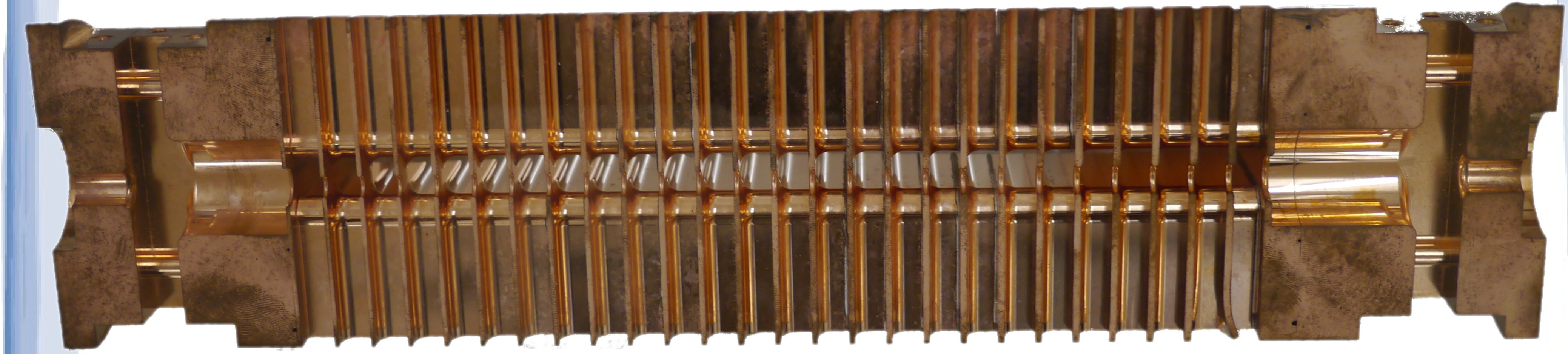
Linac optimization

FAST estimation of RF structure parameters

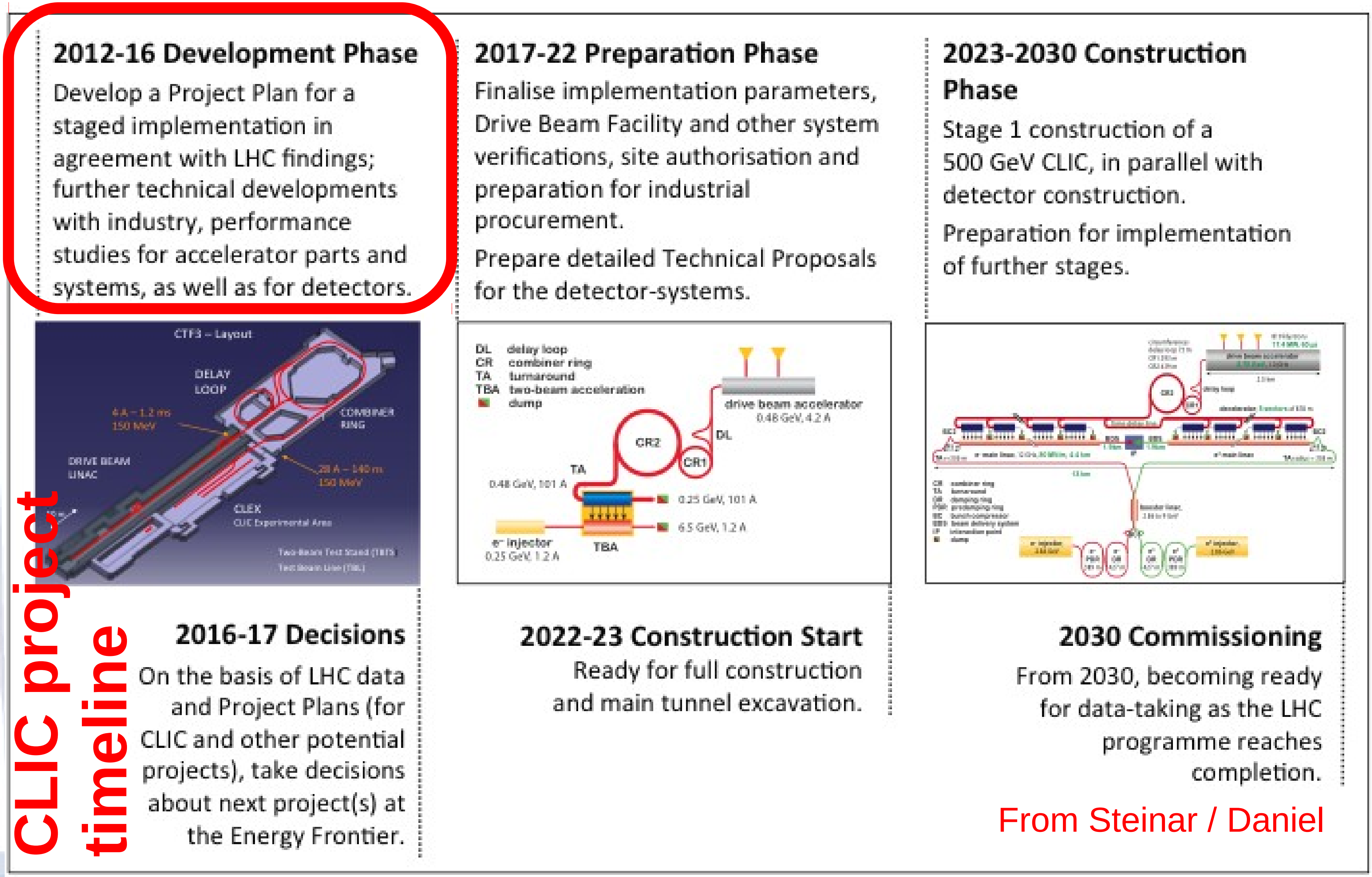


Kyrre Sjobak
June 5th, 2013
HG2013 @ Trieste

Outline

- Motivation and basic idea
- Method:
  - How it works
  - Benchmarking main mode results
  - Wakefield
  - High gradient limits
- Optimization examples
- The underlying data
  - Single cell high gradient optimization
- Summary

Motivation – why do we need fast RF parameter estimation?



CLIC project timeline

2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.

2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

From Steinar / Daniel

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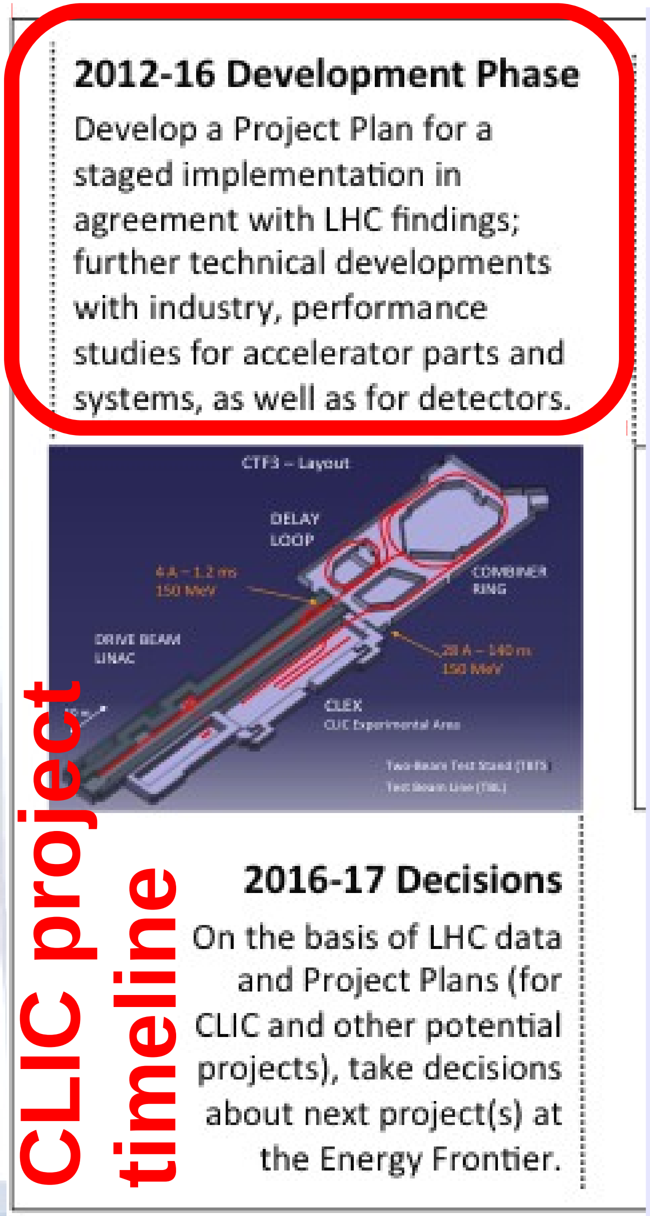

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- CLIC CDR presented initial CLIC design
- It is now time to refine this, taking new knowledge into account
  - Particle physics
  - High gradient physics
  - Cost models, new ideas etc.
- Will lead to a new CLIC overall design
- Main beam accelerating structure performance a significant factor
  - Optimal pulse length, gradient, efficiency
  - RF structure length
  - Beam current

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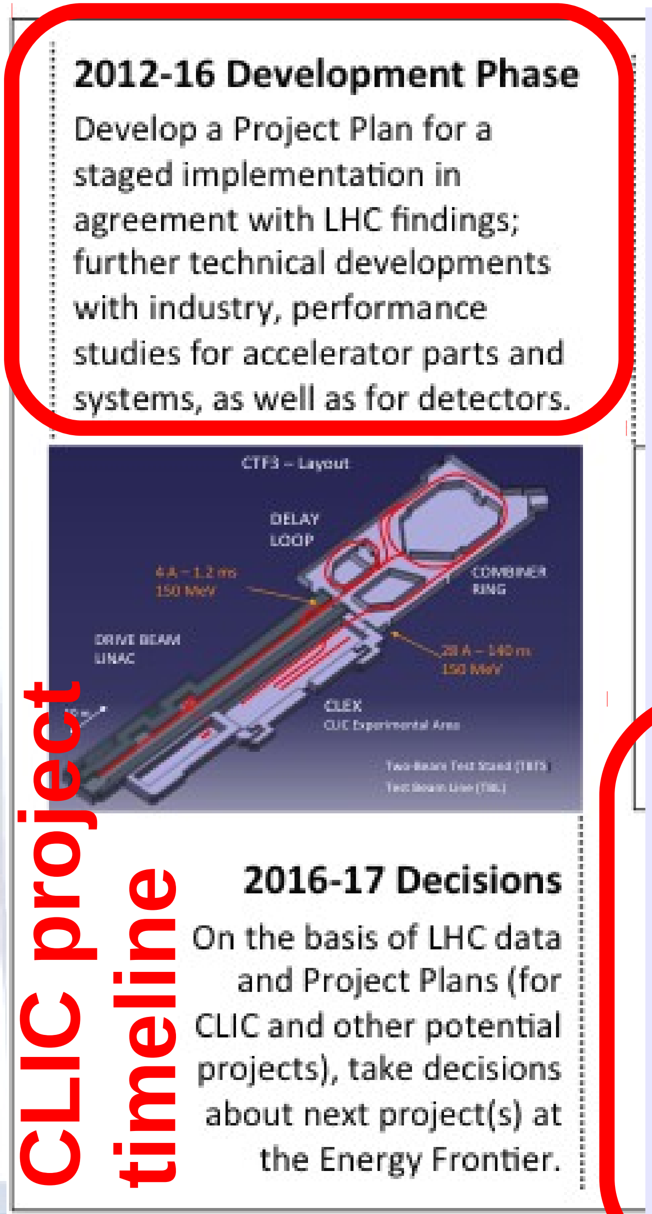

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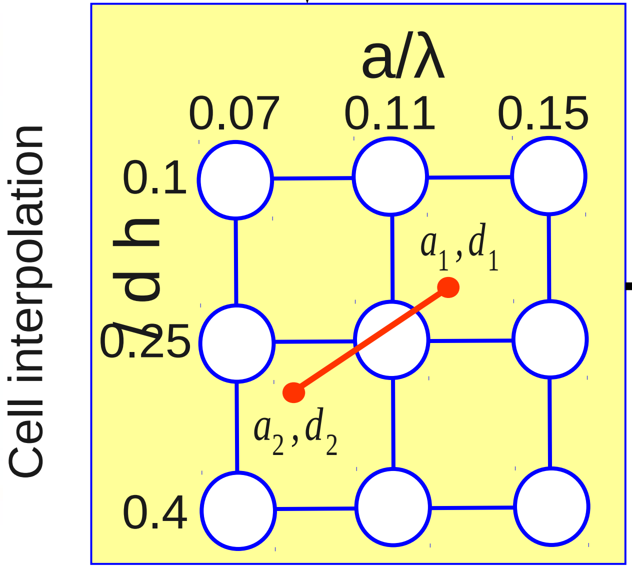
Estimate this, FAST

Basic idea

- Scan over large number of candidate RF structures
- Quick estimation of RF structure performance
  - Input: Structure parameters (length, aperture, tapering, gradient, beam current...)
  - Data: Pre-calculated single-cell parameters
  - Output:
    - Power requirements
    - Breakdown constraints
    - Long range wakefields
- Based on analytic method [1]
- Implemented as C++ library

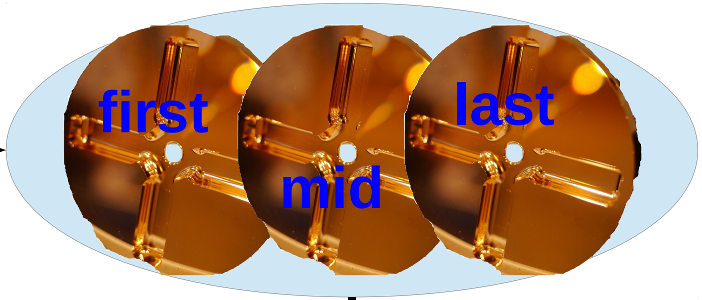
Calculating main mode parameters
Step 1: Get Q, R/Q, v_g, ... along structure

Global structure parameters:
Length, phase advance,
aperture, ...

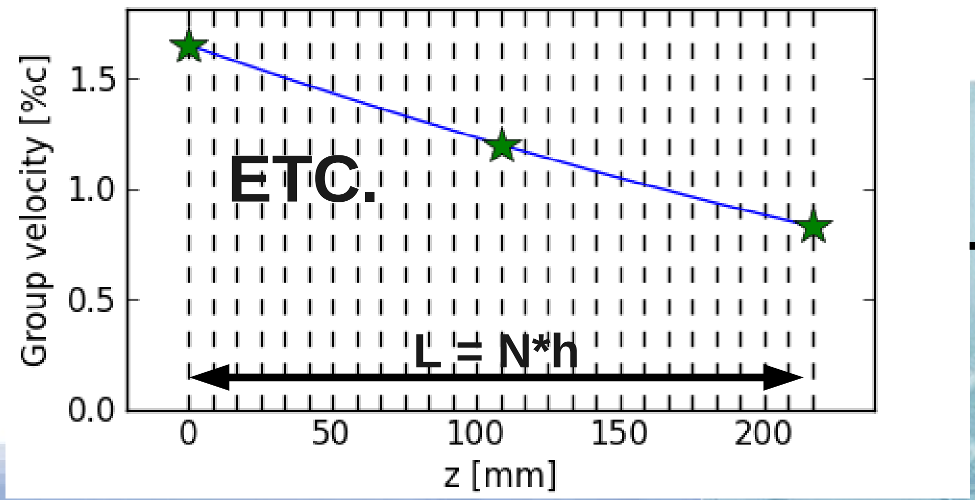


Cell database:
Q, R/Q, ... for different
cell apertures, phase advance, ...

