Simulations and Plans for a Beam-Loading Compensation Experiment in CTF3

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Outline

- Introduction and Motivation
- Possible experiments in CTF3
- Simulation of RF power production
- Optimization of RF pulse shape
- Conclusions and further steps

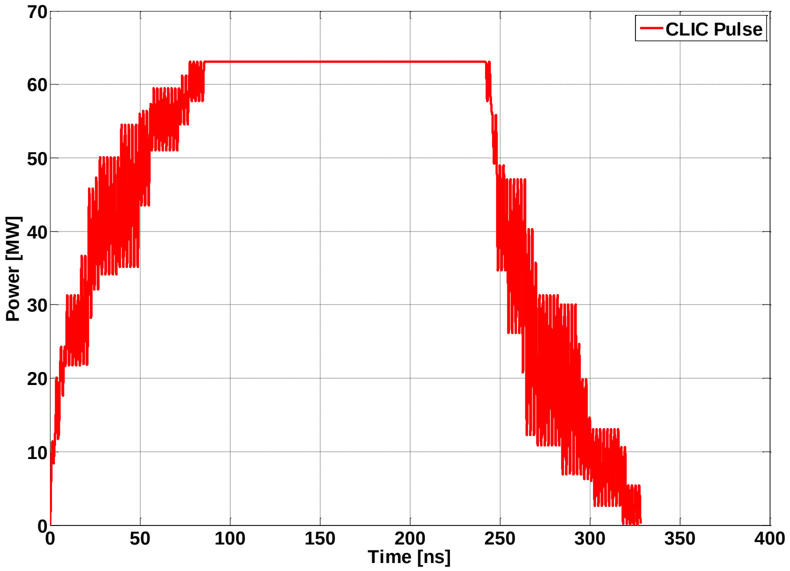
Introduction and Motivation

Beam-loading compensation is an important CLIC performance issue. In order to keep the luminosity losses less than 1% the rms of bunch to bunch relative energy spread must be below 0.03%

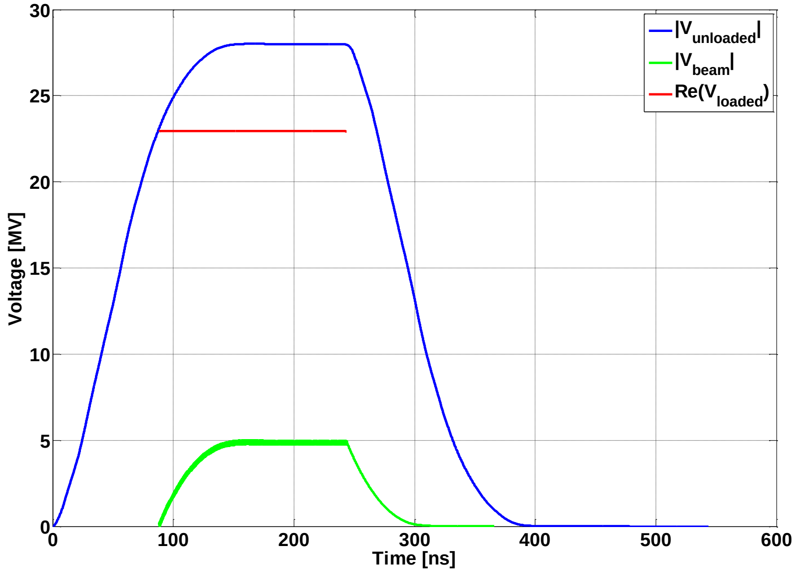
CLIC CDR, §2.5.8, http://project-clic-cdr.web.cern.ch/project-clic-cdr

Beam-Loading Compensation for CLIC

To compensate for a transient beam-loading in CLIC main linac a specially shaped ramped pulse is needed ensuring the CLIC requirement of 0.03% for the energy spread in main beam.



Optimized RF Power shape

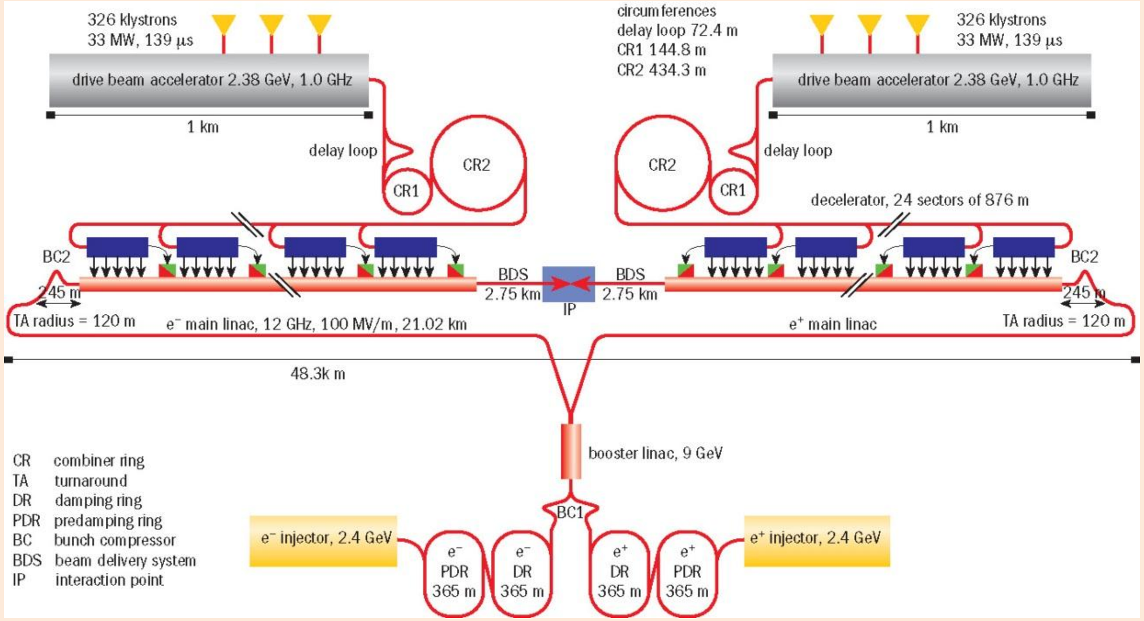


Unloaded/beam-induced/loaded voltages

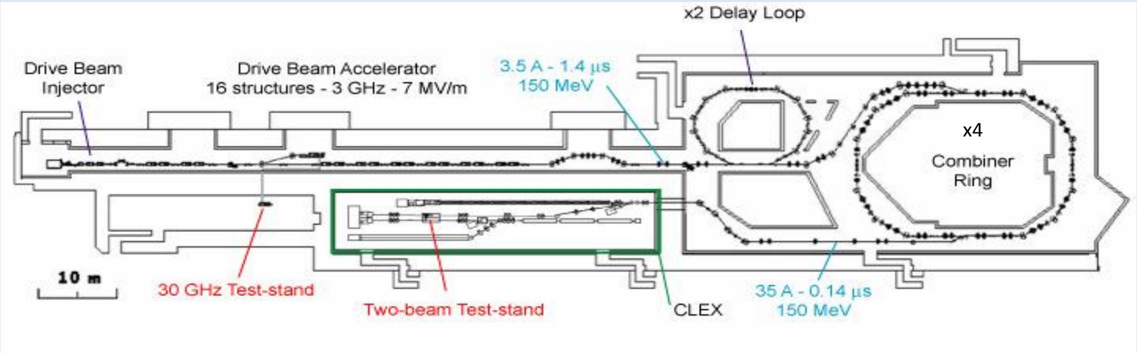
O. Kononenko and A. Grudiev, Transient beam-loading model and compensation in Compact Linear Collider main linac, Phys. Rev. ST Accel. Beams 14, 111001 (2011) http://prst-ab.aps.org/abstract/PRSTAB/v14/i11/e111001

CLIC vs CTF3: Layouts

CLIC Layout



CTF3 Layout



CLIC vs CTF3: Relevant Parameters

	CLIC	CTF3
	Drive Beam	
Delay loop	x2	x2
Combiner Ring #1	x3	x4
Combiner Ring #2	x4	-
PETS length	0.213 m	1 m
PETS power	63.1 MW	30-70 MW
Pulse length	244 ns	140-280 ns
	Main Beam	
Bunch Frequency	2 GHz	1.5 GHz
Number of Bunches	312	1-226
Bunch Charge	0.6 nC	0.1-0.6 nC
Injection Energy	2.424 GeV	177 MeV
Injection Energy Spread	1.3% (at linac injection)	<1% (from CALIFES)

CTF3 Experiments

Ultimate goal: optimize the RF power shape generated in PETS varying delays in the drive-beam buncher to minimize the energy spread in the accelerated probe beam

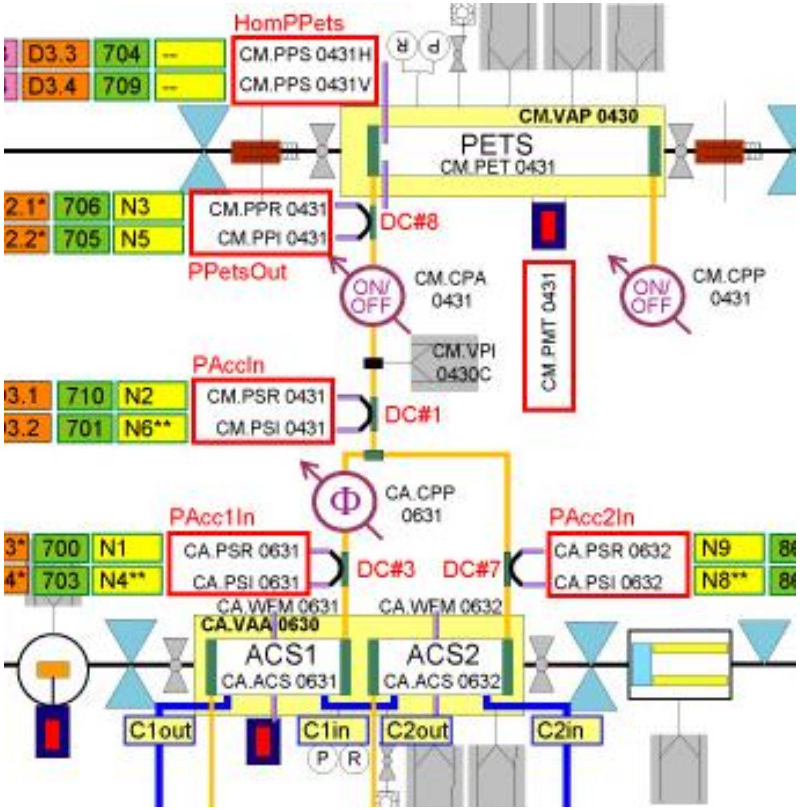
Not enough charge in probe beam to produce beam-loading effect comparable to CLIC, however we could **reduce the power and investigate the scaled phenomena**

