CLIC main linac accelerating structure optimization.

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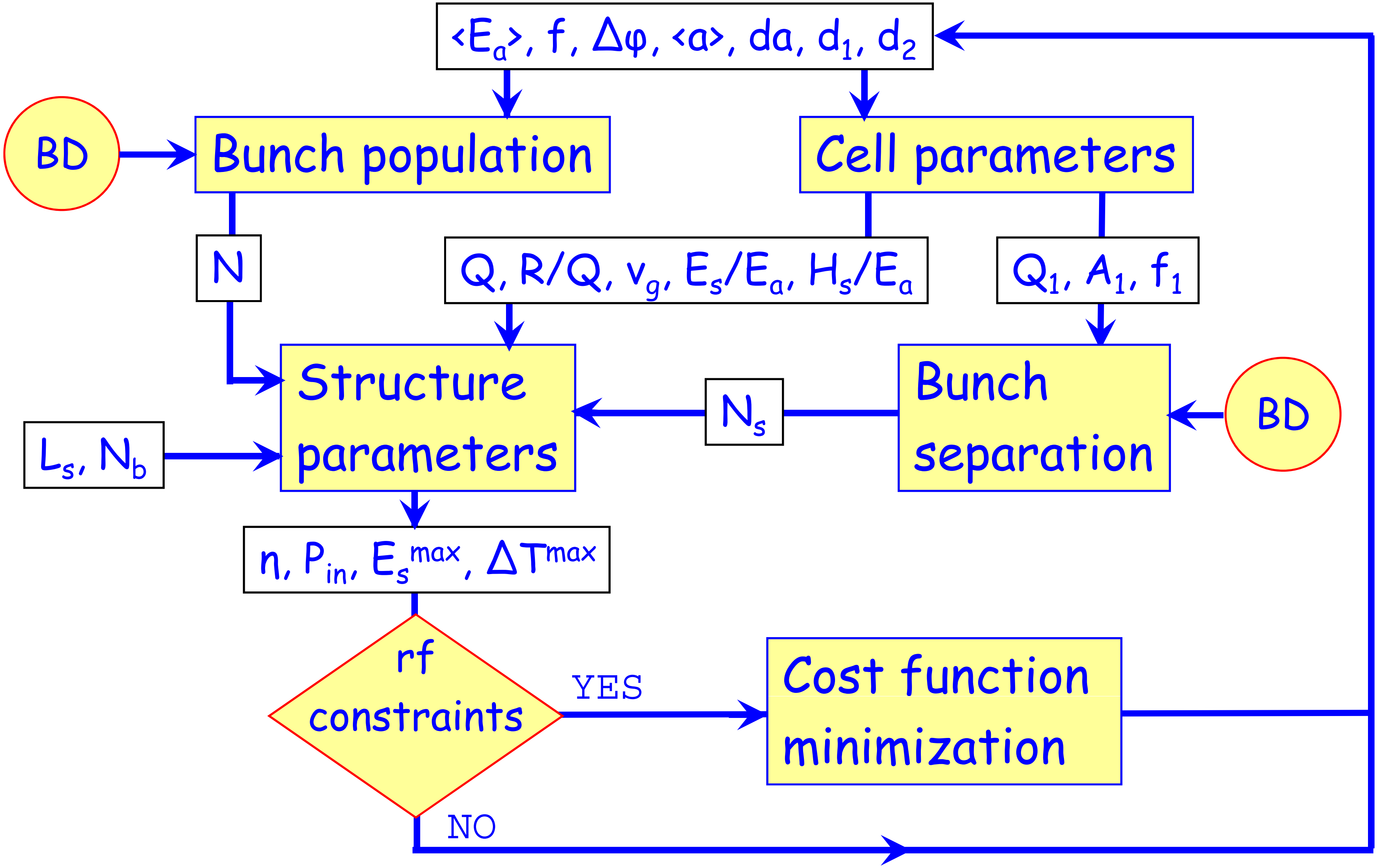
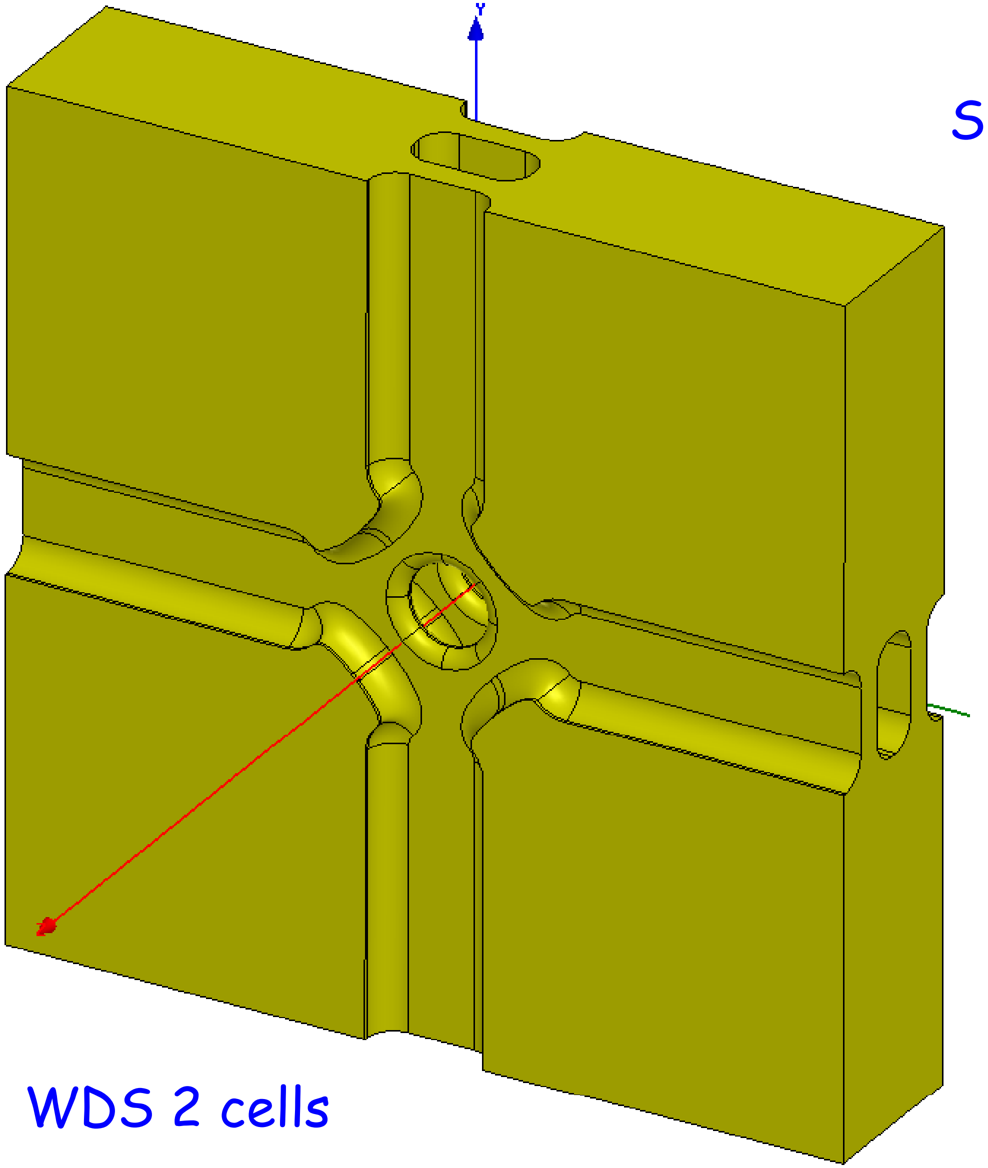
Outline

- Optimization of CLIC main linac accelerating structure
  - Optimization procedure
  - Optimization constraints
  - Optimization results
- Design of X-band accelerating structure for CLIC
  - The optimum structure
  - Modification of T53vg3MC (NLCTA test structure)

Optimization procedure

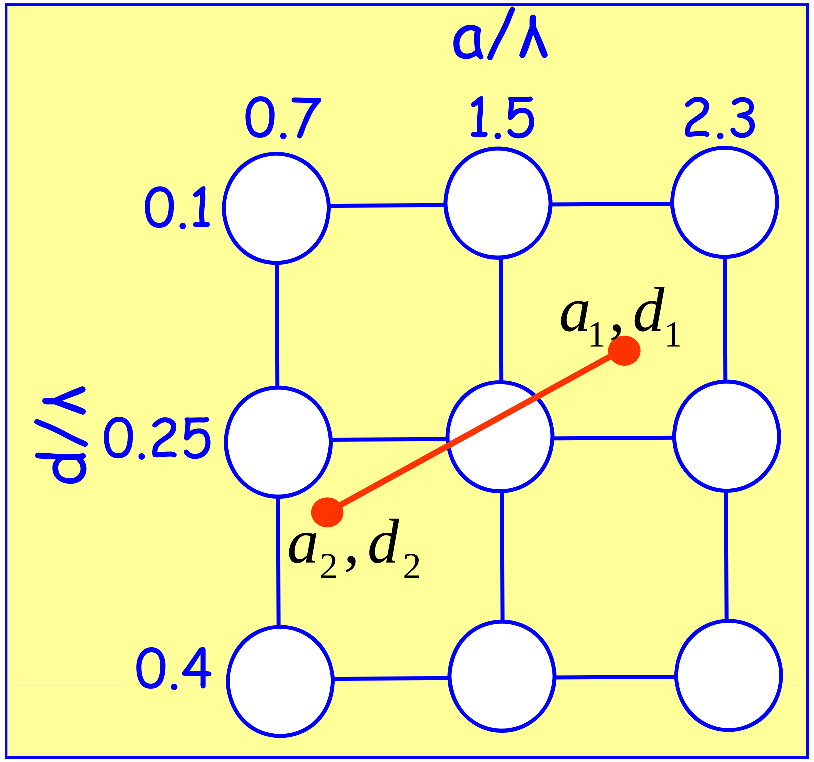


Cell parameter calculation



WDS 2 cells

Single cell parameter interpolation



Structure parameter calculation

Dipole mode:

$$W_t = \sum_{i=1}^{N_{cells}} A'_{1i}\, e^{-\frac{\omega_{1i} t}{2Q_{1i}}} \sin(\omega_{1i} t)$$

