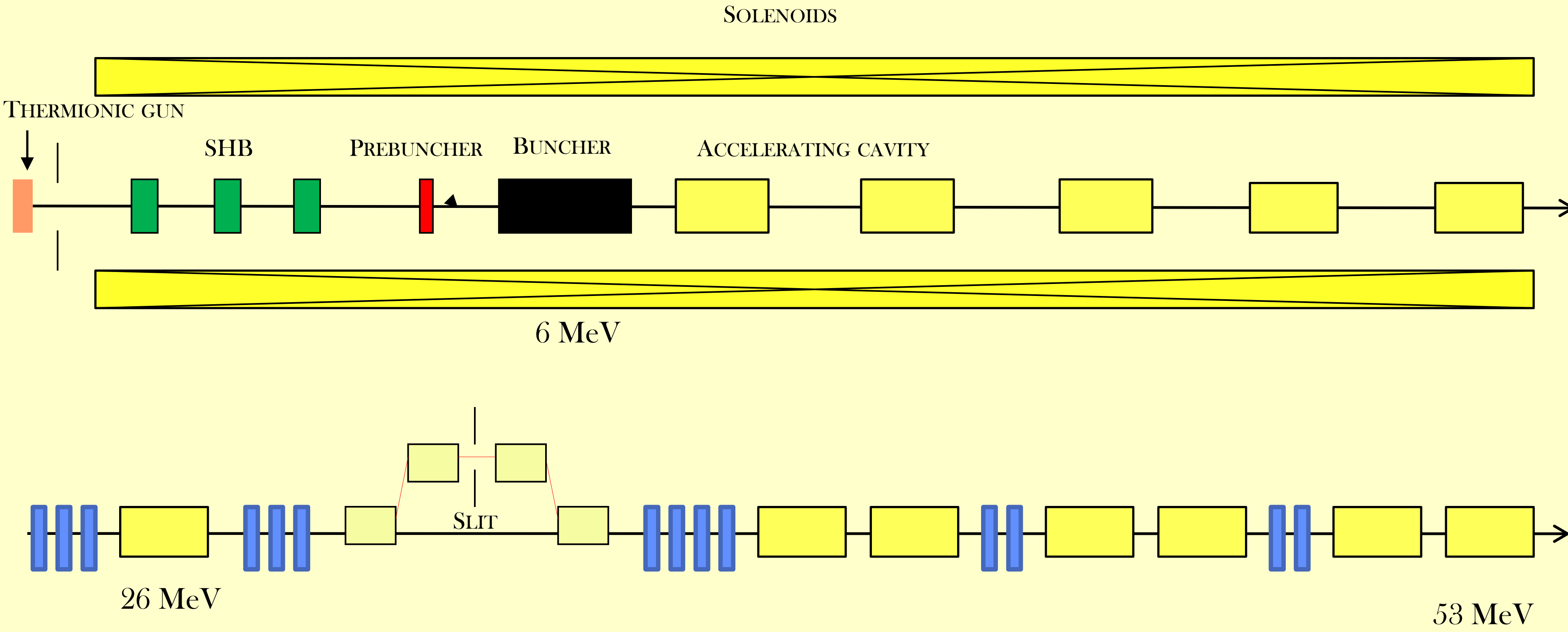
CLIC DB injector study

- Introduction
- Parameters and difficulties
- CLIC DB injector front end components status
- CLIC 0
- Conclusions

CLIC DB injector schematics



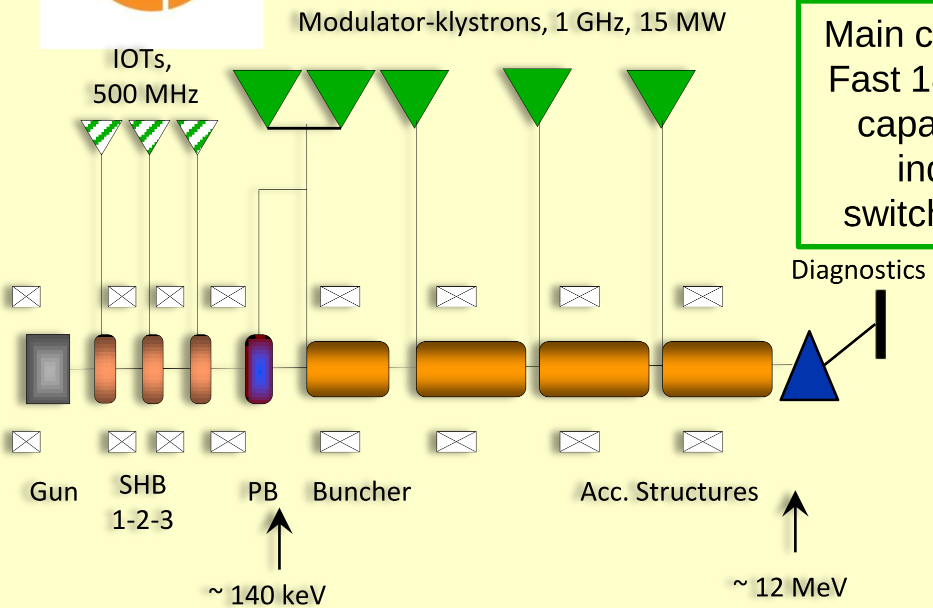
Documented in the CDR; a scaled version of CTF3

Simona Bettoni, Alessandro Vivoli

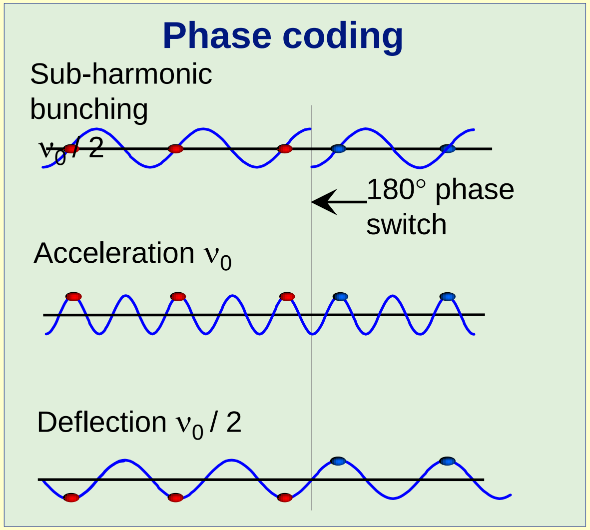
CLIC DB injector specifications and challenges

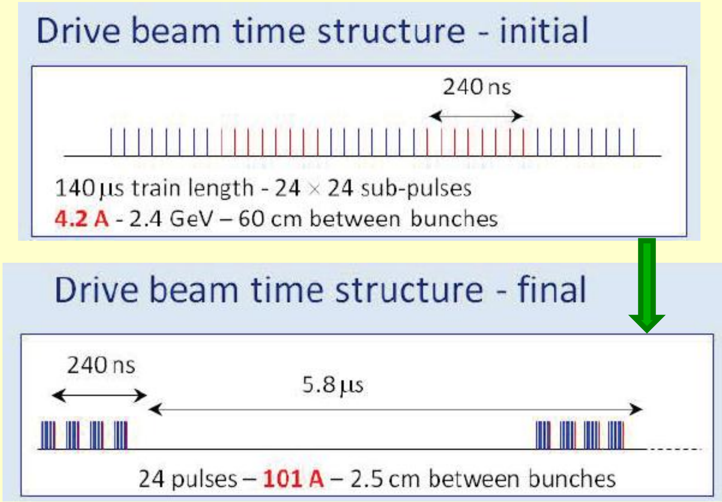
Parameter	Nominal value	Unit
Beam Energy	50	MeV
Pulse Length	**140.3** / 243.7	μs / ns
Beam current	4.2	A
Bunch charge	**8.4**	nC
Number of bunches	70128	
Total charge per pulse	**590**	μC
Bunch spacing	**1.992**	ns
Emittance at 50 MeV	100	mm mrad
Repetition rate	100	Hz
Energy spread at 50 MeV	1	% FWHM
Bunch length at 50 MeV	3	mm rms
Charge variation shot to shot	**0.1**	%
Charge flatness on flat top	**0.1**	%
Allowed satellite charge	< 7	%
Allowed switching time	5	ns

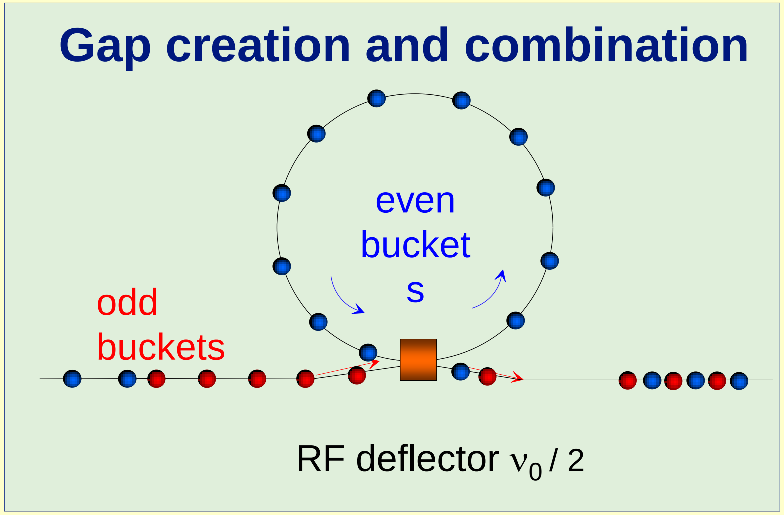
Sub Harmonic Bunchers (SHBs)



Main challenge of SHBs: Fast 180° phase flipping capability, simulation indicate < 18 ns switching time needed

