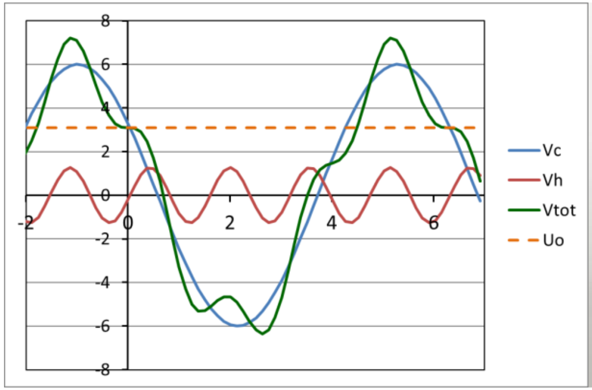
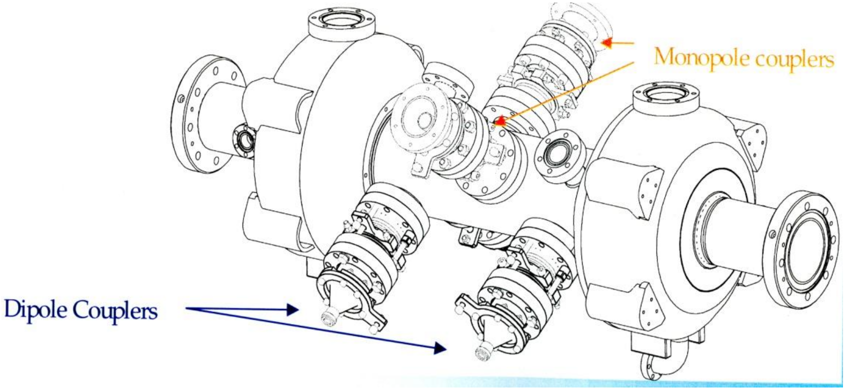
HarmonLIP Workshop

MAX IV / Lund, 10-12 October 2022

Passive vs Active Systems, DC Robinson, DLLRF

Jörn Jacob





ESRF | The European Synchrotron

→ Part of this work has been performed within the frame of the WP2 collaboration among ESRF, HZB, KEK, PSI & SOLEIL

HARMONIC RF FOR BUNCH LENGTHENING

$$V_{acc}(\phi) = V_c \sin(\phi_s + \phi) + V_h \sin(n\phi_h + n\phi)$$

Optimum Working point (1st & 2nd derivatives = 0):

$$\phi_s = \pi - \arcsin[\, n^2/(n^2-1)\ \ U_0/V_c \,]$$

$$V_{h,opt} = \mathrm{sqrt}[\, V_c^2/n^2 - U_0^2/(n^2-1) \,]$$

$$\phi_{\ h,opt} = (1/n) \arcsin[- U_0 / (V_{h,opt}\ (n^2-1) \,]$$

For instance 4th harmonic RF for the ESRF:

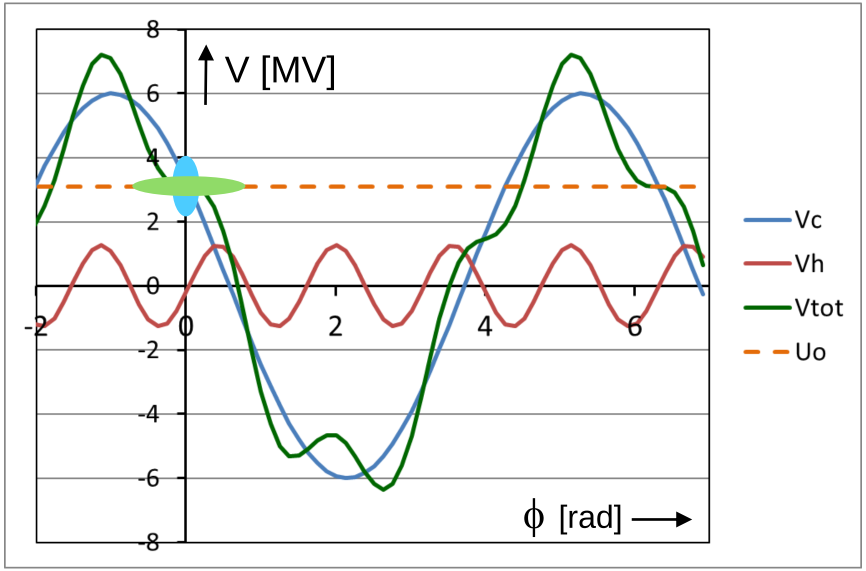
U_0 = 2.52 MeV / turn (without ID = worst case)

