380 GeV CLIC power consumption estimate

Alexej Grudiev (CERN)

11/12/2023

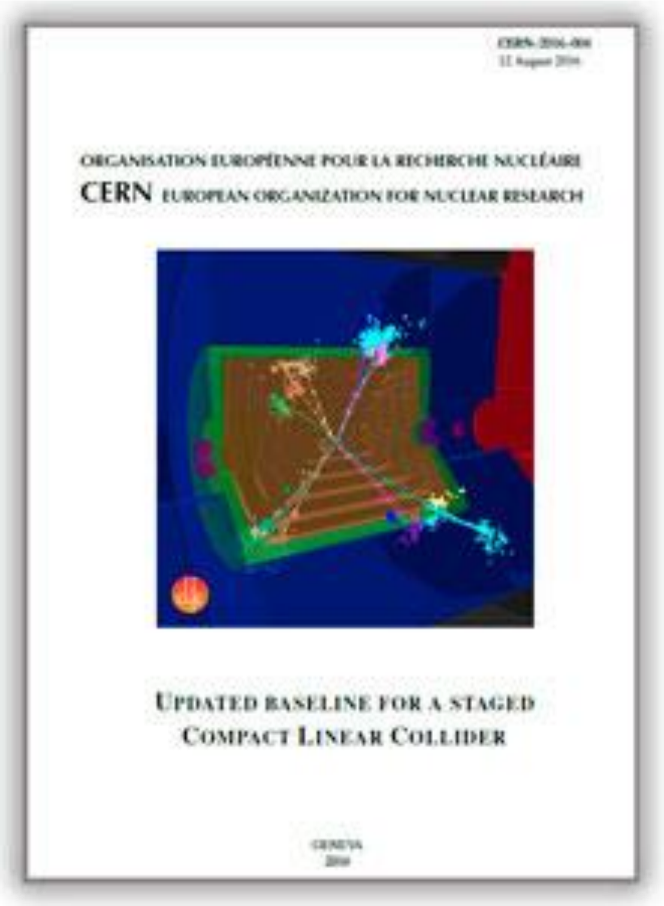
Outline

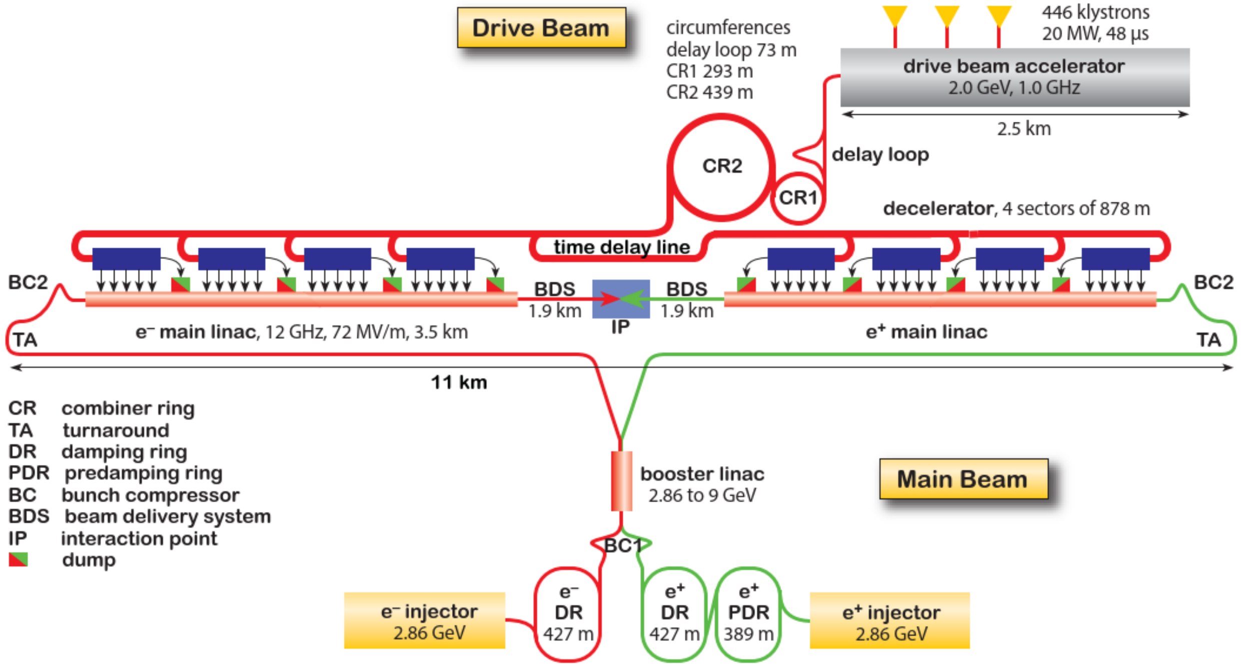
- Reminder
  - 2016 Power consumption estimate for the 1st stage optimization
  - 2018 Power consumption estimate for the Project Implementation Plan (PIP)
- Update for 100 Hz operation for high luminosity studies in 2019
- Update for the new DR design, 2021
- Update for the new DB klystron parameters, 2022
- Summary

N.B. In the following slides power consumption estimate always refer to the CLIC 380 GeV Drive beam baseline option

380 GeV CLIC layout and power consumption

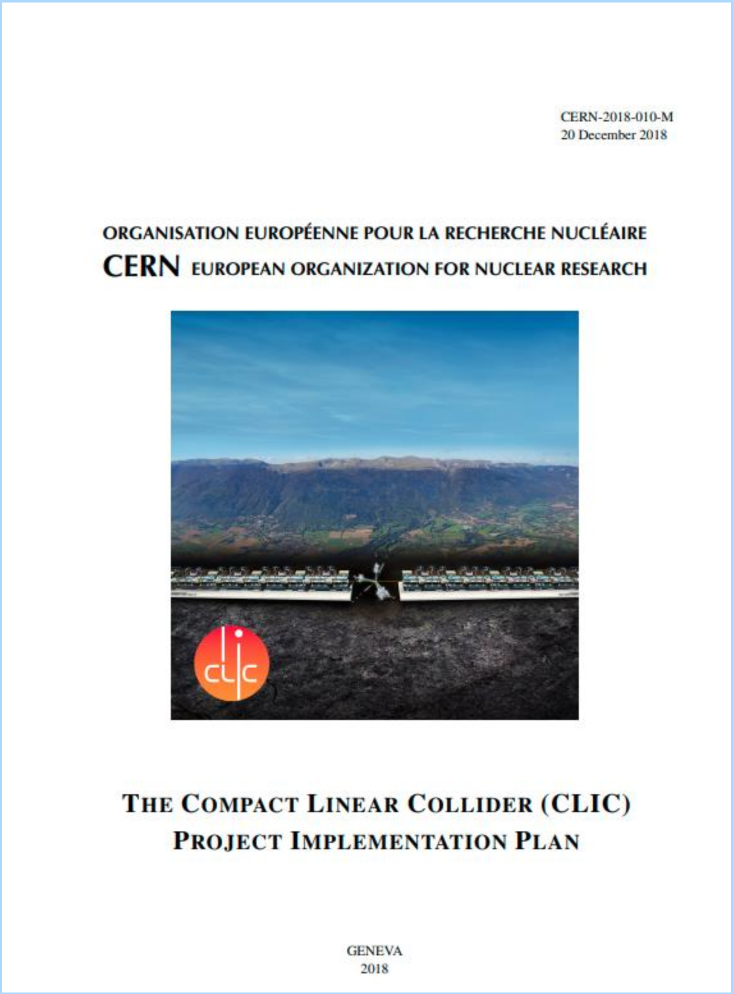
Updated baseline for a Staged Compact Linear Collider, CERN-2016-004, 2016





- Total power consumption of 380 GeV CLIC was estimated to be **252 MW**
- It was estimated using parameterized model [*] derived from the CDR power estimates at 3, 1.5 and 0.5 TeV stages and used for 1st stage optimization
- * B. Jeanneret, CLIC Total Electrical power: a parametrization, CERN-ACC-Note-2013-0020, 2013

Power consumption estimate for Project Implementation Plan (PIP) in 2018


CERN-2018-010-M
20 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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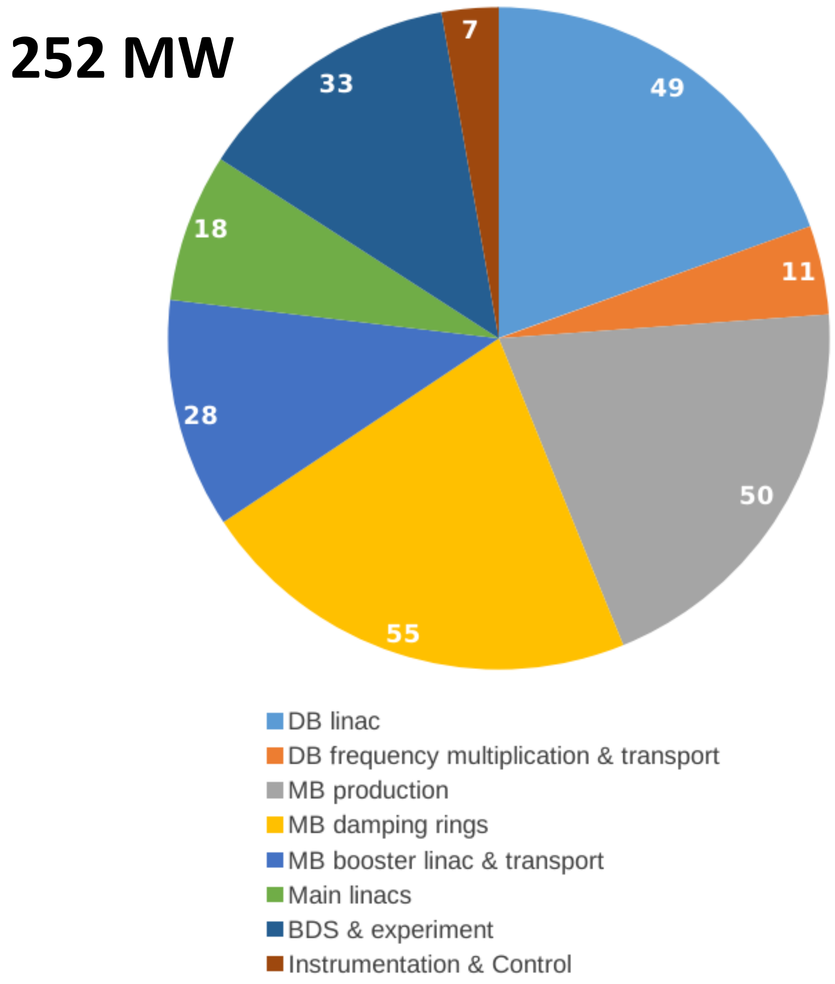
THE COMPACT LINEAR COLLIDER (CLIC)
PROJECT IMPLEMENTATION PLAN

