A CW SCRF Linac for CLIC Drive Beam

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15/06/2021

Basic concepts

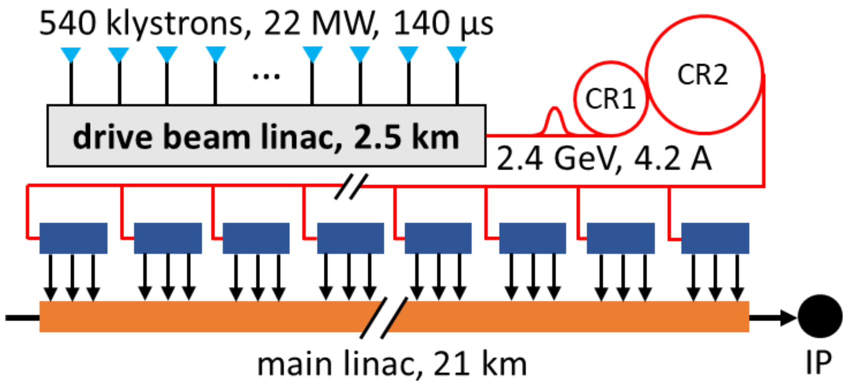
- Drive beam power (2.4 GeV, 4.2A, 35/140 μs) for CLIC operation:

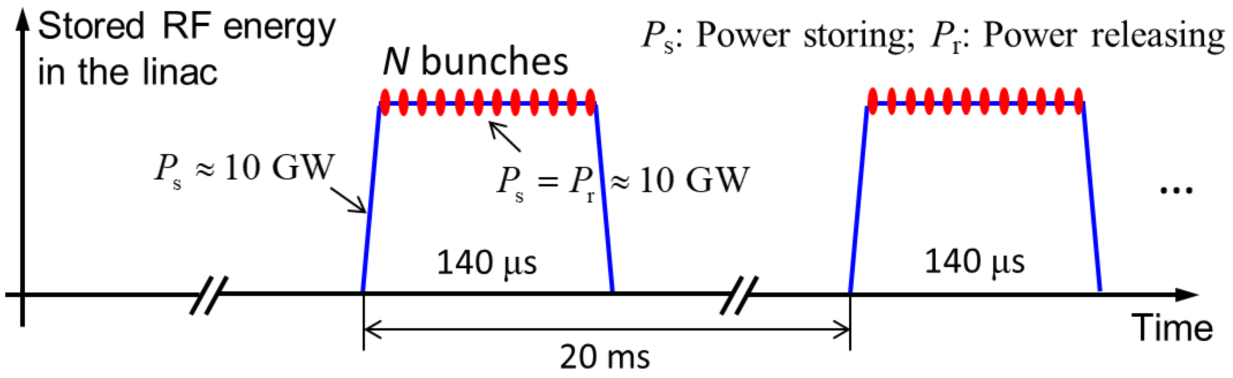
	380 GeV stage	3 TeV stage
Peak power	10 GW	10 GW
Average power	17.5 MW	70 MW

- How to transfer the energy from RF power to the beam?
  - Pulse mode: RF power 10 GW → 500×20 MW klystrons for one linac complex in all stages.

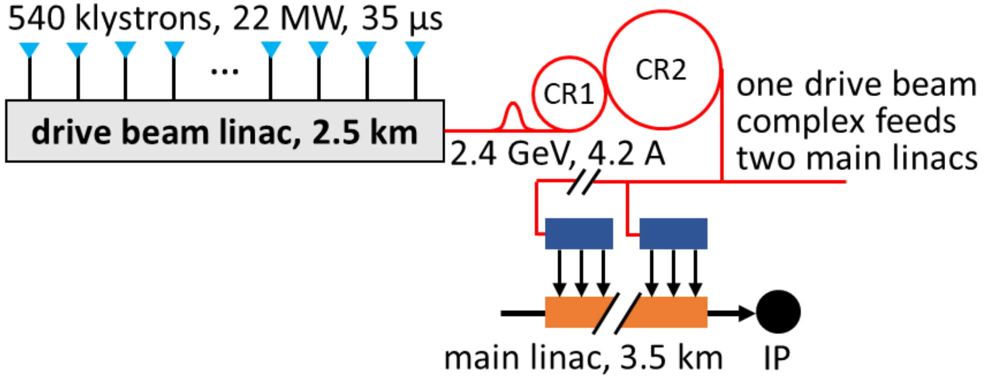
DB linac for pulse mode

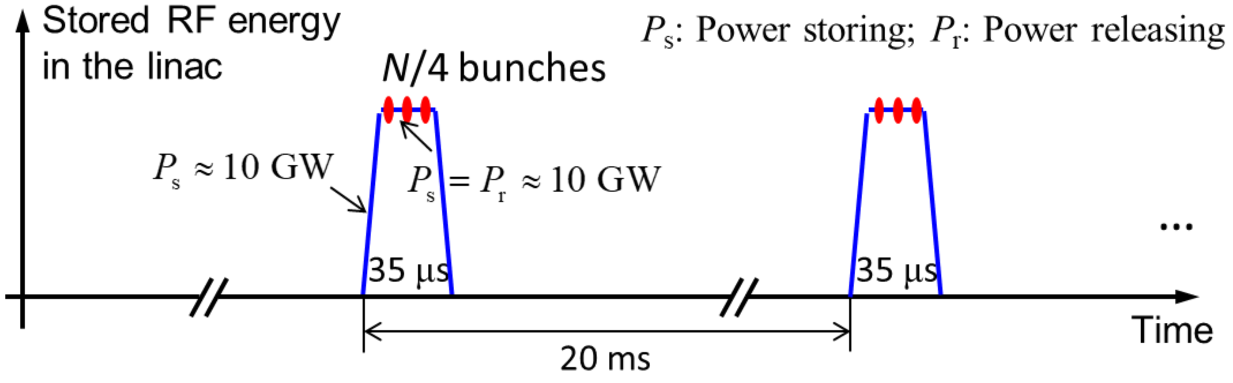
- **DB linac design in CDR:** NC structures operate at pulse mode
  - **Final 3 TeV Scheme**





  - **Initial 380 GeV Scheme:** Shorter pulse length but same power → same accelerator length and klystron amounts for one drive beam complex → high cost in the initial stage!