V_c = 6.0 MV

ϕ_s = 153.38 deg

$V_{h,opt}$ = 1.35 MV

$n\phi_{\ h,opt}$ = -7.14 deg



Principle: 4th harmonic RF system for bunch lengthening

PASSIVE NC / SC HARMONIC CAVITY

Passive NC harmonic cavity :

- ✓ MAXIV, Solaris: 3 x 100 MHz
- ✓ ALS: 3 x 500 MHz
- ✓ BESSY: 3 x 500 MHz

Pros:

- Simple, most economic solution
- V_h driven by the beam
- Only f_{res} tuning to obtain desired $V_h = f(\text{Ibeam})$
- V_h phase follows beam phase
  - $\Rightarrow$ no phase tuning required
  - $\Rightarrow$ no DC Robinson problem

Cons:

- Low total impedance → only for high current operation
- Low Q → $V_{h,opt}$ achievable if enough total current, but not $\phi_{h,opt}$:
  - → i.e.: cancelation of 1st derivative possible, but not 2nd derivative
  - → nevertheless, significant bunch lengthening achievable
- High total R/Q → Strong phase transients ~ R/Q

Passive SC harmonic cavity :

- ✓ SLS, Elettra: 3 x 500 MHz
- ✓ APS: 4 x 352.2 MHz, under development
- ✓ SOLEIL II: possibly

Pros:

- Almost purely inductive,
  - $\Rightarrow \phi_h = 0$ close to $\phi_{h,opt}$!
  - $\Rightarrow$ No beam power loading
  - $\Rightarrow$ $V_{h,opt}$ easily achievable down to low beam current
- Only f_{res} tuning to obtain desired $V_h = f(\text{Ibeam})$
- V_h phase follows beam phase
  - $\Rightarrow$ no DC Robinson problem
- Note: APS project foresees power coupler to slightly load the SC cavity and achieve also $\phi_h = \phi_{h,opt}$
- Low R/Q , → minimize phase transients

Cons:

- Operation of SC-RF technology, Cryoplant
  - → Operation requires more financial and manpower resources than NC cavities
  - → Larger risk of down time

ACTIVE NC HARMONIC CAVITY

Active NC harmonic cavity :

- ✓ ALBA, BESSY, DESY project: 3 x 500 MHz scaling of E010 EU cavity in test at BESSY
- ✓ KEK: development of 3 x 500 MHz E020 cavity
- ✓ ESRF: development of 4 x 352.37 MHz E020 cavity

Pros:

- Any Vh and ϕ_h can easily be set for any current
- Allows bunch lengthening for high and low current / few bunch filling
- Still reasonable number of cavities
- E020 cavities: similar R/Q as SC cavities
- Real alternative to SC cavities

Cons:

- Lacking operational experience
- DC Robinson stability needs to be addressed
- Requires high power RF amplifiers

GENERAL STABILITY

Different configurations are being evaluated by the HarmonLIP community w.r.t. stability:

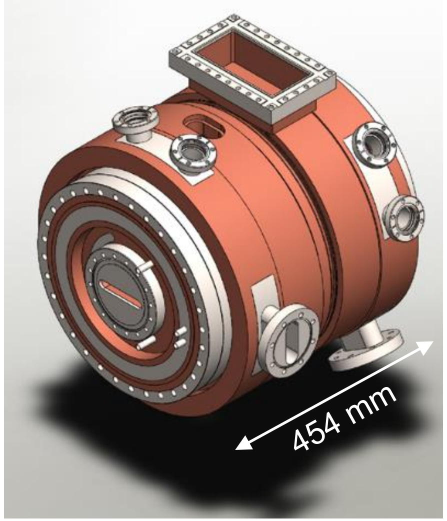
- By beam tracking simulations
- When possible: by experiments on existing systems

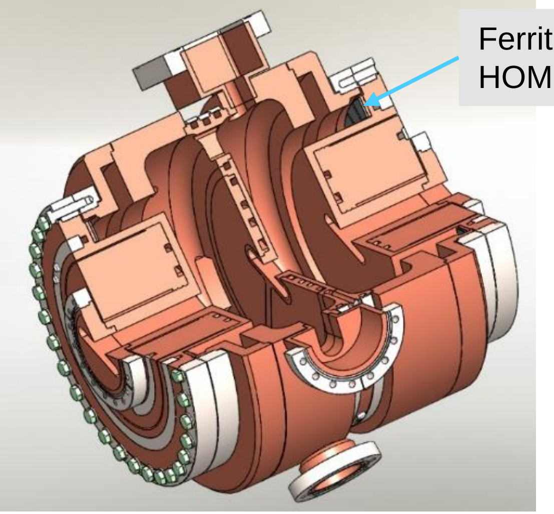
→ See other presentations

Coming slides → some considerations on:

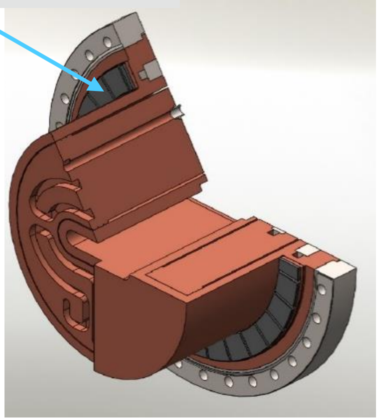
- Robinson DC for active harmonic RF systems
- Possible active control

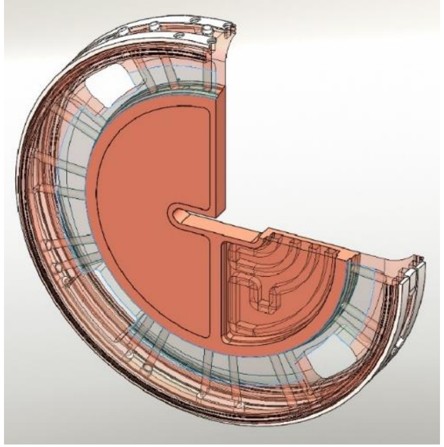
4TH HARMONIC 2-CELL E020 MODE CAVITY – ESRF IN HOUSE DEVELOPMENT





Ferrite LOM (E010 mode) &
HOM absorber

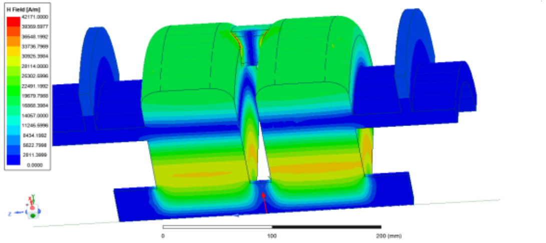




Active NC cavity design well advanced:

- ✓ 2 coupled and 2 uncoupled cells considered
- ✓ Freq = 1.409 GHz
- ✓ R/Q = 44.5 ohm/cell
- ✓ Q0 = 30500
- ✓ Smart HOM & LOM dampers almost not affecting Q0 of E020 mode
- ✓ Elaborate water cooling
- ✓ Aperture coupler: **coupling β = 1**
- ✓ Vacuum ports on HOM dampers also preserving Q0

