Basic rules for the design of RF Controls in High Intensity Proton Linacs

Particularities of proton linacs wrt electron linacs …

- Non-zero synchronous phase

  ⇒ needs reactive beam-loading compensation

- Phase slippage (inside and outside cavities)

  ⇒ larger sensitivity to cavity field fluctuations

- Different Dynamic properties of a given cavity family + phase slippage

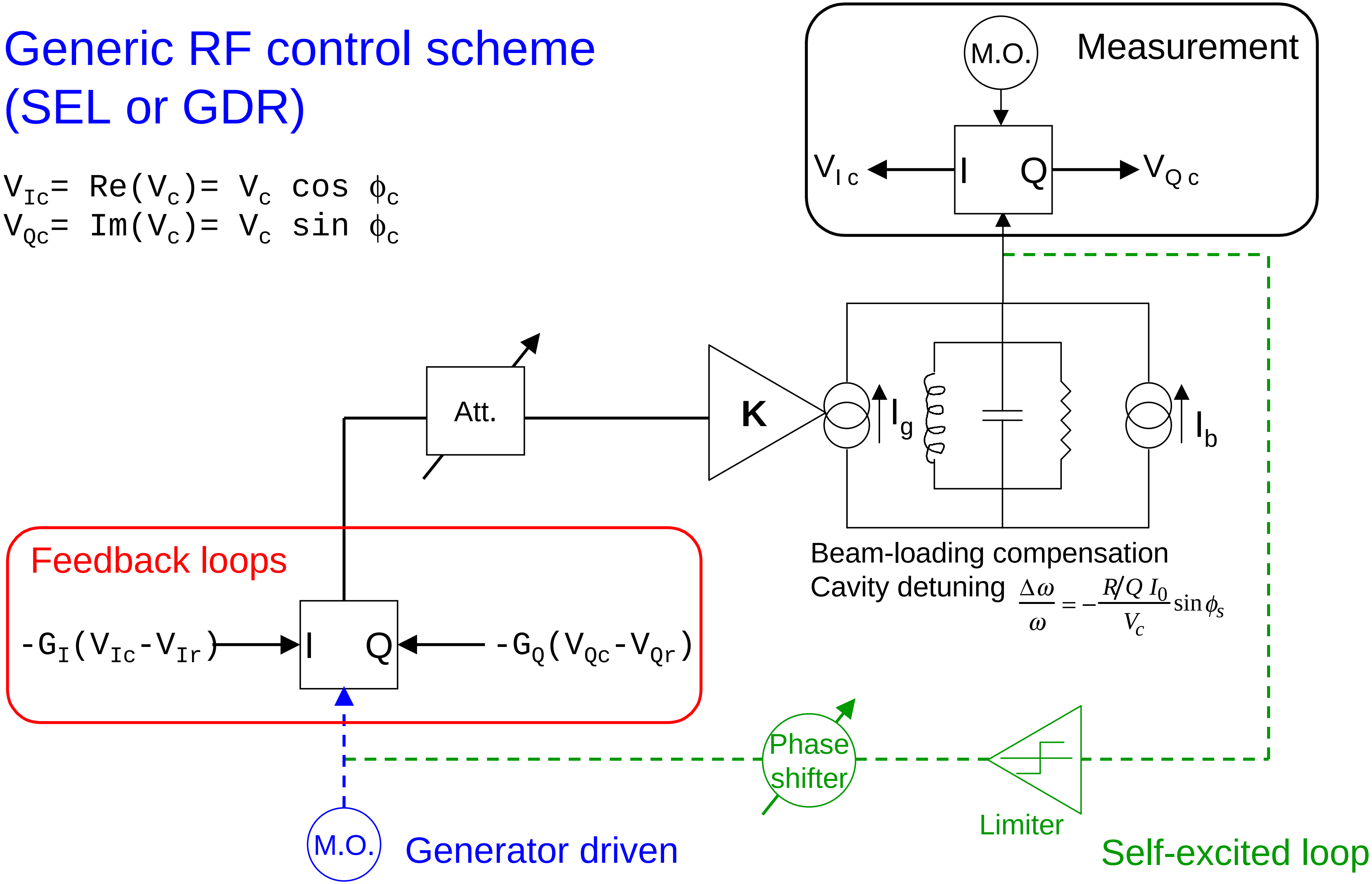
  ⇒ groups of multiple cavities driven by 1 common klystron

  can only be used at sufficiently high energy

Generic RF control scheme (SEL or GDR)

$V_{Ic} = Re(V_c) = V_c \cos \phi_c$

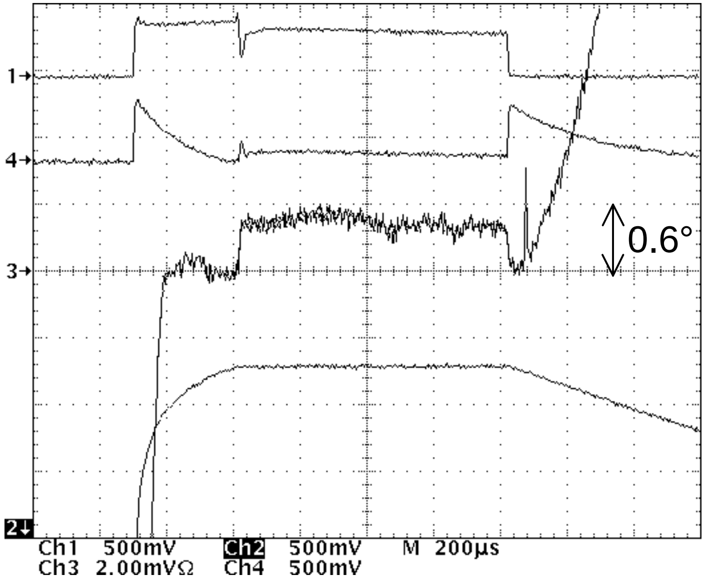
$V_{Qc} = Im(V_c) = V_c \sin \phi_c$

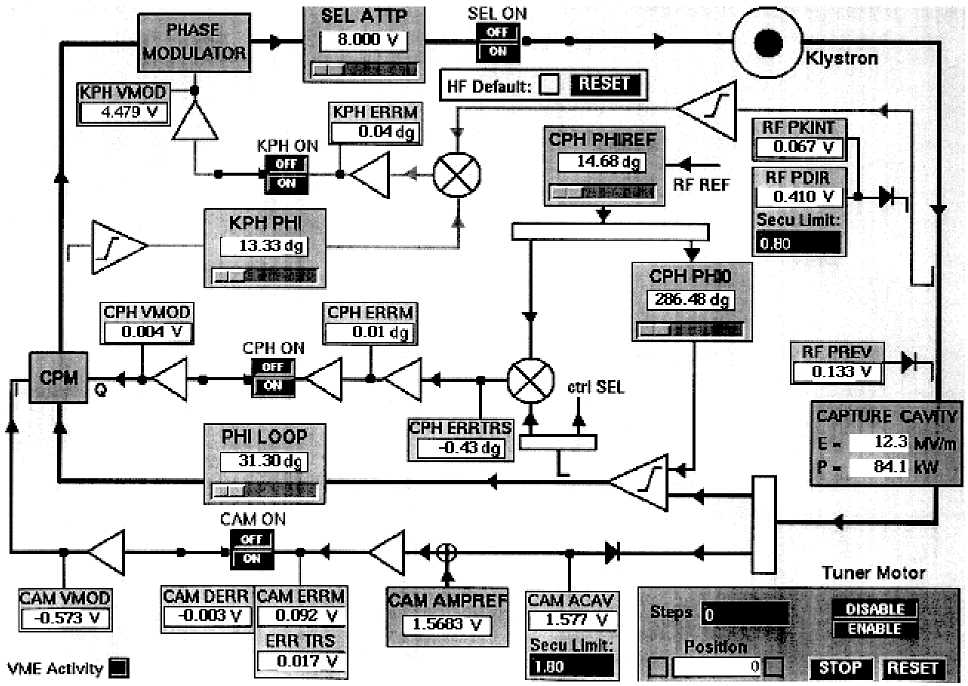


Example of SEL scheme with analog control system implemented on SC cavity with non-relativistic beam (ϕ_b = 30°) = TTF capture cavity (Ein = 250 keV)

