Design and Simulations for the Compact Linear Collider Drive-Beam

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2025/06/11

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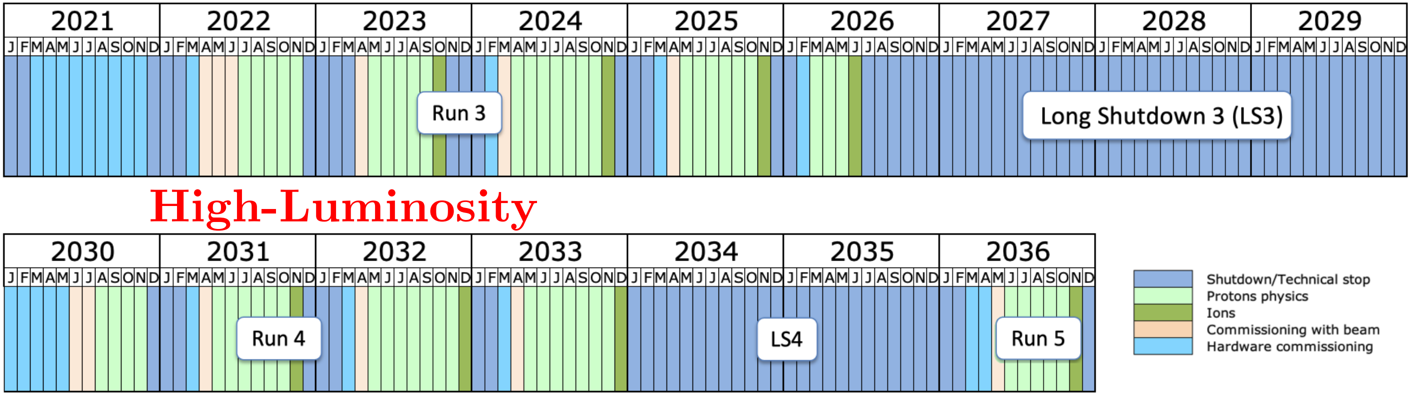
Outline

The Compact Linear Collider (CLIC)

What is CLIC and why do we need it?

LHC Schedule



Collider Physics after the LHC

proton-proton	electron-positron	proton-electron	muon-muon
Highest energy range Broad sensibility to new particles	Clean collisions High precision Model-Independent Higgs Measurements	Precision measurements of parton distribution functions Lowest cost	High energy lepton collisions Clean collisions
High background Highest cost	Synchrotron radiation Lower energy reach	Limited energy reach Intermediary background	Muon lifetime Significant technology challenges (cooling, decay)

Collider Physics after the LHC

proton-proton

- FCC-hh
- SPPC

electron-positron

- **FCC-ee**
- CEPC
- **CLIC**
- **ILC**
- C^3

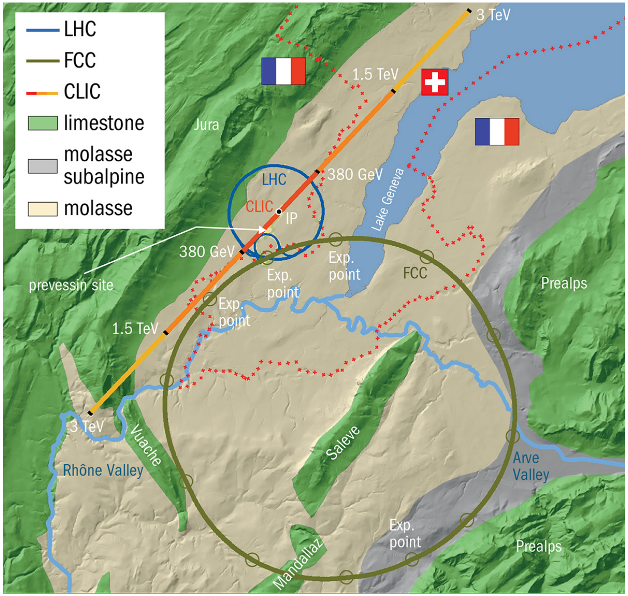
proton-electron

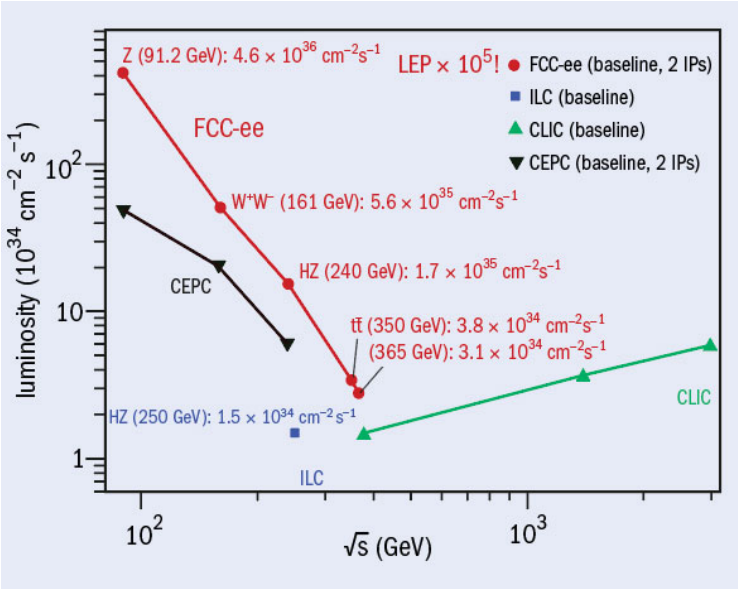
- LHeC

muon-muon

- MC

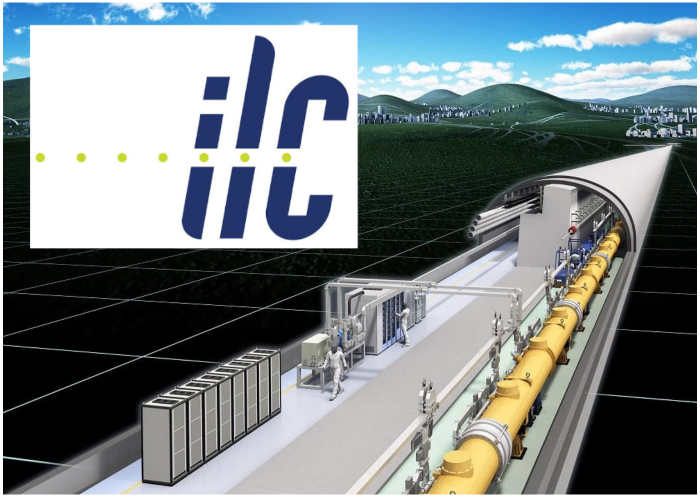
CLIC vs FCC-ee

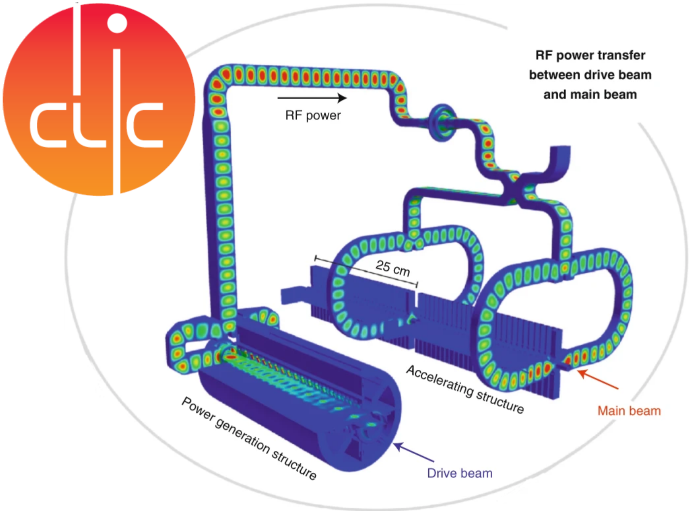




- The luminosity of the FCC-ee is higher than CLIC for the HZ and $t\bar{t}$ signals but the FCC-ee has near-zero discoverability capacity
- CLIC's first-stage (380GeV) cost is roughly half of the FCC-ee's
- CLIC's second and third stages are potential discovery experiments

CLIC vs ILC





- Super-Conducting
- Powered by klystrons in a parallel tunnel
- Cheaper early stages

- Normal-Conducting
- Powered by a parallel **Drive-Beam**
- Cheaper late stages

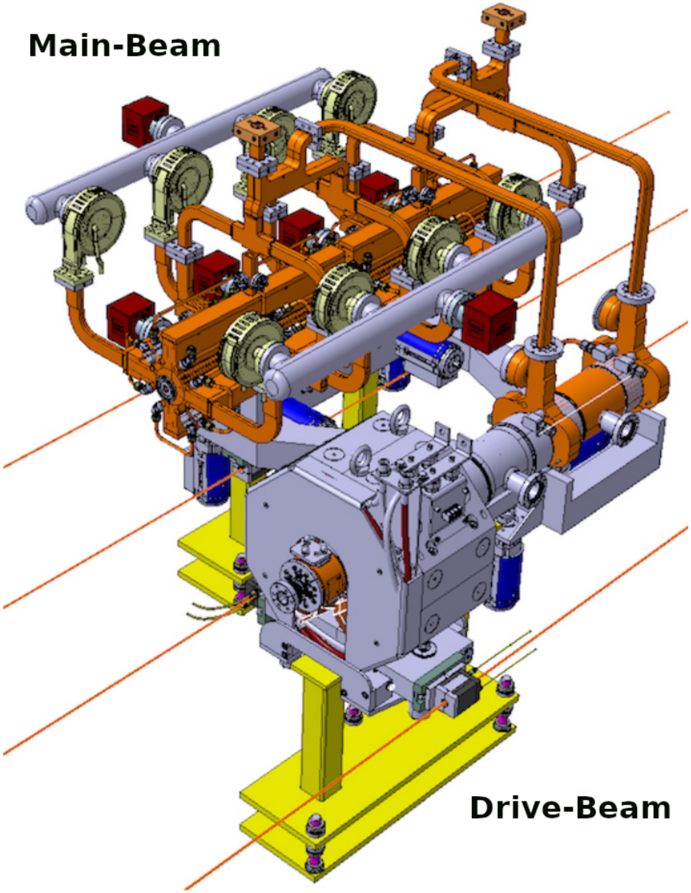
CLIC Two-Beam Acceleration Scheme

Drive-Beam:

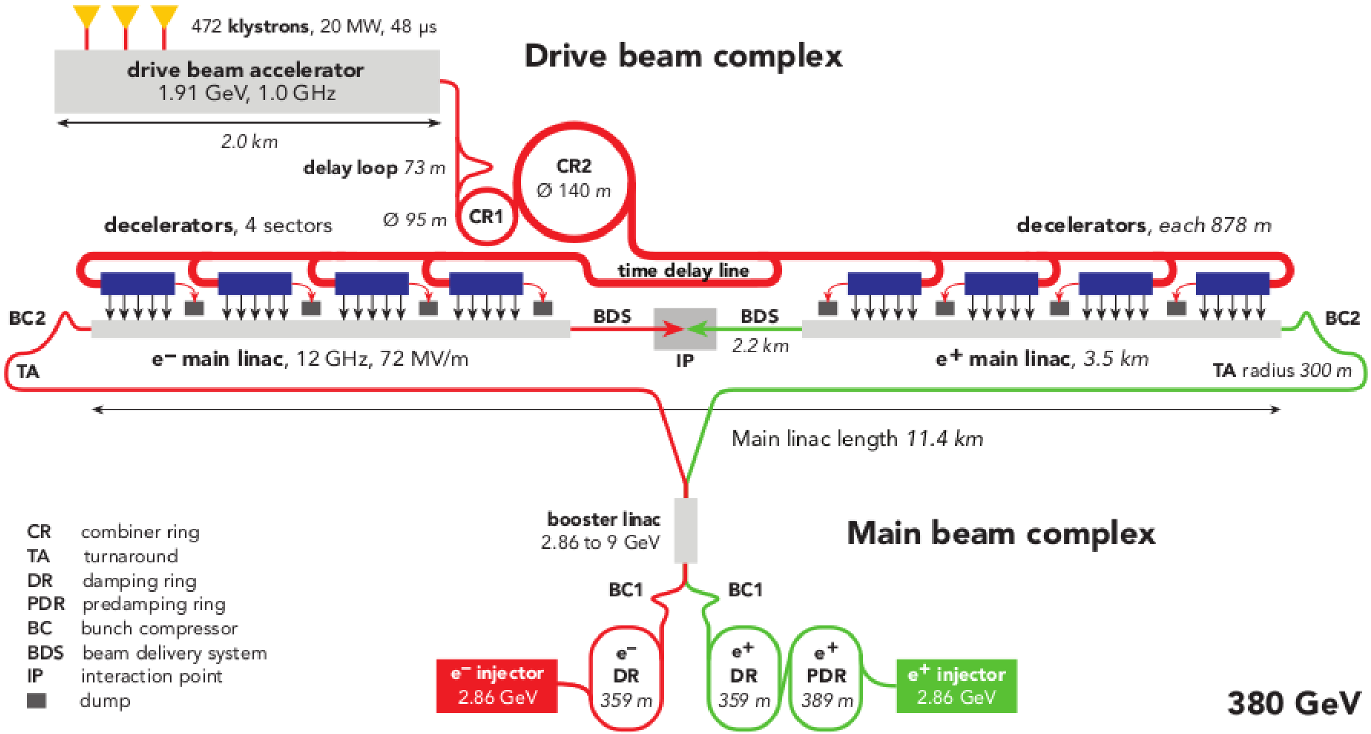
	1st-stage	3rd-stage
Energy	1.9 GeV	2.4 GeV
Frequency	12 GHz	
Current	101 A	
τ_{pulse}	244 ns	
$P_{\text{extracted}}$	$>90\%$	

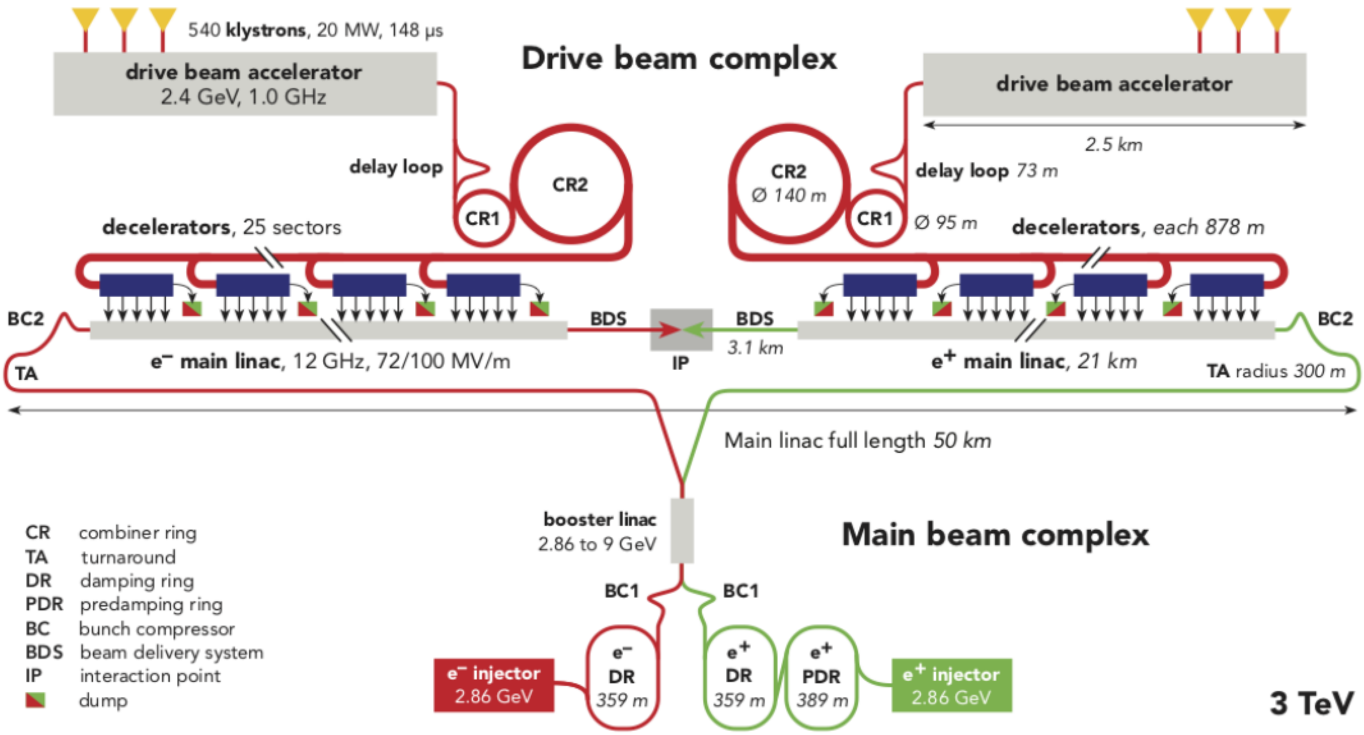
Main-Beam:

	1st-stage	3rd-stage
E_{initial}	9 GeV	
τ_{pulse}	176 ns	
Gradient	72 MV/m	100 MV/m
L_{linac}	11 km	
E_{final}	380 GeV	3 TeV



CLIC First-Stage

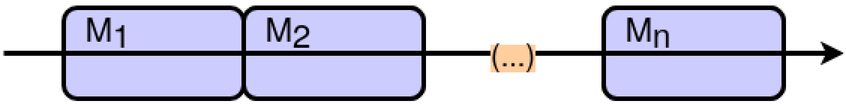



540 klystrons, 20 MW, 148 μs
Drive beam complex
drive beam accelerator
2.4 GeV, 1.0 GHz
drive beam accelerator
2.5 km
delay loop
CR2
CR1
CR2
Ø 140 m
delay loop 73 m
CR1
Ø 95 m
decelerators, 25 sectors
decelerators, each 878 m
BC2
BDS
BDS
BC2
3.1 km
TA
e⁻ main linac, 12 GHz, 72/100 MV/m
IP
e⁺ main linac, 21 km
TA radius 300 m
Main linac full length 50 km
booster linac
2.86 to 9 GeV
Main beam complex
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
BC1
BC1
e⁻ injector
2.86 GeV
e⁻
DR
359 m
e⁺
DR
359 m
e⁺
PDR
389 m
e⁺ injector
2.86 GeV
3 TeV

Accelerator Physics and Simulations

Modeling the Beamline

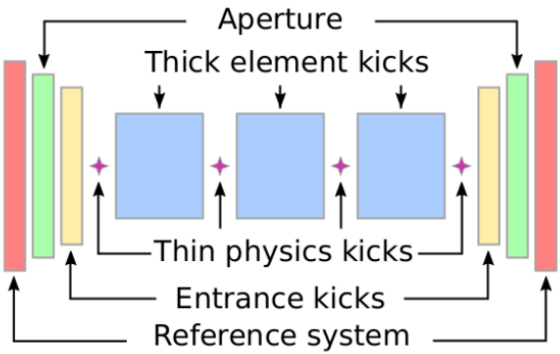
For a given sequence of elements



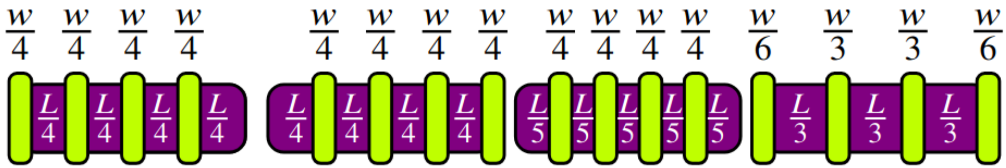
we can establish a response matrix

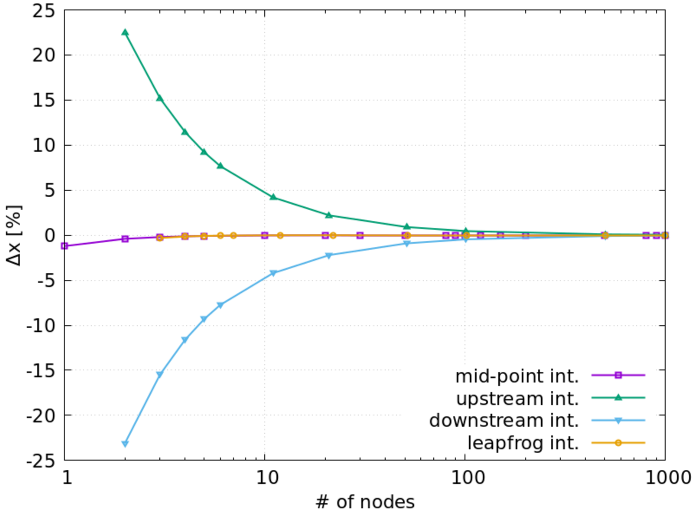
$$R = R_n \cdot ... \cdot R_2 \cdot R_1$$