Interpolated “anchor” cells



Interpolate Q, R/Q, v_g, ...
from anchor cells along the structure



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Calculating main mode parameters
Step 2: Solve power flow integrals

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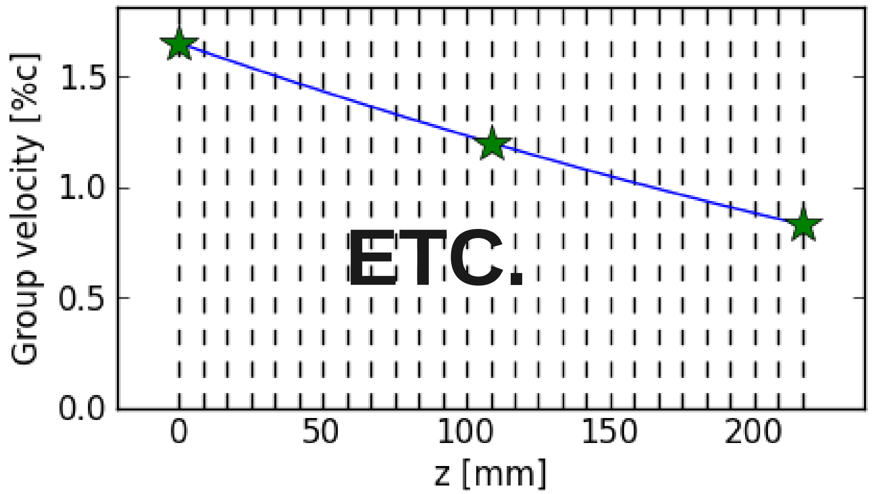
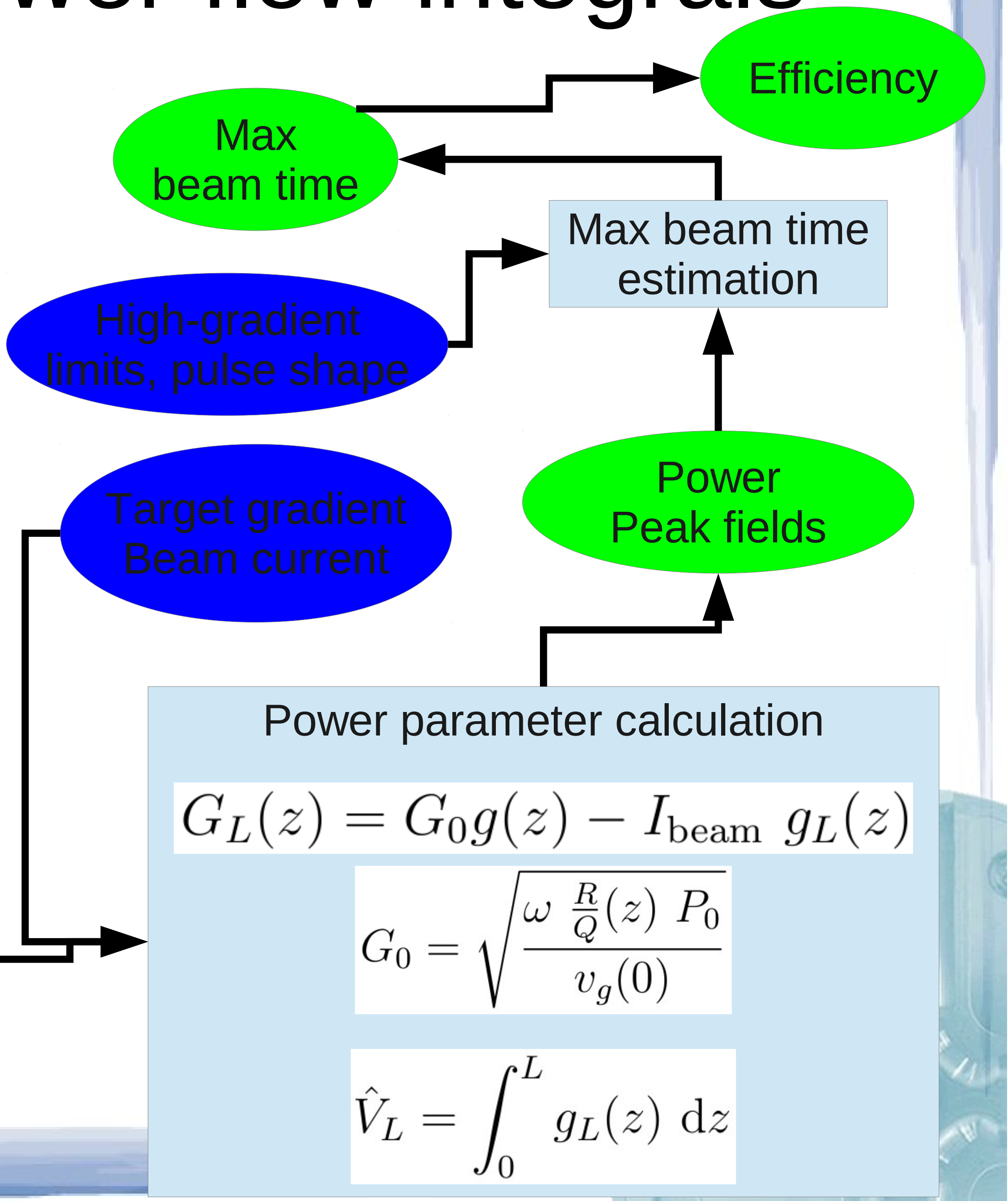


Power flow integrals

$$g(z) = \sqrt{\frac{v_g(0)\ \frac{R}{Q}(z)}{v_g(z)\ \frac{R}{Q}(0)}}\ \exp\left(-\frac{1}{2}\int_0^z \frac{\omega\ \mathrm{d}z'}{v_g(z')Q(z')}\right)$$

$$g_L(z) = g(z)\ \int_0^z \frac{\omega\ \frac{R}{Q}(z)\ \mathrm{d}z'}{g(z')2v_g(z')}$$



Efficiency

Max beam time

Max beam time estimation

High-gradient limits, pulse shape

Power Peak fields

Target gradient Beam current

Power parameter calculation

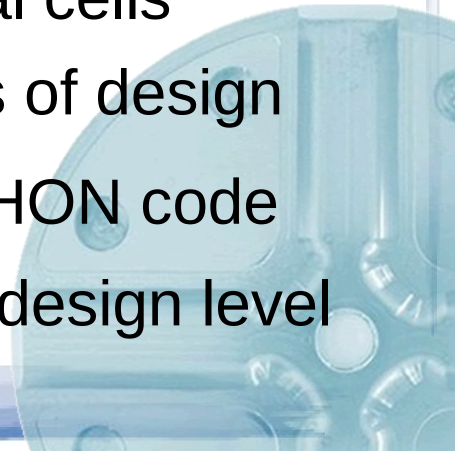
$$G_L(z) = G_0 g(z) - I_{\text{beam}}\ g_L(z)$$

$$G_0 = \sqrt{\frac{\omega\ \frac{R}{Q}(z)\ P_0}{v_g(0)}}$$

$$\hat{V}_L = \int_0^L g_L(z)\ \mathrm{d}z$$

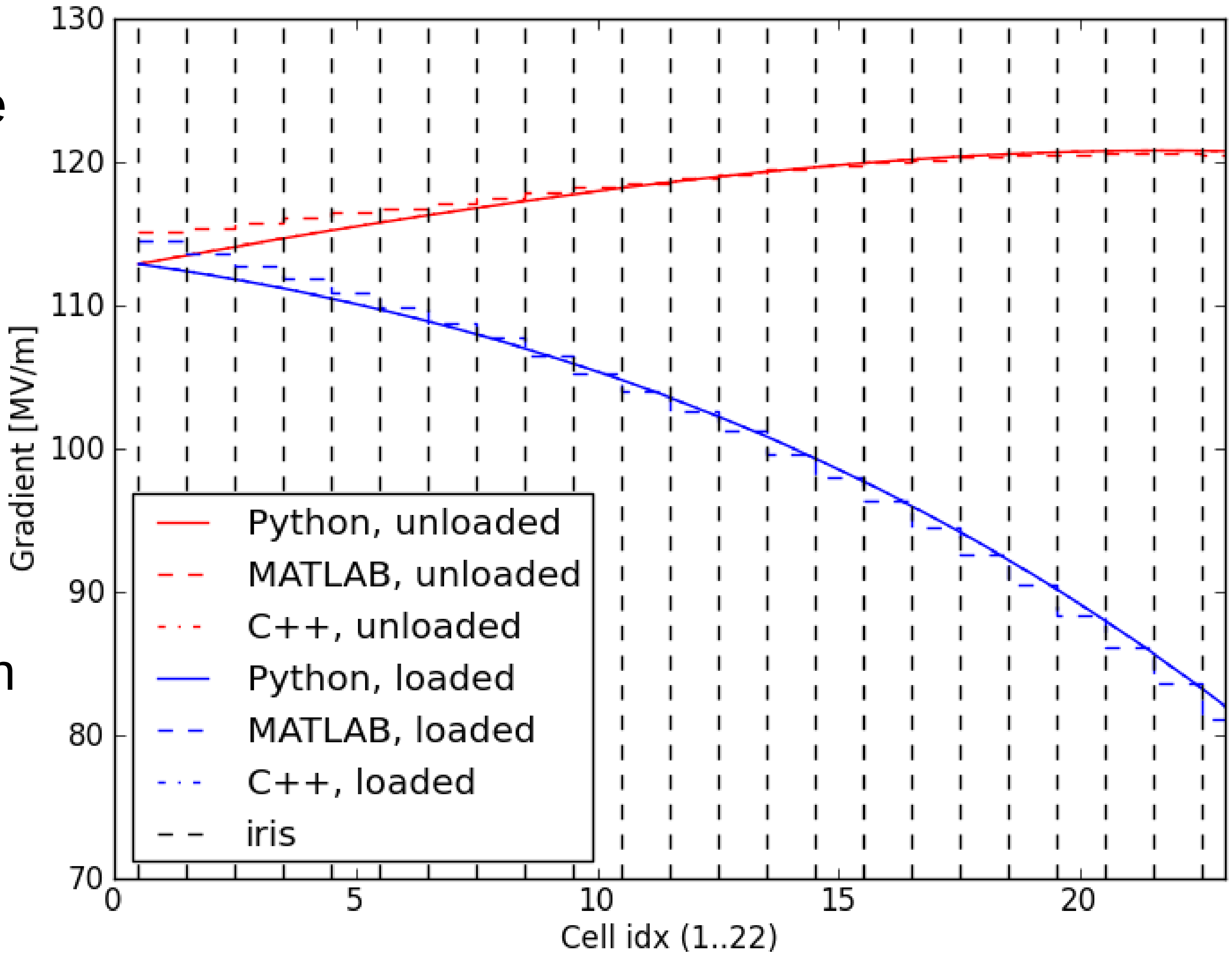
Results:
How good are the estimates?

- Remember:
  - This is only 1st step of RF design
    - Used to decide length and iris parameters
    - Step 2: Detailed optimization of “anchor” cells
    - Step 3: Full design including couplers etc.
  - Effects of couplers hard to take into account
    - With compact couplers:
      Assume the coupler cells $\simeq$ normal cells
- Compare results with other codes and later stages of design
  - Correctness – compare to MATLAB / PYTHON code
  - Prediction quality – compare to 2nd and 3rd design level



Correctness of power flow calculation

- CLIC_G_R05 structure
  - 100 MV/m loaded
- MATLAB:
  - Numerical solution
  - Solve at one point per cell
- Python / C++:
  - Analytical solution
- Same average gradient, slightly different input power



$$g(z) = \sqrt{\frac{v_g(0)\ \frac{R}{Q}(z)}{v_g(z)\ \frac{R}{Q}(0)}}\exp\left(-\frac{1}{2}\int_0^z \frac{\omega\ \mathrm{d}z'}{v_g(z')Q(z')}\right) \quad g_L(z) = g(z)\int_0^z \frac{\omega\ \frac{R}{Q}(z)\ \mathrm{d}z'}{g(z')2v_g(z')}$$

Consistency through design levels

Design level	Input power [MW]	Filling time [ns]
1st – Cells from data base	40.0	56
2nd – Hand-optimized cells	41.1	59
3rd – Full RF design (HFSS)	42.2	*

- CLIC_G with 24 regular cells
- Power to reach 100 MV/m unloaded gradient

*) HFSS yields filling time of 64.55 ns *including matching cells*, which adds 27 mm to the length.

