Beam Delivery System for 10 TeV colliders

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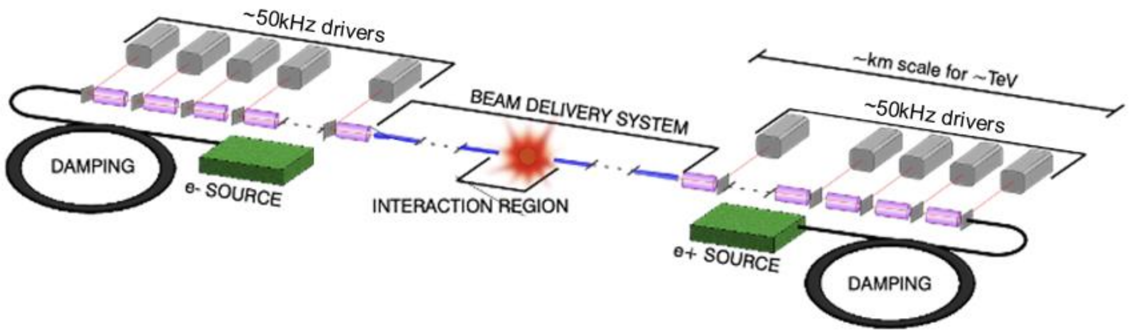
Motivation

- The 10 TeV Plasma Collider is a proposed next-generation accelerator utilizing advanced wakefield technology

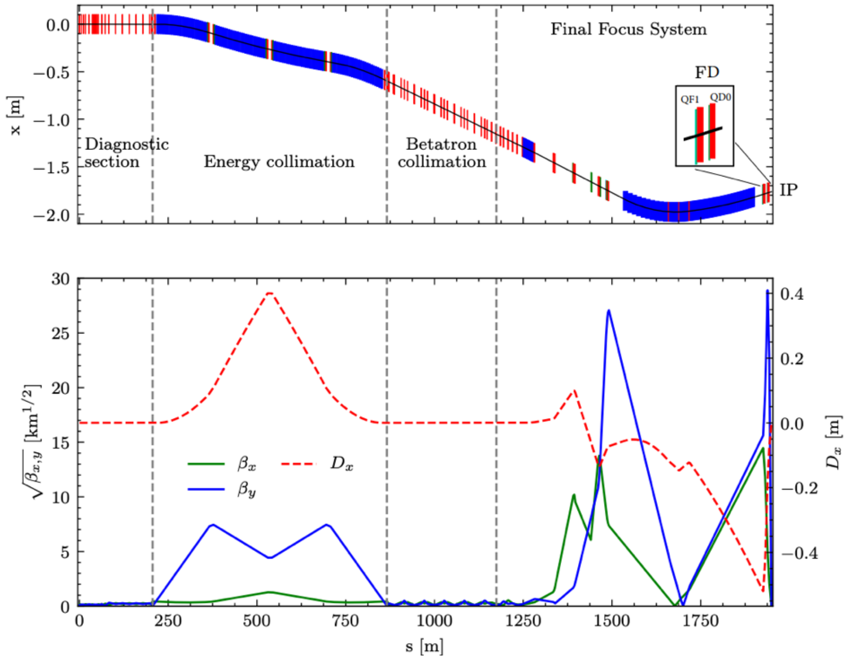
- The Beam Delivery System (BDS) is a crucial component, requiring novel solutions for high-energy beams

- This study explores BDS scaling, collimation strategies, and final focus system (FFS) designs to optimize performance



Introduction to the BDS

- The BDS is composed of:
  - Diagnostic Section (end of ML to collimation section)
  - Collimation Section (protects the downstream beamline and detector against mis-steered beams from ML and removes beam halo)
  - Final Focus System (focuses the beam to nanometer level and correct the chromaticity)



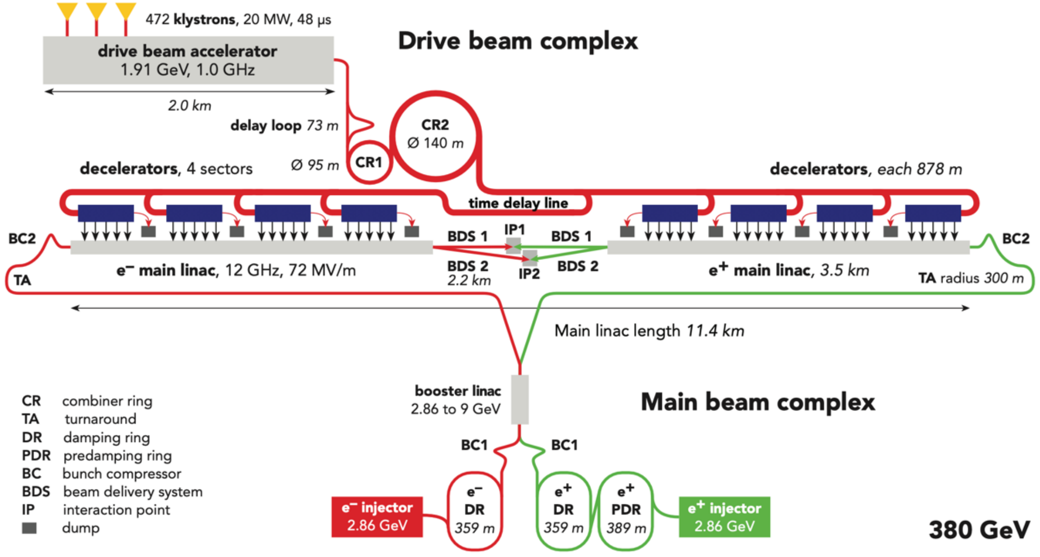


Fig. 1: Schematic layout of the CLIC complex at 380 GeV.

