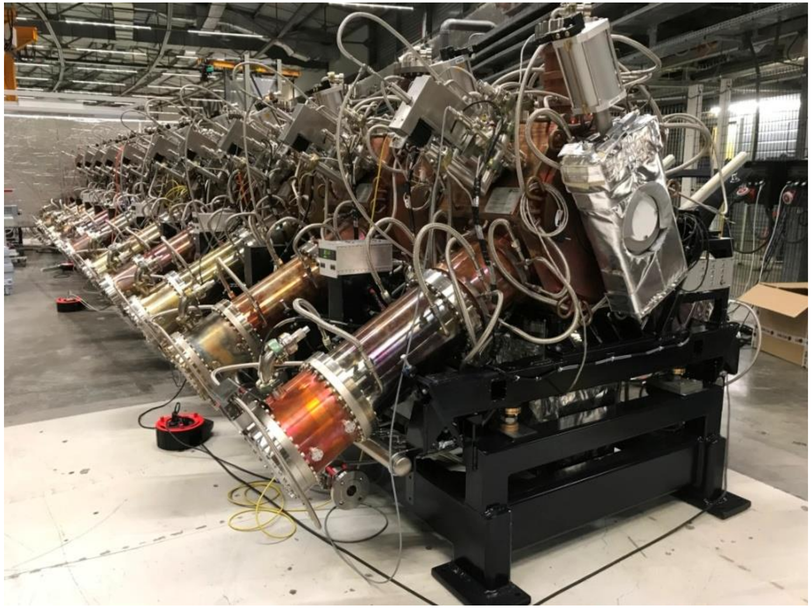
22nd ESLS RF Meeting - SOLEIL

Paris, 8-9 November 2018

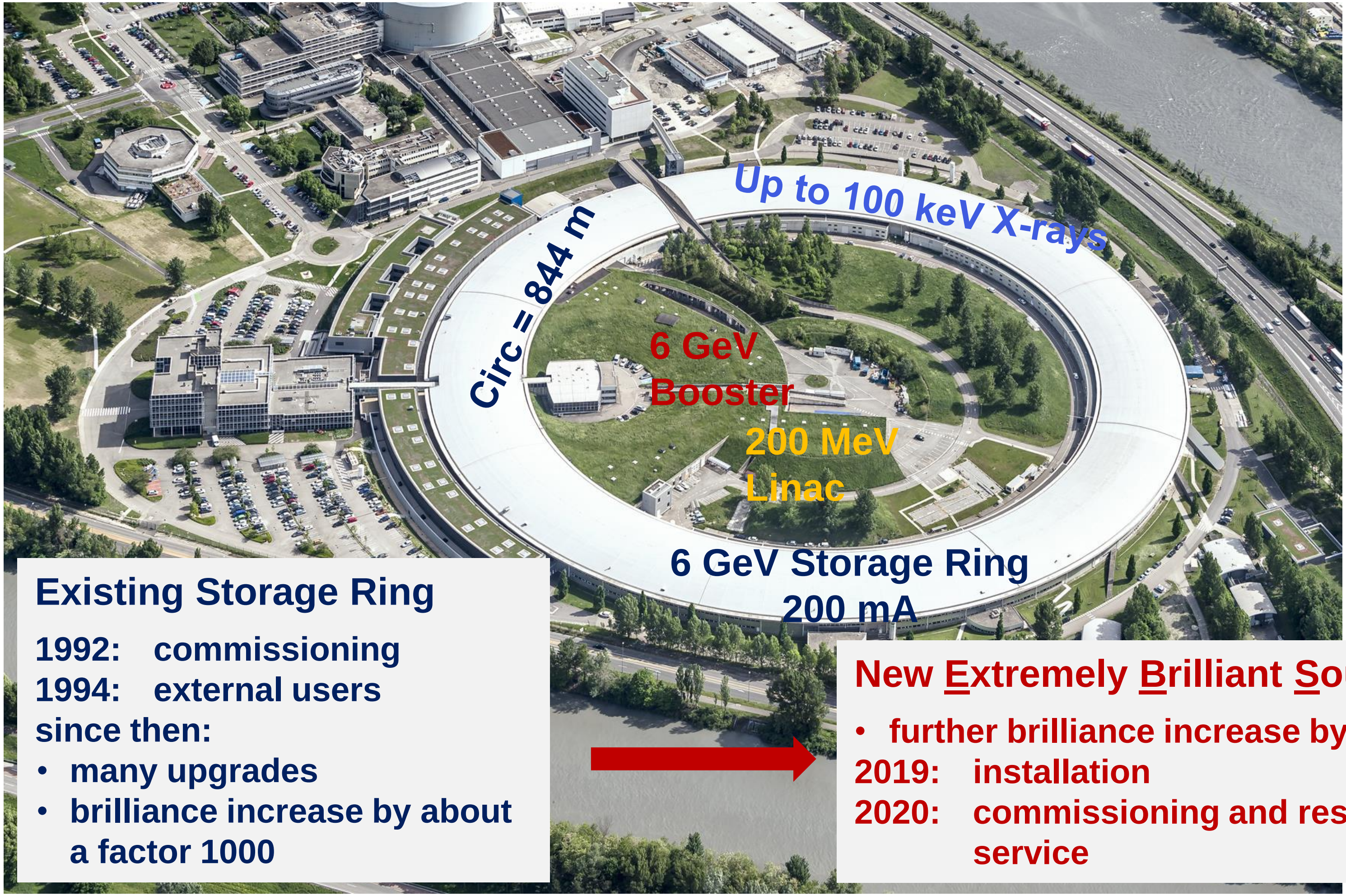
Harmonic RF systems for ESRF-EBS
- Preliminary considerations -

Jörn Jacob, Vincent Serrière



ESRF | The European Synchrotron

ESRF: FIRST 3rd GENERATION SYNCHROTRON LIGHT SOURCE



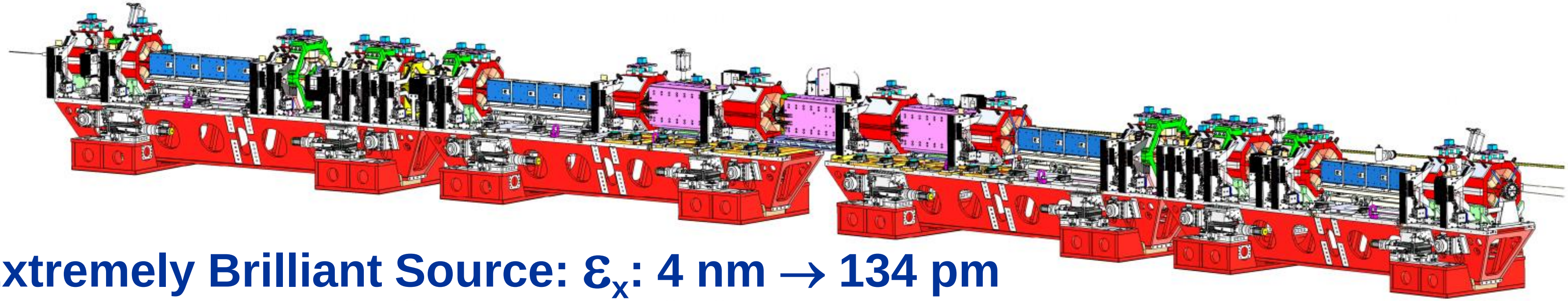
Existing Storage Ring

1992: commissioning
1994: external users
since then:
- many upgrades
- brilliance increase by about a factor 1000

