RF studies for the CLIC Booster linac

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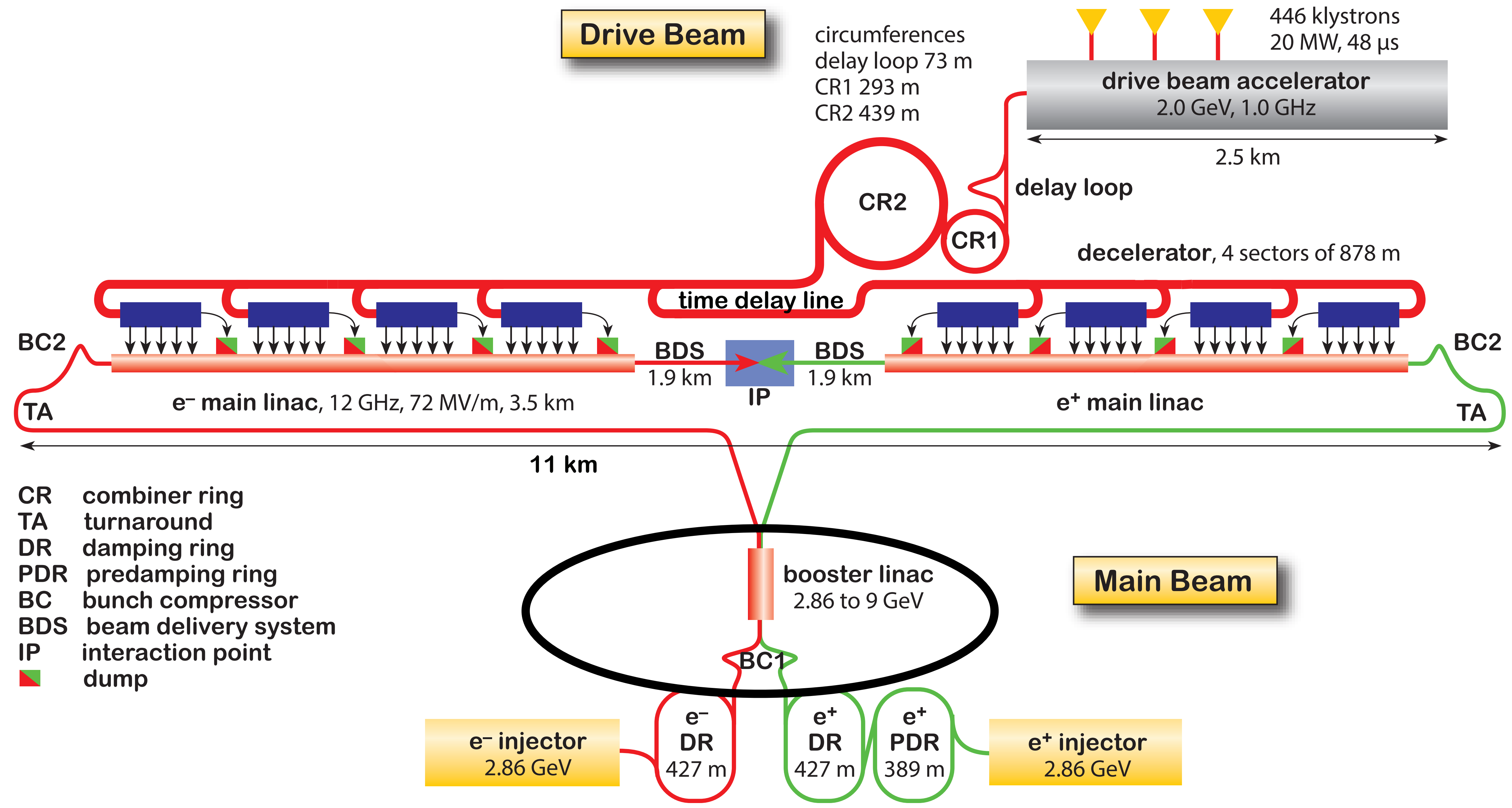
CLIC Beam physics meeting April 12, 2018

The Booster Linac



Electron and positron beams in the same linac

Bring beams from 2.86 to 9.0 GeV

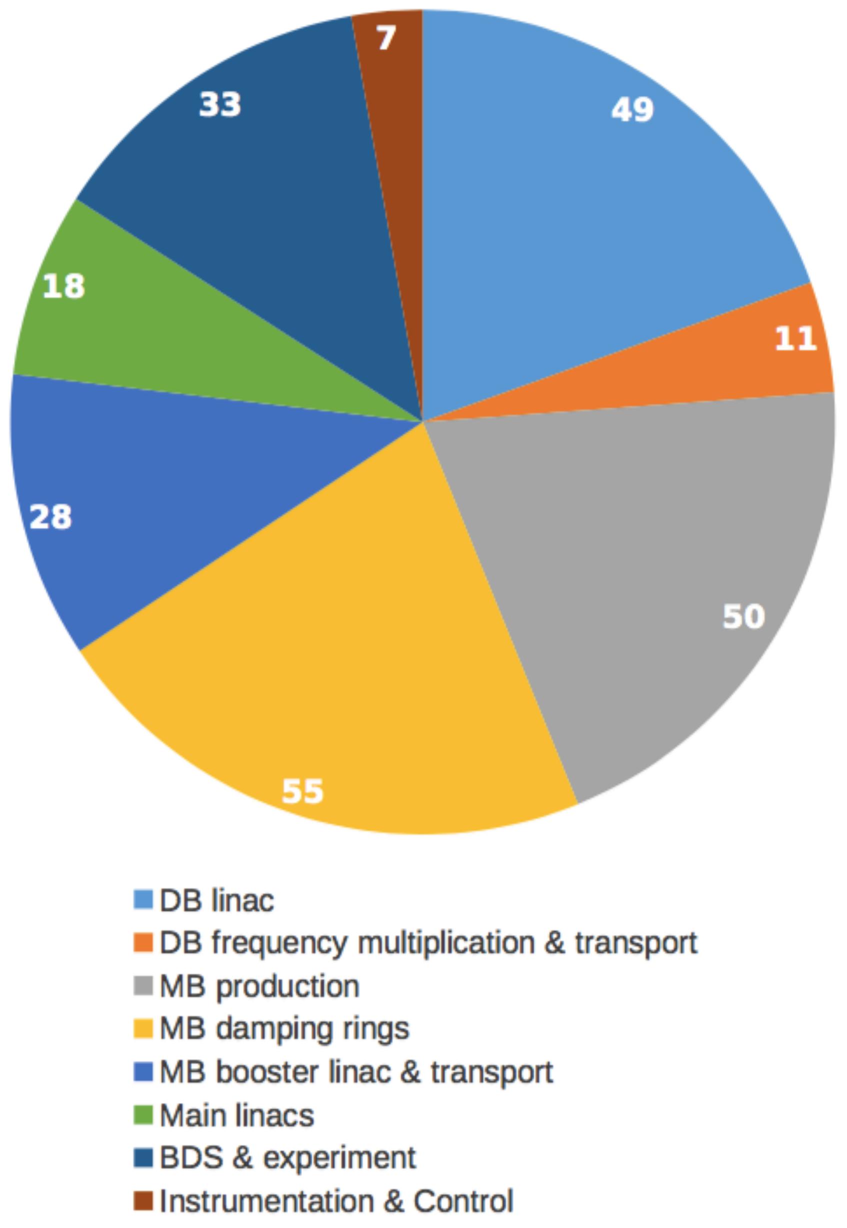
Pulse compressors to achieve sufficient power

Beams **separated in time** or interleaved bunches?

Separate klystron pulses or **double pulses from pulse compressor**?

What's new:

- Octave scripts for Pulse compressors (based on I. Syratchev's Mathcad tool)
- Extension of previous gain tables by A. Latina
- Re-optimization of the linac
- Investigations of RF frequencies above 4 GHz



Motivation:
The power consumption of the booster linac is non-negligible

Baseline parameters (RTML)

	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	1800	70	1800	44
Number of bunches	352	352	312	312
train length [ns]	176	176	156	156

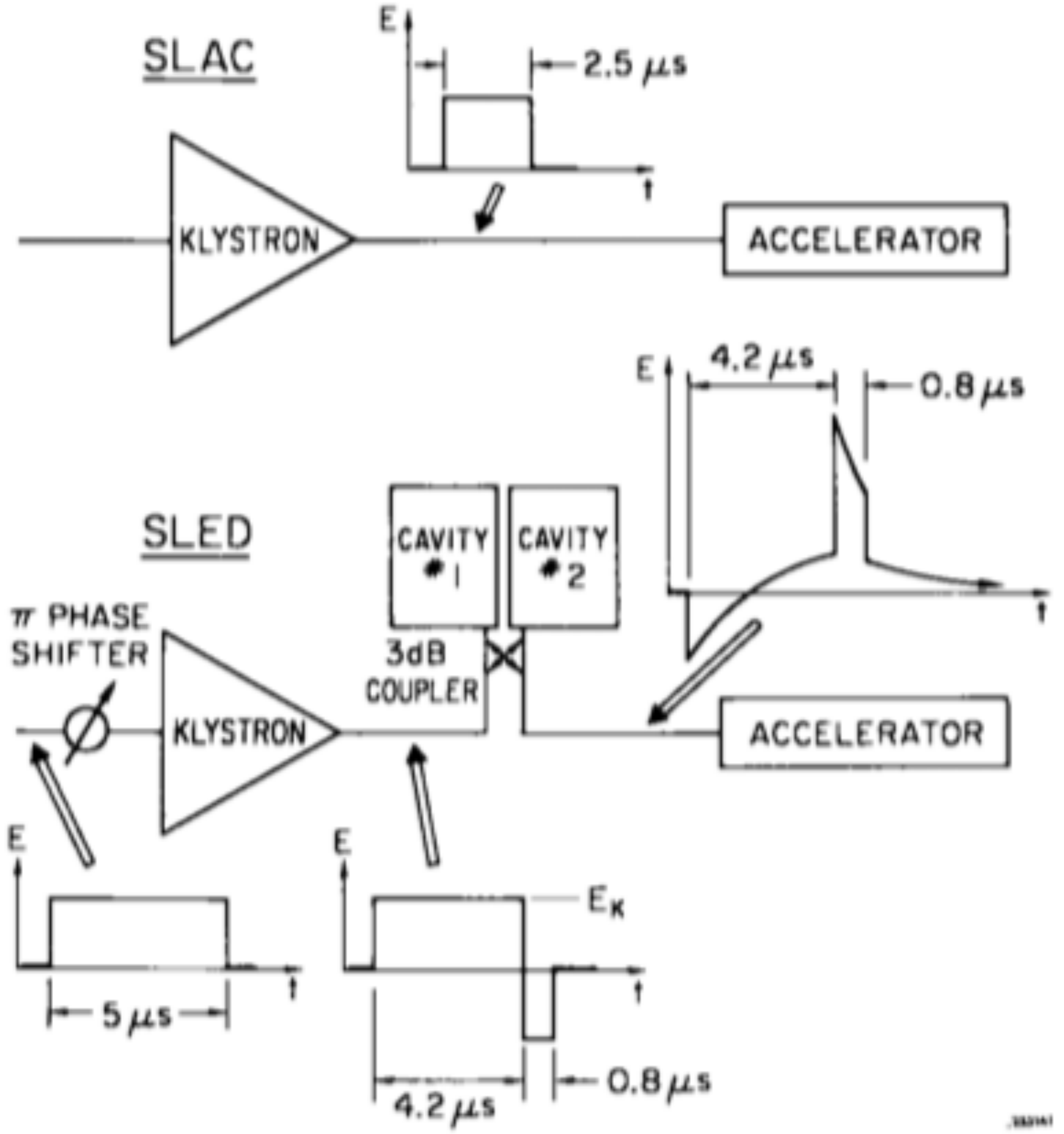
Booster baseline design (CDR):

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

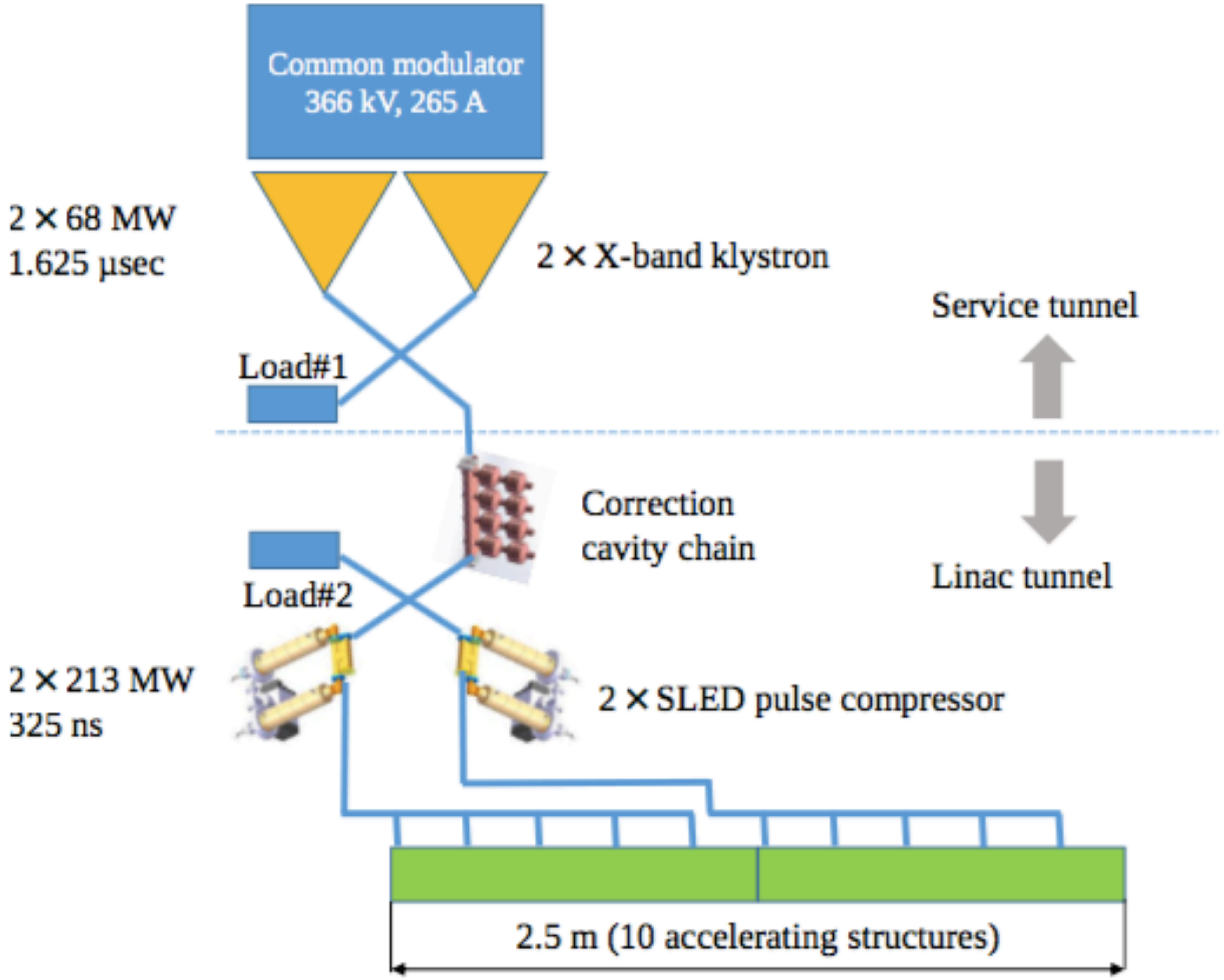
For the RTML see the work of Y. Han

Z. Farkas et al., *SLED: A method of doubling SLAC's energy,* 1974.

Pulse compressor

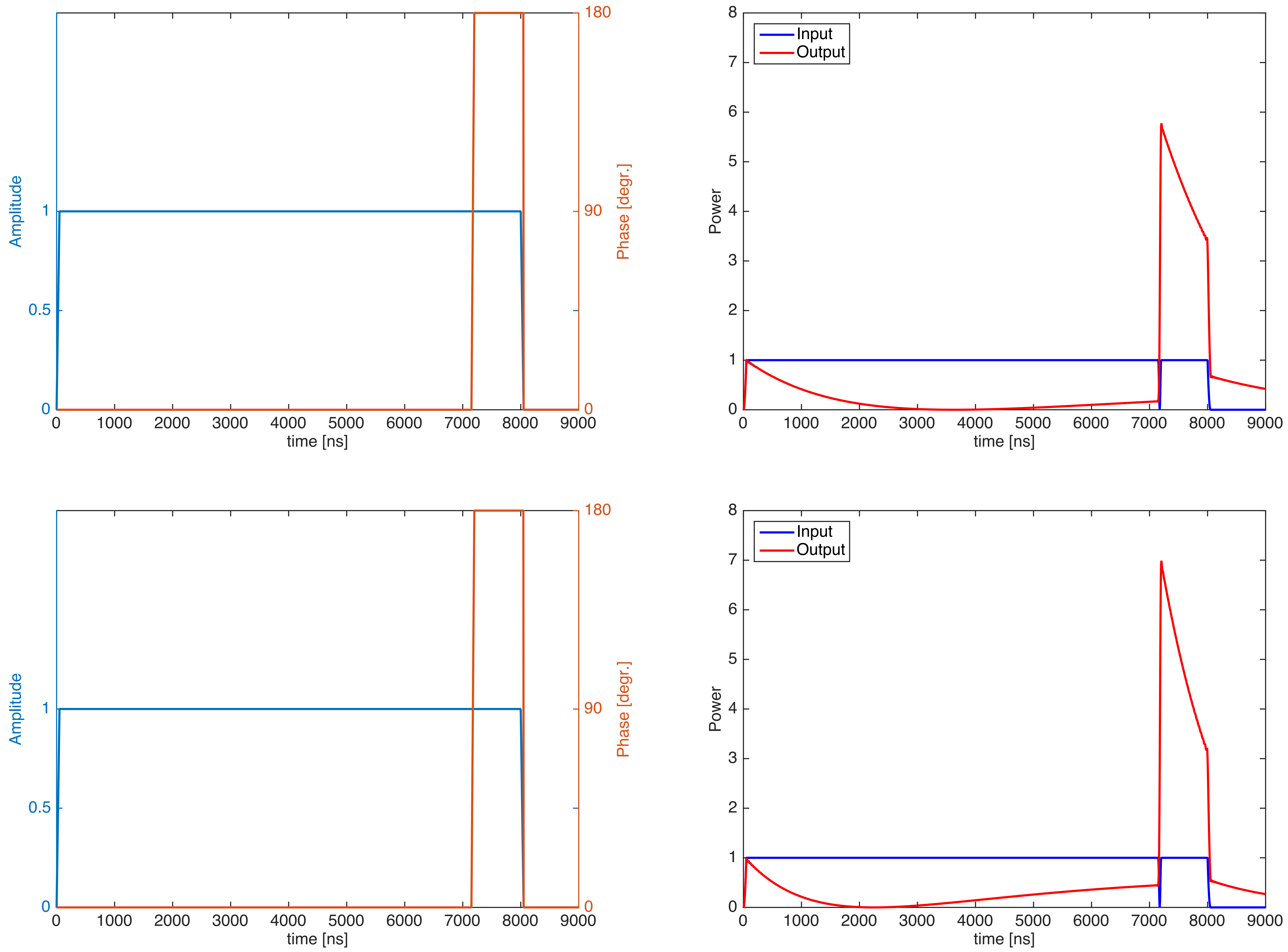


CLIC 380 GeV klystron option also uses pulse compressors



- 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

Pulse compressor (single pulse):

