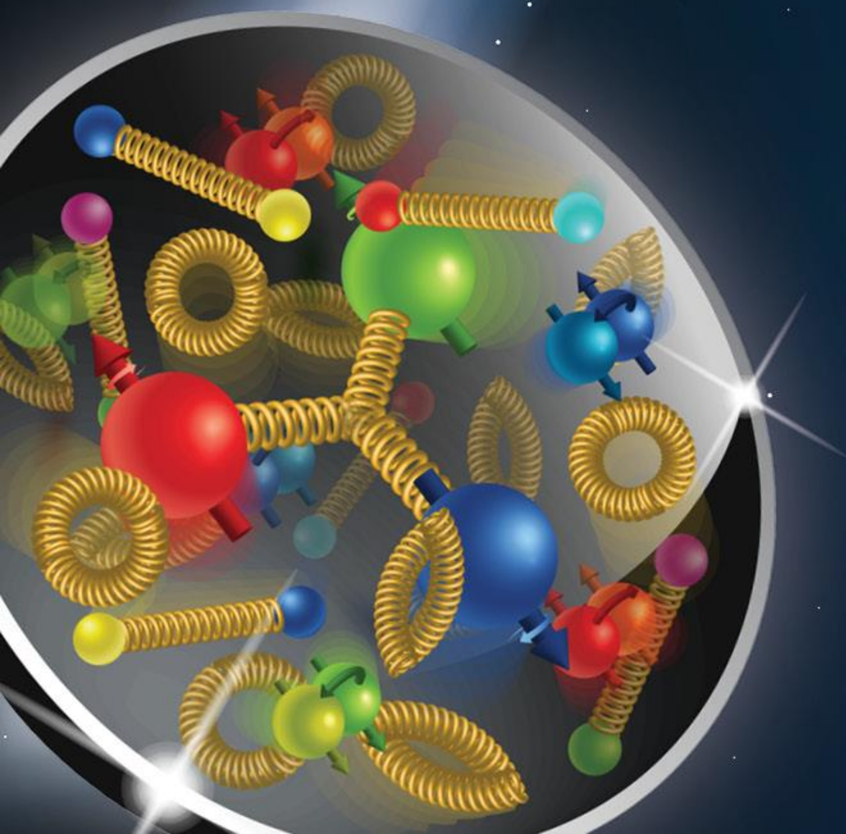
EIC ESR and HSR RF Challenges and Possible Reverse Phasing Experiment



Kevin S. Smith

APEX Workshop 2021

November 9, 2021

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Very Brief Overview of EIC RF Systems
- Challenges for EIC Ring RF (HSR and ESR)
  - Detuning
  - Transient Beam Loading
- Reverse Phasing Technique
- Summary