CTF3 Experiments

Realistic experiment: produce an optimized RF pulse shape in PETS and take beam-loading into account numerically to calculate the energy spread

We can measure RF power generated in PETS as well as scan the voltage profile in AS with a very low charge probe beam

PETS and AS’s in TBTS

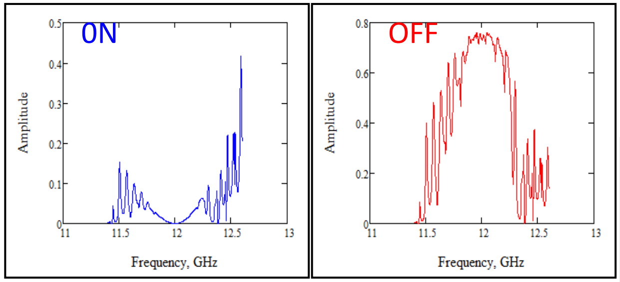


PETS and 2 AS’s as installed in TBTS
Roger Ruber, 14/09/2012

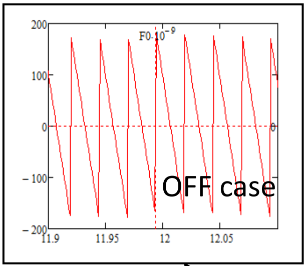
1m PETS and 2 TD24 accelerating structures are installed currently in TBTS. Recirculation is not used for the moment.

RF Generation in PETS

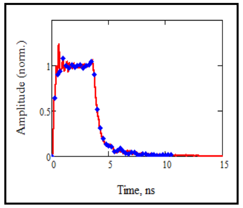
Measured transfer spectra of the recycling loop

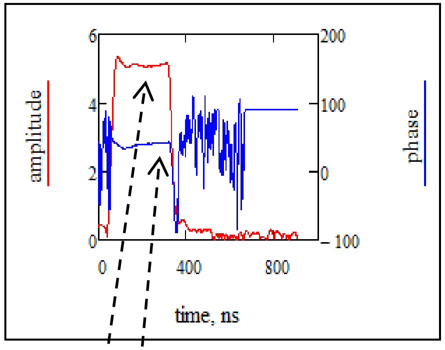


artificial RF
phase delay
for tuning



PETS single bunch
response (GDFIDL)



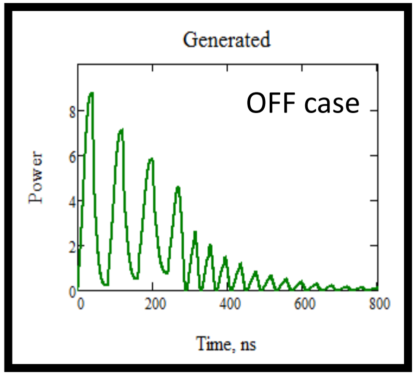


Number of
round trips

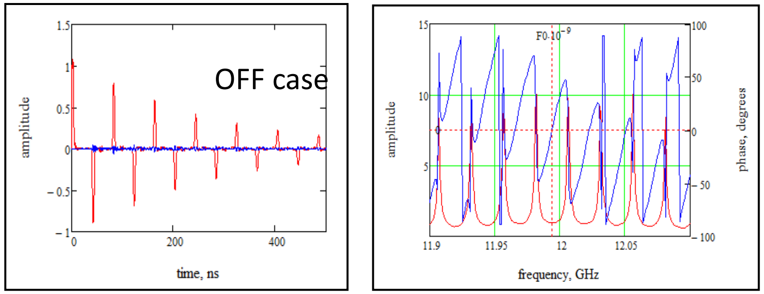
Number of
bunches

$$U(t) = FFt\left(FFw\left\{ \sum_{k=0}^{N_{rc}} FFt\left[S_{12}(\omega)^k \times e^{j\Delta\varphi} FFw(A_b(t)) \right] \right\} \times \sum_{n=0}^{N_b} a_n e^{jn\omega\times\Delta t_n} \right)$$

Multi-bunch
part



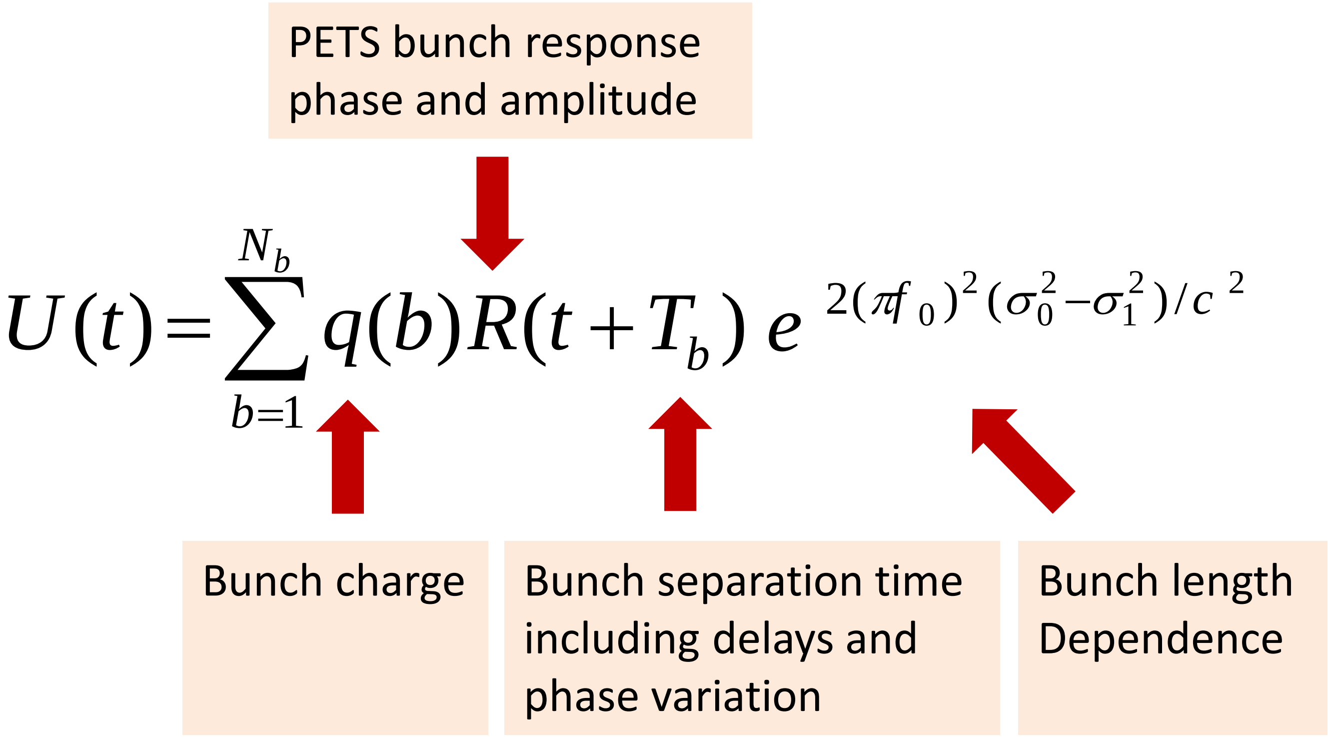
RESULT



The complete system single bunch response and spectrum

Igor Syratchev

RF Generation in PETS



PETS bunch response phase and amplitude

$$U(t)=\sum_{b=1}^{N_b} q(b)R(t+T_b)\,e^{\,2(\pi f_0)^2(\sigma_0^2-\sigma_1^2)/c^2}$$

Bunch charge

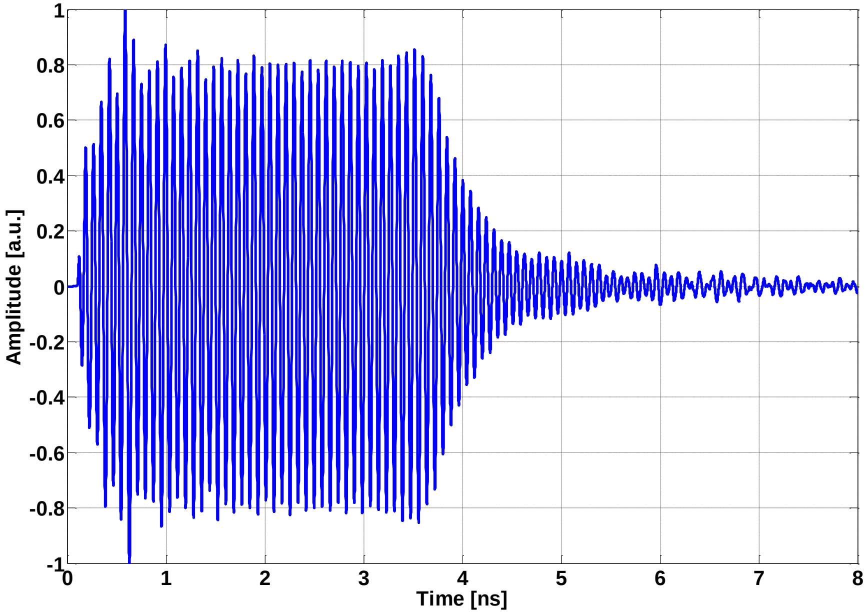
Bunch separation time including delays and phase variation

Bunch length Dependence

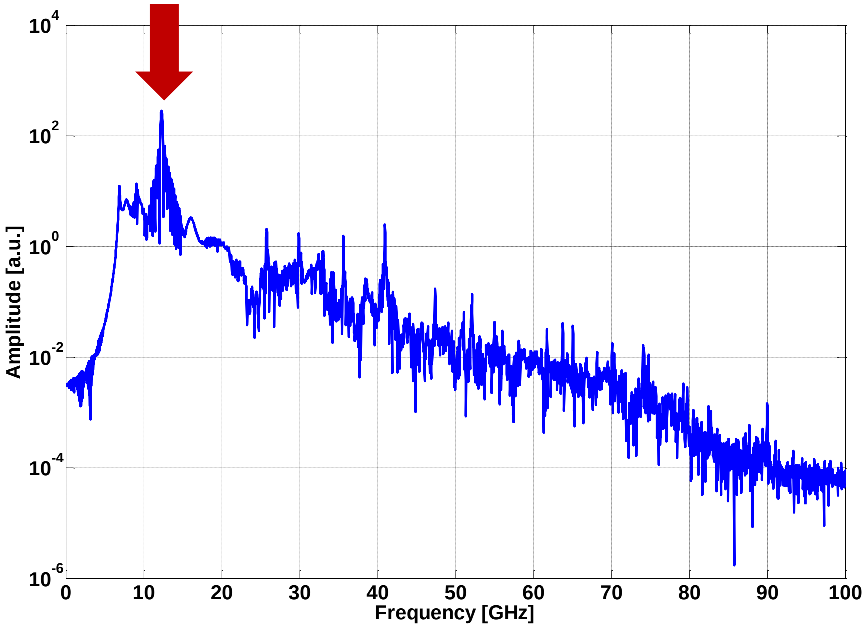
- charge variation
- phase variation
- bunch length variation
- no recirculation
- no on/off mechanism
- no artificial phase delay for tuning

PETS Bunch Response Simulation

Investigating the spectrum one can see that the operating frequency as calculated in GdfidL is higher than the design one, since the volume of the cubic mesh is smaller than the real PETS volume.