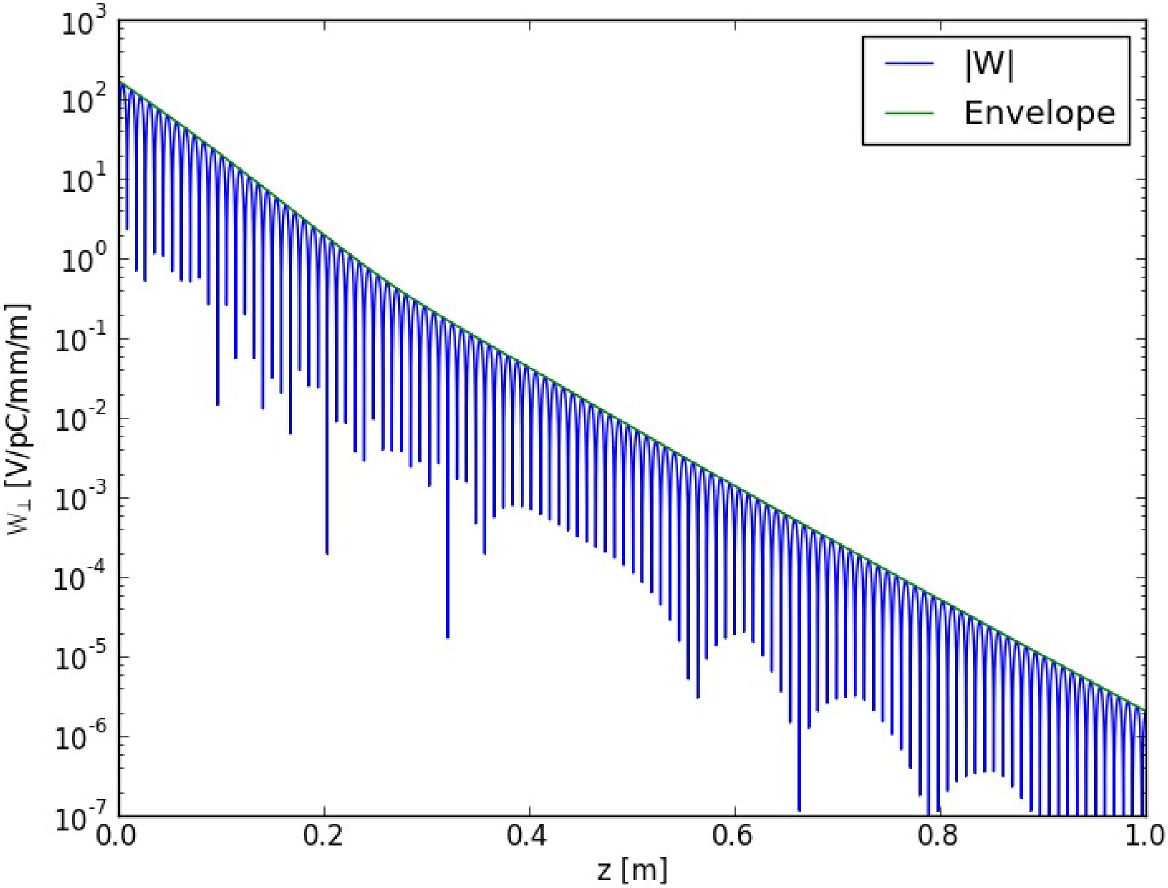
Long range wakefield estimate

- The first dipole mode in each cell is estimated, then summed across cells

$$W_T(z)=\frac{-1}{N}\sum_N W_i(z)$$

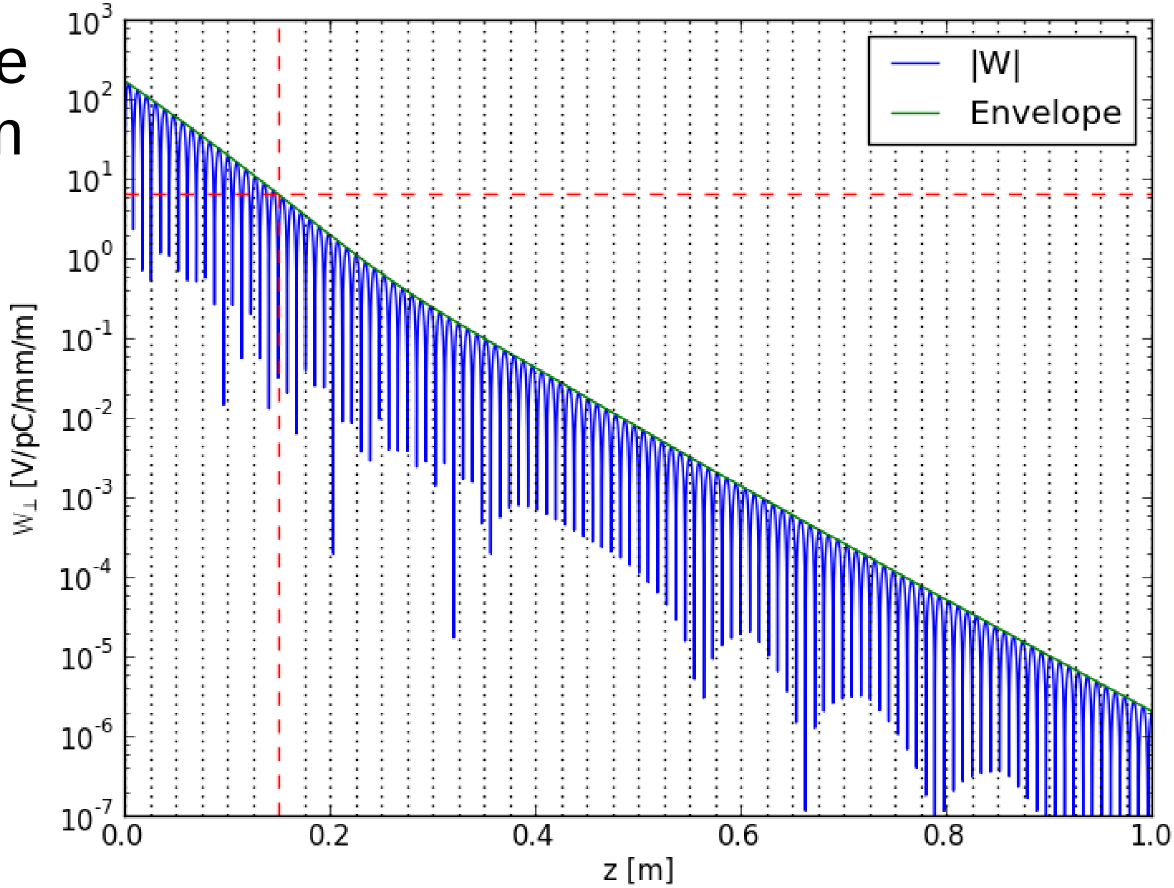
$$W_i(z)=A_i\exp\left(\frac{-\omega_i t}{2Q}\right)\sin\left(\omega_i t\sqrt{1-\frac{1}{4Q^2}}\right)$$

  - No coupling between cells
- Envelope found numerically by linear interpolation between peaks



Long range wakefield estimate

- Assuming a maximum wake envelope of 6.6 V/pC/m/mm
  - From beam dynamics
- Minimum bunch distance given wake limit extracted
- For CLIC_G, we get 6 RF cycles as expected



RF constraints – basic idea

- At a given breakdown rate, find maximum pulse length t constrained by peak field quantities and temperature
  - t defined as time where P ≥ 85% of peak power
- At BDR ≤ 10^{-6} / pulse / m:
  - $\hat{E}^6 * t \leq 220^6\ (\mathrm{MV/m})^6 * 200\ \mathrm{ns} - 250^6\ (\mathrm{MV/m})^6 * 200\ \mathrm{ns}$
  - $\hat{S}_c^{\,3} * t \leq 4.0^3\ (\mathrm{MW/mm^2})^3 * 200\ \mathrm{ns} - 5.0^3\ (\mathrm{MW/mm^2})^3 * 200\ \mathrm{ns}$
  - $(P/C)^3 * t \leq 2.3^3\ (\mathrm{MW/mm})^3 * 200\ \mathrm{ns} - 2.9^3\ (\mathrm{MW/mm})^3 * 200\ \mathrm{ns}$
  - $\Delta T(t) = C * \hat{H}^2 * \int_0^t \frac{P(t)}{\sqrt{t-t'}}\,dt' \leq 50\,K$
- Empirical constraints based on high-power RF-tests
  - Uncertainties important due to high exponents
  - Will use conservative values unless otherwise noted
- Solve these equations for t
  - Pick the smallest as the overall maximum pulse length
  - Subtract the “wasted” time to get the beam time

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No data from old database

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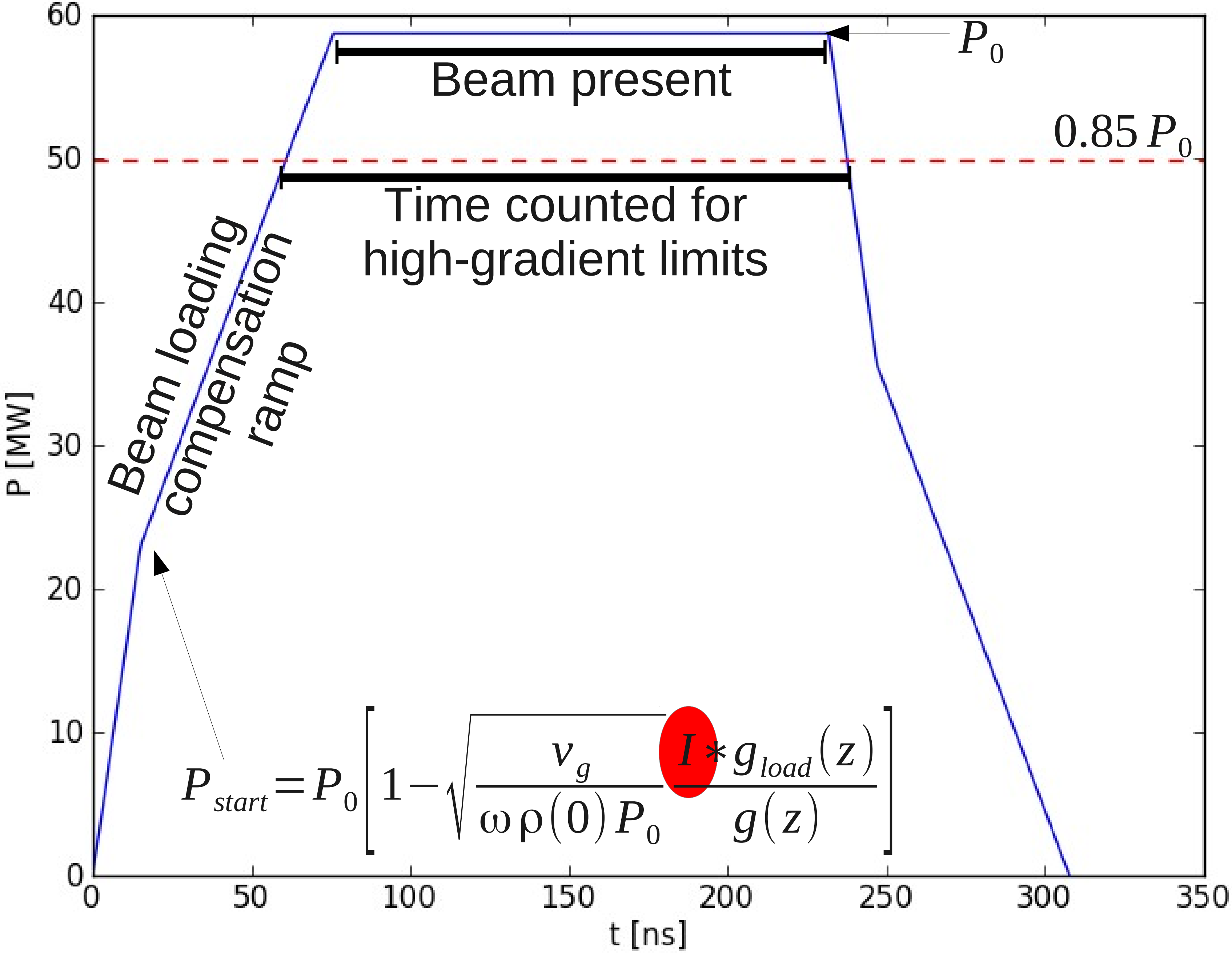
Pulse shape at structure input



Beam present

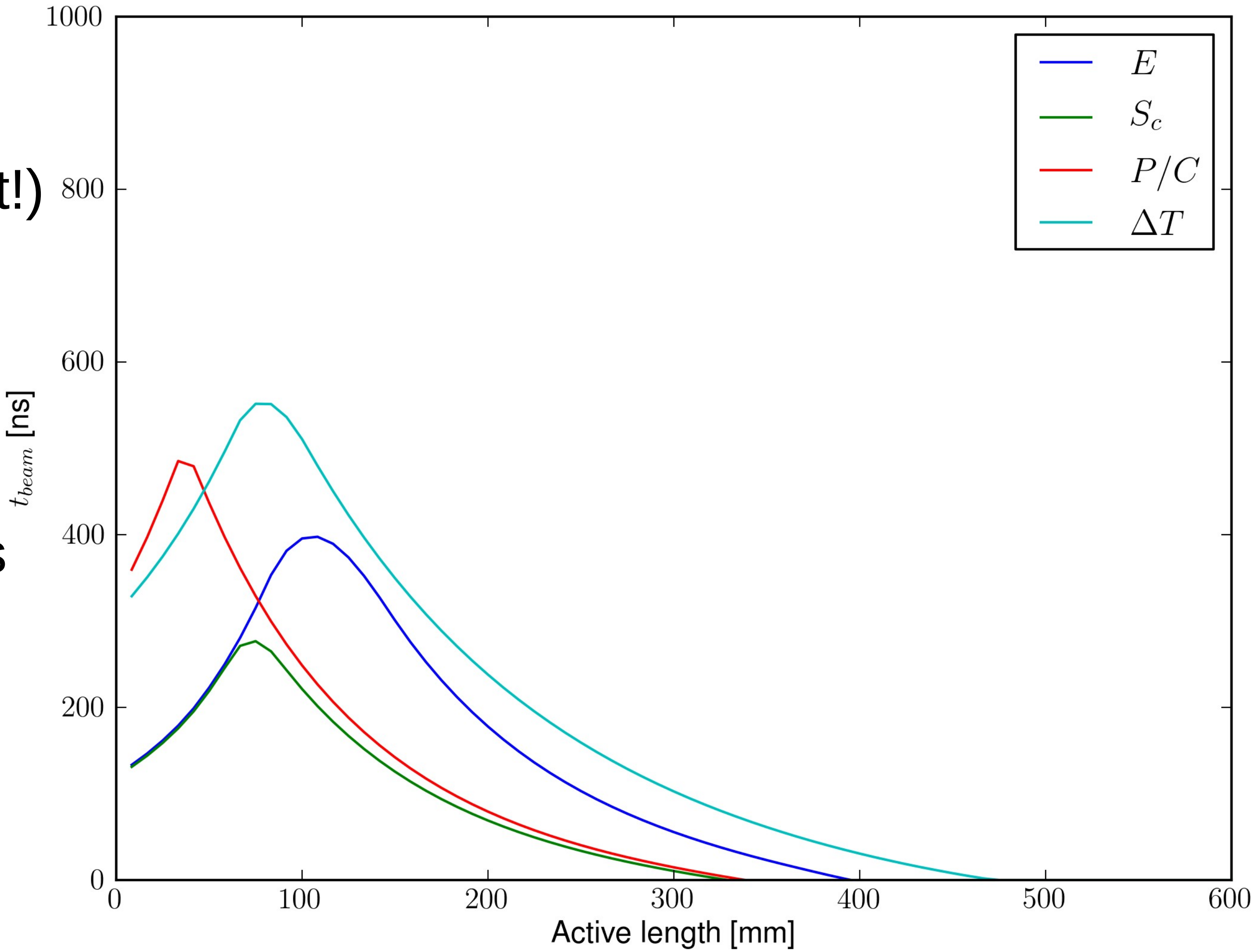
Time counted for high-gradient limits

Beam loading compensation ramp

$$P_{start}=P_0\left[1-\sqrt{\frac{v_g}{\omega\,\rho(0)\,P_0}\frac{I*g_{load}(z)}{g(z)}}\right]$$

Test optimization: Beam time vs. structure length

- CLIC_G, 2nd level design
- Varying number of cells (stretch it!)
- G_L = 100 MV/m
- I = 1.92 A
- Uncertainty in breakdown limits



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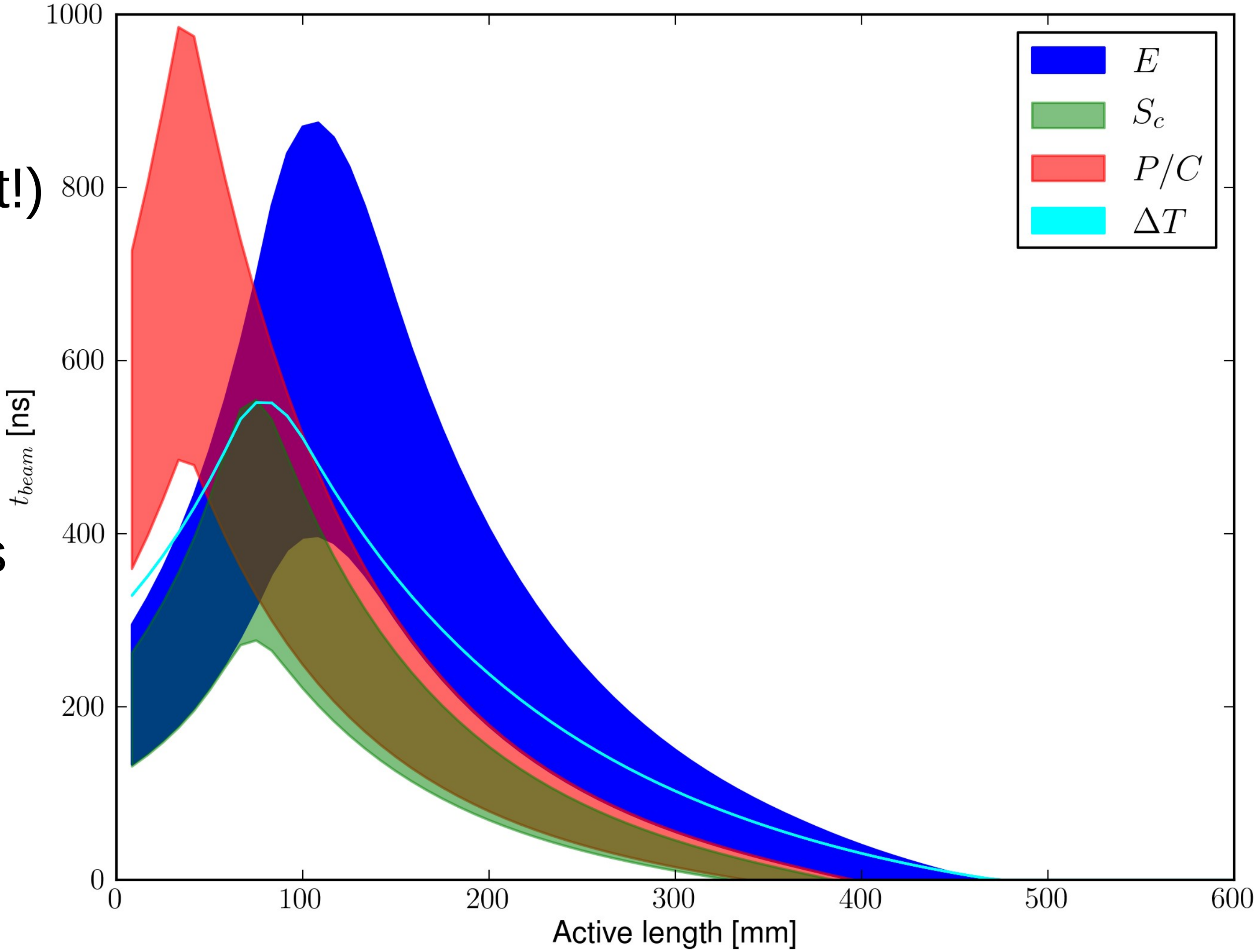