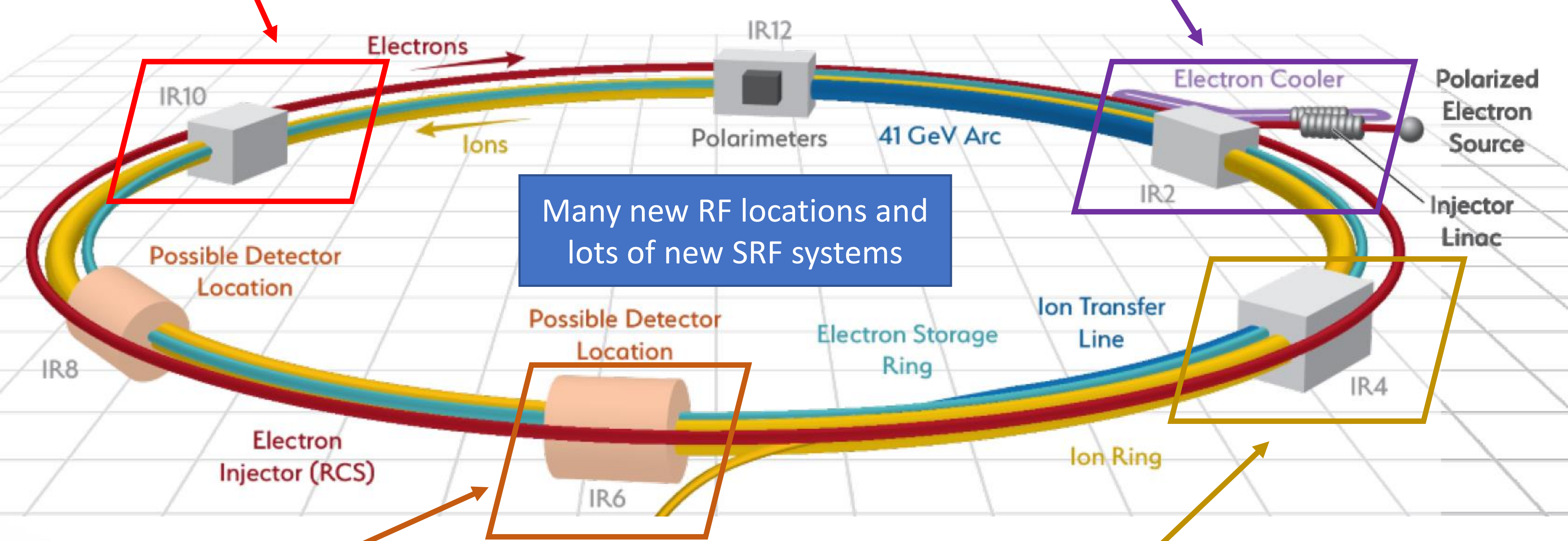
Overview – EIC RF Systems

IR-10: SRF Systems

RCS SRF
Electron Storage Ring SRF
Hadron Ring SRF

IR-2: Strong Hadron Cooling

Energy Recovery Linac (ERL)



Many new RF locations and lots of new SRF systems

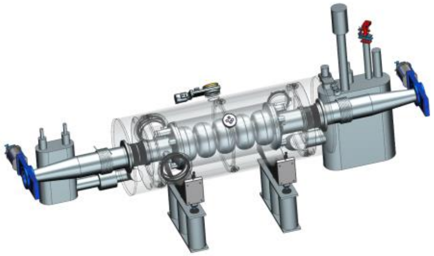
IR-6: Crab Cavity SRF Systems

197 MHz and 394 MHz Hadron Crab Cavity Systems
394 MHz Electron Crab Cavity Systems

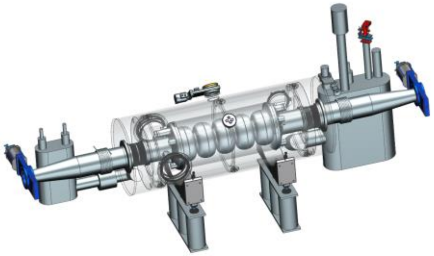
IR-4: Warm RF Systems

Current location for all RHIC RF systems
Hadron RF Systems (Hadron SRF at IR-10)
RCS Warm RF Systems (Bunch Merging)

