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SPL
LLRF simulations
Feasibility and constraints for operation with more than one cavity per klystron
Power overhead

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Acknowledgements and Participation:
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Outline

SPL parameters

Optimization of Q_{ext}

Delay and Power budget

Lorentz Force detuning

Layouts (1 cavity / 2 cavities per klystron) and
perturbations to be considered in the simulations

First simulation results for one high energy RF station (O. Piquet & M. Hernandez)

SPL parameters

SPL cavities and frequency: 704.4 MHz, cooling @ 2K He-II

Low energy part : β=0.65, 5–cell cavities, 6 cavities/cryostat,
60 cavities, R/Q = 320 Ω_{linac}
1 klystron / cavity → likely baseline

High energy part: β=1, 5-cell cavities, 8 cavities/cryostat,
160 for 4 GeV (200 for 5 GeV) cavities, R/Q = 525 Ω_{linac}
One 1.x MW klystron for 2 cacvities (LPSPL)
One 1.x MW klystron for 1 cavity (HPSPL)
One ~5.5MW klystron per 4 cavities (previous)

SPL requirement: for β=1 → 25 MV/m
Stability: 0.5% and 0.5 degrees for V_{acc} during beam pulse

LPSPL:	4 GeV	2 Hz	1.2 ms beam pulse	20 mA beam current (DC)
HPSPL:	5 GeV	50 Hz	0.4 ms / 1.2 ms beam pulse	40 mA beam current (DC)

Cavity loaded Q ~ 10^6 HPSLP: ppm change of beam pulse length ??
Fixed coupler position optimized for 40 mA operation, will give reflection @ 20 mA
ϕ_s=15 degrees

