Switching RF Parameters within the XFEL Bunch Train
(first look)

Igor's Working-Points

Cavity Operation (with transients)

- intuitive
- theory

Transient Operation

- filling
- switching (Igor's WPs, 1nC $\leftrightarrow$ 100pC)

Other WPs

- first look
- first look, modified 1nC WP

Summary, Remarks

Igor's Working-Points

Beam Dynamics and SASE Simulations for XFEL

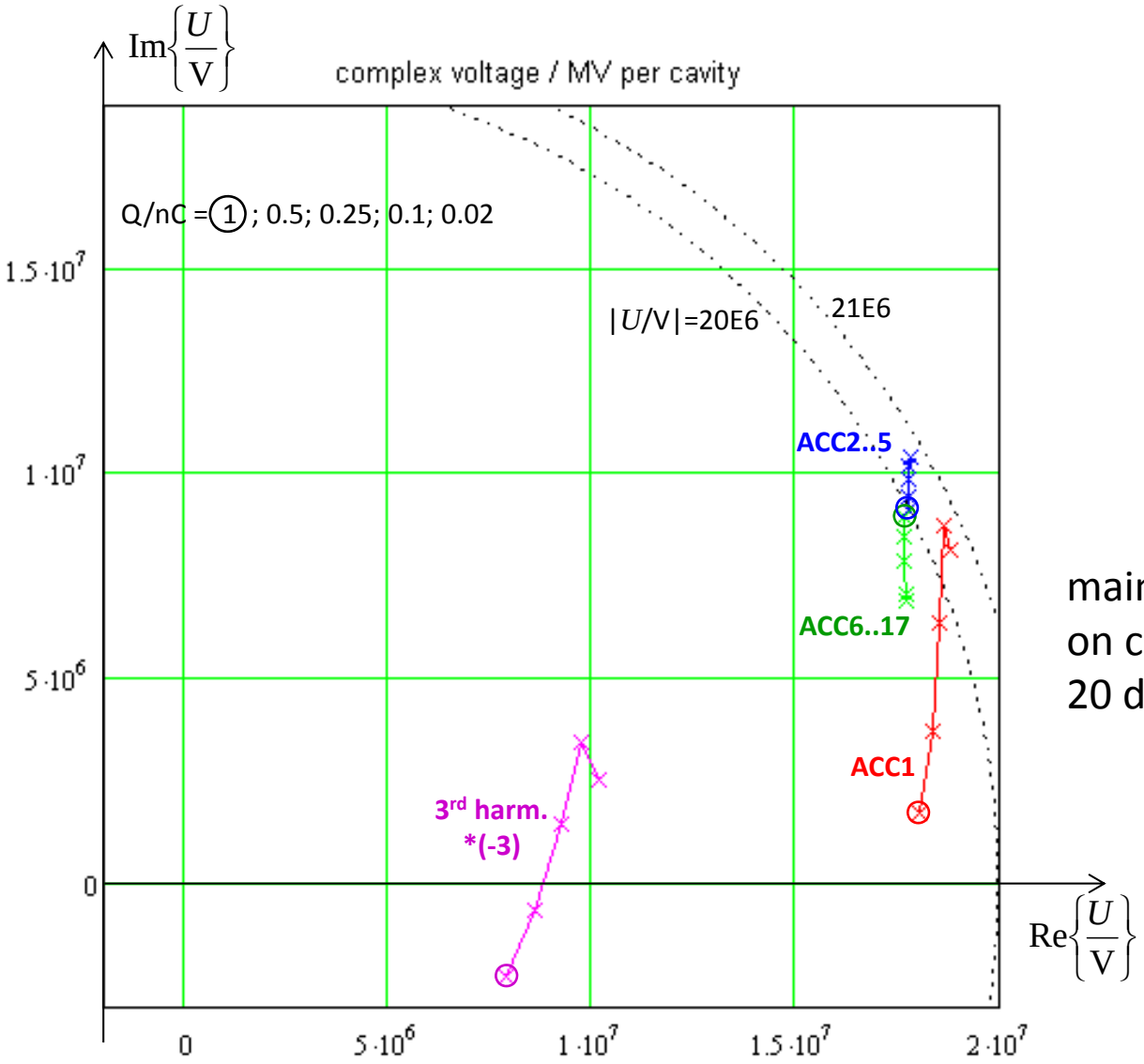
Igor Zagorodnov
14.02.2011
DESY

XFEL beam dynamic simulations for different charges

RF settings in accelerating modules

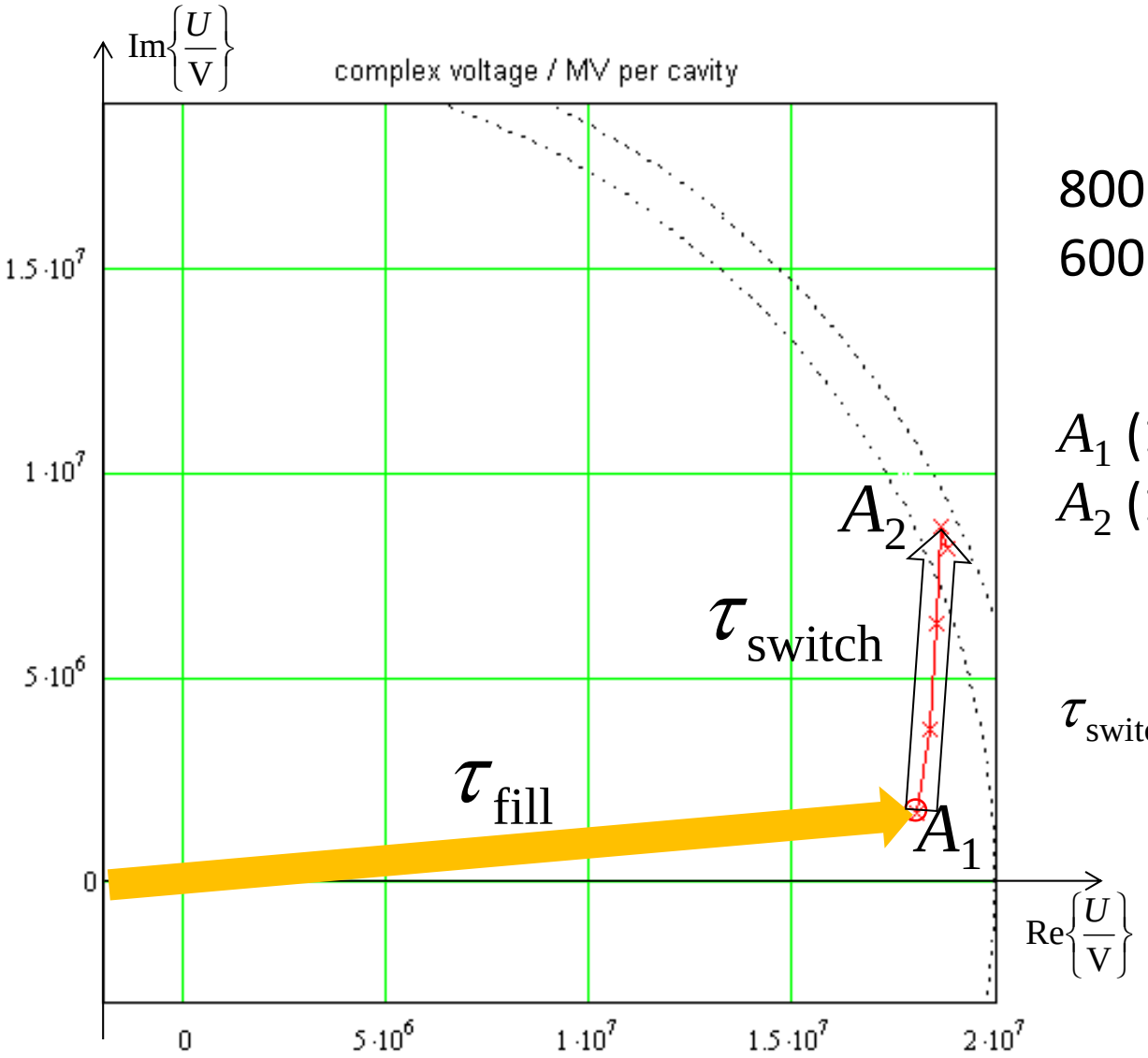
Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]	V_3, [MV]	φ_3, [deg]
1	145	5.4	22	164	656	29.7	1832	21.7
0.5	150	11.5	23.1	175.5	661	30.3	1826	21.3
0.25	157	18.9	25.1	189	652	29	1860	23.9
0.1	165	25	27.6	199.5	645	27.9	1885	25.6
0.02	164	23.4	28	194.6	640	27.1	1905	26.8

Igor's Working-Points



main linac (2.4 → 17.5) GV
on crest: 22.7 MV per cavity !
20 deg off crest: 23.5 MV/m

Cavity Operation (with transients) intuitive picture



800 µs filling time
600 µs flat top

A_1 (1nC) accuracy <1E-3
A_2 (100pC) 1E-4

$$\tau_{\text{switch}} \propto \left| \frac{A_2 - A_1}{A_1} \right| \tau_{fill}$$

Cavity Operation (with transients)

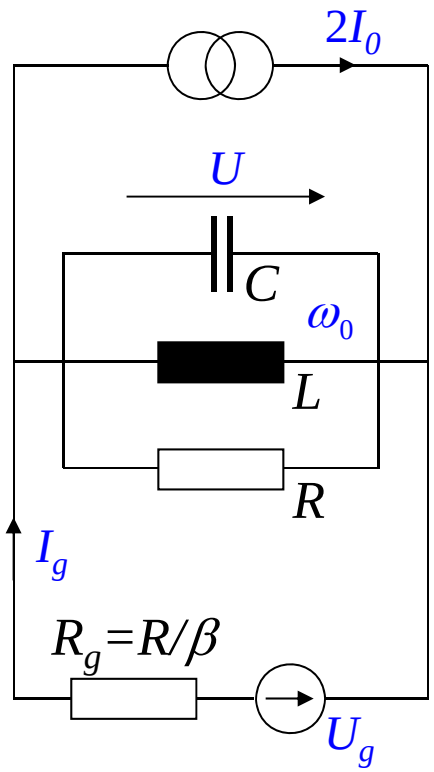
$$i_s(t) = \sum q\delta(t - nT_b) = I_0 + 2I_0 \sum \cos(n\omega_b t)$$

$$C = \frac{1}{2k}$$

$$L = \frac{2k}{\omega_0^2}$$

$$R = \frac{2k}{\omega_0} Q_0$$

$$\frac{1}{R} + \frac{1}{R_g} = \frac{\omega_0}{2k} \frac{1}{Q_L}$$



TESLA cavity

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$

$$Q_L \approx 2.5 \cdot 10^6 \quad \left(10^6 \cdots 5 \cdot 10^6\right)$$

DE for amplitudes

$$\frac{1}{k}\dot{U} + \frac{\omega_0}{2kQ_L}U = 2A\sqrt{\frac{\omega_0}{2k}\left(\frac{1}{Q_L} - \frac{1}{Q_0}\right)} - 2I_0$$

$$B = U\sqrt{\frac{\omega_0}{2k}\left(\frac{1}{Q_L} - \frac{1}{Q_0}\right)} - A$$

power flow

$$P(t) = \underbrace{\frac{1}{2}|A(t)|^2}_{P_f(t)} - \underbrace{\frac{1}{2}|B(t)|^2}_{P_b(t)}$$