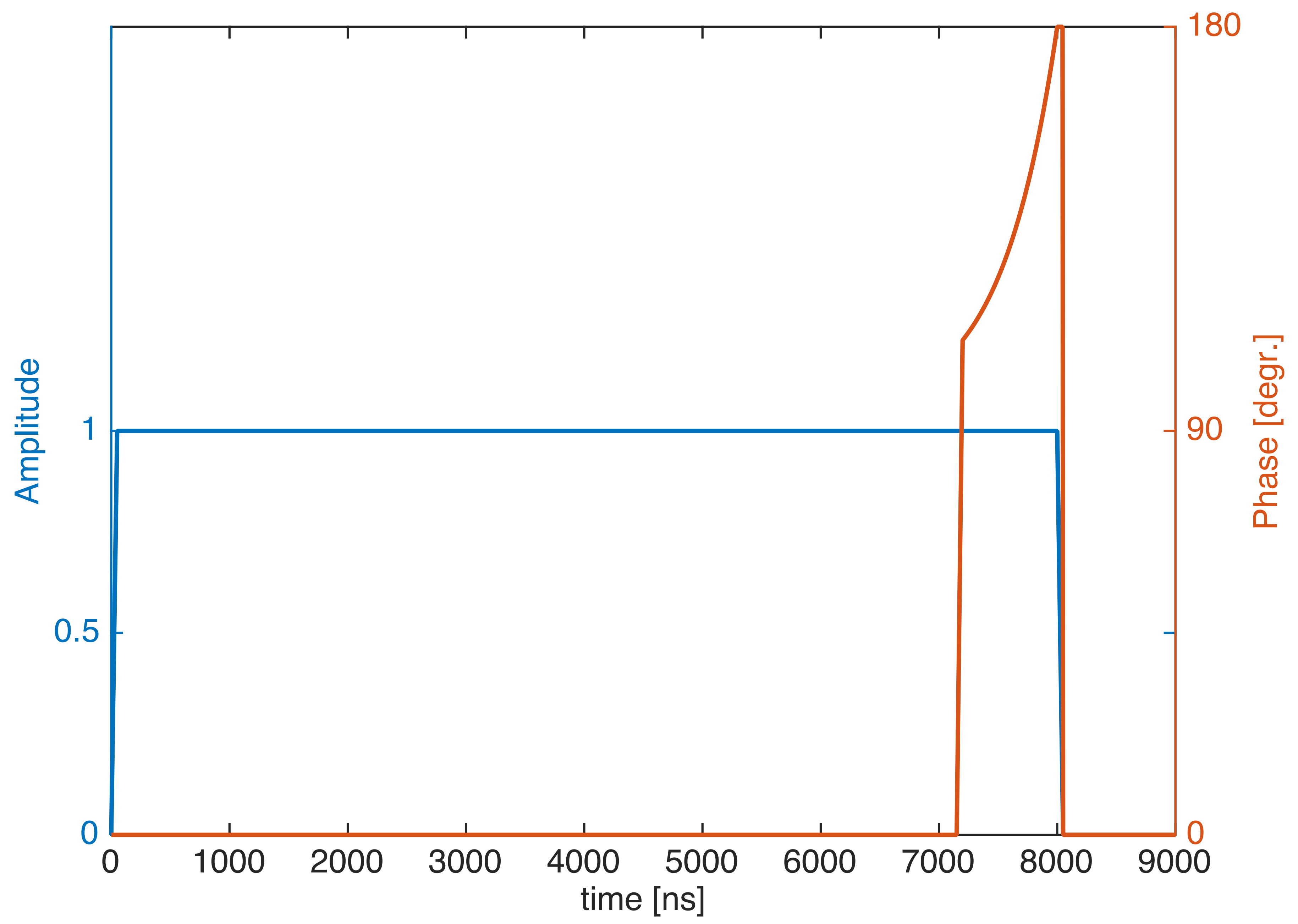


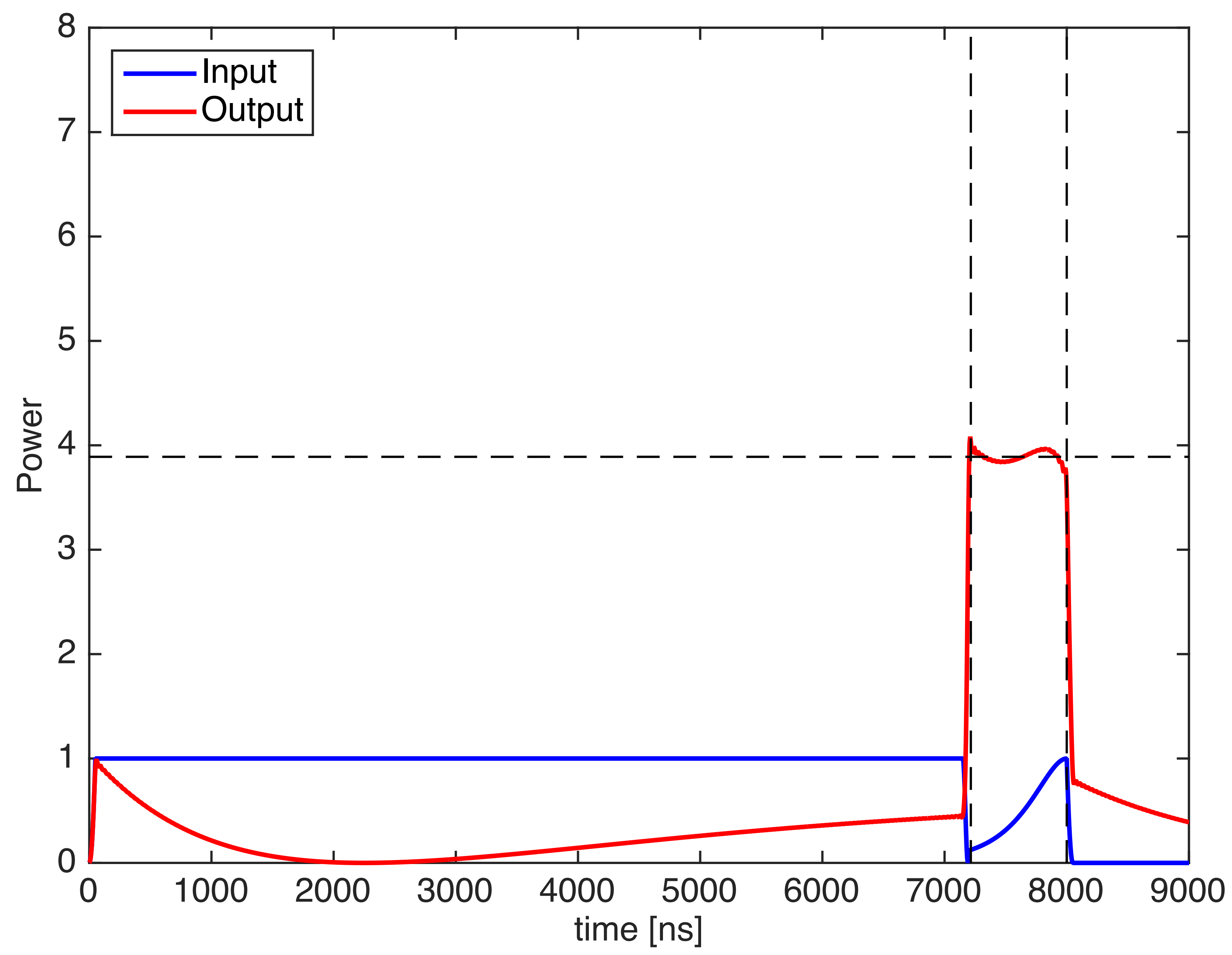
Setup:
f = 2 GHz
t_K = 8 μs
t_p = 900 ns
Q_0 = 180,000

Optimize coupling to maximize the energy in compressed pulse

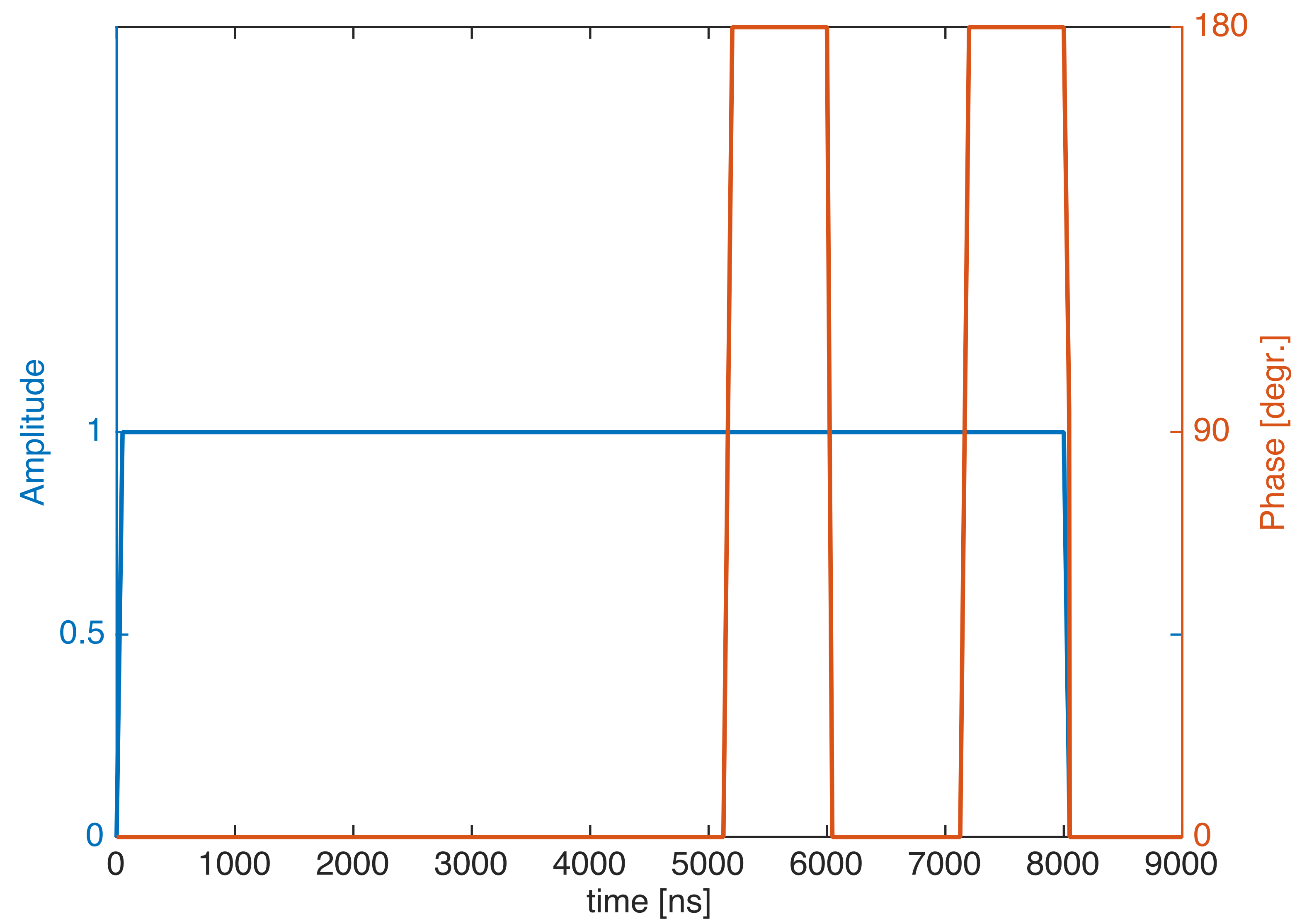
Flat pulse

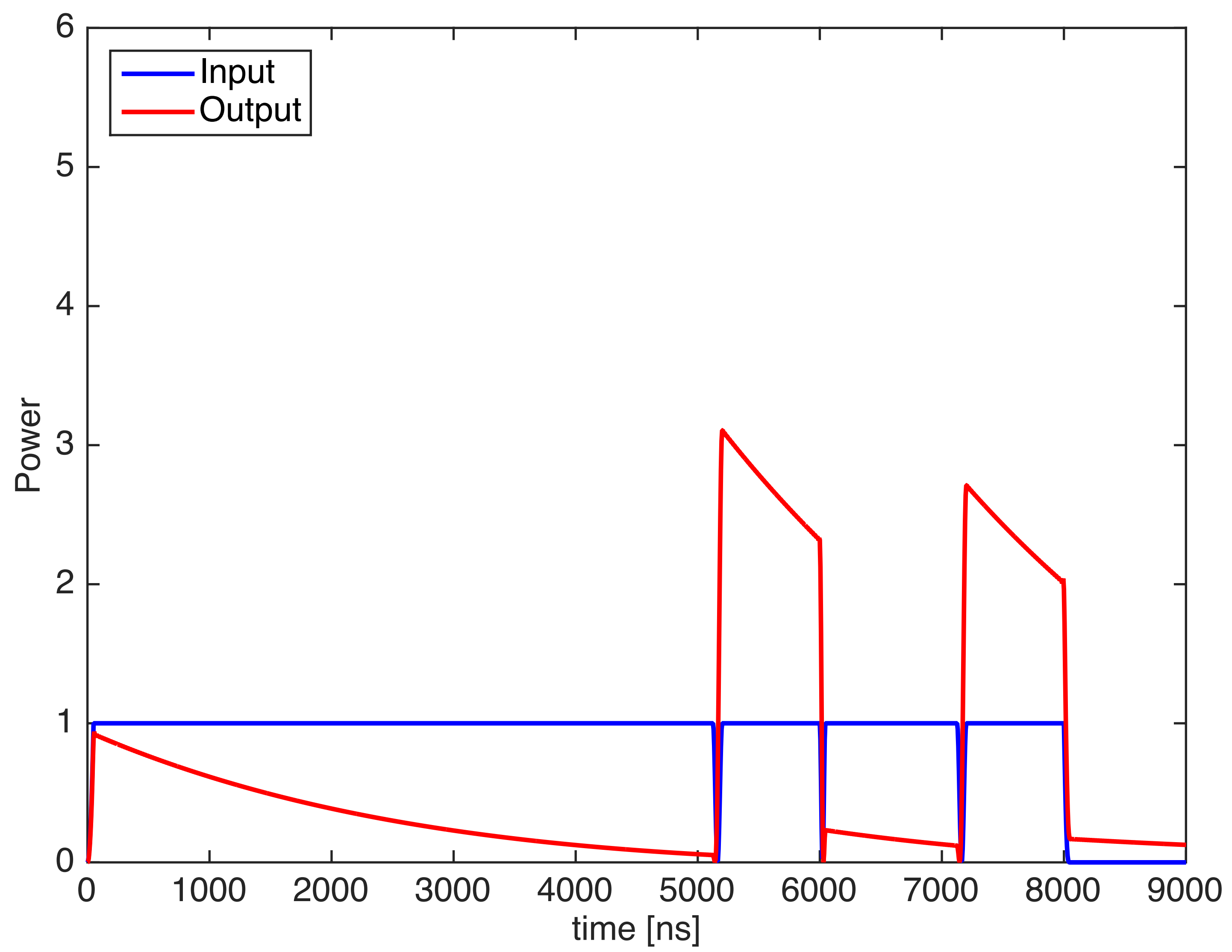
- When cavity empties the power decays exponentially
- Compensate by ramping the phase
- For a given length of the compressed pulse there is an optimum coupling
- Shorter pulse gives higher gain but worse efficiency