New Extremely Brilliant Source: EBS
- further brilliance increase by a factor 40

2019: installation
2020: commissioning and resume user service

RF UPGRADE FOR THE ESRF-EBS STORAGE RING



Extremely Brilliant Source: ε_x: 4 nm → 134 pm

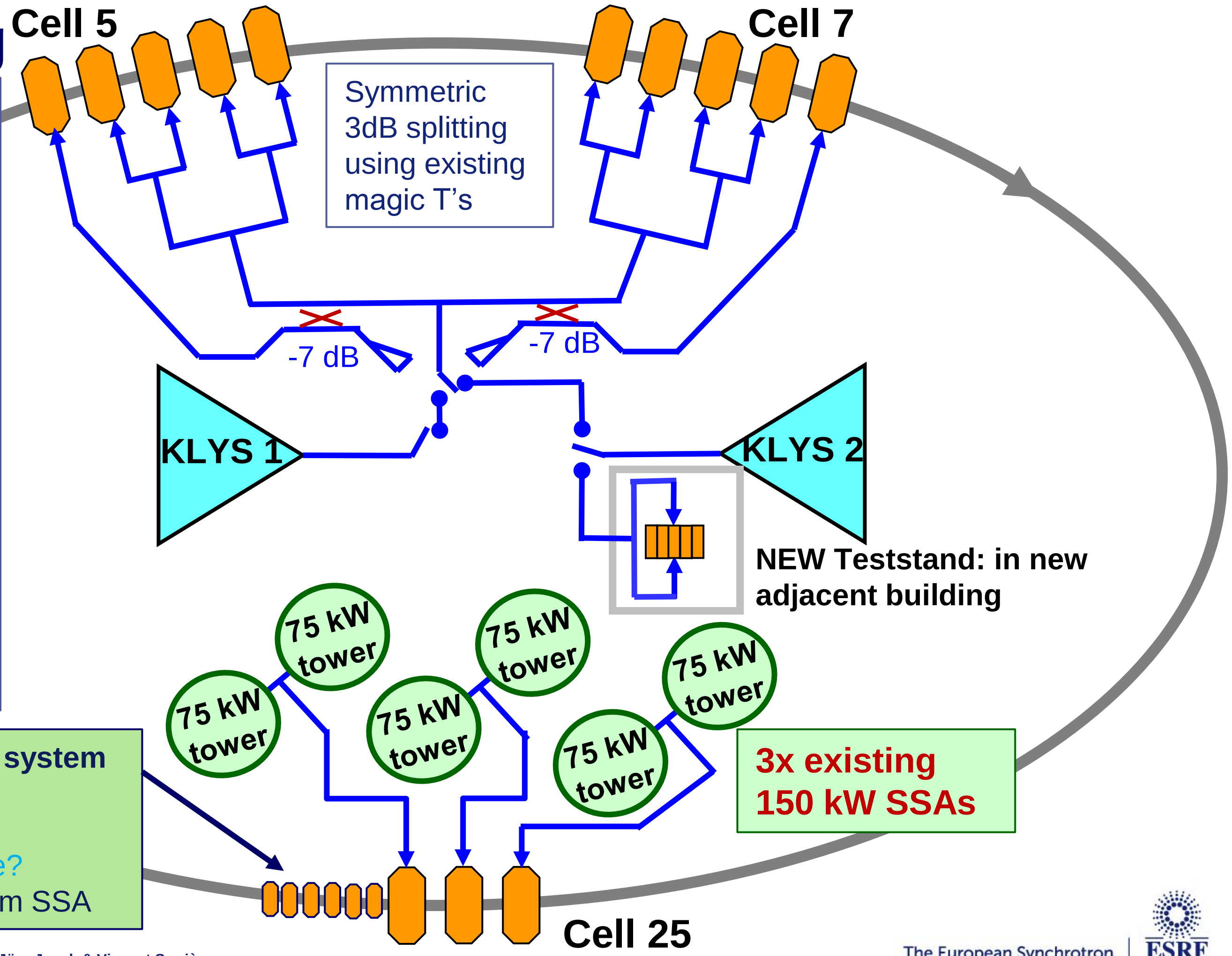
10 December 2018: shut down existing machine
2019: Installation of new machine
2020: Commissioning EBS and Beamlines
August 2020: Back to user service mode

EBS RF SYSTEM LAYOUT

EBS Storage Ring

EBS RF upgrade:

- Remove 5 five-cell cavities
- Remove 2 prototype HOM damped cavities from cell 23
- Install 13 single cell HOM damped cavities in cells 5, 7, 25
- Suppress existing 3rd Klystron transmitter in cell 25
- Move 3 x 150 kW SSAs from cell 23 to cell 25
- Rebuild waveguide distribution system
- Rebuild control system for klystron transmitters and cavities



Space for 3rd harmonic RF system

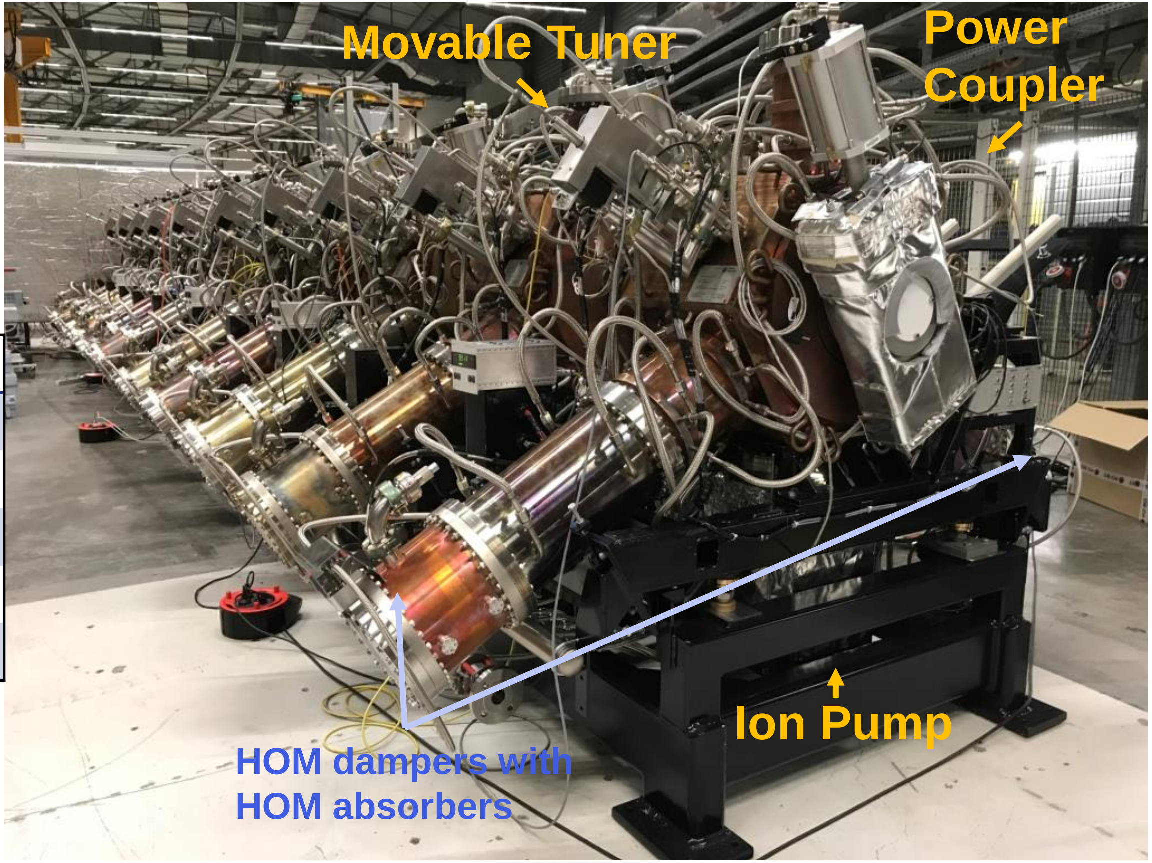
- Still under study:
  5 to 6 active NC cavities
  or passive Super3HC type?
- ≈ 40 kW per NC cavity from SSA

