Developments in Accelerator High Power RF Distribution

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Outline

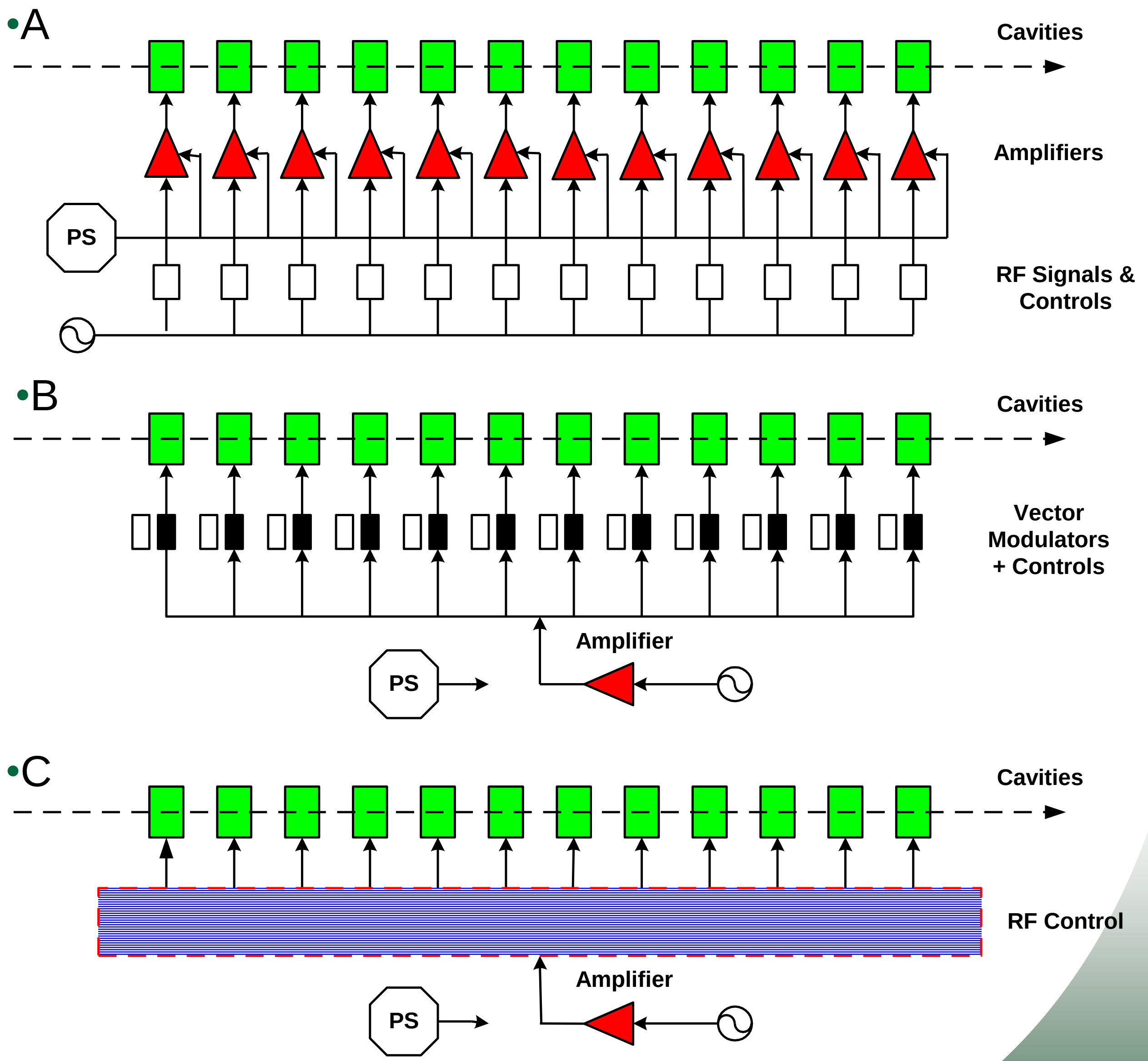
- Consideration on RF power distribution
  - Often, for high power accelerators, splitting power from a high powered generator for many cavities can save cost in construction and installation
  - Except some relativistic lepton accelerators, the amplitudes and the phases of RF in the cavities (through RF power distribution) need to be controlled independently
  - This is more important in SRF Hadron accelerators
- Singly fed system with a fixed power splitter
  - A power splitter divides power of a generator for many cavities and a high power vector modulator is placed in each cavity input
  - This approach introduces RF power loss in the system that lowers the RF transmission efficiency
- Singly fed system with reactive distribution
  - A single generator can power many cavities with high RF transmission efficiency
  - For independent control of the amplitudes and phases at the cavities, a distributed control system is needed

RF Power Distribution with Individual Control

A. Ideally, one on one configuration is needed for control of amplitude and phase of RF in individual cavities

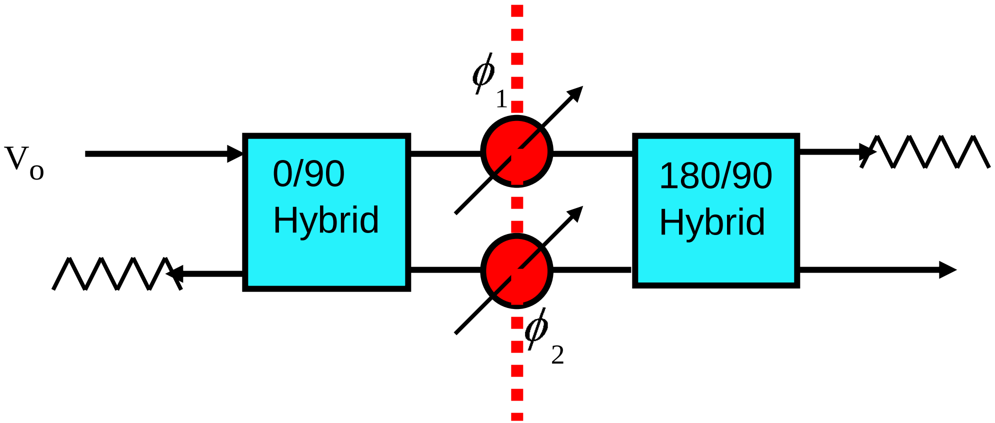
B. Using high power vector modulator in each cavity input, RF vector control in individual cavities can be possible
   - An N-way power splitter is needed for N-cavities
   - The RF power not used in the cavities is wasted