PETS bunch response


12.294 GHz

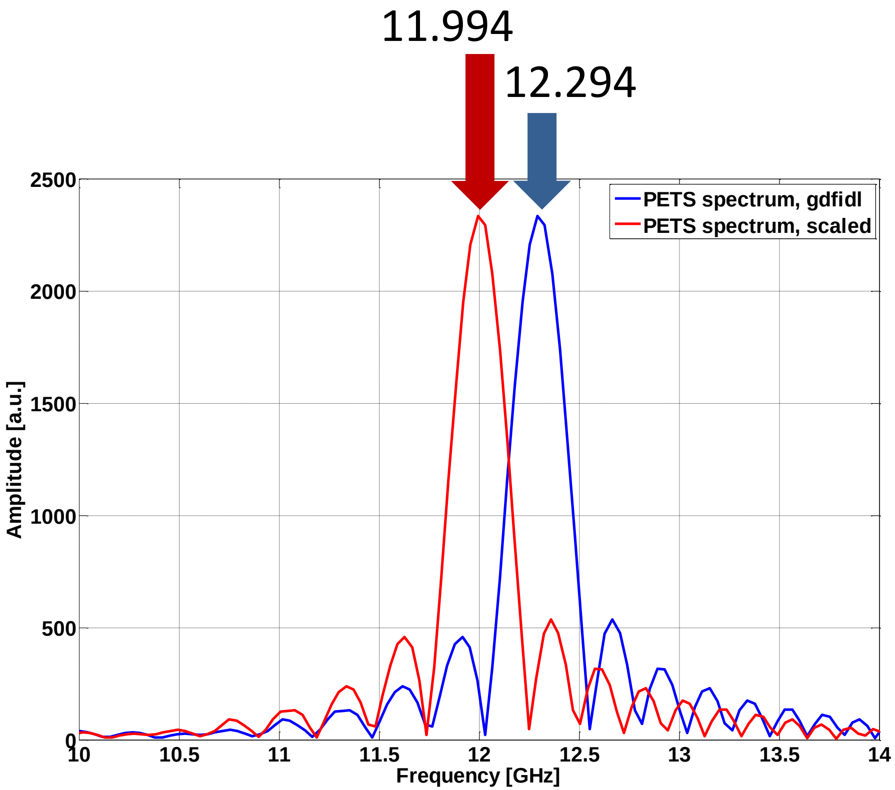
PETS bunch response spectrum

Igor Syratchev's simulation in GdfidL,
σ = 2mm

PETS Spectrum Scaling

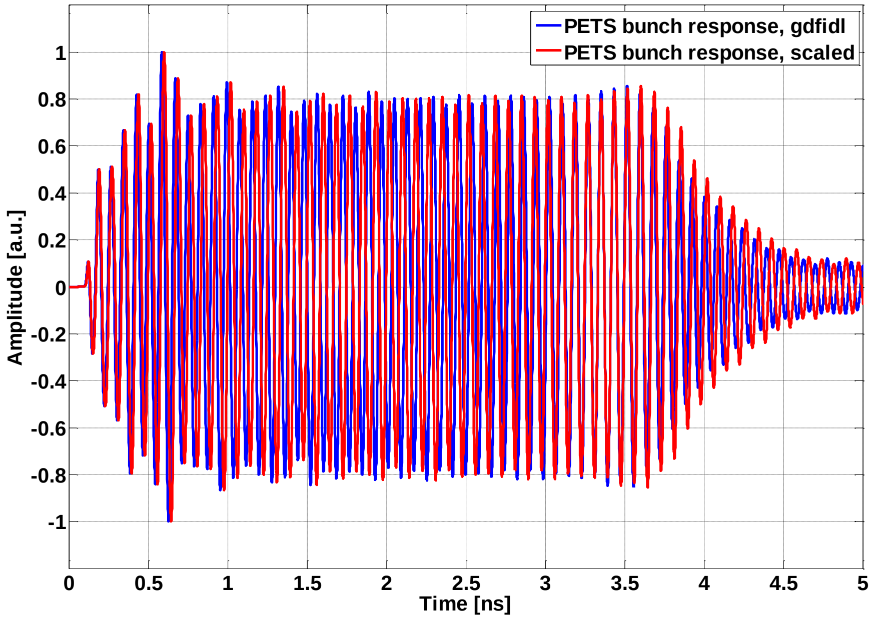
We scale the frequency range appropriately to overcome the GdfidL numerical effect:

$R_{GdfidL}(t) \rightarrow [\mathrm{fft}] \rightarrow R_{GdfidL}(f) \rightarrow [f\ \mathrm{scaling}] \rightarrow R_{scaled}(f) \rightarrow [\mathrm{ifft}] \rightarrow R_{scaled}(t)$


11.994

12.294

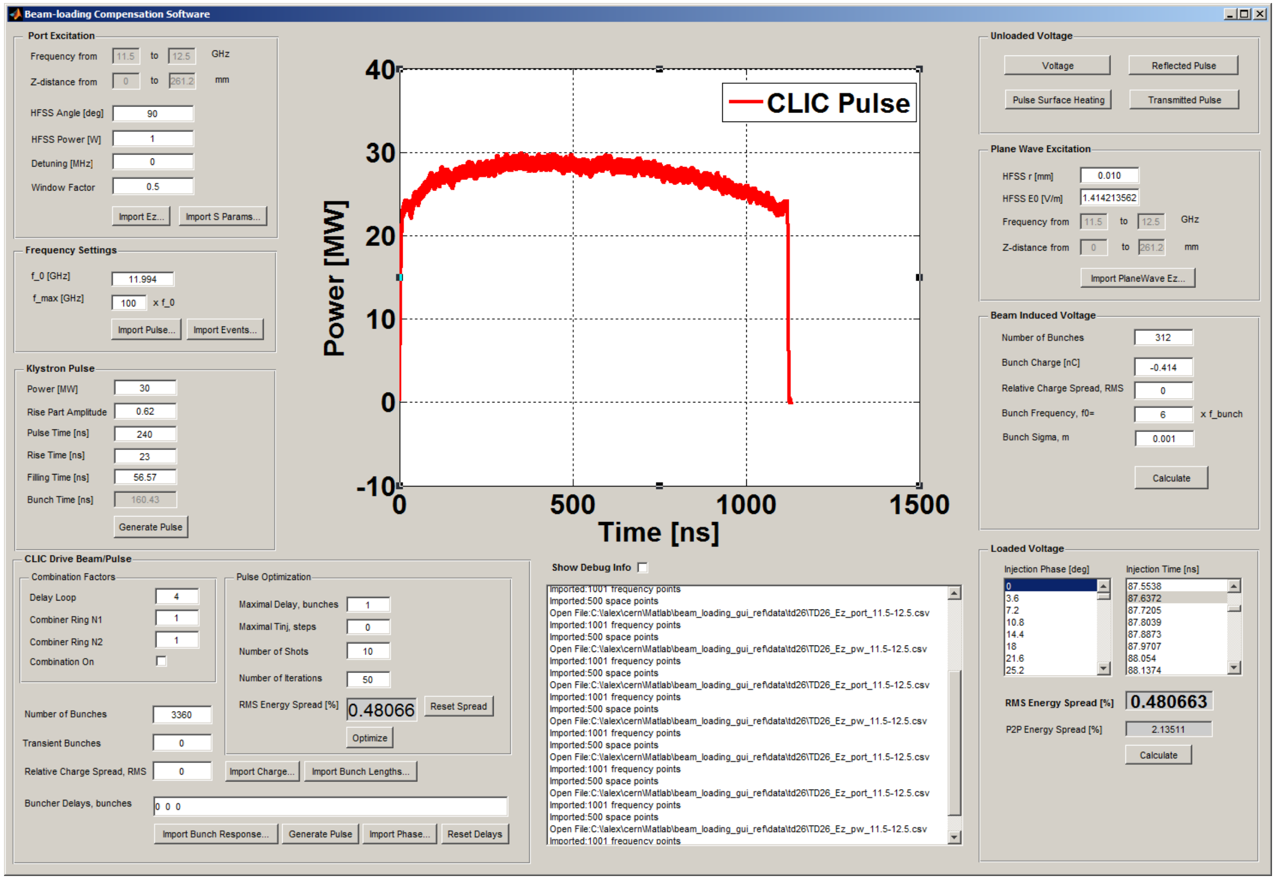
Scaled and simulated PETS spectrums



Scaled and simulated PETS bunch responses

Beam-Loading Simulation Tool

The tool has been originally developed for the CLIC RF pulse shape optimization (to compensate transient beam-loading) and now has been extended to cover CTF3.