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Linac definitions

Circuit, Synchrotrons

$$P = \frac{1}{2} V \cdot I$$

$$V = R_{\text{circuit}} \cdot I$$

$$P = \frac{1}{2} \frac{V^2}{R_{\text{circuit}}}$$

$$P = \frac{1}{2} R_{\text{circuit}} I^2$$

same V and I peak values

Linac

$$P = \frac{1}{2} V \cdot I$$

$$V = \frac{1}{2} R_{\text{linac}} \cdot I$$

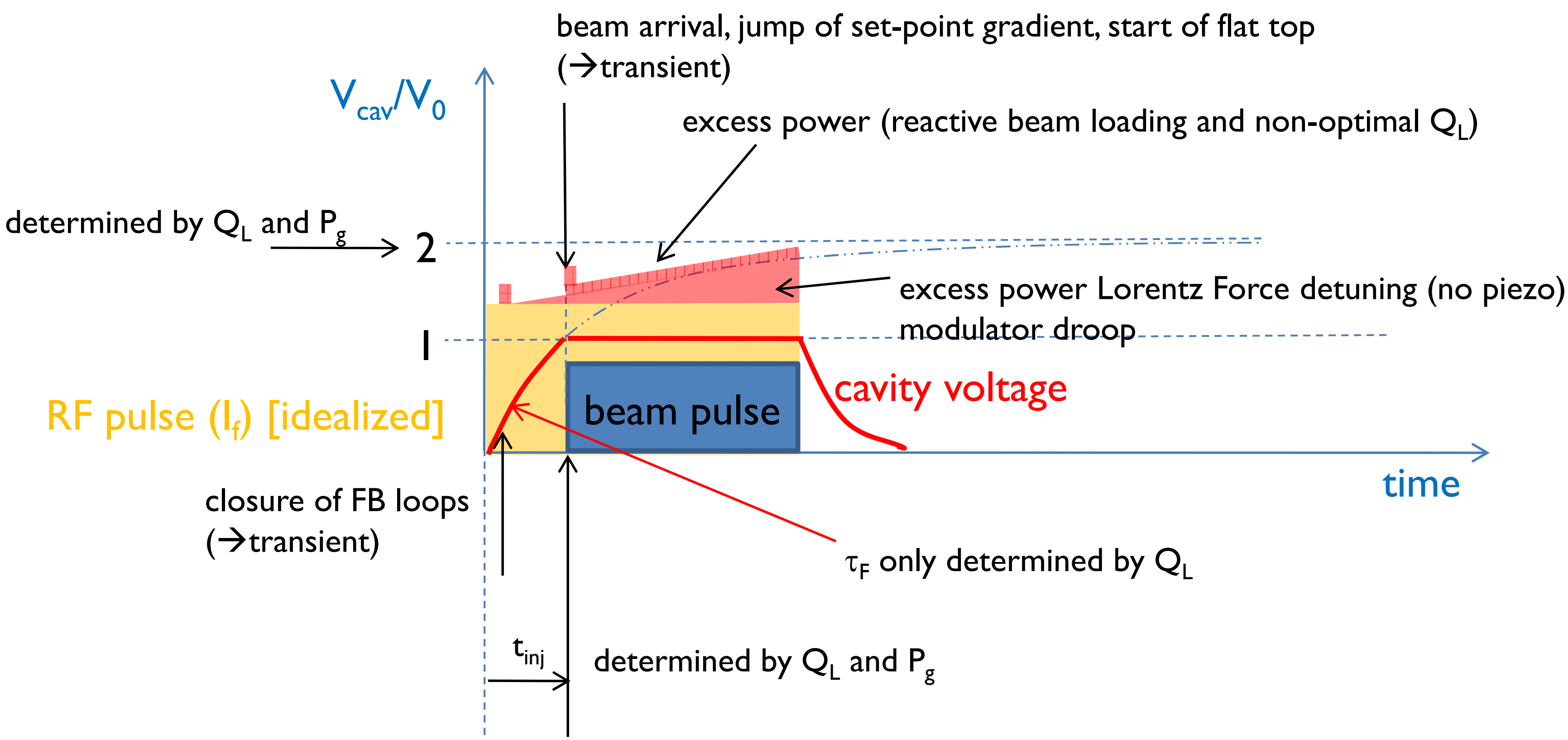
$$P = \frac{V^2}{R_{\text{linac}}}$$

$$P = \frac{1}{4} R_{\text{linac}} I^2$$

$$R_{\text{circuit}} = \frac{1}{2} R_{\text{linac}}$$

Principle of pulsed operation

SPL (with beam)



Parameters for 40 mA operation, optimized coupling for zero reflected power during beam pulse

frequency:	704.4 MHz
accelerating gradient of β=1 cavities:	25 MV/m
length of cavity L=β5λ/2:	1.06 m
cavity accelerating voltage for β=1	26.5 MV
synchronous phase angle ϕ_s	15 degrees
power delivered to beam	$P_b = I_b \cdot V_{acc} \cdot \cos\varphi_s = 1.0239\ \text{MW}$
zero refl. power during beam pulse	$Q_{ext} \approx Q_L = \dfrac{V_{acc}}{(R/Q) I_b \cos\varphi_s} = 1.3064 \times 10^6$
filling of cavity	$V(t) = 2V_0\left(1 - e^{-t/2\tau_F}\right) = 2V_0\left(1 - e^{-t/\tau_V}\right)$
filling time	$\tau_V = 2\tau_F = \dfrac{2Q_L}{\omega_0} = 0.5903\ \text{ms}$
beam injected at	$t_{inj} = \tau_V \ln 2 = \tau_F \ln 4 = 0.4092\ \text{ms}$
forward power for filling	1.0239 MW

$$P_{fwd} = \frac{V_{fwd}^2}{(R/Q) Q_L}$$

$$V_{acc} = V_0 = V_{fwd}$$

Parameters for 20 mA operation, optimized coupling for zero reflected power during beam pulse

frequency:	704.4 MHz
accelerating gradient of β=1 cavities:	25 MV/m
length of cavity L=β5λ/2:	1.06 m
cavity accelerating voltage for β=1	26.5 MV
synchronous phase angle ϕ_s	15 degrees

power delivered to beam $P_b = I_b \cdot V_{acc} \cdot \cos\varphi_s = 512\ \text{kW}$

zero reflected power during beam pulse $Q_{ext} \approx Q_L = \dfrac{V_{acc}}{(R/Q) I_b \cos\varphi_s} = 2.6128 \times 10^6$

filling of cavity $V(t) = 2V_0\left(1 - e^{-t/2\tau_F}\right) = 2V_0\left(1 - e^{-t/\tau_V}\right)$

filling time $\tau_V = 2\tau_F = \dfrac{2Q_L}{\omega_0} = 1.1806\ \text{ms}$

beam injected at $t_{inj} = \tau_V \ln 2 = \tau_F \ln 4 = 0.8184\ \text{ms}$

forward power for filling 512 kW

$$P_{fwd} = \frac{V_0^2}{(R/Q) Q_L}$$

$$V_{acc} = V_0 = V_{fwd}$$

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Forward power for reactive beam loading compensation

$$P_{\text{reactive BL comp}} = \frac{1}{4} Q_{\text{ext}} (R/Q) \left| I_{\text{b}} \cdot \sin \varphi_{\text{s}} \right|^2$$

optimized cases (40 mA , 20 mA)

$$Q_{\text{ext}} I_{\text{b}} = const = 1.3064 \times 10^6 \times 40 \ \text{mA} = 52256 \ \text{A}$$

$$P_{\text{reactive BL comp}} = 4.5944 \ \text{MV} \times I_{\text{b}}$$ for ϕ_s= 15 degrees

9.2 kW for 20 mA

18.4 kW for 40 mA

must be added to power budget during beam pulse
or corrected by detuning; then situation for charging is no longer optimal and would require more power to follow the ideal case or more time:
solution half detuning ?

Parameters for 20 mA operation, with optimized coupling for zero reflected power during 40 mA beam pulse (1)

frequency:	704.4 MHz
accelerating gradient of β=1 cavities:	25 MV/m
length of cavity L=β5λ/2:	1.06 m
cavity accelerating voltage for β=1	26.5 MV
synchronous phase angle ϕ_s	15 degrees

power delivered to beam $P_b = I_b \cdot V_{acc} \cdot \cos\varphi_s = 512\ \mathrm{kW}$

chosen (optimal value for 40 mA) $Q_{ext} \approx Q_L = 1.3064 \times 10^6$

reflected current in steady state with beam $I_r = \frac{V_{acc}}{(R/Q)} \frac{1}{Q_{ext}} - I_b \cos\varphi_s = 19.3\ \mathrm{mA}$

reflected power in steady state with beam $P_{refl} = \frac{1}{4}(R/Q) \cdot Q_{ext} \cdot |I_r|^2 = 64\ \mathrm{kW}$

forward current in steady state with beam $I_f = \frac{V_{acc}}{(R/Q)} \frac{1}{Q_{ext}} + I_b \cos\varphi_s = 58.0\ \mathrm{mA}$

forward power in steady state $P_{fwd} = \frac{1}{4}(R/Q) \cdot Q_{ext} \cdot |I_f|^2 = 576\ \mathrm{kW}$