GENEVA
2018

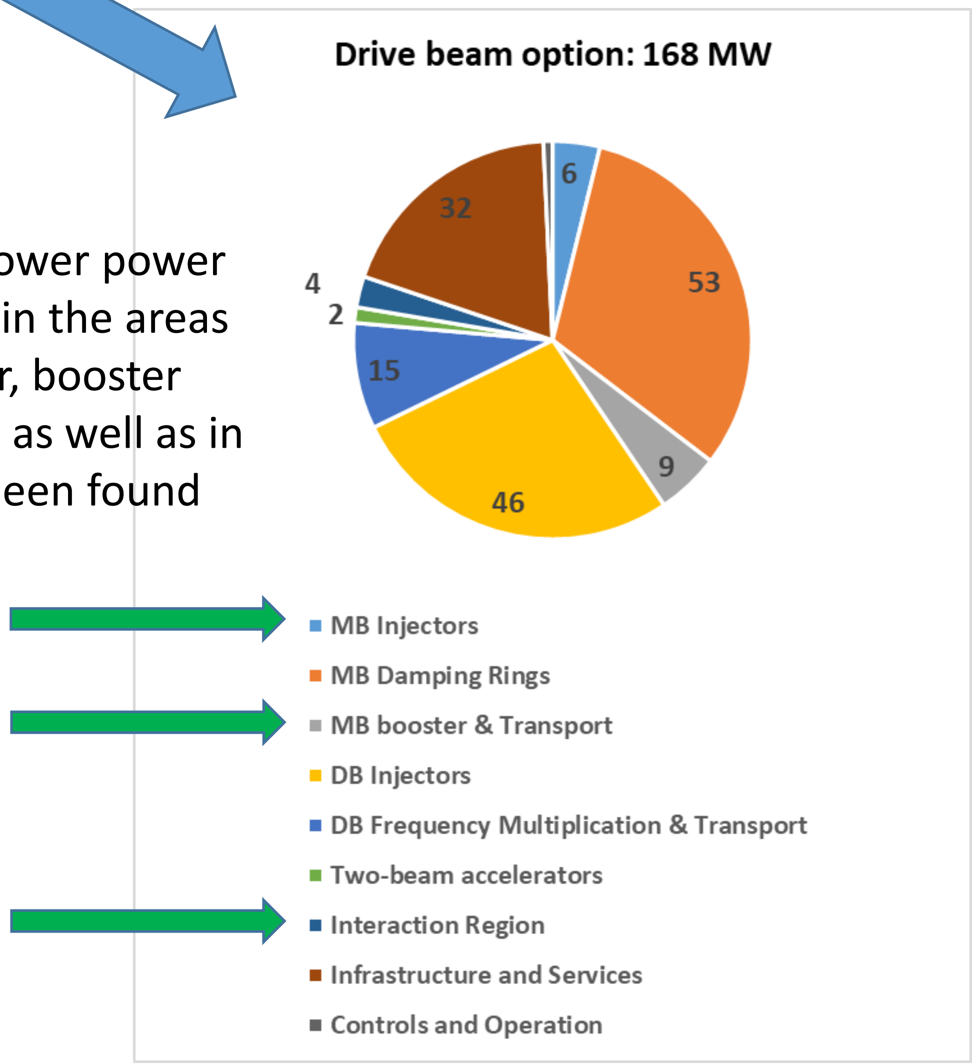
- **<u>Motivations:</u>**
- Parameterized model used in 2016 required verification at 380 GeV
- Several changes in the design parameters had been made:
  - Development of high efficiency klystrons
  - (Pre-)Damping rings bunch-to-bunch spacing reduced from 1 ns to 0.5 ns
  - Drive beam energy is reduced from 2.4 to 2.0 GeV
  - Different design of the BDS at 380 GeV
- Alternative klystron-based option of the first stage at 380 GeV needed power consumption estimate as well.

- **<u>Assumptions</u>**
- Project breakdown structure (**PBS**) of the **costing tool** has been used in order to insure the consistency of the power and the cost estimate
- **Expected Operating** (not the specification) **values** have been consistently used for the RF and magnet systems

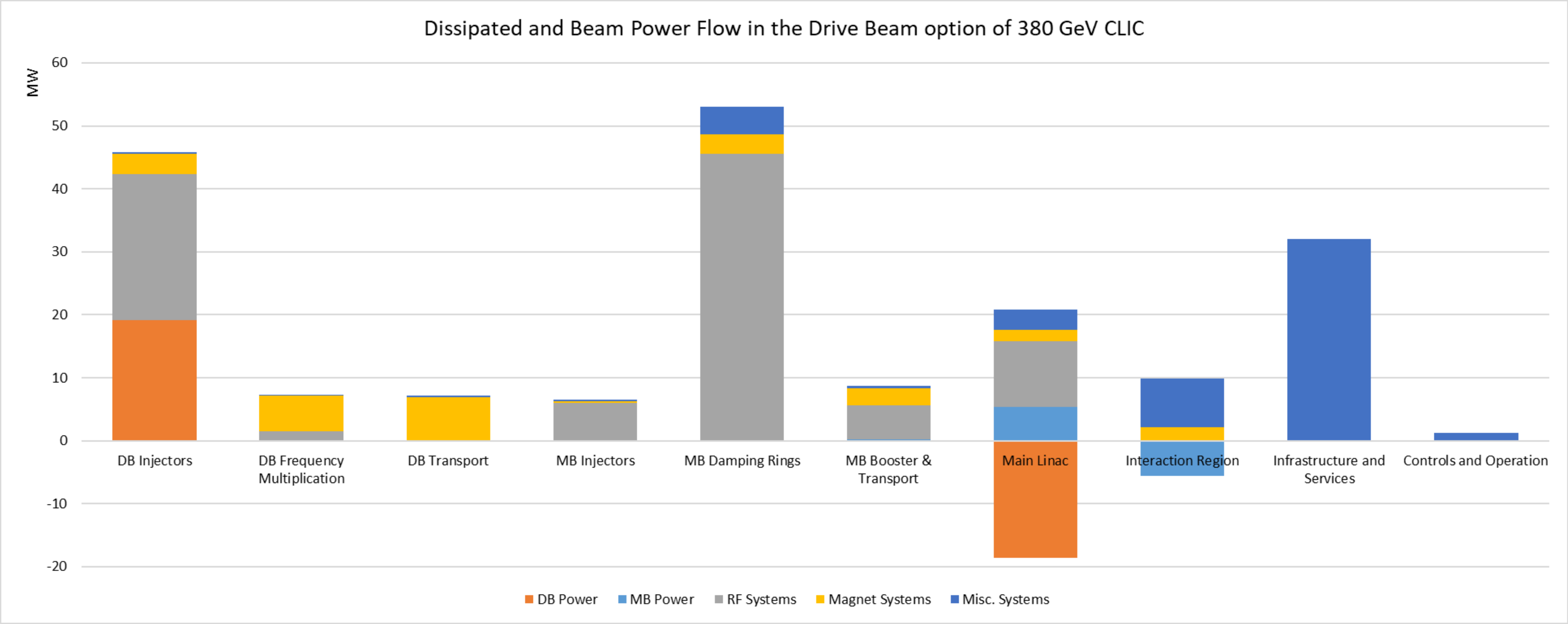
Comparison: 2016 vs 2018



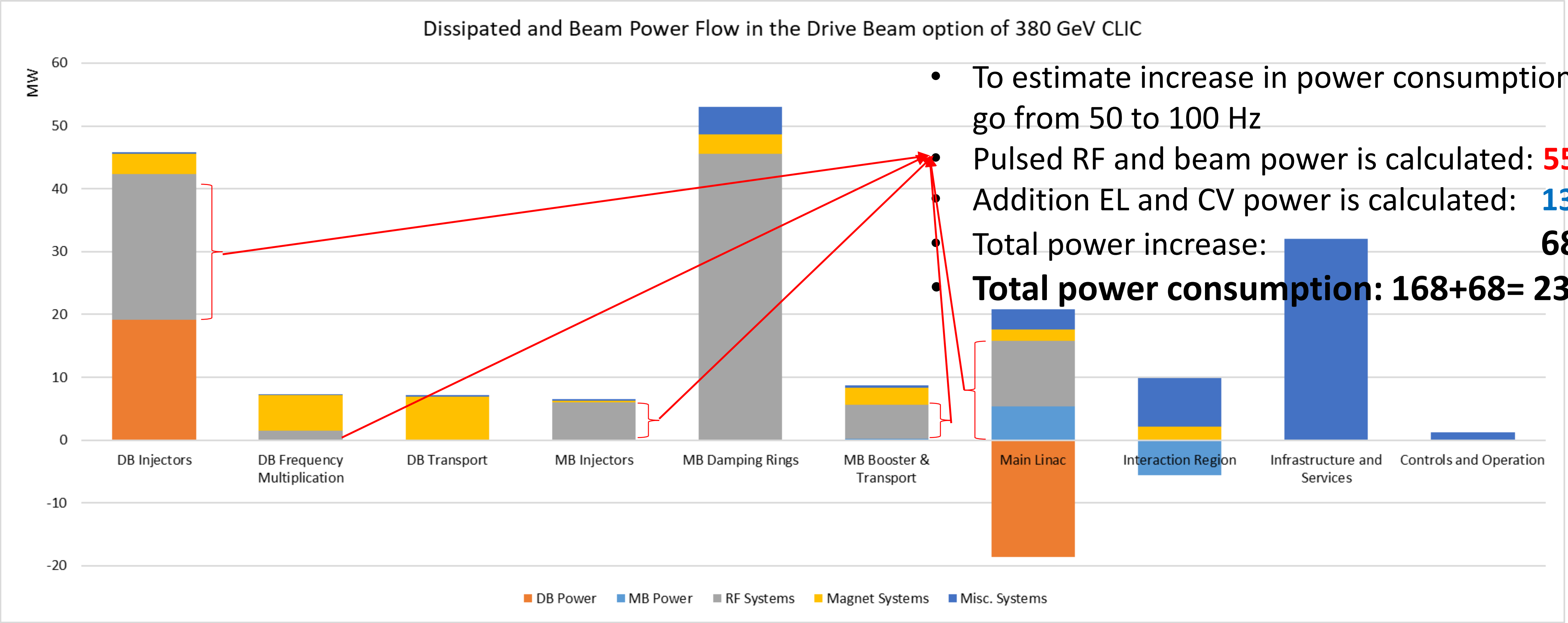
Significantly lower power consumption in the areas of MB injector, booster and transport as well as in the BDS has been found



Distribution of dissipated and beam powers



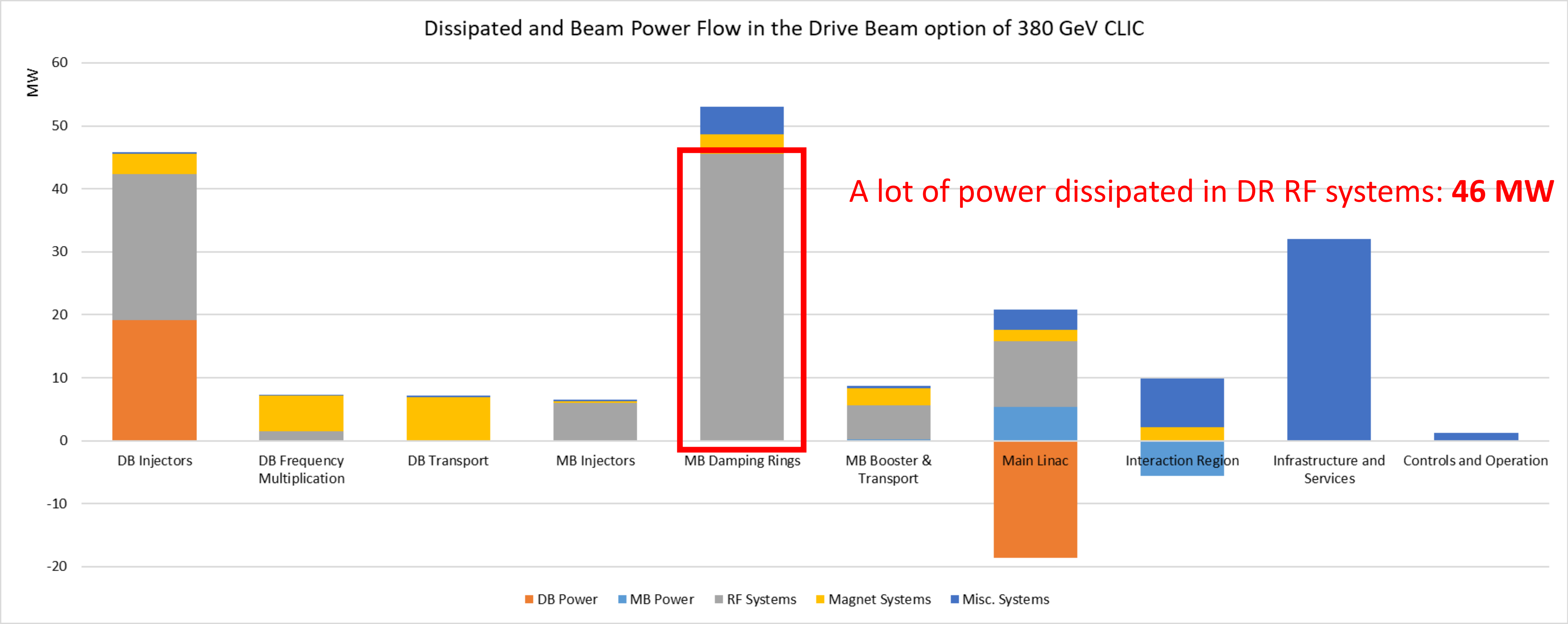
Power increase for operation mode at 100 Hz



