Parameters of EIC eSR for 9F5D in 10GeV and 10F4D in 18GeV

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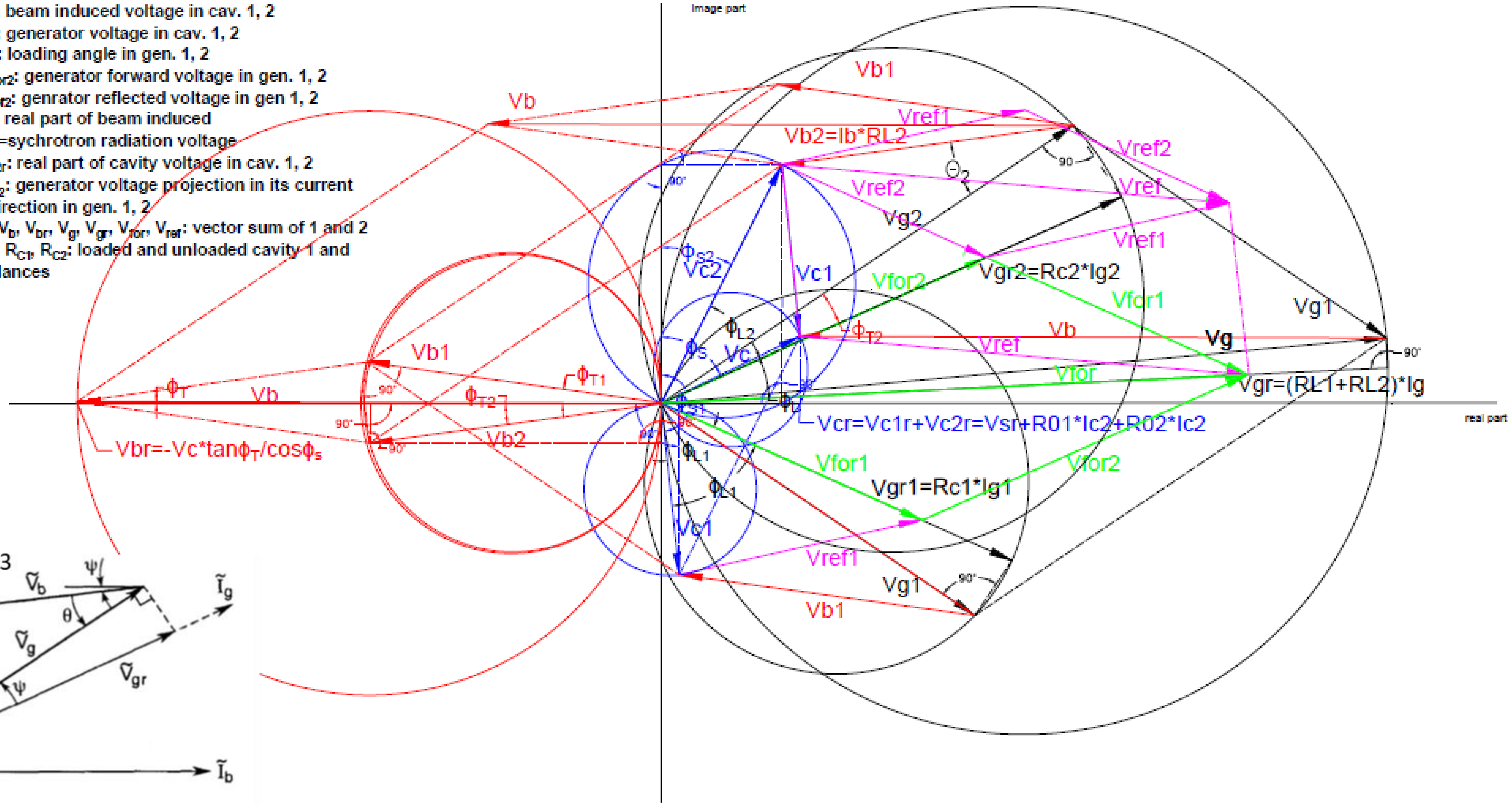
MathCAD analytical model

Includes:

- Robinson instability boundary
- Direct feedback with gain and latency delay
- Overhead klystron power requirement for static and a predicted transient beam loading
- Optimization for R/Q, Qext, detuning angle for minimization of klystron power
- Based on the beam dynamic requirement on the RF voltage bucket height, equilibrium beam bunch length and energy spread, steady state working point can be optimized
- Add the vector sum model based on P. B Wilson phasor diagram to simulate the RPO mode
- No broadband feedback, no feedforward model yet, but DF feedback circuit stability checks
- No particle tracking simulation

Reversed Phase Operation (RPO) Represented by P. Wilson Vector Sum Diagram

V_{c1}, V_{c2}: cavity voltage in cav. 1, 2
$\phi_{s1}=\phi_{s2}$: synchronous phase in Cav 1,2
ϕ_{T1}, ϕ_{T2}: tuning angle in cav. 1, 2
V_{b1}, V_{b2}: beam induced voltage in cav. 1, 2
V_{g1}, V_{g2}: generator voltage in cav. 1, 2
ϕ_{L1}, ϕ_{L2}: loading angle in gen. 1, 2
V_{for1}, V_{for2}: generator forward voltage in gen. 1, 2
V_{ref1}, V_{ref2}: genrator reflected voltage in gen 1, 2
$V_{br}=V_{sr}$: real part of beam induced voltage=sychrotron radiation voltage
V_{c1r}, V_{c2r}: real part of cavity voltage in cav. 1, 2
V_{gr1}, V_{gr2}: generator voltage projection in its current I_{g1}, I_{g2} direction in gen. 1, 2
V_c, V_{cr}, V_b, V_{br}, V_g, V_{gr}, V_{for}, V_{ref}: vector sum of 1 and 2
R_{L1}, R_{L2}, R_{C1}, R_{C2}: loaded and unloaded cavity 1 and 2 impedances



P. B. Wilson phasor diagram 1993
ϕ: synchronous phase
ψ: detune angle
$\phi_L=\phi-\theta$: loading angle

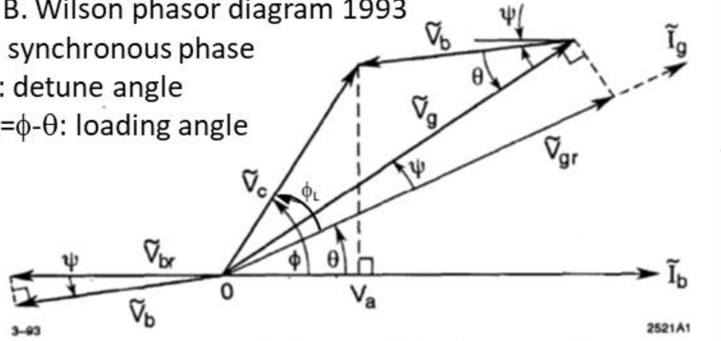


Figure 4.1.1. Diagram showing vector addition of generator and beam loading voltages in an RF cavity.