→ N_s → I ← N

Fundamental mode:

$$\frac{dP}{dz} = -\frac{\omega}{Q v_g} P - \sqrt{\frac{\omega}{v_g} \frac{R'}{Q}}\, I\, P^{\frac{1}{2}}$$

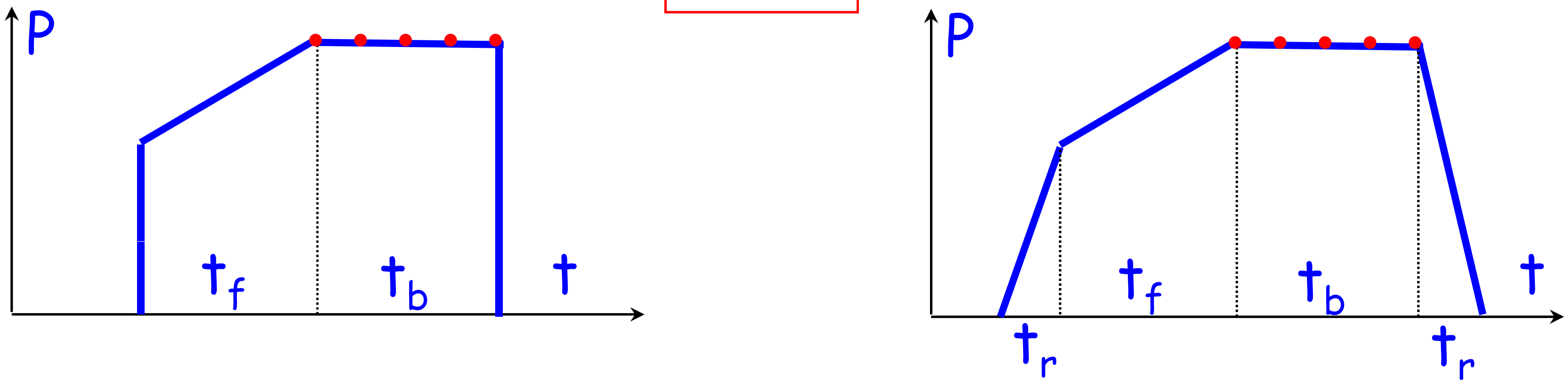
→ $P(z)$ → η, P_{in}, E_s^{max}, ΔT^{max}

Structure bandwidth model

$t_r = (\delta f)^{-1}$ – rise time

$$t_p = t_f + t_b \Rightarrow t_p' = t_f + t_b + t_r$$

$$\eta \Rightarrow \eta'$$



Optimization constraints

Beam dynamics (BD) constraints based on the simulation of the main linac, BDS and beam-beam collision at the IP:

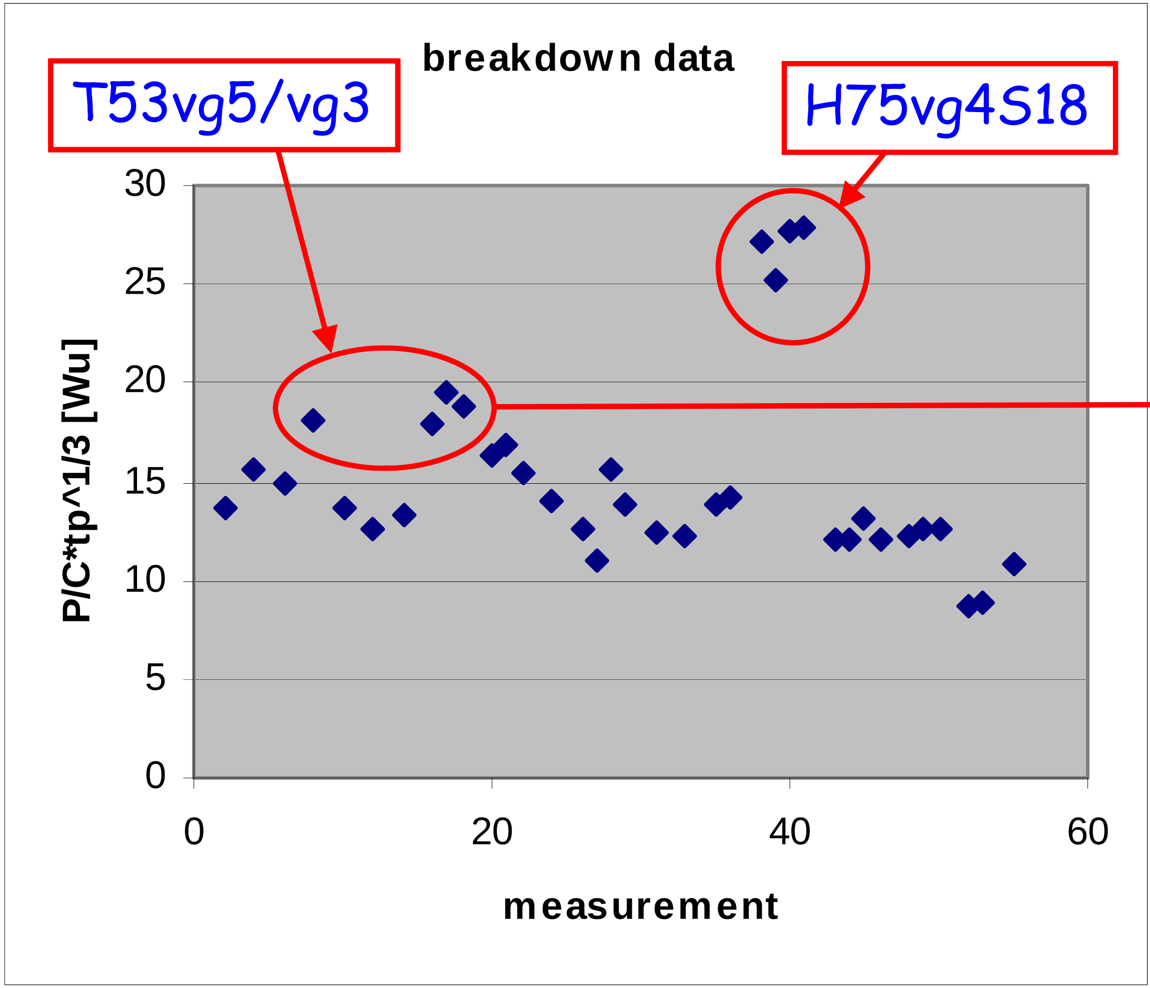
- N – bunch population depends on $\langle a \rangle / \lambda$, $\Delta a / \langle a \rangle$, f and $\langle E_a \rangle$ because of short-range wakes
- N_s – bunch separation depends on the long-range dipole wake and is determined by the condition:

$$W_{t,2} \cdot N / E_a = 10\ \text{V/pC/mm/m} \cdot 4\times10^9 / 150\ \text{MV/m}$$

RF breakdown and pulsed surface heating (rf) constraints:

- $\Delta T^{max}(H_{surf}^{max}, t_p) < 56$ K
- $E_{surf}^{max} < 380$ MV/m
- $P_{in} t_p^{1/3} / C_{in} = 18$ MW·ns$^{1/3}$/mm @ X-band