C. Can a multi-cavity distribution system be built without wasting the RF power?



Vector Modulator Configurations

- Traveling wave

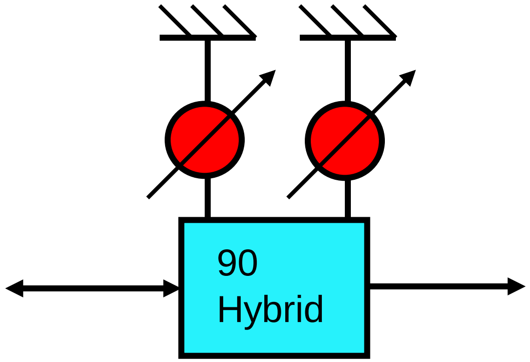


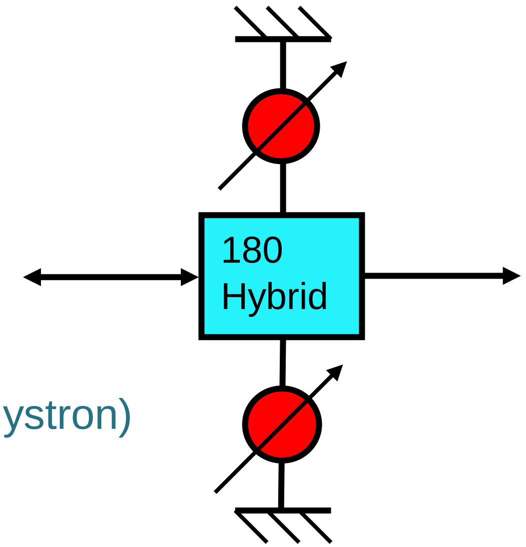
$$V_{out}(\phi_1,\phi_2) = V_o \cos\left(\frac{\phi_1-\phi_2}{2}\right) e^{-j\left(\frac{\phi_1+\phi_2}{2}\right)}$$

