Vector Modulation of High Power RF

Y. Kang
J. Wilson, M. McCarthy, M. Champion
and RF Group

Spallation Neutron Source
Oak Ridge National Laboratory

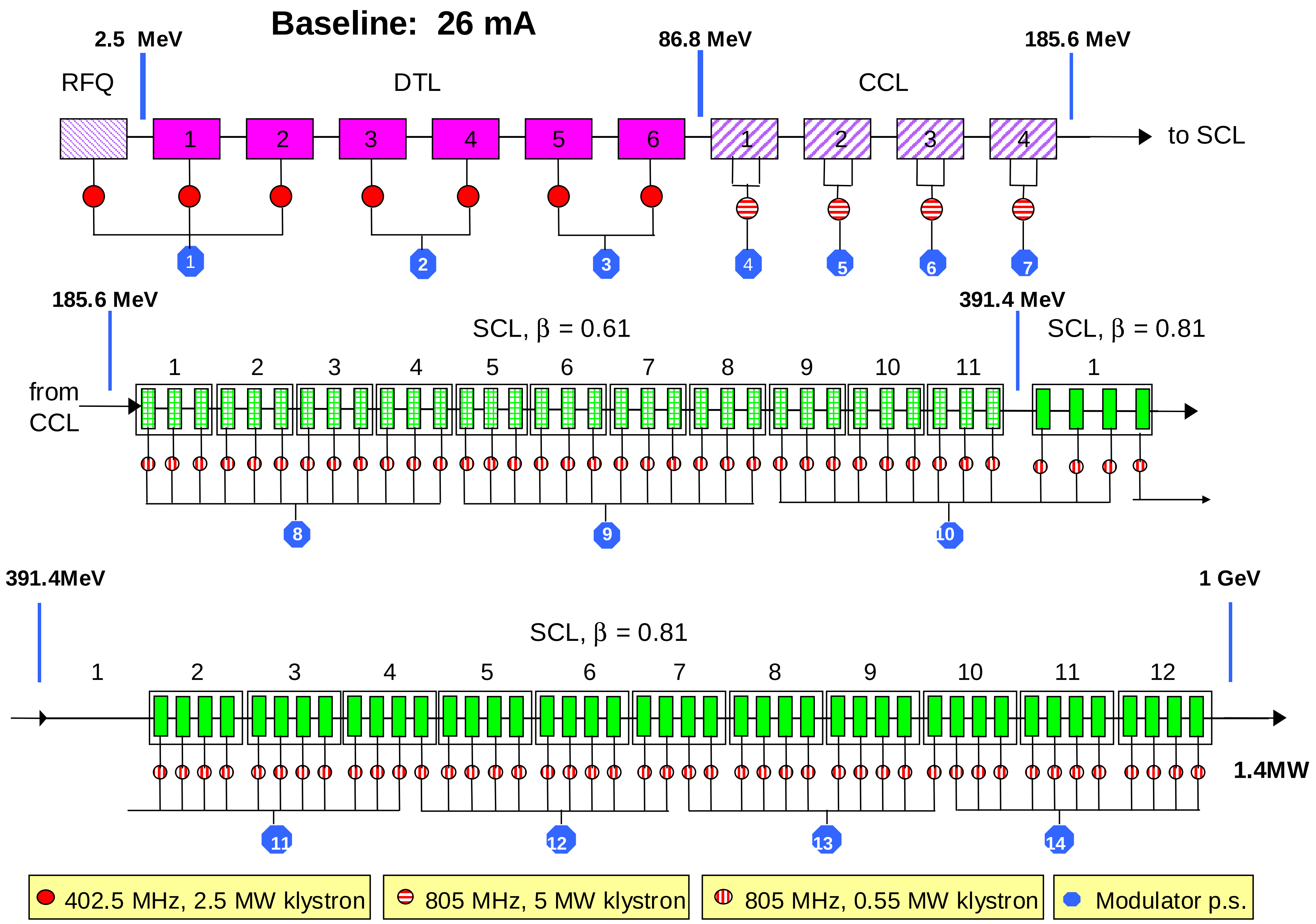
LLRF05 Workshop, CERN
10-13 October, 2005

High Power RF Vector Modulation

- For savings in construction and installation of a charged particle accelerator
  - Fanning out a higher power amplifier output to many cavities with individual amplitude and phase controls is less expensive than using an amplifier/cavity.
  - Applicable to all types of particle accelerations; cab be more effective for SRF ion accelerators
- Independent controls of amplitude and phase in high power RF transmission
  - Use two high power phase shifters with a hybrid junction (or two)
  - Well known principle not used for high power
  - Development in HPRF hardware (and LLRF control interface)
- Concept sought for possible application to the SNS linac; no time to implement
- Many new accelerator projects may benefit employing the design
- Phase shifters may be constructed using:
  - Ferrimagnetic materials
    - Control orthogonal magnetic field bias in ferrite (or YIG) material to change permeability
  - Ferroelectric materials (high frequency)
    - Control voltage bias on electro-optic material to change permittivity
  - PIN or Varacter diodes (lower power, short pulse)

