Progress in the high gradient RF design

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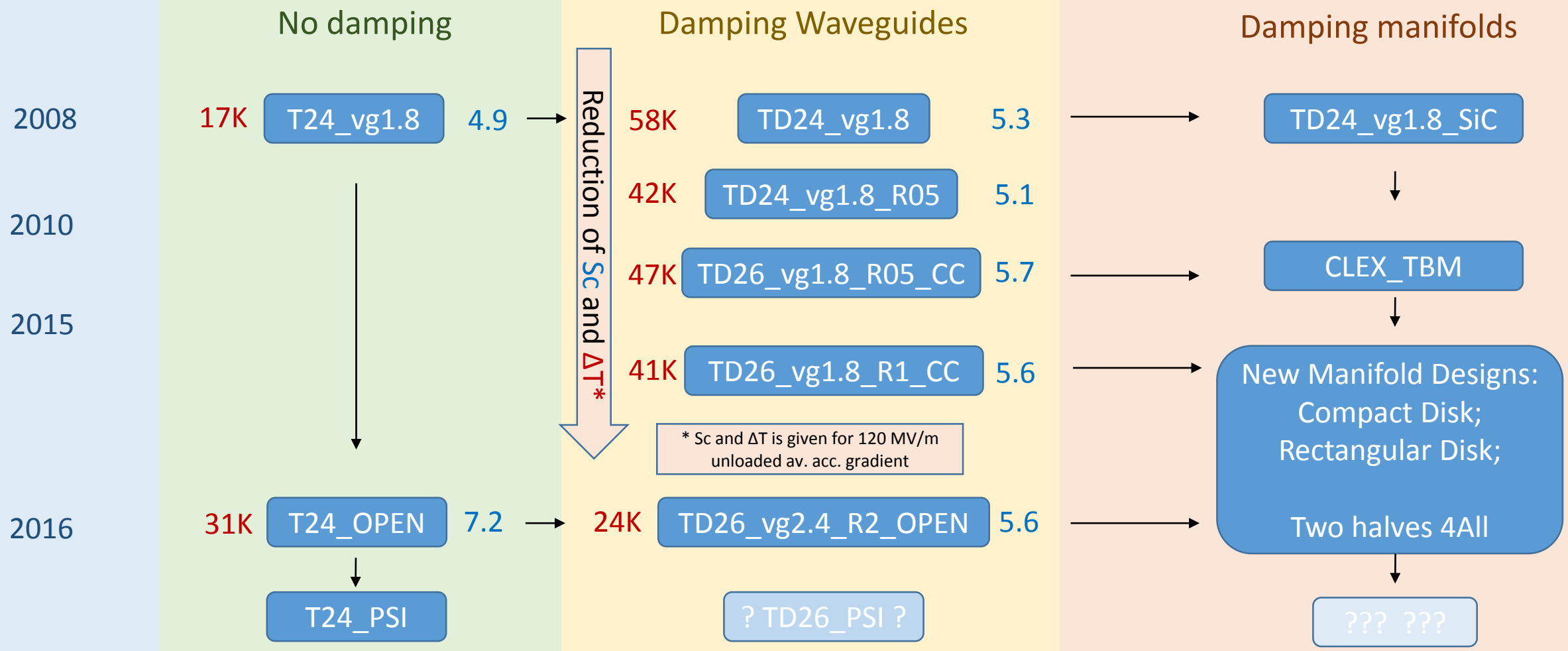
HG2017, Valencia

Outline

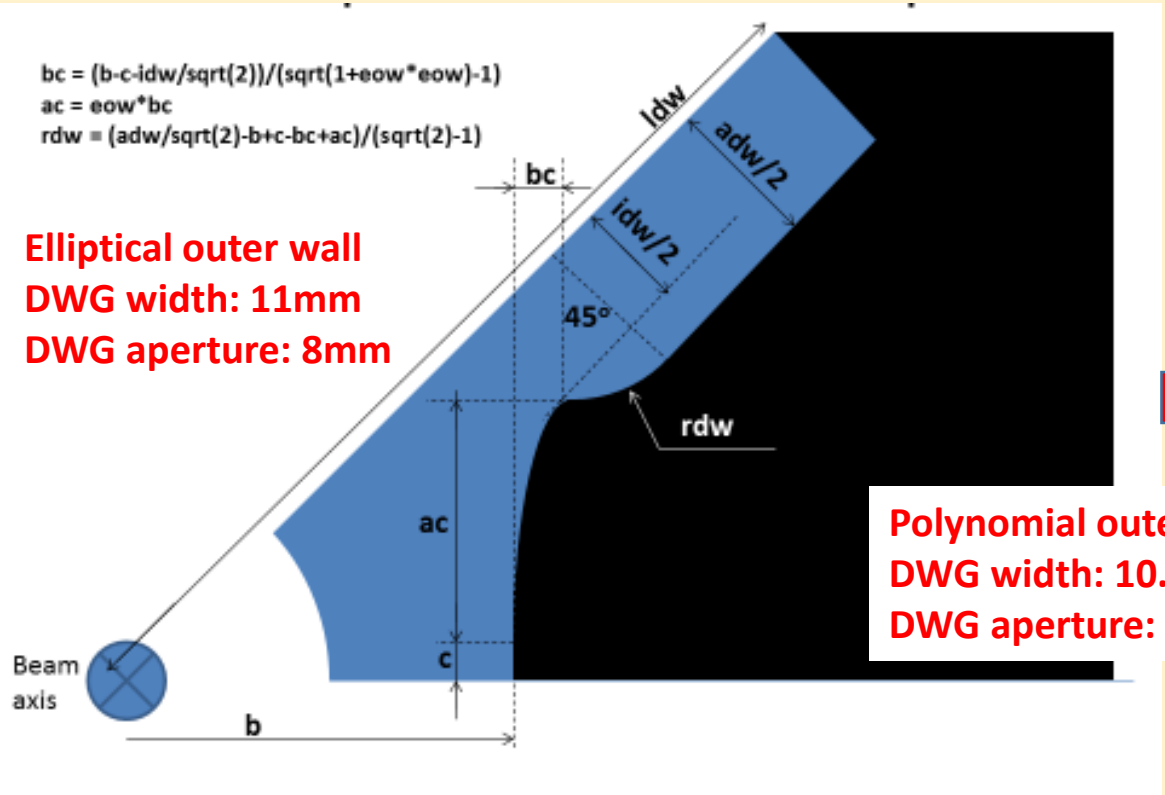
- Overview of CLIC X-band prototype design
  - Design of CLIC 380 GeV accelerating structure
- Applications of high-gradient and/or X-band structures
  - Design of X-band TDS with variable polarization
- Outlook

