CLIC main linac accelerating structure optimization.

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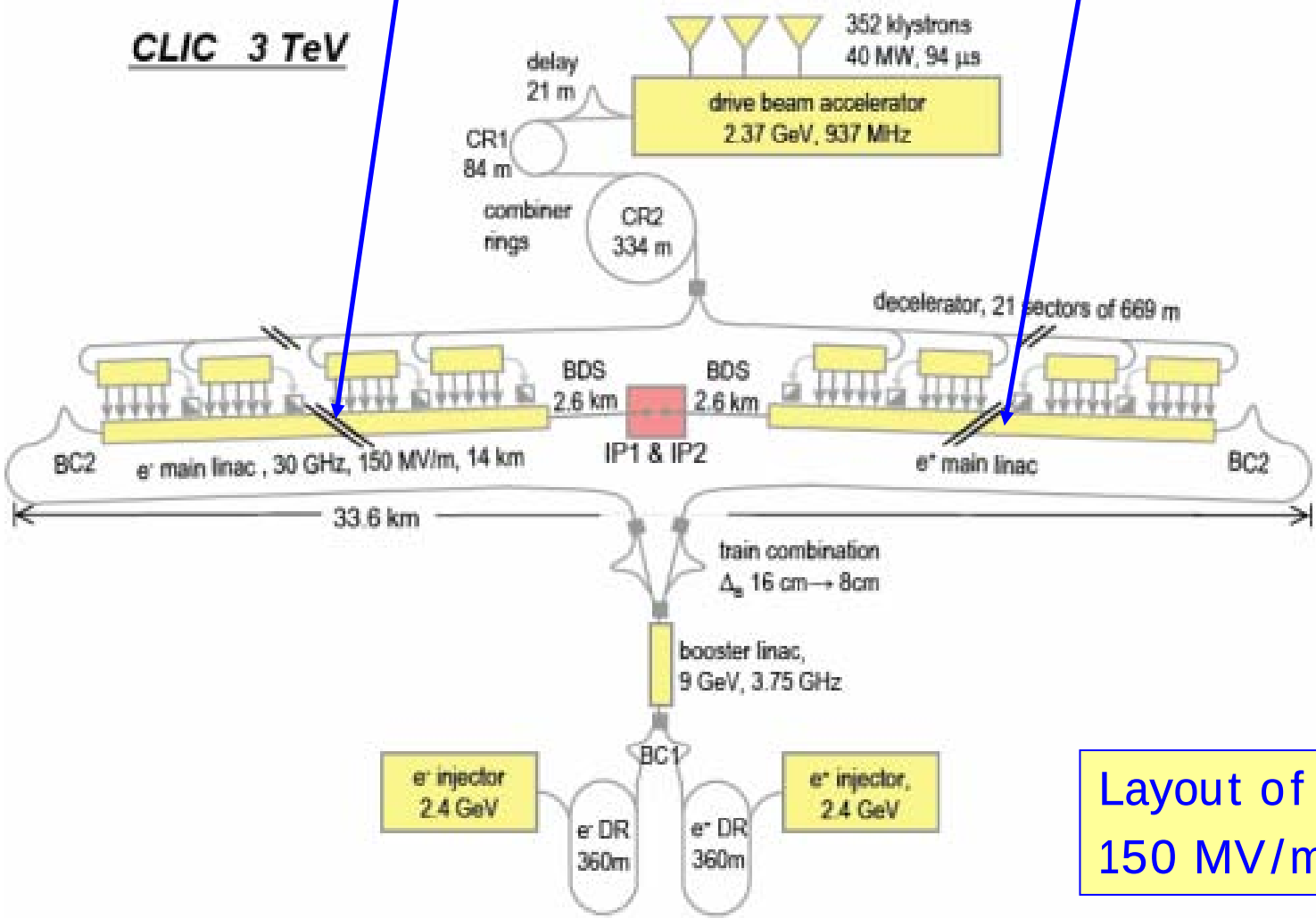
for CLIC Study team

Outline

- Introduction
- Optimum frequency and gradient for CLIC main linac
  - Optimization procedure
  - Optimization constraints
  - Optimization results
- Design of X-band accelerating structure for CLIC
  - Higher order mode damping
  - Analysis of X-band test results

Introduction

Compact LInear Collider (CLIC) main linac



Layout of CLIC for 150 MV/m, 30 GHz

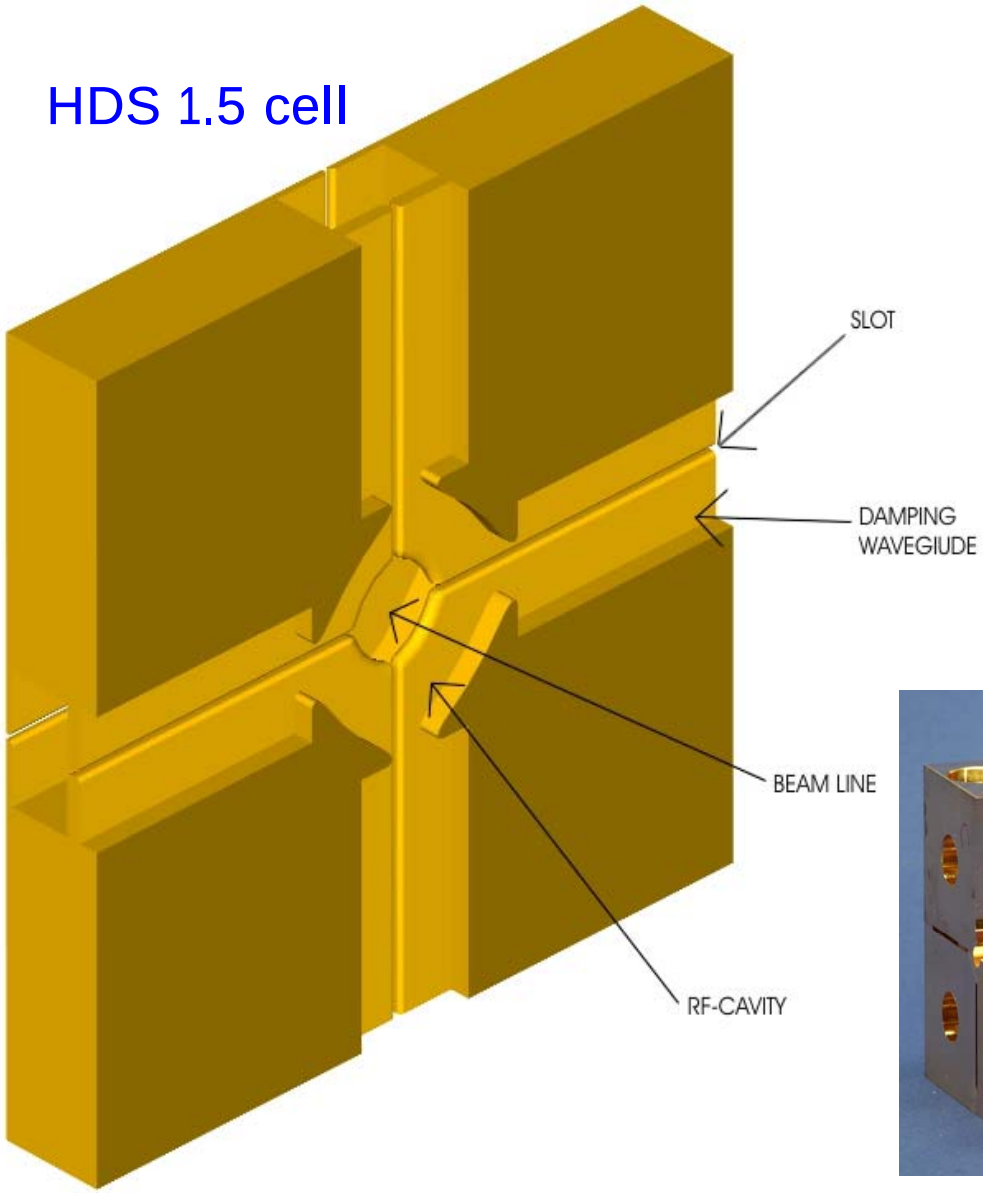
Optimization procedure

Main ingredients:

- Cell design: Hybrid Damped Structure (HDS)
- Tapered structure model: 3 cells interpolation for fundamental and dipole modes
- Structure bandwidth model
- Beam Dynamics (BD) constraints
- RF constraints:
  - Pulsed surface heating
  - RF breakdown model
  - High gradient measurement results (new data at 30 GHz become available in 2006)
- Optimization cost functions:
  - Luminosity per power
  - Total cost model (become available in 2006)

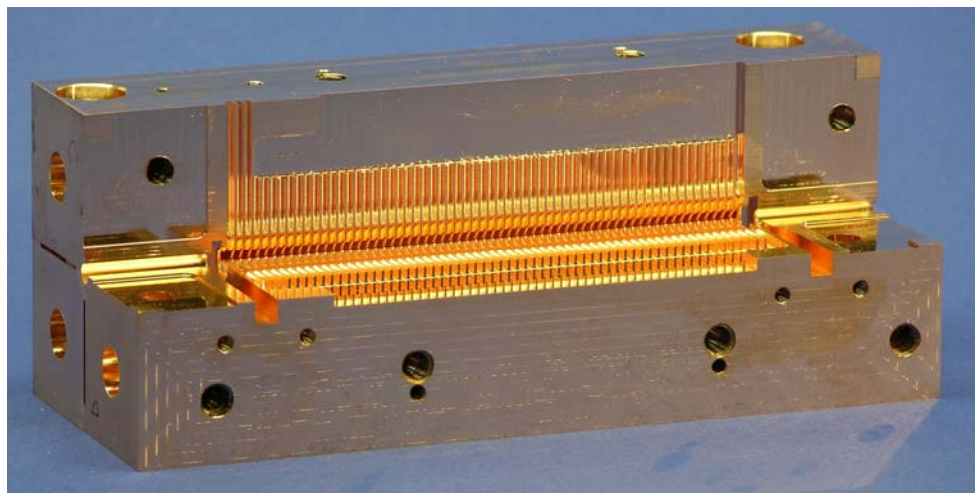
Cell design

HDS 1.5 cell

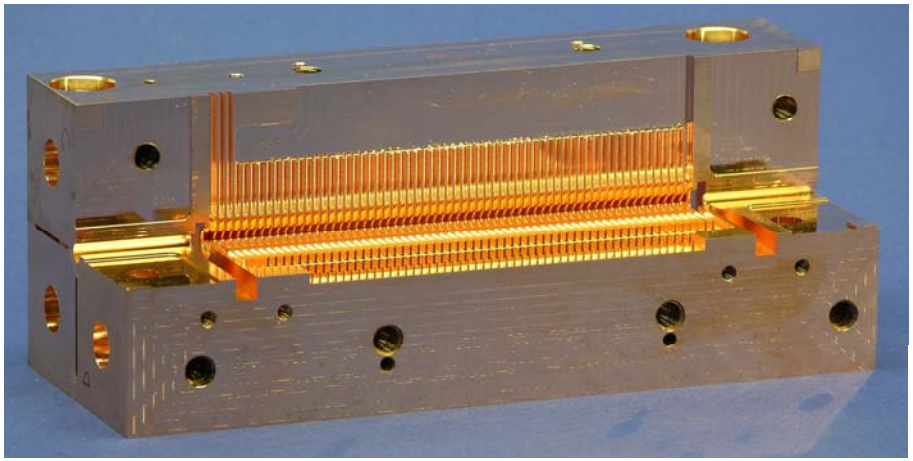


Hybrid Damped Structure (HDS)