HP Vector Modulator Development and Related Work

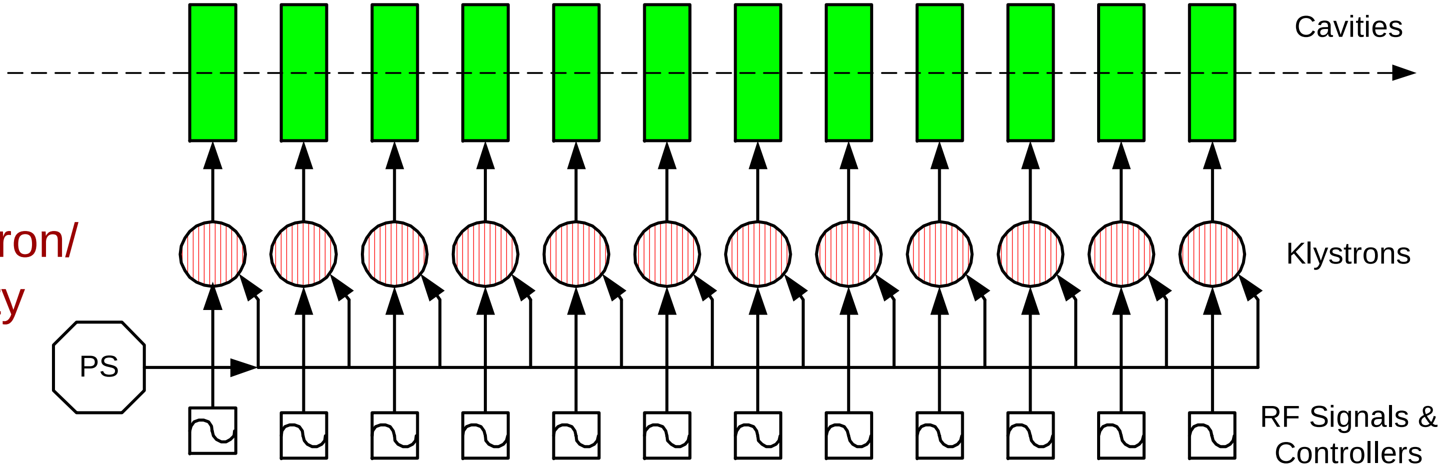
- ORNL, FNAL, CERN, and other institutions are now working on development of VMs
- HPSL 2005 Workshop, May 22-24, Naperville, IL
  - Y. Kang, “ High Power RF Distribution and Control using Ferrite Phase Shifters”
  - I. Terechkine, “High Power Phase Shifter for Application in the RF Distribution System of Superconducting Proton Linac”
  - D. Valuch, “A Fast Phase and Amplitude Modulator for the SPL”
  - D. Sun, “325 MHz IQ Modulator for the Front End of Fermilab Proton Driver”
- More
  - V. P. Yakovlev, “Fast X-Band Phase Shifter,” Advanced Accelerator Concepts: 11th Workshop, 2004
  - Y. Kang, “ Fast Ferrite Waveguide Phase Shifter,” PAC2001



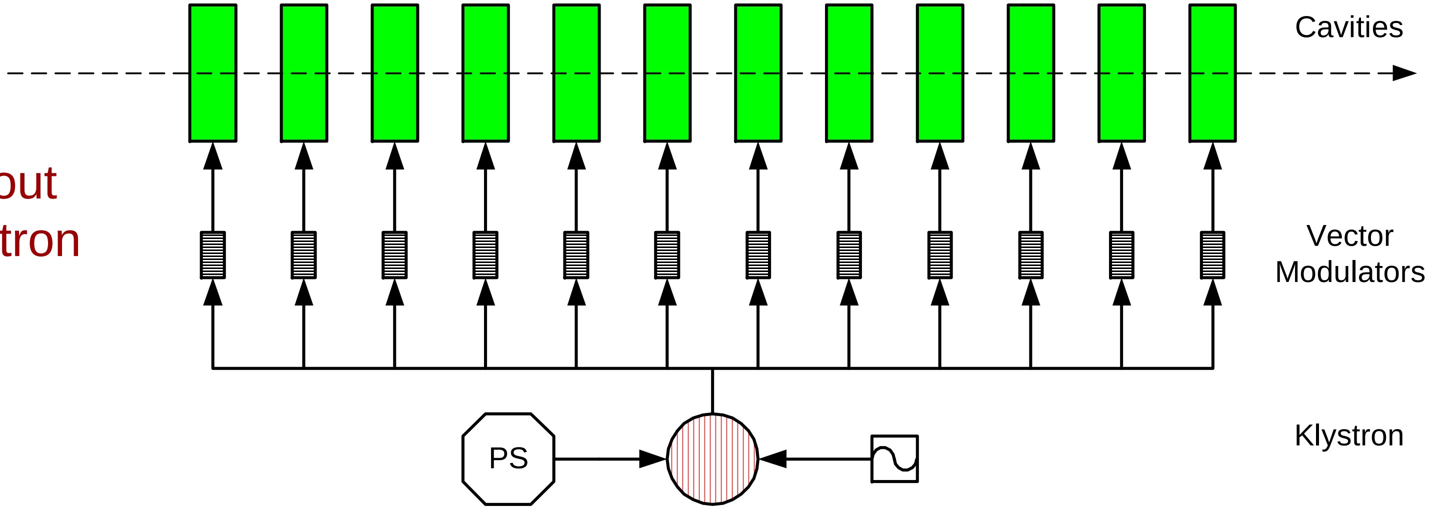
SNS Linac HPRF Systems

Comparison of Two Configurations

One Klystron/
One Cavity



Fanning out
One Klystron



Cost Savings ?

- Example: a system similar to SNS 805 MHz SRF linac
  - 25-40 mA beam current (8% duty)
  - E_{acc} ~ 10 ~ 16 MV/m
  - Q_{ext} ~ 7 x 10^5
  - ±1% amplitude, ±1° phase
  - π-mode superconducting Nb cavities will need ~200-600 kW/m
  - Klystron power spec: 550-600 kW/cavity
  - Klystron power supply (converter modulator) already fanned out to drive many klystrons