3 TeV CLIC CDR baseline: CLIC-G family

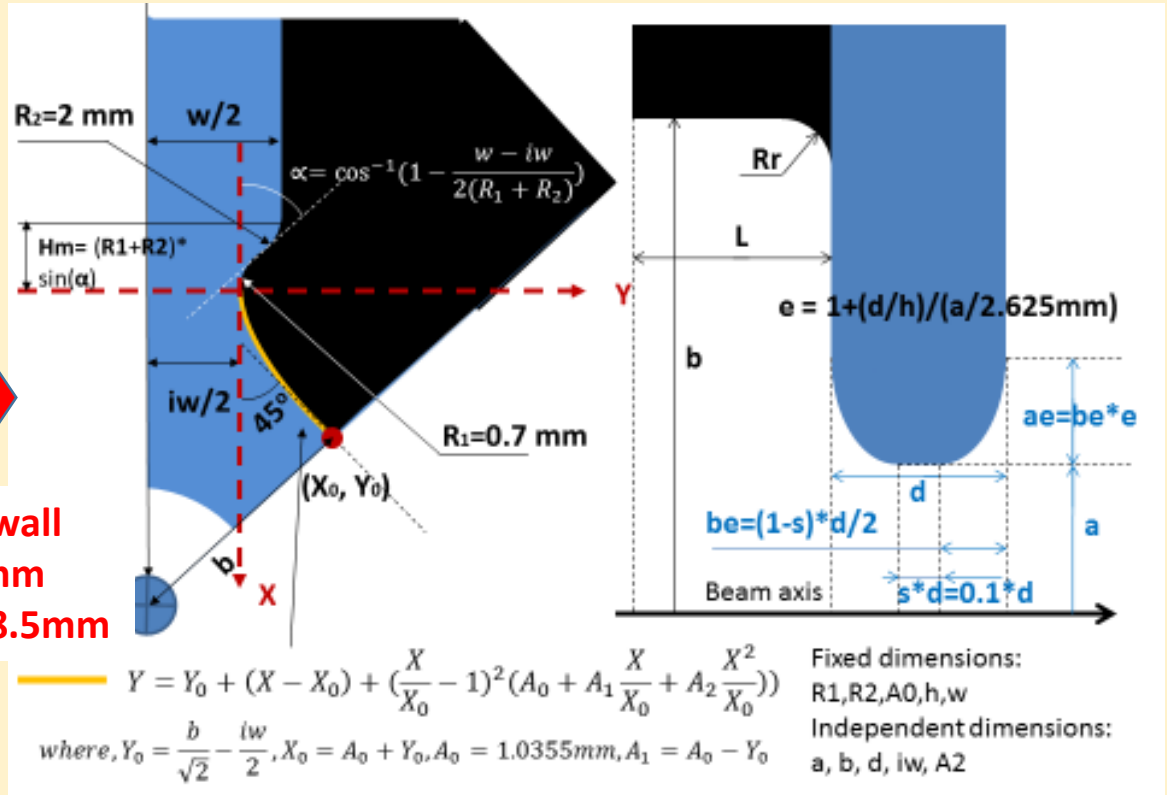


New shape of the cell outer wall and damping waveguides

CLIC-G: TD26_R05

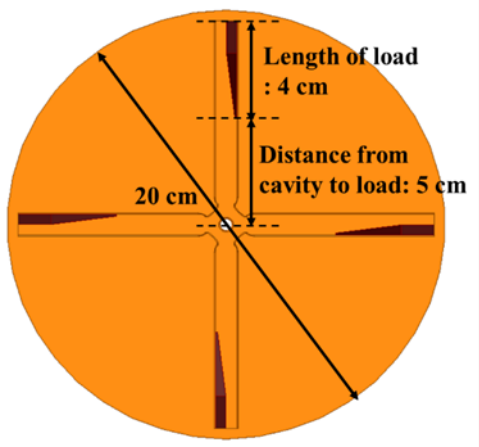


CLIC-G*: TD26_R1



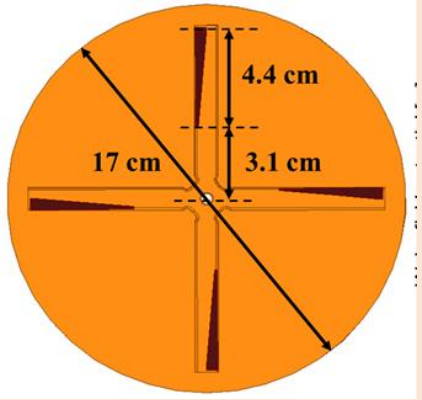
New designs of damping manifolds

TD26_vg1.8_R05_CC
CLIC-G CDR baseline

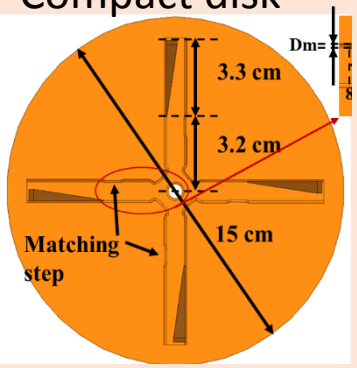


TD26_vg1.8_R1_CC: CLIC-G* new designs for more compact manifolds

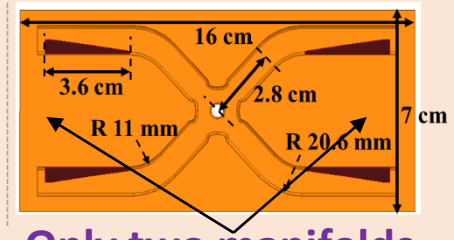
Standard disk



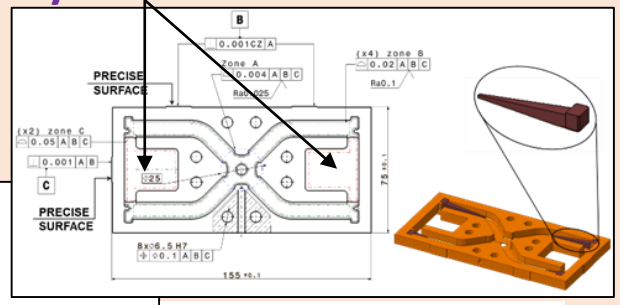
Compact disk



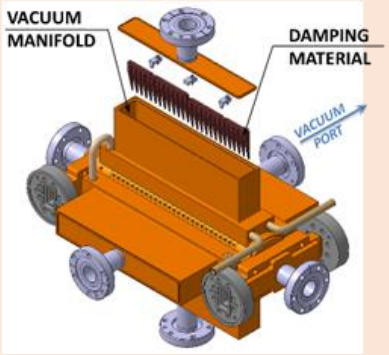
Rectangular disk

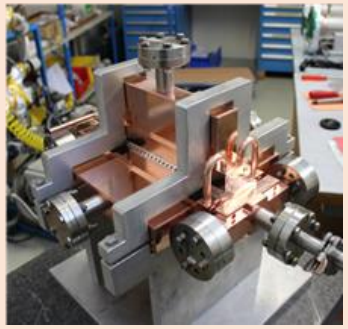


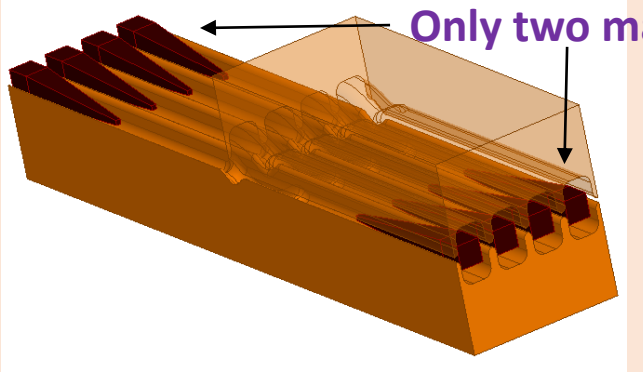
Only two manifolds

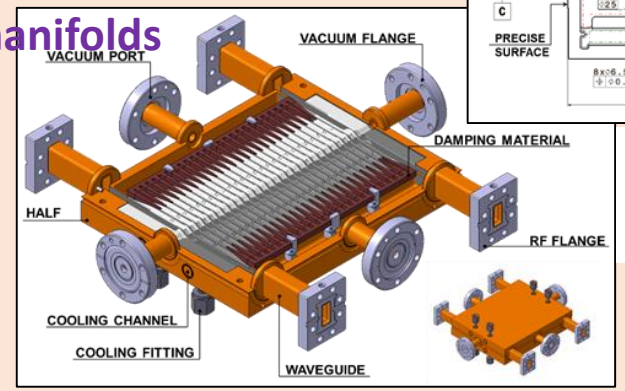


TD26_vg2.4_R2_OPEN: CLIC-HDS-A: two halves



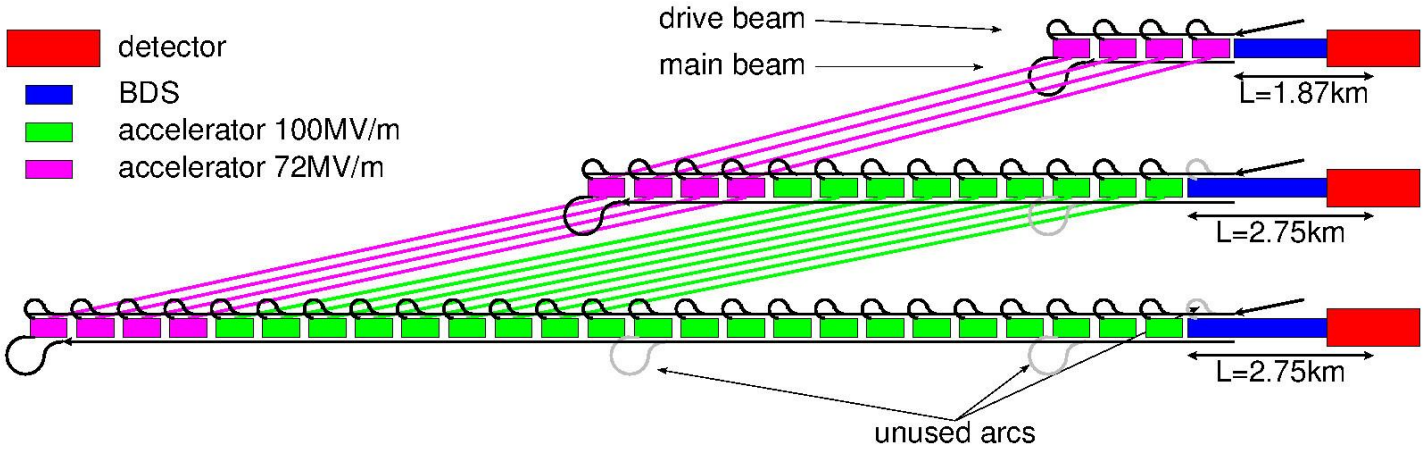






CAD models:
A. Solodko, IPAC17

Re-baselining towards staged CLIC



E_{cms}=380Gev, L=1.5x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.6

- For Higgs and top production, HEP input

E_{cms}=O(1.5TeV)

- Depends on LHC findings

E_{cms}=3TeV, $L_{0.01}$=2x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.3

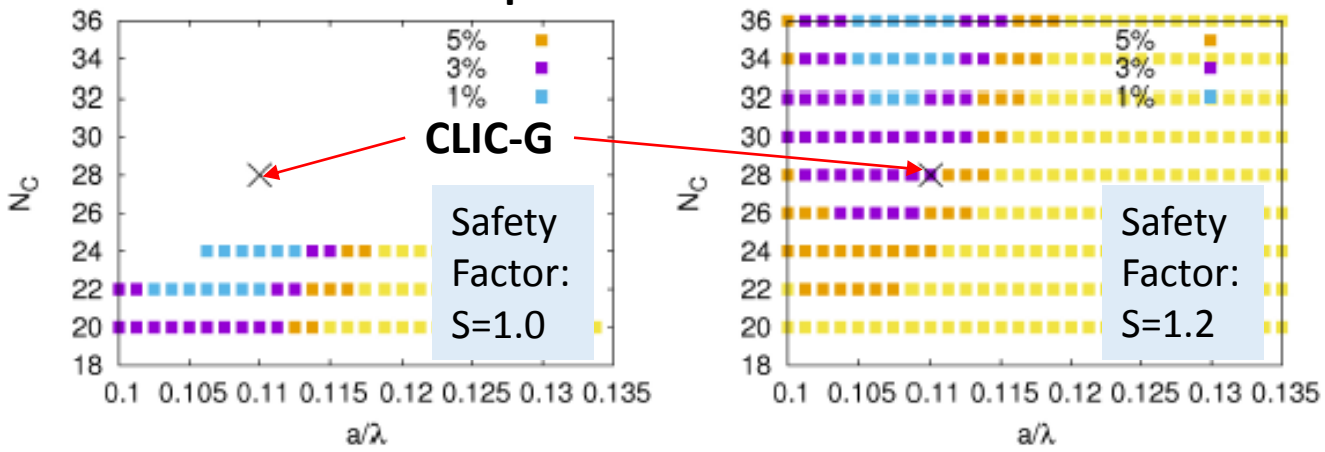
High gradient RF constraints used in optimization: S=1.0

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

- $E_s^{max} \cdot (t_p^P)^{1/6} < 250$ MV/m · $(200ns)^{1/6}$
- $P_{in}/C_{in} \cdot (t_p^P)^{1/3} < 2.8$ MW/mm · $(200ns)^{1/3}$ = 17 [Wu]
- $S_c^{max} \cdot (t_p^P)^{1/3} < 5$ MW/mm^2 · $(200ns)^{1/3}$
- $\Delta T^{max}(H_s^{max}, t_p) < 50$ K

S=1.0 has been used for 380 GeV CLIC optimization

Optimum at 3 TeV



http://clic-study.web.cern.ch/content/updated-baseline-staged-compact-linear-collider

Acc. Structure parameters for staged CLIC

	CLIC-G at 3TeV	3TeV, optimum	380 GeV, two beam	380 GeV, klystron based
Safety factor S	1.1	1	1	1
N_c	28	24	33	28
a/λ	0.126 - 0.094		0.16 - 0.1	0.145-0.09
d [mm]	1.66 - 1.0		2.52 - 1.43	2.08 – 1.12
G [MV/m]	100	100	72	75
P [MW]	61.3		59.5	42.5
Bunch population N [10^9]	3.7		5.2	3.9
Bunch number N_b	312		352	485
Bunch separation	6 rf cycles = 0.5 ns	6 rf cycles = 0.5 ns	6 rf cycles = 0.5 ns	6 rf cycles = 0.5 ns
τ_{RF} [ns]	244	244	244	325
	TD26_vg1.8_R1_CC		TD31_vg2.9_R1_CC	To be designed

