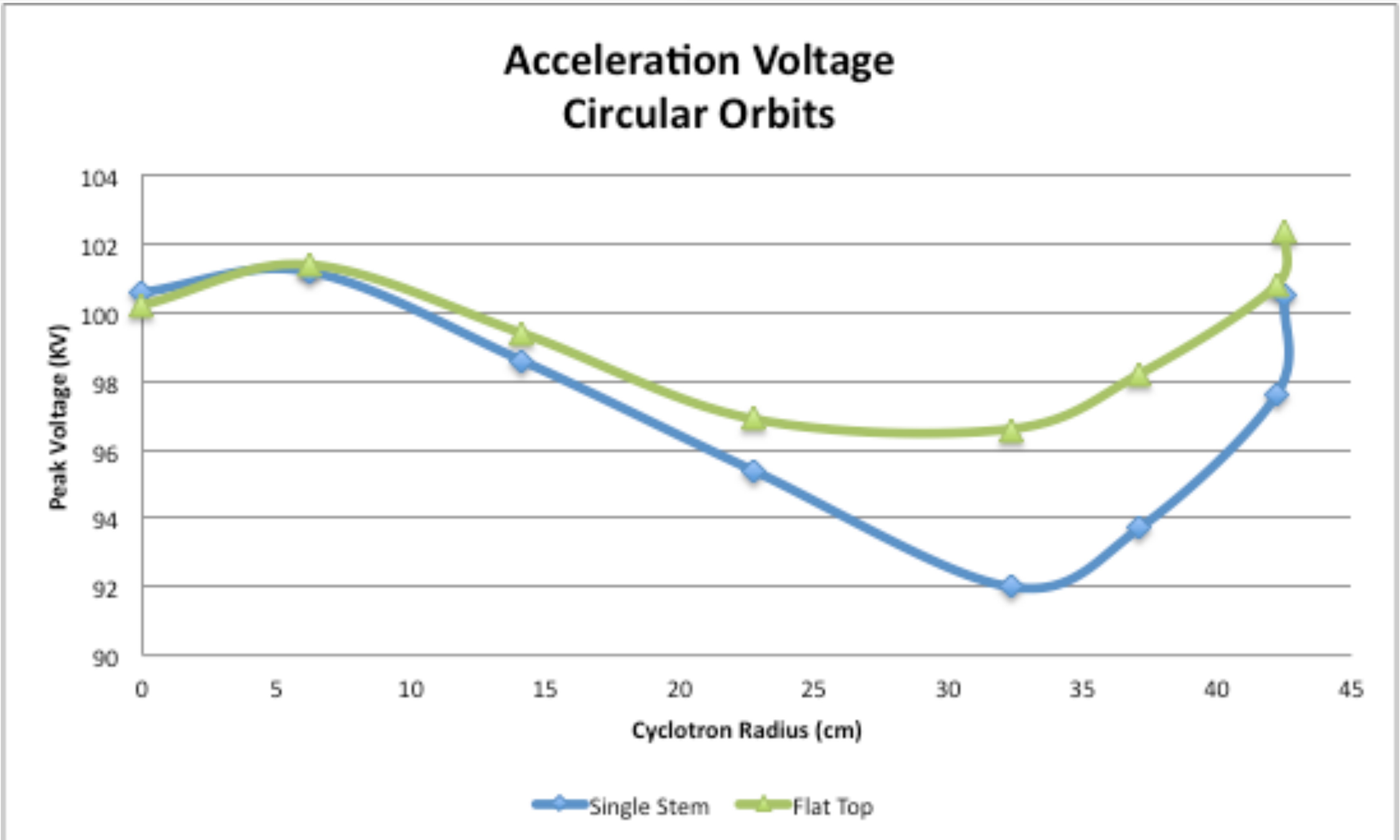
Volume H Field

Results	Operating Values	Mechanical
F = 66.9 MHz	Tip Peak Voltage = 100 KV	Valley Depth = 20 cm
Qu = 2799	Driver Power = 87.1 KW	Stem Radial Position = 30.5 cm
	Stem Current = 1710 Arms	Stem Length = 27 cm