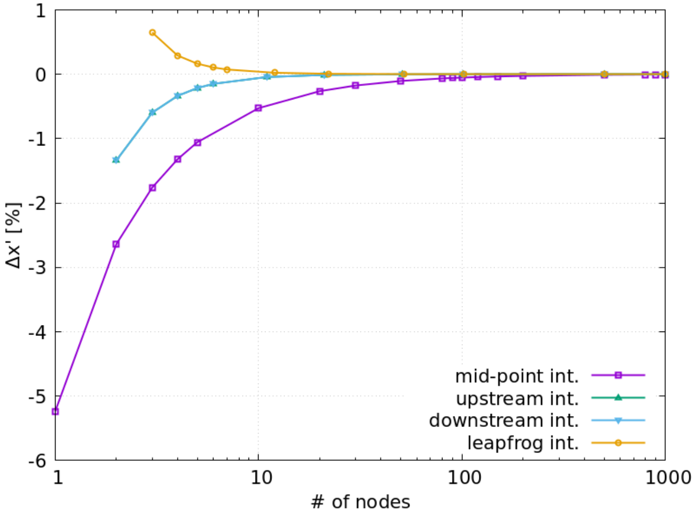
Each element can then be sub-divided



Element Slicing

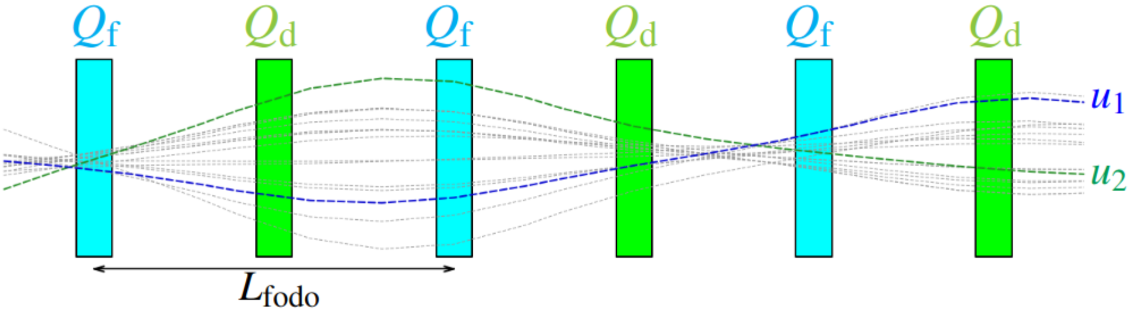






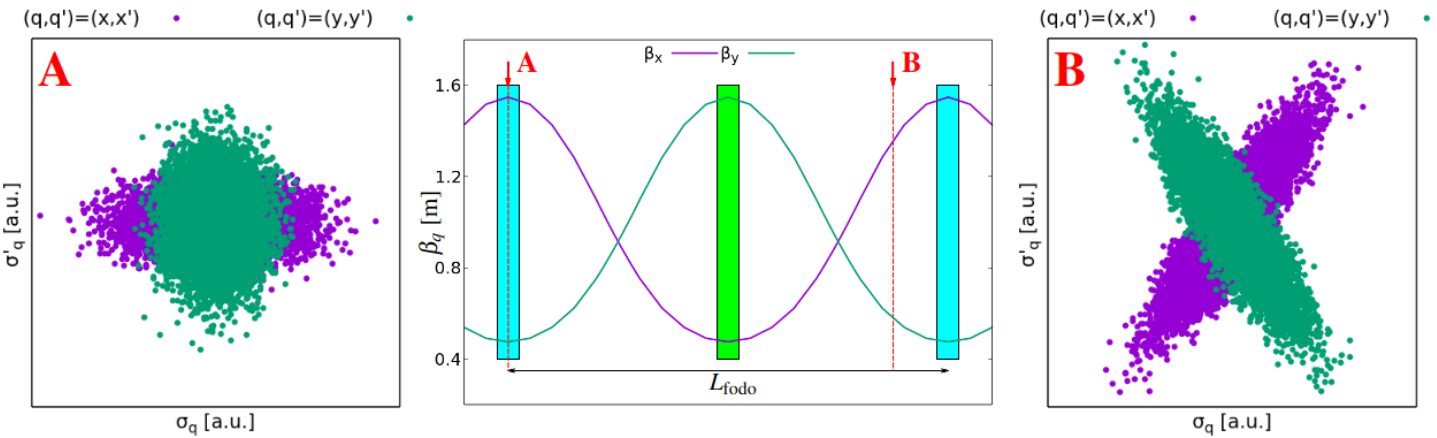
Modeling the Beam - Particles

Individual particles are described by $\{x,\ x',\ y,\ y',\ z,\ \delta\}$



Modeling the Beam - Bunches

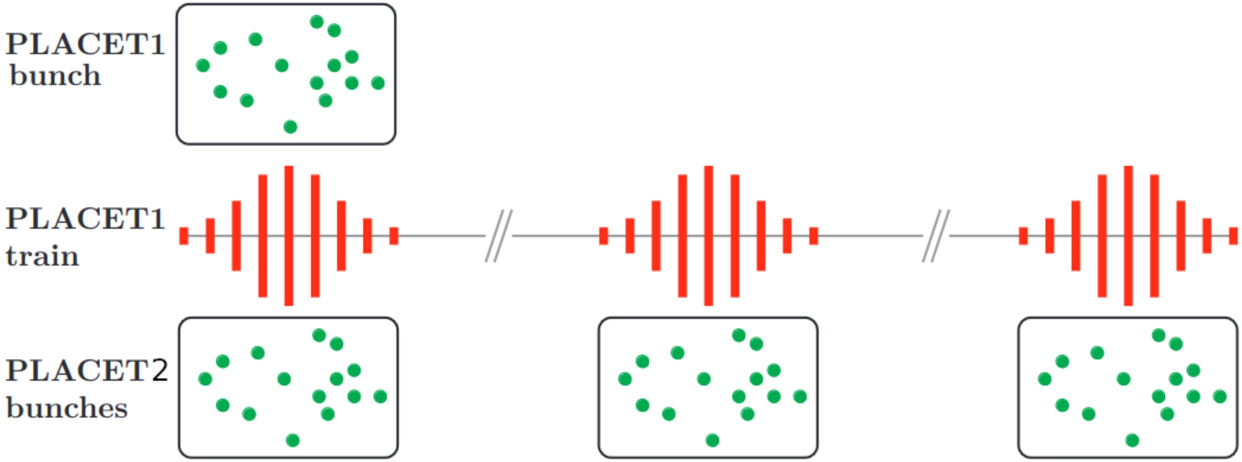
For an ensemble of particles (bunch)



$$\Sigma_x = \begin{bmatrix} \langle x, x \rangle & \langle x, x' \rangle \\ \langle x, x' \rangle & \langle x', x' \rangle \end{bmatrix} = \varepsilon_x \begin{bmatrix} \beta_x & -\alpha_x \\ -\alpha_x & \gamma_x \end{bmatrix}$$

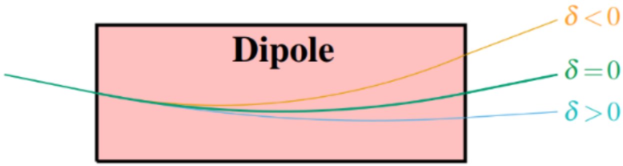
$$\sigma_x = \sqrt{\varepsilon_x \beta_x} \qquad \sigma_{x'} = \sqrt{\varepsilon_x \gamma_x}$$

