# First Thoughts on Operation of CLIC 3TeV at lower energies

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# Luminosity and Background Values

| | | CLIC(cons) | CLIC(nom) | CLIC(cons) | CLIC | CLIC(vo) | ILC | NLC |
|---|---|---|---|---|---|---|---|---|
| $E_{cms}$ | $[TeV]$ | 0.5 | 0.5 | 3.0 | 3.0 | 3.0 | 0.5 | 0.5 |
| $f_{rep}$ | [Hz] | 50 | 50 | 50 | 50 | 100 | 5 | 120 |
| $n_b$ | | 354 | 354 | 312 | 312 | 154 | 2820 | 190 |
| $\sigma_x$ | $[nm]$ | 248 | 202 | 83 | 40 | 40 | 655 | 243 |
| $\sigma_y$ | $[nm]$ | 5.7 | 2.26 | 1 | 1 | 1 | 5.7 | 3 |
| $\Delta t$ | $[ns]$ | 0.5 | 0.5 | 0.5 | 0.5 | 0.67 | 340 | 1.4 |
| $N$ | $[10^9]$ | 6.8 | 6.8 | 3.7 | 3.7 | 4.0 | 20 | 7.5 |
| $\epsilon_x$ | $[\mu m]$ | 3.0 | 2.4 | 2.4 | 0.66 | 0.68 | 10 | 3.6 |
| $\epsilon_y$ | $[nm]$ | 40 | 25 | 20 | 20 | 10 | 40 | 40 |
| $\beta_x$ | $[mm]$ | 10 | 8 | 8 | 4 | 7 | 21 | 8 |
| $\beta_y$ | $[mm]$ | 0.4 | 0.1 | 0.1 | 0.07 | 0.09 | 0.4 | 0.11 |
| $L_{total}$ | $10^{34} cm^{-2} s^{-1}$ | 0.88 | 2.3 | 2.7 | 5.9 | 10.0 | 2.0 | 2.0 |
| $L_{0.01}$ | $10^{34} cm^{-2} s^{-1}$ | 0.58 | 1.4 | 1.3 | 2.0 | 3.0 | 1.45 | 1.28 |
| $n_\gamma$ | | 1.1 | 1.3 | 1.2 | 2.2 | 2.3 | 1.30 | 1.26 |
| $\Delta E/E$ | | 0.045 | 0.07 | 0.13 | 0.29 | 0.31 | 0.024 | 0.046 |
| $N_{coh}$ | $10^5$ | $10^{-4}$ | $10^{-3}$ | $5 \times 10^2$ | $3.8 \times 10^3$ | ? | — | — |
| $E_{coh}$ | $10^3 TeV$ | 0.001 | 0.015 | $4 \times 10^4$ | $2.6 \times 10^5$ | ? | — | — |
| $n_{incoh}$ | $10^6$ | 0.03 | 0.08 | 0.11 | 0.3 | ? | 0.1 | n.a. |
| $E_{incoh}$ | $[10^6 GeV]$ | 0.14 | 0.36 | 7.2 | 22.4 | ? | 0.2 | n.a. |
| $n_\perp$ | | 8 | 20.5 | 19 | 45 | 60 | 28 | 12 |
| $n_{had}$ | | 0.07 | 0.19 | 0.75 | 2.7 | 4.0 | 0.12 | 0.1 |

# Options

- Extraction at low energy
  - but need extraction and bypass lines
  - compromises fill factor and tunnel design or requires significant hardware intervention
- Remove the end of the linac
  - go down from $3\,\mathrm{TeV}$ by removing the end of the linac
  - one way option

$\Rightarrow$ For both of these solutions charge remains unchanged

- We use a lower gradient ($G = G_0 E/E_0$)
  - constant gradient along the linac

    $\Rightarrow$ charge needs to be proportional to gradient
- We reduce the gradient in a part of the linac
  - higher gradient initially