MAIN RF PARAMETERS FOR ESRF-EBS UPGRADE

Total energy loss:	**3.2 MeV/turn**
☞ Energy loss from dipole radiation:	2.5 MeV/turn
☞ Energy loss from ID radiation:	0.7 MeV/turn
Maximum RF Voltage:	**6.6 MV**
Stored current with operational margin:	**220 mA**
HOM damped cavities:	
☞ 2 of 3 prototypes on SR since 2013:	0.5 MV / 90 kW *(standard operation)*
☞ Prototypes validated with beam up to:	0.6 MV / 150 kW *(phased for max beam loading)*
☞ All 12 series cavities conditioned to:	0.75 MV
EBS 30 % less total RF power than now:	**≈ 1 MW at nominal 200 mA**

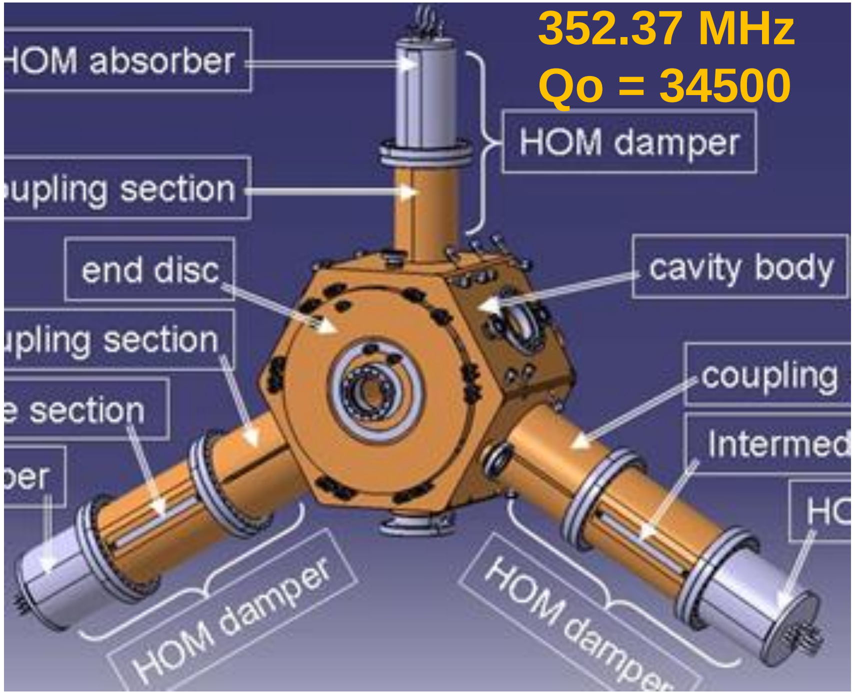
HOM DAMPED SINGLE CELL CAVITIES

f_{res}	352.372	MHz
Q_0	35700	(measured)
R/Q	145	Ω
R_s	≈ 5	MΩ
Tuning range	-350 / +900	kHz
V_{acc} nom/max	500 / 750	kV

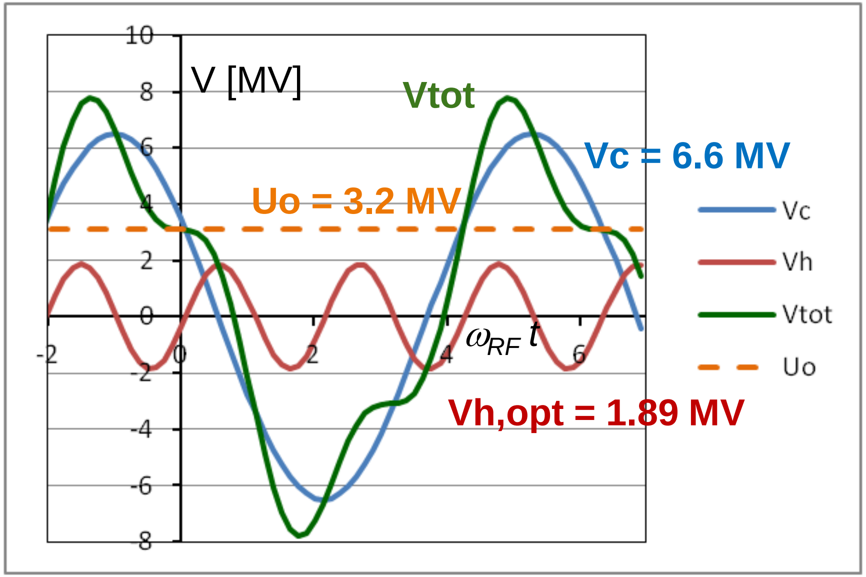


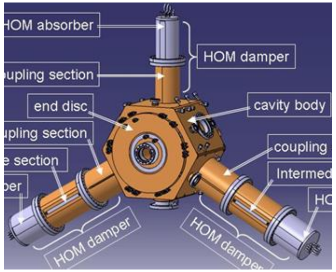
[See A. D'Elia's talk]

HARMONIC RF SYSTEM FOR BUNCH LENGTHENING

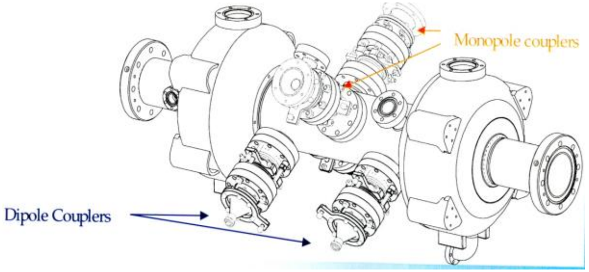


352.37 MHz
Qo = 34500





Active copper cavity:
Scaling to 1057.1 MHz
Qo = 20000
R/Q = 145 Ω



OR

Passive SC cavity:
Super3HC scaled to 1057.1 MHz

BEAM LOADING - NC ACTIVE 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 (1^{st} & 2^{nd} 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:

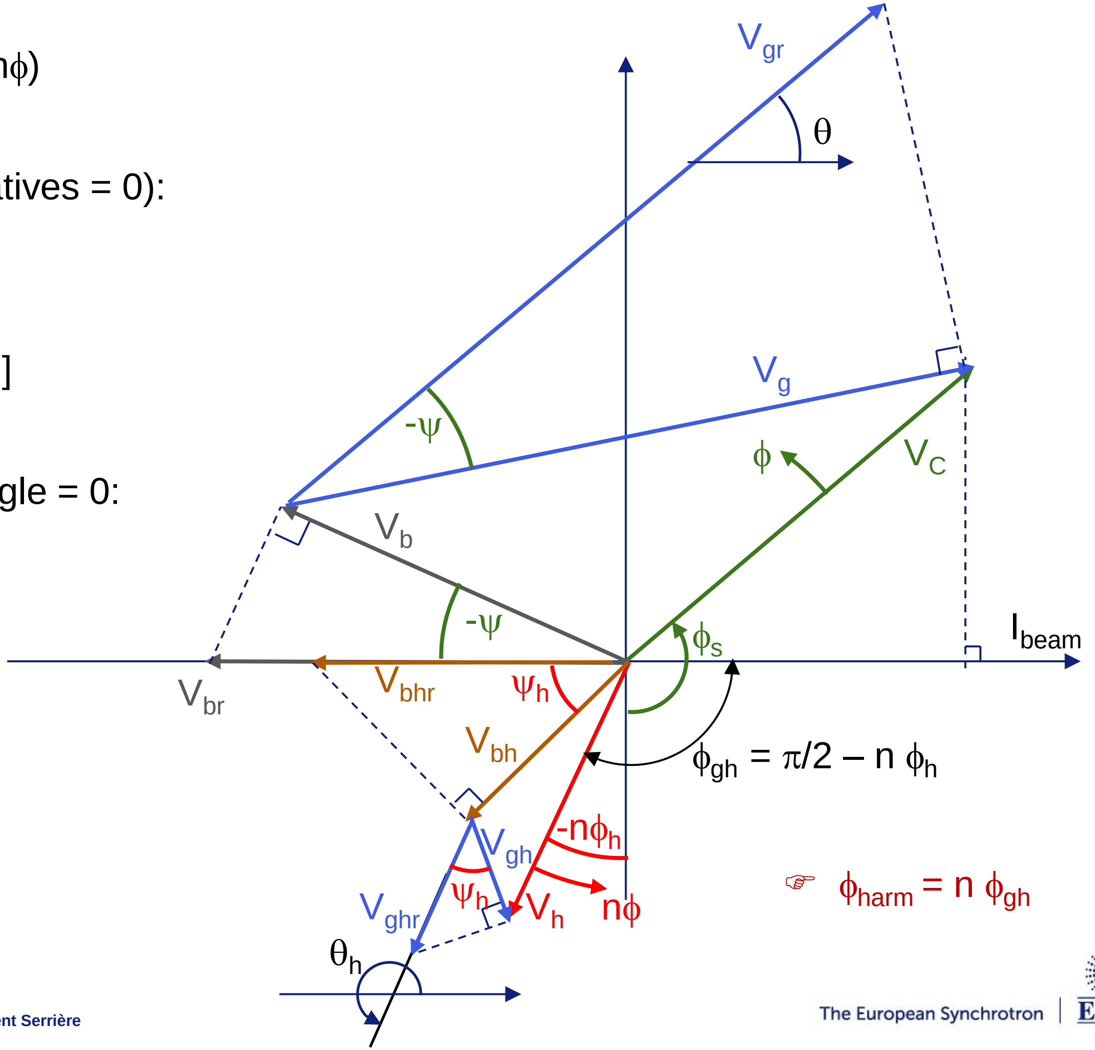
ψ such that V_{gr} // V_c

ψ_h such that V_{ghr} // V_h

Beware, in the vector diagram:

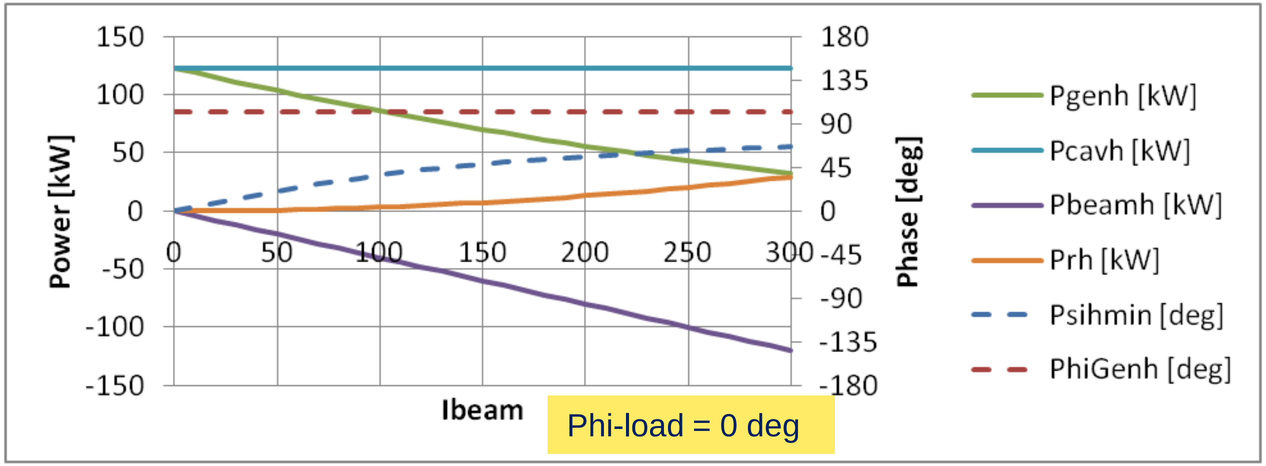
Main RF turns at $\phi = \omega t$

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



☞ $\phi_{harm} = n\,\phi_{gh}$

BEAM LOADING FOR FIVE 3^{RD} HARMONIC ACTIVE NC CAVITIES



Phi-load = 0 deg

Coupling: $\beta_h = 1$

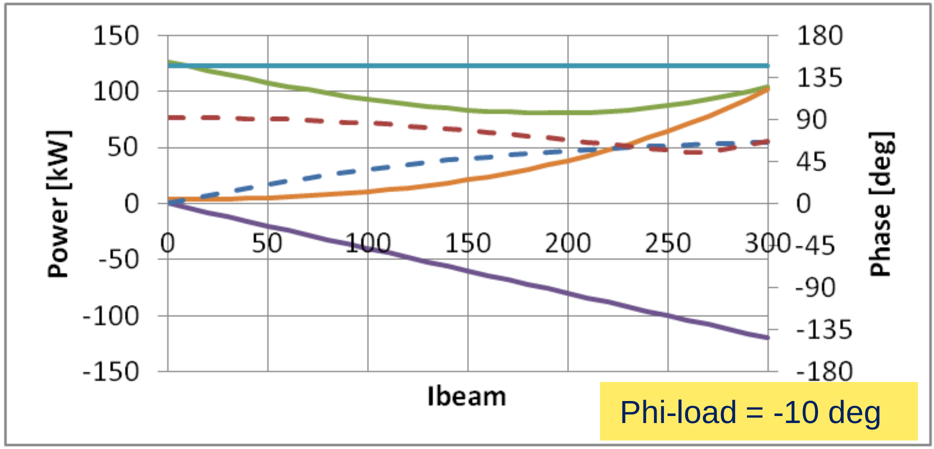
$V_h = V_{h,opt} = 1.89$ MV

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

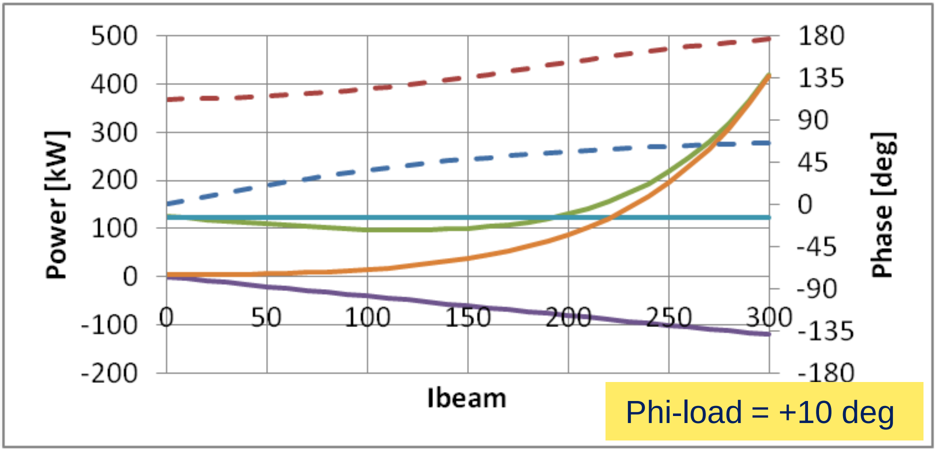
Working point very sensitive to harmonic cavity tuning

Below 200 mA:

Pgenh-max = 130 kW

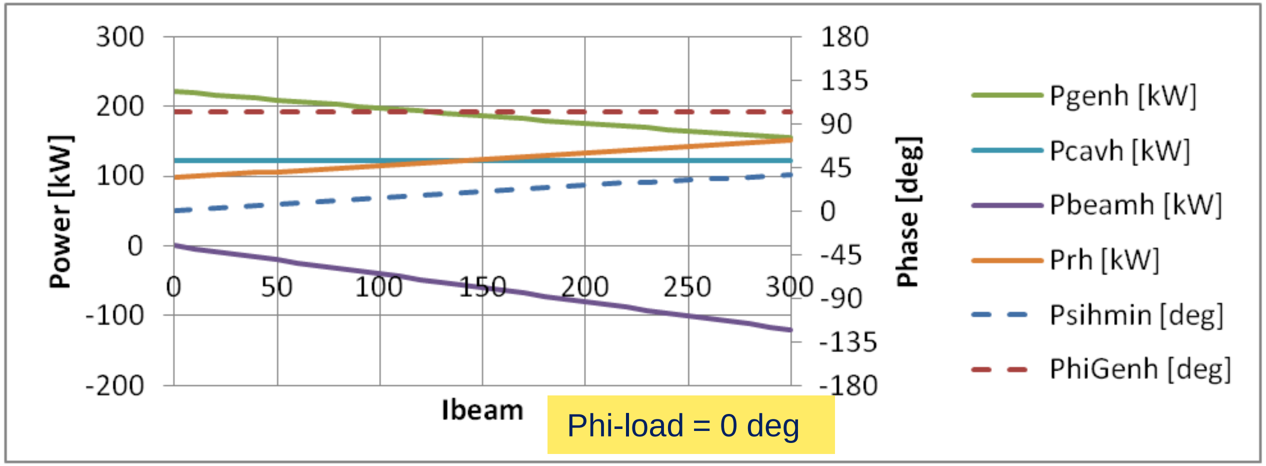


Phi-load = -10 deg



Phi-load = +10 deg

BEAM LOADING FOR FIVE 3^{RD} HARMONIC ACTIVE NC CAVITIES



Phi-load = 0 deg

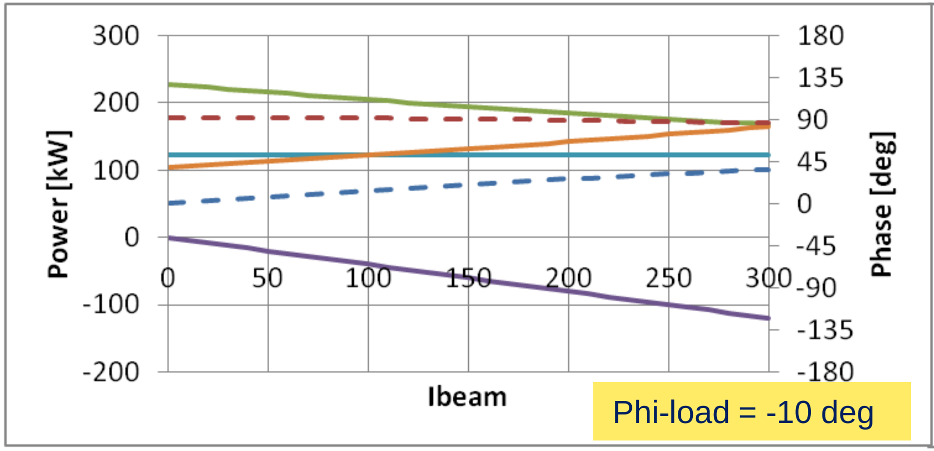
Coupling: $\beta_h = 5$

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

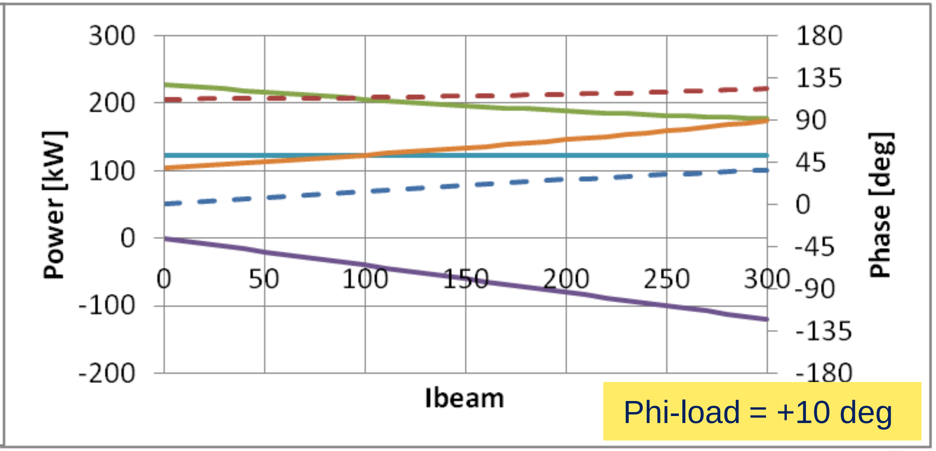
$n\phi_h = n\phi_{h,opt} = -12.2$ deg

Working point less sensitive to harmonic cavity tuning

Below 200 mA:
Pgenh-max = 230 kW



Phi-load = -10 deg



Phi-load = +10 deg

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

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

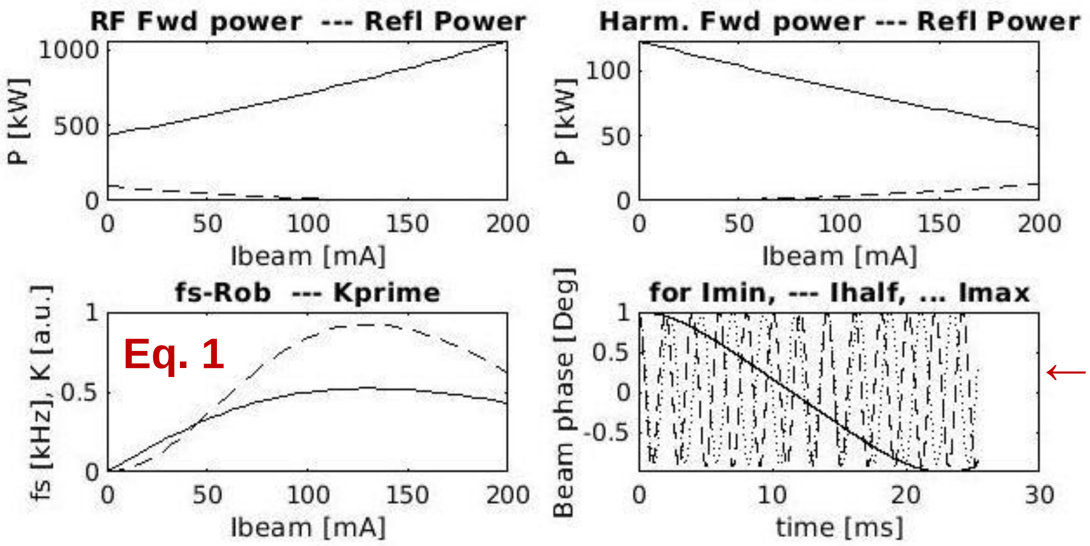
(K'<0 ⇔ DC Robinson instability)

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

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 !