CLIC BDS Designs

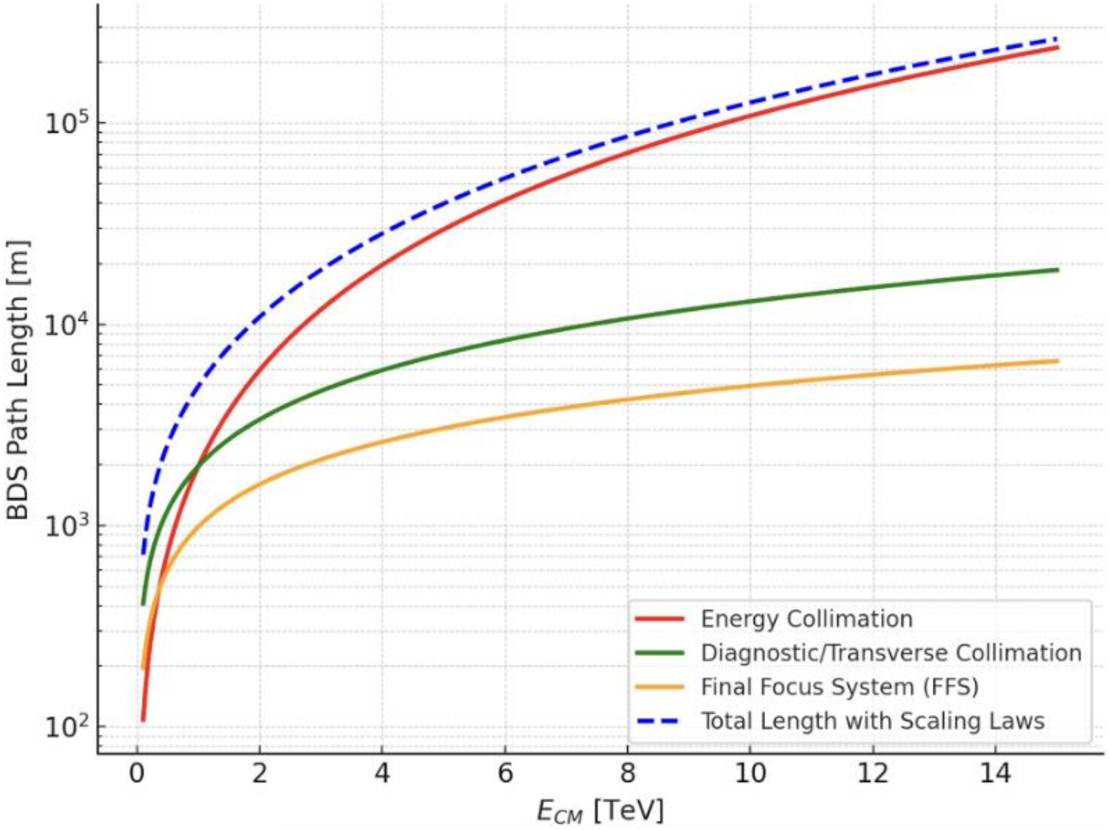
Energy [GeV]	**380**	**1500***	**380†**	**1500†**	**3000***
Final drift $L*$ $[m]$	6	6	6	6	6
FFS length $[m]$	770	770	550	550	770
BDS length $[km]$	1.94	3.12	1.72	2.62	3.12
Norm. emittance (IP) $\epsilon_{n,x}/\epsilon_{n,y}$ $[nm]$	920/15	660/20	920/15	660/20	660/20
Beta function (IP) β_x^*/β_y^* $[mm]$	8/0.07	8/0.11	6/0.08	6/0.08	7/0.12
Beam size @ IP (rms) σ_x^*/σ_y^* $[nm]$	145/2.5	60/1.5	120/3.9	57/1.2	40/0.9
Bunch length σ_z $[\mu m]$	70	44	70	44	44
Energy spread δ_p [%]	0.3	0.3	0.3	0.3	0.3
Bunch population N $[\times 10^9]$	5.2	3.72	5.2	3.72	3.72
Number of bunches N_b	352	312	352	312	312
Repetition rate f $[Hz]$	50	50	50	50	50
Crossing angle $[mrad]$	18.3	20	18.96	20	20
Total luminosity $\mathcal{L}_{tot}$ $[10^{34} cm^{-2} s^{-1}]$	2.25	3.70	2.65	4.71	5.9

- CLIC BDS Design goes from 1.7 km at 380 GeV to 3.1 km at 3 TeV (only one BDS)
- Fundamental is the choice of the L* (distance from the last magnet to the IP) in the design

BDS Scaling with Length

- As we venture into higher energy frontiers, the role of BDS becomes increasingly critical

- The scaling laws of the different parts of the BDS* from literature are:
  - Energy Collimation scales between $L \sim E$ and $L \sim E^2$
  - Diagnostic and Transverse Collimation scale between $L \sim \sqrt{E}$ and $L \sim E$
  - FFS scales as $L \sim E^{7/10}$