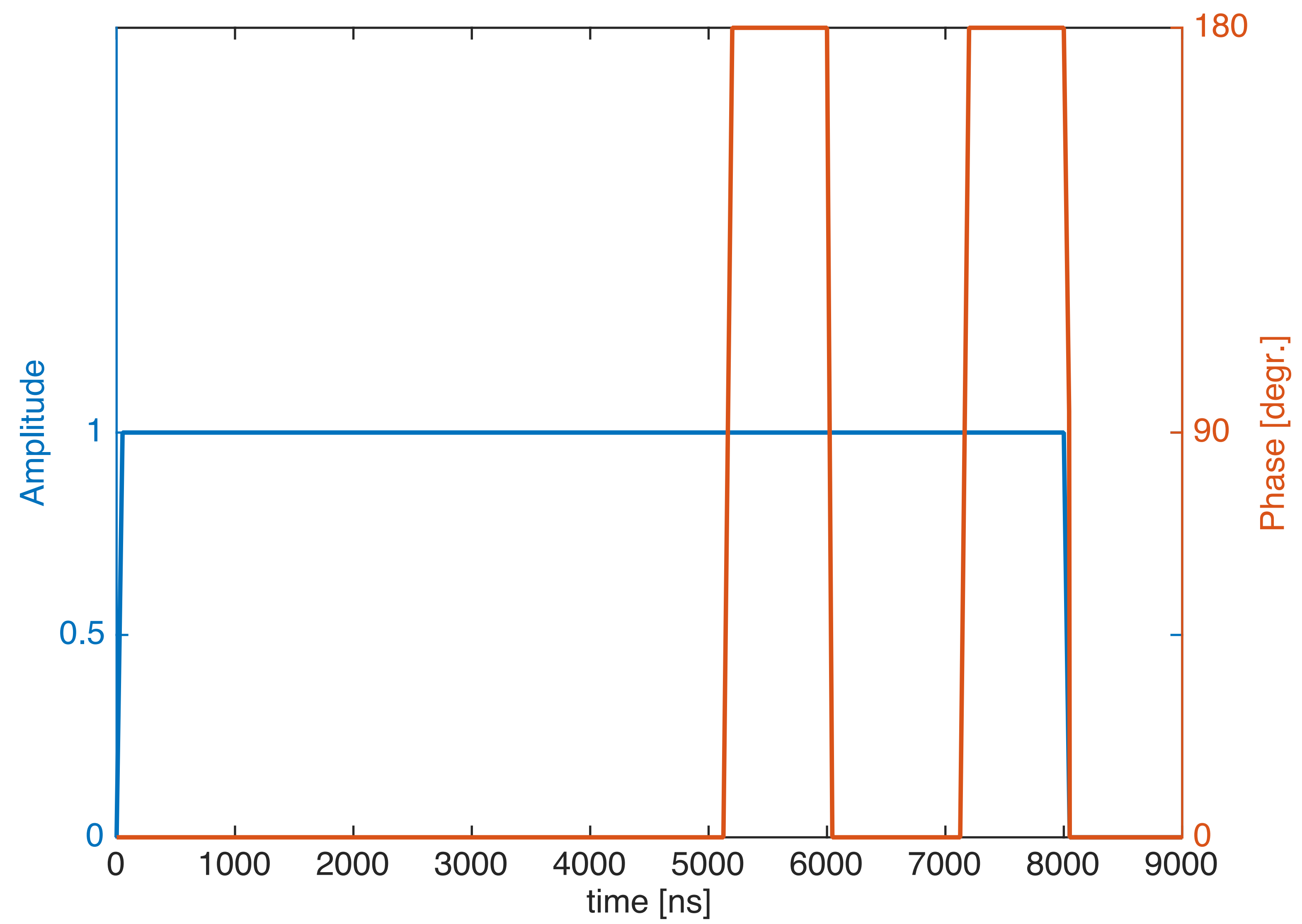


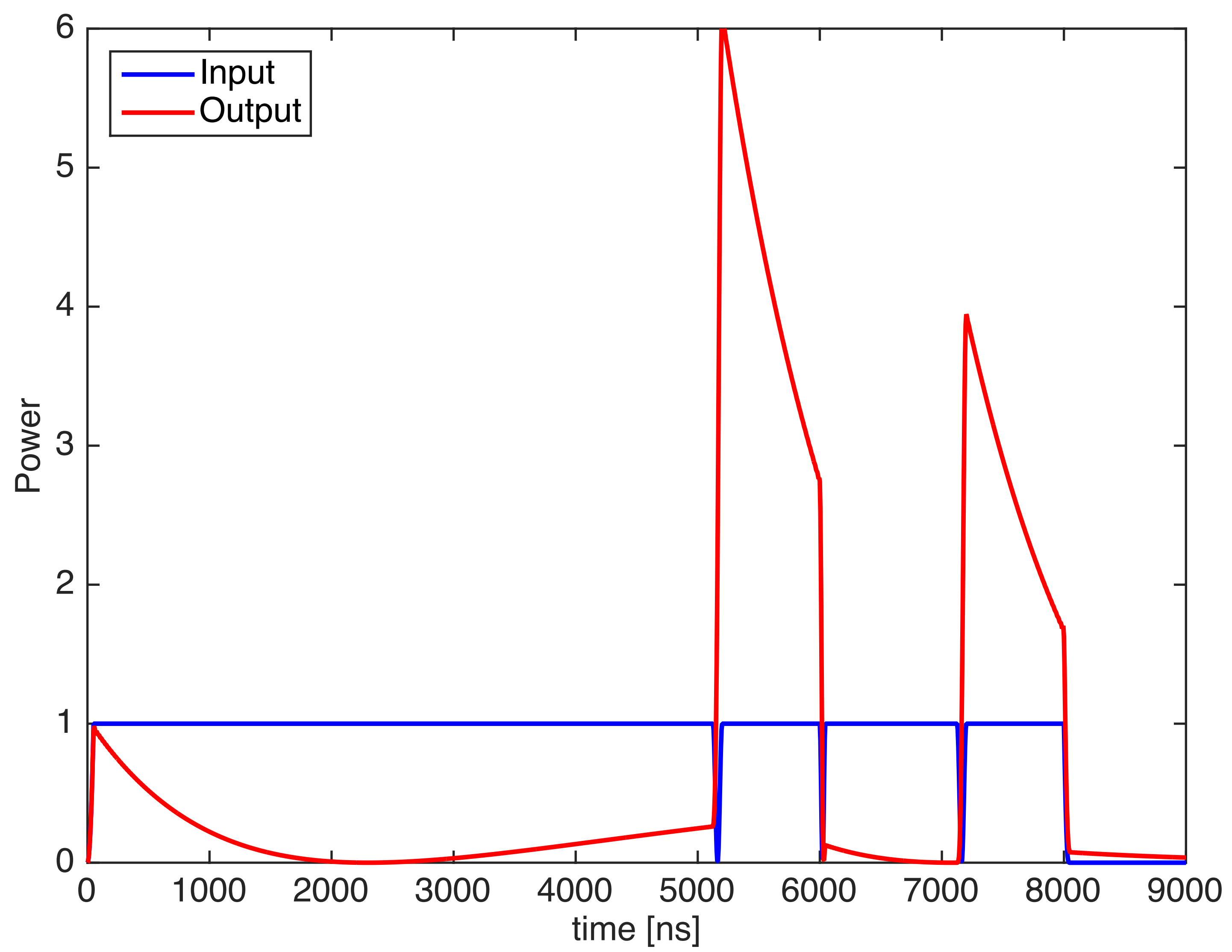
Double pulse





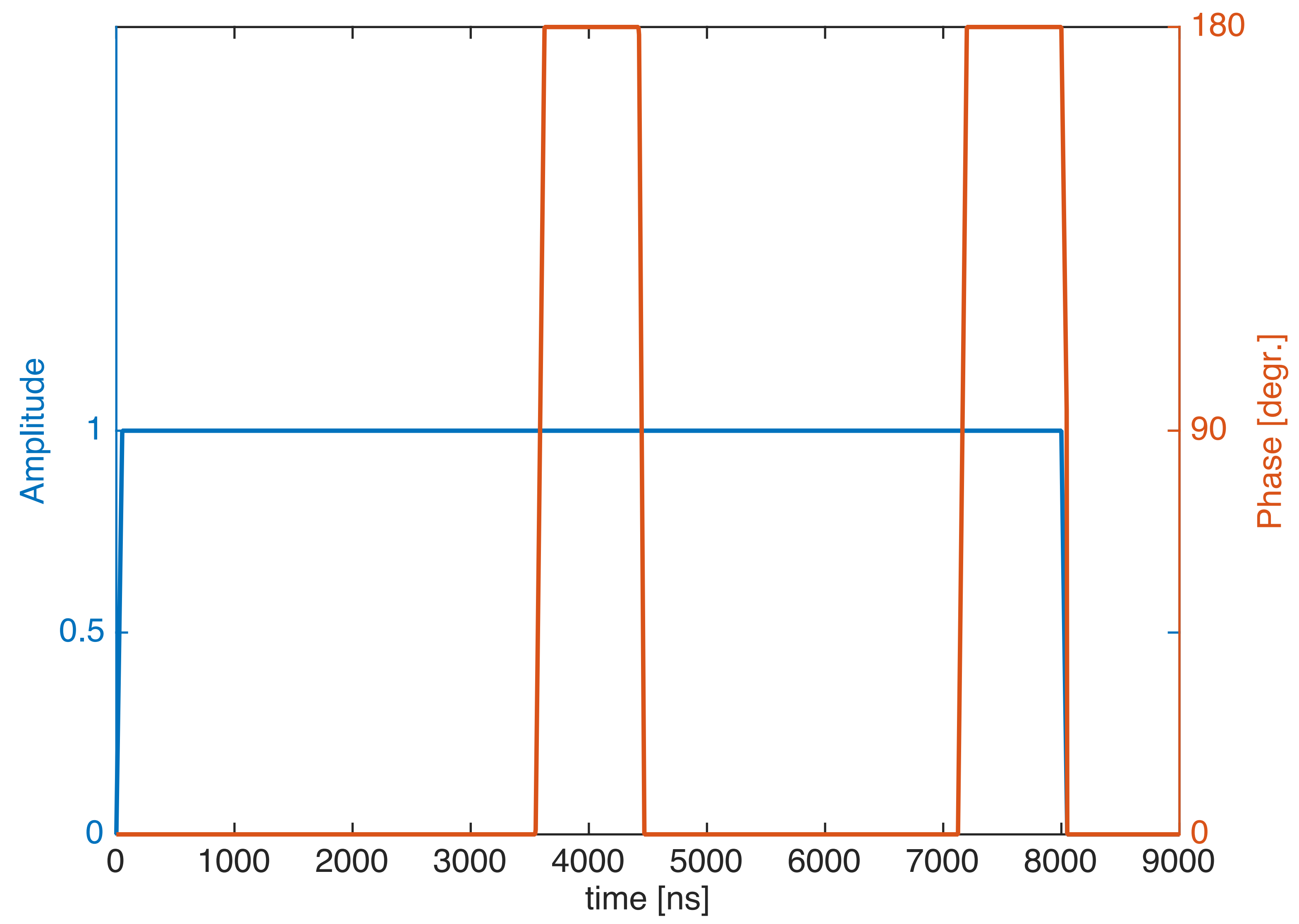
Two phase ramps

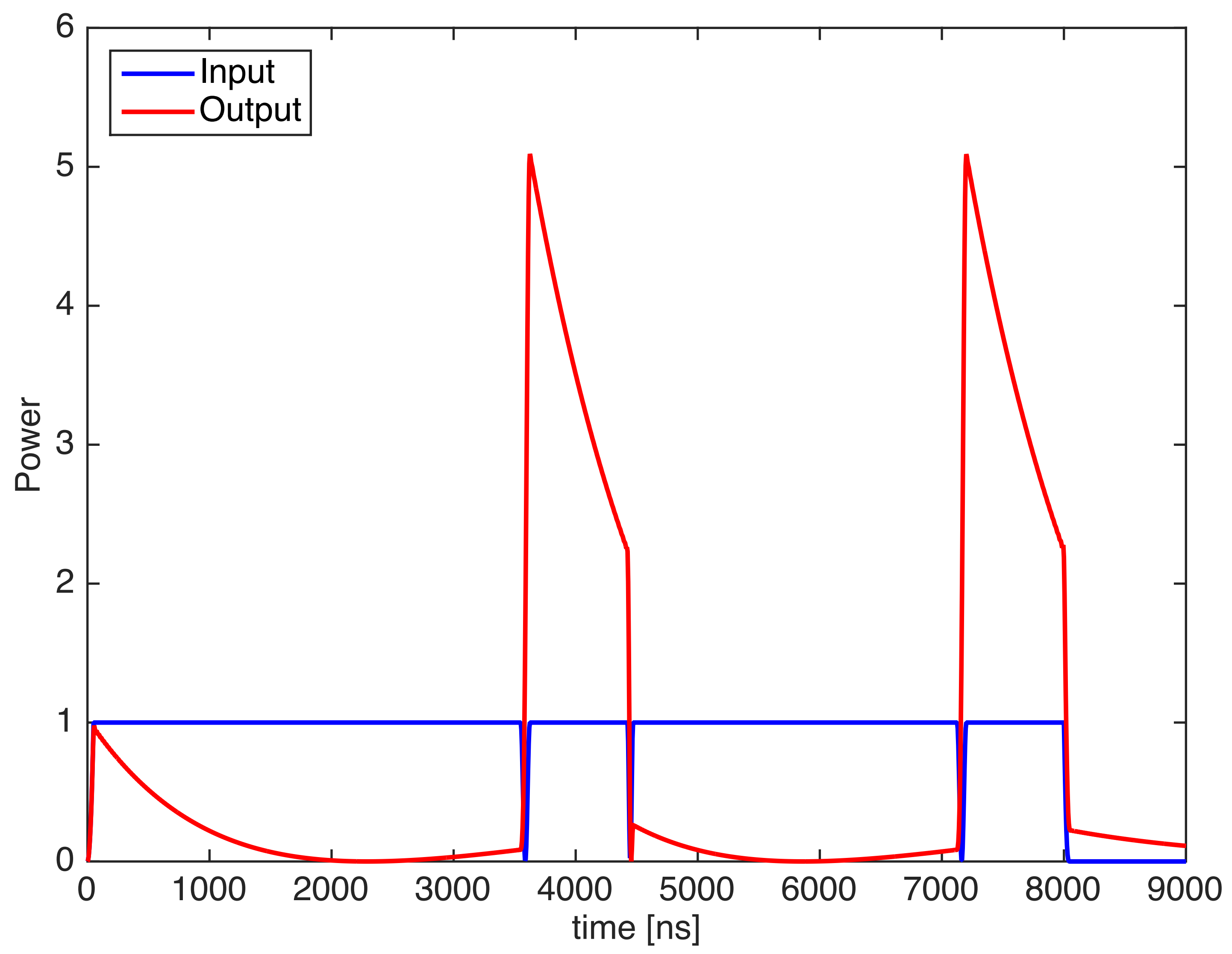




Optimize coupling for maximum energy in the 2 pulses

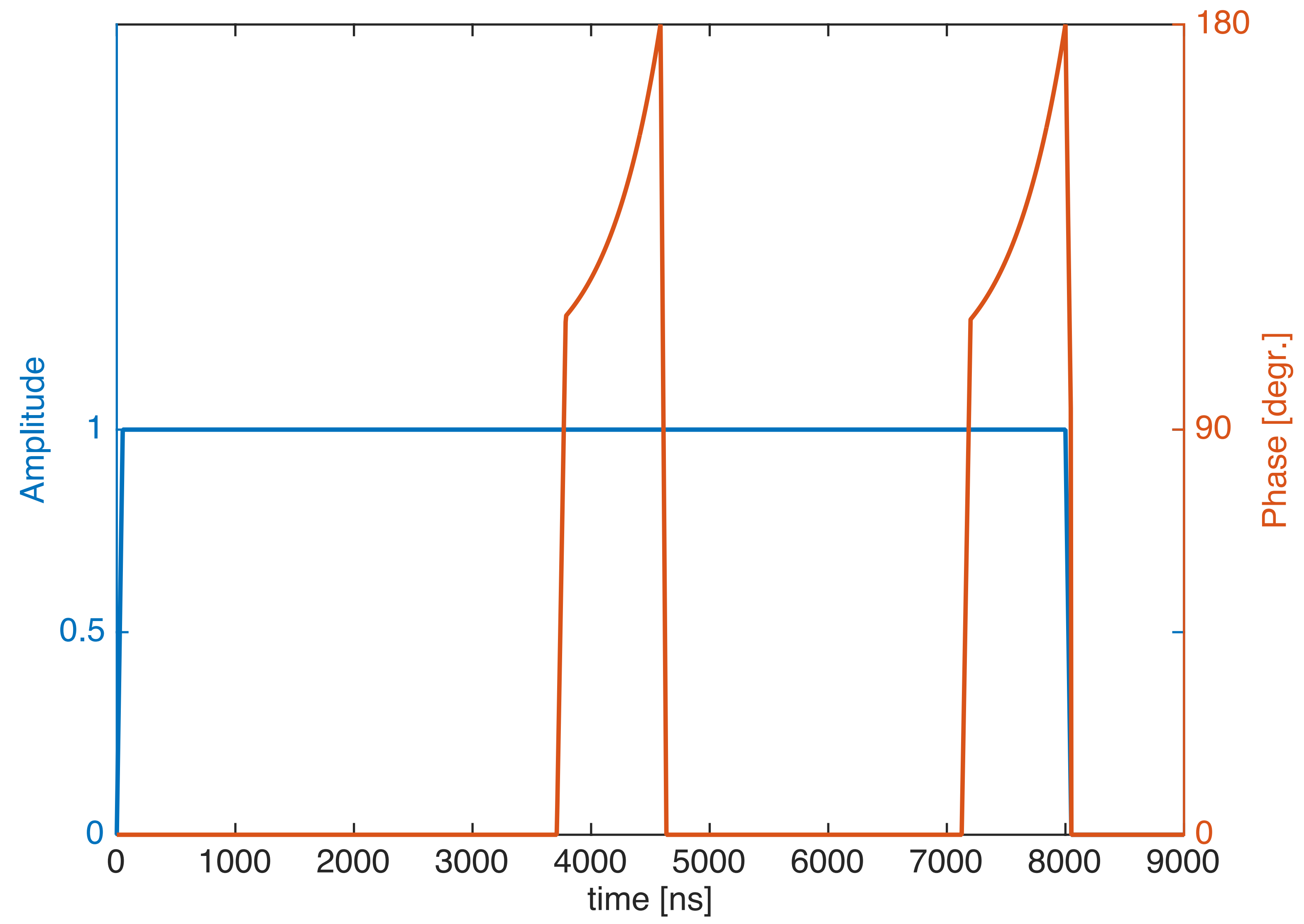
Double flat pulse

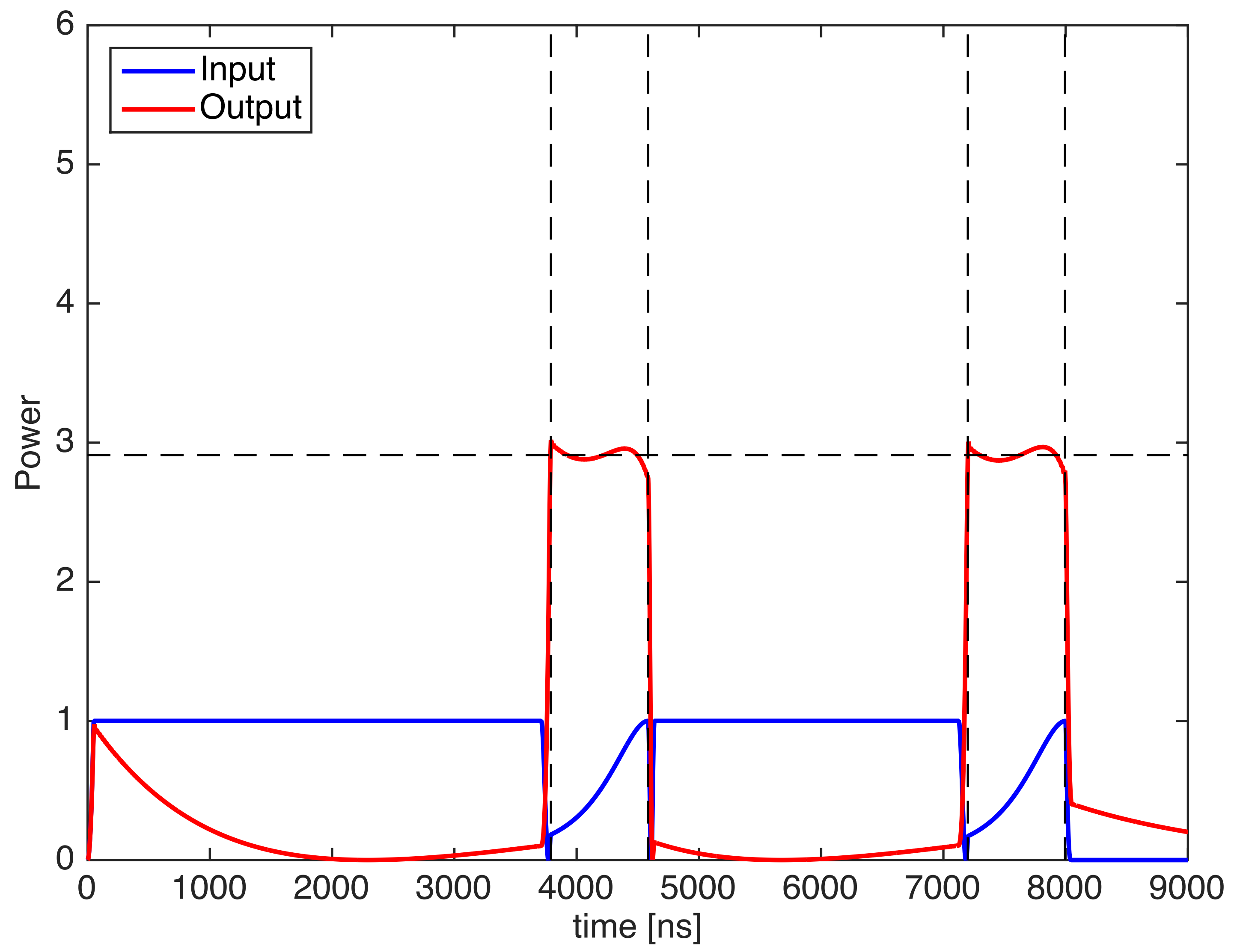




Adjust pulse separation to achieve equal pulses

Ramp phase for flat pulses





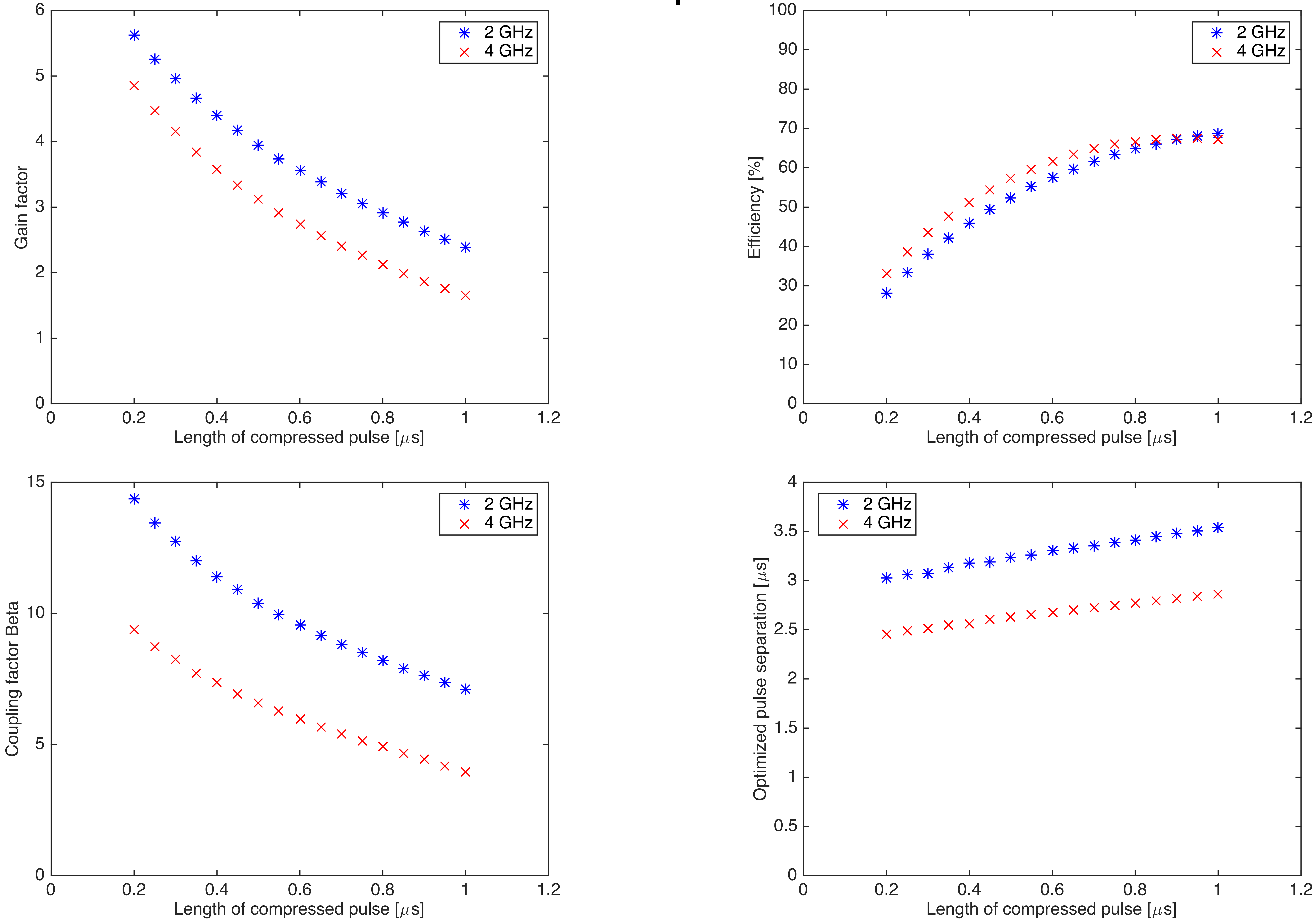
For different pulse length:
- 2 GHz and 4 GHz case
- Compression
- Efficiency

Compression table: gain factors

Optimize for different pulse length for 2 GHz and 4 GHz case
Similar gain factors compared to previous results from A. Latina

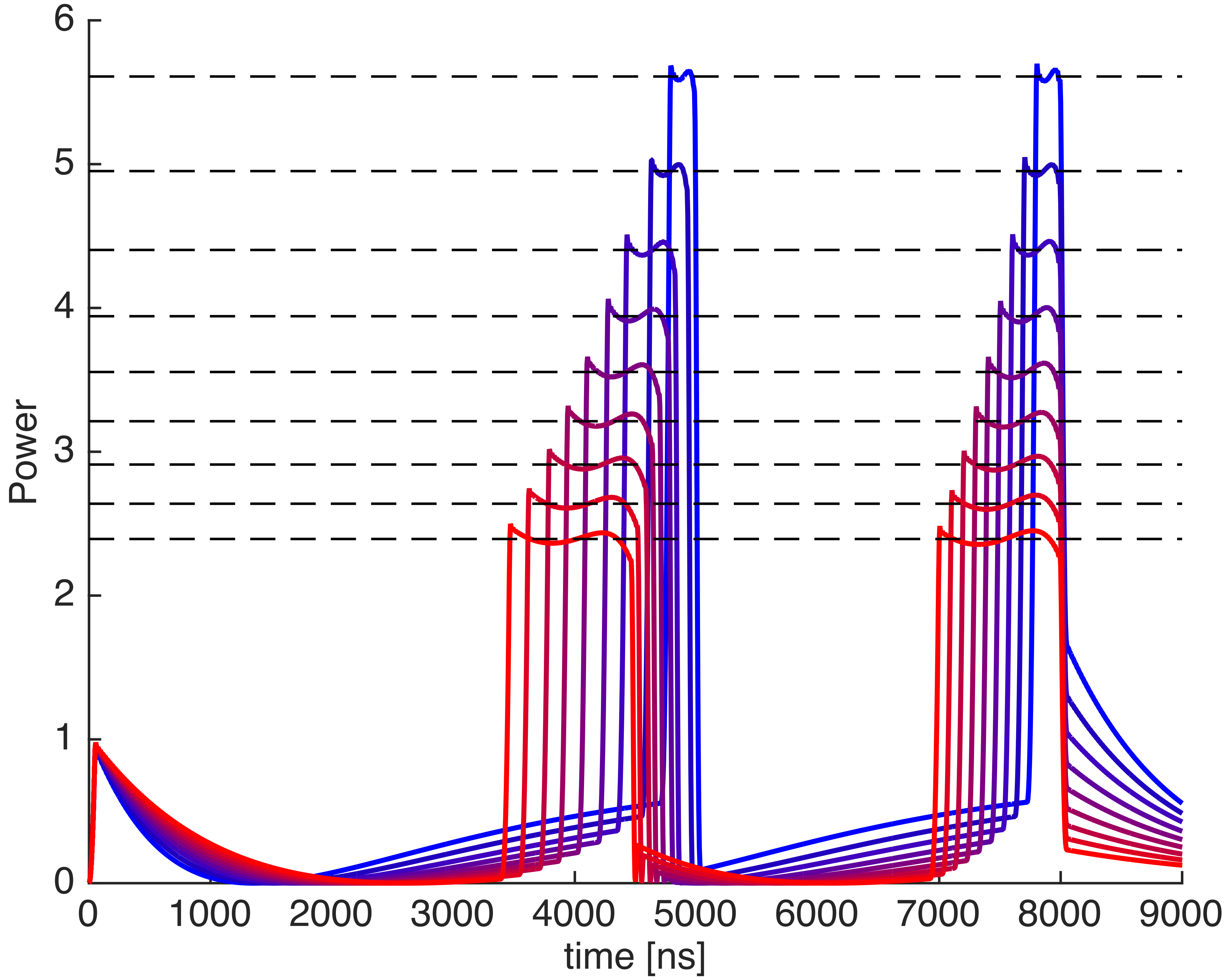
Pulse length [ns]	2 GHz	4 GHz	2 GHz (A. Latina)	4 GHz (A. Latina)
200	5.6	4.8	5.41	4.74
300	5.0	4.1	-	-
400	4.4	3.6	4.17	3.51