Port Excitation

Frequency from 11.5 to 12.5 GHz

Z-distance from 0 to 261.2 mm

HFSS Angle [deg] 90

HFSS Power [W] 1

Detuning [MHz] 0

Window Factor 0.5

Frequency Settings

f_0 [GHz] 11.994

f_max [GHz] 100 x f_0

Klystron Pulse

Power [MW] 30

Rise Part Amplitude 0.62

Pulse Time [ns] 240

Rise Time [ns] 23

Filling Time [ns] 56.57

Bunch Time [ns] 160.43

CLIC Drive Beam/Pulse

Combination Factors

Delay Loop 4

Combiner Ring N1 1

Combiner Ring N2 1

Combination On ☐

Pulse Optimization

Maximal Delay, bunches 1

Maximal Tinj, steps 0

Number of Shots 10

Number of Iterations 50

RMS Energy Spread [%] 0.48066

Number of Bunches 3360

Transient Bunches 0

Relative Charge Spread, RMS 0

Buncher Delays, bunches 0 0 0

Show Debug Info ☐

```
Imported:1001 frequency points
Imported:500 space points
Open File:C:\alex\cern\Matlab\beam_loading_gui_ref\data\td26\TD26_Ez_port_11.5-12.5.csv
Imported:1001 frequency points
Imported:500 space points
Open File:C:\alex\cern\Matlab\beam_loading_gui_ref\data\td26\TD26_Ez_pw_11.5-12.5.csv
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Imported:1001 frequency points
Imported:500 space points
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Imported:1001 frequency points
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Open File:C:\alex\cern\Matlab\beam_loading_gui_ref\data\td26\TD26_Ez_pw_11.5-12.5.csv
Imported:1001 frequency points
```

Unloaded Voltage

Plane Wave Excitation

HFSS r [mm] 0.010

HFSS E0 [V/m] 1.414213562

Frequency from 11.5 to 12.5 GHz

Z-distance from 0 to 261.2 mm

Beam Induced Voltage

Number of Bunches 312

Bunch Charge [nC] -0.414

Relative Charge Spread, RMS 0

Bunch Frequency, f0= 6 x f_bunch

Bunch Sigma, m 0.001

Loaded Voltage

Injection Phase [deg]	Injection Time [ns]
0	87.5538
3.6	87.6372
7.2	87.7205
10.8	87.8039
14.4	87.8873
18	87.9707
21.6	88.054
25.2	88.1374

RMS Energy Spread [%] 0.480663

P2P Energy Spread [%] 2.13511

- combination schemes: with/without DL, CR1, CR2
- transient bunches during phase switch
- phase variation
- charge variation
- bunch length variation

Simulation of RF Power Production

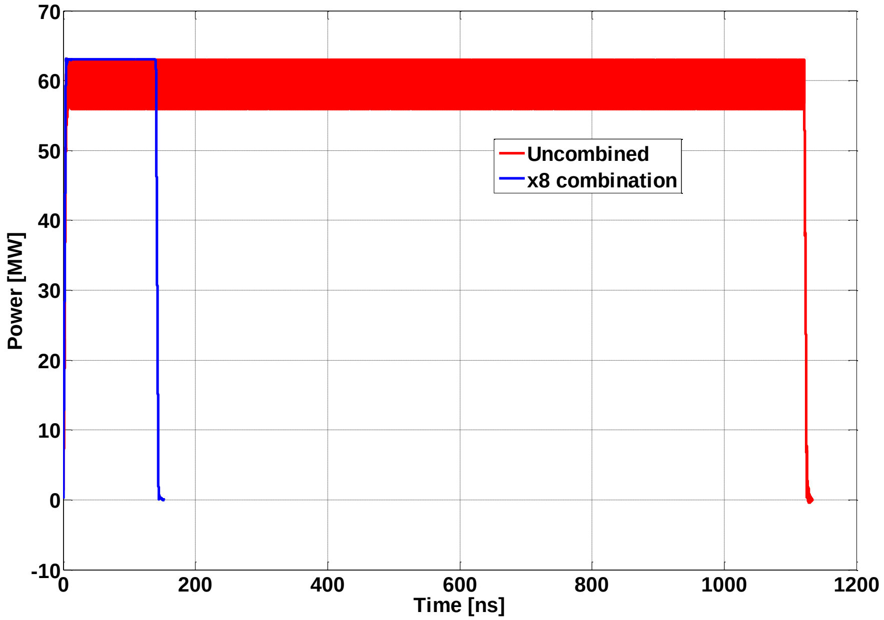
We're simulating power shapes for different drive beam profiles as well as taking phase, charge and bunch length variations into account. For these simulations we normalize the power to the CLIC power level of 63.1 MW.

Frequency, GHz	Combination Factor	Uncombined Pulse Length, μs	Combined Pulse Length, μs	Number of Bunches
1.5	-	1.12	1.12	1680
1.5	2x4	1.12	0.14	1680
3	-	1.12	1.12	3360
3	4	1.12	0.28	3360

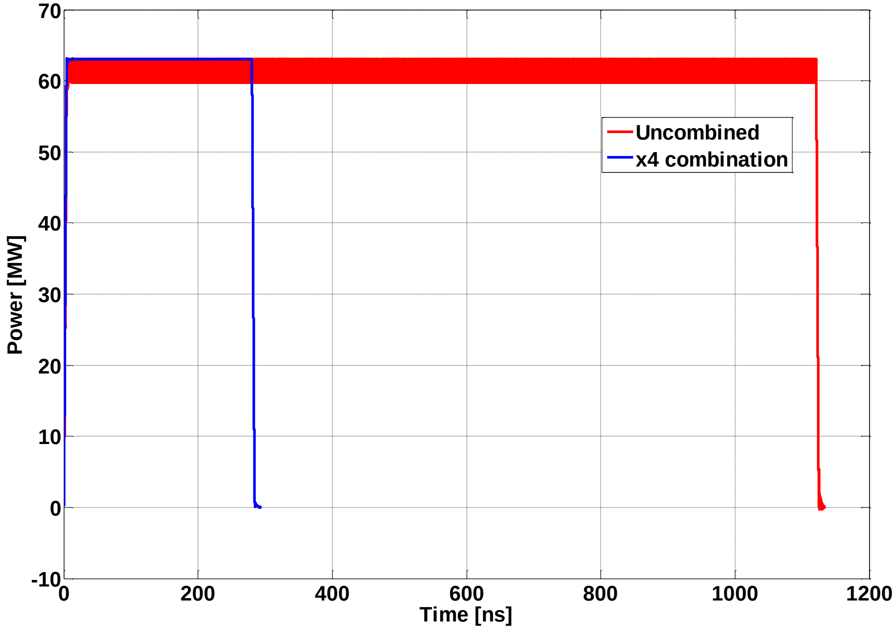
Combination schemes currently available in CTF3

Frequency Effect

Frequency, GHz	Combination	Phase variation	Charge variation	Bunch length variation
1.5/3	**x8/x4/No**	No	No	No



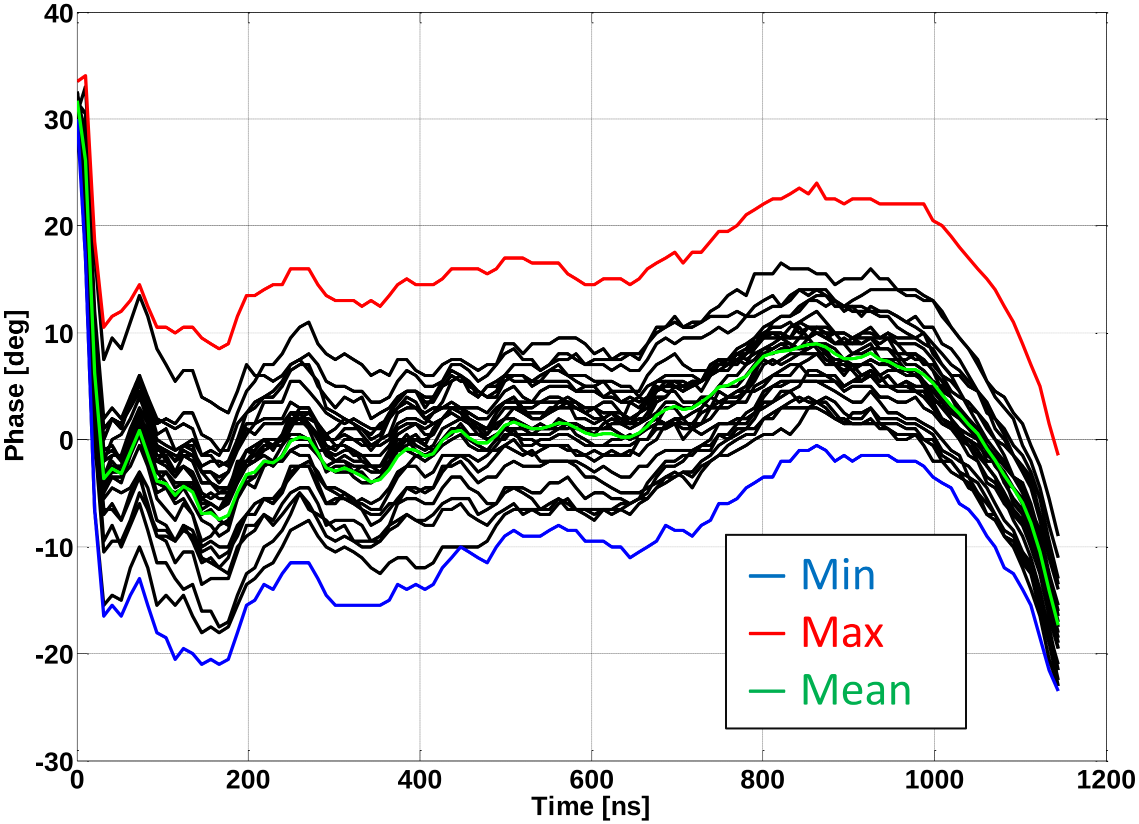
Power for 1.5 GHz drive beam



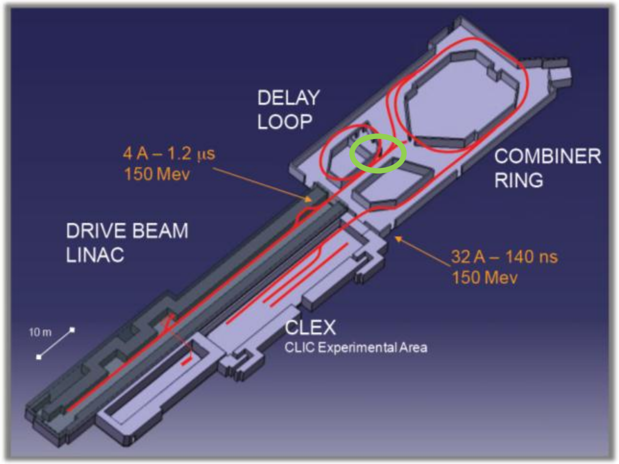
Power for 3 GHz drive beam

Drive Beam Phase Measurements

Drive beam phase variation measured by Emmanouil Ikarios on 19.09.2012 at **CT.STBPR0532S**, 10.4 ns time resolution, 1217 pulses.