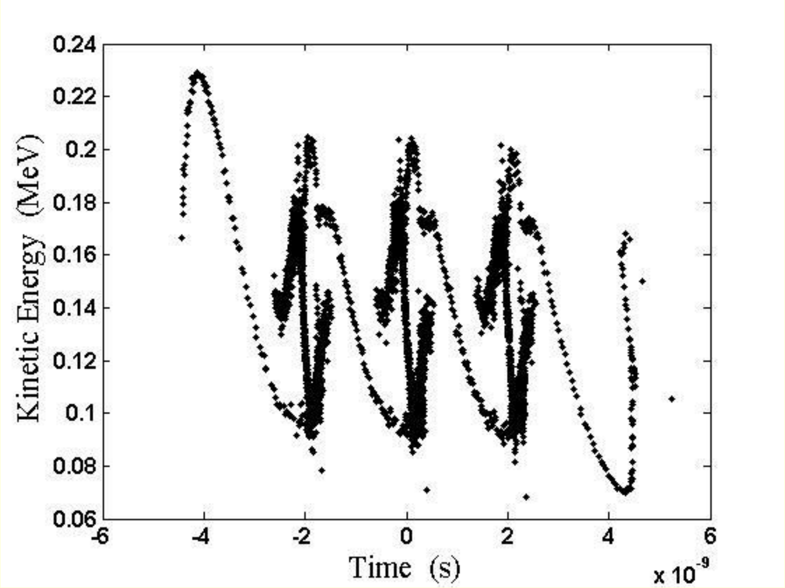


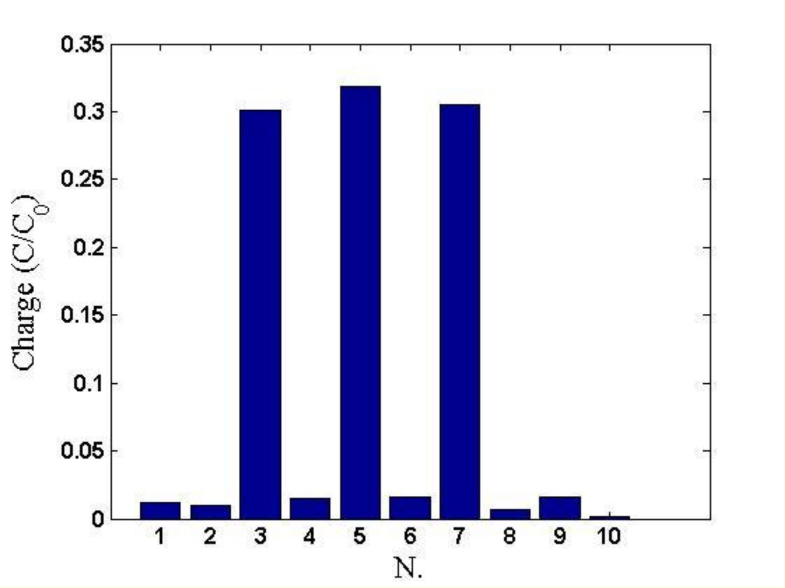




Hamed Shaker

Simulation results





Longitudinal phase space after sub-harmonic bunching
Same total gap-voltage but fewer cells (2 instead of 6)
35-39 KV needed

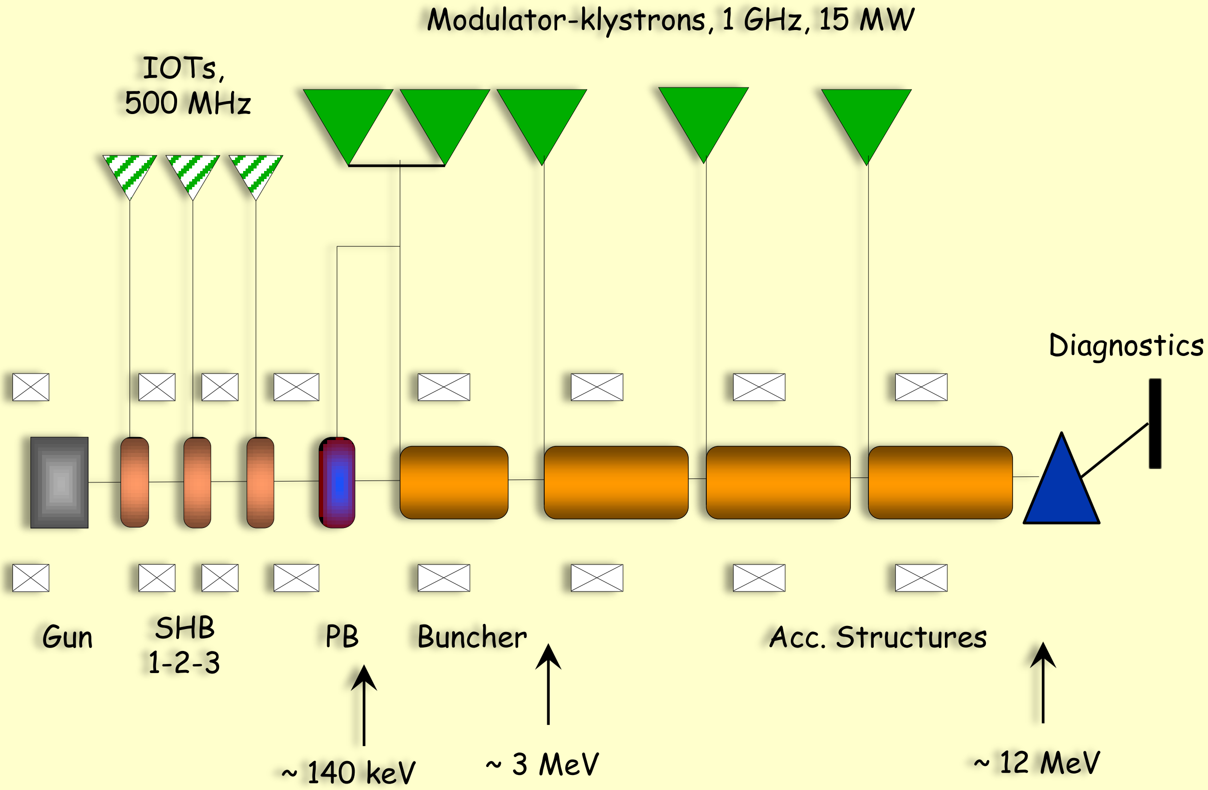
Simulation results

Parameter	Unit	Simulations	CLIC
Energy	MeV	53.2	
Bunch charge	nC	8.16	8.4
Bunch length (rms)	mm	2.83	3 (@ 50 MeV)
Energy spread (rms)	MeV	0.45 (@53 MeV)	< 0.50 (@ 50 MeV)
Horizontal normalized emittance (rms)	µm rad	32.9	≤ 100
Vertical normalized emittance (rms)	µm rad	28.7	≤ 100
Satellites population	%	4.9	As small as possible

- Specifications can be fulfilled but still high satellite population and high losses in cleaning chicane
- Some ideas to improve the satellites and total losses
- Beam loading and wake field effects to be studied

- Some inconsistencies due to a lack of realistic rf-parameters (simulations have to be redone with new parameters)

CLIC DB front end, Post CDR Project



Gun, sub-harmonic bunching, bunching, three accelerating structures, 5 long pulse klystrons and modulators, diagnostics

What do we plan to do until 2016

Optimistic and rough planning

Task	2012	2013	2014	2015	2016
Space needed		prepare gun test facility	prepare Klystron test sand	prepare injectot building	injector building
Gun	conceptunal design	design and construction	GUN test facility	GUN test facility	
SHB Buncher	design	fabrication	testing		
500 MHz power source	specification	purchase	testing		
Buncher	specification	design and purchase	reception, low power test	high power test	
1 GHz structure	specification	design and purchase	reception	low power test	high power test
Diagnostis	specification, purchase		IC in gun test		
LLRF		specification	fabrication+test	ready for klystron test	
1 GHz klystrons	tender	design at manufacturer	fabrication of prototype	Receive Klystron 1	Klystron 2
1 GHz Modulator	tender	R&D	R&D	Receive first MDK	MDK2
Injector integration, vacuum, controls, magnets, diagnostics	on hold	on hold	design		

Create a gun test facility to test the source
and a high power test stand to test the klystron, modulator and rf structures

Gun options

1. CTF3 type gridded gun with a HV modulator,
   Modulator stability, grid survival, several SHB needed, can be purchased

2. Modulated anode gun, needs new design and simulation, Can't be bought of the shelf, not sure if modulation fulfills requirements

3. RF modulated grid,
   IOT-type gun, very attractive but needs tests and simulation, dark current issue, emittance ?, reliability, can be purchased, no SHB, no satellites, likely R&D needed

   RF Modulate classical gun, typical pulse length 1 ns, could have very low satellites, can this deliver enough current, space charge problems

Sub-harmonic bunching system

Status:
RF design existing, ready to start mechanical design and launch prototype or cold model

Power source:
500 MHz, ~100 kW, wide band (70 MHz) sources needed for fast phase switching. Started to discuss with industry.

Candidates: IOT, frequency and power available, bandwidth to be seen
tests are planned with an 800 MHz IOT for SPS

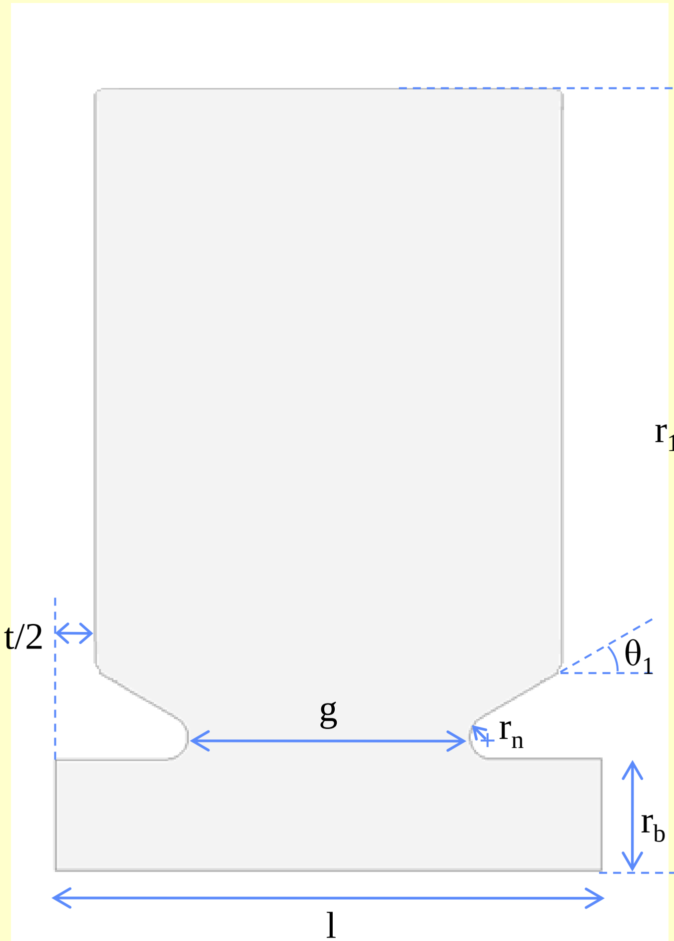
Solid state amplifier, bandwidth, power, cost ?