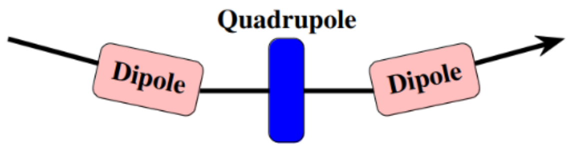
Modeling the Beam - Tracking

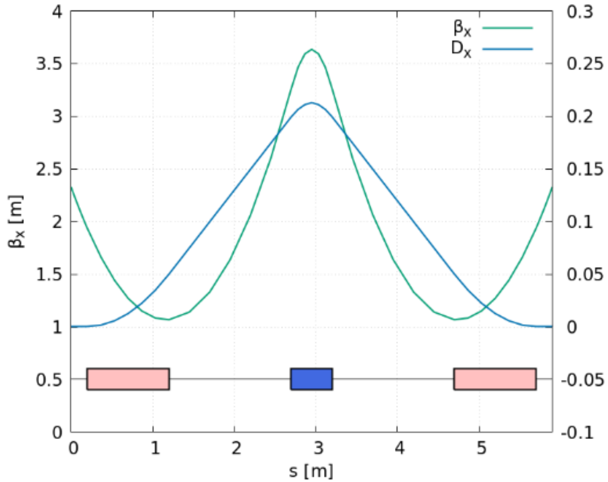


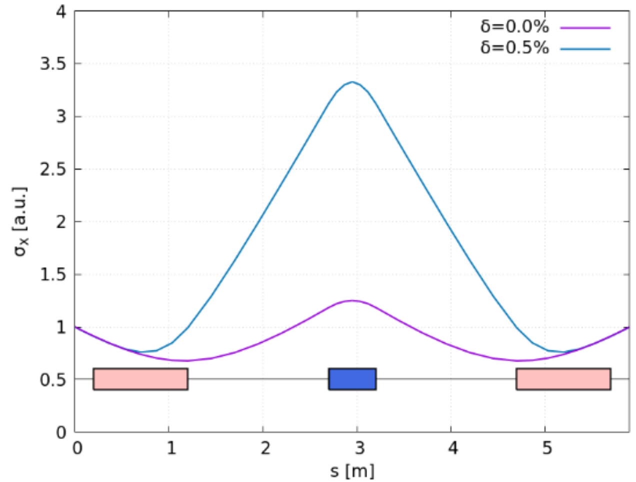
- PLACET1 uses 3 different bunch models:
  - a 4D single-bunch macro-particle ensemble
  - a 6D single-bunch macro-particle ensemble (for dispersion)
  - a sliced-beam model for accelerating structure and PETS (that can also be used to model a full train)
- PLACET3 can model each bunch individually as a 6D ensemble. It also allows for different-weighted particles (usefull for halo/tail studies)

Dispersion

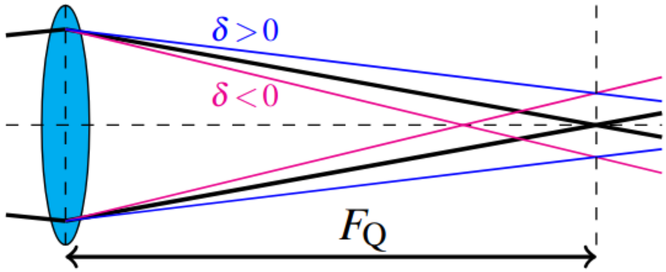

Dipole
$\delta < 0$
$\delta = 0$
$\delta > 0$

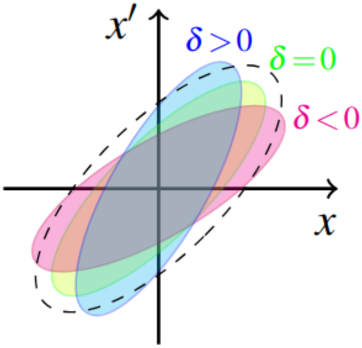

Quadrupole
Dipole
Dipole

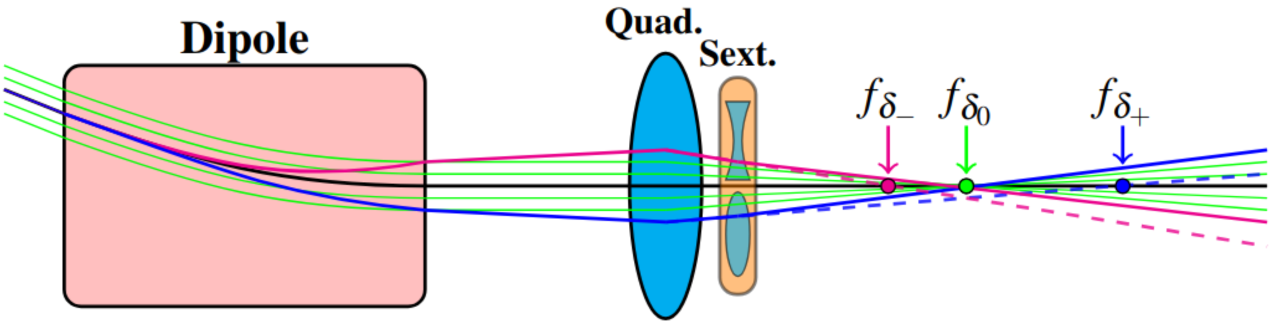

β_x
D_x
β_x [m]
D_x [m]
s [m]


δ=0.0%
δ=0.5%
σ_x [a.u.]
s [m]

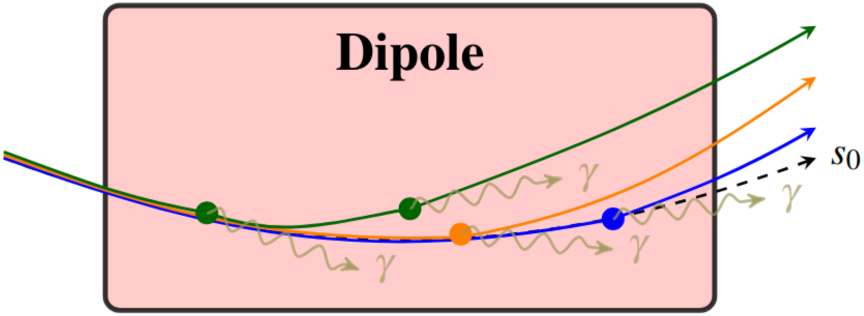
Chromaticity





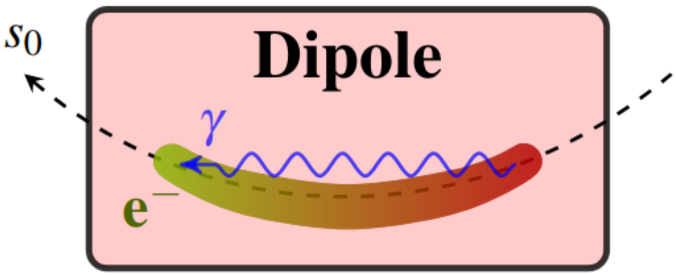


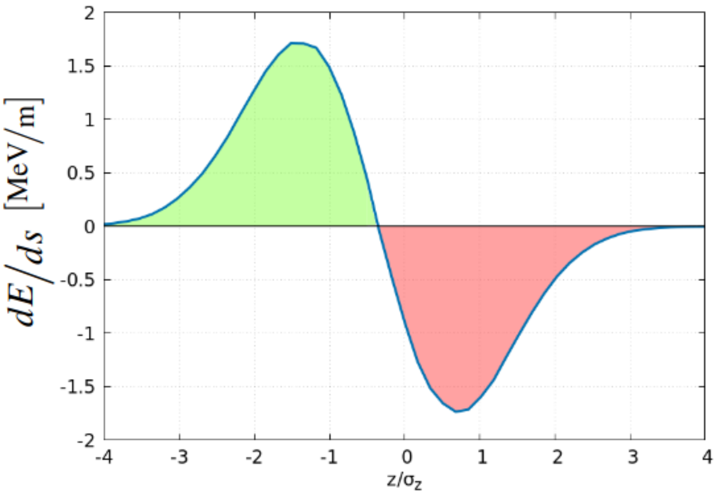
Incoherent Synchrotron Radiation



$$\Delta E = \frac{2}{3}\frac{\theta}{\rho}q^2\left(\frac{E}{m_0c^2}\right)^4$$

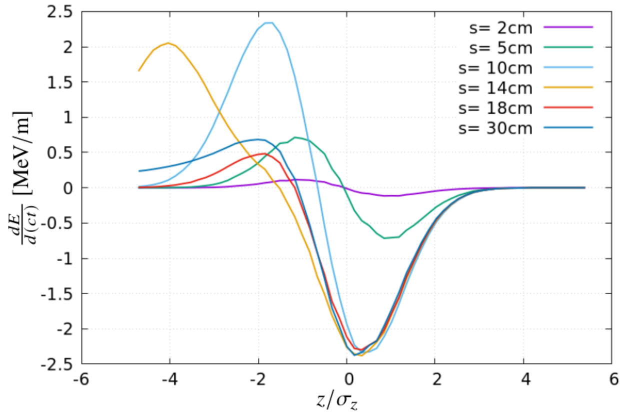
Coherent Synchrotron Radiation

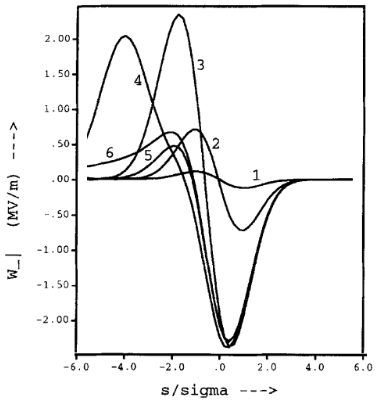




$$\frac{dE(z,\phi)}{d(ct)} = -\frac{2Nr_c mc^2}{3^{1/3}\rho^{2/3}}\left\{\frac{\lambda(z-z_\mathrm{s})-\lambda(z-4z_\mathrm{s})}{z_\mathrm{s}^{1/3}} + \int_{z-z_\mathrm{s}}^{z}\frac{\lambda'(z')}{(z-z')^{1/3}}dz'\right\}$$

$$I_\mathrm{CSR}(z,\phi) = \frac{3}{2}\left\{z_\mathrm{s}^{2/3}\lambda'(z-z_\mathrm{s}) + \int_{z-z_\mathrm{s}}^{z}(z-z_\mathrm{s})^{2/3}\lambda''(z')\,dz'\right\}$$