- To estimate increase in power consumption when go from 50 to 100 Hz
- Pulsed RF and beam power is calculated: **55 MW**
- Addition EL and CV power is calculated: **13 MW**
- Total power increase: **68 MW**
- **Total power consumption: 168+68= 236 MW**

This estimate was used in CLIC – Note – 1143: HIGH-LUMINOSITY CLIC STUDIES

CLIC DRs



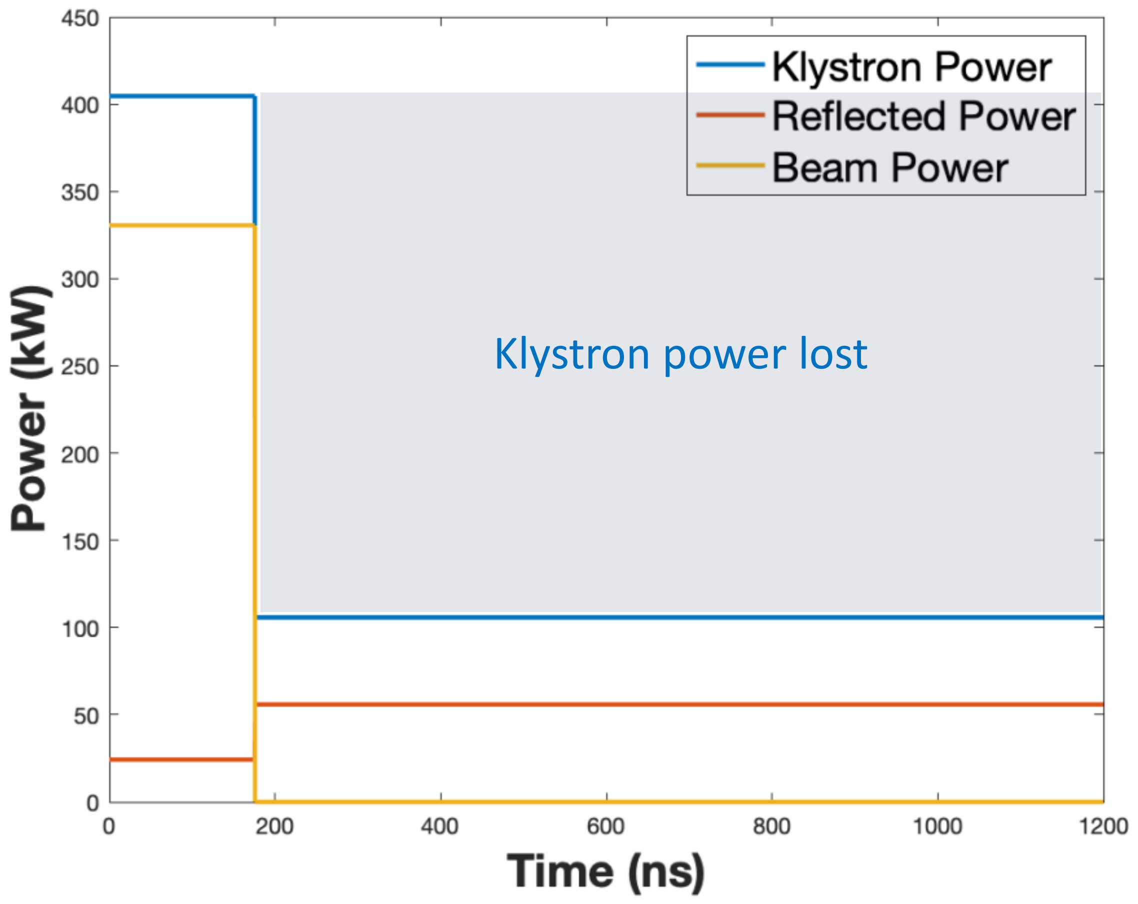
Dissipated and Beam Power Flow in the Drive Beam option of 380 GeV CLIC
MW
60
50
40
30
20
10
0
-10
-20
DB Injectors
DB Frequency Multiplication
DB Transport
MB Injectors
MB Damping Rings
MB Booster & Transport
Main Linac
Interaction Region
Infrastructure and Services
Controls and Operation
DB Power
MB Power
RF Systems
Magnet Systems
Misc. Systems
A lot of power dissipated in DR RF systems: **46 MW**

CLIC DR summary of PIP baseline

Cavity type	ARES
RF frequency [GHz]	**2**
Cavity R/Q [Ω]	**7.5**
Number of cavities	32
Cavity Q0	55000
BL compensation method	feedforward
Beam phase variation [º]	**~1**
Peak input power [kW/cavity]	405
Total peak input power [kW]	12960

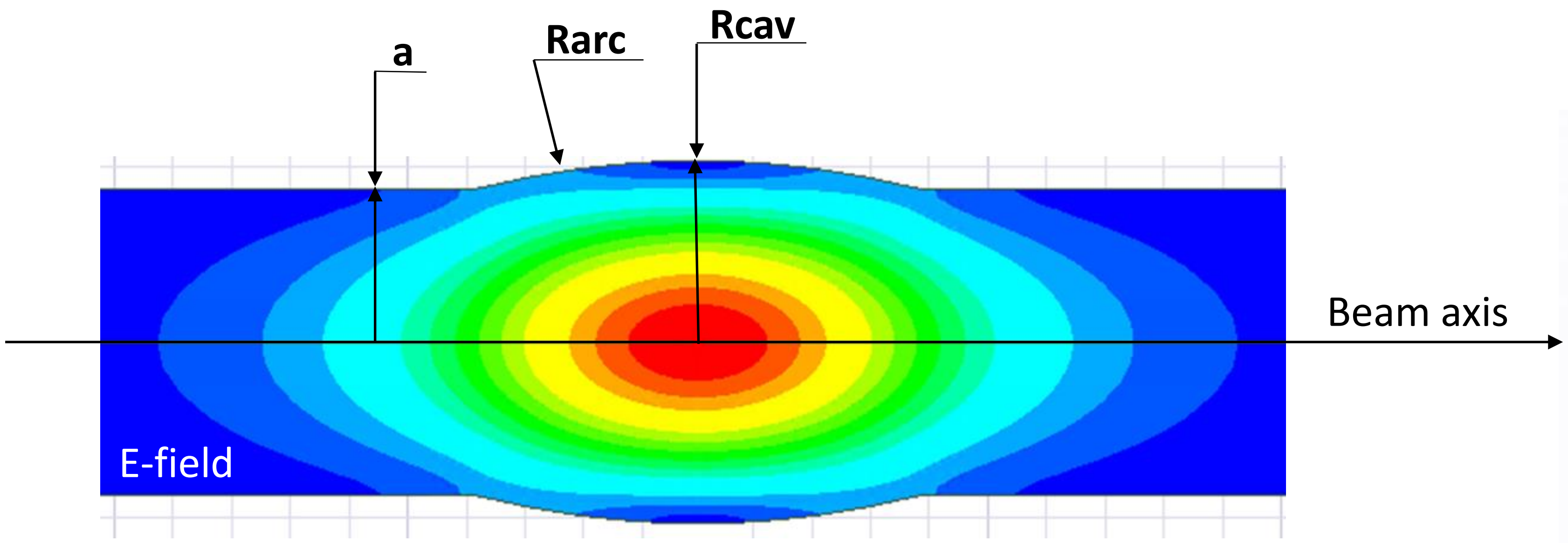
Strong transient beam loading effects cause:

- **Very high peak power**
- **Larger klystron bandwidth**
- **Strong peak power modulations on each turn**
- **Inefficient due to most of average power lost**



(NIMA V985, 164659, 2021)

Novel cavity: Barrel Cell Cavity (BCC) geometry for ultra low R/Q

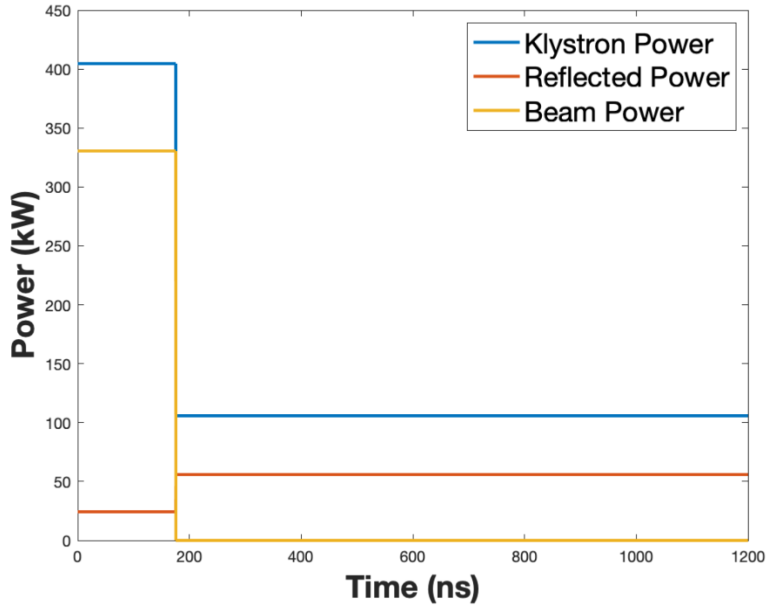


- **Large aperture => low R/Q**
- **Long cell: ~λ   => low transit time factor**
- **Low field on the cavity wall**

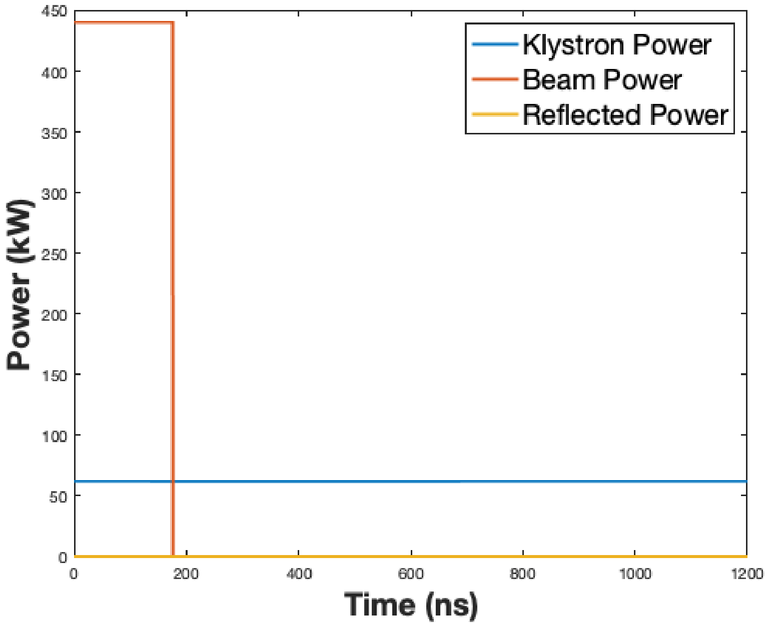
More details in: CLIC-note-1173,
or in [rf development meeting (22 September 2021)]