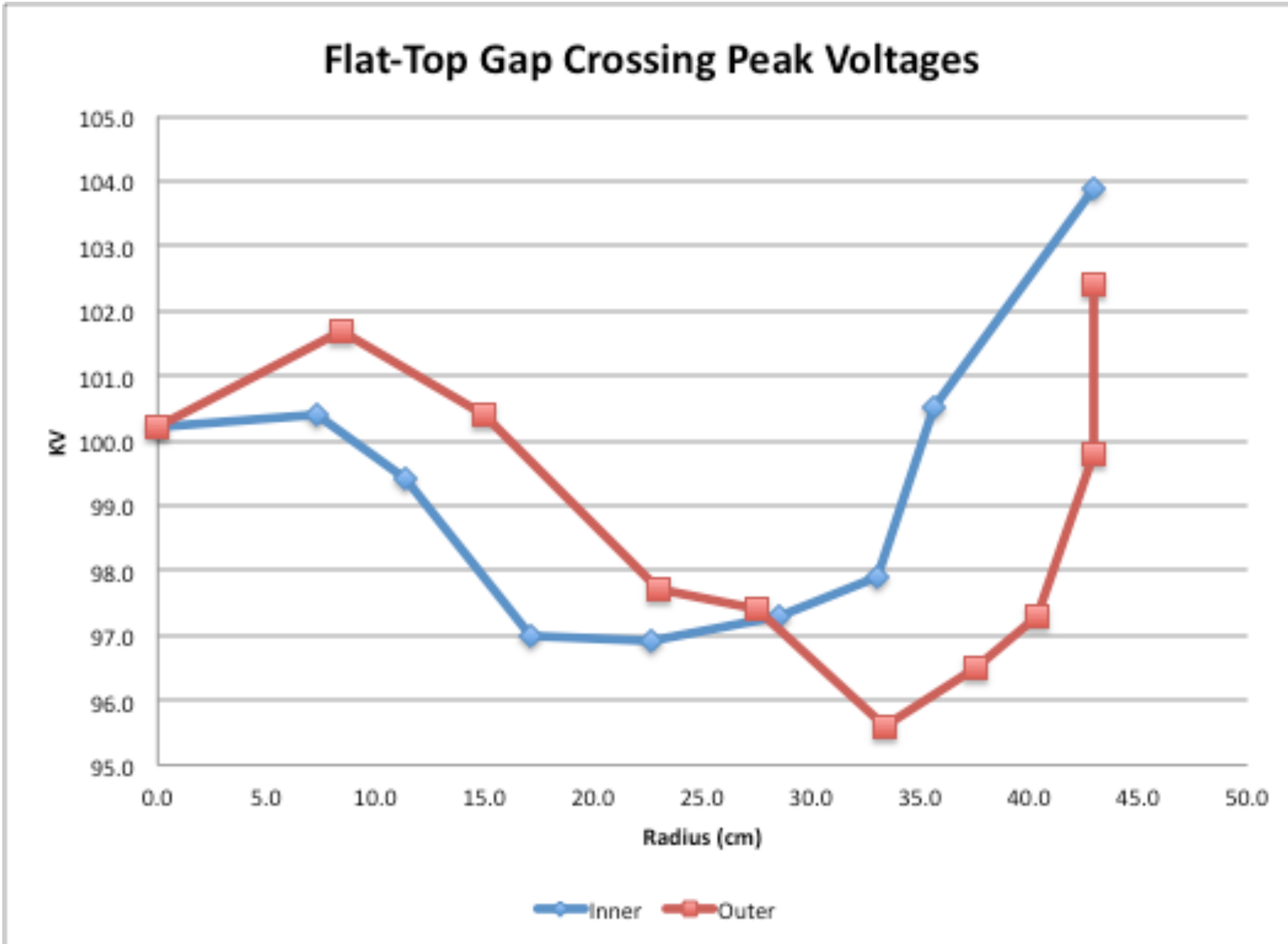
Resulting Resonator Parameters

	Single Stem	Flat Top
HFSS		
Qu	3120	2799
Wc (KW)	66.0	87.1
Vc (KV) peak at Dee Tip	100.6	100.2
f_{oc}(MHz)	69.3	66.9
Stem Current (Amperes RMS)	1478	1710
Specs		
WB (KW)	125	125
Model (at Dee Tip)		
Q_L	1560	1400
$f_c = (2\pi f_{oc})/2Q_L$ (KHz)	140	150.2
R_e (KΩ)	19.7	16.8
IDrive (Amperes Peak)	7.6	8.5
IBeam (Amperes Peak)	2.5	2.5

Resonator Voltage Distribution



Resonator Voltage Distribution



Resonator Plans

- Final resonator model will be analyzed following detailed mechanical design.
  - Dee and Stem design.
  - Input Coupler and Fine Tuner.
  - HFSS model updated with the actual mechanical design to finalize design details – such as stem length.

- Since the stem current is too high to allow a sliding short with fingers, a design and manufacturing method must be found to allow setting the center frequency experimentally with the tuner in a fixed specified location.

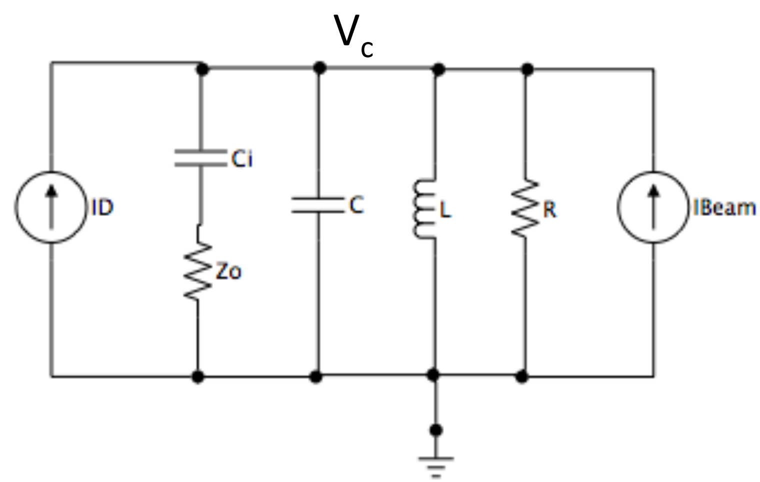
System Modeling Introduction

- A linear resonant RF cavity behaves exactly as a resonant RLC circuit within its bandwidth about resonance.
  - The equivalent circuit will be designed to match the resonator parameters as if measured at the cyclotron center.