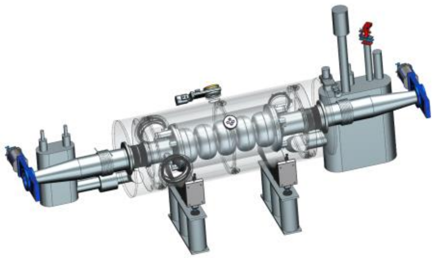
Scope Overview – SRF and NCRF Systems



RCS - 591 MHz 5-Cell Cavity
Acceleration Cavity

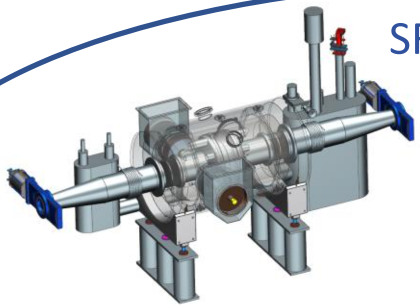


HSR - 591 MHz 5-Cell Cavity
Bunch Compression

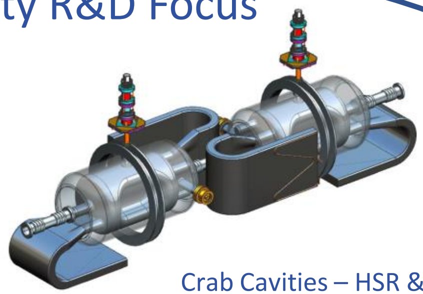


SHC- 591 MHz 5-Cell and
1773 MHz 5-Cell ERL Cavities

SRF Cavity R&D Focus

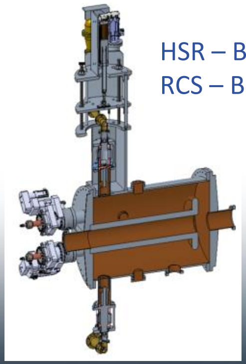


591 MHz ESR 1-Cell Cavity



Crab Cavities – HSR & ESR

HSR – 24.5 MHz Capture & Acceleration
Reuse 28 MHz system with Modifications



HSR – Bunch Splitting (New)
RCS – Bunch Merging (New)

HSR - 197 MHz Bunch Compression
Reuse with Modifications

Cavity Detuning

- The high beam currents and low voltages in some operating scenarios require large detuning of cavities to compensate reactive beam loading.
  - Detuning is necessary in that it reduces required RF power.
  - But too large a detuning can lead to coupled bunch instabilities.

Generator current is in phase with voltage, delivering real power to cavity and beam.

Generator current 90 deg out of phase with voltage. Reactive power reflects back to generator.

$$I_g = \left[\frac{V}{2\,(R/Q)}\left(\frac{1}{Q_{ext}} + \frac{1}{Q_0}\right) + I_{b,DC}\,F_b sin(\phi)\right] + i\left[I_{b,DC}\,F_b\,cos(\phi) - \frac{V\Delta\omega}{\omega(R/Q)}\right]$$

Can make this term zero by choice of detuning.

$$\frac{\Delta\omega_{opt}}{\omega} = \frac{I_{b,DC}\,F_b\,cos(\phi)(R/Q)}{V}$$

ESR 591 MHz Parameters and Detuning

Parameter	Units	18 GeV	10 GeV	5 GeV
# Cavities		17	17	17
V_{sync}	MV	37	3.75	1.17
V_{total}	MV	61.5	21.6	9.8
ϕ_s	Deg	142.9	170.0	173.1
Bucket Height	1E-3 rms	10	10	10
I_{beam}	A	0.227	2.50	2.50
P_{beam}	MW	8.4	9.4	2.9
Detuning	kHz	-1.1	-42.4	-94.2

- Note that in the next parameter table, the 5 GeV detuning is even larger.
- Due to reduction in required bucket height from 1E-2 to 5E-3.
- This leads to a reduction in required voltage and ϕ_s.

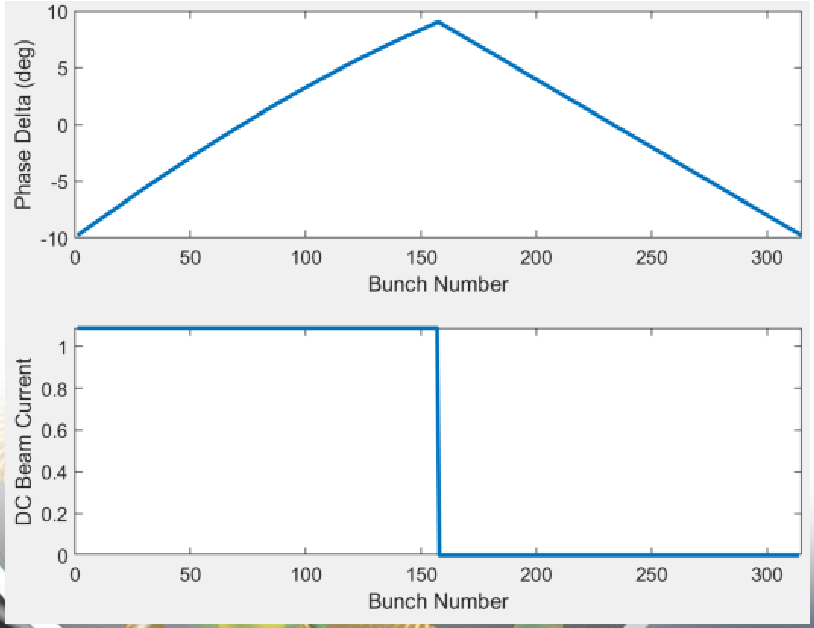
$$\frac{\Delta\omega_{opt}}{\omega} = \frac{I_{b,DC}\, F_b \cos(\phi)(R/Q)}{V}$$