500	3.9	3.1	-	-
600	3.6	2.7	3.42	2.68
700	3.2	2.4	-	-
800	2.9	2.1	2.82	2.06
900	2.6	1.9	-	-
1000	2.4	1.6	2.34	1.61
6000	-	1	-	1
8000	1	-	1	-

Double pulses:



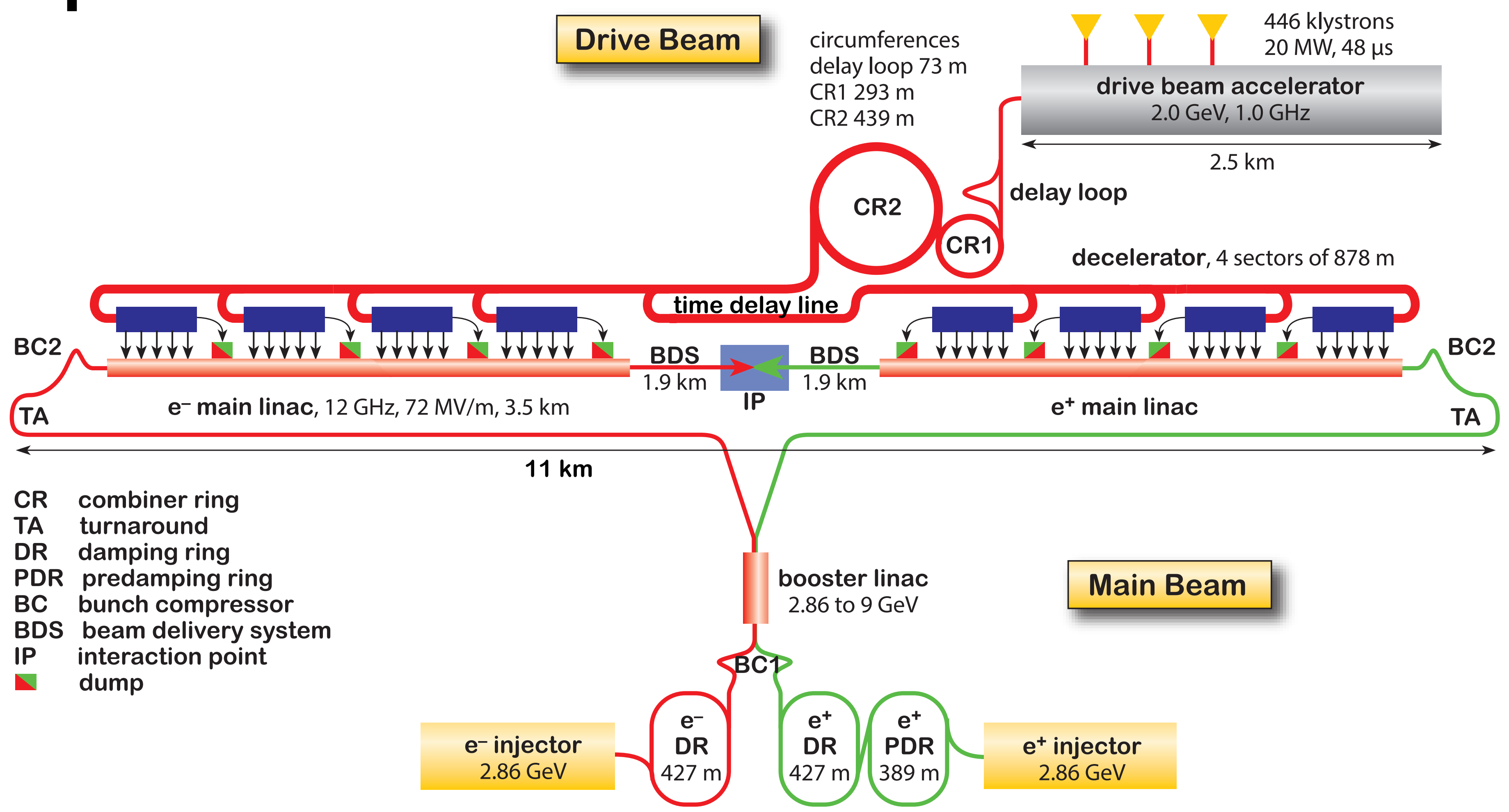
Optimum for different pulse lengths

- For a given pulse length there is an optimum coupling (max energy)
- To make pulses equal the pulse separation must be adjusted
- Optimized for a specific pulse length
- For a given setup, how much flexibility do we have?

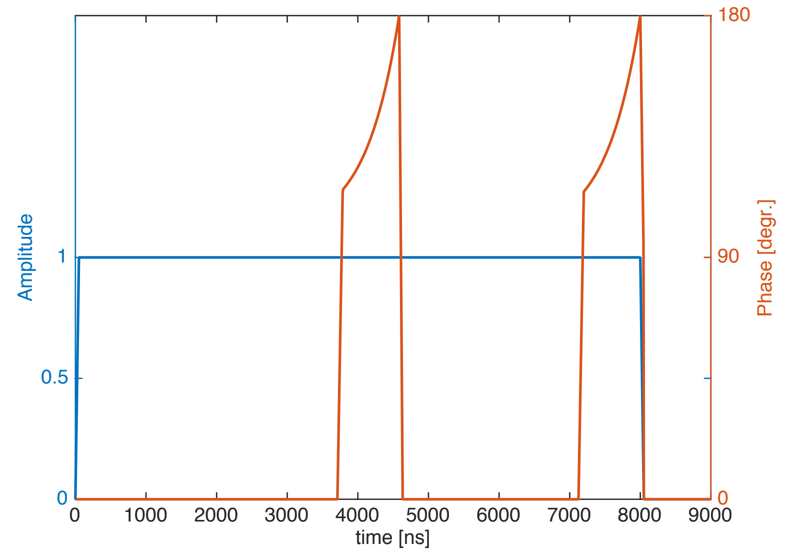


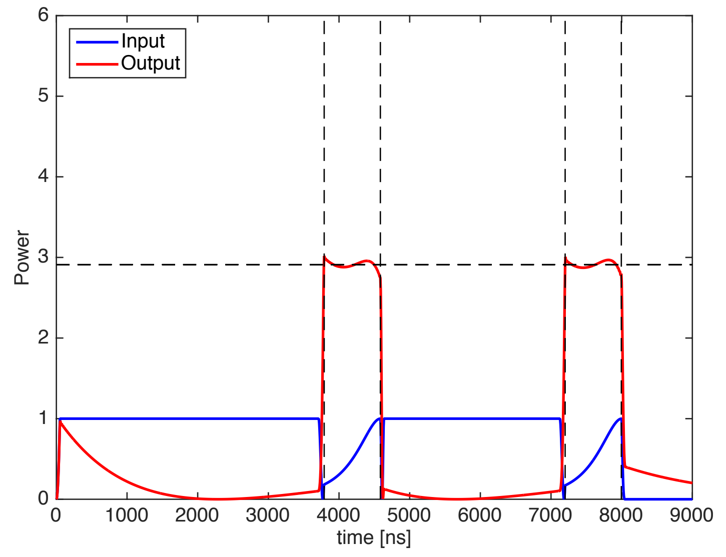
Variable pulse amplitudes

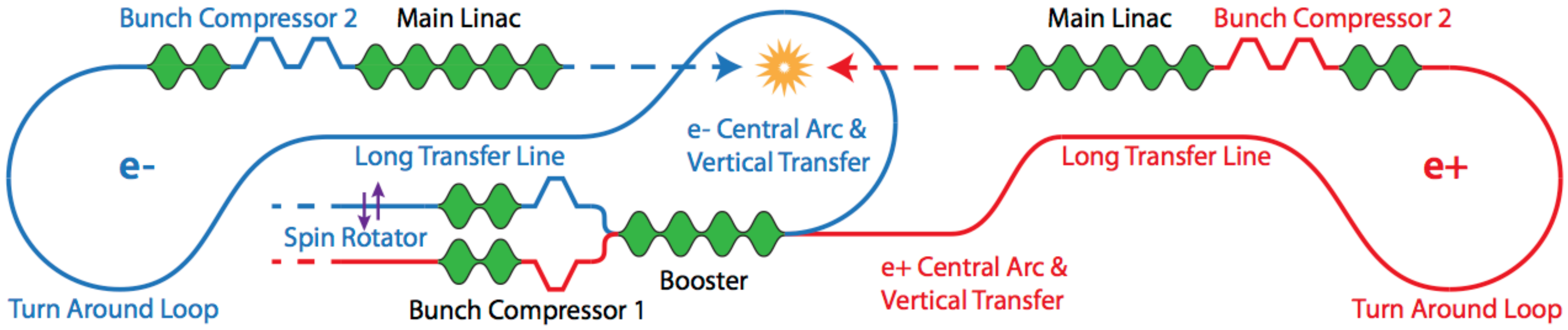
- Using a single klystron pulse and a double pulse from pulse compressor
- Flexibility in operation?
- The two beams at different energies/currents?
- Can we adjust the output power in one pulse?
- Pulse separation determines path difference
- Pulse **separation must be fixed**



