A bit chaotic view on the 380 GeV CLIC power and Design studies

Alexej Grudiev (CERN)

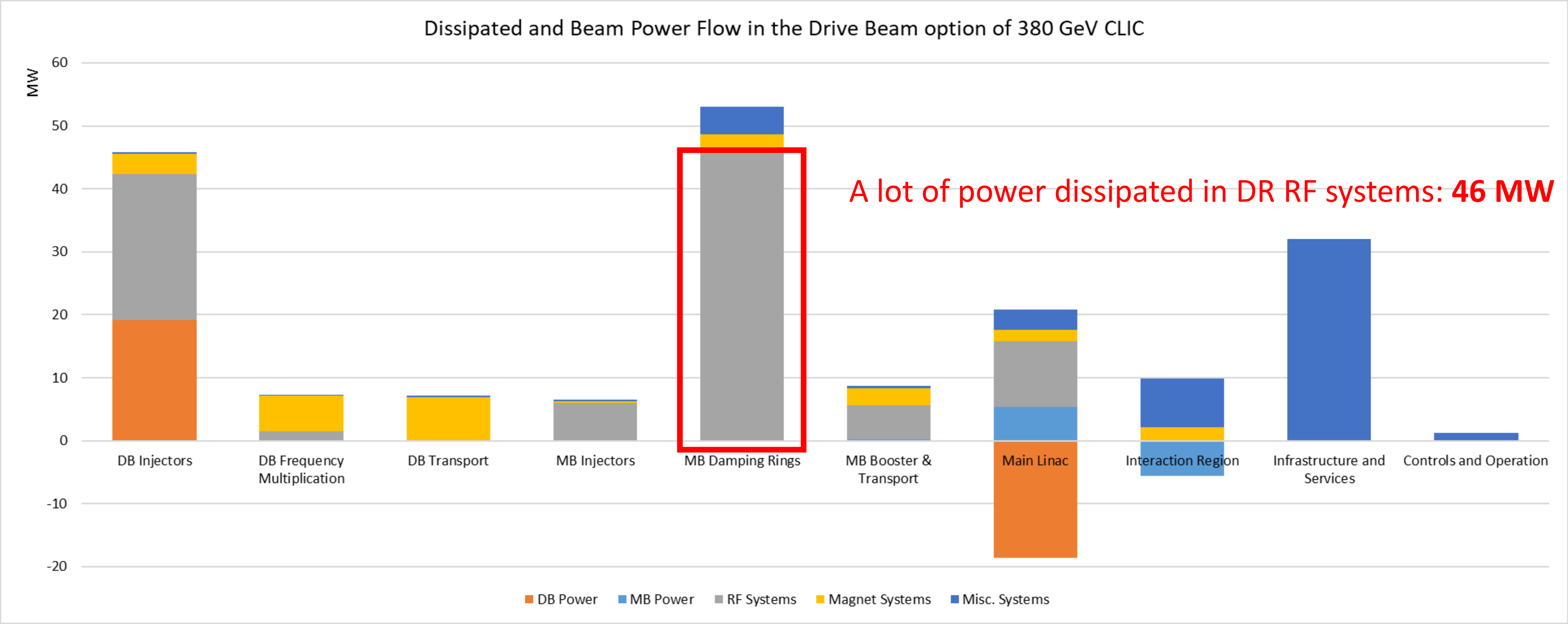
CLIC towards Readiness Report 2025-26 meeting

8/11/2022

Outline

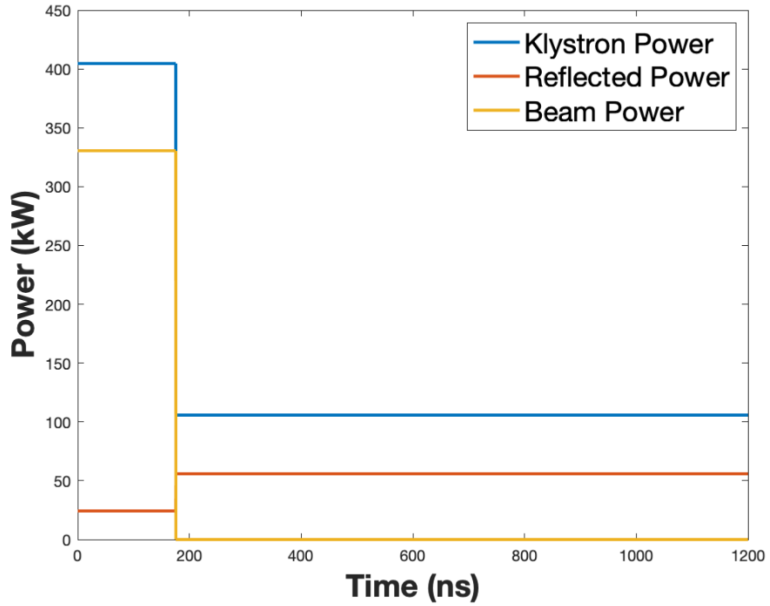
- CLIC 380 power with new DR RF, 2021
- Update for the new DB klystron (TS MBK) parameters, 2022
- Possible further ways for power reduction
  - DB complex magnets
  - MB injector linacs
  - MB main linac
- MB injector complex layout and RF optimization
- Standing wave damped distributed coupling structure – possible way to improve efficiency and/or gradient in main linac

CLIC DRs (PIP design)

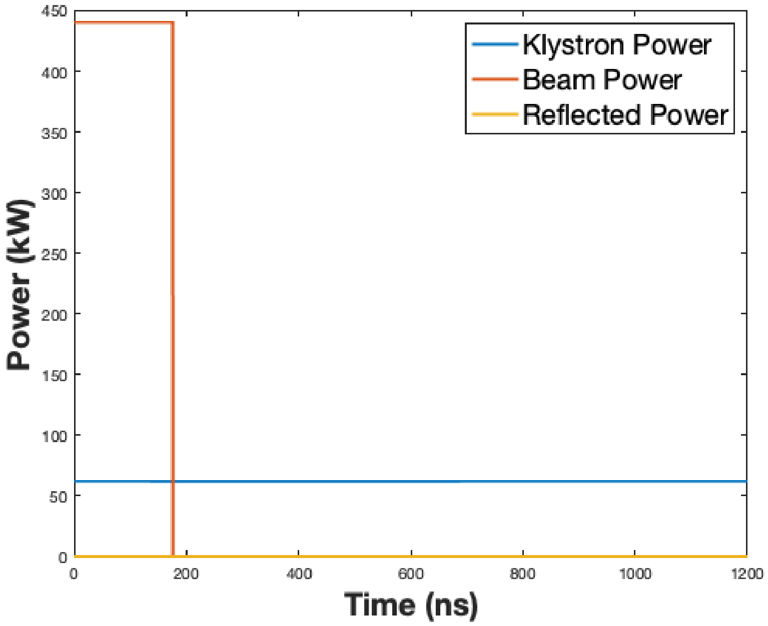


DR Comparison: PIP baseline vs new proposal

PIP baseline



New proposed design #1



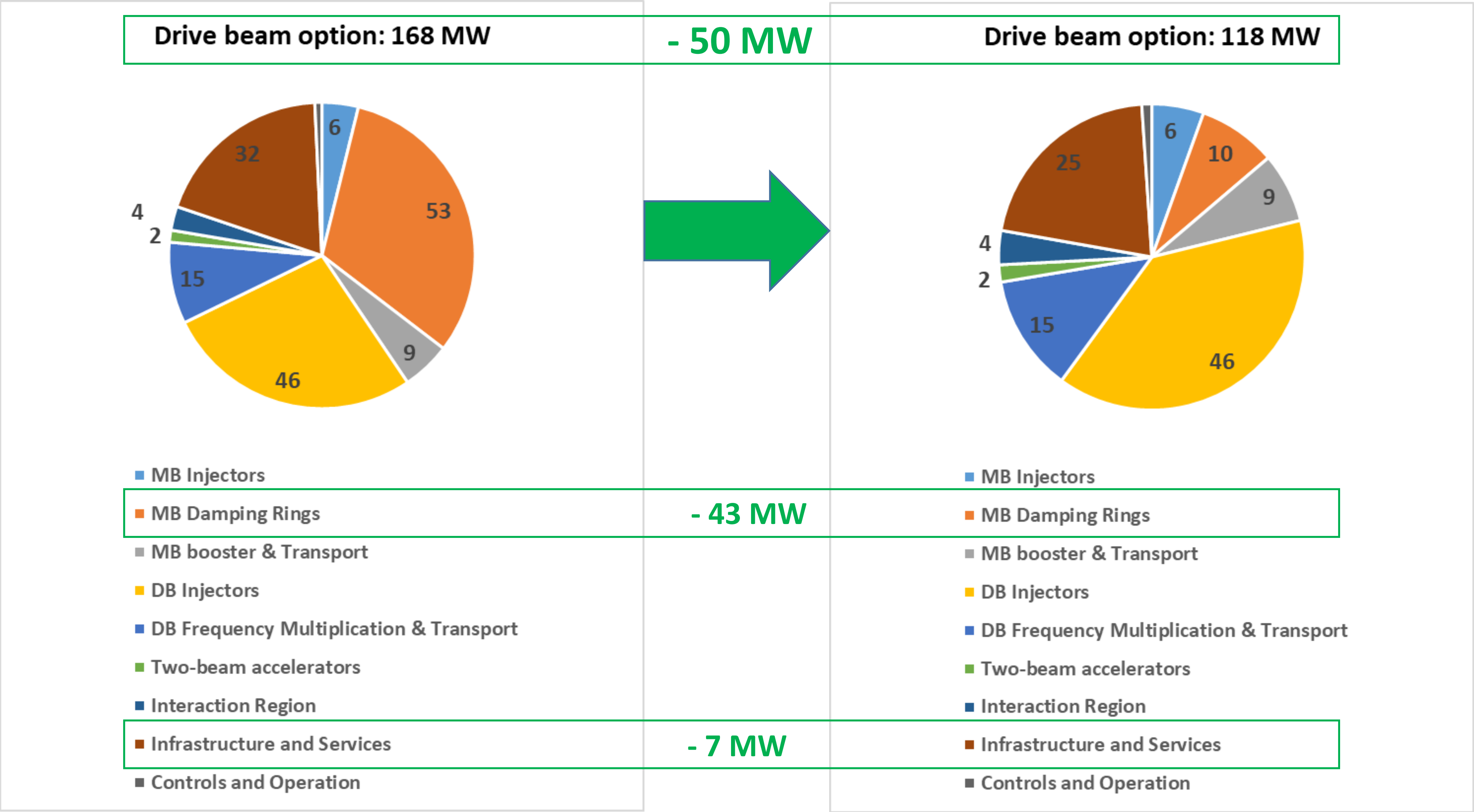
Cavity type	ARES	BCC
Cavity R/Q [Ω]	**7.5**	**0.6**
N of cavities	32	24
Peak input power [kW/cavity]	405	62.2
Total peak input power [MW]	**13**	**1.5**

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

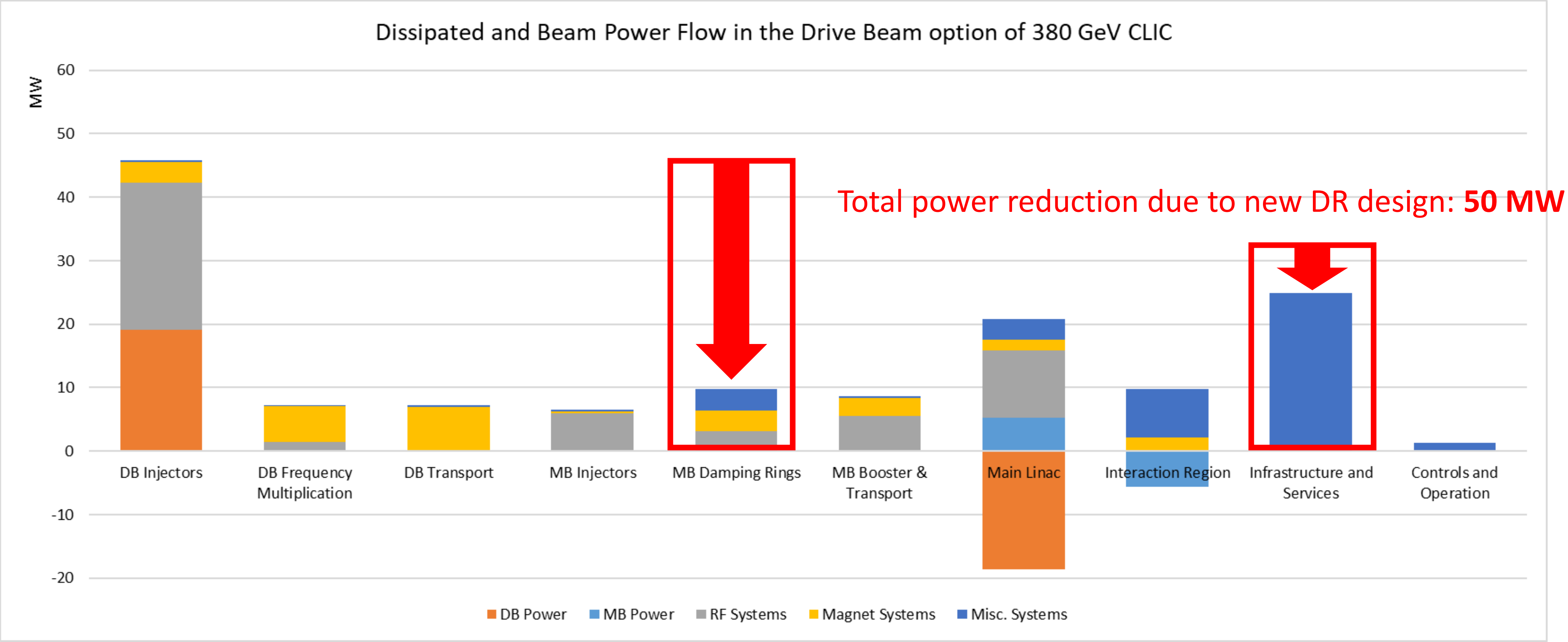
Updated layout of the DR is required for the new DR RF system