X-band data @ BDR=10^{-6}

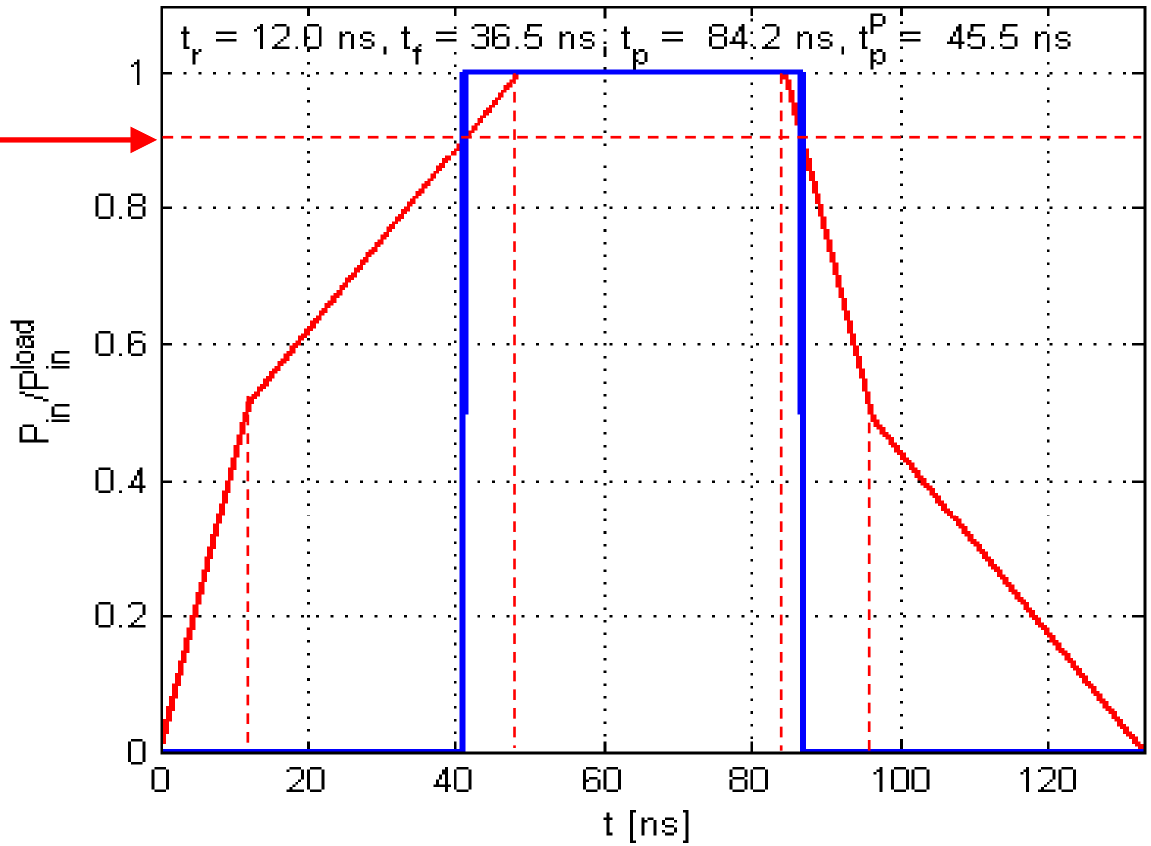


$P_{in}t_p^{1/3}/C_{in}$

$= 18 Wu$

Pulse shape dependences

$P_{in}/P_{in}^{load} = 0.9$



η: $t_p = t_b + t_f + t_r$

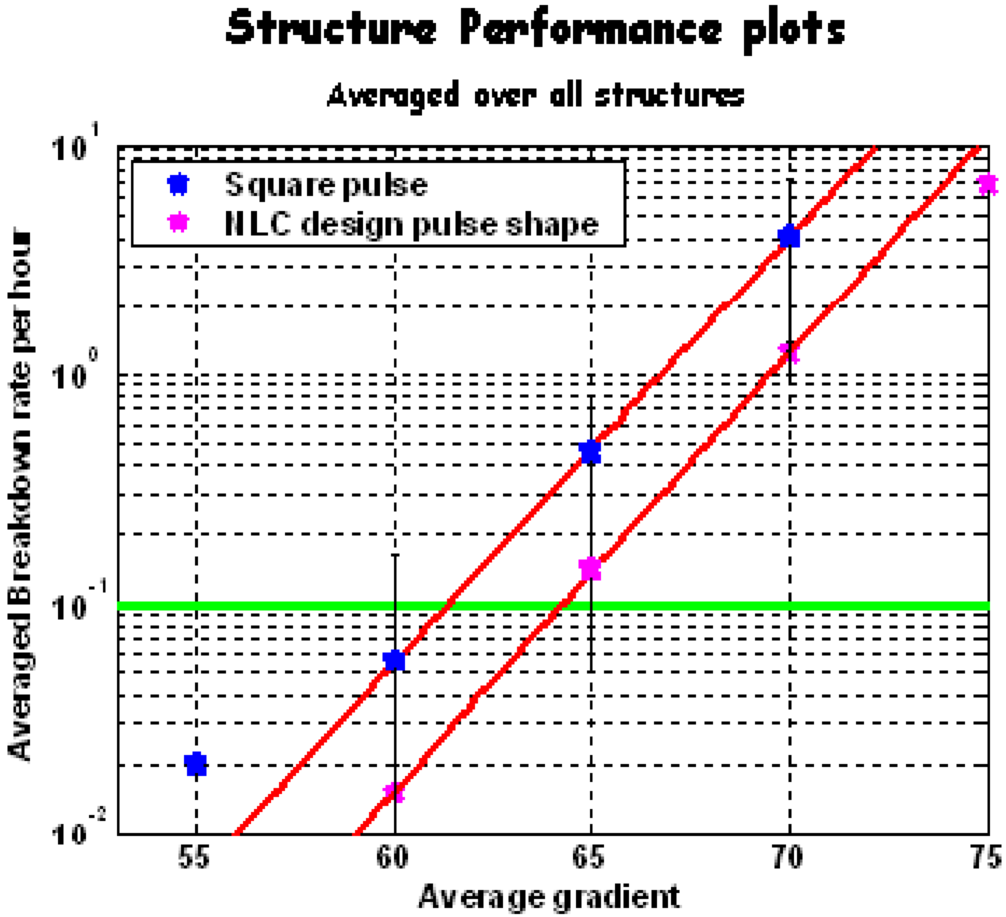
$\Delta T \sim (t^T_p)^{1/2}$: $t^T_p = [(t_b + t_f + t_r)^{1/2} - 0.5(t_f + t_r)^{1/2}]^2$

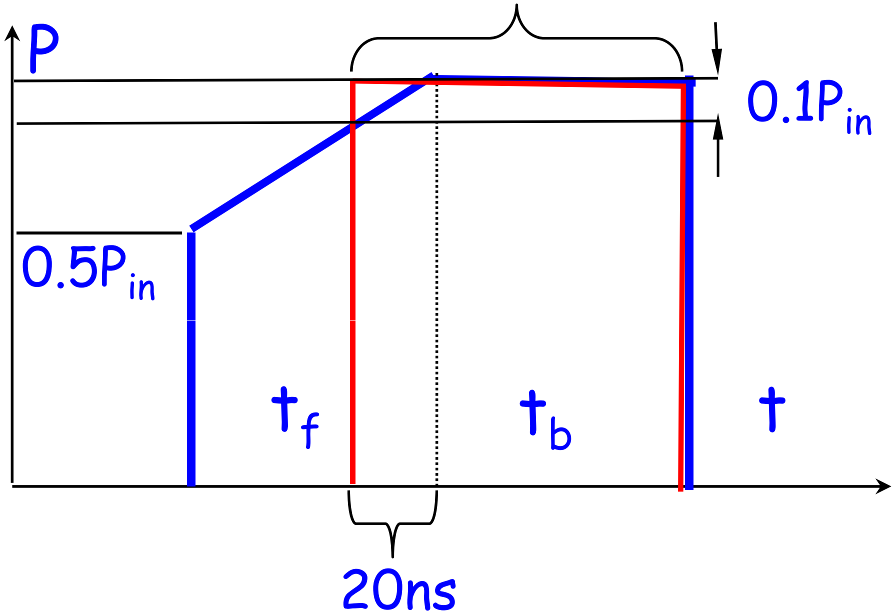
$P/C^*(t^P_p)^{1/3}$: t^P_p = time when $P_{in}/P_{in}^{load} > 0.9$

Effective pulse length for breakdown

Rect-pulse => NLC-pulse
65 MV/m => 67.5 MV/m

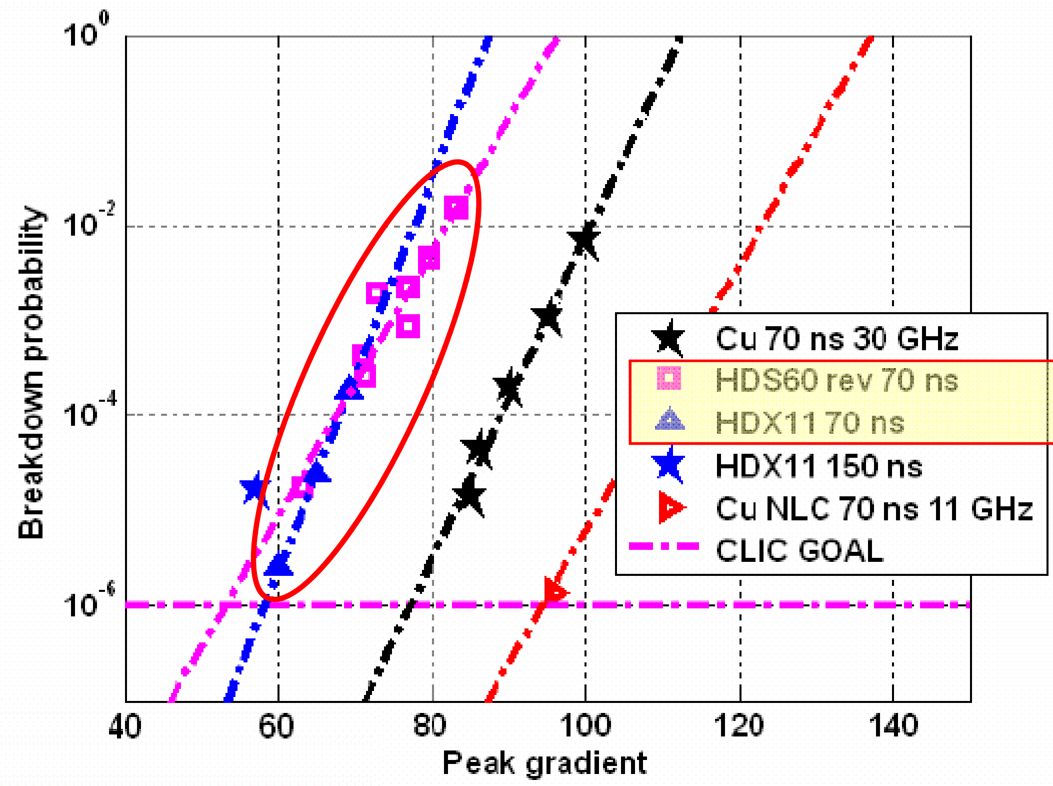
Assuming: $E_a * t_p^{1/6} = const$
400ns => 320ns