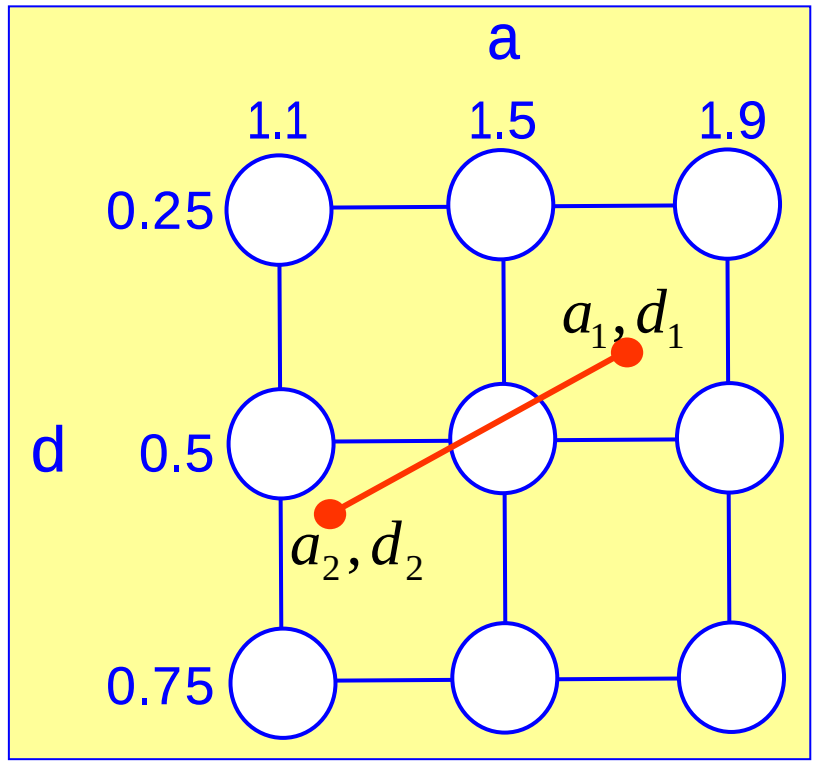
- Excellent wakefield damping
- E_{surf} /E_{acc} and H_{surf} /E_{acc} are only by 7 and 9 % higher than in undamped cell, respectively
- 4 metal pieces per structure
- No brazing is necessary
- Good pumping capabilities



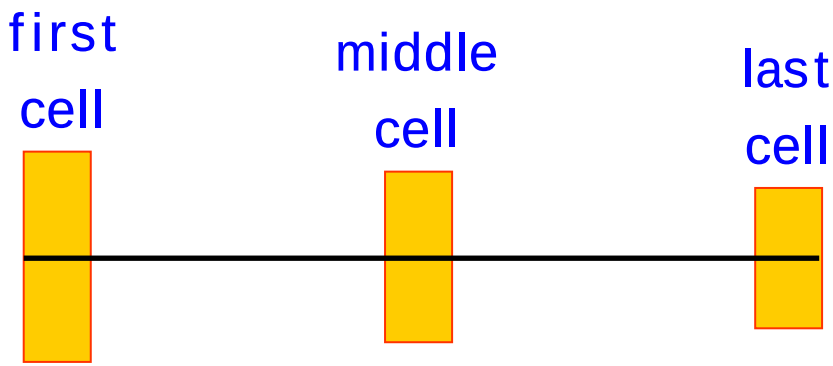
Optimization procedure



Single cell parameter interpolation



Structure parameters are calculated using parameters of the three cells:

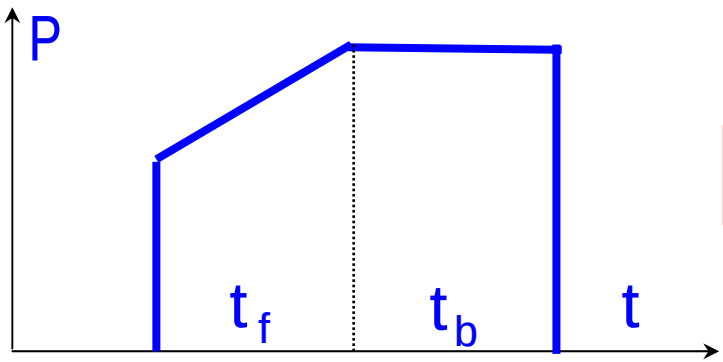


Structure bandwidth model

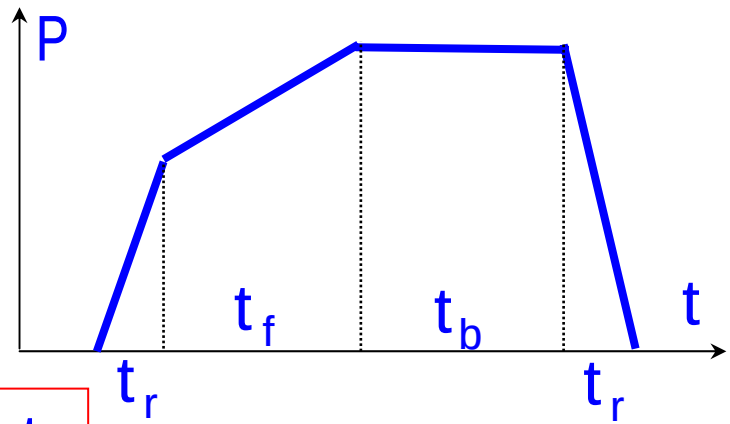
a [mm]	v_g/c	δf@-3dB [GHz]	$\delta f/f$@-3dB
1.9	0.08	1.8	0.06
1.6	0.051	1.0	0.033
1.2	0.02	0.38	0.013
0.8	0.005	0.07	0.002

$\delta f/f = 1.48 \bullet (v_g/c)^{5/4}$ -is the best fit

$t_r = (\delta f)^{-1} = (f \bullet 1.48 \bullet (v_g/c)^{5/4})^{-1}$ – rise time



$\eta \Rightarrow \eta'$



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

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 $\langle E_{acc} \rangle$ because of short-range wakes
- N_s – bunch separation depends on the long-range dipole wake and is determined by the condition:

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

RF breakdown and pulsed surface heating (rf) constraints:

- $\Delta T^{max}(H_{surf}^{max}, t_p) < 56K$ for CuZr
- $E_{surf}^{max} < 380MV/m$
- $P_{in} t_p^{1/3}/C_{in} = const$