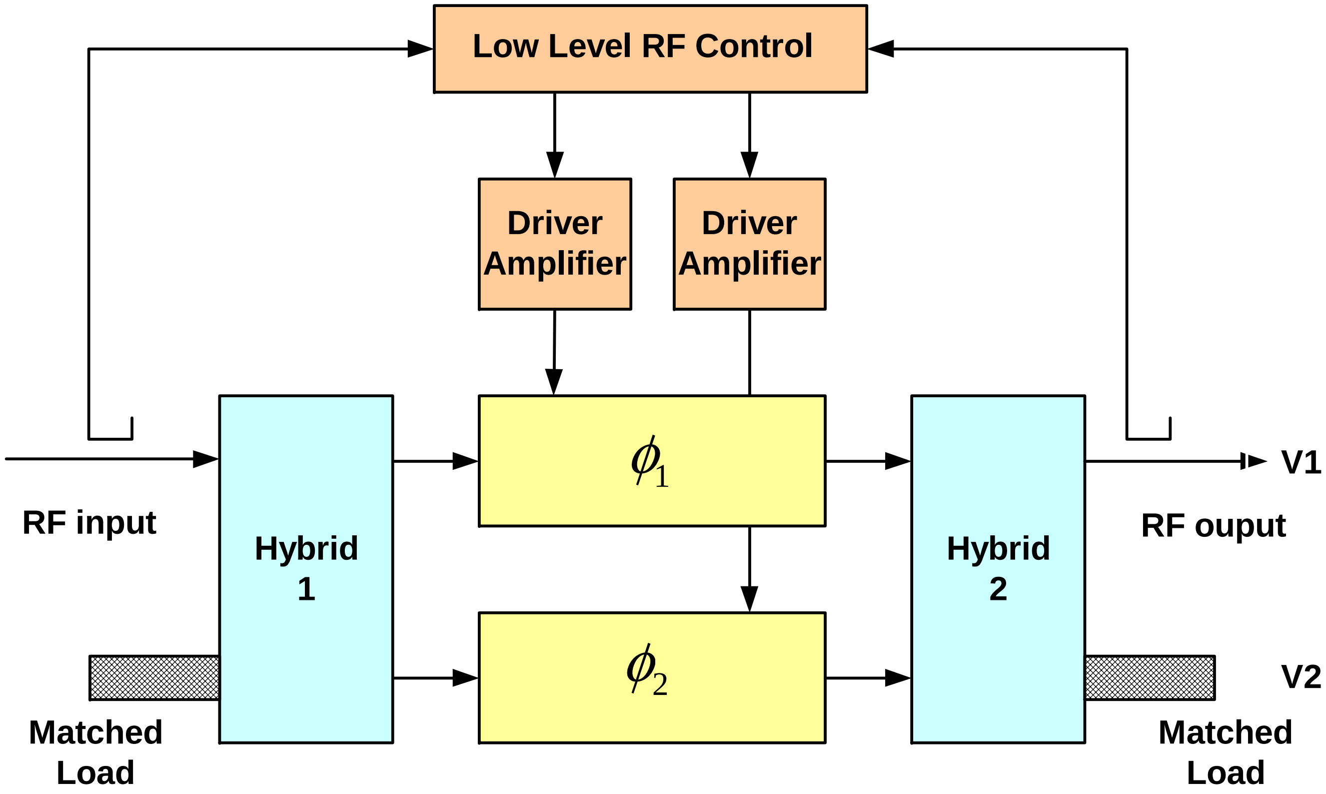
- Fan out configuration
  - Can use klystrons with ~10 – 50 times higher RF power output
  - Savings in construction and installation: klystrons, waveguides, labor and buildings
  - Extra cost for the vector modulators and control components

Linac RF Cost for a 805 MHz System

(non-official estimate for a linac with100 cavities)

	One/one			Fan out (1:20)			Savings
	Quantity	Unit Price ($k)	Total ($k)	Quantity	Unit Price ($k)	Total ($k)	($k)
Klystron	100	150	15,000	5	700	3,500	11,500
Transmitter + Power Supply	5	700	3,500	5	700	3,500	0
Circulator + Loads	100	50	5,000	100	50	5,000	0
RF Controls	100	105	10,500	100	135	13,500	-3,000
Waveguide	100	46	4,600	5	250	1,250	3,350
Gallery	40,000	0.20	8,000	5,000	0.20	1,000	7,000
Labor for WG/Klystron	10,000	0.10	1,000	2,000	0.10	200	800
Subtotal ($)			**47,600**			**27,950**	19,650
Other items							**Can be more**

Vector Modulation

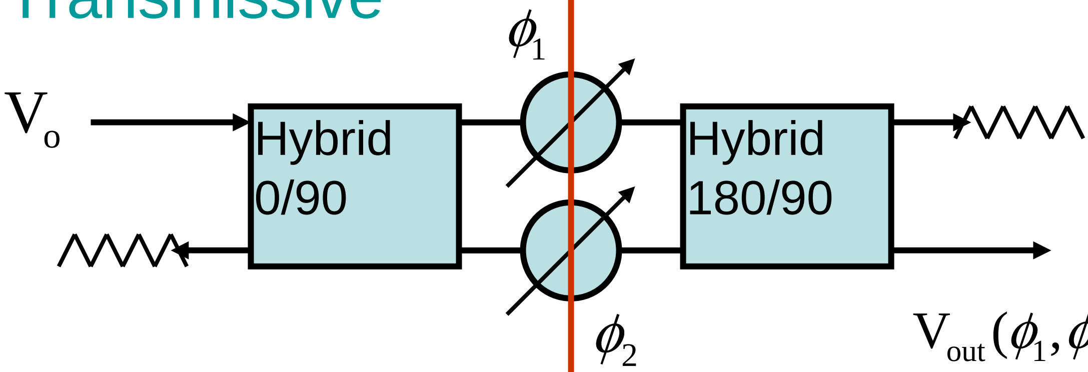


$$V_{out,1}(\phi_1,\phi_2) = V_0 \sin\left(\frac{\phi_1 - \phi_2}{2}\right) e^{-j\left(\frac{\phi_1+\phi_2}{2}\right)}$$

$$V_{out,2}(\phi_1,\phi_2) = V_0 \cos\left(\frac{\phi_1 - \phi_2}{2}\right) e^{-j\left(\frac{\phi_1+\phi_2}{2}\right)}$$