Basic concepts

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	380 GeV stage	3 TeV stage
Peak power	10 GW	10 GW
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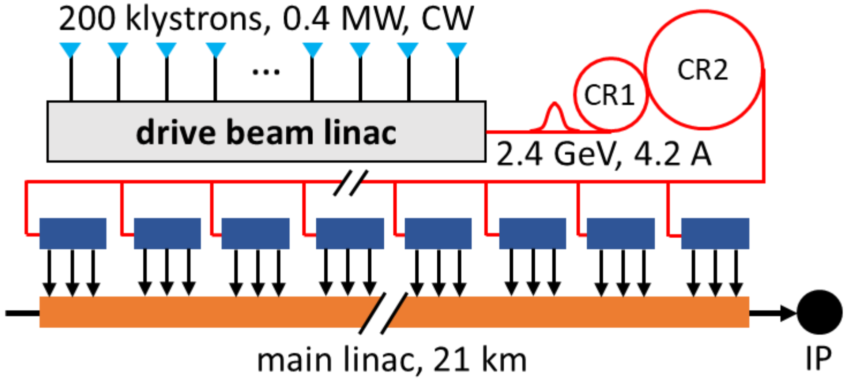
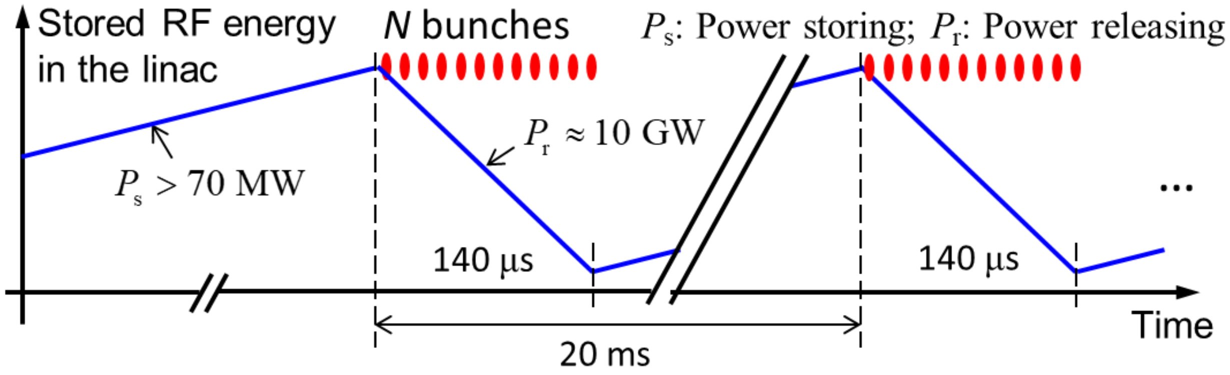
- How to transfer the energy from RF power to the beam?
  - Pulse mode: RF power 10 GW → 500 × 20 MW Klystrons.
  - CW mode: RF power
    - 17.5 MW → 50 × 350 kW Klystrons (380 GeV)
    - 70 MW → 200 × 350 kW Klystrons (3 TeV)

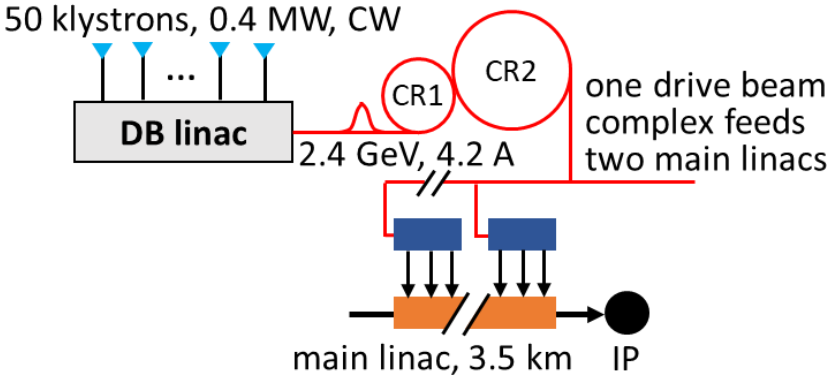
DB linac for CW mode

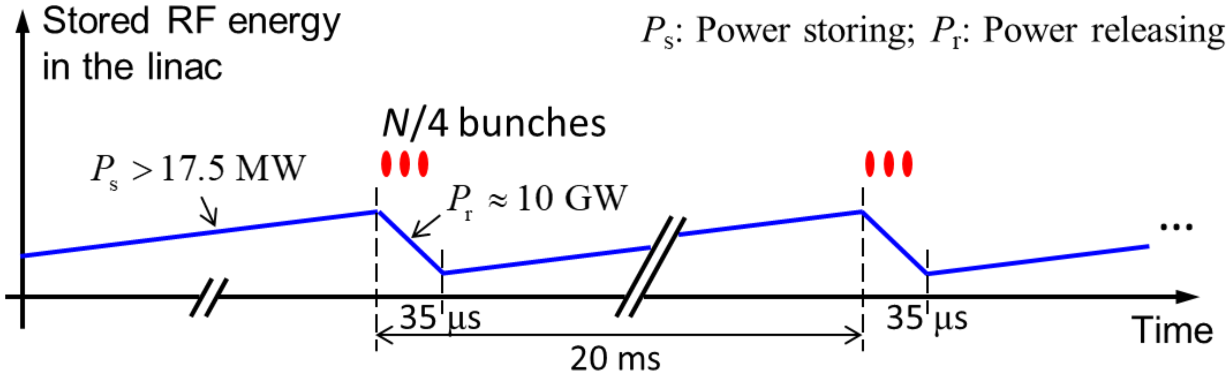
- **An alternative scheme:** SC structures run at CW mode
  - **Final 3 TeV Scheme:** Less amount of power source and no modulator.





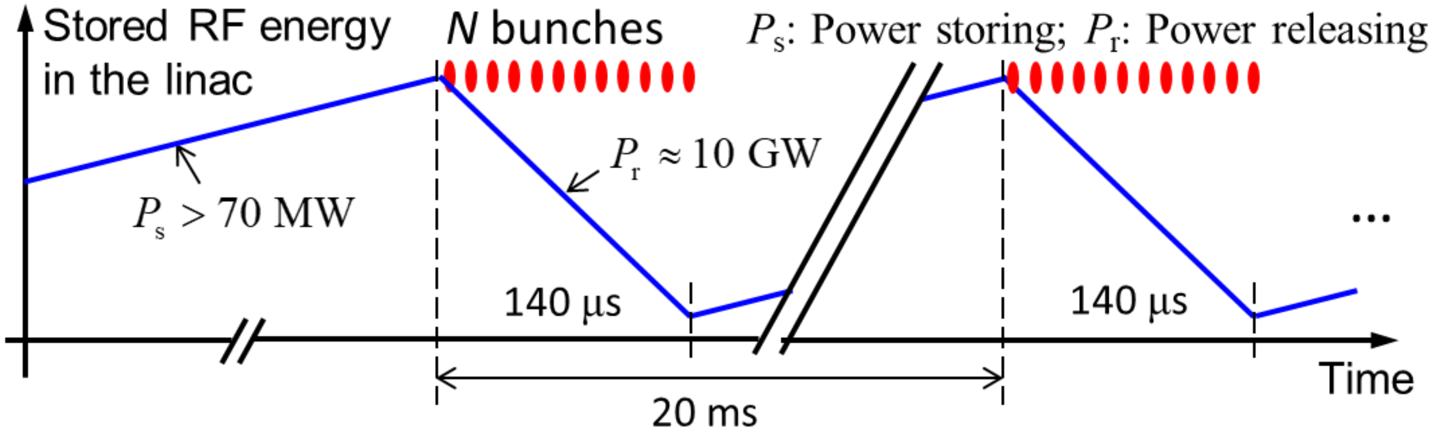
  - **Initial 380 GeV Scheme:** less energy storage → less power source and shorter structure length → possible lower cost in the initial stage!