Cavity Operation (with transients)

steady state (with beam)

$$A = \left(\frac{1}{2} \sqrt{\frac{\omega_0}{2kQ_L}} U + \sqrt{\frac{2kQ_L}{\omega_0}} I_0 \right) \cdot \left(1 - \frac{Q_L}{Q_0} \right)^{-1/2}$$

switch operation (without beam)

$$U(t_1) = U_1$$

$$U(t) = U_1 + (U_2 - U_1) F \left(\exp\left(-(t - t_1) \frac{\omega_0}{2Q_L} \right) - 1 \right) \qquad \text{with} \quad F = \frac{1}{\exp\left(-(t_2 - t_1) \frac{\omega_0}{2Q_L} \right) - 1}$$

$$U(t_2) = U_2$$

$$A = \frac{1}{2} \sqrt{\frac{\omega_0}{2kQ_L}} \left(1 - \frac{Q_L}{Q_0} \right)^{-1/2} \left((1 + F) U_1 - F U_2 \right)$$

for both cases

$$B = U \sqrt{\frac{\omega_0}{2k} \left(\frac{1}{Q_L} - \frac{1}{Q_0} \right)} - A$$

Transient Operation (without beam)
filling

example: filling of ACC1 cavities for 1nC case

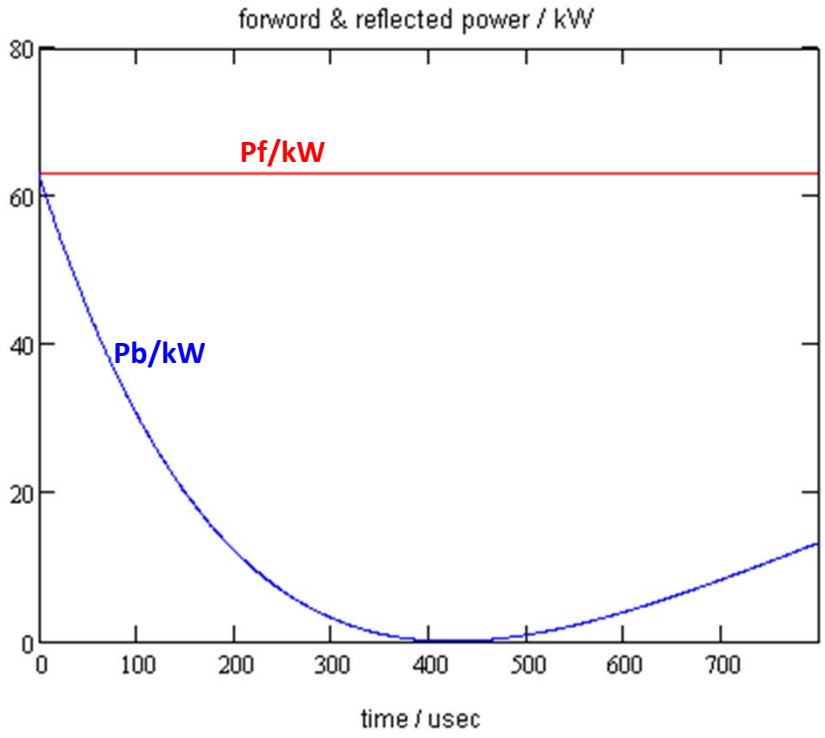
800 µs filling time

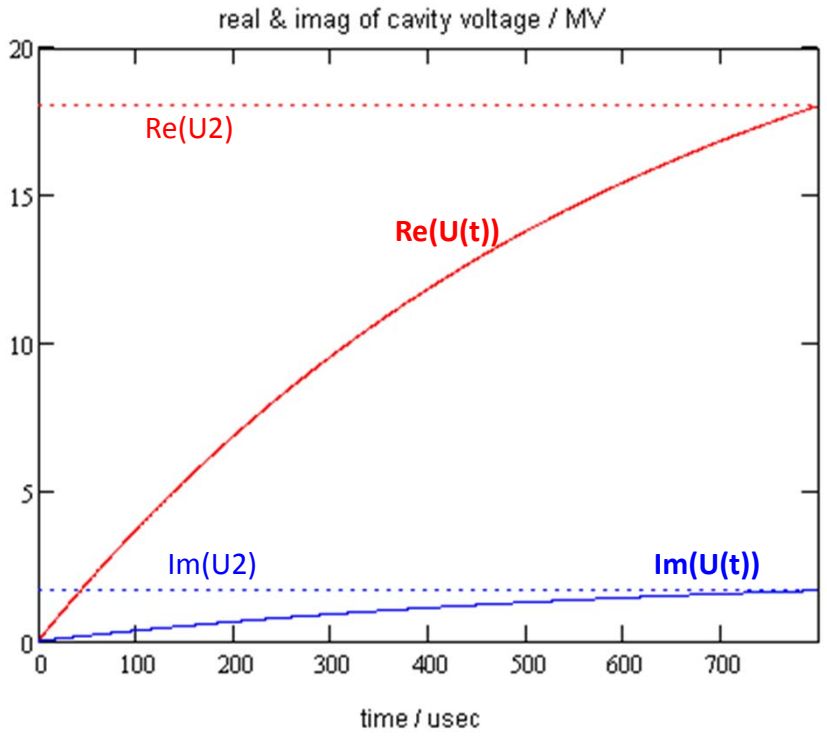
$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$

$$Q_L \approx 2.5 \cdot 10^6$$





nominal filling time

nominal flat top

Transient Operation (without beam)
filling

example: filling to 23.5 MV/m · 1.035 m

800 µs filling time

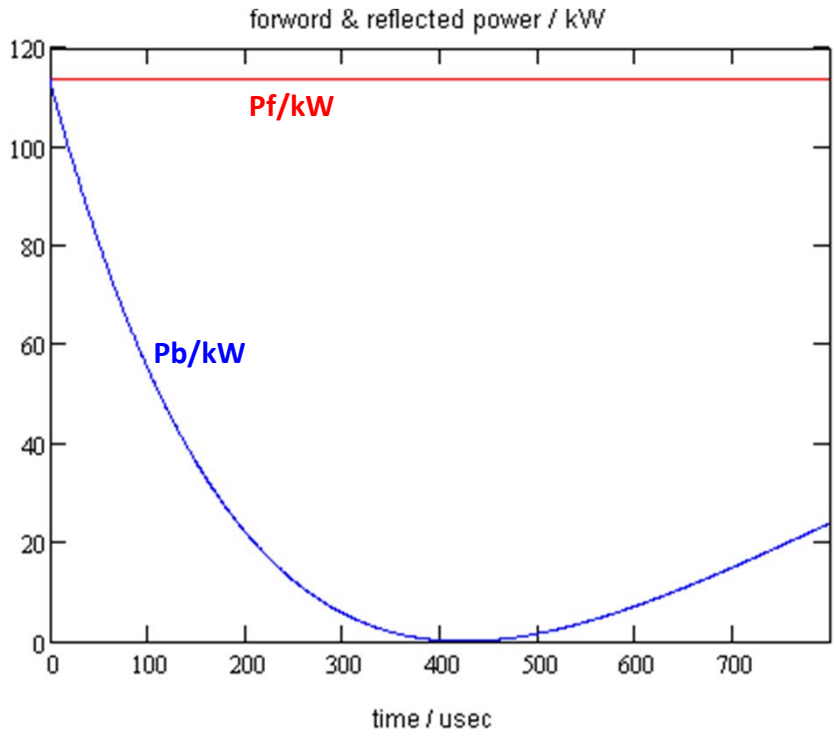
114 kW forward power

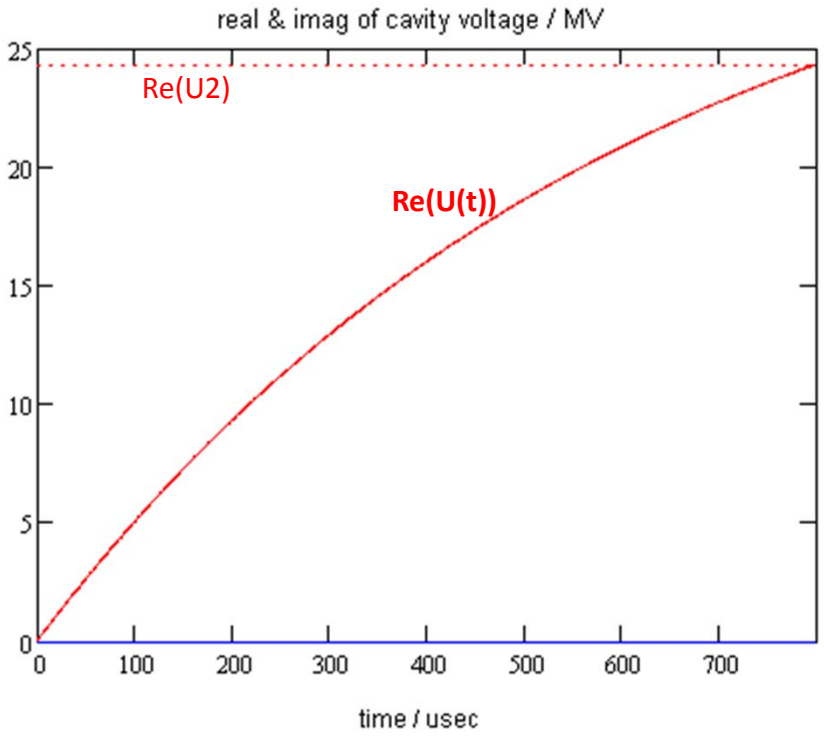
$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$

$$Q_L \approx 2.5 \cdot 10^6$$





nominal filling time

nominal flat top

Transient Operation (without beam)