- A systems model of the circuit is derived in the frequency domain using Laplace transform techniques.
  - The model is designed for the "loaded Q" condition without beam loading.
  - Beam loading is modeled as a disturbance input.

System Modeling – Dee Cavity 1

Plant: Resonator Equivalent Circuit



- Circuit Elements
  - R, L, and C represent a cyclotron resonator
  - Ci, and Zo represent the input coupler and 50 Ohm line.
  - ID represents the effective drive current phasor
  - Ibeam represents the effective beam current phasor

System Modeling – Dee Cavity 2

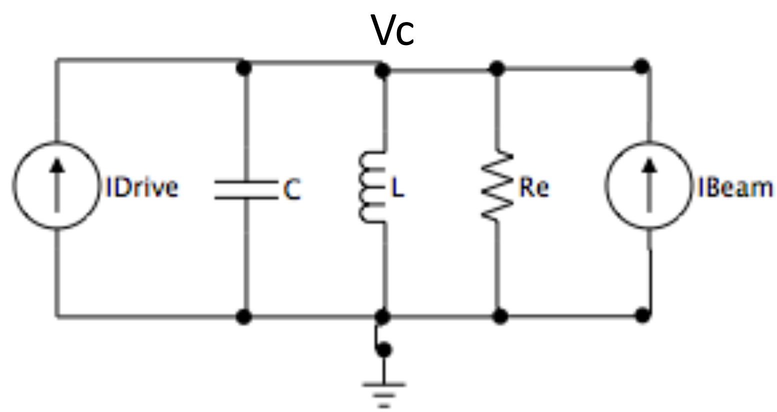
- The previous model may be simplified to:

HFSS calculates the:

Q_u: Unloaded Q
W_c: Cavity losses at Vc
U: Stored energy at Vc
ω_{oc}: Resonant Frequency

Other parameters include:

W_B: Beam Power
W_i: Coupler Load
Q_L: Loaded Q



The coupling circuit is designed to "match" a 50 Ohm feed-line to the cavity at full voltage and beam power.

The coupling circuit causes $Q_L = ½Q_u$ at full beam power

System Modeling – Dee Cavity 3

- The circuit is designed to respond accurately to two inputs Idrive and Ibeam. This requires R_e be chosen as:

$$R_e = \frac{V_c^2}{2\left(2W_c + W_B\right)}$$

- The rest of the elements are chosen as normal:

$$C = \frac{2W_c Q_u}{\omega_{oc} V_c^2} \qquad L = \frac{1}{\omega_{oc}^2 C} \qquad I_{Beam} = \frac{2W_B}{V_c}\angle 180^o \qquad I_{Drive} = \frac{4\left(W_c + W_B\right)}{V_c}\angle 0^0$$

Note: I_{drive} is twice the actual value to account for the loaded Q being ½ the cavity Q. This is an anomaly of the model needed to get the proper dynamic response. The actual drive requirement is ½ of this value. Current and voltage values are peak sinusoidal values. (power = ½ v*i)

System Modeling – Dee Cavity 4

- Transfer Function = Plant Impedance

$$\frac{V_c}{I} = Z = \frac{\frac{1}{C}s}{s^2 + \frac{1}{R_e C}s + \frac{1}{LC}}$$

- This equation is recast as:

$$\frac{V_c}{I} = Z = \frac{\frac{\omega_{oc} R_e}{Q_L}s}{s^2 + \frac{\omega_{oc}}{Q_L}s + \omega_{oc}^2}$$

System Modeling – Dee Cavity 5

- We seek the "envelope response" for amplitude and phase at modulation frequencies <<< $\omega_{o,}$ in other words within the cavity bandwidth $\Delta\omega = Q_L/\omega_o$

- Determine Z(s + jω) to remove the RF frequency and noting once the RF frequency is removed s << ω_o and the small bandwidth causes $\omega_o \cong \omega$. After much manipulation this yields:

$$Z(s + j\omega) \approx \frac{R_e \frac{\omega_{oc}}{2Q_L}}{s - j(\omega_{oc} - \omega) + \frac{\omega_{oc}}{2Q_L}}$$

- The quantity ($\omega_o - \omega$) in the above expression is referred to as "The Detuning Frequency" in the accelerator community and expresses the amount the cavity is being driven off resonance. Notice when this term is 0, the above expression becomes a simple first order transfer function.