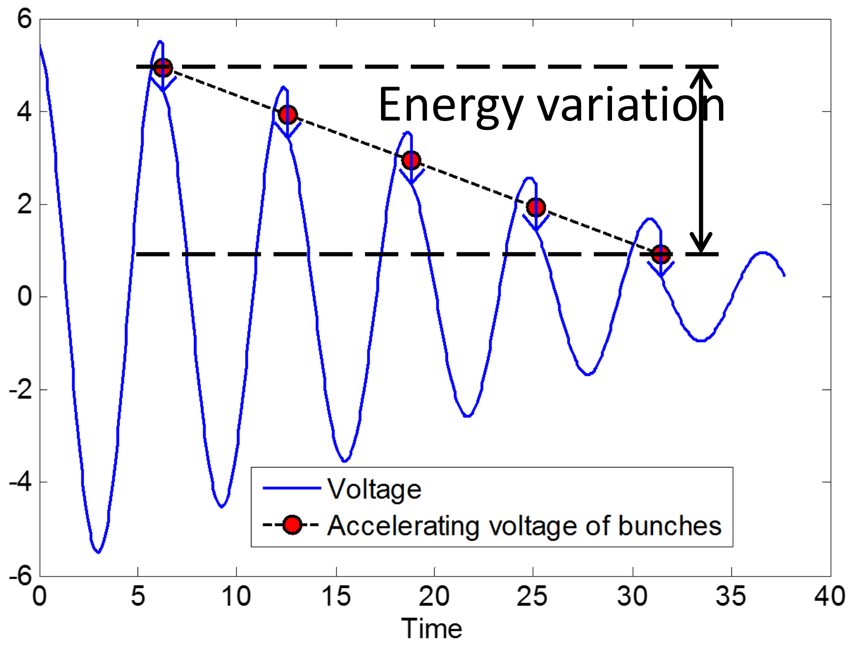




Challenges in the CW-DB linac

- Big challenge: Heavy beam-loading effect !
- Cavity stored energy (voltage) drop fast due to strong beam-loading during beam time.
- A flat energy distribution (variation < 1%) of drive beam is required for the acceptance of the combiner ring.

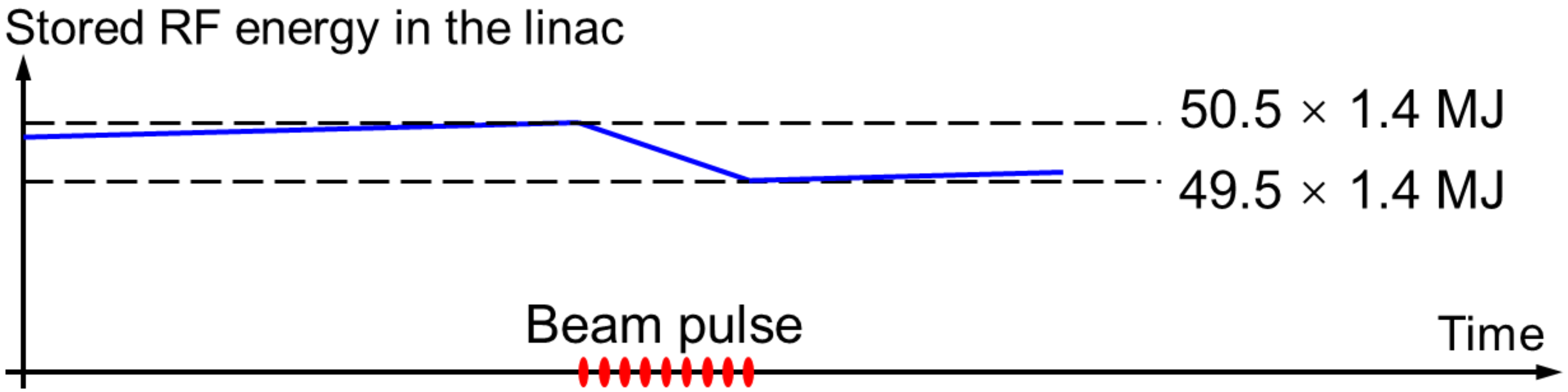




Solution 1: stores more RF energy

- Beam energy in one pulse: 1.4 MJ.
- The variation of acc. voltage is ±1%, when max. stored energy is 50.5×1.4 MJ.
- Stored energy in a SC cavity is limited by surface B-field (120 mT).
- More stored energy →

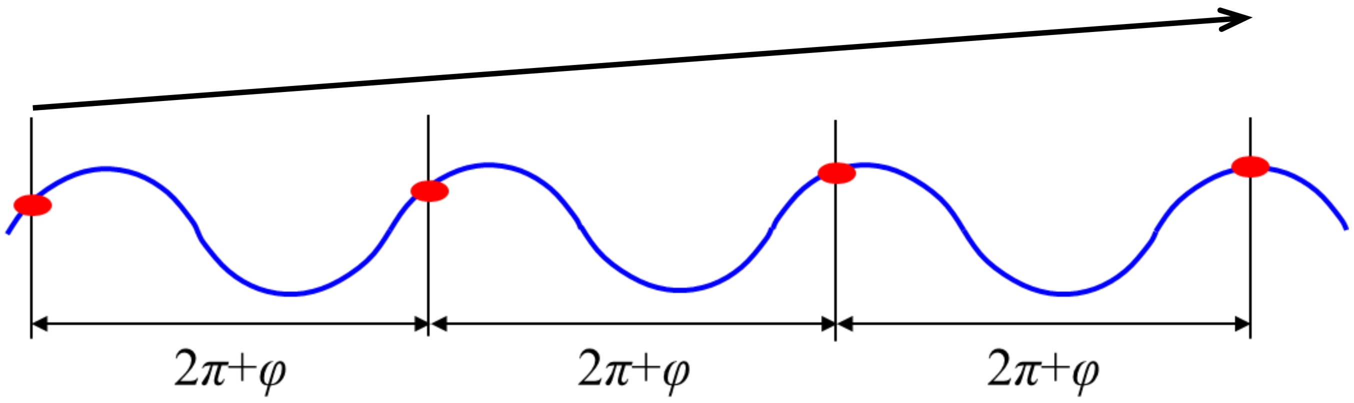
	Per 1.4 MJ	50.5×1.4 MJ
Structure length	2.2 km	110 km
Heat load @ 2 K	80 kW	4 MW
Cost of two linacs	3.4 BCHF	170 BCHF