$$\frac{A_{out}}{A_{in}} = \cos\left(\frac{\phi_1-\phi_2}{2}\right)$$

$$\phi_{out} = -\frac{\phi_1+\phi_2}{2}$$

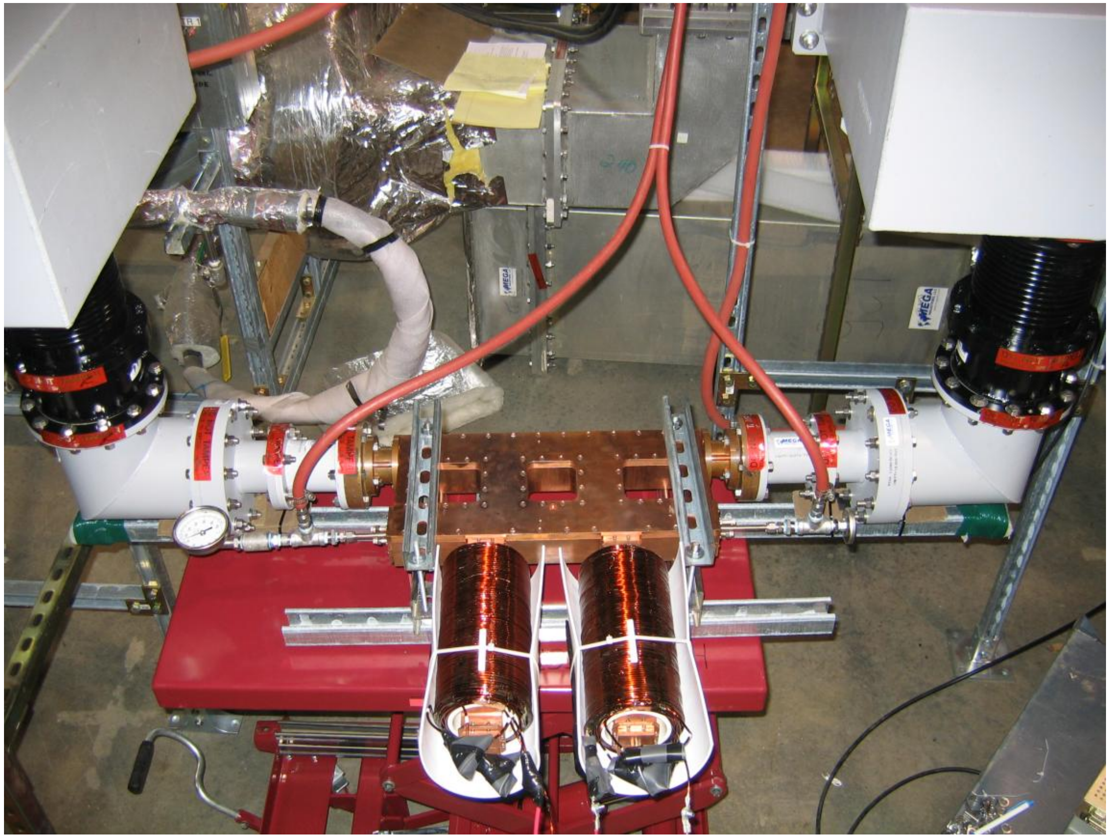
- Standing wave

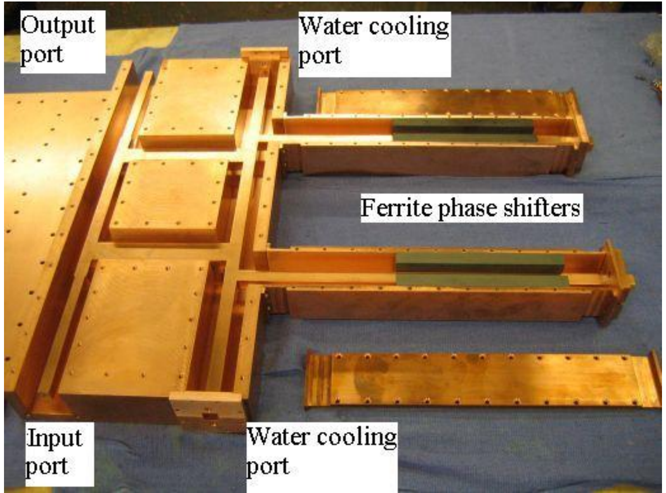


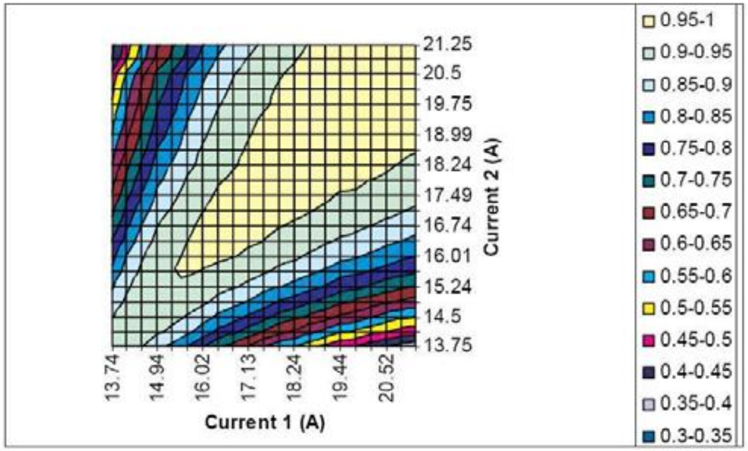


  - Isolation required between RF generator (klystron) and VM
  - 2 x peak voltage develops