Heifets/Teytelman Model with Direct Feedback

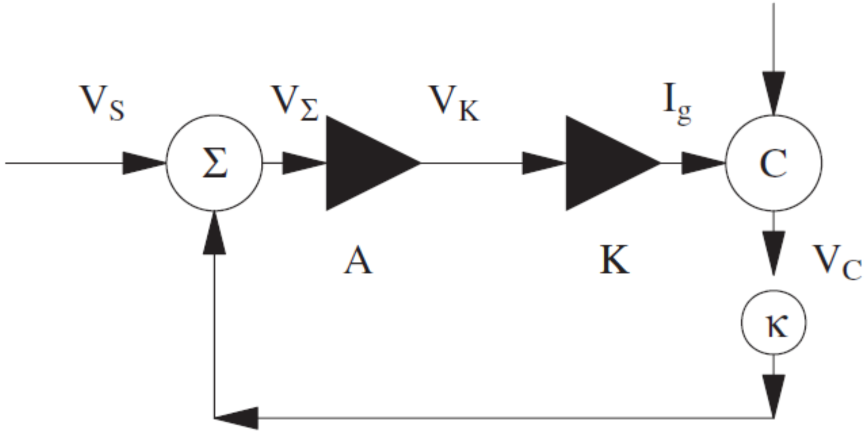
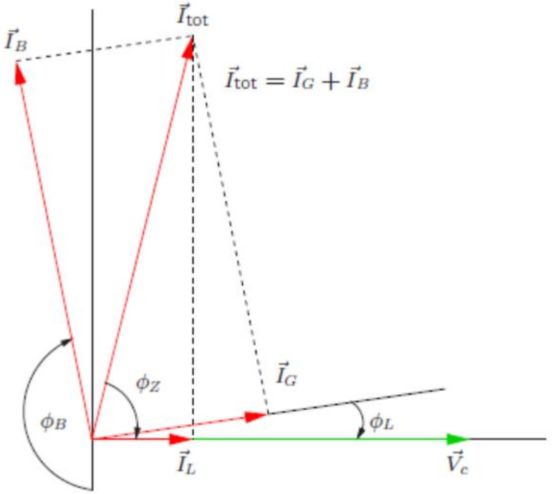
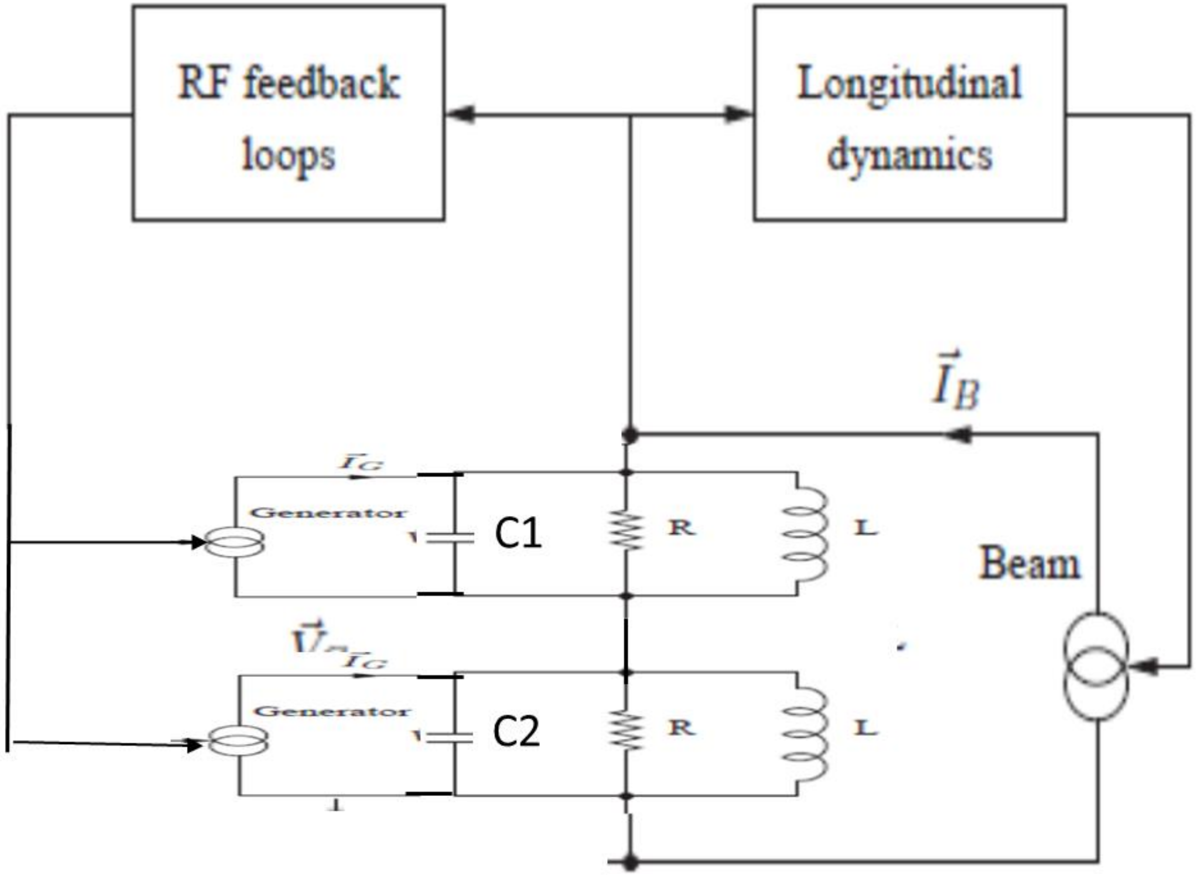


FIG. 1. Schematic of the longitudinal rf FB system.



Equivalent circuit modification for vector sum (RPO)



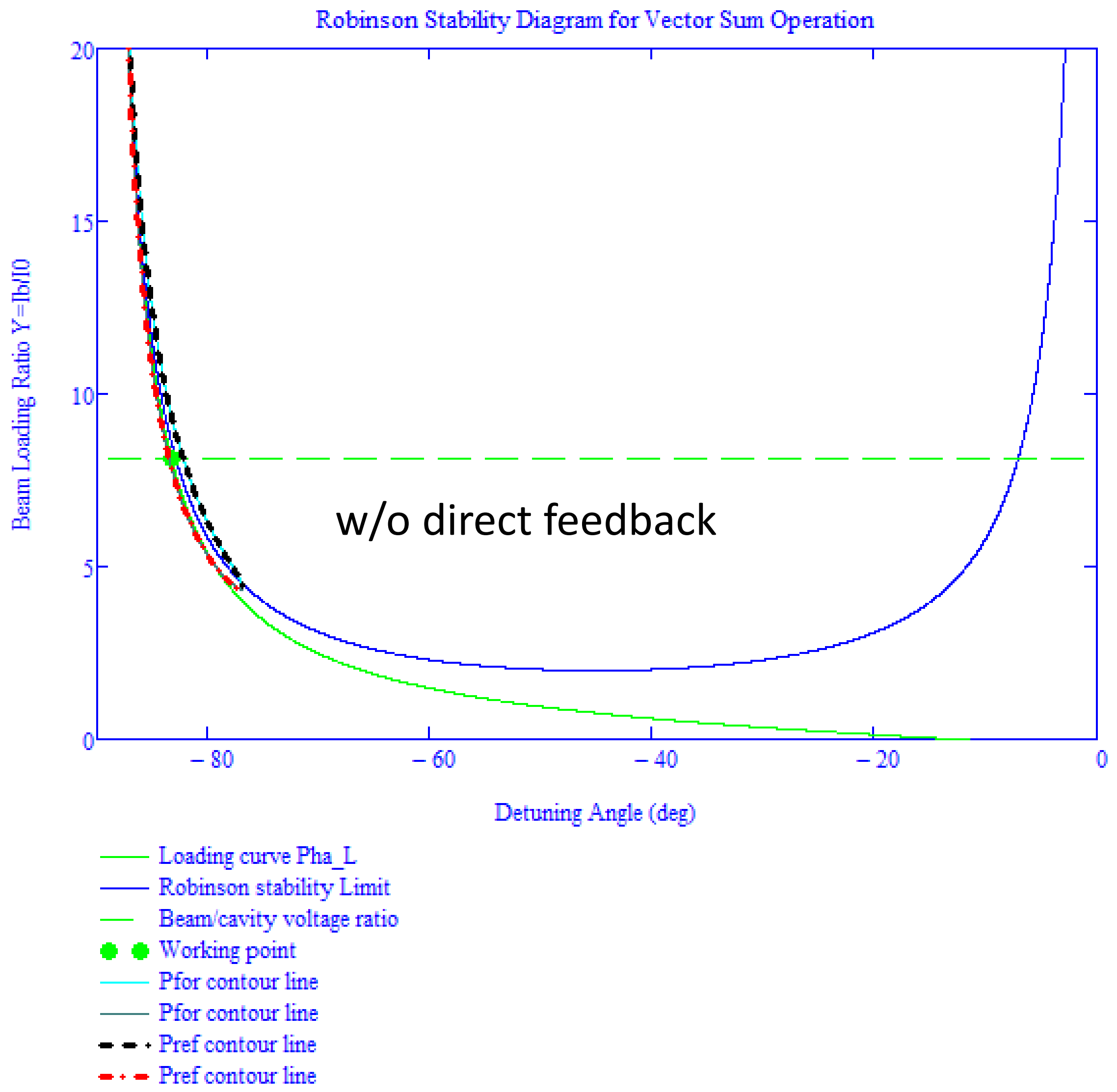
First feedback:

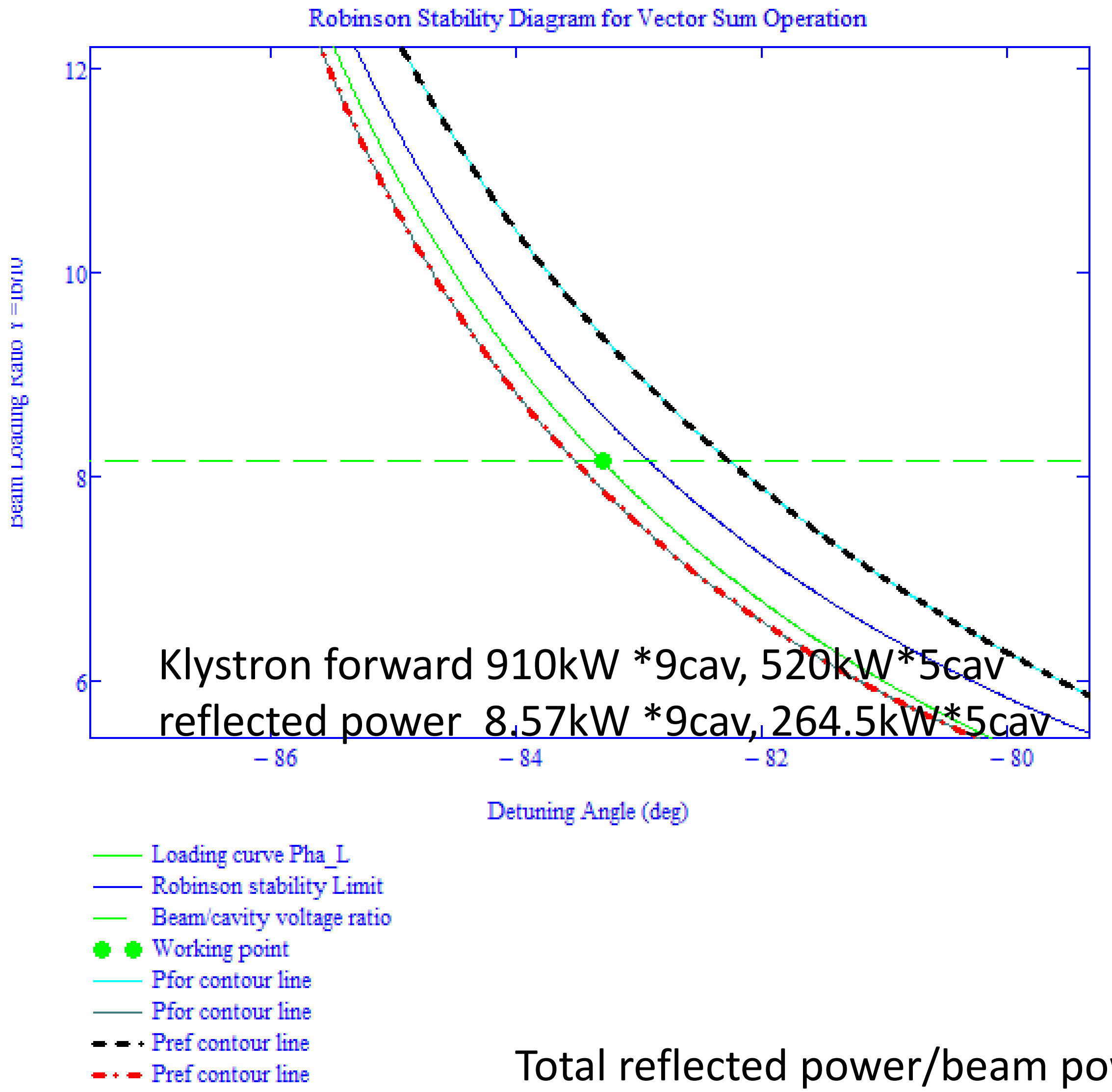
- Implement tracking code with Direct Feedback model with variables of gain H and delay τ_d for the direct feedback control
- Current working point with parameter set provided without a gap is too close to the Robinson instability line. Only feedback gain can bring the working point further away from this instability. The cost is needing more klystron power to control the gap or any other transient
- An comparable data set calculated by the MathCAD analytics has been given for the benchmark/cross-check
- Robinson and Peterson stability diagrams with constant klystron power contour lines have been given for inspection
- Suggestions for next iteration and optimization

1. Increase the reversed phased cavity number (can be as many as forward phased cavity number to reduce effective R/Q), but also increase the forward phased cavity voltage
2. Try to bring the synchronous phase more toward to the crest, so more real part of voltage is available to compensate the synchrotron radiation loss and less imaginary part of voltage for bunch compression, but the vector sum of the cavity voltage is high enough to keep the RF bucket height for injection beam capture
3. The net cavity detuning should be adjusted toward to the forward phased direction. The vector sum of the cavity voltage can be optimized to just have an enough imaginary voltage to overcome the beam induced voltage in the opposite direction which is responsible for the beam loading transient and bunch over-compression
4. By using reverse phased cavities, If the bunch length is not too short and the energy spread is good enough for the Landau damping, we might not need the third harmonic cavities for the bunch lengthening
5. Adjusting the feedback gain H to let the Klystron loading angle nearly zero is the way to save klystron power
6. Vector sum model has been developed for this optimization
7. Need particle tracking and Simulink combined modeling to benchmark this steady state analytics.

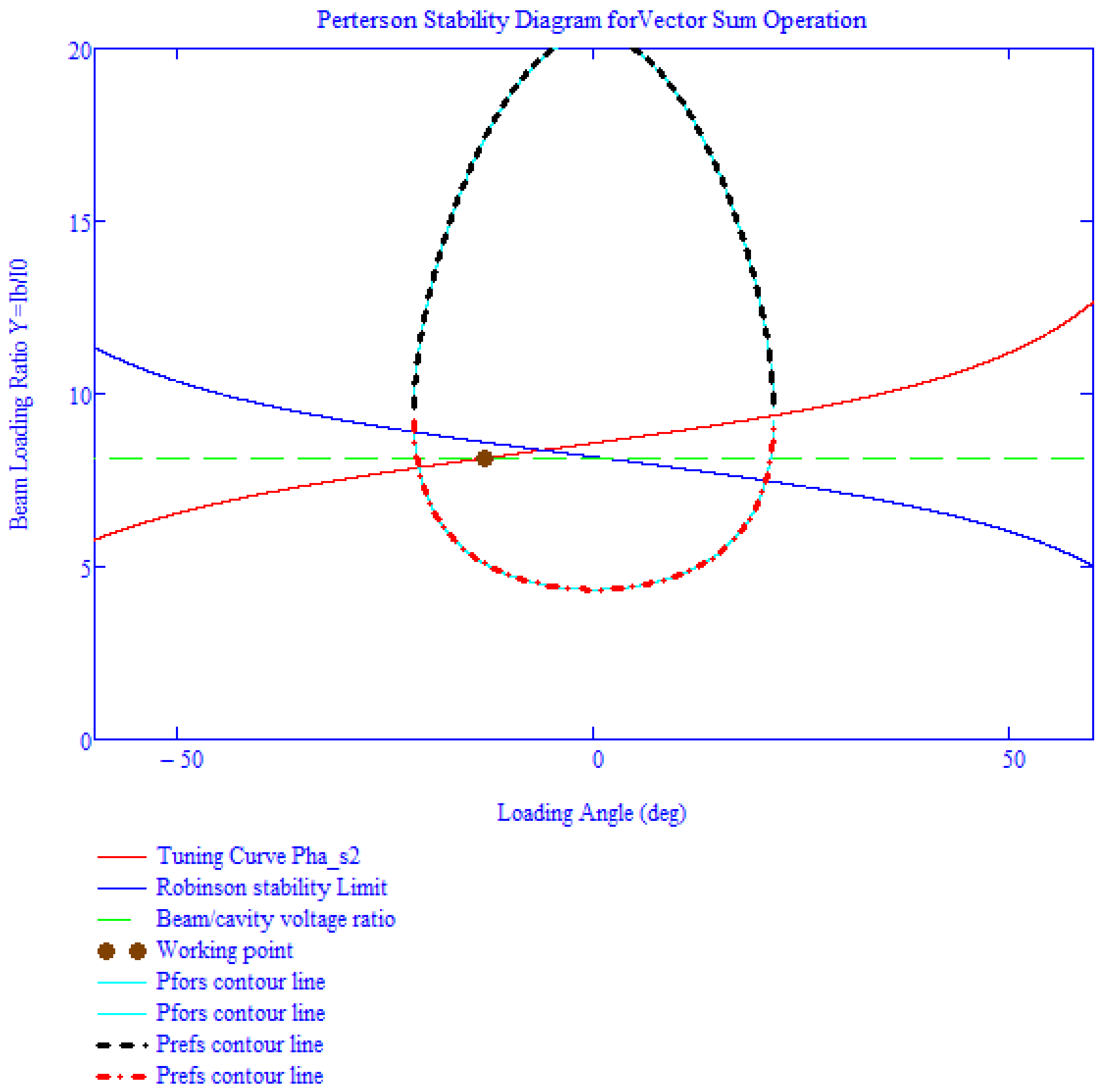
Beam Parameter	V1	Unit	MathCAD Value	RF Parameter		Unit	MathCAD Value
eRHIC circumference	CF	m	3833.844719	synchronous phase F/D	ϕ_s	deg	173.9 / 6.1
revolution frequency	f_r	kHz	78.196296	generator frequency	f_{rf}	MHz	591.164
beam energy	E	GeV	10	Cavity numbers F/D	n_0 / n_1		9 / 5
average current	I_b	A	2.5	2-cell cavity R/Q	R/Q	Ohm	2*74
number of bunches	h_b		630	cavity voltage, F/D	V_f / V_d	MV	3.4 / 0.51
gap	g		50	Vector sum voltage	V_{vs}	MV	28.11
gap transient max+-	$\Delta\phi_{max}$	deg	7.437	VS klystron load angles	$\phi_{L1,2,S}$	deg	0, 0, 0.48
momentum compaction	η		1.301e-3	F cavity detune	Δf_{res0}	kHz	-1.251
transition gamma	γ_T		27.73	D cavity detune	Δf_{res1}	kHz	19.49
rms energy spread	ε_e		5.4e-4	Equi. F loading angle	Φ_{Le1}	deg	77.43
synchrotron frequency (no HHCs)	f_s	kHz	5.166	Equi. D Loading angle	Φ_{Le2}	deg	-82.29
Energy loss per turn	U_0	MeV	3.509	Vector sum loading angle	Φ_{Ls}	deg	-13.0
longitudinal radiation damping time	τ_d	ms	36.33	cavity gradient F/D	E_{acc}	MV/m	6.704, 1.006
natural rms bunch length	σ_z	mm	6.487	Cavity Q_{ext}, F/D	Q_{ext}		8.6e4, 8.6e4
RF bucket height +-ΔE/E	RFBH	%	1.21	klystron forward power F/D	P_{fors}	kW	910*9 / 520*5
total beam power	P_{rad}	MW	8.772	klystron reflected power F/D	P_{refs}	kW	6.755*9 / 135.5*5
total synchronous voltage	V_{sr}	MV	3.523	direct feedback gain F/D	H_0/H_1		0 / 0
synchrotron tune (no HHCs)	ν_s		0.066	legacy group delay F/F		ns	320 / 320