Parameters for 20 mA operation, with optimized coupling for zero reflected power during 40 mA beam pulse (2)

1) choice: keep forward power constant at arrival of beam: 576 kW, i.e. fill with higher power

2) choice: during filling use 512 kW

filling time fixed by coupling and not affected by available power

1) 512 kW

$$V_\infty = V_{\mathrm{fwd}} + V_{\mathrm{refl}} = 2\sqrt{P_{\mathrm{fwd}} Q_{\mathrm{L}} (R/Q)} = 37.48 \;\mathrm{MV} = \sqrt{2} V_0$$

$$V(t) = \sqrt{2} V_0 \left(1 - e^{-t/2\tau_{\mathrm{F}}}\right) \rightarrow V_0 \qquad \sqrt{2} - 1 = \sqrt{2} e^{-t_{\mathrm{inj}}/2\tau_{\mathrm{F}}}$$

$$t_{\mathrm{inj}} = 2\tau_{\mathrm{F,40\,mA,opt}} \ln \frac{\sqrt{2}}{\sqrt{2}-1} \approx 2.456 \times \tau_{\mathrm{F,40\,mA,opt}} \approx 0.7249 \;\mathrm{ms}$$

compared to 40 mA opt. $t_{\mathrm{inj}} = 2\tau_{\mathrm{F,\,40mA,opt}} \ln 2 \approx 1.386 \times \tau_{\mathrm{F,40\,mA,opt}} \approx 0.4092 \;\mathrm{ms}$

20 mA opt. $t_{\mathrm{inj}} = 2\tau_{\mathrm{F,20mA,opt}} \ln 2 \approx 1.386 \times \tau_{\mathrm{F,20\,mA,opt}} \approx 0.8184 \;\mathrm{ms}$

Parameters for 20 mA operation, with optimized coupling for zero reflected power during 40 mA beam pulse (3)

2) 576 kW $V_\infty = V_{\mathrm{fwd}} + V_{\mathrm{refl}} = 2\sqrt{P_{\mathrm{fwd}} Q_{\mathrm{L}} (R/Q)} \approx 49.73 \text{ MV} \approx 1.5 \times V_0$

$$V(t) \approx \frac{3}{2} V_0 \left(1 - e^{-t/2\tau_{\mathrm{F}}}\right) \rightarrow V_0 \qquad \frac{1}{3} \approx e^{-t_{\mathrm{inj}}/2\tau_{\mathrm{F}}}$$

$$t_{\mathrm{inj}} \approx 2\tau_{\mathrm{F,40\,mA,opt}} \ln 3 \approx 2.198 \times \tau_{\mathrm{F,40\,mA,opt}} \approx 0.648 \text{ ms}$$

compared to 40 mA opt. $t_{\mathrm{inj}} = 2\tau_{\mathrm{F,\,40mA,opt}} \ln 2 \approx 1.386 \times \tau_{\mathrm{F,40\,mA,opt}} \approx 0.4092 \text{ ms}$

20 mA opt. $t_{\mathrm{inj}} = 2\tau_{\mathrm{F,20mA,opt}} \ln 2 \approx 1.386 \times \tau_{\mathrm{F,20\,mA,opt}} \approx 0.8184 \text{ ms}$

$Q_{\mathrm{ext}} \approx Q_{\mathrm{L}} = 1.3064 \times 10^6$

- $t_{\mathrm{inj}} = 0.648 \text{ ms}$ — 0.576 MW, 2 cavities → 1.152 MW
- $t_{\mathrm{inj}} = 0.4092 \text{ ms}$ — 1.024 MW, 1 cavity → 1.024 MW

12.5 % more power required for two cavities / klystron due to non optimal Q_{ext}

Waveguide group delay

The maximum frequency range in which a rectangular wave guide supports the propagation of only one mode is one octave

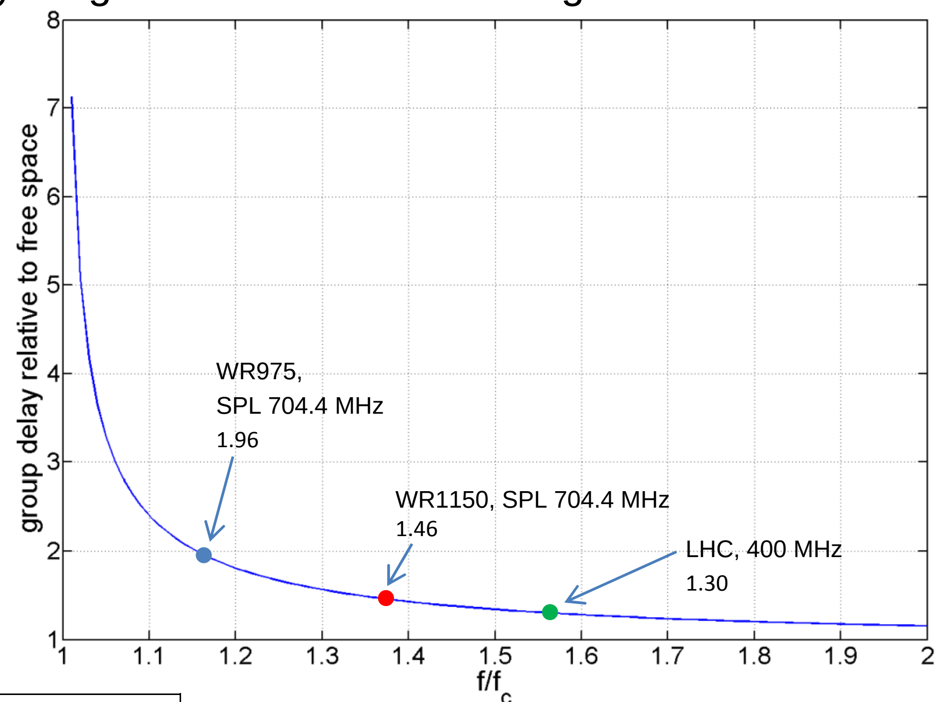
To obtain this maximum frequency range the width of the wave guide has to be at least a factor 2 of its height