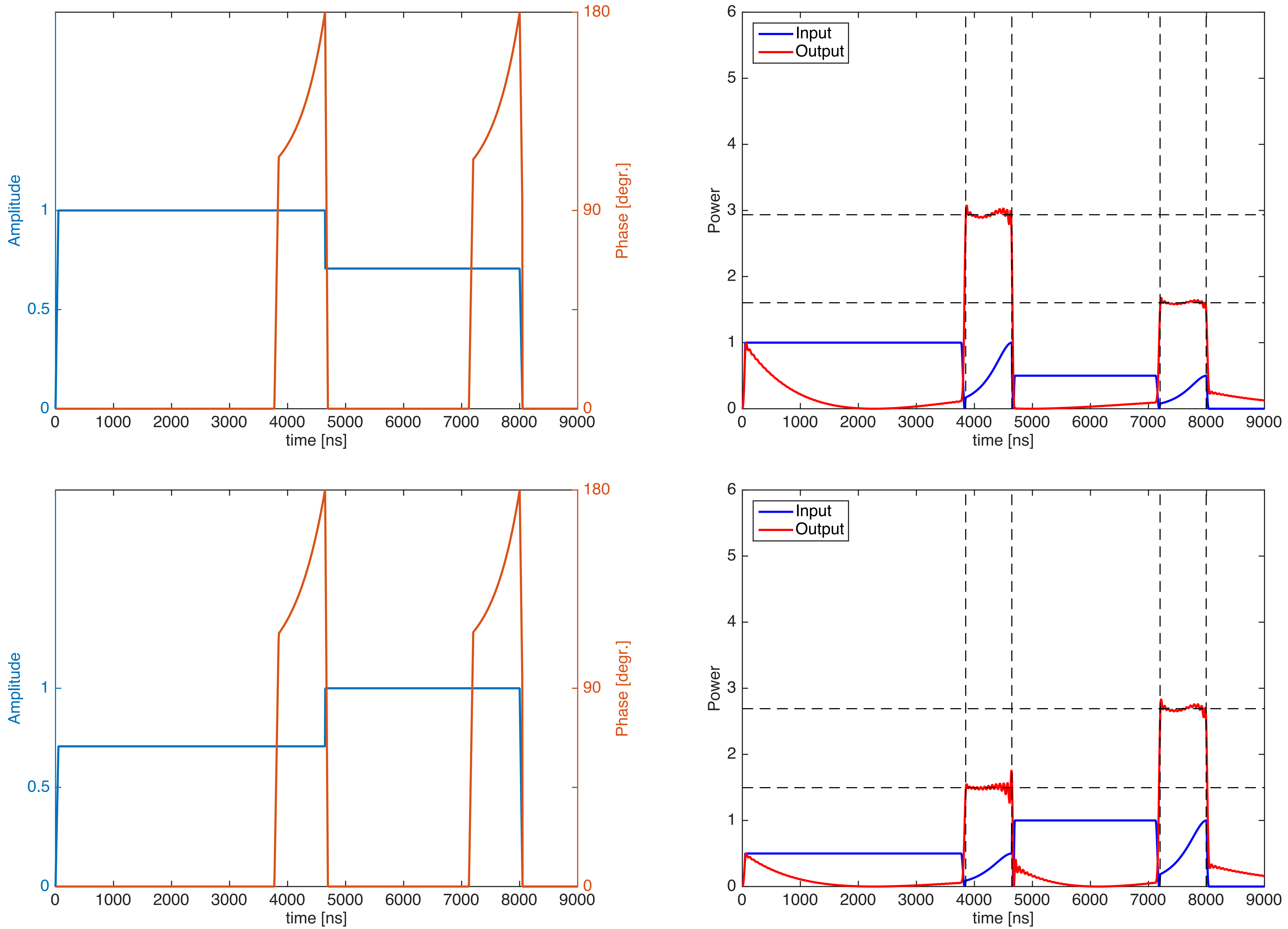
Pulse separation determines the geometry and location of the injector complex!







Change klystron amplitude

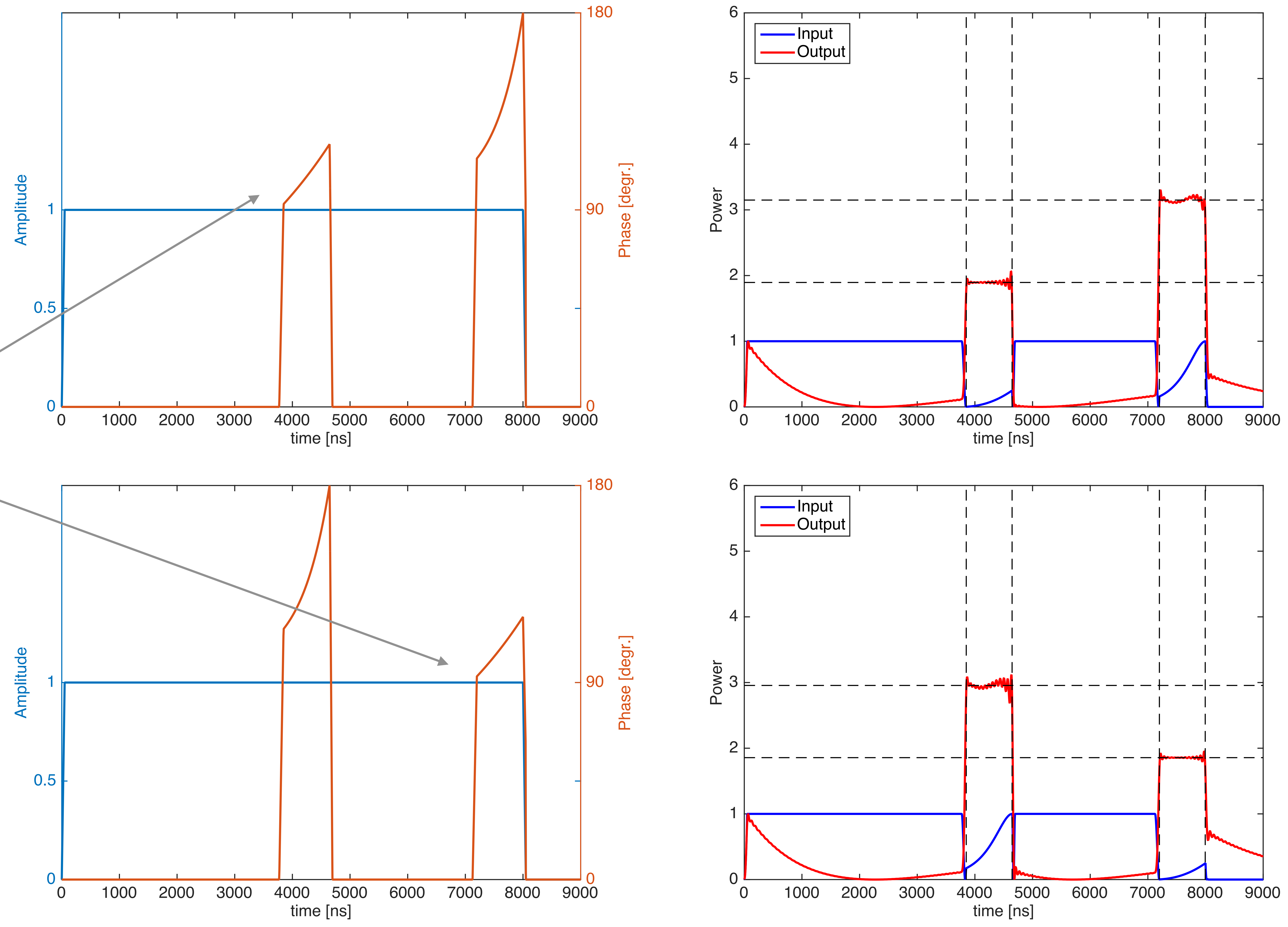


Lower the klystron amplitude in the first or second pulse

Not ideal for the klystron:
Better option, do not ramp the phase all the way to 180 degrees.
=> next slide

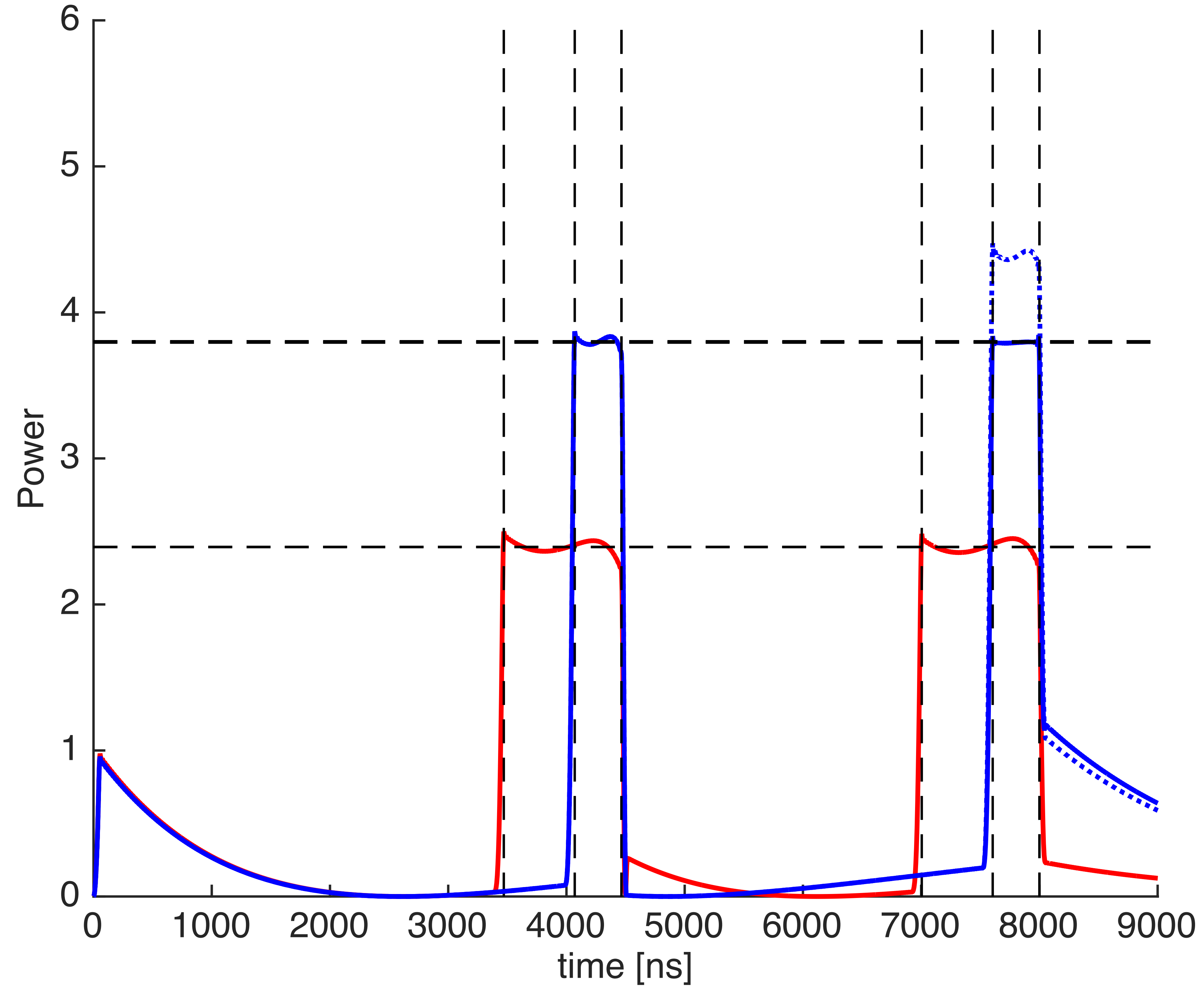
Change phase ramp

End phase ramp before 180 degrees



Given configuration - change pulse length

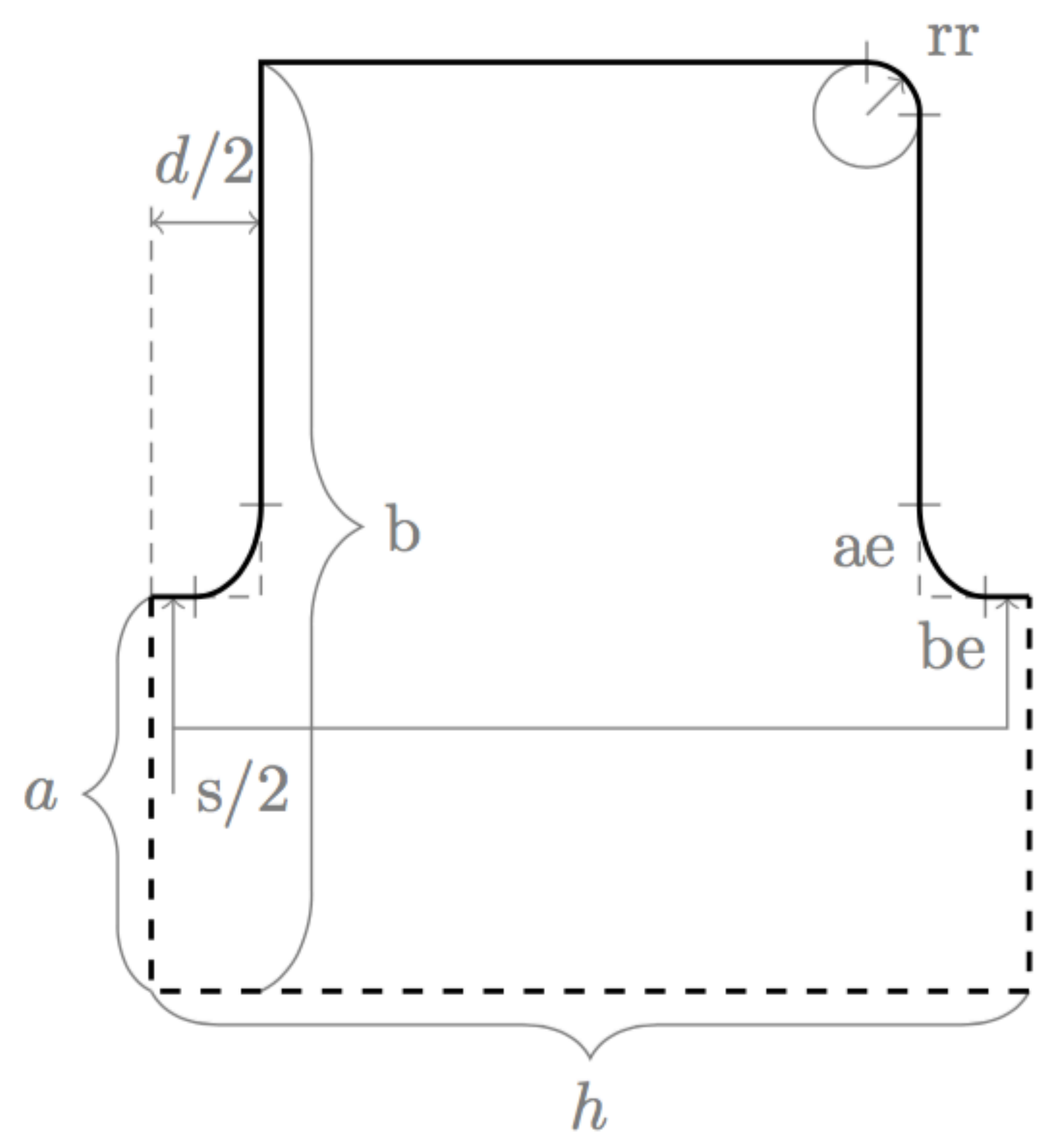
- Configuration optimized for 1000 ns pulse length
- Operate same cavity at 400 ns pulse length
- Keep pulse separation constant
- End phase ramp earlier to level pulses
- Flexibility at cost of efficiency



RF Structure optimization

Structure optimization

- Accelerating structure data from the C++ library ”CLICopti”:
  K. Sjobak and A. Grudiev, *The CLICopti RF structure parameter estimator,* CLIC-note-1028



From K. Sjobak’s thesis

- 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:

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

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 etc.