HSR 24.5 MHz Cavity Transient Beam Loading

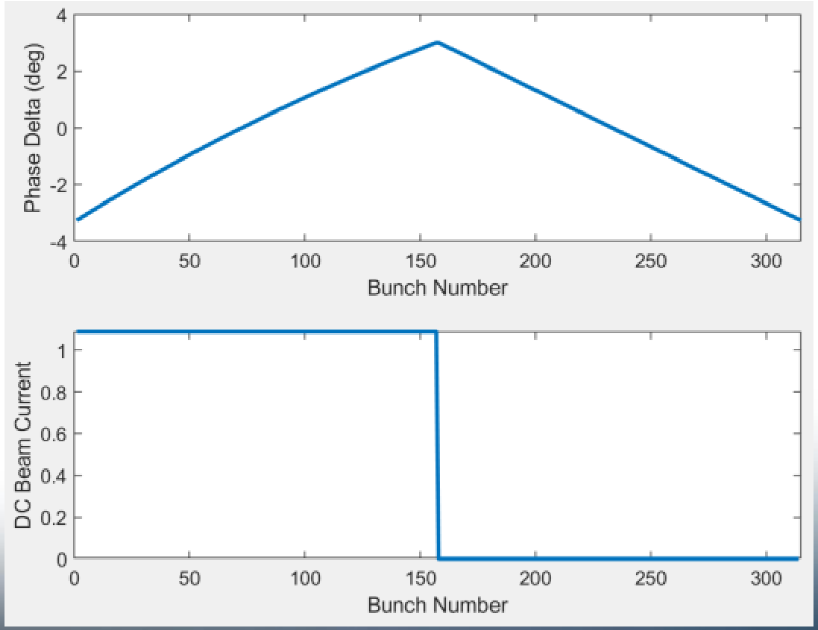
- Add in the presence of a partially filled ring, and transient beam loading becomes an added challenge.
  - Transient beam loading leads to a progressive phase (time) shift in bunches along the turn, leading e.g. to bunch by bunch crabbing errors, collision point shifts.

Half filled ring (worst case TBL for RF, store/collision is milder with just a 1us abort gap but that matters to collision timing), 24.6 MHz, h = 315