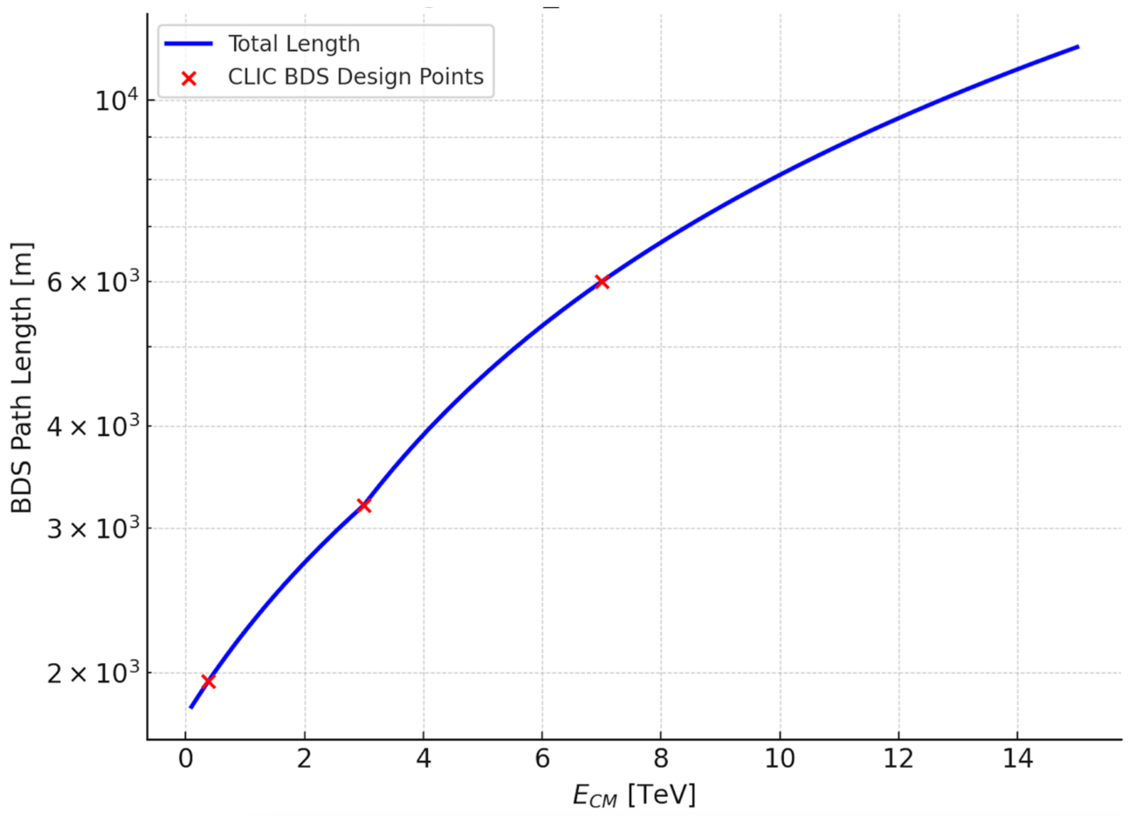


*White, G., et al. "Beam delivery and final focus systems for multi-TeV advanced linear colliders." *Journal of Instrumentation* 17.05 (2022): P05042.

BDS Scaling with Length

- **Starting from the CLIC BDS Designs at 380 GeV, 3 TeV, and 7 TeV:**
    - Approximately, the BDS length of the 10 TeV wakefield collider would be 8 km (keeping the beam flat, having the parameters close to the CLIC ones, and considering an L* of 6 m)

- **The starting point for the BDS design at 10 TeV:**
    - The CLIC BDS design at 7 TeV (shown in next slides)



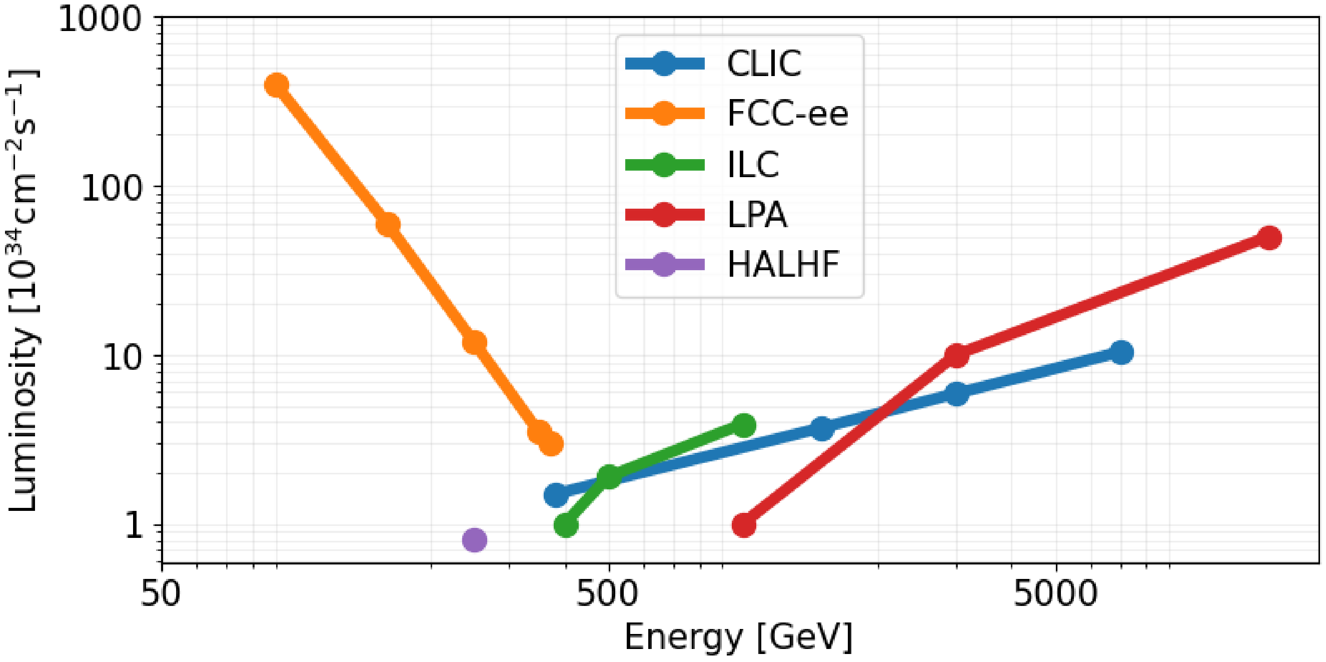
CLIC 7 TeV BDS Design

Target Luminosity-the starting point

- The target CLIC luminosity at 7 TeV is obtained by extrapolating the existing targets from the previous old design luminosities:

Energy [GeV]	380	1500	3000
Total luminosity $\mathcal{L}$ $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	1.5	3.7	5.9
Peak luminosity $\mathcal{L}_{1\%}$ $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	0.9	1.4	2

- Resulting in a target luminosity for the 7 TeV design of 10.4 $[10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}]$



CLIC 7 TeV BDS Design

Optimization of the Collimation Section

- The length of the transverse collimation system (L_{TCS}) scales proportionally to the energy $L_{TCS} \propto \gamma \propto E$ assuming that $\beta_y \propto L_{TCS}$.