Main features :

- self-excited loop (which ensures the cavity frequency tracking during the filling time)
- Cavity field controlled by means of I/Q modulator (during filling and beam-on time)
- starting phase of the self oscillator fixed by injection of a very low level signal
- klystron phase loop including a phase modulator to compensate any phase shift of the klystron





tests at DESY in February 1997 Eacc=12.5 MV/m, 6 mA

Amplitude & phase errors : ± 4 10^{-4} & ± 0.1°peak-to-peak fluctuations mainly from high frequency noise (uncorrelated from cavity to cavity ⇒ small effect on beam energy spread)

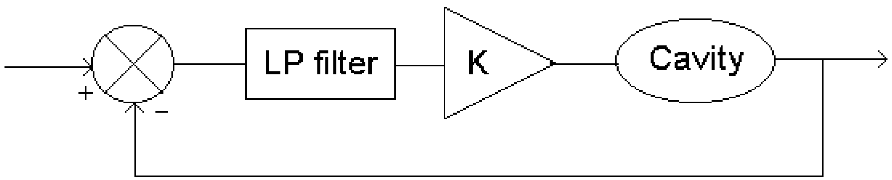
Basic Model for Gain-Stability Considerations

2 Control loops for field stabilization in cavity : real part loop and imaginary part loop

These 2 loops can be considered as independent for the stability discussion, having the same transfer function. A simple representation can be found with several, but however realistic assumptions in the case of SC cavity :

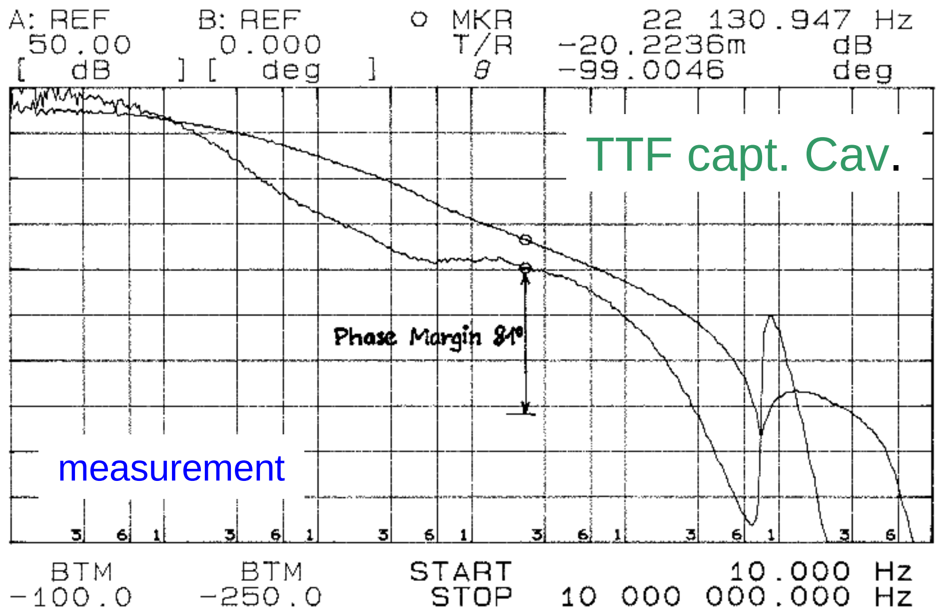
- klystron and I/Q modulator bandwidths are much higher than that of the cavity,
- closest harmonic mode (5π/6 for SNS and 8π/9 for TESLA about 800 kHz from the fundamental mode in both cases) is filtered out properly using HF pass-band filter and audio notch filter.

Simple model for analog feedback



$$H_{LP}(p) = \frac{\omega_{LP}}{p + \omega_{LP}}, H_{cav}(p) = \frac{\omega_{cav}}{p + \omega_{cav}}, \omega_{cav} = \pi \cdot \frac{F_0}{Q_L}$$

For f_{LP} = 400 kHz, K = 180, F_0 = 1.3 GHz, and $Q_L = 3\ 10^6$, the phase margin from the model is 86°.

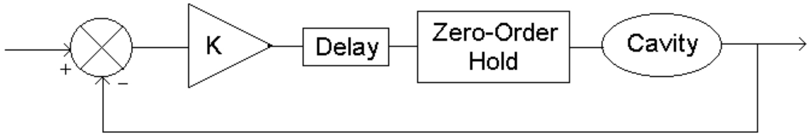


High gain and good phase margin are allowed for proportional analog feedback

Gain-Delay Discussion in Proportional Digital Feedback Control

(Assuming : sampling period = delay)

Without low-pass filter



Open loop transfer function

$$H_{analog}(p) = K.e^{-T_d p}\,\frac{1-e^{-T_d p}}{p}\,\frac{\omega_{cav}}{p+\omega_{cav}}$$

Z transform

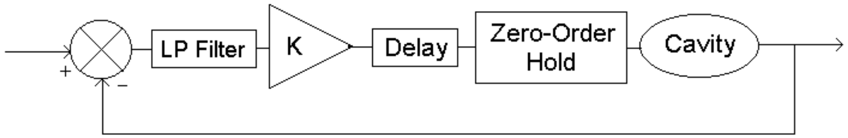
$$H_{digital}(z) = \frac{K\left(1-e^{-\omega_{cav}T_d}\right)}{z\left(z-e^{-\omega_{cav}T_d}\right)}$$

Roots of equation : $1 + H_{digital}(z) = 0$ should lie inside the unity circle for stability of the closed loop.