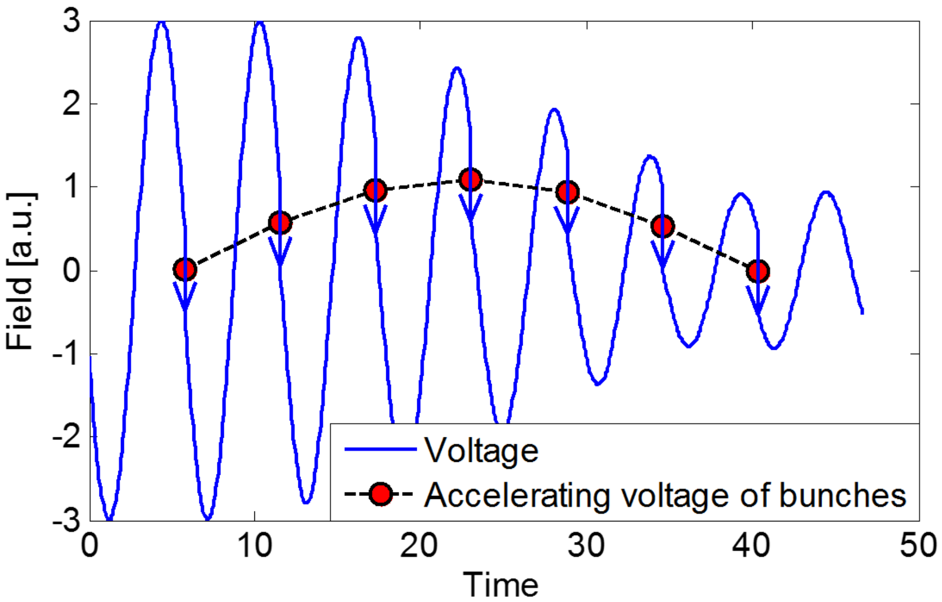


Solution 2: frequency shift

- f_c (frequency of cavity) ≠ f_b (Bunches) → bunches see changing phases
- Allowance of the accelerating energy variation still matters:
  - 1% variation → stored energy = 4×1.4 MJ
  - 14% variation → stored energy = 1.5×1.4 MJ
  - 60% variation → stored energy = 1.08×1.4 MJ

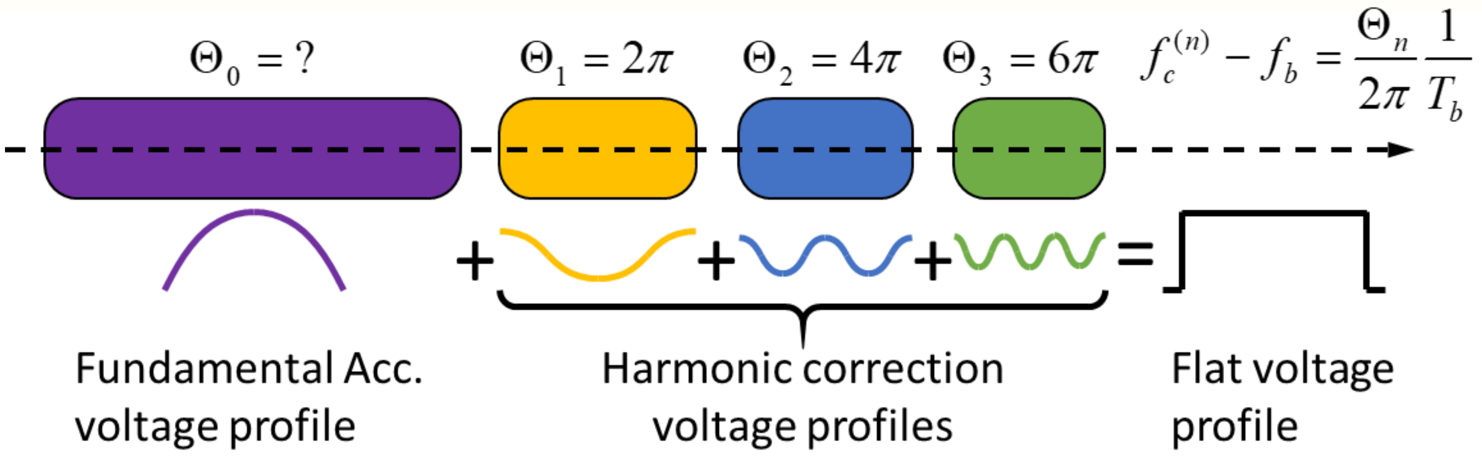
The phase increasing compensate the voltage dropping



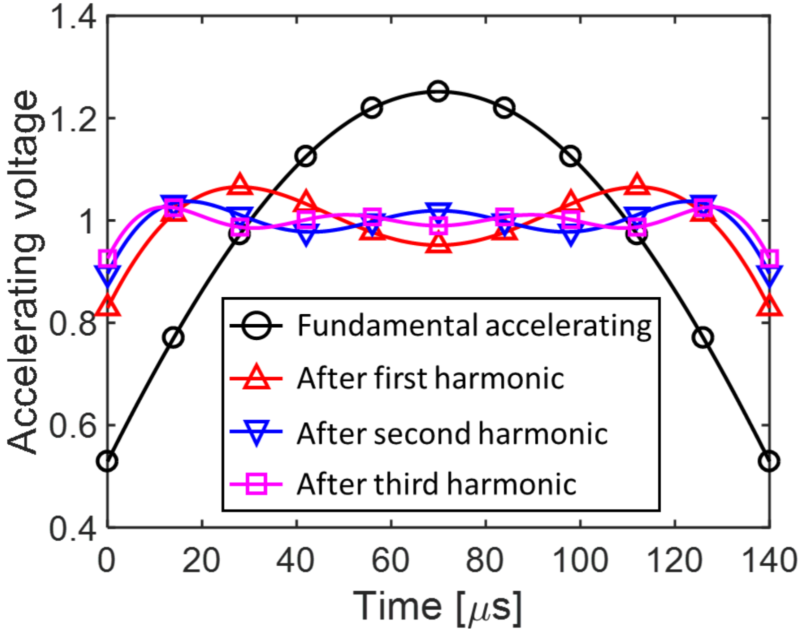


Concept of harmonic correction

The way of Fourier series expansion:

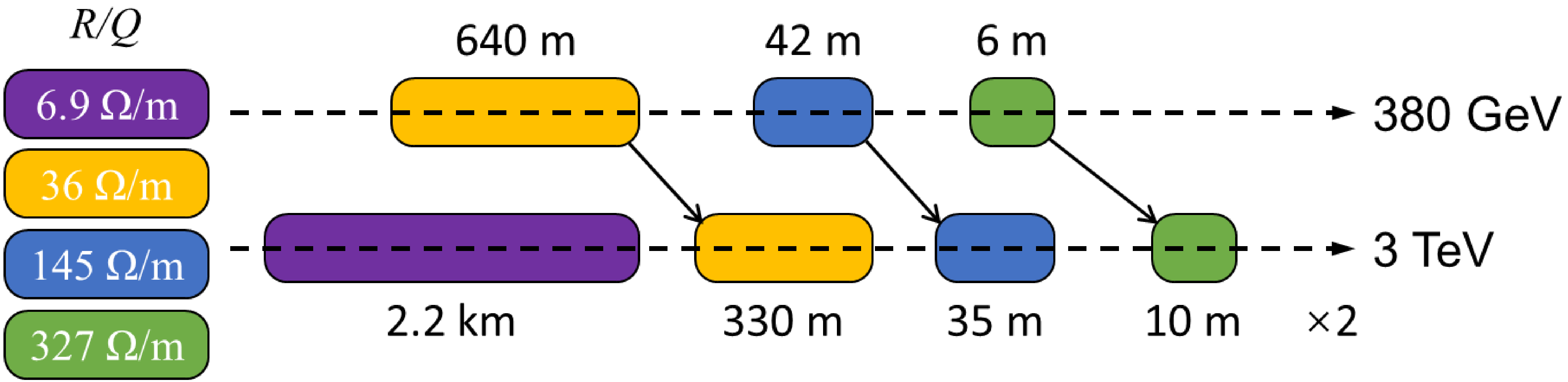


- **Benefits of harmonic correction:**
  - Allows larger energy variation for accelerating structure
  - Length of accelerating structure = 2.2 km
  - Length of correction structures = 0.4 km
  - Total stored energy ≈ 1.2 × 1.4 MJ



Structure scheme

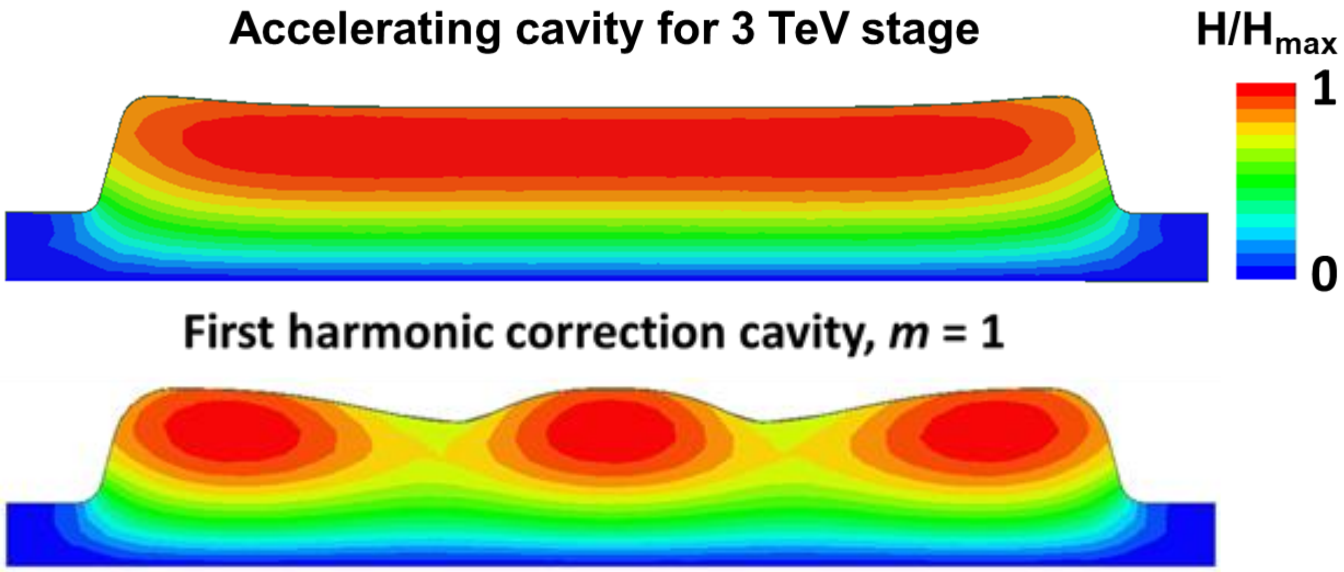
- Reuse the fundamental accelerating structure for the 380 GeV stage as the 1-st harmonic correction structure for the 3 TeV stage.
- Reuse the n-th harmonic correction structure for the 380 GeV stage as the (n+1)-th harmonic correction structure for the 3 TeV stage.



Preliminary design of cavities

Parameters	Acc. Cavity
Frequency	500 MHz
Effective length	1.40 m
Beam pipe radius	90 mm
Max. stored energy U_M	1210 J
R/Q	5.9 Ω/m
Q_0	5×10^{10}
Q_{ext}	2.5×10^{7}
Dynamic heating at 2 K	35.6 W
Max. acc. gradient	5.6 MV/m
Avg. operated gradient	3.7 MV/m
Max. surface E-field	47 MV/m
Max. surface B-field	120 mT

Due to heavy beam loading, the shunt impedance should be very low.