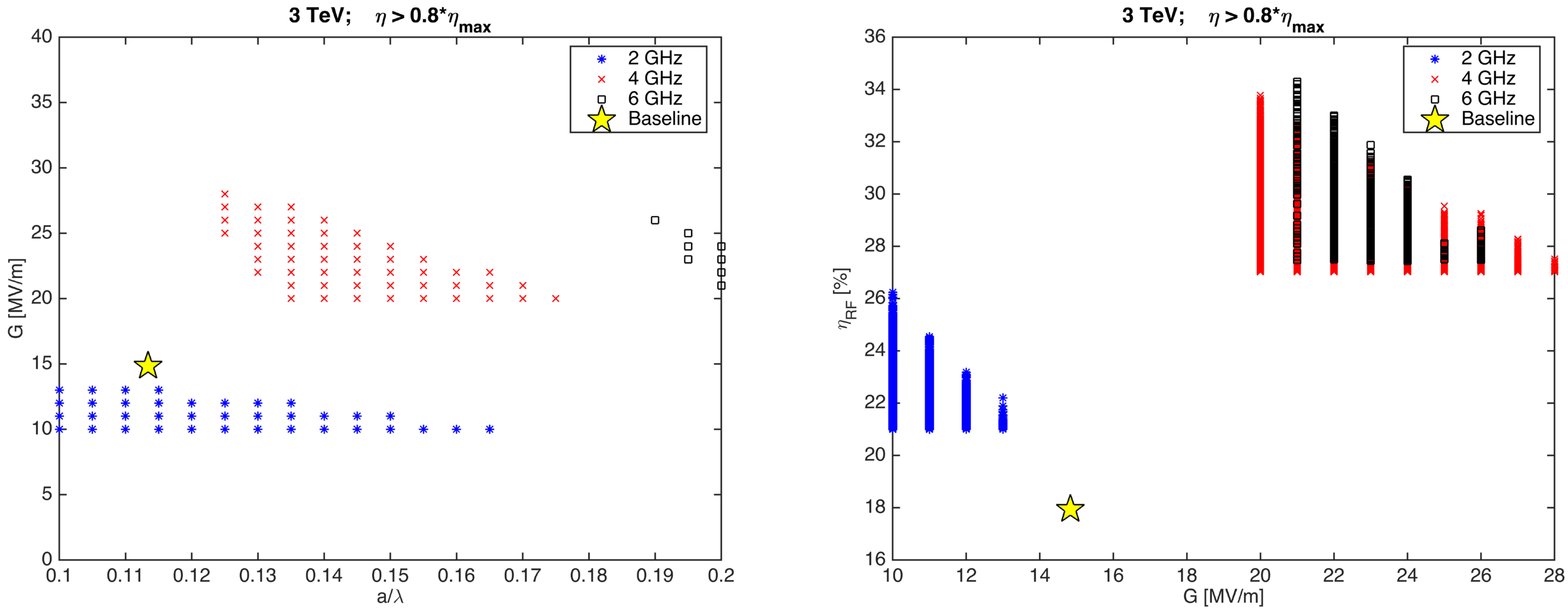
Structure optimization cont'd

- 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 3 TeV bunch parameters and assume 300 μm bunch length in booster

Based on: A. Latina, *Pulse compressors and Booster linac optimisation*

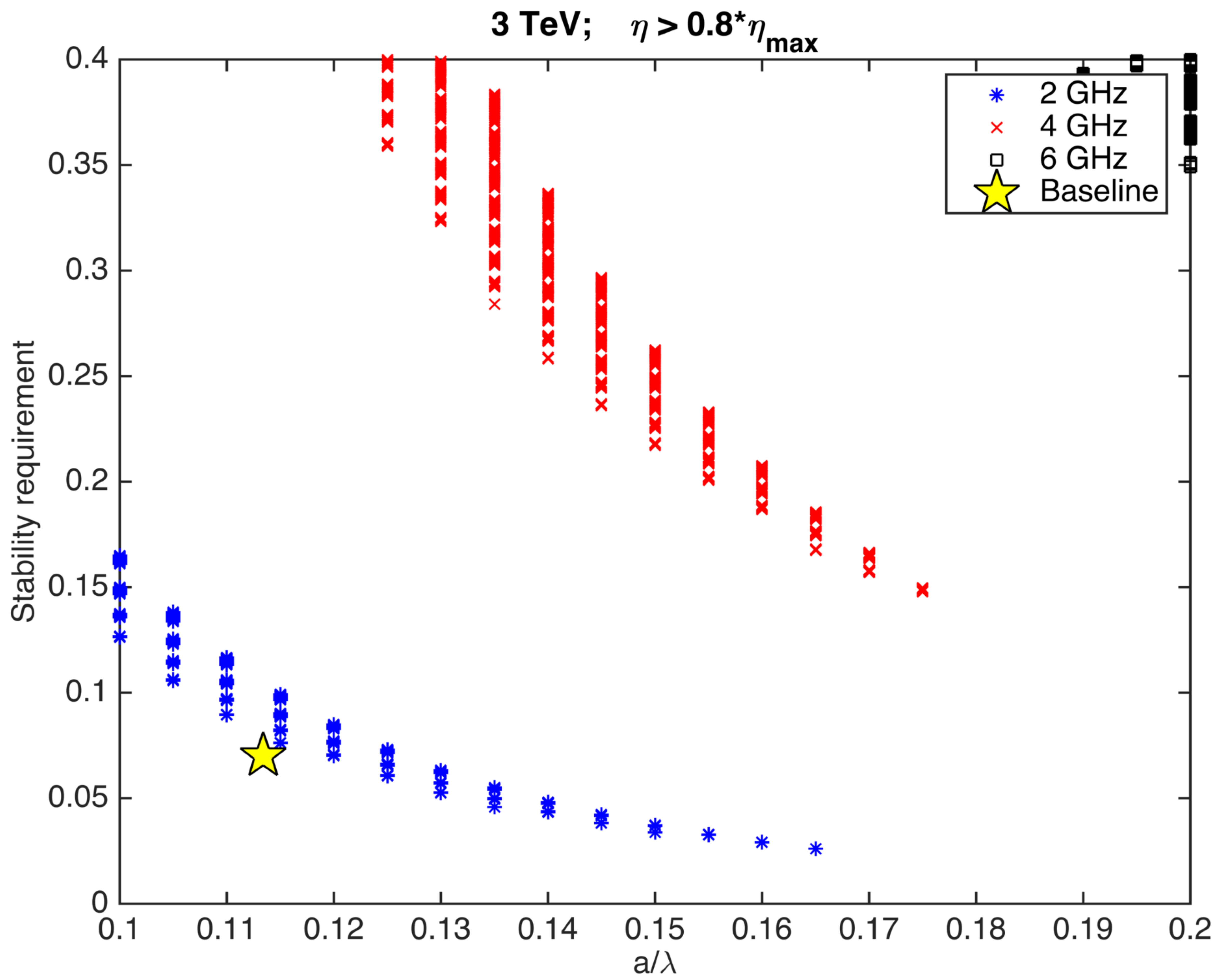
New results

Similar to results by A. Latina.



- Include Booster 2 GHz baseline design
- Higher frequency gives better efficiency and allows for higher gradients
- Lower gradient structures improves efficiency
- 6 GHz only stable solutions for largest apertures

Transverse stability condition < 0.4

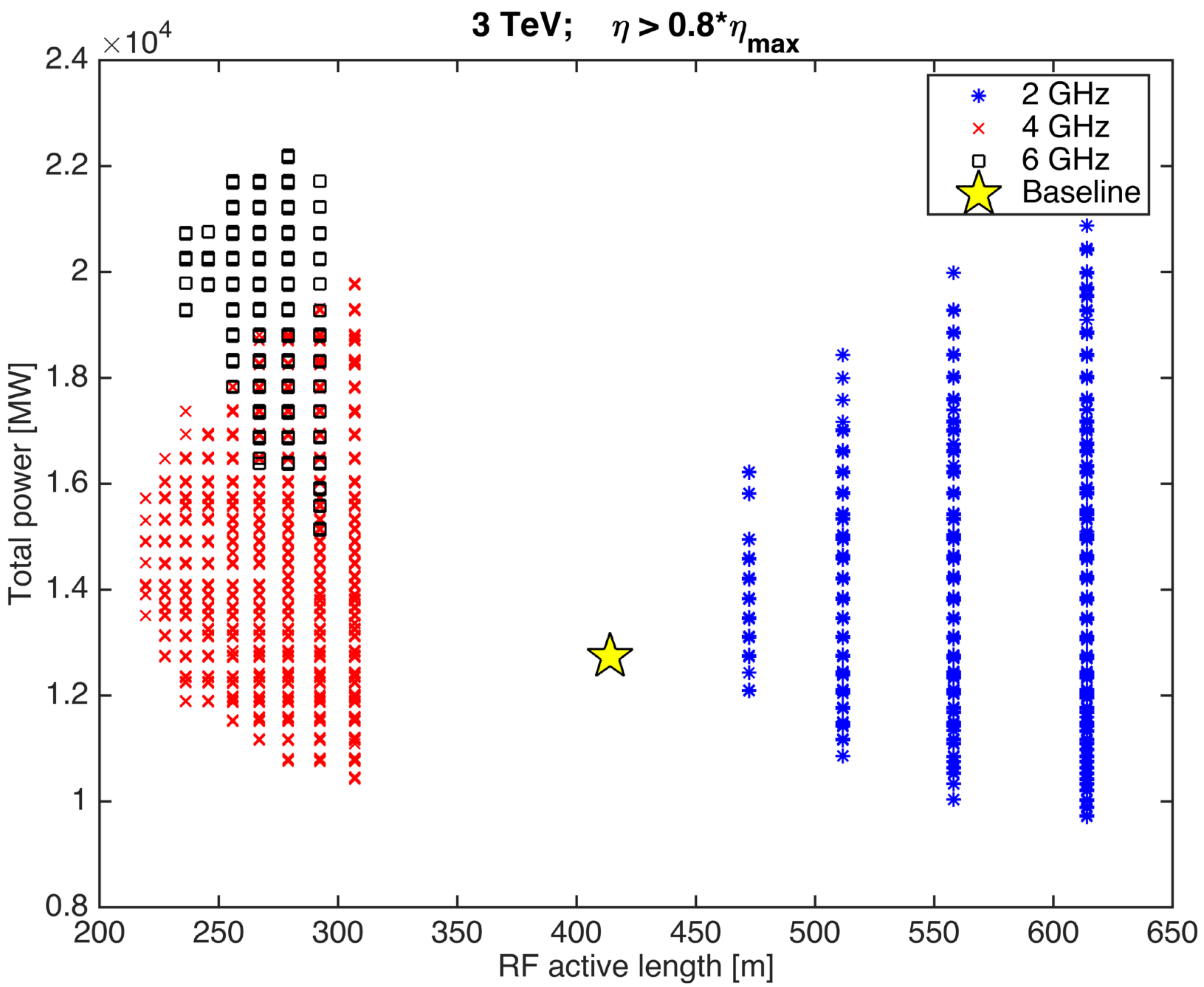


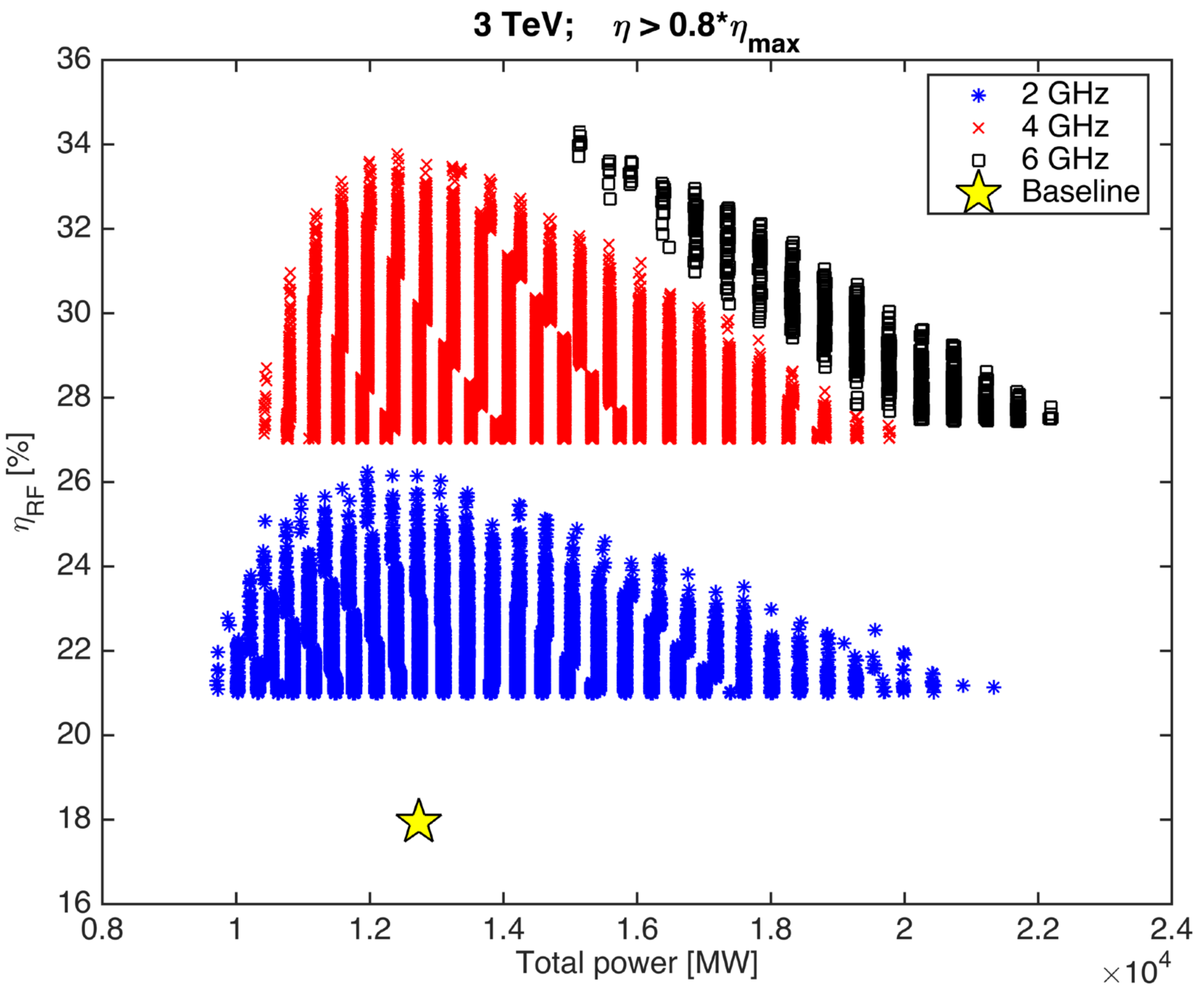
For 6 GHz only the largest aperture structures fulfilled the stability requirement 0.4

More relaxed stability for 2 GHz

Only possible 6 GHz solutions are on the margin of stability
=> not feasible?