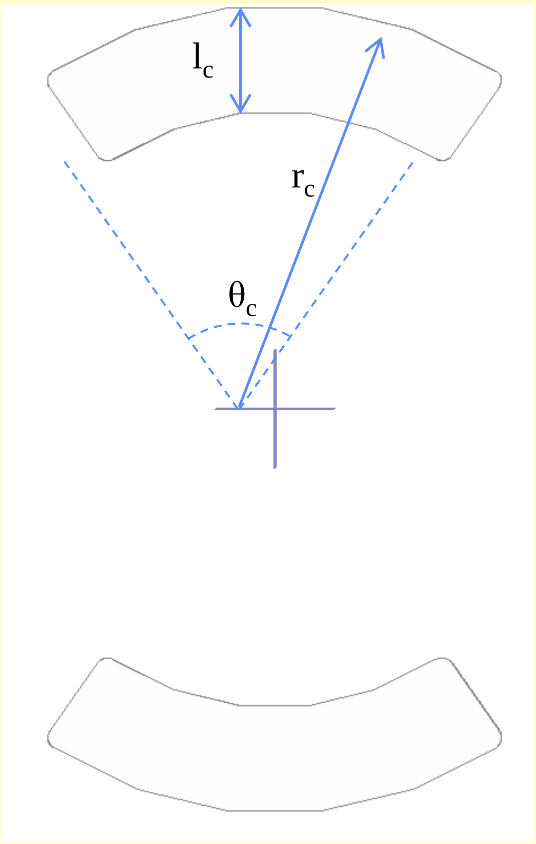
RF design of 1 GHz pre-buncher and travelling wave buncher existing

Magnetic coupling TW structure

For the known gap voltage and filling time our goal is to increase **R/Q** to reduce the input power.

τ=10ns
V=36.5 KV





g	40 mm
r_b	45 mm
r_n	4 mm
θ_1	25°
t (disk thickness)	15 mm
Frequency	499.75 MHz
l (for 108° phase advance per cell)	≈115.18 mm
r_1	161.55 mm
r_c	142 mm
l_c	54 mm
θ_c	86°
Phase velocity	0.64c

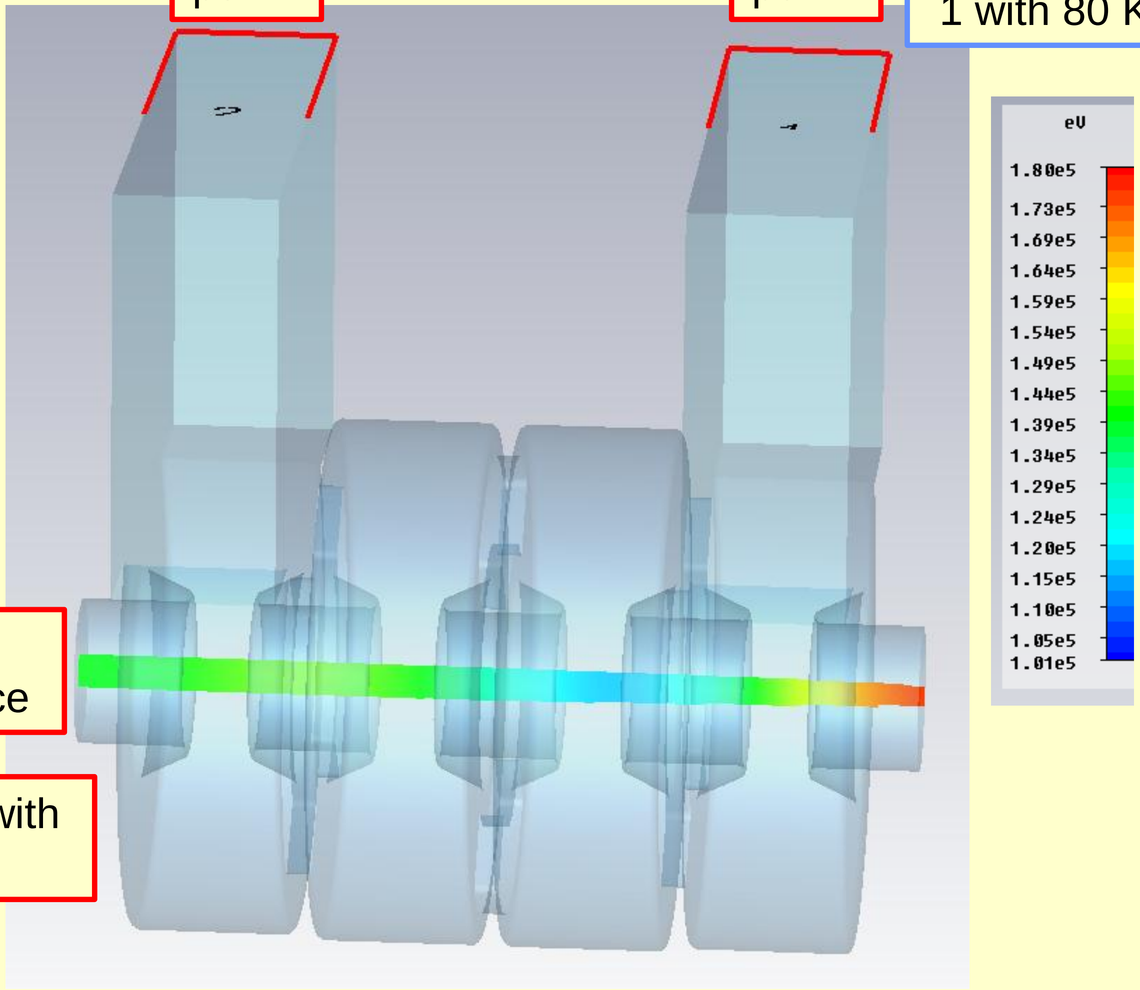
$$\frac{R'}{Q}=\frac{(\frac{V}{L})^2}{\omega W'}=\frac{(\frac{V}{L})^2}{\omega\frac{P}{v_g}}\Rightarrow\frac{R}{Q}=\frac{V^2}{\omega P\frac{L}{v_g}}\Rightarrow P=\frac{V^2}{\omega\tau\frac{R}{Q}}$$

Phase flipping simulation with beam – 10 ns

port 2

port 1

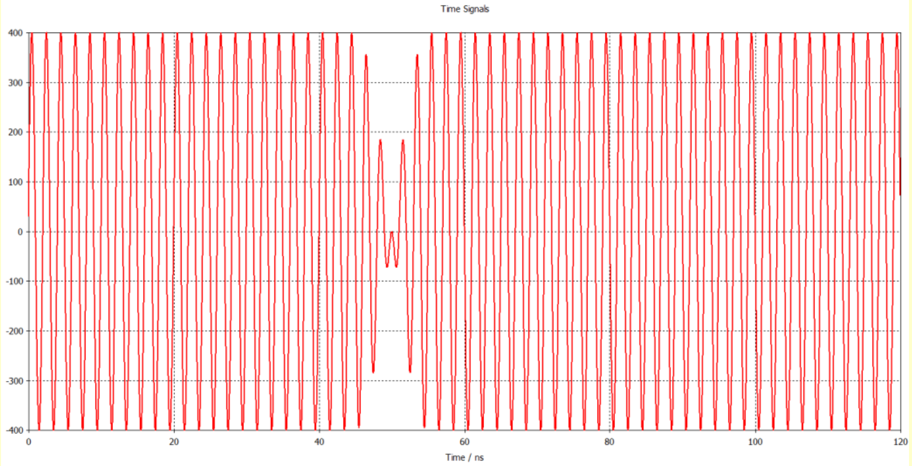
Excitation signal from port 1 with 80 KW peak power.



