Low Energy Running for CLIC

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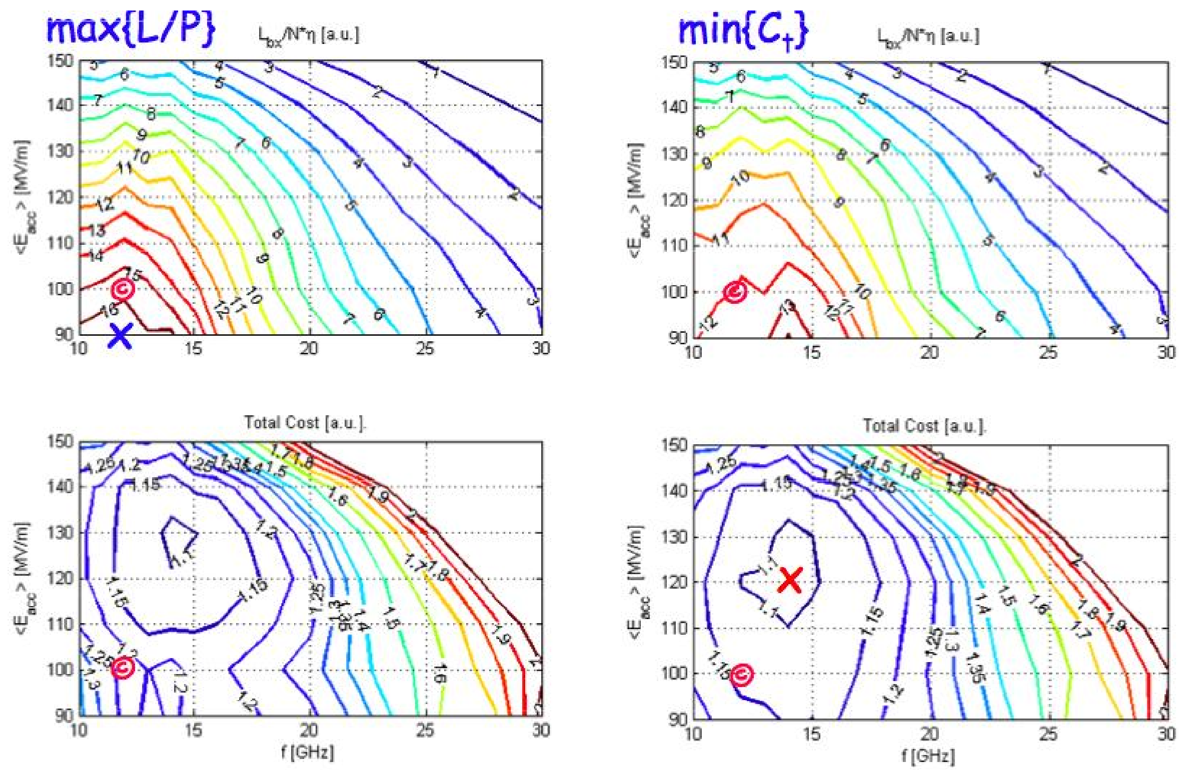
Introduction

- Luminosity below $3\,\mathrm{TeV}$ is also important
- Two strategies to adress this
  - build a lower centre-of-mass energy machine first
    $\Rightarrow$ energy staging
  - operate the $3\,\mathrm{TeV}$ CLIC at lower energies
    $\Rightarrow$ energy scan capability
- The energy scan capability is also import if one first needs to identify the interesting energy
- For CLIC, we do not yet have a full energy staging
  - but a conceptual design for $500\,\mathrm{GeV}$ based on the $3\,\mathrm{TeV}$
- We also developed an energy scan concept for $3\,\mathrm{TeV}$

Reminder: 3 TeV Design

- The 3 TeV design has been fully optimised for cost
- Limits were taken into account from
  - accelerating RF structures
  - beam physics
- The power efficiency is very high for the final parameter set
- Further improvements might be possible as studies continue



Rational for CLIC 500 GeV Design

- The energy has been picked as an example
  - should eventually design for specific energy (e.g. 350 GeV for Higgs+top)
- The parameter choice for 500 GeV has been performed as for 3 GeV
  - but less information available in the moment (e.g. no cost model)

  $\Rightarrow$ more work is required for further optimisation
- The 500 GeV design has been made
  - keeping the upgrade to 3 TeV in mind
    - e.g. constant RF pusle length, so drive beam complex can be re-used
  - but not optimising the cost of the staged approach
  - not even fully optimising the cost of the 500 GeV

Parameters for $500\,\mathrm{GeV}$

- Upgrade has been repected by
  - keeping RF pulse length constant
  - using similar power per structure

  $\Rightarrow$ so CLIC drive beam components can be re-used for $3\,\mathrm{TeV}$
- Some parameters have been modified to ease requirements
  - larger horizontal beam emittances, to ease damping ring requirements
  - we aimed for better luminosity spectrum than at $3\,\mathrm{TeV}$ (comparable to ILC)

  $\Rightarrow$ the optimisation drives toward larger bunch charges
- Optimisation yielded
  - lower main linac gradient($80\,\mathrm{MV/m}$)
  - larger bunch charge
  - slightly more bunches per train

parameter	units	CLIC	CLIC	ILC (RDR)
E_{cms}	$[\mathrm{TeV}]$	0.5	3.0	0.5
f_{rep}	$[\,\mathrm{Hz}]$	50	50	5
n_b		354	312	2625
σ_x	$[\mathrm{nm}]$	202	40	655
σ_y	$[\mathrm{nm}]$	2.26	1	5.7
Δt	$[\mathrm{ns}]$	0.5	0.5	369
N	$[10^9]$	6.8	3.7	20
ϵ_x	$[\mu\mathrm{m}]$	2.4	0.66	10
ϵ_y	$[\mathrm{nm}]$	25	20	40
β_x	$[\mathrm{mm}]$	8	4	21
β_y	$[\mathrm{mm}]$	0.1	0.07	0.4
L_{total}	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9	2.0
$L_{0.01}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.4	2.0	1.45
n_γ		1.3	2.2	1.3

Beam-Beam Effects and Background

- Luminosity and luminosity spectrum are comparable to ILC
- Background is reduced
  - coherent pairs virtually disappear
  - hadronic events comparable to ILC
  - incoherent pairs comparable to ILC

parameter	units	CLIC	CLIC	ILC (RDR)
E_{cms}	[TeV]	0.5	3.0	0.5
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n_γ		1.3	2.2	1.3
$\Delta E/E$		0.07	0.29	0.024
N_{coh}	$[10^5]$	10^{-3}	3.8×10^3	—
E_{coh}	$[10^3\ \mathrm{TeV}]$	0.015	2.6×10^5	—
n_{incoh}	$[10^6]$	0.08	0.3	0.1
E_{incoh}	$[10^6\mathrm{GeV}]$	0.36	22.4	0.2
$n_\perp$		20.5	45	28
n_{had}		0.19	2.7	0.12

Draft Physics Request for Energy Scan

- Applies to CLIC at $3\,\mathrm{TeV}$
- Run at full energy first, based on the results then run at lower energy
- Operation at lower energies with
  - luminosity in peak 60% of the value at $1.5\,\mathrm{TeV}$
  - luminosity in peak 40% of the value at $1\,\mathrm{TeV}$
- At each energy one must be able to perform scans with limited range
- Here, we will focus on large energy variations
  - assuming runs are for some months, so setup time is not too important
  - with limited hardware modification at the time of energy change, i.e. final doublet may need to be exchanged to increase aperture
- Note: small scans can be performed by tuning magnets strengths and RF

Options to Change Beam Energy

- Why not just change the gradient and keep the other beam parameters?

  - we push the beam current at $3\,\mathrm{TeV}$ as much as we dare

  $\Rightarrow$ at lower energy the beam is not stable

  $\Rightarrow$ the beam energy spread will be larger

- So options are

  1) extract beam at low energy

  2) remove the end of the linac (so you better do not want to go up again)

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

  3) use a lower gradient ($G = G_0 E/E_0$)

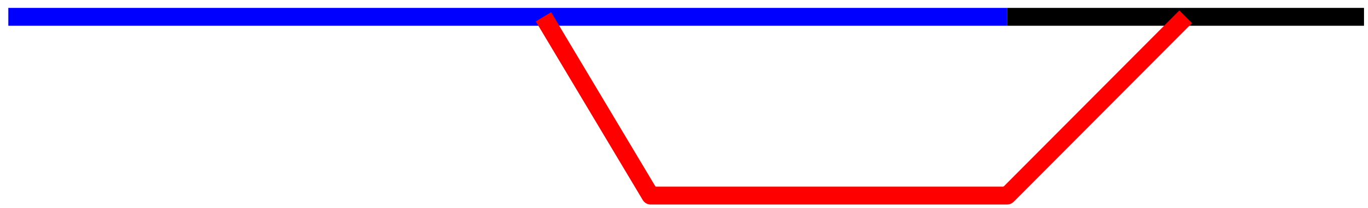
  - adjust the bunch charge

  4) reduce the gradient in the second part of the linac or even decelerate

  - wastes power

Extraction at Low Energy

- Can extract the beam at low energy with a dog-leg



- Extraction points can be built in from the beginning
  - need several extraction points
  - loose length for each extraction point (F. Stulle: example design about 200 m at 500 GeV)
  - need space for the transport line for the low energy beam
  - local change of fill factor impacts drive beam cost/efficiency

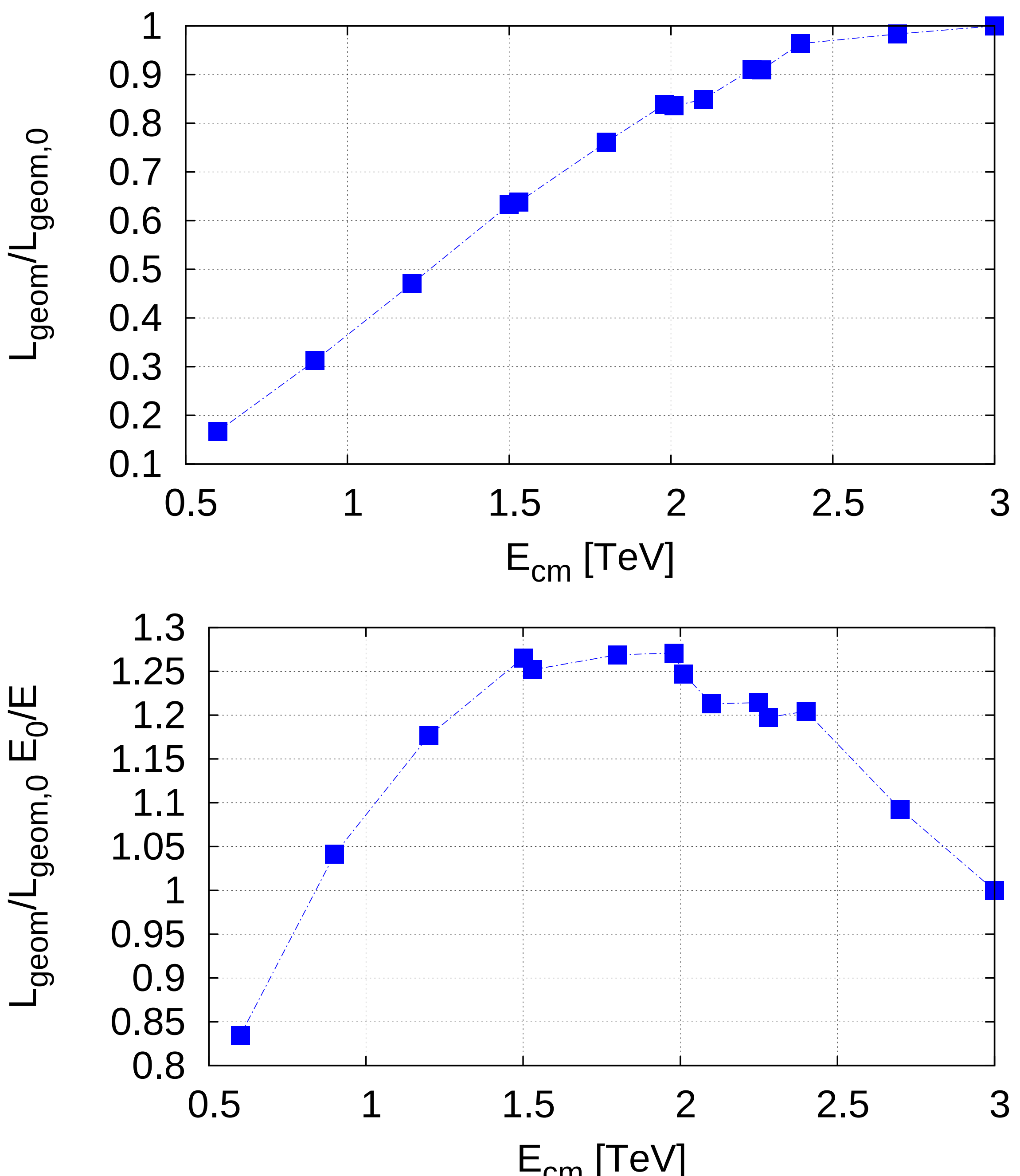
$\Rightarrow$ this option can be considered if the cost is acceptable