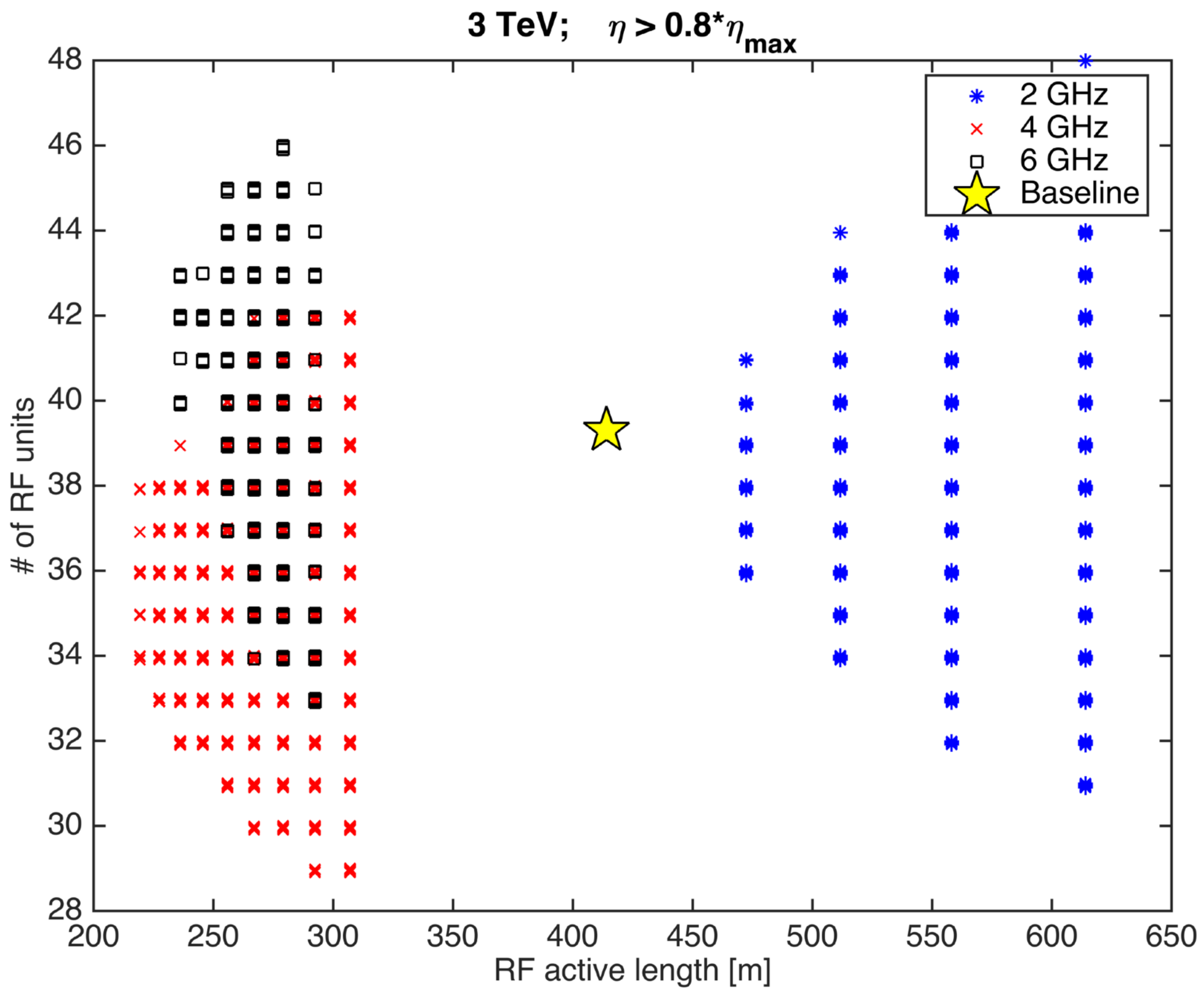
Total peak power

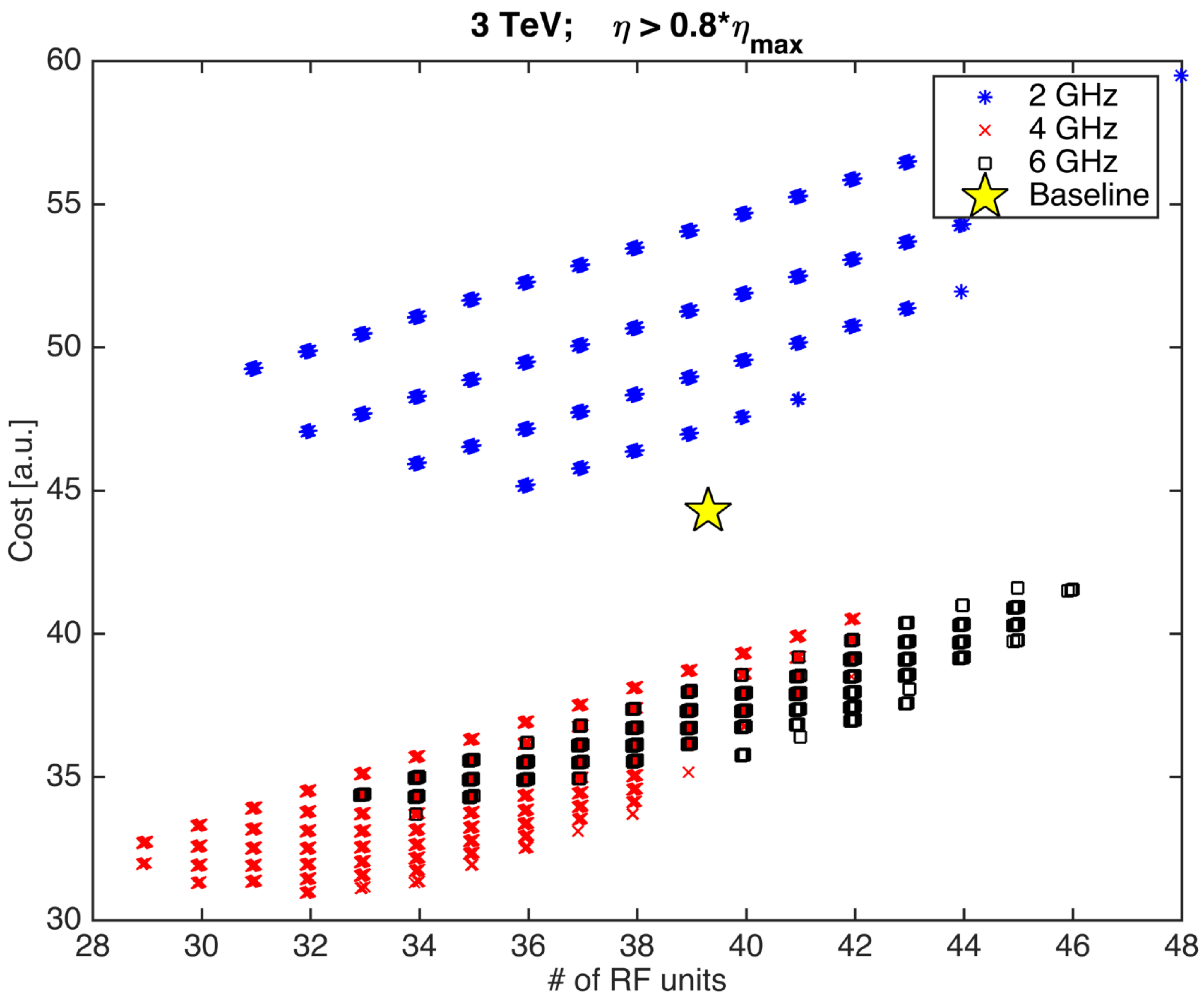




- Total peak power input to structures
- Need also to consider the fill time (total RF pulse length)

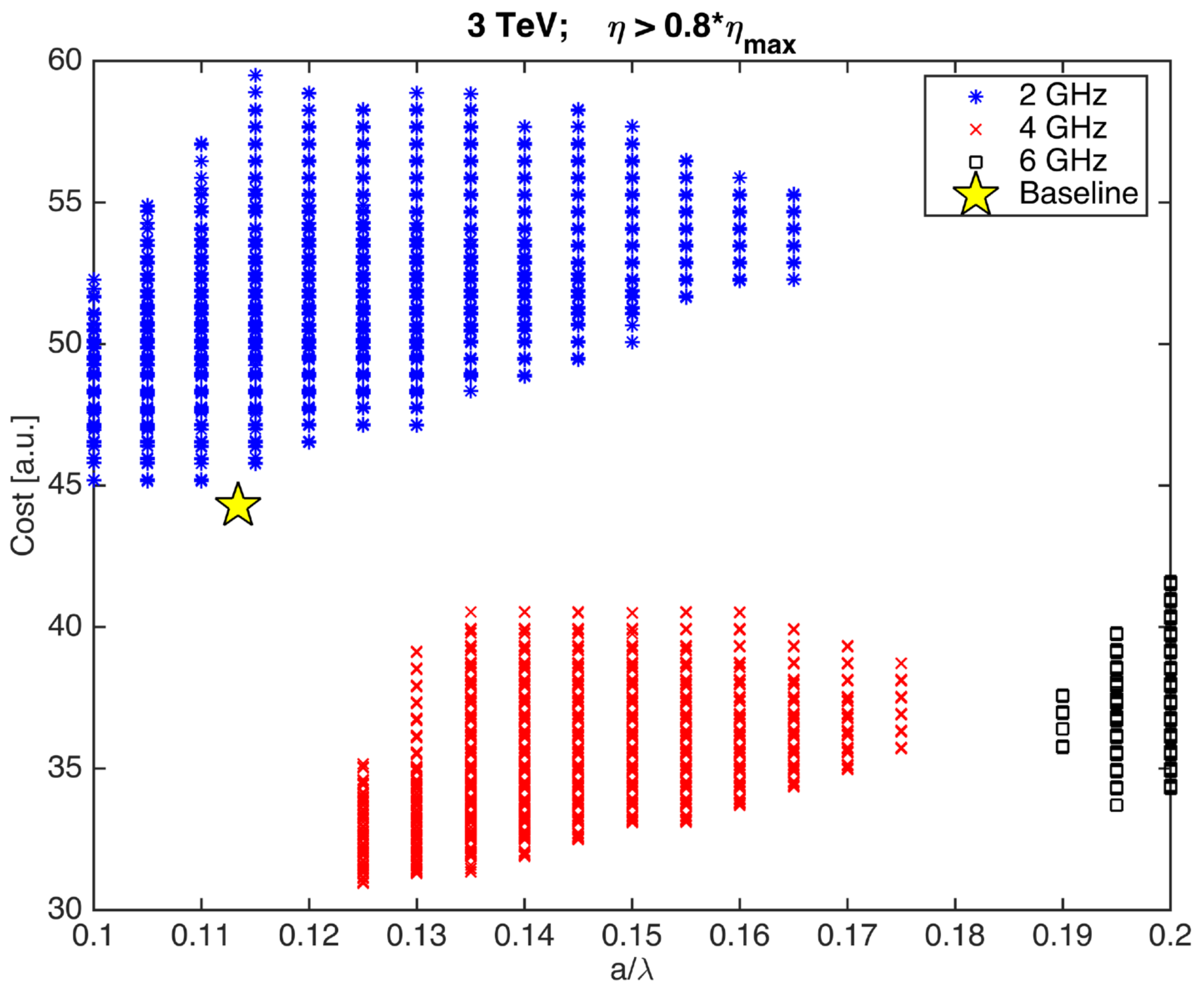
RF units





- The required installed power (# of RF units) is a better measure of efficiency
- Number of RF units also drives the cost
- Baseline design shorter and cheaper?

Cost estimation



Crude cost model:

$$Cost = N_{RF\_units}*(2*C_{klystron}) + L_{RF\_length}*C_L$$

with

$C_{klystron}$ = 300 kCHF/klystron

C_L = 50 kCHF/m

assume same for 2, 4 and 6 GHz
(needs update)

Cost estimates for 6 GHz is based on the same klystron as 4 GHz since
I had no information about a 6 GHz klystron

Higher frequency allows for a shorter a potentially cheaper linac but smaller
aperture and reduced stability margin

Comparison of cost optima for 3 TeV

Parameter	2 GHz Baseline	2 GHz (cost opt.)	4 GHz (cost opt.)	4 GHz (larger apert.)	6 GHz (cost opt.)
Gradient [MV/m]	14.9	13	26	23	23
a/λ	0.11	0.10	0.12	0.15	0.20
Number of cells	30	28	51	75	81
L_struct [m]	1.5	1.4	1.27	1.87	1.35
RF activelength [m]	414	472	236	267	265
Stability	0.07	0.09	0.39	0.23	0.40
Fill time [ns]	430	339	237	233	94
# of units	276	338	185	142	198
Power (loaded) [MW]	46	38	67	89	83
Efficiency (%)	18	21	28	27	32
Total power [GW]	12.7	12.7	12.3	12.7	16.4
# RF units	39	36	32	33	34
Cost [a.u.]	44	45	31	33	34

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Cost opt. worse than baseline?

New cut

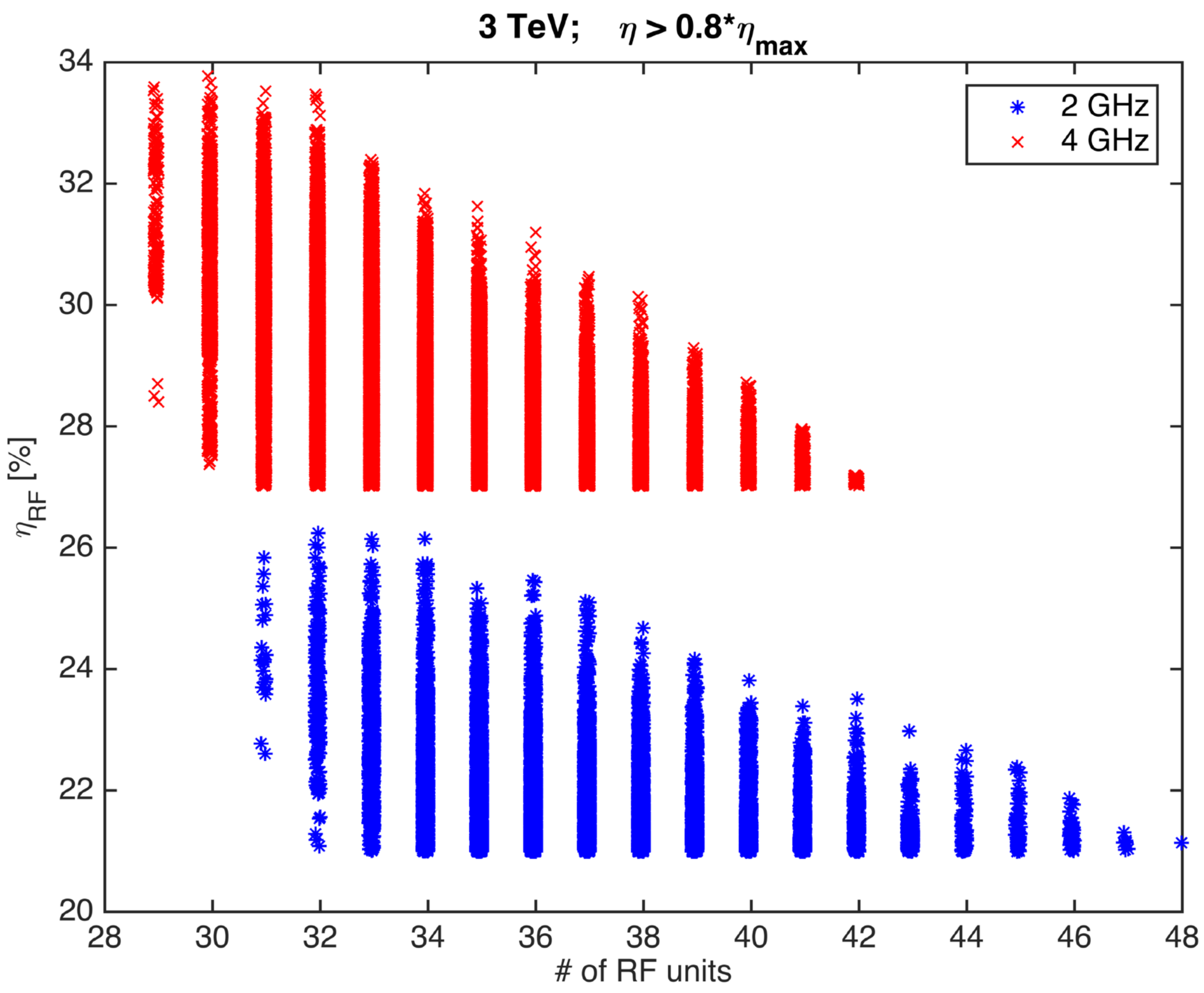
- We used the efficiency defined by the structure

$$\eta_{\text{total}} = \eta_{\text{flattop}} \cdot \frac{t_b}{t_r + t_f + t_b}$$

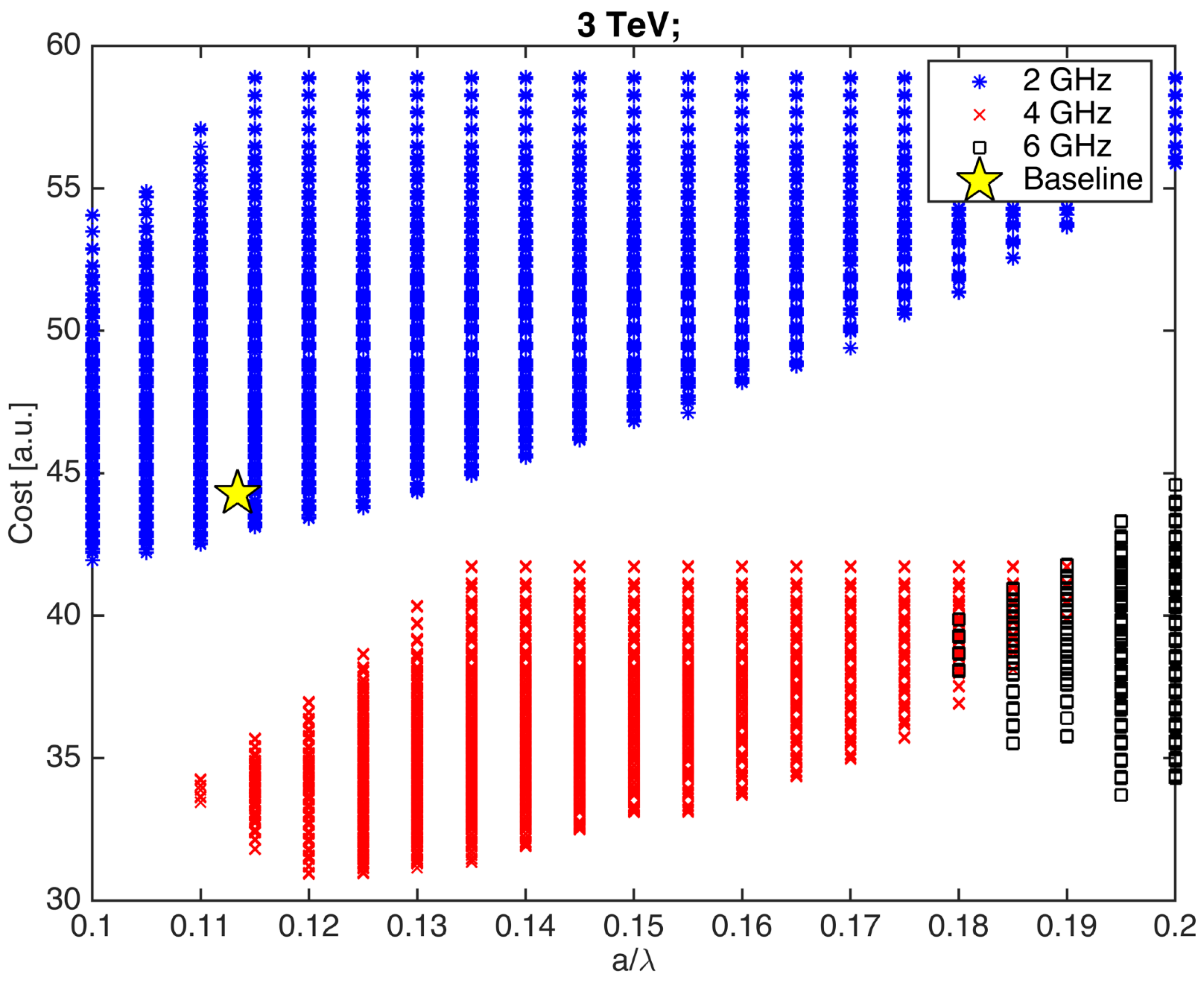
- Use the number of RF units as measure of RF efficiency, (this includes the efficiency by the pulse compressor)