The propagation constant is

$$\beta(\omega) = \frac{2\pi \cdot f}{c}\sqrt{1-\left(\frac{f_c}{f}\right)^2}$$

The group delay is

$$\tau_g = \frac{L/c}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$$



	WR-975	WR-1150	LHC (WR-2300)
cut-off in MHz	605	513	257
group delay (rel to free space)	1.96	1.46	1.3
group delay (rel to WR-975)	1	0.74	0.66
rel cross section	1	1.18	2.36
cross section for 200 waveguides (full height, in m**2), net	6.16	7.27	15.54

multiply by a factor 3-5 for required space

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Group delay budget (tentative)

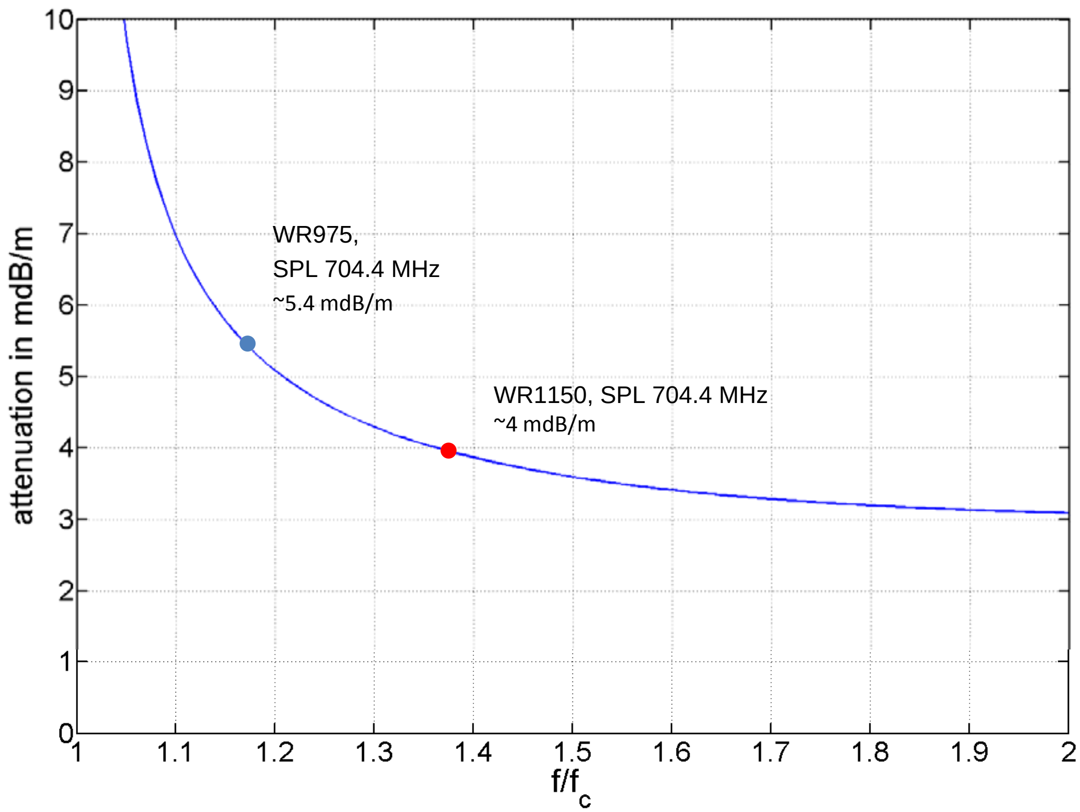
klystron:	250 ns ?
80 m waveguides (WR-1150)	360 ns (WR-1150)
80 m cabling (0.9 velocity factor)	270 ns
driver amplifier	40 ns
waveguide components (circulator etc.)	40 ns ?
local cabling (LLRF to klystrons etc.)	50 ns
LLRF latency	250 ns ?
total:	1260 ns
part related to 80 m distance (surface to underground)	630 ns (50 %)
savings 60 m → 15 m (2nd tunnel)	510 ns (40 %)

80 m seems ok (feedback does not need high bandwidth)

unknown, details to be studied: beam transients, chopping, HV ripple

Waveguide attenuation

From the attenuation point of view it is also better to stay away from the cut-off frequency, i.e. $f/f_c > 1.5$



Fundamental mode in full-height rectangular waveguide (Al 37.7×10^6 1/Ωm)
AL alloys, Al Mg Si 0.5 → 35 % to 45 % higher losses !