- installation after construction not excluded but not nice

Luminosity for Low Energy Extraction

- Use Rogelio's $3\,\mathrm{TeV}$ BDS
- BDS magnetic fields scaled
  - final double most likely needs to be exchanged for changes of more than $\approx 10\%$
  - allows to have larger aperture
- To first order expect linear decrease of luminosity with energy

  $\Rightarrow$ see slightly better performance at medium energies
  - most likely due to reduced radiative effects



Gradient Reduction

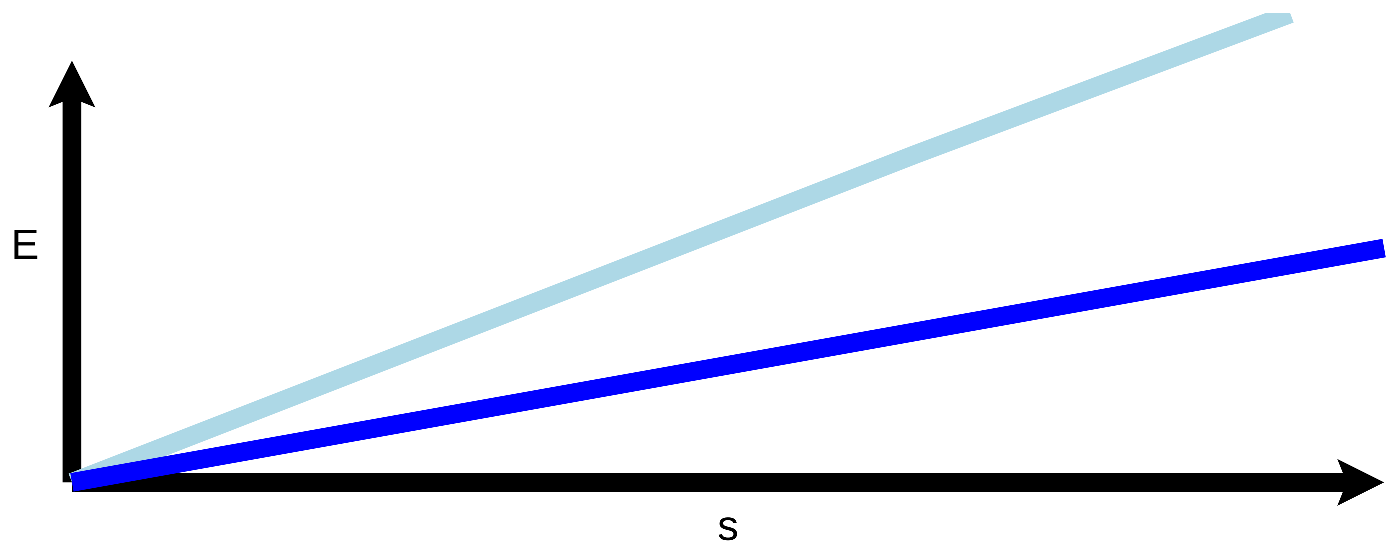
- We can use a lower accelerating gradient ($G \approx G_0 E/E_0$)
  - constant gradient along the linac

  $\Rightarrow N/N_0 = G/G_0$ ensures constant beam stability

$$\frac{\Delta y'}{\sigma_{y'}} \propto \frac{N\sigma_y}{E}\frac{1}{\sigma_{y'}} \propto \frac{N\beta}{E}$$

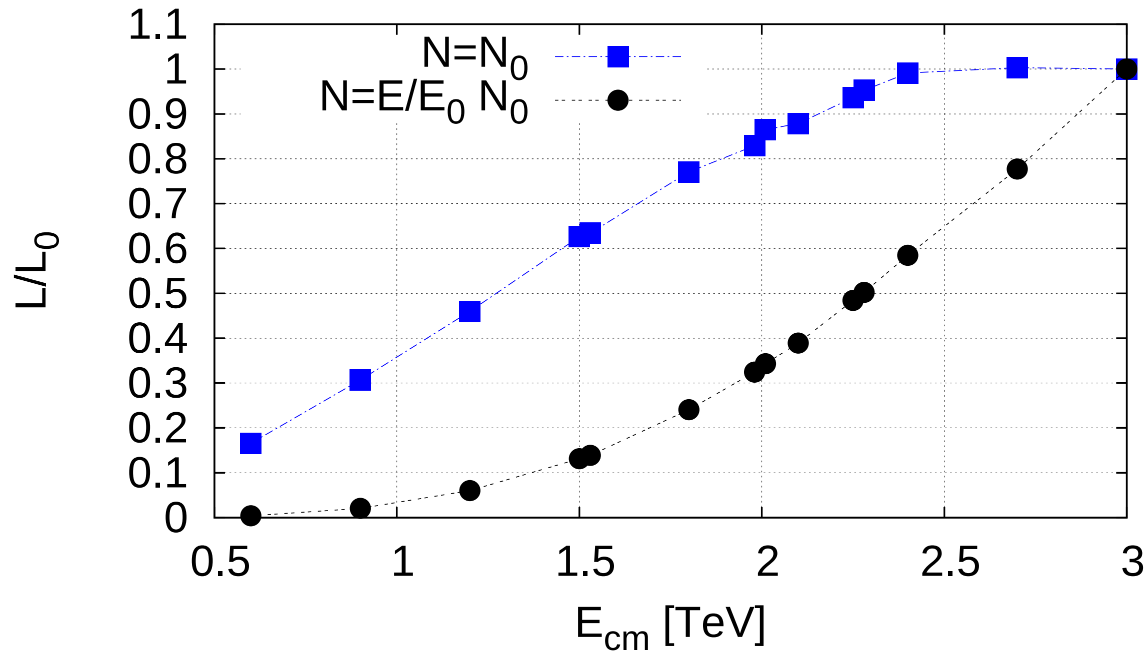
  - can keep BDS apertures constant, but could profit further from larger final quadrupole aperture

  $\Rightarrow$ static imperfections will be less severe $\Rightarrow$ slight gain in emittances