← Numerical integration

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

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

5 cavities, $\beta_h = 1$

→ stable

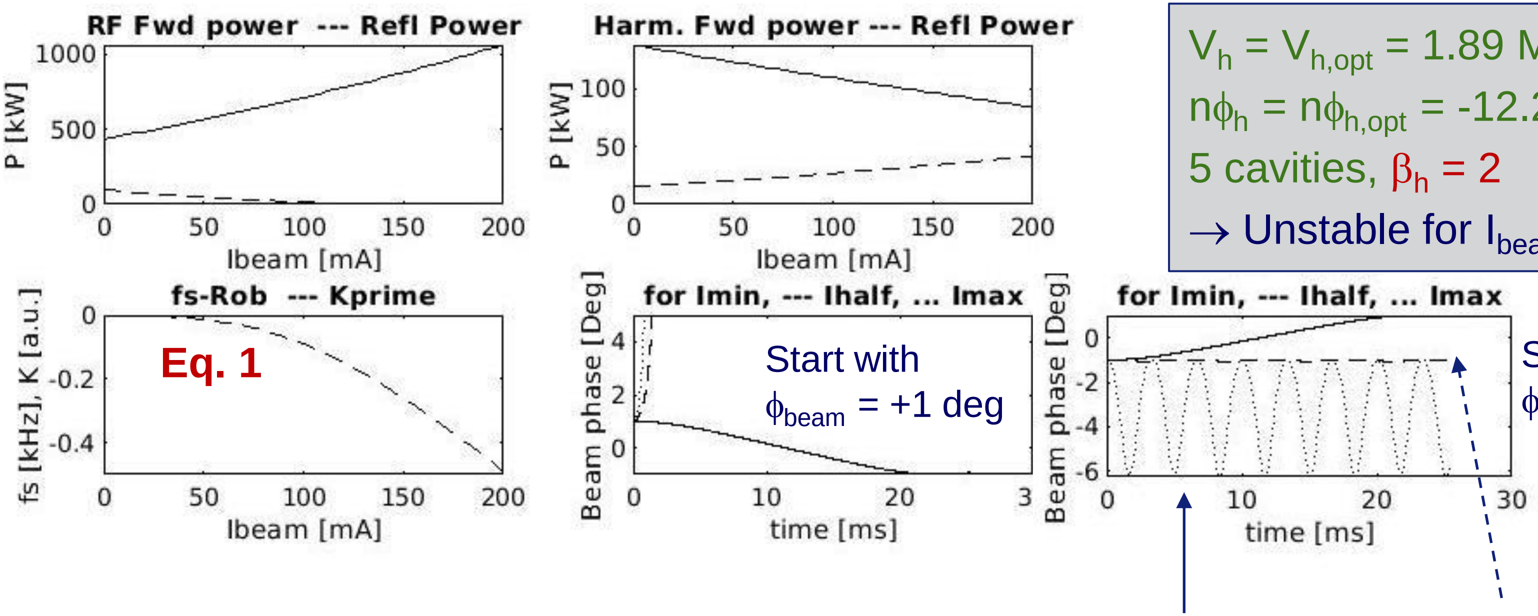
ROBINSON DC (2^{ND} TYPE) – INTEGRATION OF SYNCHROTRON EQUATION

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

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

5 cavities, $\beta_h = 2$

→ Unstable for $I_{beam} > 0$



Eq. 1

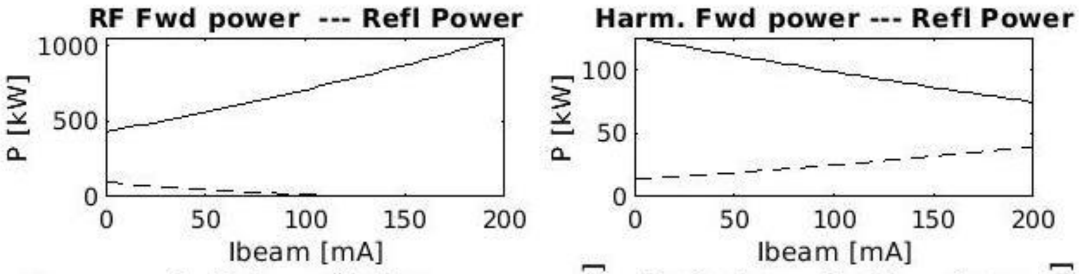
Start with $\phi_{beam} = +1$ deg

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

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

Equilibrium for ≈ 100 mA

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

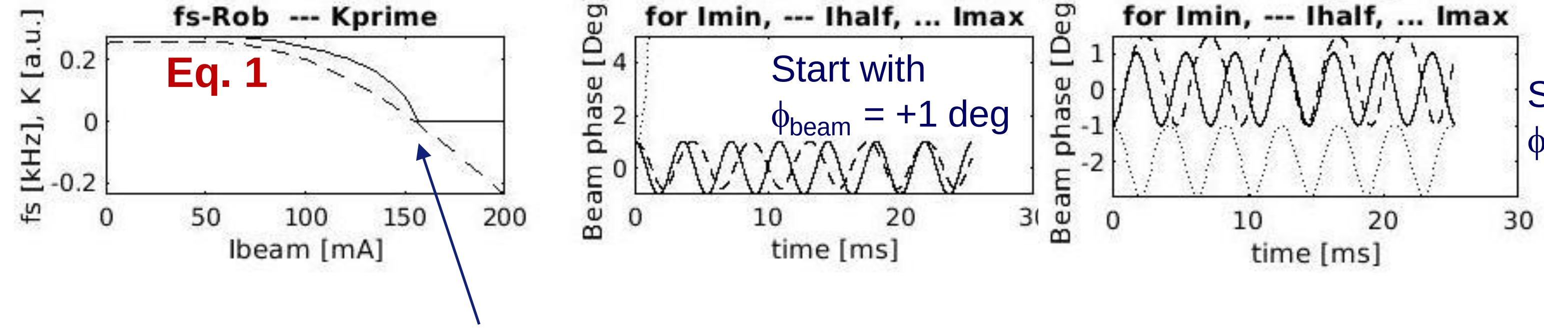


V_h = 1.80 MV ($\neq V_{h,opt}$)

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

5 cavities, β_h = 2

→ Unstable for I_{beam} > 150 mA



Eq. 1

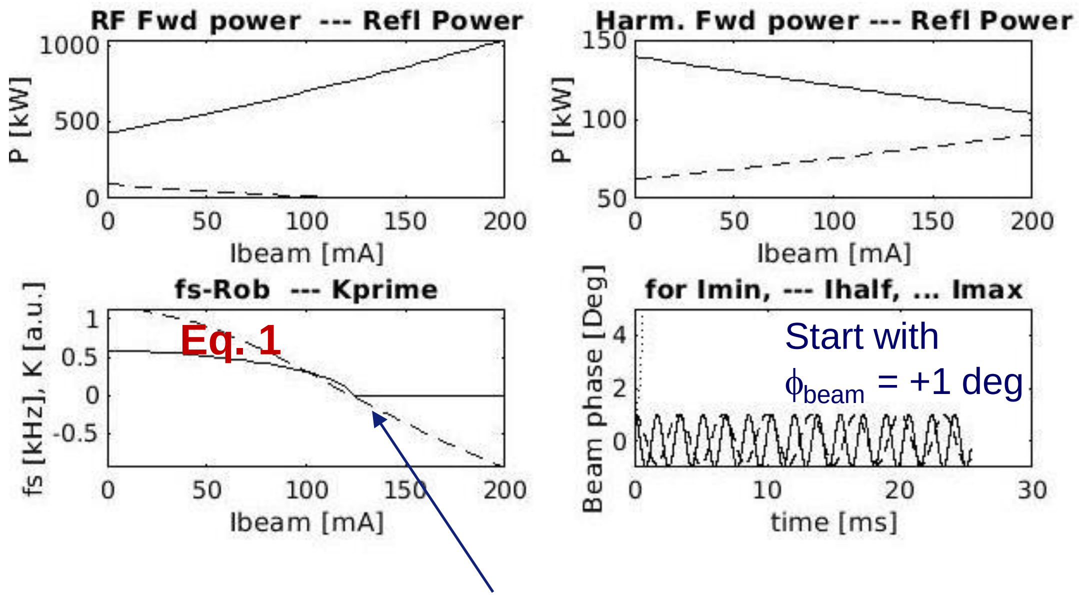
Start with ϕ_{beam} = +1 deg

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



Eq. 1

Start with
ϕ_{beam} = +1 deg

Threshold at ≈ 130 mA confirmed by numerical integration

For active system, Integration of synchrotron equation indicates:

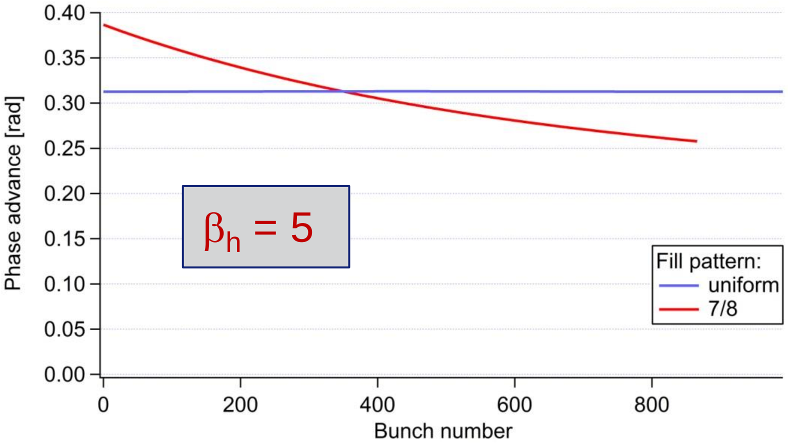
- ➢ Robinson stable if Harmonic RF beam loading > Main RF beam loading
  - ⇒ Sufficient harmonic cavity impedance,
  - ⇒ Sufficient number of harmonic cavities
  - ⇒ Upper limit for coupling β_h