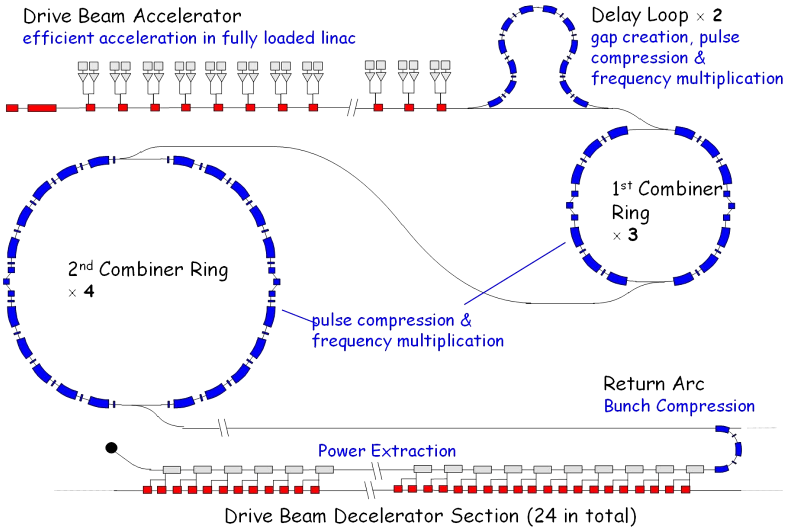
M. Dohlus, T. Limberg / Nucl. Instr. and Meth. in Phys. Res. A 393 (1997) 494–499

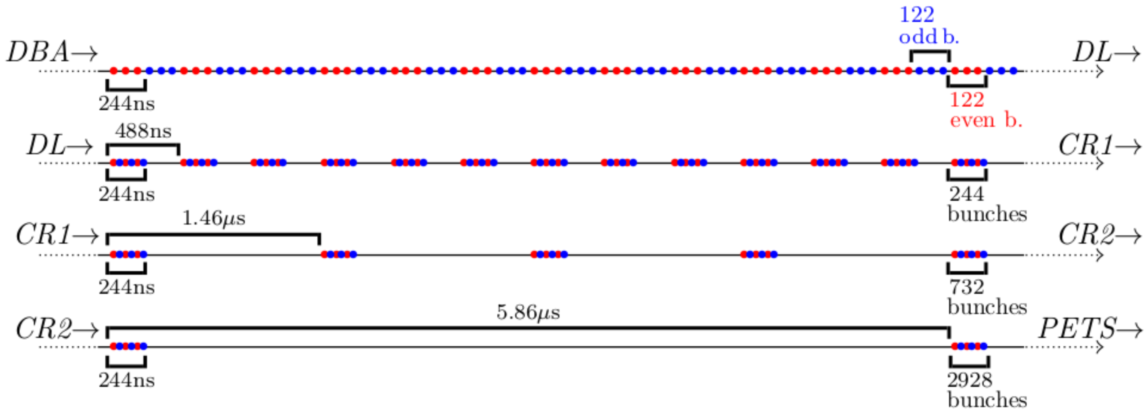
$$\frac{dE\left(z,\phi\right)}{d\left(ct\right)} = -\frac{2Nr_c mc^2}{3^{1/3}\rho^{2/3}}\left\{\frac{\lambda\left(z-z_{\mathrm{s}}\right)-\lambda\left(z-4z_{\mathrm{s}}\right)}{z_{\mathrm{s}}^{1/3}} + \int_{z-z_{\mathrm{s}}}^{z}\frac{\lambda'\left(z'\right)}{\left(z-z'\right)^{1/3}}dz'\right\}$$

$$I_{\mathrm{CSR}}\left(z,\phi\right) = \frac{3}{2}\left\{z_{\mathrm{s}}^{2/3}\lambda'\left(z-z_{\mathrm{s}}\right) + \int_{z-z_{\mathrm{s}}}^{z}\left(z-z_{\mathrm{s}}\right)^{2/3}\lambda''\left(z'\right)dz'\right\}$$