- This is our baseline option

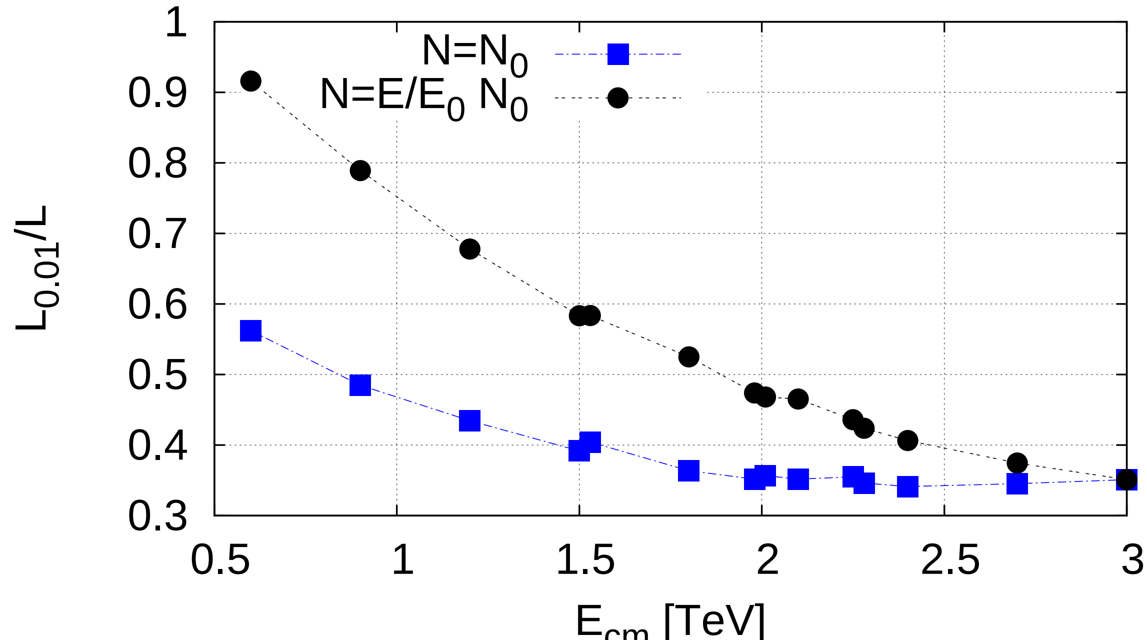
Total Luminosity



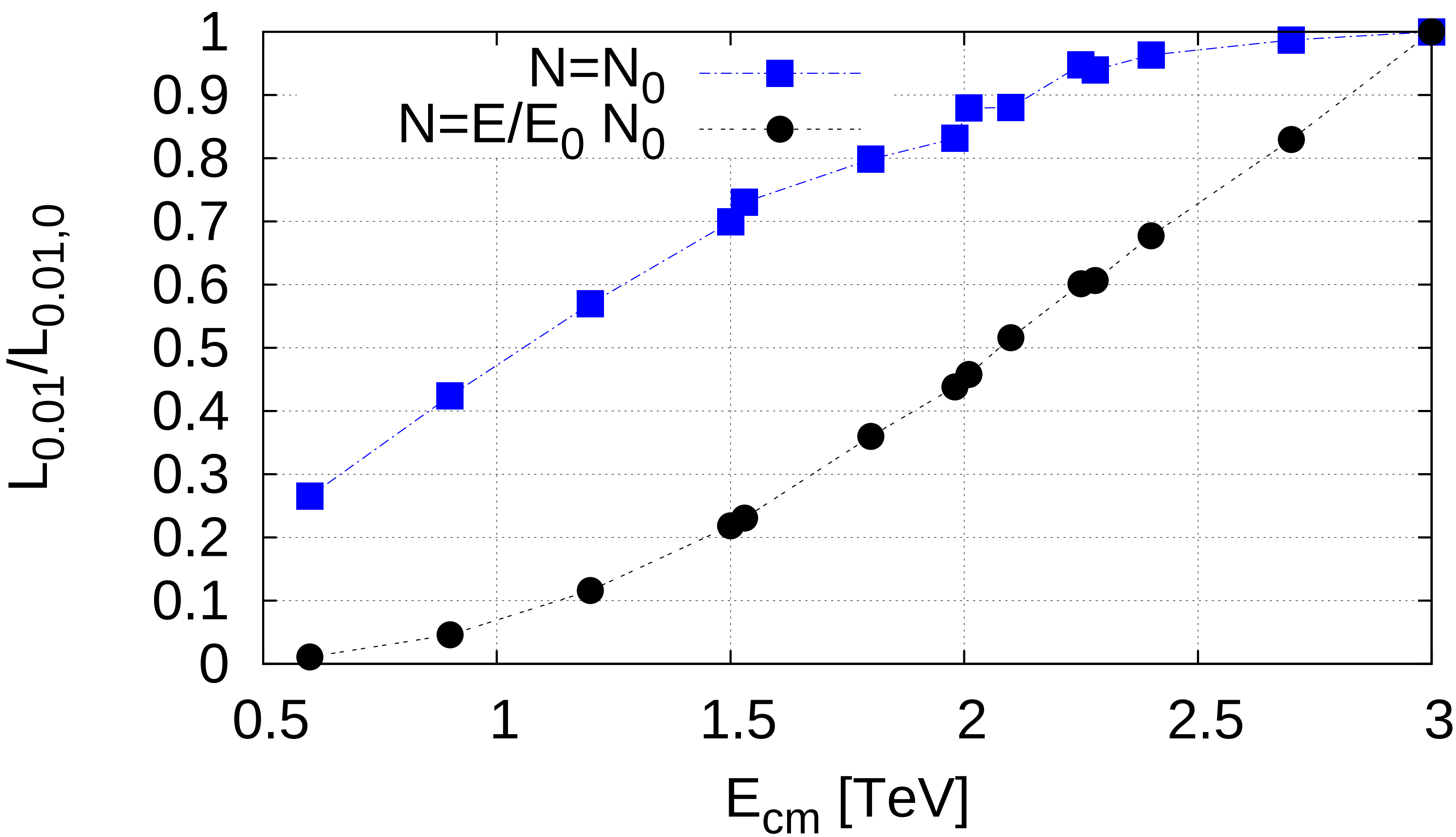
- Significant luminosity loss due to charge reduction

⇒ Need to compensate

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



Luminosity in Peak



Gradient Reduction and Luminosity Recovery Strategy

- The gradient is reduced by reducing the drive beam current via

  a) reducing the bunch charge

  $\Rightarrow$ can increase repetition rate

  b) reducing the number of bunches per unit time

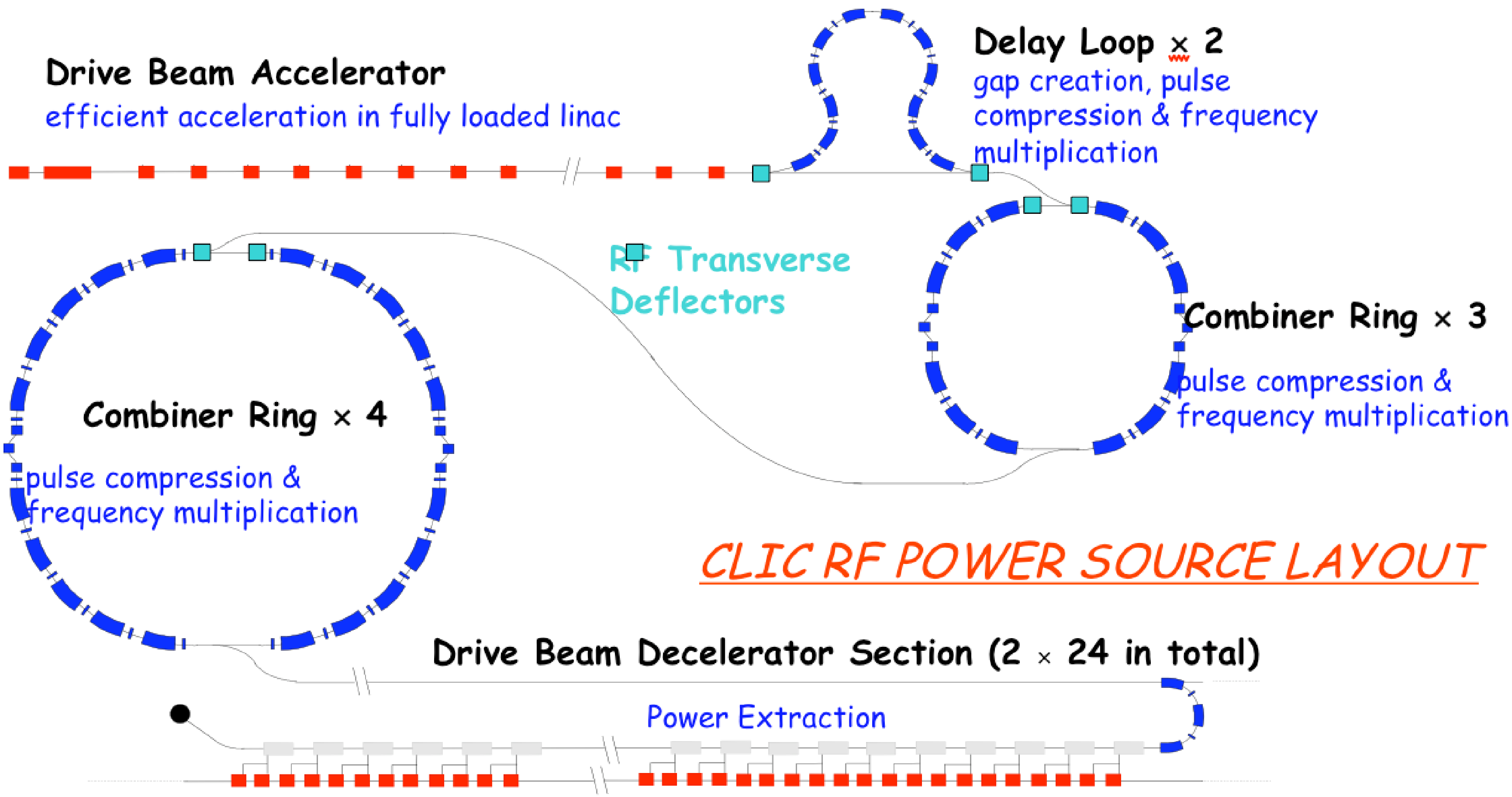
  $\Rightarrow$ can increase main beam pulse length

  c) using the on/off mechanism

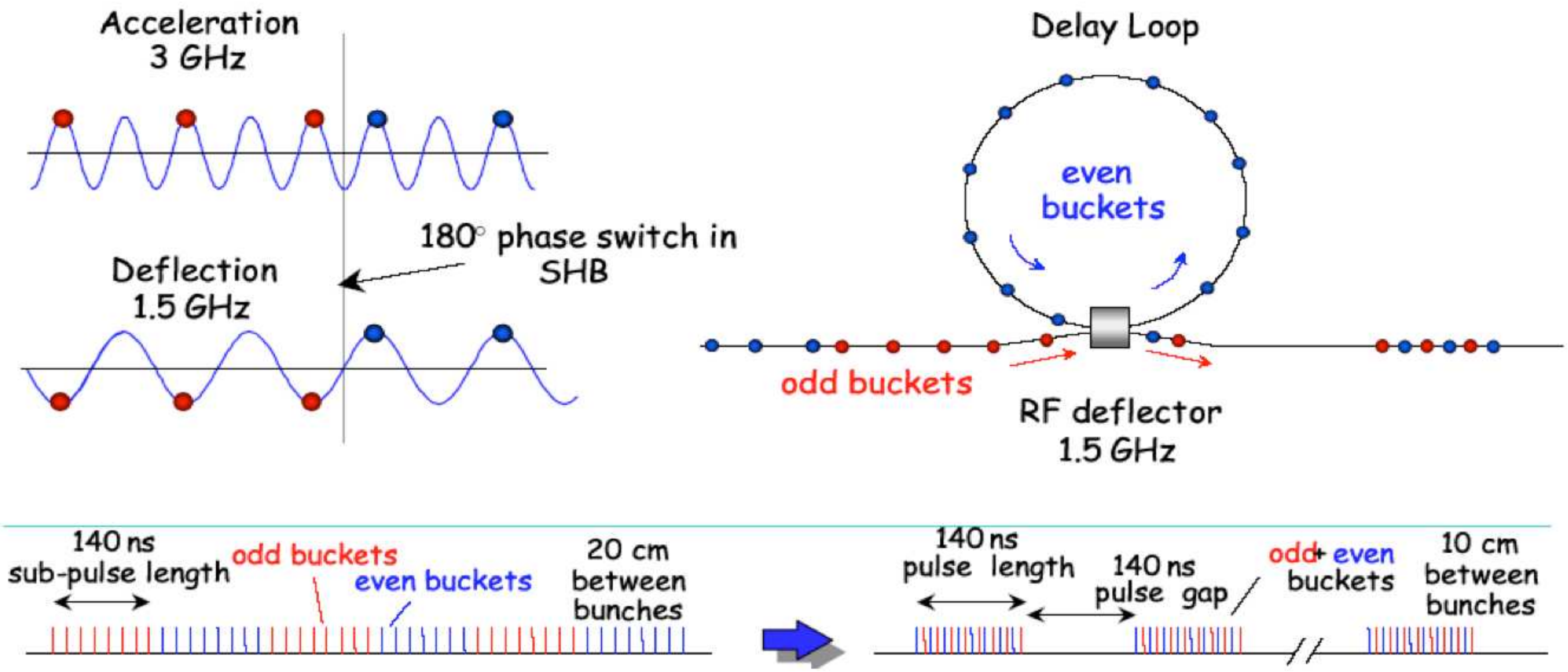
- c) is used for fine-tuning but would waste power $\Rightarrow$ ignore it