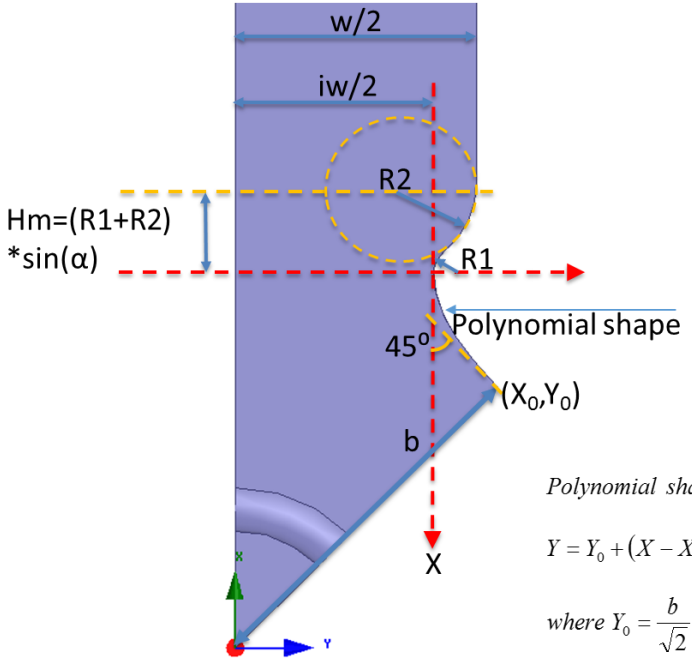
Design of CLIC 380 GeV accelerating structure

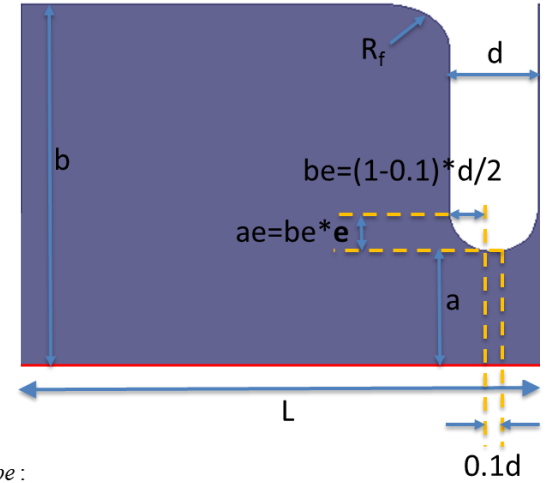
More details in :
Xiaoxia Huang, “RF design of the X-band accelerating structure for 380 GeV CLIC”
https://indico.cern.ch/event/577810/contributions/2484987/

CLIC380: Cell shape optimization

Similar to CLIC-G*:

- Polynomial shape is used to minimize H-field on the outer cell wall
- Elliptical profile is used to minimize Sc on the iris

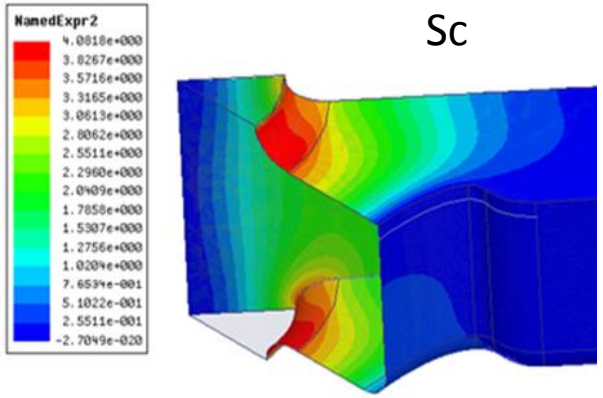


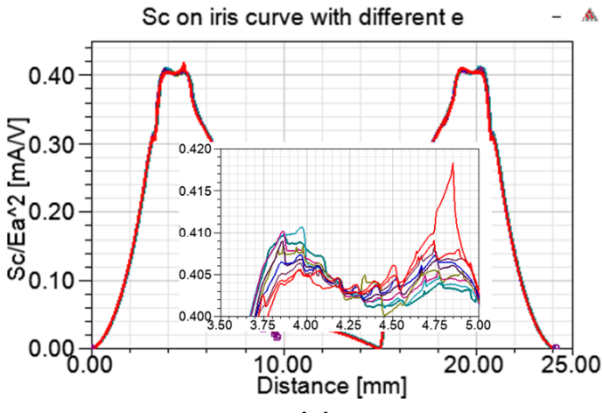


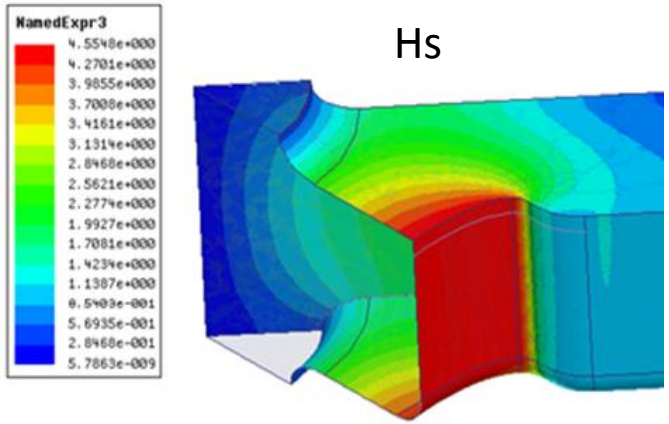
Polynomial shape:

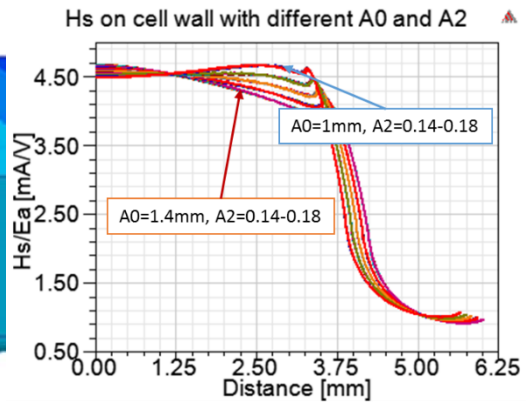
$$Y = Y_0 + (X - X_0) + \left(\frac{X}{X_0} - 1\right)^2 \left(A_0 + A_1 \frac{X}{X_0} + A_2 \frac{X^2}{X_0}\right)$$

$$\text{where } Y_0 = \frac{b}{\sqrt{2}} - \frac{iw}{2},\ X_0 = A_0 + Y_0,\ A_1 = A_0 - Y_0$$









Damping transverse long-range wakefields

Multi-bunch calculations in the CLIC main linac.
D. Schulte. PAC2009

$$a_{jk} = \begin{cases} C \cdot W_T(z_{j-k}) \cdot N_e e^2 , & j > k \\ 0 , & j \le k \end{cases}$$

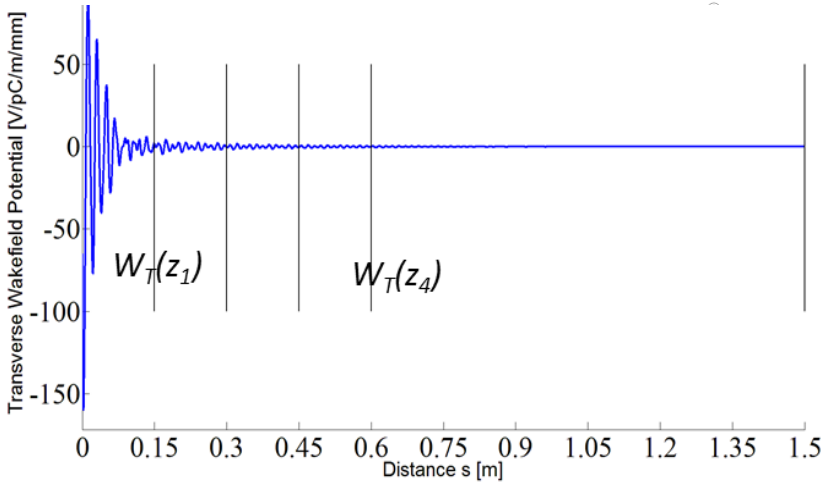
$$A = e^a = \sum_{m=0}^{N_b} \frac{(ia)^m}{m!}$$

$$F_c = \frac{1}{N_b} \sum_j \left| \sum_k A_{jk} \right|^2$$

$$F_{rms} = \frac{1}{N_b} \sum_{j=1}^{N_b} \sum_{k=1}^{j} \left| A_{jk} \right|^2$$

$$F_{worst} = max\left(Eigenvalues\ of\ matrices\left(\overline{A^T} \cdot A \right) \right)$$

Transverse beam jitter enhancement factors:
F_c, F_{rms}, F_{worst}

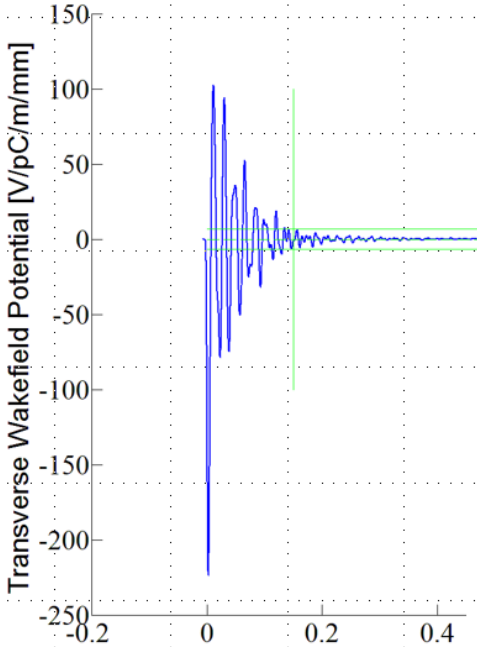


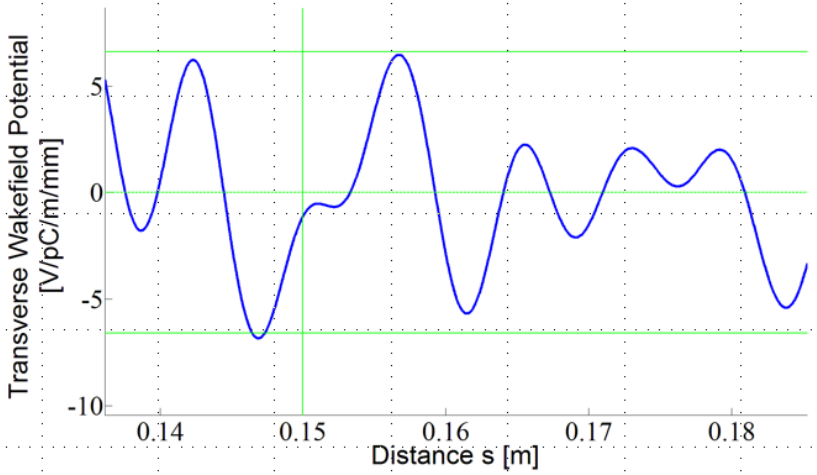
Transverse wake damping in CLIC-G*

E=3TeV, N_e=3.7*10^9, N_b=312

F_c=1.0147
F_rms=1.1134
F_worst=2.1866

Envelope:
F_c=1.3155
F_rms=4.8981
F_worst=22.3739





Wakefield suppression:
W_T < 6.6 V/pC/m/mm (s=0.15m)
Beam dynamics requirement:
F_rms < 5