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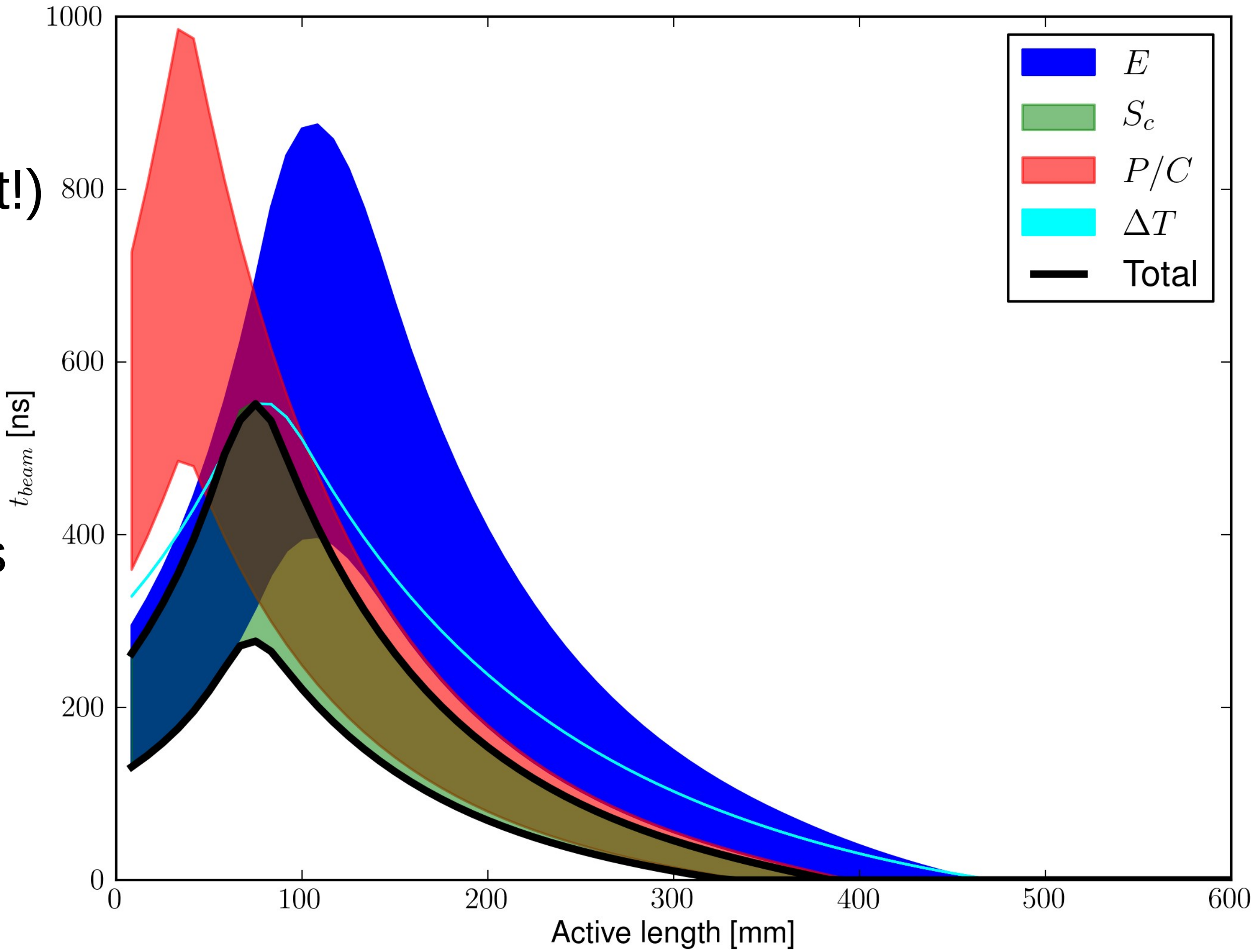
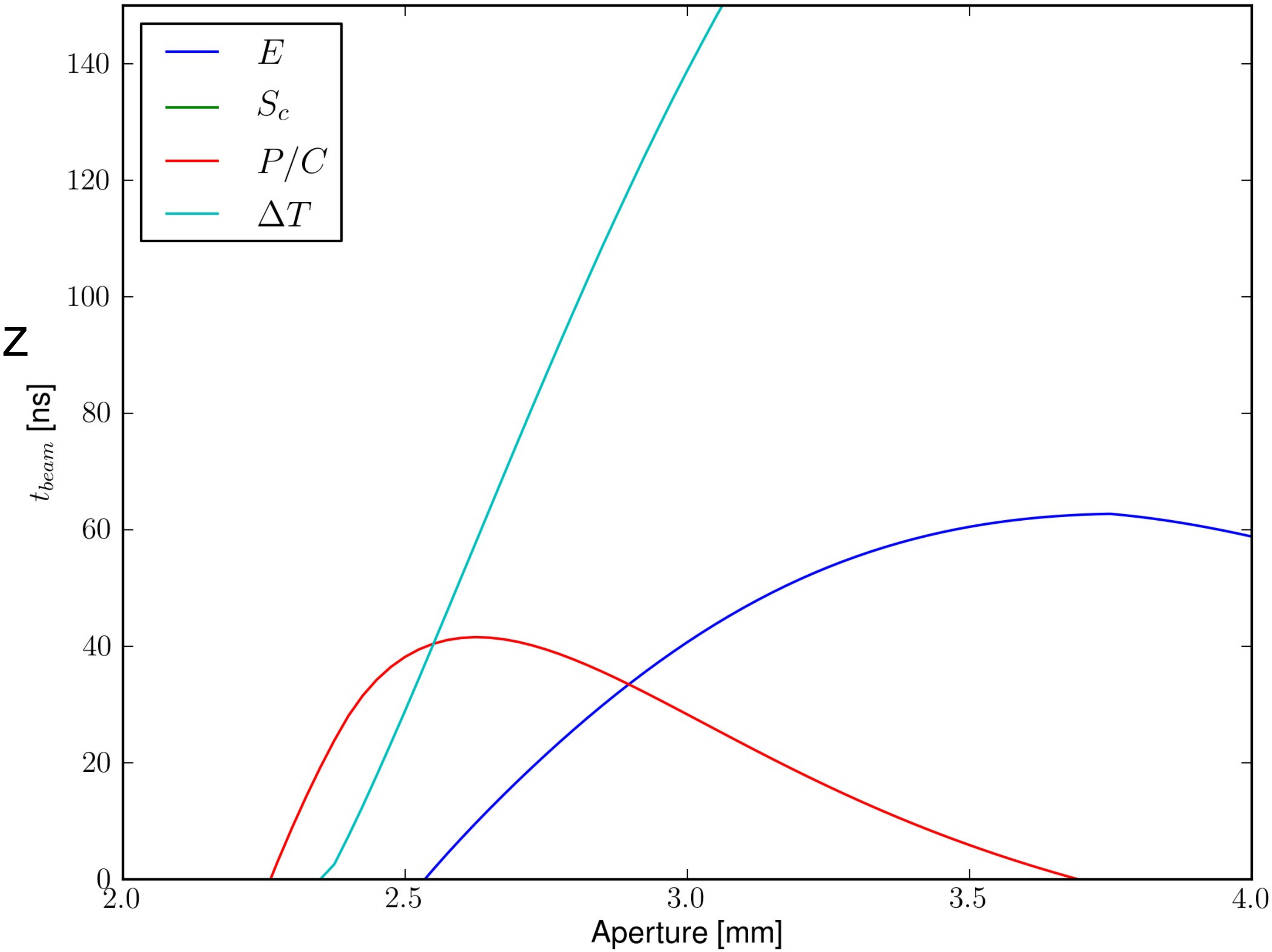


Test optimization: Aperture scan

- Constant impedance structure
- 26 cells, 120°, 11.9942 GHz
- L = 216 mm
- 100 MV/m
- 1.92 A
- Choose: a = 2.9 mm



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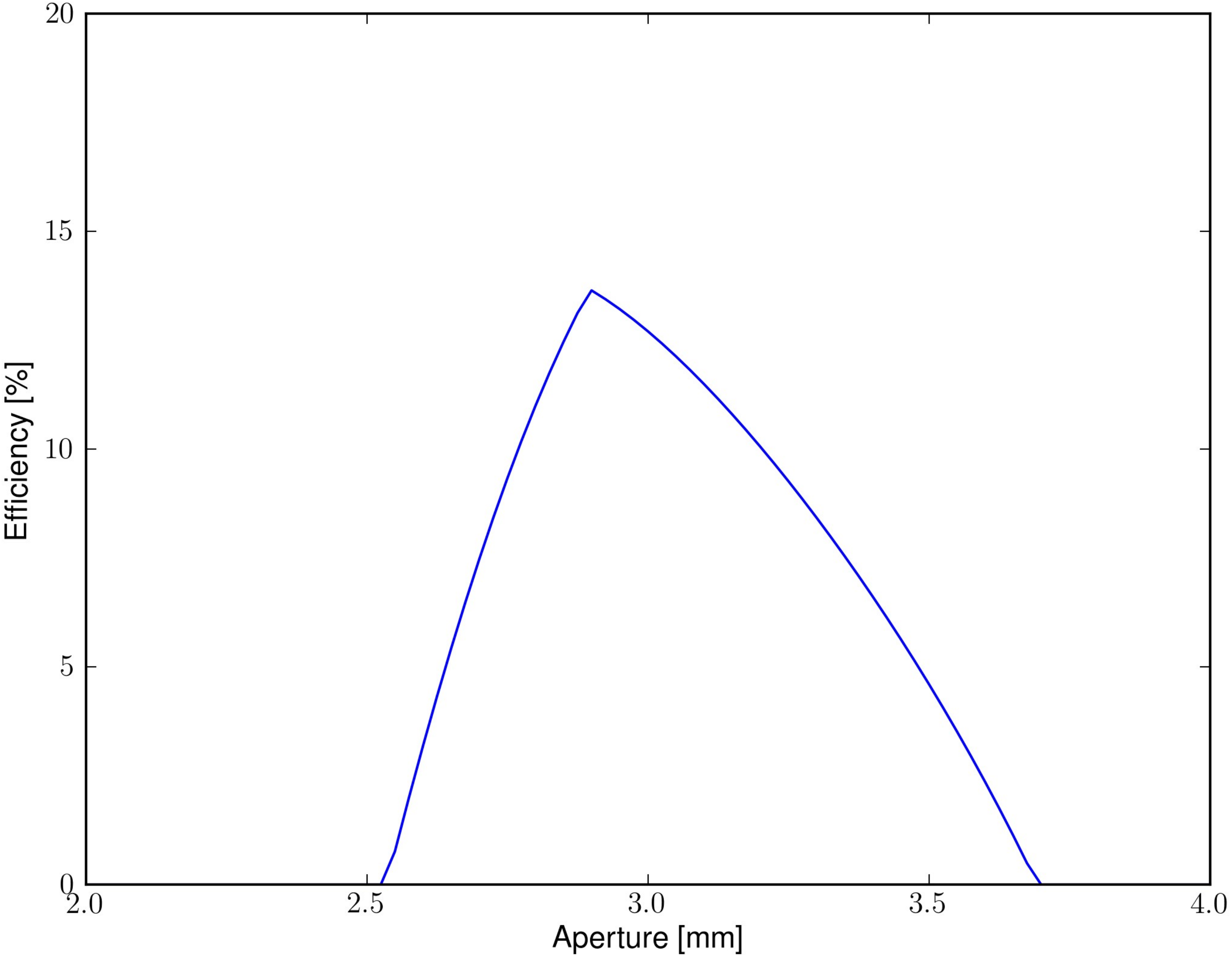