Power budget (very tentative)

power minimum two cavities / klystron	1152 kW
reactive beam loading reserve	20 kW
detuning res. (Lorentz Force + micr.ph.)	20 kW ?
transients for loops	50 kW
variation in Q_L	15 kW ?
variation in cavity parameters	15 kW ?
beam current fluctuations	40 kW ?
power at cavity input:	1302 kW ?

1532/1152 = 1.33

from klystron:	100%
end of life klystron reserve	0%
unusable (last 3%)	3%
waveguide losses	7% (more ?)
circulator losses	3%
reserve for imperfect matching	0% ?
ripple and noise due to HV	3% ?

→ 85%

klystron peak (saturated) power: 1532 kW → no reserve for unforeseen items

How much we need to stay away from klystron saturation – depends on klystron characteristics

Need simulations to better quantify these needs (see presentation by M. Hernandez)

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Lorentz Force Detuning (1)

Magnet field component of cavity field and image current result in a force (Lorentz force) that deforms the cavity shape and consequently changes its tune

The ensemble of the cavity mounted in its tuner frame and He vessel in the cryostat is a complex mechanical object with many mechanical modes of oscillation, usually with frequencies as low as 100 Hz to 200 Hz for the lowest longitudinal mode of oscillation.

Tune change due to mechanical mode of oscillation:

$$\frac{d^2\Delta\omega_m}{dt^2}+\frac{\omega_m}{Q_m}\frac{d\Delta\omega_m}{dt}+\omega_m^2\Delta\omega_m=-2\pi k_m\omega_m^2\left(\frac{V_{cav}}{L_{acc}}\right)^2$$

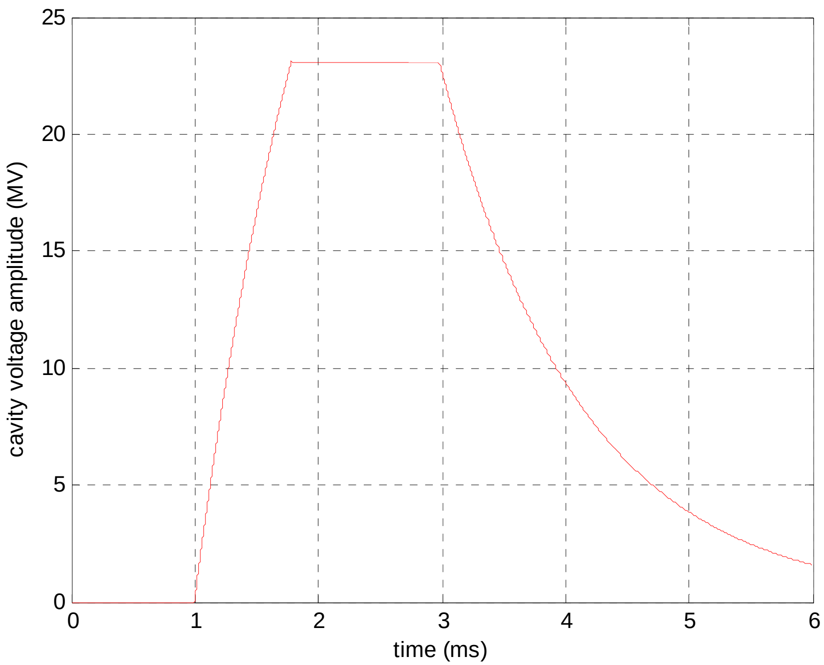
For a single short pulse or very low repetition rate, 1st order system (symplification), sum of collective effect of all modes

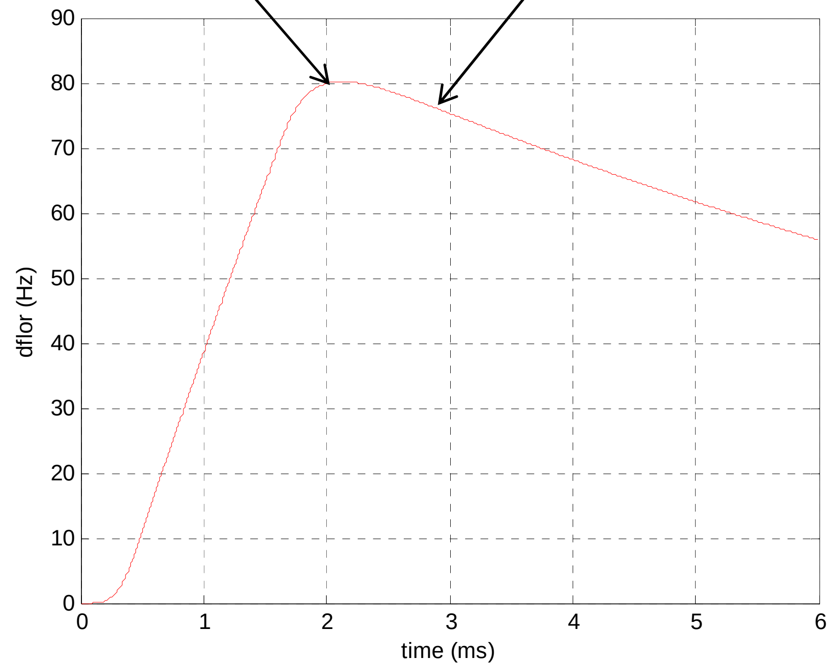
$$H(s)=\frac{K_0}{\tau_L s+1},$$

Typical values $K_0=-1...-2\ \text{Hz}/(\text{MV}/\text{m})^2$

$\tau_L=5\ \text{ms}...10\ \text{ms}$

Lorentz Force Detuning (2)