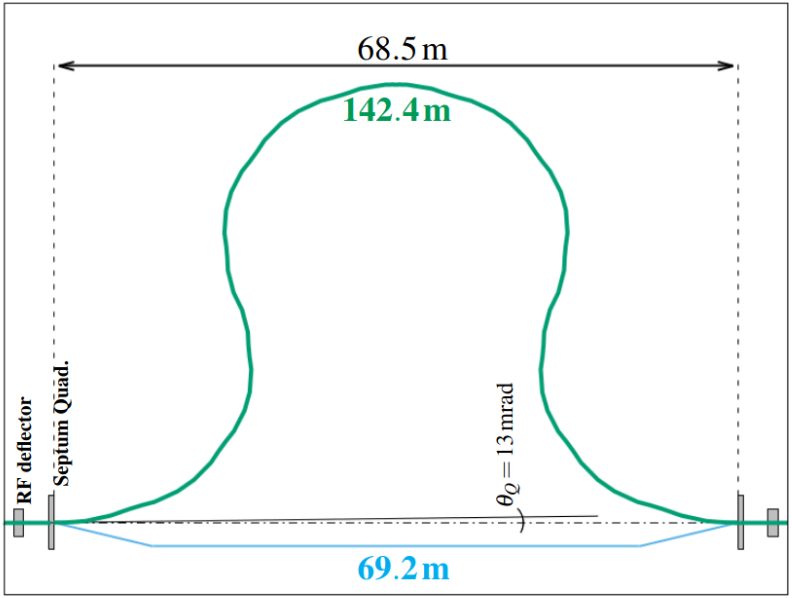
The Drive-Beam Recombination Complex

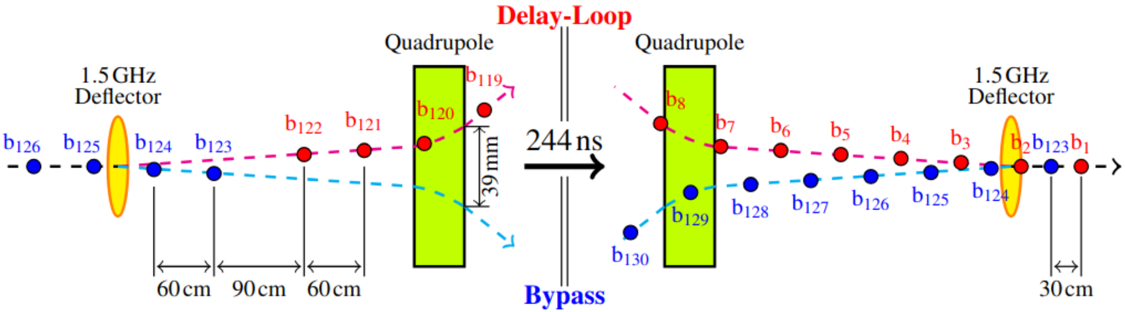
The Drive-Beam Recombination Complex



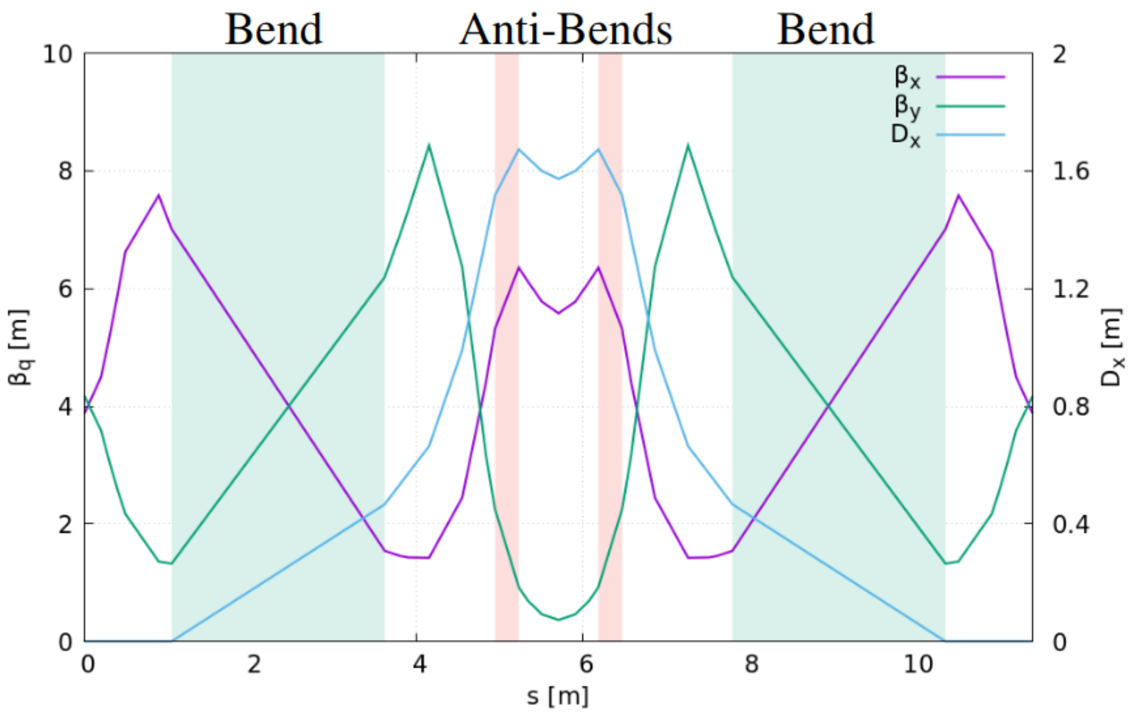


The Delay Loop

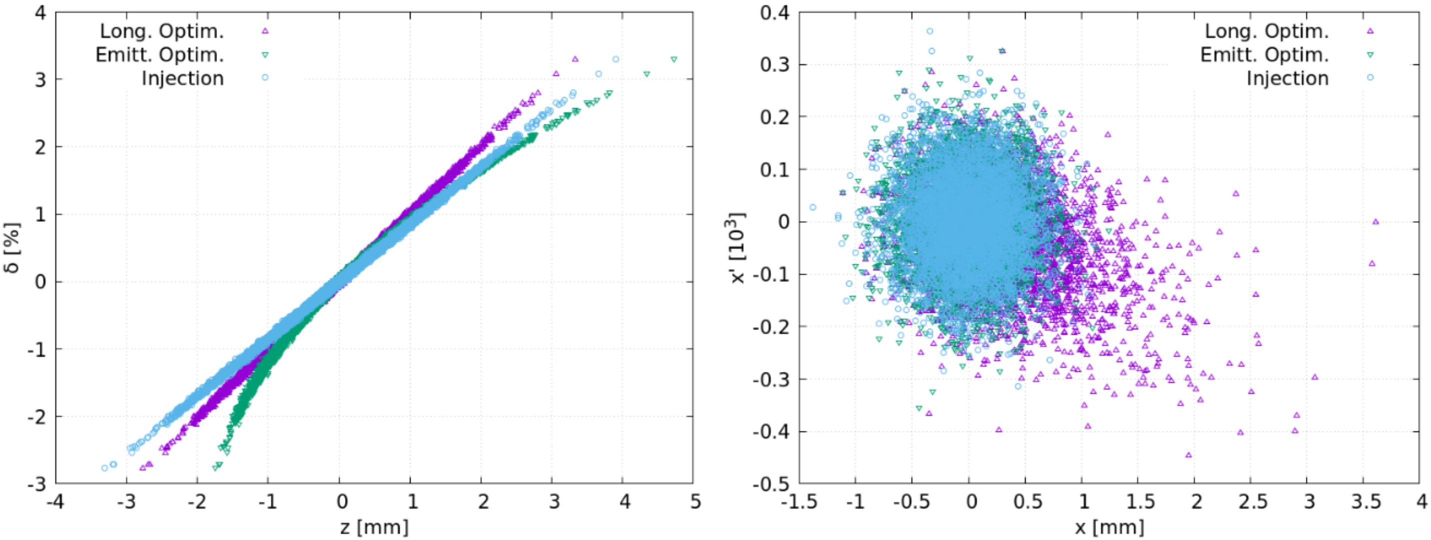




Delay Loop - Arc Optimization



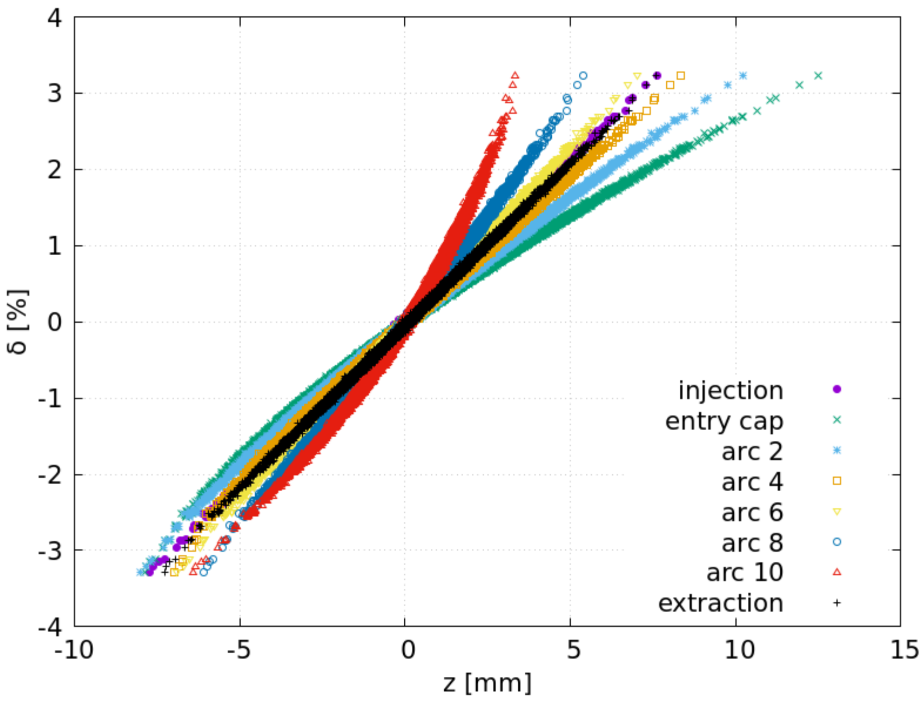
Delay Loop - Arc Optimization



8 Sextupoles:

- Capable of correcting chromaticity
- Capable of correcting T_{566} (longitudinal banana-shape)
- Not capable of correcting both

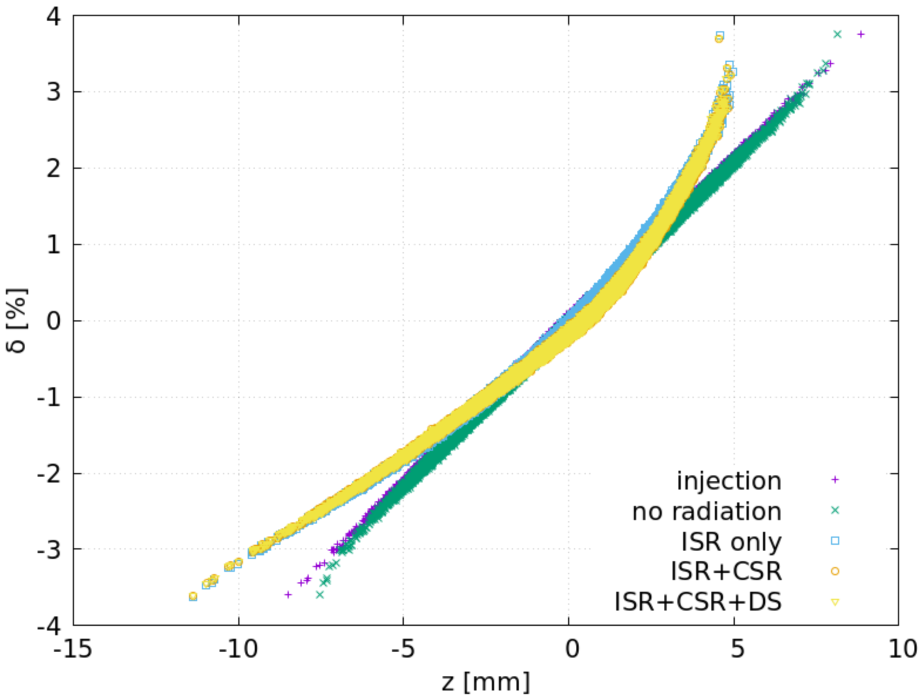
Delay Loop - Arc Optimization



Solution:

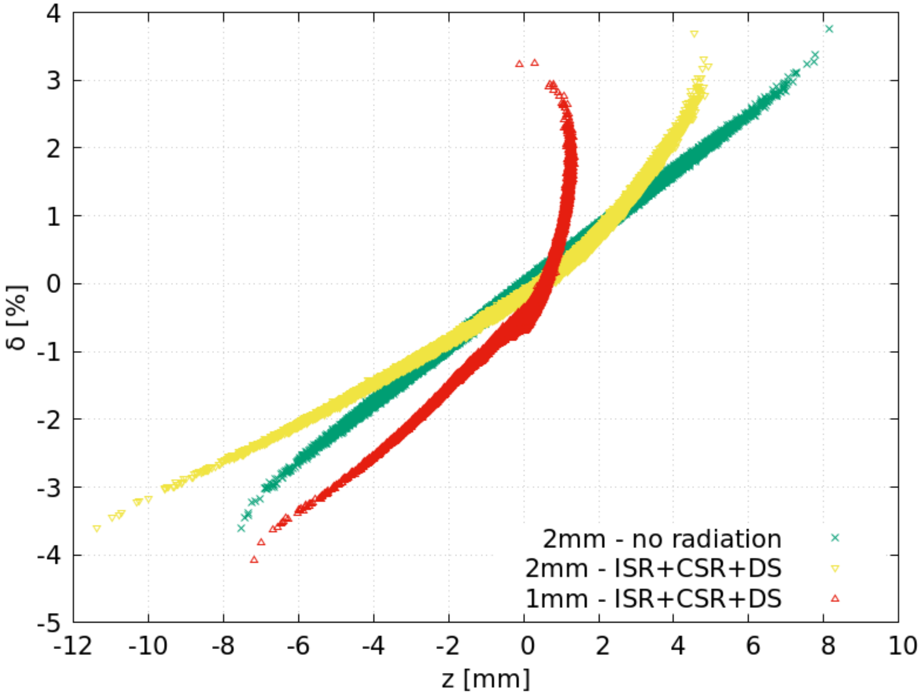
- organizing sextupole optimization in 2-arc super-cells

Delay Loop - Impact of Radiation



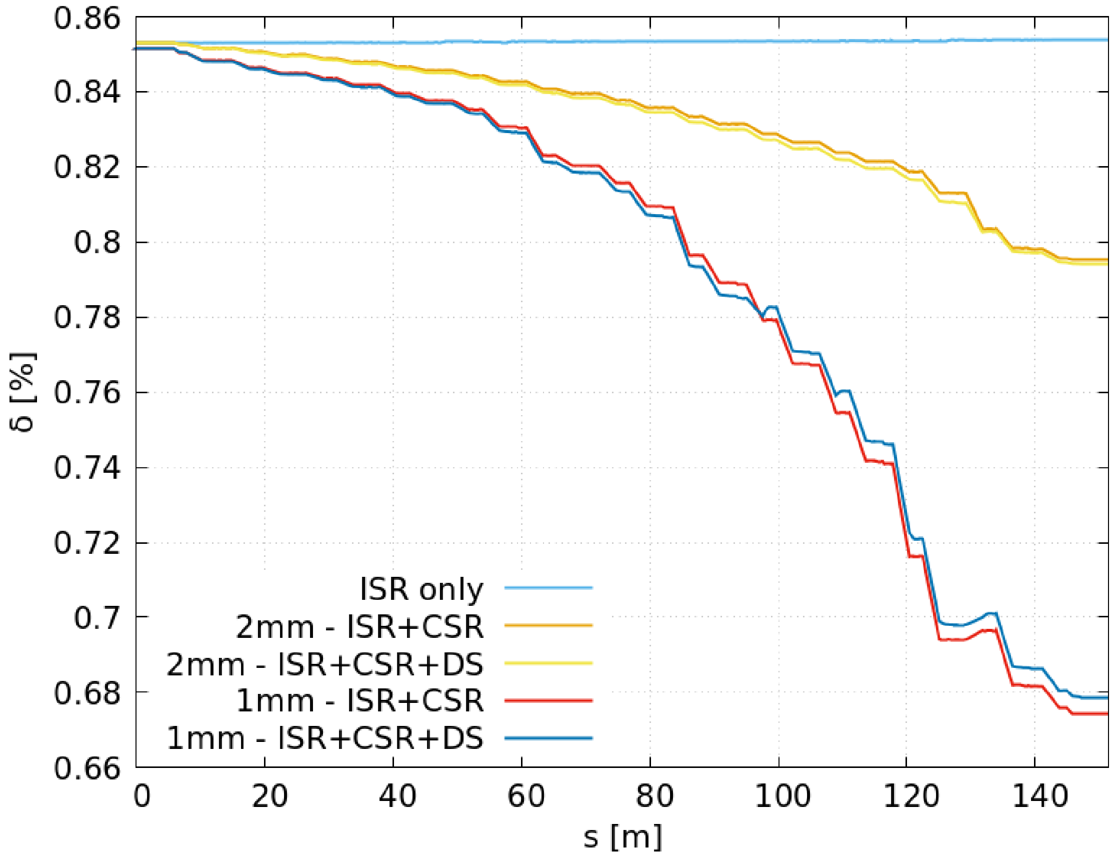
		No radiation	ISR	ISR+CSR	ISR+CSR+DS
ε_x	$[\mu m]$	102	104	118	120
ε_y	$[\mu m]$	100	100	101	101