System Modeling – Dee Cavity 6

- Defining $V_c = V_I + jV_Q$, $I_{drive} = I_I + jI_Q$ and recasting $Z(s + j\omega)$ as V_c/I_{Drive} then converting back into the time domain and separating into real and imaginary parts yields the MIMO system:

$$\begin{bmatrix} \frac{d}{dt}V_I \\ \frac{d}{dt}V_Q \end{bmatrix} = \begin{bmatrix} -\frac{\omega_{oc}}{2Q_L} & -(\omega_{oc}-\omega) \\ (\omega_{oc}-\omega) & -\frac{\omega_{oc}}{2Q_L} \end{bmatrix} \begin{bmatrix} V_I \\ V_Q \end{bmatrix} + \begin{bmatrix} R\frac{\omega_{oc}}{2Q_L} \\ R\frac{\omega_{oc}}{2Q_L} \end{bmatrix} \begin{bmatrix} I_I \\ I_Q \end{bmatrix}$$

- Notice when the detuning frequency is 0, the equations are totally decoupled.
- The RF amplitude and phase are:

$$|V_c| = \sqrt{V_I^2 + V_Q^2}$$

$$\phi = \tan^{-1}\left(\frac{V_Q}{V_I}\right)$$

System Modeling – Transfer Function 1

- Previously it has been shown that the I and Q signals are decoupled when the cavity is driven at the resonant frequency and that these signals are first order (n = 1). The amplifier string adds an additional pole (n = 1 + 1 = 2).

- The response of these loops will be designed and analyzed for both the PID and ADRC type control.

- I and Q, eventually leading to "amplitude" and "phase" control, will be separate control loops with ADRC treating the particular dynamics and coupling between them as unspecified dynamics to be observed and dealt with in real time.

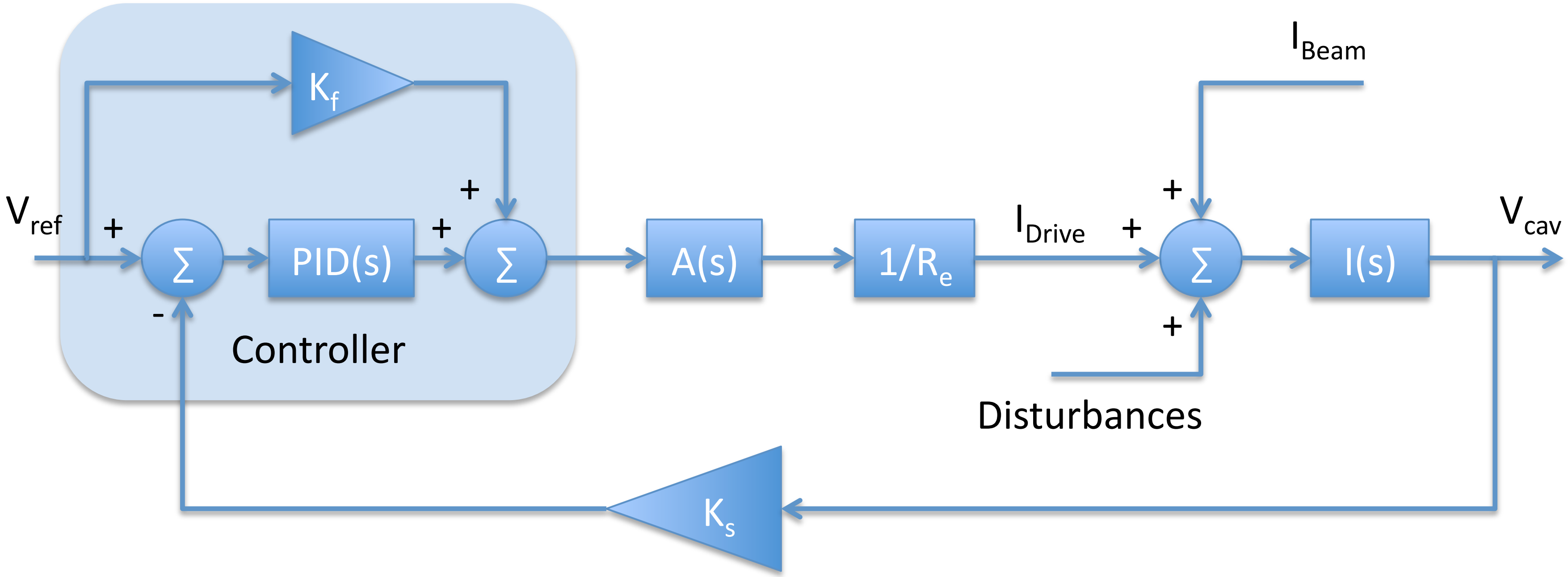
System Modeling – Transfer Function 2

$$I(s) = \frac{R_e \dfrac{\Delta\omega}{2}}{s + \dfrac{\Delta\omega}{2}} \equiv \frac{R_e \omega_c}{s + \omega_c} \;, \quad A(s) \equiv \frac{K_v \omega_a}{s + \omega_a}$$

$$G(s) = I(s)A(s) = \frac{\mathrm{R}_e K_v \omega_c \omega_a}{s^2 + \left(\omega_c + \omega_a\right)s + \omega_c \omega_a} \equiv \frac{b_0}{s^2 + \left(\omega_c + \omega_a\right)s + \omega_0^2}$$