Beam Parameter	V2	Unit	MathCAD Value	RF Parameter		Unit	MathCAD Value
eRHIC circumference	CF	m	3833.844719	synchronous phase F/D	ϕ_s	deg	173.9 / 6.1
revolution frequency	f_r	kHz	78.196296	generator frequency	f_{rf}	MHz	591.164
beam energy	E	GeV	10	Cavity numbers F/D	n_0 / n_1		9 / 5
average current	I_b	A	2.5	2-cell cavity R/Q	R/Q	Ohm	2*74
number of bunches	h_b		630	cavity voltage, F/D	V_f / V_d	MV	3.44/ 0.43
gap	g		50	Vector sum voltage	V_{vs}	MV	28.86
gap transient max+-	$\Delta\phi_{max}$	deg	7.597	VS klystron load angles	$\phi_{L1,2,S}$	deg	76.433, 81.135, -13.322
momentum compaction	η		1.301e-3	F cavity detune	Δf_{res0}	kHz	-1.251
transition gamma	γ_T		27.73	D cavity detune	Δf_{res1}	kHz	30.17
rms energy spread	ε_e		5.4e-4	Equi. F loading angle	Φ_{Le1}	deg	77.348
synchrotron frequency (no HHCs)	f_s	kHz	5.236	Equi. D Loading angle	Φ_{Le2}	deg	-82.212
Energy loss per turn	U_0	MeV	3.518	Vector sum loading angle	Φ_{Ls}	deg	-13.322
longitudinal radiation damping time	τ_d	ms	36.33	cavity gradient F/D	E_{acc}	MV/m	6.783, 0.848
natural rms bunch length	σ_z	mm	6.401	Cavity Q_{ext}, F/D	Q_{ext}		8.6e4, 8.6e4
RF bucket height +-ΔE/E	RFBH	%	1.23	klystron forward power F/D	P_{fors}	kW	910*9 / 520*5
total beam power	P_{rad}	MW	8.7	klystron reflected power F/D	P_{refs}	kW	3.871*9 / 405.8*5
VS synchronous angle	ϕ_s	deg	173.578	direct feedback gain F/D	H_0/H_1		0 / 0
synchrotron tune (no HHCs)	ν_s		0.066	legacy group delay F/F		ns	320 / 320

