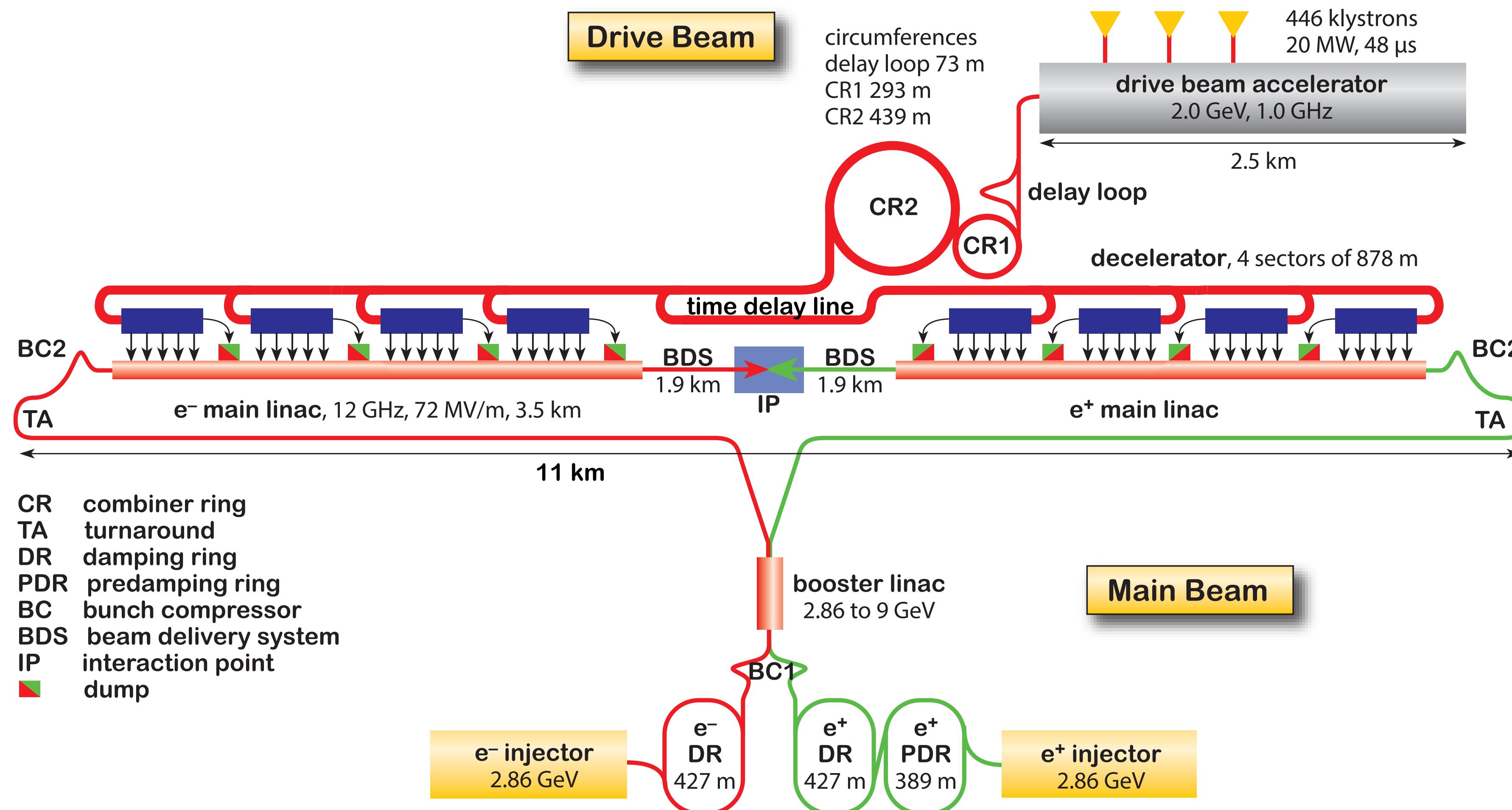


Optimization of the CLIC RTML RF System

Jim Ögren

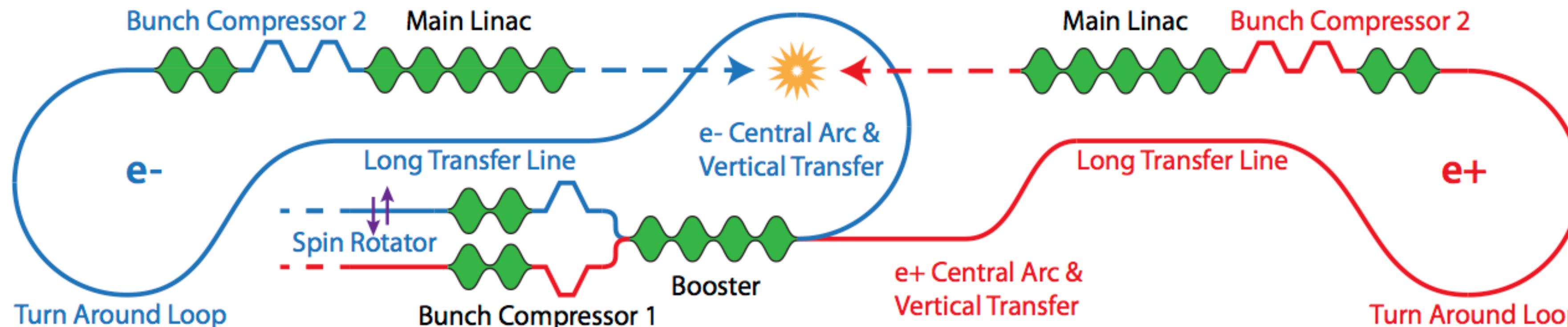
*Asian Linear Collider Workshop
May 28 - June 1, 2018, Japan*

Compact Linear Collider (CLIC)



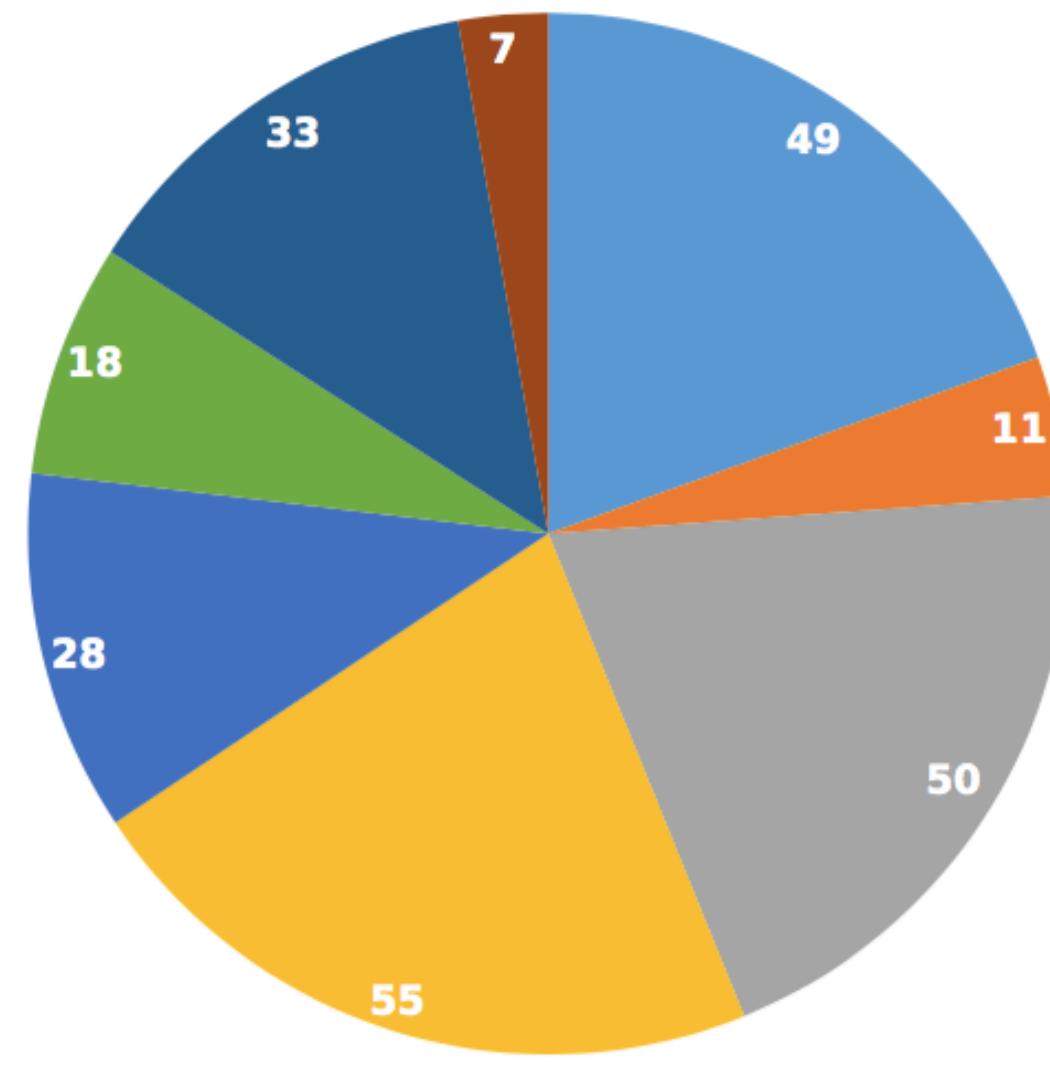
Ring to main linac (RTML)