MULTIBUNCH / SINGLE PARTICLE TRACKING – ROBINSON & PHASE TRANSIENTS

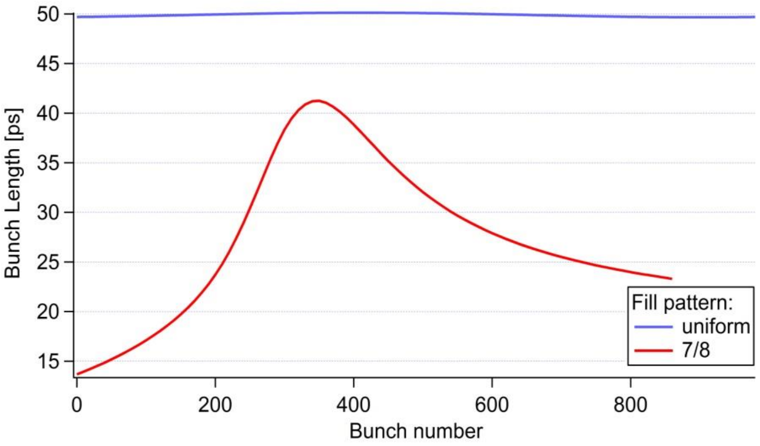
$V_h = V_{h,opt}$

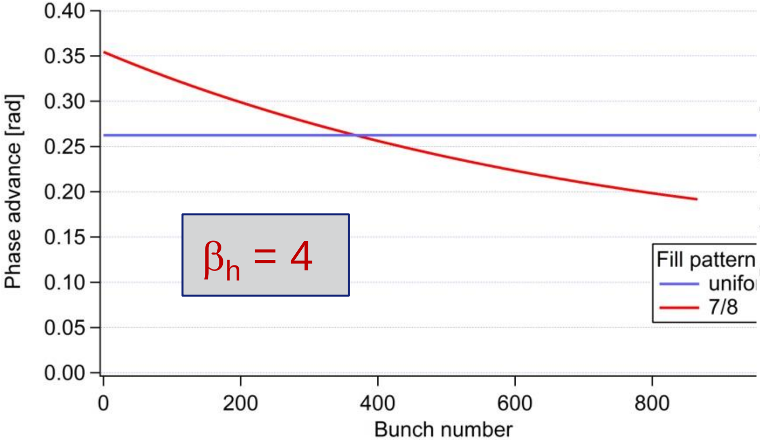
$\phi_h = \phi_{h,opt}$

5 active NC cavities

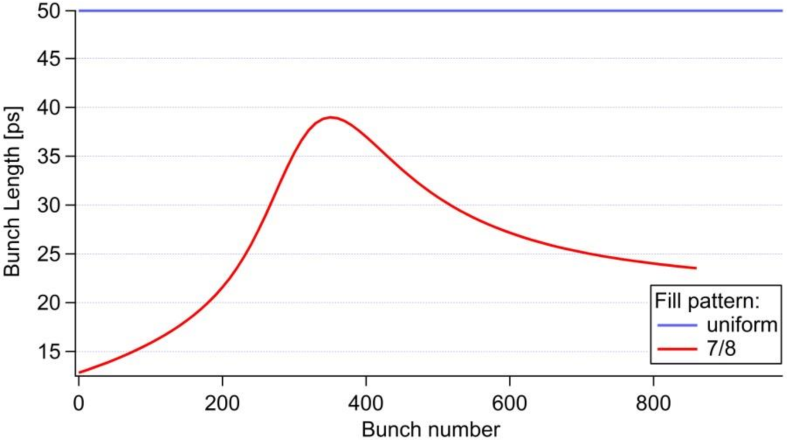


$\beta_h = 5$





$\beta_h = 4$



For both cases: Phase transients: 0.16 rad,

! DC Robinson stable for large β_h !