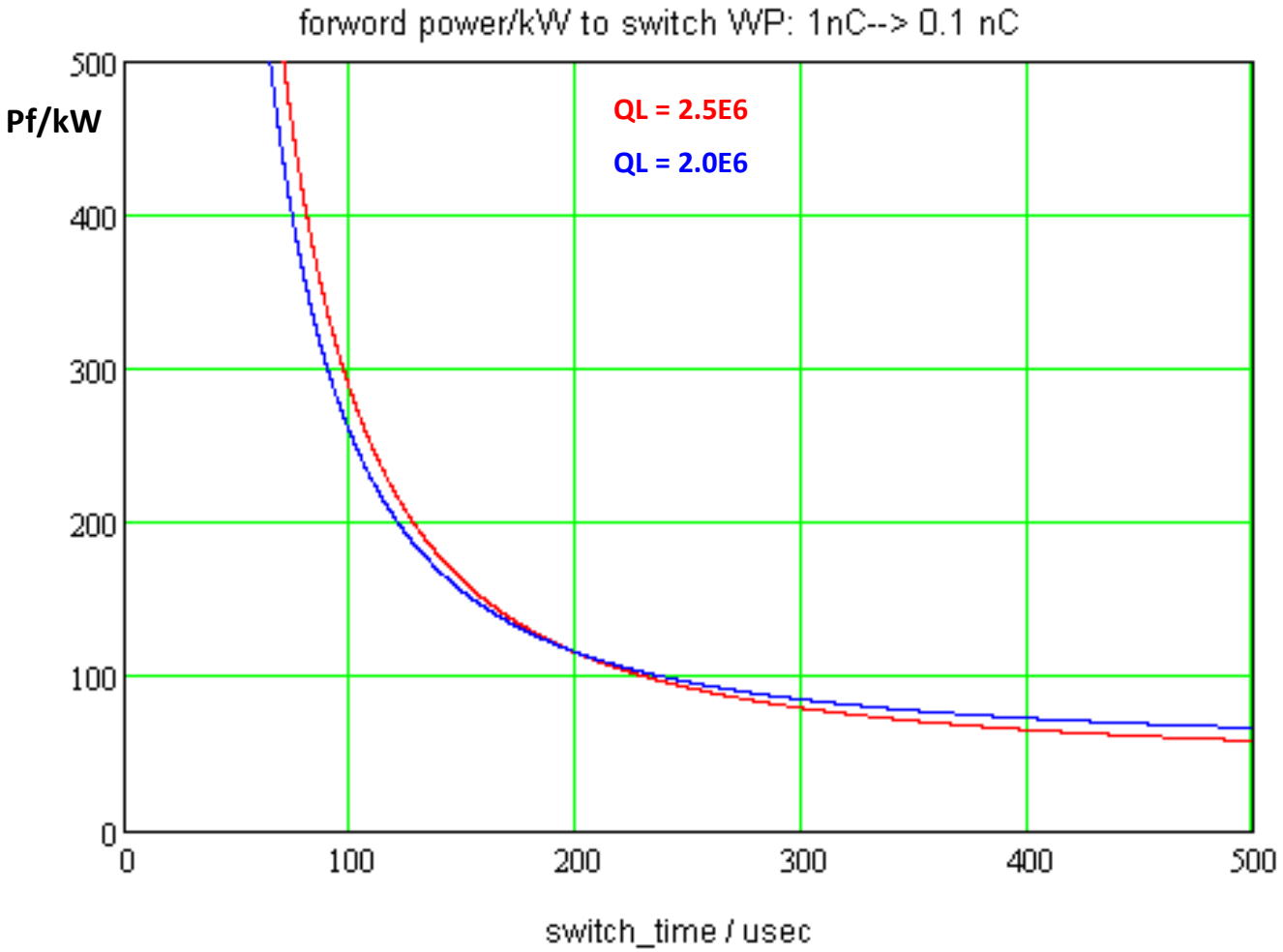
switching, Igor's WPs

example: switching of ACC1 cavities (1nC → 100pC)-case

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$



Transient Operation

switching, Igor's WPs

example: switching of ACC1 cavities (1nC → 100pC)-case

800 µs filling time

600 µs "flat top" = (250 + 100 + 250) µs

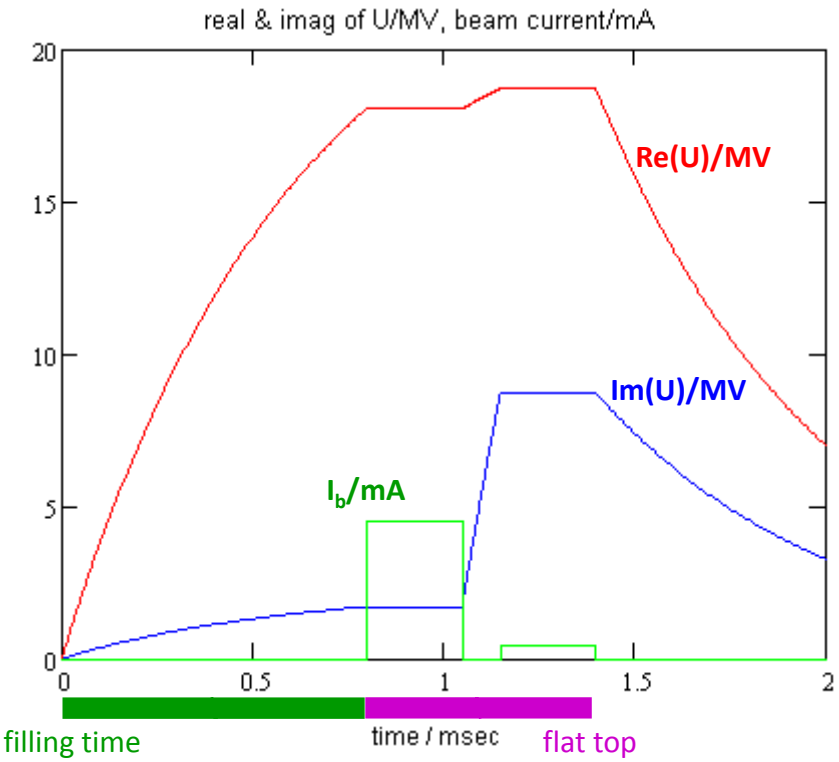
1nC switch 100pC

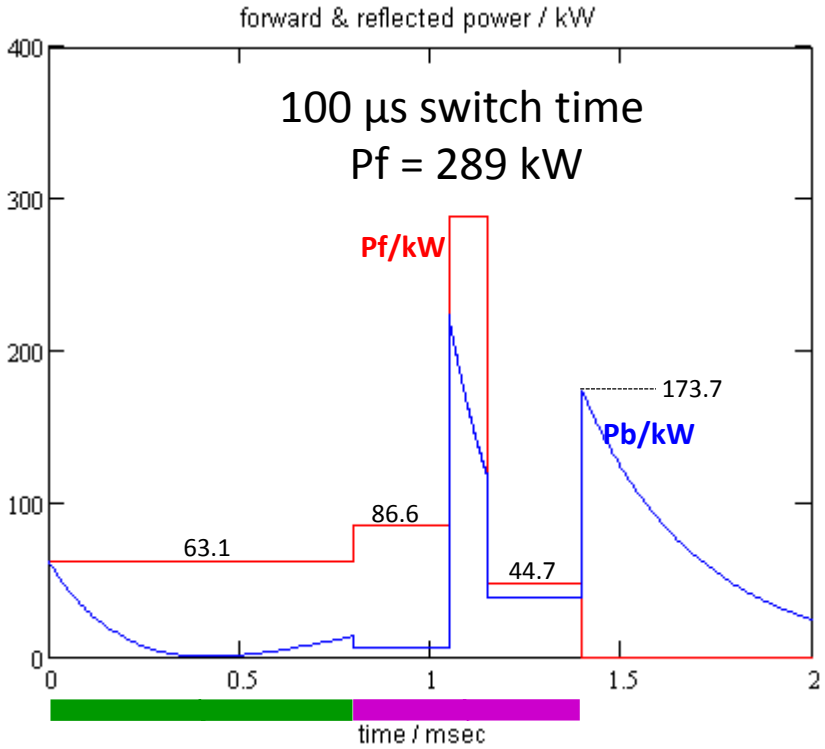
$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$

$$Q_L \approx 2.5 \cdot 10^6$$





Transient Operation

switching, Igor's WPs

example: switching of ACC1 cavities (100pC → 1nC)-case

800 µs filling time

600 µs "flat top" = (250 + 100 + 250) µs

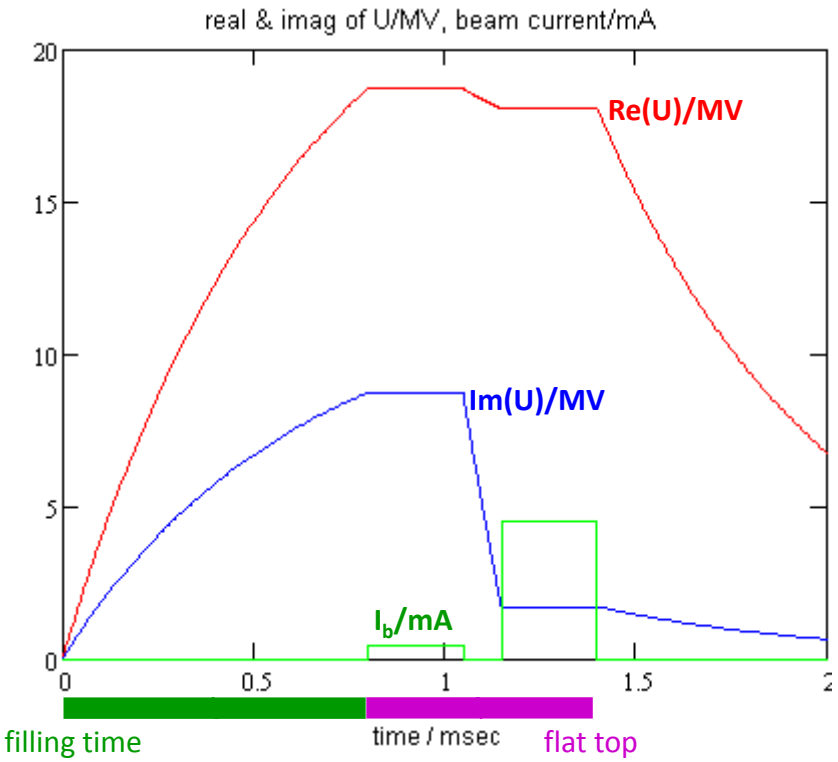
100pC switch 1nC

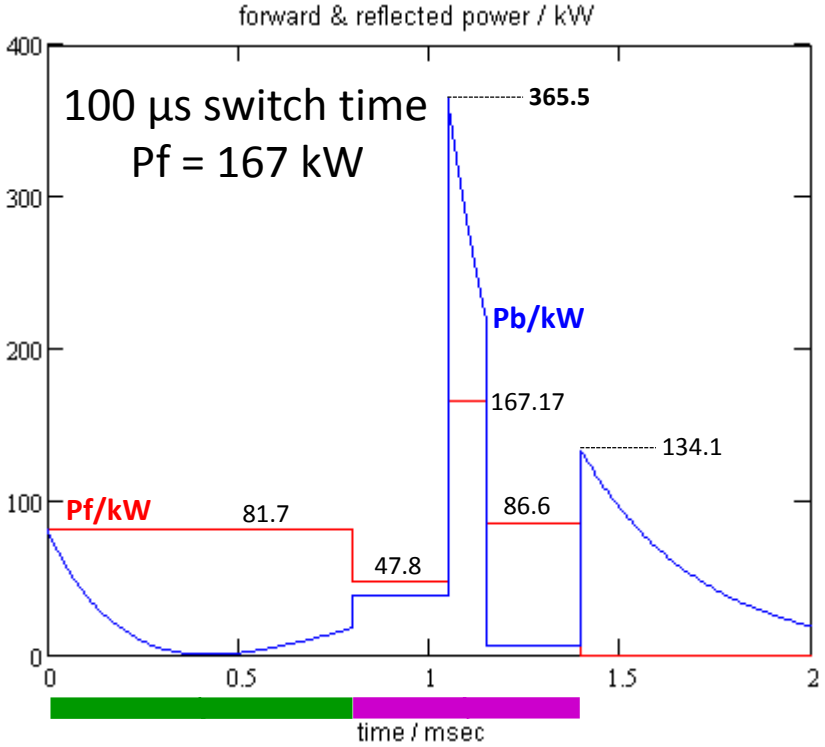
$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$

$$Q_L \approx 2.5 \cdot 10^6$$





Transient Operation (without beam)