Layout



	380 GeV		3 TeV	
	DR exit	ML entrance	DR exit	ML entrance
Beam energy [GeV]	2.86	9.0	2.86	9.0
Hor. emittance [nm]	700	700	500	500
Ver. emittance [nm]	5	5	5	5
N per bunch [10^9]	5.2	5.2	3.7	3.7
Bunch length [μm]	1800	70	1800	44
Number of bunches	352	352	312	312
train length [ns]	176	176	156	156

The Booster Linac



- DB linac
- DB frequency multiplication & transport
- MB production
- MB damping rings
- MB booster linac & transport
- Main linacs
- BDS & experiment
- Instrumentation & Control

Motivation:

The power consumption of the booster linac [28 MW] is non-negligible

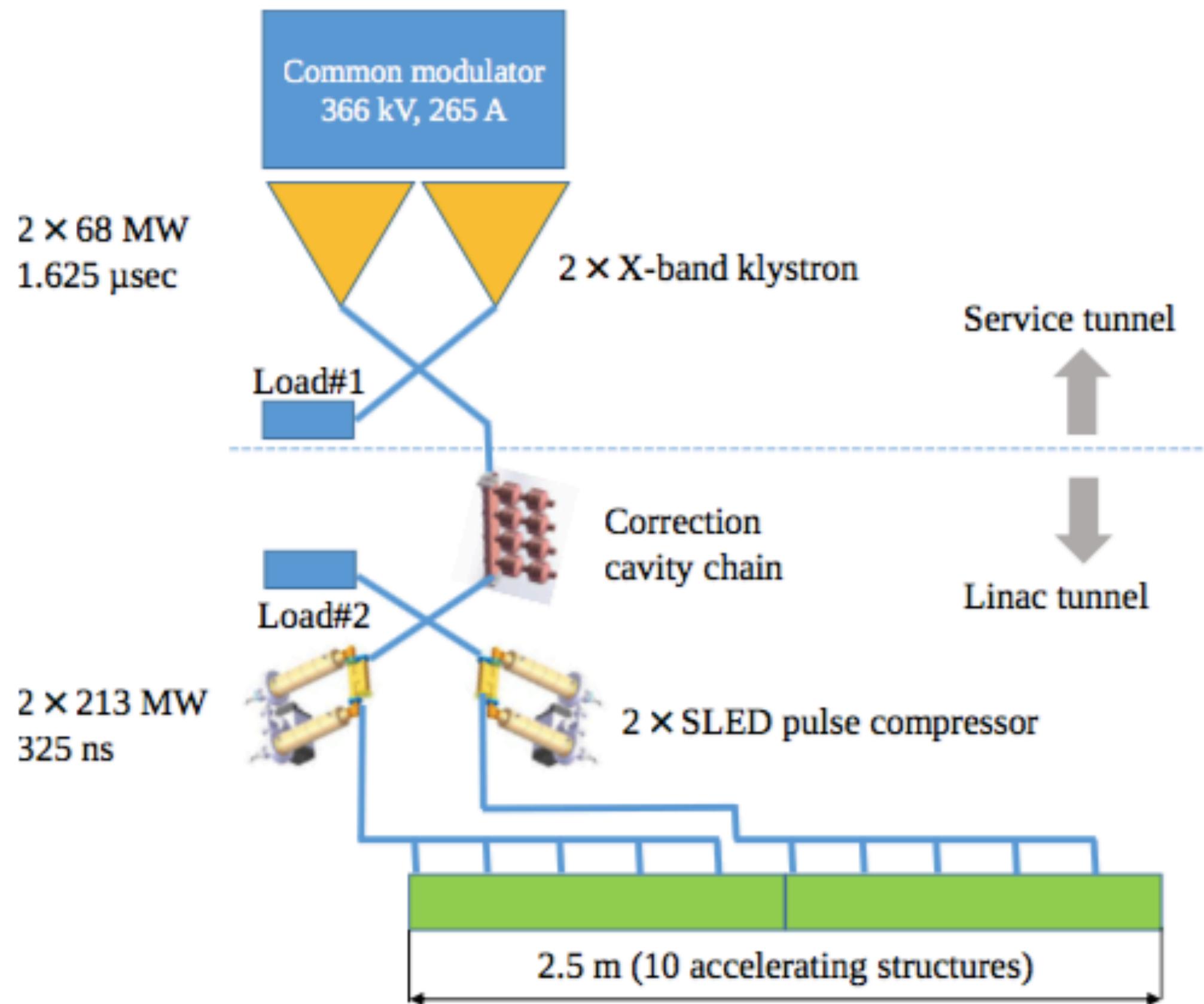
Electron and positron beams in the same linac
Bring beams from 2.86 to 9.0 GeV
Pulse compressors to achieve sufficient power
Beams **separated in time** or interleaved bunches?
Separate klystron pulses or **double pulses from pulse compressor?**

Booster baseline design (CDR), for 3 TeV CLIC:

- RF frequency: 2 GHz
- 34 FODO cells, each with 8 Accelerating structures
- Total active RF length 414 m
- Bunch length ~300 μ m