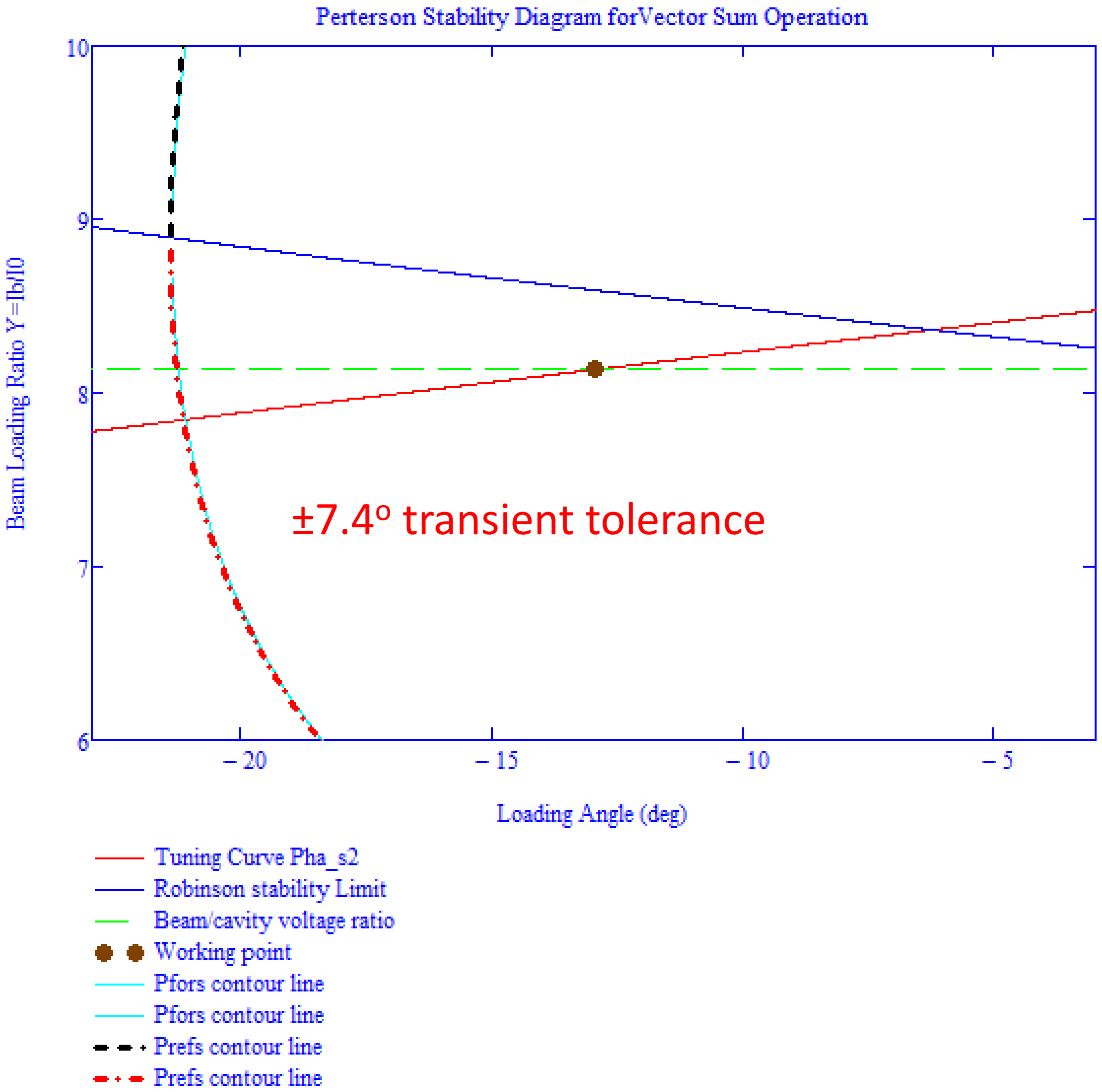




Total reflected power/beam power =15.71%



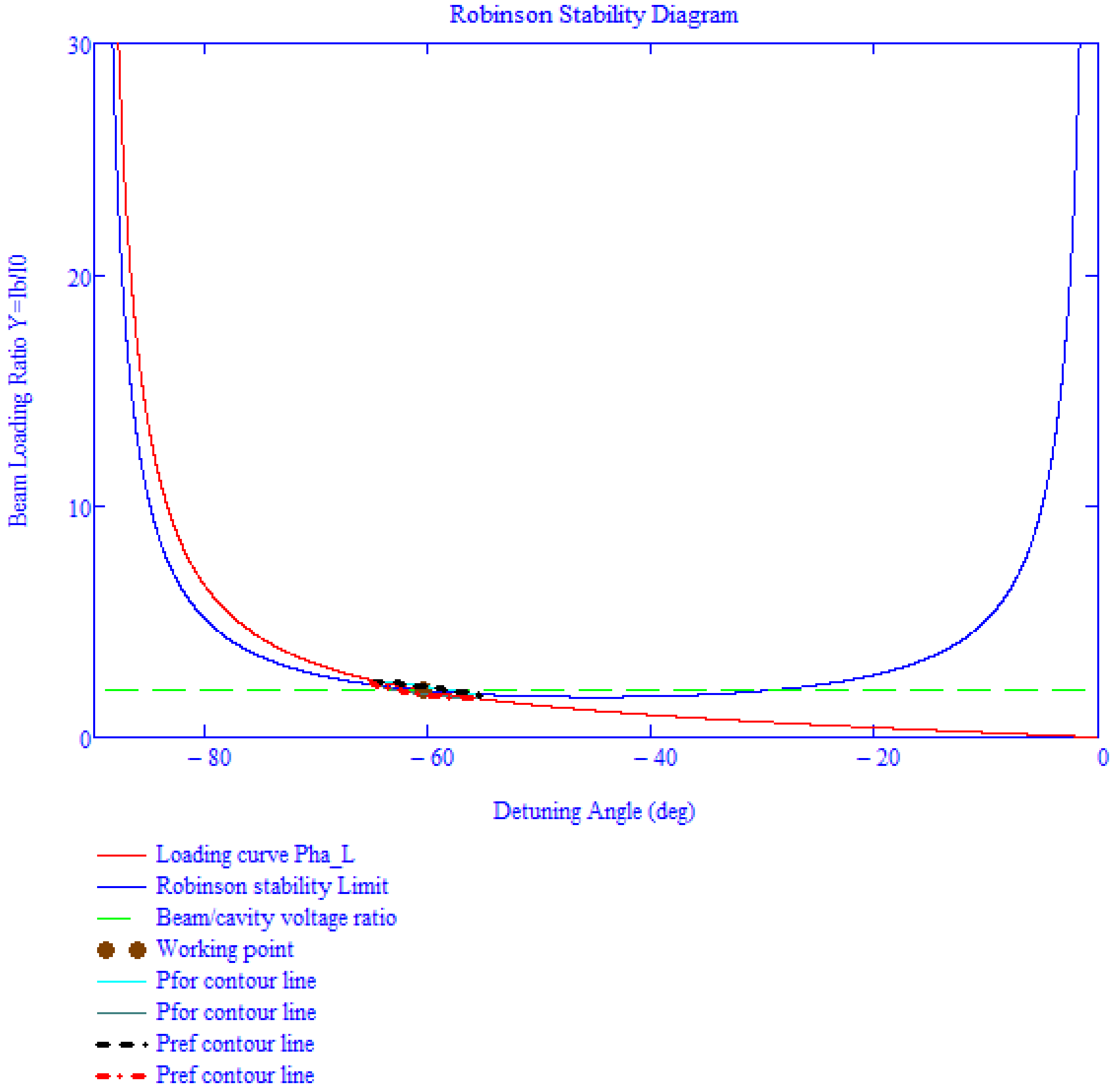
Perterson Stability Diagram forVector Sum Operation
Beam Loading Ratio Y=Ib/I0
Loading Angle (deg)
20
15
10
5
0
− 50
0
50
Tuning Curve Pha_s2
Robinson stability Limit
Beam/cavity voltage ratio
Working point
Pfors contour line
Pfors contour line
Prefs contour line
Prefs contour line

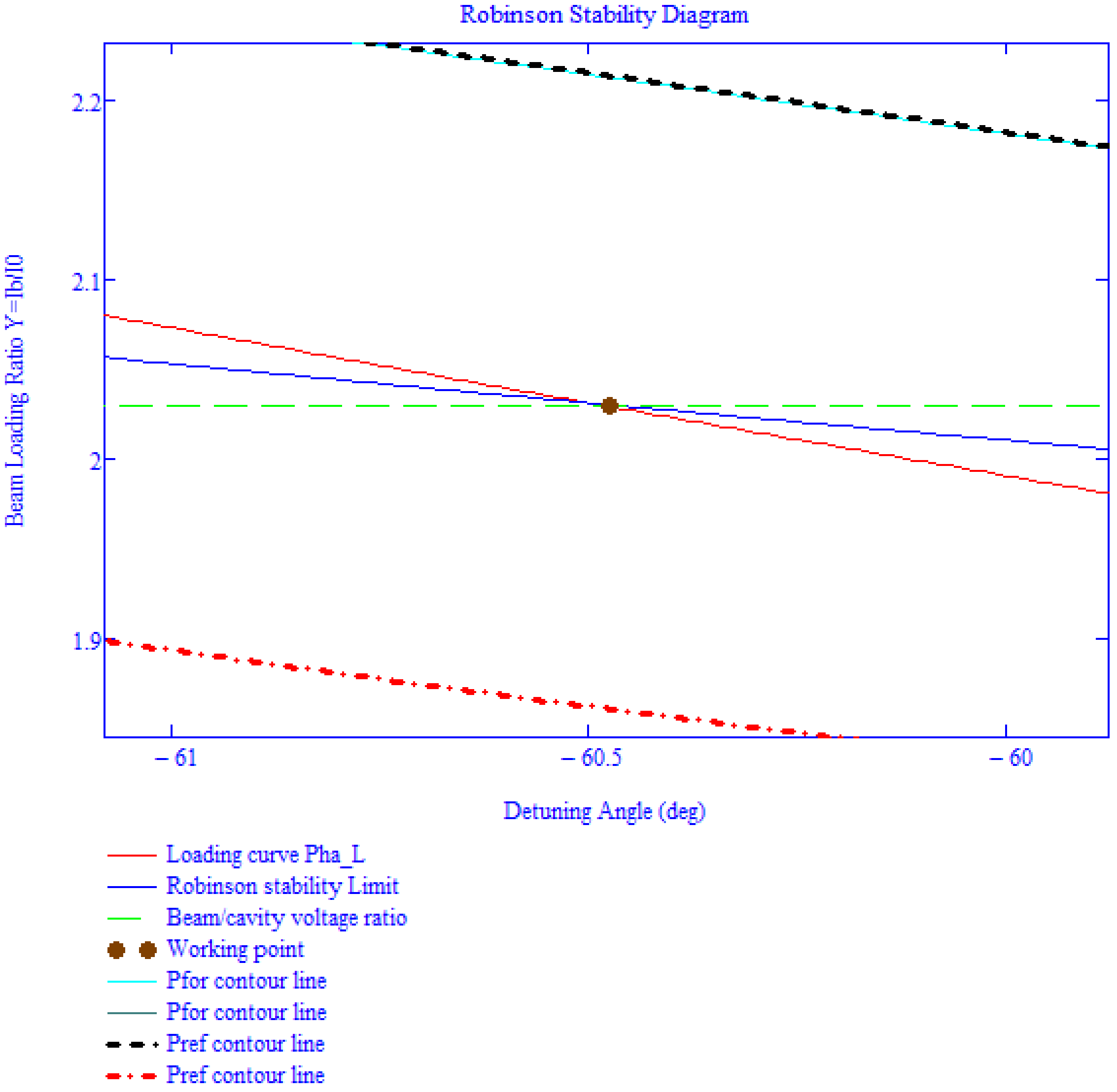


Perterson Stability Diagram forVector Sum Operation
Beam Loading Ratio Y=Ib/I0
Loading Angle (deg)
10
9
8
7
6
− 20
− 15
− 10
− 5
±7.4° transient tolerance
Tuning Curve Pha_s2
Robinson stability Limit
Beam/cavity voltage ratio
Working point
Pfors contour line
Pfors contour line
Prefs contour line
Prefs contour line