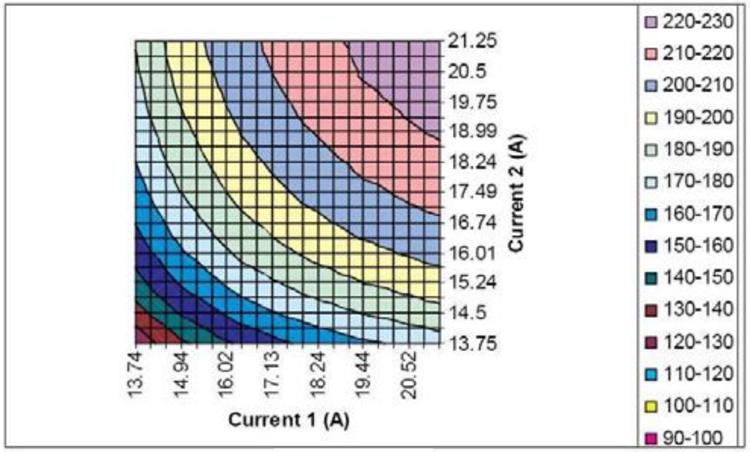
402 MHz Coaxial Vector Modulator







Amplitude

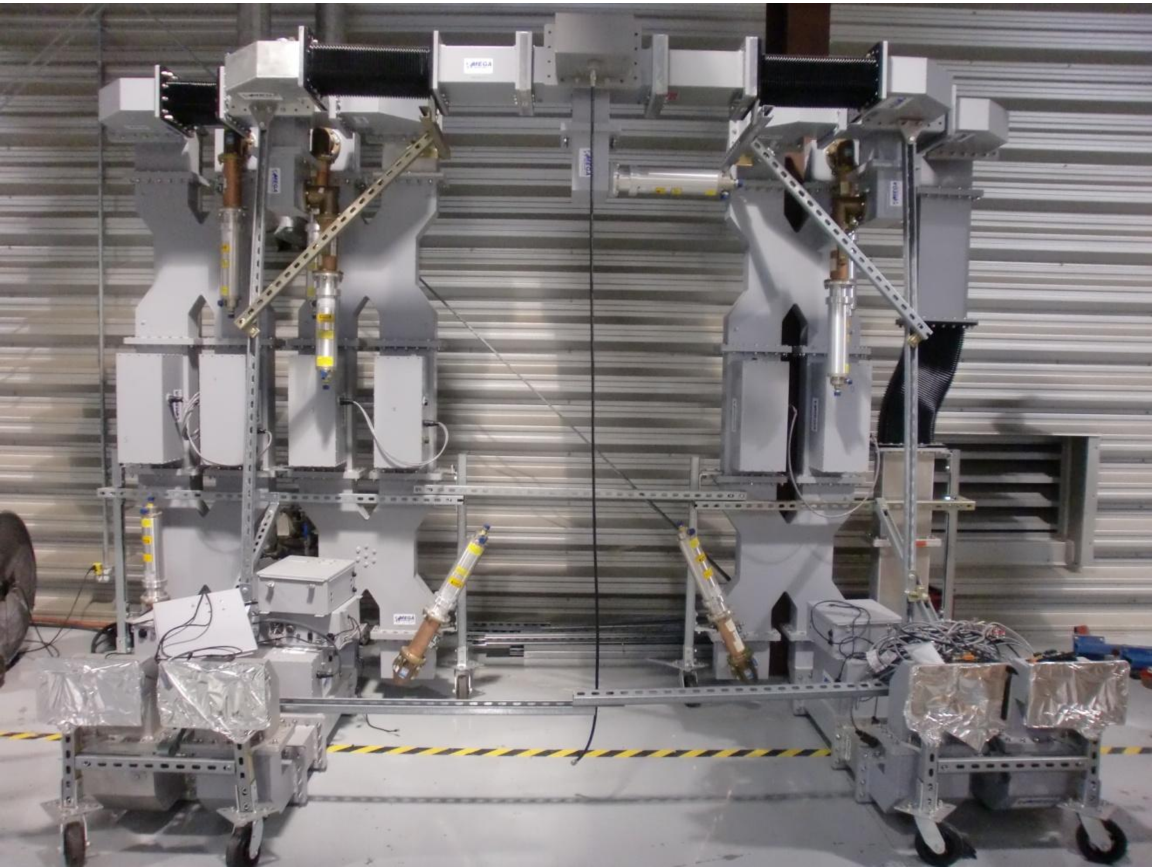


Phase

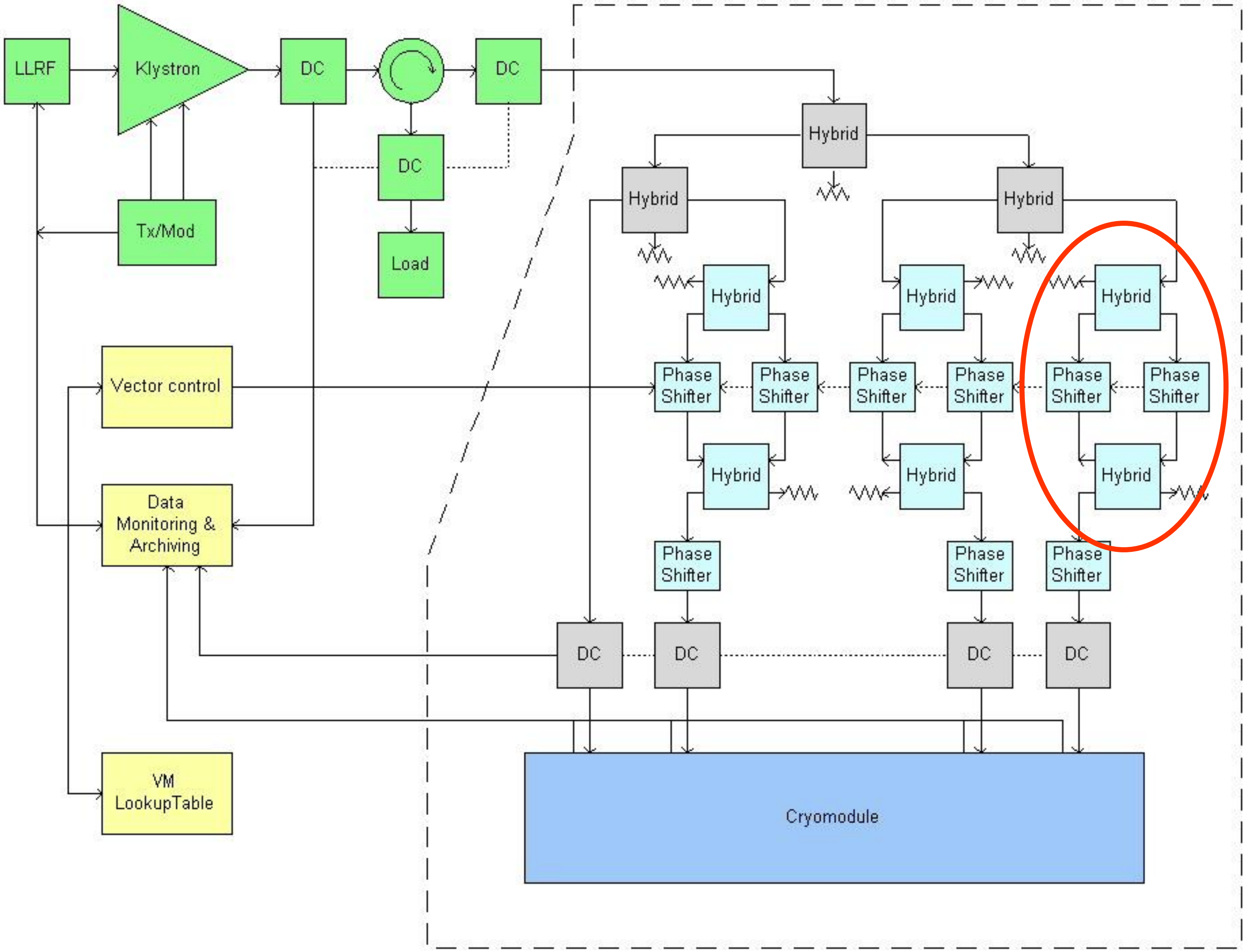
- Square coaxial design with 10dB in amplitude and +- 45-degrees in phase
- High power tested to 400 kW at 3% duty

Waveguide Feed Network for Four Cavity Conditioning

- Feed four SCL cavities with one klystron (available 5 MW tubes)
- Use waveguide vector modulator employing the mechanical phase shifters
- Adjust the power of four outputs connected to cavities to ±40% in amplitude and ±30° in phase