Delay Loop - The Need for Bunch-Lengthening

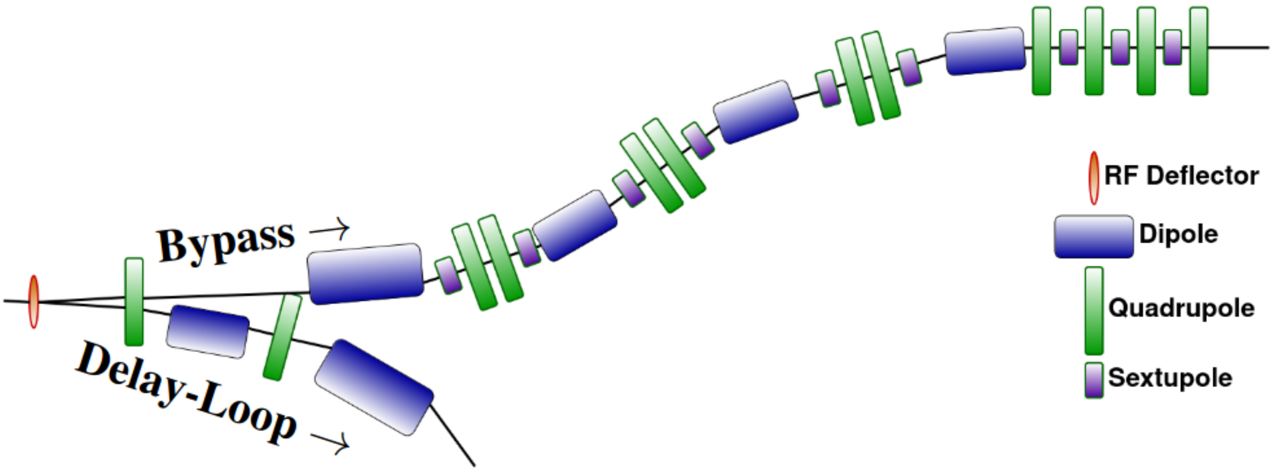


		$\sigma_z = 1\,\text{mm}$		$\sigma_z = 2\,\text{mm}$	
		ISR+CSR	**ISR+CSR+DS**	**ISR+CSR**	**ISR+CSR+DS**
ε_x	[μm]	322	348	118	120
ε_y	[μm]	101	100	101	101