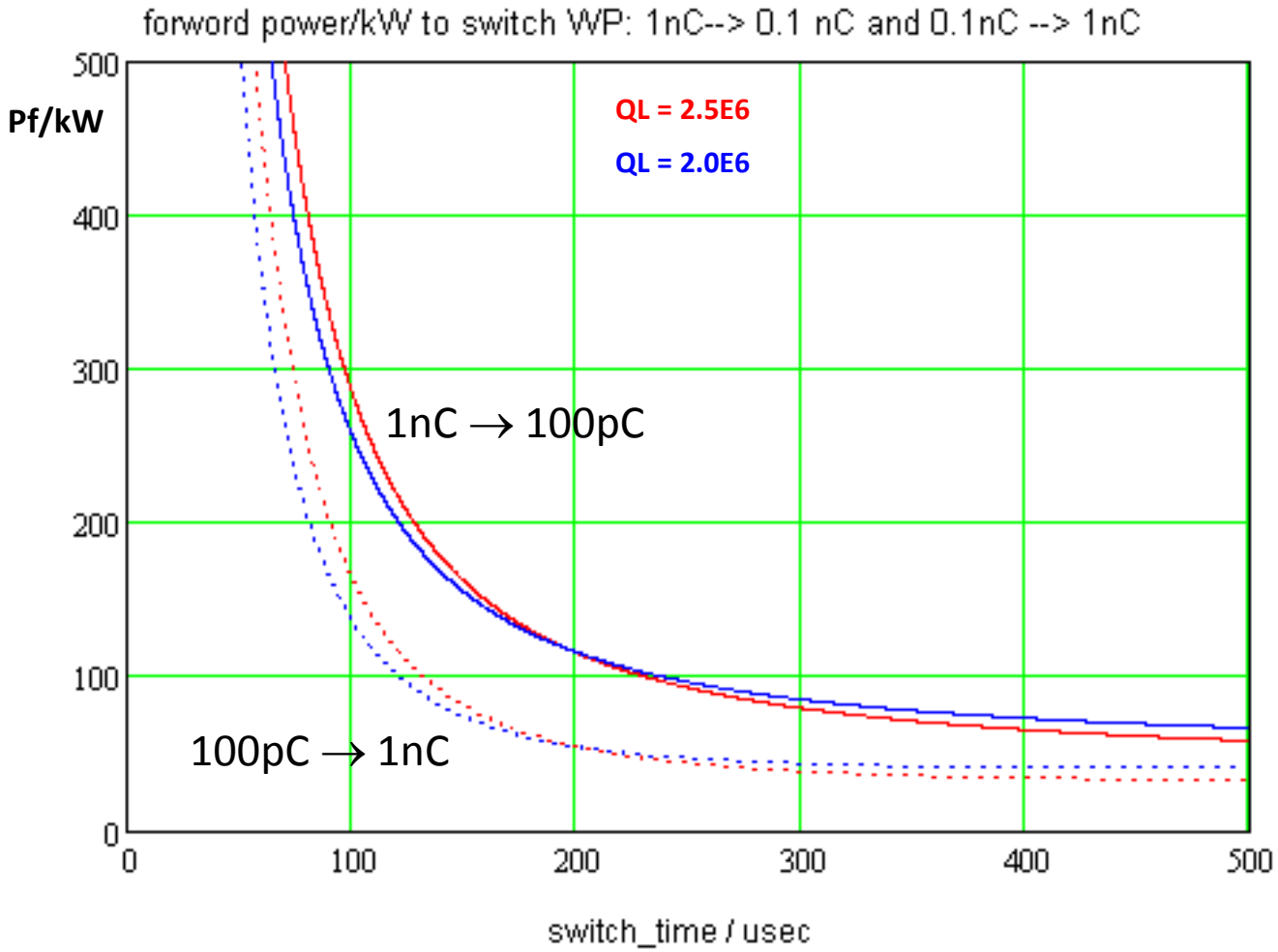
switching, Igor's WPs

example: switching of ACC1 cavities (1nC ↔ 100pC)-case

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$



Igor's Working-Points

switching, Igor's WPs

Q/nC = 1; 0.5; 0.25; 0.1; 0.02

r56/mm = 100; 89; 78; 71; 67 (BC0)

54; 50; … (BC1)

20; … (BC2)

XFEL beam dynamic simulations for different charges

RF settings in accelerating modules

Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]	V_3, [MV]	φ_3, [deg]
1	145	5.4	22	164	656	29.7	1832	21.7
0.5	150	11.5	23.1	175.5	661	30.3	1826	21.3
0.25	157	18.9	25.1	189	652	29	1860	23.9
0.1	165	25	27.6	199.5	645	27.9	1885	25.6
0.02	164	23.4	28	194.6	640	27.1	1905	26.8

Other Working-Points
first look

find WPs with constant r56 (per compressor)

working hypothesis:

100 pC and 1 nC bunch with same initial bunch length
uncorrelated (slice) energy spread is determined by laser heater
compression to 5 kA, therefore total compression of 1000 and 100

the real 100 pC case is probably more relaxed: shorter bunch, better emittance, therefore less compressed current for same gain length; $\rightarrow$ lower compression

Other Working-Points

first look

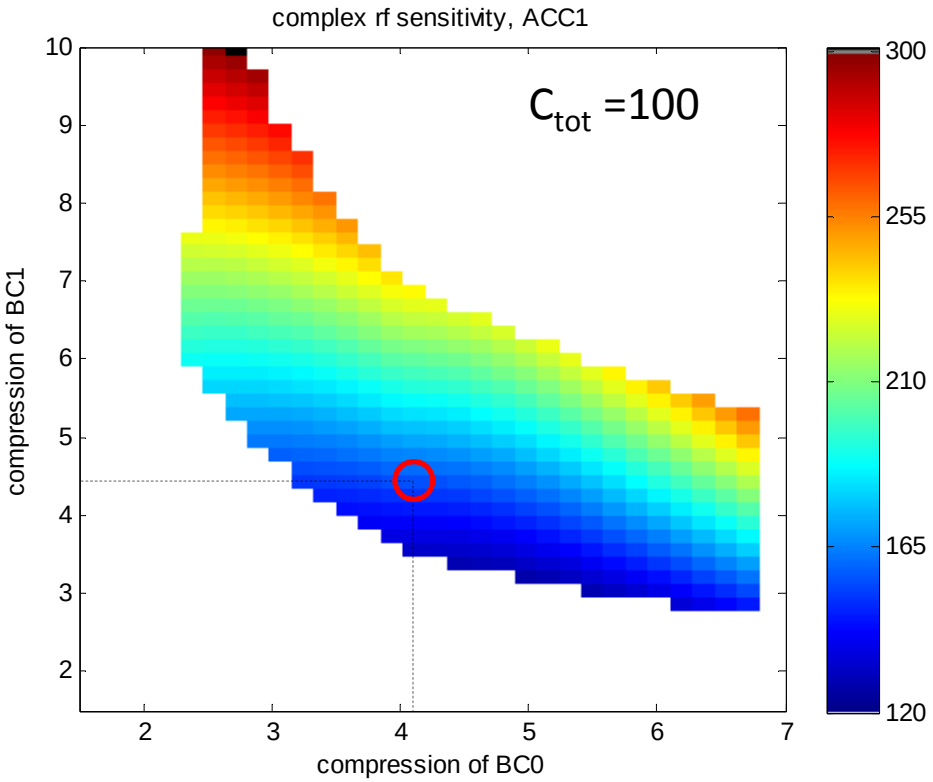
no SC, no CSR

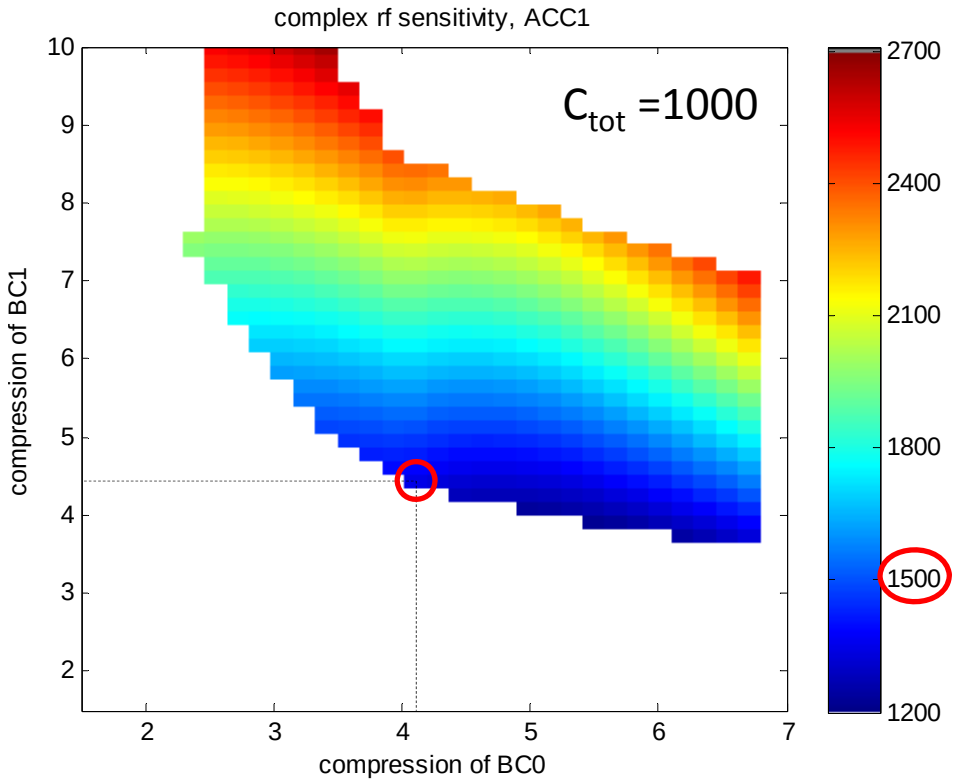
rf tolerance diagram (ACC1)