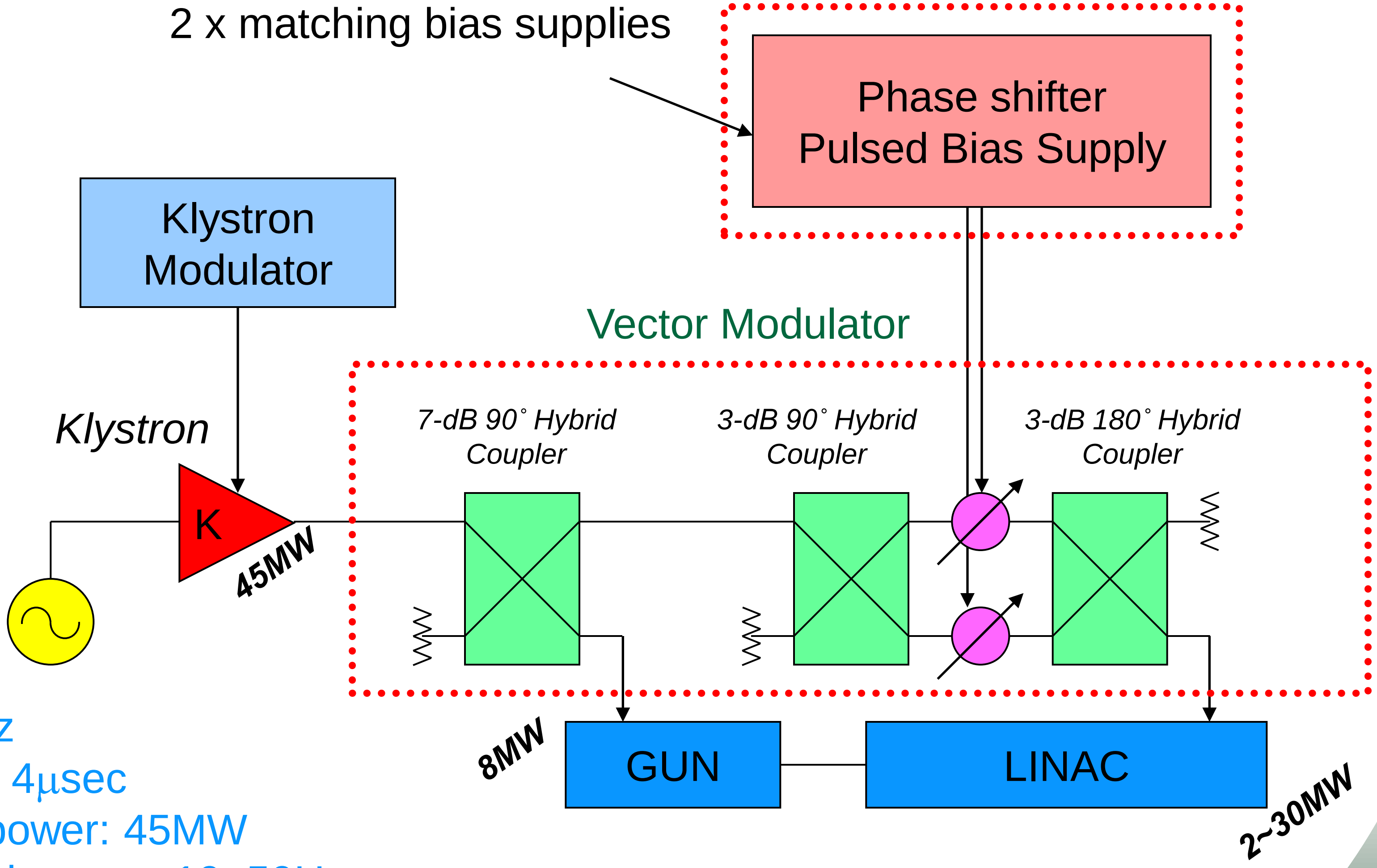


RF Distribution Setup for Cryomodule Test (up to 4 cavities)