DR Comparison: PIP baseline vs BCC

PIP baseline



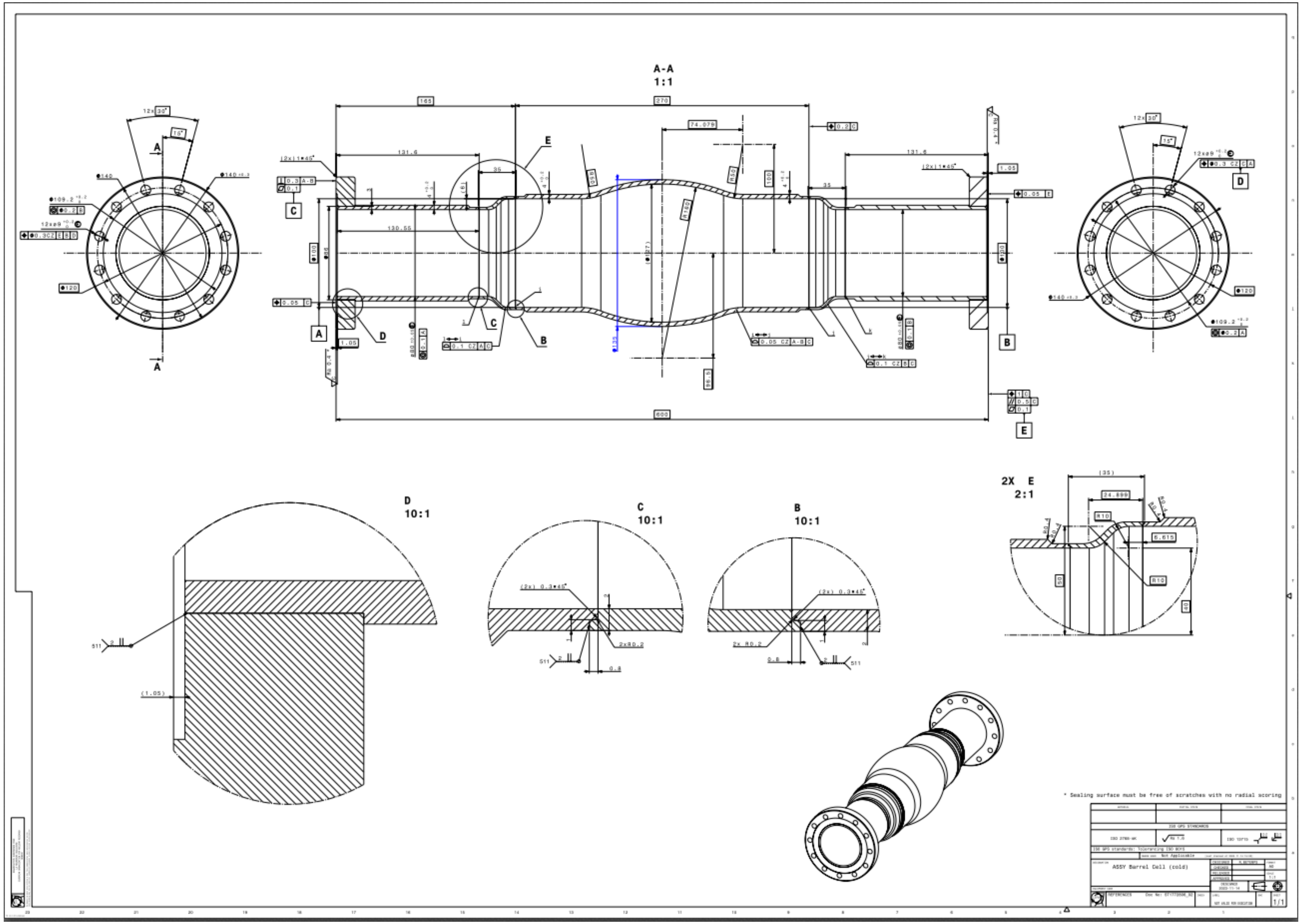
BCC design #1



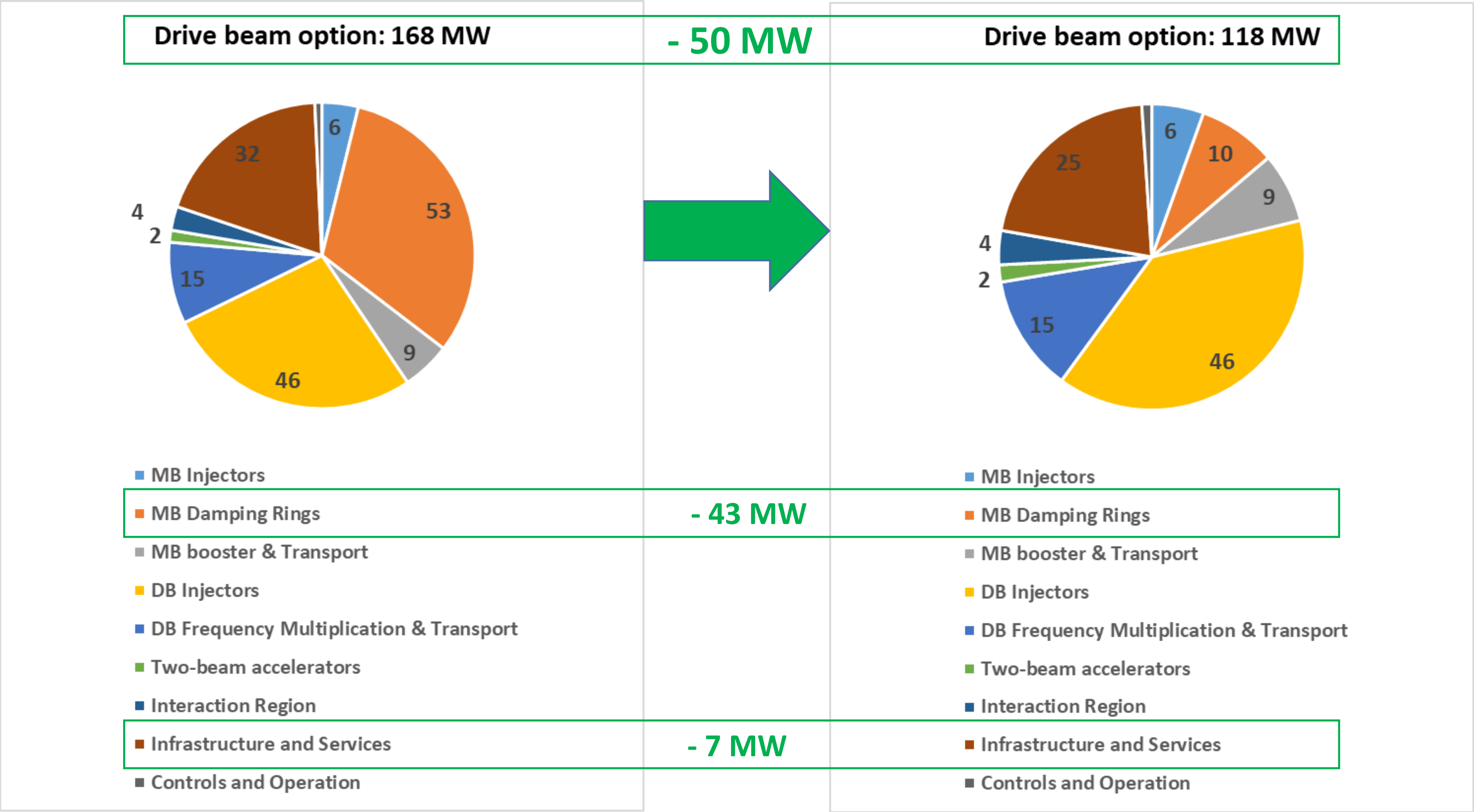
Cavity type	PIP b.	BCC
Cavity R/Q [Ω]	**7.5**	**0.6**
N of cavities	32	24
Peak input power [kW/cavity]	405	62.2
Total peak input power [MW]	**13**	**1.5**

- **RF power match the average beam power => efficient**
- **No klystron power modulation => no large bandwidth**
- **Peak power requirements are SIGNIFICANTLY reduced => cost, size**

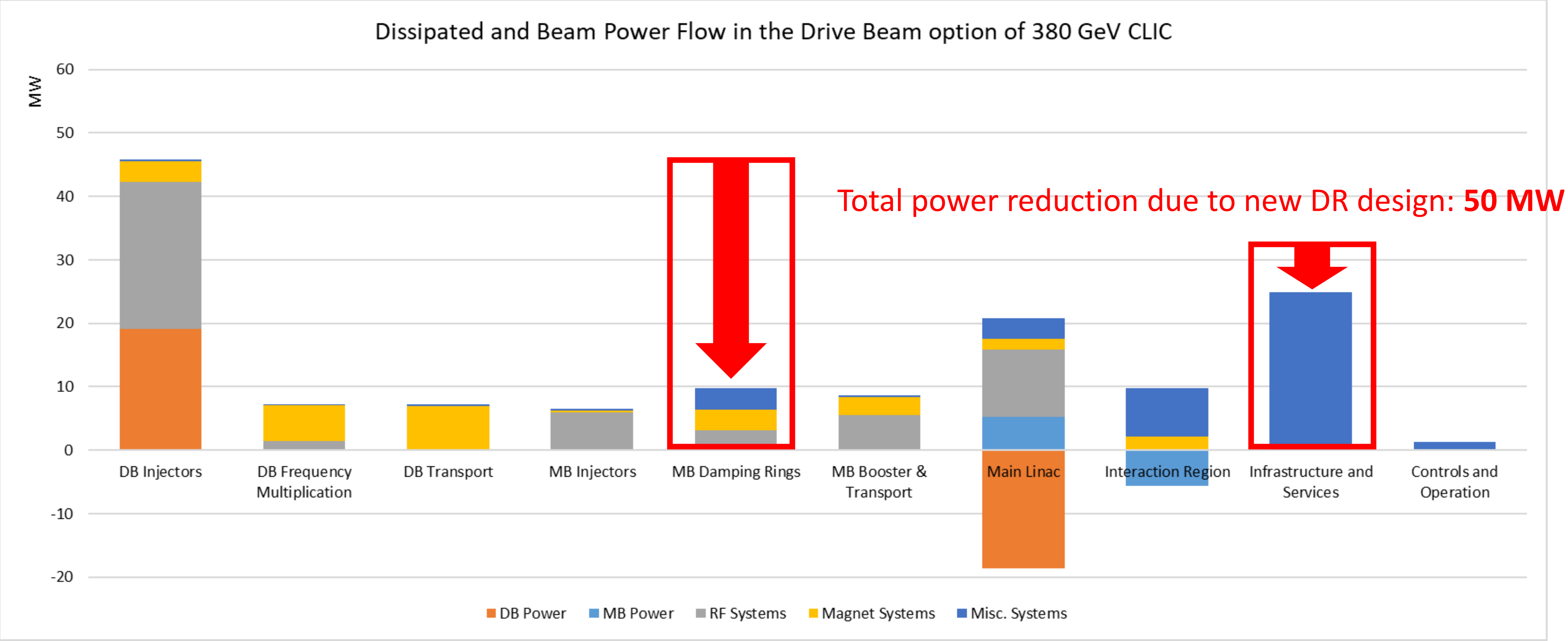
BCC prototype planned to be built at CERN and tested at FNAL 2024



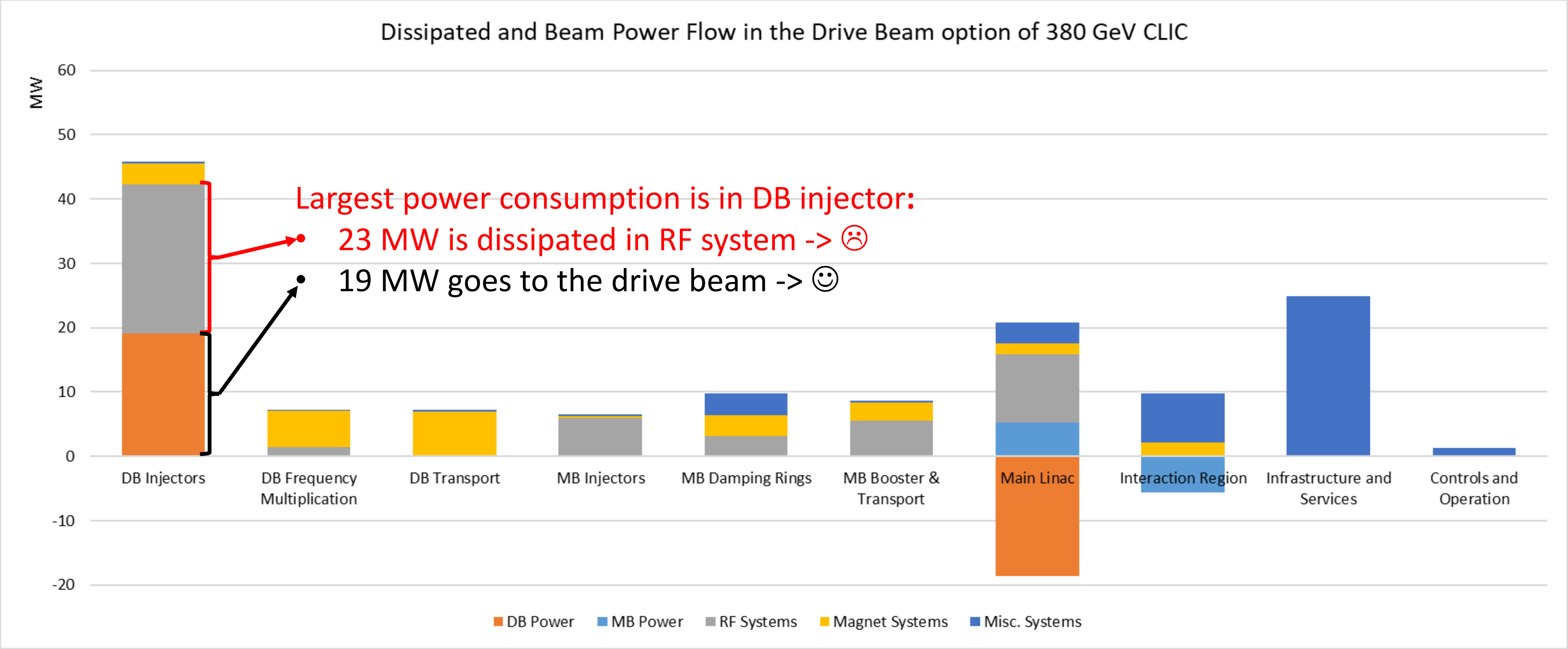
Comparison DR: PIP baseline vs BCC design