Limit of stability :

$$T_d = \frac{1}{\omega_{cav}} Ln\left(\frac{K}{K-1}\right), \text{ with } \omega_{cav} = \pi\frac{f_0}{Q_L}$$

With low-pass filter for noise reduction



Open loop transfer function

$$H(z) = \frac{K\left(1-e^{-\omega_{cav}T_d}\right)}{z\left(z-e^{-\omega_{cav}T_d}\right)}\,\frac{1-e^{-\omega_{LP}T_d}}{z-e^{-\omega_{LP}T_d}}$$

Closed loop discrete transfer function

$$G(z) = \frac{H(z)}{1+H(z)} = \frac{a}{z^3+b\,z^2+c\,z+d}$$

$$a = K\left(1-e^{-\omega_{cav}T_d}\right)\left(1-e^{-\omega_{LP}T_d}\right),$$

$$b = -\left(e^{-\omega_{cav}T_d}+e^{-\omega_{LP}T_d}\right),$$

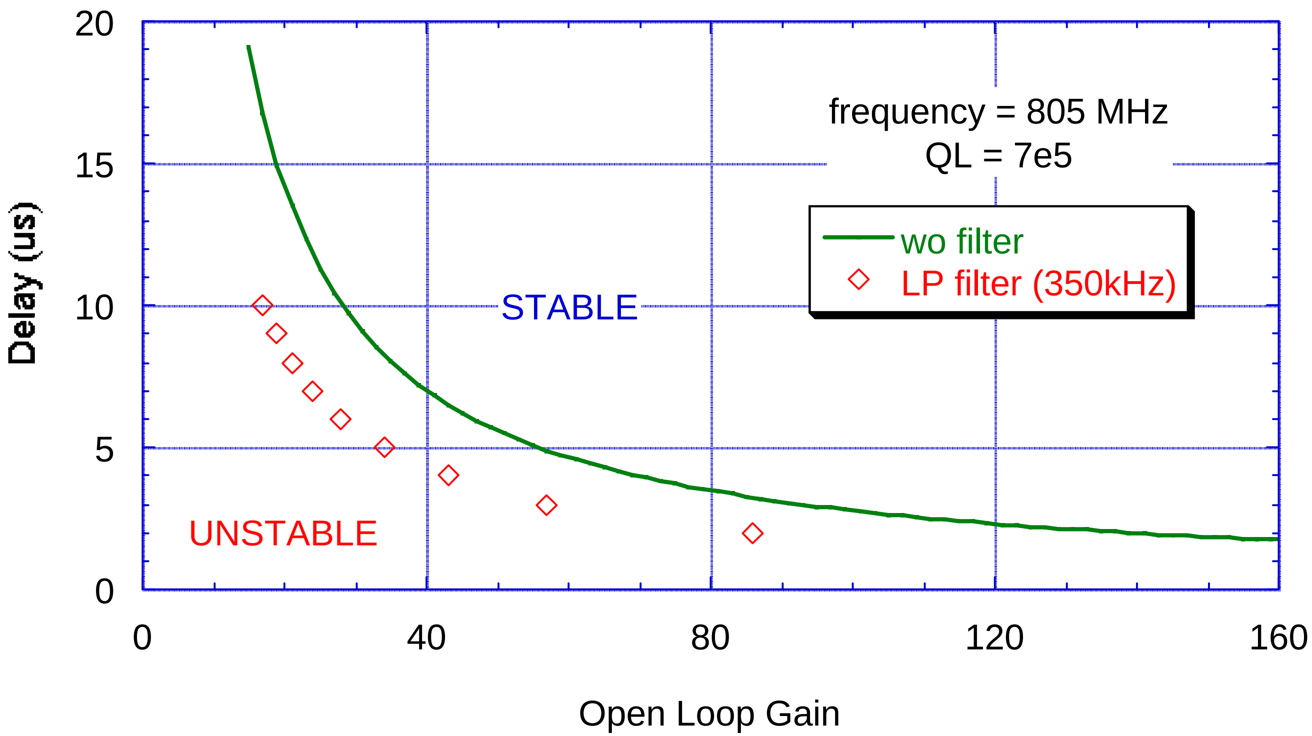
$$c = e^{-(\omega_{cav}+\omega_{LP})T_d}, \quad d = K\,(1+b+c)$$

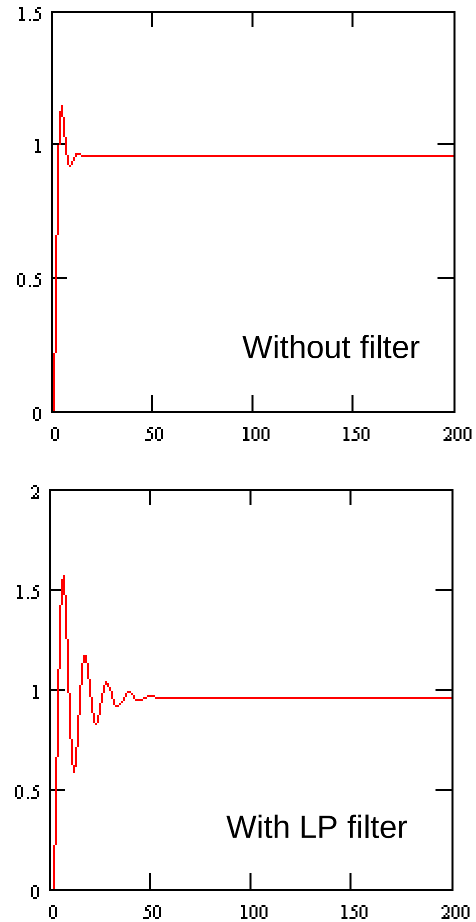
Recursion equation for time domain response

$$y_n = a\,x_{n-3} - b\,y_{n-1} - c\,y_{n-2} - d\,y_{n-3}$$

Gain-Delay Discussion in Proportional Digital Feedback Control

Results for the case of SNS





$K = 25$, $T_d = 5\ \mu s \Rightarrow$ Phase margin = 40° w/o filter and 30° with filter
Time response to a step excitation (on the right)