Reference cavities: PIP-II HB-650

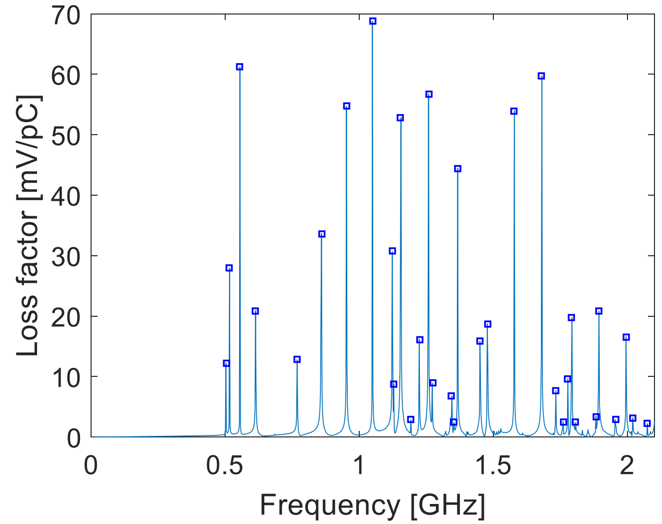
$Q_0 = 5\times10^{10}$ @ 2 K, the peak B-field =125 mT

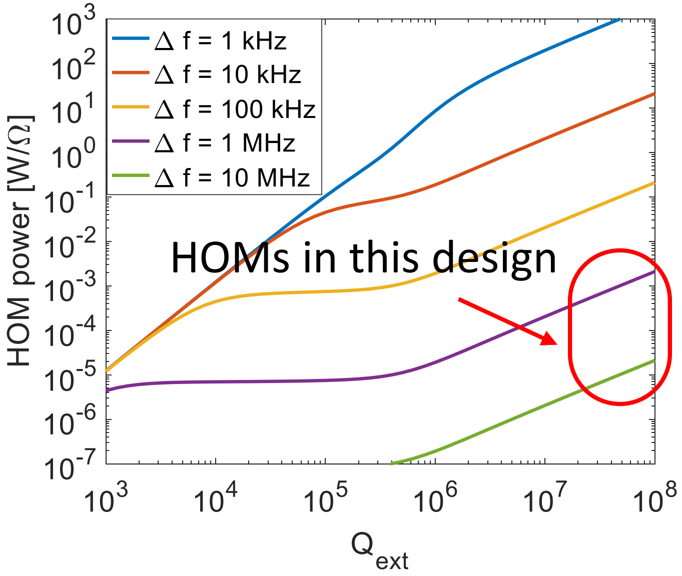
The PIP-II Collaboration, *The PIP-II Reference Design Report*, 2015.

S. Mishra, *Fermilab PIP-II Status and Strategy*, in HB2016, 2016.

HOM issue

- **Large beam current (4.2 A) → HOM effect is significant:**
  - Bunch length = 6 mm → only consider HOMs below 50 GHz
  - Beam pipe aperture = 90 mm → HOMs higher than 1.28 GHz will be propagated into warm section, results in a low Q factor (~ 10^4)
  - HOMs below 1.28 GHz have a higher Q factor (~ 10^8)
- Extra heat load due to HOMs: **5~10 mW per cavity** (dynamic heating of working frequency = 36 W per cavity)
- Transverse wake potential HOMs at the second following bunch: **1 V/m/mm** (Wy of ILC is 200 V/m/mm)
- **HOM issue should not be critical since R/Q is very low!**

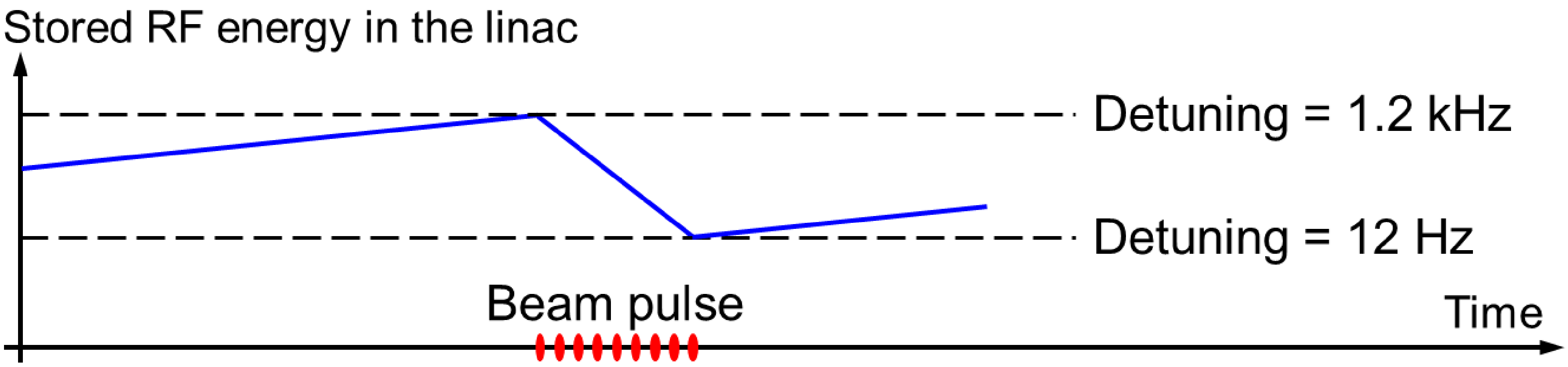




Bandwidth issue & microphonic effect

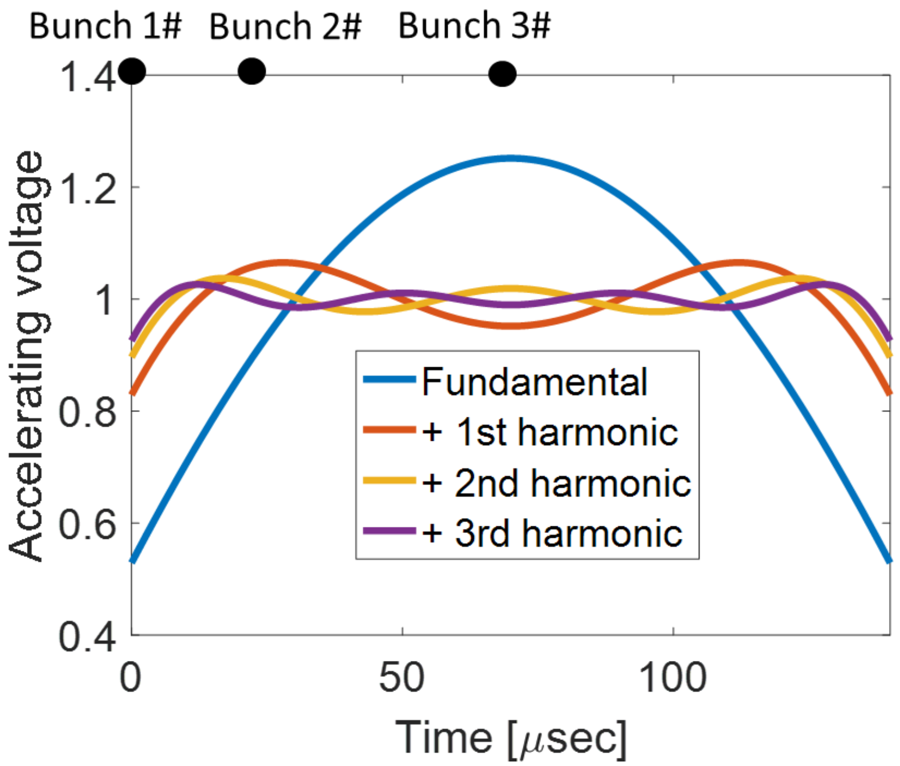
- Optimum Q_e = 2.5×10^7 → Bandwidth of cavity ≈ 20 Hz
- Lorentz force detuning ≈ 1.2 KHz >> 20 Hz (Assume deformation is 33 Hz/Torr)
- Microphonic effect: slowly damped → inhomogeneous frequency detuning
- Possible solutions:
  - External stiffener structures on the cavity wall
  - Fast tuner (precise control within milliseconds)