- We use a) as a baseline, option b) is studied as an alternative

Pulse Length Variation: Drive Beam Scheme

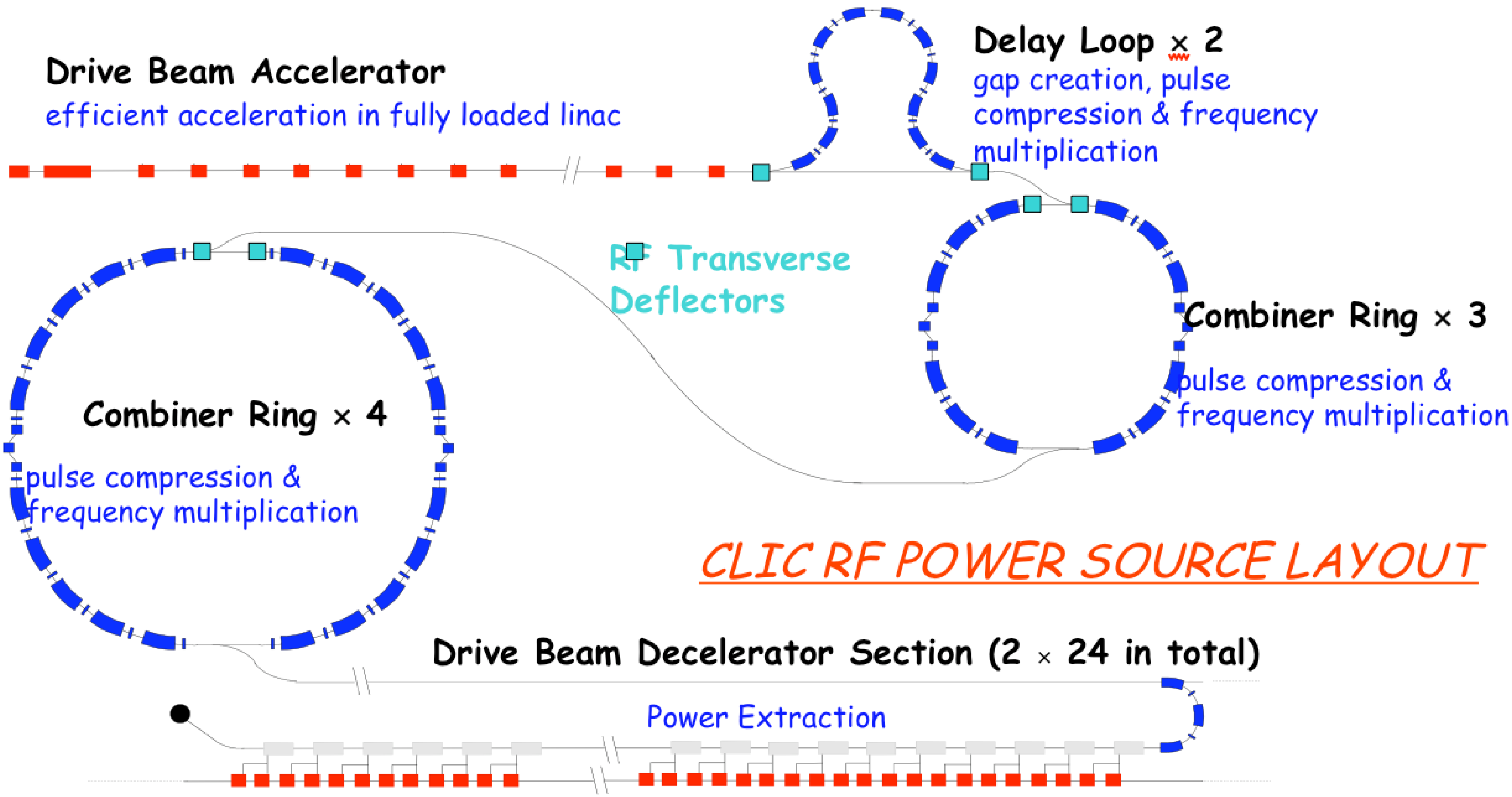


Delay Loop

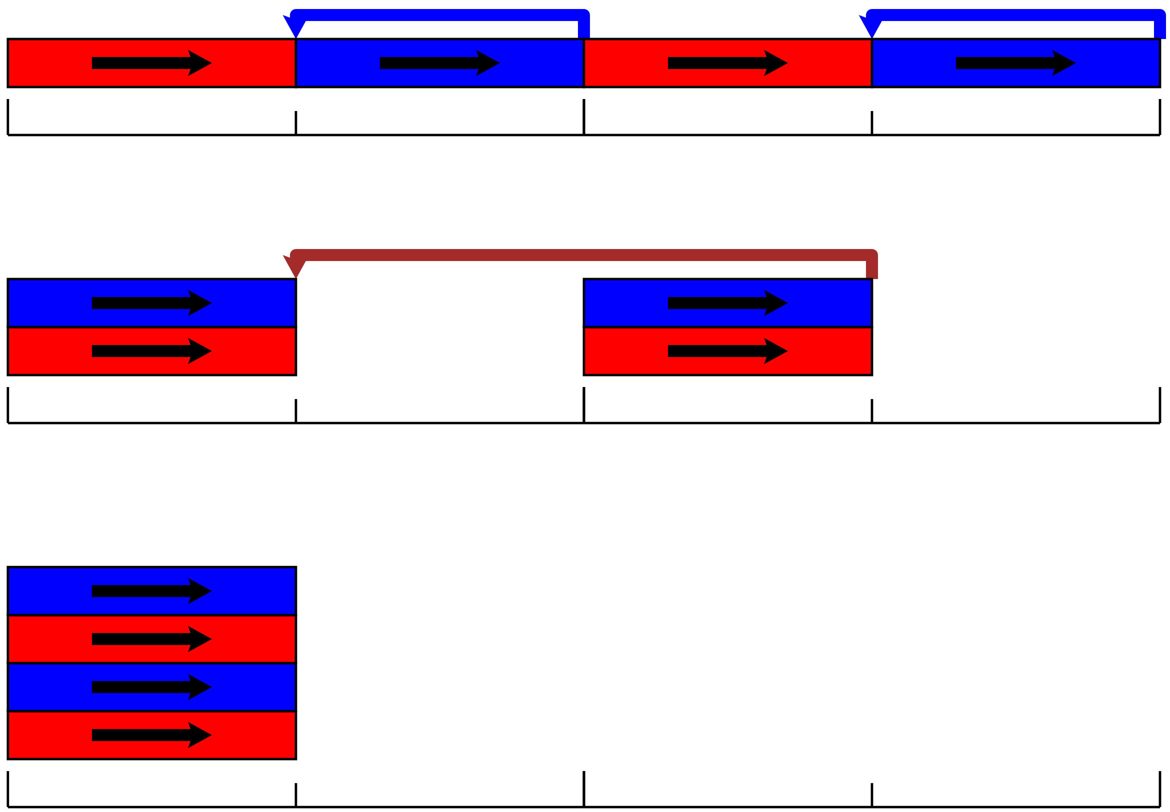


Acceleration
3 GHz
Deflection
1.5 GHz
180° phase switch in
SHB
Delay Loop
even
buckets
odd buckets
RF deflector
1.5 GHz
140 ns
sub-pulse length
odd buckets
even buckets
20 cm
between
bunches
140 ns
pulse length
140 ns
pulse gap
odd+ even
buckets
10 cm
between
bunches

Drive Beam Scheme II



Nominal Delay Loop and Combiner Ring



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

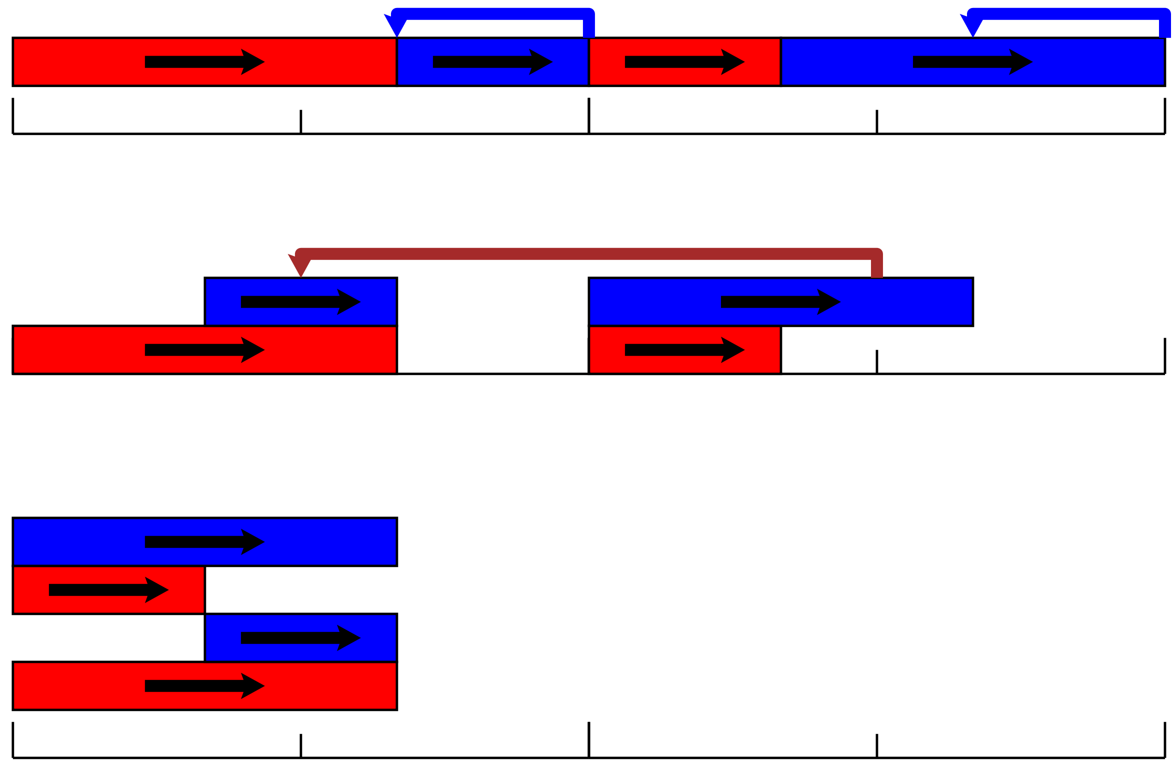
  ⇒ cannot change it arbitrarily

Modified 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



Operation Modes and Luminosity

E/E_0	n_b	$n_{\mathcal{L}}$	$Q_p/Q_{p,0}$
1.0	312	1.0	1.0
0.75	472	1.5	1.12
0.667	552	1.77	1.18
0.5	792	2.54	1.27
0.375	1112	3.56	1.34
(0.333)	(1272)	(4.08)	(1.36)