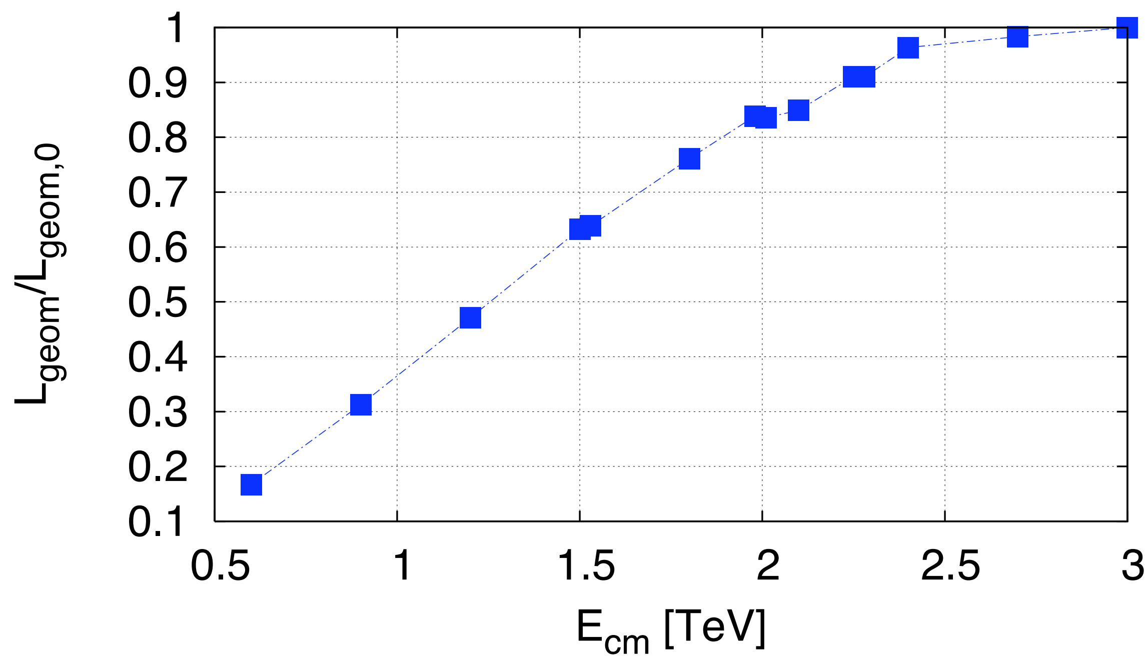
  $\Rightarrow$ charge can be somewhat higher but use full power

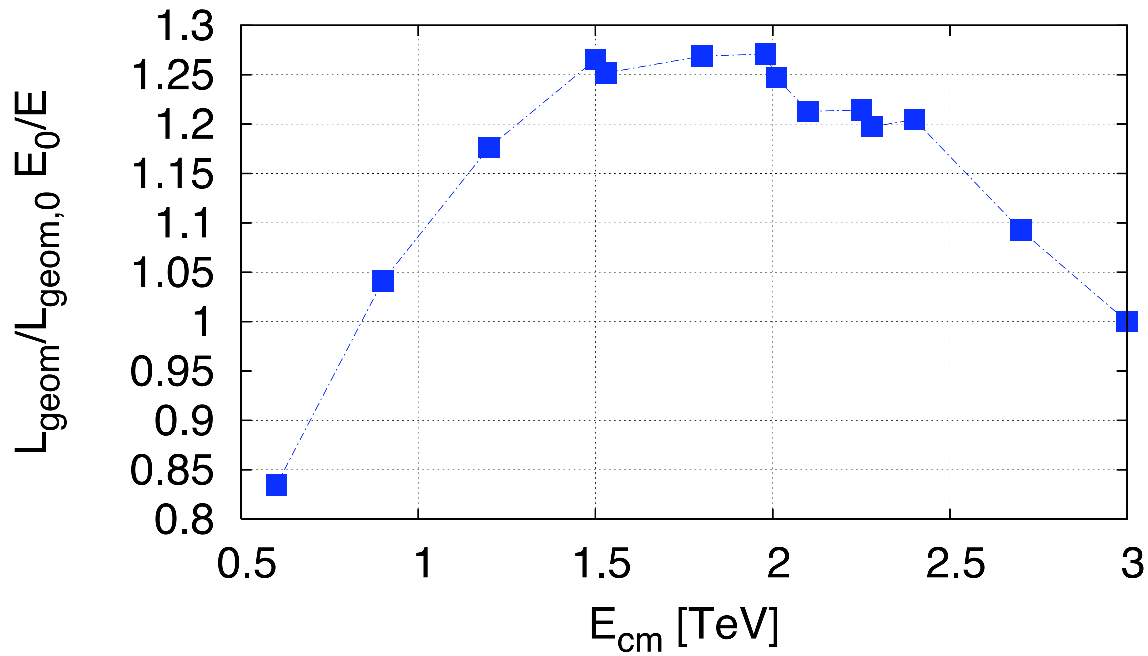
# Luminosity for Constant Charge

- BDS magnetic fields scaled
  - final double needs to be exchanged for changes of more than $\approx 10\%$
- Geometric luminosity (for constant charge) does not decrease linearly

$\Rightarrow$ Need to understand reason

  - could be improvement of BDS performance due to reduce radiation at lower energy