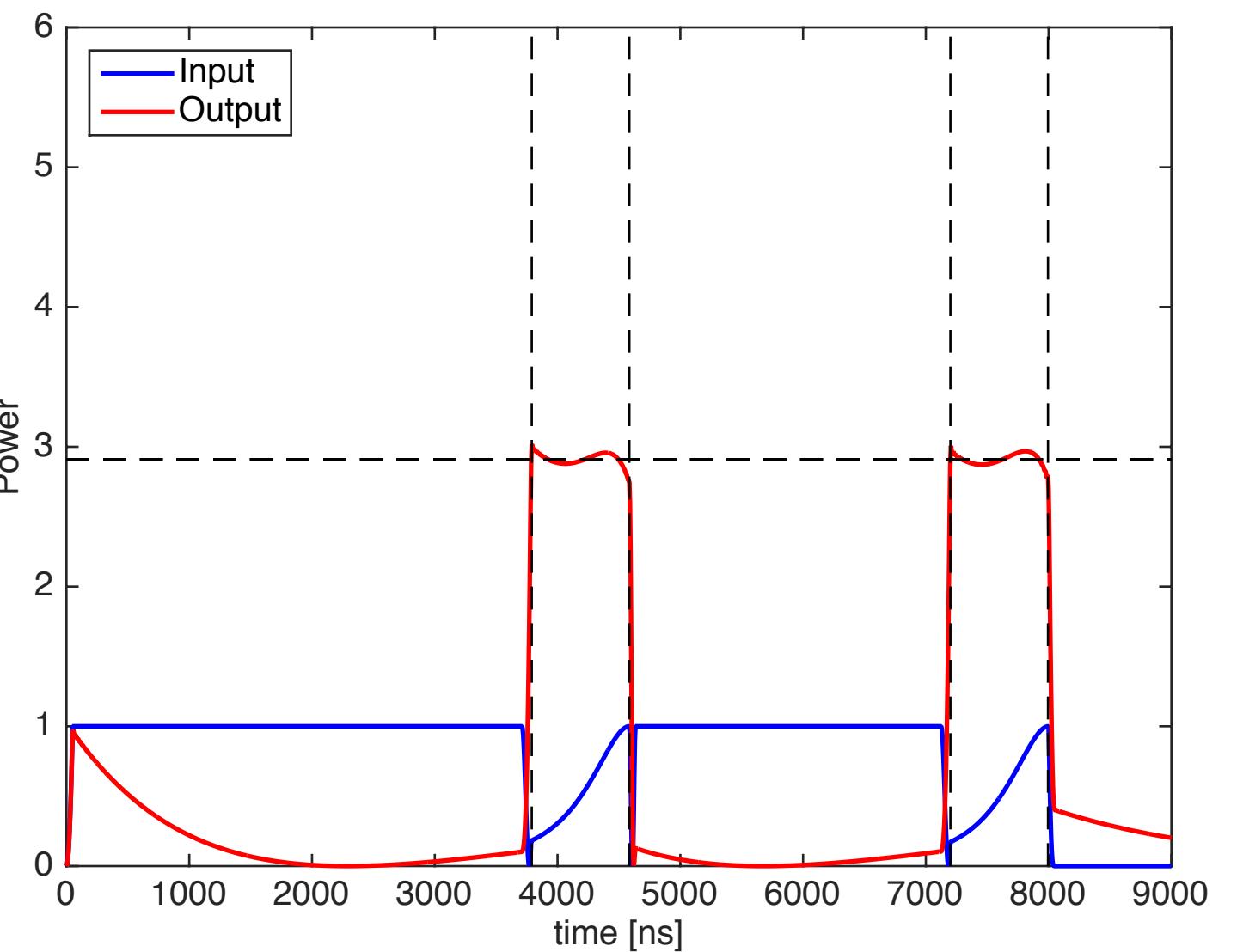
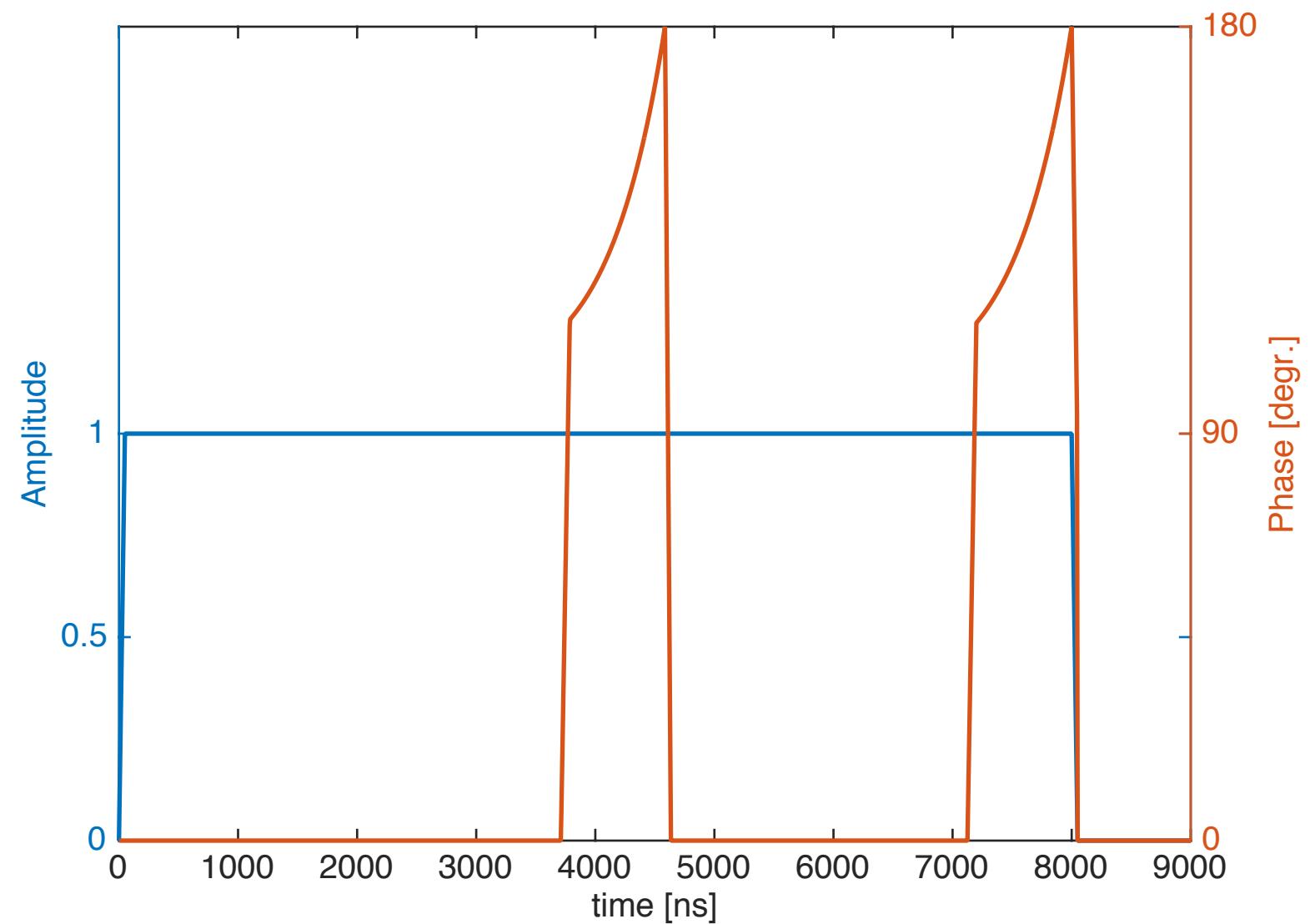
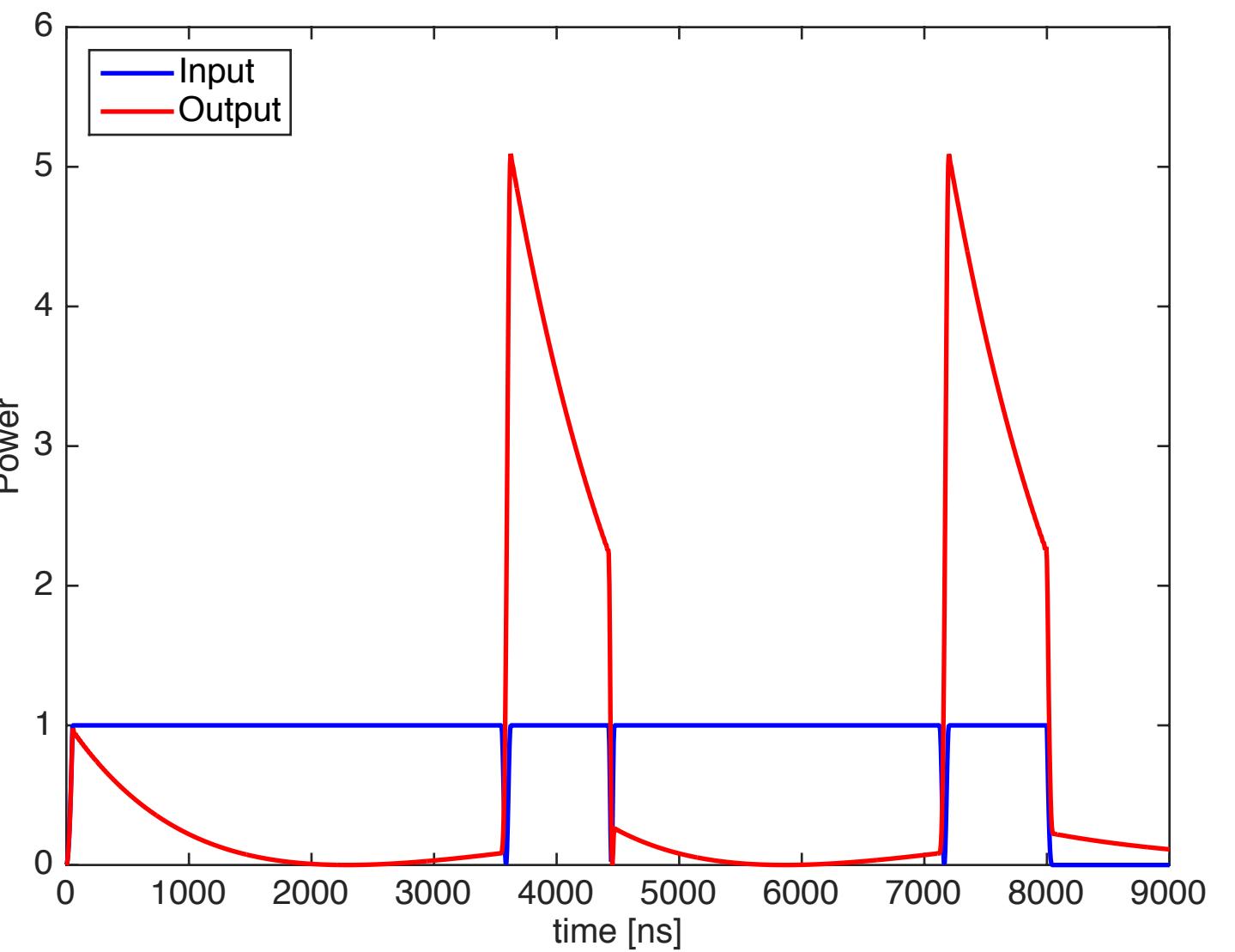
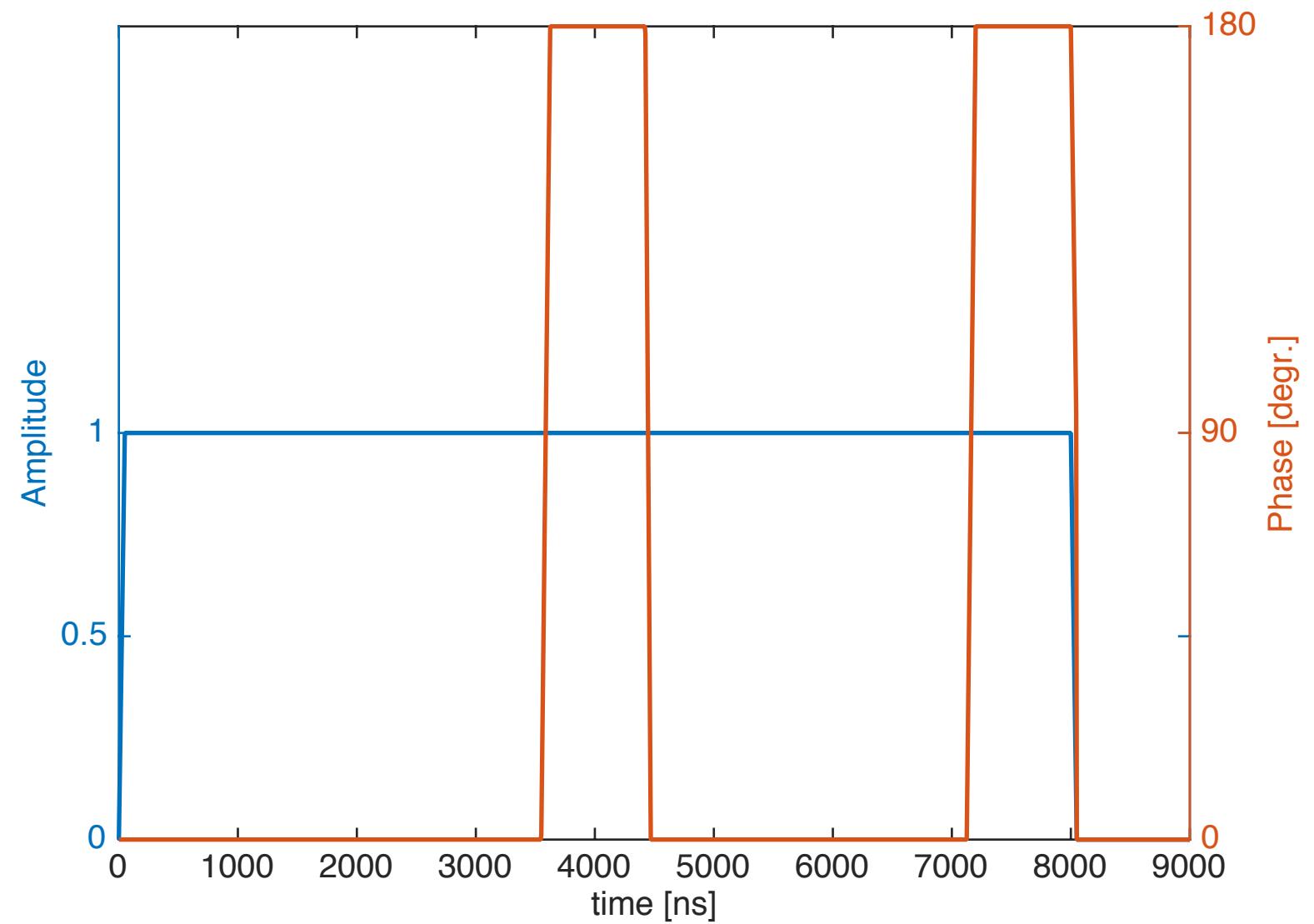
Pulse compressor