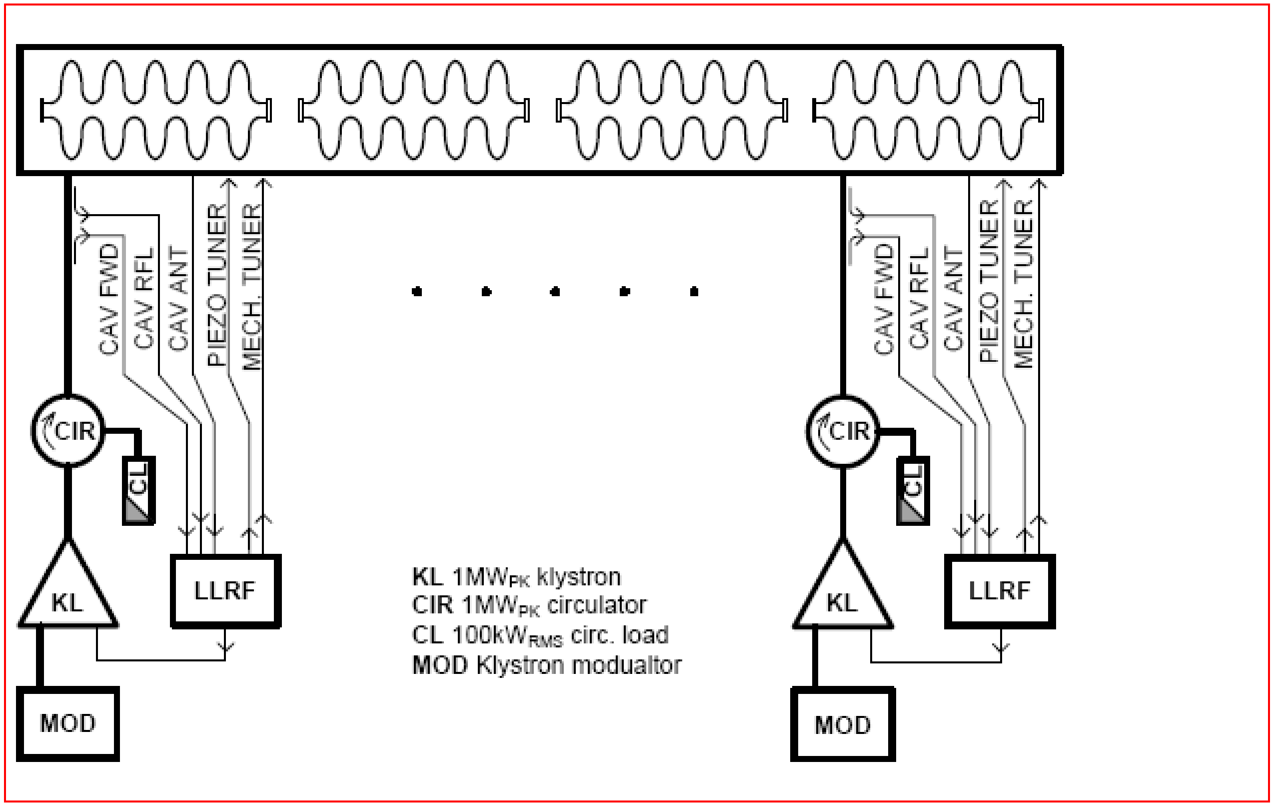
time offset 1 ms, i.e. 0→1 ms on left hand side graph
detuning negative !

This case (O. Piquet, CEA Saclay, simulation)

$$K_0 = -1 \text{ Hz}/(\text{MV}/\text{m})^2 \qquad \tau_\text{L} = 10 \text{ ms} \qquad H(s) = \frac{K_0}{\tau_\text{L} s + 1},$$

considerable spread from cavity to cavity to be expected !

Many possible Layouts, final for high energy part of HPSPL ?