- For the energy collimation system (ECS), length and bending angles have to be scaled

- The length scaling follows the equation: $L_{ECS} \propto \gamma \propto E$

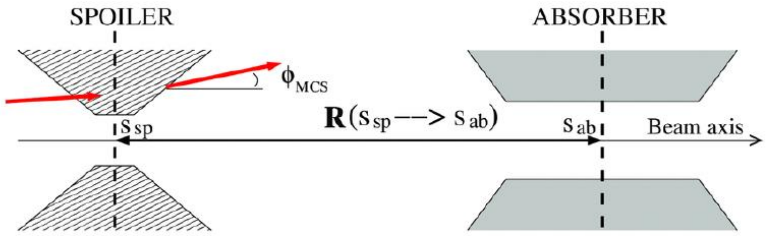
- To minimize the effect of the SR is necessary to reduce the bending angles instead
  - To do that we need to compute the min gap available and the max, with δ_p varying from 0.005% and 1.3%:

$$g_{min} = 15\sigma_x + D_x\delta_p$$

$$g_{max} = D_x\delta_{p,1.3\%}$$

  - Then the min dispersion is computed from the min and the max gaps:

$$D_{x,min} = \frac{15\sigma_x}{\delta_{p,1.3\%} - \delta_p} = 0.033$$



- **The min half-gap size is then 0.43 mm**

CLIC 7 TeV BDS Design

Optimization of the Collimation Section

7 TeV collimation system is not fully demonstrated. The survival of the spoiler against an impact of the full beam has not been checked yet, as the corresponding scaling was not applied to the full extent.

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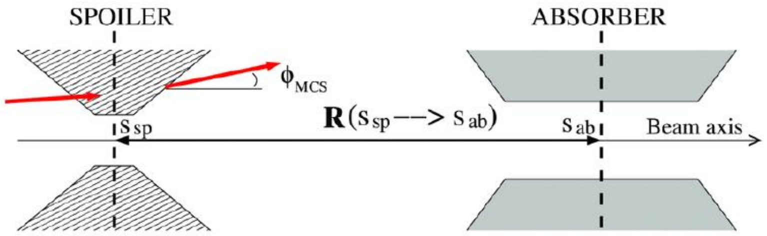


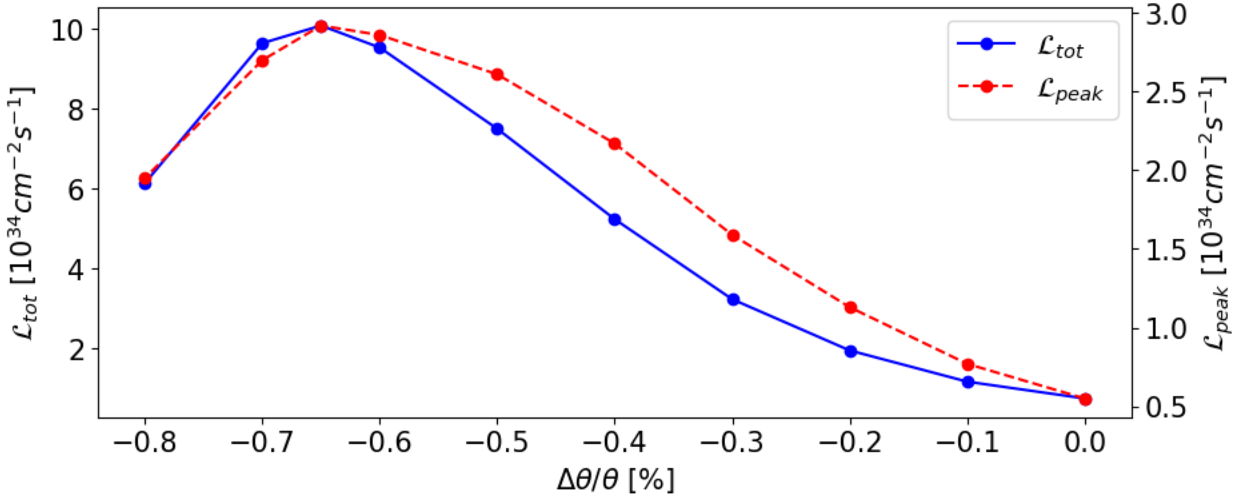
- **The min half-gap size is then 0.43 mm**

CLIC 7 TeV BDS Design

FFS optimization-scaling of the bending angles

Starting luminosity:

$$\mathcal{L}_{\text{tot}} = 0.76 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$$