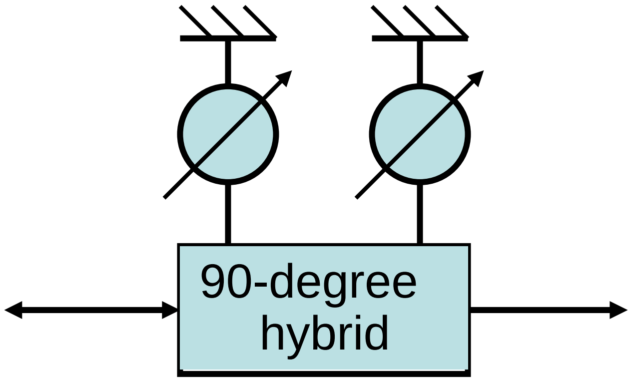
Vector Modulators

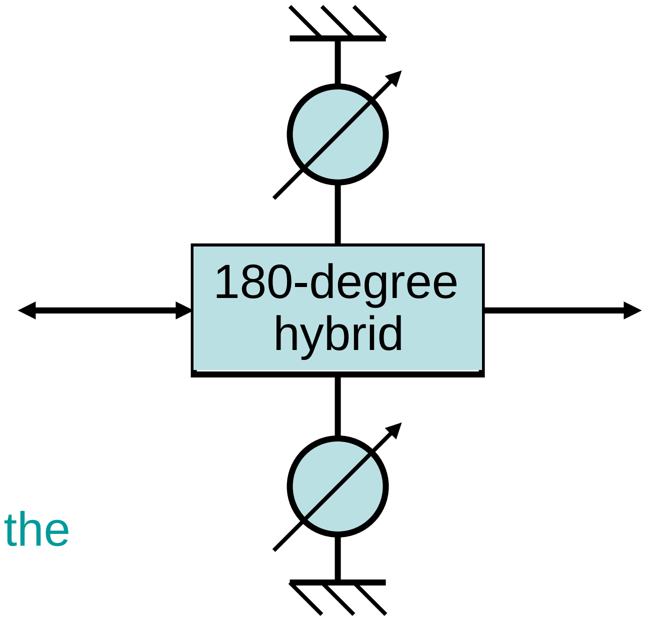
- Transmissive



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

- Reflective

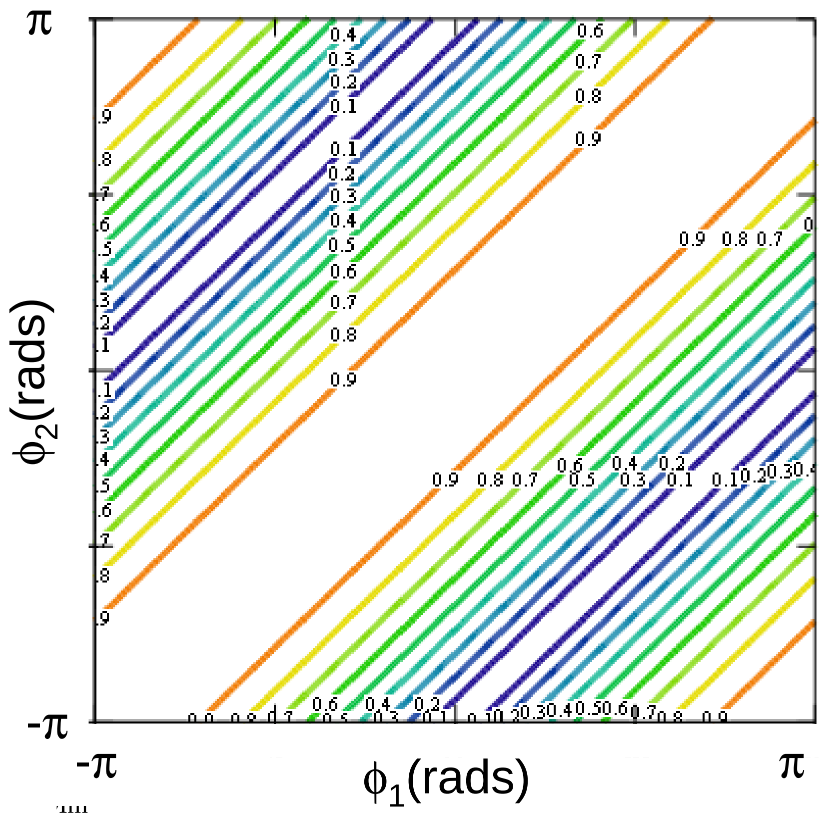




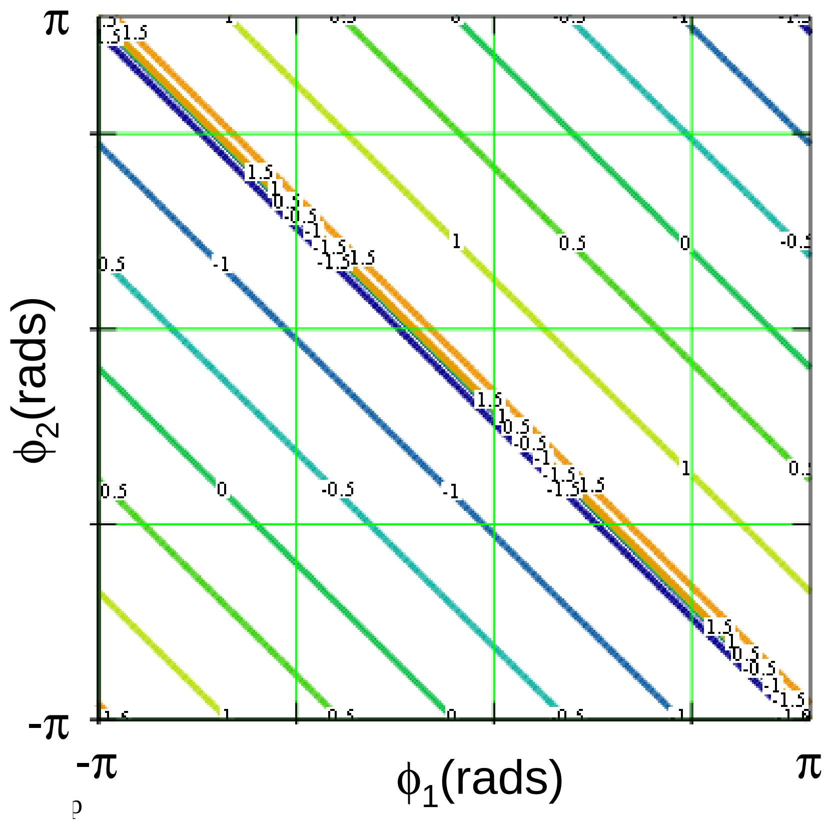
  - Standingwave is formed
  - Reflected wave must be trapped before the RF generator (klystron): circulator