$$y'' + \left(\omega_c + \omega_a\right)y' + \omega_0^2 y = b_o u_o$$

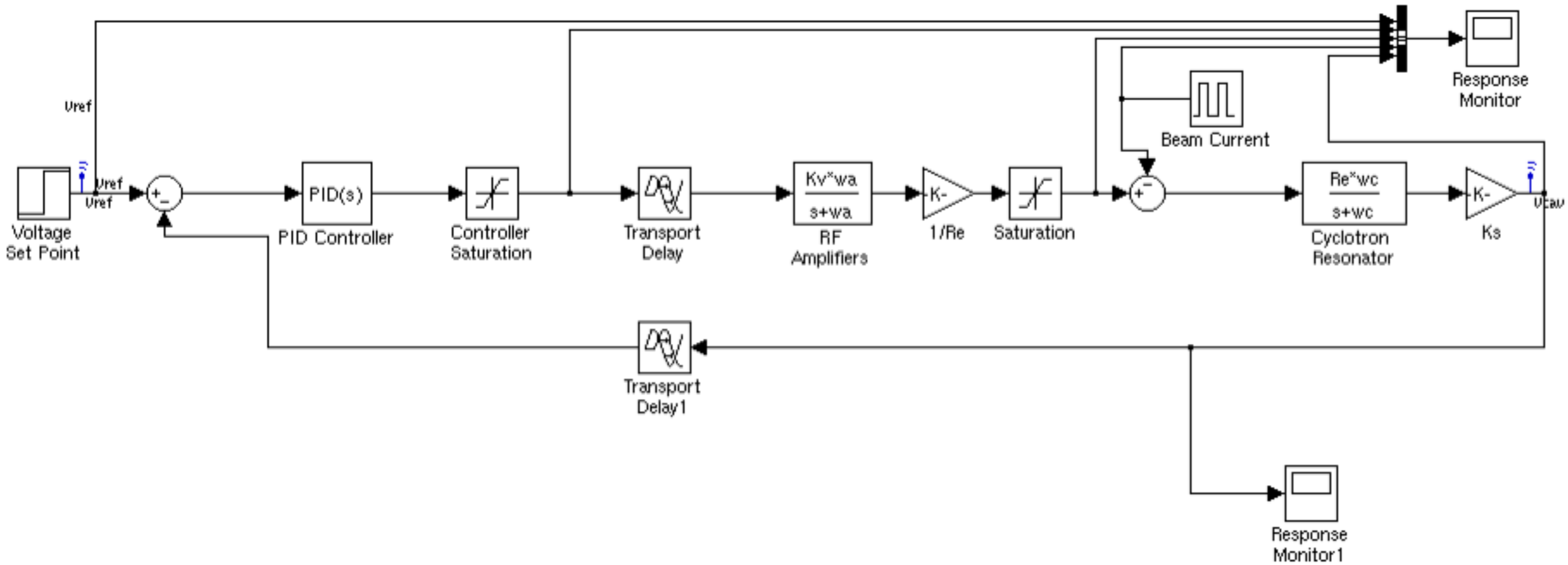
System Modeling – PID



V_{ref} : Cavity Setpoint
K_f : Feed-Forward Gain
K_s : Sensor Gain
PID(s) : Control TF

A(s) : Amplifier TF
I(s) : Dee Cavity TF

System Modeling – Simulink PID



- The Kv gain transforms 10V from the controller to 125KV.
- The 1/Re gain transforms the 100KV voltage into the effective drive current.
- The “Saturation” blocks clamp the control efforts and current to the real world equivalents.

System Modeling – PID Response

Cavity voltage perturbation due to 100% beam current step is less than 8.52% using PID

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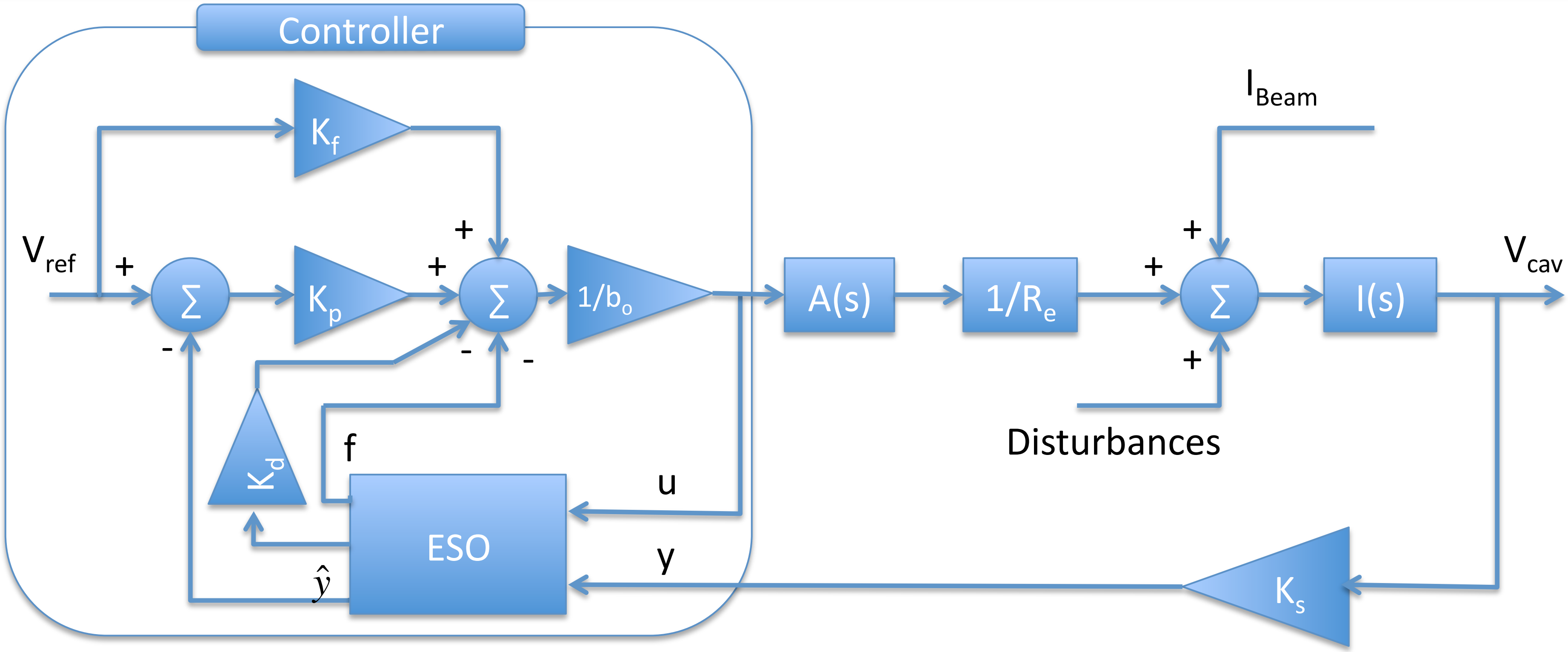
ADRC – Active Disturbance Rejection Control