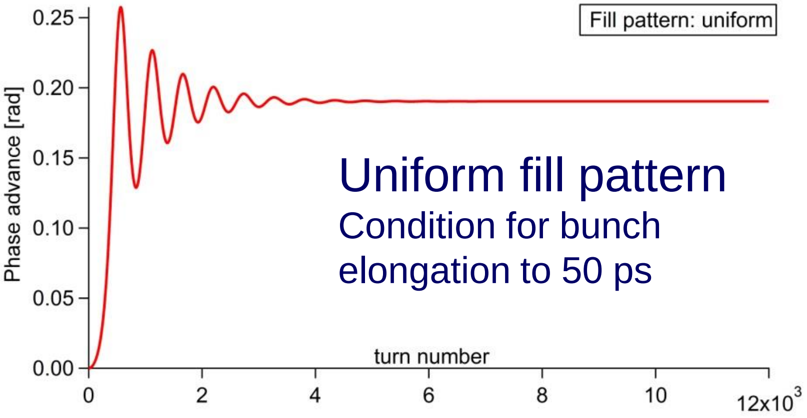
MULTIBUNCH / SINGLE PARTICLE TRACKING – ROBINSON & PHASE TRANSIENTS

$V_h = V_{h,opt}$

$\phi_h = \phi_{h,opt}$

5 active NC cavities

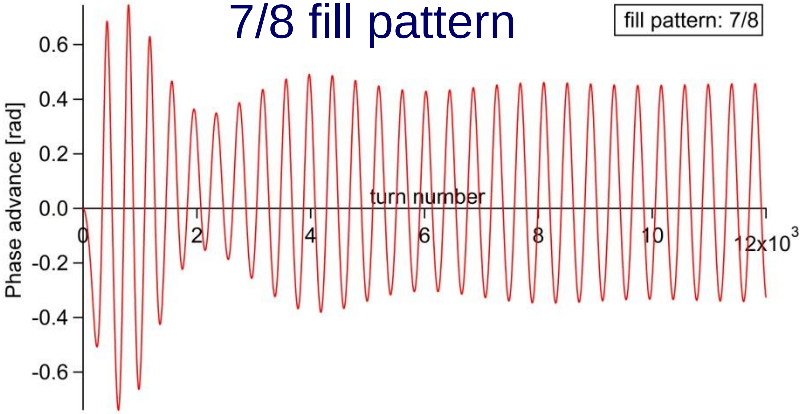
$\beta_h = 3$



Uniform fill pattern

Condition for bunch elongation to 50 ps

7/8 fill pattern

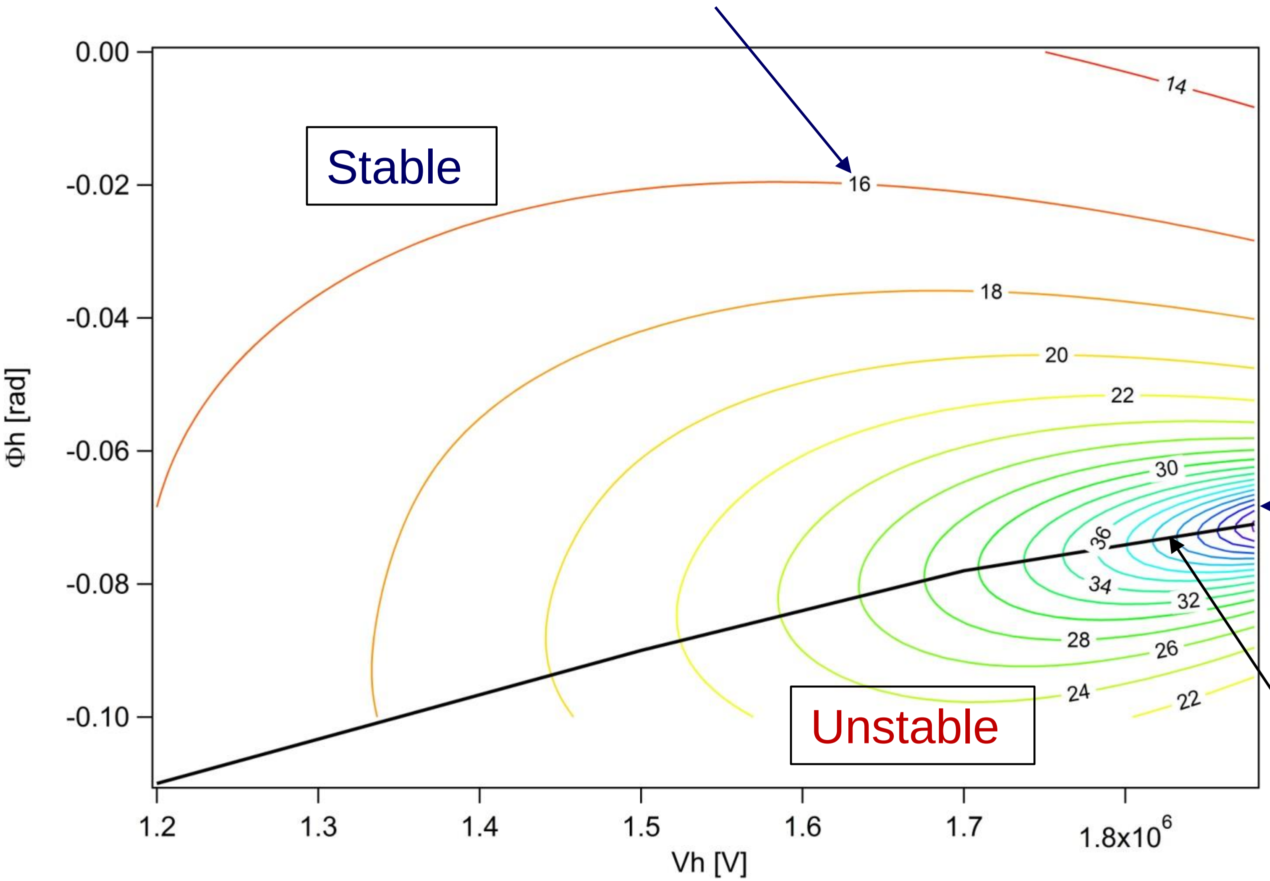


- It looks like AC Robinson instability,
- BUT: needs to be checked with multibunch multiparticle tracking codes !

$\beta_h < 3$: AC like instabilities also for uniform filling

MULTIBUNCH / SINGLE PARTICLE TRACKING – ROBINSON

Bunch length computed with theoretical formula for the obtained total voltage



5 active NC cavities

$\beta_h = 5$

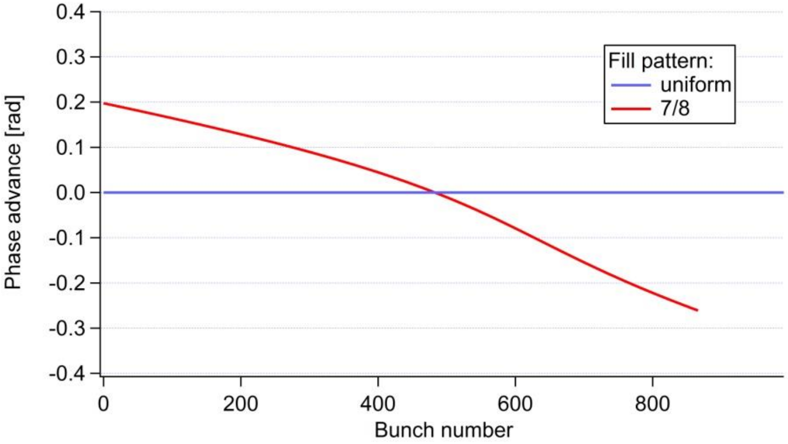
UNIFORM filling

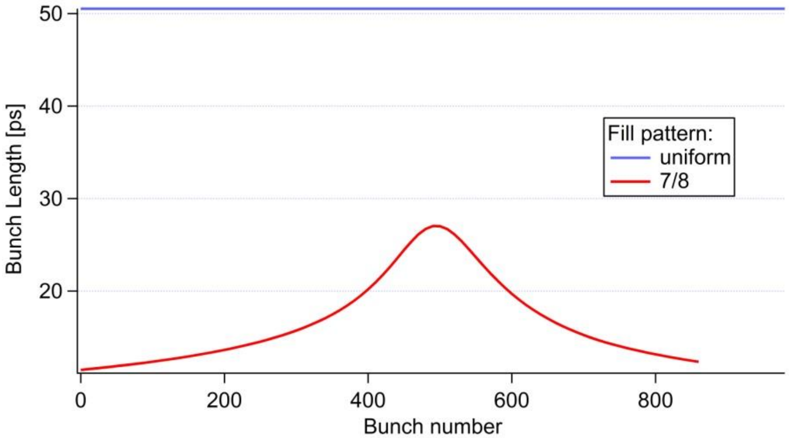
Optimum Bunch Lengthening

DC Robinson threshold given by Tracking*

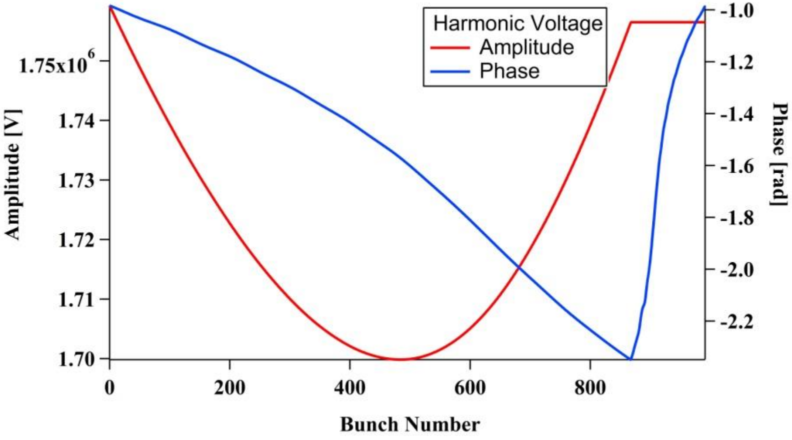
MULTIBUNCH / SINGLE PARTICLE TRACKING – ROBINSON & PHASE TRANSIENTS

Passive SC Cavity: R/Q = 90 Ω , Q_0 = 2e8





# SC passive Cavities	1	2	3	4	5
Phase Transient [rad]	0.45	0.46	0.54	0.58	0.67



CONCLUSIONS OF THESE VERY PRELIMINARY CALCULATIONS

1. **Active normal conducting cavities**
   - Integration of synchrotron equation indicates that strong beam loading from the harmonic cavities would be needed to avoid Robinson DC
   - This is in contradiction with multibunch single particle tracking results requiring high β_h for stability
   - Is the obtained AC like instability real? -> to be checked with multiparticle multibunch tracking
   - Working points around $[V_{h,opt}, \phi_{h.opt}]$ look close to region of instability: this also needs to be confirmed
2. **Passive Super3HC like SC cavities**
   - Former studies indicate that bunch lengthening operation at low current (e.g. few bunch fillings) is unstable (Robinson AC) unless several SC cavities are installed
   - Phase transients with passive harmonic cavities, even with low R/Q as for SC cavities, seem to be stronger than with active cavities: to be confirmed
3. **More studies are needed**
   - The results presented here are very preliminary and partially contradictory
   - We decided to show them in order to trigger discussions and motivate further studies