VM Output Amplitude and Phase vs. ϕ_1 and ϕ_2

Amplitude



Phase

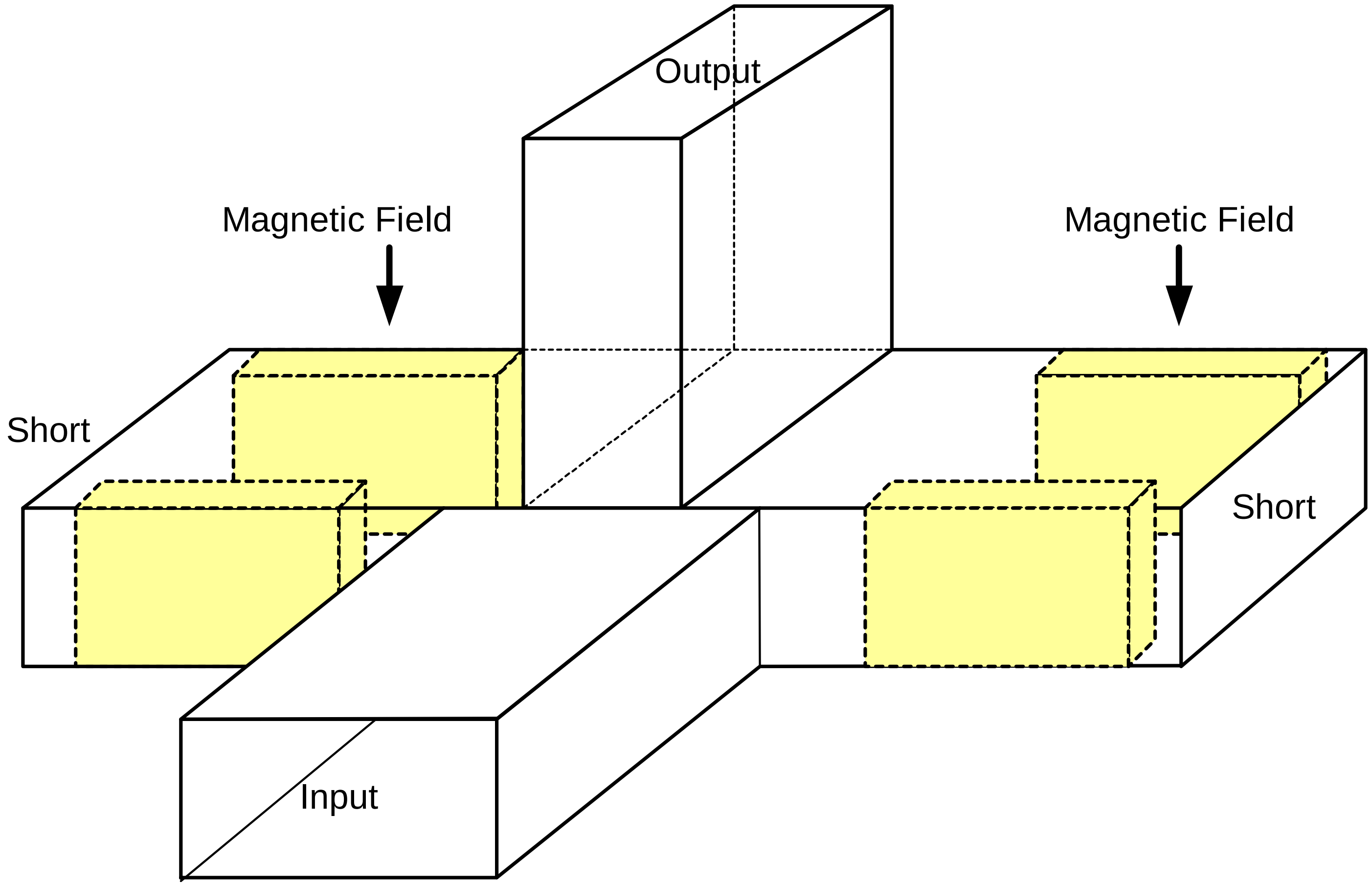


VM with Ferrite Phase Shifters

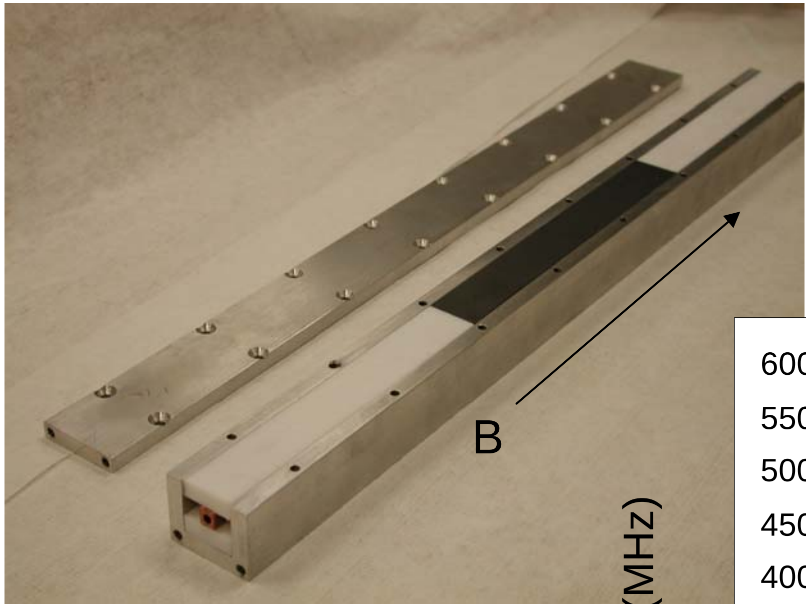
- Phase shifter uses ferrimagnetic material (ferrite, YIG)
  - Magnetic bias field is orthogonal to the RF magnetic field in the material
  - Magnetic field bias (usually high current, H_b ~ 10-50 kA/m) can change the permeability of the magnetic material
  - Waveguide type (FNAL and others) and coaxial type (ORNL) being demonstrated

- Design optimization:
  - High power handling
  - low RF loss
  - Dimensions
    - Waveguide design may be too bulky for SRF accelerator frequencies (especially < 1000 MHz)
  - LLRF Control
  - Fast response time
  - Reliability
  - Cost