Vector modulator

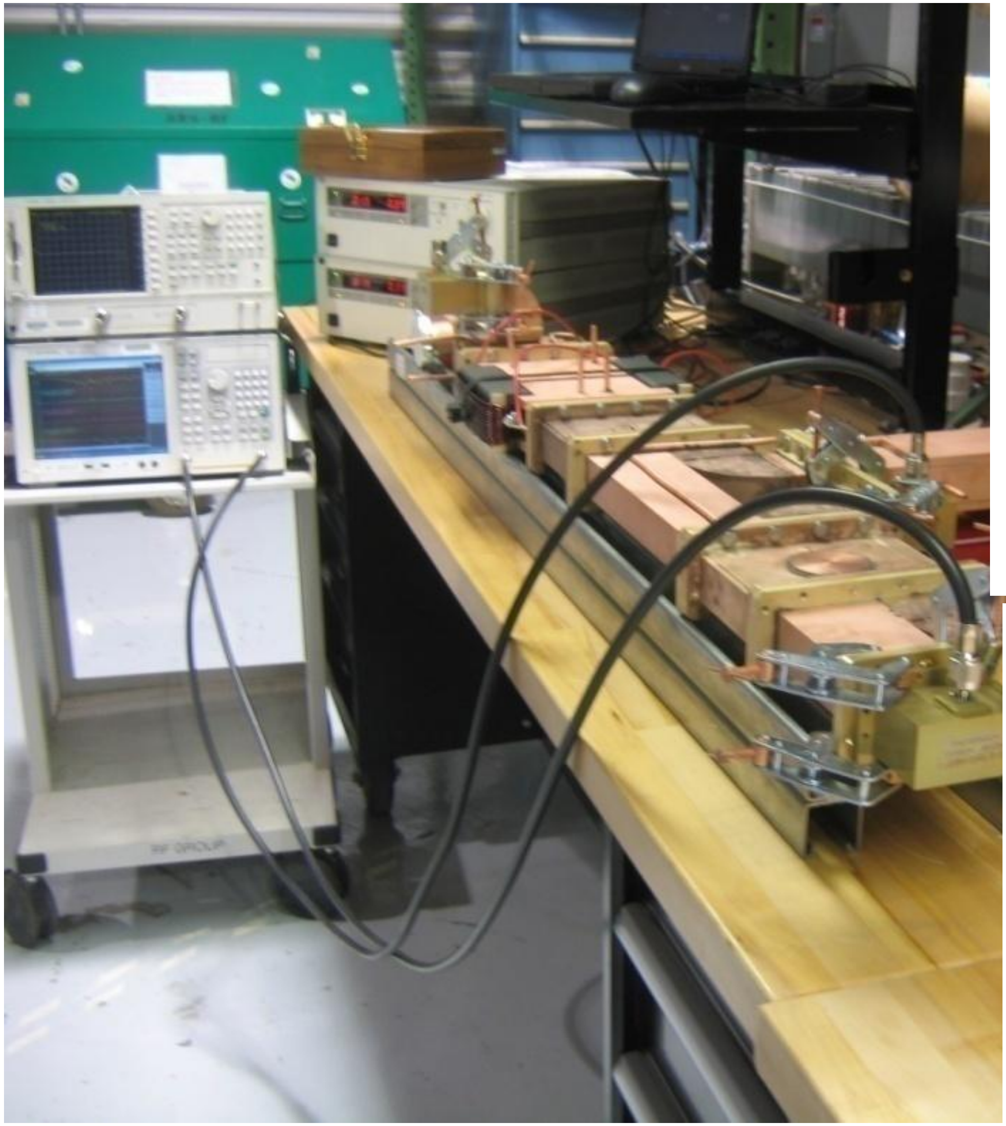
RF Control in S-band Accelerator System

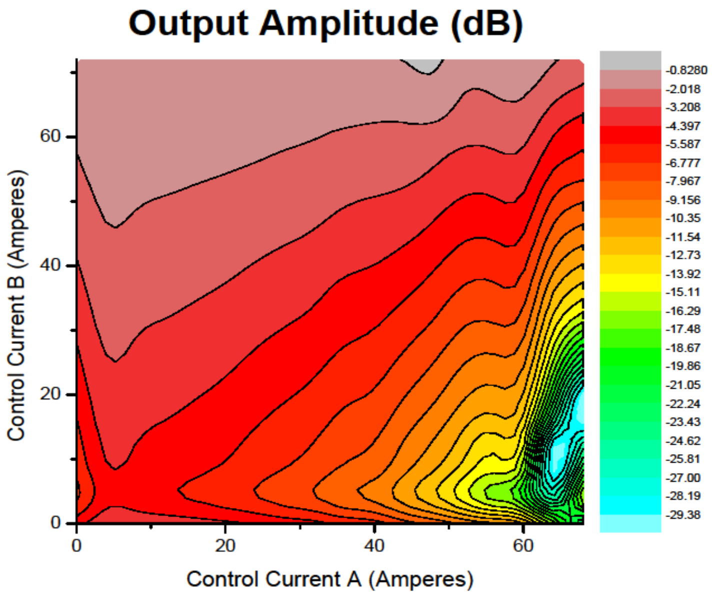


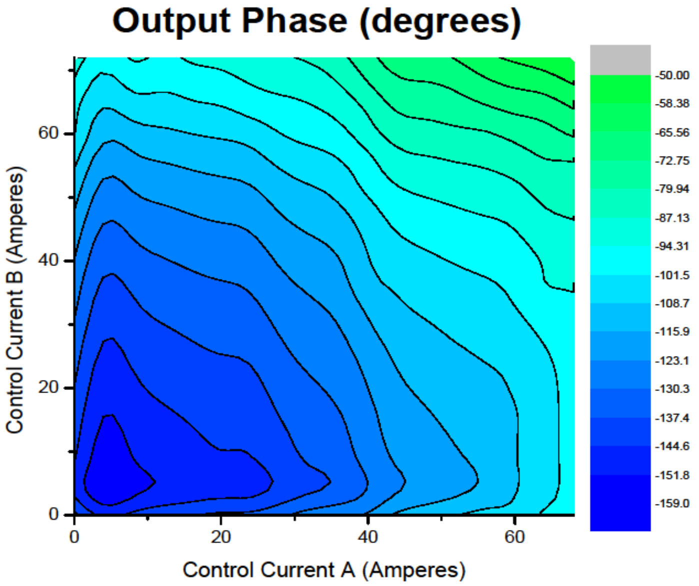
Note: No circulator is needed at klystron output.

f_0=2.856GHz
Pulse width: 4μsec
Peak input power: 45MW
Pulse repetition rate: 10~50Hz

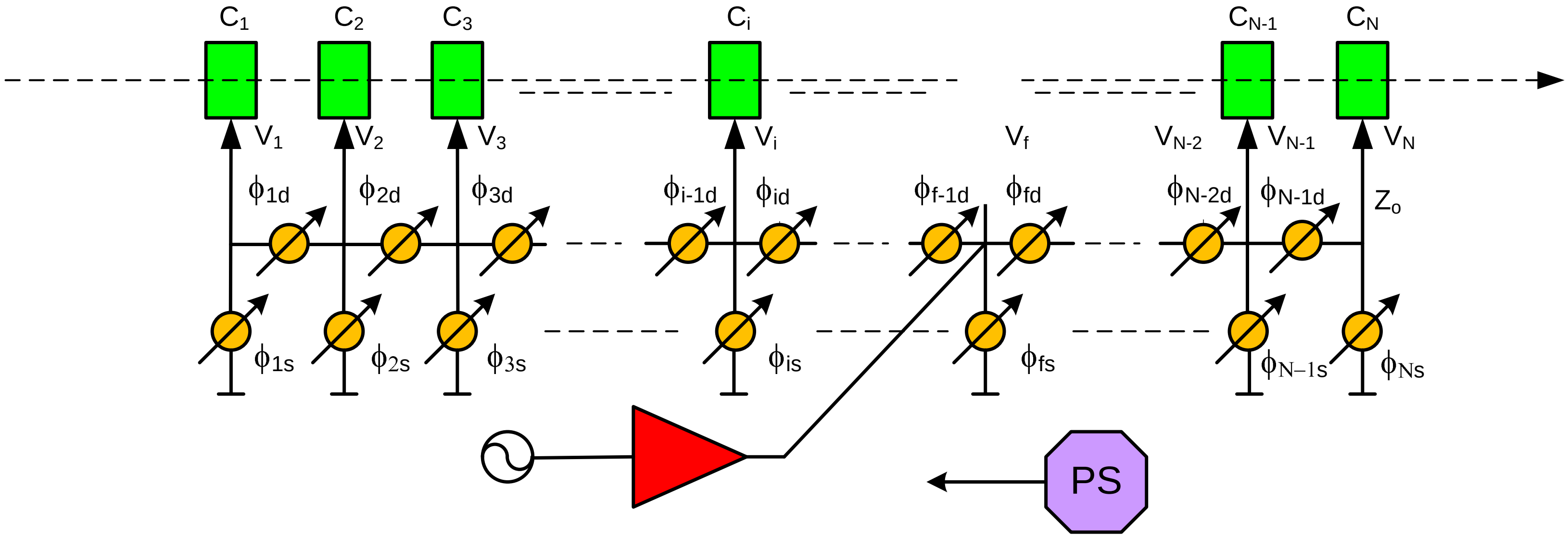
Low Power Measurements @ 2.856 GHz




Output Amplitude (dB)