Cryogenic system design is needed both for RF and wigglers -> power estimate

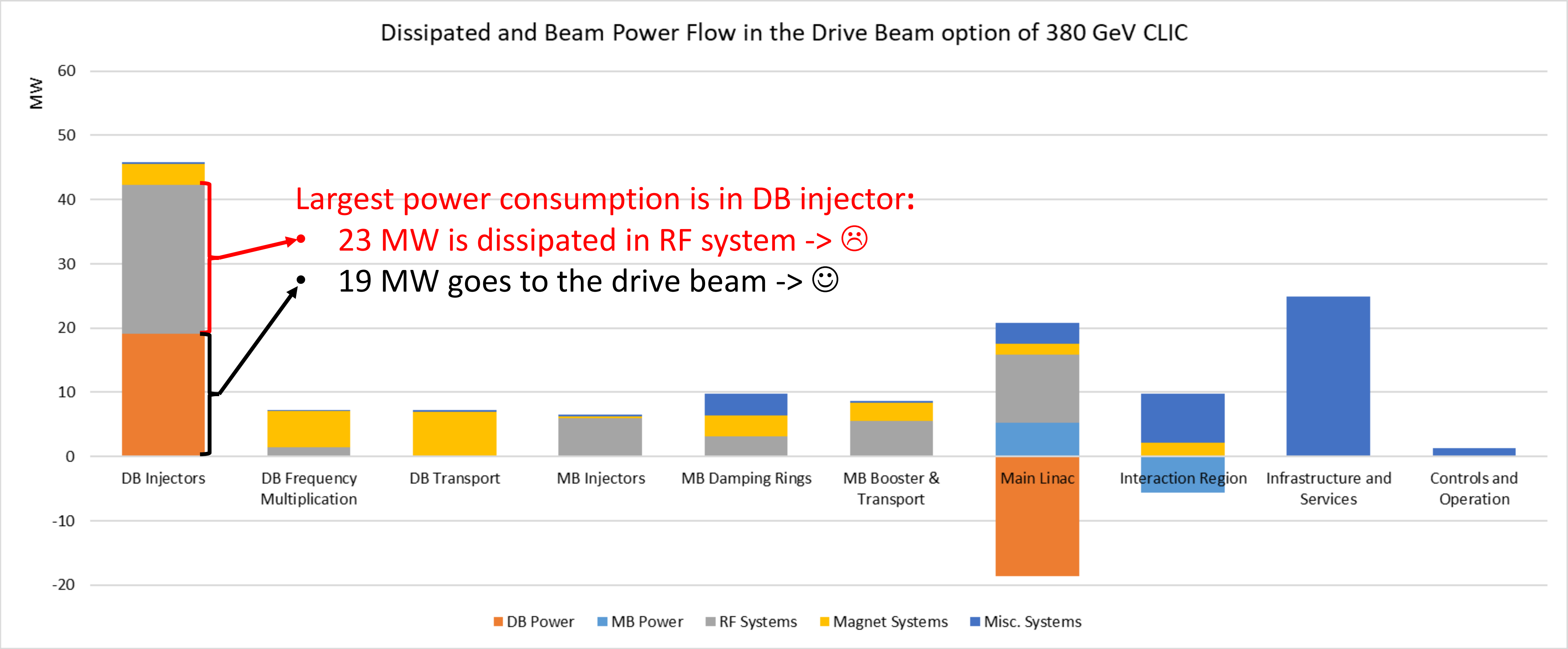
Comparison DR: PIP baseline vs new proposal



CLIC DRs: power reduction due to new 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)

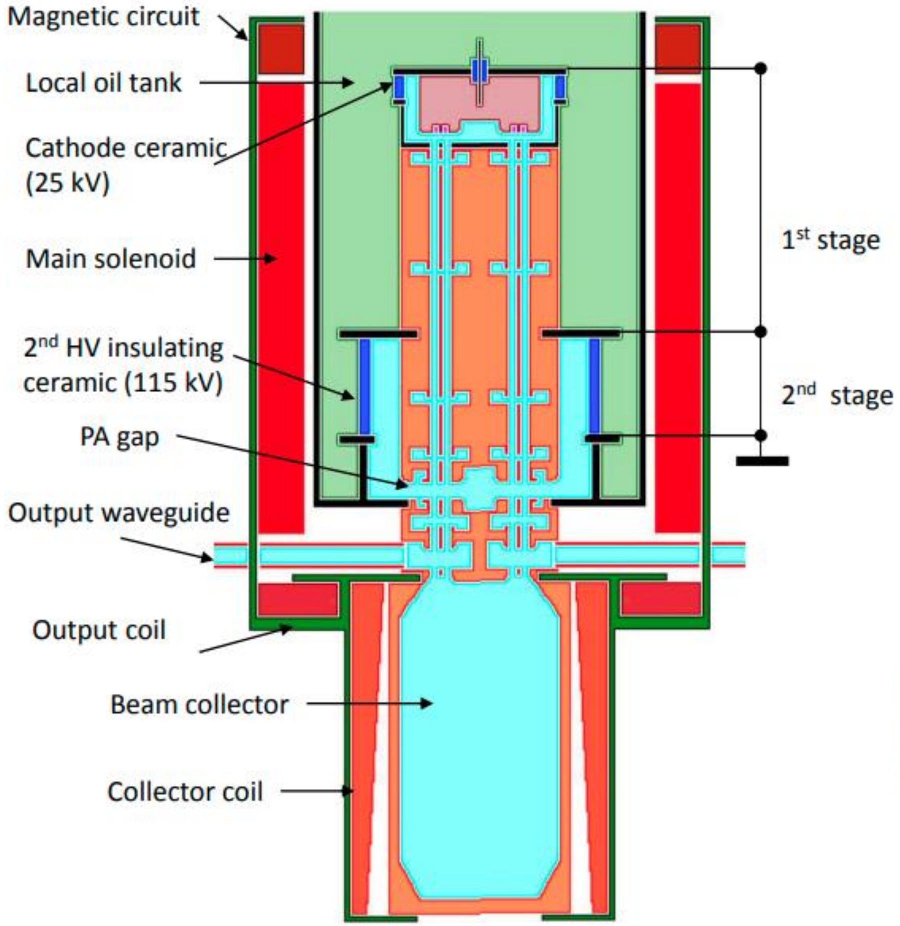
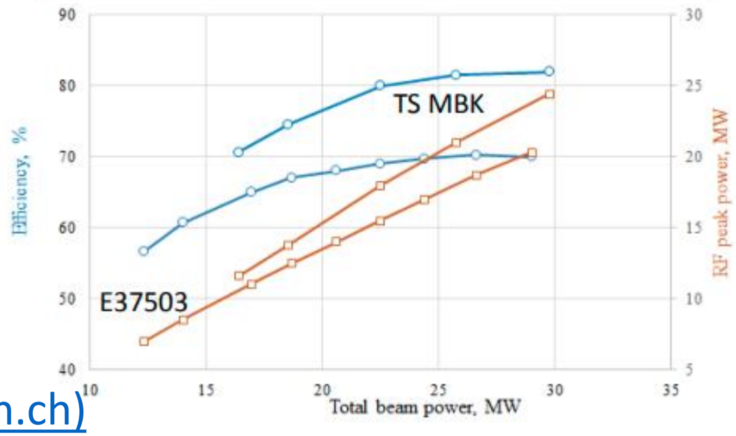


TABLE I. DESIGN AND SIMULATED PARAMETERS (CST/3D) OF THE CLIC TS MBK AND CANON MBK E3750 CATALOGUE DATA

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	μA/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)]

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)

Updated BD design of the DBI linac is required for new configuration

Step 2: Applying higher efficiency 70 -> 82%

- 70% -> **82%** is straightforward
- 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]

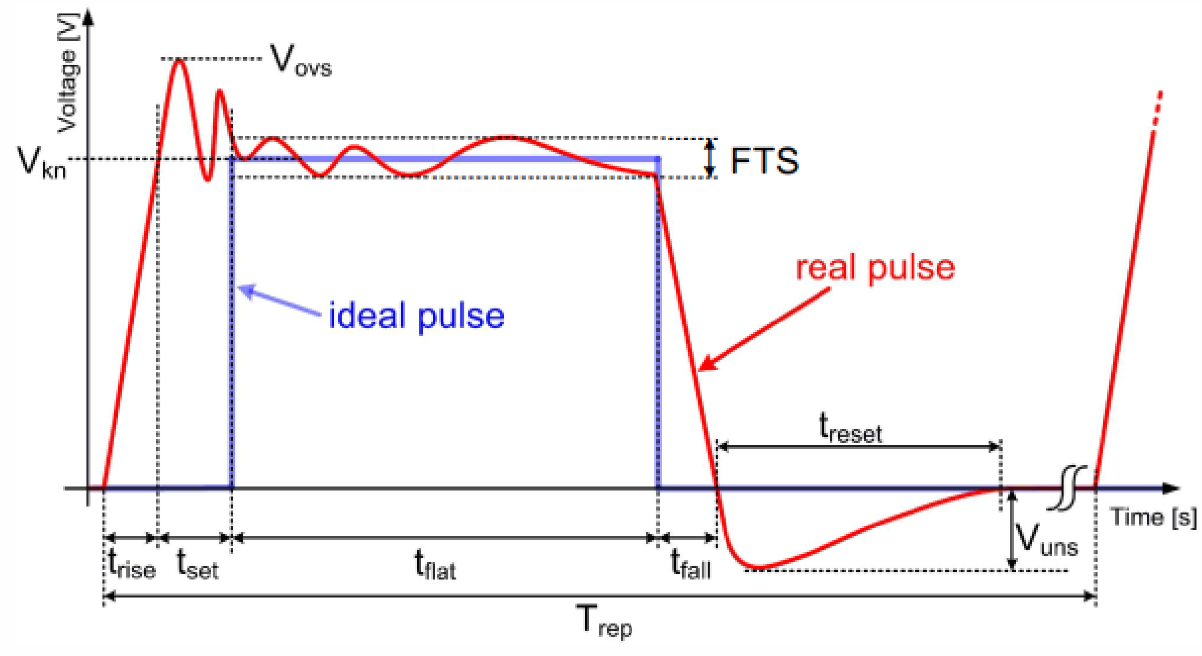


Fig. 1. Modulator output voltage performances definitions.

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

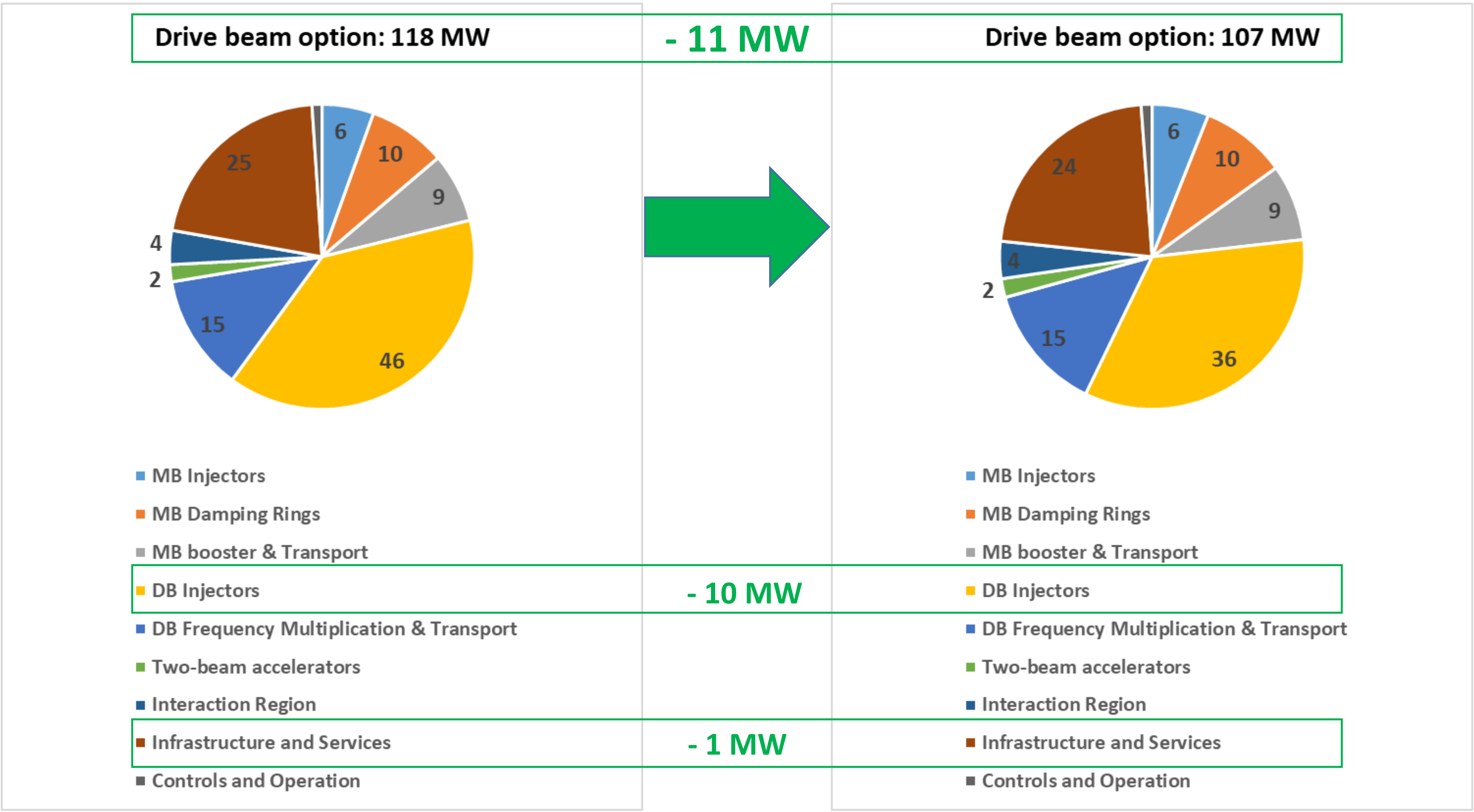
Aguglia (2011) optimized for **3TeV** case. **95%** achieved (t_{flat}=140us, t_{set}=5us, t_{rise}=3us)

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

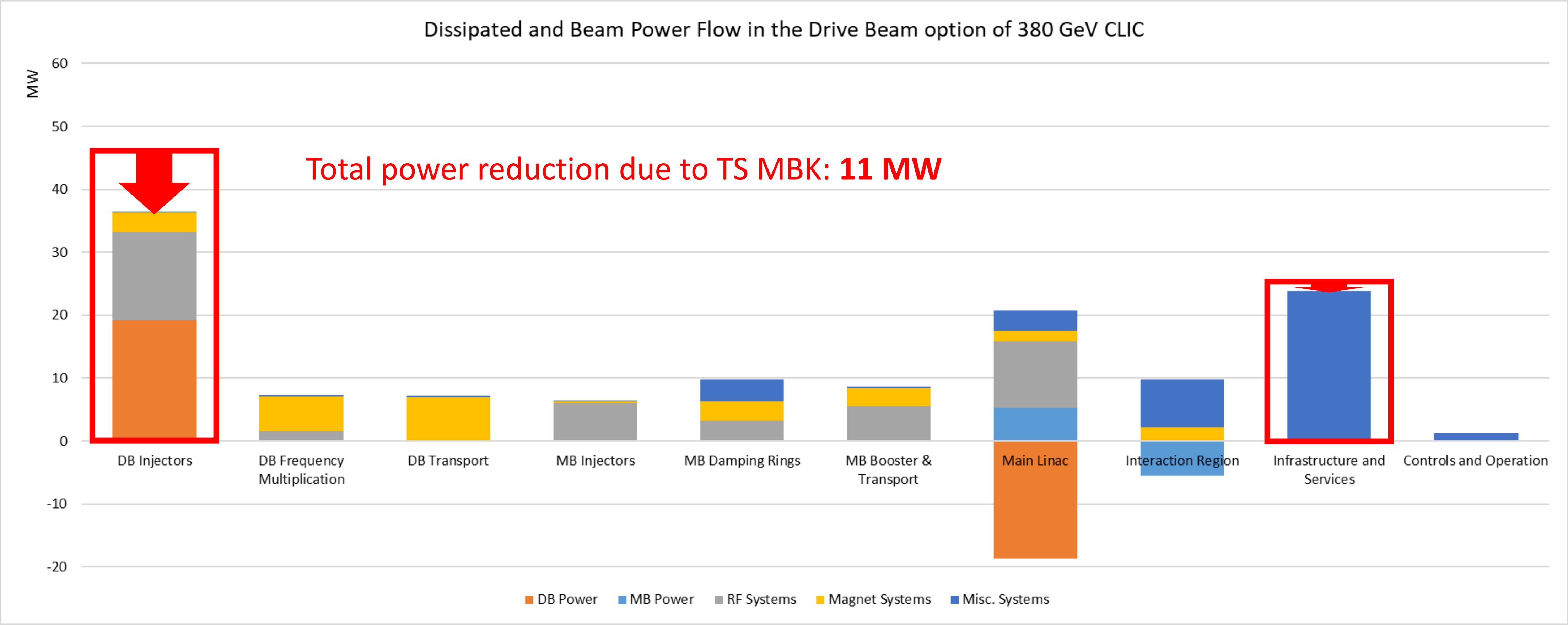
Igor said: TS MBK allow significant reduction of set time to practically zero: Eff_{pulse} = **94%**