H-Field

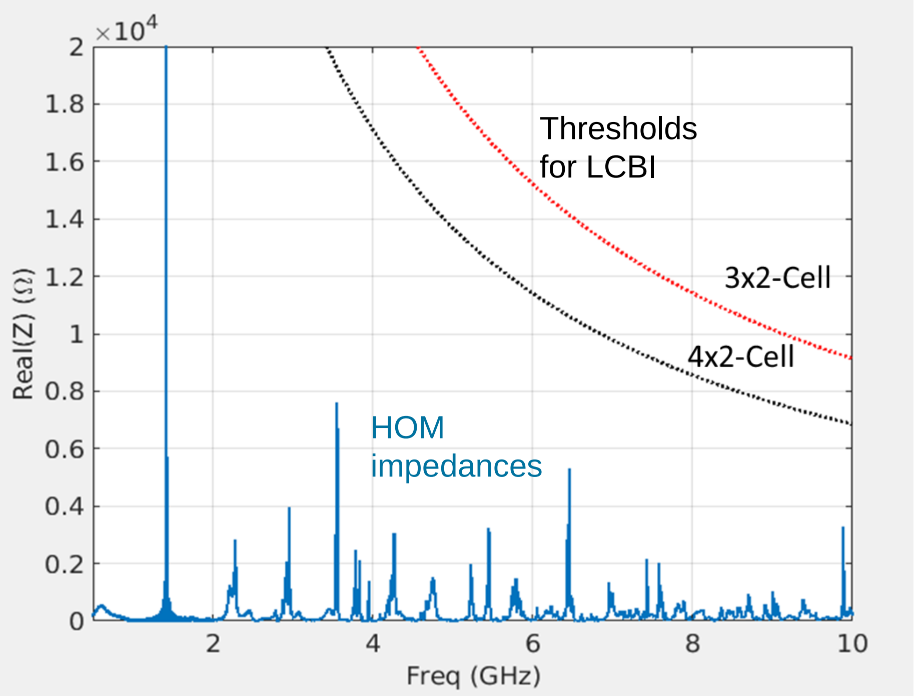


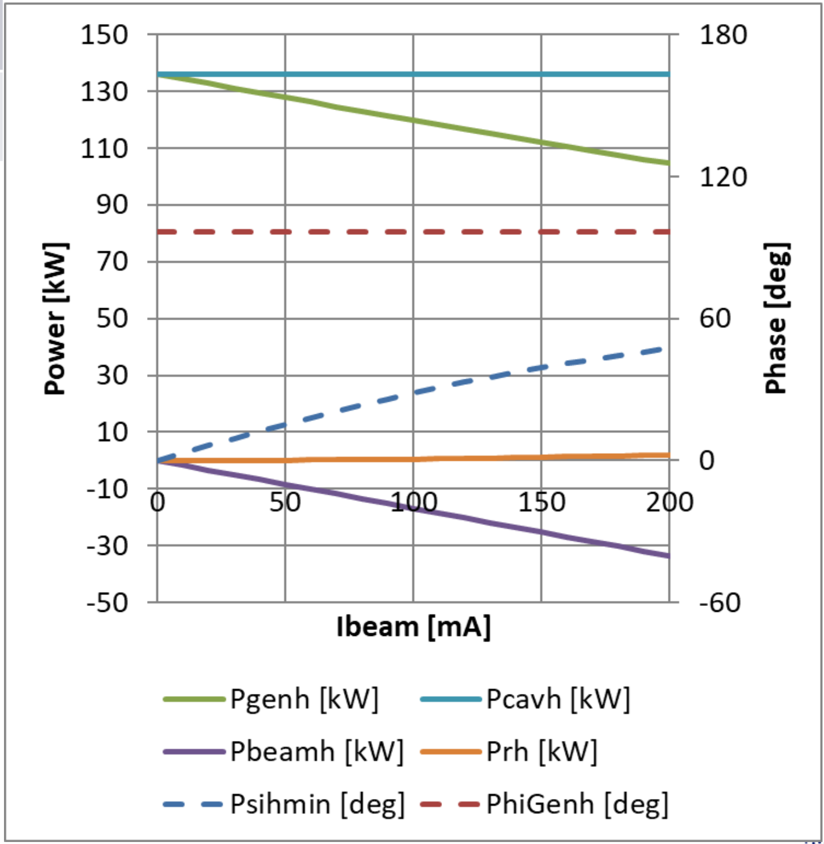
[E020 proposed by Naoto Yamamoto, KEK
ESRF design by Alex D’Elia, Vincent Serrière]

ACTIVE HARMONIC SYSTEM - POWER REQUIREMENTS

Main RF Voltage	Harmonic RF Voltage	3 x 2 Harm Cav cells	4 x 2 Harm Cav cells
6.5 MV	1.49 MV	46 kW	26 kW
6.0 MV (nominal)	1.35 MV	38 kW	22 kW

Optimum harmonic cavity tuning: **Load angle = 0** (exactly as for main RF)





BEAM LOADING DIAGRAM WITH HARMONIC CAVITY FOR BUNCH LENGTHENING

$V_{acc}(\phi) = V_c \sin(\phi_s + \phi) + V_h \sin(n\phi_h + n\phi)$

Optimum Working point (1st & 2nd derivatives = 0):

$\phi_s = \pi - \arcsin[\, n^2/(n^2-1)\ \ U_0/V_c \,]$

$V_{h,opt} = \mathrm{sqrt}[\, V_c^2/n^2 - U_0^2/(n^2-1) \,]$

$\phi_{\ h,opt} = (1/n) \arcsin[- U_0 / (V_{h,opt}\ (n^2-1)\,]$

Optimum tuning (min power) ⇔ load angle = 0:

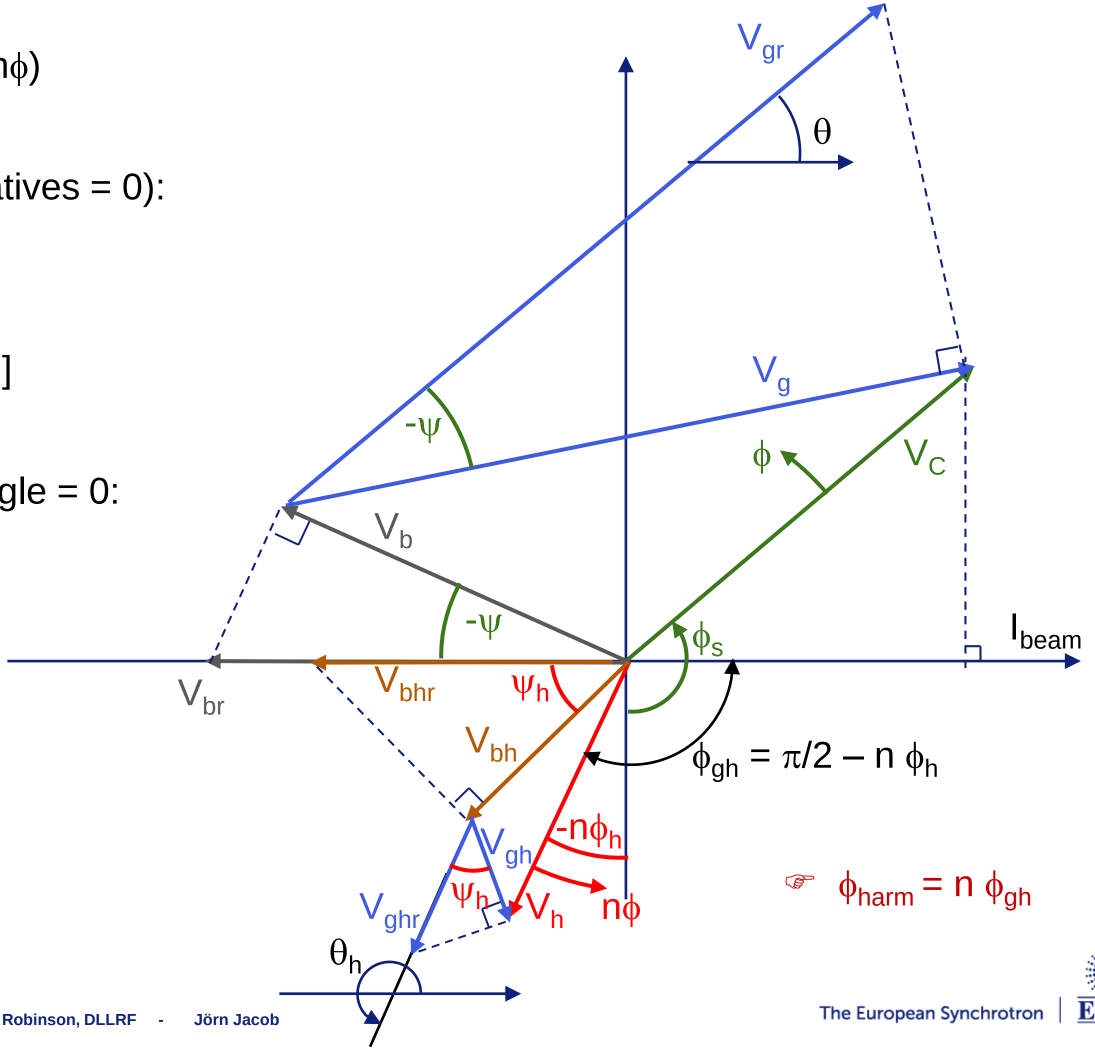
ψ such that V_{gr} // V_c

ψ_h such that V_{ghr} // V_h

Beware, in the vector diagram:

Main RF turns at $\phi = \omega t$

Harmonic RF at $n\phi = n\omega t$



☞ $\phi_{harm} = n\ \phi_{gh}$

ROBINSON DC (2^{ND} TYPE) – INTEGRATION OF SYNCHROTRON EQUATION

Assumptions:

RF loops (Amp, Phi, tuning	slower than	Synchrotron motion	slower than	Cavity Bandwidths (main & HC)
B ≈ 1 Hz	<<	fs ≈ 1 kHz …	<<	Above ≈ 40 kHz

⇓

1. Tuning angles, generator amplitudes and phases are constant at the scale of the synchrotron motion

2. The beam induced voltages in the cavities follow the beam phase

$$f_s = f_{rf} \text{ x sqrt } [\, \alpha\, K' / (2\pi\, h\, E_0/e)\,],$$

(K'<0 ⇔ DC Robinson instability)

$$K' = \underbrace{-V_c \cos\phi_s}_{\substack{>0\\ \text{Main RF,}\\ \text{giving } f_{s0}}} \quad \underbrace{- nV_h \cos(n\phi_h)}_{\substack{<0\\ \text{Harm. RF, for}\\ \text{cancelling } f_s}} \quad \underbrace{+ V_b \sin\psi}_{\substack{<0\\ \text{Main RF}\\ \text{beam loading}\\ \text{(Robinson term)}}} \quad \underbrace{+ nV_{bh} \sin\psi_h}_{\substack{>0\\ \text{Harm. RF,}\\ \text{beam loading}\\ \text{(Stabilizing effect)}}} \qquad \textbf{(Eq. 1)}$$