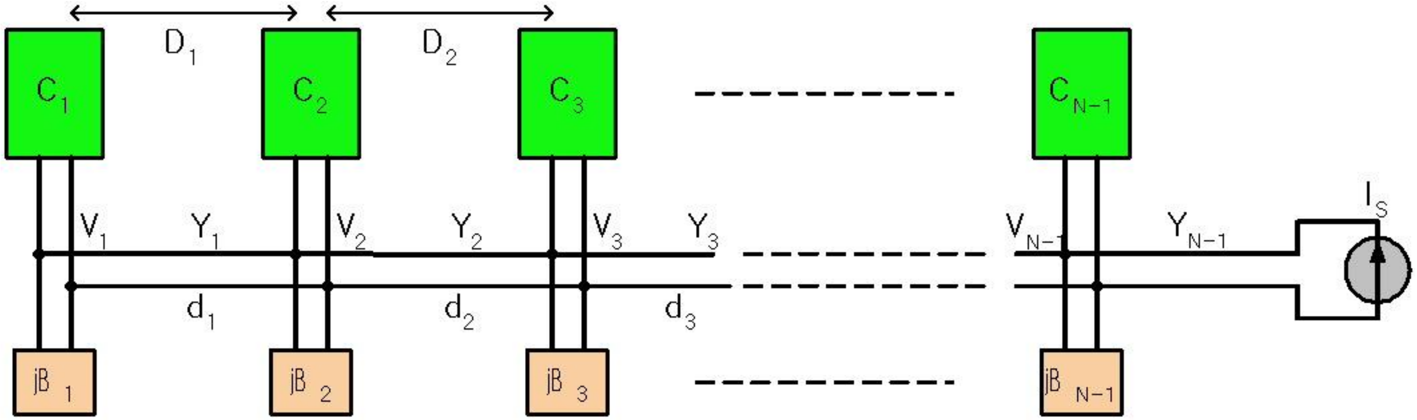

Output Phase (degrees)

Singly Fed Reactive Distribution



- The reactive fan-out power distribution system can eliminate power overhead to achieve maximum RF efficiency
- The fan-out system can be controlled as a whole to deliver the exactly required amplitudes and phases of RF voltages at the cavities only with phase shifters
  - With a source, a set of specified voltages [V_i] can be supplied to the load cavities by adjusting the transmission-line lengths, and reactive loads
  - Varying the transmission-line lengths, and reactive loads can be done only with phase shifters
  - Any cavities missing or need to be disabled in the system can be set to have 0 voltage vector

System Equation (I)



Consider an array of *N*-cavity loads connected to a transmission-line network. Let *[V^P]* be the port voltage vector of a set of specific cavity excitations for an optimum operation.

$$[V^P]^t = [V_1^P \quad V_2^P \quad V_3^P \quad \cdots \quad V_{N-1}^P]$$

The relation between the terminal currents *[I^S]* and the terminal voltages *[V^P]* is

$$[I^S] = [Y^S][V^P]$$

where the short-circuit terminal admittance matrix of the whole system

$$[Y^S] = [Y^P] + [Y^T] + [Y^L]$$

[Y^P] = port admittance matrix for the cavities,

[Y^T] = short circuit admittance matrix of the transmission line network,

and [Y^L] = load admittance matrix.

System Equation (II)

The port admittance matrix only with the loads with no couplings between the cavities

$$[Y_p] = \begin{pmatrix} Y_{in,1} & 0 & 0 & \cdots & 0 \\ 0 & Y_{in,2} & 0 & \cdots & 0 \\ 0 & 0 & Y_{in,3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & Y_{in,N} \end{pmatrix}$$

If a cavity is mismatched, the port admittance matrix at the input of a cavity is found as:

$$Y_{in} = Y_o \frac{Y_L \cos \beta d^c + jY_o \sin \beta d^c}{Y_o \cos \beta d^c + jY_L \sin \beta d^c}$$

where Y_o and d^c are the characteristic impedance and the length of the transmission line connects the cavity to the network, respectively, Y_L is the cavity load impedance, and β is the phase constant. The load is related to the reflection coefficient

$$Z_L = Z_o \frac{1+\Gamma(z)}{1-\Gamma(z)}$$

The transmission line admittance matrix

$$[Y_T] = \begin{pmatrix} -jY_1 \cot \beta d_1 & jY_1 \csc \beta d_1 & 0 & \cdots & 0 \\ jY_1 \csc \beta d_1 & -j(Y_1 \cot \beta d_1 - Y_2 \cot \beta d_2) & jY_2 \csc \beta d_2 & \cdots & 0 \\ 0 & jY_2 \csc \beta d_2 & -j(Y_2 \cot \beta d_2 - Y_3 \cot \beta d_3) & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & -jY_{N-1} \cot \beta d_{N-1} \end{pmatrix}$$

System Equation (III)

The reactive load admittance matrix

$$[Y^L] = \begin{pmatrix} jB_1 & 0 & \cdots & 0 \\ 0 & jB_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & jB_N \end{pmatrix}$$

If the *n-th* terminal is used for feeding, only $I_n = 1$ in the current matrix

$$[I^S]^t = [0 \quad 0 \quad \cdots \quad 1 \quad \cdots \quad 0]$$

The input impedance is found by selecting the element Z_{ii} in impedance matrix $[Z^s]$

$$[Z^S] = [Y^S]^{-1}$$

From $[Y^S] = [Y^P] + [Y^T] + [Y^L]$ the *m-th* element of the current vector is found as

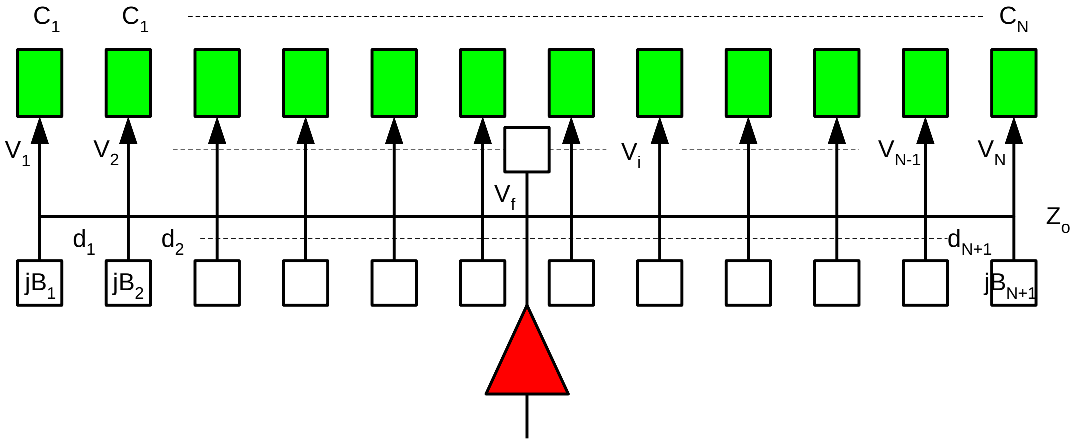
$$I^S\delta_{nm} = y_m^{in}V_m^P - j\{Y_{m-1}^T V_{m-1}^P \csc(\beta d_{m-1}) + Y_{m-1}^T V_m^P \cot(\beta d_{m-1}) + Y_m^T V_m^P \cot(\beta d_m) + Y_m^T V_{m+1}^P \csc(\beta d_m)\} + jV_m^T B_m$$

(for m=1, 2, ..N) where *n* is the feed port index.