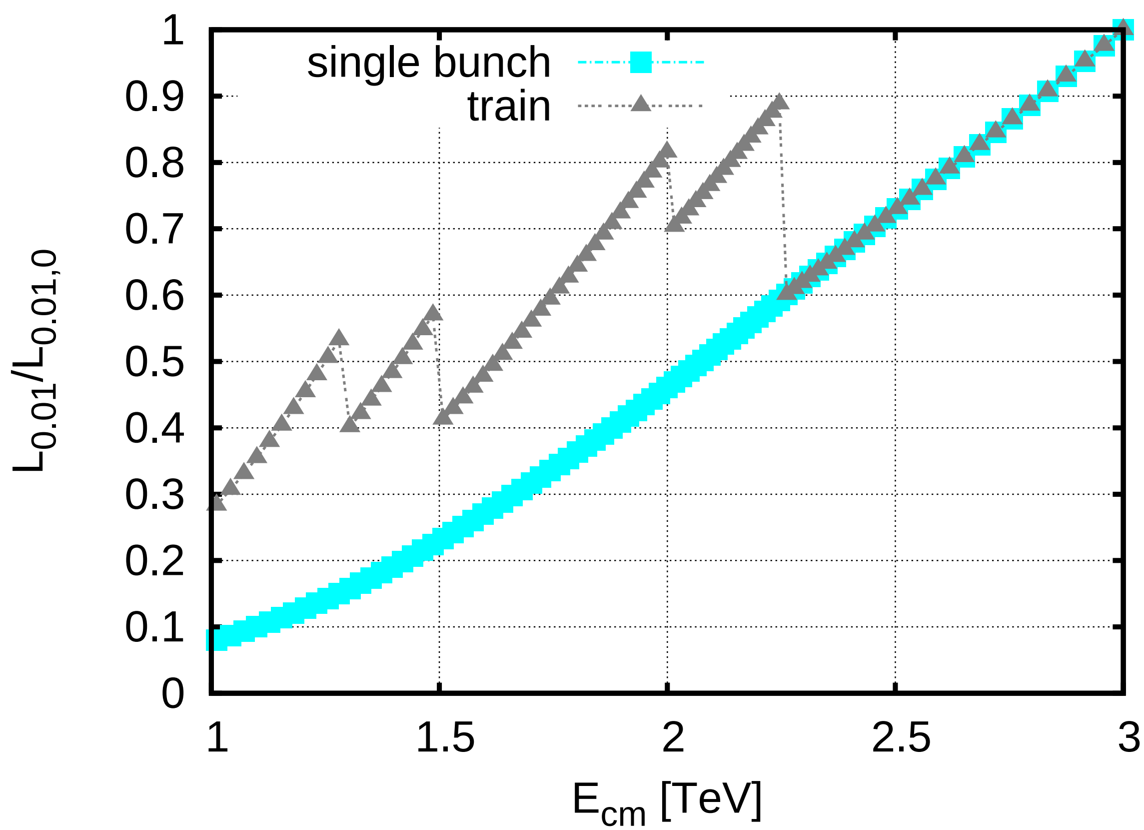
E maximum centre-of-mass energy for operation mode

n_b number of bunches per main beam pulse

$n_{\mathcal{L}}$ resulting increase in luminosity

$Q_p/Q_{p,0}$ maximum charge per pulse compared to nominal case

Note: last mode conflicts with damping ring at $1\,\mathrm{GHz}$ and is not part of the baseline

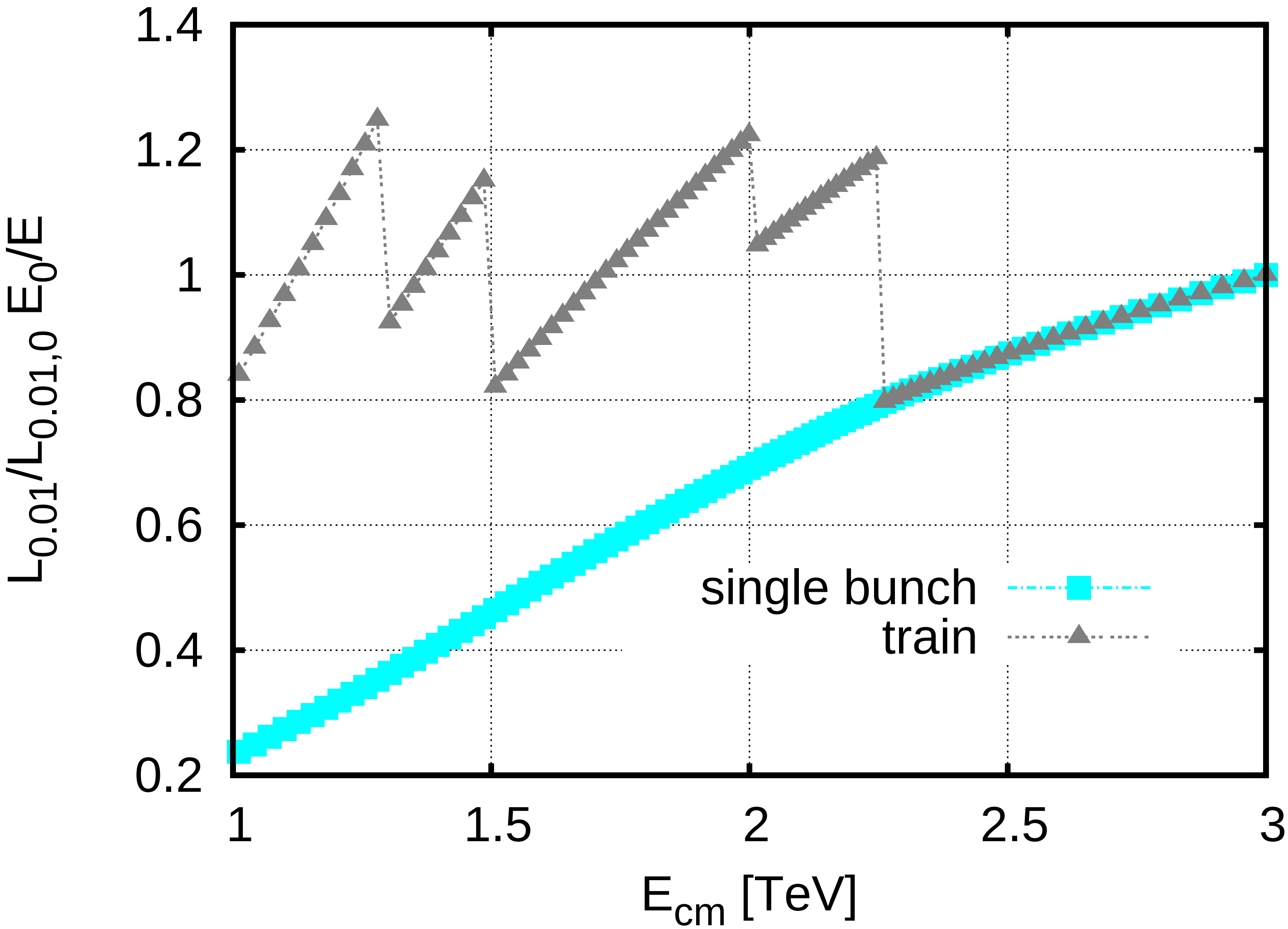


⇒ Achieve about $28\,\%$ at $1\,\mathrm{TeV}$

⇒ Achieve about $57\,\%$ at $1.5\,\mathrm{TeV}$

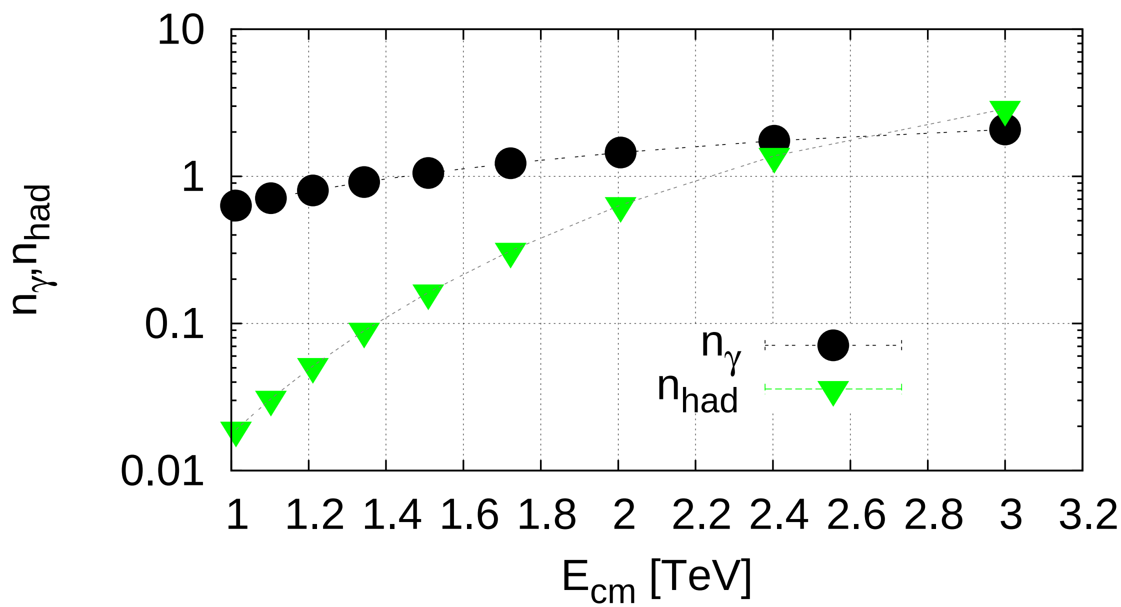
⇒ Achieve about $80\,\%$ at $2\,\mathrm{TeV}$

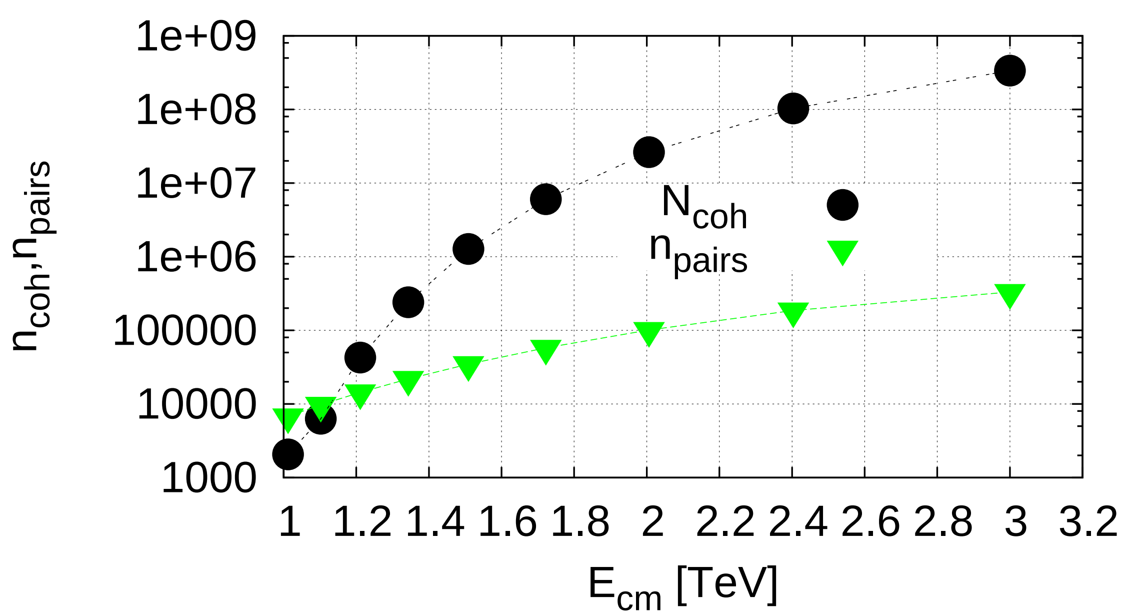
Comparison to Natural Scaling



⇒ Very close to natural scaling of $\mathcal{L}/\mathcal{L}_0 \propto E/E_0$

Beam-Beam Effects and Background





- At lower energy background is reduced
  - luminosity is lower
  - number of photons is smaller