1 klystron per cavity: individual control possible without RF vector modulator

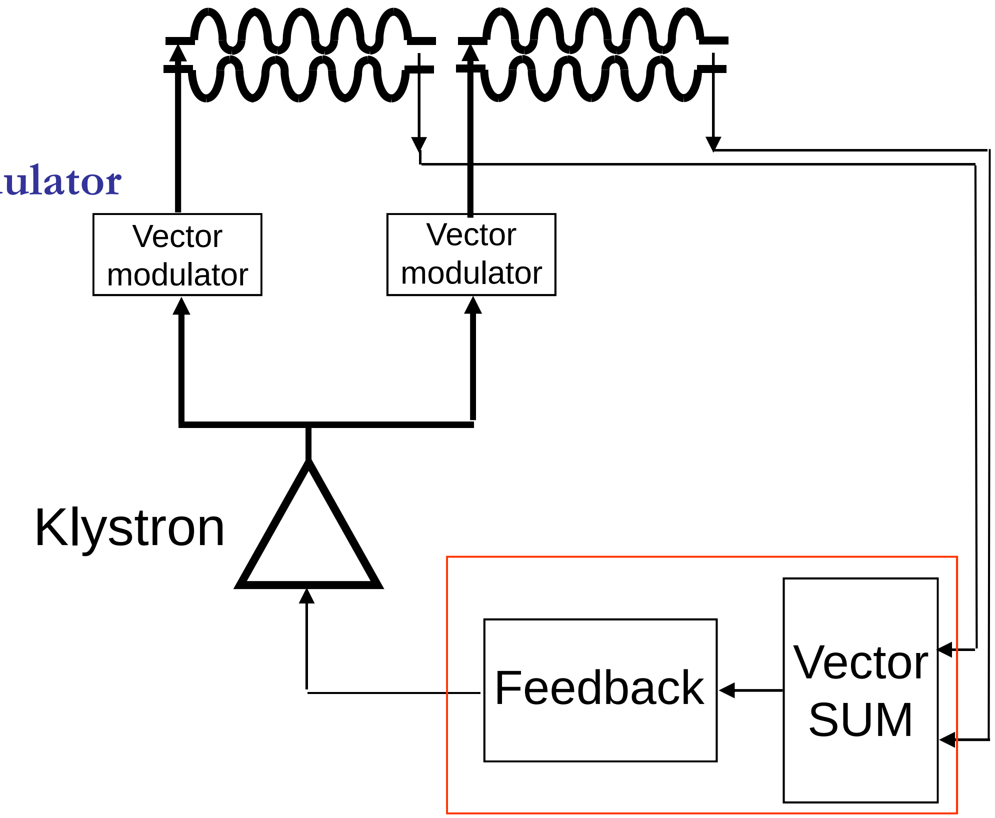
Disadvantage: Many klystrons required

Advantage: Easiest for control, considered adopted solution for low energy part

In this case and all following cases we assume individual Lorentz-force detuning compensation with a fixed pulse on the piezo or an adaptive feedforward (pulse-to-pulse)

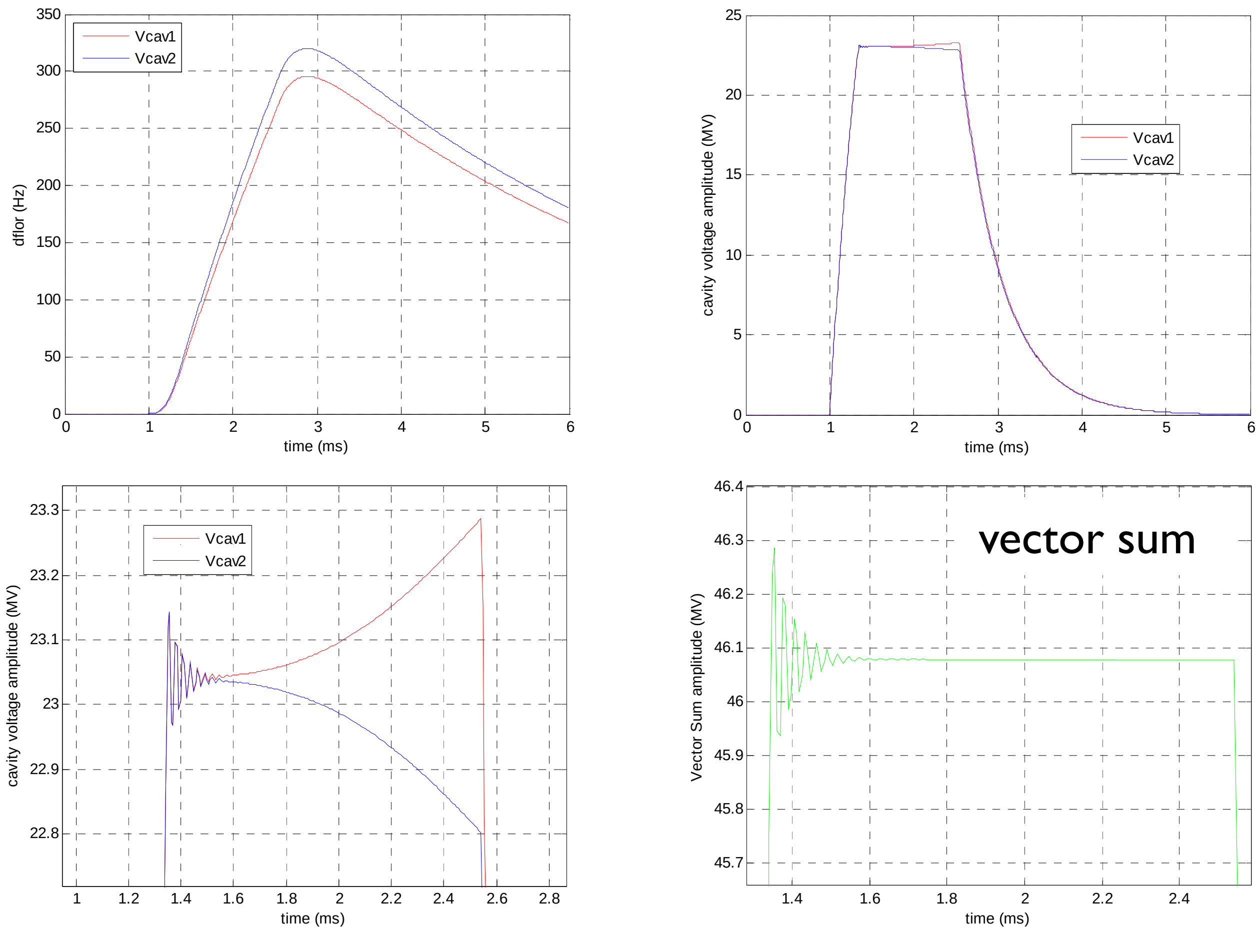
Many possible Layouts, initial for high energy part of LPSPL ?