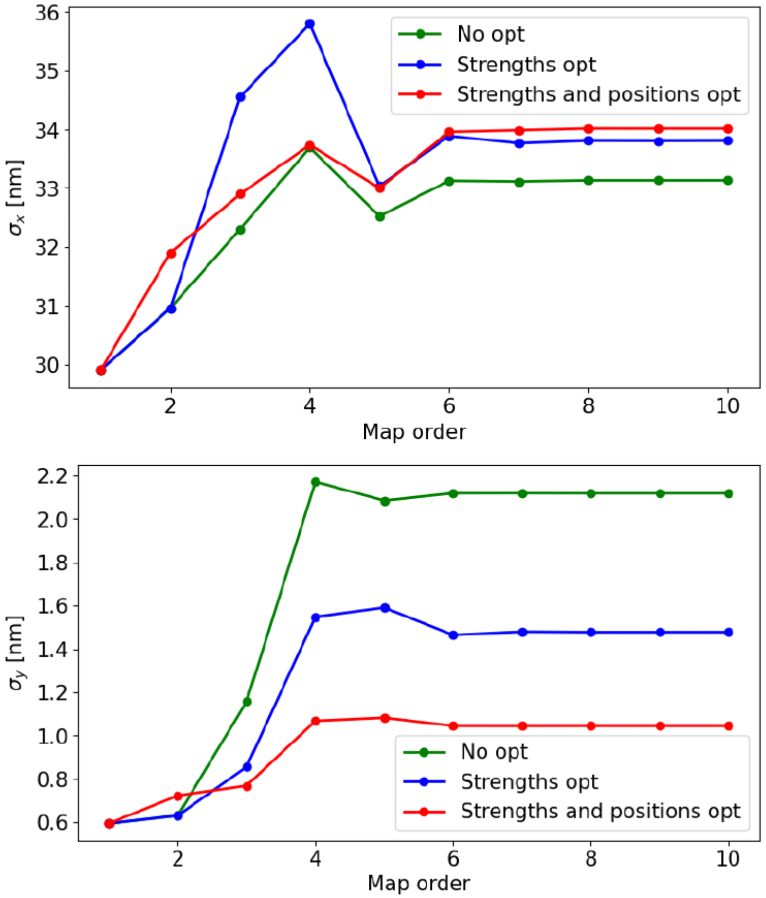


- Reduction of the FFS bending angles
- Compensate the dispersion reduction by scaling the sextupole strengths at each steps by a factor $\left(\frac{\Delta\theta}{\theta}\right)^{-1}$

$\mathcal{L}_{\text{tot}} = 10 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ for $\Delta\theta/\theta$ = -65%

CLIC 7 TeV BDS Design

Beam size optimization



Optimization of the beam size at the IP by varying:

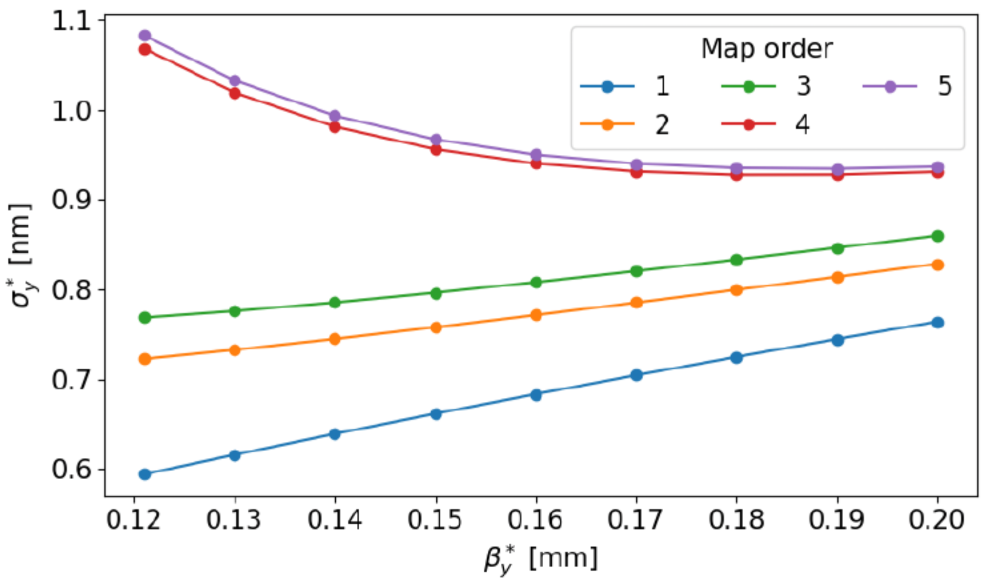
1. only the magnet strengths (blue)

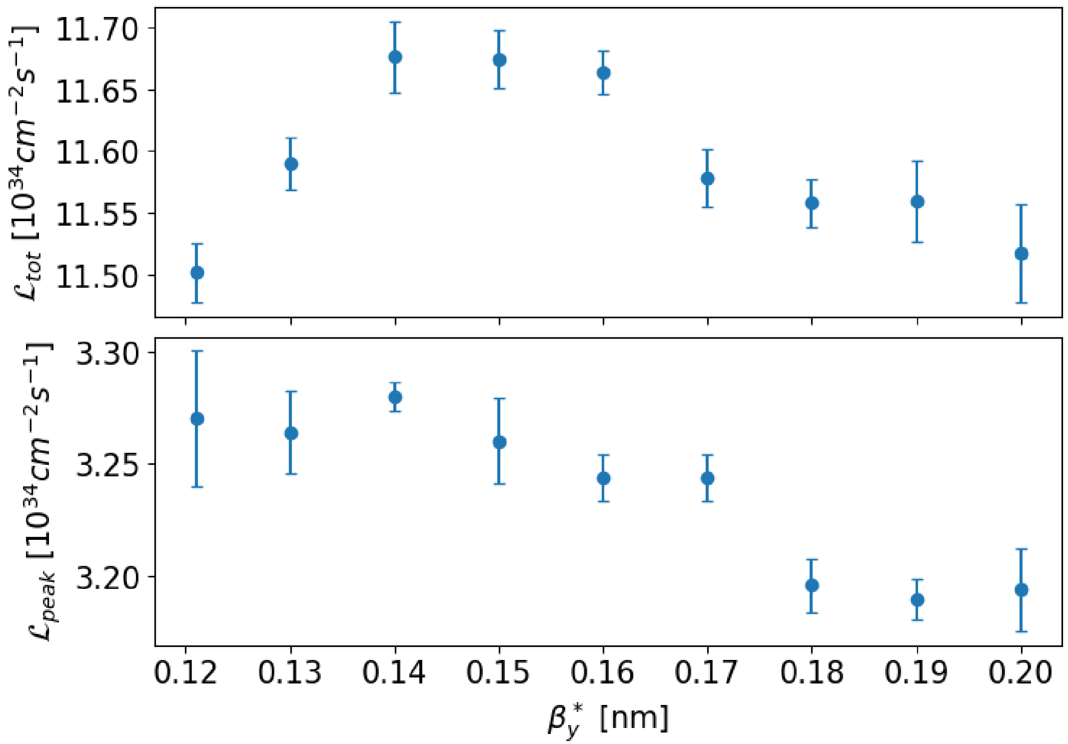
2. the magnet strengths and the positions (red)