# Gradient and Bunch Charge

- Scaling $N/N_0 = G/G_0$ and $\sigma_z = \mathrm{const}$ keep the relative energy spread $\delta(s)$ constant
- We require BNS damping for beam stability

$$\delta(s) \approx \beta_1^2(s)\frac{Ne^2W_\perp}{E(s)}$$

- Emittance growth due to dispersive imperfections scales as

$$\Delta\epsilon_y \propto \left(\frac{\sigma_E}{E}\Delta y\right)^2$$

$\Rightarrow$ independent of $G$, for our scaling

- Emittance growth due to wake fields scales as

$$\Delta\epsilon_y \propto \left(\frac{NW_\perp(2\sigma_z)}{E}\Delta y\right)^2 E$$

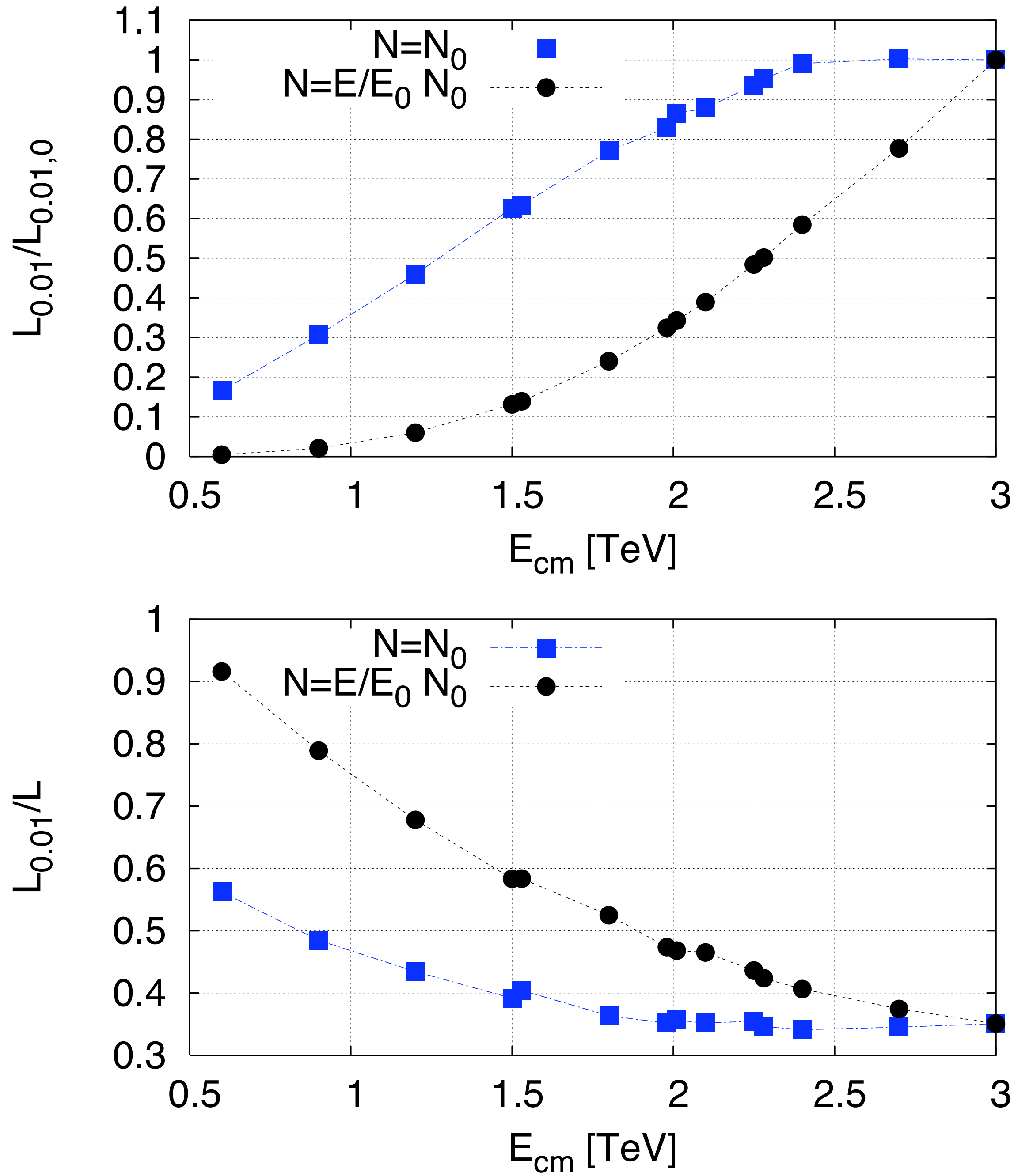
$\Rightarrow$ improves with smaller $G$, for our scaling