⇒ Very good experimental conditions

B. Dalena

Beam-beam Effects for Early Extraction

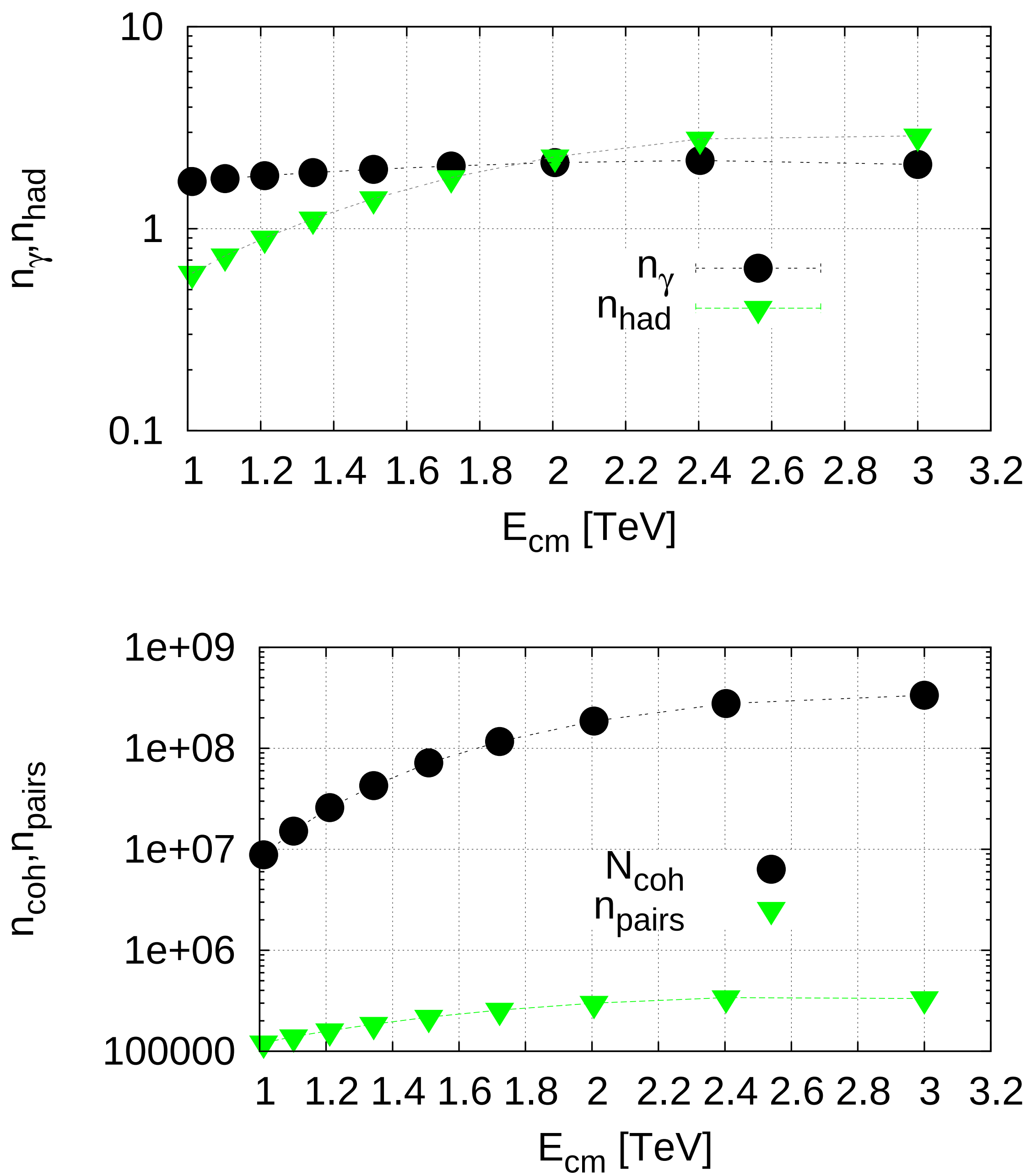
- At lower energies the luminosity spectrum improves

  $\Rightarrow$ could try to squeeze beam more for more luminosity

  - but hard to do, requires detailed study

- The background is reduced

  B. Dalena



Issues of Baseline Solution

- We went through the impact of the baseline energy scan on the CLIC design

  ⇒ some small adjustments were needed to cope with longer bunch trains

  ⇒ but straightforward

- Some beam dynamics issues have been studied

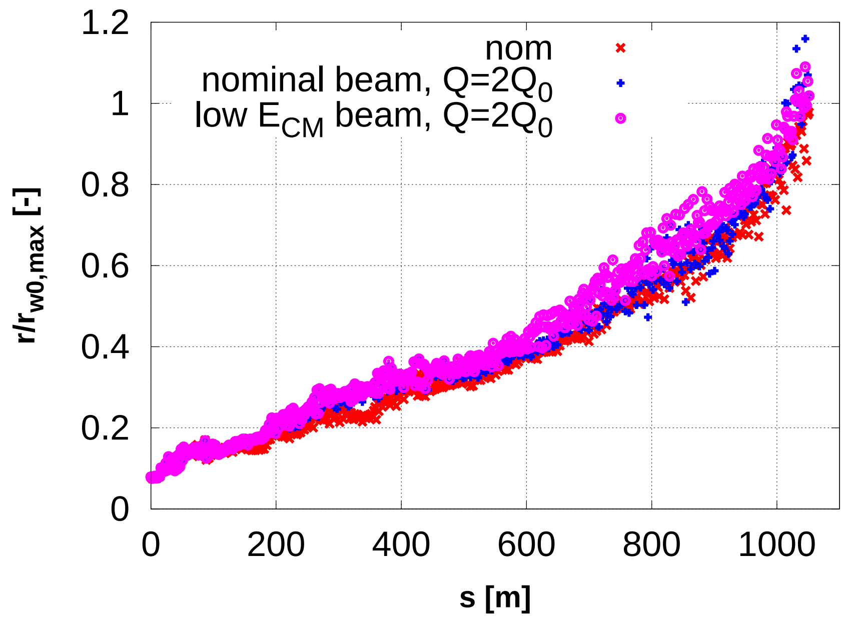
  - Do the gaps in the drive beam pulse cause problems in the decelerator?

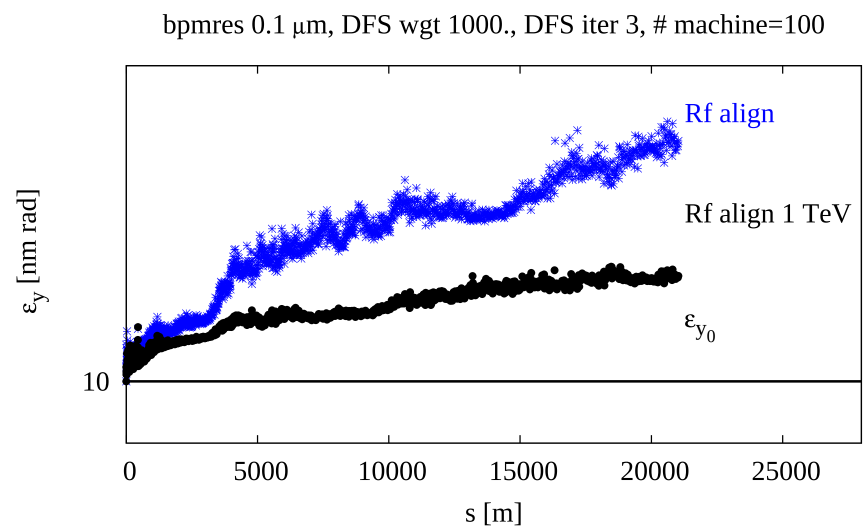
    ⇒ No.

  - What is the emittance growth in the main linac (slower damping of energy spread)?

    ⇒ Better than at nominal energy

E. Adli, B. Dalena

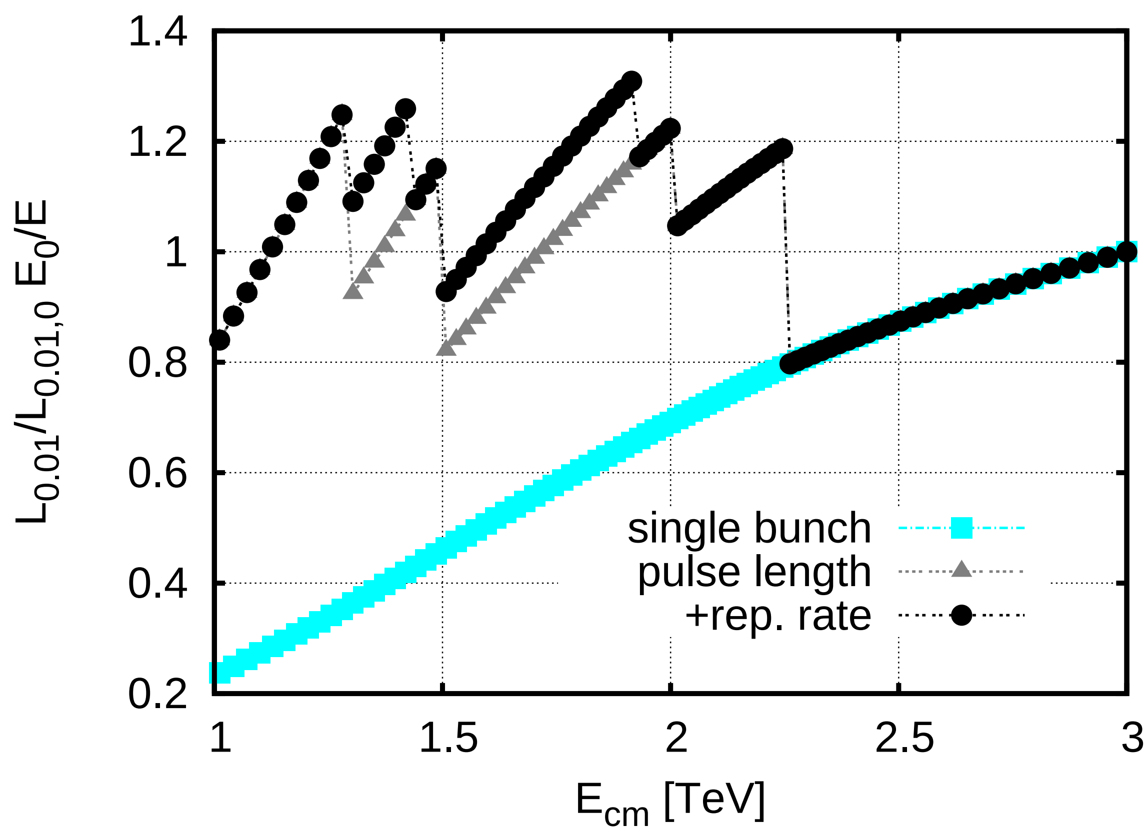




Additional Option: Repetition Rate Increase

- Can reduce the drive beam bunch charge
  - ⇒ can reduce drive beam energy
  - ⇒ need less power in drive beam accelerator
  - ⇒ at $\approx$ $70\,\mathrm{MV/m}$ half the drive beam power needed
  - ⇒ could use this to double the repetition rate
- But a number of problems to solve
  - klystron efficiency is reduced at lower power
  - machine protection has less time

⇒ More work needed



Further Work

- Improvement of details of current baseline
  - optimisation of the BDS for lower energies in energy scan, without compromising $3\,\mathrm{TeV}$ performance
  - reduction of emittances for smaller bunch charges
- Study the higher repetition rate option
  - klystron efficiency at lower power
  - machine protection (shorter time between pulses)
  - ...
- Study extraction option if required
  - will reduce maximum beam energy or lengthen machine/increase cost
- Explore energy scan of $500\,\mathrm{GeV}$ machine