r56 depends on C0 and C1 but not on C_{tot}

r56_BC2 = const = 28 mm

energy levels: 130 MeV, 700 MeV, 2.4GeV





C0 = 4.0	r56/mm = 105.6
C1 = 4.4	42.0
C2 = 5.7; 57	28.0

10 % current stability needs

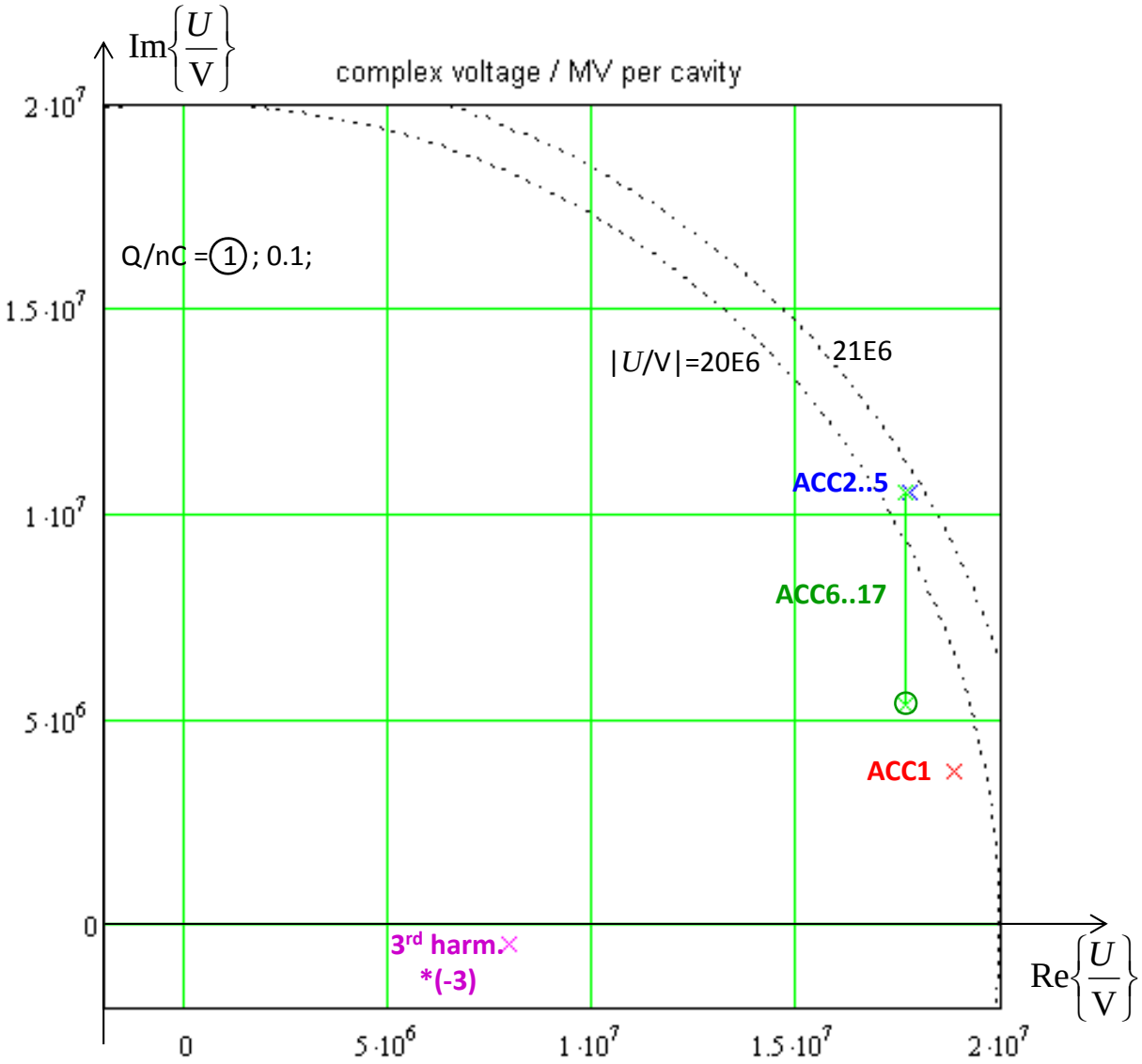
10%/1500 complex-amplitude stability!

(for C_{tot} = 1000)

Other Working-Points

first look

no SC, no CSR

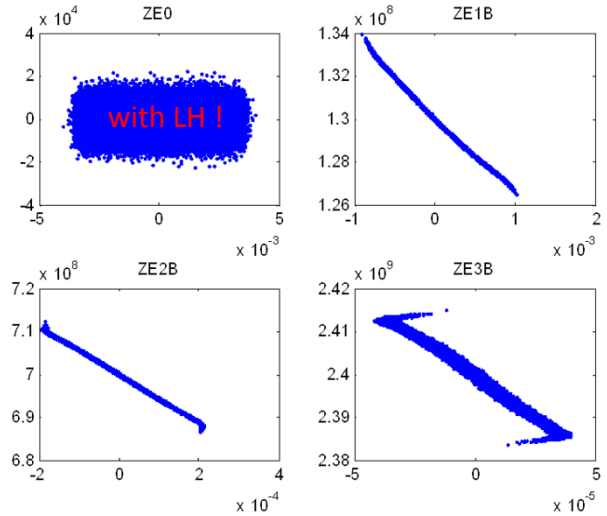


Other Working-Points

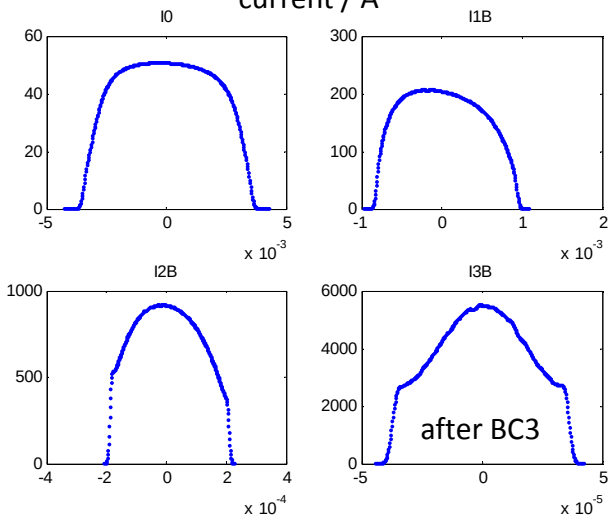
first look rf settings with self effects cavity wake & SC, no CSR