V_{cav} = 100 kV, $d\phi$ = 18.8°



V_{cav} = 300 kV, $d\phi$ = 6.3°



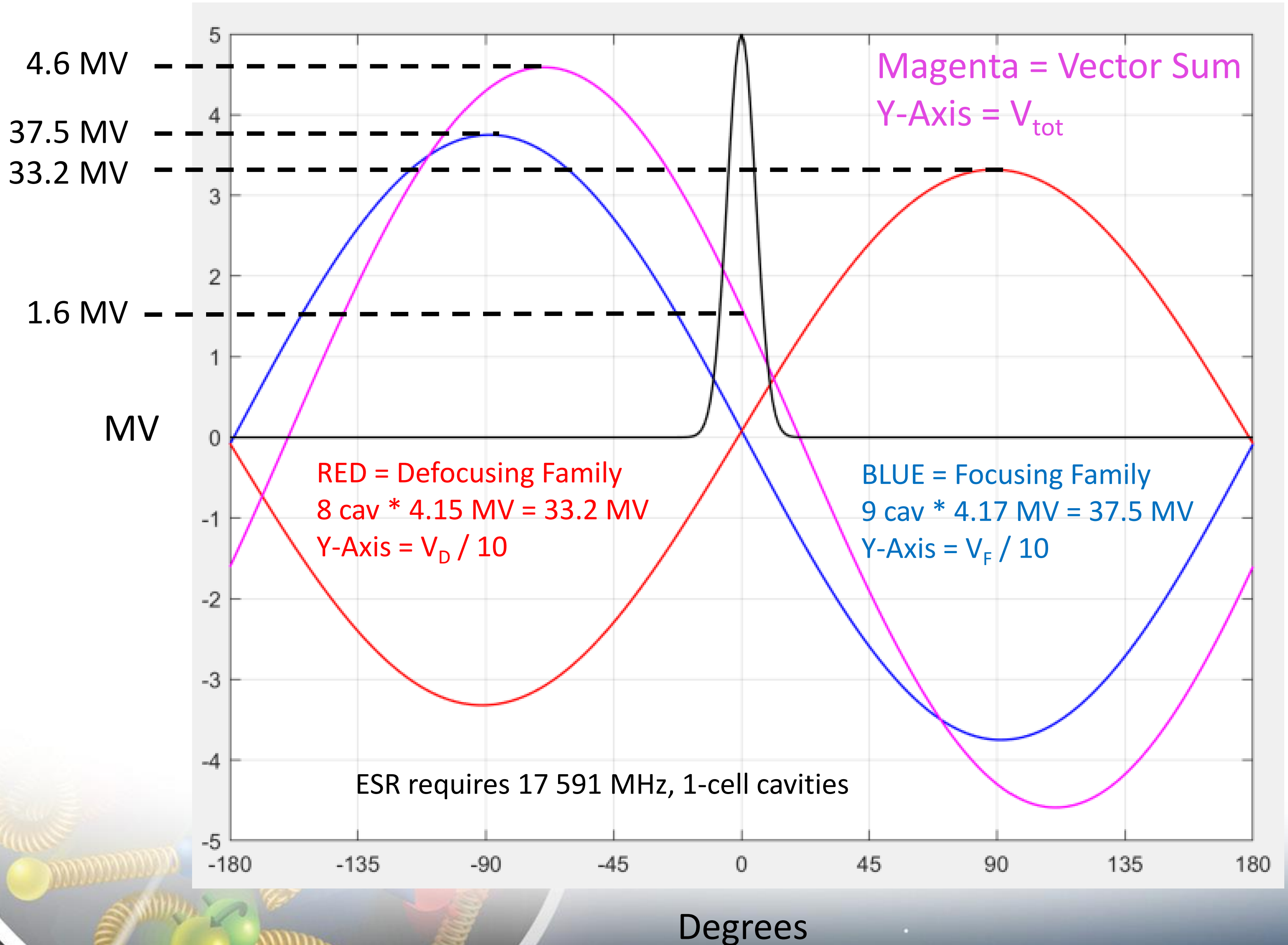
ESR TBL and Detuning Mitigation

- A possible mitigation is to operate cavities at as high a voltage as practical, which minimizes required detuning and transient beam loading.