NLC: t_f = 100 ns; t_b = 300 ns

Frequency scaling of power constraint



Experimental data at X-band and 30 GHz

Scaled structures

Scaled structures show the same gradient at X-band and at 30 GHz:

$$E_a t_p^{1/6} = const$$

$$P/C \cdot t_p^{1/3} \cdot f = const$$

Optimizing Figure of Merit

Luminosity per linac input power:

$$\frac{L}{P_l} = \frac{L_{b\times} N_b f_{rep}}{\frac{e E_c N N_b f_{rep}}{\eta}} = \frac{1}{e E_{cm}} \bullet \frac{L_{b\times}}{N} \eta$$

Collision energy is constant

Figure of Merit (FoM = $\eta L_{bx}/N$)
in [a.u.] = [1e34/bx/m2•%/1e9]

Cost model

Total cost = Investment cost + Electricity cost for 10 years

$$C_t = C_i + C_e$$

$$C_i = \text{Excel}\{f_r;\ E_p;\ t_p;\ E_a\ ;\ L_s\ ;\ f\ ;\ \Delta\varphi\}$$

Repetition frequency;

Pulse energy;

Pulse length;

Accelerating gradient;

Structure length (couplers included);

Operating frequency;

rf phase advance per cell

$$C_e = (0.032 + 2.4/\text{FoM})$$

Optimization parameter space

All structure parameters are variable:

$\langle E_{acc} \rangle$ = 90 – 150 MV/m,

f = 10 – 30 GHz,

$\Delta\varphi$ = 120°, 150°,

$\langle a \rangle / \lambda$ = 0.09 - 0.21,

$\Delta a / \langle a \rangle$ = 0.01 – 0.6,

d_1 / λ = 0.025 - 0.1, $d_2 > d_1$

L_s = 10 – 100 mm.

N structures:

7

14

2

24

60

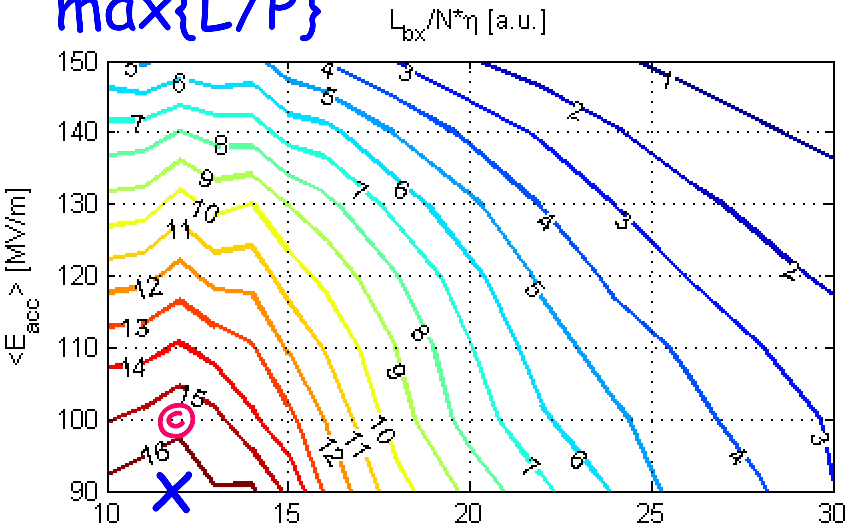
61

4

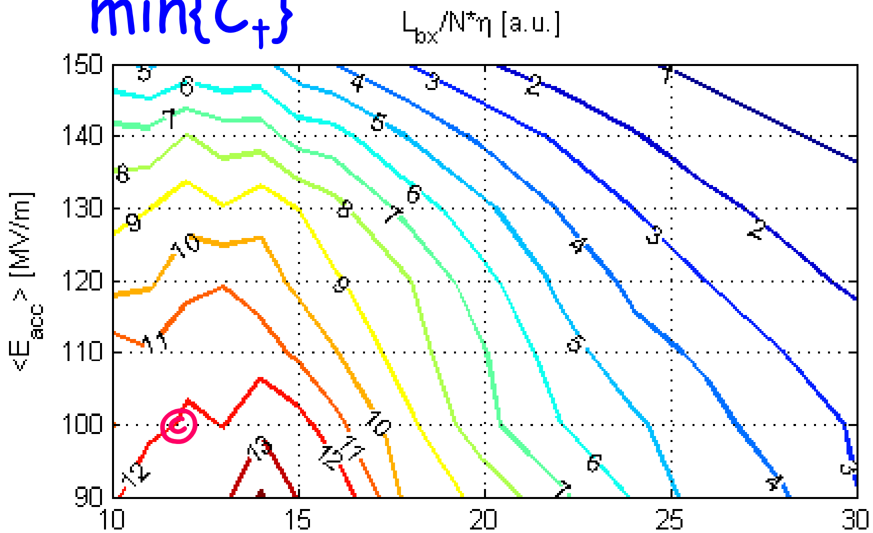
68.866.560

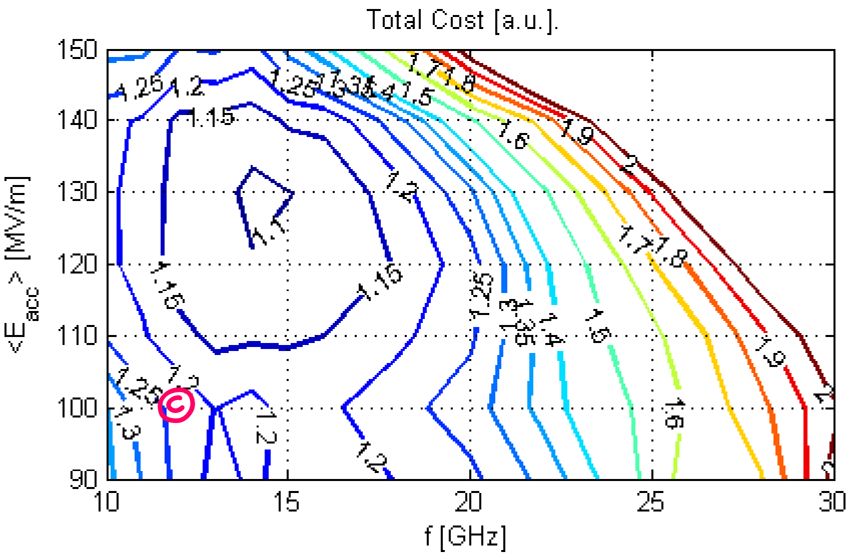
Optimizing L/P and C_t

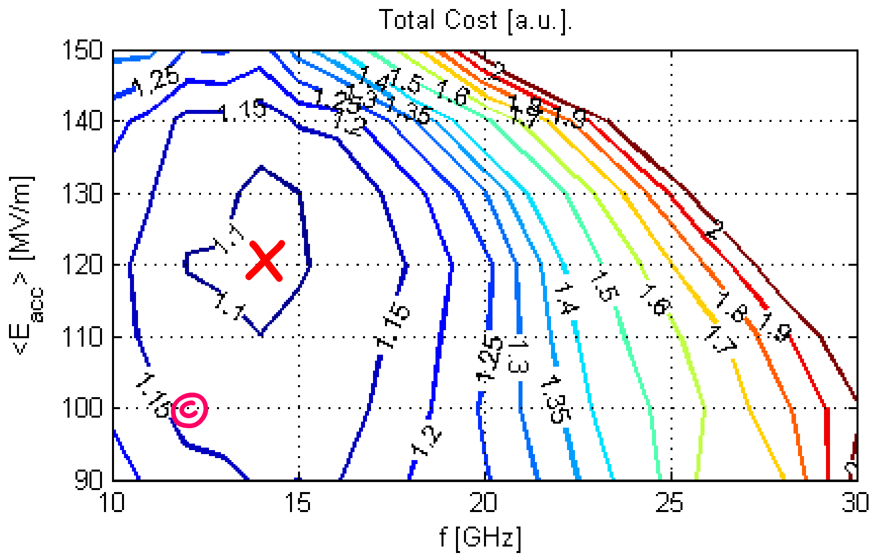
max{L/P}



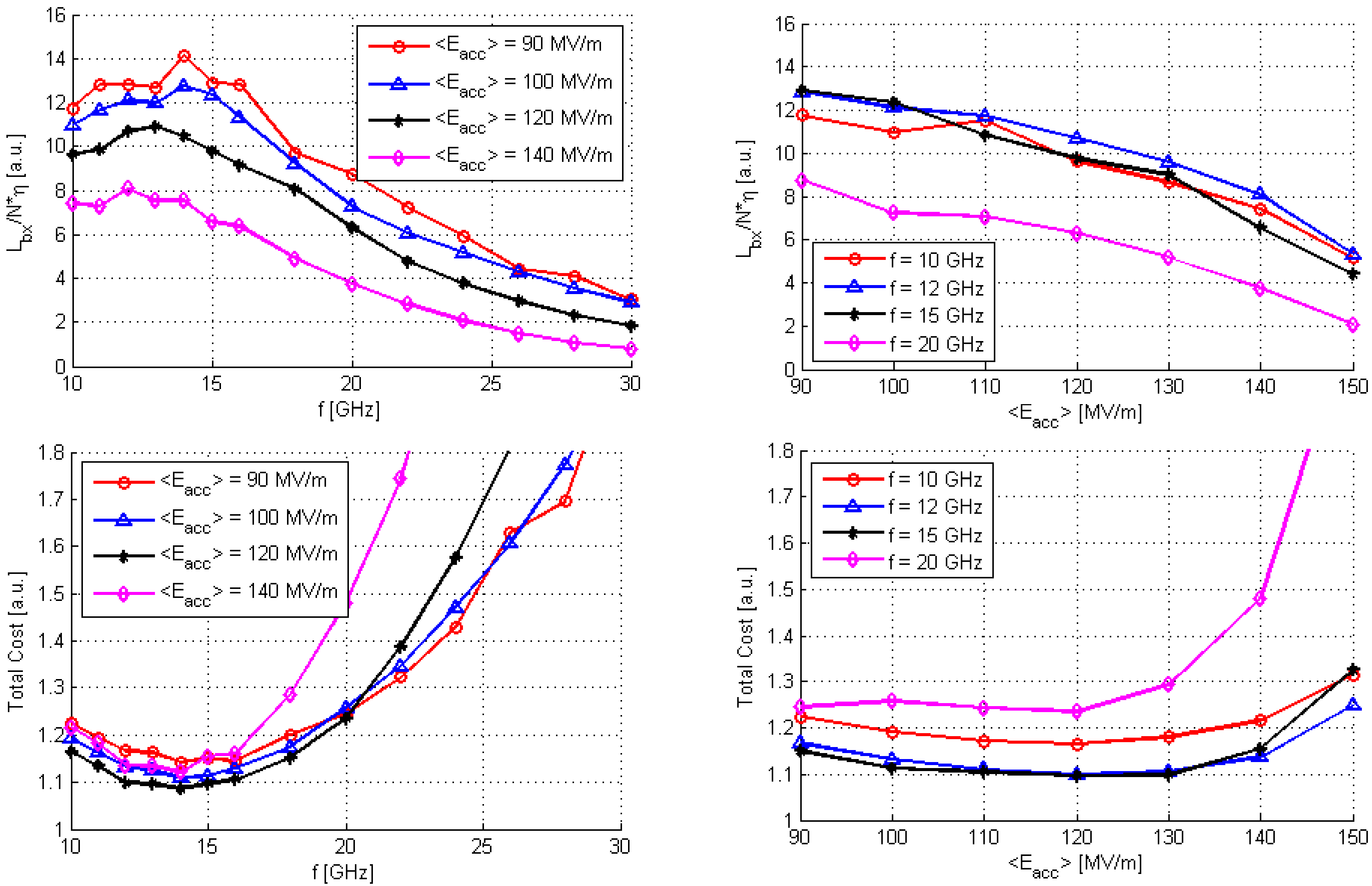
min{C_t}







Total Cost optimization



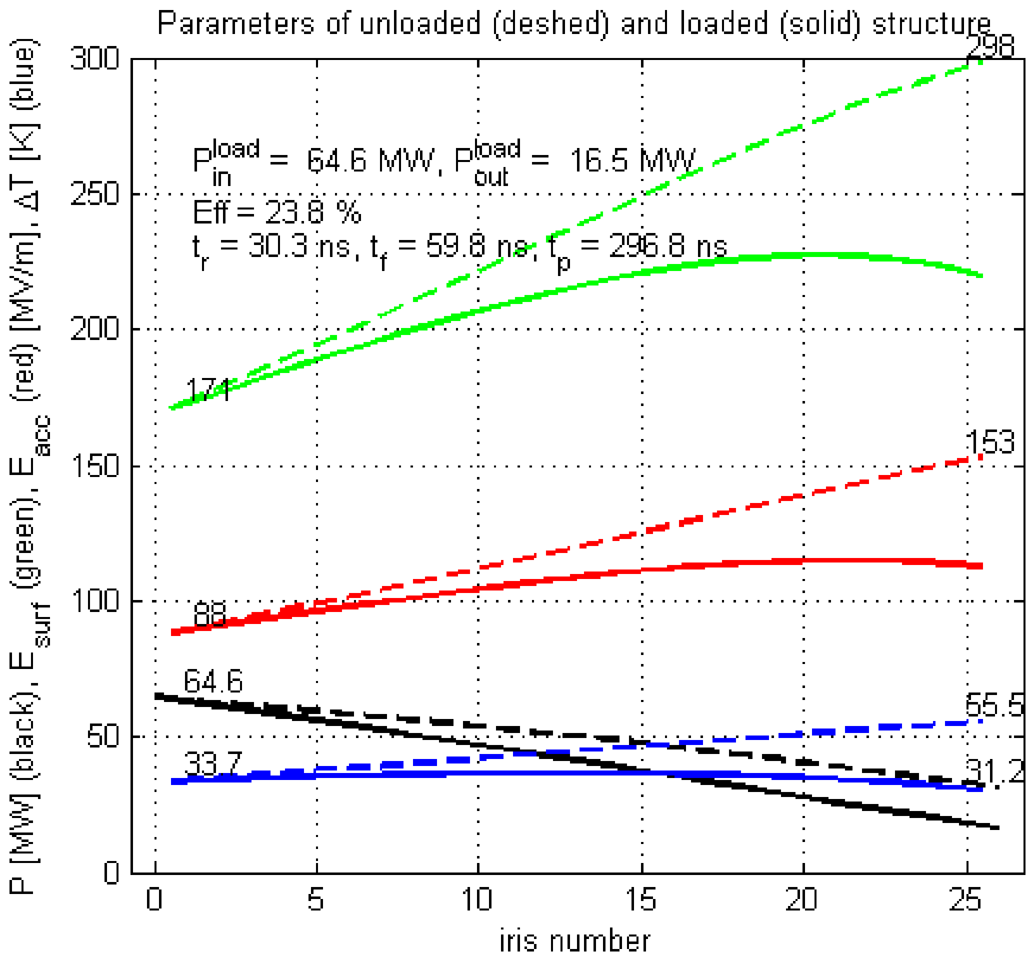
Parameters of CLIC acc. structure

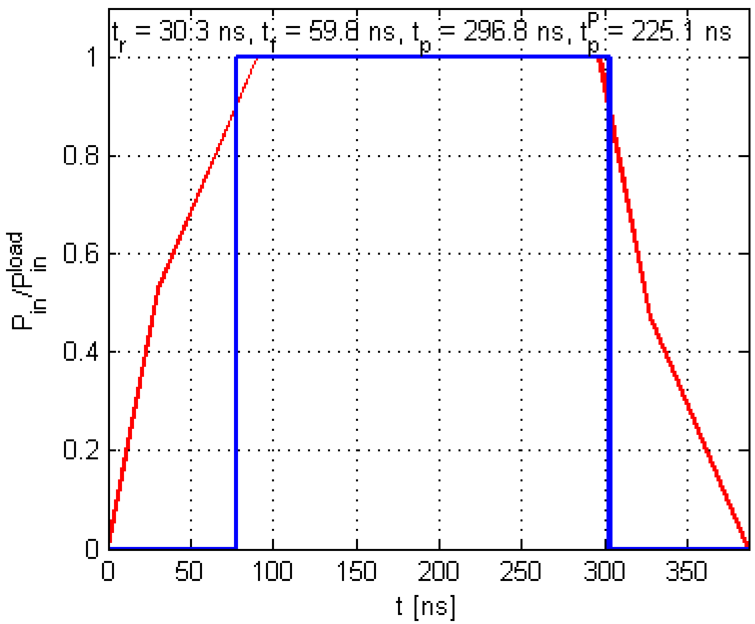
Structure	A	B	C
RF phase advance per cell: $\Delta\varphi$ [º]	120	120	120
Average iris radius/wavelength: $\langle a \rangle/\lambda$	0.12	0.12	0.12
Input/Output iris radii: $a_{1,2}$ [mm]	3.87, 2.13	3.87, 2.13	3.87, 2.13
Input/Output iris thickness: $d_{1,2}$ [mm]	2.66, 0.83	2.66, 0.83	2.66, 0.83
Group velocity: $v_g^{(1,2)}/c$ [%]	2.39, 0.65	2.39, 0.65	2.39, 0.65
N. of reg. cells, str. length: N_c, l [mm]	24, 229	24, 229	24, 229
Bunch separation: N_s [rf cycles]	7	8	8
Number of bunches in a train: N_b	265	311	311
Pulse length, rise time: τ_p, τ_r [ns]	244, 30	297, 30	297, 30
Input power: P_{in} [MW]	76	69	64.6
Max. surface field: E_{surf}^{max} [MV/m]	323	309	298
Max. temperature rise: ΔT^{max} [K]	57	60	56
Efficiency: η [%]	31.0	28.8	23.8
Luminosity per bunch X-ing: $L_{b\times}$ [m^{-2}]	2.6×10^{34}	2.5×10^{34}	1.3×10^{34}
Bunch population: N	5.8×10^{9}	5.2×10^{9}	4.0×10^{9}
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	13.7	13.8	7.7