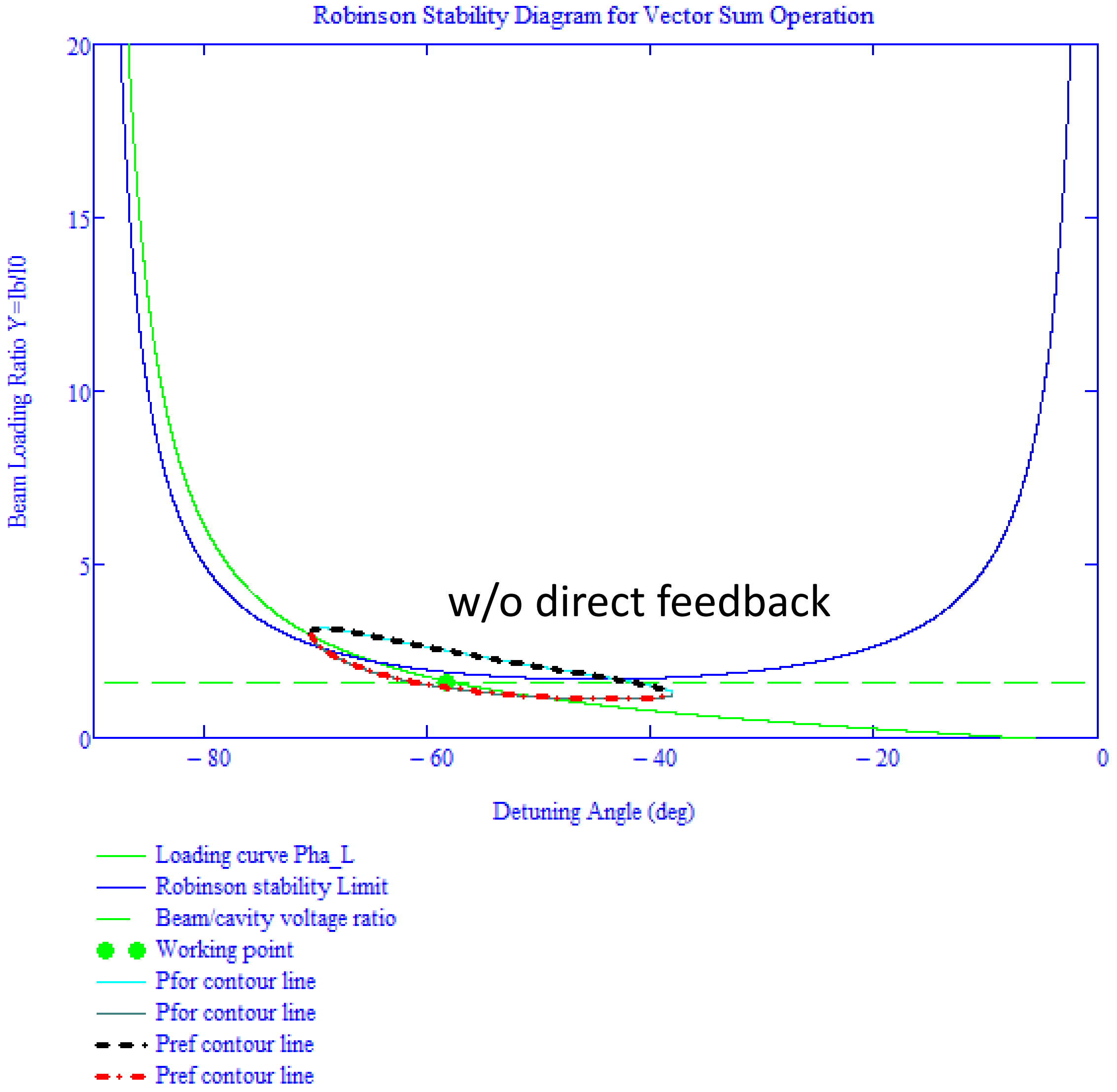
Beam Parameter	V1	Unit	MathCAD Value	RF Parameter	V1	Unit	MathCAD Value
eRHIC circumference	CF	m	3833.844719	synchronous phase F/D	ϕ_s	deg	150.5 / 29.5
revolution frequency	f_r	kHz	78.196296	generator frequency	f_{rf}	MHz	591.164
beam energy	E	GeV	18	Cavity numbers F/D	n_0 / n_1		10 / 4
average current	I_b	A	0.27	2-cell cavity R/Q	R/Q	Ohm	2*74
number of bunches	h_b		290	cavity voltage, F/D	V_f / V_d	MV	7.09 / 0.424
gap	g		58	Vector sum voltage	V_{vs}	MV	68.06
gap transient max+-	$\Delta\phi_{max}$	deg	4.95	VS klystron load angles O/C	$\phi_{LO,C}$	deg	-8.108, -7.145
momentum compaction	η		6.716e-4	F cavity detune	Δf_{res0}	kHz	-0.1154
transition gamma	γ_T		38.586	D cavity detune	Δf_{res1}	kHz	4.061
rms energy spread	ε_e		9.72e-4	Equi. F loading angle	Φ_{Le1}	deg	39.11
synchrotron frequency (no HHCs)	f_s	kHz	3.991	Equi. D Loading angle	Φ_{Le2}	deg	-38.99
Energy loss per turn	U_0	MeV	37.00	VS close loop loading angle F/D	$\Phi_{LS1,2}$	deg	39.112, -38.987
longitudinal radiation damping time	τ_d	ms	6.229	cavity gradient F/D	E_{acc}	MV/m	13.98, 2.09
natural rms bunch length	σ_z	mm	7.805	Cavity Q_{ext}, F/D	Q_{ext}		3.6e5, 2.0e5
RF bucket height +-ΔE/E	RFBH	%	1.21	klystron forward power F/D	P_{fors}	kW	950*10 / 520*4
total beam power	P_{rad}	MW	9.99	klystron reflected power F/D	P_{refs}	kW	7.354*10 / 379.1*4
VS synchronous angle	ϕ_s	deg	147.472	direct feedback gain F/D	H_0/H_1		0 / 0
synchrotron tune (no HHCs)	ν_s		0.051	legacy group delay F/F		ns	320 / 320

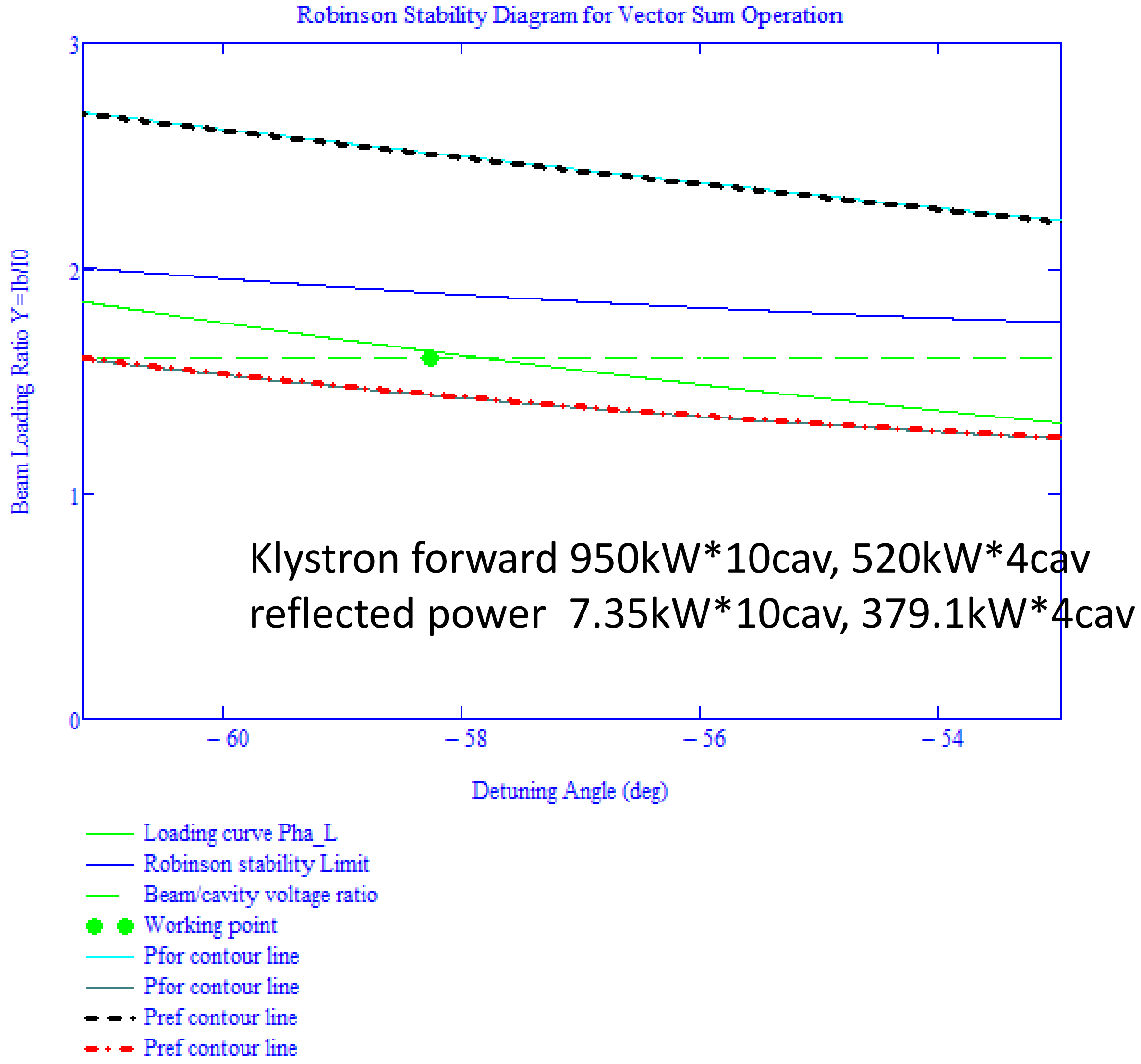
Beam Parameter	V2	Unit	MathCAD Value	RF Parameter	V2	Unit	MathCAD Value
eRHIC circumference	CF	m	3833.844719	synchronous phase F/D	ϕ_s	deg	150.5 / 29.5
revolution frequency	f_r	kHz	78.196296	generator frequency	f_{rf}	MHz	591.164
beam energy	E	GeV	18	Cavity numbers F/D	n_0 / n_1		10 / 4
average current	I_b	A	0.27	2-cell cavity R/Q	R/Q	Ohm	2*74
number of bunches	h_b		290	cavity voltage, F/D	V_f / V_d	MV	7.09 / 0.428
gap	g		58	Vector sum voltage	V_{vs}	MV	68.79
gap transient max+-	$\Delta\phi_{max}$	deg	4.914	VS klystron load angles O/C	$\phi_{LO,C}$	deg	-8.210, -7.253
momentum compaction	η		6.716e-4	F cavity detune	Δf_{res0}	kHz	-0.1154
transition gamma	γ_T		38.586	D cavity detune	Δf_{res1}	kHz	4.061
rms energy spread	ε_e		9.72e-4	Equi. F loading angle	Φ_{Le1}	deg	39.112
synchrotron frequency (no HHCs)	f_s	kHz	3.99	Equi. D Loading angle	Φ_{Le2}	deg	-38.74
Energy loss per turn	U_0	MeV	37.02	VS close loop loading angle F/D	$\Phi_{LS1,2}$	deg	39.112, -38.74
longitudinal radiation damping time	τ_d	ms	6.229	cavity gradient F/D	E_{acc}	MV/m	13.98, 2.09
natural rms bunch length	σ_z	mm	7.807	Cavity Q_{ext}, F/D	Q_{ext}		3.6e5, 2.0e5
RF bucket height +-ΔE/E	RFBH	%	1.21	klystron forward power F/D	P_{fors}	kW	950*10 / 520*4
total beam power	P_{rad}	MW	9.996	klystron reflected power F/D	P_{refs}	kW	7.354*10 / 377.7*4
VS synchronous angle	ϕ_s	deg	147.443	direct feedback gain F/D	H_0/H_1		0 / 0
synchrotron tune (no HHCs)	ν_s		0.051	legacy group delay F/F		ns	320 / 320