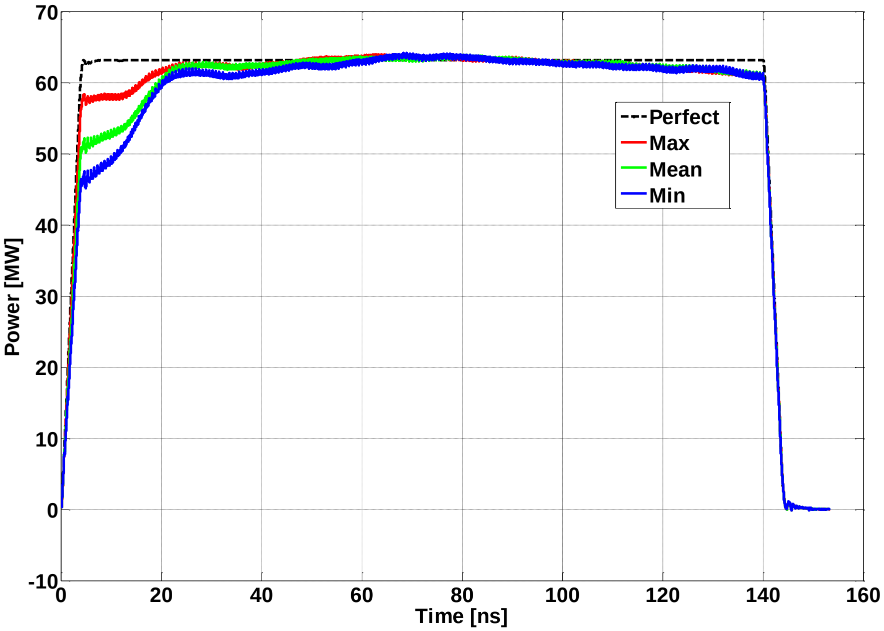
Phase variation along the drive beam @3 GHz



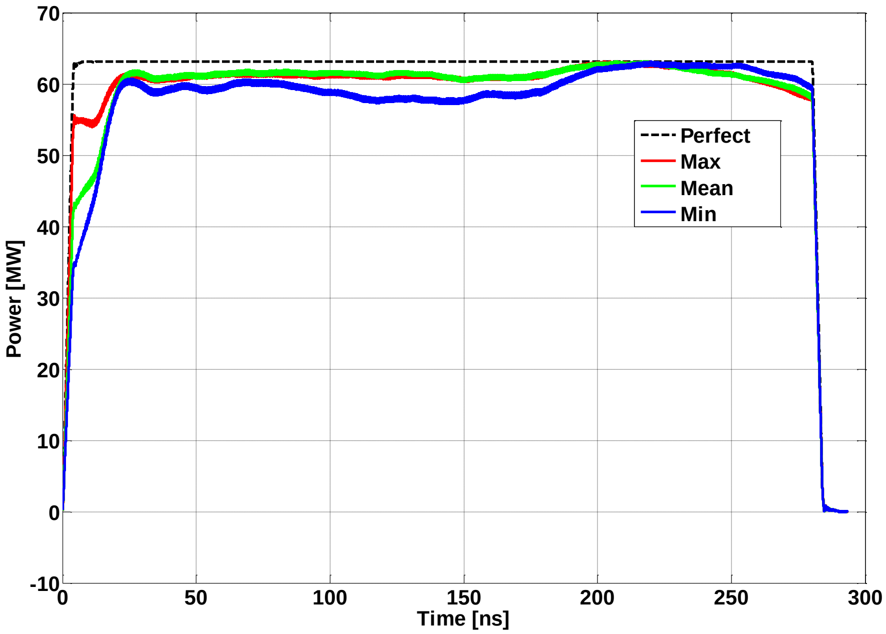
Position of CT.STBPR0532S in CTF3

Phase Variation Effect

Frequency, GHz	Combination	Phase variation	Charge variation	Bunch length variation
1.5/3	**x8/x4**	**Yes/No**	No	No



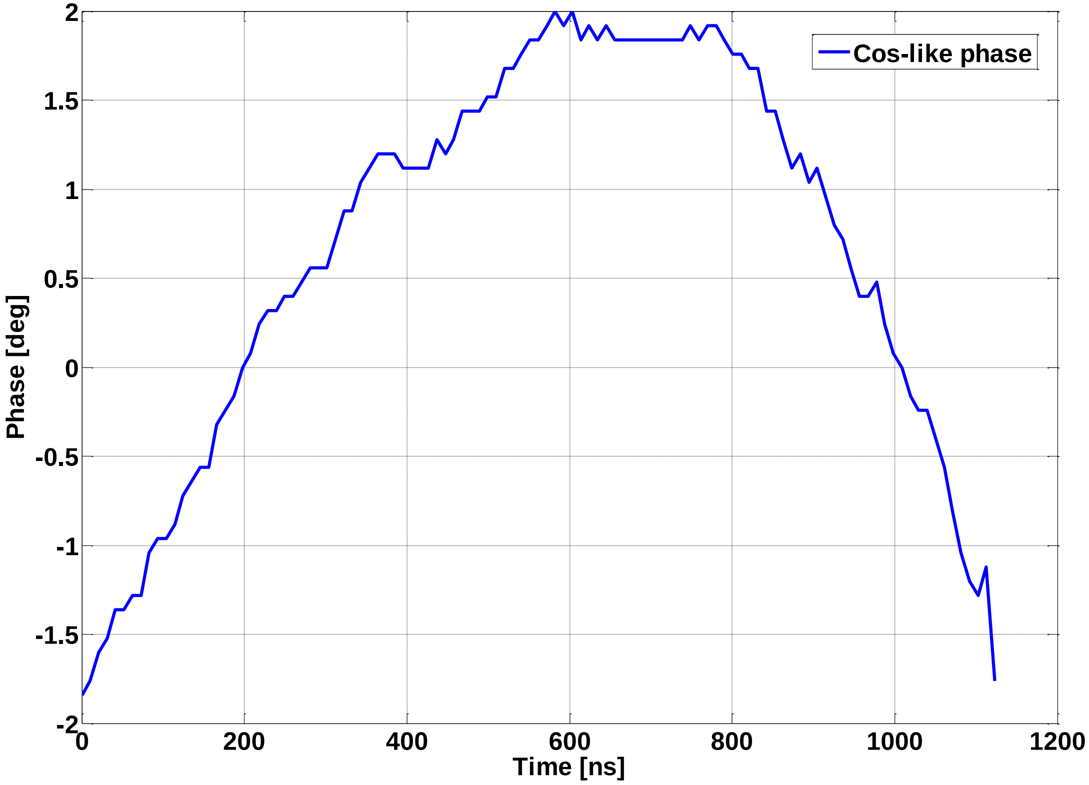
Power for 1.5 GHz x8 drive beam



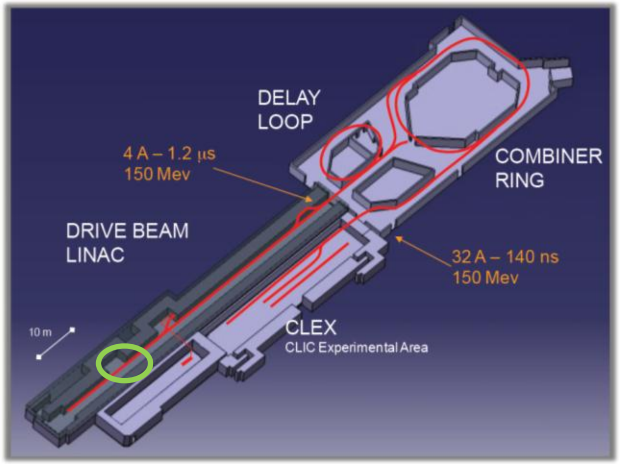
Power for 3 GHz x4 drive beam

Phase Measurements: Improved Phase

Improved phase variation measured by Frank Tecker on 09.10.2012 at **CL.STBPR0475S**, 10.4 time resolution



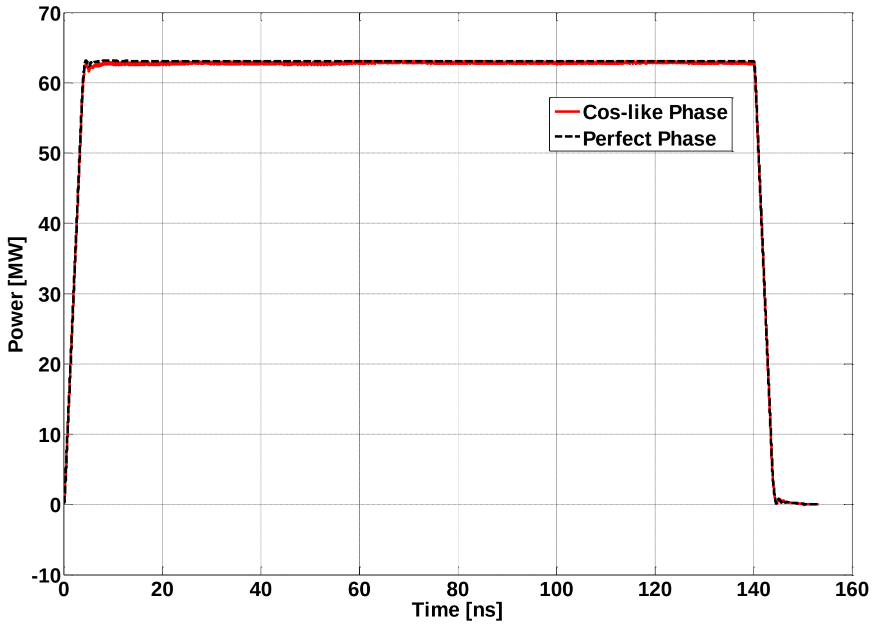
Phase variation along the drive beam @1.5 GHz