Parameters of CLIC main linac

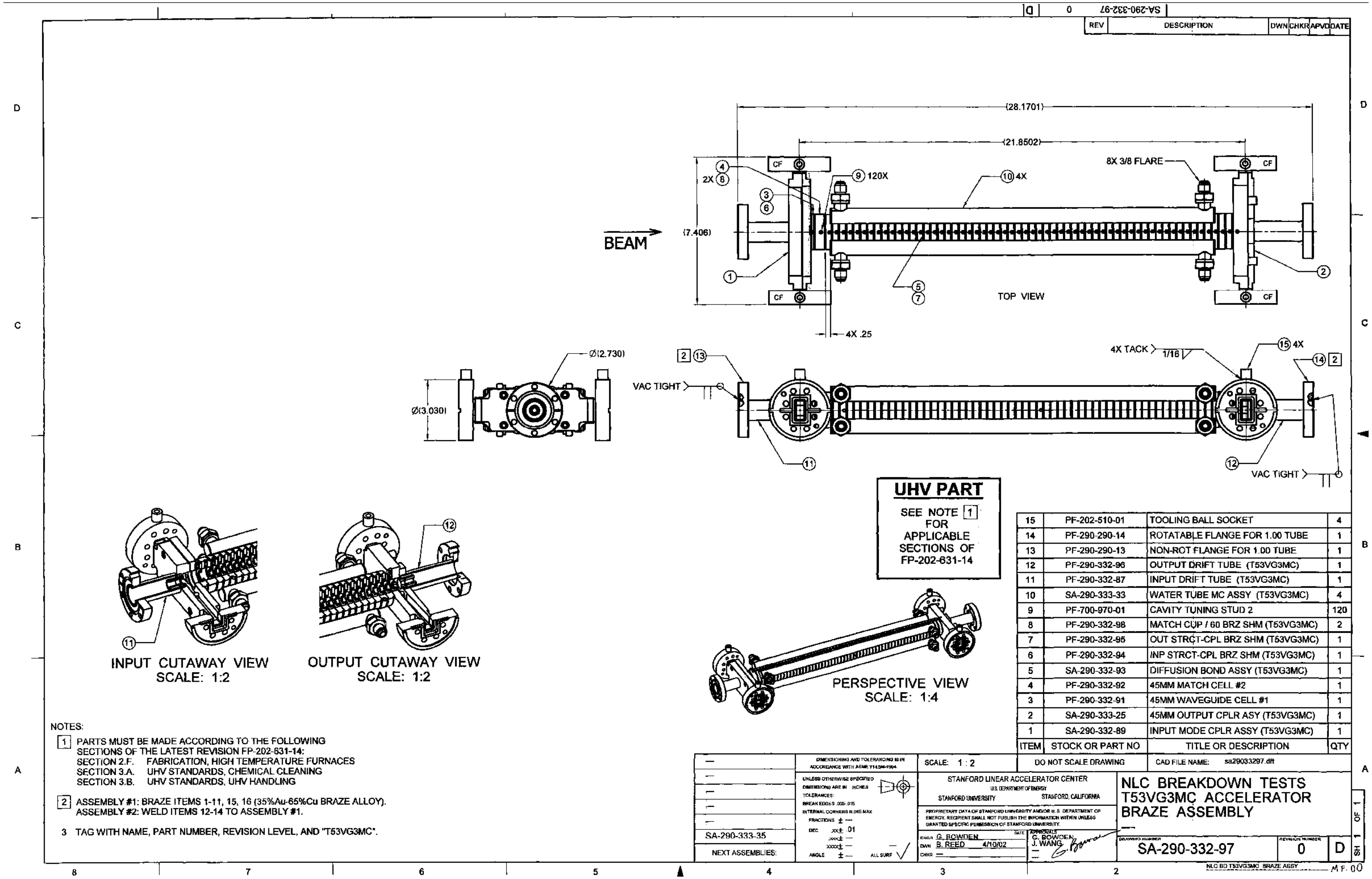
Structure	A	B	C
Luminosity : L_1[10^{34}cm^{-2}s^{-1}]	3.3	4.0	2.0
Repetition frequency: f_{rep}[Hz]	48	50	50
RF input power: P_l [MW/linac]	58.3	69.3	62.1
RF energy per pulse: P_l/f_{rep} [kJ/linac]	1210	1347	1255
Electricity cost for 10 years: C_e [a.u.]	0.2	0.2	0.36
Investment cost: C_i [a.u.]	0.97	1.00	0.98

Parameters of CLIC structure (C)





T53vg3MC structure



T53vg3MC structure

Manufactured: 08.2002

It requires 41 MW for 65 MV/m average gradient

Test results:

$\langle E_a \rangle$ = 73MV/m @ 400ns with BDR = 0.04 BD/h =>

$\langle E_a \rangle$ = 78MV/m @ 400ns with BDR = 10^{-6} =>

P_{in} = 60MW @ 400ns with BDR = 10^{-6}

In the following slides no P/C scaling is involved.
Only $P_{in}*(t^P{}_p)^{1/3}$ = const has been used to scale the maximum pulse length versus input power.

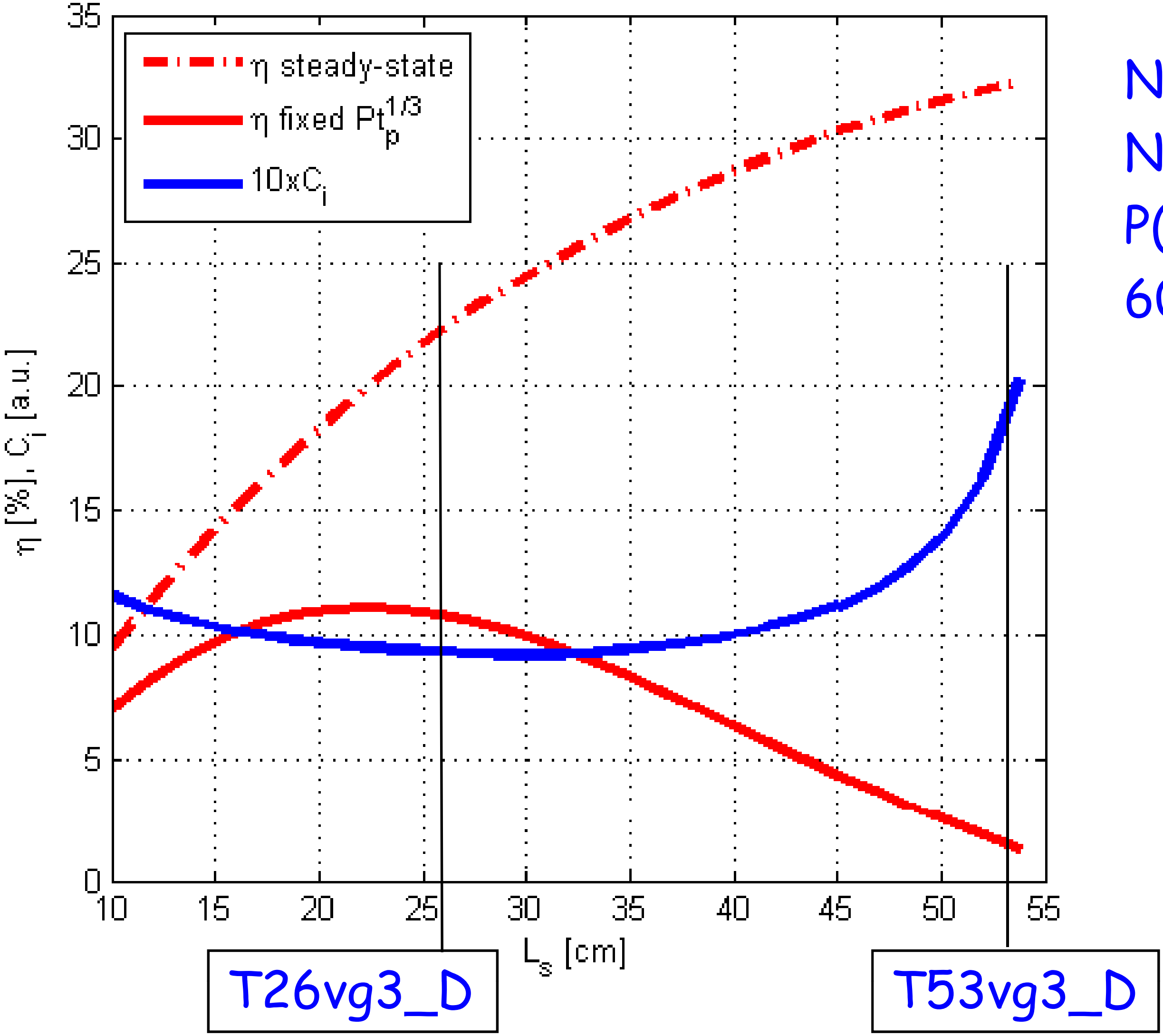
T53vg3MC cells w/o and with damping

Name	NDS: first / last	WDS: first/last
a [mm]	3.89 / 3.17	3.89 / 3.17
Q^{Cu}	6810 / 6780	5480 / 5400
v_g/c [%]	3.29 / 1.64	2.86 / 1.42
R'/Q [LinacΩ/m]	13500 / 15700	11700 / 13550
E_{surf}^{max}/E_a	2.0 / 1.9	1.95 / 1.8
H_{surf}^{max}/E_a [mA/V]	2.75 /2.6	4.6 / 4.5
P_{in} [MW] @ 100MV/m	102 / 44	102 / 44

Modifications:

1. Introduce damping
2. Change structure length

T53vg3 performance versus length



N = 4x10^9

N_s = 8

$P(t_p^P)^{1/3}$ =

60MW(400ns)$^{1/3}$

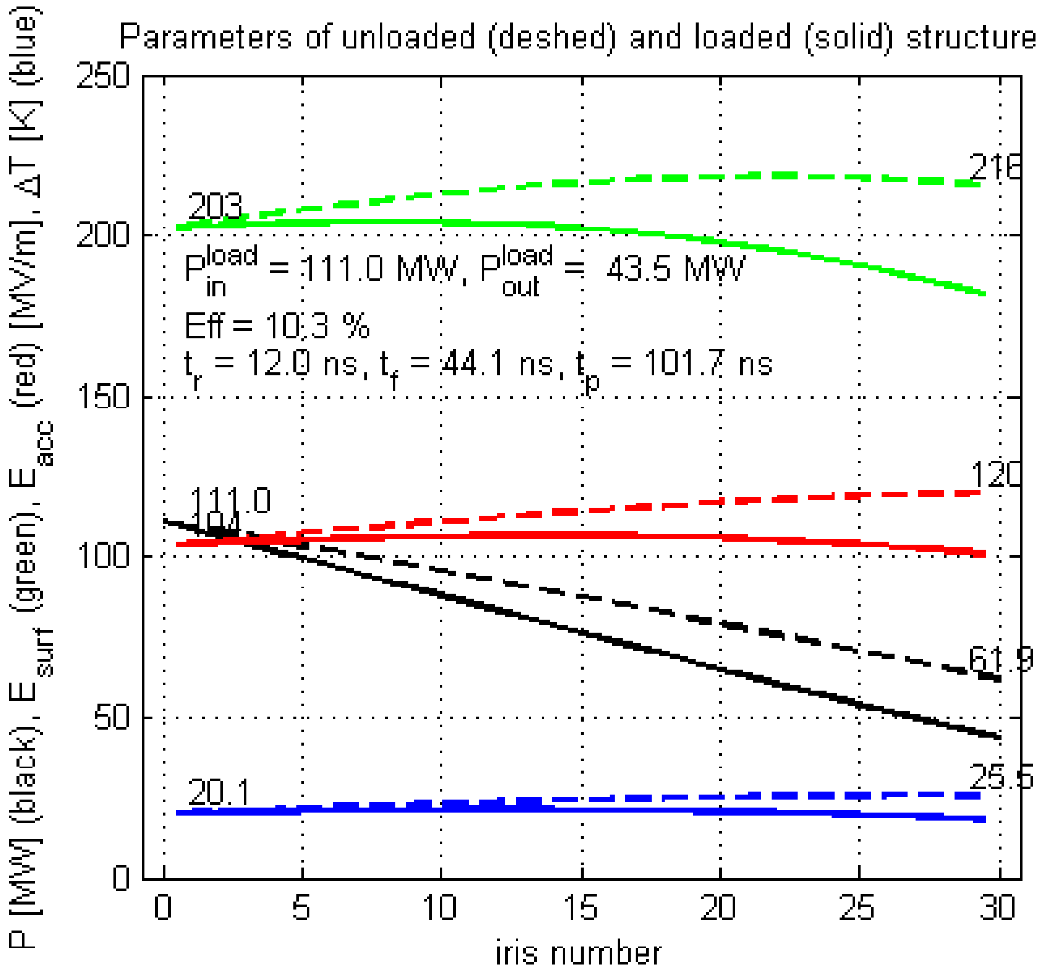
Parameters of CLIC acc. structures

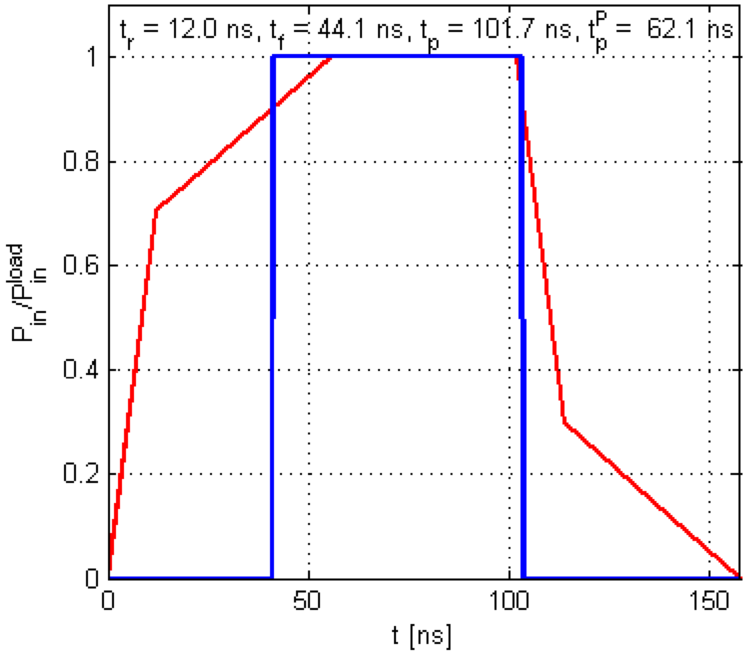
Structure	CLIC_C	T26vg3_D
Frequency: f [GHz]	12	11.424
Average iris radius/wavelength: $\langle a\rangle/\lambda$	0.12	0.134
Input/Output iris radii: $a_{1,2}$ [mm]	3.87, 2.13	3.89, 3.17
Input/Output iris thickness: $d_{1,2}$ [mm]	2.66, 0.83	1.66
Group velocity: $v_g^{(1,2)}/c$ [%]	2.39, 0.65	2.86, 1.42
N. of reg. cells, str. length: N_c, l [mm]	24, 229	28, 270
Bunch separation: N_s [rf cycles]	8	8
Number of bunches in a train: N_b	311	66
Pulse length, rise time: τ_p, τ_r [ns]	297, 30	102, 12
Input power: P_{in} [MW]	64.6	111
Max. surface field: E_{surf}^{max} [MV/m]	298	216
Max. temperature rise: ΔT^{max} [K]	56	26
Efficiency: η [%]	23.8	10.3
Luminosity per bunch X-ing: $L_{b\times}$ [m^{-2}]	1.3×10^{34}	1.3×10^{34}
Bunch population: N	4.0×10^{9}	4.0×10^{9}
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	7.7	3.3

Parameters of CLIC main linac

Structure	CLIC_C	T26vg3_D
Luminosity : L_1[10^{34}cm^{-2}s^{-1}]	2.0	2.0
Repetition frequency: f_{rep}[Hz]	50	233
RF input power: P_l [MW/linac]	62.1	143
RF energy per pulse: P_l/f_{rep} [kJ/linac]	1255	614
Electricity cost for 10 years: C_e [a.u.]	0.36	0.74
Investment cost: C_i [a.u.]	0.98	0.93