We need to check if Igor is right

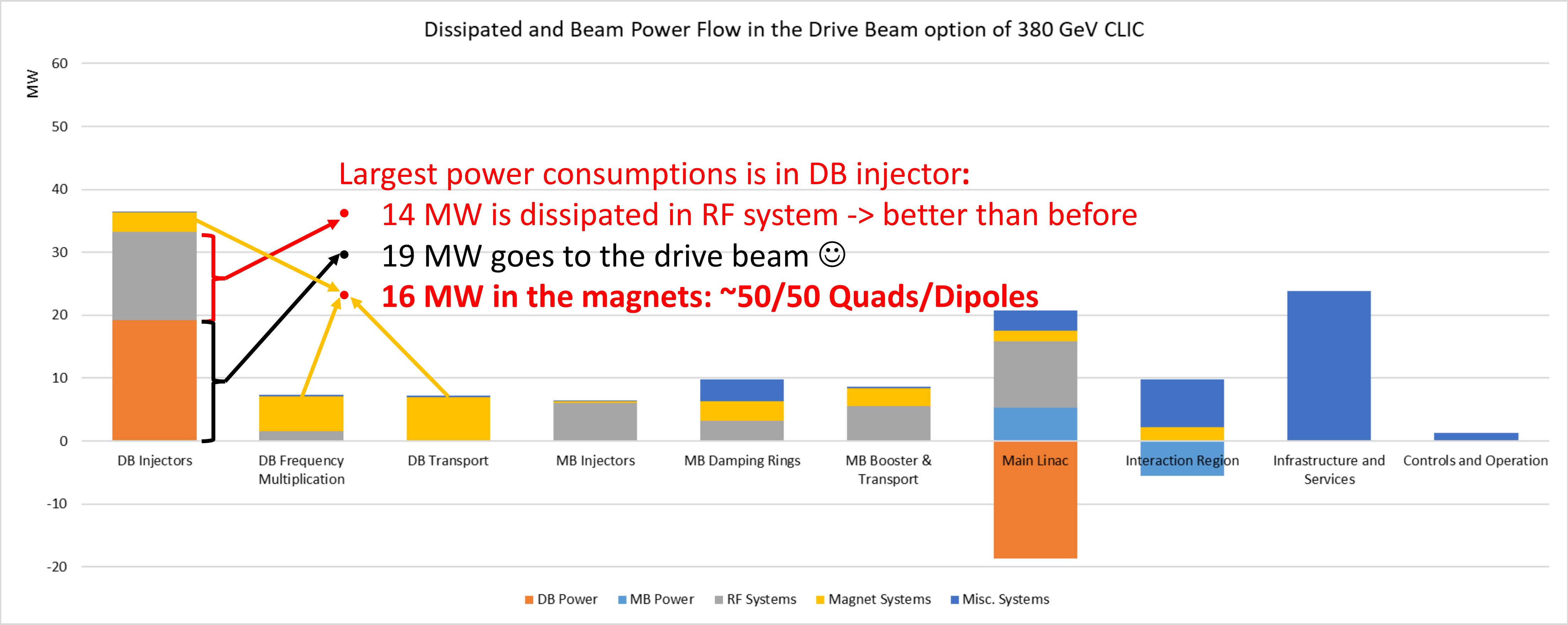
Comparison: 20MW MBK vs 24MW TS-MBK



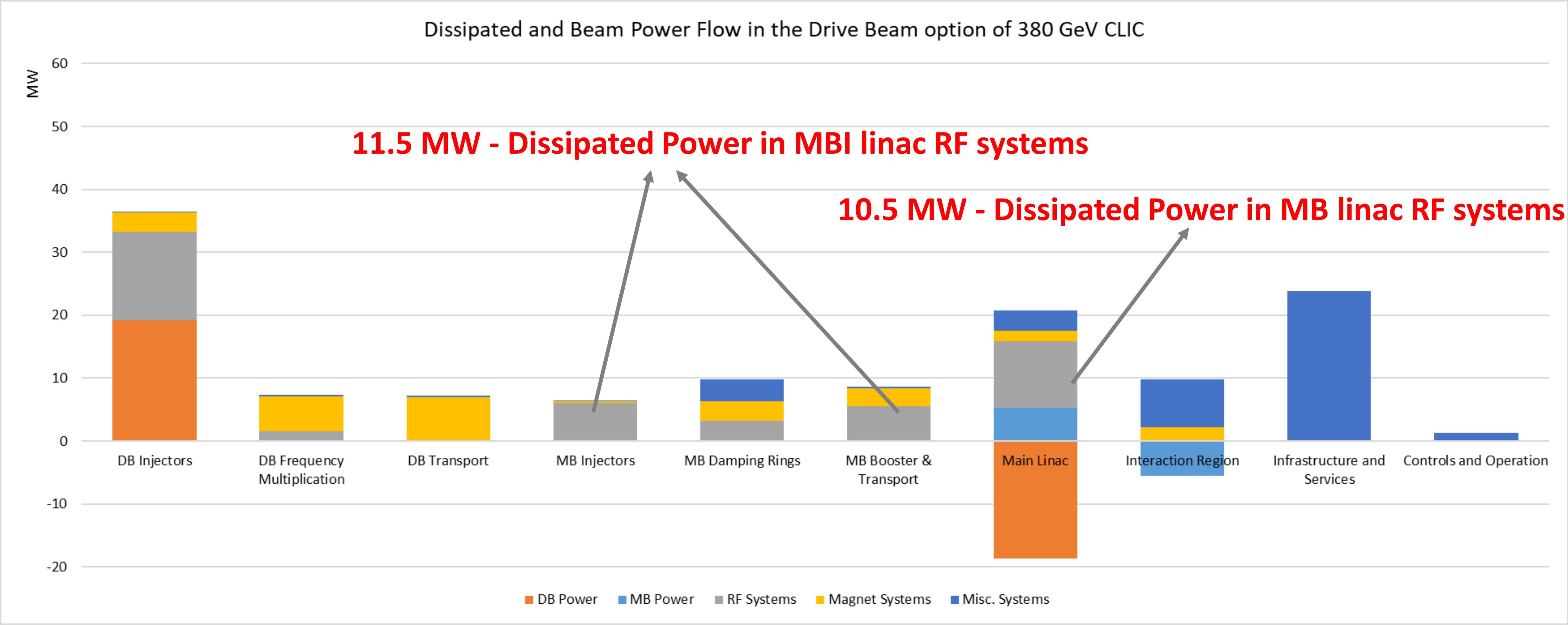
Power reduction due to TS MBK



Power consumption in DB magnets



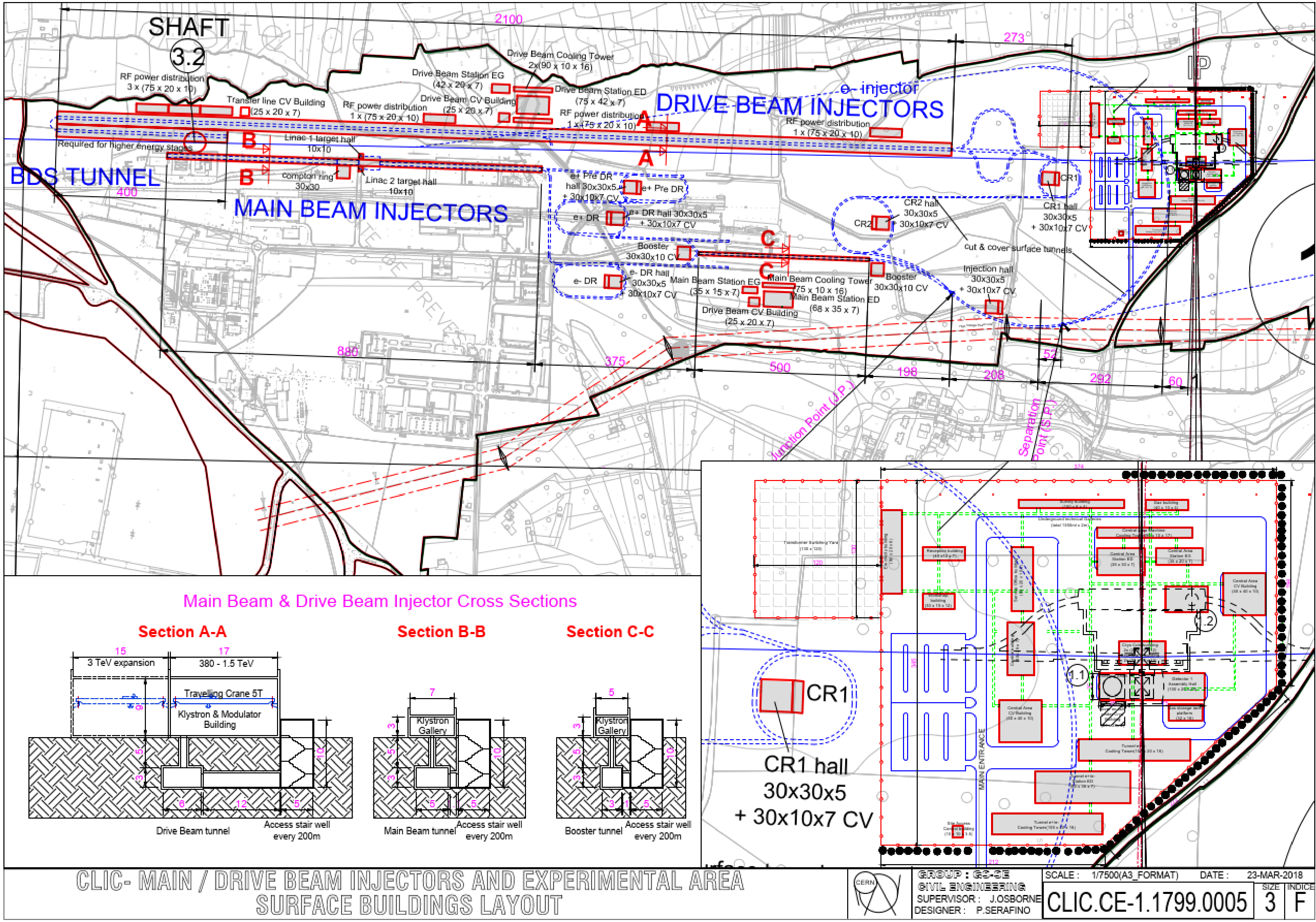
Power consumption in MB linac RF systems



Potential area of power reduction

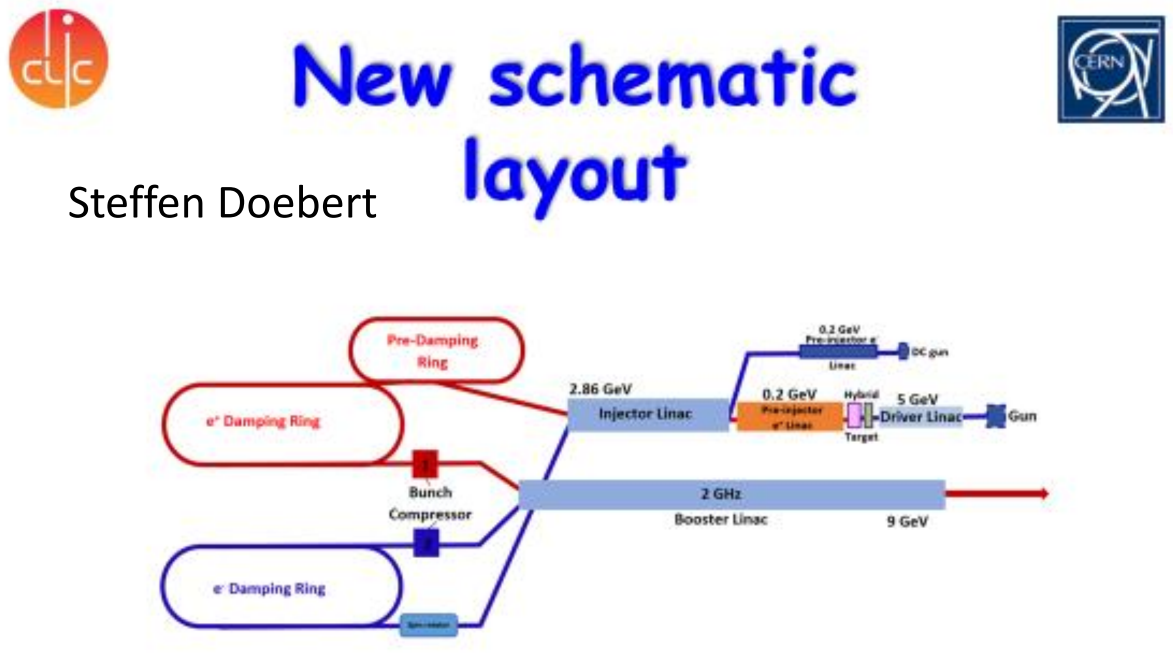
- DB complex magnets **16 MW**:
  - Large aperture Quads and Dipoles -> potential power reduction by using PM or SC technology is possible
- MB linacs share similar power consumption between the injector linacs **11.5 MW** and X-band Two-Beam Accelerator (TBA): **10.5 MW**
  - Where as X-band TBA has been extensively optimized, MBI linacs might be possible to optimize further to reduce power and cost