Beam Entrance

Continues beam with 6A current

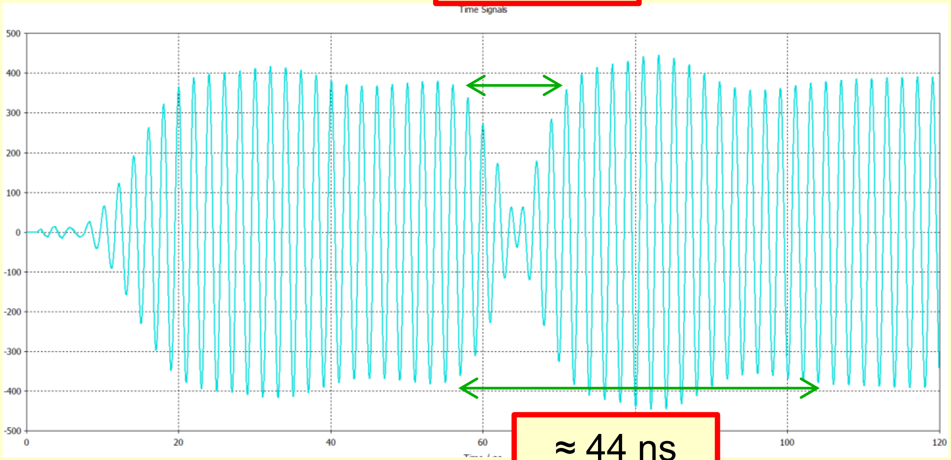
Phase flipping simulation with beam – 10 ns



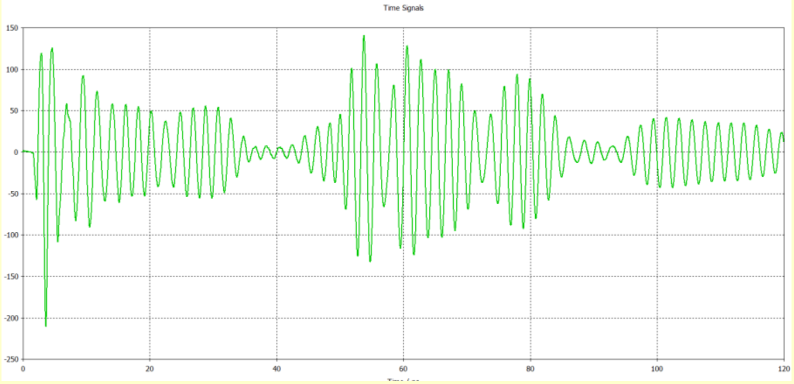
Excitation signal – port 1

Output signal – port 2

≈ 12 ns



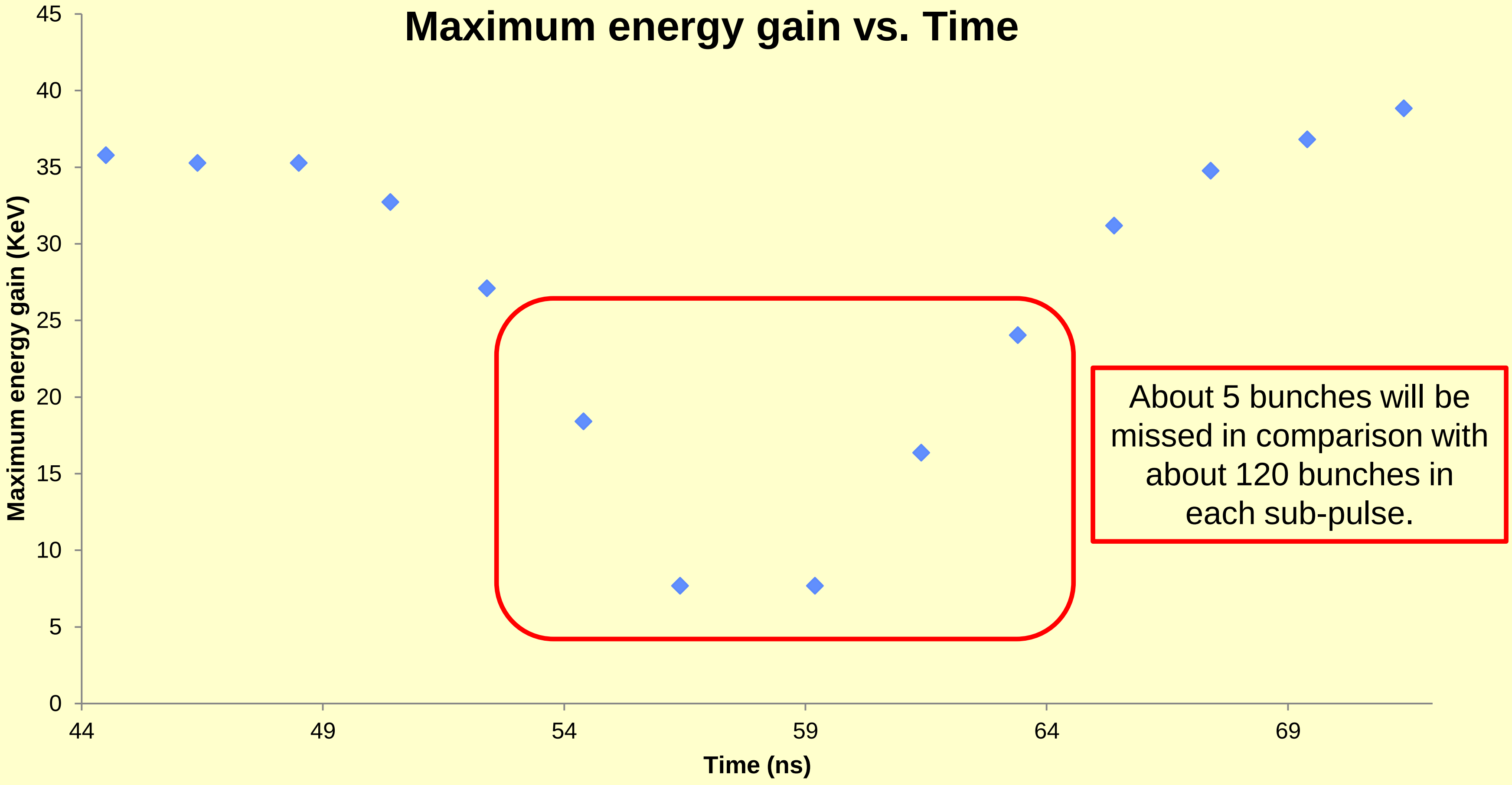
≈ 44 ns



Output signal – port 1

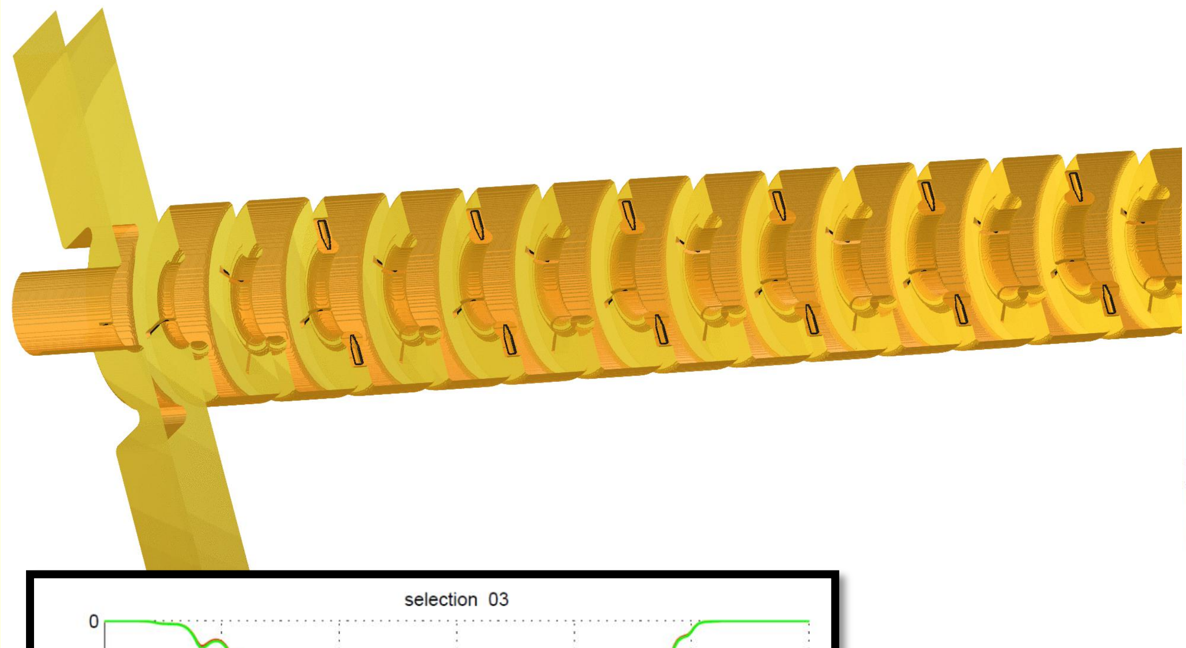
Hamed Shaker

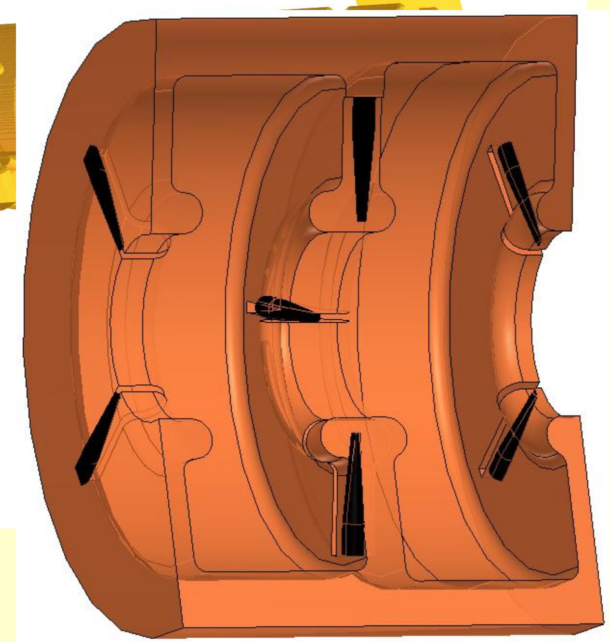
Phase flipping simulation with beam – 10 ns