Stability could be more critical for digital feedback because of delay

Sampling of the measurement …

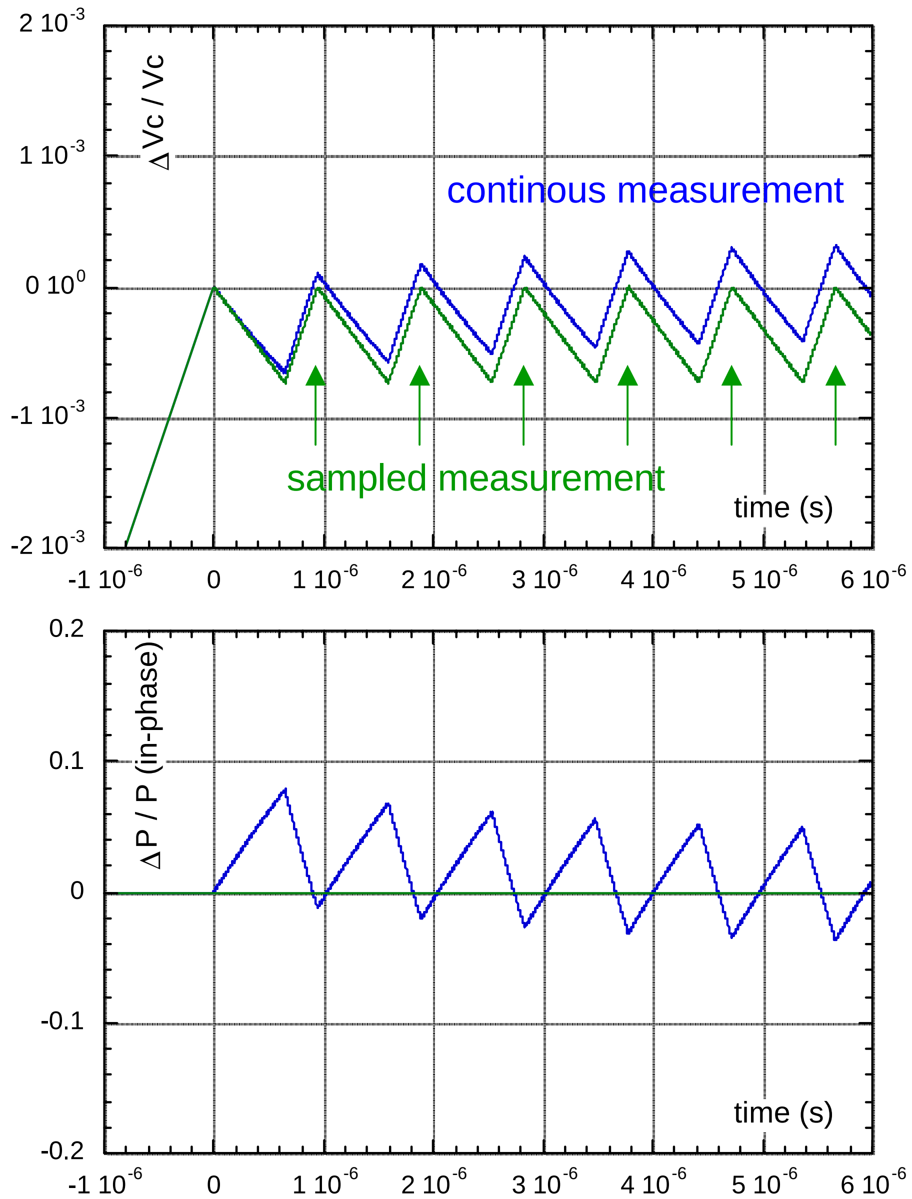
Bunch Trains are 945 ns spaced apart
⇒ Systematic cavity voltage drop
due to beam-loading

Better to sample field measurement
Just before beginning of bunch train*

In order to avoid systematic extra-power
from feedback loops
Even in absence of any perturbation

* in case of digital system with delay,
sampling time should be multiple
of bunch train spacing

Fast feedback loops (G=100)
1st medium-beta SNS cavity
Beam current = 52 mA
Chopper duty factor = 68 %



Beam-loading compensation

<u>during beam pulse</u>

detuning angle such that cavity voltage looks "real"

generator current and cavity voltage in phase $\phi_c=\phi_g$

$\tan\Psi + Y\sin\phi_b = 0$ steady-state regime with beam

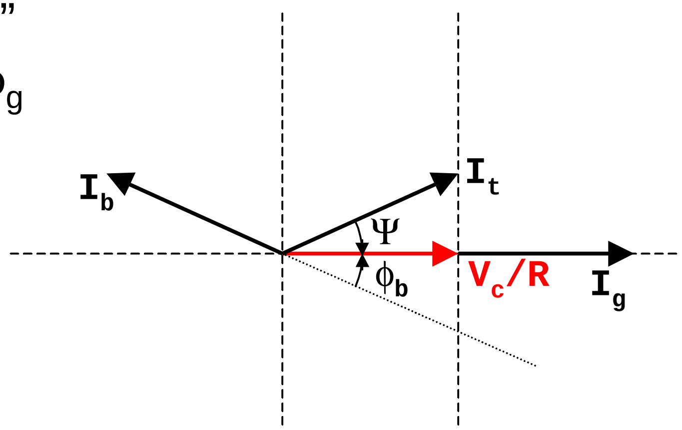
$V_g = (1+Y\cos\phi_b)\,V_c$ ("flat" V_c and $\phi_c$curves)

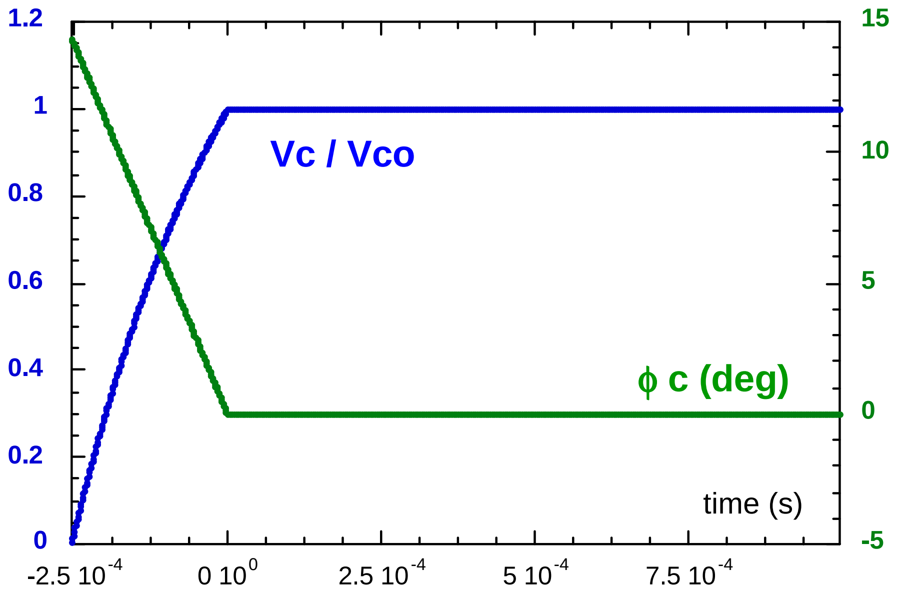
<u>during cavity filling</u>

One wants at fill end $\phi_c=\phi_g$ whatever the detuning

Automatically satisfied with SEL scheme

Not the case for a pure GDR scheme





$$P_g = P_g\frac{(\beta+1)^2}{4\beta}\left[(1+Y\cos\phi_b)^2 + (\tan\Psi + Y\sin\phi_b)^2\right]$$

beam - loading parameter $Y = \dfrac{R_L I_b}{V_c}$

detuning angle $\tan\Psi = 2\,Q_L\dfrac{\Delta\omega}{\omega}$

Simulation code = PSTAB

- initially developed for relativistic beams has been extended to low beta beams
- can handle all major field error sources
  (Lorentz forces, microphonics, input energy offsets, beam charge jitter,
  multiple cavities driven by one single power source, etc)
- includes feedback system and extra power calculation (+ delay for digital system)
- with N cavities driven by a common klystron,
  solves the 6xN coupled differential equations per power source :

- 3 differential equations per cavity for beam-cavity interaction

once the linac configuration has been defined (cavity types, number of cryomodules, design accelerating field and synchronous phase) a reference particle is launched through the linac in order to set the nominal phase of the field with respect to bunch at the entrance of all cavities

- 3xN equations per klystron for cavity field

dynamics of each resonator described by 2 first order differential equations,
plus another one modelling dynamic cavity detuning by the Lorentz forces
beam-loading is modelled by a cavity voltage drop during each bunch passage with a magnitude varying from cavity to another (particle speed varies)