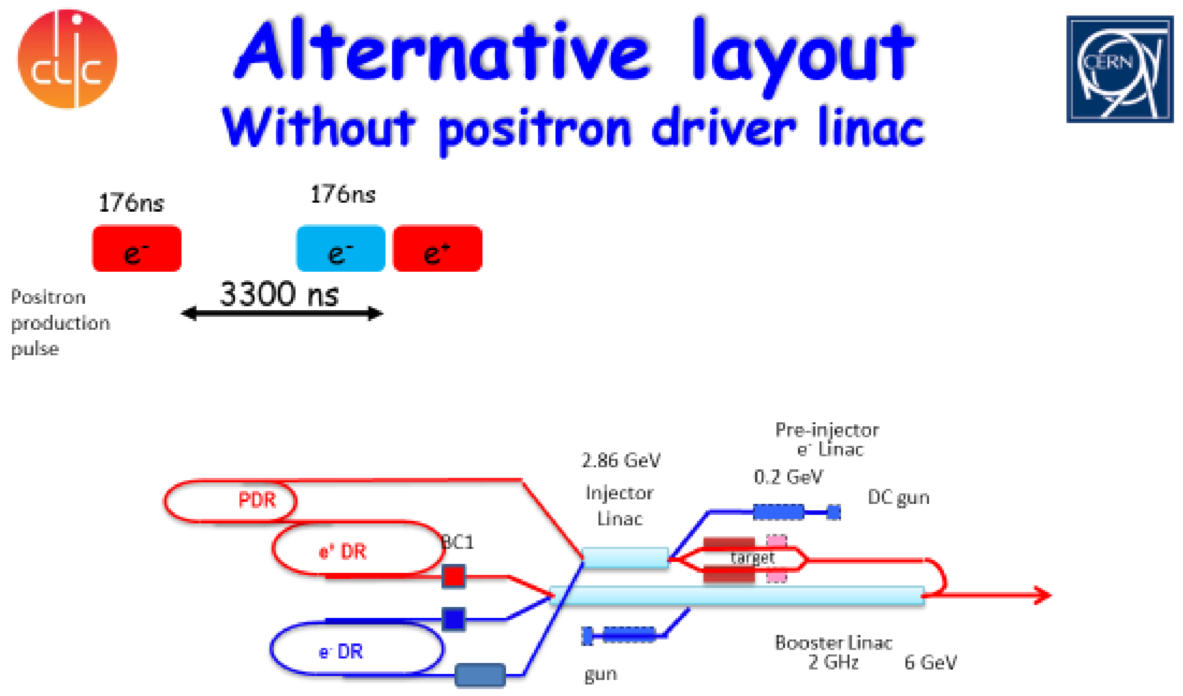
CDR MBI layout



MBI layout for PIP and alternative

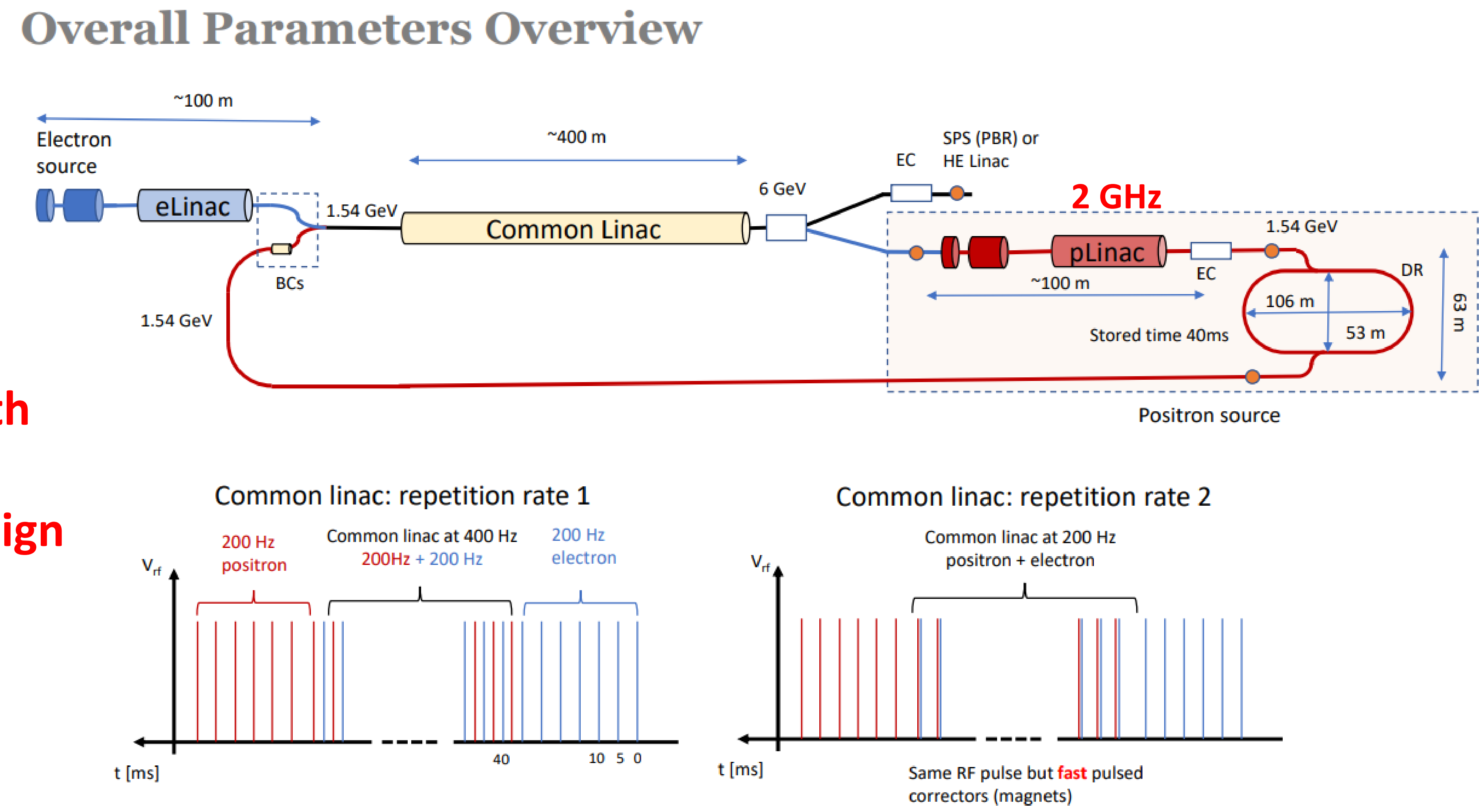
Steffen Doebert





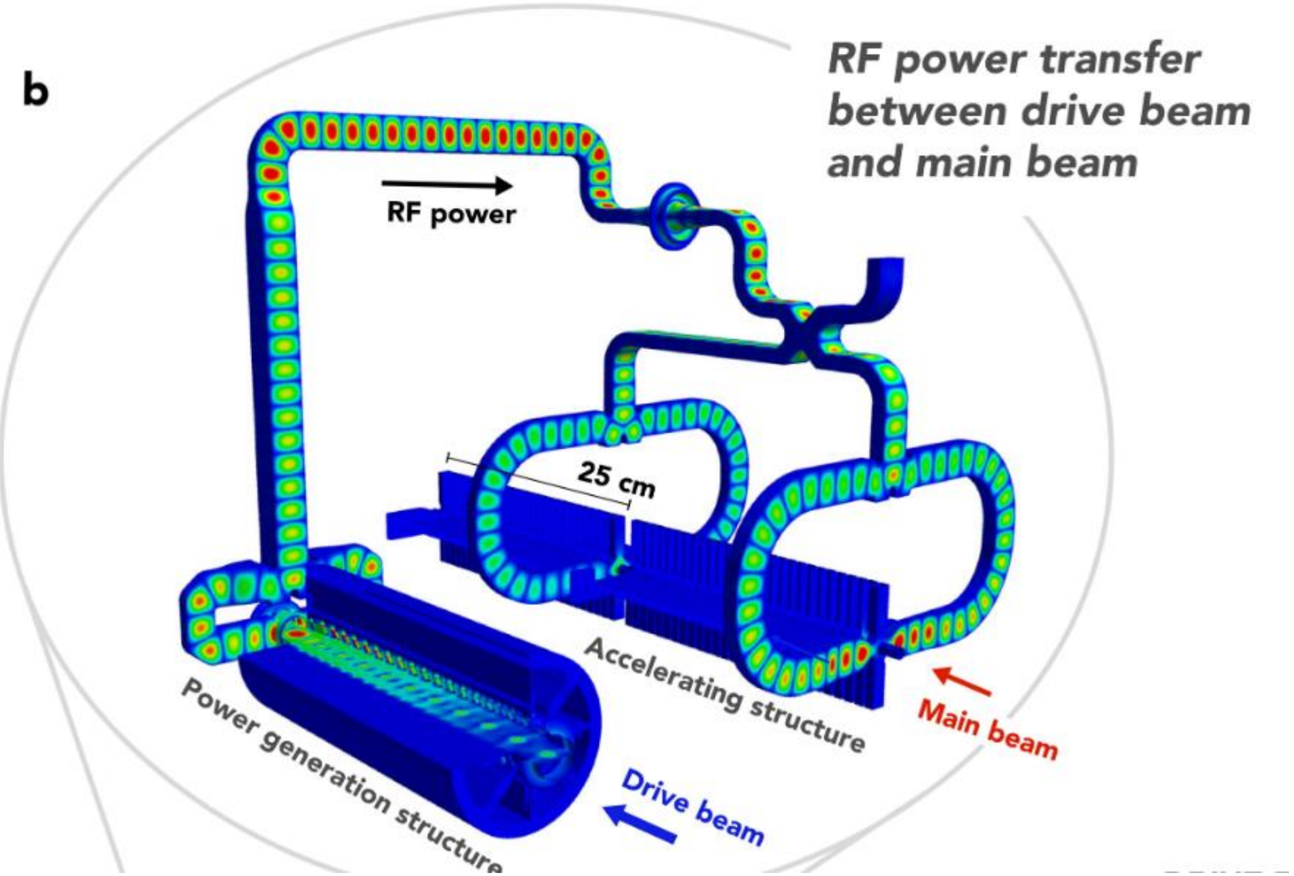
- **Alternative layout with shorter total length of the linacs may reduce both cost and power. One possible layout proposed by Steffen, but not studied**
- **Further optimization of accelerating structure and RF pulse compression system**

FCCee injector complex design collaboration



Injector complex optimization studies can be combined with on-going FCC-ee injector complex design studies

TBA RF system and power losses



Average (50 Hz) beam and dissipated power in SAS RF unit:

- Beam power : 514 W
- **SAS losses : 603 W**
- **RF loads : 328 W**
- WG network : 60 W
- PETS : 10 W

AS RF-to-beam efficiency:

P_B/P_RF =

514/(514+603+328) = **35.6%**

Possible way to improve MB AS efficiency

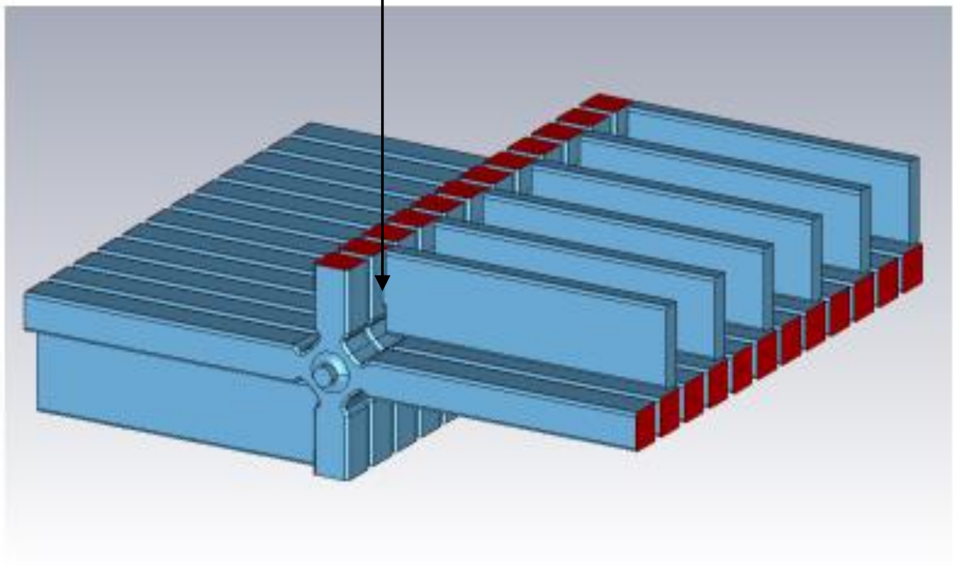
- Recent work by Evan Ericson: rf development meeting (28 September 2022) · Indico (cern.ch)
- Standing wave (SW) accelerating structure: power to RF loads -> 0
- Single or few cells distributed coupling structures:
  - higher gradient, OR
  - higher shunt impedance design for same gradient
- The main challenge is to provide required HOM damping performance combined with distributed coupling WG network

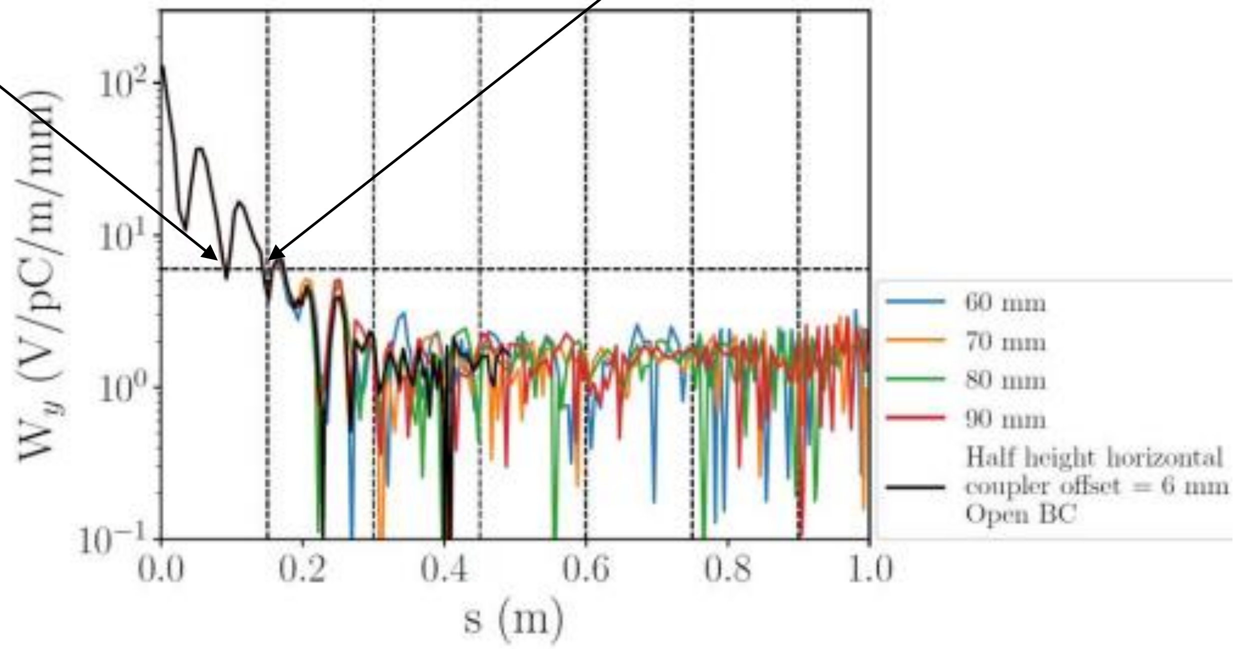
Wakefield damping and distributed power coupling