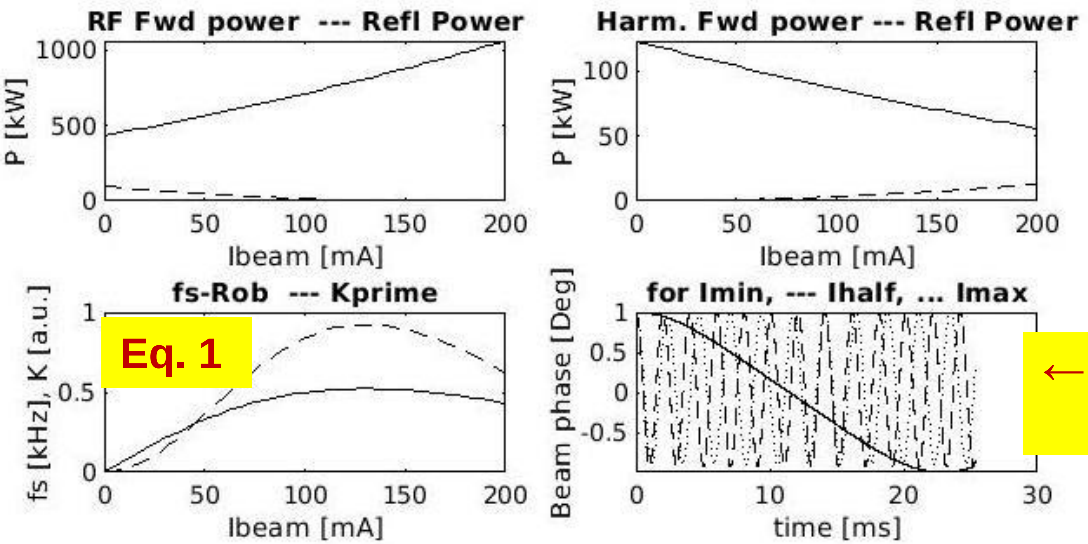
Coming examples already shown
at
ESLS RF meeting at SOLEIL in November 2018

Computed for 3rd harmonic RF system
(and not for actual 4th harmonic project)

ROBINSON DC (2^{ND} TYPE) – INTEGRATION OF SYNCHROTRON EQUATION

Numerical integration of synchrotron equation:

- Uniform filling (no transients)
- Starting with beam phase offset by +1 or -1 deg
- Tracking V_b, V_{bh} and ϕ_{beam} turn by turn
- Checking convergence (neglecting synchrotron oscillation damping)
- No linearization !