CLIC 7 TeV BDS Design

β_y^* Scan

- Scan of β_y^* in step of 0.1 mm
- No sextupoles optimization



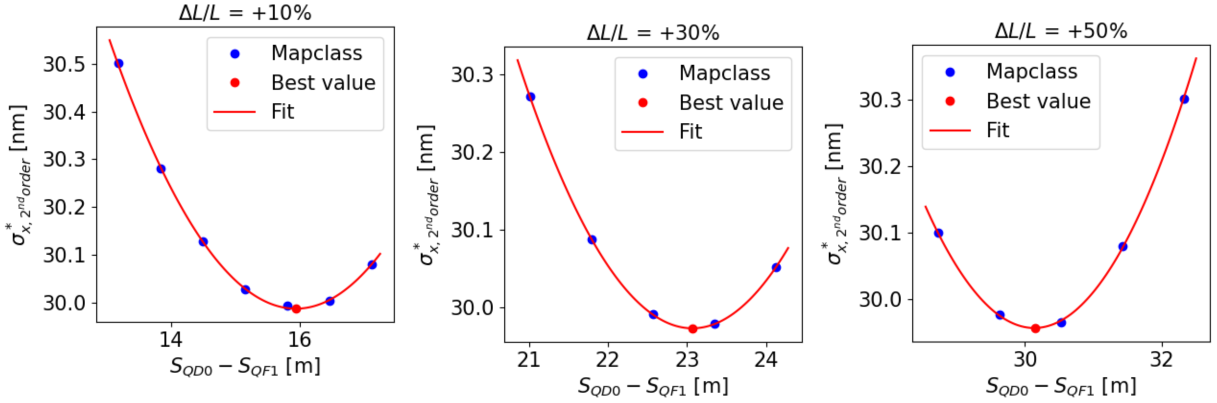


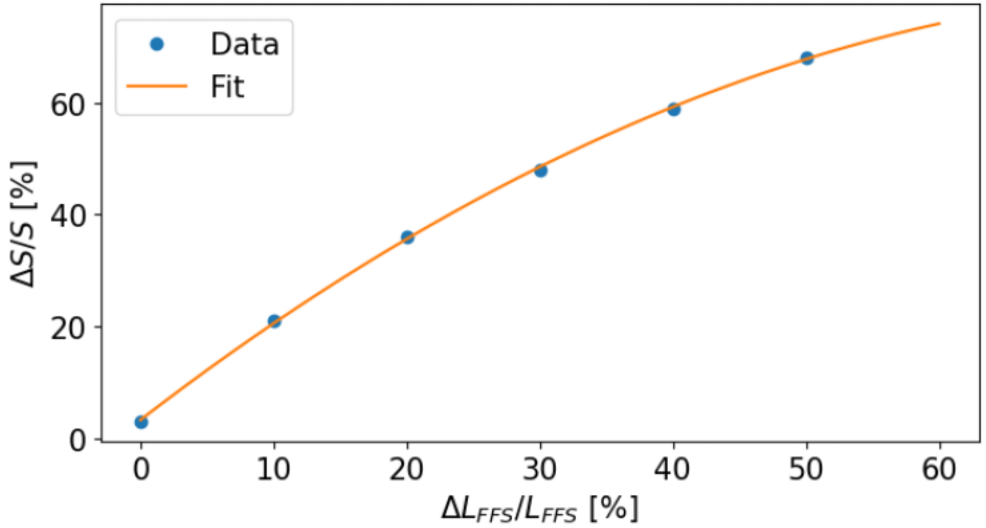
Best $\beta_y^* = 0.14$ mm

CLIC 7 TeV BDS Design

Length scaling-best QF1-QD0 distance

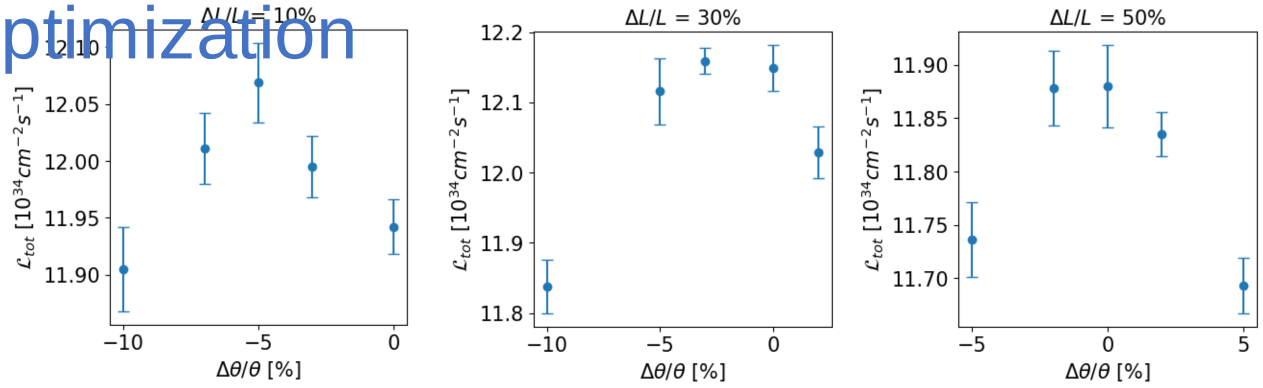
- Increase the length of the FFS to reduce the magnetic field into the dipoles that leads to a decrease in an energy loss by Synchrotron Radiation
- FFS length increased in steps of 10%
- Optimization of the distance between QD0 and QF1 to minimize the horizontal chromaticity