- ADRC is now introduced, applied, simulated, and compared to the PID results.
  - John Vincent, et. al, "On active disturbance rejection based control design for superconducting RF cavities" Nuclear Instruments and Methods in Physics Research, A , 643: 1, pp. 11-16, 2011.

- Basic ADRC Premise: ADRC creates an additional state to the system that captures the unknown dynamics, non-stationary dynamics, or disturbances consistent with the system order.
  - The additional state increases the order of the original system by 1 to n +1.
  - The additional state is created through the application of an "Extended State Observer" (ESO) that separates the desired dynamics from the undesired signals and outputs them separately.

ADRC Block Diagram



V_{ref} : Cavity Setpoint
K_f : Feed-Forward Gain
K_s : Sensor Gain
K_p : Proportional Gain

A(s) : Amplifier TF
P(s) : Cavity TF
f : Unwanted Dynamics
K_d : Derivative Gain

ARDC 3rd Order ESO

$$z' = Az + Bu + L(y - \hat{y}),\ \hat{y} = Cz = z_1,\ z_3 \equiv f$$

$$L \equiv \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix}, C = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} z_1' \\ z_2' \\ z_3' \end{bmatrix} = \begin{bmatrix} -\beta_1 & 1 & 0 \\ -\beta_2 & 0 & 1 \\ -\beta_3 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} \beta_1 & 0 \\ \beta_2 & b_o \\ \beta_3 & 0 \end{bmatrix} \begin{bmatrix} y \\ u \end{bmatrix}$$

$$A = \begin{bmatrix} -\beta_1 & 1 & 0 \\ -\beta_2 & 0 & 1 \\ -\beta_3 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} \beta_1 & 0 \\ \beta_2 & b_o \\ \beta_3 & 0 \end{bmatrix}$$

ADRC Mechanics - 2

Desired Eigenvalues: $$(\lambda+\omega_o)^3 = \lambda^3 + 3\omega_o\lambda^2 + 3\omega_o^2\lambda + \omega_o^3 = 0$$

ESO Eigenvalues: $$|I\lambda - A| = \begin{vmatrix} \lambda+\beta_1 & -1 & 0 \\ \beta_2 & \lambda & -1 \\ \beta_3 & 0 & \lambda \end{vmatrix} = \lambda^3 + \beta_1\lambda^2 + \beta_2\lambda + \beta_3 = 0$$

$$\therefore \beta_1 = 3\omega_o,\ \beta_2 = 3\omega_o^2,\ \beta_3 = \omega_o^3$$

$$\omega_o \rightarrow Desired\ ESO\ bandwidth$$

ADRC Mechanics - 3

Final ESO:

$$\begin{bmatrix} z_1' \\ z_2' \\ z_3' \end{bmatrix} = \begin{bmatrix} -3\omega_o & 1 & 0 \\ -3\omega_o^2 & 0 & 1 \\ -\omega_o^3 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} 3\omega_o & 0 \\ 3\omega_o^2 & b_0 \\ \omega_o^3 & 0 \end{bmatrix} \begin{bmatrix} y \\ u \end{bmatrix}$$