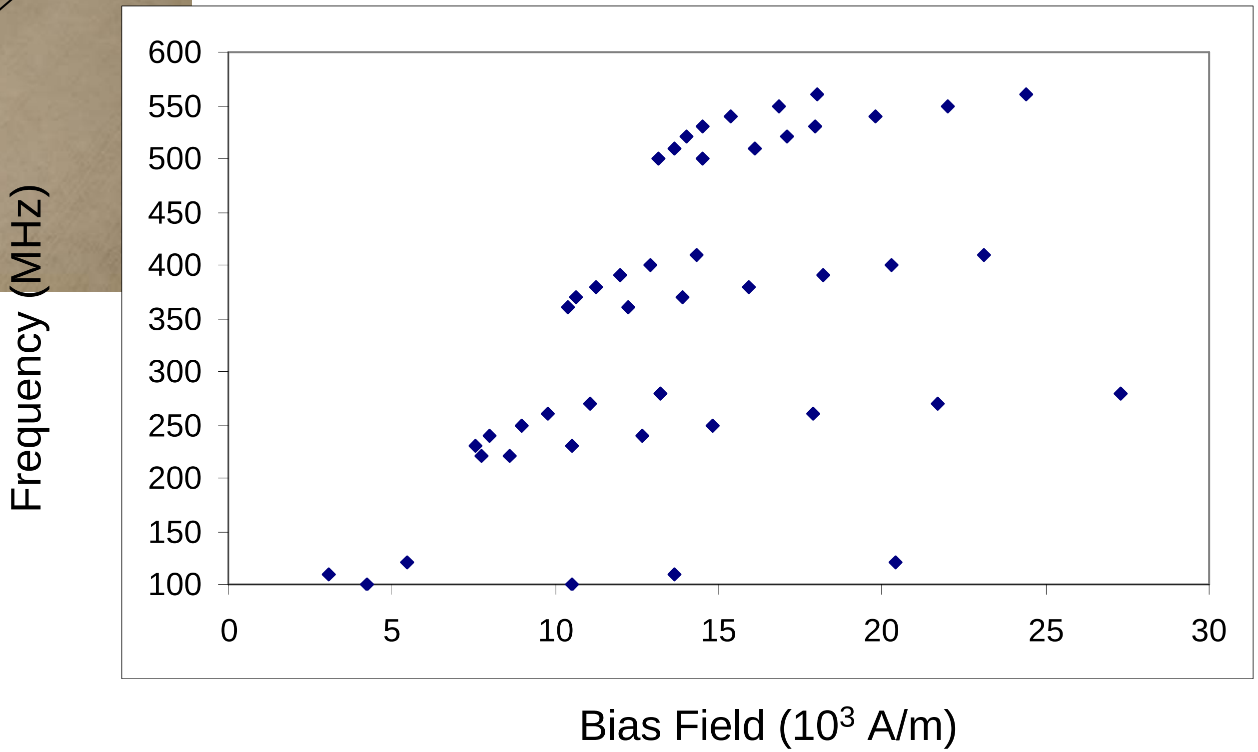
Waveguide Vector Modulator (FNAL)



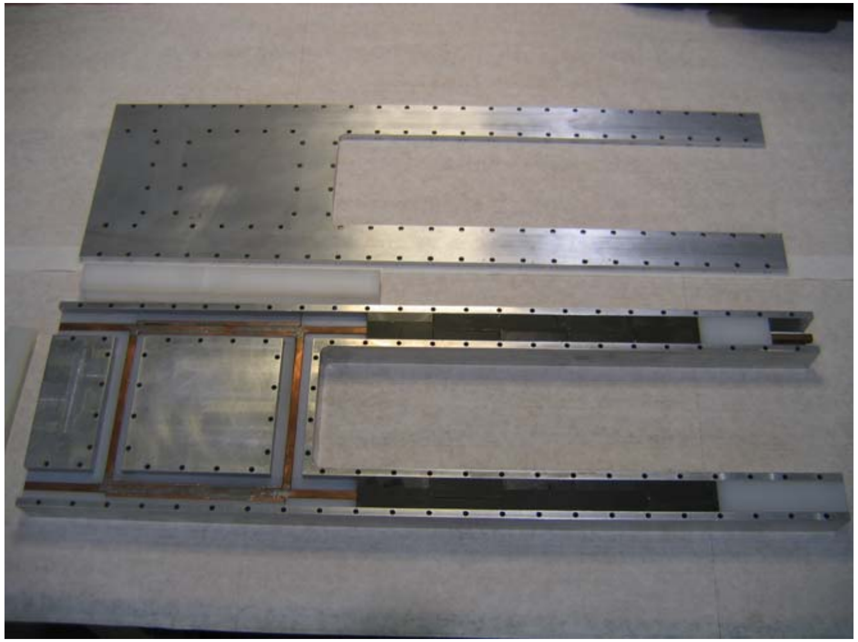
Square Coaxial Phase Shifter Measurement (ORNL)



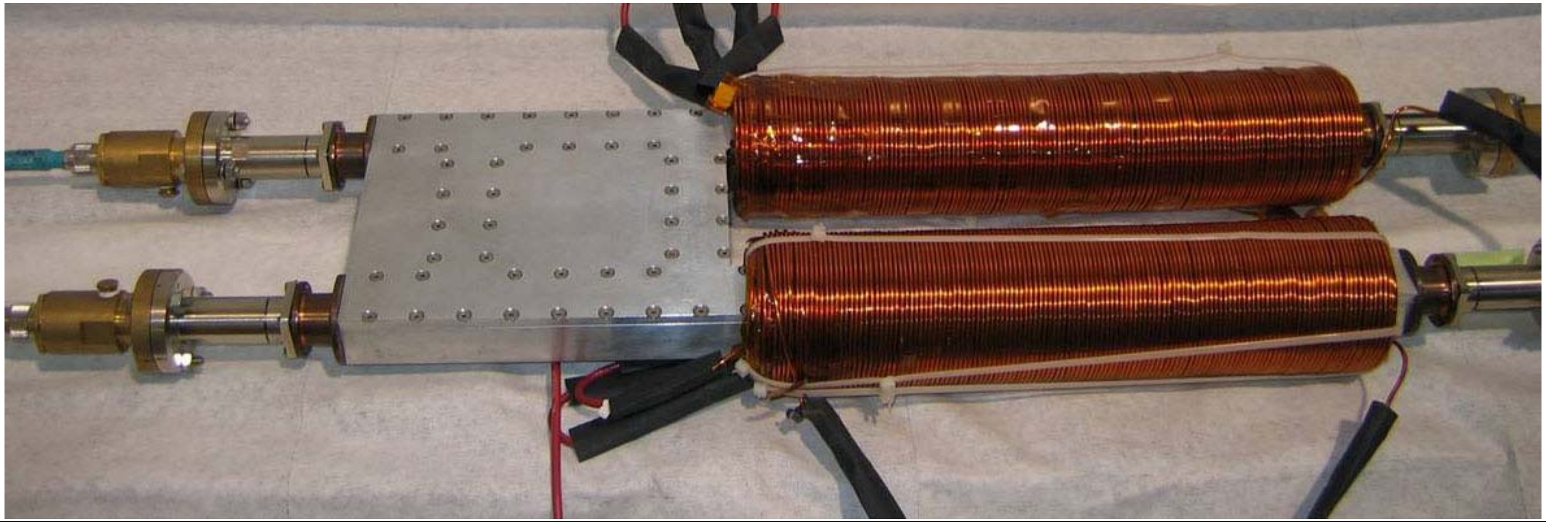
Operating Frequency vs. Bias Current of a Phase Shifter (10” active length)