# Total Luminosity with Gradient Change

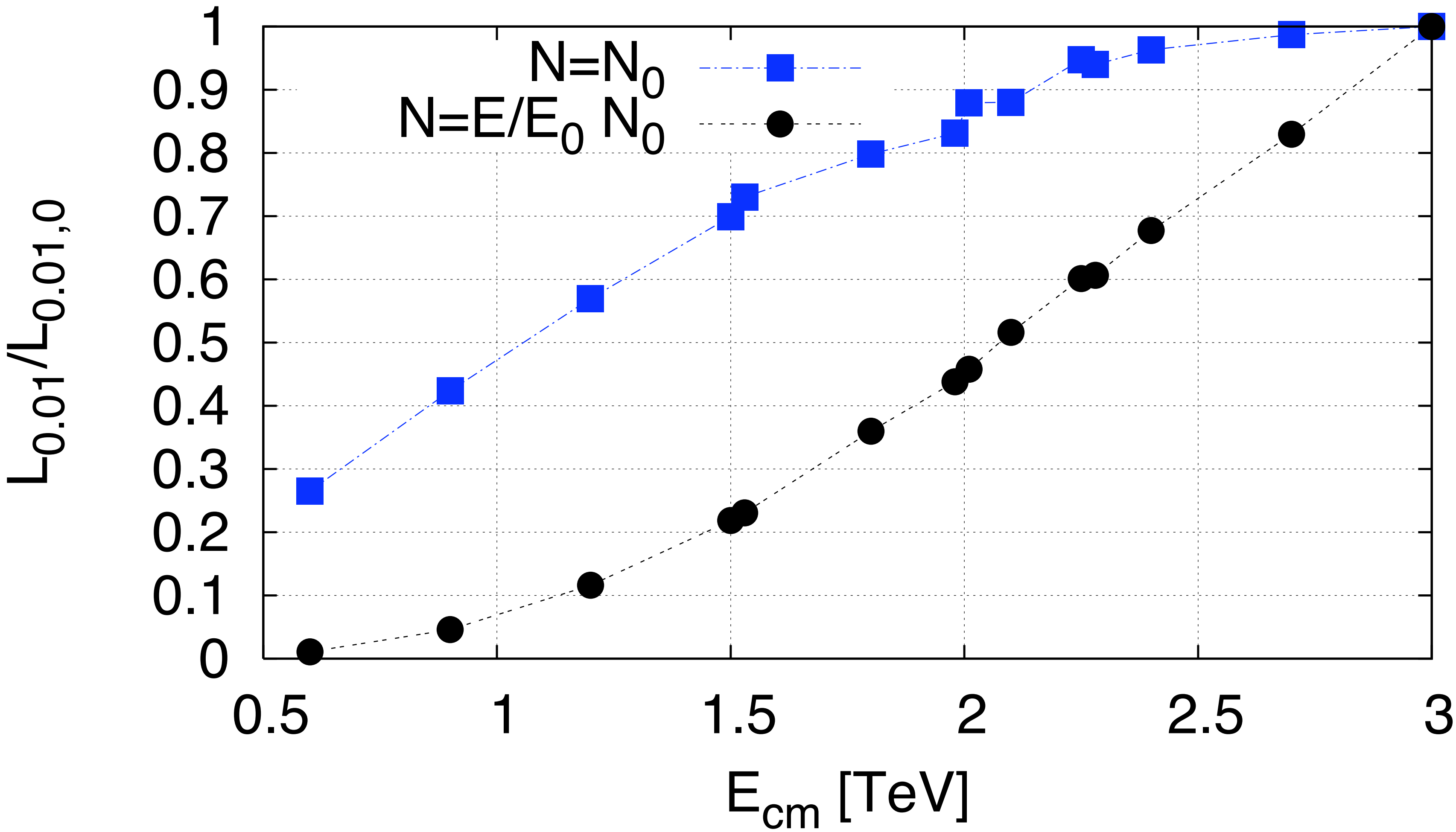
- Significant luminosity loss due to charge reduction

$\Rightarrow$ Need to compensate

- Spectrum improves with lower energy
  - in particular for reduced charge



Luminosity in Peak with Gradient Change



# Mitigation Strategies

- Change structure design to increase bunch charge for $3\,\mathrm{TeV}$
  - less luminosity loss for lower energies
  - but need to compromise $3\,\mathrm{TeV}$ performance
  - first indication is that this would be serious (A. Grudiev)
- Increase repetition frequency of drive beam
  - but what about beam dynamics and klystrons
- Increase pulse length
  - but pulse length is built into the geometry of CLIC