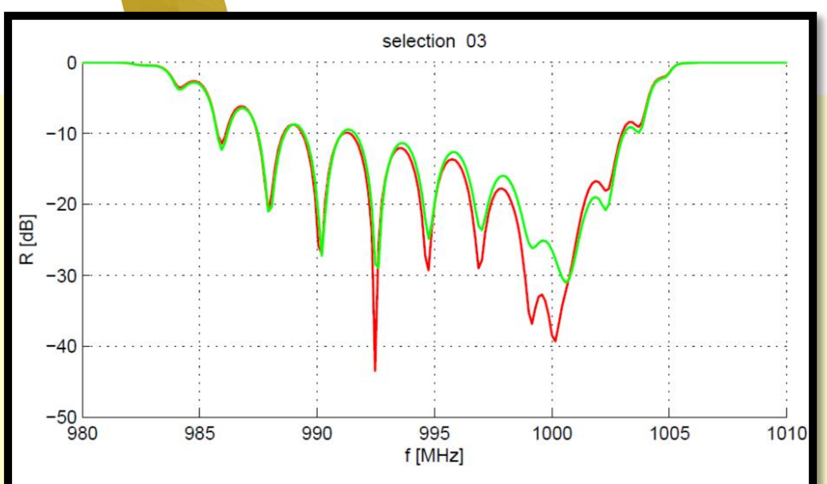


DB-accelerator structure

RF-design existing,
next steps: mechanical design and prototype



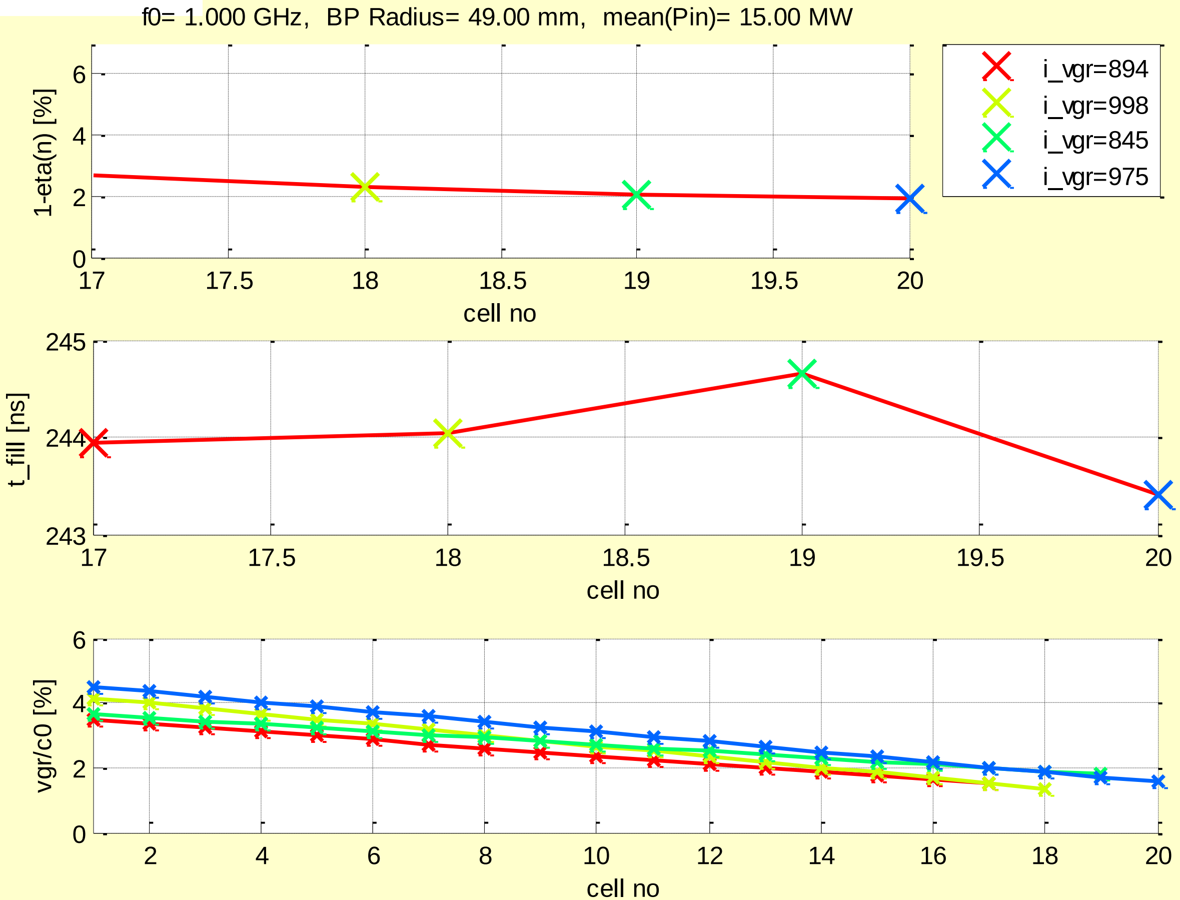




Input and output coupler design finished
Correct match, input reflection < 30 dB.
(red and green: two different geometries; red is final)

Rolf Wegener

DB-accelerator structure



Parameters:

f = 999.5 MHz

P_{in} = 15 MW

R_B = 49 mm

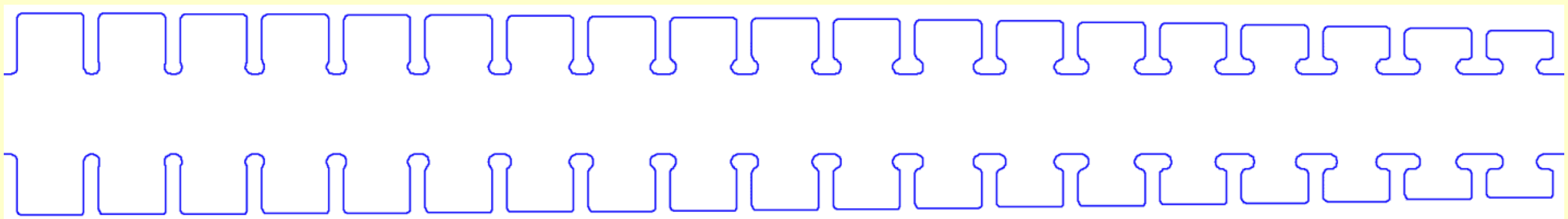
N = 19 cells

OD= 300 mm

L= 2.4 m

T_{fill} = 245 ns

$\eta_{\text{RF-Beam}}$= 97.5 %



Rolf Wegener

RF power sources
1 GHz high efficiency klystron

Scenarios	2012	2013	2014	2015	2016	2017
Multi beam klystron (ILC-based, 65% efficiency)	Tender/ Order	Design		Klystron 1	Klystron 2	Klystron 3 ?
Ultimate efficiency (>70%) based on Chiara Marrelli's work	Study	Study ?				
Ultimate effiency based on EuCard2		Start of Progam	EuCard study	EuCard study	EuCard study	Transfer to Industry

<u>Development and Purchasing strategy:</u>

Launch tender to develop and purchase high efficiency klystrons in industry. Aim for multiple vendors. Klystrons could arrive from 2015 in line with modulator development

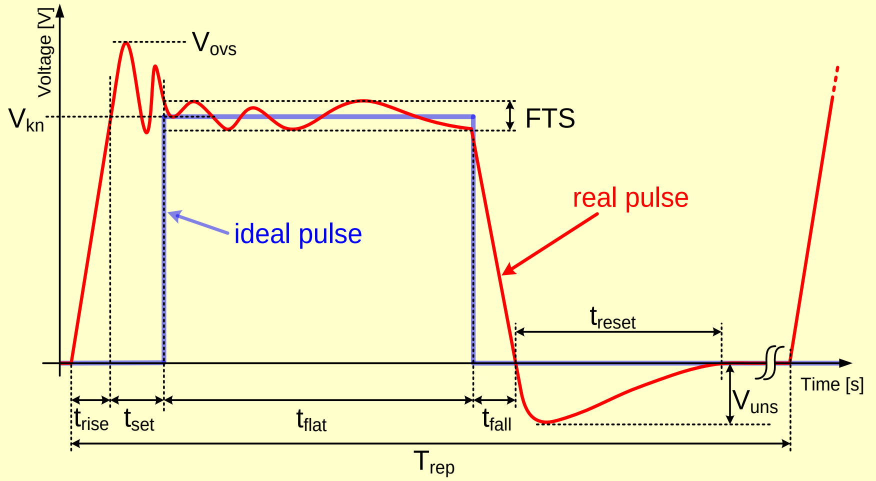
Plan to hold a workshop on high efficiency klystrons and modulators in spring 2013 (EuCard2 network on high efficiency rf sources).
Seeking collaborations for this topic !

Tentative klystron parameters

PARAMETER	VALUE	UNITS
RF Frequency	999.5	MHz
Bandwidth at -1dB	tbd	MHz
RF Power:		
Peak Power	≥ 18	MW
Average Power	135	kW
RF Pulse width (at -3dB)	150	µs
HV pulse width (at full width half height)	165	µs
Repetition Rate	50	Hz
High Voltage applied to the cathode	tbd, 150 (max)	kV
Tolerable peak reverse voltage	tbd	kV
Efficiency at peak power	≥ 65	%
RF gain at peak power	tbd, > 50 ?	dB
Perveance	tbd	$\mu A/V^{1.5}$
Stability of RF output signal		
0.5-1.0 of max. power and 0.75 -1.0 of max. cathode HV to be:		
RF input vs output phase jitter [*]	±0.5 (max)	RF deg
RF amplitude jitter	±1 (max)	%
Pulse failures (arcs etc.) during 14 hour continuous test period	≤ 1	
Matching load, fundamental and 2^{nd} harmonic	tbd	vswr
Radiation at 0.1m distance from klystron	≤ 1	µSv/h
Output waveguide type	WR975	

CLIC studies & klystron modulators specs

Modulator main specifications			
Pulse voltage	V_{kn}	150	kV
Pulse current	I_{kn}	160	A
Peak power	P_{out}	24	MW
Rise & fall times	$\mathbf{t_{rise}}$	**3**	**μs**
Flat-top lenght	t_{flat}	140	μs
Repetition rate	Rep_r	50	Hz
Flat-top stability	FTS	0.85	%
Pulse reproducibility	**PPR**	**10**	**ppm**



~300MW required for kly. mod.