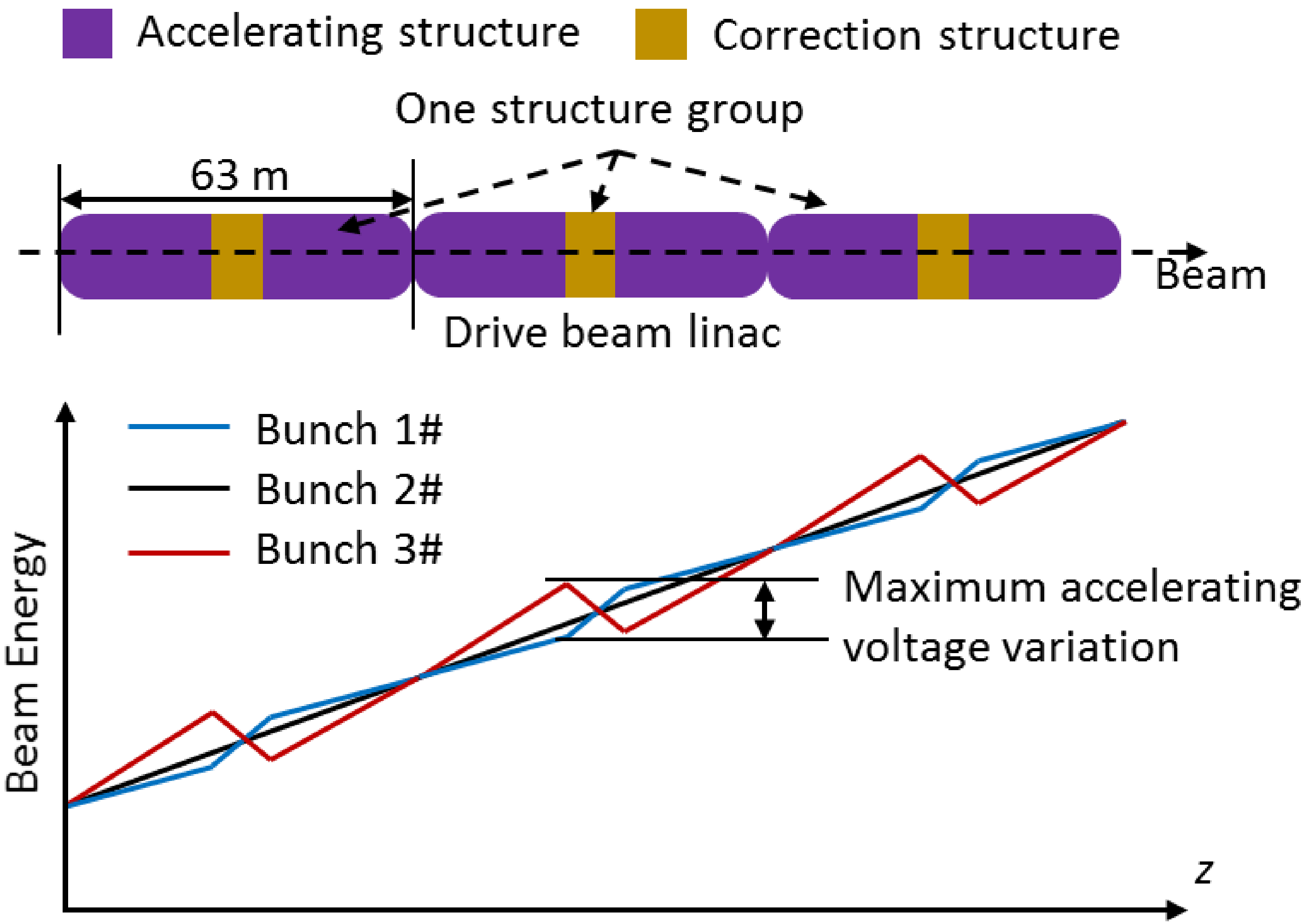
  } The feasibility is hard to be assessed at current time



Beam dynamic & lattice design

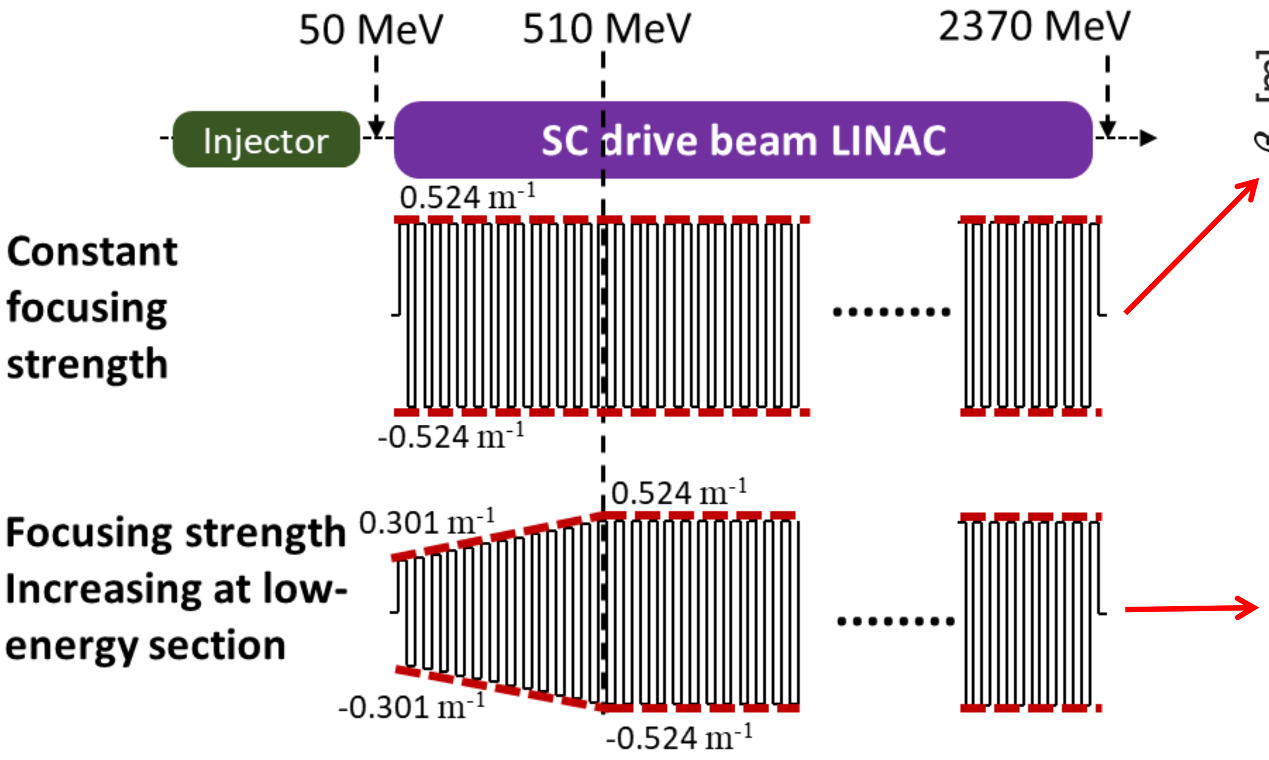
- Bunches are accelerated in different paces → large energy variation in the DB linac