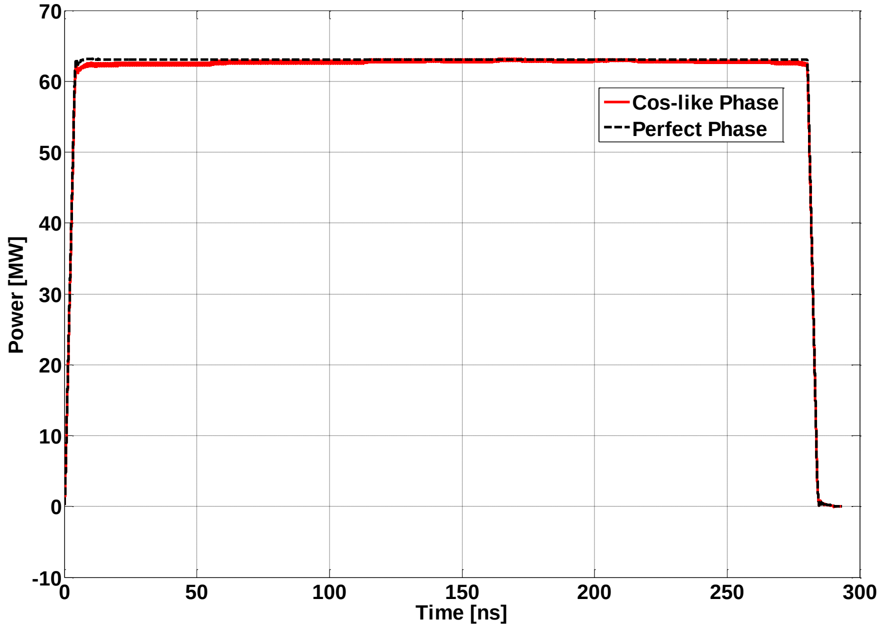
Position of CL.STBPR0475S in CTF3

Phase Variation Effect

Frequency, GHz	Combination	Phase variation	Charge variation	Bunch length variation
1.5/3	**x8/x4**	**Yes/No**	No	No



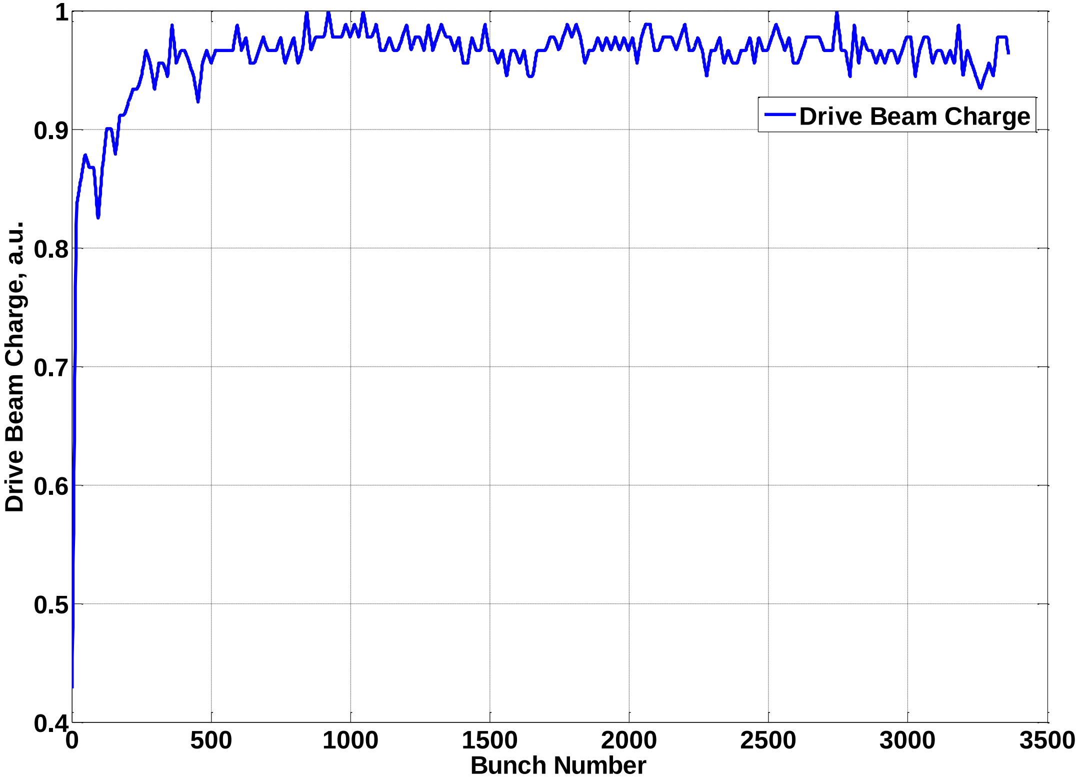
Power for 1.5 GHz x8 drive beam



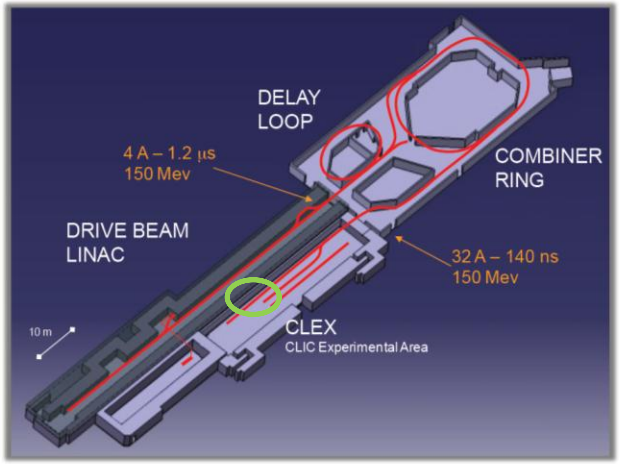
Power for 3 GHz x4 drive beam

Drive Beam Charge Measurements

Drive beam charge variation measured by Reidar Lunde Lillestol on 20.11.2012 at **SVBPM0150S** 5.2 ns time resolution, R56 = 0.2



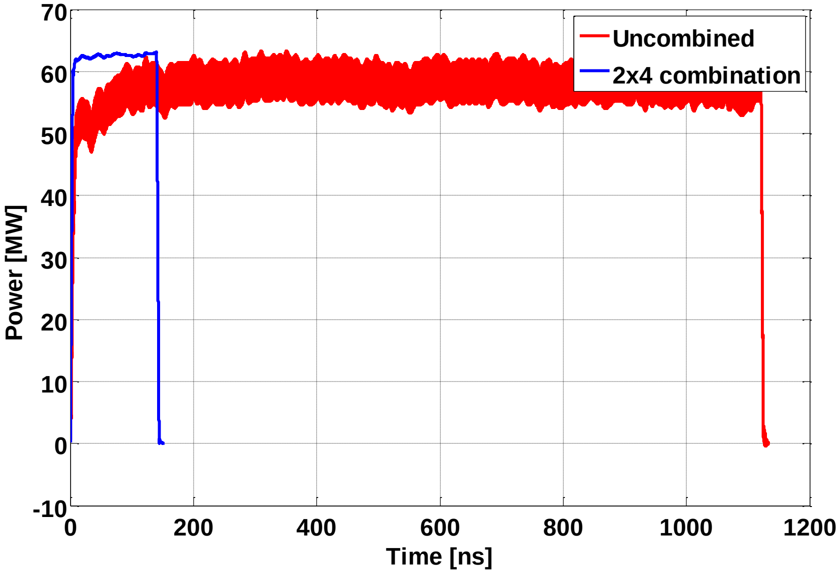
Charge variation along the uncombined drive beam @3 GHz



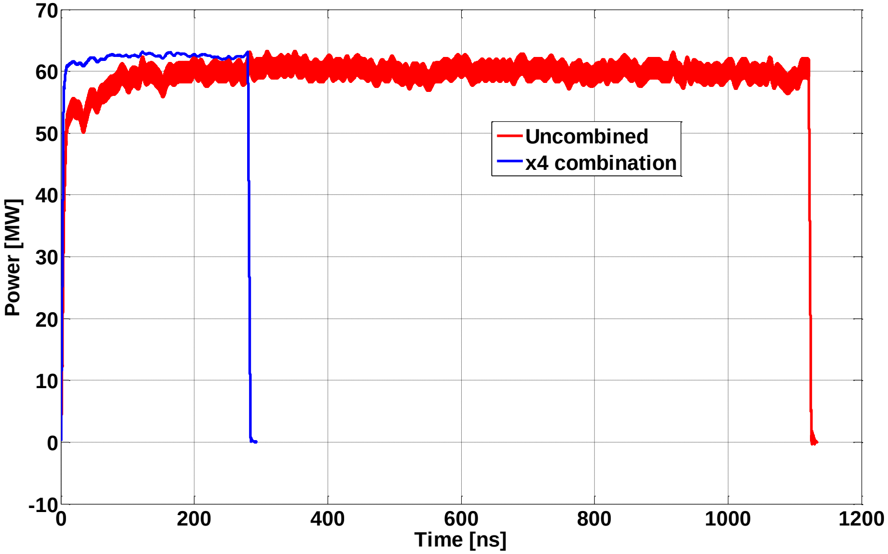
Position of SVBPM0150S in CTF3

Charge Variation Effect

Frequency, GHz	Combination	Phase variation	Charge variation	Bunch length variation
1.5/3	**x8/x4/No**	No	**Yes**	No