Parameters of T26vg3_D

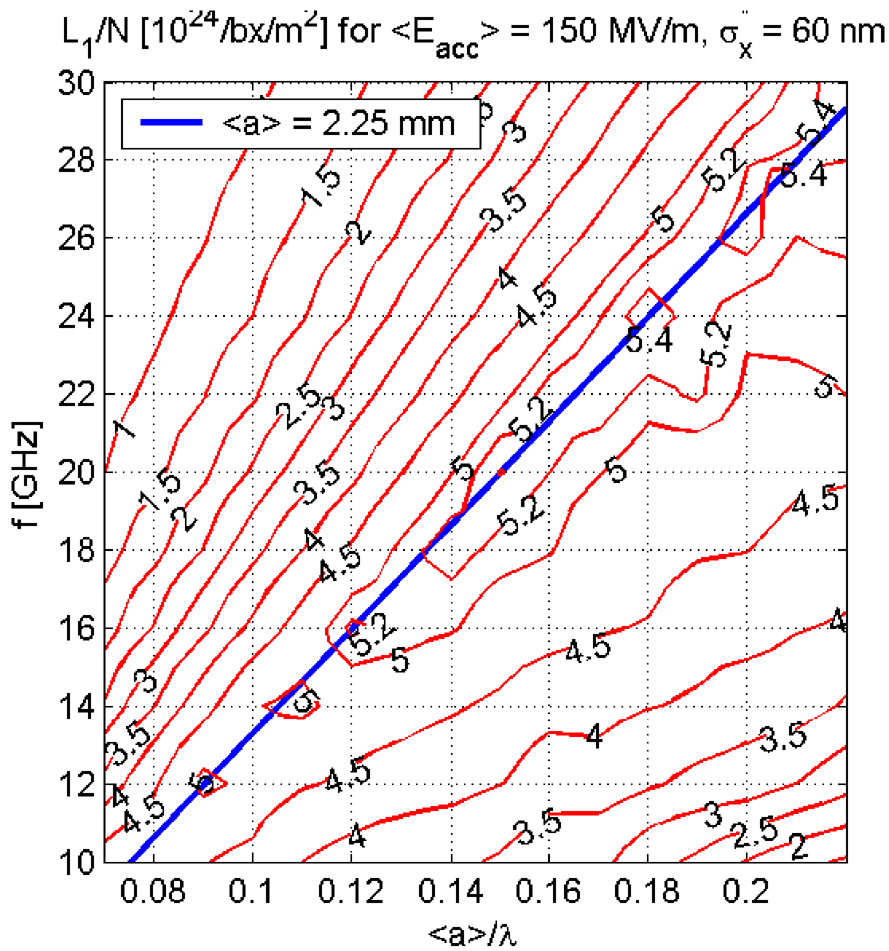


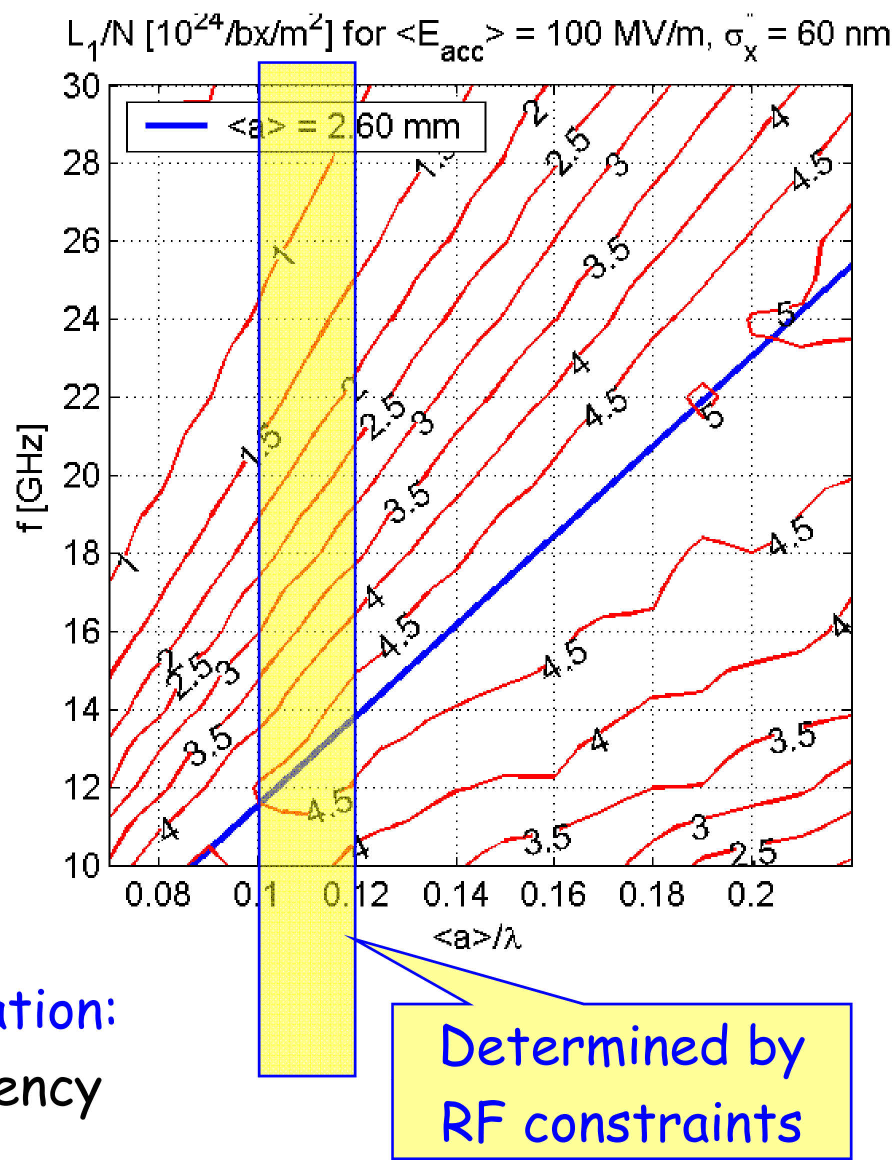


Summary

- Optimization of CLIC frequency and gradient has been done, based on the cost model and taking into account new experimental data at 30 GHz and NLCTA measurement results at X-band
- This (together with some other considerations) resulted in major change of CLIC parameters (from 150MV/m@30GHz to 100MV/m@12GHz)
- RF design of X-band CLIC accelerating structure has been done based on the results of optimization

L_{bx}/N for different gradients





Why X-band ? A simplistic explanation:

Crossing gives the optimum frequency

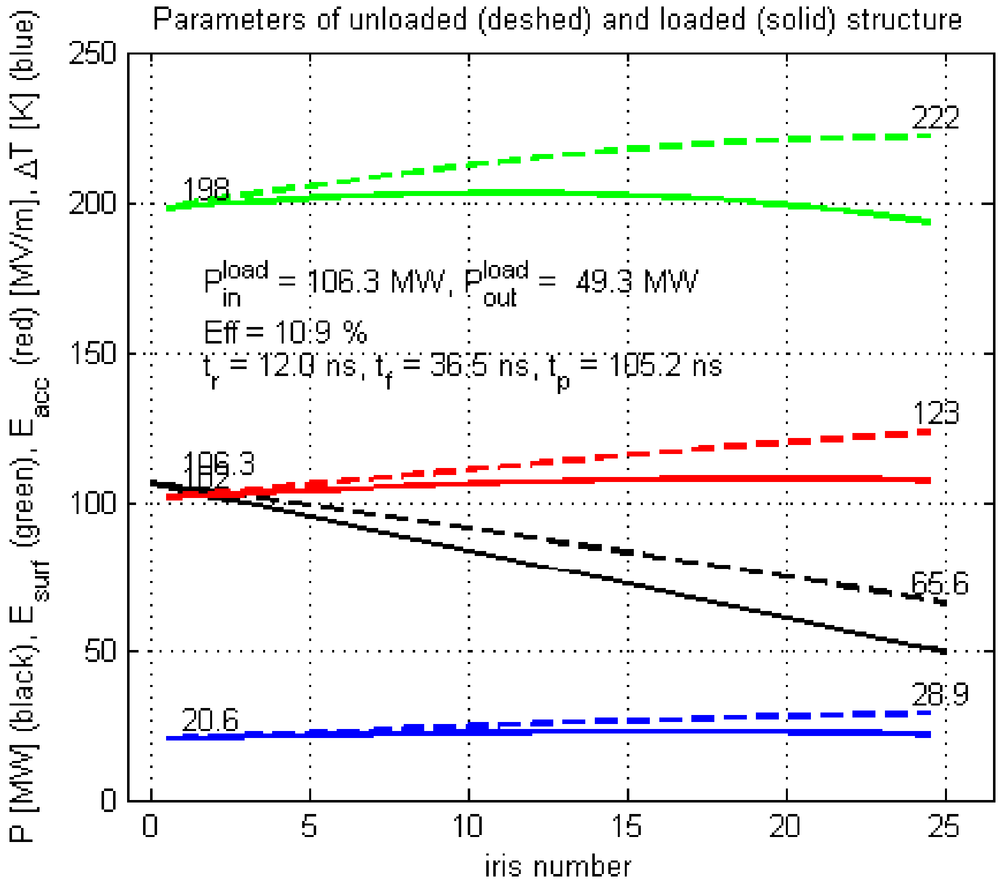
Parameters of CLIC acc. structures

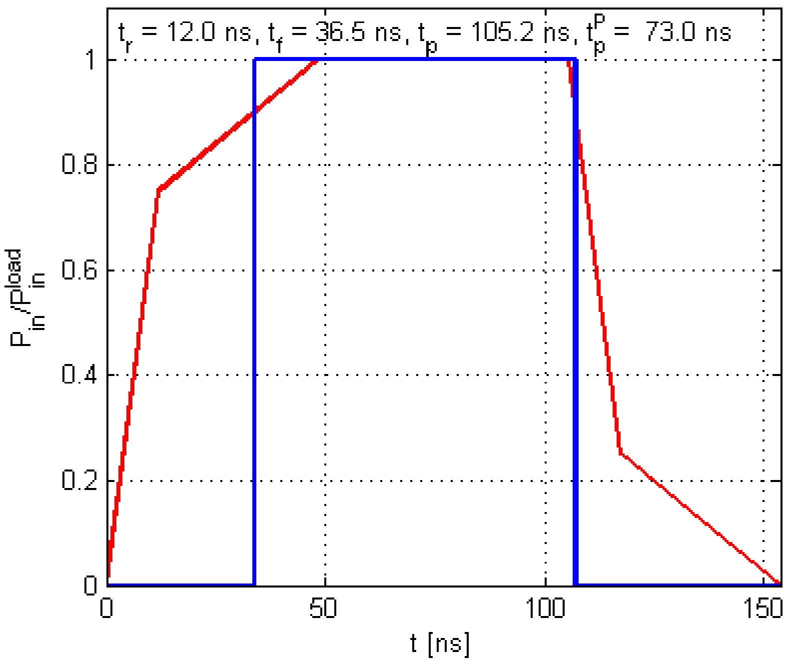
Structure	CLIC_C	T23vg3_D	T53vg3_D
Frequency: f [GHz]	12	11.424	11.424
Average iris radius/wavelength: $\langle a \rangle/\lambda$	0.12	0.134	0.134
Input/Output iris radii: $a_{1,2}$ [mm]	3.87, 2.13	3.89, 3.17	3.89, 3.17
Input/Output iris thickness: $d_{1,2}$ [mm]	2.66, 0.83	1.66	1.66
Group velocity: $v_g^{(1,2)}/c$ [%]	2.39, 0.65	2.86, 1.42	2.86, 1.42
N. of reg. cells, str. length: N_c, l [mm]	24, 229	23, 232	58, 530
Bunch separation: N_s [rf cycles]	8	8	8
Number of bunches in a train: N_b	311	82	6
Pulse length, rise time: τ_p, τ_r [ns]	297, 30	105, 12	103, 12
Input power: P_{in} [MW]	64.6	106	155
Max. surface field: E_{surf}^{max} [MV/m]	298	222	240
Max. temperature rise: ΔT^{max} [K]	56	29	23
Efficiency: η [%]	23.8	10.9	1.3
Luminosity per bunch X-ing: $L_{b\times}$ [m^{-2}]	1.3×10^{34}	1.3×10^{34}	1.3×10^{34}
Bunch population: N	4.0×10^{9}	4.0×10^{9}	4.0×10^{9}
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	7.7	3.6	0.4

Parameters of CLIC main linac

Structure	CLIC_C	T23vg3_D	T53vg3_D
Luminosity : L_1[10^{34}cm^{-2}s^{-1}]	2.0	2.0	2.0
Repetition frequency: f_{rep}[Hz]	50	188	2564
RF input power: P_l [MW/linac]	62.1	136	1145
RF energy per pulse: P_l/f_{rep} [kJ/linac]	1255	724	447
Electricity cost for 10 years: C_e [a.u.]	0.36	0.71	5.7
Investment cost: C_i [a.u.]	0.98	0.95	2.0

Parameters of T23vg3_D





Parameters of T53vg3_D