CLIC 380 GeV klystron option also uses pulse compressors



- Use pulse compressor to increase RF power
- Klystron charges two cavities
- Flip the phase and empty the cavities
- Conservation of energy => increased power
- Best case: 3x the amplitude/9x the power
- Octave script to estimate the gains

Double flat pulse



Adjust pulse separation
to achieve equal pulses

Ramp phase for flat
pulses

For different pulse length:
- 2 GHz and 4 GHz case
- Compression
- Efficiency

Pulse compressor: gain factors

Pulse length [ns]	2 GHz	4 GHz	6 GHz
200	5.6	5.0	4.5
300	4.9	4.4	3.9
400	4.4	3.8	3.3
500	3.9	3.4	2.9
600	3.6	3.0	2.5
700	3.2	2.7	2.2
800	2.9	2.4	2.0
900	2.6	2.2	1.7
1000	2.4	1.9	1.5
6000	-	-	1.0
7000	-	1.0	-
8000	1.0	-	-

Pulse compressor

- Assume Q = 180,000
- Higher frequency is less efficient
- Short pulse gives higher compression but with lower efficiency
- We include the pulse length-dependent efficiency in our optimization

Klystron parameters:

2 GHz: 80 MW, 8 μ s
4 GHz: 65 MW, 7 μ s
6 GHz: 50 MW, 6 μ s

RF Structure optimization

Structure optimization

- Given boundary conditions: 2.86 => 9.0 GeV
- Limited by beam stability and tolerable emittance growth
- We want to find cost optimum
- Trade-off between power consumption and linac length
- Smaller iris aperture means higher gradient per input power but causes stronger short-range wakefields

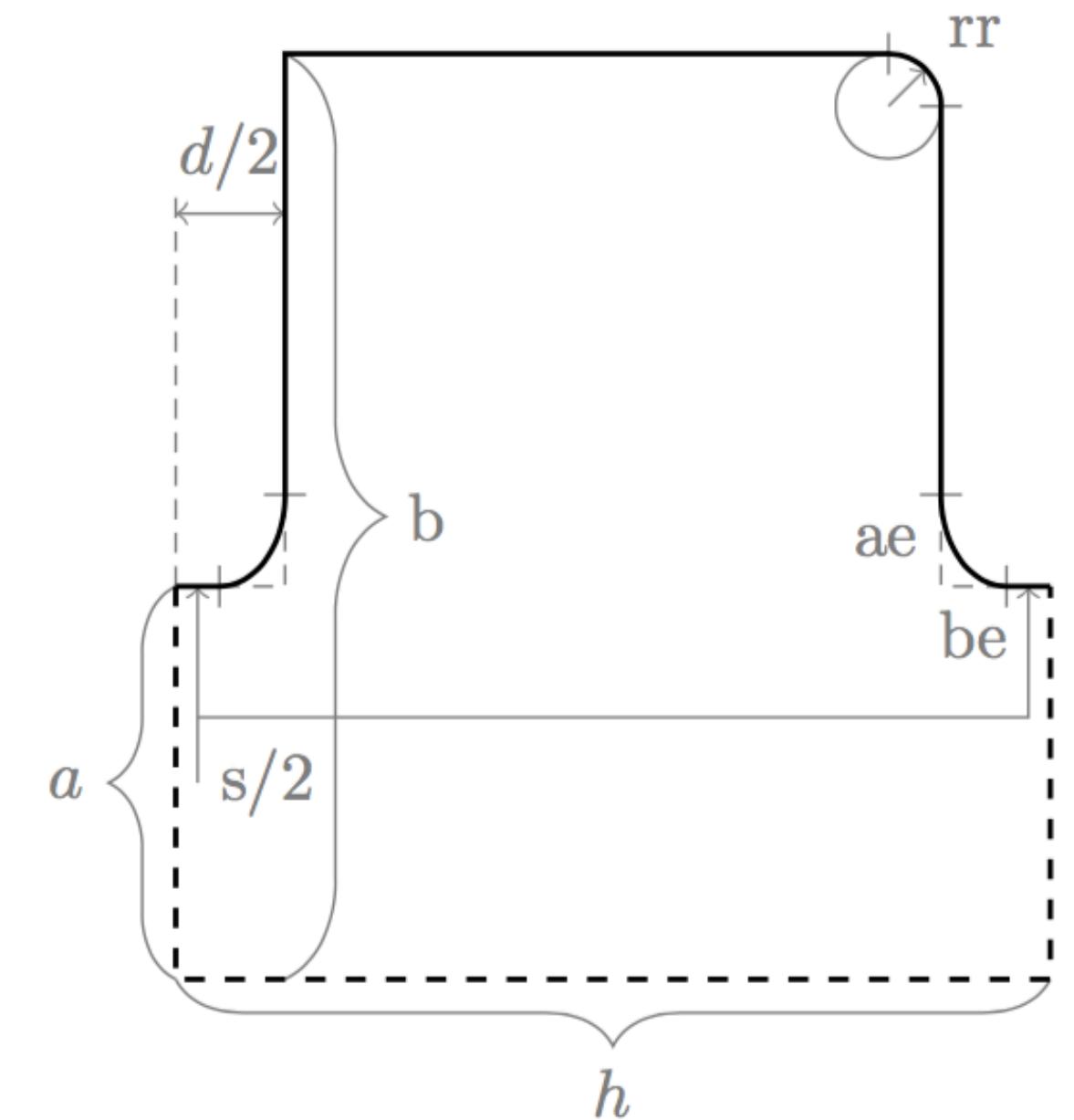
Structure optimization cont'd

- Accelerating structure data from the C++ library "CLICopti":
K. Sjobak and A. Grudiev, *The CLICopti RF structure parameter estimator*, CLIC-note-1028
- Converts cell geometry (i.e. a/λ and d/h) to RF parameters such as input power, safe pulse length, **wakefields** etc.
- Condition for single bunch transverse beam stability:

$$A = \int_0^L \frac{\beta}{2E} ds \langle W_{\perp} \rangle Ne^2 < 0.4$$

See presentations: D. Schulte: LC School or
D. Schulte, *CLIC Interest in high gradient FEL design*, Trieste, 2013

- We calculate the total number of structures needed, total power consumption, beam stability etc



From K. Sjobak's thesis

Structure optimization cont'd

- For each RF frequency: test all structures with:
 - Apertures a/λ : 0.10, ..., 0.20
 - Iris thickness d/h : 0.11, ..., 0.40
 - Gradient: 10, ..., 50 MV/m (2 GHz)
 - Gradient: 20, ..., 60 MV/m (4 GHz)
 - Gradient: 20, ..., 70 MV/m (6 GHz)
 - Number of cells per structures: 10, ..., 200
- Accept structures that fulfil
 - Transverse stability condition < 0.4
 - Fill time < 600 ns
 - Efficient RF configurations (e.g. #.9 RF units needed)
 - Sufficient allowable beam time
- We show only the 80% most efficient acceptable solutions
- We use 380 GeV beam parameters and assume 300 μm bunch length in booster

Lattice beta function

- The average beta function of the lattice impacts stability
- To make a fair comparison between different RF frequencies with need to adjust the focusing
- We assume that the magnet radius $r_0 = 0.3\lambda$ and a magnet fill factor (FF) of 5%