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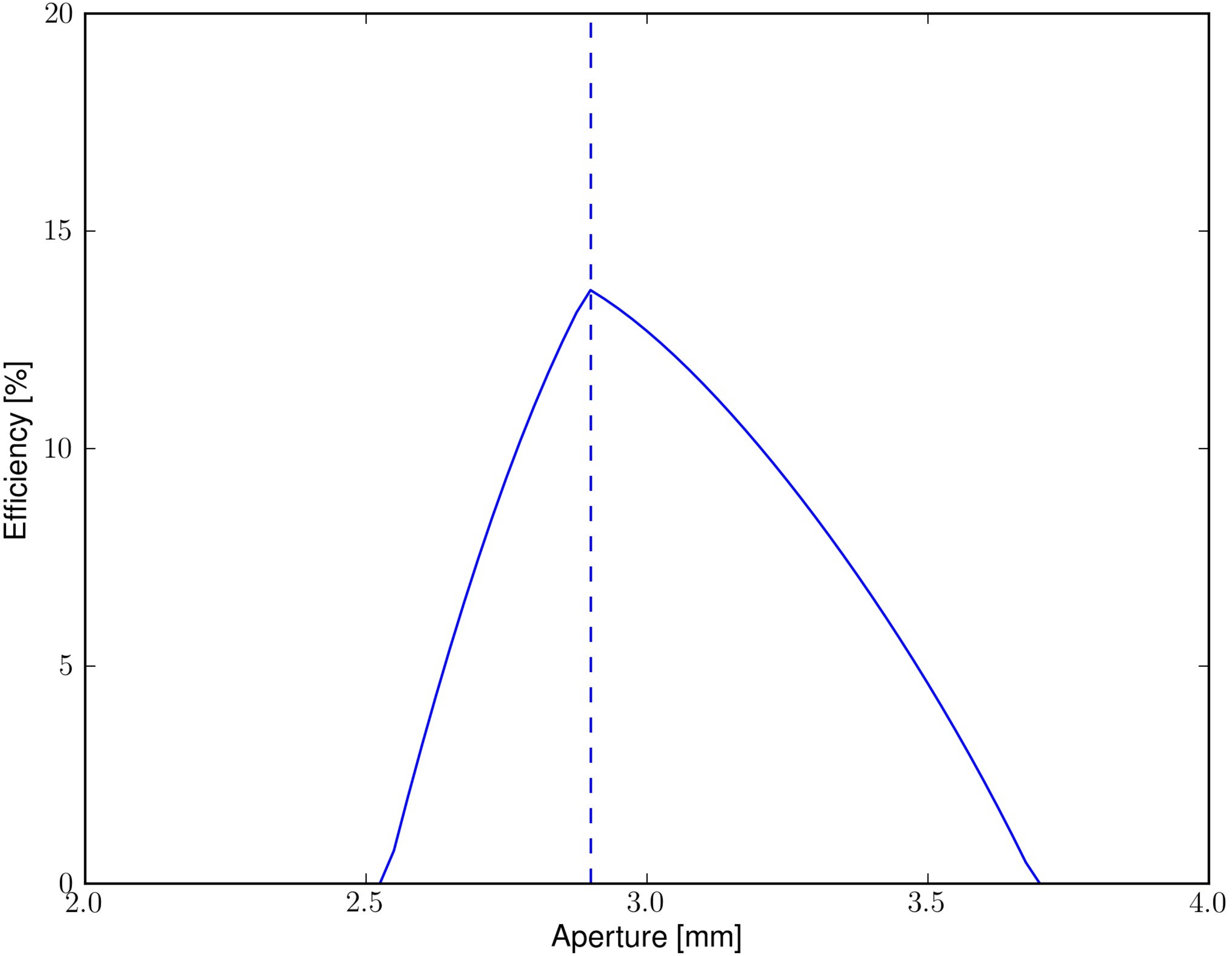
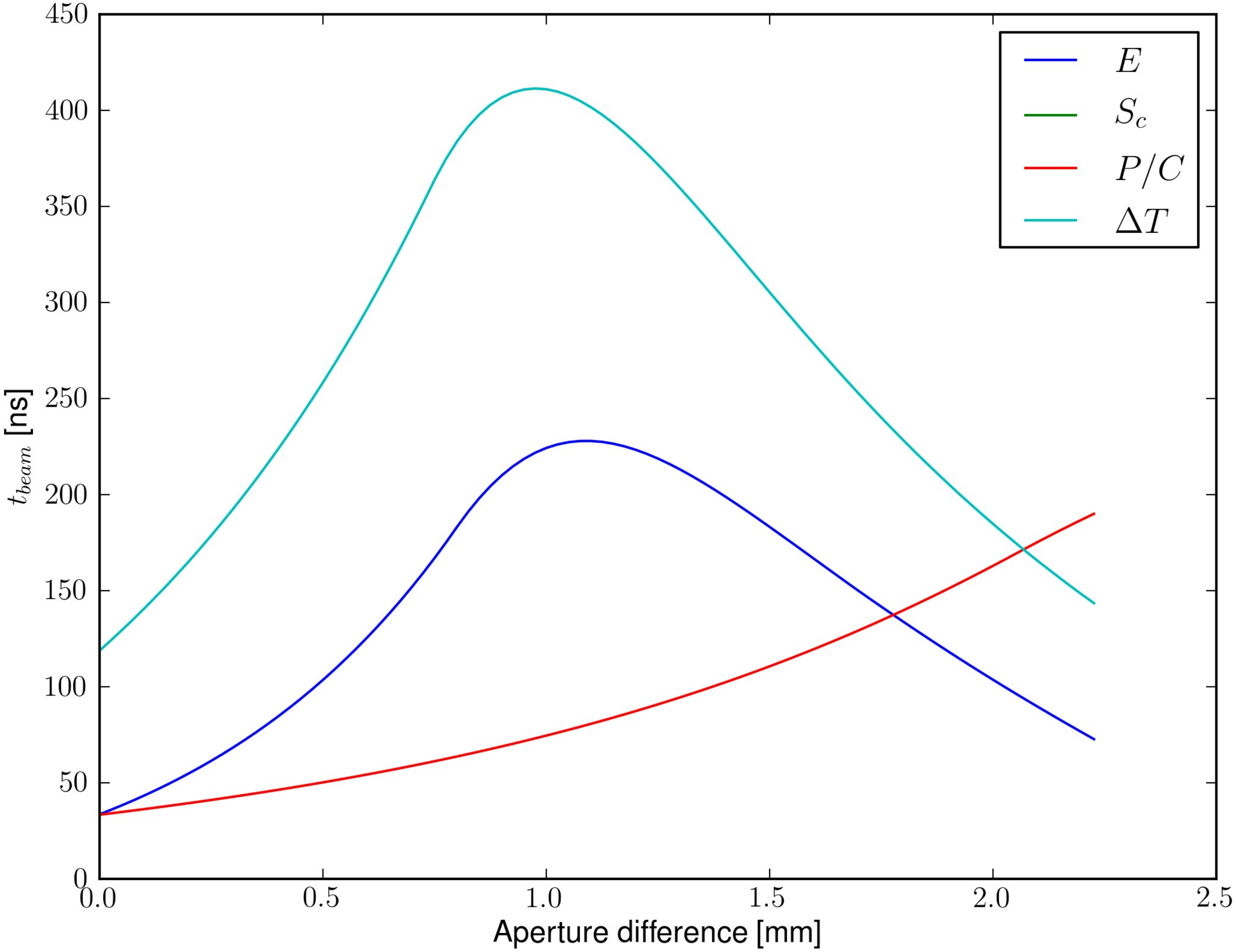


Test optimization: Aperture tapering scan

- Keeping a = 2.9 mm, introducing a front-to-back linear iris tapering
- Constant iris thickness
- Assume optimum Δa = 1.75mm



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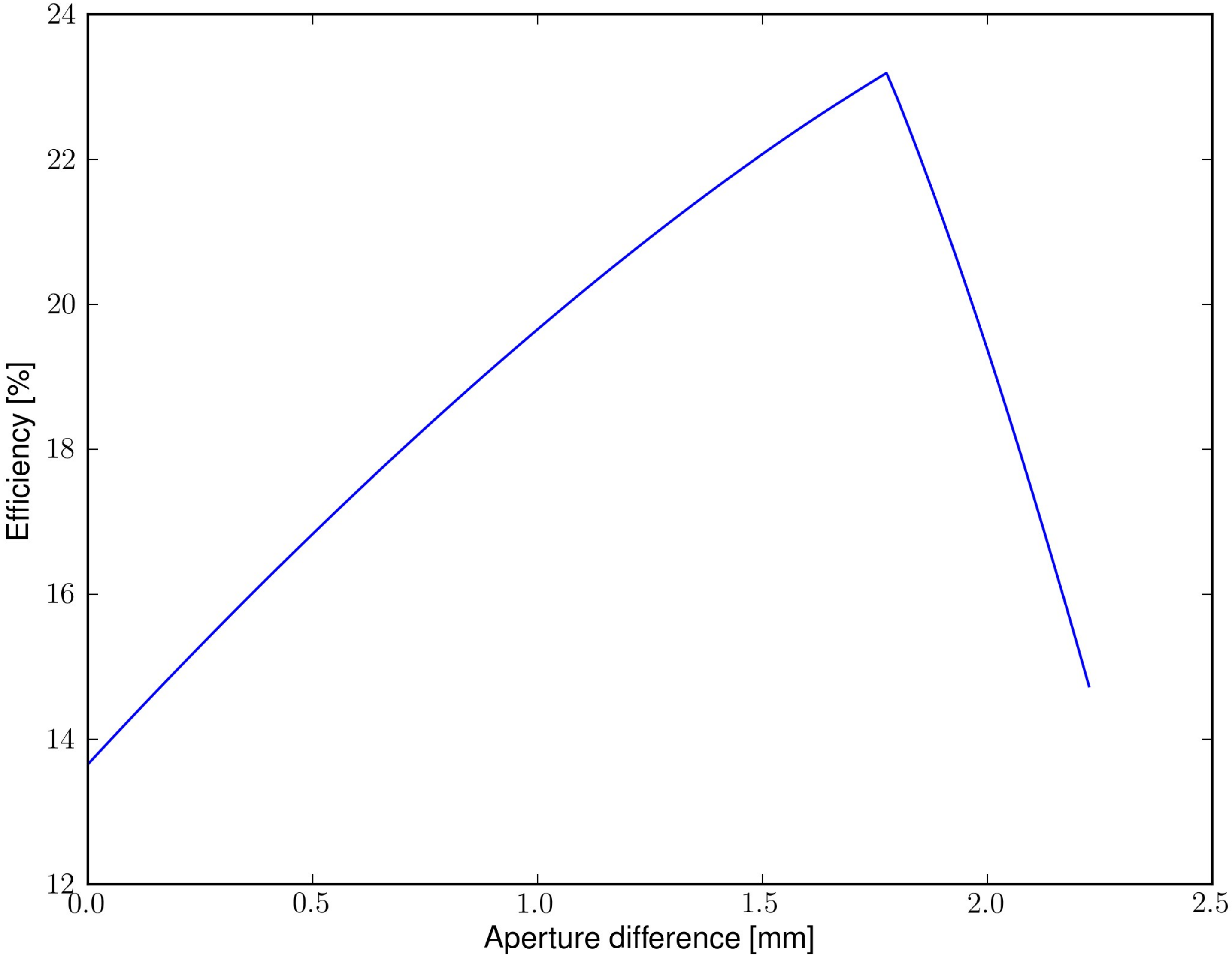

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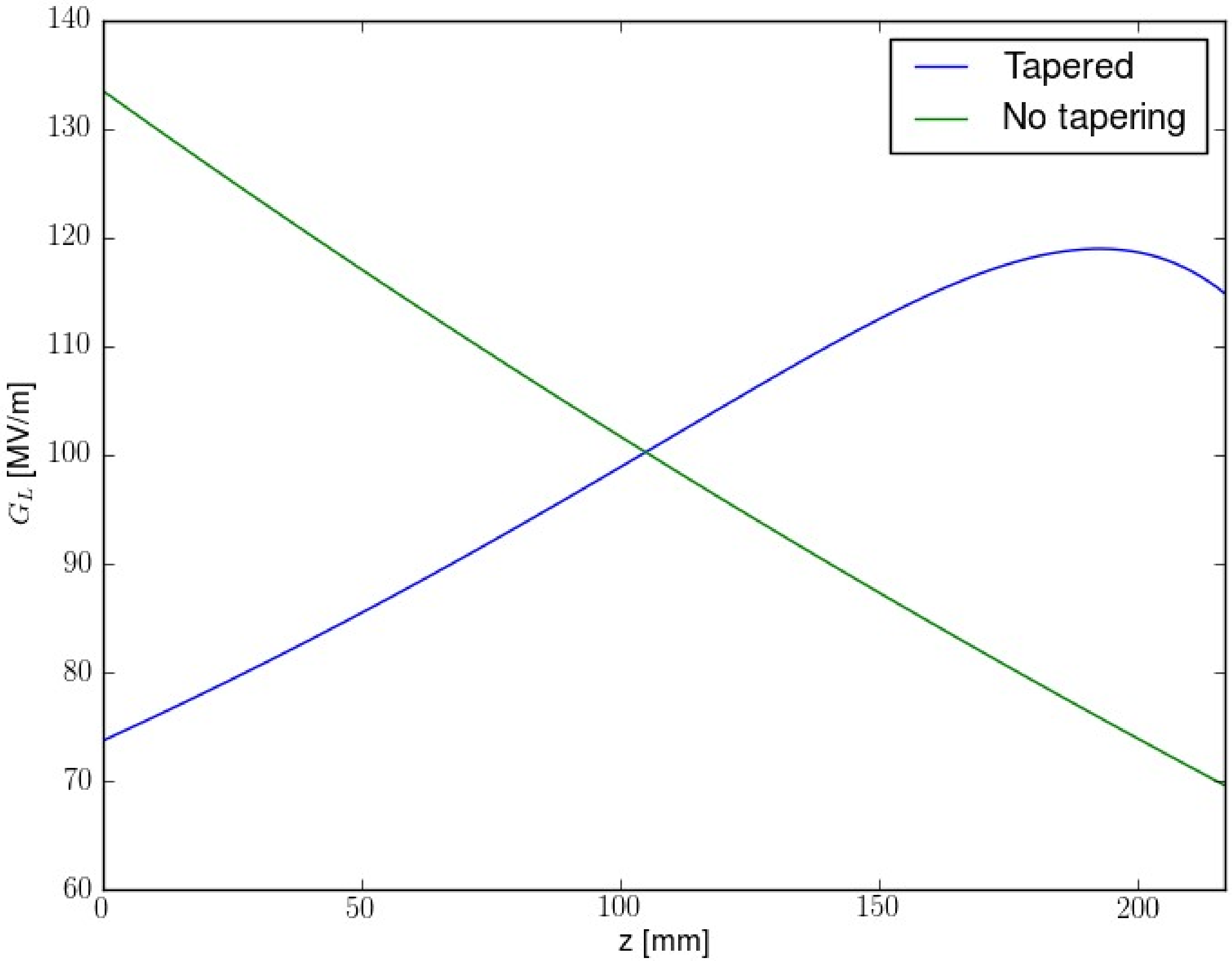

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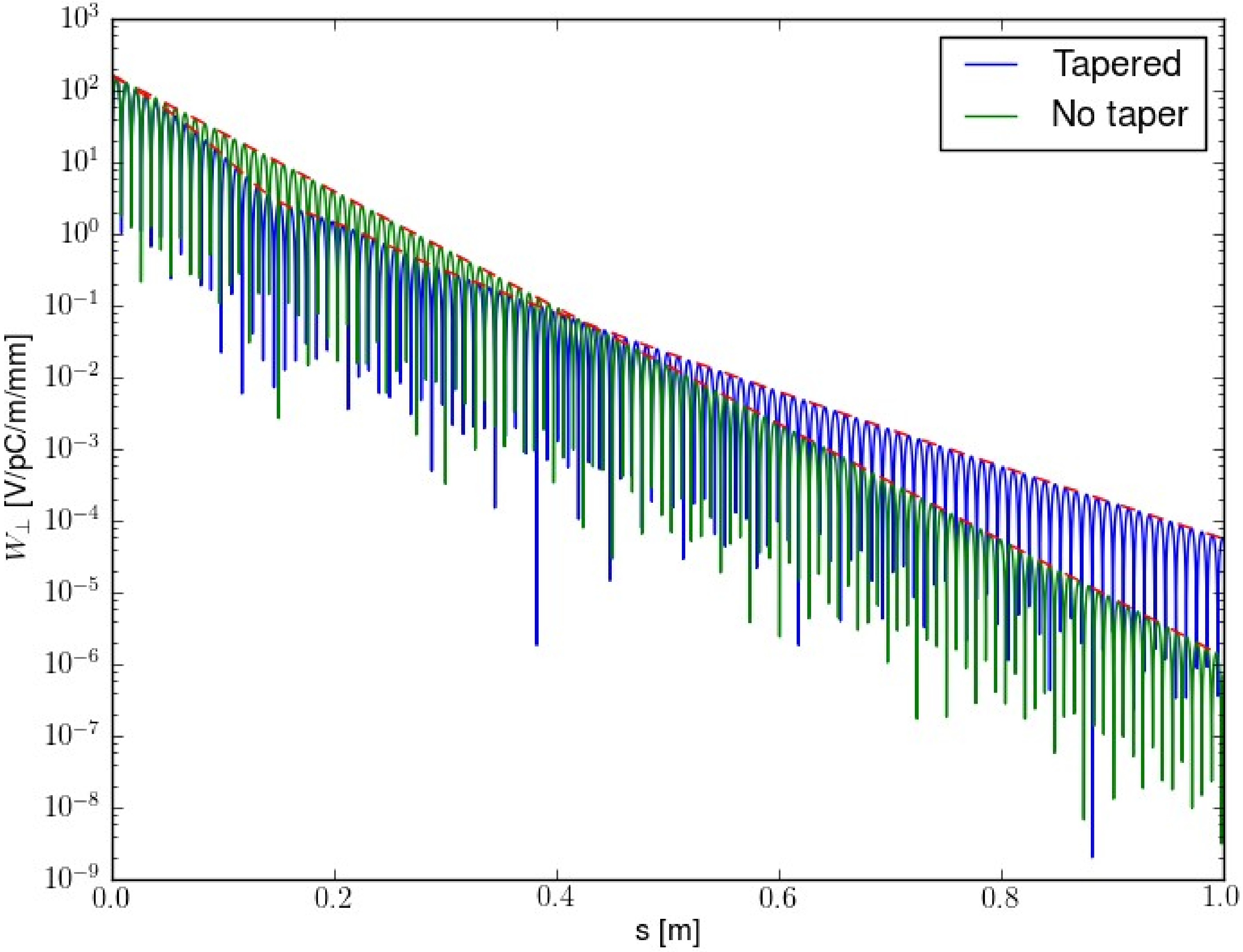
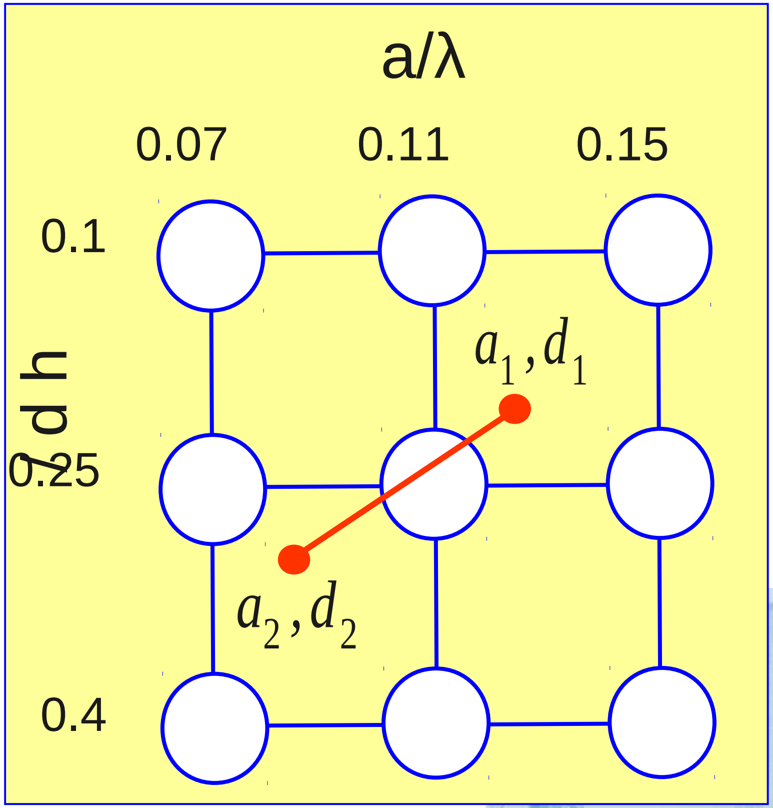