Pulse efficiency definition

$$\eta_{pulse} = \frac{E_{ideal\_p}}{E_{real\_p}}$$

Approach:
Develop and explore with collaboration partners technologies to meet the ultimate specification for CLIC with the goal to have two working prototypes in 2015-2016.
First collaboration with ETH Zürich started, prototype in 2015

Demonstration goals for the injector front end

- Demonstrate rf system at full pulse length and beam loading
  High efficiency klystron
  High efficiency and stable modulator
  Full loaded accelerating structure (validate technology)

- Demonstrate beam quality and stability requirements for long pulse
  Current stability 0.1%
  Beam phase stability
  Emittance and energy and position jitter

- Demonstrate electron source and phase coding
  Life time, reliability, routine operation

- Demonstrate diagnostics suitable for long pulse and machine protection

- DB Injector suitable for CLIC zero and CLIC

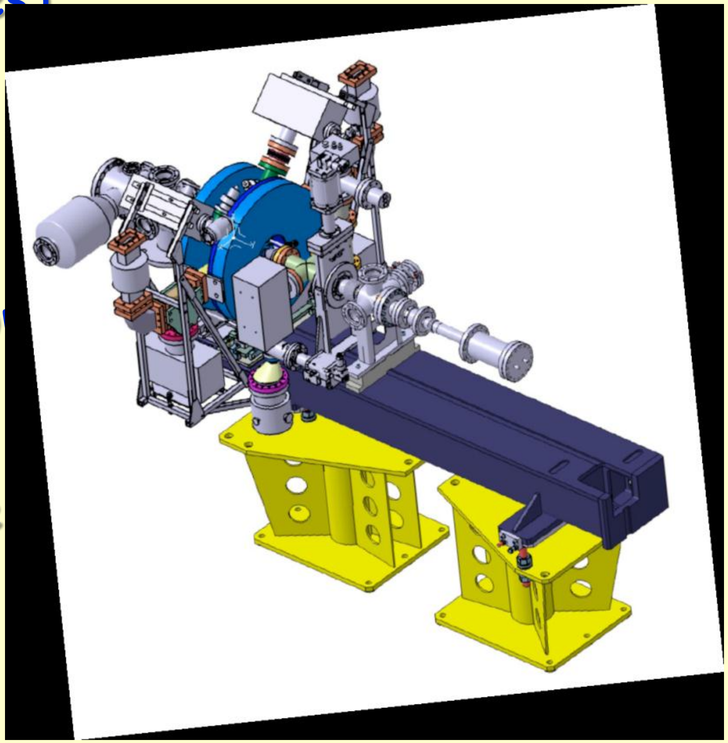
Photo injector option

Advantages

- No satellites or tails, phase coding on the laser side
- No or less bunching needed, possibly better emittance
- Flexible time structure (single bunches)

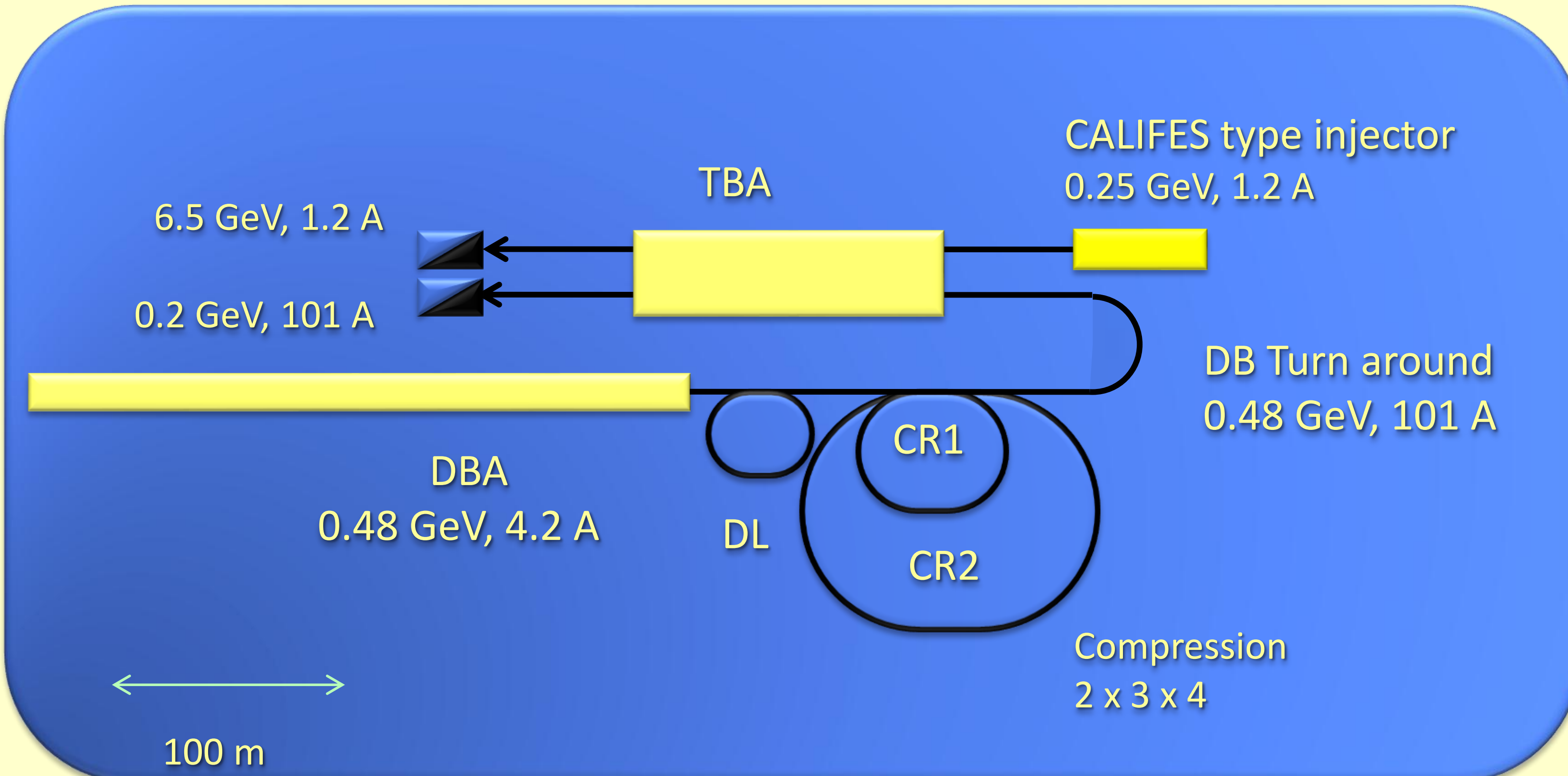
Concerns

- Cathode lifetime
- Challenging laser, peak and average po
- Intensity stability
- Maintenance and operation
- Very little resource available for time



Introduction to C zero

20 % of the CLIC Drive Beam and 10 % of a CLIC decelerator



H. Braun, CLIC 2008 Workshop

Motivation for $CLIC_{zero}$

- Demonstrate nominal drive beam parameters (except the energy)
  Full combination scheme to 100 A, full pulse length in injector

- Realize two beam acceleration with nominal hardware for a significant length (~100 m)

- Drives industrialization, needed to be ready for CLIC
  Significant size series production of cost and performance driving hardware (46 two beam modules, 276 x-band structures, 138 PETS, 140 L-band klystrons, modulators and structures)

- Most hardware reusable for CLIC

- Could be a beam driven processing facility for the x-band structures

Drawbacks:

- Expensive
- Beam dynamics for combination might be more difficult due to lower energy
- Does not address sufficiently emittance preservation and luminosity issues

Conclusions

- Unusual parameter space for an injector
- Rough conceptual design for the injector exists, now we have to get really started
- Plans for purchasing the key hardware items have been developed and need to be followed up now
- We seeking collaborations for this work, anybody interested ?

End

Klystron specifications

TH1802, ILC MBK klystron

FREQ	Vklystron	Iklystron	V pulse width	RF pulse width	Peak RF Power	Repetition rate	Average Power	Gain	Efficiency	Waveguide
MHz	kV	A	µs	µs	MW	Hz	kW	dB	%	
1300	115	132	1700	1500	10	10	150	47	65	WR 650

CLIC DB klystron design goal, ~ 150kV voltage was assumed for time being

FREQ	Vklystron	Iklystron	V pulse width	RF pulse width	Peak RF Power	Repetition rate	Average Power	Gain	Efficiency	Waveguide
MHz	kV	A	µs	µs	MW	Hz	kW	dB	%	
999.52				**150**	**15-20**	**50**	**113**		**70**	

Features of $CLIC_{zero}$

- Nominal CLIC DB injector
- Nominal DB rf system (Klystron, Modulator, accelerating structure)
- Nominal 100 A drive beam (6 μs)
- 20 % drive beam energy

- Nominal Delay Loop and Combiner Rings (1/5 of the energy)
- Drive beam pulse shaping can be studied
- DB turn around to study phase feed forward

- 46 nominal two beam modules (type 1; ~ 100 m)
- 10% of a decelerator (last 10 % most difficult)
- 6.25 GeV electron beam, 1.2 A
- Nominal beam loading

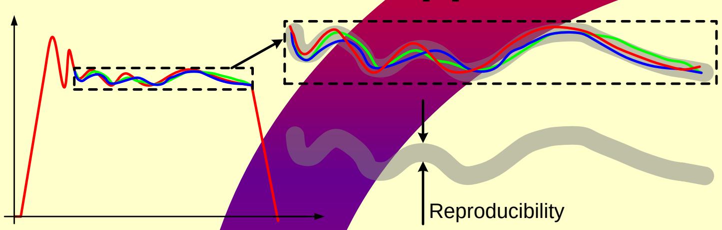
CLIC$_{zero}$ Parameters

Parameter	Nominal value	Unit
Drive Beam Energy	480	MeV
Pulse Length	**6-140**/ 243.7	μs / ns
Drive Beam Current (linac)	4.2	A
Decelerator Current	**101**	A
Combination Factor	24	
Bunch Spacing	1.992	ns
Drive Beam Emittance	~100	mm mrad
Decelerator Bunch Length	1	mm
Repetition Rate	50	Hz
Main Beam Energy	6.5	GeV
Main Beam Current	1.2	A
Main Beam Pulse Length	156	ns
Main Beam Bunch Length	~0.5	mm
Main Beam Emittance	~30	mm mrad

CLIC studies & klystron modulators specs

Technology challenges

Pulse to pulse reproducibility: 10 to 100ppm



Modulator and voltage measurement reproducibility **never achieved before**!