Damping transverse wakes in CLIC 380 GeV

Some parameters

	CLIC-G at 3TeV	CLIC 380 GeV
N_e [10^9]	3.7	**5.2**
N_b	312	**352**
Bunch separation	0.15m	0.15m
C [m^2GeV^{-1}]	≈380	≈**190**
λ [pC·m·mm/V]	0.2273	0.1583

$$a_{jk} = \begin{cases} C \cdot W_T(z_{j-k}) \cdot N_e e^2 , & j > k \\ 0 , & j \le k \end{cases}$$

$$A = e^a = \sum_{m=0}^{N_b} \frac{(ia)^m}{m!}$$

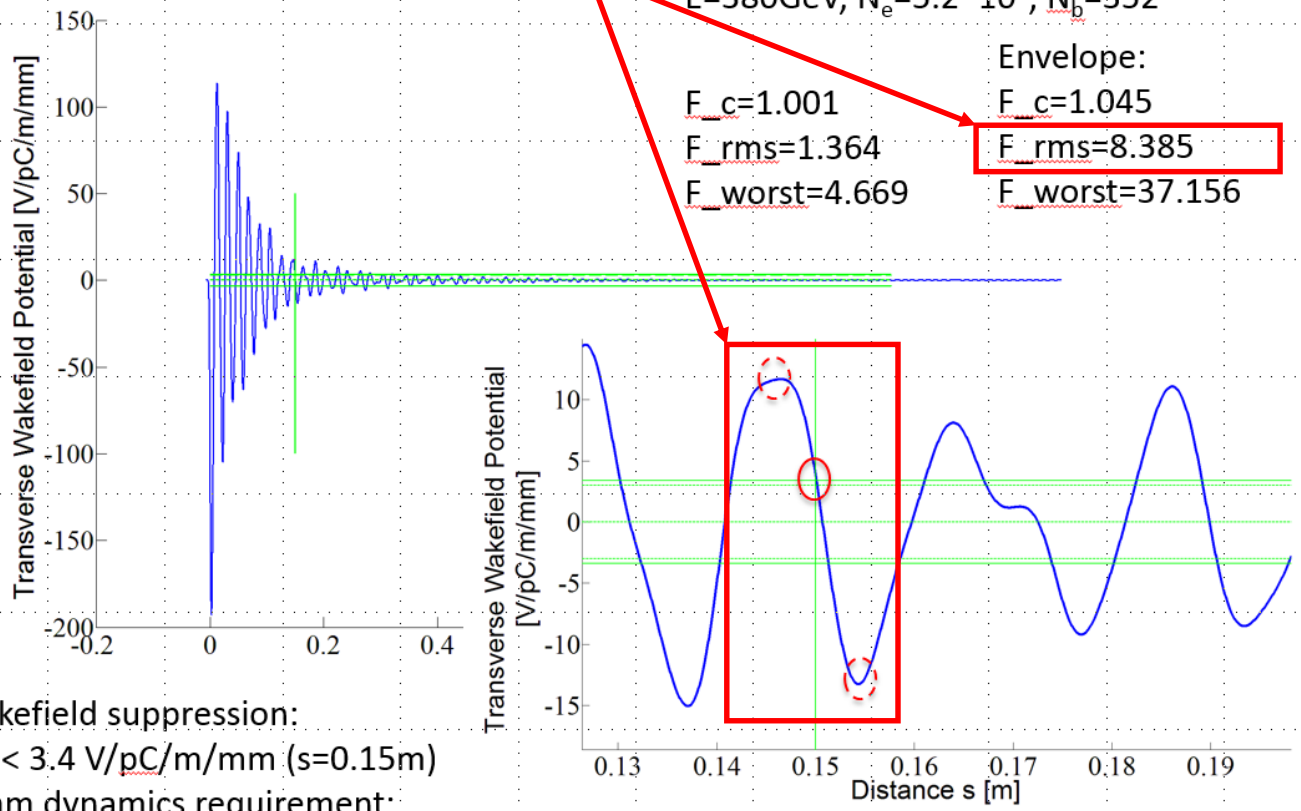
$$F_c = \frac{1}{N_b} \sum_j \left| \sum_k A_{jk} \right|^2$$

$$F_{rms} = \frac{1}{N_b} \sum_{j=1}^{N_b} \sum_{k=1}^{j} |A_{jk}|^2$$

$$F_{worst} = max\left(Eigenvalues\ of\ matrices\left(\overline{A^T} \cdot A\right)\right)$$

CLIC380 requires stronger damping compared to CLIC-G* => Lower W_T (s=0.15m)

Transverse wake damping in CLIC380 using CLIC-G* Damping WG w=10.1mm; iw=8 => **NON GOOD ENOUGH**



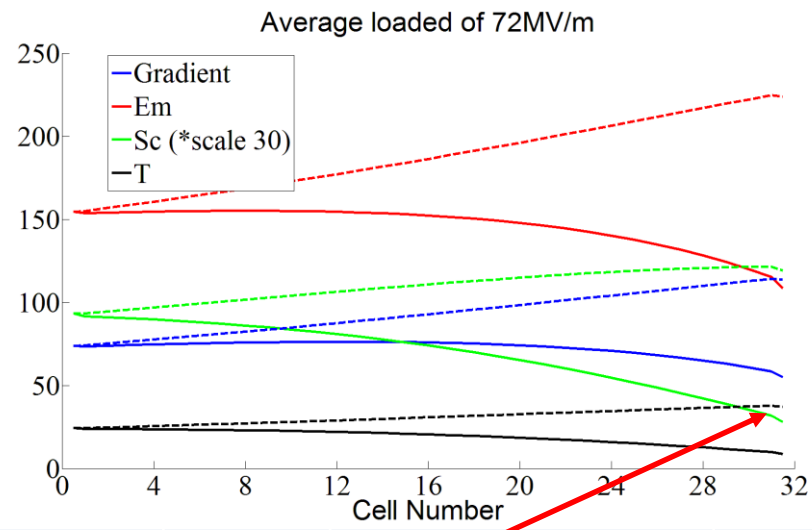
Wakefield suppression:
W_T < 3.4 V/pC/m/mm (s=0.15m)
Beam dynamics requirement:
F_rms < 5

Damping transverse wakes versus surface H-field

Constant aperture to damping WG: iw

w (mm)	iw (mm)	F_c	F_rms (<5)	F_worst	Envelope F_c	Envelope F_rms (<5)	Envelope F_worst	Max Em (MV/m)	Max Sc (MW/mm²)	T (K)
10.1	8.0	1.001	1.364	4.669	1.045	8.385	37.156	224.8	4.05	37.70
10.5	8.6	1.001	1.377	4.336	1.009	1.818	5.996			
10.6	8.4	1.000	1.063	1.920	1.005	1.429	3.567			
10.6	8.6	1.000	1.094	2.130	1.004	1.340	3.073	220.4	3.92	45.47
10.6	8.7	1.000	1.102	2.163	1.003	1.274	2.805	219.3	3.89	47.49
10.6	8.8	1.000	1.093	2.070	1.003	1.222	2.579	218.5	3.90	48.71
10.6	8.9	1.000	1.082	1.949	1.002	1.159	2.312			
10.7	8.2	1.000	1.034	1.524	1.007	1.787	4.854			
10.7	8.4	1.000	1.058	1.866	1.005	1.414	3.535			
10.7	8.5	1.000	1.077	2.031	1.004	1.345	3.219	218.9	3.88	43.78
10.7	**8.6**	**1.000**	**1.074**	**1.997**	**1.003**	**1.298**	**2.994**	**218.9**	**3.88**	**45.22**
10.7	**8.7**	**1.000**	**1.085**	**2.065**	**1.003**	**1.238**	**2.755**	**219.83**	**3.89**	**46.99**
10.7	8.8	1.000	1.078	1.990	1.002	1.197	2.576			
10.7	8.9	1.000	1.061	1.843	1.002	1.132	2.279			
10.8	8.5	1.000	1.055	1.733	1.006	1.483	4.158			
10.8	8.6	1.000	1.055	1.704	1.005	1.399	3.870			
10.8	8.7	1.000	1.058	1.680	1.004	1.312	3.596	219.4	3.96	47.75
10.9	8.5	1.000	1.058	1.817	1.006	1.514	4.280			
10.9	8.6	1.000	1.058	1.780	1.005	1.427	3.985			

wakes are low but dT is higher (In the last cell)



loaded case				
P_in (MW)	57.28			
P_out (MW)	5.55			
t_r (ns)	12.83			
t_f (ns)	55.67			
t_b (ns)	175.5			
t_p (ns)	237.52			
Efficiency	41.42%			
	Accelerating gradient G	Maximum electric field Em	Poynting vector Sc	Temperature rises T
loaded_first cell	73.50	153.56	3.05	23.91
loaded_last cell	58.52	115.26	1.07	9.91
unloaded_first cell	74.18	154.97	3.11	24.36
unloaded_last cell	114.13	224.80	**4.05**	**37.70**

dT is OK but wakes are not low enough

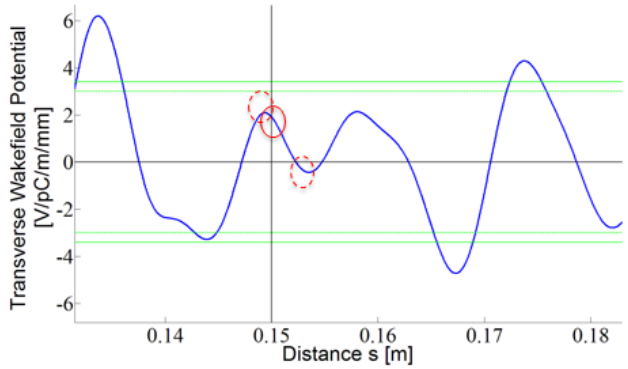
Damping transverse wakes versus surface H-field

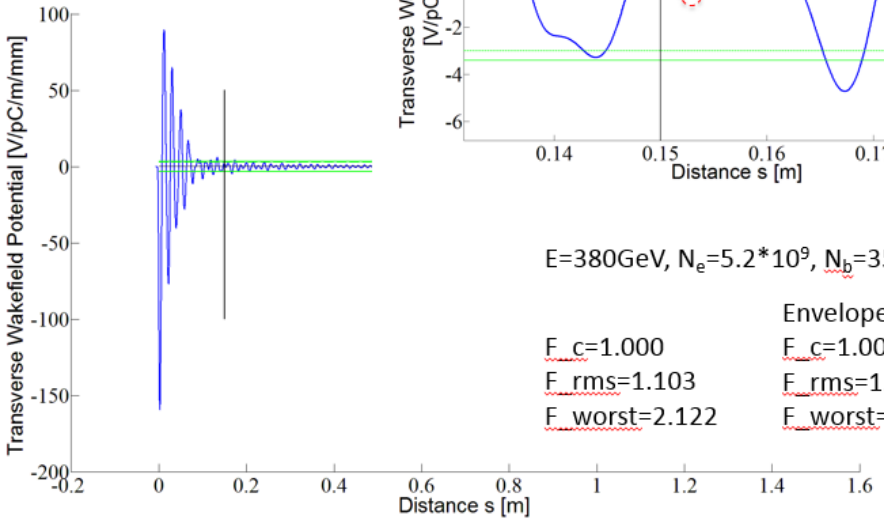
Tapered aperture to damping WG: iw; w = 10.7

iw (mm)					Envelope			Max		
First iris	Last iris	F_c	F_rms (<5)	F_worst	F_c	F_rms (<5)	F_worst	Em (MV/m)	Sc (MW/mm²)	T (K)
8.8	8.4	1.000	1.147	2.429	1.003	1.262	2.864	204.4	3.71	41.21
9.0	8.2	1.000	1.145	2.411	1.003	1.219	2.727	205.5	3.68	38.37
9.2	8.2	1.000	**1.103**	2.122	1.002	**1.152**	2.371	205.5	3.68	**38.32**