The cell data base

- Interpolating the “anchor cells” from pre-calculated cells
- Today these are scaled from 30 GHz cells
- No S_c information
- Want to have re-optimized data base
- High gradient optimization of large number of cells
    - Main mode calculation in Omega3P
    - Assisted by software [2]
    - Time domain wakefield calculation using T3P



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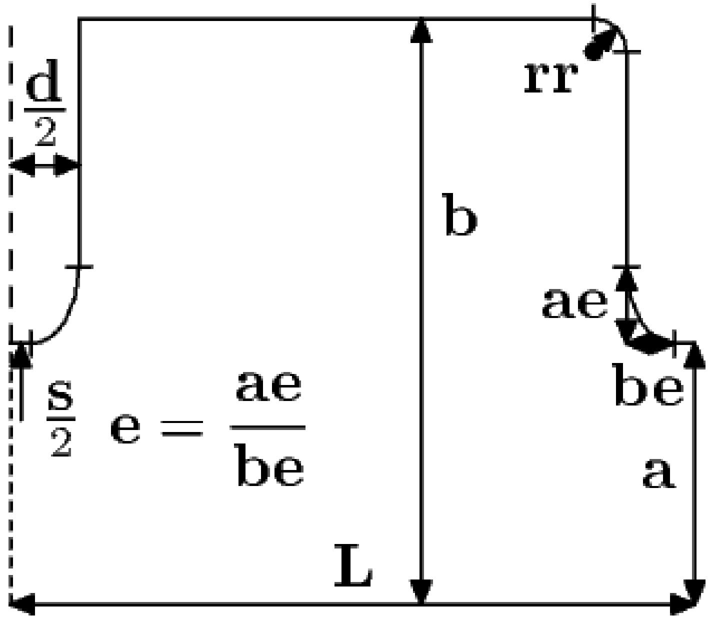

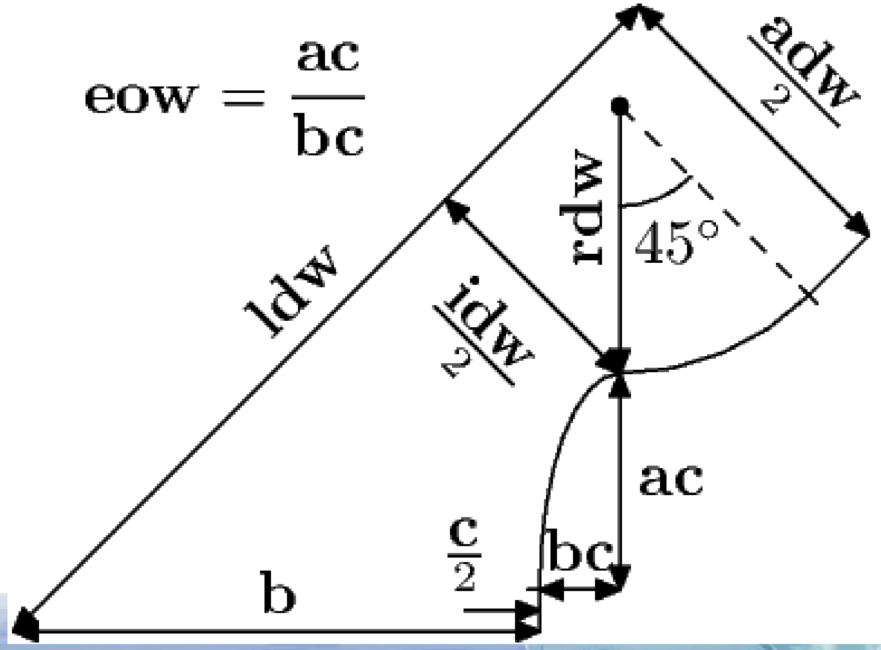

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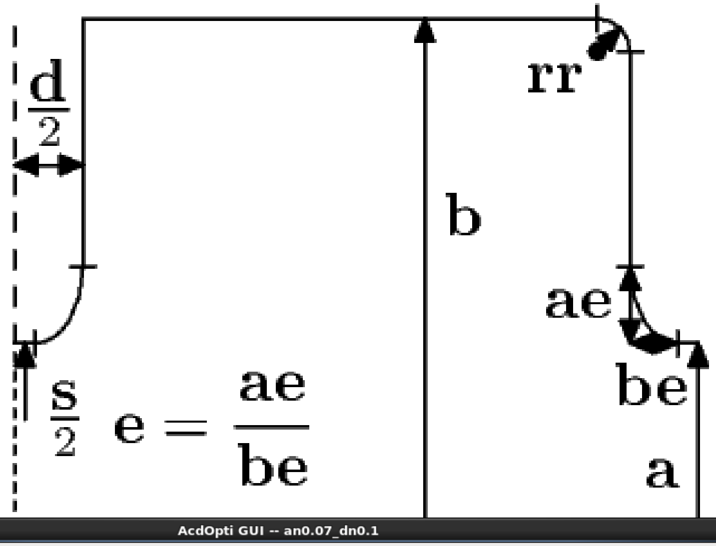

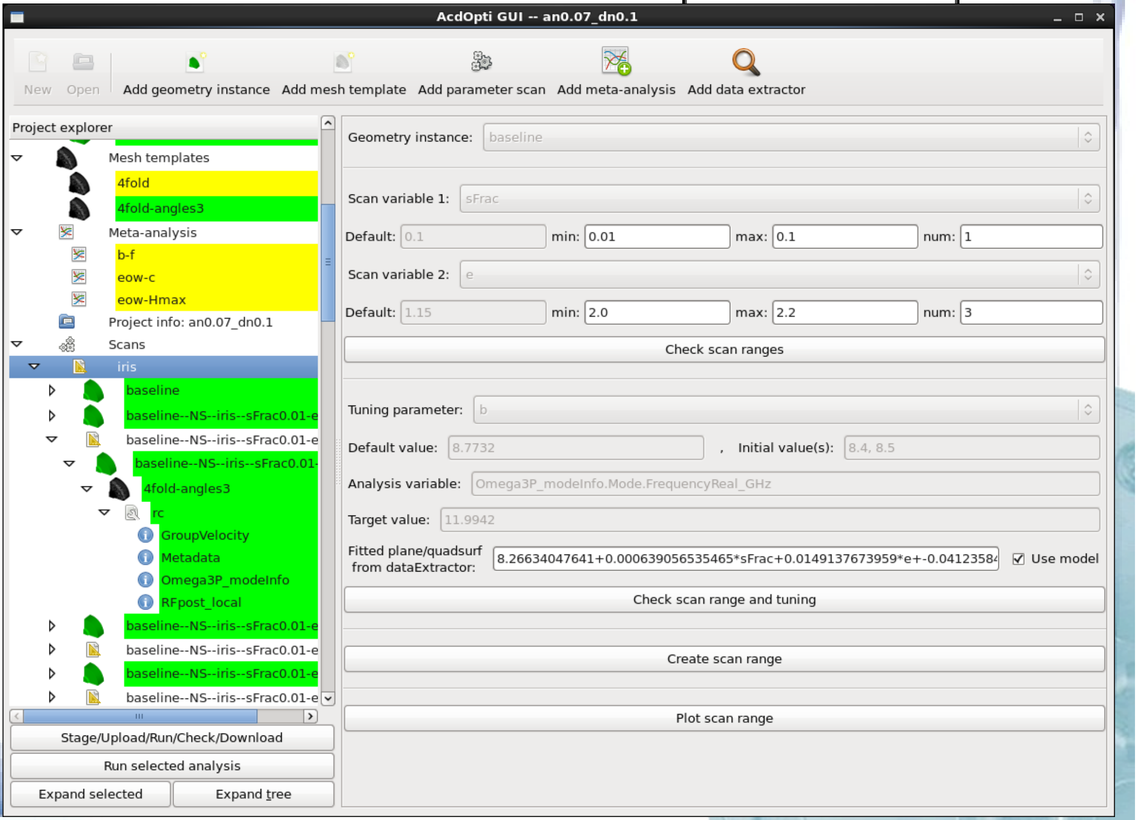

Geometry instance: baseline

Scan variable 1: sFrac

Default: 0.1 min: 0.01 max: 0.1 num: 1

Scan variable 2: e

Default: 1.15 min: 2.0 max: 2.2 num: 3

Tuning parameter: b

Default value: 8.7732 , Initial value(s): 8.4, 8.5

Analysis variable: Omega3P_modelnfo.Mode.FrequencyReal_GHz

Target value: 11.9942

Fitted plane/quadsurf from dataExtractor: 8.26634047641+0.000639056535465*sFrac+0.0149137673959*e+-0.0412358 ☑ Use model

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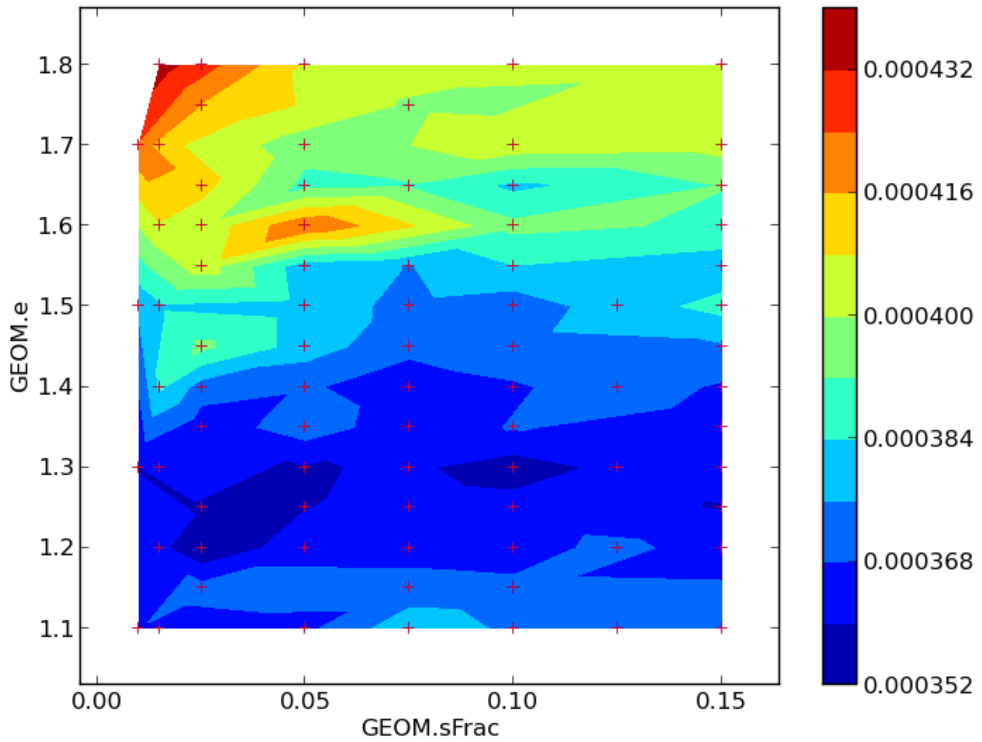