Cu rf constraints: X-band

$$P/C \bullet t_p^{1/3} = \text{const}$$

H60VG4S17: a_1 = 5.7 mm; P=59 MW for $\langle E_a \rangle$ = 65 MV/m

demonstrated: $\langle E_a \rangle$ = 85 MV/m @ 100ns, BDR=10^{-6}

=> $P/C \bullet t_p^{1/3} = 13.0\ \text{MW/mm} \bullet \text{ns}^{1/3}$

H90VG3: a_1 = 5.4 mm; P=95 MW for $\langle E_a \rangle$ = 70 MV/m

demonstrated: $\langle E_a \rangle$ = 70 MV/m @ 100ns, BDR=10^{-6}

=> $P/C \bullet t_p^{1/3} = 13.0\ \text{MW/mm} \bullet \text{ns}^{1/3}$

Cu rf constraints: 30 GHz

$$P/C \bullet t_p^{1/3} = \text{const}$$

CTF3-120°-Cu: a_1 = 1.75 mm; P=54 MW for $\langle E_a \rangle$ = 150 MV/m

demonstrated: $\langle E_a \rangle$ = 90.5 MV/m @ 70ns, BDR=10^{-3}

=> $P/C \bullet t_p^{1/3} = 7.3\ \text{MW/mm} \bullet \text{ns}^{1/3}$

CTF3-120°-Cu: a_1 = 1.75 mm; P=54 MW for $\langle E_a \rangle$ = 150 MV/m

scaled: $\langle E_a \rangle$ = 63 MV/m @ 70ns, BDR=10^{-6}

=> $P/C \bullet t_p^{1/3} = 3.6\ \text{MW/mm} \bullet \text{ns}^{1/3}$

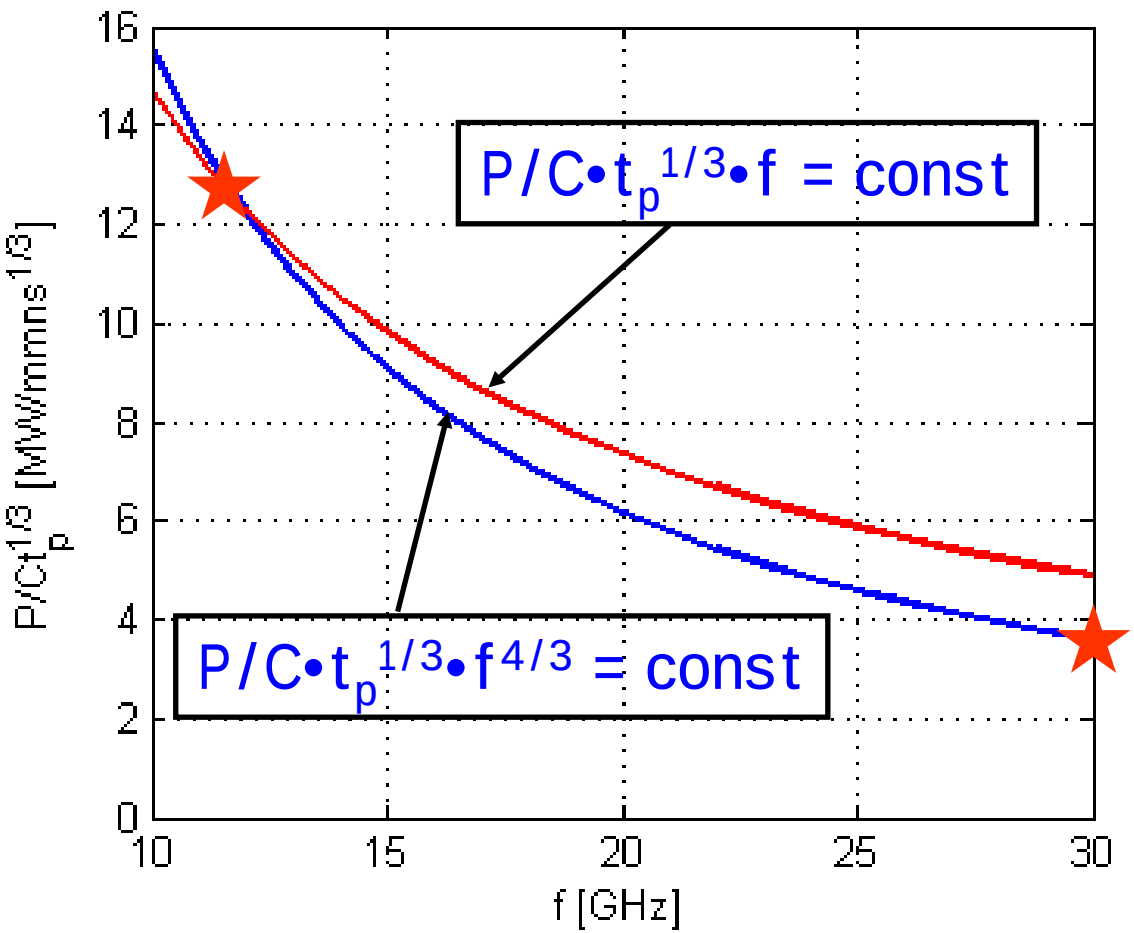
HDS60-Cu:

demonstrated: $(P/C)_{HDS} = \frac{3}{4}(P/C)_O$

Connecting X-band and 30 GHz data

$P/C \bullet t_p^{1/3} \bullet f^q = const$ connects two frequency with one parameter

★ - Experimental results for circular structures scaled to BDR=10^{-6}

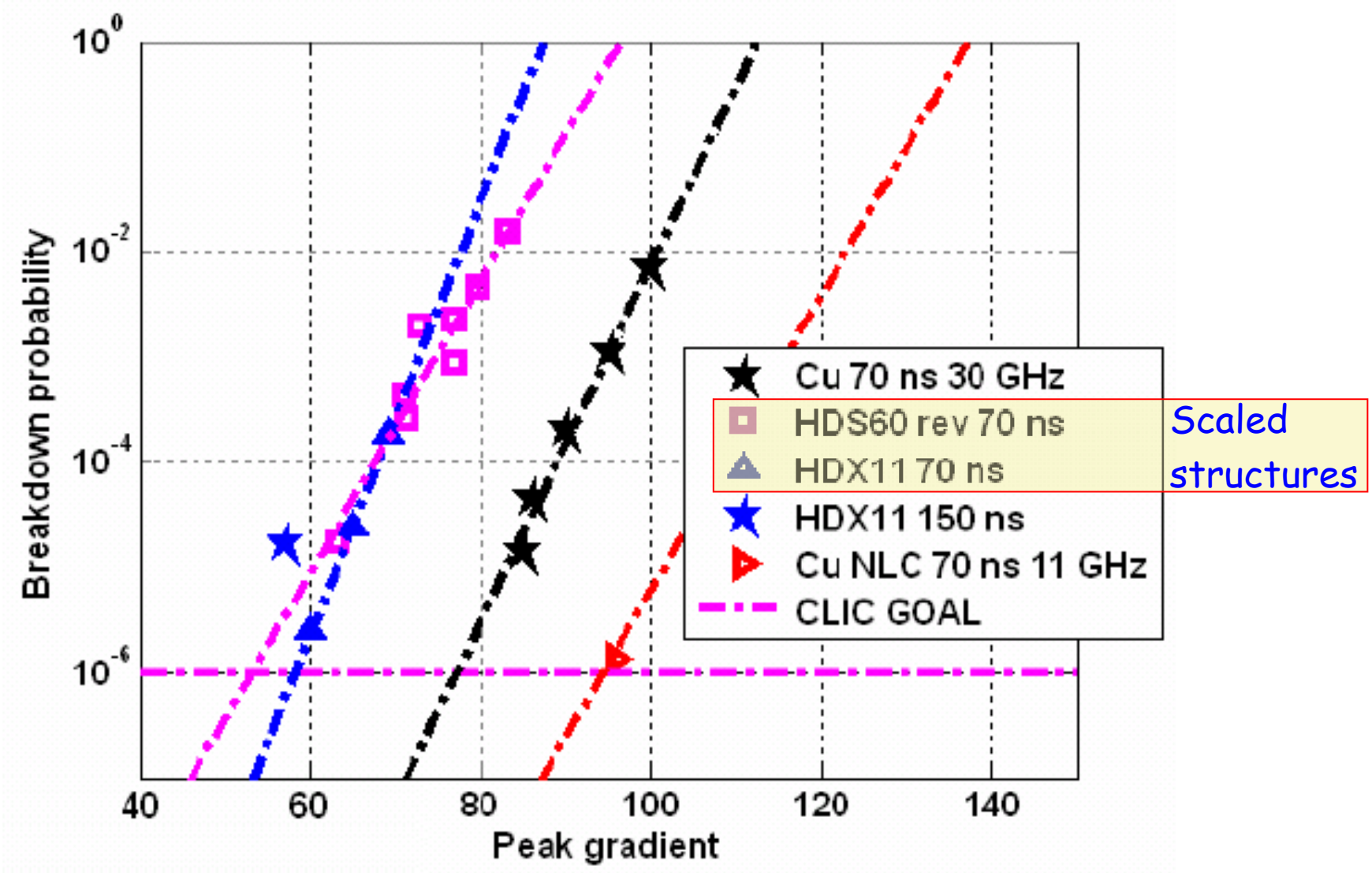


$13.0 \bullet 11.4^q = 3.6 \bullet 30^q$

N.B. For two structures with scaled geometry that would mean:

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

Experimental data at X-band and 30 GHz



Optimization figure of merit

Luminosity per linac input power:

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

Collision energy is constant

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

Cost model of 2006

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

$$C_e = (0.008 + 0.6/\text{FoM})$$

Optimization parameter space

All structure parameters are variable:

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

$f = 10 - 30$ GHz,

$\Delta\varphi = 50^o - 130^o$,

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

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

$d_1 / \lambda = 0.025 - 0.1$, $d_2 > d_1$

$N_{cells} = 15 - 300$.

N structures:

7

10

9

24

60

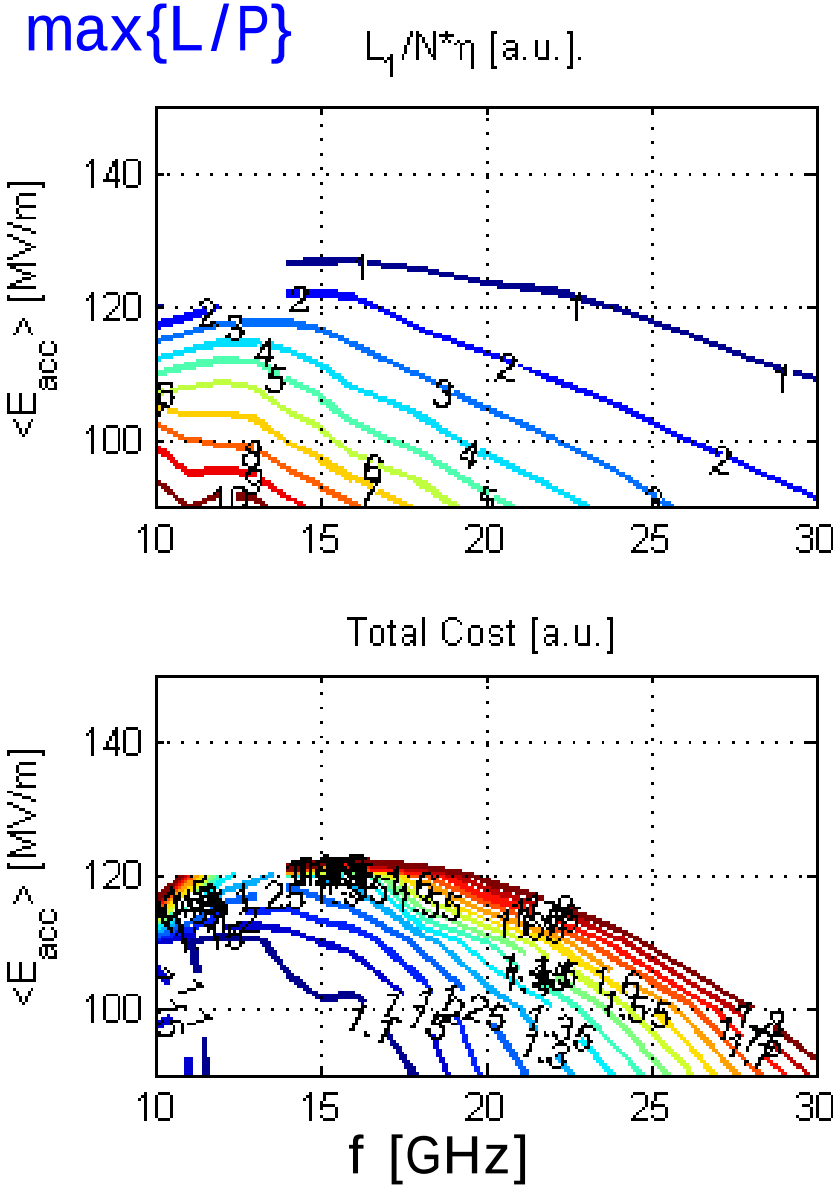
61

4

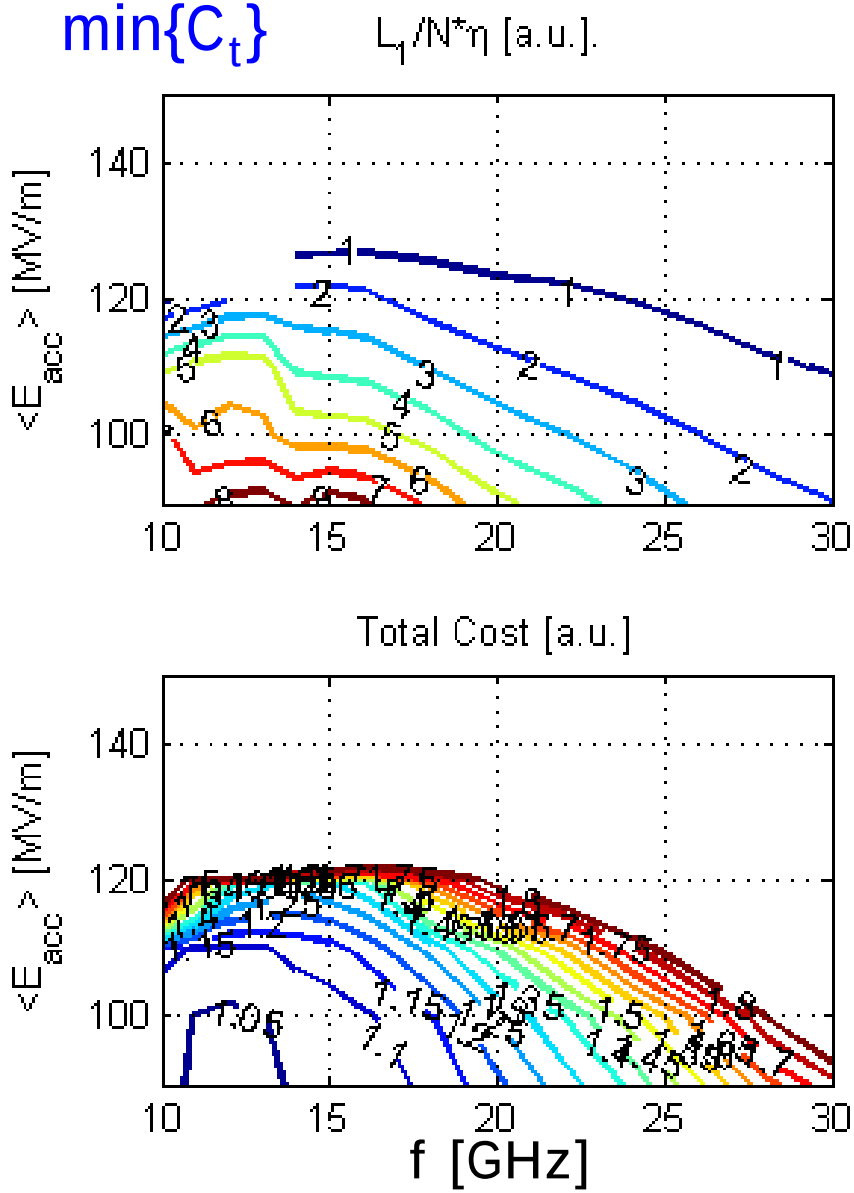
221.356.800

Optimizing L/P and C_t

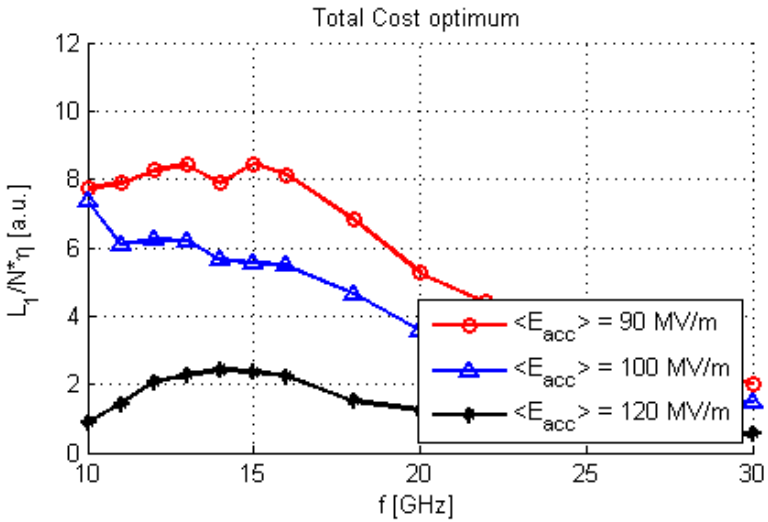
max{L/P}

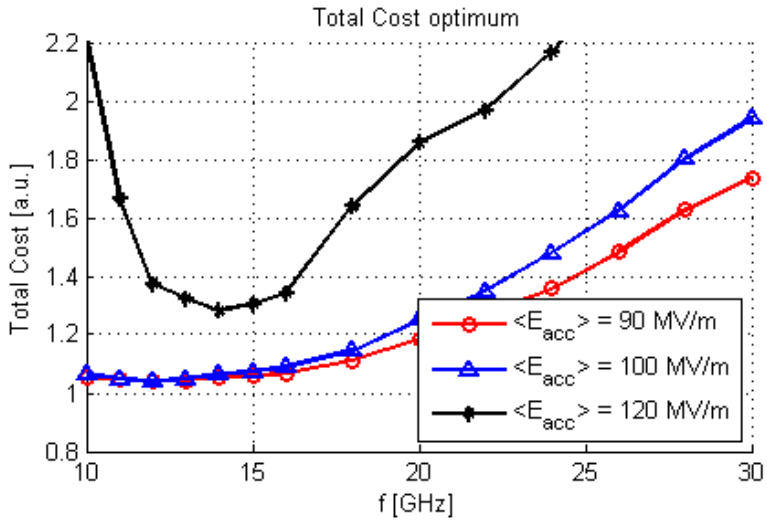


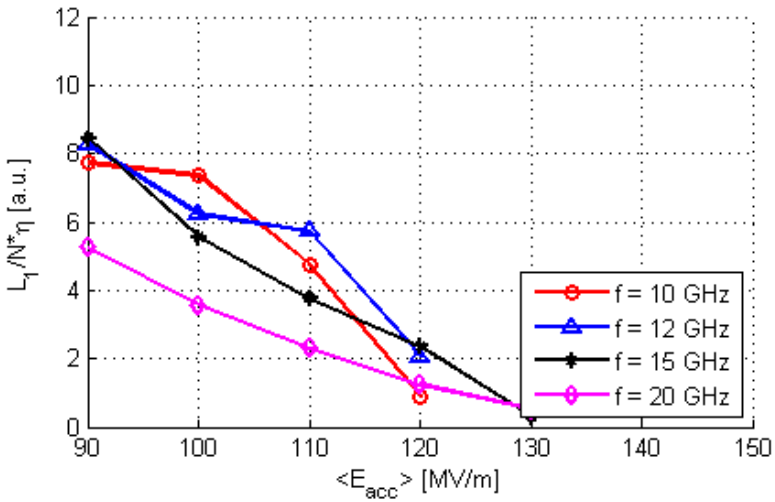
min{C_t}

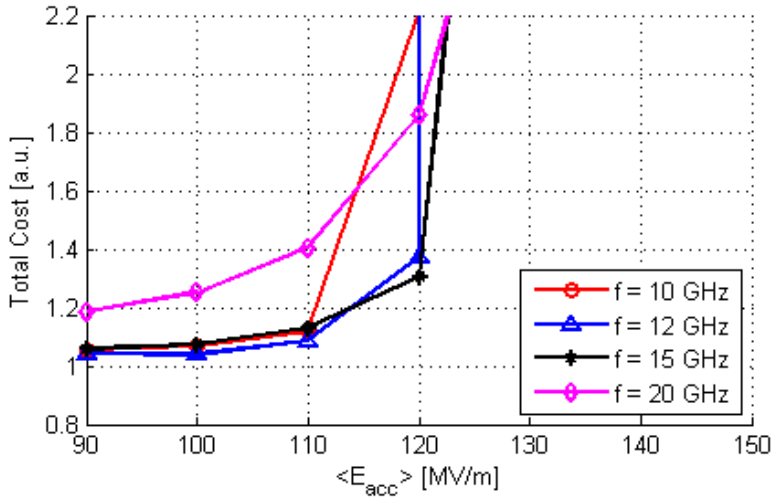


Total Cost optimization

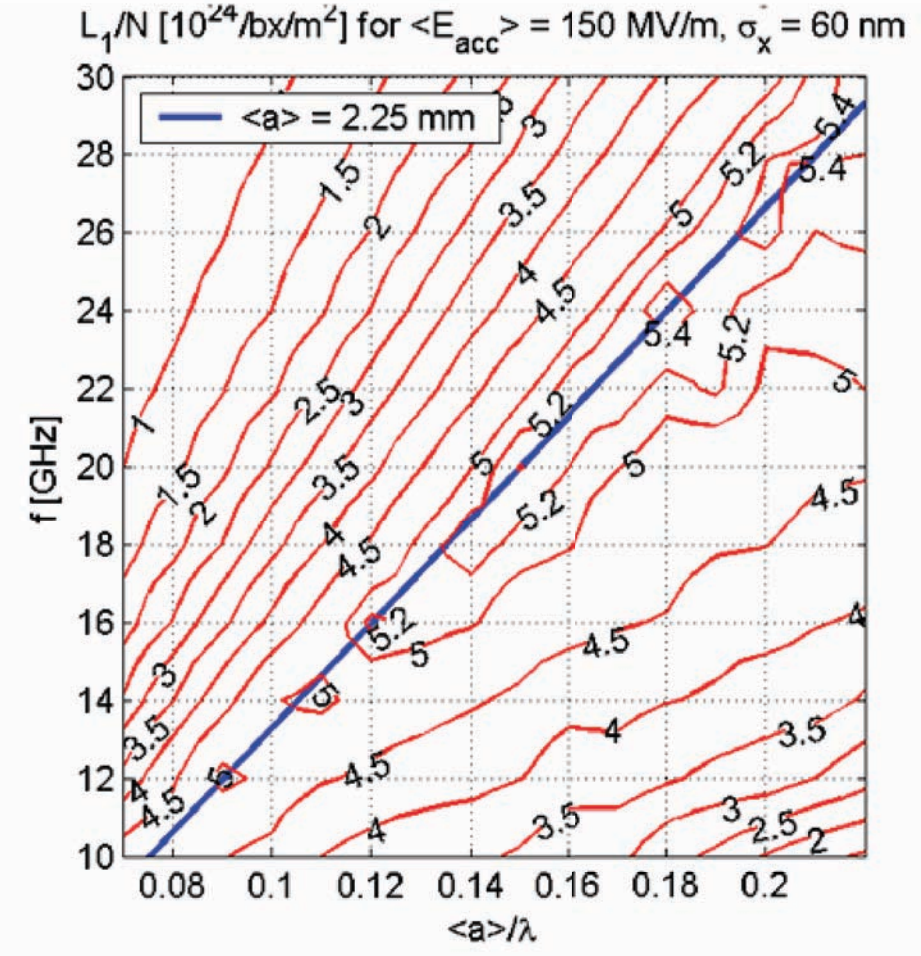


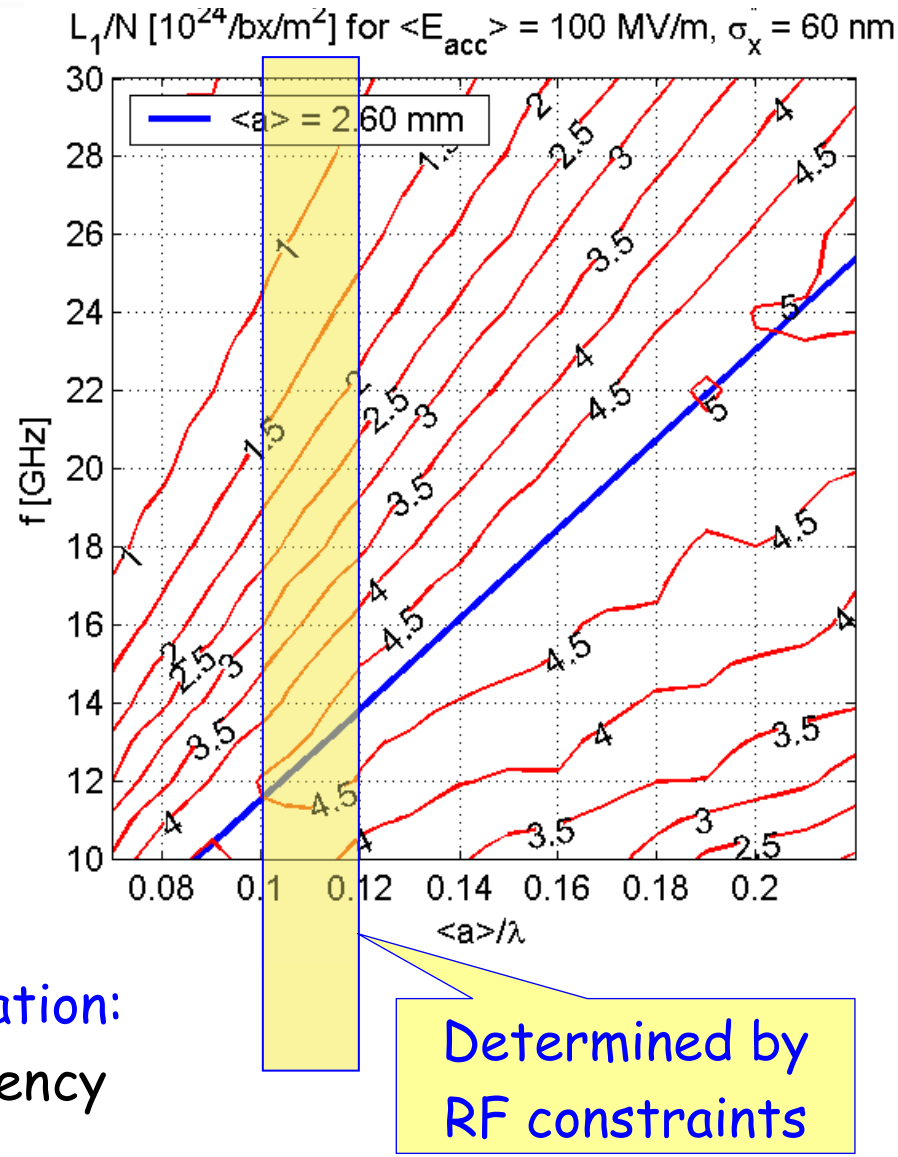






L_1/N for different gradients





Why X-band ? A simplistic explanation:

Crossing gives the optimum frequency

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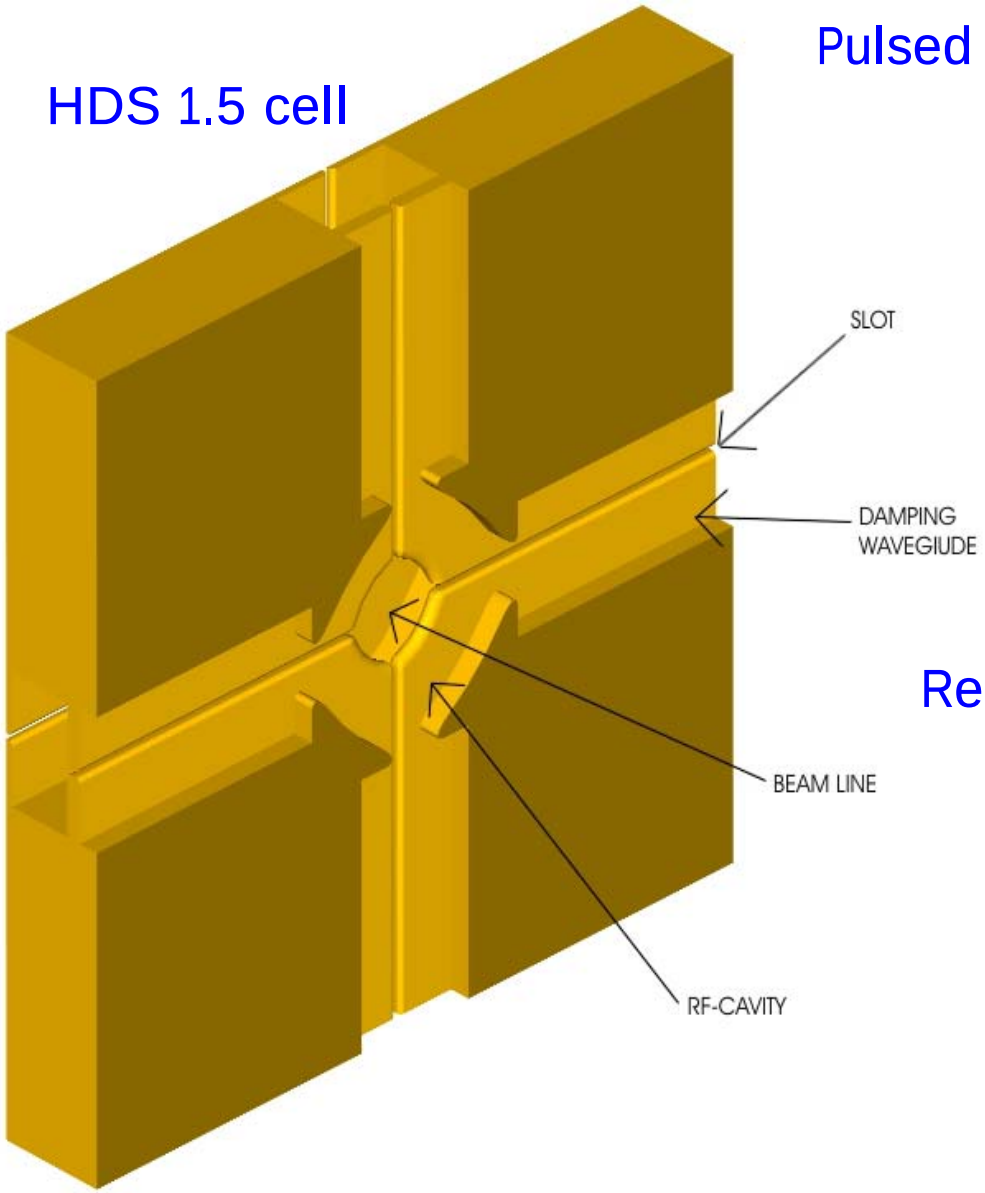
Different damping

HDS 1.5 cell



Pulsed surface heating temperature rise:

$$\Delta T^{max} \sim E_a^2 \cdot (H_{surf}^{max}/E_a)^2 \cdot f^{1/2} \cdot t_p^{1/2}$$

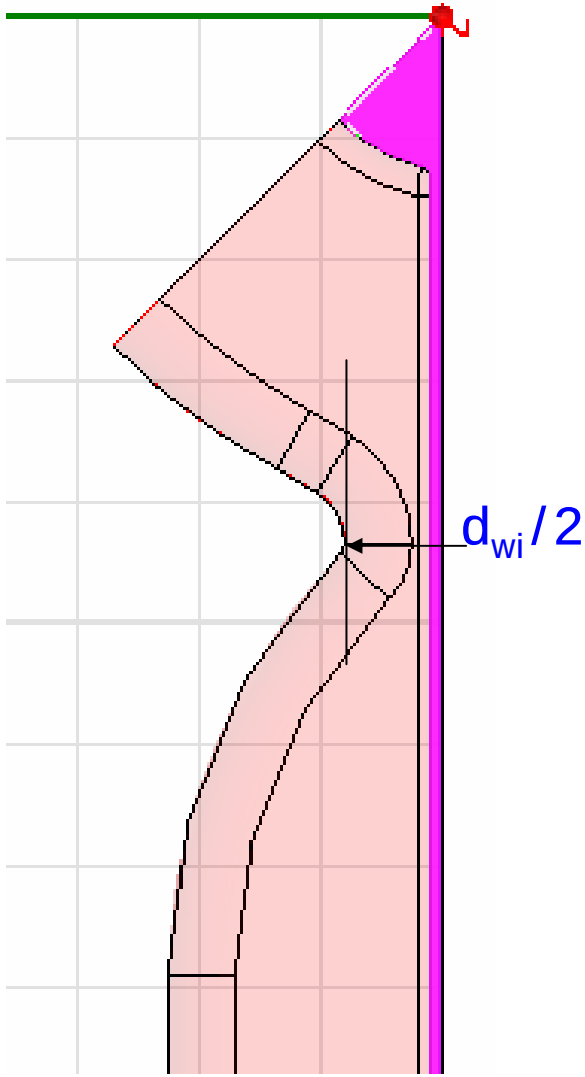
Reducing gradient from 150 to 100 MV/m gives factor 1.5 margin in surface fields which can be used in cell redesign. For example, it allows to increase H_{surf}^{max}/E_a by 1.5