optional
RF vector modulator



This case was analysed, see O. Piquet, CEA Saclay, simulation, LLRF09 workshop and presentation by M. Hernandez Flano

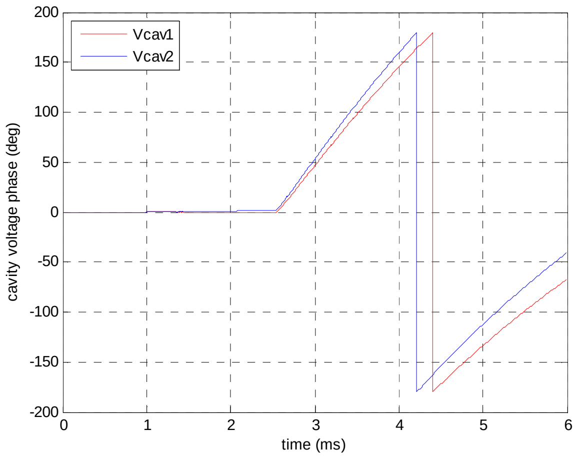
Two cavities per klystron high energy part of LPSPL

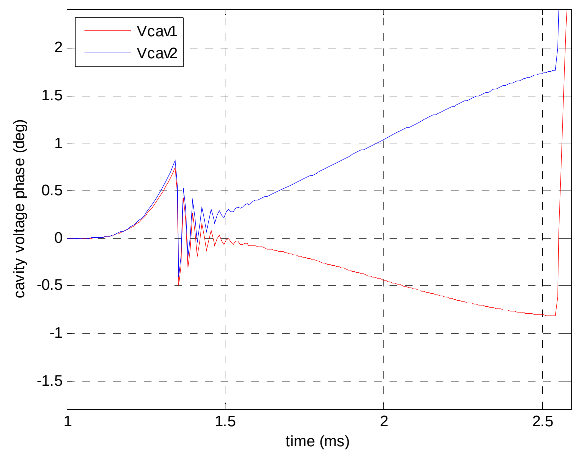


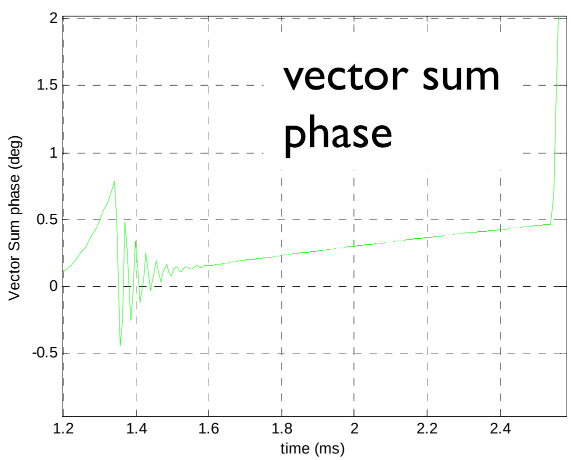
10% variation in Lorentz Force detuning
$K_{L,1}$=-2.0 Hz/(MV/m)^2
$K_{L,2}$=-2.2 Hz/(MV/m)^2
PI FB controller
5 µs delay in FB loop
loop closed at start of beam pulse

O. Piquet, CEA Saclay, simulation, LLRF09 workshop

Two cavities per klystron high energy part of LPSPL







Typical results needing refinement, but showing that delay is not (so) crucial

O. Piquet, CEA Saclay, simulation, LLRF09 workshop

Power overhead due to field stabilization, perturbations

Lorentz force detuning (cavity is not on tune during entire beam pulse)

Micro-phonics (cavity tune oscillating due to external perturbations)

Ripple+droop from high voltage leading to a modulation of the klystron phase

Transients at loop closure (and opening)

Transients at beam arrival (and beam out), effect of chopping of beam

Feedforward can be used, pulse to pulse, but many perturbations will have varying or non-correlated parts from pulse-to-pulse

A low group delay in the loop is desirable in order to be able to keep cavity voltage in phase and amplitude within specs in presence of non-repetitive perturbations, simulations needed to show limits as function of group delay

Simulations continue to justify a reasonable overhead in installed RF power

Conclusions

SPL parameters reviewed

Optimization of Q_{ext} very important,
should settle to a nominal QL and error bars for simulation

Delay and Power budget, power more critical, ~1→2 μs delay ok

Lorentz Force detuning and its compensation crucial, need more input from tests for modeling and realistic assumptions of residual detuning not compensated by piezos

Layouts and perturbations to be considered in the simulations

First simulation results for one high energy RF station (O. Piquet & M. Hernandez)

Future: continue simulations towards a string of cavities and move to low energy part, include β change along accelerator, model klystron, circulator …