CLIC DRs: power reduction due to BCC design



Drive beam injector complex



New ideas for CLIC 1GHz klystron for DB linac

High Efficiency 24 MW, 1 GHz, CLIC TS MBK performance summary (PIC CTS/3D)

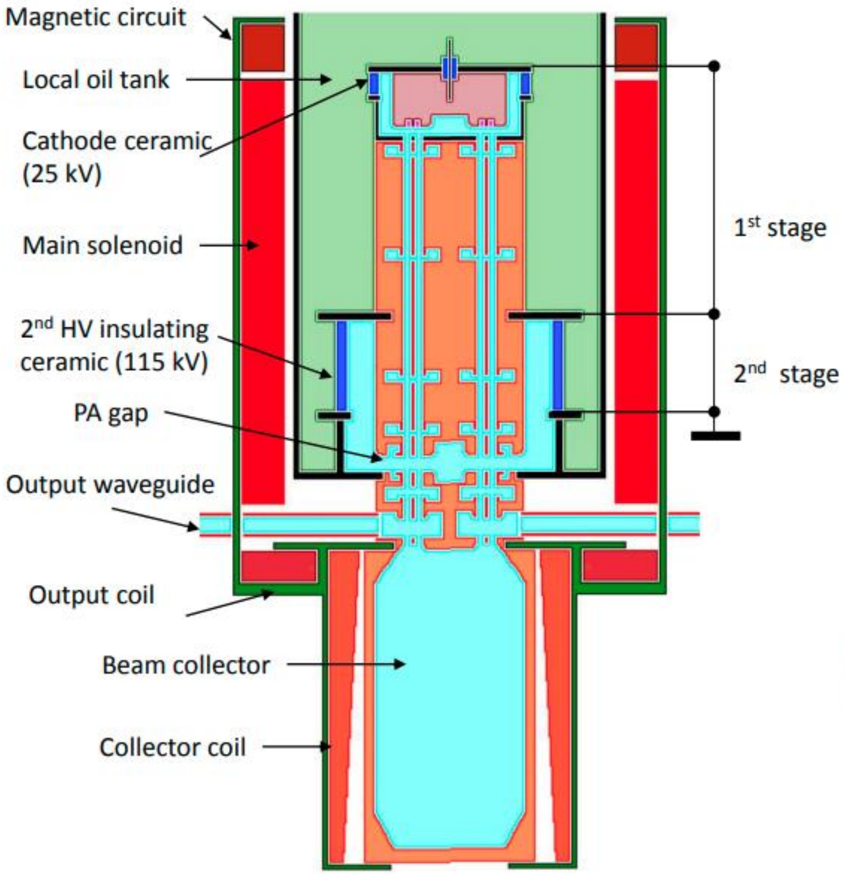
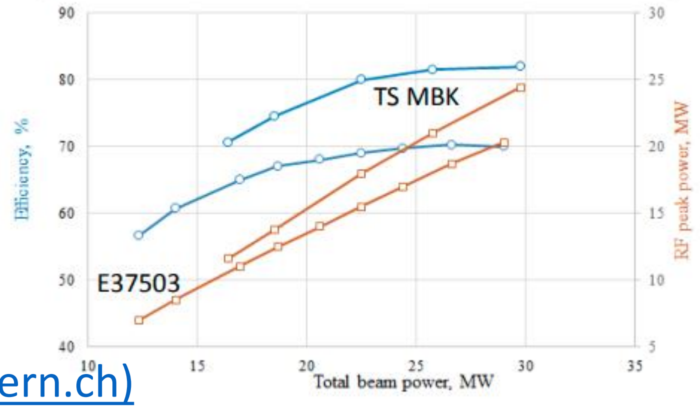


TABLE I. DESIGN AND SIMULATED PARAMETERS (CST/3D) OF THE CLIC TS MBK AND CANON MBK E3750 CATALOGUE DATA

Parameter	TS MBK	E37503	Unit
Operating frequency	1000	1000	MHz
Voltage at the 1st stage	25	160	kV
Voltage at the 2nd stage	140		
Total beam current	212	180	A
Number of beamlets	30	6	
Number of cavities	6	6	
Perveance at the 1st stage	1.77	0.47	$\mu A/V^{3/2}$
Perveance at the 2nd stage	0.133		
Output RF power	24.1	20	MW
Saturated power gain	52	54	dB
Saturated efficiency	82	70	%
Length of RF circuit	900	1500	mm



Novel design Two-Stage (TS) Multi-Beam Klystron (MBK)

2nd stage is not pulsed: **More efficient modulator**

It has more power per klystron compared to PIP baseline: **20 MW -> 24 MW** Significant **cost** impact

It has higher Efficiency compared to PIP baseline: **70 % -> 82 %** Significant impact on **power consumption**

CLIC project meeting 15 June 2021 Igor Syratchev (cern.ch)

TS MBK concept will be test at 400 MHz for FCC-ee tube

Step 1: Scaling AS from 20 to 24 MW

RF acc. structure (AS) parameters for CLIC 380	**PIP 20 MW MBK**	**New 24MW TS-MBK**
Beam current	4.2	4.2
active length	2.3	2.5
Peak input power for Full Beam Loading (FBL)	18	21.5
Unloaded acc. Voltage	7.92	9.45
Loaded acc. voltage	4.08	4.875
Loaded acc gradient	1.77	1.94
RF-to-beam Efficiency	95	95
Linac parameters		
Number of AS in DBL1	62	52
Number of AS in DBL2	398	333
Total number of AS (klystron, modulators)	460	385
Total number of quads	204	172

Nominal AS input power for FBL is lower than klystron power due to margins:

- WG losses: **5%**
- Power margin for bunching (off crest operation): **3%**
- Power margin for operation and availability: **5%**
- All together **~10%** less power available for FBL acceleration

More power per klystron, modulator, AS unit => less AS, less quads (TBC by BD)

Step 2: Applying higher efficiency 70 -> 82%

- 70% -> **82%** is straightforward to do
- However, it should be noted that there are several other efficiencies at similar level:
- WG losses: 5% -> Efficiency : **95%**
- Modulator CW efficiency: **94%**
- Modulator Pulse efficiency: **86%** See next slide
- AS RF-to-beam efficiency: **95%**
- So, there is a limit to which point it make sense to push the klystron efficiency. Maybe we are approaching this limit !

Step 3: Modulator pulse efficiency increase

Klystron Modulator Technology Challenges for the Compact Linear Collider (CLIC)

D. Aguglia[1], *Member, IEEE*, C. A. Martins[2], *Member, IEEE*, M. Cerqueira Bastos[1], D. Nisbet[1], *Member, IEEE*, D. Siemaszko[1], *Member, IEEE*, E. Sklavounou[1], and P. Viarouge[2]

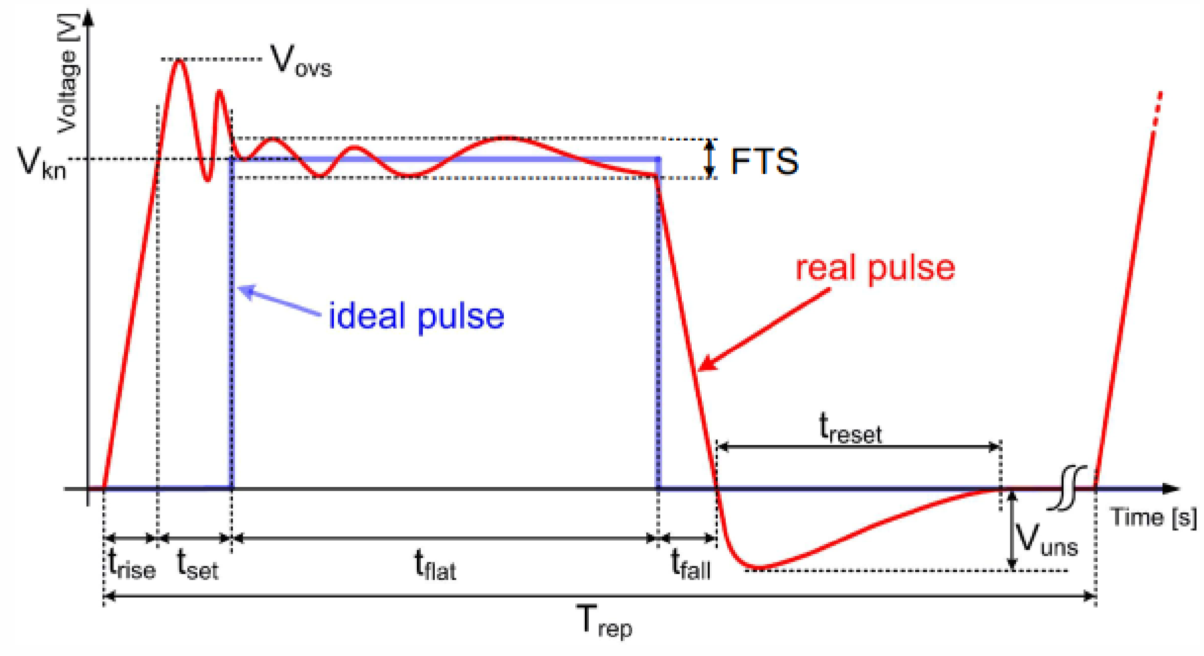


Fig. 1. Modulator output voltage performances definitions.