805 MHz Vector Modulator Construction

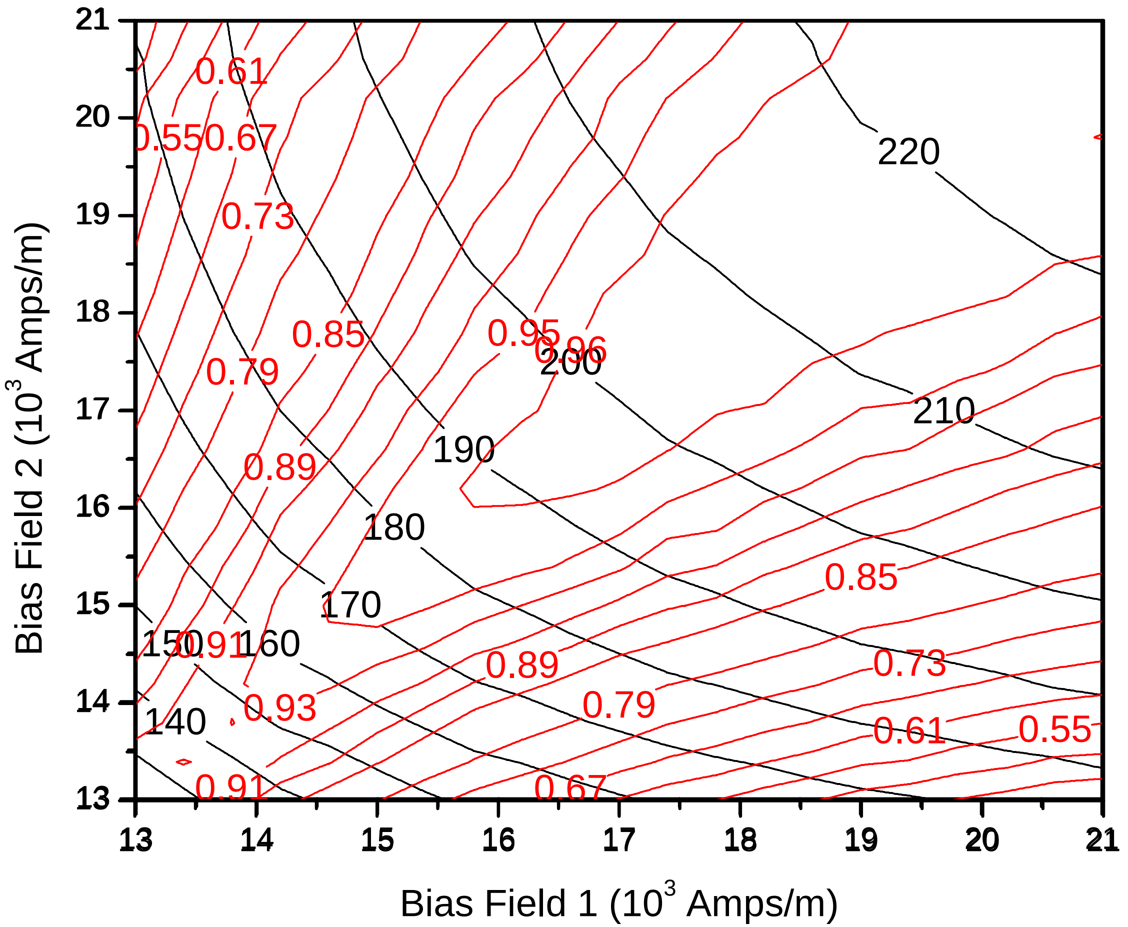


- Prototype construction and measurement
  - Square coaxial TEM transmission line design
  - For 402.5 MHz operation
  - 100-300 kW peak power
  - 10 kW average power
  - 10” active length