Each cell has individual power coupling WG in addition with 4 damping waveguides

It might be possible to satisfy HOM Damping requirement even for 1/3 ns

HOM Damping requirement are OK for 0.5 ns



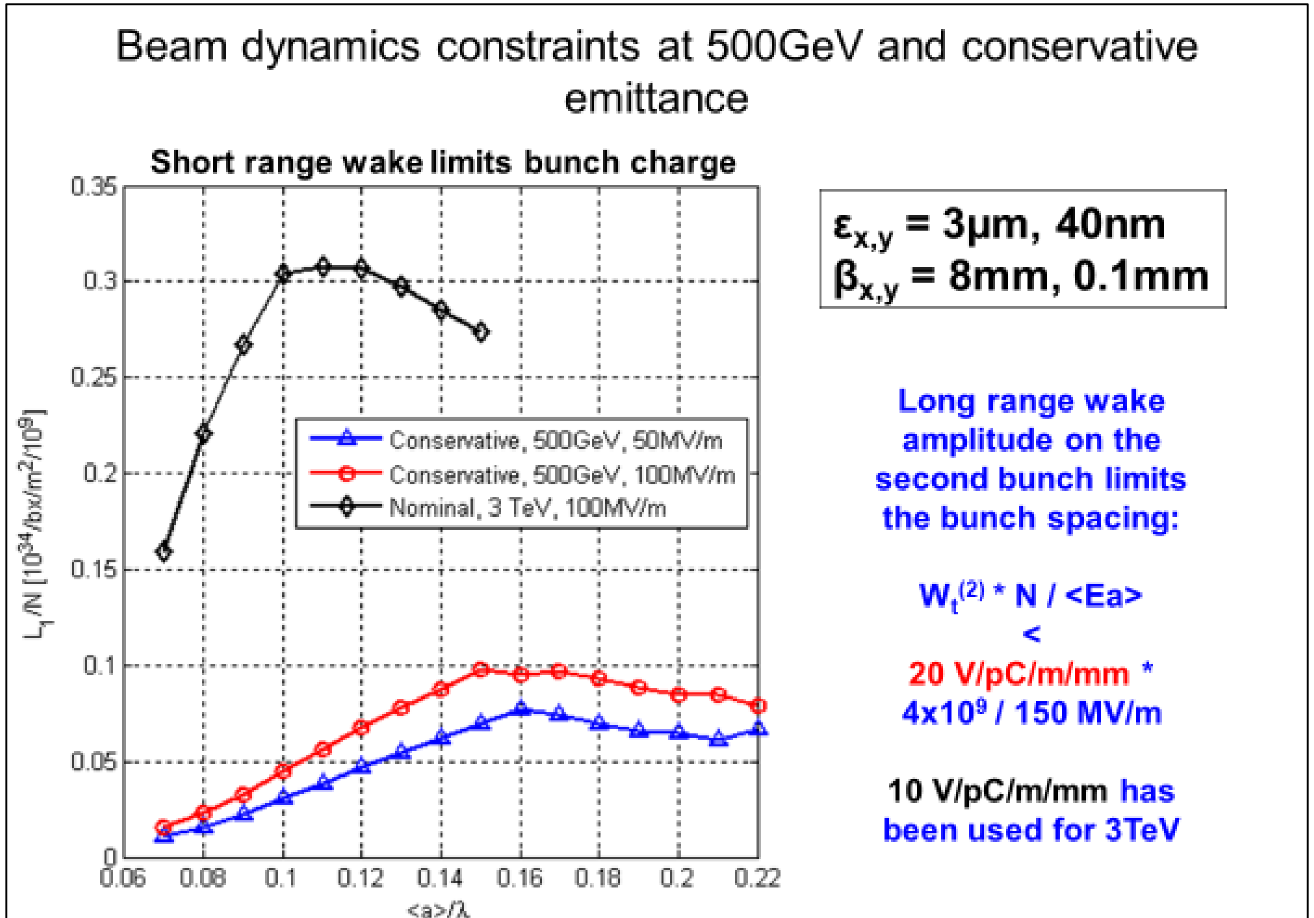


RF-to-beam efficiency of SW AS

- Evan's work is done for 3TeV structure: aperture and MB current
- Potentially high gradient limit was improved
- RF-to-beam Efficiency was been increased from **28** -> **31** %
- 31% = SS Eff. * Pulse eff = 47% * 66%
- Assuming **1/3 ns** bunch spacing is possible from HOM damping point of view: SS Eff: 47% -> 57%; Pulse Eff.: 66% -> 80% => Eff. 31% => **46%**
- To access power efficiency improvements for CLIC 380, design of dedicated SW accelerating structure is required.
- If the efficiency scales similarly (?) for CLIC380**: 35% -> 39% -> 58%**

Bunch spacing of 1/3 ns would require significant changes in the injector: 2 GHz -> 3 GHz

Luminosity per beam power optimization

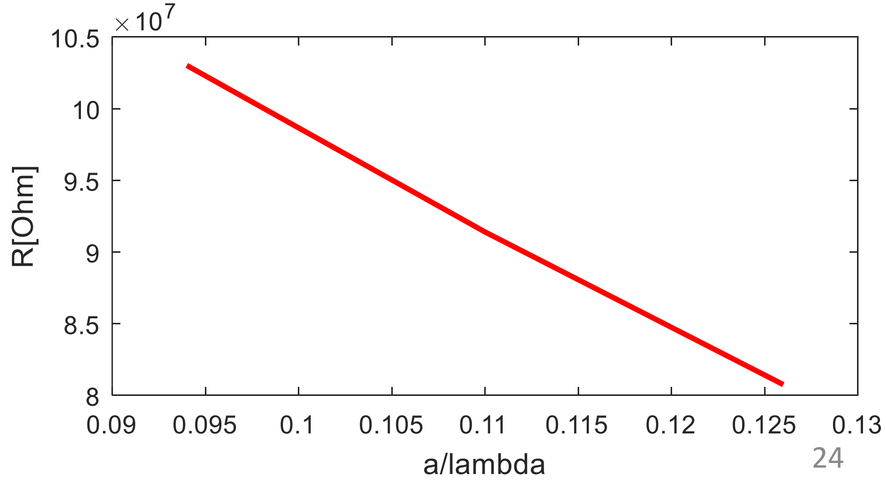


Very old plot, 2010

- For CDR and for staging Luminosity per beam power has been optimized:
  - **L/P ~ L_{bx}/N * RF2Befficiency**
- CLIC 3TeV, a/lambda = 0.11
- CLIC 380GeV, a/lambda = 0.133

- **Maybe it is time to make this plots again?**

- For the shunt impedance the smaller aperture the better



Summary list of possible actions

- New DR RF system should be integrated in DR BD layout and Cryo-power both for DR RF and for wigglers should be estimated

  SRF cavity prototype
- New DBI based on TS-MBK require revisiting modulator parameters and BD layout
- Quads and dipoles in DB complex optimization using PM or SC technology may reduce Power consumption
- MB injectors optimization (layout and RF) is important to reduce power and cost. Can profit from on-going FCCee injector design collaboration
- MB X-band TBA is still the point where improving efficiency is important. Investigation of SW AS and revisiting Lbx/N versus RF-to-beam efficiency optimization should be considered even for 380 GeV.

  X-band SW cavity prototype
- Possibility to change from 2 to 3 GHz bunch spacing should be investigated. It has strong impact on RF-to-beam efficiency ☺ BUT also on the injector complex design☺?☹.

Backup slides

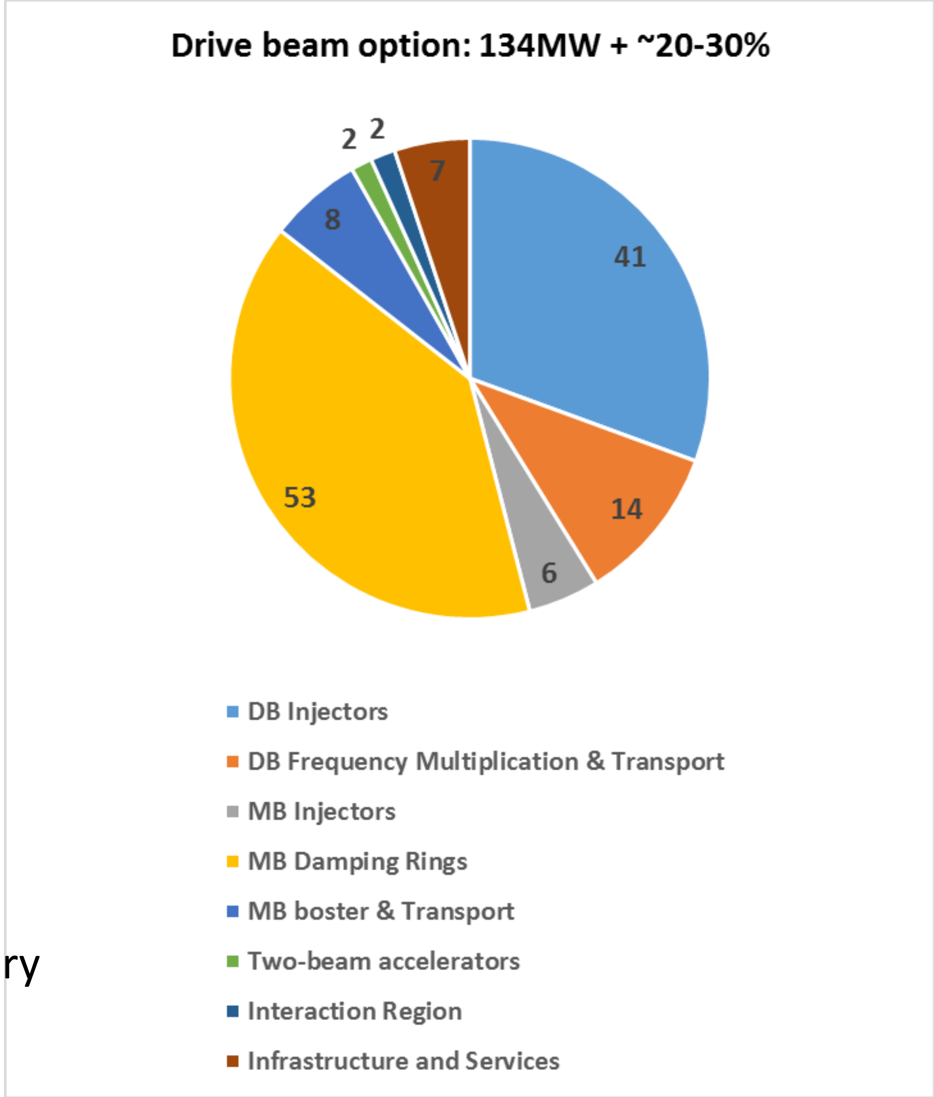
Summary

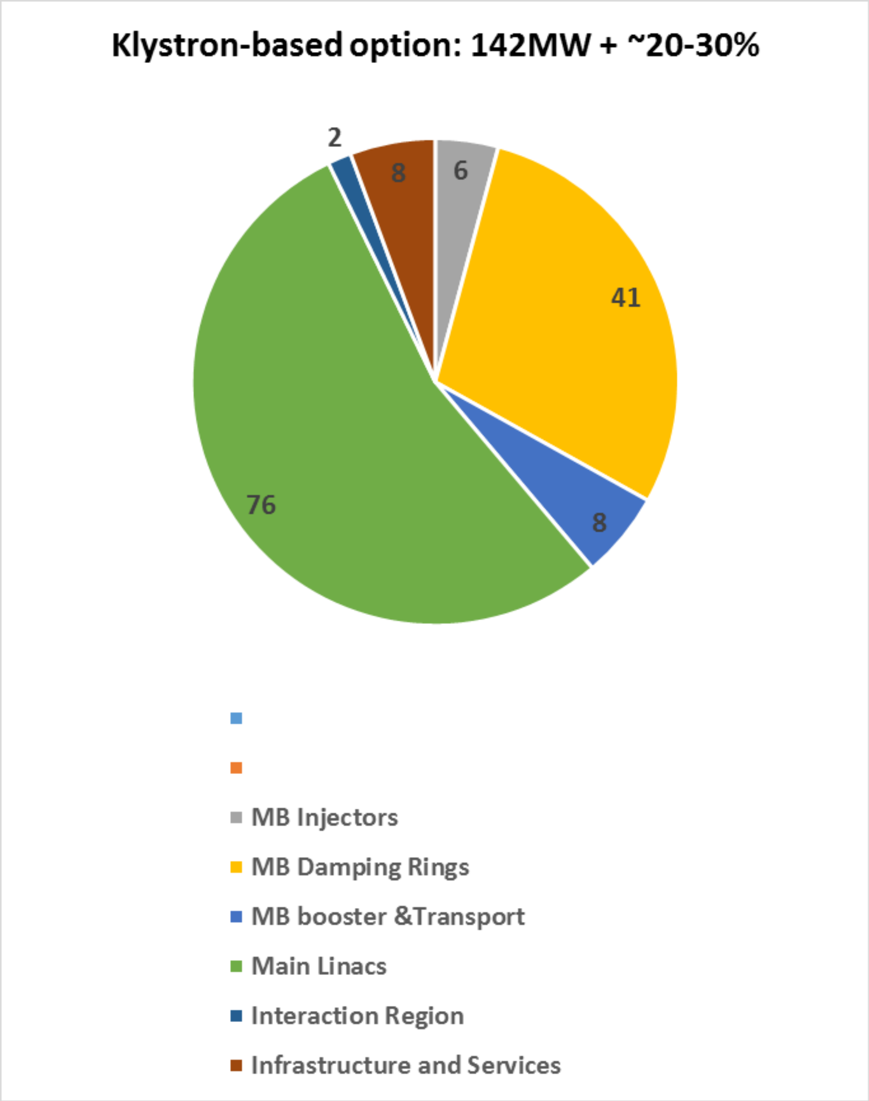
- CLIC 380 GeV power estimate has been updated to include several possible changes
- Increase in repetition rate from 50 to 100 Hz result in increase in power consumption by 68 MW from 168 to 236 MW
- New design of the DRs demonstrates significant reduction of the power consumption by 50 MW from 168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

Comparison of wall plug to beam efficiencies

	PIP baseline	New 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**

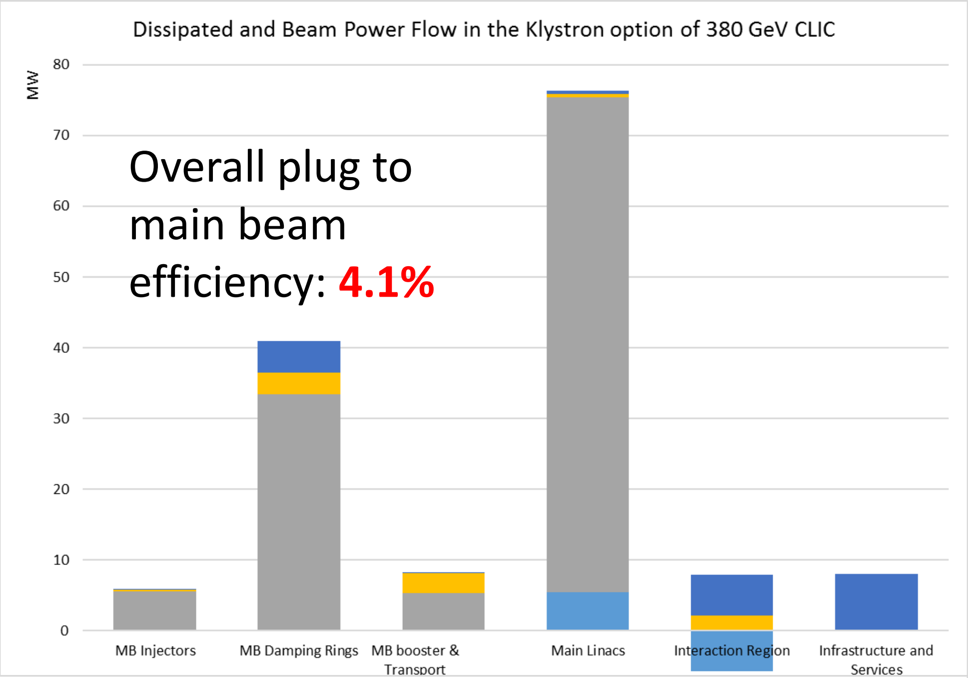
Comparison of Drive beam and Klystron options