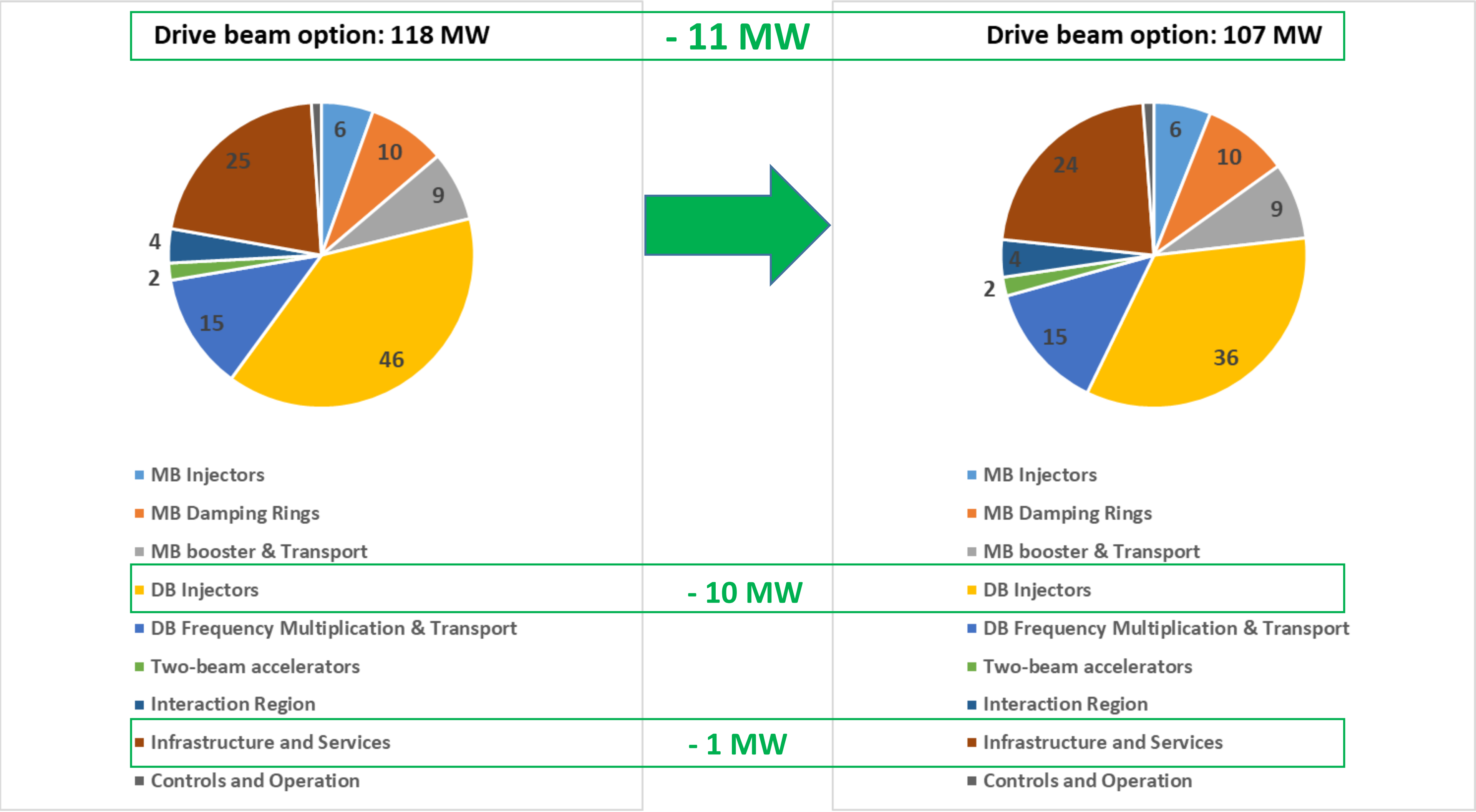
Modulator pulse efficiency: $Eff_{pulse} = t_{flat}/(t_{flat}+t_{set}+t_{rise})$

Aguglia (2011) optimized for 3TeV case. **95%** achieved (t_{flat}=140us, t_{set}=5us, t_{rise}=3us)

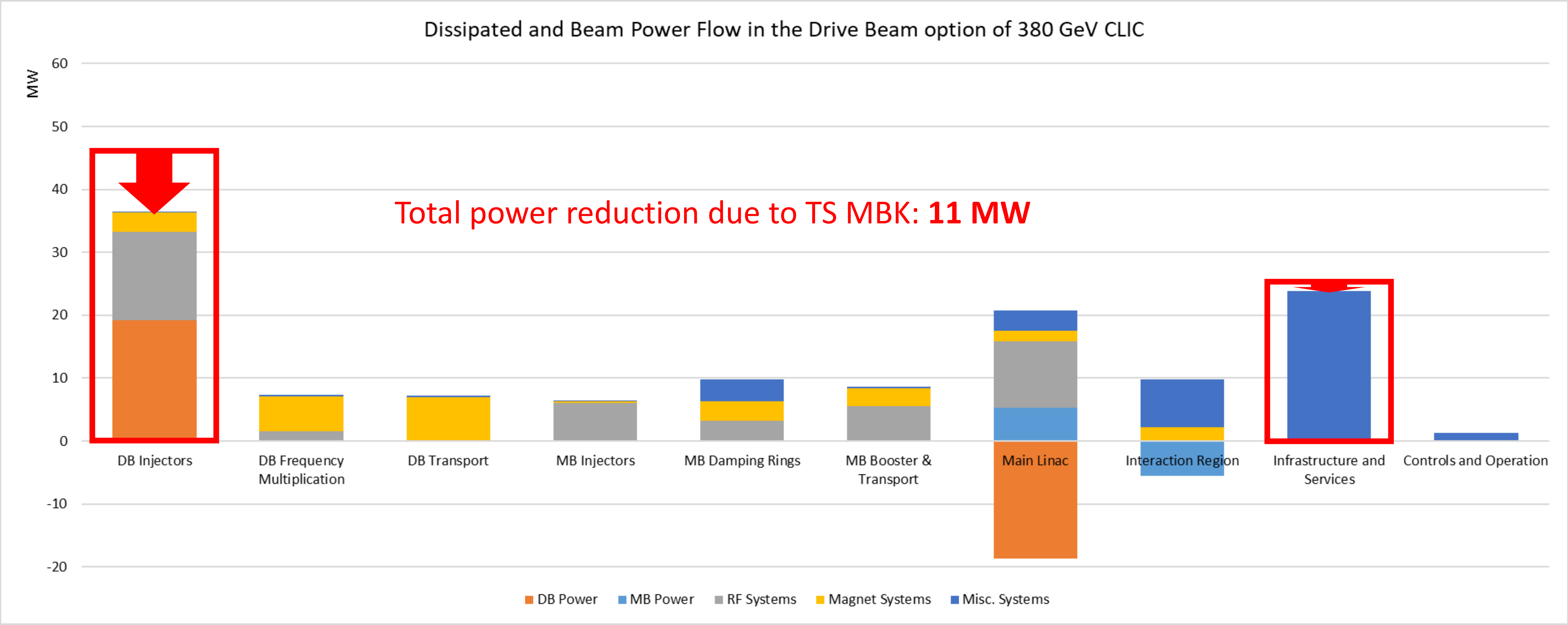
For 380 GeV, set and rise time are significant fraction of the pulse (48 us): Eff_{pulse}= **86%** only

Igor said: TS MBK allow significant reduction of set time to practically zero: Eff_{pulse} = **94%**

Comparison: 20MW MBK vs 24MW TS-MBK



Power reduction due to TS MBK



Comparison of wall plug to beam efficiencies

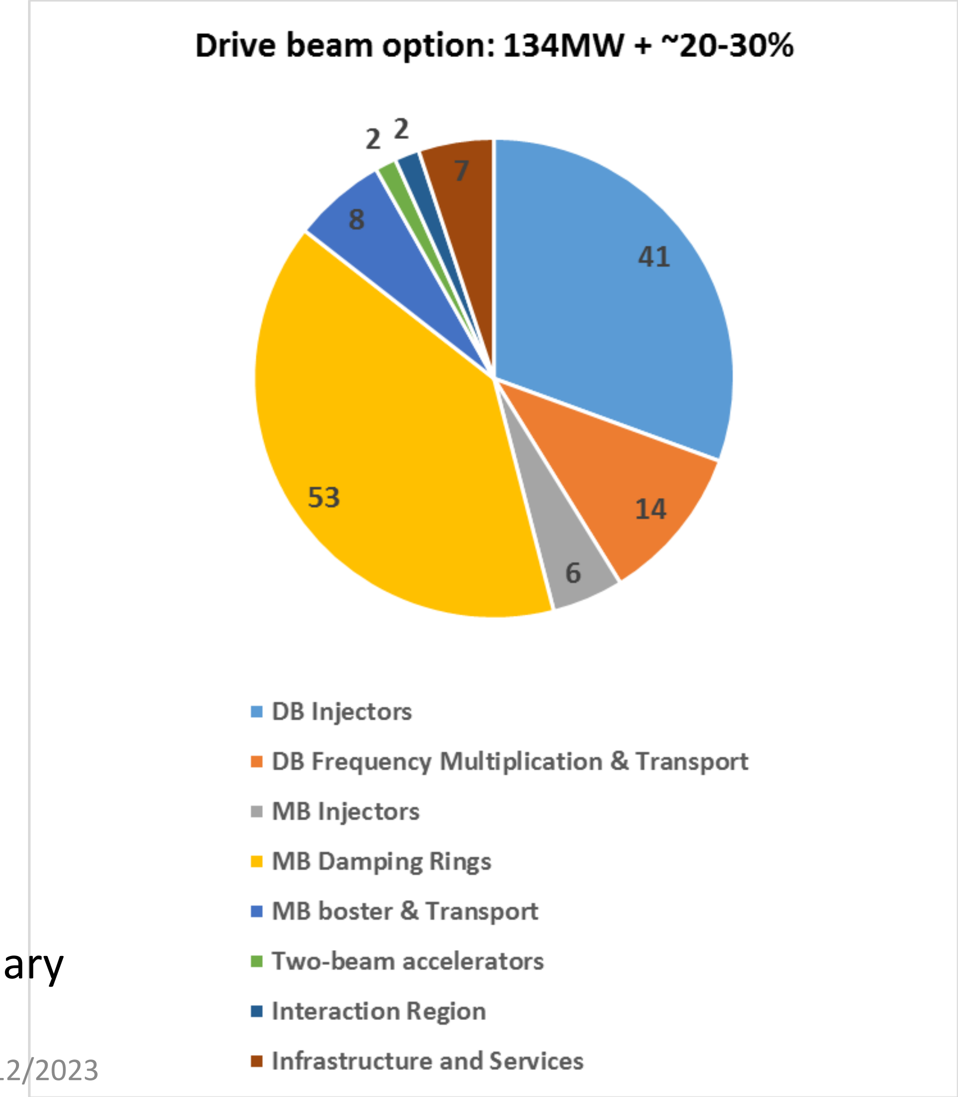
	PIP baseline	**New BCC DR**	**New TS MBK**
DB klystron efficiency [%]	70	70	82
DB modulator pulse efficiency [%]	86	86	94
DB complex Wall plug to DB efficiency [%]	**31.8**	**31.8**	**37.6**
DR wall plug to MB efficiency [%]	7.9	56.7	56.7
CLIC Wall plug to MB efficiency [%]	**3.3**	**4.8**	**5.2**

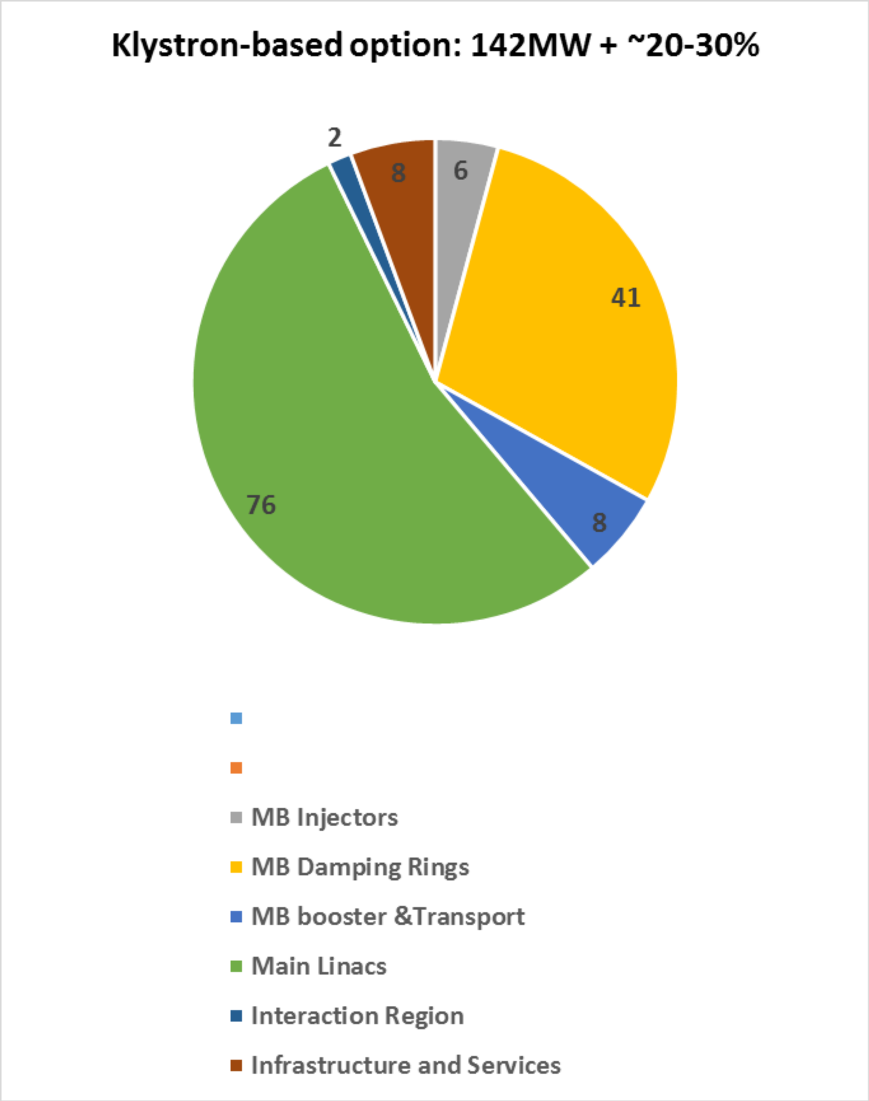
Summary

- CLIC 380 GeV power estimate has been updated to include several possible changes
- Increase in repetition rate from 50 to 100 Hz result in increase in power consumption by 68 MW from 168 to 236 MW
- New design of the DRs demonstrates significant reduction of the power consumption by 50 MW from 168 to 118 MW
- Using new Two Stage MBK results in 11 MW reduction in CLIC power consumption from 118 to 107 MW