Machine availability

With more than 1600 modulators, reliability, modularity & redundancy must be optimized for maximum accelerator availability

Modulator topology selection considering:

- Efficiency maximization (max. power limited)
- Reproducibility
- Constant power consumption
- Satisfactory accelerator availability

AC power quality optimization

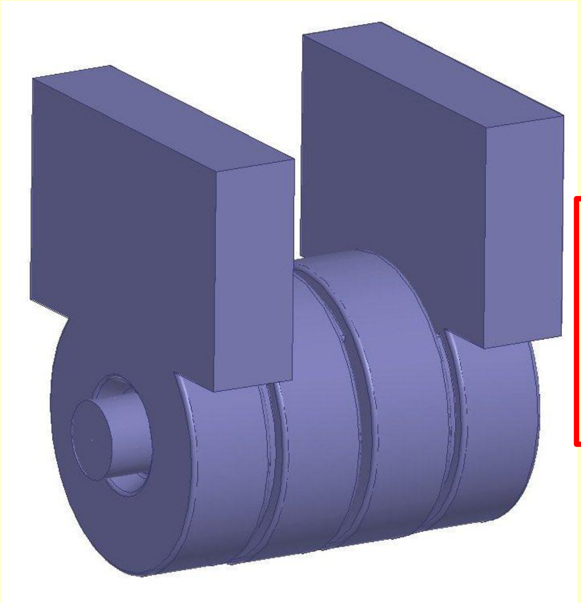
More than 1600 modulators pulsing synchronously! Utility grid power fluctuation minimized (~1%) – tough charger design

Need for a global approach! Different solutions must be explored (transformer based, fully solid state, HV & LV solutions)

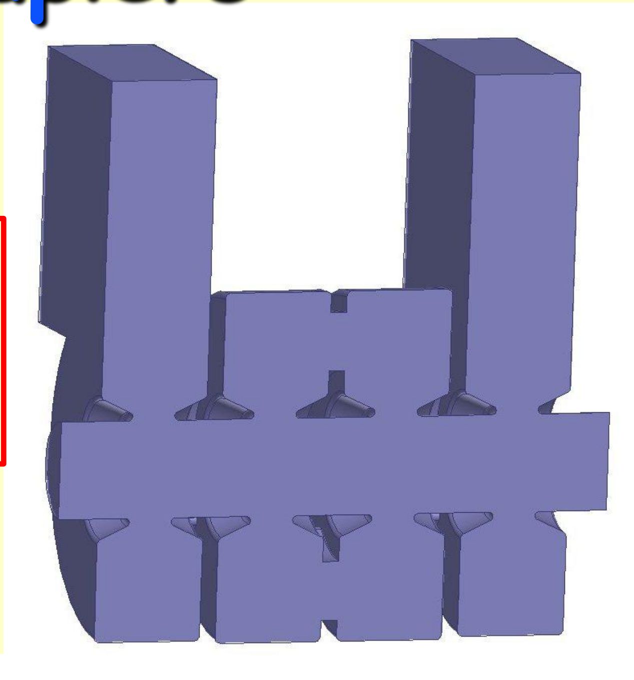
What is needed to get ready for $CLIC_{zero}$

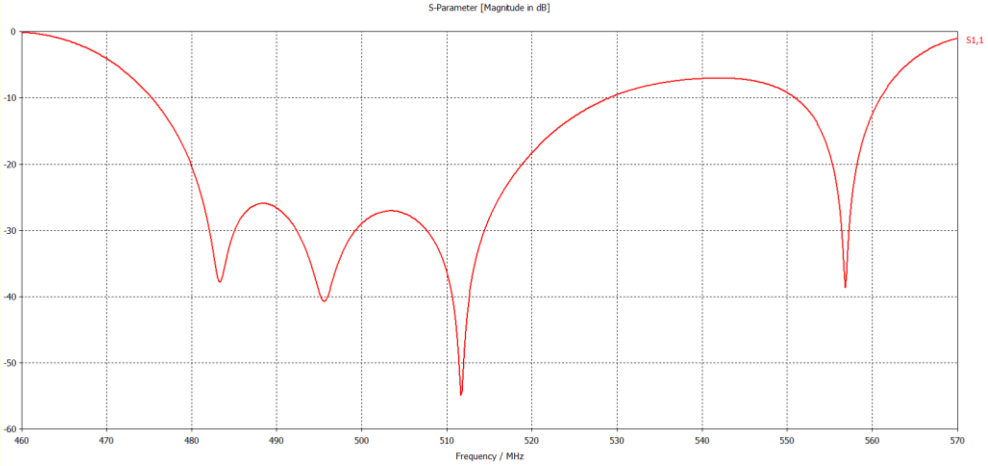
- Prototyping and small series production of major hardware
  DB-klystron, DB acc-structure, Modulator,
  Diagnostics, two beam modules
- DB injector design and demonstration (Source, phase coding, stability)
  includes prototyping of DB rf system
- Technical design of the DB linac
- Technical design of the beam combination complex
  (delay loop, combiner rings)
- Technical design of the turn around loop
- Technical design of the probe beam injector
- Technical design and prototyping of the two beam modules
  (acc-structure, PETS, diagnostics, Quads, stabilization and alignment)
- Study and prepare location and implementation (tunnel, building)
- …..

Four cells structure with waveguide couplers



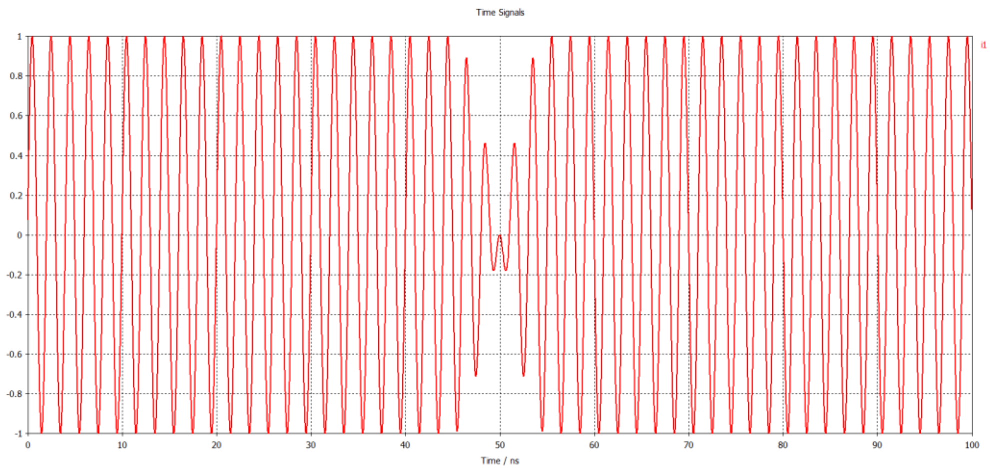
In this design for the first SHB about 73 kW peak power is needed for 10ns filling time and 36.5 KV gap voltage.