Q=1nC, C_{tot} =100

long. phase space

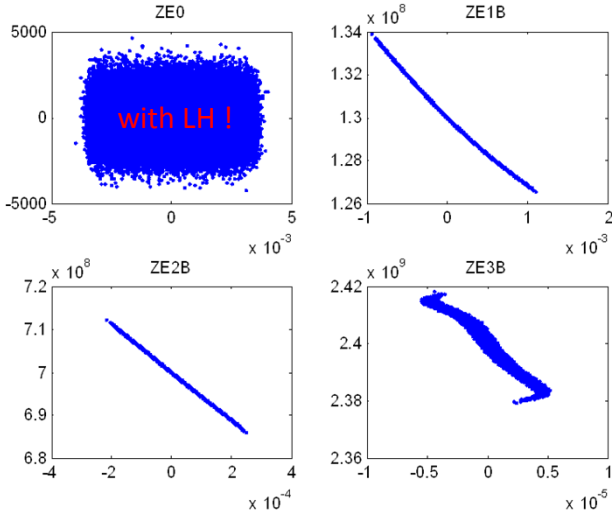


current / A

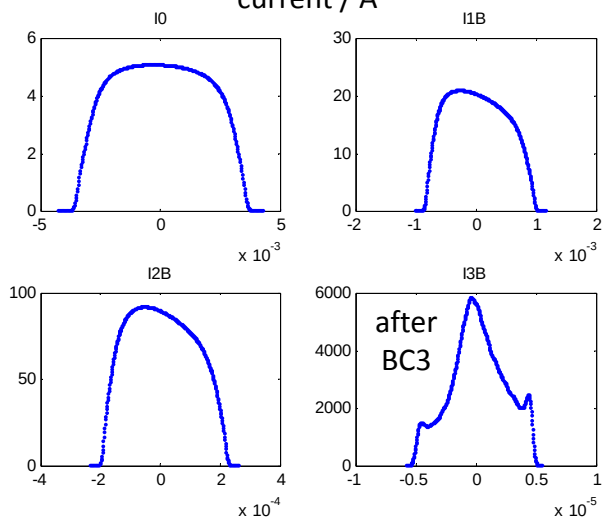


Q=100pC, C_{tot} =1000

long. phase space



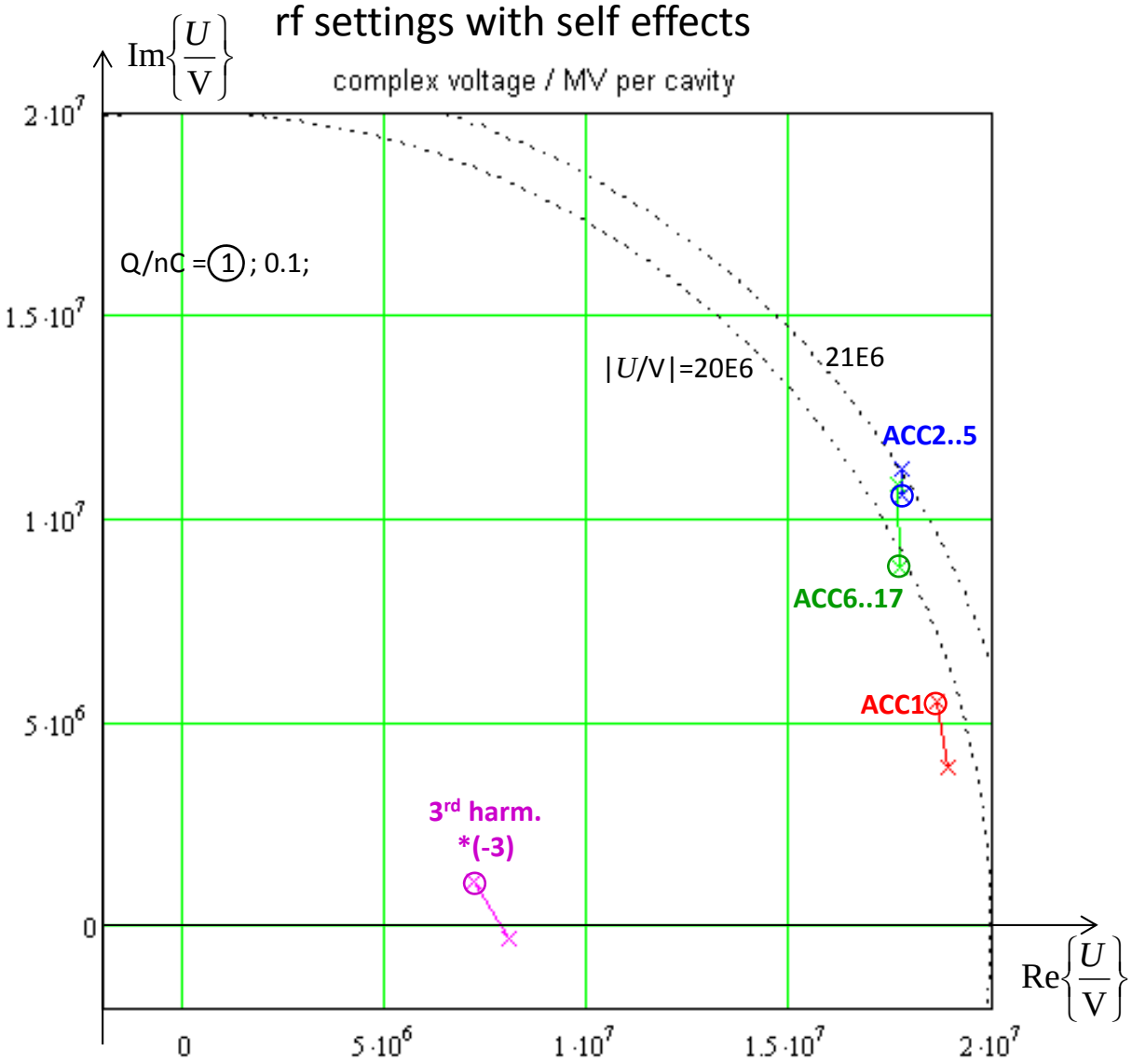
current / A



Other Working-Points

first look

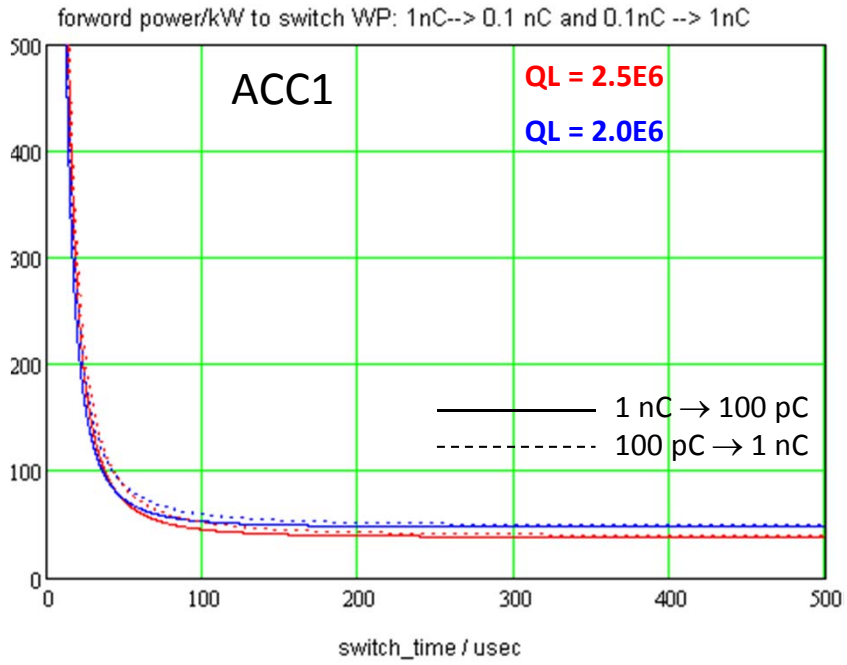
cavity wake & SC, no CSR

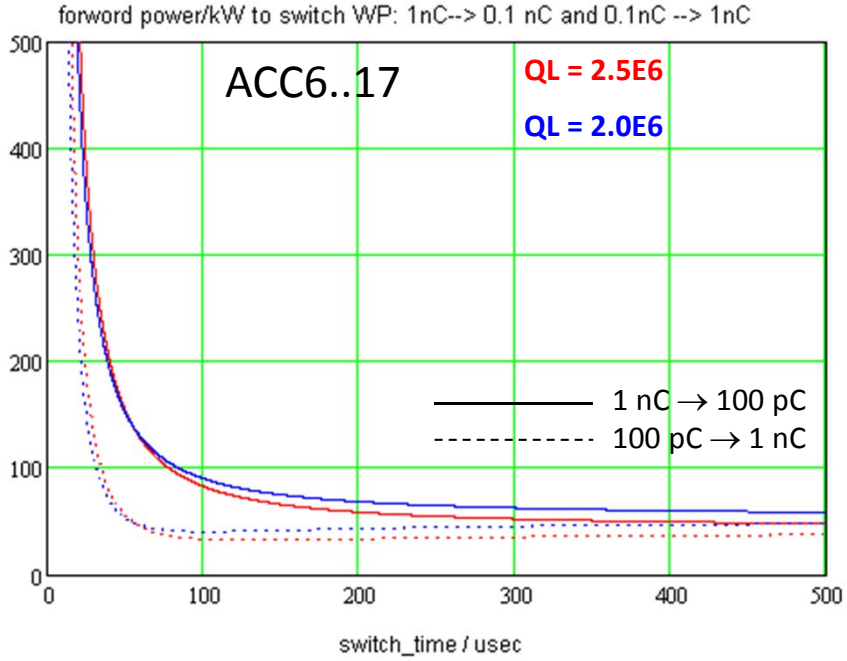


Other Working-Points
first look

switching cavities (1nC ↔ 100pC)-case

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$
$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$
$$Q_0 \approx 10^{10}$$

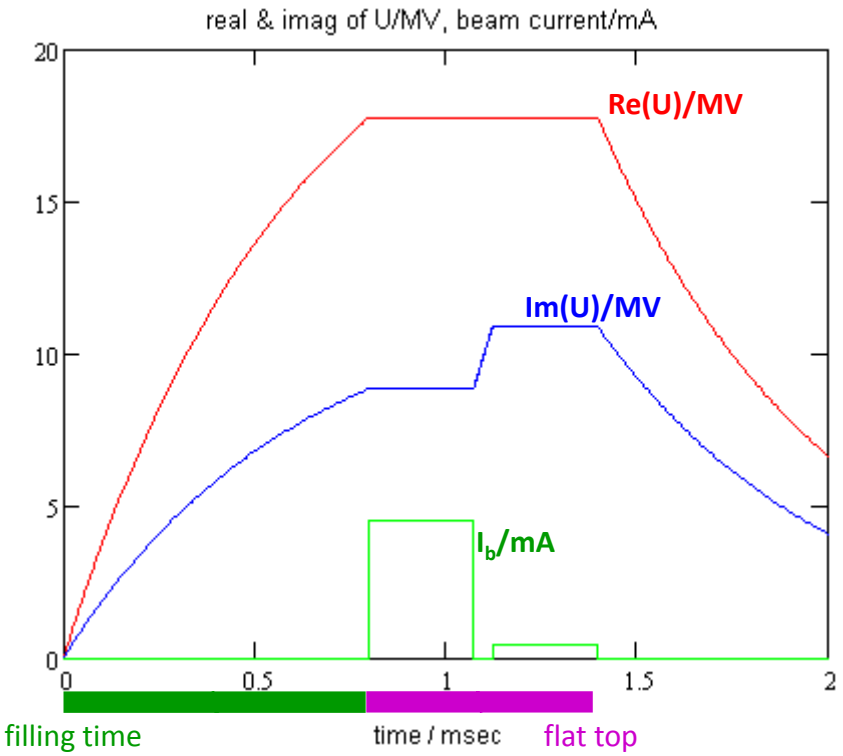


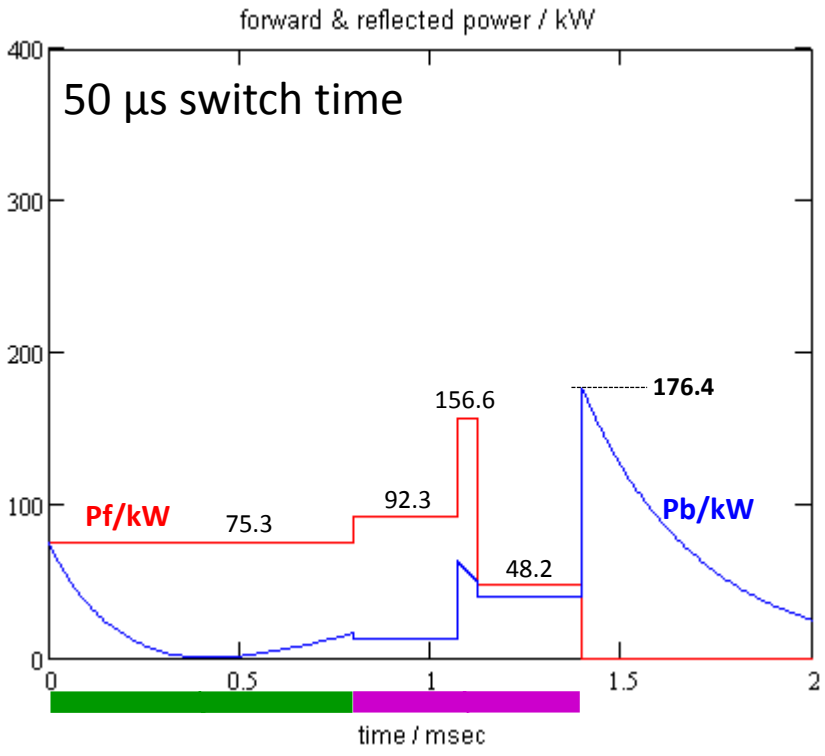


Other Working-Points
first look

ACC6..17
800 µs filling time
600 µs “flat top” = (275 + 50 + 275) µs
1nC switch 100pC

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$
$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$
$$Q_0 \approx 10^{10}$$
$$Q_L \approx 2.5 \cdot 10^6$$