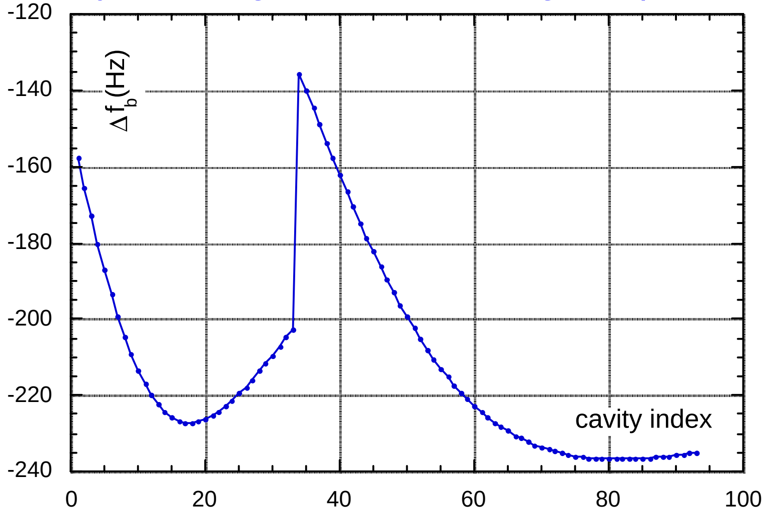
To minimize the needed RF power :

1) Qex is set near the optimal coupling " 7.10^5 for SNS
2) Cavity is detuned to compensate the reactive beam-loading due ϕ_s ? 0
   and fine tuning adjustement for minimizing Lorentz force effects

Example of PSTAB simulations with SNS parameters

```
Beam parameters
***************
Peak Beam current (mA)  :  52.
Current fluctuation (%) :  0.
Harmonic (Frf/Fb)       :  2.
Nb of bunches / train   : 260
Nb of missing bunches   : 120
Nb of bunch trains      : 1060
```

Cavity detuning for beam-loading compensation

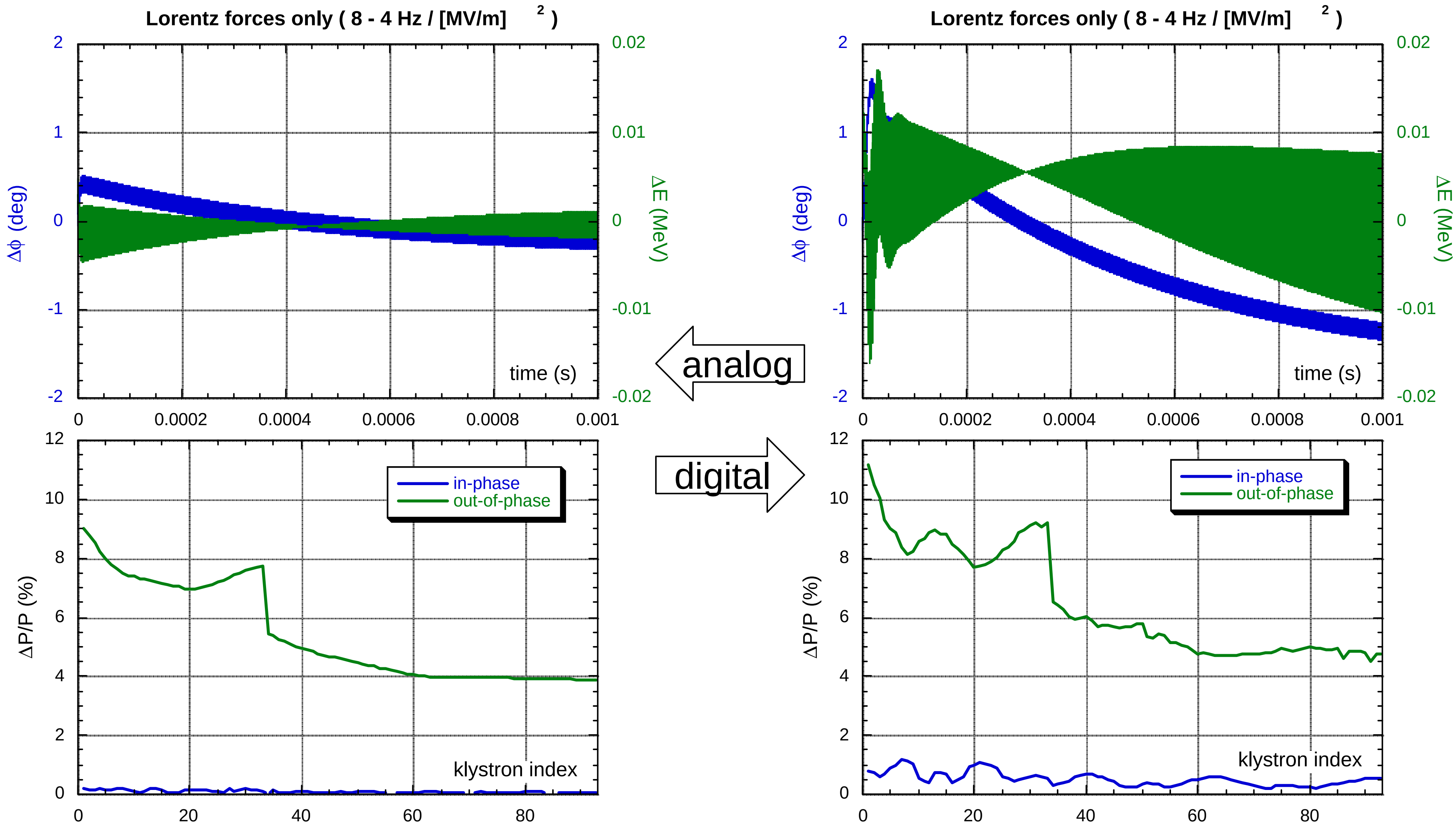


2 systems were tested :
analog (G=100) & digital (G=25 delay 4.7us)

```
Linac Description
*****************
Starting Energy (MeV)   : 185.6
Nb sectors              :  2

*** Sector with Cavity Type 1
Acc gradient (MV/m)       :  10.11
Nb Cav / cryomodule       :  3
Nb cryomodules            :  11
Cavity spacing (m)        :  0.51
Inter-cryom drift (m)     :  2.7752
Nb cavities / Klystron    :  1
Beam phase standard (deg) : -22.

*** Sector with Cavity Type 2
Acc gradient (MV/m)       :  12.56
Nb Cav / cryomodule       :  4
Nb cryomodules            :  15
Cavity spacing (m)        :  0.48
Inter-cryom drift (m)     :  2.866
Nb cavities / Klystron    :  1
Beam phase standard (deg) : -22.

    Total Nb cavities = 93
    Total Nb klystrons = 93

Linac Phasing
*************
    Sector 0  Ending Energy = 185.600
    Sector 1  Ending Energy = 388.526
    Sector 2  Ending Energy = 974.595
```