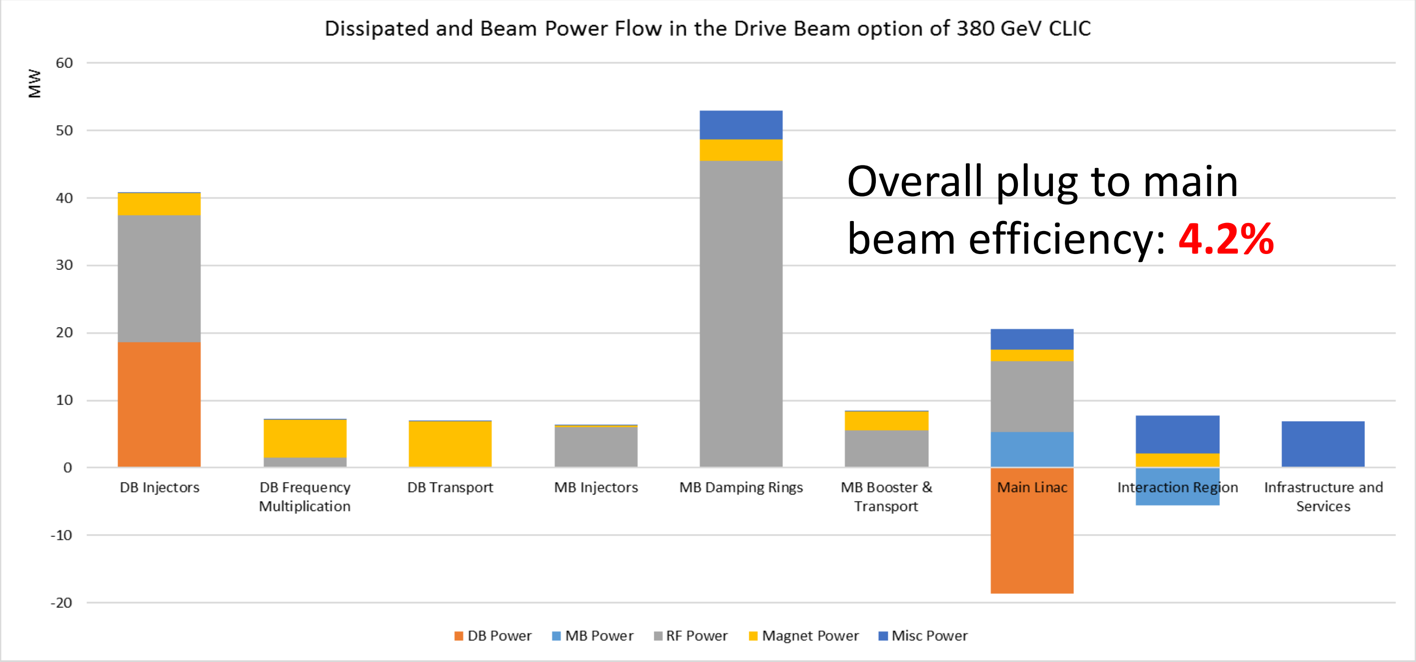




Preliminary
2018

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	$\mathbf{f_{RF}}$	**2**	**GHz**
Harmonic number	h	2493	
Energy loss per turn	$\mathbf{eV_A}$	**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	$\mathbf{I_b}$	**1.8**	**A**

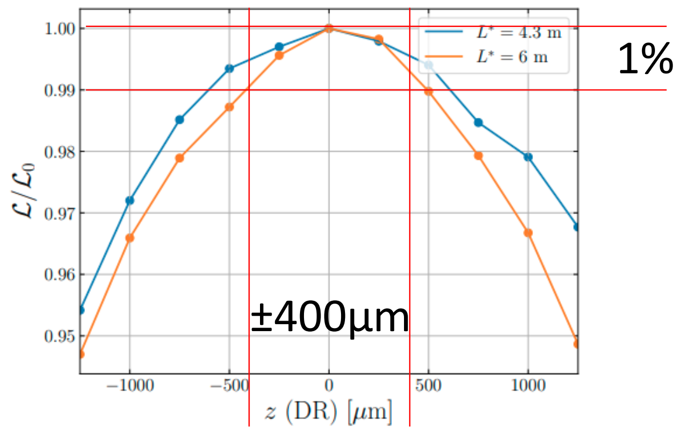


Figure 10: Luminosity against the longitudinal bunch position from the DRs.

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

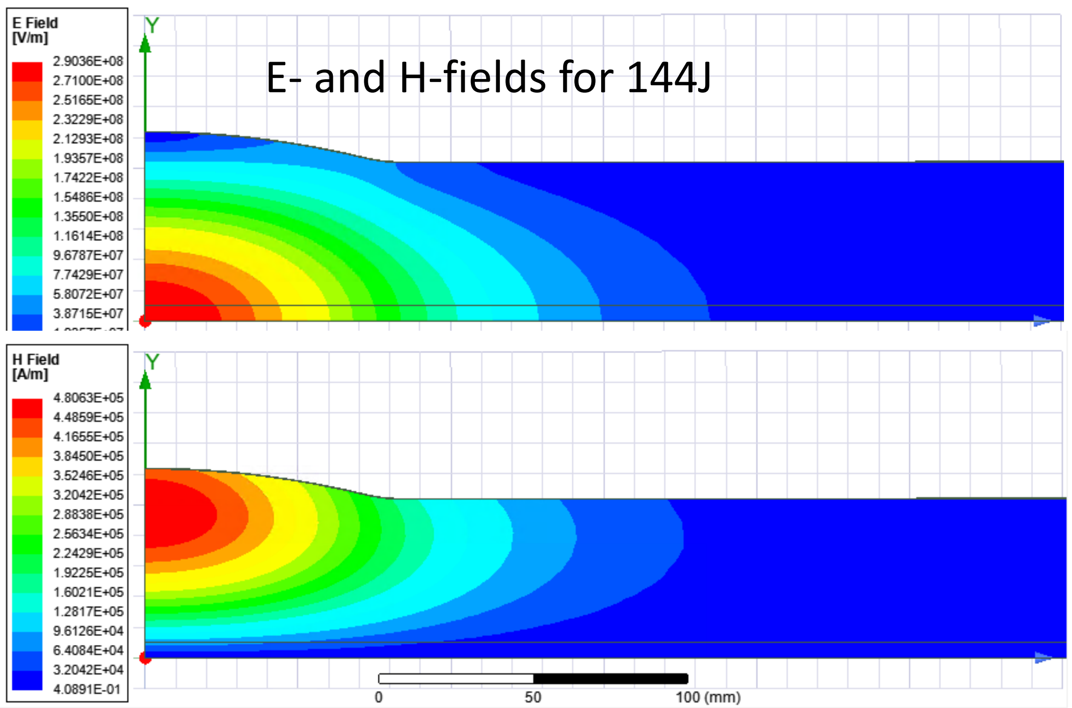
This is difficult to maintain due to **strong transient beam loading effects** caused by large difference between **peak** and **average beam power** values of 10.4 MW and 1.5 MW, respectively

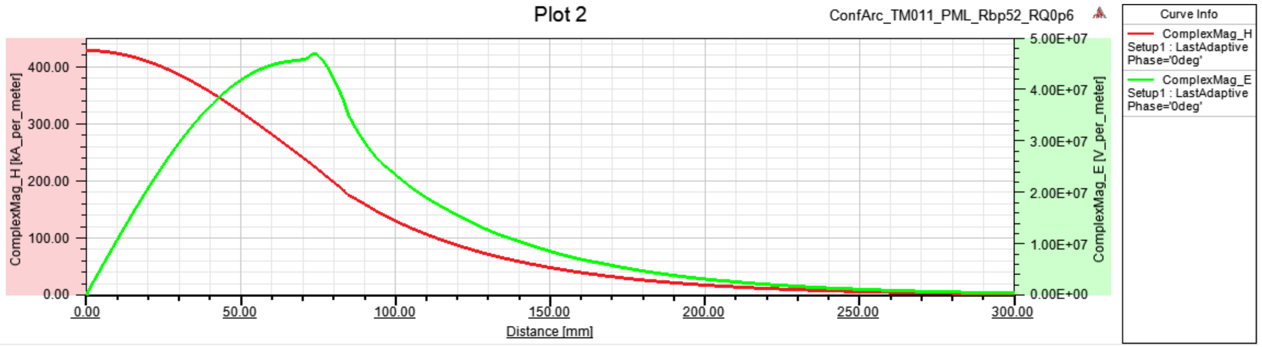
Design philosophy for Ultra low R/Q RF cavity

- 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

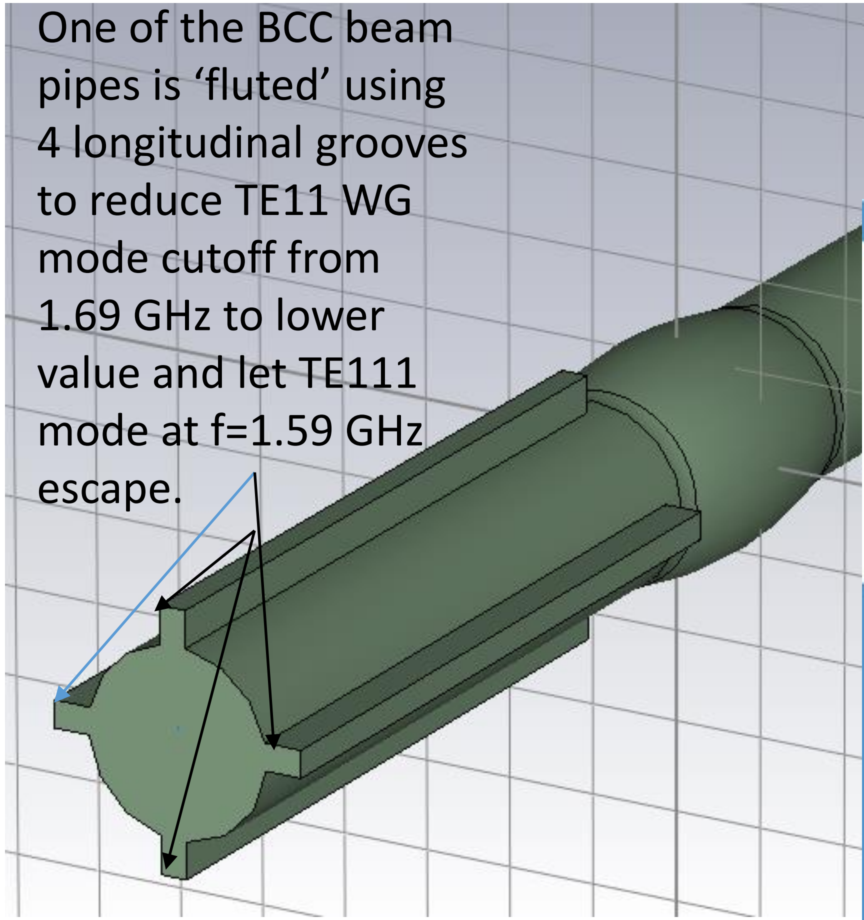
Vmax per cavity is 6.5MV/Ncav

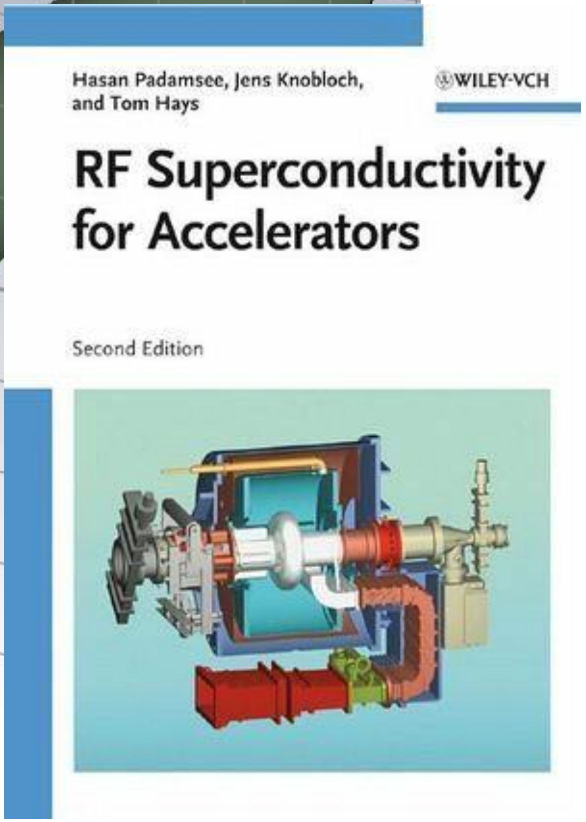
Ncav = 24

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

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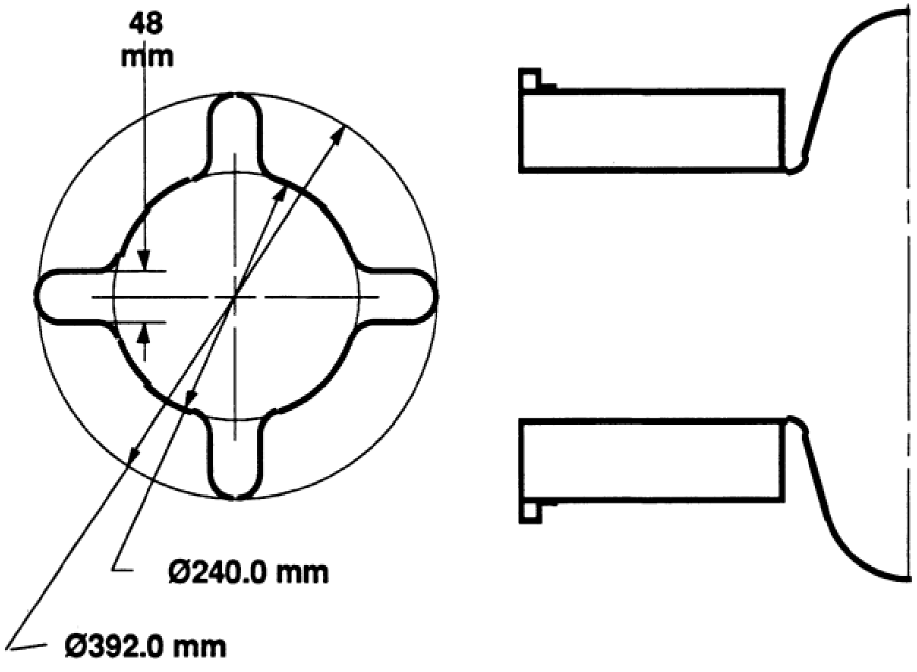


FIGURE 5: Geometry of fluted beam pipe

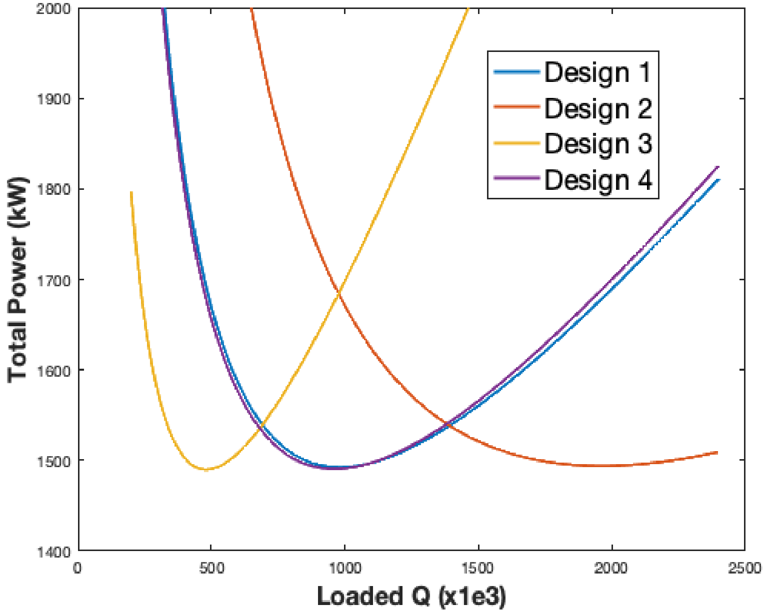
Summary table. More details : CLIC-note-1173, or in rf development meeting