Backup slides

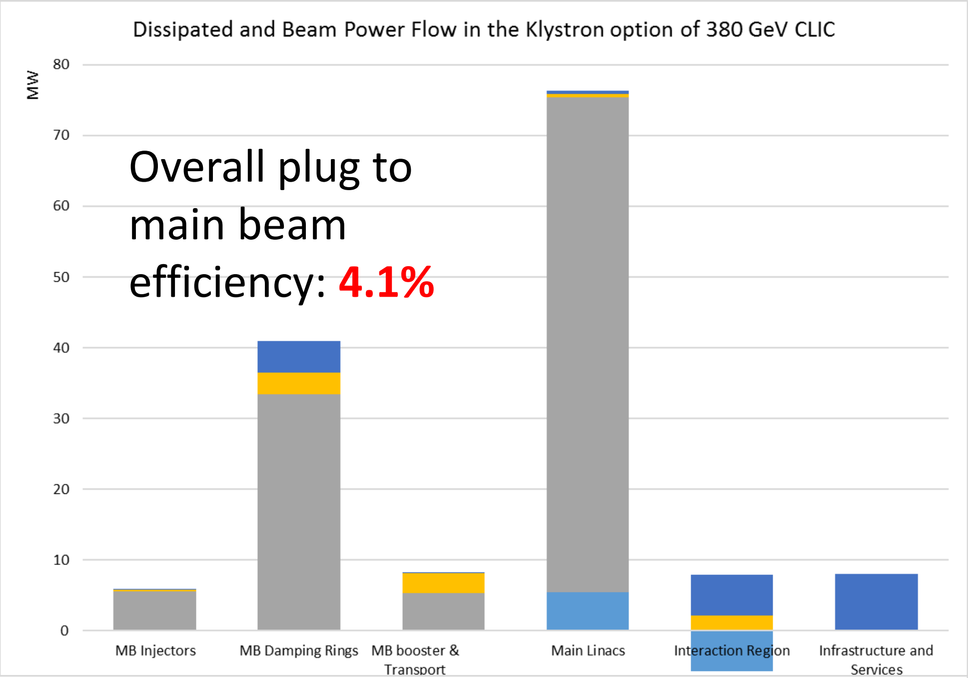
Comparison of Drive beam and Klystron options

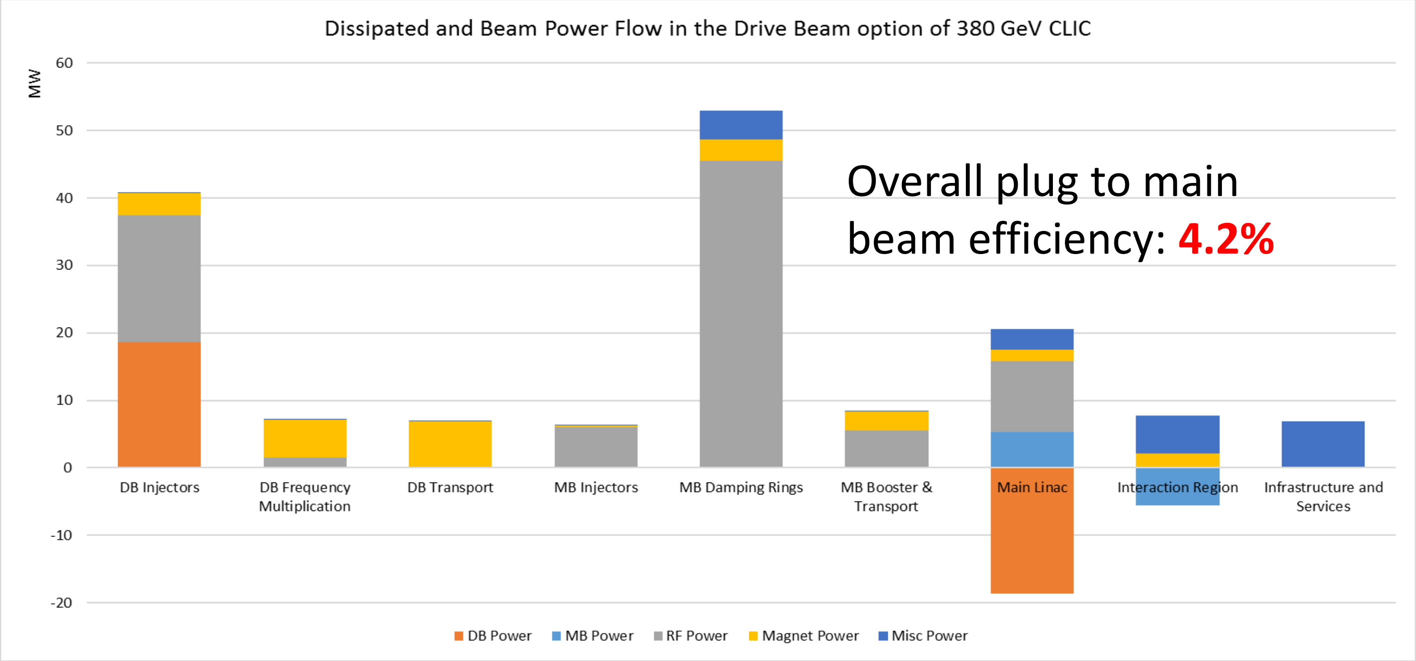




Preliminary
2018

Comparing power flows: Drive beam and Klystron options





Preliminary 2018

380 GeV CLIC DR parameters (PRAB22, 091601)

Parameter of DR		value	unit
Energy	E	2.86	GeV
Circumference	C	373.7	m
Revolution frequency	f_0	802	kHz
RF frequency	f_{RF}	**2**	**GHz**
Harmonic number	h	2493	
Energy loss per turn	eV_A	**5.8**	**MeV**
RF voltage	V_C	6.5	MV
RF stable phase	ϕ	-26.8	o
Bunch population	N_e	5.7	1e9
Number of bunches per train	N_b	352	
Number of trains	N_t	1	
Peak beam current	I_b	**1.8**	**A**

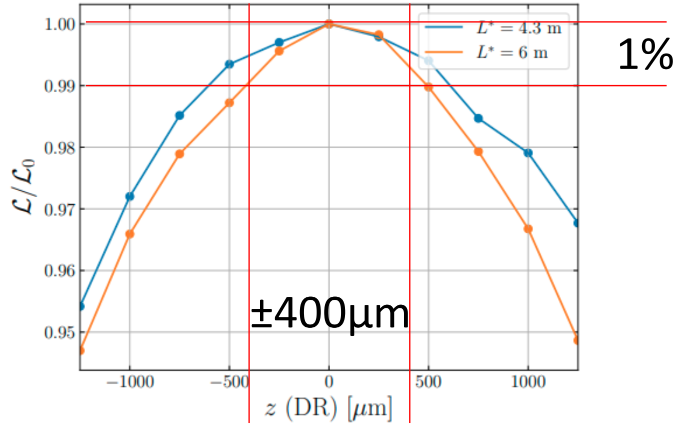


Figure 10: Luminosity against the longitudinal bunch position from the DRs.

Strict specifications on the bunch spacing variation: $\delta\phi_b < \pm 1^o$ at 2 GHz (±400µm) for Luminosity loss < 1% (CLIC-Note-1138)

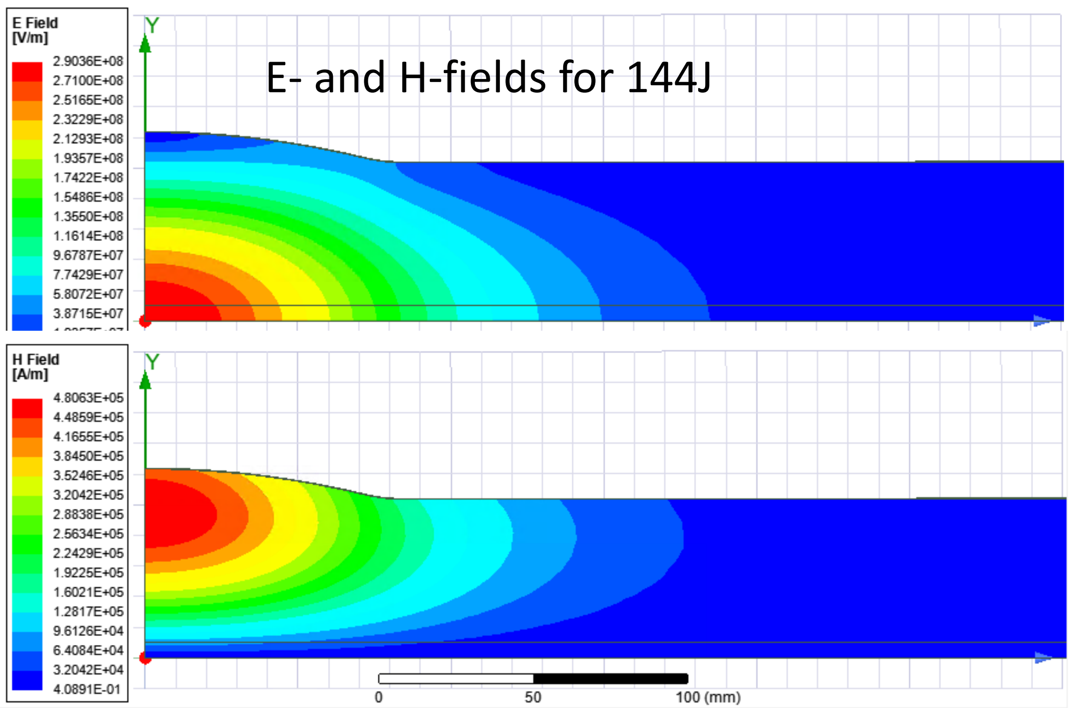
This is difficult to maintain due to **strong transient beam loading effects** caused by large difference between **peak** and **average beam power** values of 10.4 MW and 1.5 MW, respectively

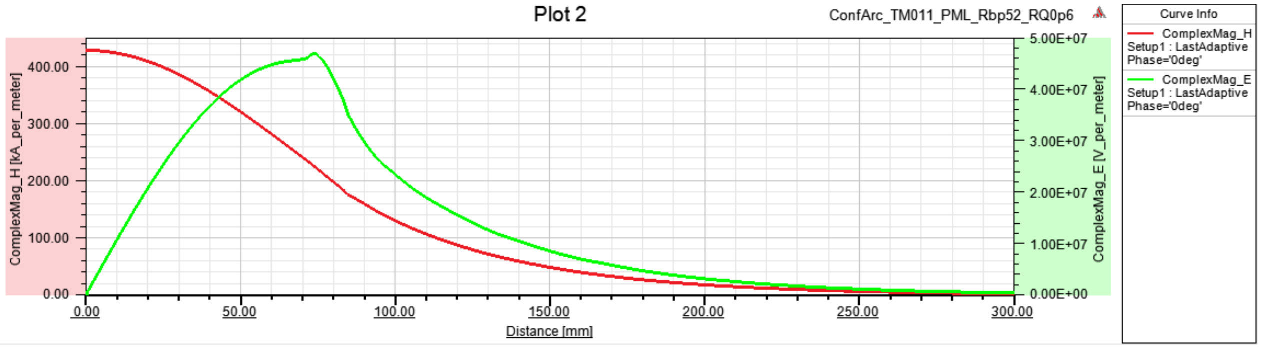
Design philosophy for Ultra low R/Q RF cavity