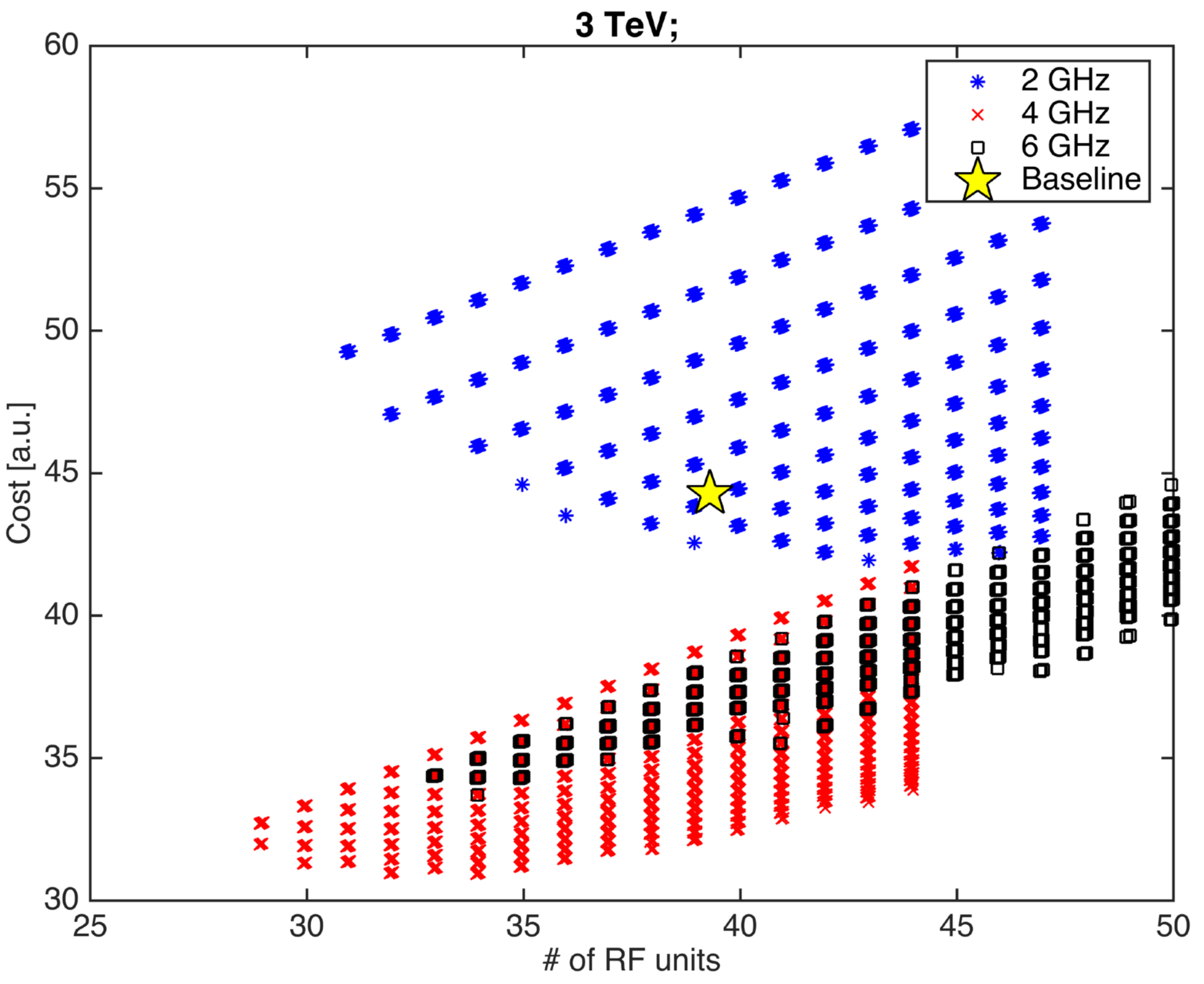
- New cut: display only solutions with:
  *# RF units < 1.5*min(# RF units)*

- This includes some more cost effective solutions



New plots


3 TeV;
Cost [a.u.]
a/λ
2 GHz
4 GHz
6 GHz
Baseline
60
55
50
45
40
35
30
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2


3 TeV;
Cost [a.u.]
# of RF units
2 GHz
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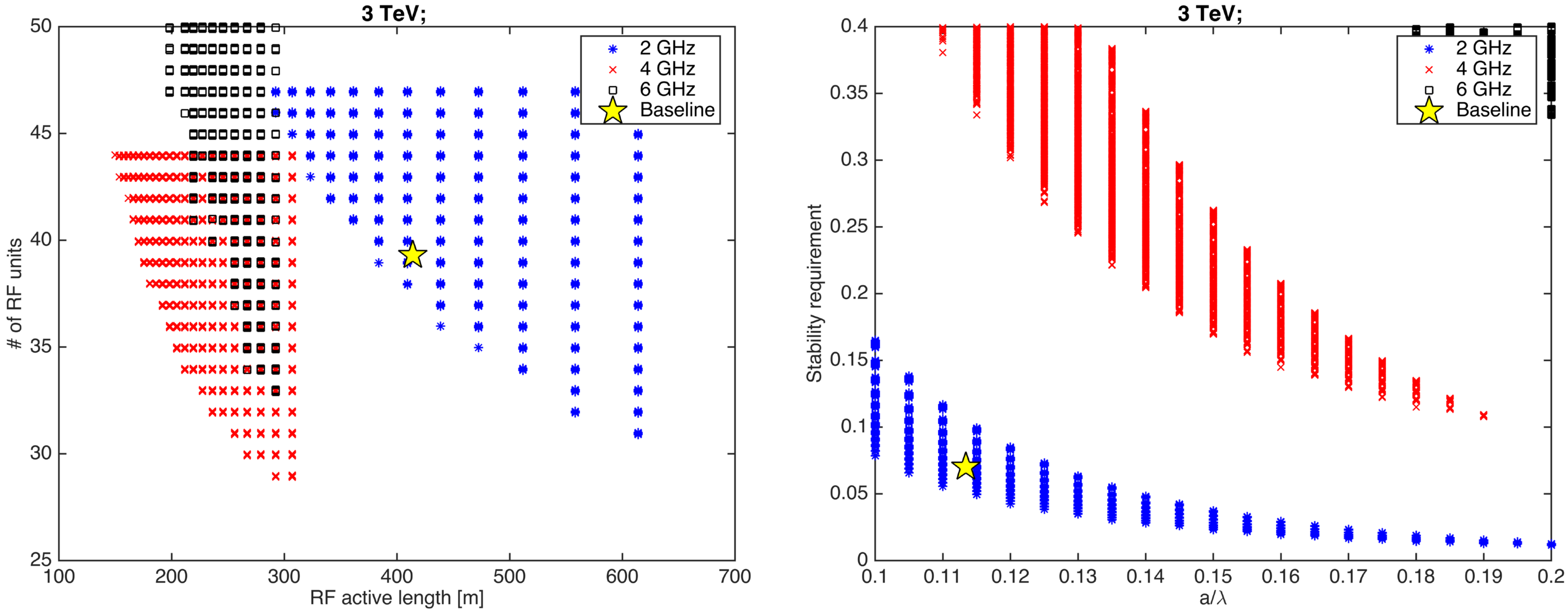
6 GHz
Baseline
60
55
50
45
40
35
30
25
30
35
40
45
50


3 TeV;
2 GHz
4 GHz
6 GHz
Baseline
# of RF units
RF active length [m]
3 TeV;
2 GHz
4 GHz
6 GHz
Baseline
Stability requirement
a/λ

Updated: cost optima for 3 TeV

Parameter	2 GHz Baseline	2 GHz (cost opt.)	2 GHz (Eff. opt.)	4 GHz (cost opt.)	4 GHz (Eff. opt.)
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Number of cells	30	28	33	40	70
L_struct [m]	1.5	1.4	1.65	1.00	1.75
RF activelength [m]	414	323	614	212	307
Stability	0.07	0.09	0.12	0.40	0.38
Fill time [ns]	430	436	382	242	229
# of units	276	231	372	212	176
Power (loaded) [MW]	46	59	28	62	64
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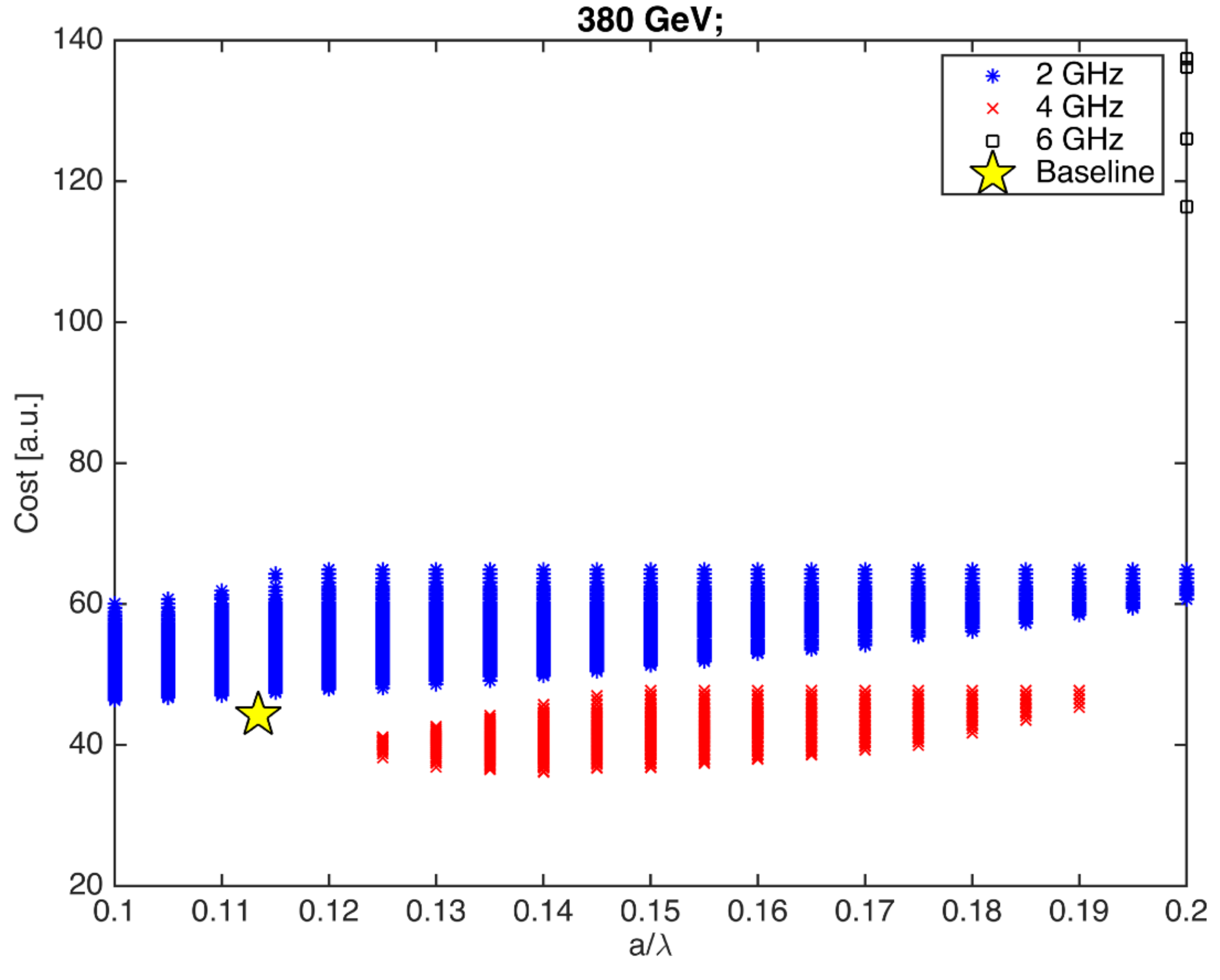
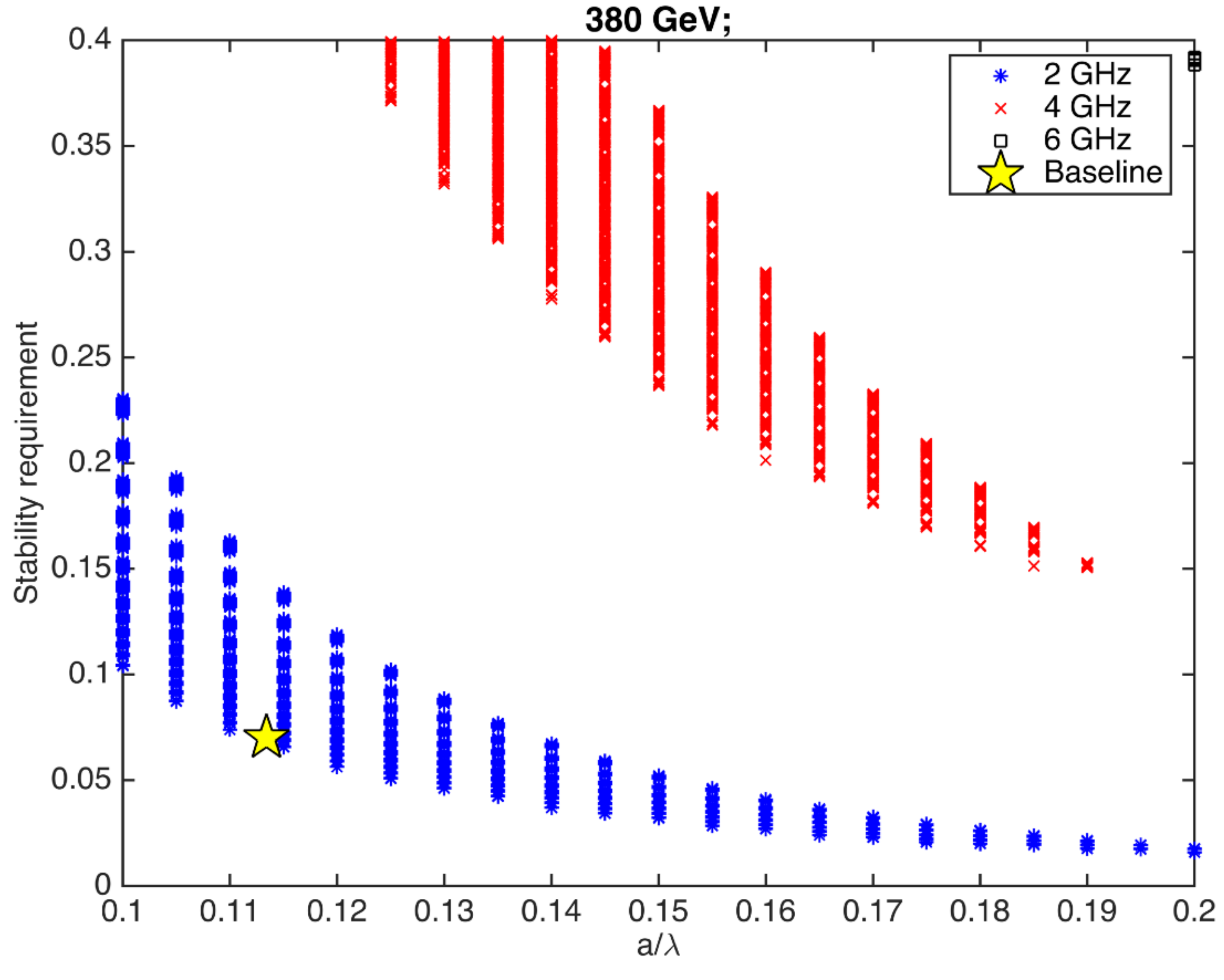
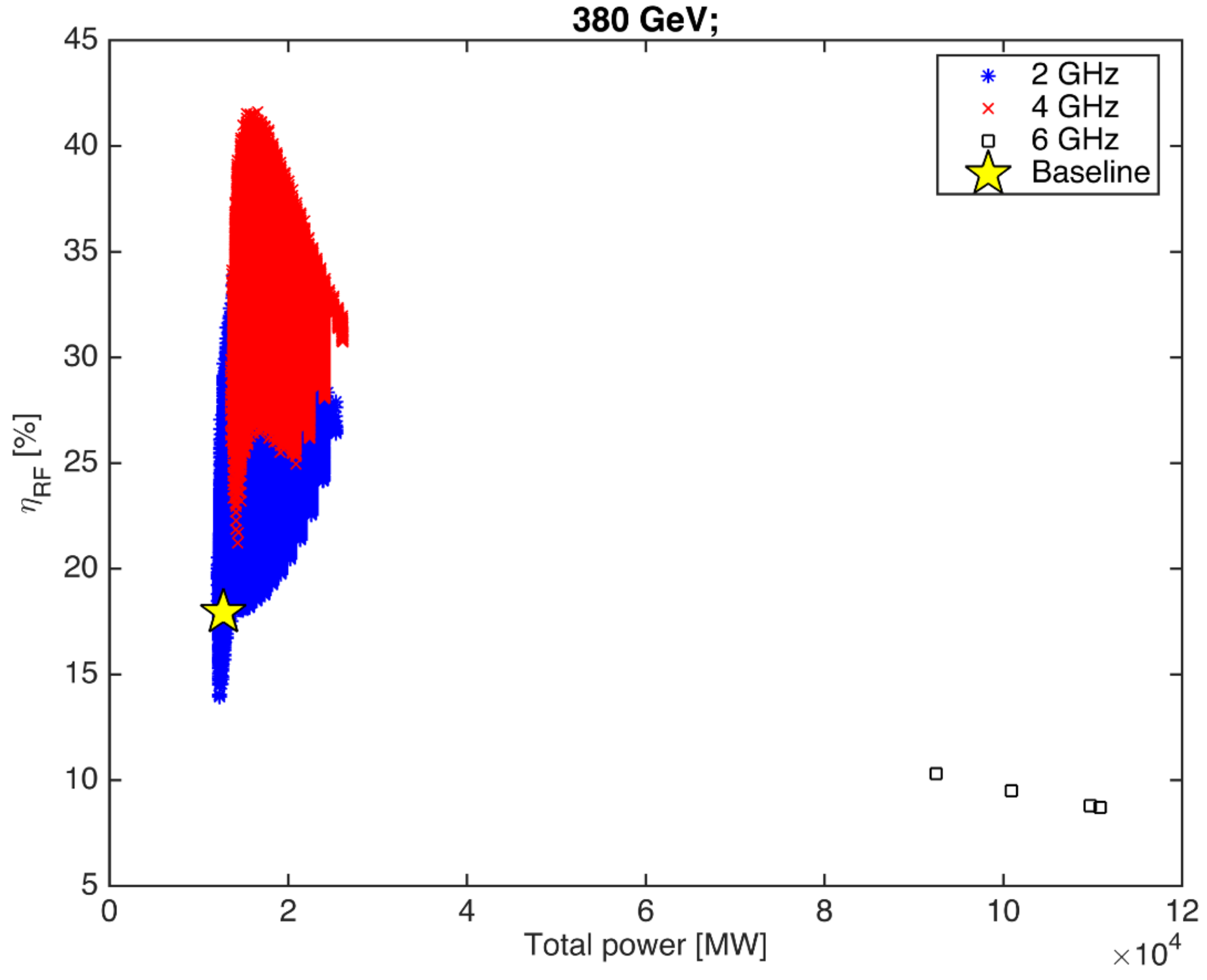
Results 380 GeV







- 6 GHz does not seem like a feasible option

Conclusions

- Octave scripts for pulse compressor
  - Not very fast but seems to work properly and is automatic
  - More optimization could be done but this is probably sufficient for estimating gain and efficiency
  - Available on SVN: `~/clicbp/trunk/Jim/PulseCompressor`

- Booster linac optimization
  - Interesting problem with many constraints
  - Trade-off: flexibility, installation cost, efficiency and length
  - 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
  - 6 GHz possible solution for 3 TeV but seem to gain little compared to 4 GHz
  - Need update with structure selection and further checks

- Future work
  - More work needed to understand what is optimum
  - Update cost model?
  - More investigations on flexibility: energy scan operation?
  - Compare 3 TeV and 380 GeV cases. Minimum upgrade option?
  - Tracking studies for 2 GHz and 4 GHz solutions