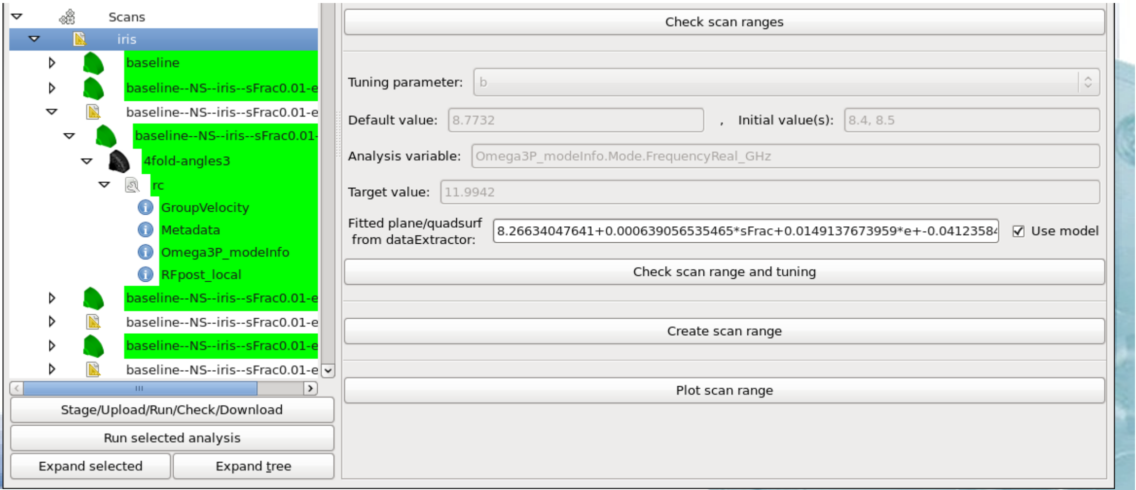

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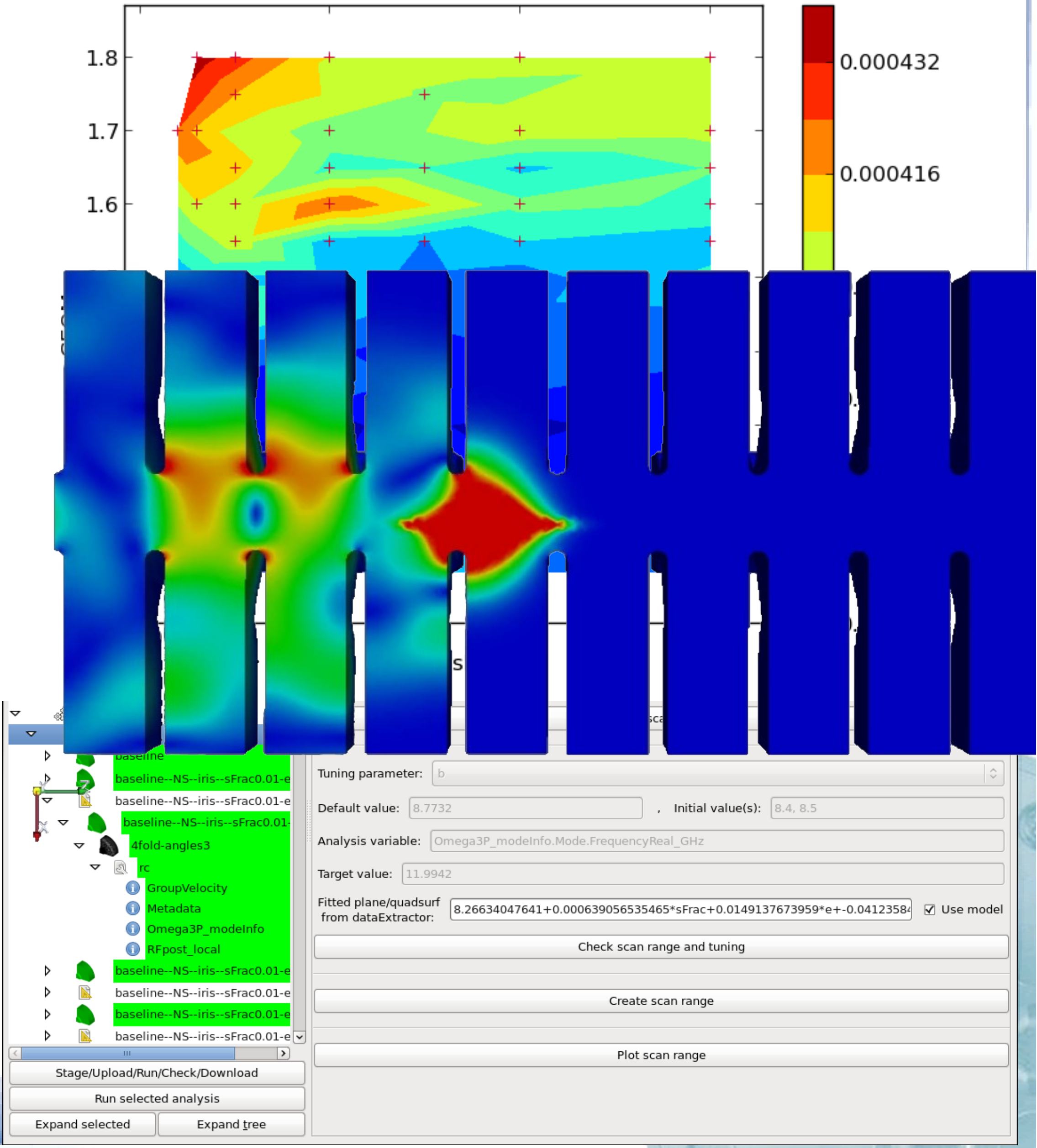

baseline
baseline--NS--iris--sFrac0.01-e
baseline--NS--iris--sFrac0.01-e
baseline--NS--iris--sFrac0.01-
4fold-angles3
rc
GroupVelocity
Metadata
Omega3P_modeInfo
RFpost_local
baseline--NS--iris--sFrac0.01-e
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Summary and conclusions

- Have developed tool for estimating RF structure parameters
  - Results match well with final HFSS design
- More work needed to define breakdown limits
  - Scaling laws and their constants
- Building of new cell database in progress
  - Have tool to do this

References

[1] *Analytical solutions for transient and steady state beam loading in arbitrary traveling wave accelerating structures*
A. Lunin, V. Yakovlev and A. Grudiev

[2] *SURFACE FIELD OPTIMIZATION OF ACCELERATING STRUCTURES FOR CLIC USING ACE3P ON REMOTE COMPUTING FACILITY*
K. Sjobak, A. Grudiev and E. Adli

Thank you for your attention!

BACKUP SLIDES

Here may be dragons...

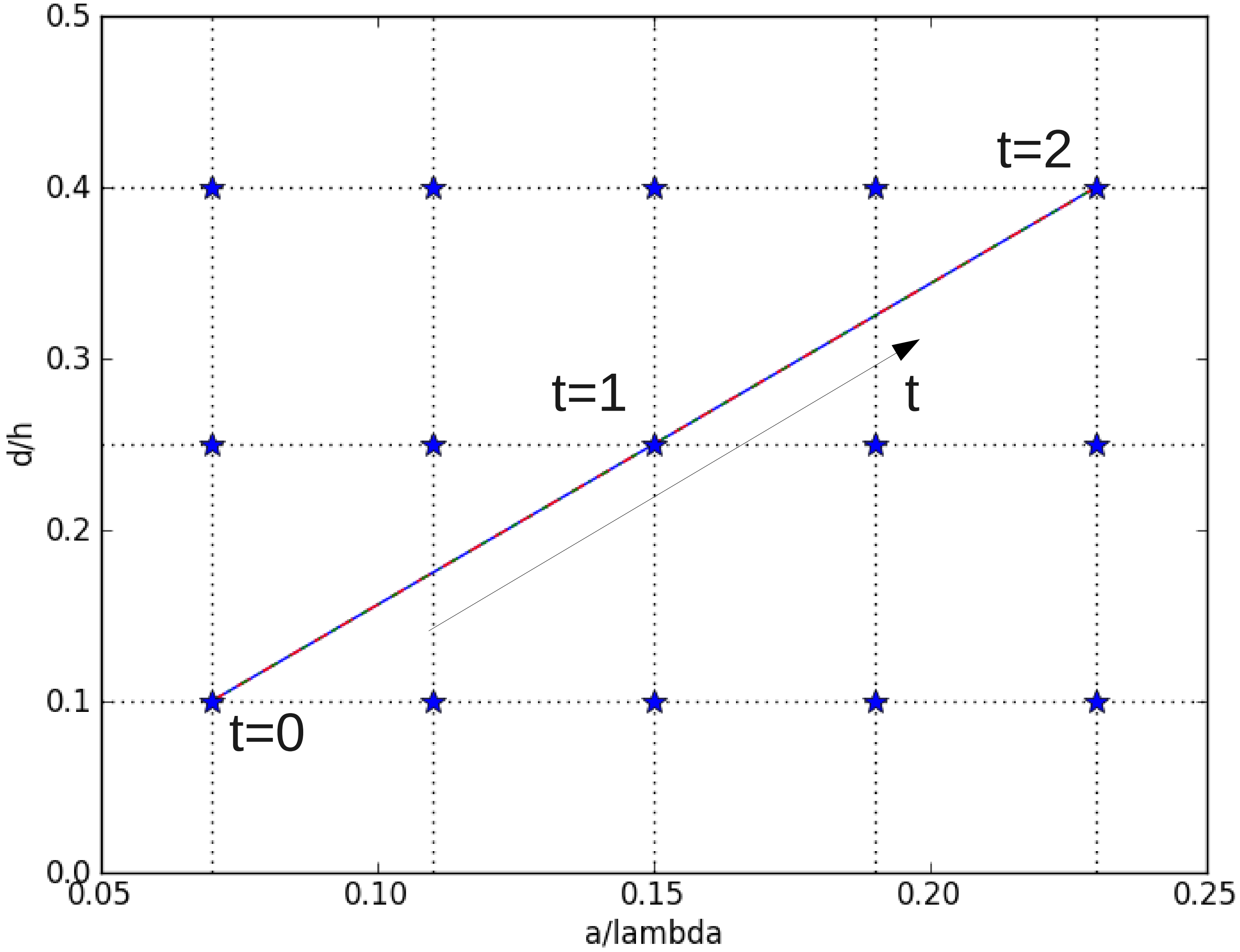
http://www.flickr.com/photos/jrobblee/4702245780

The cell database: Frequency scaling, data range

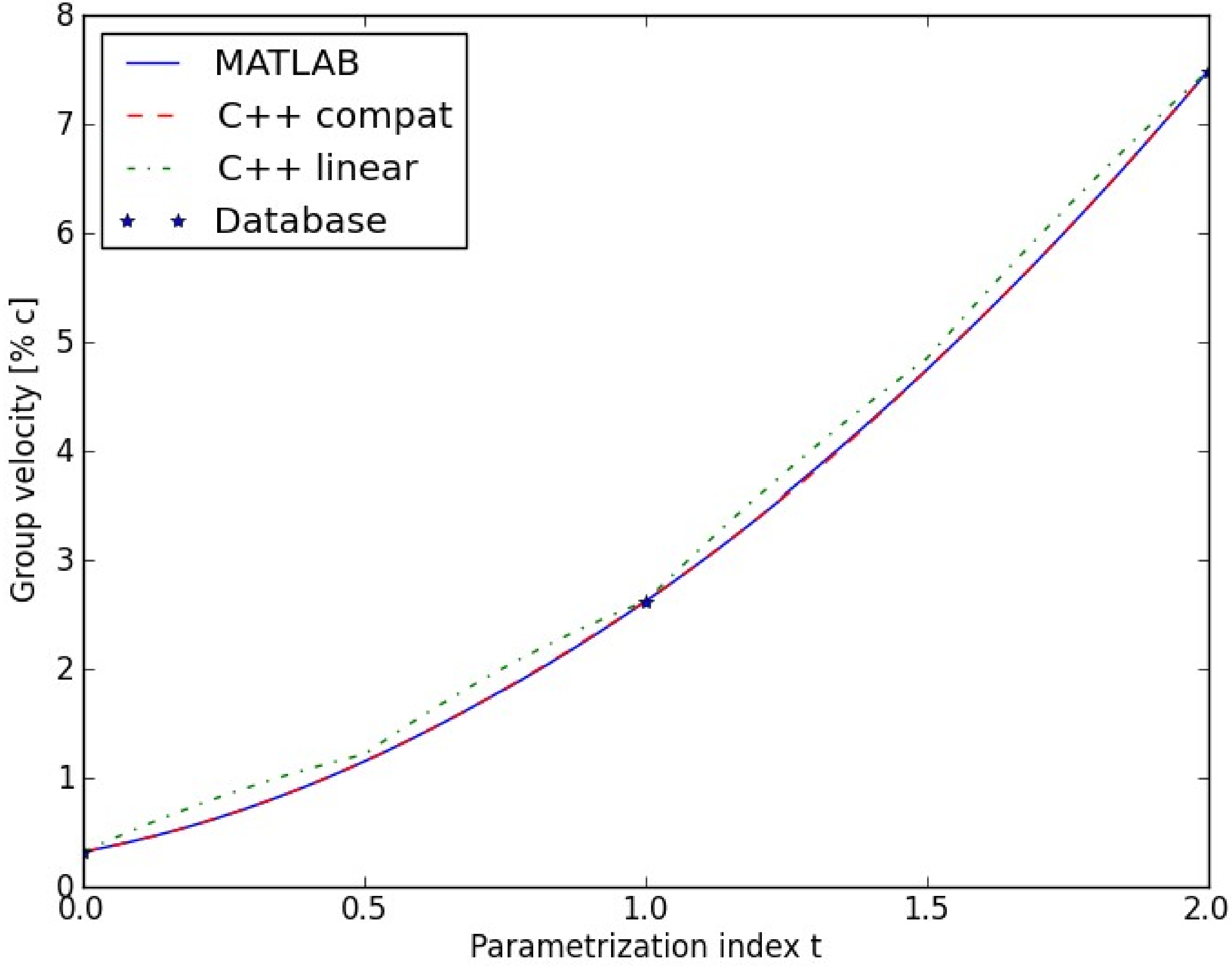
- $Q' = \mathrm{sqr\ t}(f / f') * Q$
- $R/Q = f'/f * R/Q$
- $f_w' = f'/f * f_w$
- $A_w' = (f'/f)^3 A_w$
- $a' = f/f' * a$
- $h' = f/f' * h$

- a/lamda = {0.07, 0.11, 0.15, 0.19, 0.23}
- d/h = {0.1, 0.25, 0.4}
- dsi = {120°, 150°}

The cell data base – cell interpolation



The cell data base – cell interpolation



Scaling the data to 200 ns, 1e-6 bpp/m

For rectangular pulse of length t_p

For a fixed pulse length

$$BDR \sim E_a^{30}$$

For a fixed BDR

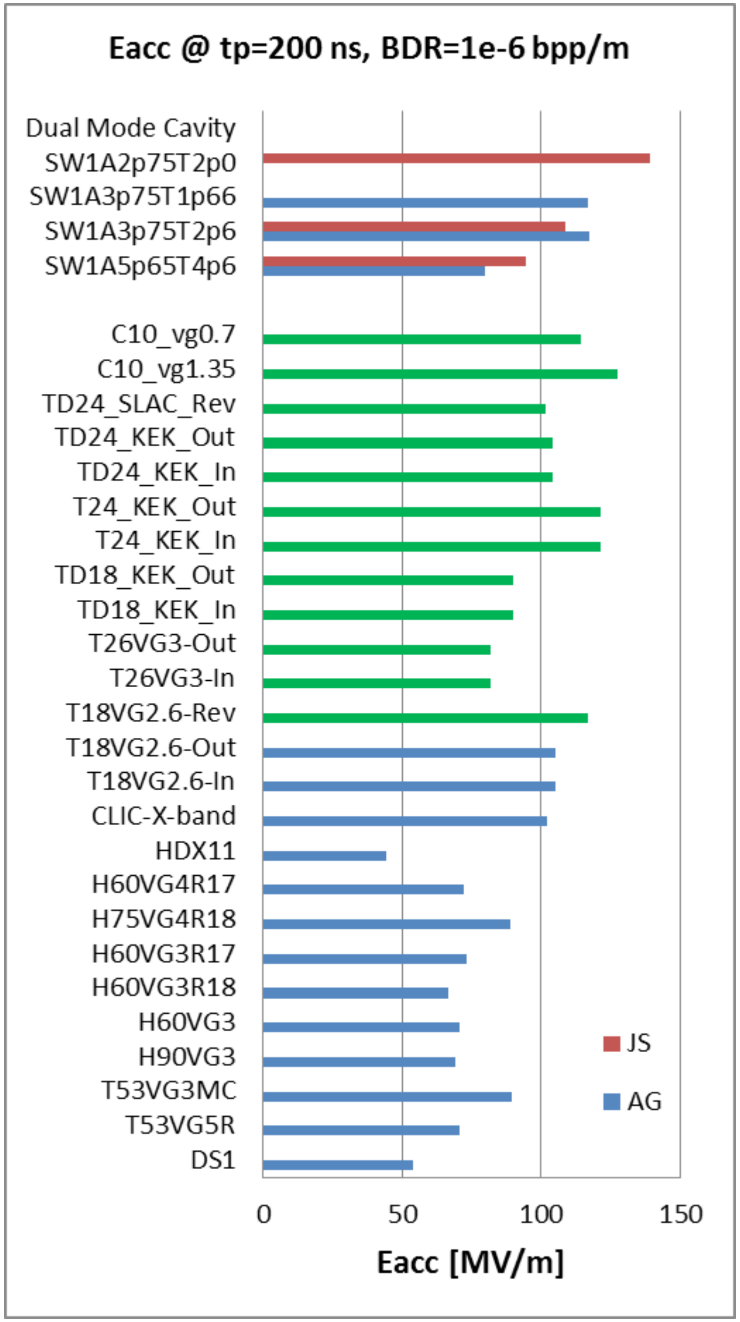
$$E_a \cdot t_p^{1/6} = const$$

$$\frac{E_a^{30} \cdot t_p^{5}}{BDR} = const$$

Slides by A. Grudiev

For pulse with a ramp (SW and some of TW structures), effective pulse length is used which is the time when the