Conclusion

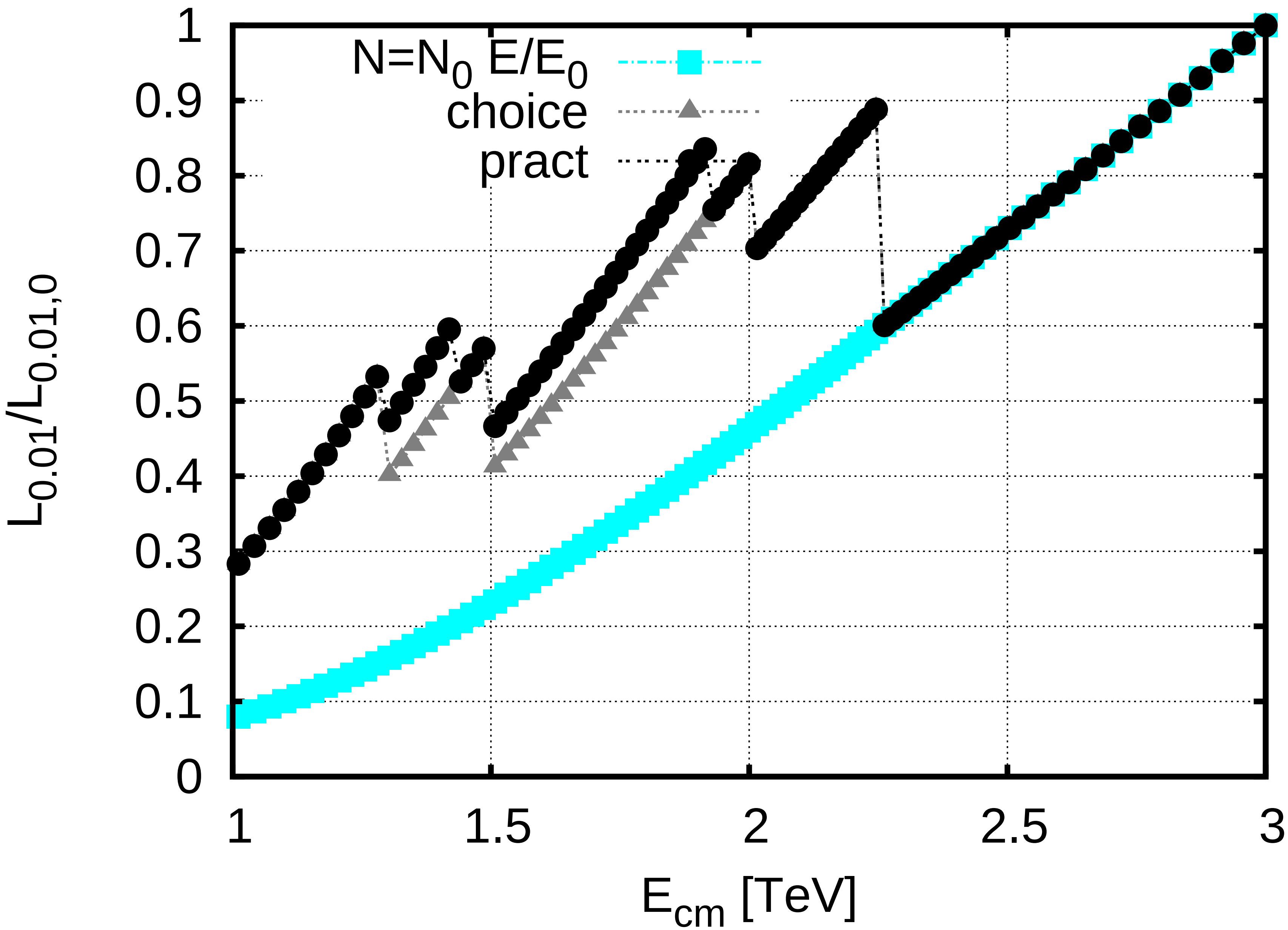
- CLIC parameters and conceptual design exist for for $500\,\mathrm{GeV}$
  - better integration into energy staging possible
- A baseline exists for the low energy operation of the $3\,\mathrm{TeV}$ CLIC
  - achieves $\mathcal{L}_{0.01}/\mathcal{L}_{0.01,0} \approx 27\,\%$ at $1\,\mathrm{TeV}$
  - and $\mathcal{L}_{0.01}/\mathcal{L}_{0.01,0} \approx 55\,\%$ at $1.5\,\mathrm{TeV}$
  - further improvements possible
- alternative options require more study
  - early extraction points
  - higher repetition rate
- Energy scan for $500\,\mathrm{GeV}$ machine and design of $1\,\mathrm{TeV}$ machine

Reserve

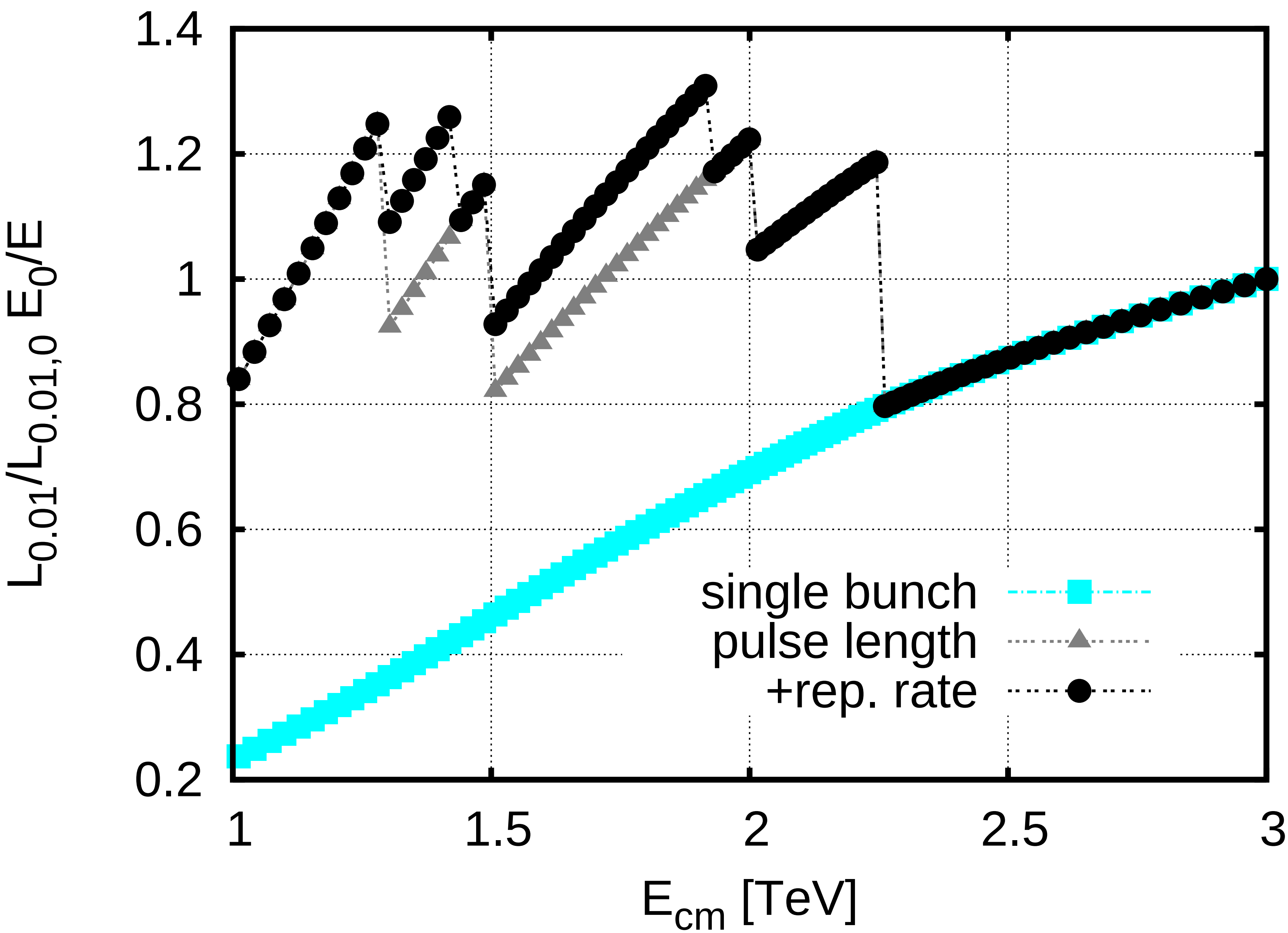
Luminosity and Background Values

parameter	units	CLIC(cons)	CLIC(nom)	CLIC(cons)	CLIC	ILC (RDR)
E_{cms}	[TeV]	0.5	0.5	3.0	3.0	0.5
f_{rep}	[Hz]	50	50	50	50	5
n_b		354	354	312	312	2625
σ_x	[nm]	248	202	83	40	655
σ_y	[nm]	5.7	2.26	1	1	5.7
Δt	[ns]	0.5	0.5	0.5	0.5	369
N	$[10^9]$	6.8	6.8	3.7	3.7	20
ϵ_x	[μm]	3.0	2.4	2.4	0.66	10
ϵ_y	[nm]	40	25	20	20	40
β_x	[mm]	10	8	8	4	21
β_y	[mm]	0.4	0.1	0.1	0.07	0.4
L_{total}	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.88	2.3	2.7	5.9	2.0
$L_{0.01}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.58	1.4	1.3	2.0	1.45
n_γ		1.1	1.3	1.2	2.2	1.30
$\Delta E/E$		0.045	0.07	0.13	0.29	0.024
N_{coh}	$[10^5]$	10^{-4}	10^{-3}	5×10^2	3.8×10^3	—
E_{coh}	$[10^3\ \mathrm{TeV}]$	0.001	0.015	4×10^4	2.6×10^5	—
n_{incoh}	$[10^6]$	0.03	0.08	0.11	0.3	0.1
E_{incoh}	$[10^6\mathrm{GeV}]$	0.14	0.36	7.2	22.4	0.2
$n_\perp$		8	20.5	19	45	28
n_{had}		0.07	0.19	0.75	2.7	0.12

Resulting Luminosity I



Resulting Luminosity II



Modified Pulse Length (cont.)