Eq. 1

$V_h = V_{h,opt} = 1.89$ MV

$n\phi_h = n\phi_{h,opt} = -12.2$ deg

5 cavities, $\beta_h = 1$

→ stable

← Numerical integration

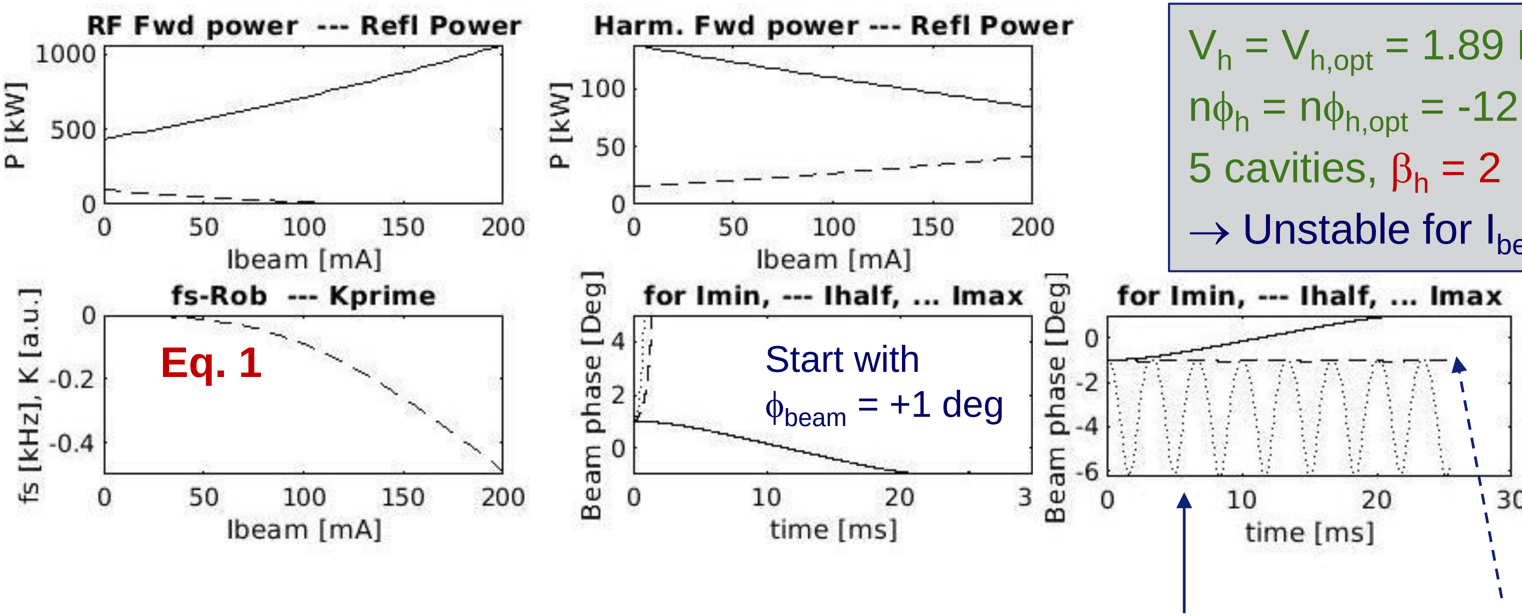
ROBINSON DC (2^{ND} TYPE) – INTEGRATION OF SYNCHROTRON EQUATION

$V_h = V_{h,opt} = 1.89$ MV

$n\phi_h = n\phi_{h,opt} = -12.2$ deg

5 cavities, $\beta_h = 2$

$\rightarrow$ Unstable for $I_{beam} > 0$



Eq. 1

Start with $\phi_{beam} = +1$ deg

Start with $\phi_{beam} = -1$ deg

Only for negative beam phases: stabilization through non-linearity of voltage waveform

Equilibrium for ≈ 100 mA

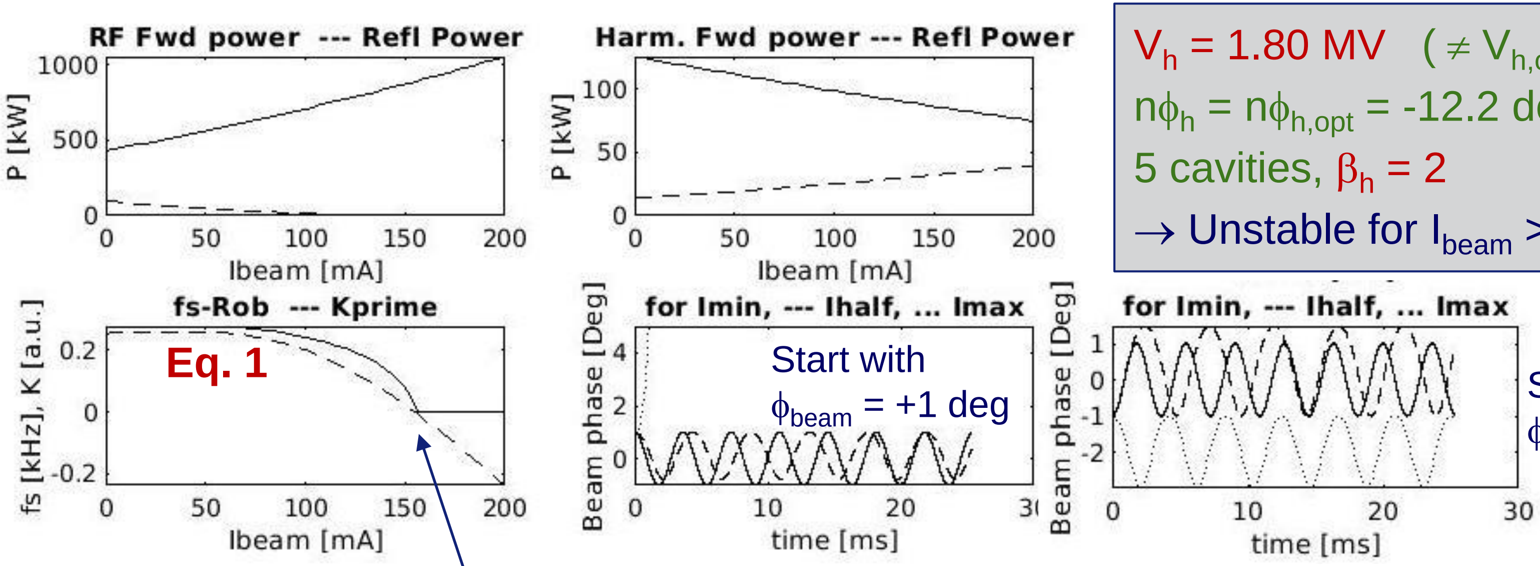
ROBINSON DC (2^{ND} TYPE) – INTEGRATION OF SYNCHROTRON EQUATION

V_h = 1.80 MV ($\neq V_{h,opt}$)