Parameters and wakefields in the optimum structure for CLIC 380 GeV

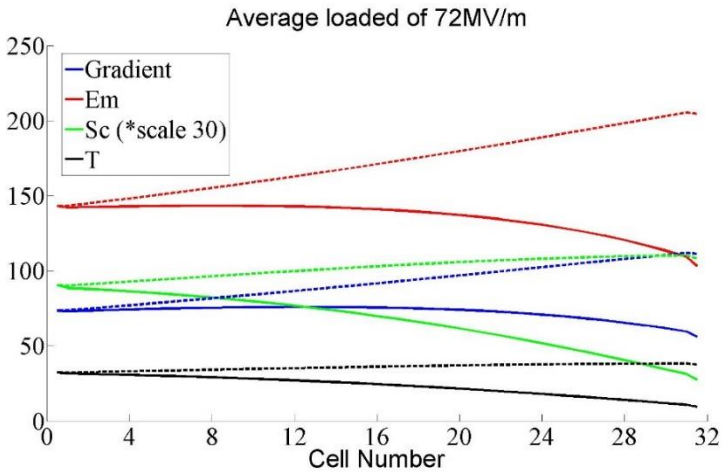
Wakefield suppression:
W_T < 3.4 V/pC/m/mm (s=0.15m)
Beam dynamics requirement:
F_rms < 5





E=380GeV, N_e=5.2*10^9, N_b=352

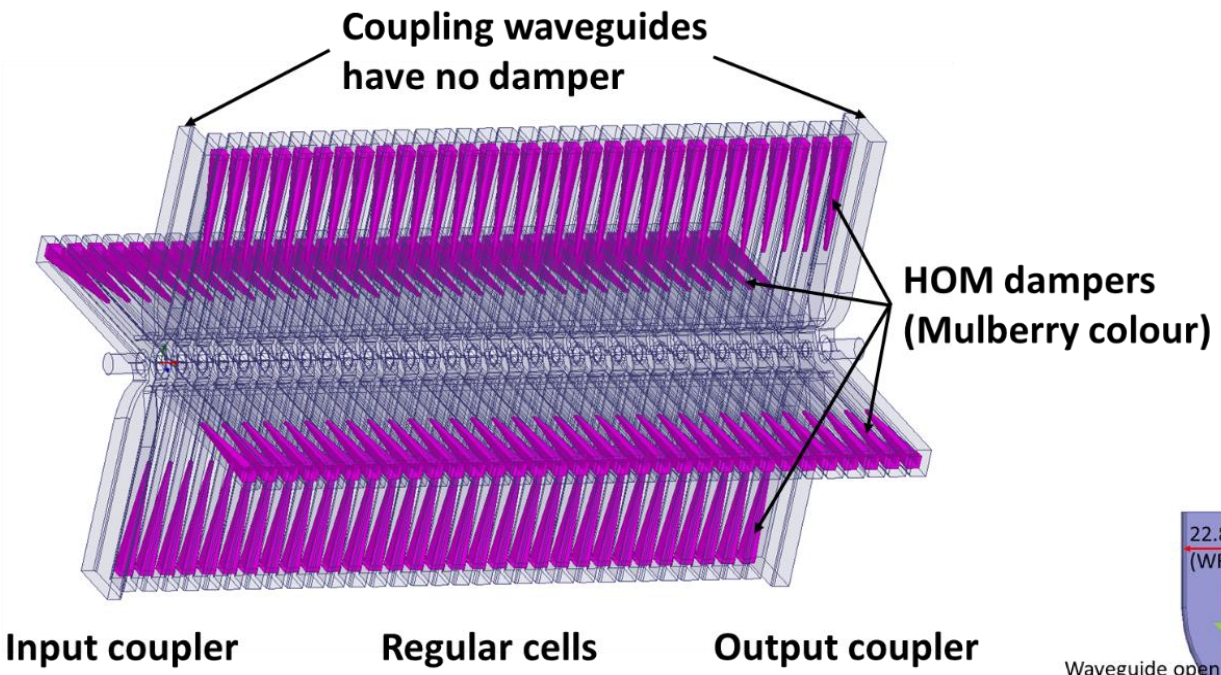
	Envelope:
F_c=1.000	F_c=1.002
F_rms=1.103	F_rms=1.152
F_worst=2.122	F_worst=2.371

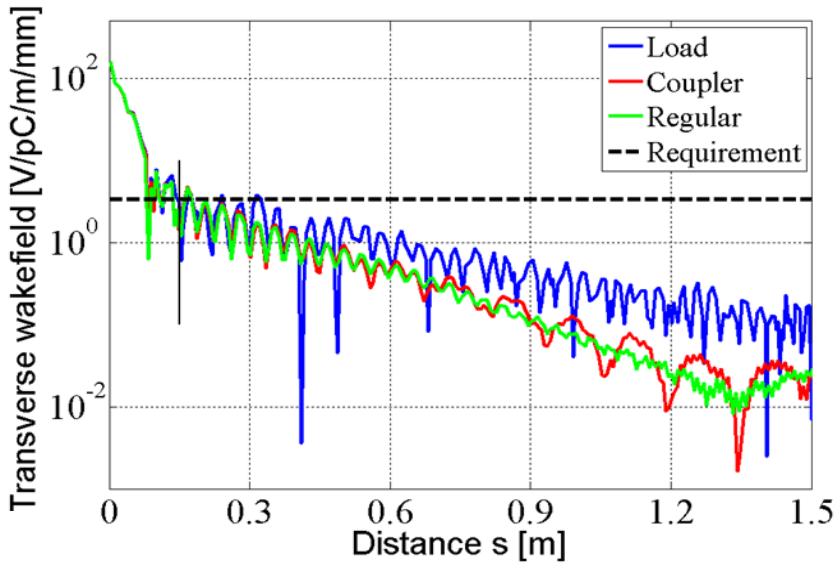


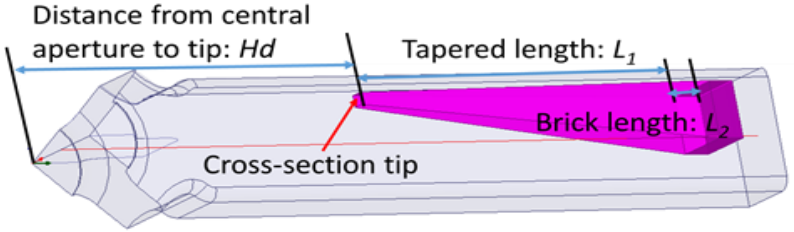
P_in (MW)	59.66 (59.5 for Daniel)
P_out (MW)	6.26
P_in_unloaded (MW)	36.39
t_r (ns)	13.39
t_f (ns)	55.11
t_b (ns)	175.5
RF-to-beam efficiency	39.77%

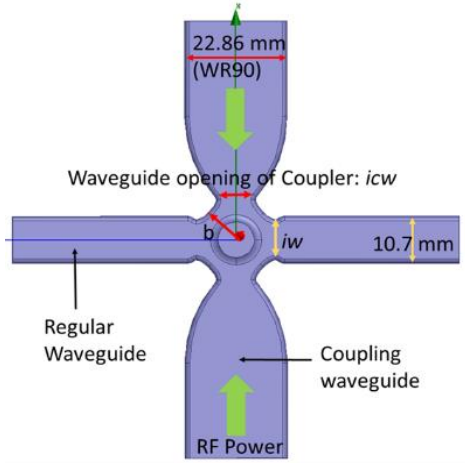
	Accelerating gradient G	Maximum electric field Em	Poynting vector Sc	Temperature rises T
loaded_first cell	73.16	142.14	2.95	31.74
loaded_last cell	59.59	109.35	1.04	10.85
unloaded_first cell	73.80	143.39	3.01	32.30
unloaded_last cell	111.97	205.49	3.68	38.32

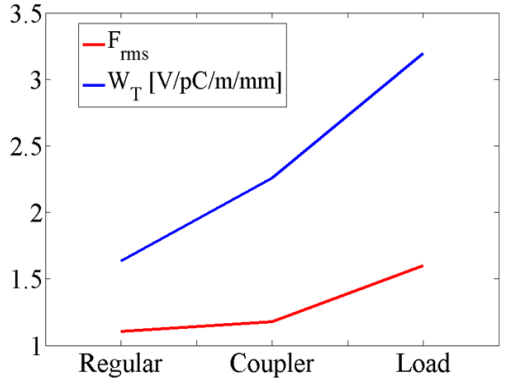
Compact coupler and HOM load design











Applications of high gradient and/or X-band structures

- This is done in a strong collaborations with many institutes around the world.
- More over it is driven by these collaborations

High-gradient S-band structures:

- Backward-Travelling wave accelerating structure for TULIP (TERA-CERN) (under test, see HG17)
- High-gradient S-band structure for Fermi-Trieste upgrade (FERMI-CERN) (under design)
- High gradient CCL structure for PROBE (ULAN – CERN) (under fabrication, see HG17)
- …

X-band deflecting strictures:

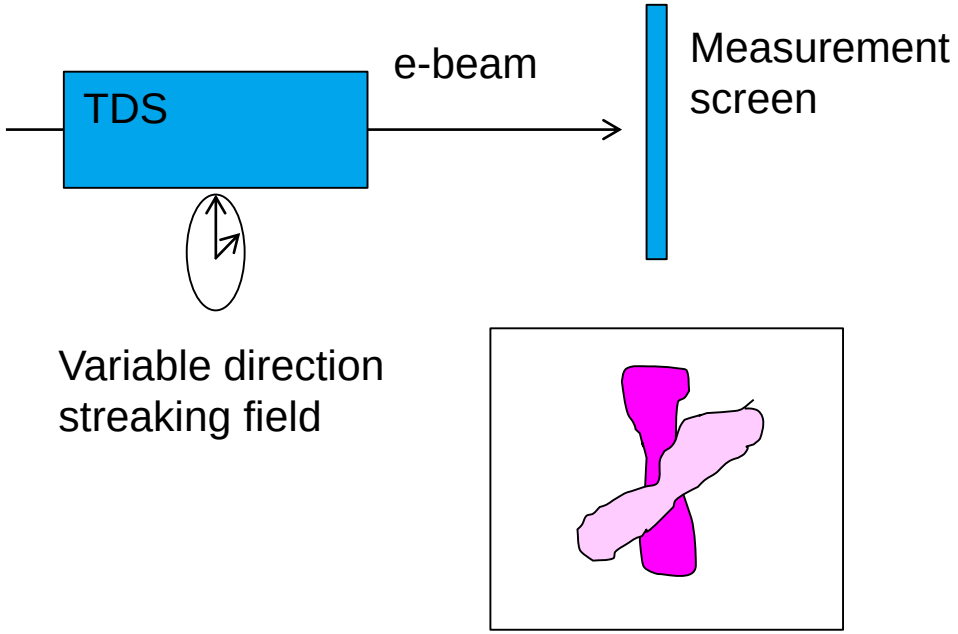
- CLIC carb cavity (ULAN – CERN) (tested and cut)
- X-band TDS with variable polarization (DESY-PSI-CERN) (under design)
- …