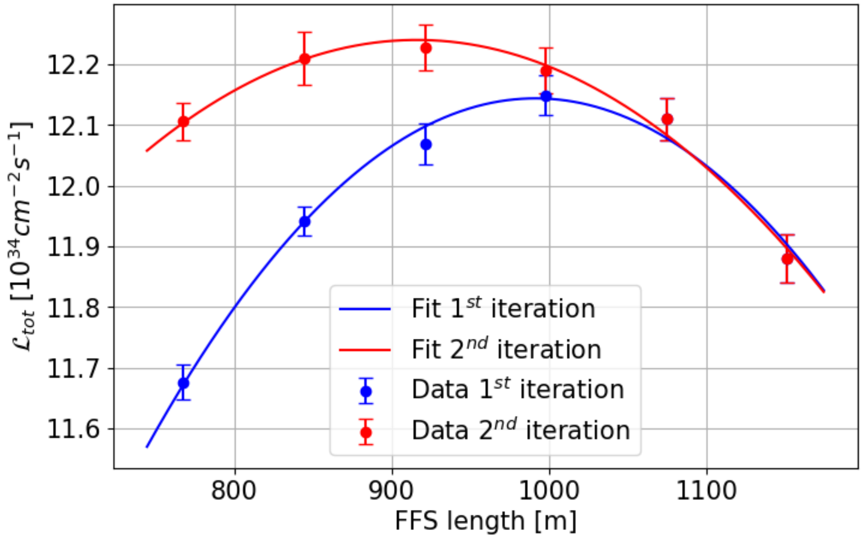




CLIC 7 TeV BDS Design

Length scaling-dispersion optimization





1. Optimization of the beam size with Mapclass (1st iteration)
2. Dispersion reduction to reduce the Synchrotron Radiation effects
3. Optimization of the beam size with Mapclass (2nd iteration)

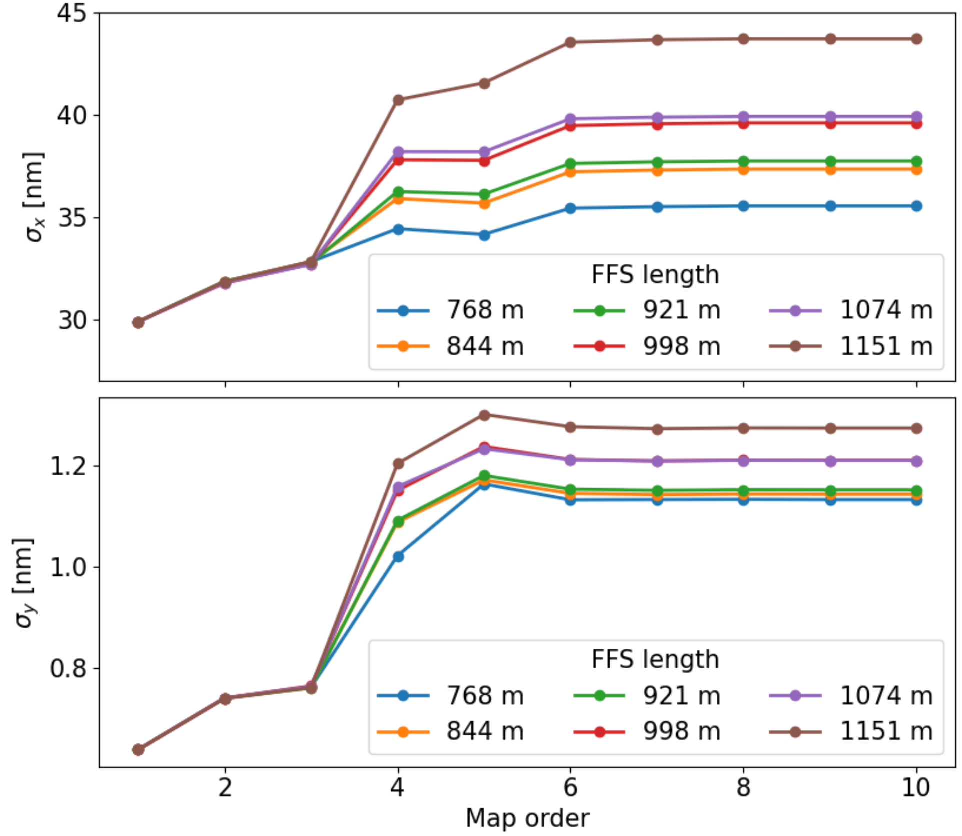
Best: $\Delta L_{FFS}/L_{FFS} = +20\%$
FFS length = 921 m

$$\mathcal{L}_{tot} = (12.23 \pm 0.04) \cdot 10^{34} cm^{-2} s^{-1}$$

CLIC 7 TeV BDS Design

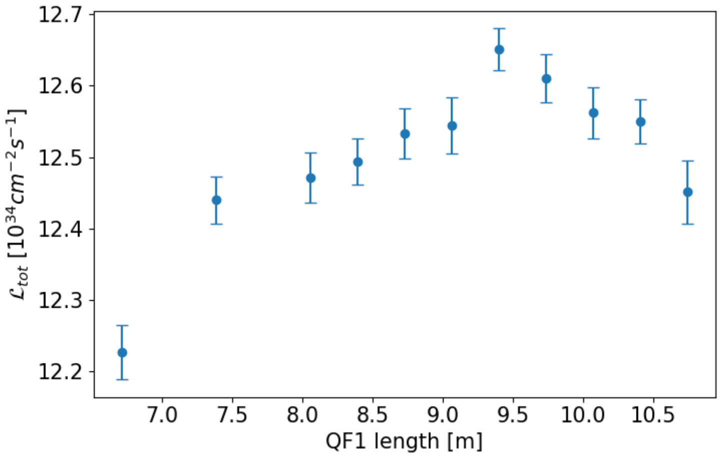
Length scaling-beam size

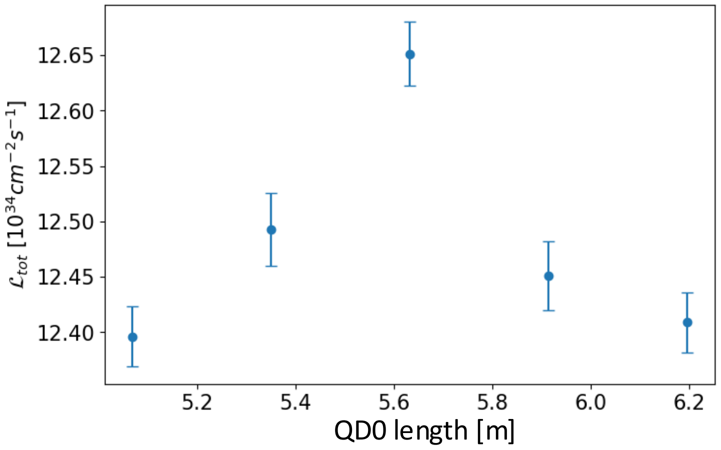
- At each FFS length, the beam size with Mapclass has been optimized
- $1^{st}, 2^{nd}$ and 3^{rd} map orders are dominant for the luminosity calculations
- Relaxing the 4^{th} and 5^{th} orders to minimize the lower ones