The above equations can be solved for a specified load voltages $[V^P]$ if any one out of the three parameters is given: *transmission-line characteristic admittances, transmission-line lengths, and reactive loads. If a standard transmission line impedance Y^S is used, the lengths d_m (d_{m-1}), and reactive loads B_m can be found.* Y^S_{m-1} *(Y^S_m) and, d_{m-1} (d_m) are given so that the d_m (d_{m-1}), and reactive loads B_m are found.*

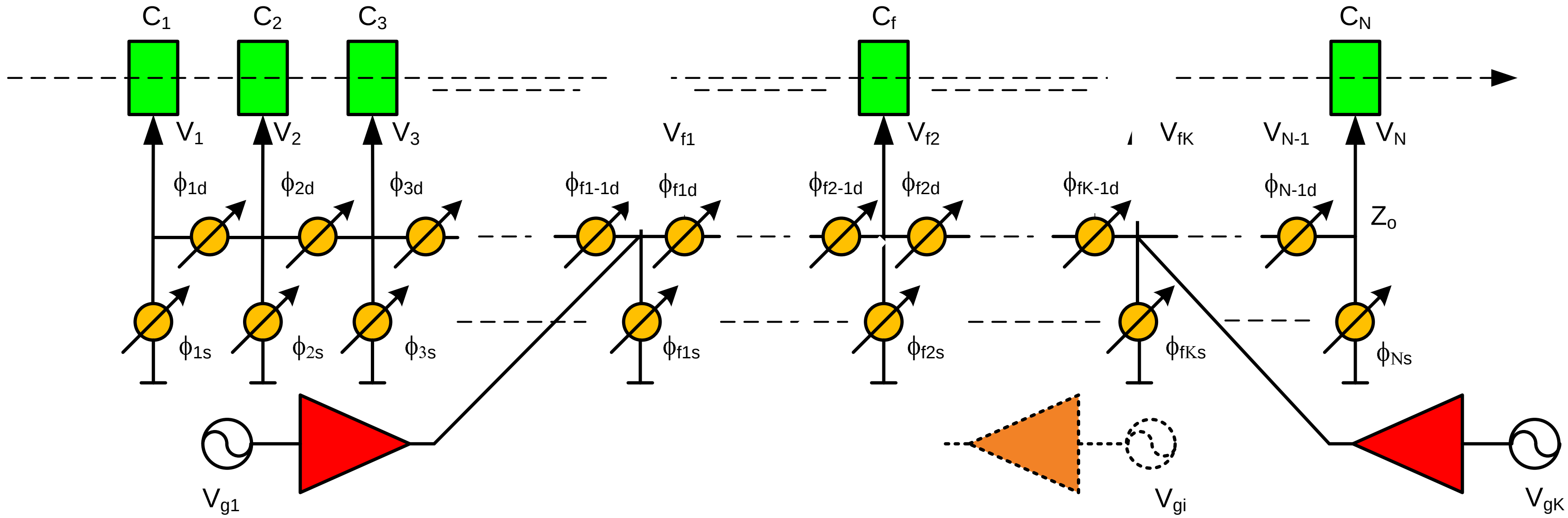
Example

12 cavities @ f = 805 MHz, cavities are critically coupled



Cavity	Distance (m)	Voltage (V)	Zo (Ω)	d_i (m)	jB_i (Ω)
1	1.50	1.0000 /0 °	50.0000	1.8742	- 0.0056i
2	1.50	1.0500 /10 °	50.0000	1.8690	- 0.0026i
3	1.50	1.1000 /20 °	50.0000	1.8673	+ 0.0020i
4	1.50	1.1500 /30 °	50.0000	1.8664	+ 0.0056i
5	1.50	1.2000 /40 °	50.0000	1.8659	+ 0.0088i
6	1.50	1.2500 /50 °	50.0000	1.8330	+ 0.0715i
7		(3.9083 /0 °)	50.0000		- 0.0544i
8	1.50	1.2500 /50 °	50.0000	1.8330	+ 0.0715i
9	1.50	1.2000 /40 °	50.0000	1.8659	+ 0.0088i
10	1.50	1.1500 /30 °	50.0000	1.8664	+ 0.0056i
11	1.50	1.1000 /20 °	50.0000	1.8673	+ 0.0020i
12	1.50	1.0500 /10 °	50.0000	1.8690	- 0.0026i
13	1.50	1.0000 /0 °	50.0000	1.8742	- 0.0056i

Singly Fed Reactive Distribution with more Redundancy



- The reactive fan-out distribution system can be flexible to include more than one power generators

$$\left[s \quad t \right] = \left[\quad \cdots \quad I_1 \cdots \quad 0 \cdots \quad I_k \quad \cdots \quad 0 \right]$$

  - Generator power outputs of the generators can be arbitrary
  - Any cavity load or power generator can be disabled

Summary

- Often splitting power of a high powered generator for many cavities may save cost in construction and installation of high power accelerators
- For most accelerators, the amplitudes and the phases of RF in the cavities (through RF power distribution) need to be controlled independently
- A fixed power splitter fan-out distribution using vector modulators can be useful for certain application
  - The generator power can be constant
  - Power not used by the cavities can be wasted
- The reactive fan-out distribution system can eliminate power overhead to achieve efficient operation
  - The system is controlled as a whole to deliver the exactly required RF voltage vectors (and power) at the cavities only with high power phase shifters
  - Superposition of several generators in arbitrary points in the network can add flexibility and redundancy
  - Any RF power generators can be shut off
  - Any load cavity can be disconnected or disabled with the load voltage set to zero voltage
- For the above fan-out distribution systems, complete and fast low-level RF control systems are yet to be developed