X-band accelerating structures:

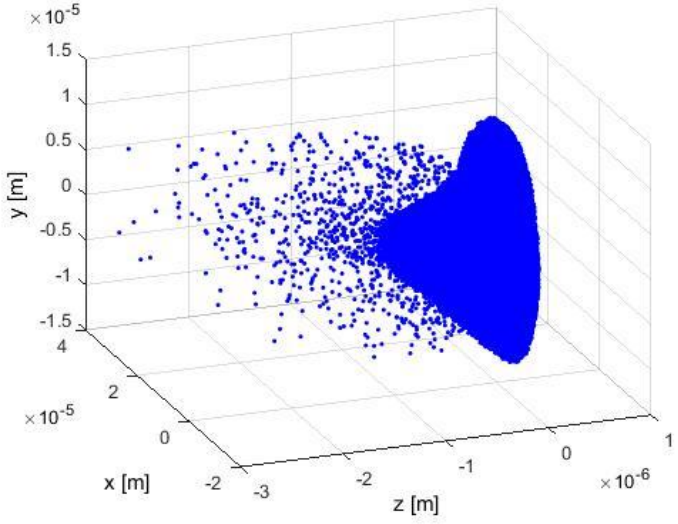
- X-band linearizer for FERMI/SwissFEL (PSI-FERMI-CERN) (in operation)
- X-band linearizer for CALRA (Darsbery-CERN) (see HG17)
- High gradient X-band linac for EuSPARC (INFN-CERN) (under design, see HG17)
- …

Potential applications of the variable polarization TDS

- Next generation TDS
- Exciting new opportunities for e-bunch characterization (e.g. slice emittance measurement on different planes, tomography …)

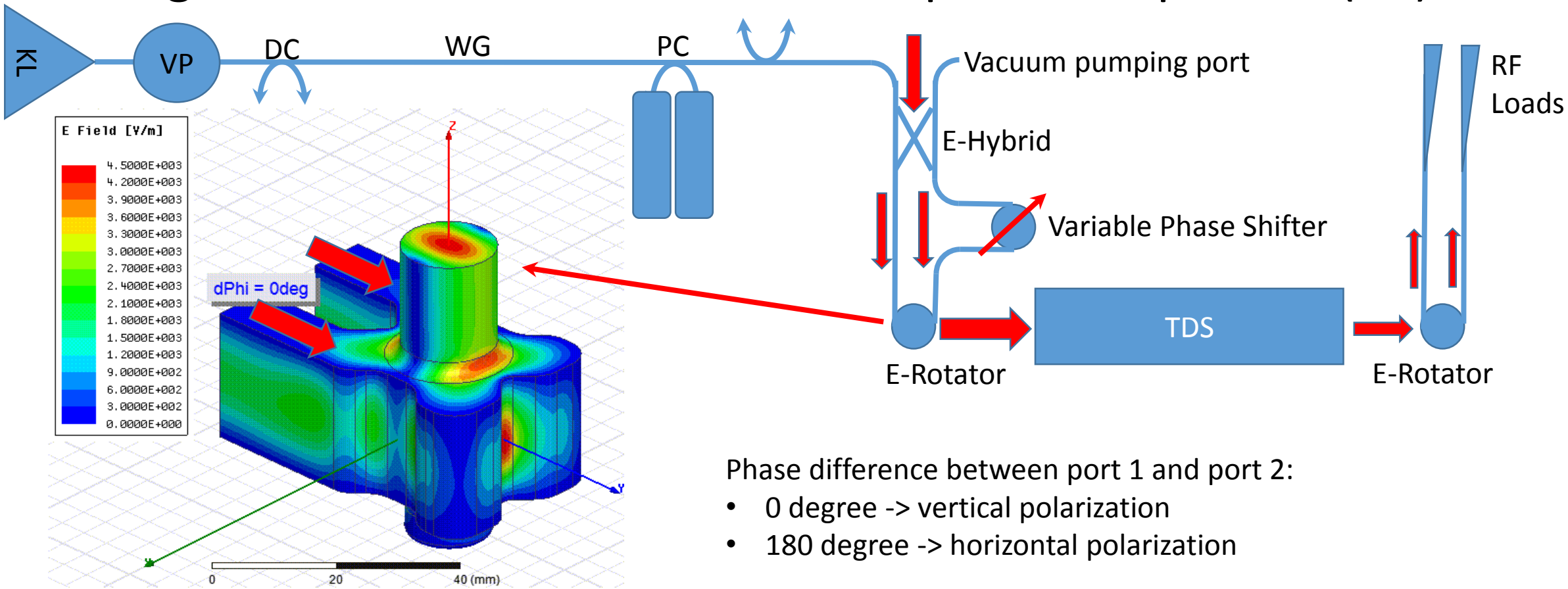


- 3D reconstruction of the charge distribution
- Identify correlations, tilts of the beam distribution in 3D



X-band TDS with variable polarization

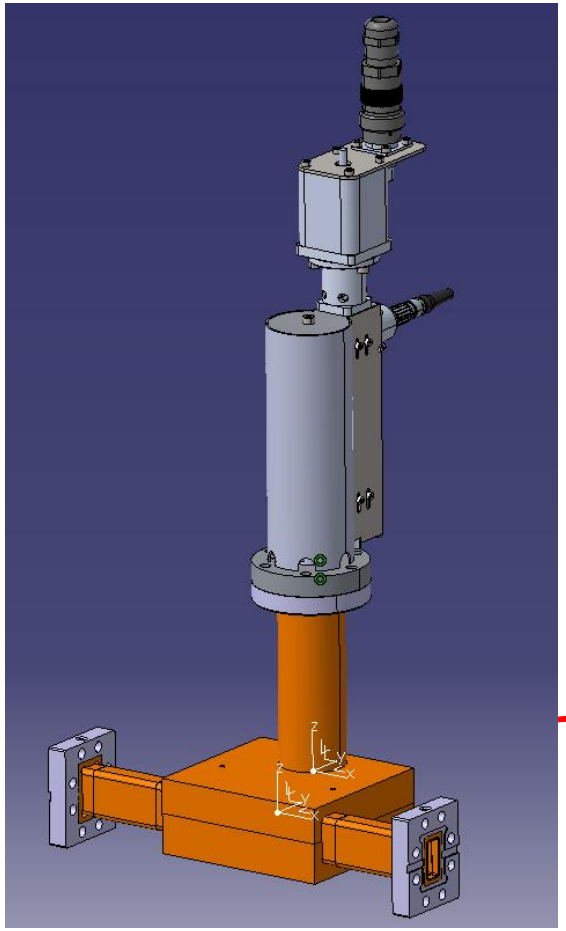
RF design takes into account both TDS + pulse compressor (PC)

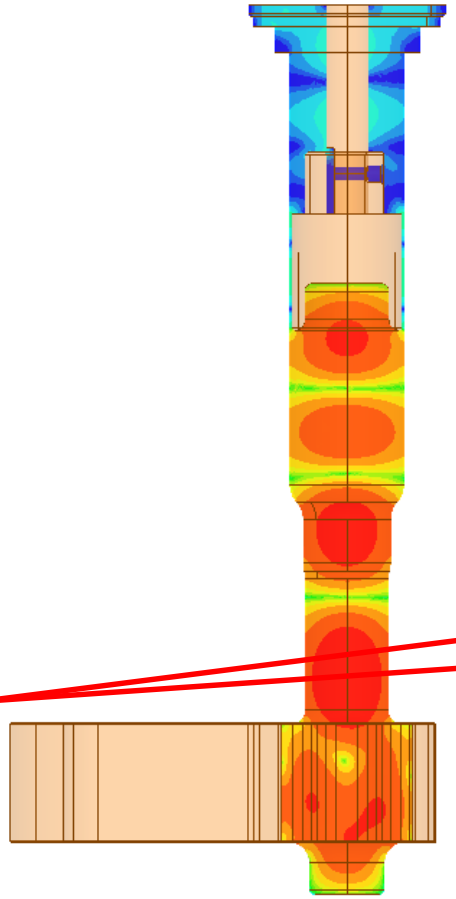


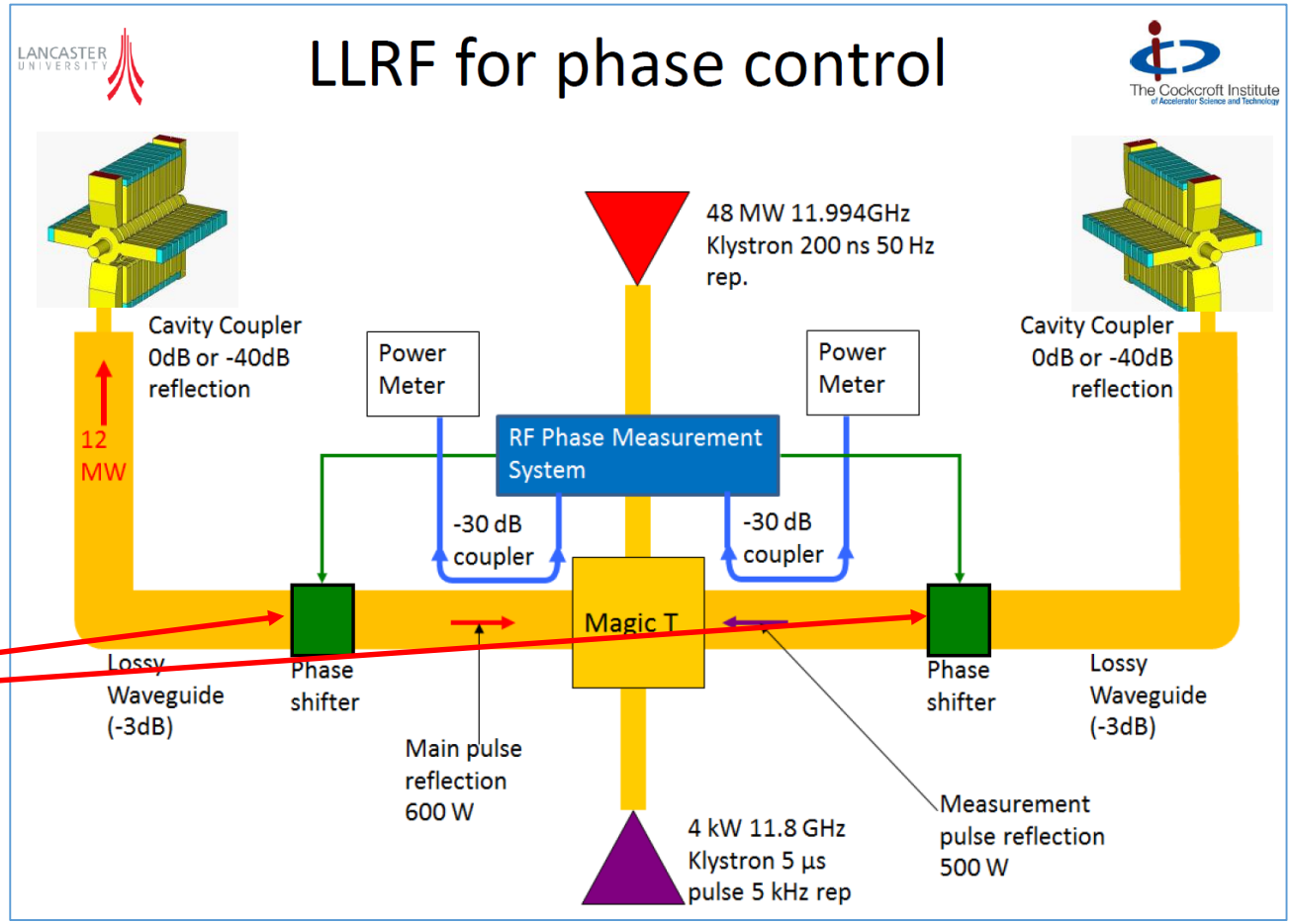
Phase difference between port 1 and port 2:

- 0 degree -> vertical polarization
- 180 degree -> horizontal polarization

RF phase shifter for CLIC crab cavity system



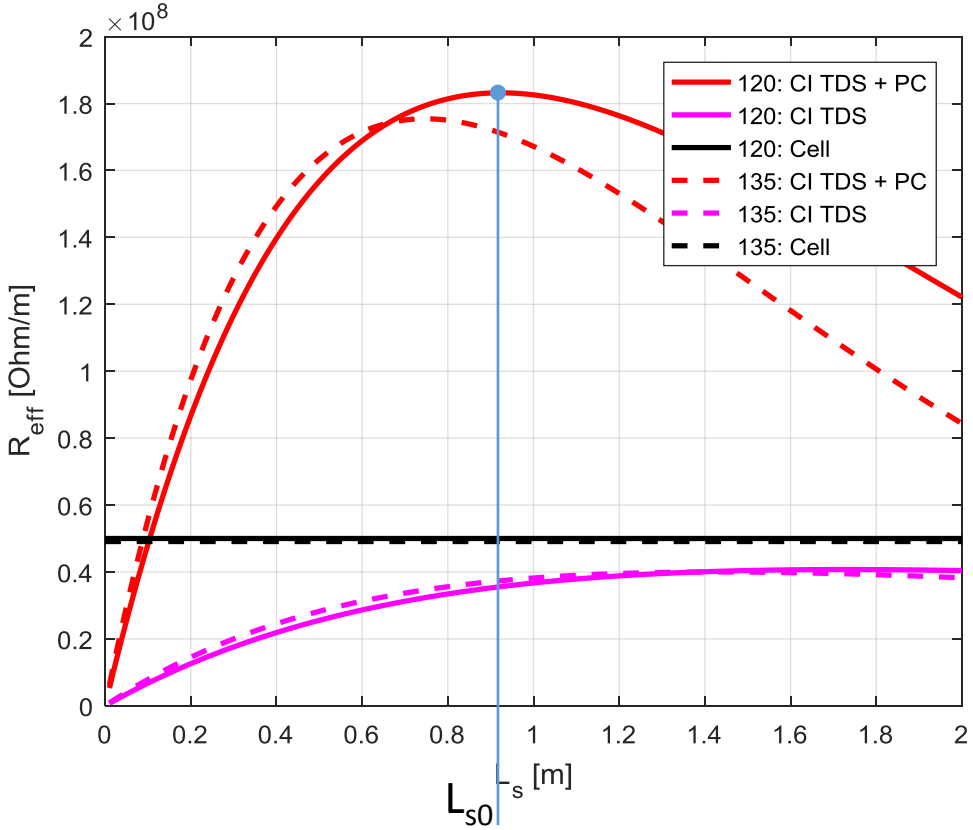


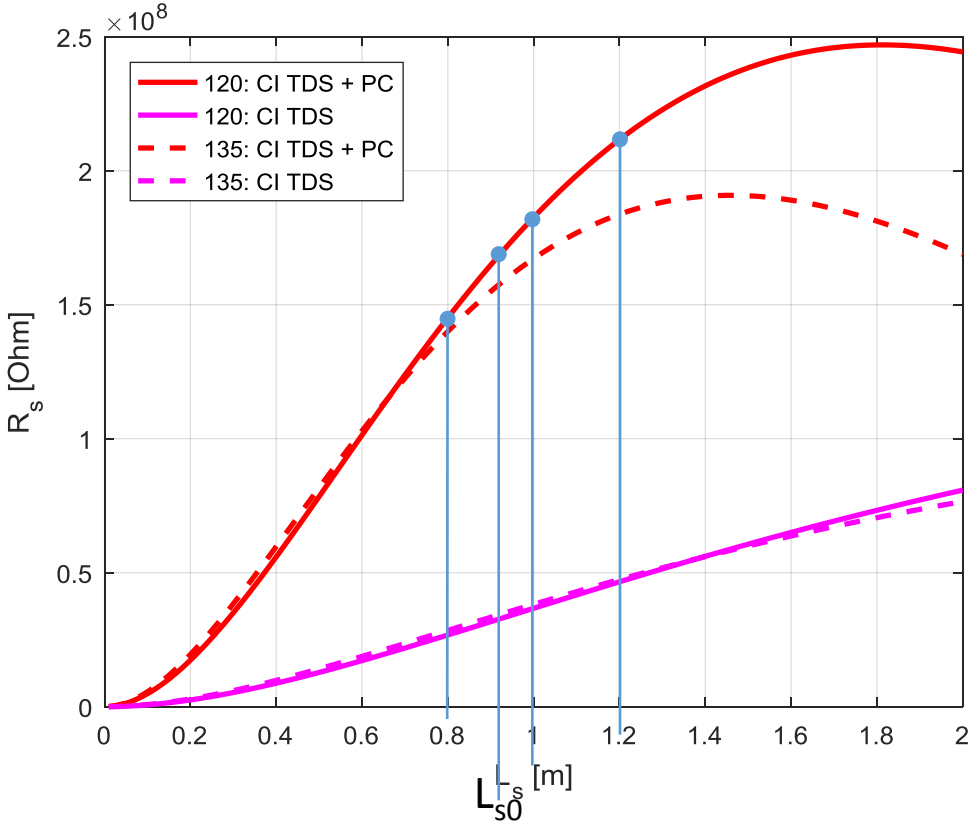


CAD model: Samuel Smith (ULAN)

The variable polarization feature can also be useful in CLIC CC for kick plane correction, might be important for flat beams

Effective shunt impedance of TDS+PC vs structure length





Effective shunt impedance per meter length: R_{eff}.
Optimum active length: L_{s0} = 0.927 m; R_{eff} = 183 MOhm/m

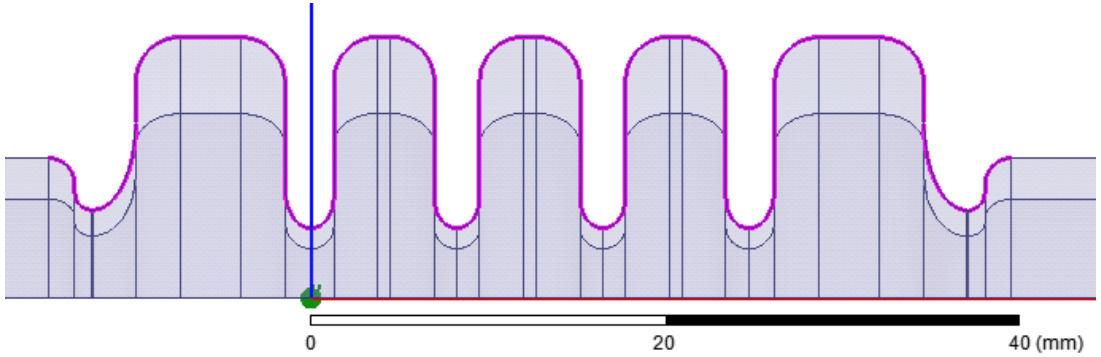
- This is the optimum for a long system with many structure
- **120 deg RF phase advance (solid) is better than 135 deg one (deshed) for Ls > 0.8m**

Effective shunt impedance per structure: $R_s = R_{eff}L_s$ increasing with L_s till 1.6m

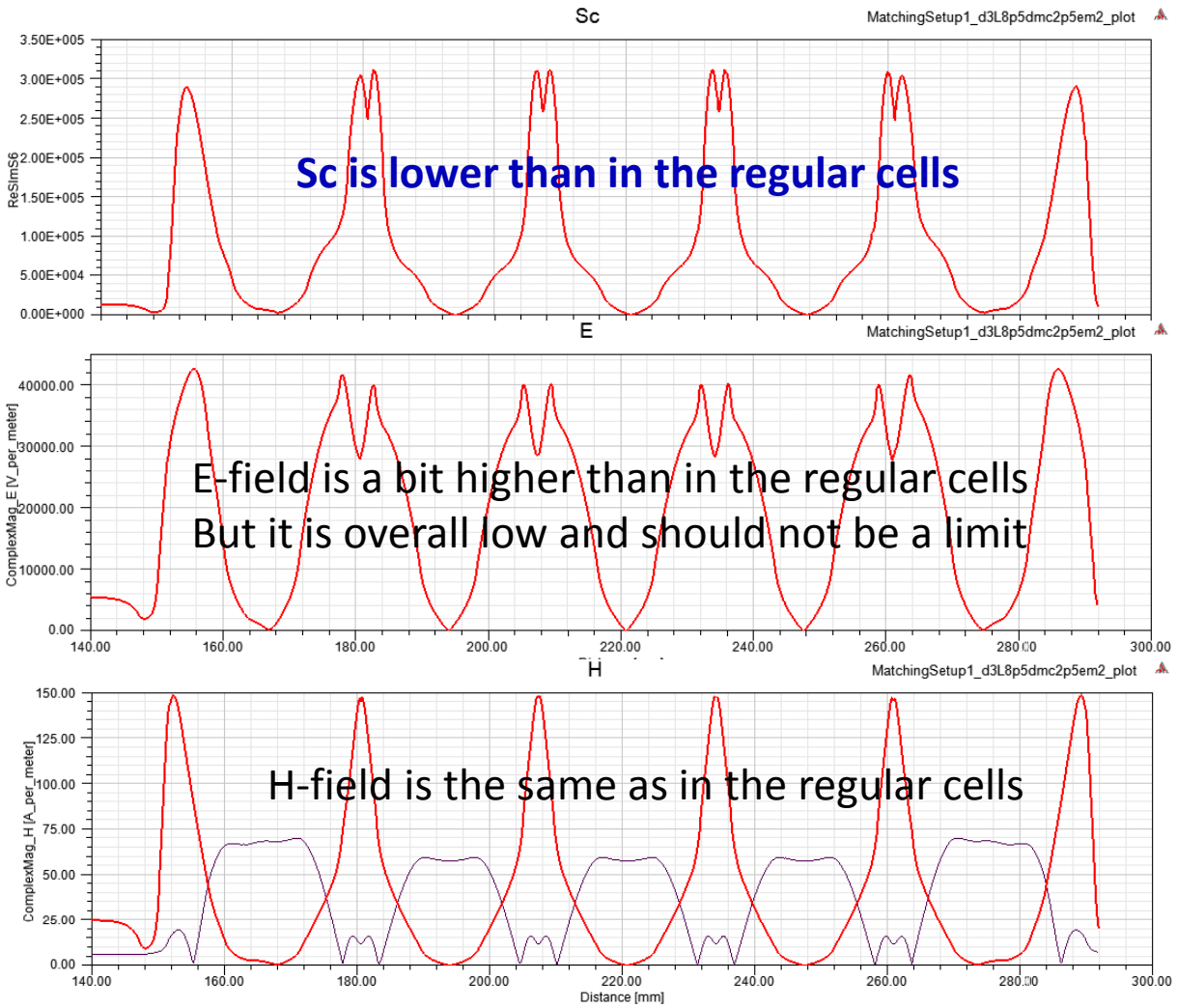
- For a single structure increasing the length results in higher effective shunt impedance per structure.
- **It is better to increase L_s if some length is available in the beam line**