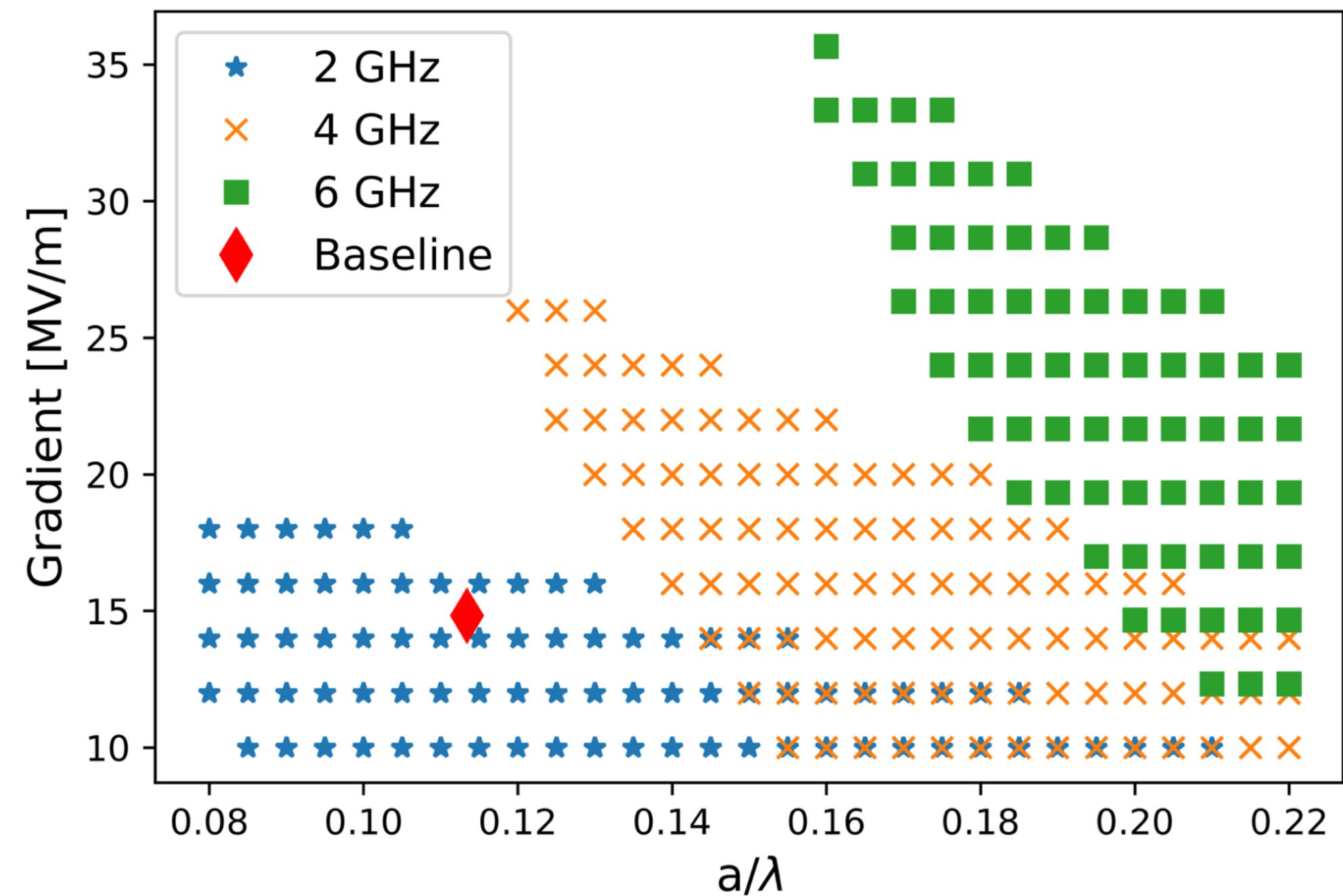
$$\langle \beta \rangle = \sqrt{\frac{8(B\rho)r_0 \sin(\phi/2)}{\eta B_{poletip} \sin^2(\phi) FF}}$$

$$A = \int_0^L \frac{\beta}{2E} ds \langle W_\perp \rangle Ne^2 < 0.4$$

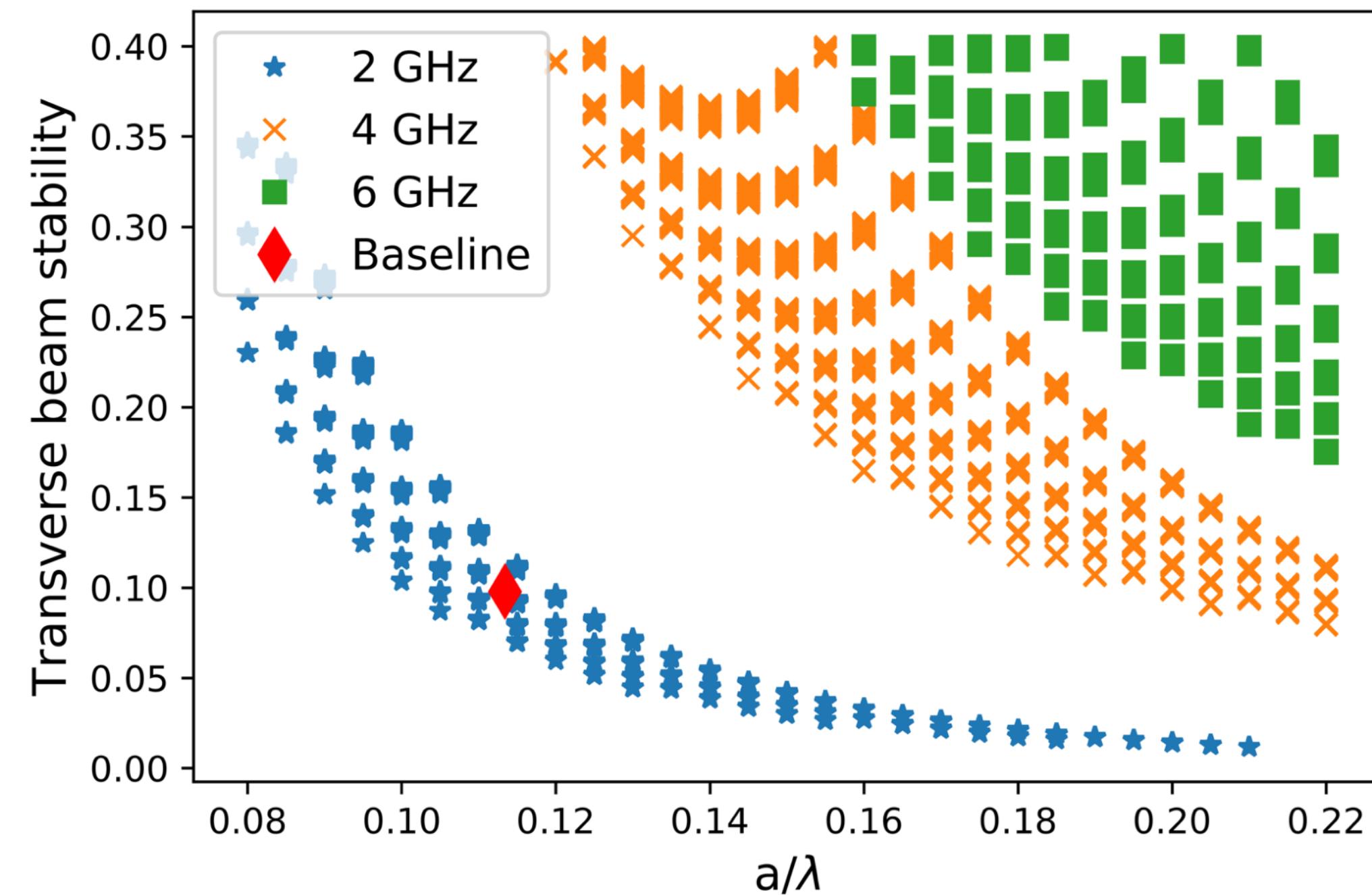
	2 GHz	4 GHz	6 GHz
$\langle \beta \rangle$ [m]	13	10	8