Different damping

HDS

d_{wi}=1.6mm

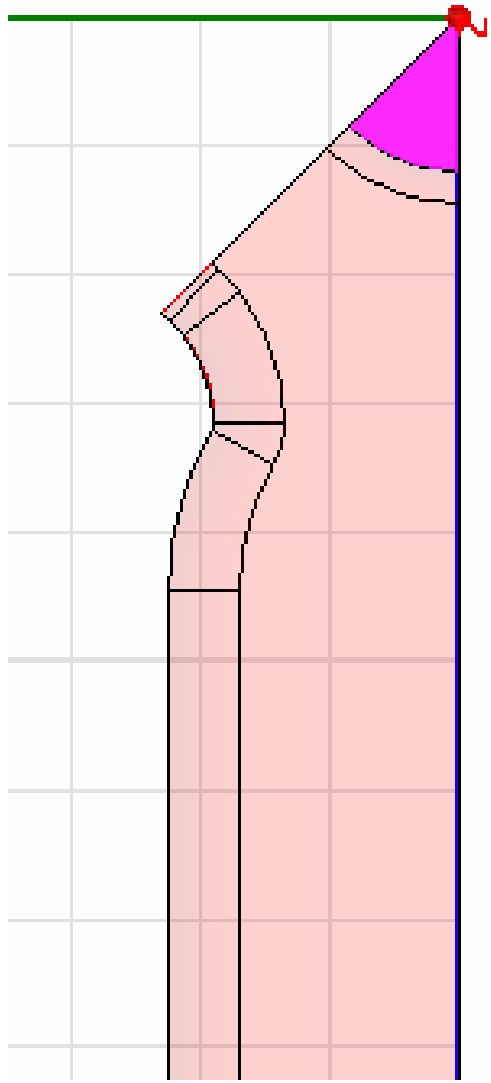
H_{surf}^{max}/E_a
=2.8 mA/V



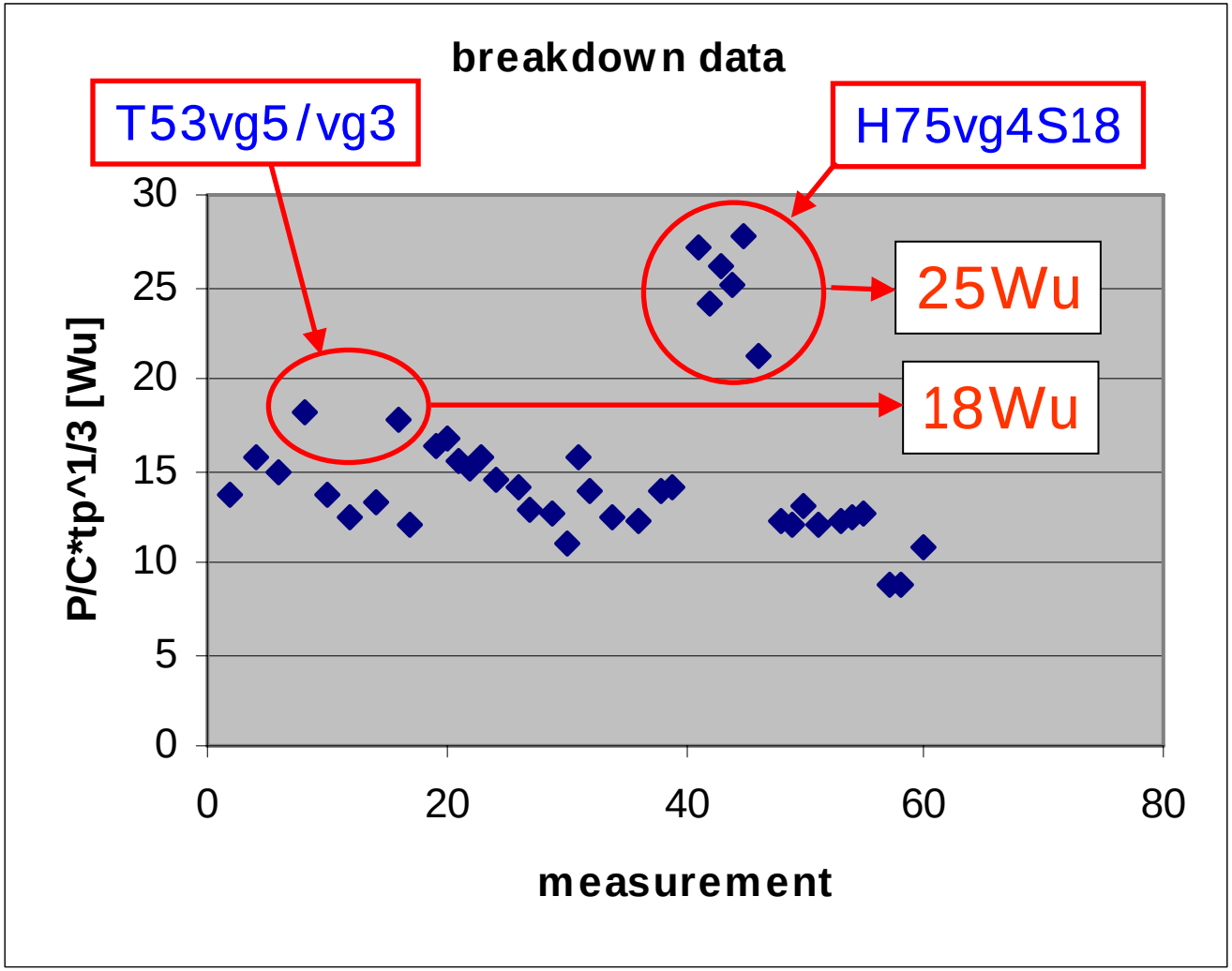
Waveguide Damped Structure (WDS)

d_{wi}=3.5mm

H_{surf}^{max}/E_a
=4.2 mA/V



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

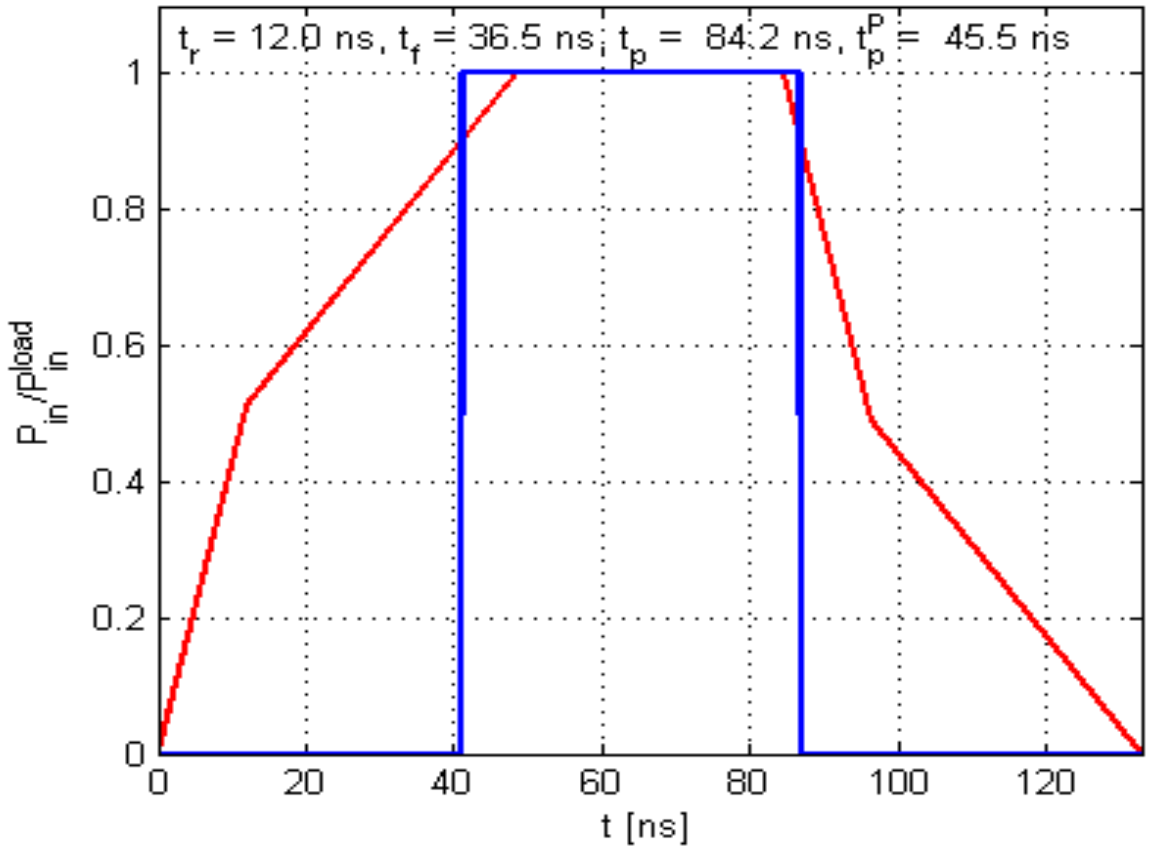


$\langle P/C * t_p^{1/3} \rangle$
$= 15.2$ Wu

[Wu] = [MW/mm·ns$^{1/3}$]