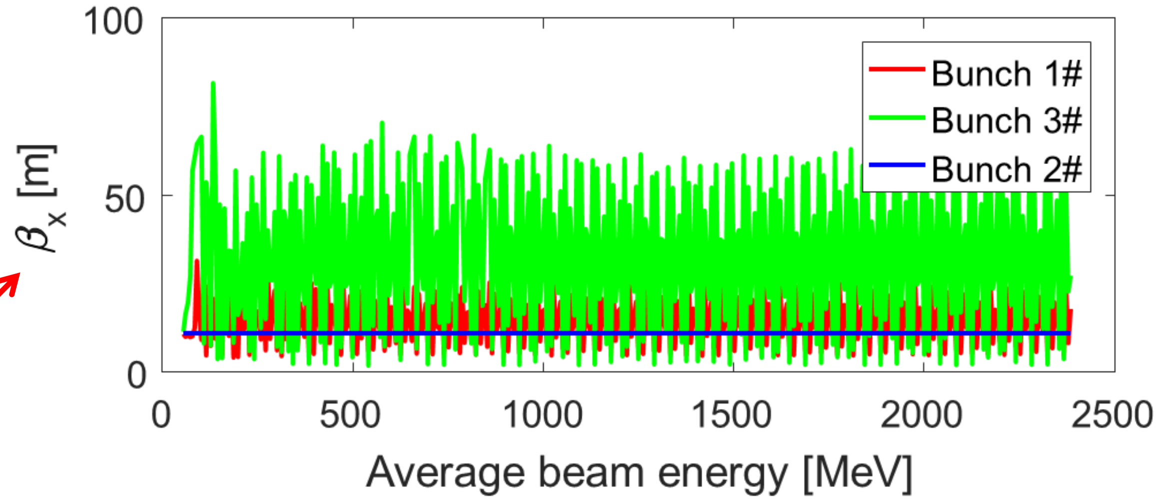


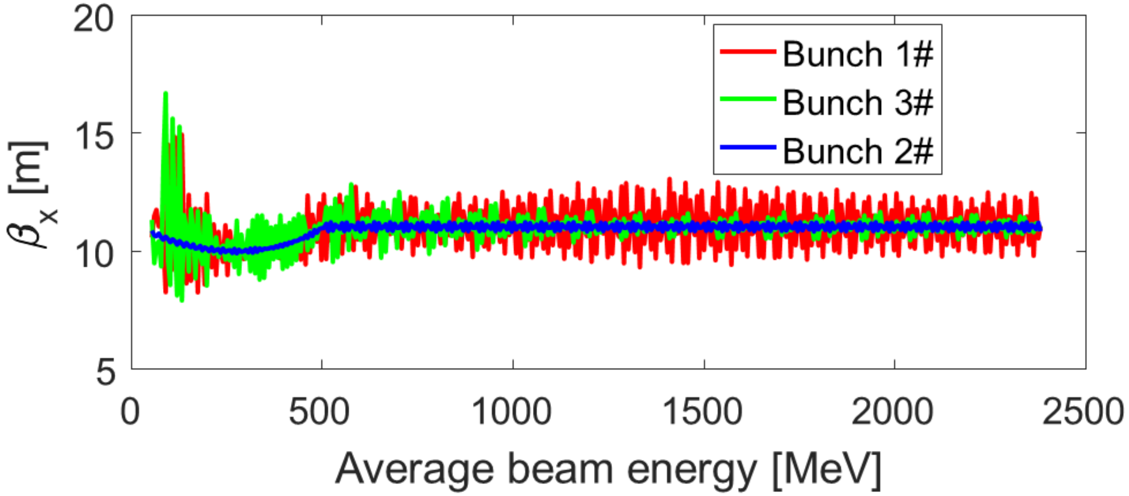


Beam dynamic & lattice design

- ➢ A dedicate lattice is designed for larger energy allowance.







Cost estimations

- SC linac design shows **a potentially lower entry cost but more expensive at later stages** than the baseline NC linac design.

Parameters	SC linacs		NC linacs	
	380 GeV	3 TeV	380 GeV	3 TeV
Number of cavities	360	2800	446	1080
Number of klystrons	45	435	446	1080
Klystron power	420 kW	420 kW	22 MW	22 MW
Length of one linac	0.67 km	2.6 km	2.0 km	2.5 km
Total AC power	52 MW	382 MW	49 MW	305 MW
Cost	0.6 BCHF	4.1 BCHF	1.2 BCHF	2.7 BCHF

Cost reduction for future developments

Nominal design:
Total = 4.1 BCHF

Cost of cryogenics

Cost of SC cavities

Cost of klystrons & other

Low frequency (500 MHz) cavity is possible to work at **4.5 K**
Assume $Q_0 = 2\times10^{10}$

→ 0.7

Increase the B-field limitation to **150 mT**, reduce the amount of cavities
(Reference: 35 MV/m ILC cavity design)

→ 1.0

Future design:
Total = 2.7 BCHF

Same as NC designs
But lower entry cost for 380 GeV stage

Summary

- The SC drive beam linac operating at CW mode has been investigated.
- A mixed-structures scheme was proposed:
  - Fundamental accelerating structure: a cosine voltage function for all bunches.
  - Harmonic correction structure: Fourier series expansion of cosine voltage function.
- Several major challenges of this scheme has been analyzed:
  - Beam-induced HOMs issue
  - Narrow cavity bandwidth
  - Beam dynamic and lattice design …
- SC drive beam linac scheme has the potential to reduce the entry cost of CLIC.
- For the final 3 TeV stage of CLIC, detailed investigation and breakthrough on the SC cavities should be realized in the future.

Thanks for your attention!