Results

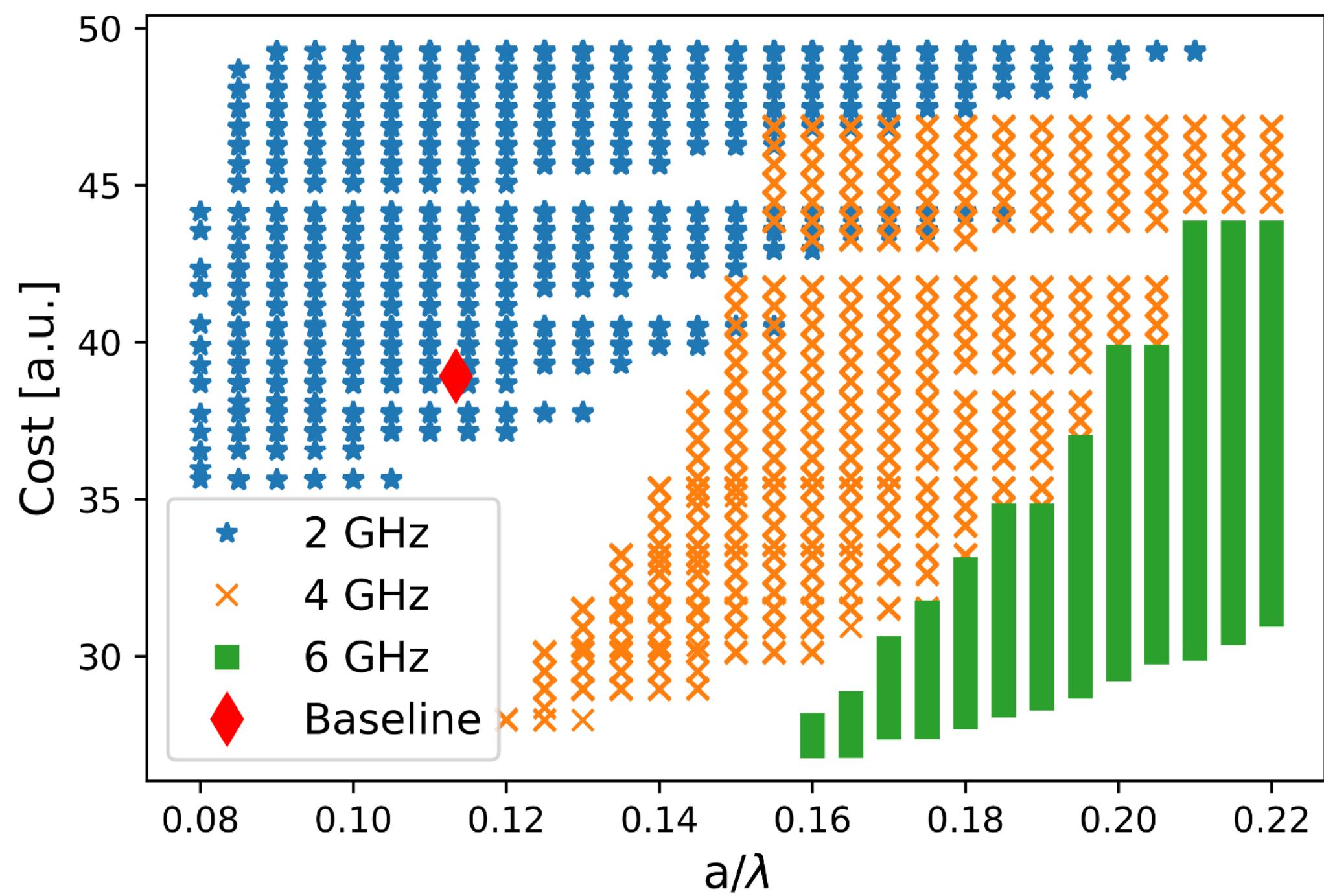
Aperture vs Gradient



Aperture vs Stability



Cost estimation



Crude cost model:

$$\text{Cost} = N_{RF_units} * (2 * C_{klystron}) + L_{RF_length} * C_L$$

with

$$C_{klystron} = 300 \text{ kCHF/klystron}$$

$$C_L = 50 \text{ kCHF/m}$$

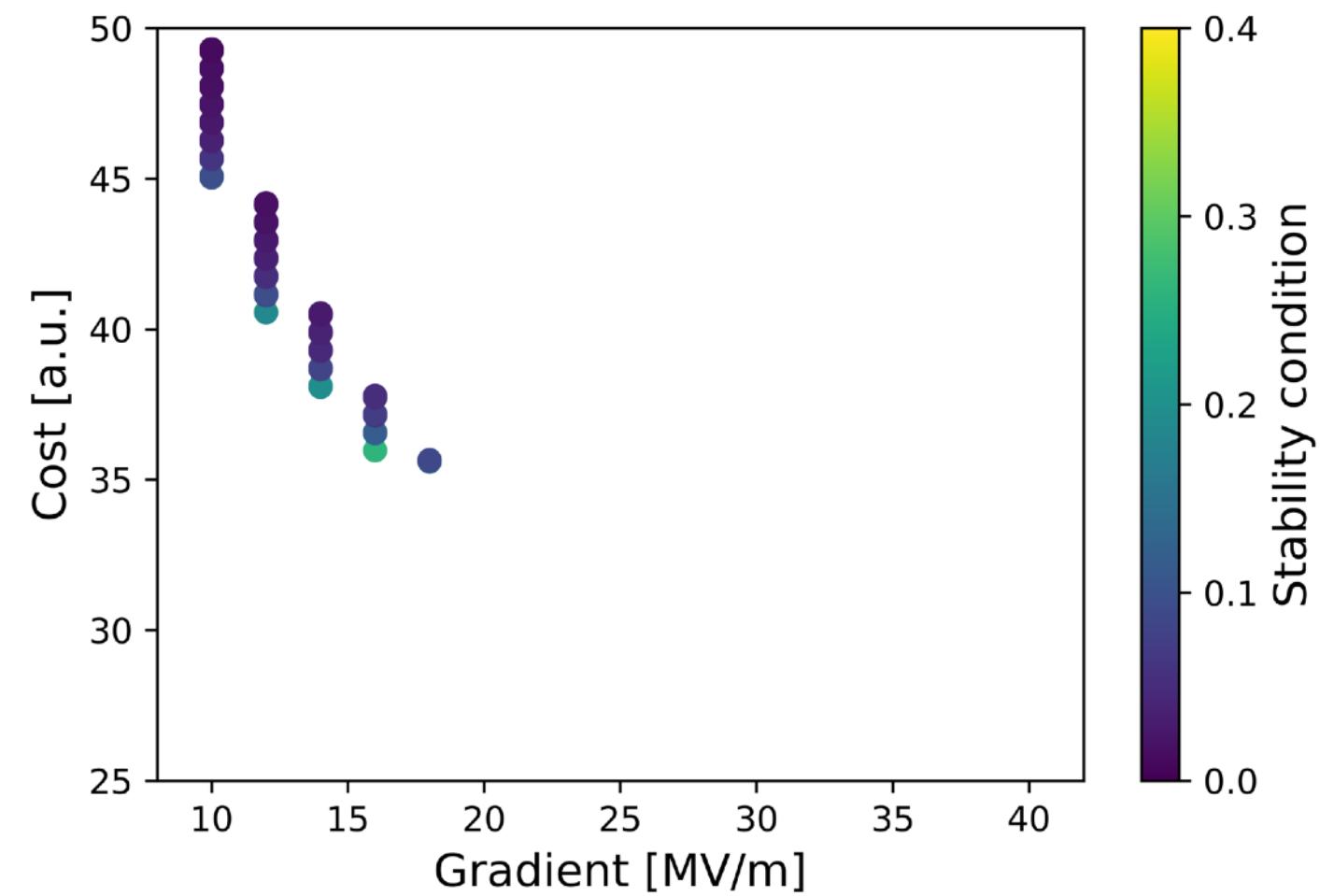
assume same for 2, 4 and 6 GHz

Smaller irises allow for higher gradients => shorter linac

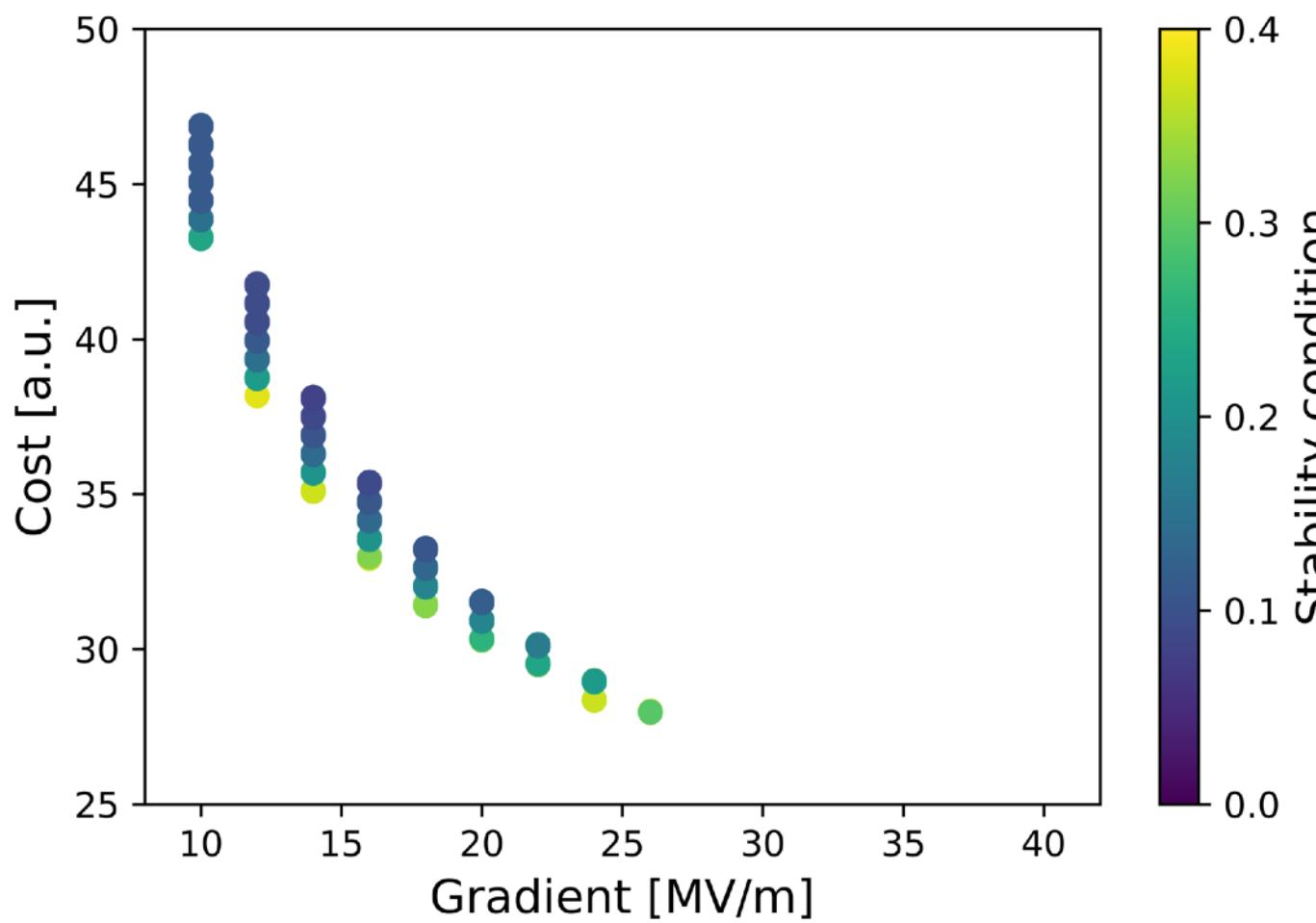
Higher frequency allows for higher gradients => shorter linac