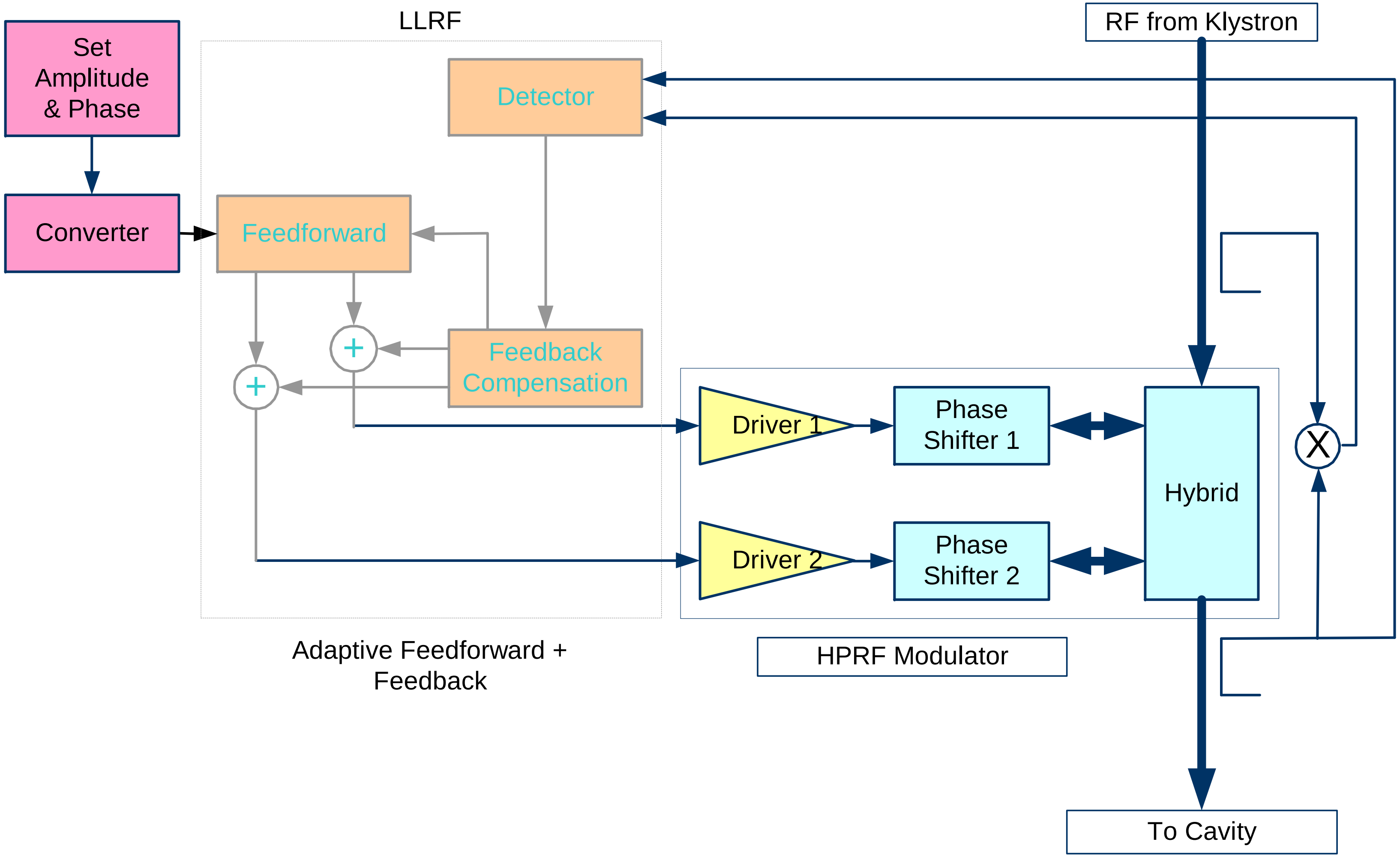


Amplitude and Phase vs. Bias Fields

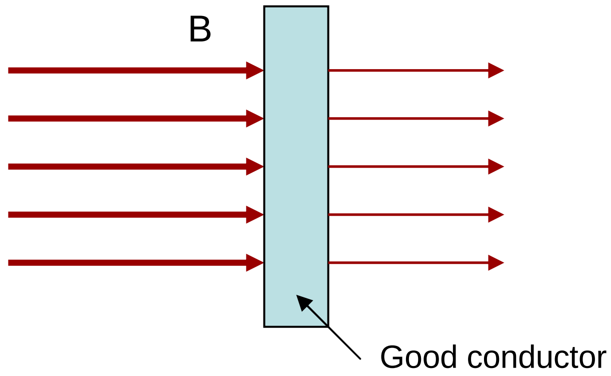
The lookup table

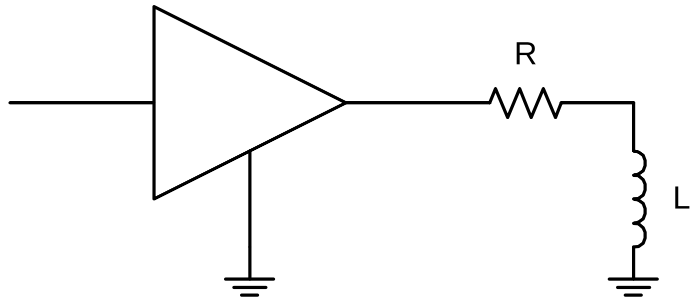


VM RF Control (preliminary)



Control Response Consideration





- Bandwidth limitation due to conductive housing:
  - Skin depth causes control field loss through the phase shifter housing => $\delta = 1/(\pi f \mu \sigma)^{1/2}$

  Ex) for copper wall t=δ=1mm, f=4.2kHz

- Magnetic bias field control :
  - Time constant of solenoid circuit => $R = \omega L$

  Ex) for solenoid L=10 μH, R=1Ω: -3dB frequency = 15.9 kHz, Time constant τ=L/R=10 μsec

- Time constant may be reduced:
  - by control loop gain of the detector/driver
  - by putting a zero in loop to cancel pole
  - The conductor loss also be minimized by properly slitting or laminating the housing for elimination of Eddy current

System Design with VMs
Amplitude/Phase Variable Range

- Accelerators RF cavities
  - SNS SCL like configuration uses only few cavity designs that match to few beam beta's
  - Variable ranges of phase and amplitude have to be greater
- Phase range requirement
  - Broader range is always desirable – some wants full 360-deg phase scanning for flexibility – expensive
  - If accelerator operates with any disabled (and detuned) cavity, a greater phase tuning range is needed at a cavity to compensate the phase slippage
  - With the knowledge, the right cavity phases can be predetermined for each case - the range can be smaller
- Amplitude range requirement (...)
  - all adjoining cavities will require all predetermined field distribution
  - To control the beam energy, the klystron power can be controlled
- Use additional slow phase shifters between the cavities
  - A slower inexpensive phase shifter, either ferrite or motorized mechanical stub types can be used in each cavity for sustained phase settings

VM RF Control Consideration

- The steady state characteristics of the phase shifters and the vector modulator can be measured and a lookup table can be provided
- Current (or voltage) drivers selected and transfer functions characterized
- LLRF development - adaptive feedforward with feedback control needed like in many other systems
- Frequency responses of phase shifters, bias circuits, and current/voltage drivers
- Other important factors:
  - Accelerator beam specification and control system requirements
  - Pulsed or CW
  - Temperature regulation
  - Power supply regulation
- Dynamic Range/Slew Rate/Linearity/Noise
  - Driver amplifier/power supply performance
  - Control system performance
- Optimization of bias circuits: Slow high current supply + Fast lower current supply

Summary

- VM using YIG ferrite material
  - 402.5 MHz square coaxial TEM phase shifter design prototyped for
    - Size and Integration
    - Manufacturing cost
    - Cooling
  - Low power bench measurements performed
  - High power testing being prepared
    - Housing and solenoid designs optimized
    - Power supplies/audio amplifiers
  - High power RF measurement and test to be completed
    - First goal is to demonstrate 100-300 kW pulsed system
    - Will be modified for higher power operation (> 500 kW)
    - SNS RFTF has been equipped and readied for the testing

- LLRF Control
  - Initial high power testing will have only simplest feedforward
  - Preliminary design and bench testing of the VM LLRF

  - Full LLRF controls to be demonstrated with cavity load
  - Needed for HPRF improvement