# Drive Beam Acceleration

- Constant final energy

  ⇒ many beam dynamics issues improve relative apertures remain the same
- Final energy scaled as the current

  ⇒ beam dynamics issues remain the same relative apertures become worse

- Effective gradient in DBA

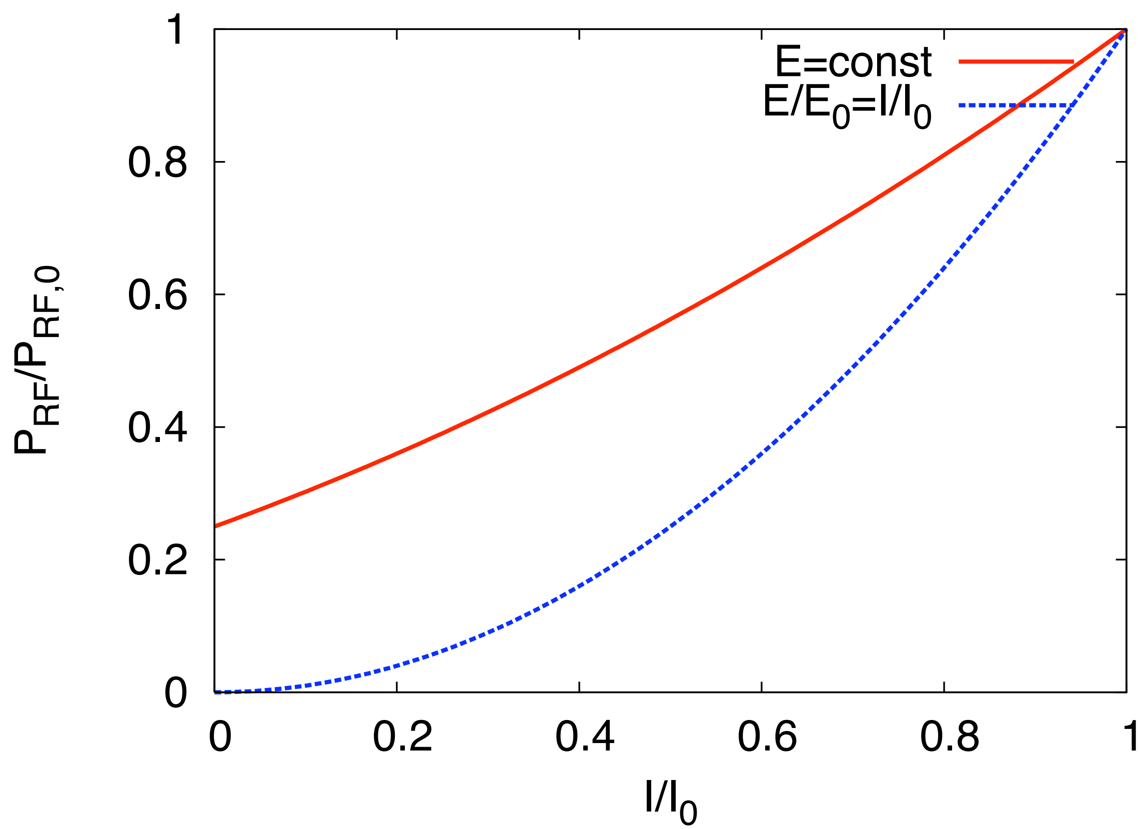
$$\frac{G}{G_0} = 2\sqrt{\frac{P_{RF}}{P_{RF,0}}} - \frac{I}{I_0}$$

- For constant final energy

$$\frac{P_{RF}}{P_{RF,0}} = \left(\frac{1+\frac{I}{I_0}}{2}\right)^2$$

- For $E/E_0 = I/I_0$

$$\frac{P_{RF}}{P_{RF,0}} = \left(\frac{I}{I_0}\right)^2$$




⇒ If we want to increase repetition frequency in steps of $50\,\mathrm{Hz}$ can go to $100\,\mathrm{Hz}$ at $E_{cm} \approx 1.2\,\mathrm{TeV}$