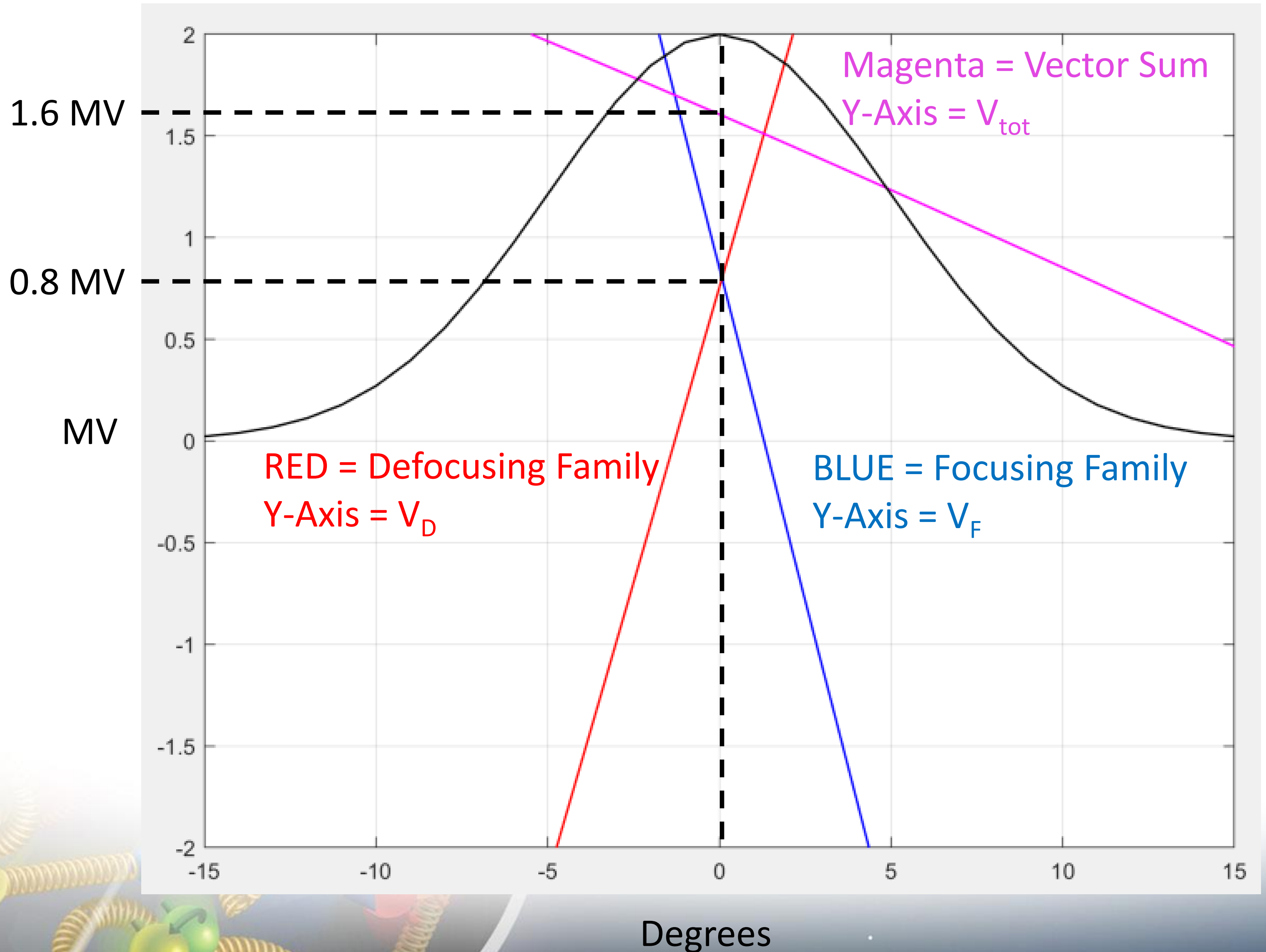
- But operating with high voltage in a conventional "all cavities in phase" mode results in short bunches and high synchrotron tunes – neither of which are desirable.

- Possible alternative – operate individual cavities as high in voltage as practical, but use a "Reverse Phasing" (KEK) technique so that:
  - Beam sees a vector sum which is the minimum voltage needed to provide required beam power and bucket height.
    - Maximum bunch length and minimum synchrotron tune
  - All cavities provide the same real power to the beam.
    - All cavity power couplers share the power load equally.

What Does Reverse Phasing Look Like?