Stability

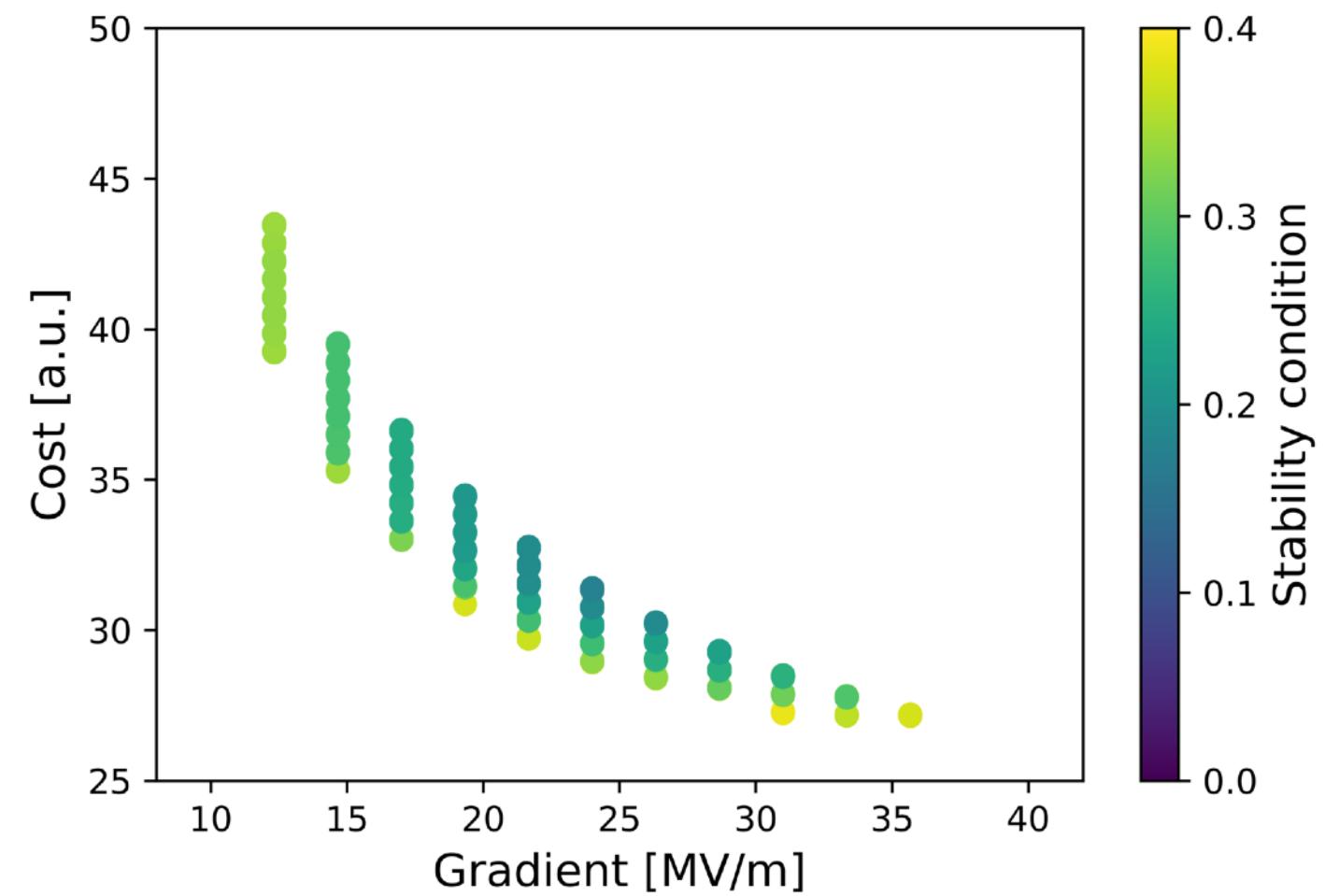
2 GHz



4 GHz



6 GHz

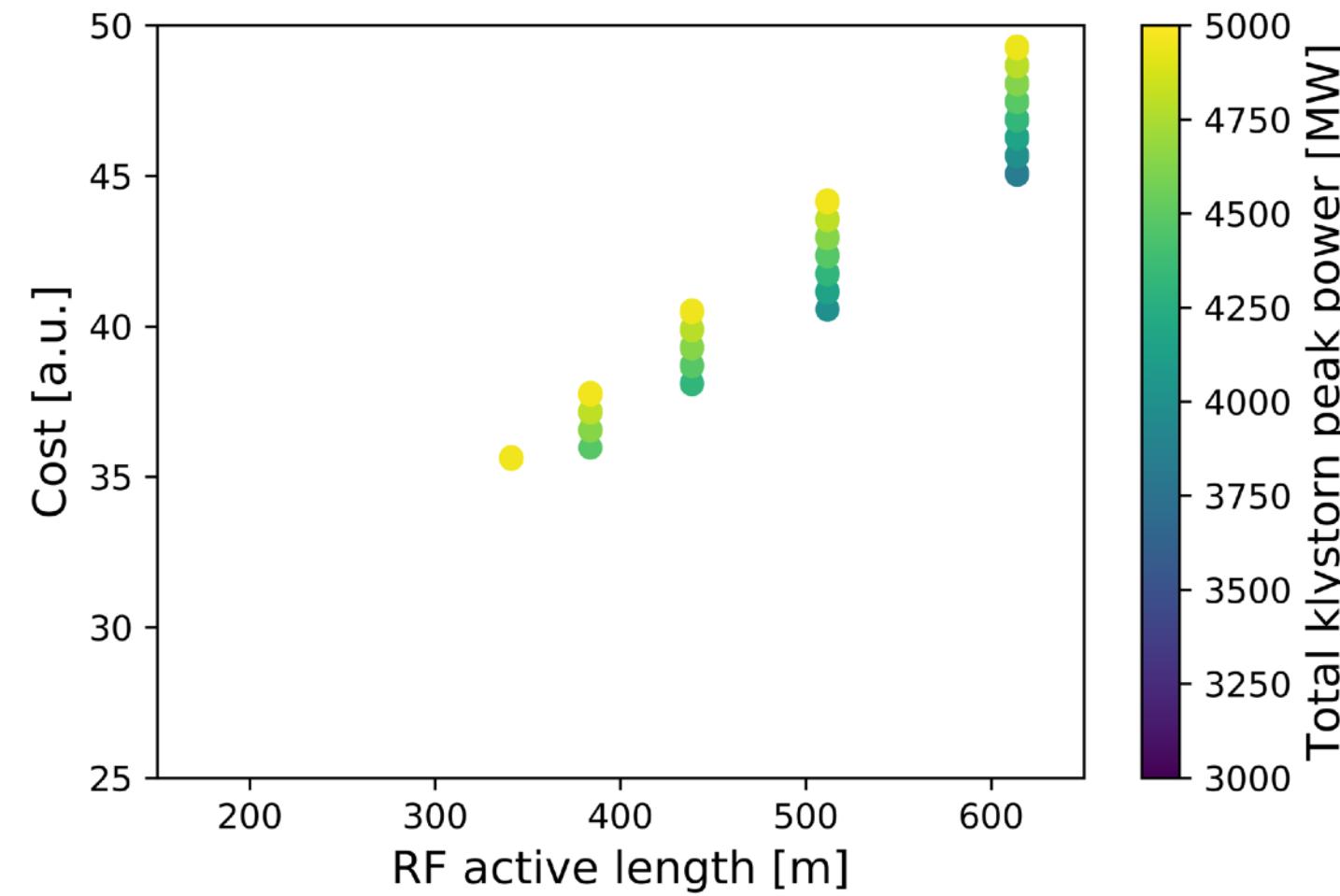


Cost for different gradients with color-coded transverse stability

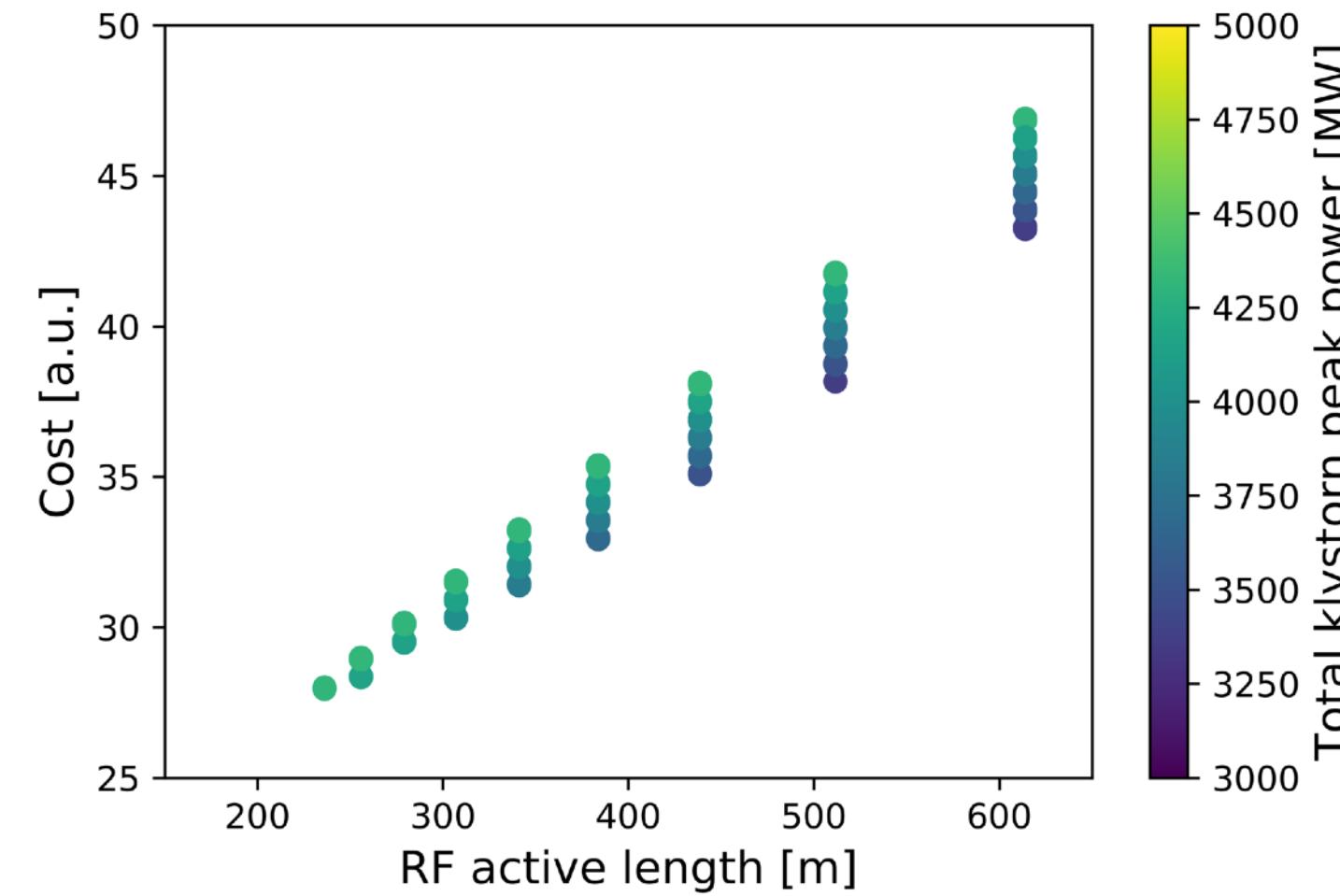
- higher frequency is a more cost effective option
- but at the cost of less stability margin

Installed klystron peak power

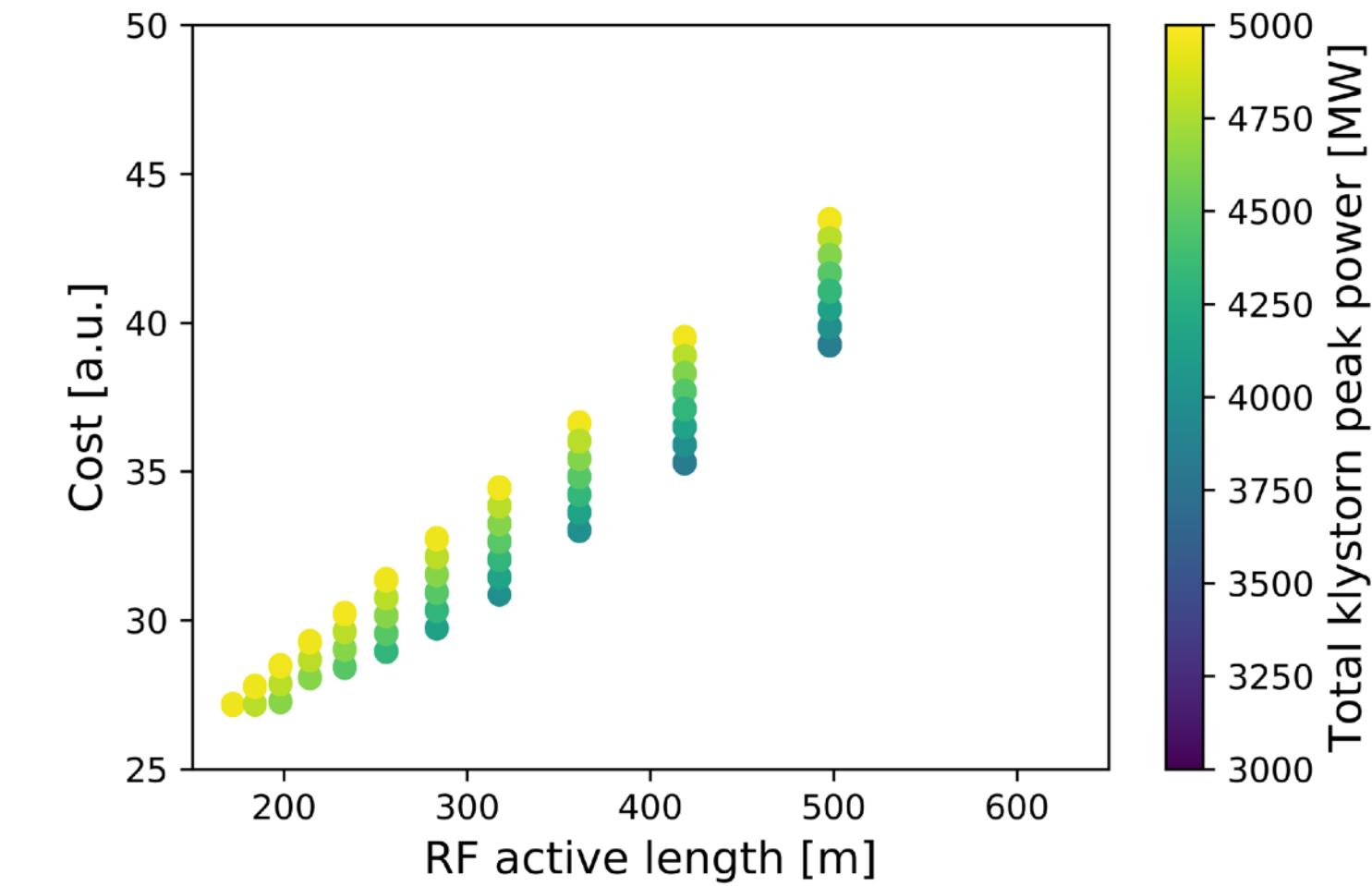
2 GHz



4 GHz



6 GHz



Cost for different active RF lengths with color-coded installed klystron power

- 4 GHz is a more efficient solution than 2 GHz and 4 GHz
- The worse efficiencies for the 6 GHz structures is due to the relatively large apertures

Cost optima for 380 GeV Booster linac

Parameter	2 GHz Baseline	2 GHz	4 GHz	6 GHz
Gradient [MV/m]	15	18	26	36
a/λ	0.11	0.09	0.12	0.16
Number of cells	30	10	51	108
L_struct [m]	1.5	0.50	1.27	1.8
RF activelength [m]	414	341	236	172
Stability condition	0.10	0.19	0.34	0.37
Fill time [ns]	429	365	218	166
# of structures	276	683	185	96
Power (loaded) [MW]	53	24	80	166
Total power [GW]	4.8	4.9	4.3	4.9
# klystrons	60	62	54	62
Cost [a.u.]	39	36	28	27

Conclusions

- Booster linac optimization
 - Interesting problem with many constraints
 - CLICopti library a power tool
 - Trade-off: gradient, length, cost and efficiency
 - Solutions for 2, 4 and 6 GHz
 - Not enough stability for 8 or 12 GHz, due to low energy and long bunch length
 - 4 GHz option seem to substantially lower cost and total length of booster linac compared to baseline
 - Need update with structure selection and further checks
- Future work
 - More work needed to understand what is optimum
 - Update cost model
 - Limitations from long range wakefields
 - Tracking studies