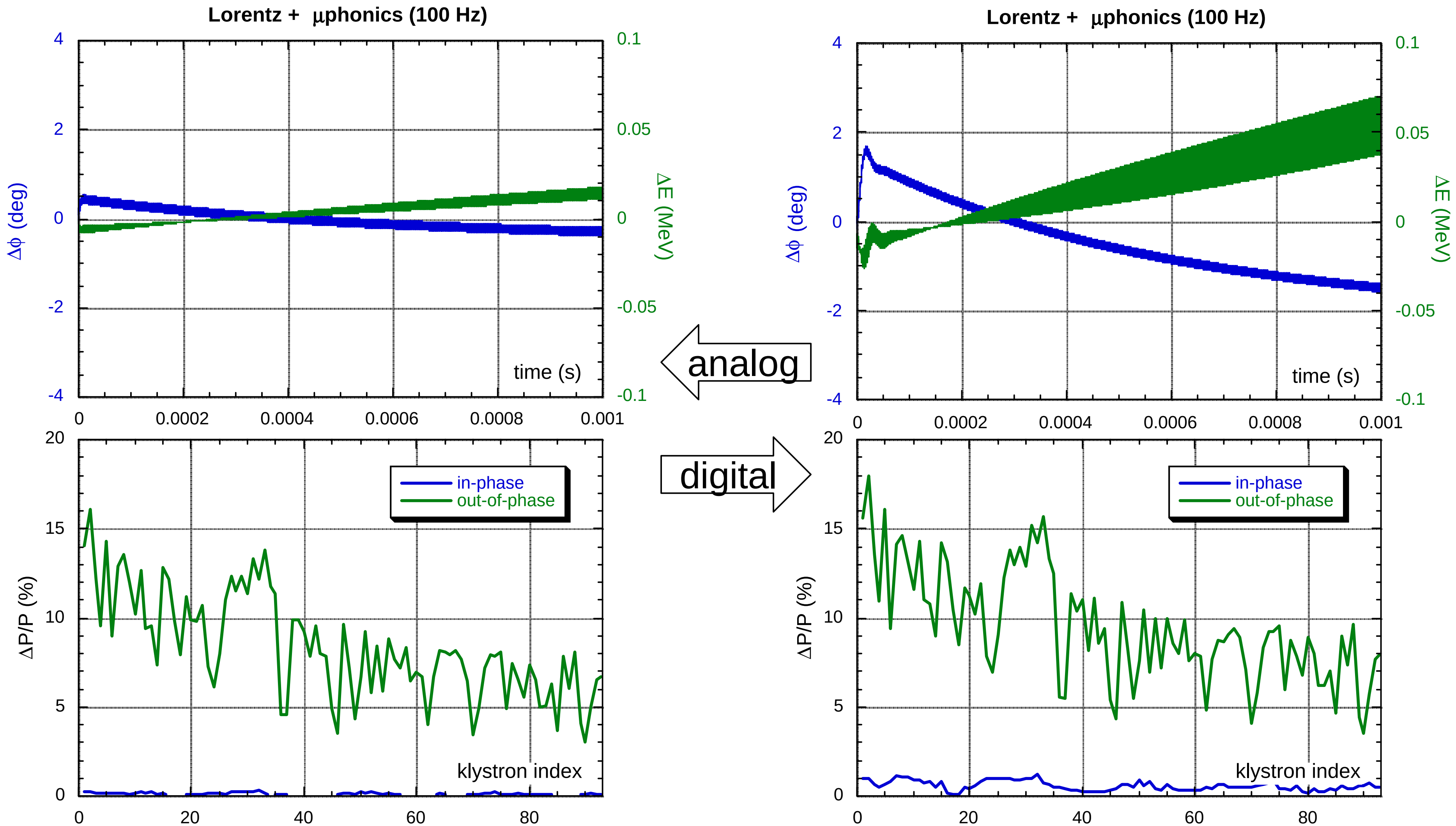
⇒ Lorentz forces effects

In order to decrease RF power ⇒ pre-detuning of the cavity ($f_{res} = f_{ope}$ at approximately half the beam pulse)
Total detuning = Sum of detunings for Lorentz forces + beam-loading compensation



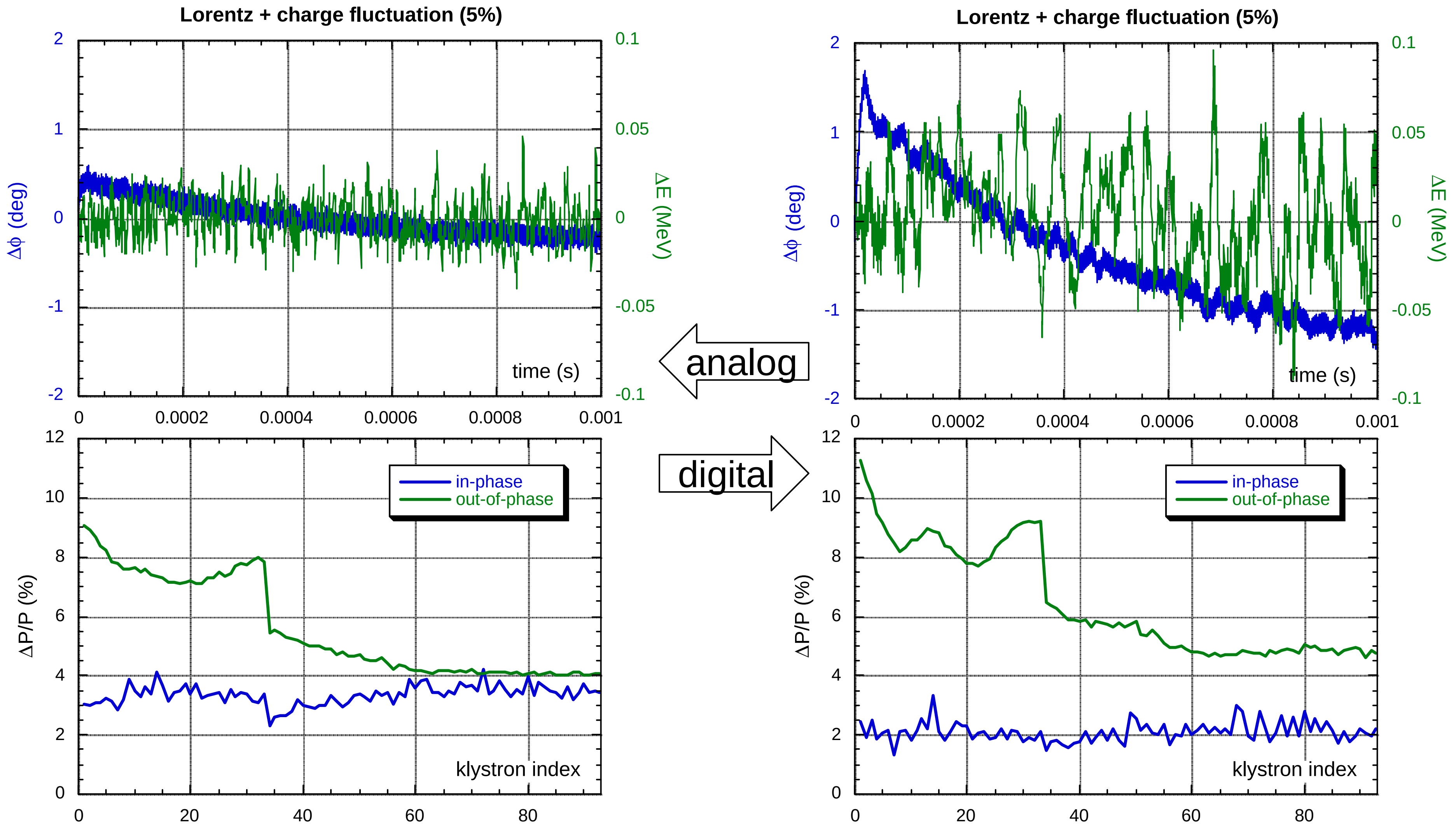
⇒ Additional microphonics effects

With mechanical vibrations, feedback loops closed during the filling time, following pre-determined amplitude and phase laws, to ensure min RF power during beam pulse