- Increase cavity aperture to reduce loss factor => reduce R/Q per cavity
- Increase cavity length to reduce transit time factor => reduce R/Q per cavity
- Optimize cavity wall shape to minimize H-field to reach largest stored energy per cavity under the H-field limit of **80 kA/m** (100 mT, private communication, W. Venturini, 2021) => reduce number of cavities
- R/Q per cavity x N of cavities must be below Total R/Q: **14.3 Ω**

More details in: CLIC-note-1173, or in rf development meeting (22 September 2021)

Design of the cavity for total R/Q=14.3Ω





TM011	
a [mm]	52
f [GHz]	2
a/λ	0.347
Lc [mm] (0.01Hmax)	~520
Rarc [mm]	307
Rcav [mm]	61.95
R/Q [Ω]	**0.6**
Emax/Vacc [1/m]	31.6
Hmax/Vacc [mA/Vm]	291

Hmax limit: 80kA/m
⇒ **Vmax = 0.275 MV**
⇒ Umax = 5.0 J
⇒ Emax = 8.7 MV/m

To get this design parameters, two conditions must be met:

R/Q per cavity is 14.3Ω/Ncav

AND

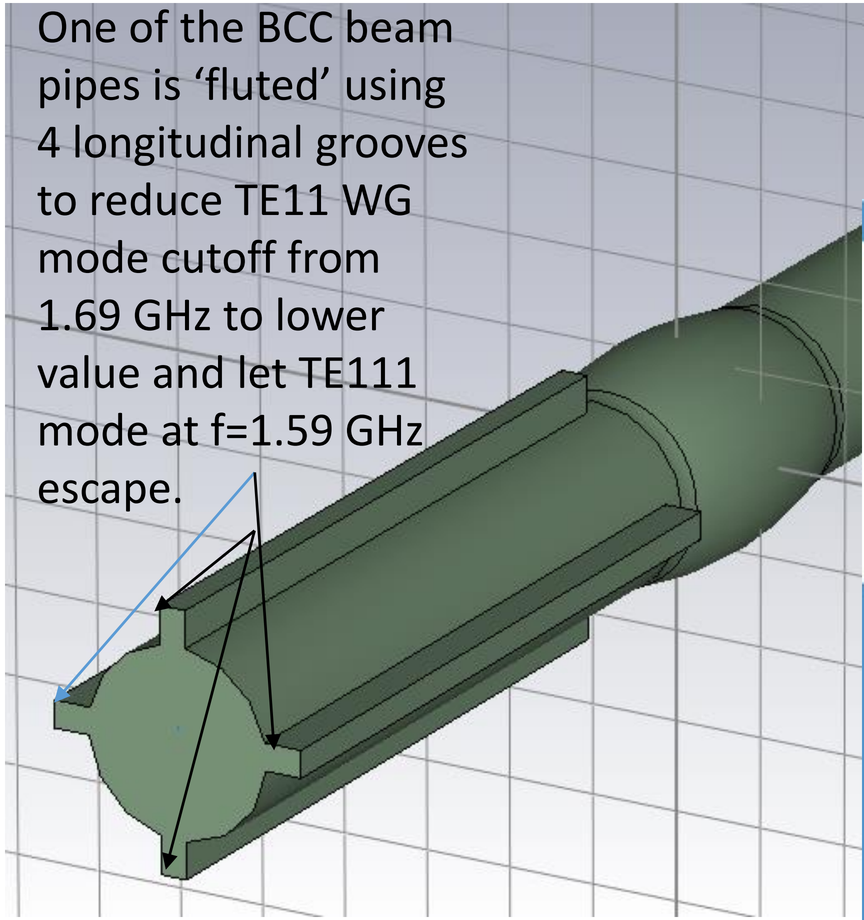
Vmax per cavity is 6.5MV/Ncav

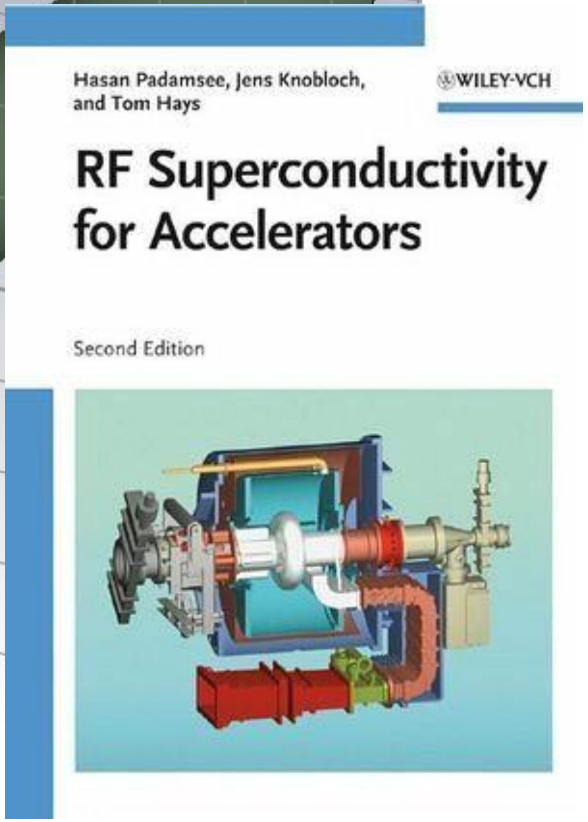
Ncav = 24

All LOM and HOMs damped

The magic flute helps to damp dipole LOM

One of the BCC beam pipes is 'fluted' using 4 longitudinal grooves to reduce TE11 WG mode cutoff from 1.69 GHz to lower value and let TE111 mode at f=1.59 GHz escape.





Particle Accelerators, 1992, Vol. 40, pp.17–41
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DESIGN CHALLENGES FOR HIGH CURRENT STORAGE RINGS*

H. PADAMSEE, P. BARNES, C. CHEN, W. HARTUNG, J. KIRCHGESSNER, D. MOFFAT, R. RINGROSE, D. RUBIN, Y. SAMED, D. SARANITI, J. SEARS, Q.S. SHU and M. TIGNER

Laboratory of Nuclear Studies, Cornell University

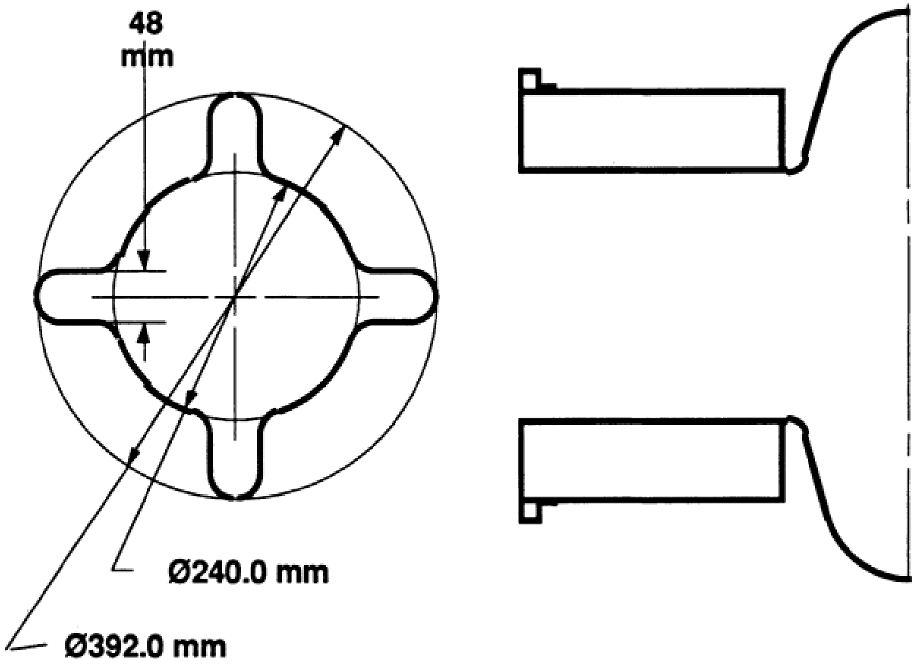


FIGURE 5: Geometry of fluted beam pipe

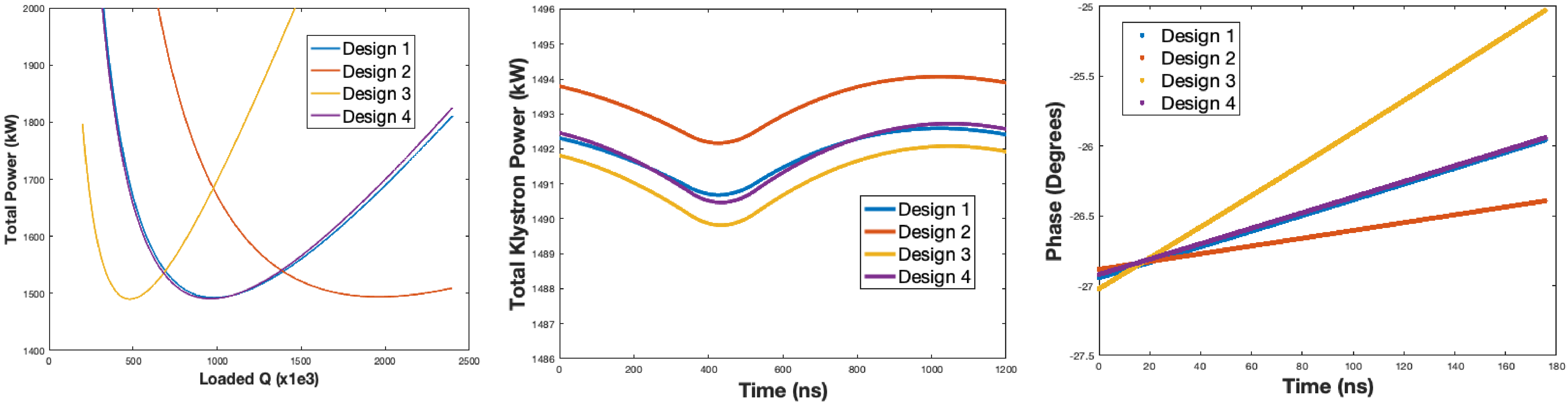
Summary table. More details : CLIC-note-1173, or in rf development meeting

Case	1	2	3	4
Cavity R/Q [Ω]	0.6 →		2.04	
a [mm]	52		50	
Lc [mm] (0.01Hmax)	520		500	
Rarc [mm]	307		160	
Rcav [mm]	61.95		63.55	
Total R/Q [Ω]	14.3	7.15	28.6	14.3
Bunch phase variation [°] @2GHz	1	0.5	**2**	1
Ncav	**24**	12	14	7
Cavity input power Pin [kW]	60	120	103	**206**
Bmax [mT]	100 →	**200**	100 →	**200**
Hmax [kA/m]	80	160	80	160
Emax [MV/m]	8.7	17.4	11.7	23.4
Cavity voltage Vc [MV]	0.275	0.55	0.47	0.94
Cavity stored energy Uc [J]	5.0	20.0	4.3	17.1

LLRF simulation results

Design	Δf (Hz)	Q_L	Peak power per klystron (kW)	Total peak power (MW)	ϕ_b	$\Delta\phi$
1	-514	983e3	62.2	1.49	-26.8˚	**0.99˚**
2	-257	1962e3	125	1.49	-26.8˚	**0.49˚**
3	-1020	496e3	107	1.49	-26.8˚	**1.99˚**
4	-510	990e3	213	1.49	-26.8˚	**0.98˚**

T. Mastoridis



Due to the very high cavity filling time, the closed-loop response of the RF/LLRF system is slow. In addition, there is a 350 ns delay in the RF loop. Very small klystron power modulation