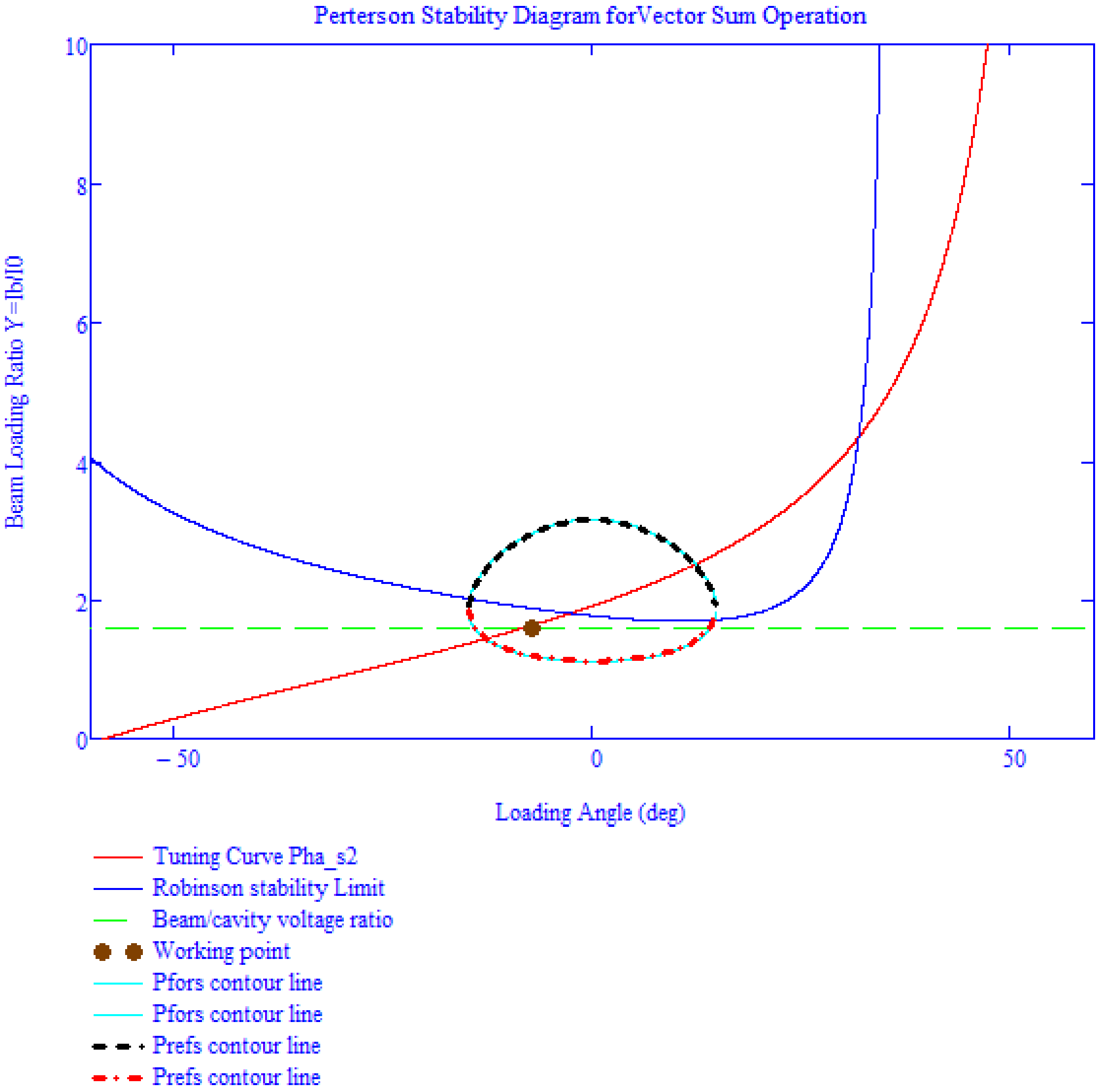


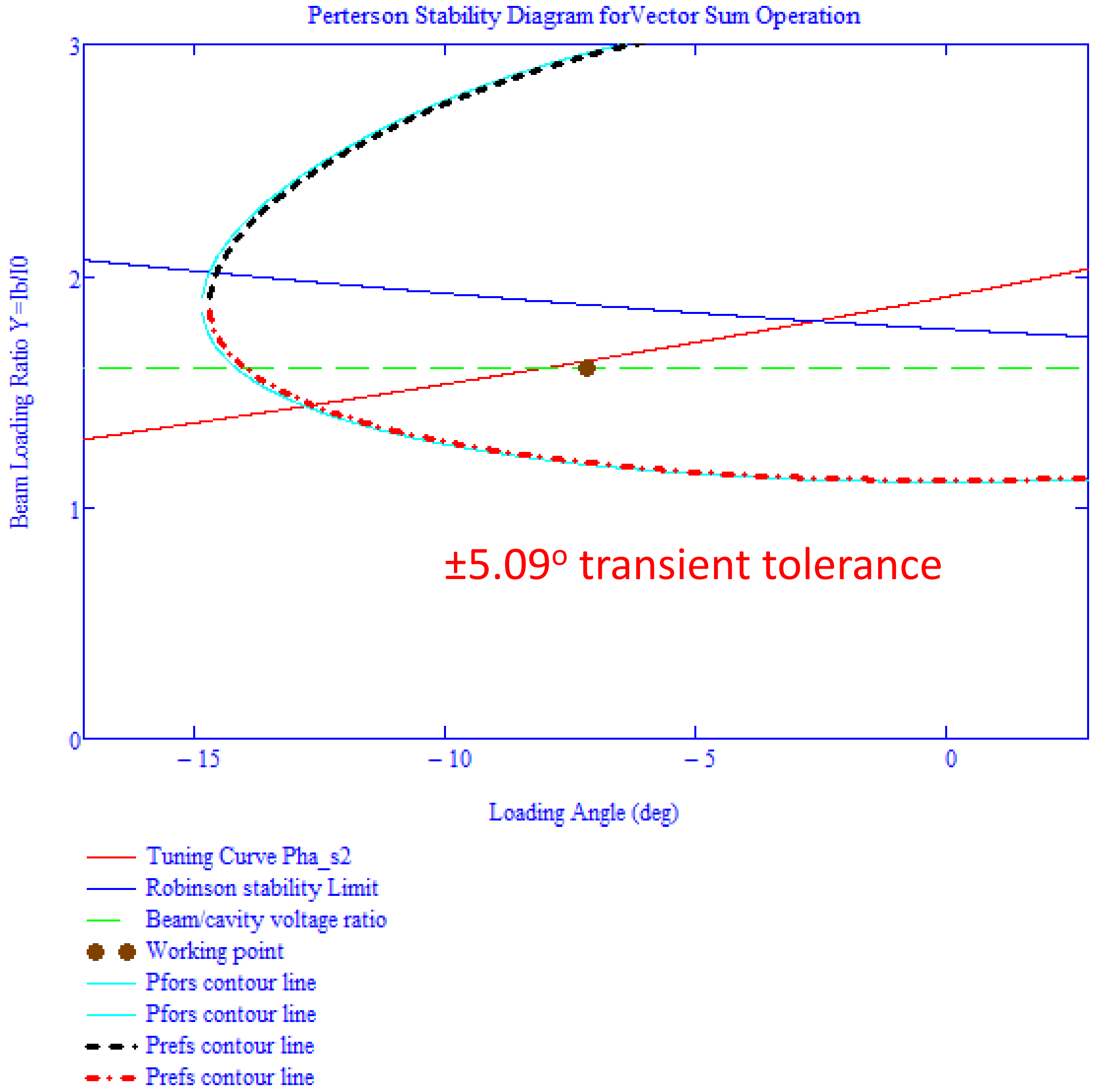
Individual phased cavity could be unstable if the working point is fighting the transient along