⇒ Additional current fluctuation effect

With random bunch charge fluctuation, the feedback system prevents from dramatic cumulative effects of several consecutive bunch charge errors

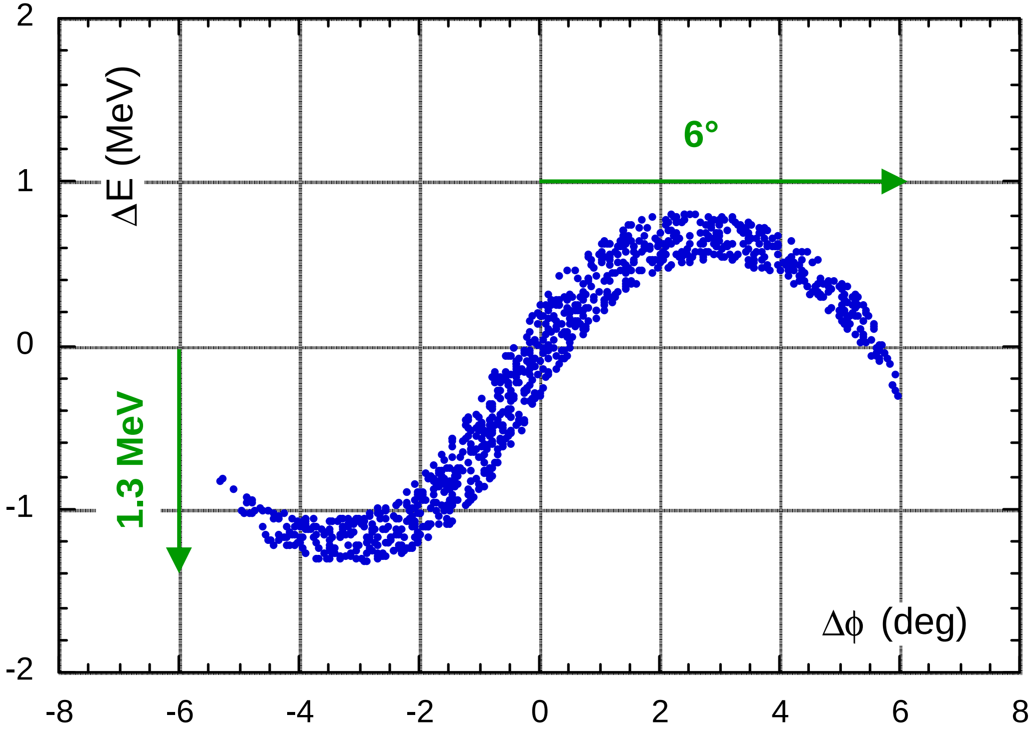


⟹ input beam offset

With random energy and phase errors of the input beam (**± 1 MeV ± 1 deg**) and assuming no fluctuations of the cavity fields

⇒ the final energy and phase can not be smaller than **1.3 MeV and 6 deg**.

input beam offset (± 1 MeV ± 1 deg)
with constant fields



SEL scheme **analog system** **digital system (4.7 µs delay)**

	ΔE max (keV)	Δϕ max (deg)	$\Delta P/P_I$ (%)	$\Delta P/P_Q$ (%)
Lorentz forces only 8 - 4 Hz/[MV/m]^2	4.8 17.1	0.51 1.61	0.2 1.2	9.0 11.2
with µphonics A=100 Hz Freq = 100 Hz	17.8 70.4	0.53 1.68	0.3 1.3	16.1 17.9
with µphonics A=100 Hz Freq = 1000 Hz	40.7 158.5	0.43 1.78	0.3 1.3	15.3 16.9
with tuning drift ± 100 Hz (random)	12.3 57.6	0.54 1.75	0.3 1.2	16.6 18.3
with charge fluctuation ± 5 % (random)	46.5 96.3	0.59 1.68	4.2 3.3	9.1 11.3
with input beam offset ± 1 MeV ± 1 deg (random)	1303.7 1329.0	6.14 6.76	5.9 4.1	11.6 11.1
multi-perturbation*	1321.0 1405.5	6.25 7.10	7.8 5.7	18.5 18.0

* Lorentz forces + µphonics (Freq=100 Hz) + charge fluctuation + input beam offset

GDR scheme **analog system** **digital system (4.7 µs delay)**

	ΔE max (keV)	$\Delta\phi$ max (deg)	$\Delta P/P_I$ (%)	$\Delta P/P_Q$ (%)
Lorentz forces only 8 - 4 Hz/[MV/m]^2	5.7 27.9	0.51 1.51	0.5 2.0	8.7 9.4
with µphonics A=100 Hz Freq = 100 Hz	17.8 96.3	0.52 1.56	0.7 3.1	15.5 15.7
with µphonics A=100 Hz Freq = 1000 Hz	39.8 165.3	0.42 1.60	0.8 3.2	14.7 14.7
with tuning drift ± 100 Hz (random)	12.6 48.4	0.54 1.63	0.8 3.2	16.0 16.4
with charge fluctuation ± 5 % (random)	46.6 108.3	0.59 1.58	4.3 4.2	8.8 9.5
with input beam offset ± 1 MeV ± 1 deg (random)	1304.1 1332.5	6.14 6.70	6.2 5.1	11.2 9.4
multi-perturbation*	1322.1 1407.1	6.25 7.05	8.2 7.4	17.9 15.6

* Lorentz forces + µphonics (Freq=100 Hz) + charge fluctuation + input beam offset

Conclusion

- SEL scheme vs GDR scheme

  SEL requires smaller in-phase power and larger out-of-phase power
  (SEL keeps naturally the amplitude but shifts the phase)

- Analog vs digital

  generally digital with delay increases extra-power and errors
  unless total delay time " 1 µs

  for a random input beam offset :

    extra-power is slightly smaller but final errors are larger
    (because feedback can't follow with sudden changes)

Multiple cavities per klystron

↳ With relativistic electron beams, multiple cavities powered by a single power source easily controlled by the vector sum of the cavity voltages

↳ With proton beams, even when the vector sum kept perfectly constant individual cavity voltages can fluctuate with large amplitudes
(phase slippage + change of dynamic behaviour of low-β cavities as energy ↗)