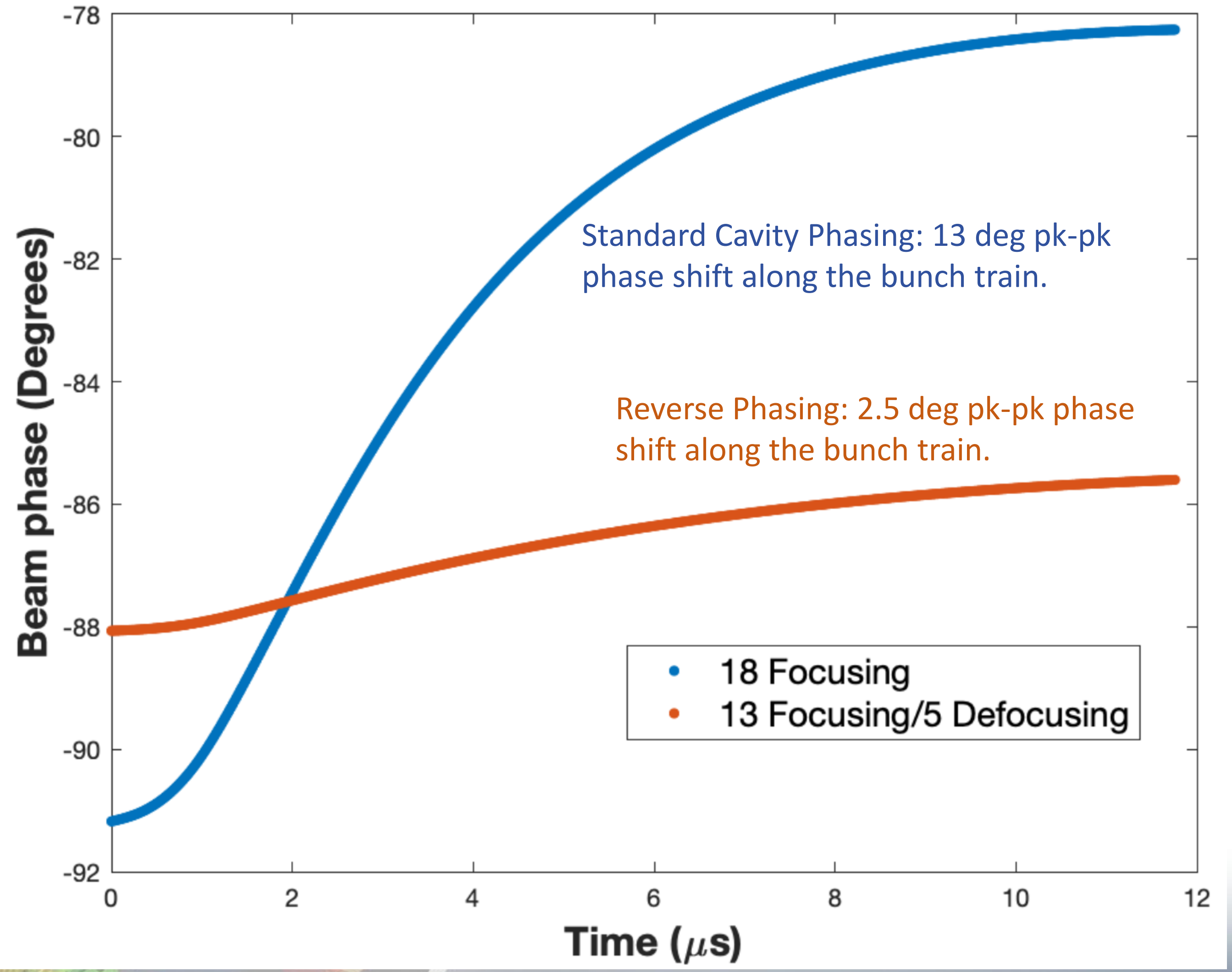
What Does Reverse Phasing Look Like? (Zoom)



18 GeV and 5 GeV Detuning (Std and RP)

Parameter	Units	18 GeV (Std)	5 GeV (Std)	5 GeV (RP)
I_{beam}	A	0.227	2.50	2.50
P_{beam}	MW	10.0	4.42	4.42
Bucket Height	1E-3 rms	10.8	5.5	5.5
# Cavities (F)		17	17	9
V_{sync}	MV	37	1.55	0.82
V_{total} [V_{cav}]	MV	64.5 [3.70]	4.6 [0.27]	37.5 [4.17]
ϕ_s	Deg	144.9	160.3	178.7
P_{beam}	MW	10.0	4.42	2.34
Detuning	kHz	-1.3	-216.0	-14.9
# Cavities (D)		0	0	8
V_{sync}	MV			0.73
V_{total} [V_{cav}]	MV			33.2 [4.15]
ϕ_s	Deg			1.3
P_{beam}	MW			2.08
Detuning	kHz			+15.0

ESR 10 GeV Transient Beam Loading (Std and RP)



T. Mastoridis

Summary

- Reverse Phasing Operation
  - Developed and demonstrated at KEK but not used operationally.
  - Proposed for RF systems in the EIC ESR to ameliorate transient beam loading and required detuning.
  - 18 GeV vs 5 GeV standard phasing shows the extreme range of parameters we'll be dealing with.
  - 5 GeV standard phasing (std) vs 5 GeV reverse phasing (RP) shows potential benefit of reverse phasing.
  - Not a formal proposal yet, but we will likely want to experiment with the RHIC RF system to verify operational aspects and look for unanticipated behaviors.