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

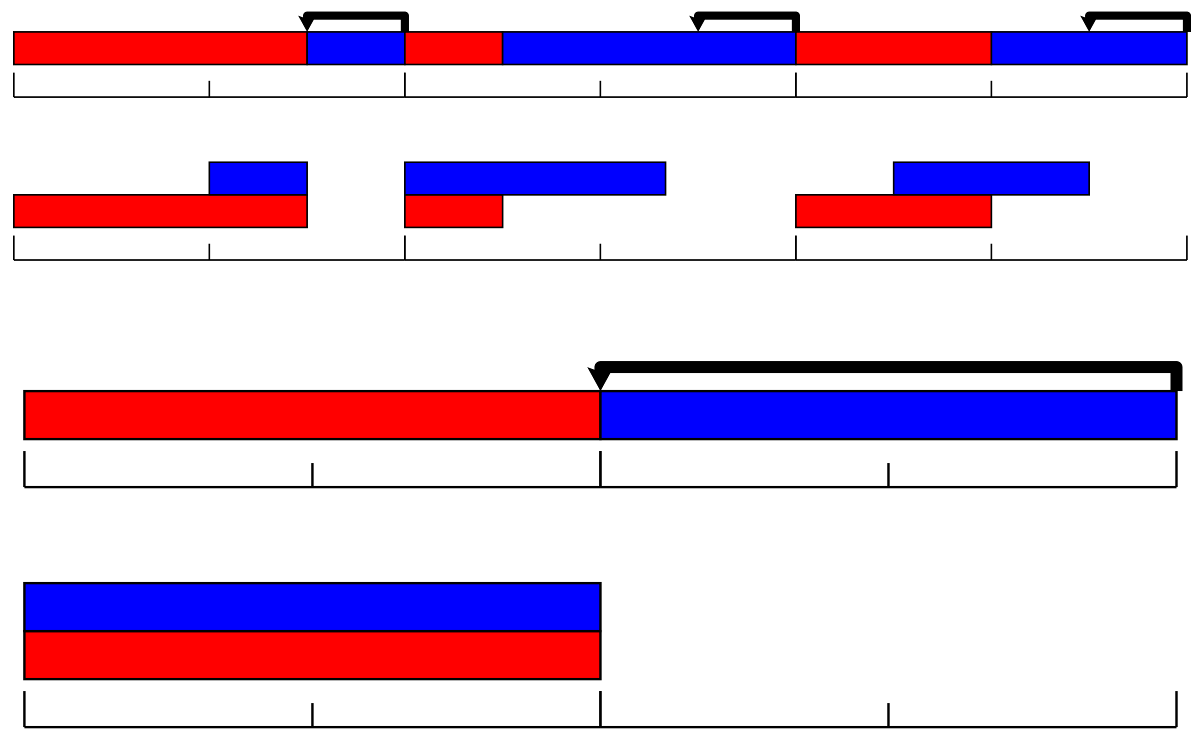
  - would need larger combiner ring with two pulses as baseline

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

  $\Rightarrow 480$ extra bunches per train

- For $G/G_0 \leq 3/8$ and $G/G_0 \leq 1/3$ similar solutions can be used

  - up to 1280 bunches at 1/3 of the charge



- Other options should be investigated

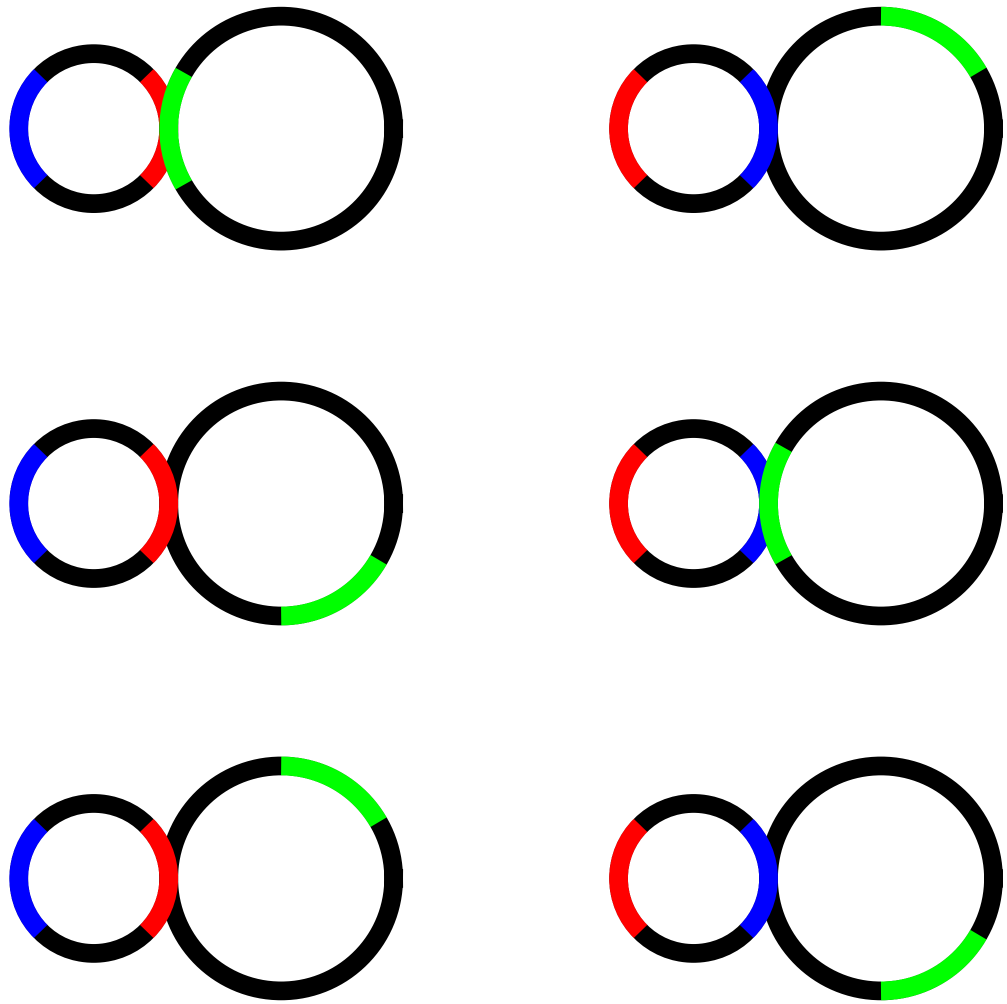
First Combiner Ring

- Original first combiner rings did not allow pulse that are twice as long as nominal

  ⇒ need to double circumference

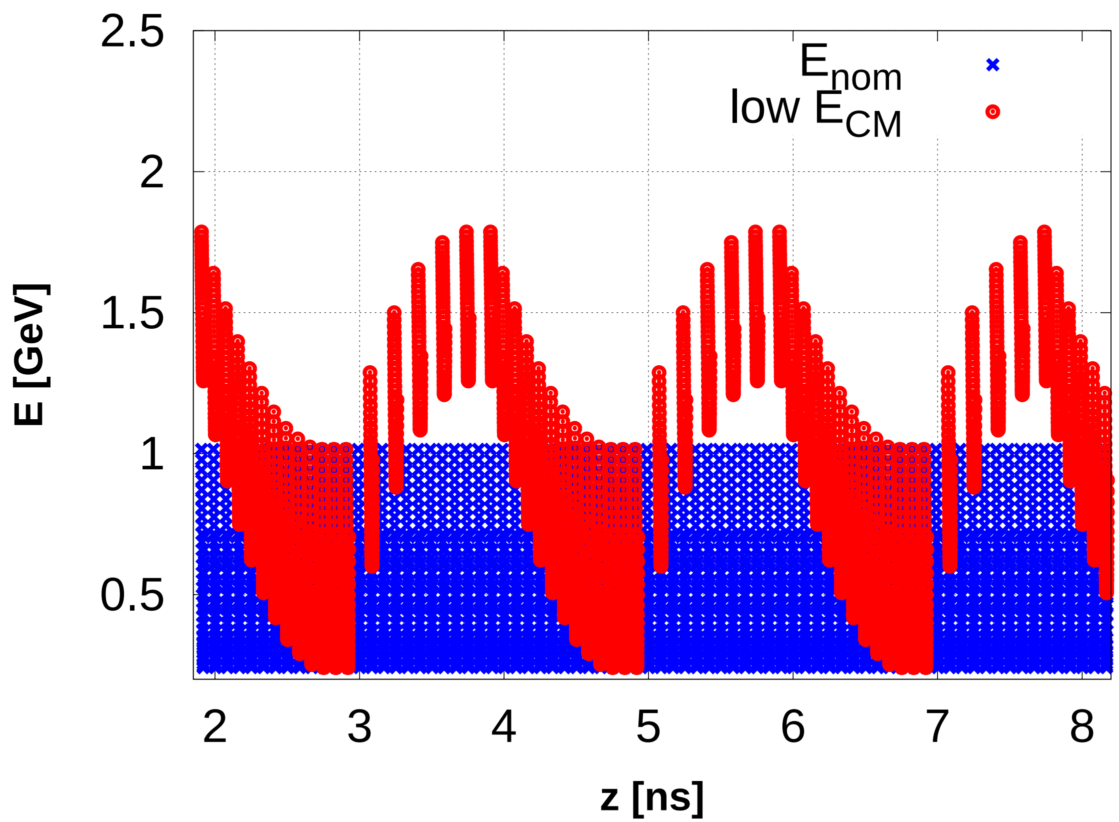
  ⇒ loose one train at the beginning, one at the end of the pulse

- Larger ring should ease design issues



Drive Beam Decelerator

- Note the maximum deceleration in the decelerator does not change necessarily
  - gaps tend to be created in the first or second half of a superbucket
  - so tend to have ne fill time of consecutive bunches
- Developed small code to simulate the combination
  - to play with patterns
  - for phase stability studies

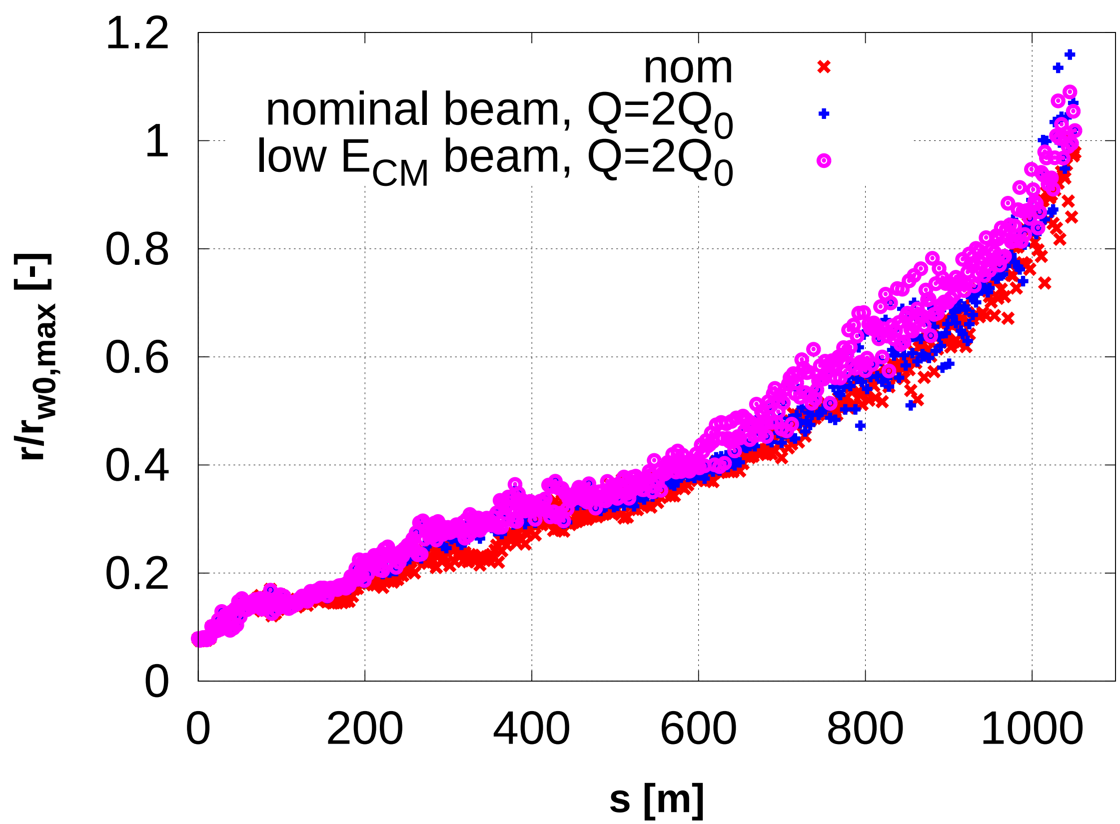


E. Adli

Beam Envelope Growth

- Gaps in the train can cause increased envelope growth

  ⇒ does not seem to be a problem



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