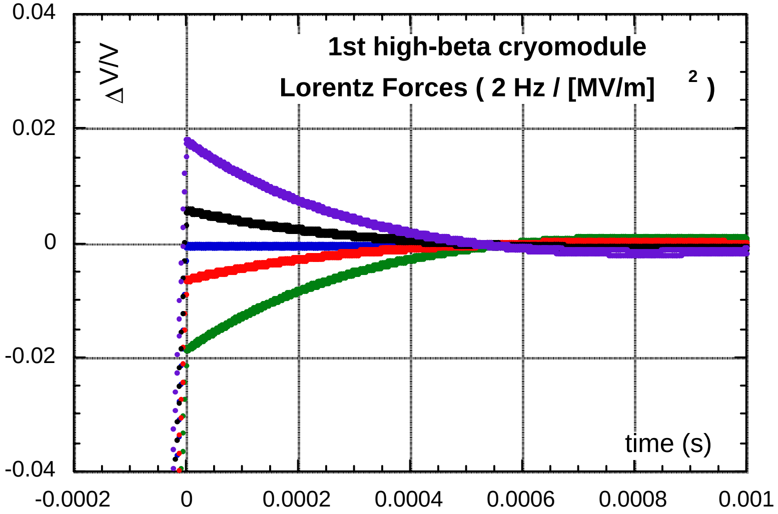
We could however envisage
to feed individually the cavities at the low energy part of the SC linac &
to feed groups of cavities by common klystrons at the high energy part
(lower phase slippages + closer dynamic cavity properties)

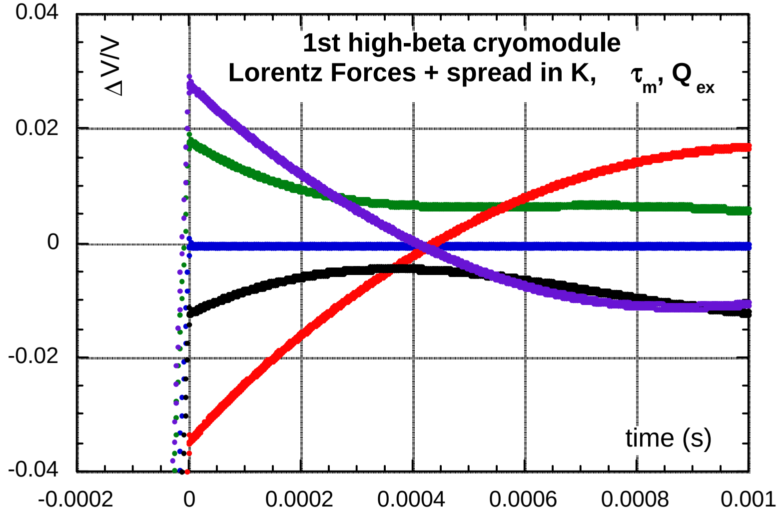
For example, groups of 4 cavities only for high-β cavities in SNS Linac
Simulations with spreads in

➢ Lorentz force detuning	K	20 %	2 Hz / $[MV/m]^2$
➢ mechanical time constant	τ_m	20 %	
➢ cavity coupling	Q_{ex}	20 %	

Ex. Cavity voltages of 1st high-beta cryomodule

(analog system G = 100)

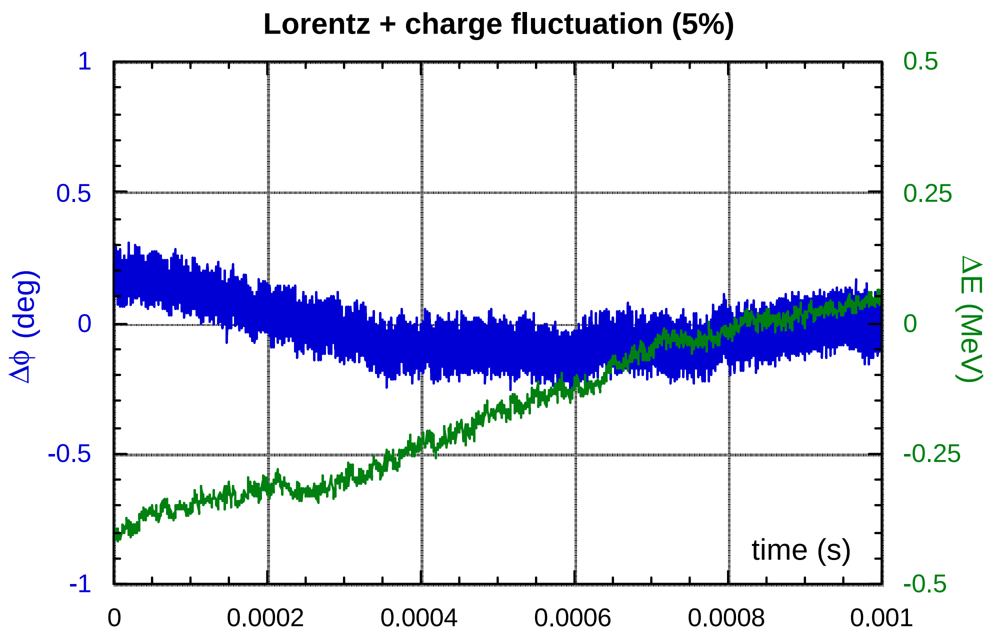


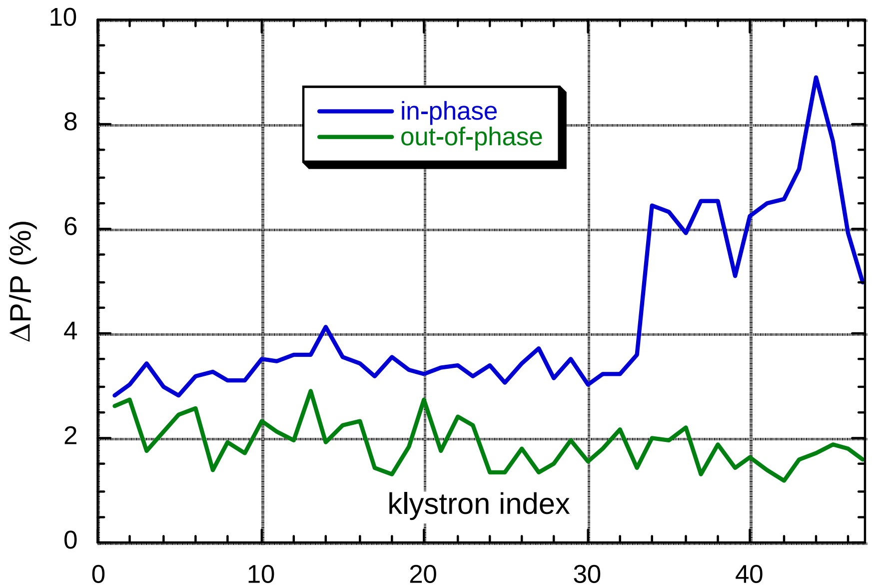


⇒ Lorentz forces & charge fluctuation (5%) effects

Bunch energy deviations at beginning mainly induced by Qex spread

Extra-power at end mainly induced by current fluctuations





SEL scheme **analog system**

	ΔE max (keV)	$\Delta\phi$ max (deg)	$\Delta P/P_I$ (%)	$\Delta P/P_Q$ (%)
Lorentz forces only 4 - 2 Hz/[MV/m]^2	418	0.26	1.6	2.8
with µphonics A=100 Hz Freq = 100 Hz	688	0.93	2.5	6.4
with charge fluctuation ± 5 % (random)	418	0.31	8.9	2.9
with input beam offset ± 1 MeV ± 1 deg (random)	1600	6.1	11.9	5.8
multi-perturbation*	1875	6.4	16.3	8.9

* Lorentz forces + µphonics (Freq=100 Hz) + charge fluctuation + input beam offset