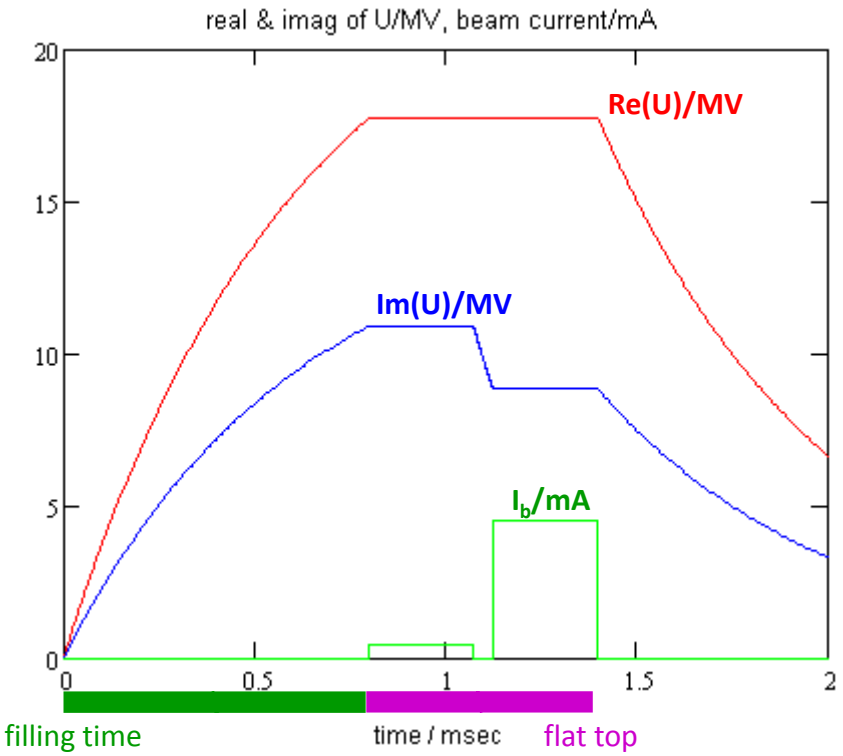


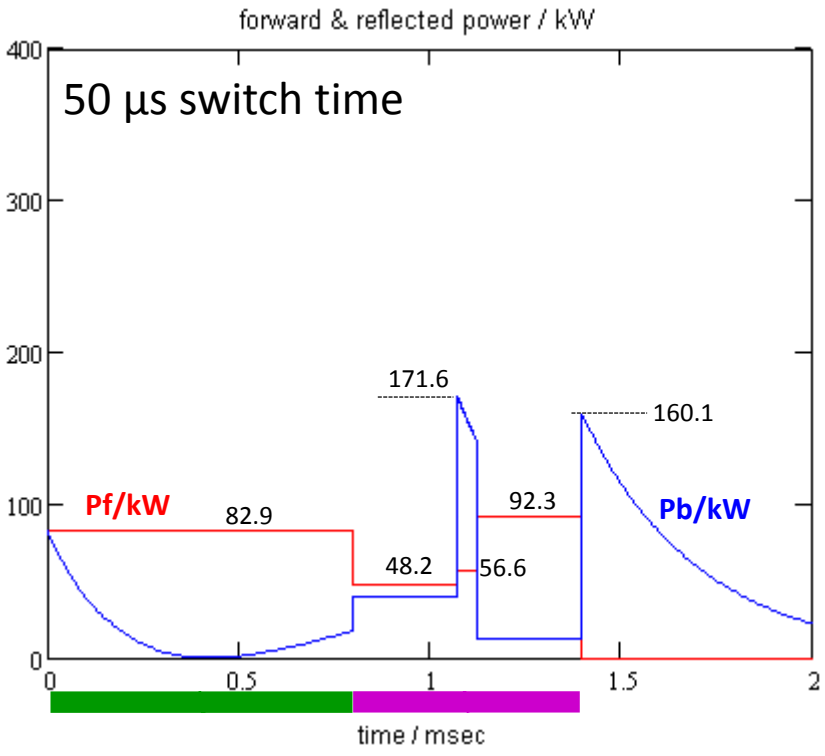


Other Working-Points
first look

ACC6..17
800 µs filling time
600 µs “flat top” = (275 + 50 + 275) µs
100pC switch 1nC

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$
$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$
$$Q_0 \approx 10^{10}$$
$$Q_L \approx 2.5 \cdot 10^6$$





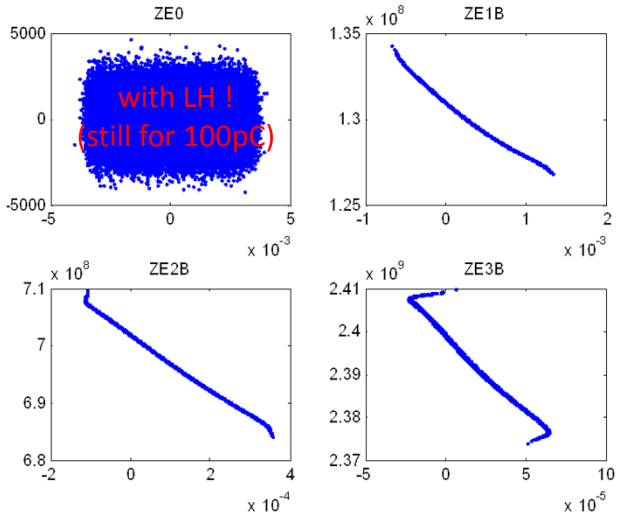
Other Working-Points

first look, **modified 1nC WP** rf settings with self effects cavity wake & SC, no CSR

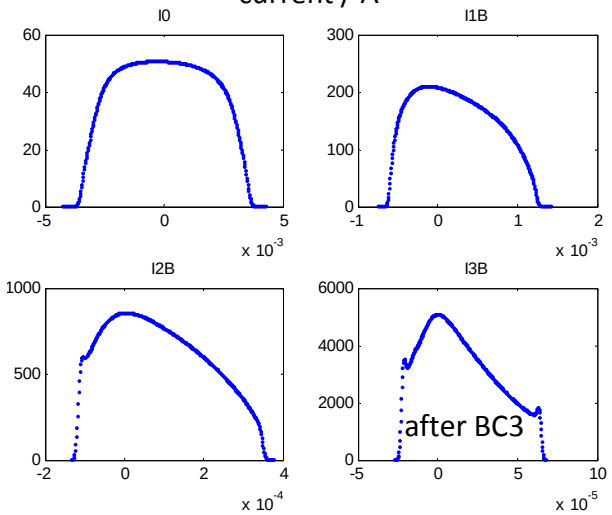
it is the modified 100pC working point !