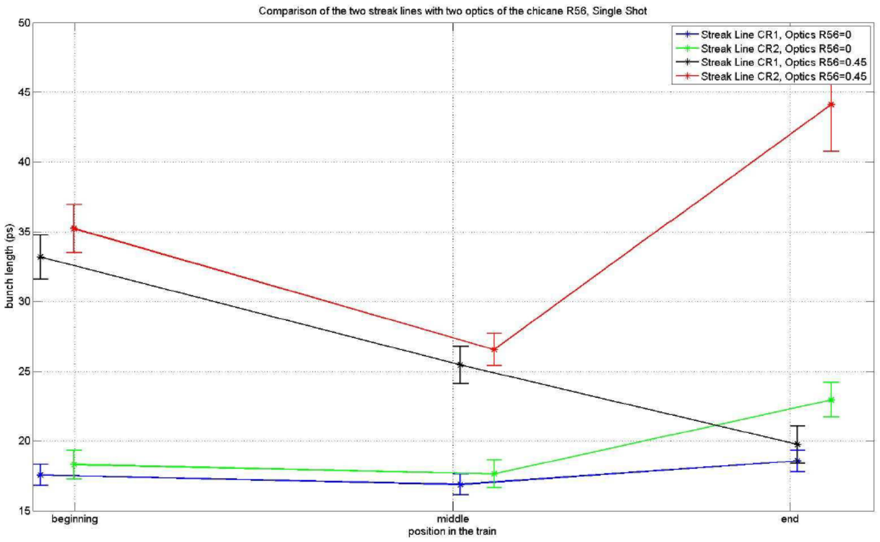


Power for 1.5 GHz drive beam

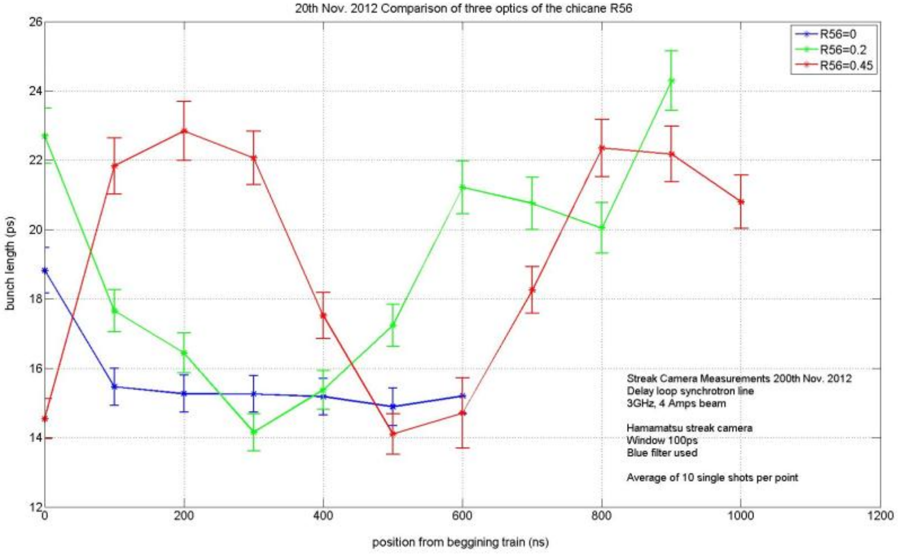


Power for 3 GHz drive beam

Bunch Length Measurements


Comparison of the two streak lines with two optics of the chicane R56, Single Shot

Javier Barranco Garcıa, “R56 and bunch length measurement”, https://indico.cern.ch/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=211350


20th Nov. 2012 Comparison of three optics of the chicane R56

Streak Camera Measurements 200th Nov. 2012
Delay loop synchrotron line
3GHz, 4 Amps beam

Hamamatsu streak camera
Window 100ps
Blue filter used

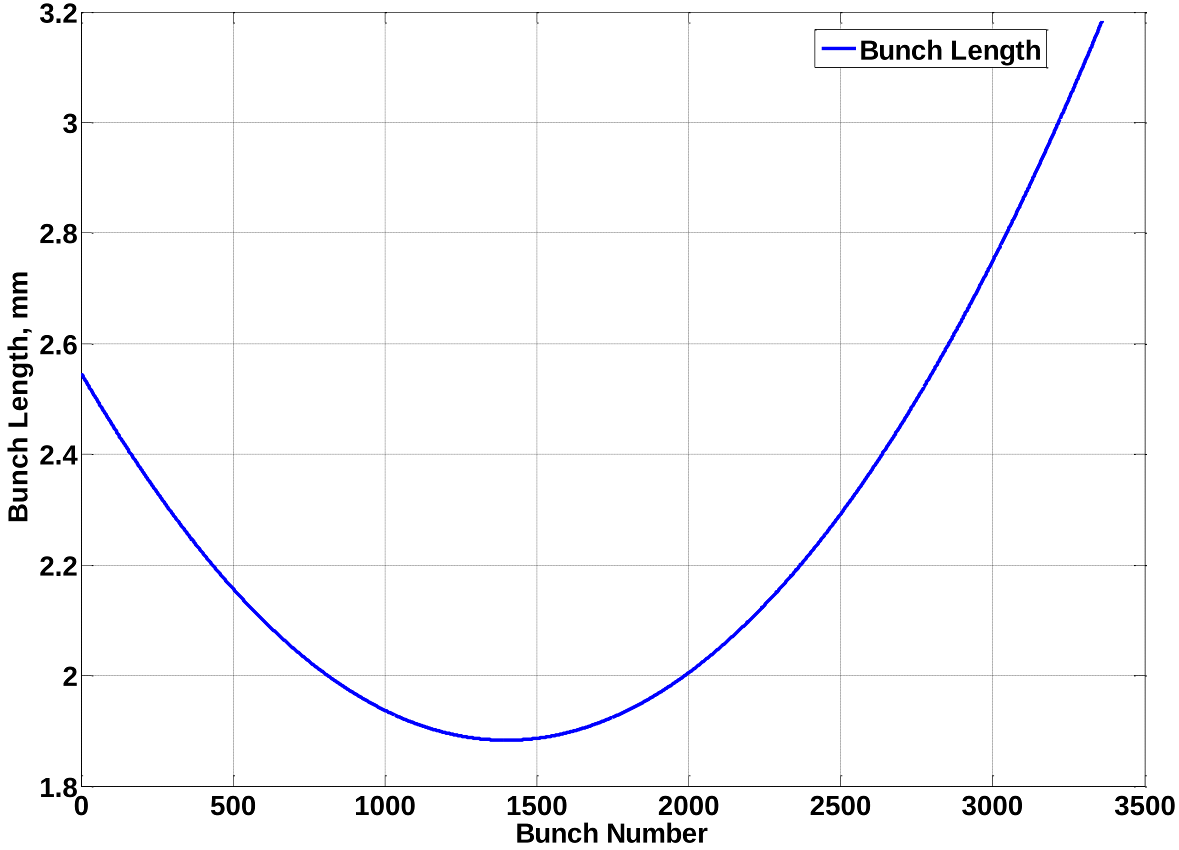
Average of 10 single shots per point

Bunch length measurements in CTF3, http://elogbook/eLogbook/eLogbook.jsp?shiftId=1049890

We also take into account that the measurements “length” is indeed FWHM, so we use the formula to convert to sigmas:

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\sigma \approx 2.3548200\,\sigma.$$

Fitted Bunch Length Variation

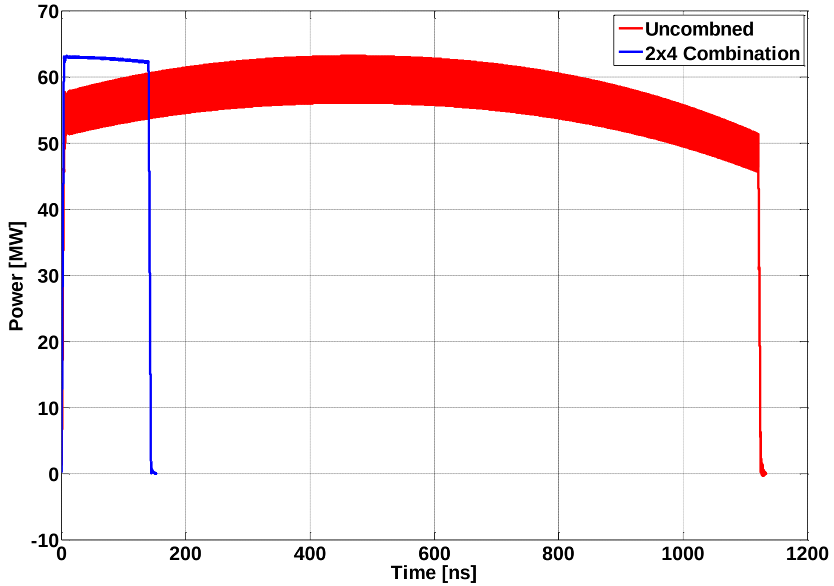


This corresponds to 20-15-25 ps lengths in time domain, @1.5 GHz

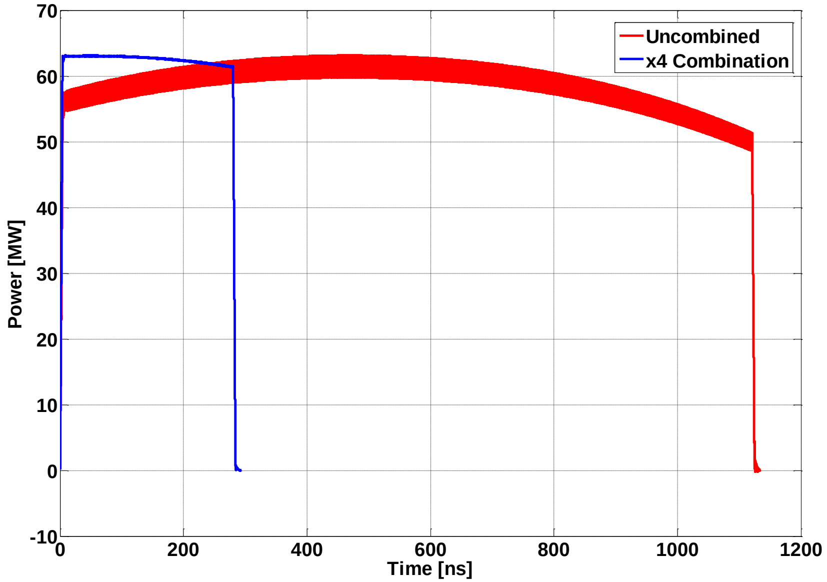
Fitted typical bunch length variation along the 3GHz drive beam

Bunch Length Effect

Frequency, GHz	Combination	Phase variation	Charge variation	Bunch length variation
1.5/3	**x8/x4/No**	No	No	**Yes**