$$\hat{y} = z_1 = \hat{V}_{cav},\ z_3 \equiv f$$

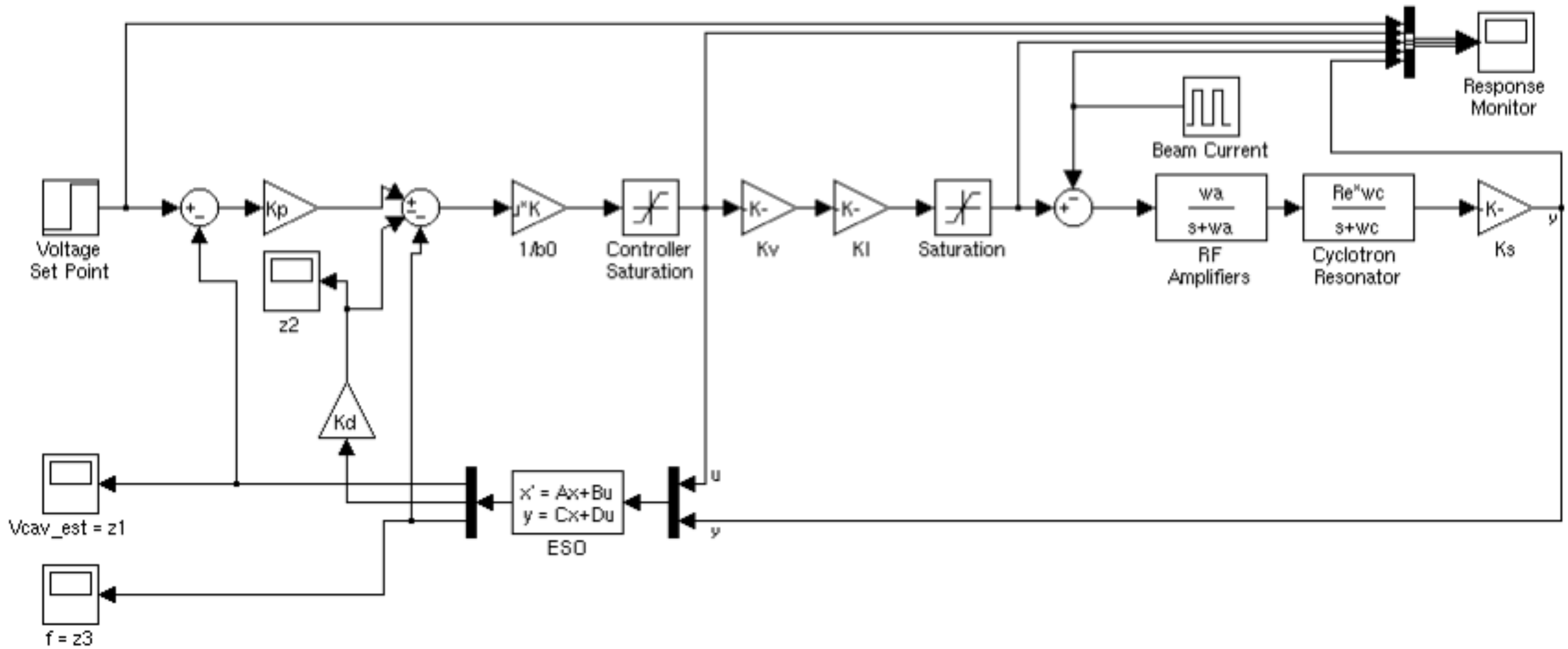
Control Design:

$$u \equiv \frac{u_o - z_3}{b_o} \Rightarrow y'' = V''_{cav} = b_o \left[\frac{u_o - f}{b_o} \right] + f = u_o$$

$$u_o \equiv K_p \left(V_{ref} - \hat{V}_{cav} \right) - K_d \left(\hat{V}'_{cav} \right)$$

$$\therefore V''_{cav} = K_p \left(V_{ref} - \hat{V}_{cav} \right) - K_d \left(\hat{V}'_{cav} \right)$$

System Modeling – Simulink ADRC



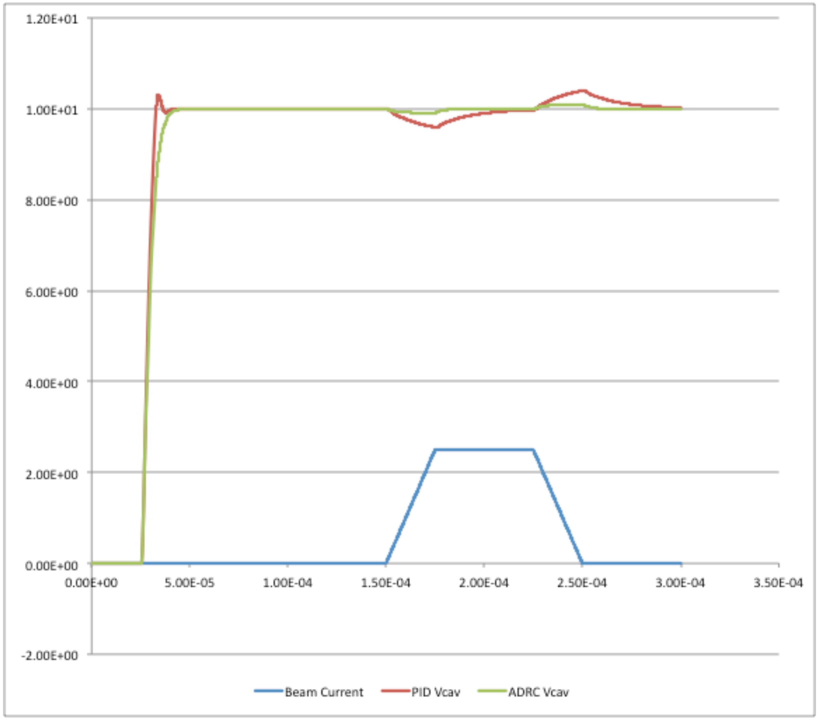
- The Kv gain transforms 10V from the controller to 125KV.
- The 1/Re gain transforms the 100KV voltage into the effective drive current.
- The “Saturation” blocks clamp the control efforts and current to the real world equivalents.