# Comments on Klystron Power and Pulse Rate

- In principle could hope to increase repetition frequency up to

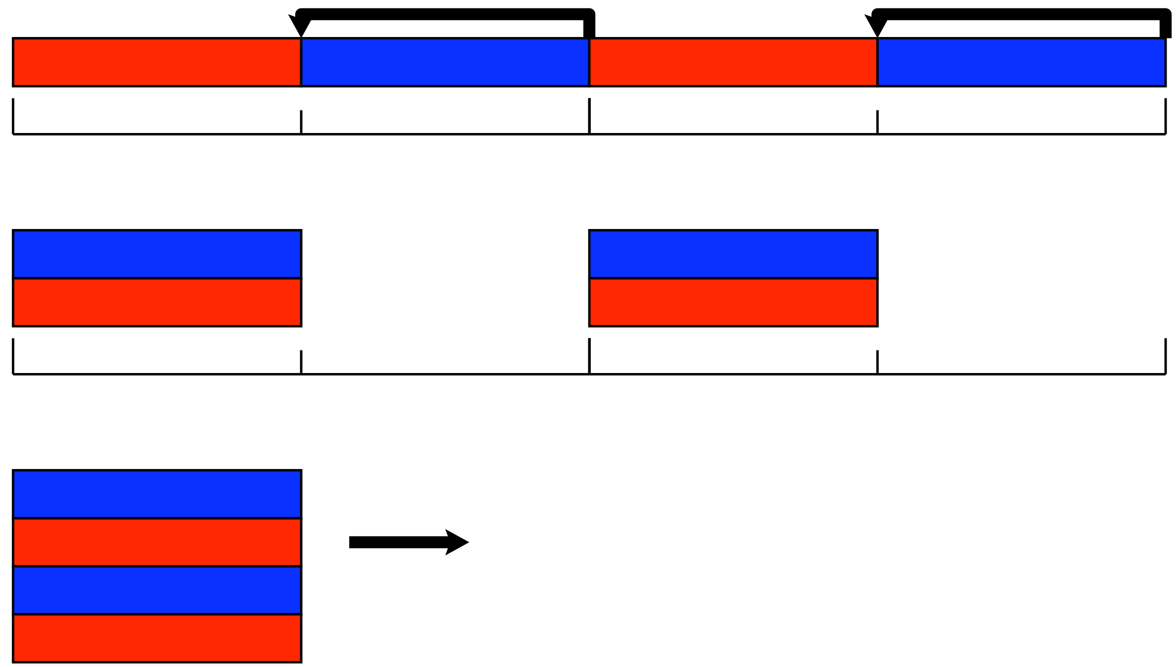
$$f_{rep} = f_{rep,0} \left(\frac{G_0}{G}\right)^2 \frac{\eta}{\eta_0}$$

- But klystron efficiency goes down for lower output power
- But should only run at multiples of $50\,\mathrm{Hz}$
- Igor Syratchev estimates that we can expect to run at 120Hz at a quarter of the nominal power

  $\Rightarrow$ does not work if we run with full drive beam energy

  $\Rightarrow$ could give factor two at $1.5\,\mathrm{GeV}$ if drive beam energy is reduced
- Could improve this by new klystron design (E. Jensen, I Syratchev)
  - but needs exploration
- Also need to check that we can achieve stable beam