Thanks to C. Adolphsen and S.Doebert for providing the data

Pulse shape dependences



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

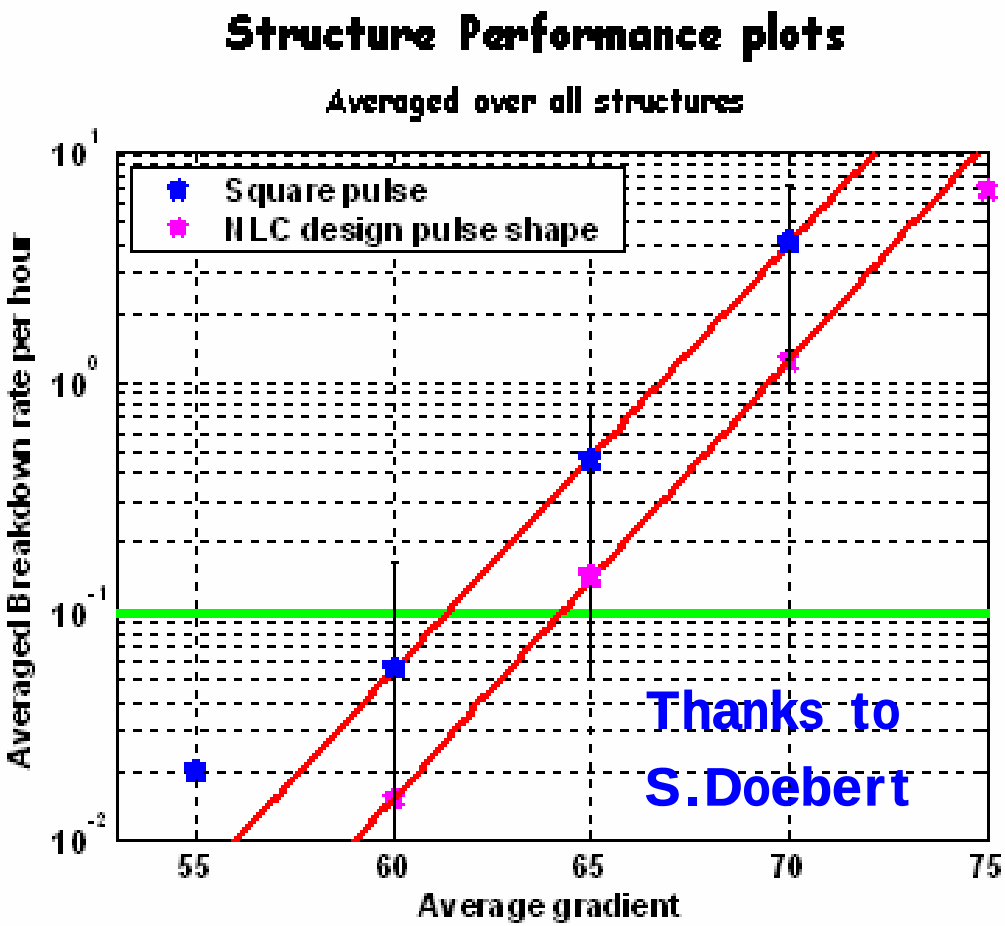
Effective pulse length for breakdown

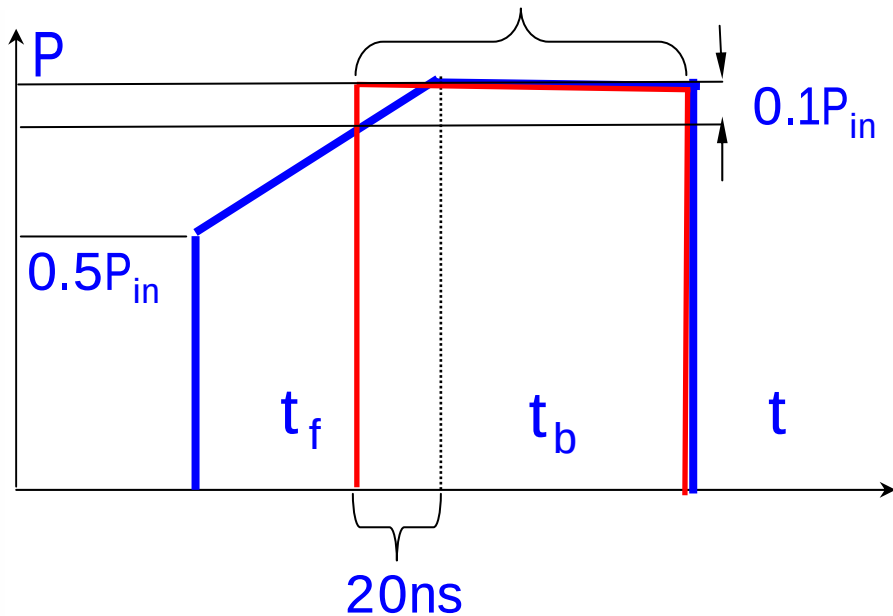
Rect-pulse => NLC-pulse

65 MV/m => 67.5 MV/m

Assuming: $E_a * t_p^{1/6} = const$

400ns => 320ns

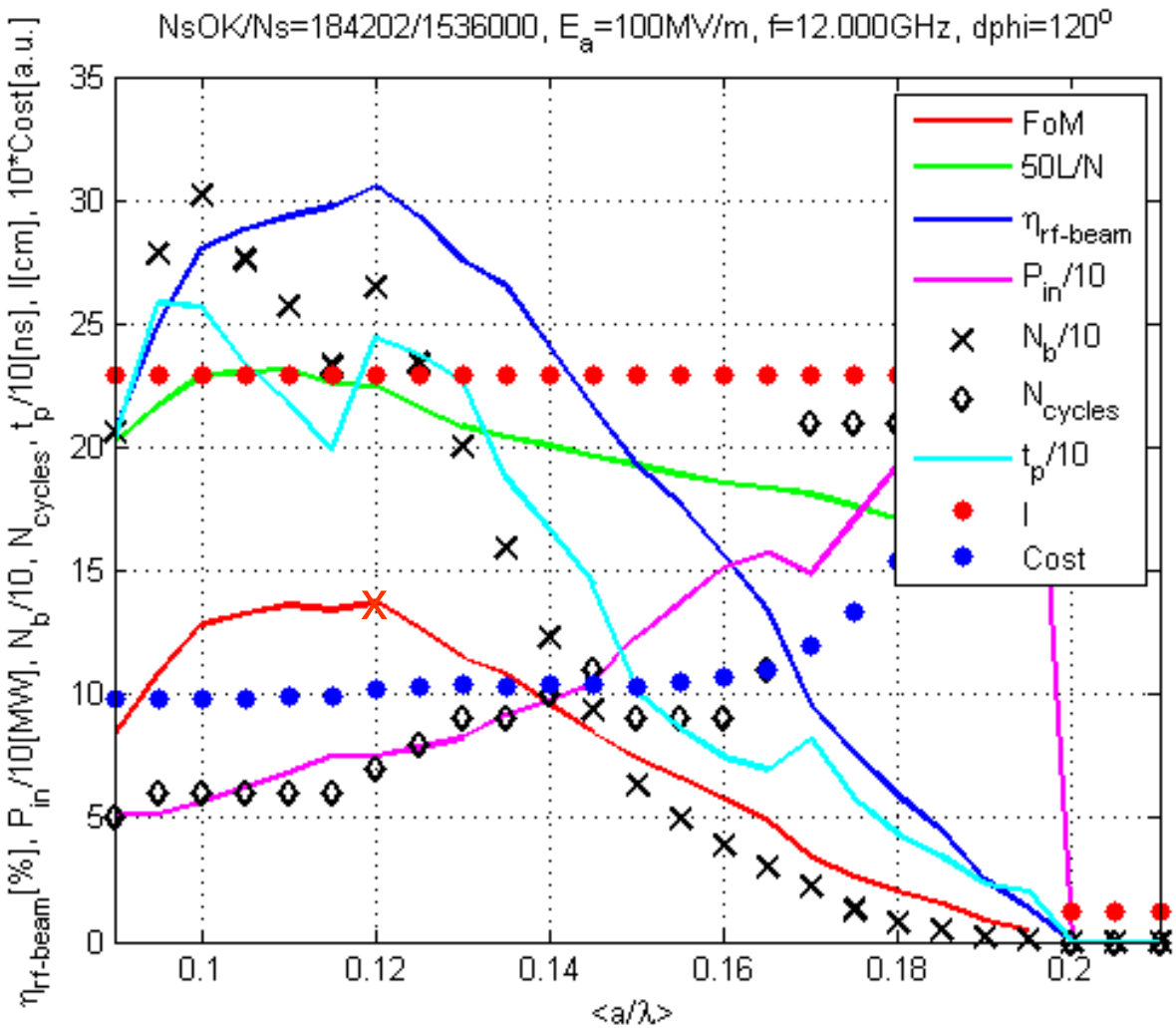




NLC: t_f = 100 ns; t_b = 300 ns

WDS120 optimum versus <a>/λ

18 Wu



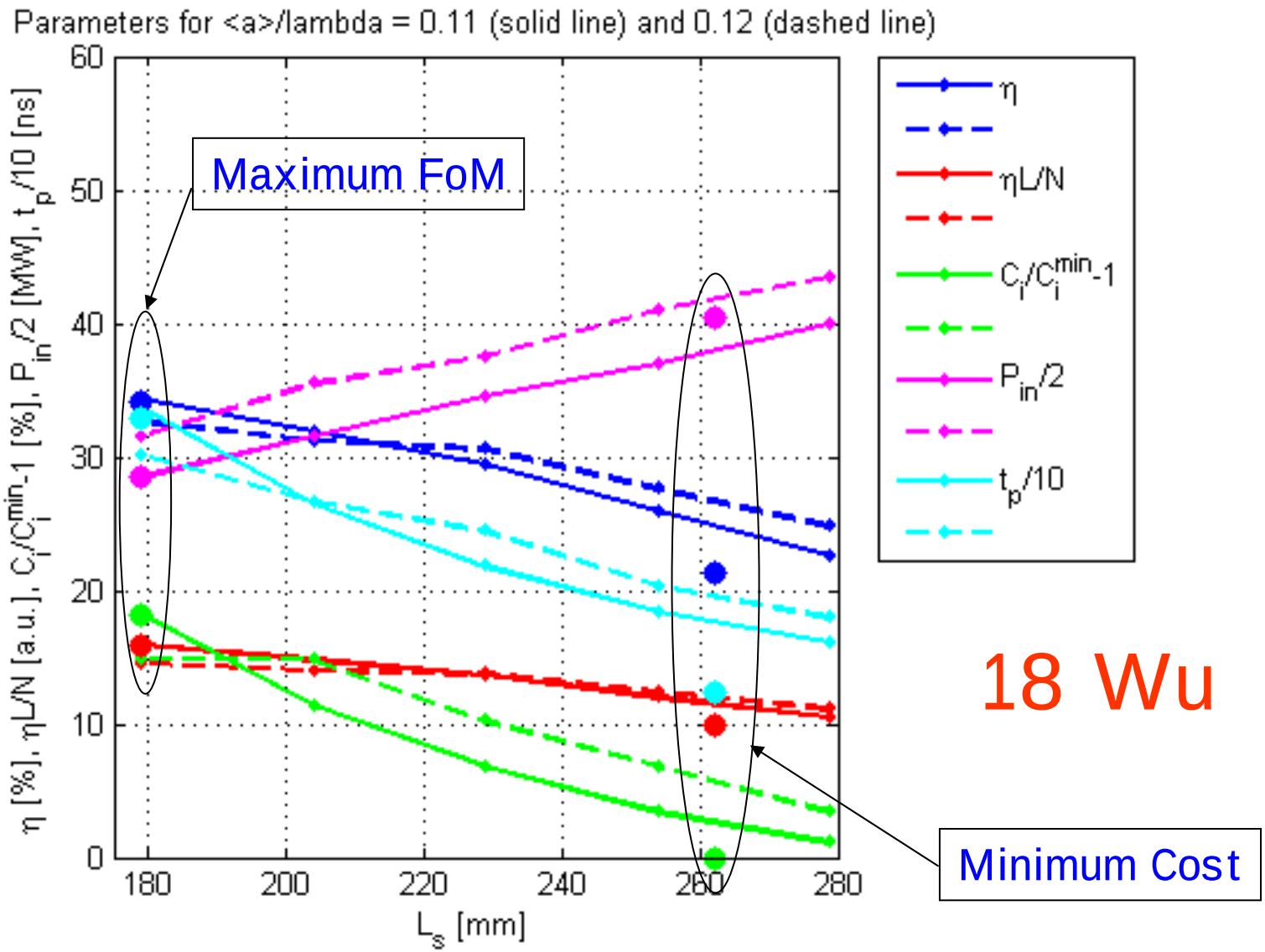
Maximum FoM

L_s = 23 cm

Optimum

<a>/λ = 0.12

Parameters versus structure length



18 Wu

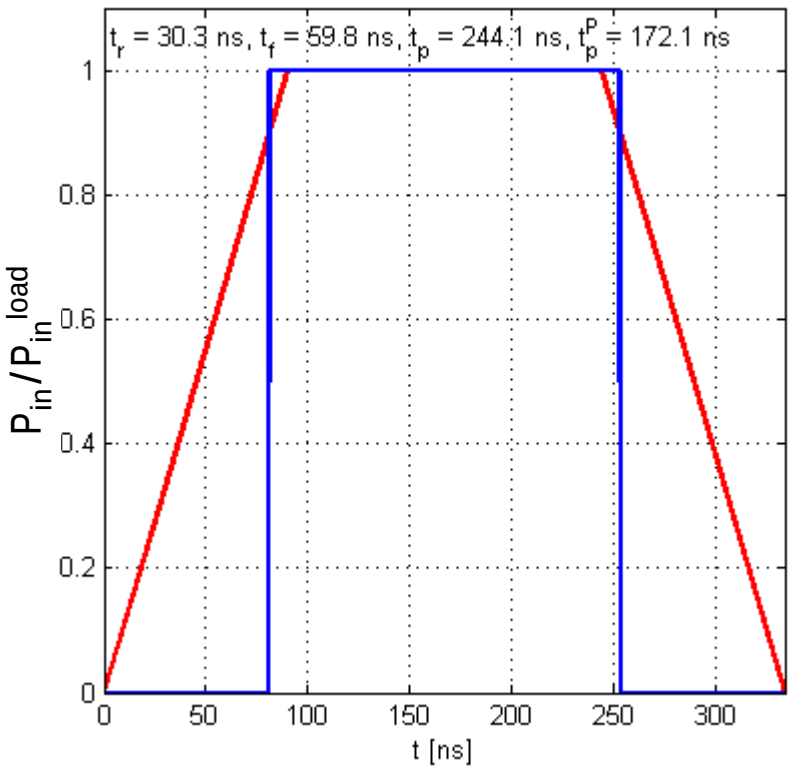
Parameters of CLIC acc. structure

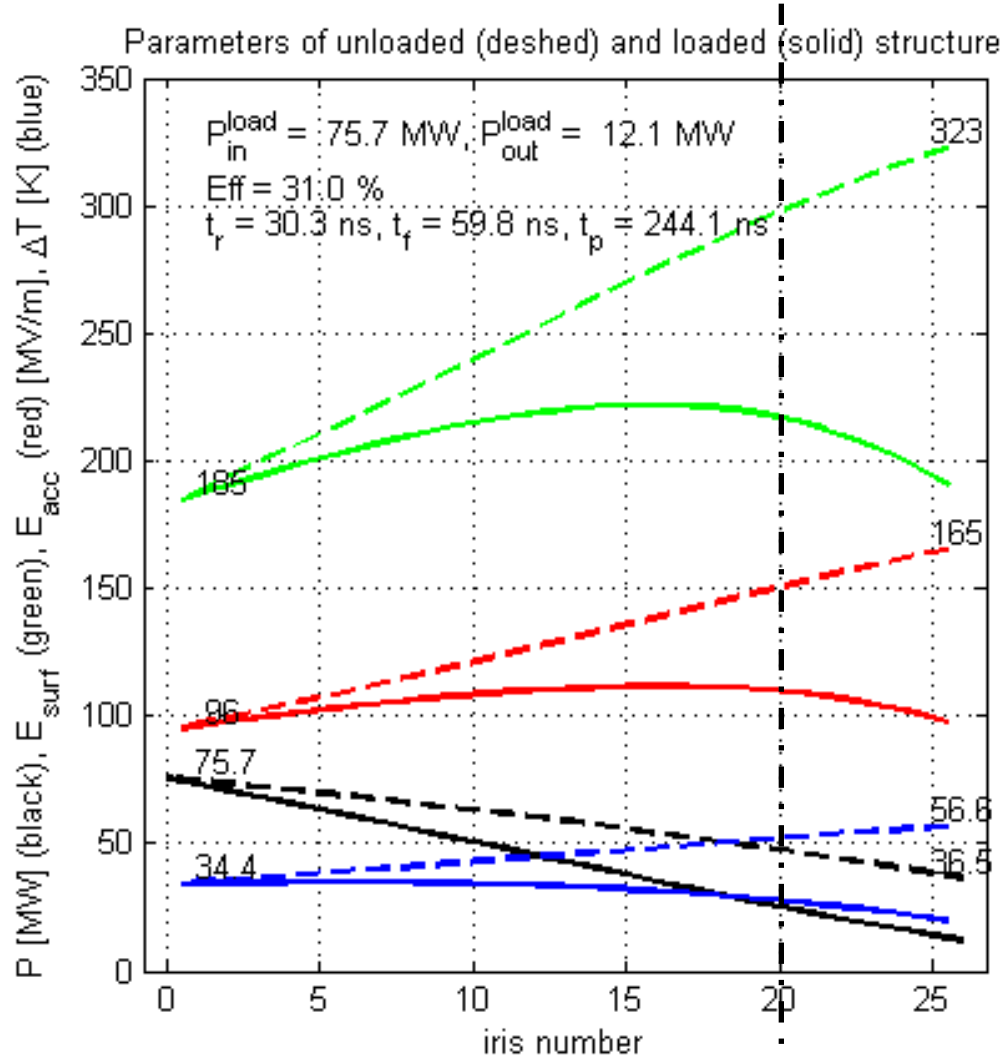
Structure name	CLIC nominal	CLIC_vg1 test
RF phase advance per cell: $\Delta\varphi$ [°]	120	120
Average iris radius/wavelength: $\langle a\rangle/\lambda$	0.12	0.128
Input/Output iris radii: $a_{1,2}$ [mm]	3.87, 2.13	3.87, 2.53
Input/Output iris thickness: $d_{1,2}$ [mm]	2.66, 0.83	2.66, 1.25
Group velocity: $v_g^{(1,2)}/c$ [%]	2.39, 0.65	2.4, 0.95
N. of reg. cells, str. length: N_c, l [mm]	24, 229	18, 179
Bunch separation: N_s [rf cycles]	7	7
Number of bunches in a train: N_b	265	261
Pulse length, rise time: τ_p, τ_r [ns]	244, 30	208, 19
Input power: P_{in} [MW]	76	81
Max. surface field: E_{surf}^{max} [MV/m]	323	304
Max. temperature rise: ΔT^{max} [K]	57	54
Efficiency: η [%]	31.0	31.1
Luminosity per bunch X-ing: $L_{b\times}$ [m^{-2}]	2.6×10^{34}	3.0×10^{34}
Bunch population: N	5.8×10^{9}	7.0×10^{9}
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	13.7	13.4

18 Wu

Parameters of CLIC acc. structure

18 Wu





Test structure

Summary

- In 2006, 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 some of the NLCTA measurement results at X-band
- This (together with some other consideretions) 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 waveguide damping and taking into account most of NLCTA measurement results
- X-band test structure has been designed in order to test most of the assamptions made in rf design of CLIC accelerating structure

"to do" list

- New CLIC parameters list
- High power testing
  - CLIC_vg1 test structure
  - Non-damped version of CLIC_vg1 test structure
  - Comparison of the same rf design but made in brazed disks and in quadrants
  - Testing of pulse shape dependence of the structure gradient
- New (or old) concepts and ideas in rf design of accelerating structures. Application to CLIC.
  - Different damping
  - Power feeding and distribution schemes
- RF breakdown modeling

See more at http://clic-study.web.cern.ch/CLIC-Study/