CLIC 7 TeV BDS Design

Final Doublet optimization





- Variation of QF1 and QD0 length to minimize the radiation emission due to the Oide effect
- Length variation in steps of 5% starting from QF1
- Best scaling for QF1: +40%
- No scaling for QD0

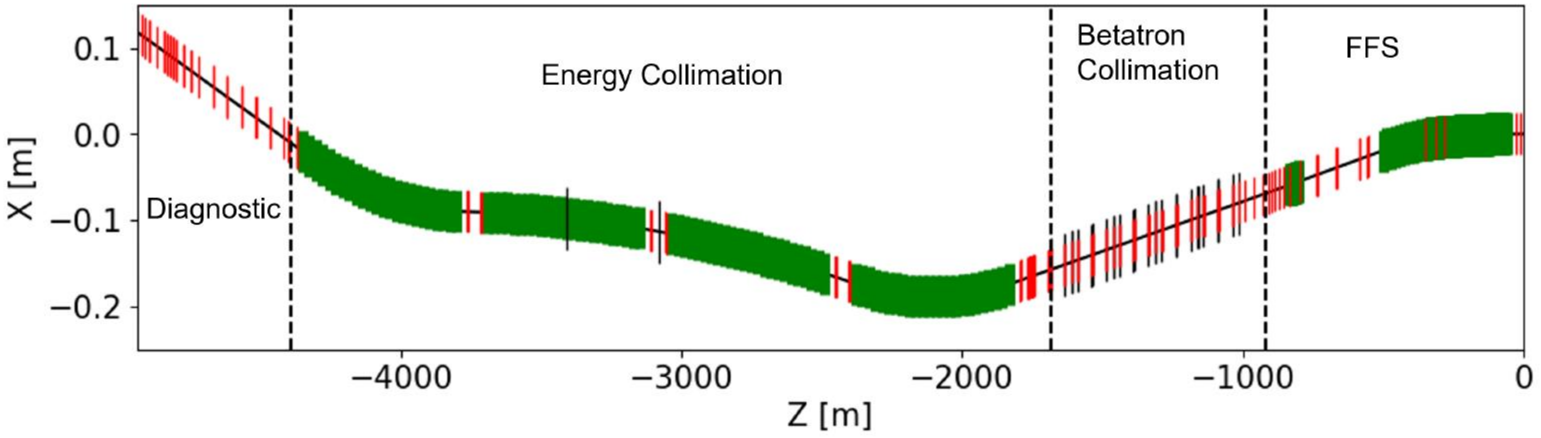
$$\mathcal{L}_{tot} = (12.65 \pm 0.03) \cdot 10^{34} cm^{-2} s^{-1}$$

CLIC 7 TeV BDS Design

Summary

L* [m]	6
BDS length [m]	4940
L_{QD0} [m]	5.6
L_{QF1} [m]	9.4
FFS length [m]	921
Norm. emittance $\gamma\epsilon_x$ [nm]	660
Norm. emittance $\gamma\epsilon_y$ [nm]	20
IP beta function β_x^* [mm]	9
IP beta function β_y^* [mm]	0.14
IP beam size σ_x^* [nm]	30
IP beam size σ_y^* [nm]	0.7
Vertical chromaticity ξ_y^* $[10^3]$	43
Bunch length σ_z^* $[\mu m]$	44
Bunch population N_e $[10^9]$	3.72
Number of bunches n_b	312
Repetition rate f_{rep} [Hz]	50
Crossing angle [mrad]	20
Luminosity $[10^{34} cm^{-2} s^{-1}]$	11.9

- The final BDS design is:



- Final Lenghts:
  - 547 m Diagnostic Section
  - 3472 m Collimation Section
  - 921 m FFS

Key challenges for a 10 TeV plasma collider BDS

- **What are the key challenges?**
  - Synchrotron radiation in bending magnets
  - For round beams, using a triplet and not a doublet
  - Highly problematic chromaticity correction scheme with very small betas and large emittances → maybe need to use the traditional FFS scheme
  - Magnet aperture and technology → normal conducting could not work, limiting beta*, requiring a longer system or needing Nb_3Sn (depending on emittance values)

- **What technologies and techniques will be considered?**
  - For energy collimation, try to implement a laser-based collimation system → need R&D
  - One IP or two IPs ?
  - Plasma lenses ?
  - Nonlinear collimation scheme already used in CLIC BDS design (https://cds.cern.ch/record/1344632/files/CLIC-Note-883.pdf?version=1)

Conclusions

- CLIC 7 TeV Design:
  - A first design for the FFS at 7 TeV has been proposed
  - FFS optimized and scaled differently from all the other sections of the BDS
  - Strong radiation effects have been minimized
  - An optimization of all the elements into the line has been performed to maximize the luminosity

- 10 TeV plasma collider BDS:
  - The length will be longer than 8 km
    - Challenges: SR in bending magnets, strong aberrations, physical aperture
  - We should do R&D on the possibility to take advantage of plasma linac in the BDS
    - Plasma lenses or laser-based collimation system
  - My ongoing work on the HALHF BDS is highly synergistic with the 10 TeV efforts ➞ tool development, consideration of plasma-friendly beam parameters e.g. higher emittance, new concepts for outsourcing BDS functionality to the plasma linac, etc.

- **Design is very challenging and needs a lot of R&D**

Thank you for the attention!