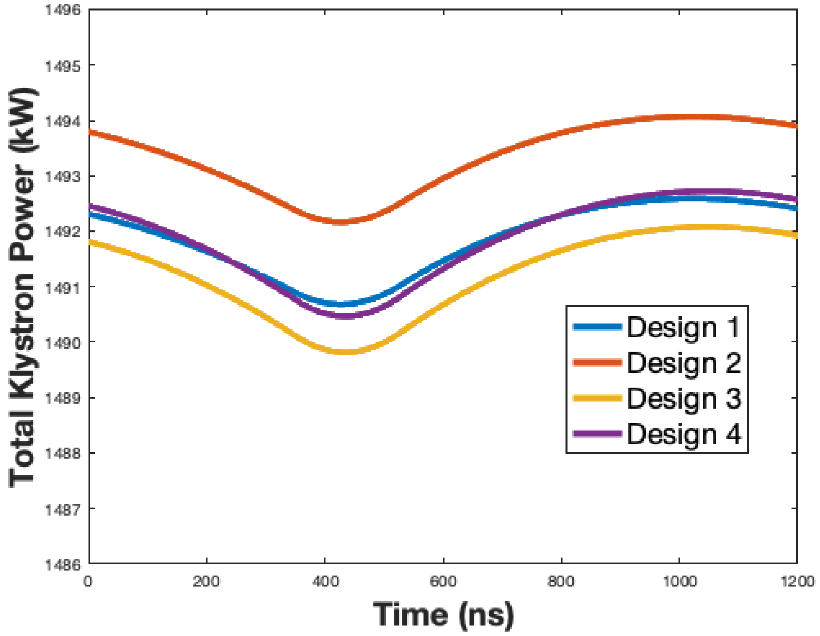
Case	1	2	3	4
Cavity R/Q [Ω]	0.6	→	2.04	
a [mm]	52		50	
Lc [mm] (0.01Hmax)	520		500	
Rarc [mm]	307		160	
Rcav [mm]	61.95		63.55	
Total R/Q [Ω]	14.3	7.15	28.6	14.3
Bunch phase variation [°] @2GHz	1	0.5	**2**	1
Ncav	**24**	12	14	7
Cavity input power Pin [kW]	60	120	103	**206**
Bmax [mT]	100 →	**200**	100 →	**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

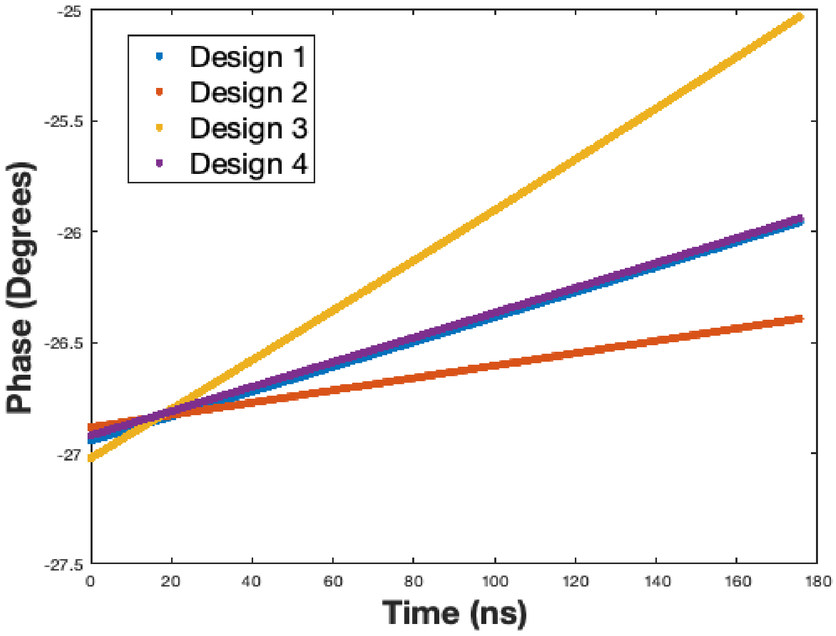
LLRF simulation results

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



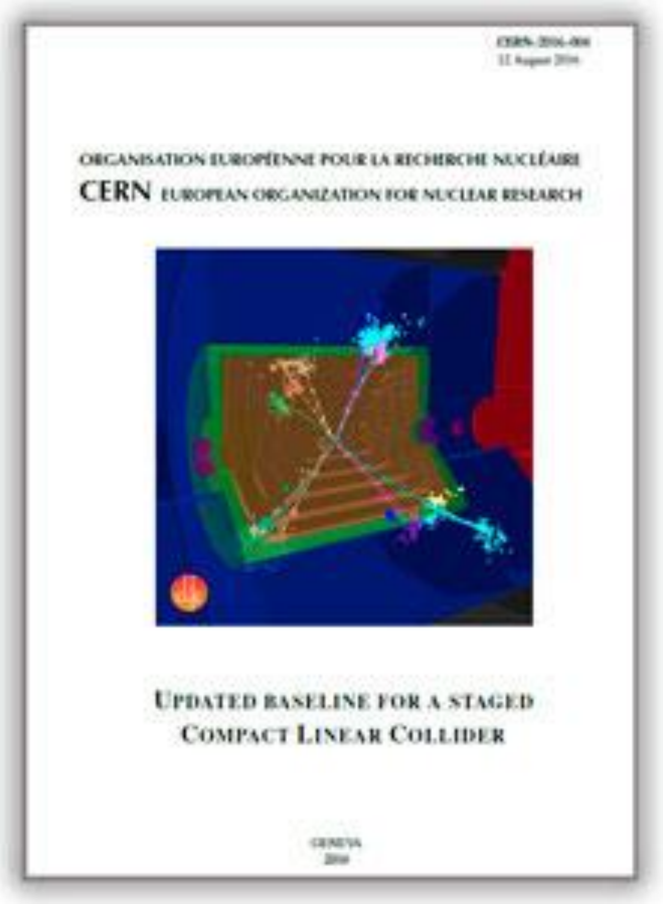


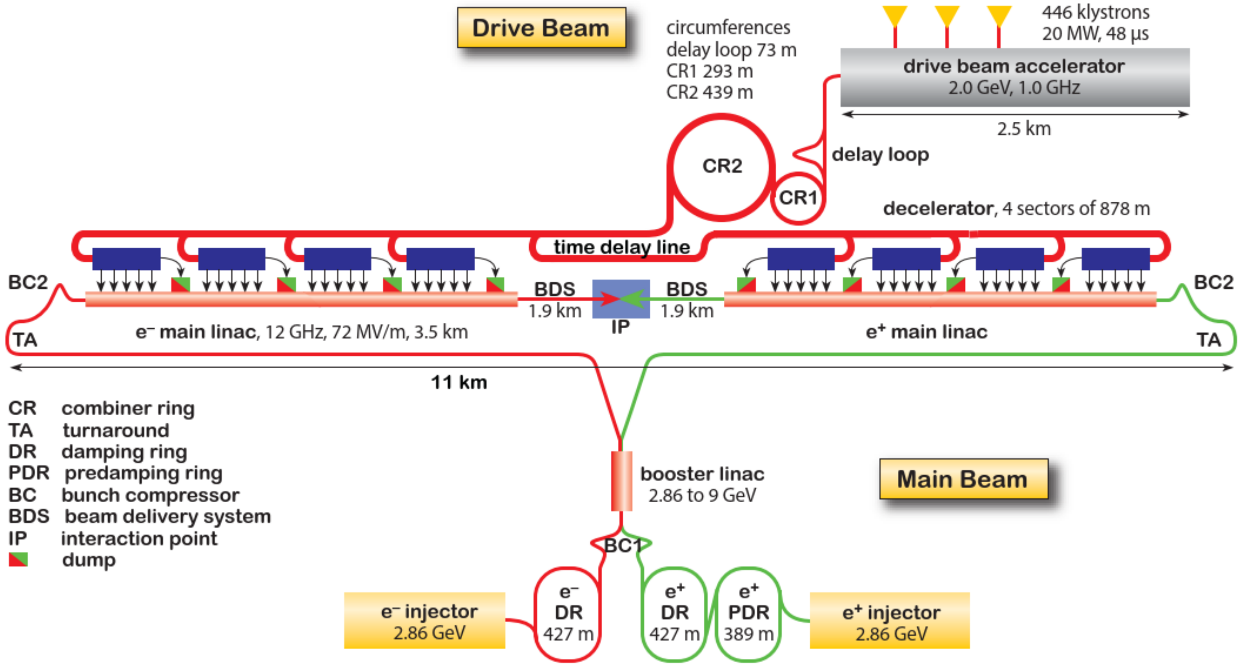


Due to the very high cavity filling time, the closed-loop response of the RF/LLRF system is slow. In addition, there is a 350 ns delay in the RF loop. Very small klystron power modulation

380 GeV CLIC layout and power consumption

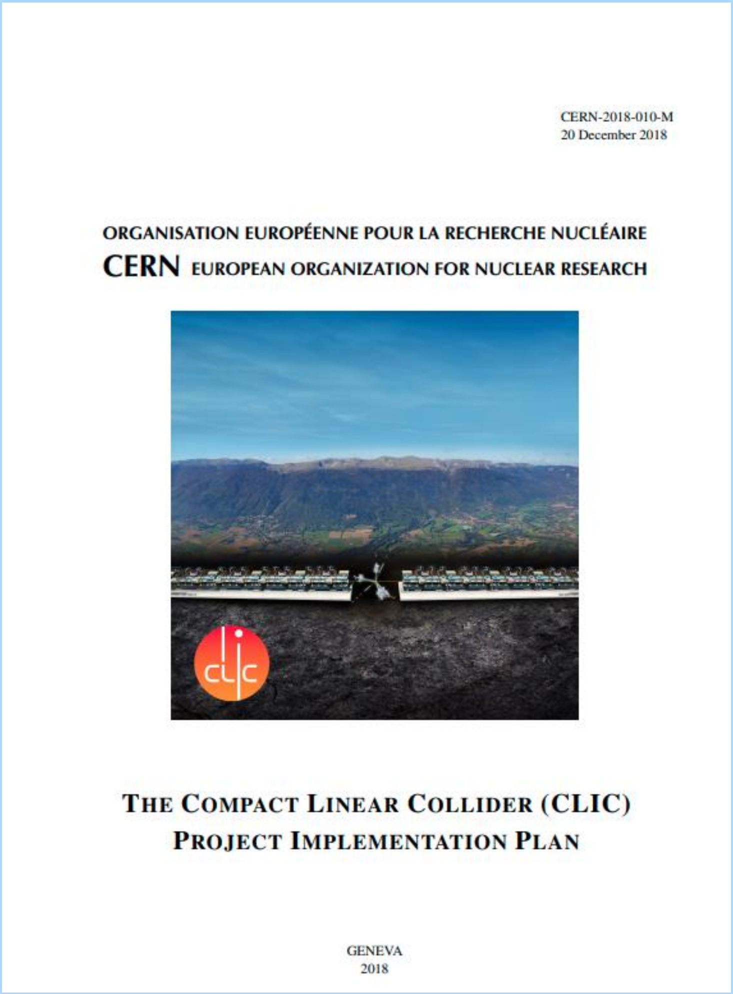
Updated baseline for a Staged Compact Linear Collider, CERN-2016-004, 2016





- 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
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