# Pulse Length



- The pulse length is defined by the geometry of the accelerator

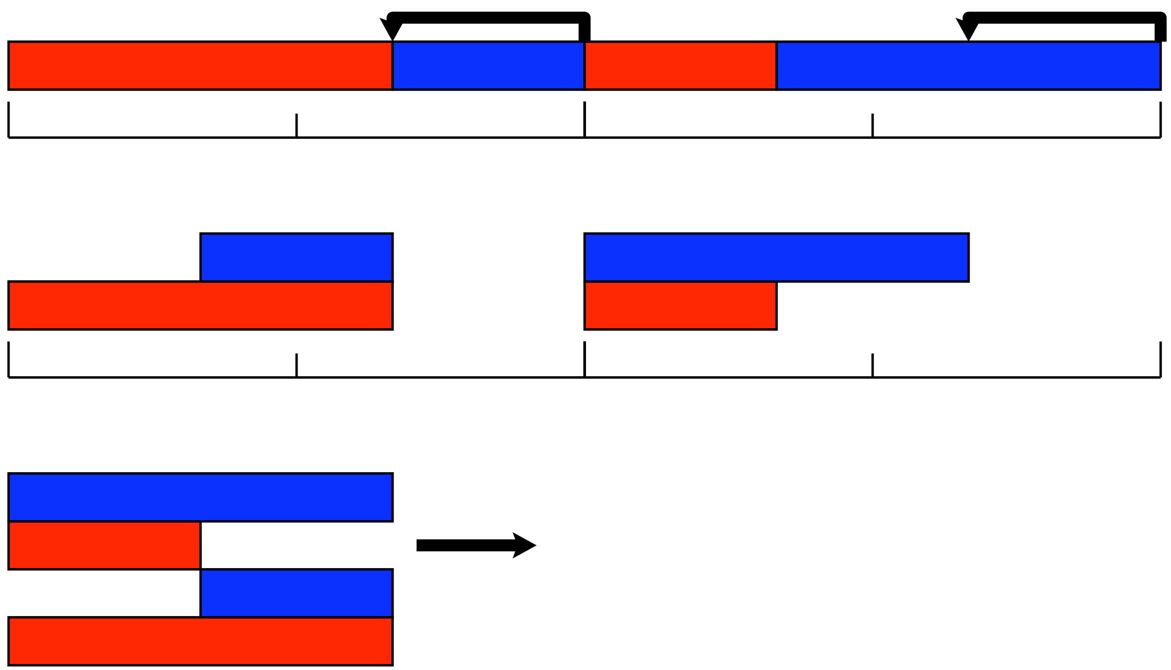
  ⇒ cannot change it arbitrarily

# Pulse Length

- Well, some bird triggered an idea
  - With small modification of delay loop we can change the combination factor and increase the pulse length
  - Can accept longer pulses in main linac since the power is lower
    - strongest constraint from temperatur $P\sqrt{\tau} \leq P_0\sqrt{\tau_0}$
  - For $G/G_0 \leq 3/4$ can use upper scheme

    $\Rightarrow 80\,\mathrm{ns}$ longer pulse

    $\Rightarrow 160$ extra bunches per train



# Pulse Length (cont.)

- For $G/G_0 \leq 2/3$ can use lower scheme

  $\Rightarrow$ $120\,\mathrm{ns}$ longer pulse

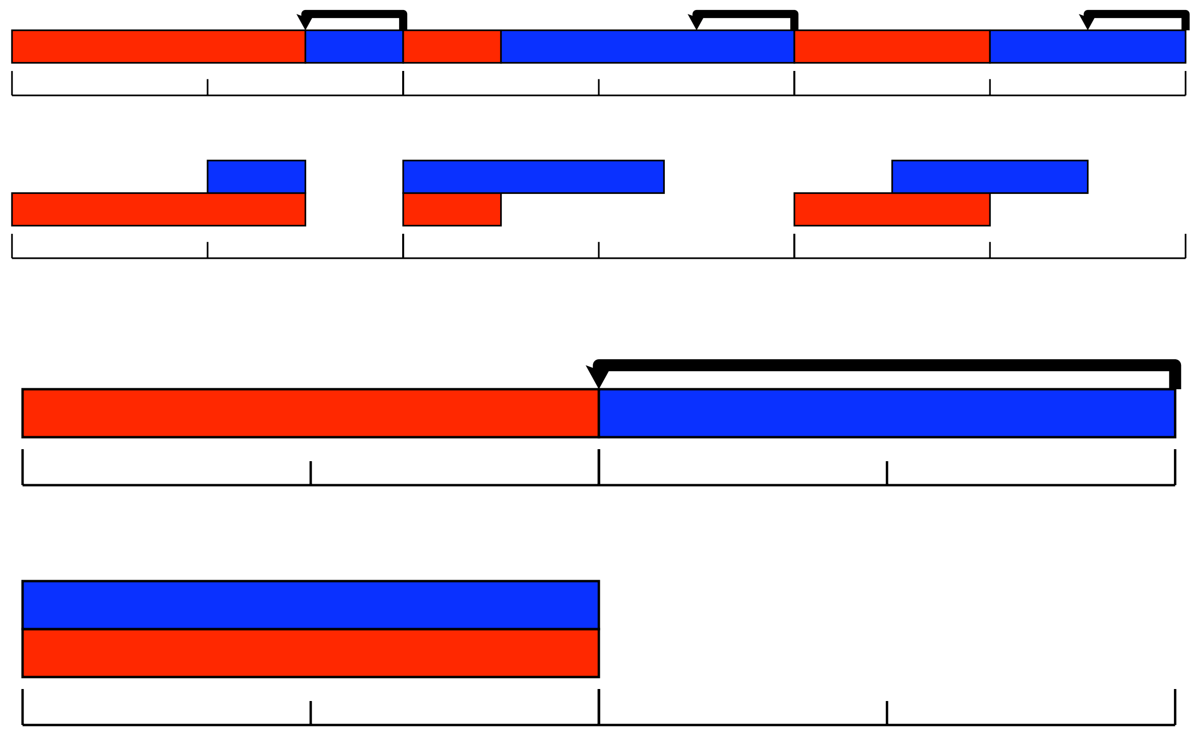
  $\Rightarrow$ $240$ extra bunches per train