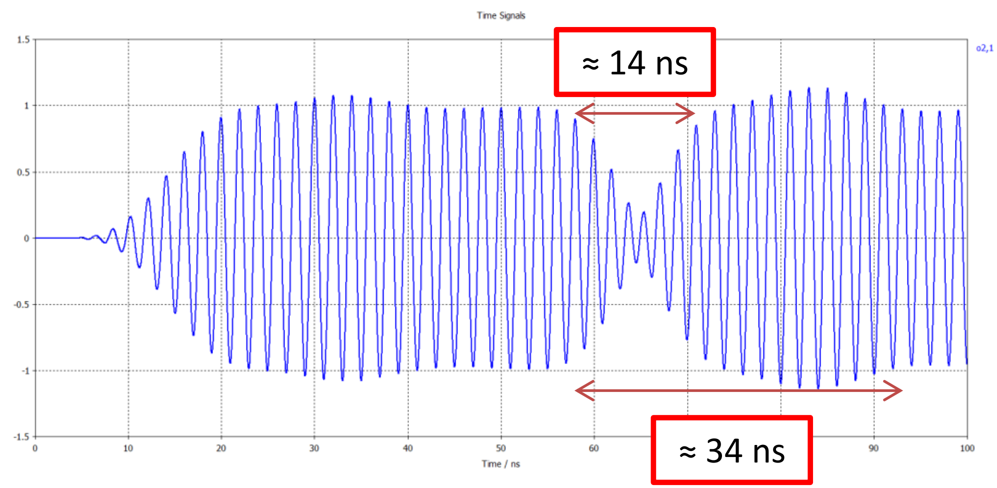
Hamed Shaker

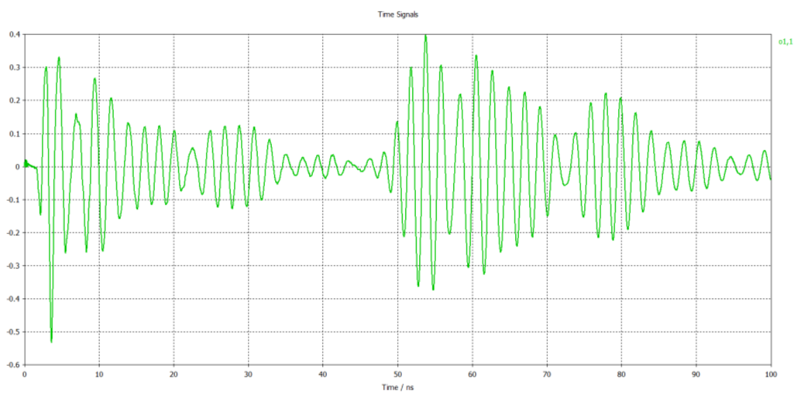
Phase flipping simulation – 10 ns



Excitation signal – port 1

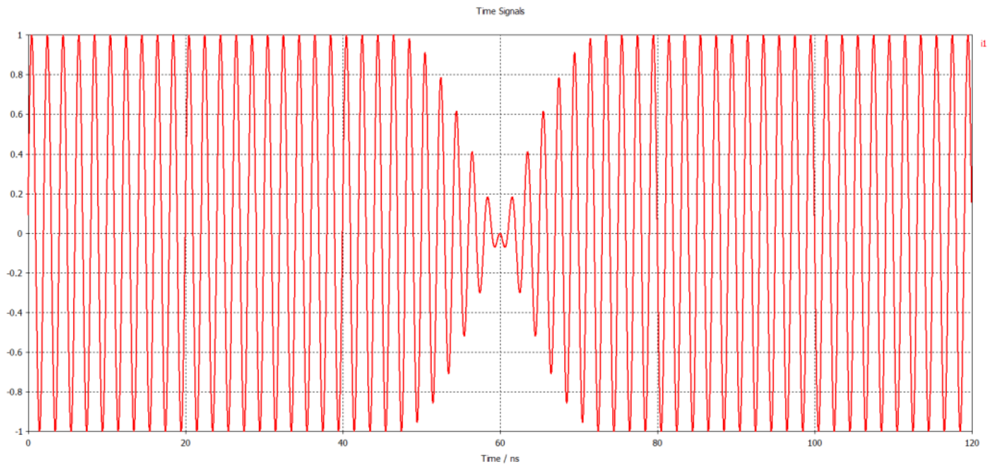
Output signal – port 2





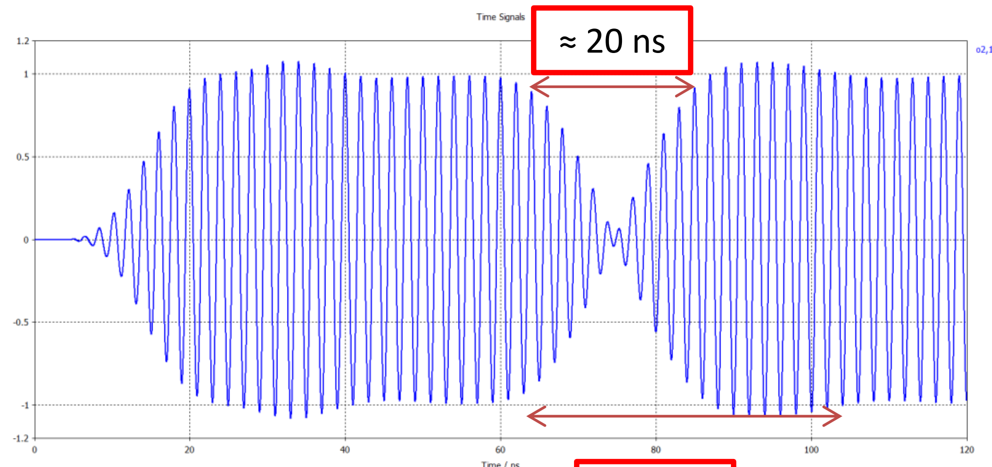
Output signal – port 1

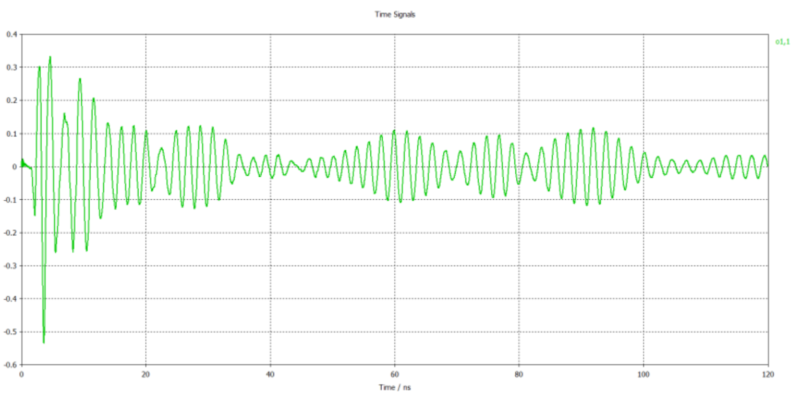
Phase flipping simulation – 26 ns



Excitation signal – port 1

Output signal – port 2

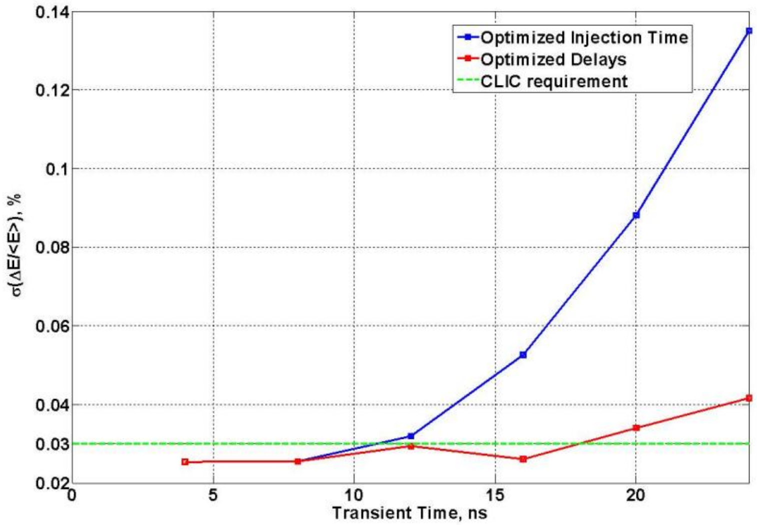


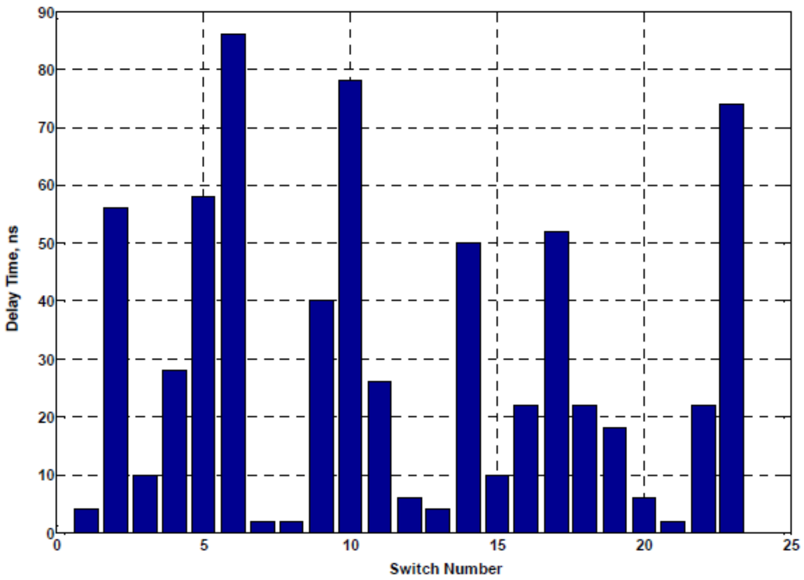


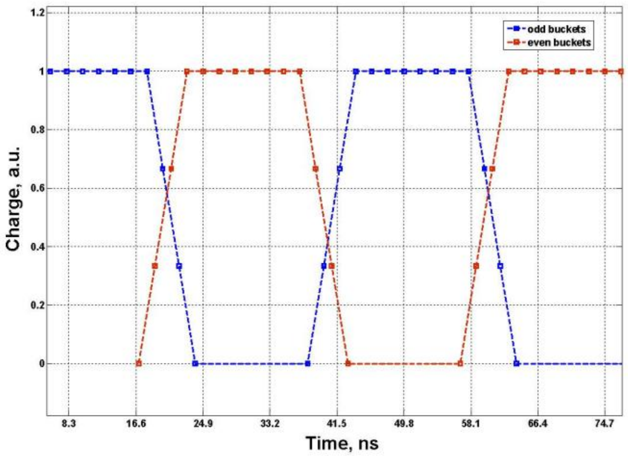
Output signal – port 1

Borrowed from Oleksiy Kononenko

Phase flipping- how fast?







In the normal case the time interval between phase switching is constant (243.7 ns). In the Oleksiy model these intervals are not constant to have better energy dispersion at the end of main beam linac. It also give us an idea that how much the minimum phase flipping should be. The result shows us it should be less than 18ns. In my design I use 10ns similar to CTF3 SHBs.

Parameter for optimization

Travelling Wave Structure

$$\frac{R'}{Q} = \frac{(\frac{V}{L})^2}{\omega W'} = \frac{(\frac{V}{L})^2}{\omega \frac{P}{v_g}} \Rightarrow \frac{R}{Q} = \frac{V^2}{\omega P \frac{L}{v_g}} \Longrightarrow P = \frac{V^2}{\omega \tau \frac{R}{Q}}$$

$$P = \frac{V^2}{\omega \tau \frac{R}{Q}} = \frac{V^2}{\omega \tau} \times \frac{1}{n\left(\frac{R}{Q}\right)_{cell}}$$

R : Effective shunt impedance
R': Effective shunt impedance per length
Q : Unloaded quality factor
P: Source power
V : Gap voltage
W' : Stored energy per length
L: Structure length
v_g : Group velocity
n : Cell numbers

P_d : Power disappears on surface.
β : Coupling coefficient
$Q_e = \omega\tau$: External quality factor
τ : Filling time

For the known gap voltage and filling time our goal is to increase **R/Q** to reduce the input power.

τ=10ns
V=36.5 KV

Electron source options

Some simple considerations

CTF3: 1.6 μs, 9.6μC per pulse
1 % droop specs
→7 nF, ~70 J stored energy

CLIC: 140 μs, 700 μC per pulse
0.1 % droop specs
→ 5 μF, ~50 kJ stored energy
gridded cathode might not survive

CTF3 gun concept might be not scalable for CLIC