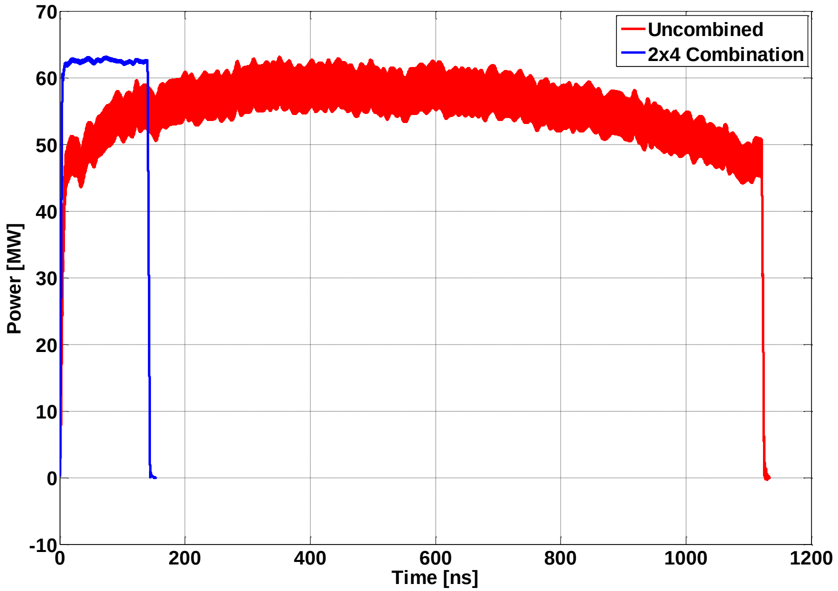
Power for 1.5 GHz drive beam



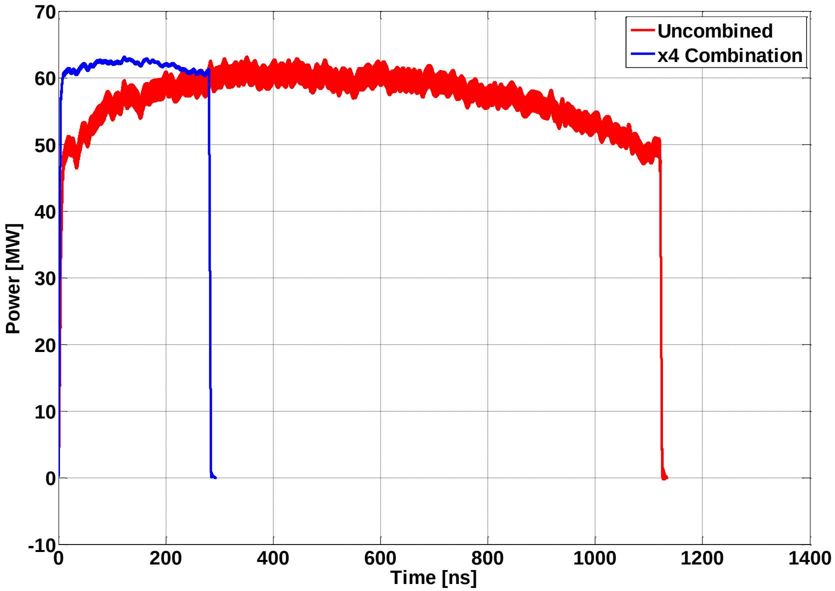
Power for 3 GHz drive beam

RF Power Production Simulation

Frequency, GHz	Combination	Phase variation	Charge variation	Bunch length variation
1.5/3	x8/x4/No	Yes	Yes	Yes



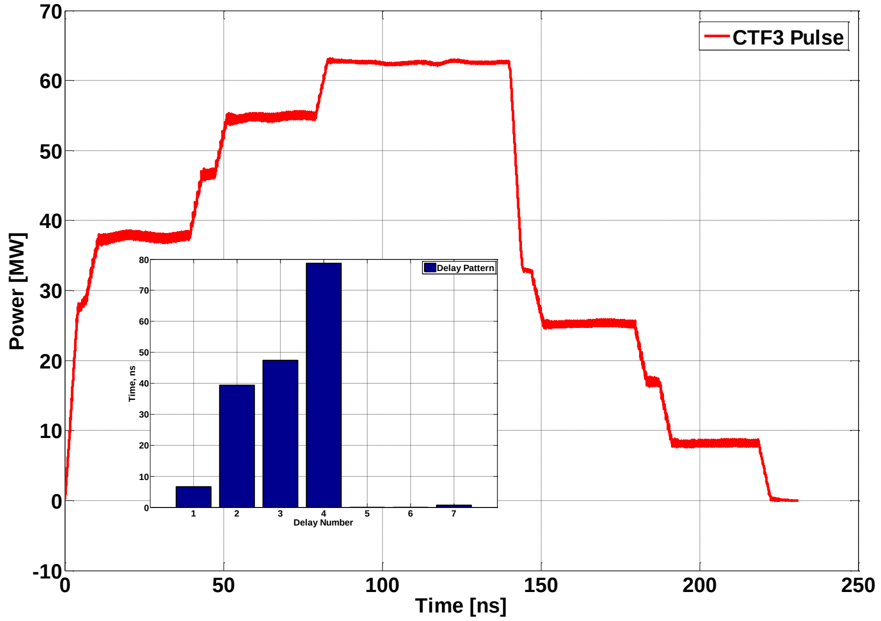
Power for 1.5 GHz drive beam



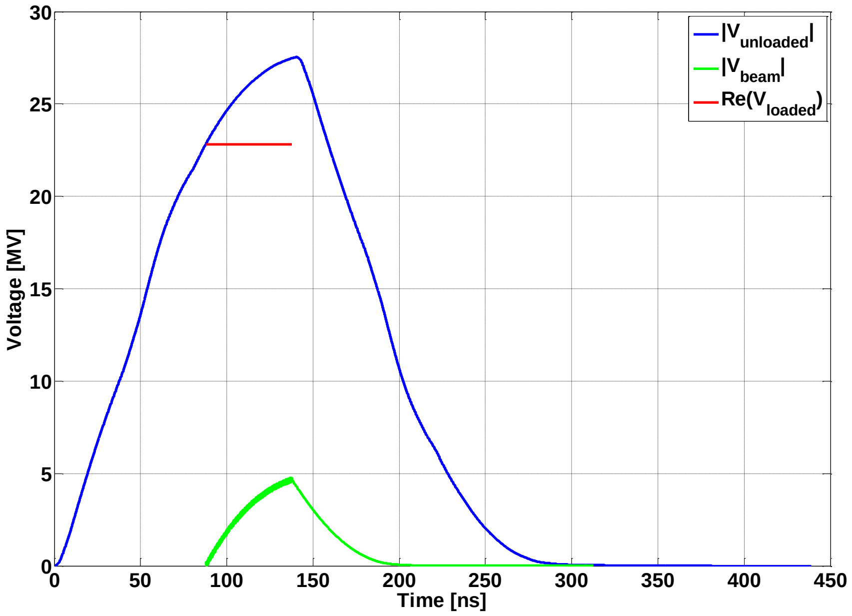
Power for 3 GHz drive beam

Optimized Power for 2x4 Combination

We consider 1.5 GHz beam and 2x4 combination, normalizing to the CLIC power level of 63.1 MW since in this case we can produce upto 70MW of power in CTF3. We do the optimization only for N_b = 100 in main beam, since the RF pulse is only 140ns.



RF Power shape optimized with 7 knobs

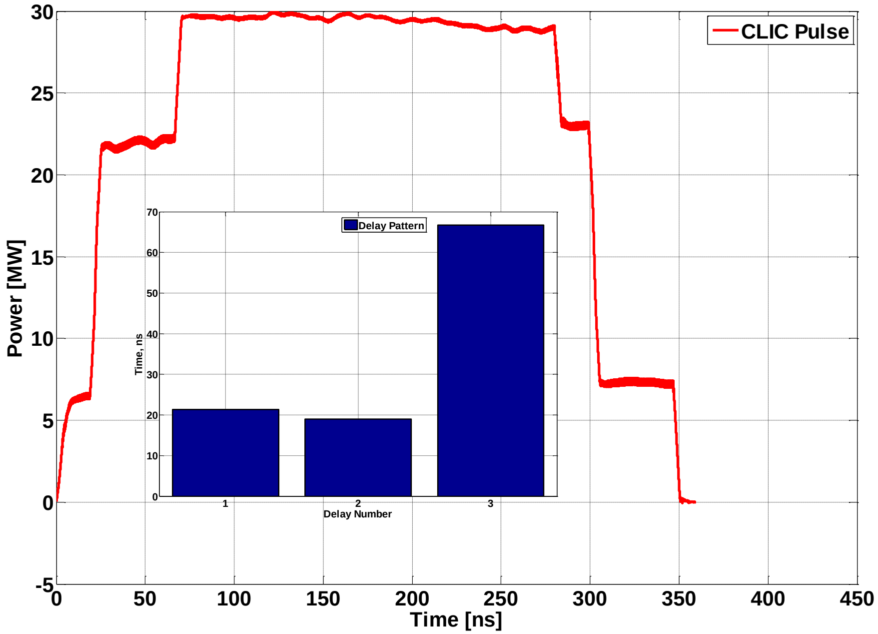


Unloaded/loaded/beam-induced voltages

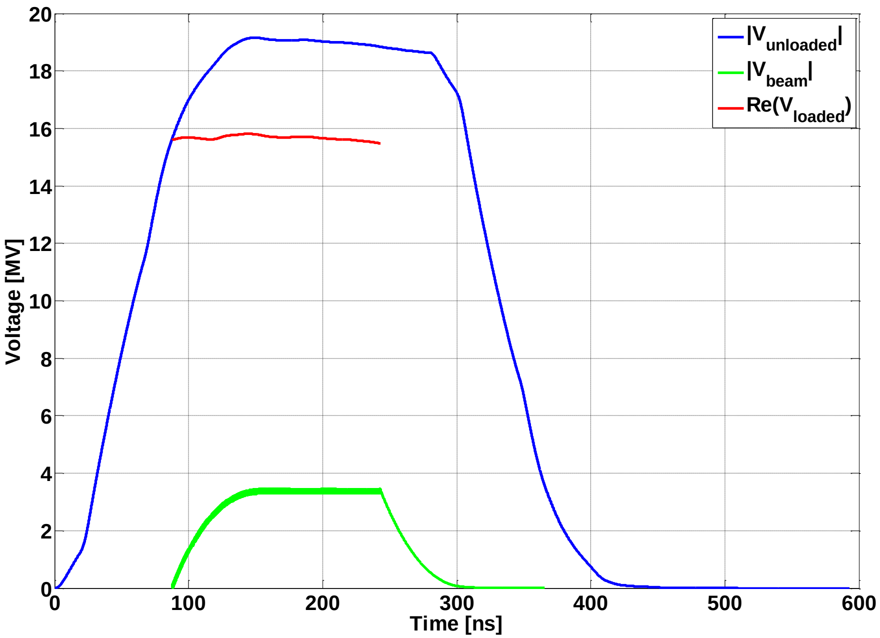
Energy spread = 0.02%, T_{inj} = 88.054 ns

Optimized Power for x4 Combination

We consider 3 GHz beam and x4 combination normalizing to 30 MW power level. We downscale the beam-loading to keep the $V_{unloaded}/V_{beam}$ ratio constant.



RF Power shape optimized with 3 knobs



Unloaded/loaded/beam-induced voltages

Energy spread = 0.48%, T_{inj} = 87.637 ns

Conclusions and Further Steps

- Variety of the performed RF power simulations illustrates that we need to take into account many measured drive-beam parameters and settings in order to predict the generated power correctly

- Pulse shape optimization results look reasonable and we could proceed with the measurements and comparisons

- Experiment is scheduled for the beginning of February 2013

Thank you for your attention!

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