Q=1nC, C_{tot} =100

long. phase space

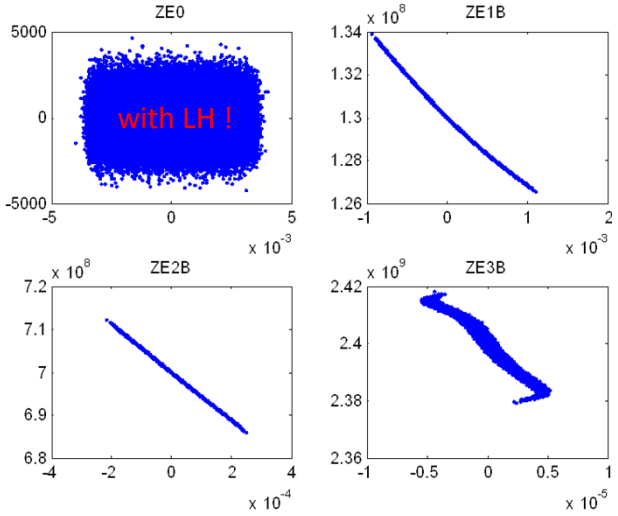


current / A

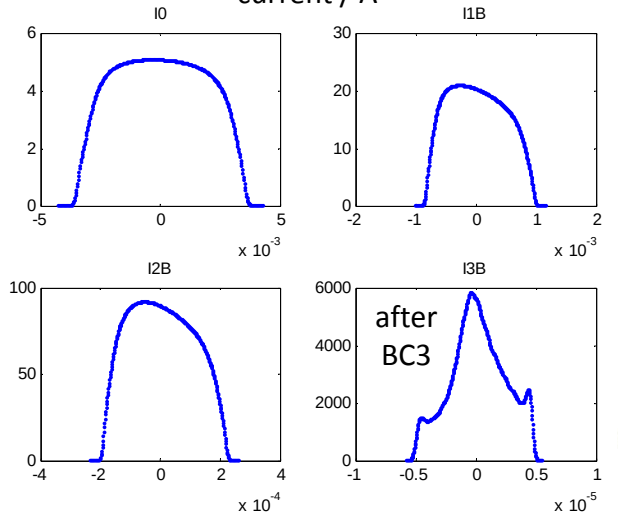


Q=100pC, C_{tot} =1000

long. phase space



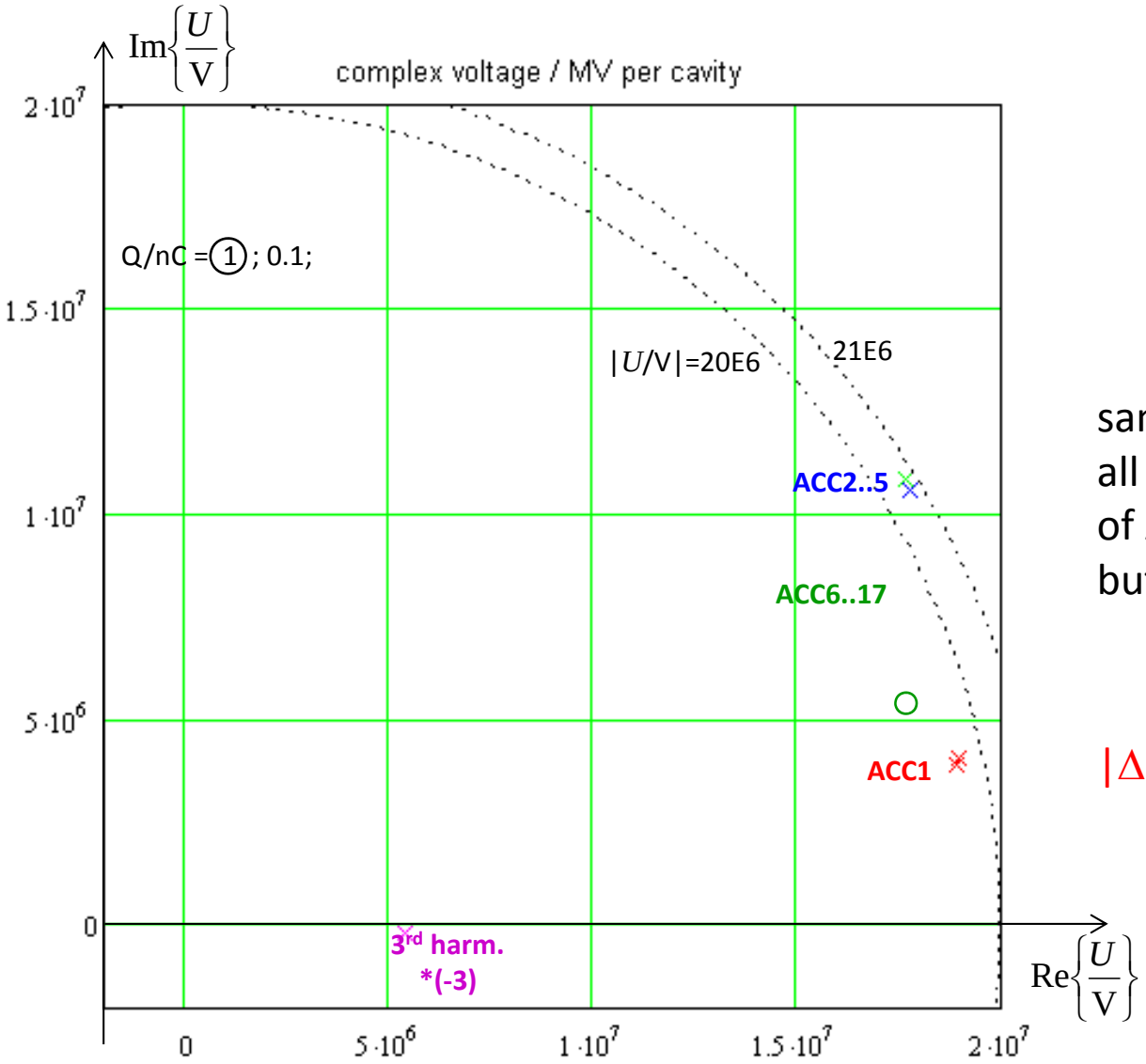
current / A



Other Working-Points

first look, **modified 1nC WP**

cavity wake & SC, no CSR



same cavity voltage in
all cavities with exception
of ACC1 !
but different beam loading

$|\Delta U_{ACC1}| = 0.16$ MV

Transient Operation (without beam)

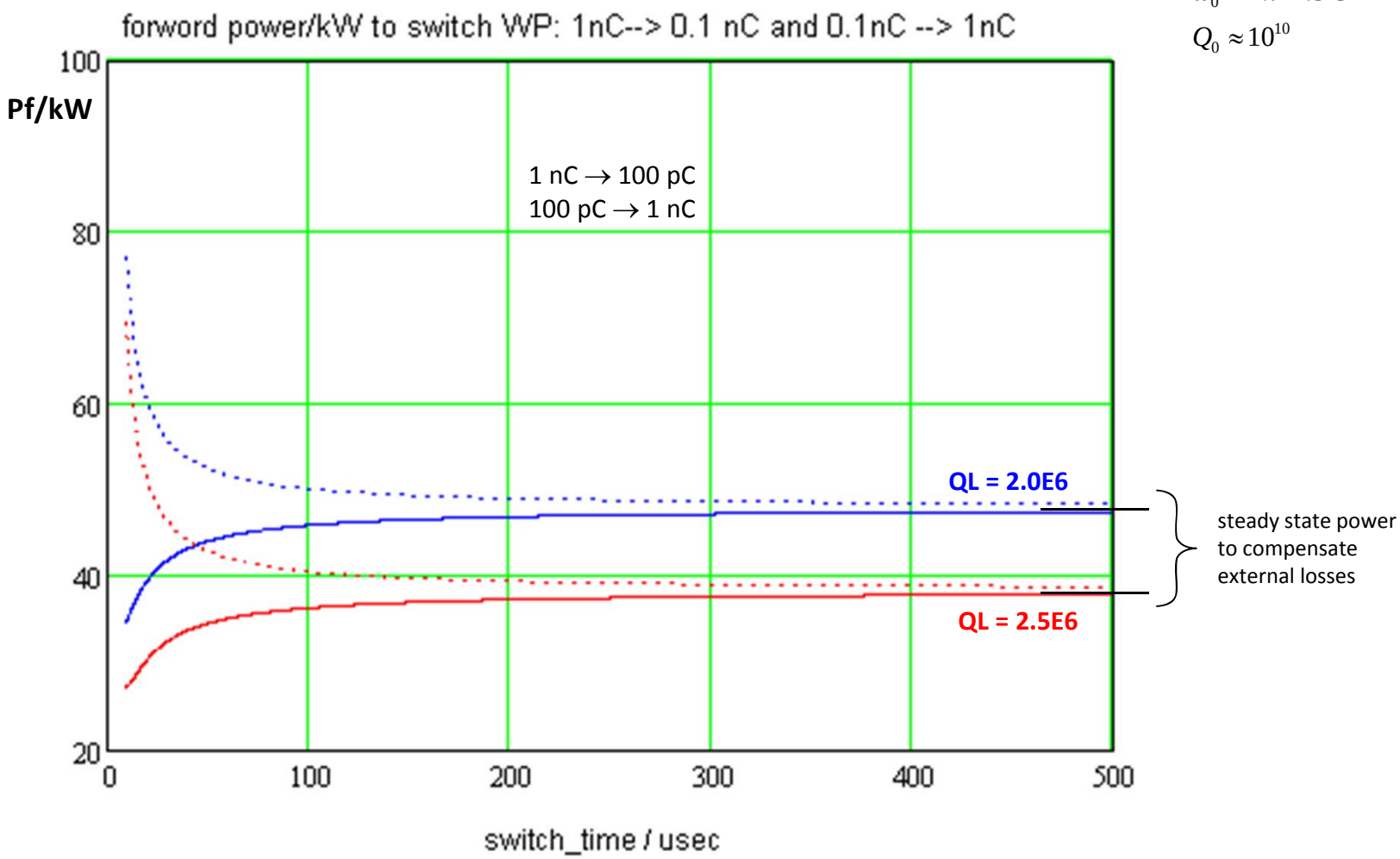
first look, **modified 1nC WP**

switching of ACC1 cavities (1nC ↔ 100pC)-case

$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$



Transient Operation (without beam)

first look, **modified 1nC WP**

ACC1

800 µs filling time

600 µs “flat top” = (290 + 20 + 290) µs

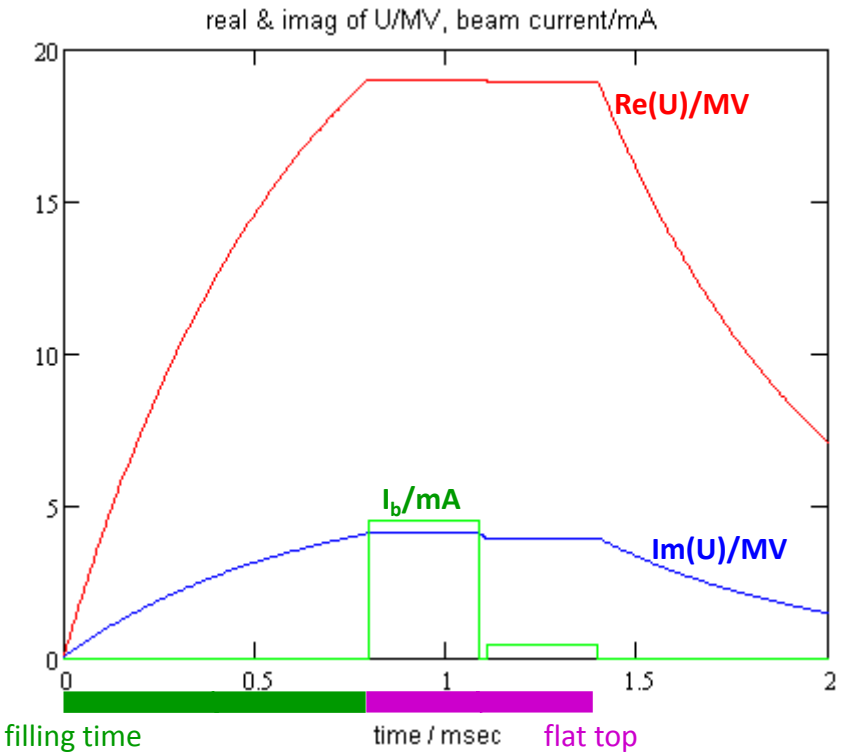
1nC switch 100pC

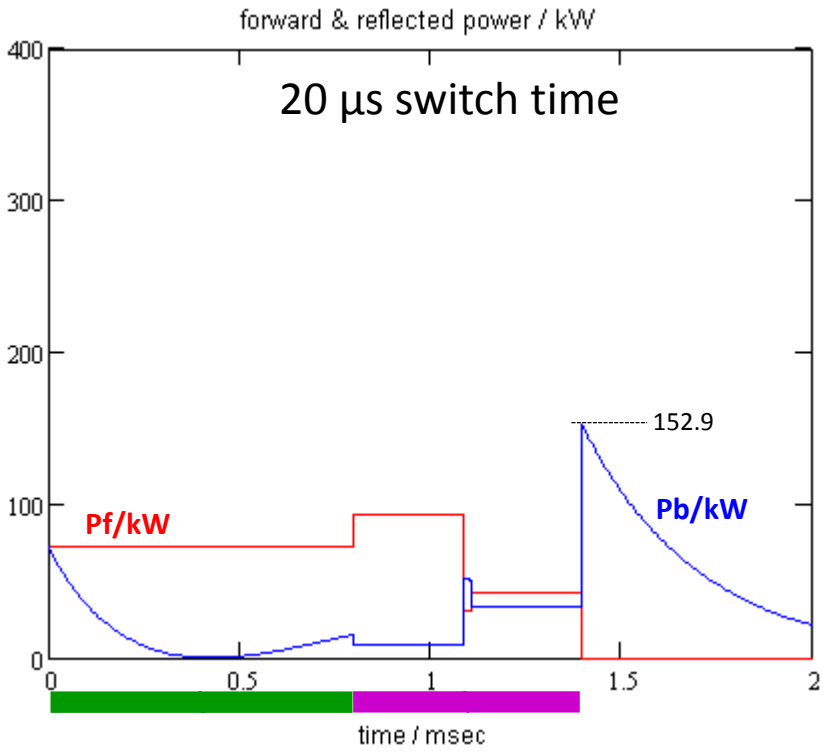
$$k \approx 2 \cdot 10^{12} \frac{\mathrm{V}}{\mathrm{As}}$$

$$\omega_0 \approx 2\pi \cdot 1.3\,\mathrm{GHz}$$

$$Q_0 \approx 10^{10}$$

$$Q_L \approx 2.5 \cdot 10^6$$





Summary, Remarks

gun operation

- switching of WPs: laser, rf, magnets, cooling
- realistic input distributions for s2e simulations

longitudinal dynamics

- bunch compression
  - switching of WPs: constant r56
    - rf-WPs with weak amplitude variation
    - beam loading helps !!!
    - rf-tolerances
- micro-bunch amplification
  - switching of laser heater necessary
    - laser amplitude
    - overlap photon- particle-beam

transverse dynamics

- WP dependent coupler kick
- space charge optics (? weak SC from end_acc1→begin_bc2)