- For $G/G_0 \leq 1/2$ can use lower scheme

  - need to modifiy first combiner ring
  - could consider using larger combiner ring with double pulses as baseline

  $\Rightarrow$ $240\,\mathrm{ns}$ longer pulse

  $\Rightarrow$ $480$ extra bunches per train



- Other options should be investigated

# Conclusion

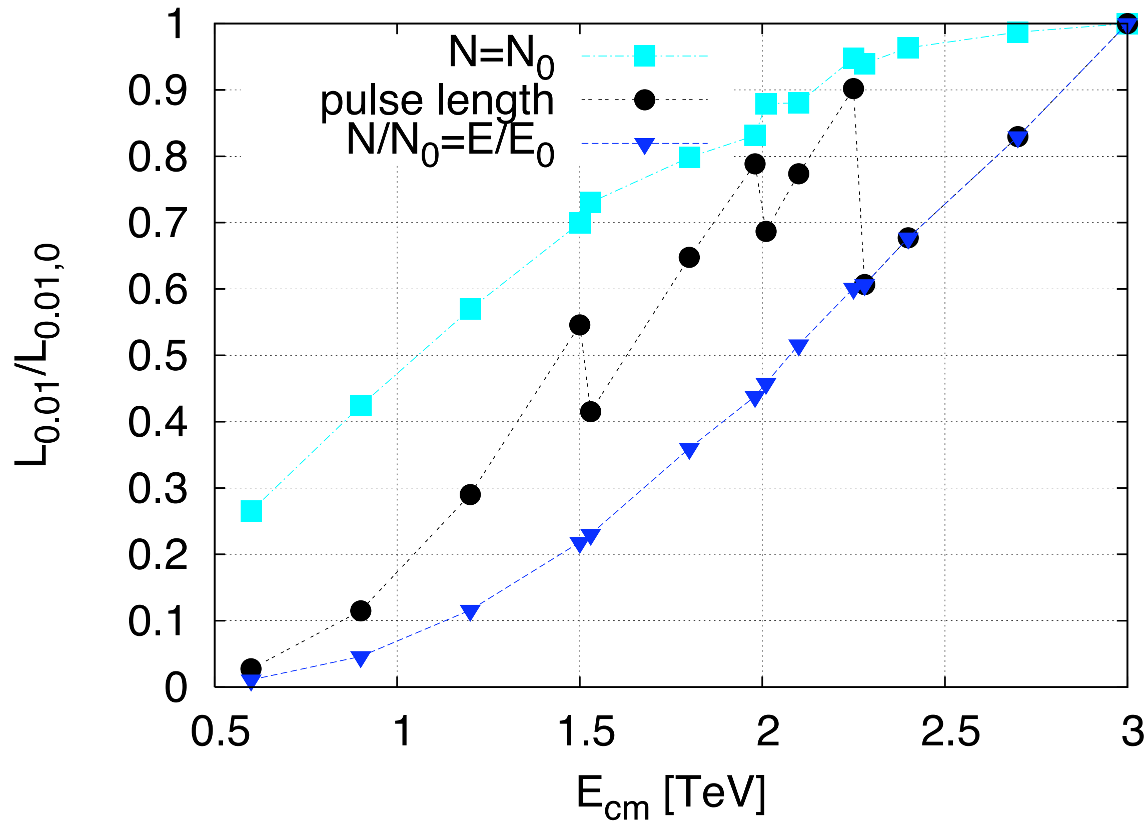
⇒ Luminosity is improved using longer pulses

⇒ This appears practical

- but need to check that we did not miss a problem

⇒ Other options need more work

- RF experts
- physics
- beam dynamics




- Attempted only to improve down to 1.5 $\mathrm{TeV}$
- We will work on further improvements
- Background reduced at lower energies, e.g. $n_H = 0.16$ at $1.5\,\mathrm{TeV}$

# Outlook and Questions to Answer

- How much is the klystron efficiency affected if we change the repetition frequency and power?
  - Is this acceptable in all subsystems?
  - Can we tolerate the lower drive beam energy?
- Can we change the pulse length?
  - Can the subsystems handle longer bunch trains?
  - The bunch charge would be lower, e.g. 800 bunches with half the charge
- How much do we compromise the $3\,\mathrm{TeV}$ performance if we increase $a/\lambda$?
- For optimisation need more input from experiments, minimise

$$\sum_i \frac{\int \mathcal{L}(s)dt}{\mathcal{L}(s)}$$

- To which energy do we need to go?