Surface fields in the matching and regular cells

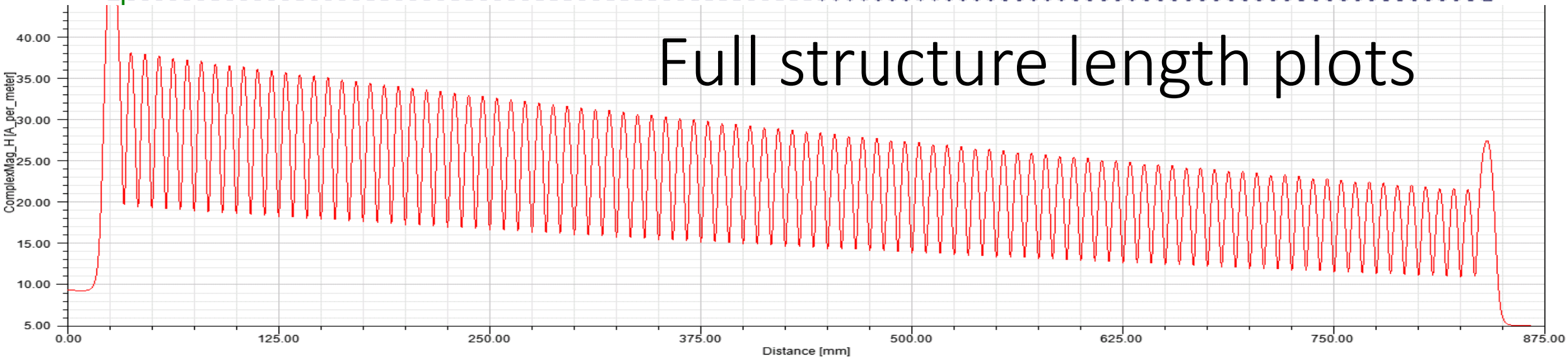
Distribution of the Sc, E and H fields along the polyline shown below for Pin = 4W

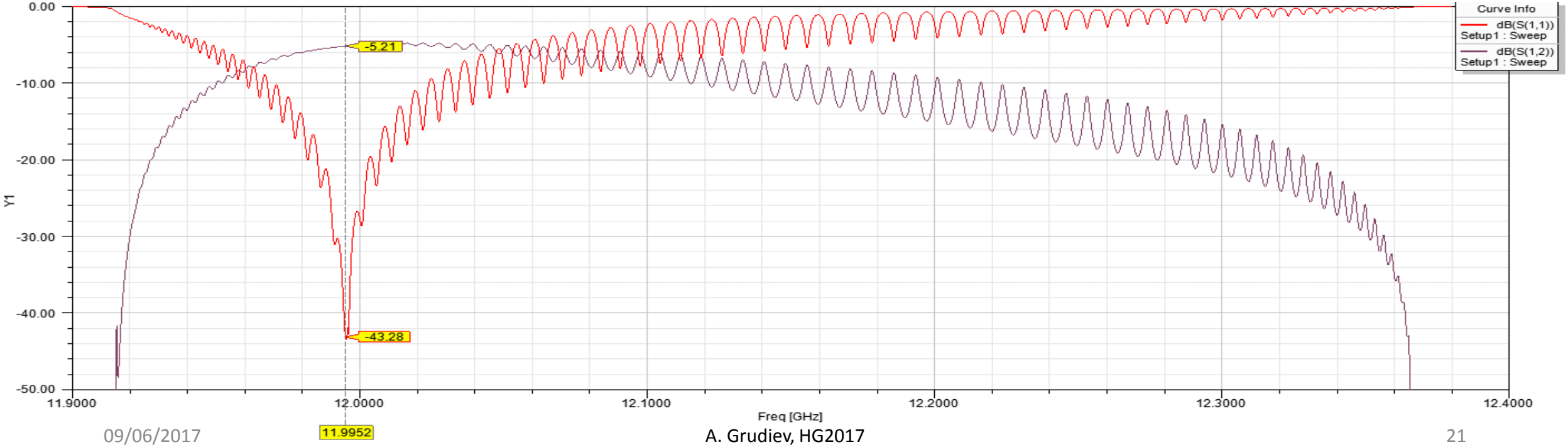


Max Surface Fields	at Pin=1W	at Pin=50MW
E [MV/m]	0.021	150
H [kA/m]	0.075	530
S [MW/mm^2]	8e-8	4



Full structure length plots

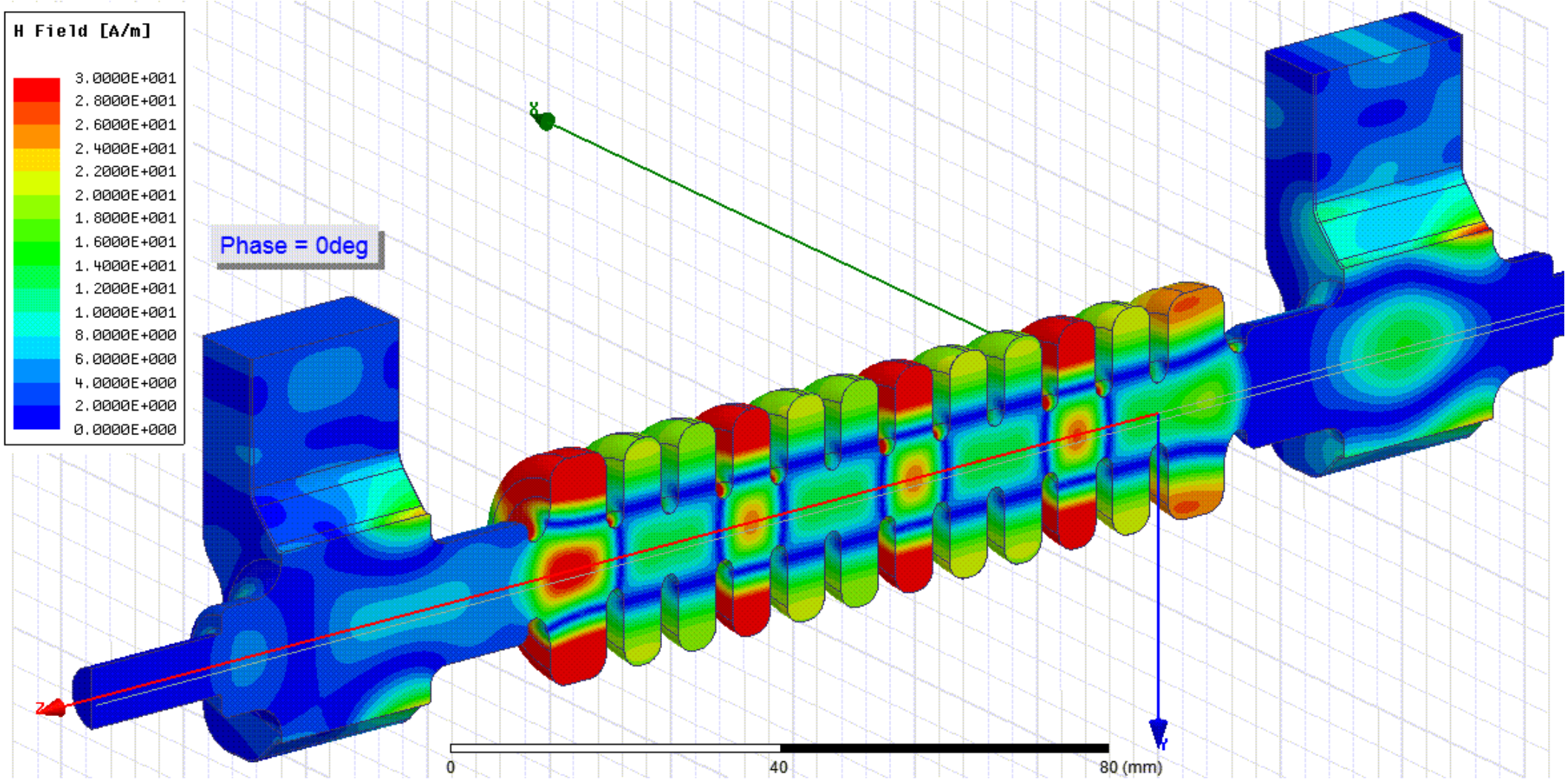




Parameters of X-band TDS

Parameters X-band TDS system					
f_0 [GHz]	11.9952				
T [degree C]	30				
Cell parameters					
a [mm]	4				
$\Delta\phi_0$ [degree]	120				
Q	6490				
v_g/c [%]	-2.666				
R_x [MΩ/m]	50				
TDS along parameters	Base line		Option		
N_c	96		120		Number of regular cells
L_s [m]	0.8		1		Active length
L [m]	0.98		1.18		Preliminary total length (flange2flange)
t_f [ns]	104.5		129.5		Filling time
R_s [MΩ]	27.3		37.5		Shunt impedance of TDS
V_d [MV] @ P_k = 6 MW	12.8		15.0		
TDS+PC parameters					PC = Pulse compressor
Q_0	180000				Q-factor of the PC
Q_e	20100	37800	20100	37800	External Q-factor of PC
t_k [ns]	1500	6000	1500	6000	Klystron pulse length
R_s [MΩ]	145	159	182	209	Effective Shunt impedance of TDS+PC
V_d [MV] @ P_k = 6 MW	29.5	30.9	33.0	35.4	

H-field in Backward Travelling Wave TDS for N_c=10



Outlook