$n\phi_h = n\phi_{h,opt}$ = -12.2 deg

5 cavities, β_h = 2

→ Unstable for I_{beam} > 150 mA



Eq. 1

Start with ϕ_{beam} = +1 deg

Start with ϕ_{beam} = -1 deg

Threshold at ≈ 150 mA confirmed by numerical integration

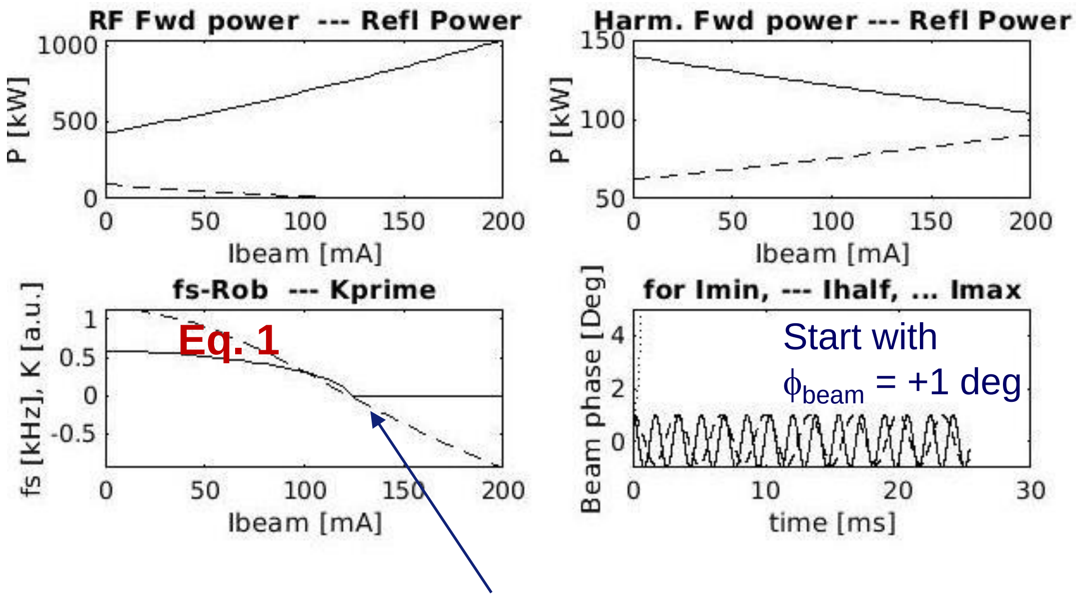
ROBINSON DC (2^{ND} TYPE) – INTEGRATION OF SYNCHROTRON EQUATION

V_h = 1.50 MV   ($\neq V_{h,opt}$)

$n\phi_h = n\phi_{h,opt}$ = -12.2 deg

5 cavities, β_h = 5

→ Unstable for I_{beam} > 130 mA



Start with ϕ_{beam} = +1 deg

Threshold at ≈ 130 mA confirmed by numerical integration

For active system, Integration of synchrotron equation indicates:

- Robinson stable if Harmonic RF beam loading > Main RF beam loading
  - ⇒ Sufficient harmonic cavity impedance,
  - ⇒ Sufficient number of harmonic cavities
  - ⇒ Upper limit for coupling β_h

DIRECT RF FEEDBACK

Analog RF feedback on MAIN RF system:

- Gain G
- Impedance for coherent in phase longitudinal beam motion reduced by factor 1/G

⇒ Reduction of Robinson term in Eq. 1 by a factor 1/G

$$f_s = f_{rf} \ \text{x sqrt} \left[\alpha \, \mathbf{K'} / (2\pi \, h \, E_0/e) \right], \qquad (K'<0 \Leftrightarrow \text{DC Robinson instability})$$

$$\mathbf{K'} = \underbrace{-V_c \cos\phi_s}_{\substack{>0 \\ \text{Main RF,} \\ \text{giving } f_{s0}}} \quad \underbrace{- nV_h \cos(n\phi_h)}_{\substack{<0 \\ \text{Harm. RF, for} \\ \text{cancelling } f_s}} \quad \underbrace{+ V_b \sin\psi \ \mathbf{/ \ G}}_{\substack{<0 \\ \text{Main RF} \\ \text{beam loading} \\ \text{(Robinson term)}}} \quad \underbrace{+ nV_{bh} \sin\psi_h}_{\substack{>0 \\ \text{Harm. RF,} \\ \text{beam loading} \\ \text{(Stabilizing effect)}}} \qquad \textbf{(Eq. 1)}$$

DLLRF SYSTEM FOR FAST DIGITAL RF FEEDBACK

1. To stabilize main RF, one can compute the optimum correction for a fast RF feedback:

$$\begin{pmatrix} \Delta I_{gr} \\ \Delta Q_{gr} \end{pmatrix} = \frac{1}{\cos\psi} \begin{bmatrix} \cos(\psi - \varphi_{tune}) & \sin(\psi - \varphi_{tune}) \\ -\sin(\psi - \varphi_{tune}) & \cos(\psi - \varphi_{tune}) \end{bmatrix} \begin{pmatrix} \Delta I_c \\ \Delta Q_c \end{pmatrix}$$

where $\psi = f(V_c, I_{beam}, N_{cav}, R_s, \beta, \varphi_{tune})$, (→ φ_{tune} = *Load angle, mostly zero*)

2. Alternative: simulate behaviour of a passive cavity

→ Feedback harmonic voltage phase to lock on beam phase

→ Results of synchrotron equation integration need to be cross-checked with particle tracking simulations

→ The two RF feedback approaches need to be included in the simulations and checked

MANY THANKS FOR YOUR ATTENTION