Combined phase cavities could be stable if detuned frequencies, Qexts and Feedbacks are optimium matched





Combined phase cavities could fight the transient too if detuned frequencies, Qexts and Feedbacks are optimized

Robinson Stability check for Vector Sum model:

$dV_{vs}/d\phi_s<0$ check:

$$\frac{-y_{s2}\cdot\cos(\Psi_{s2})\cos(\Psi_{s2}+\phi_s)}{1+y_{s2}\cdot\cos(\Psi_{s2})\cdot\sin(\Psi_{s2}+\phi_s)} = -4.295\times 10^{-3}$$

equation on left is propotional to $dV_{vs}/d\phi_s$, proposed by P. B. Wilson in 1993 [2].

So P. Wilson stability condition is satisfied

V_{vs}: Vector sum of cavity voltage
ϕ_s: Vector sum of synchronous phase
ψ_{s2}: Vector sum of tuning angle in DF close loop if any
Y_{s2}: beam loading factor in vector sum in DF close loop if any

Tuning sensitivity requirement for the beam stability

Beam stability

Vector sum amplitude control

phase stability requirement

$$\boxed{\frac{2(1+sin^2\emptyset_T)}{sin(2\emptyset_T)}\Delta\emptyset_T \le \frac{\Delta I_b}{I_b} - \frac{\Delta V_f + \Delta V_d}{V_{c\Sigma}} - \tan(\phi_s)\Delta\phi_s}$$

$\emptyset_T$: cavity vector sum tuning angle

$V_{c\Sigma}$: vector sum cavity voltage

V_f , V_d: focus, defocus cavity voltage

I_b: average beam current

ϕ_s: synchronous phase angle

$\emptyset_s \neq 90^0$ or very large ⟶ Unstable, zero bucket height

$nears$ 0 or 180^o $is\ easier\ to\ be\ controlled$

$\emptyset_T \neq 0\ or\ 90^0$ ⟶ Unstable or Infinite klystron power?

$\emptyset_T = 45^0$ ⟶ optimum

Initial conclusion:

- The MathCAD analytics using Vector Sum method has been developed for the RPO mode analysis
- Parameter sets of 9F5D at 10GeV and 10F4Dat 18GeV have been optimized for a fixed RF bucket height, minimum gap transient and, minimum RF power without a direct feedback loop
- Initial steady state analysis has indicated that a very promised RPO mode could ease the RF transient beam loading problem without Robinson instability problem, but tuning and phase control remain challenges
- The detuned frequencies, external Qs (feedback gains) on both forward and reversed phase cavities need to be carefully optimized in order to keep the vector sum of the working point in a stable region
- Either in forward phase only or reversed phase only cavity, when the working point is not stable, but combined phase operation could be stable. Optimization have to take care of both stability and tuning sensitivity in order to minimize the klystron power
- With an optimized parameter set, we need 14 SRF cavities installed, klystron power provided to each forward and revised phase cavity could be 950kW each. In 18GeV operation, klystrons operate at 950kW*10 (F), 520kW*4 (D), in ~13% of power saving comparing all in forward phase case. In 10GeV operation, klystron power drops from 910kW*9 (F), 520kW*5 (D) in ~19% of power saving. The RPO can be used as the transient phase tolerance control
- Due to the F/D mode operation, the electron bunch length at some energy in storage could be optimized without using 3rd harmonic cavities for Landau damping and bunch lengthening??
- Need further particle tracking and Simulink combined simulation to confirm these applausble results

References

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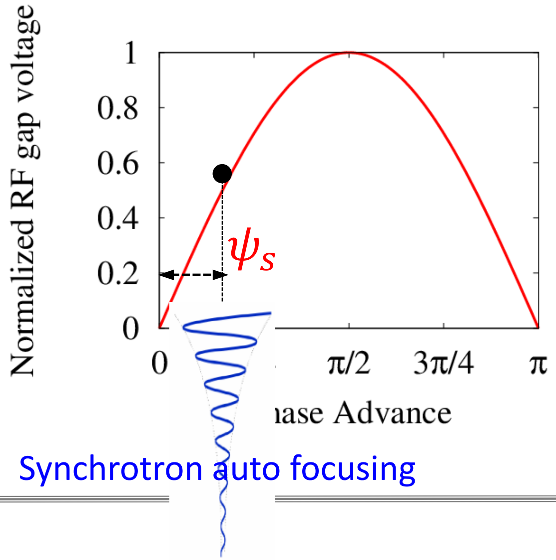
Different Definitions of Synchronous Phase

Below transition



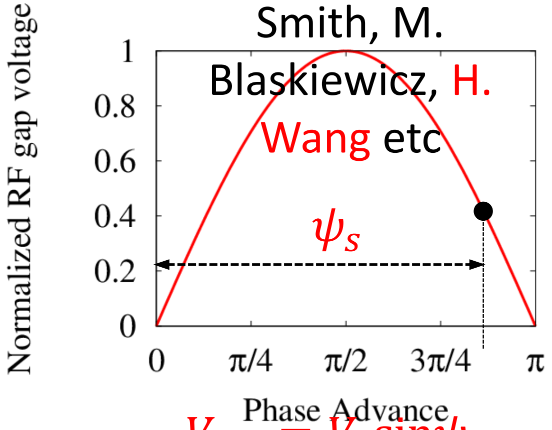
Synchrotron auto focusing

SY Lee, Dugan etc

$V_{acc} = V_0 \sin\psi_s$

Above transition

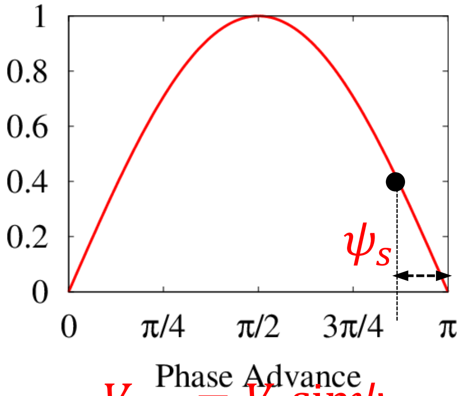
SY Lee, Dugan, K. Smith, M. Blaskiewicz, H. Wang etc



$V_{acc} = V_0 \sin\psi_s$

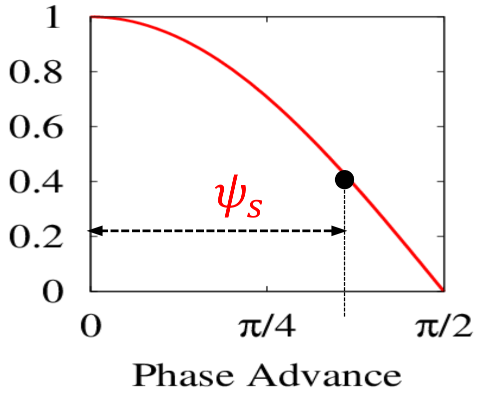
I use this definition now on since April 2020

Wiedemann, Boussard, R. W. Robinson, S. Peterson, S. Wang, D. Teytelman, Koscielniak etc



$V_{acc} = V_0 \sin\psi_s$

P. B.Wilson, L. Merminga, S. Heifets, F. Pedersen, K. Bane etc



$V_{acc} = V_0 \cos\psi_s$