Third Order ADRC Simulation

Cavity voltage perturbation due to 100% beam current step is less than 0.84% using ADRC

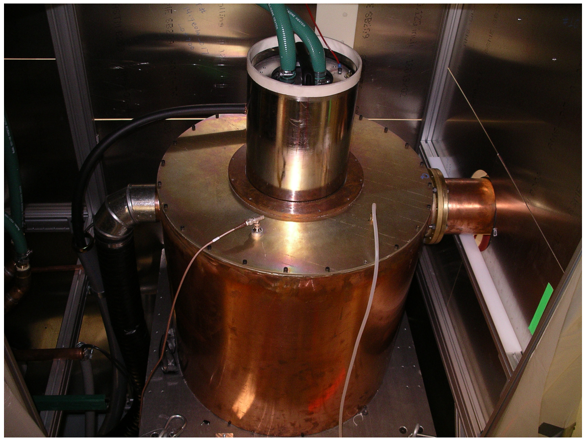
System Modeling & Control Summary

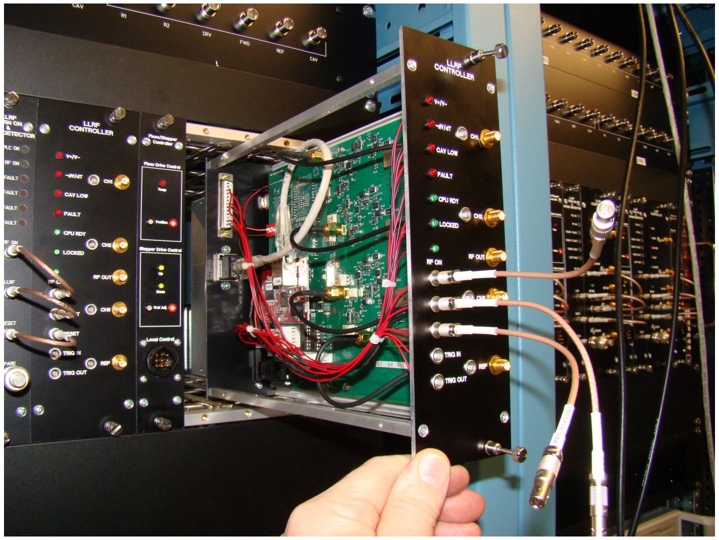
- The cyclotron RF system was modeled and two control strategies were evaluated: PID and ADRC.
- The results make ADRC the clear choice.



Necessary Technology

- RF Amplifiers and Controls
  - 250KW RF Amplifier parts package delivered to MIT for fabrication.
  - RF Controls & Instrumentation to be fabricated in Phase 2B by MSU.
  - Components list delivered to MIT and substantially procured.
- MIT to Mechanically Design
  - Cyclotron Resonators
  - RF Input Couplers & Drives
  - RF Tuners & Drives
- Issues to be addressed by MSU
  - Reflected power & tuning





Cost Estimate

		Cost Each			Cost Total		
Description	**Qty**	**Materials ($)**	**Engineering (hrs)**	**Trades (hrs)**	**Materials ($)**	**Engineering (hrs)**	**Trades (hrs)**
RF Support & Management	2.5	$3,000	925	925	$7,500	2313	2313
RF Controls & Instrumentation							
LLRF System	2	$15,097	24	94	$30,193	48	187
RF Clock	1	$8,886	23	25	$8,886	23	25
RF Amplifiers							
Driver Amplifier	2	$75,850	80	80	$151,700	160	160
Final Amplifier	2	$779,600	1134	2119	$1,559,200	2267	4238
Cyclotron Components							
Resonator	2	$25,000	925	1850	$50,000	1850	3700
Coupler	2	$15,000	240	160	$30,000	480	320
Trimmer	2	$5,000	160	160	$10,000	320	320
Recommended Spares							
50KW DC Module	2	$55,000	2	2	$110,000	4	4
2KW Amplifier Module	2	$8,000			$16,000	0	0
LLRF Module	2	$12,564	23	87	$25,128	47	174
Total					**$1,998,607**	**7512**	**11441**
with Contengency					**$2,500,000**	**9000**	**13500**

RF System Summary

- Total RF System cost including materials and labor is expected to be less than $5M.
- RF Amplifier and Controls
  - Amplifier design is complete and may be procured, fabricated, and assembled by MIT.
  - Suitable control strategies have been designed and the electronics may be procured, fabricated, assembled and programmed by MSU is phase 2B
  - A manual will be prepared by MSU in Phase 2B
- Cyclotron Resonators, Couplers, and Trimmers require mechanical design and detailing by MIT.