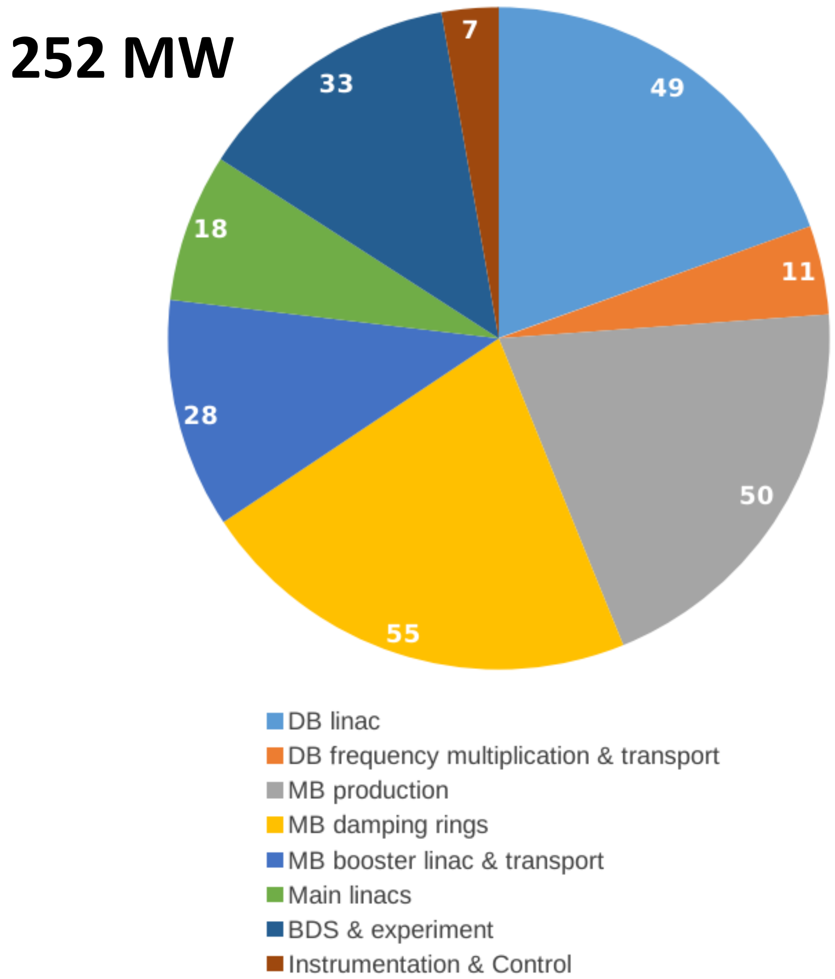
THE COMPACT LINEAR COLLIDER (CLIC)
PROJECT IMPLEMENTATION PLAN

GENEVA
2018

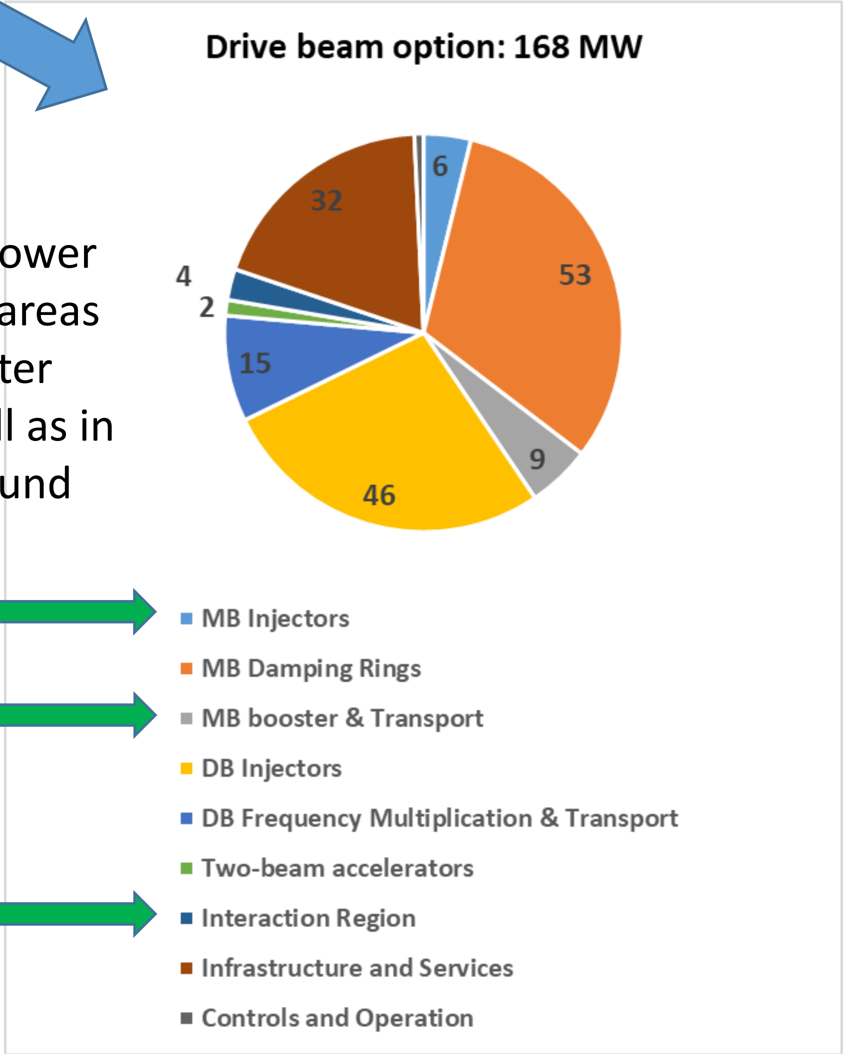
- **<u>Motivations:</u>**
- Parameterized model used in 2016 required verification at 380 GeV
- Several changes in the design parameters had been made:
  - Development of high efficiency klystrons
  - (Pre-)Damping rings bunch-to-bunch spacing reduced from 1 ns to 0.5 ns
  - Drive beam energy is reduced 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

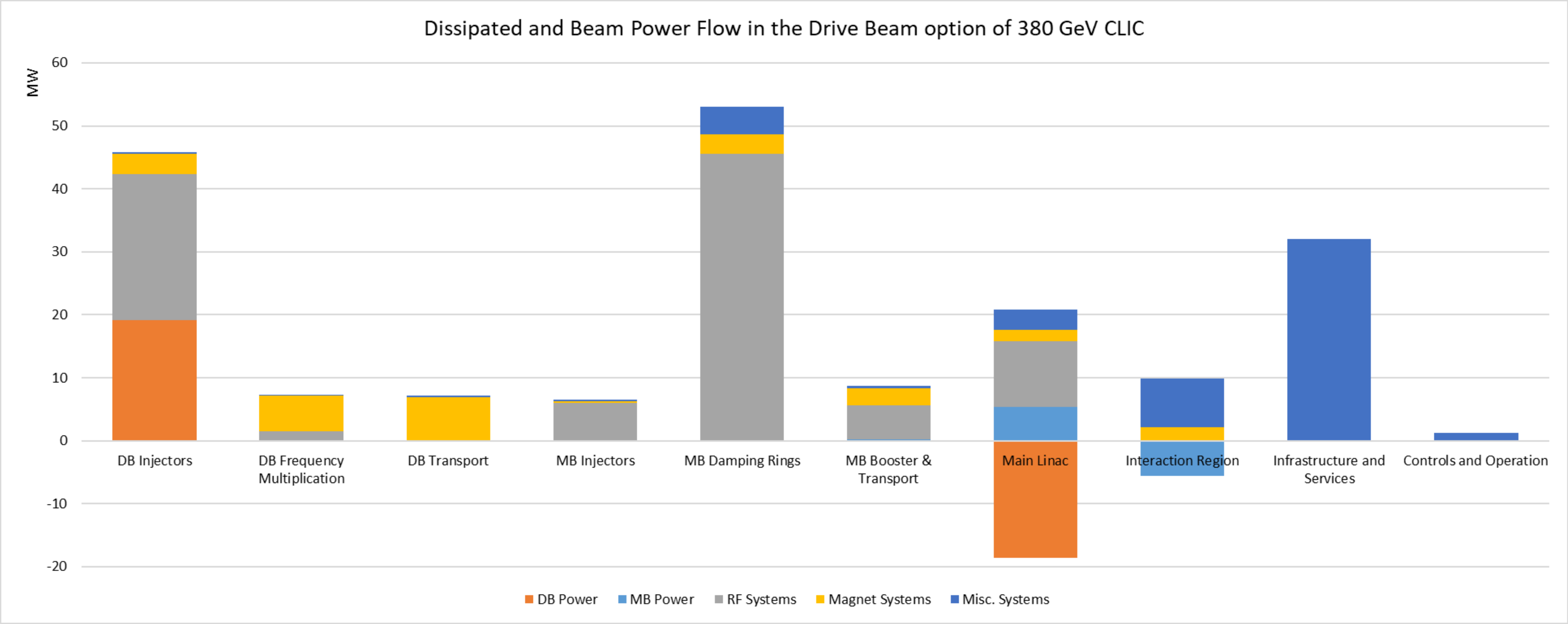
Comparison: 2016 vs 2018



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

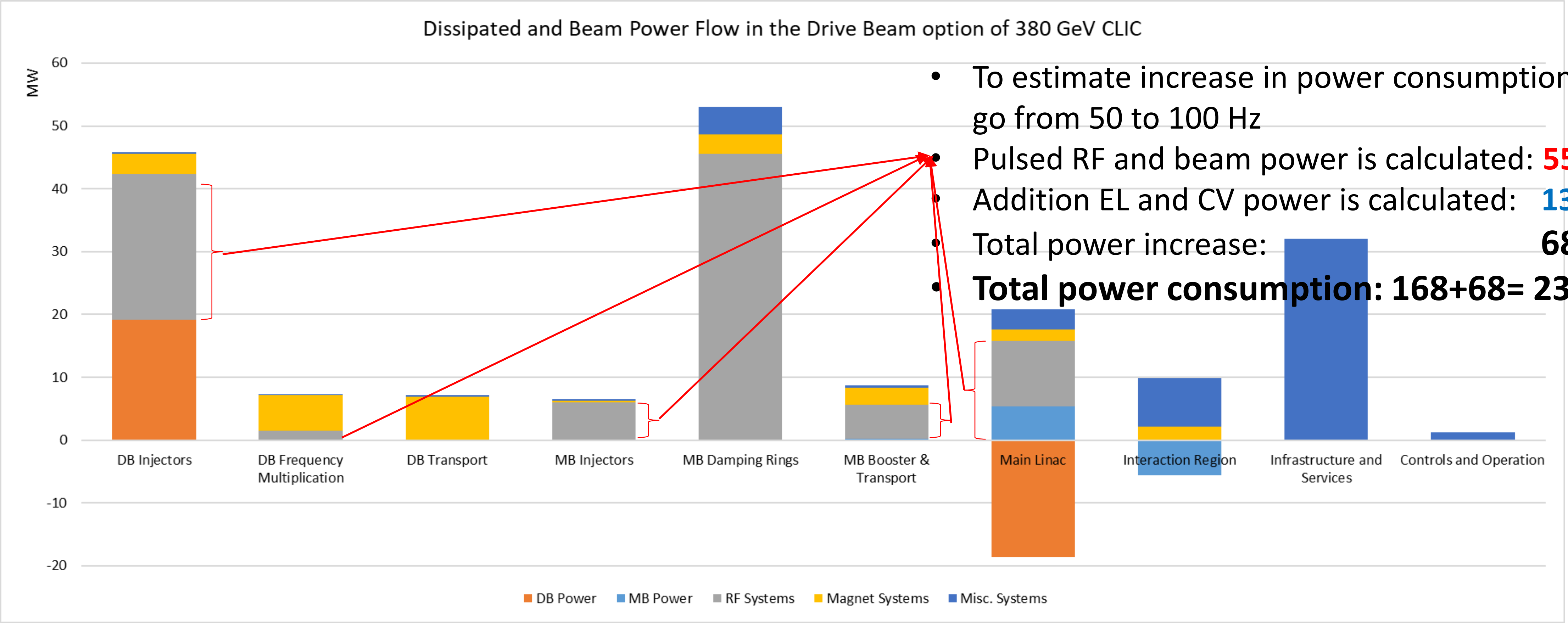


Distribution of dissipated and beam powers



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**



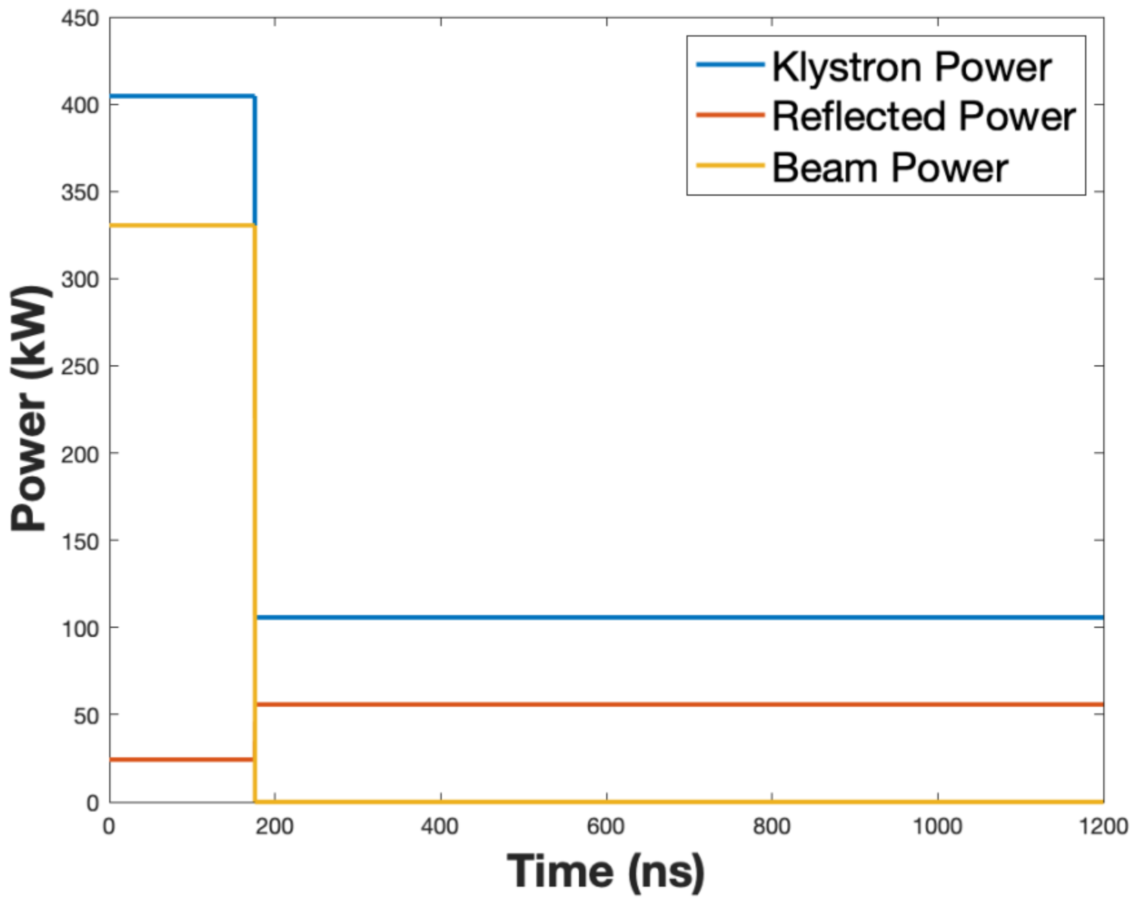
This estimate was mentioned in CLIC – Note – 1143: HIGH-LUMINOSITY CLIC STUDIES

CLIC DR summary of PIP baseline

Cavity type	ARES
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
Cavity power loss [kW]	~50
Total peak input power [kW]	12960

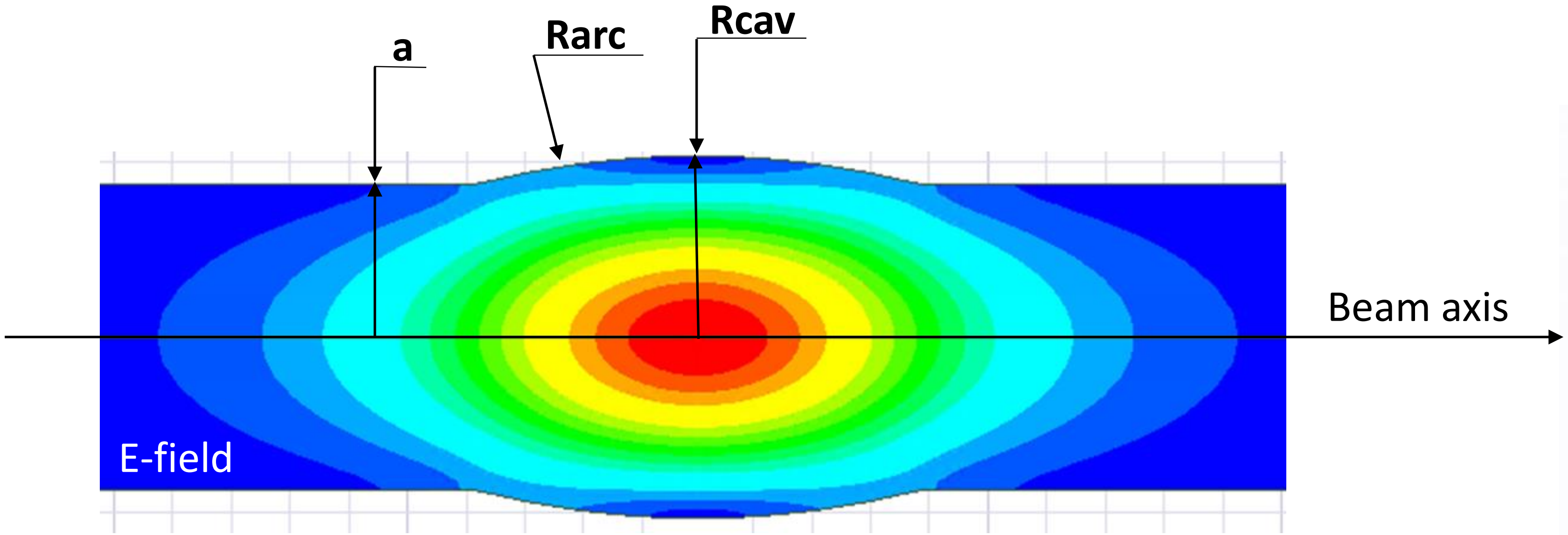
Strong transient beam loading effects cause:

- **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)