Pin(t) > 0.85 Pinmax



N.B. Brown and Green are new data points.
JS = Jiaru Shi; AG = Alexej Grudiev

Maximum surface electric and magnetic fields

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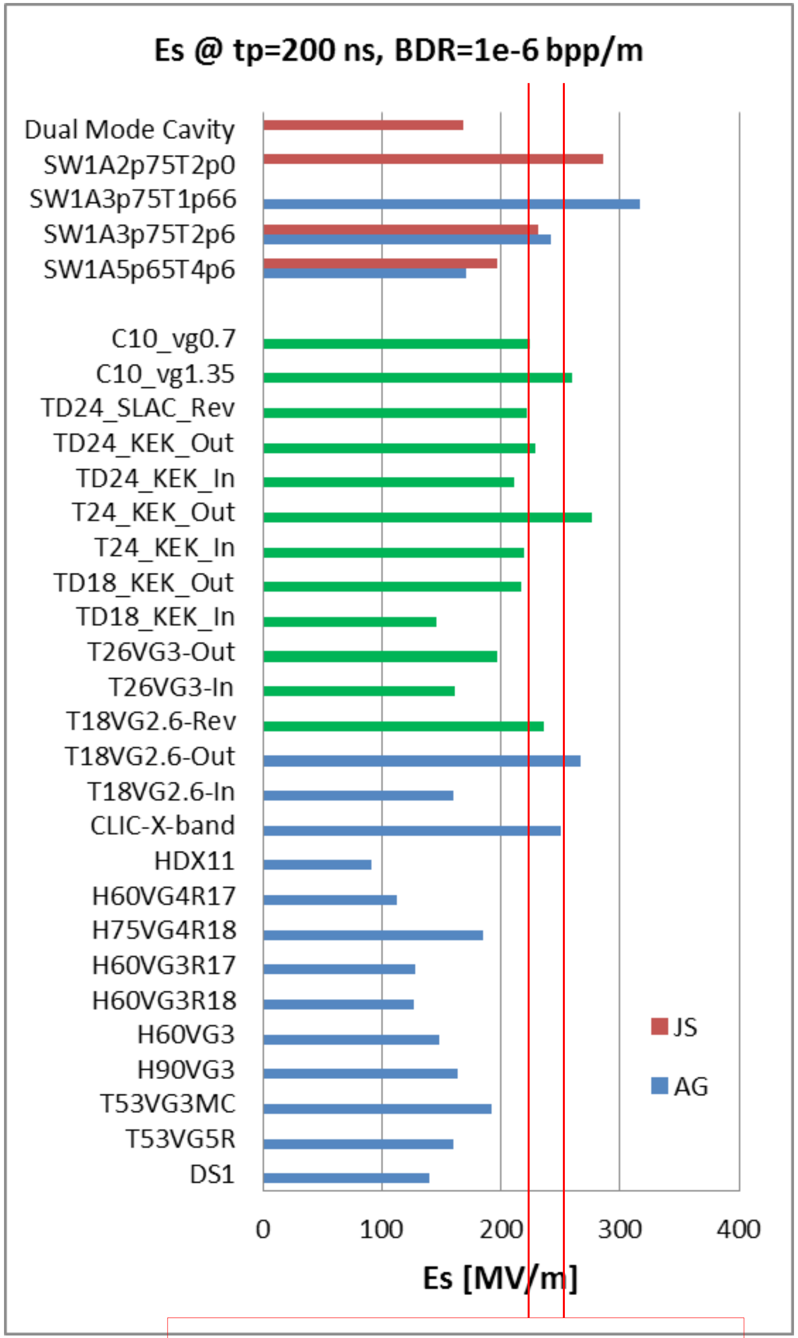
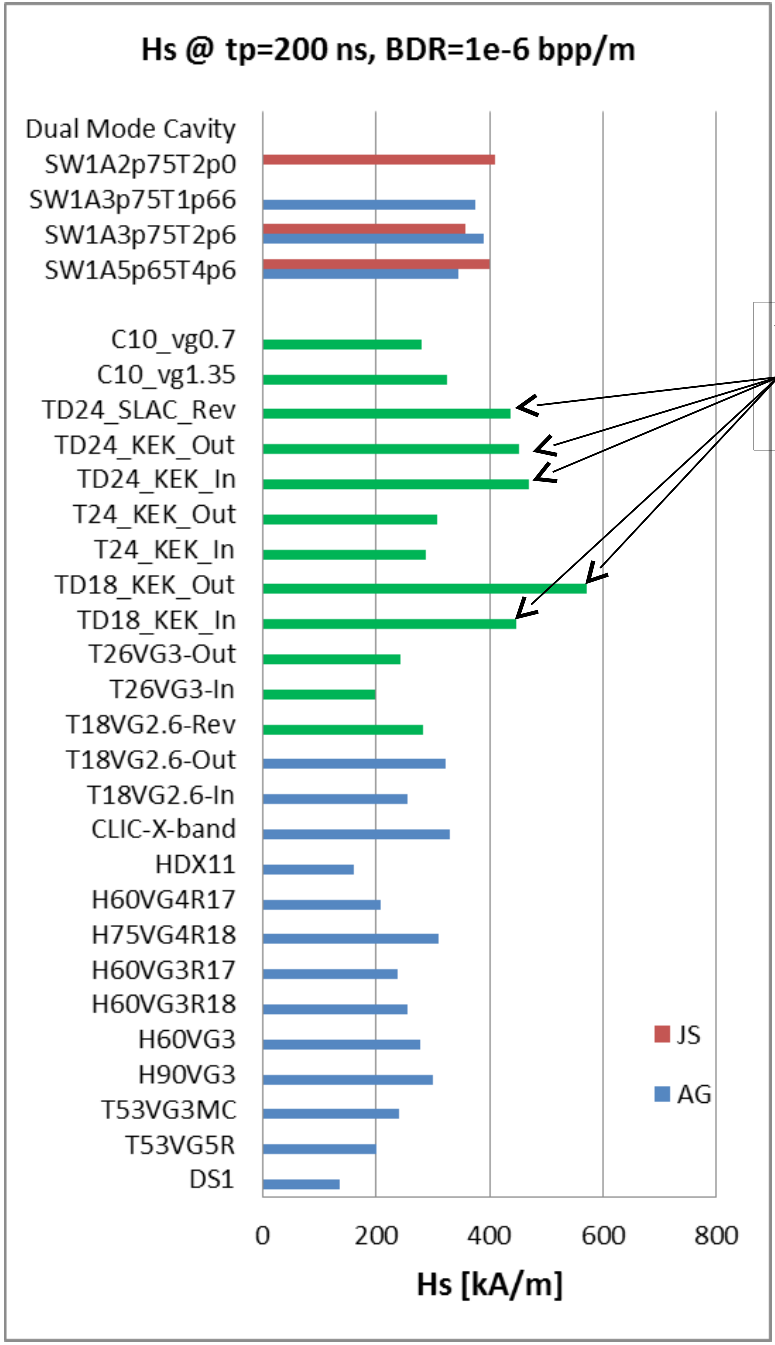

Es @ tp=200 ns, BDR=1e-6 bpp/m

Es = 220 - 250 MW/mm2


Hs @ tp=200 ns, BDR=1e-6 bpp/m

Waveguide damped

Power flow related quantities: Sc and P/C

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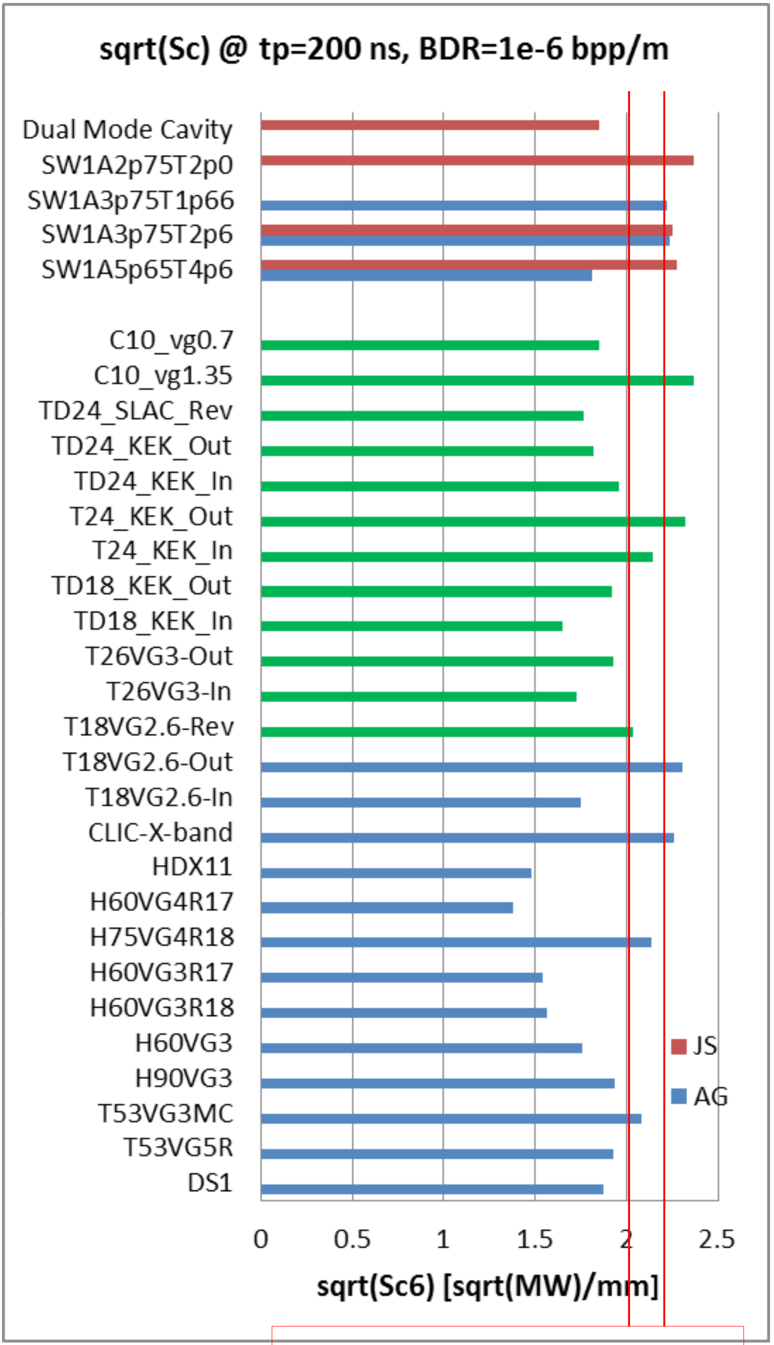
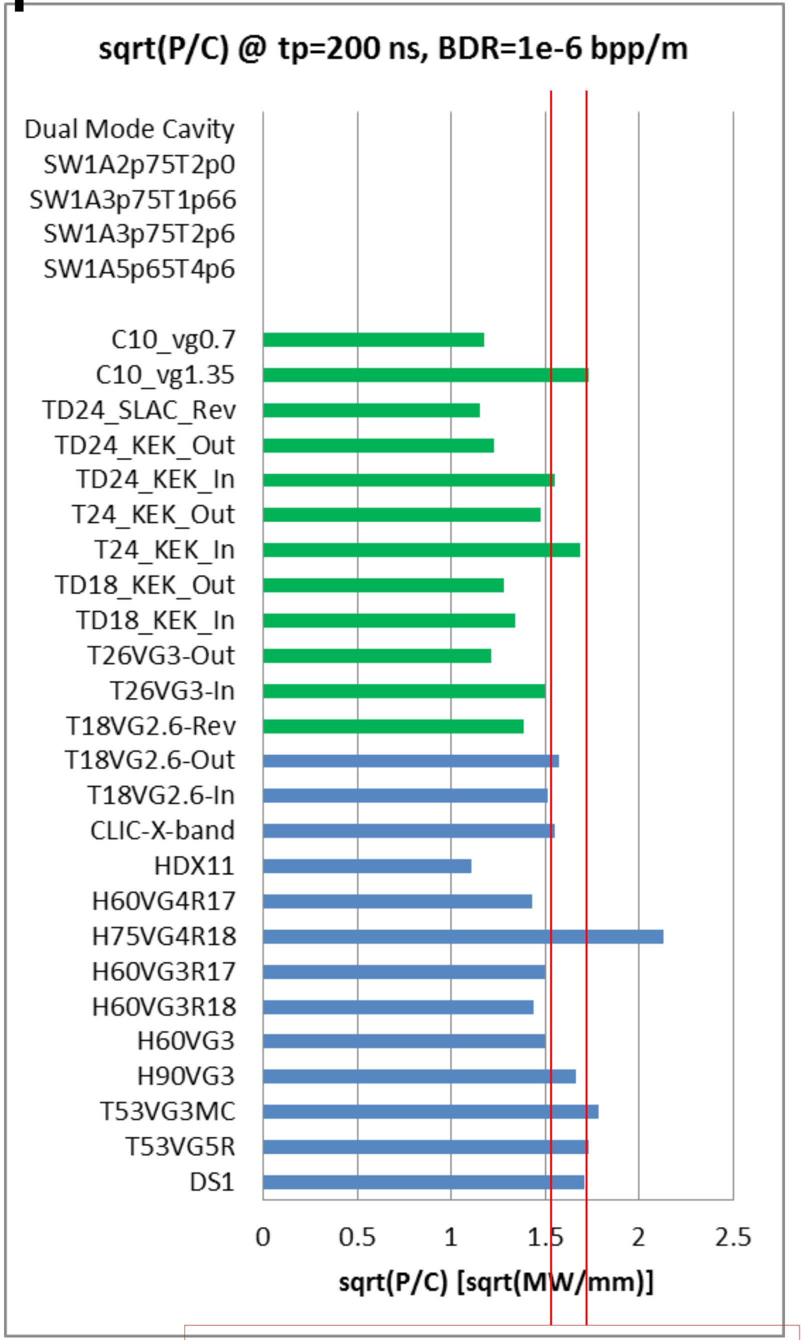


Sc = 4 - 5 MW/mm2



P/C = 2.3 – 2.9 MW/mm

Summary on the high-power RF constraints

RF breakdown and pulsed surface heating constraints used for CLIC_G design (2007):

- Esmax < 250 MV/m
- Pin/Cin▪(tpP)1/3 = 18 MW·ns1/3/mm
- ΔTmax(Hsmax, tp) < 56 K

Optimistic RF breakdown and pulsed surface heating constraints for BDR=10-6 bpp/m:

- Esmax ▪(tpP)1/6 < 250 MV/m · (200ns)1/6
- Pin/Cin▪(tpP)1/3 < 2.8 MW/mm · (200ns)1/3 = 17 [Wu]
- Scmax ▪(tpP)1/3 < 5 MW/mm2 · (200ns)1/3

and

- ΔTmax(Hsmax, tp) < 50 K

- Depending on degree of our optimism a safety margin has to be applied.
- Varying RF constraints in the optimization how much money one can save by being optimistic.

Slides by A. Grudiev

Power flow equations

$$P = W v_g, \quad W = \frac{G^2}{(R/Q)\omega} \quad \Rightarrow$$

$$\frac{dP}{dz} = -\frac{W\omega}{Q} - G I = W \frac{d v_g}{dz} + v_g \frac{dW}{dz}$$

$$= \frac{G^2}{\omega R/Q} \frac{d v_g}{dz} + \frac{v_g}{\omega}\left[\frac{2G}{(R/Q)} \frac{dG}{dz} - \frac{G^2}{(R/Q)^2} \frac{d(R/Q)}{dz} \right]$$