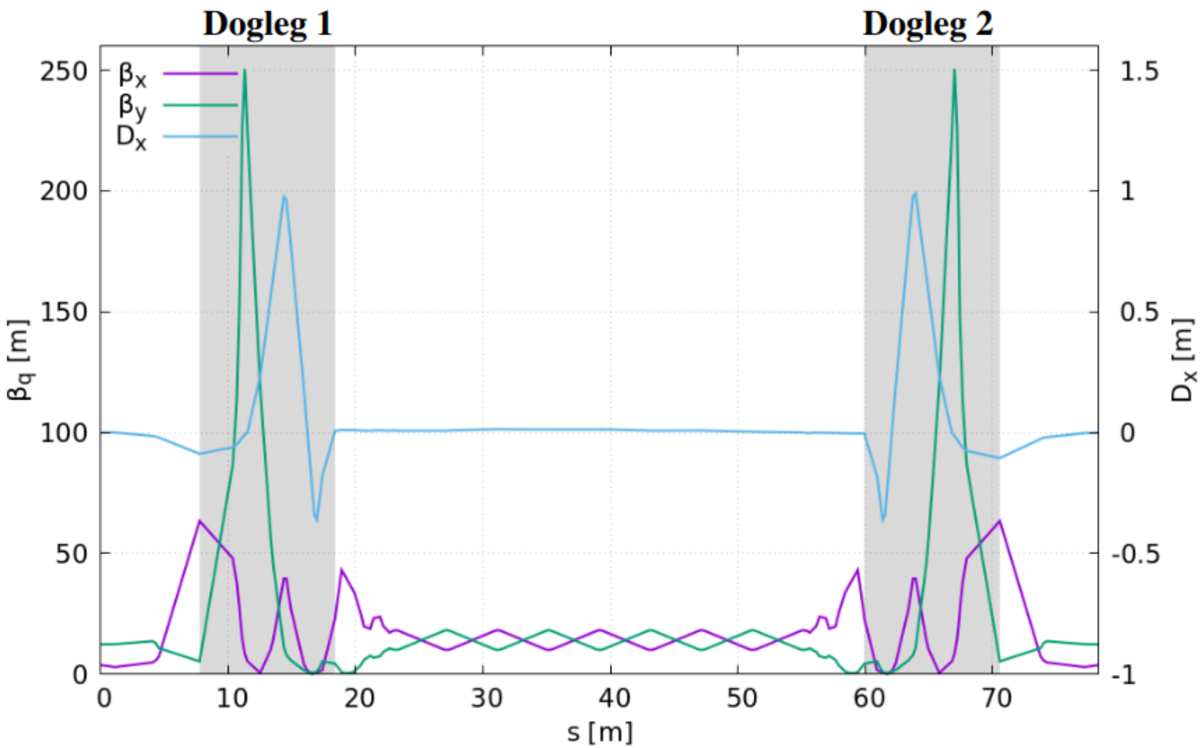
Delay Loop - Impact of Radiation



Delay Loop Bypass



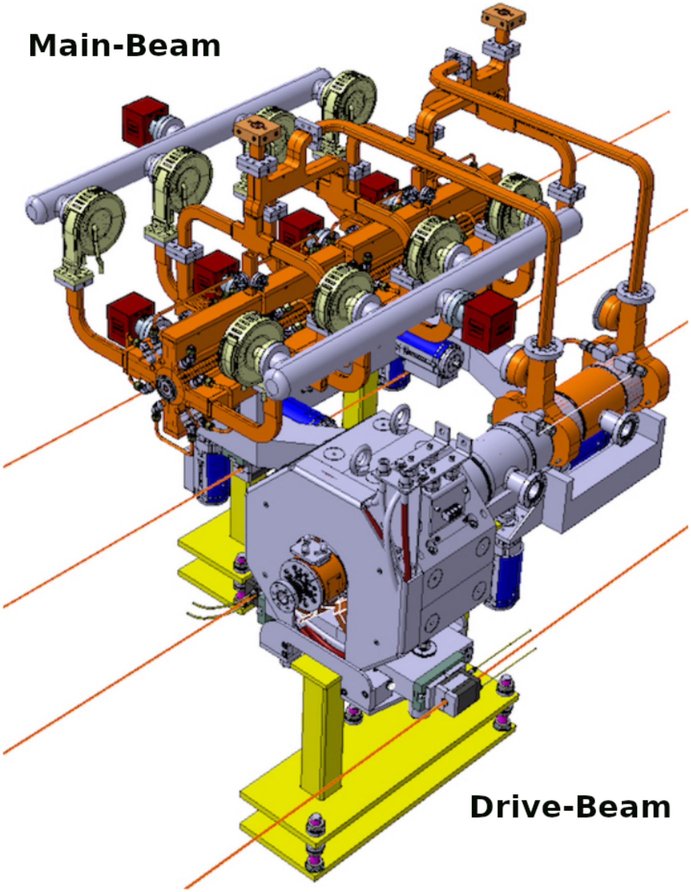
Delay Loop Bypass



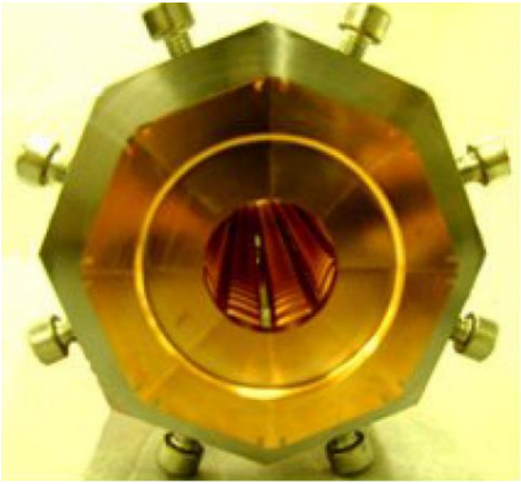
The Drive-Beam Decelerators

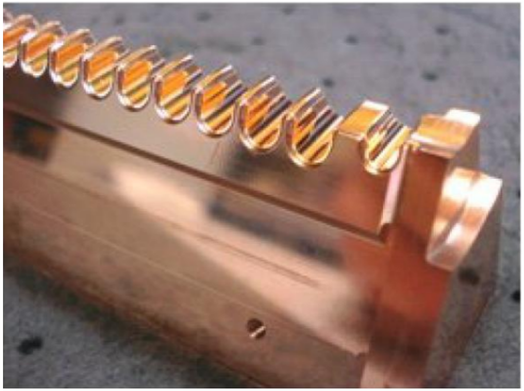
The Drive-Beam Decelerators

Two-Beam Acceleration



PETS

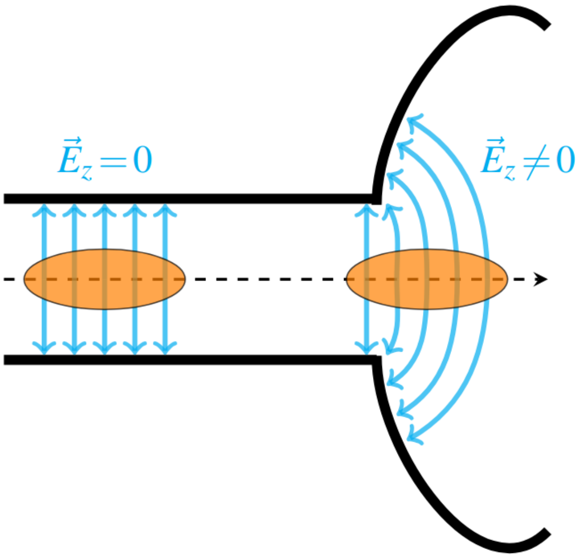




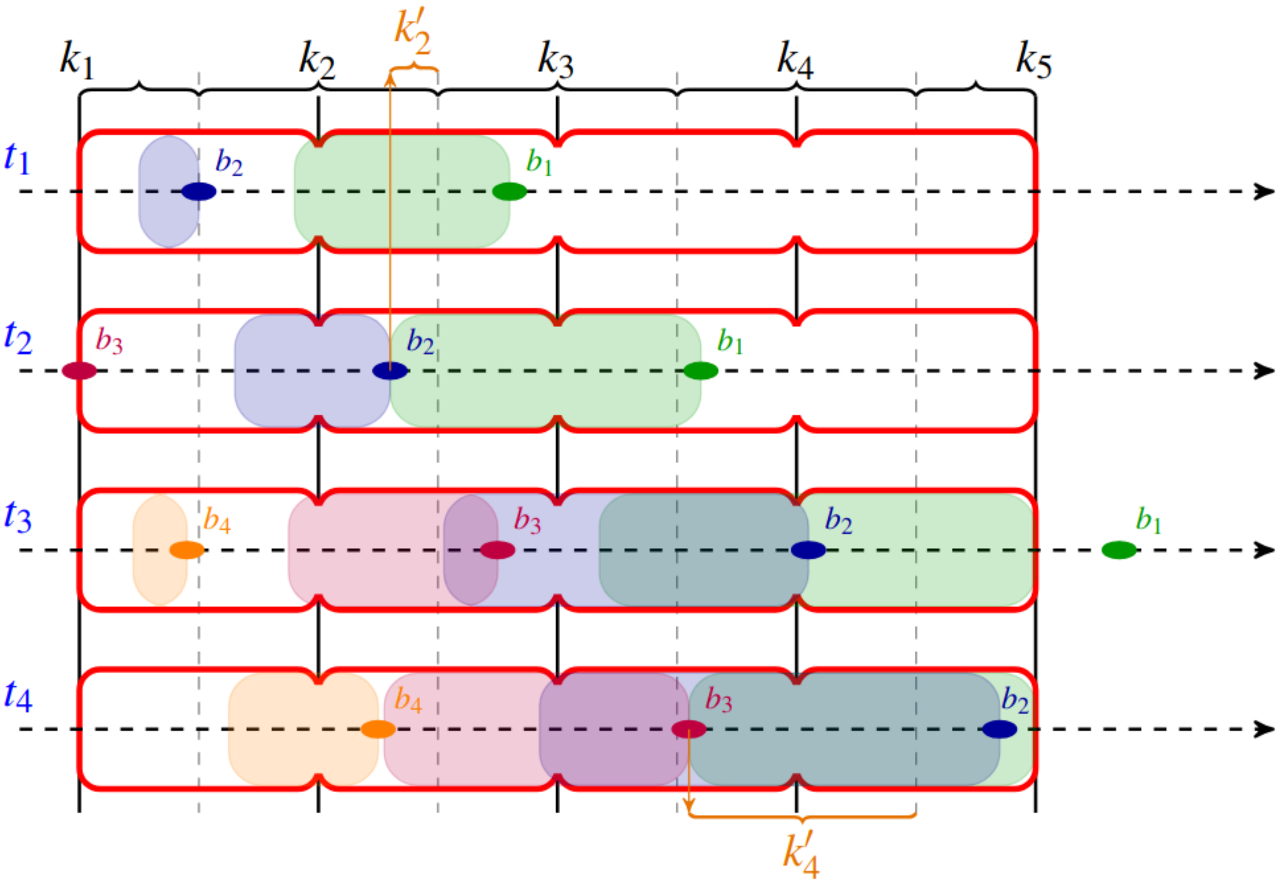
Wakefield Interactions

$$W_L(\tau) = \int_{-\infty}^{\tau} \omega_L(t-\tau)\,\lambda(t)\,dt$$

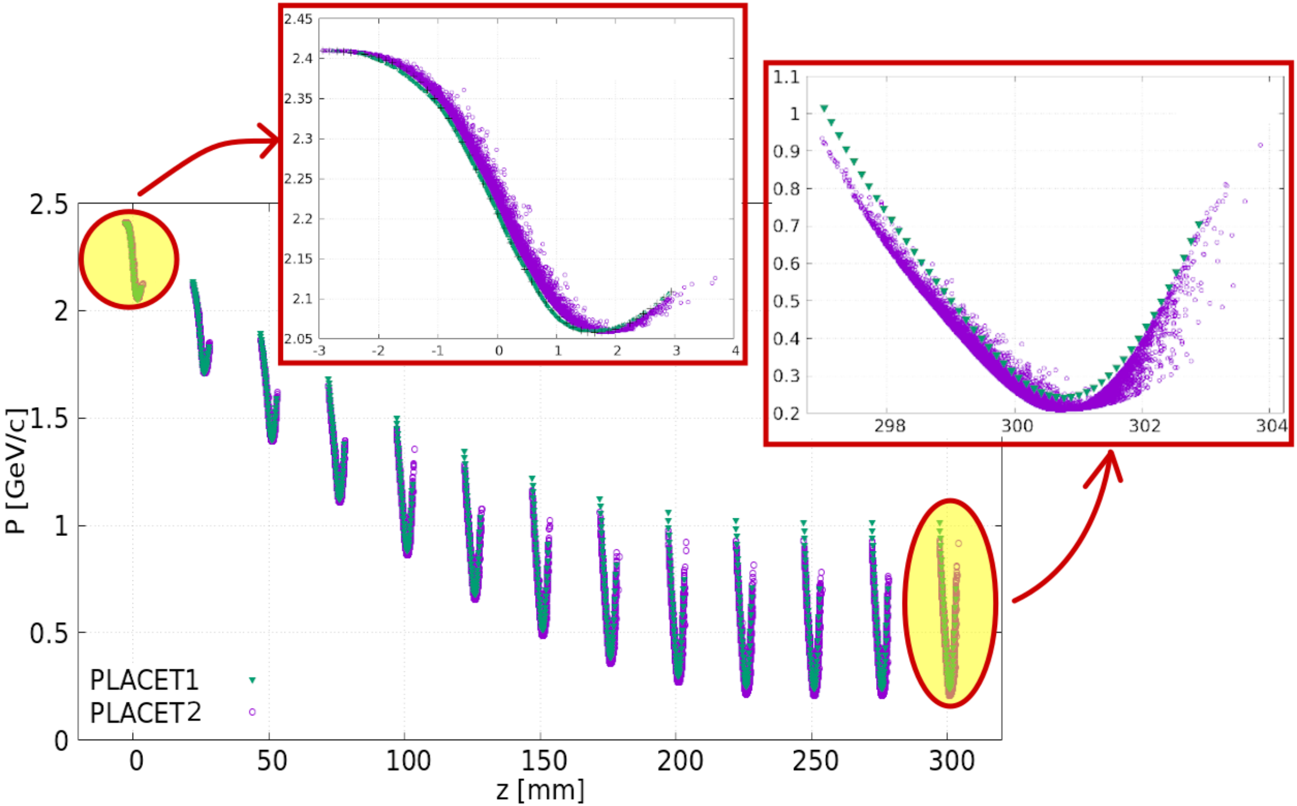
$$W_T(\tau) = \int_{-\infty}^{\tau} \omega_T(t-\tau)\,\mu(t)\,\lambda(t)$$



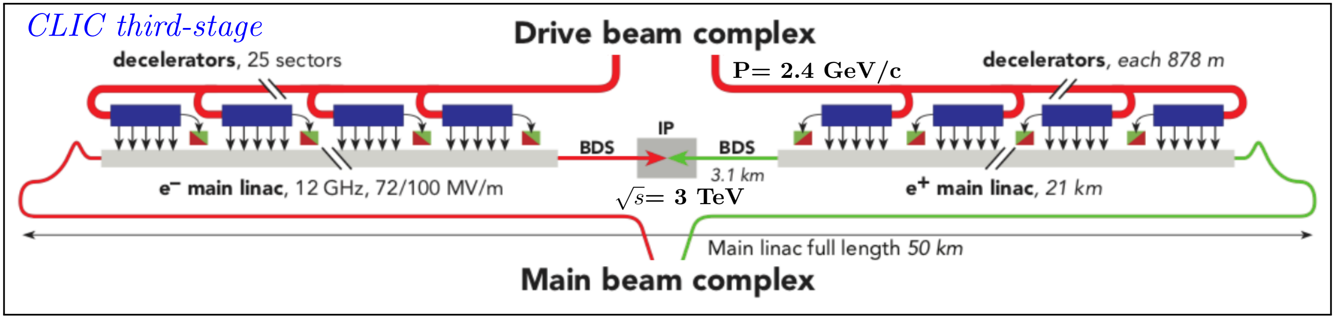
Long-Range Wakefields

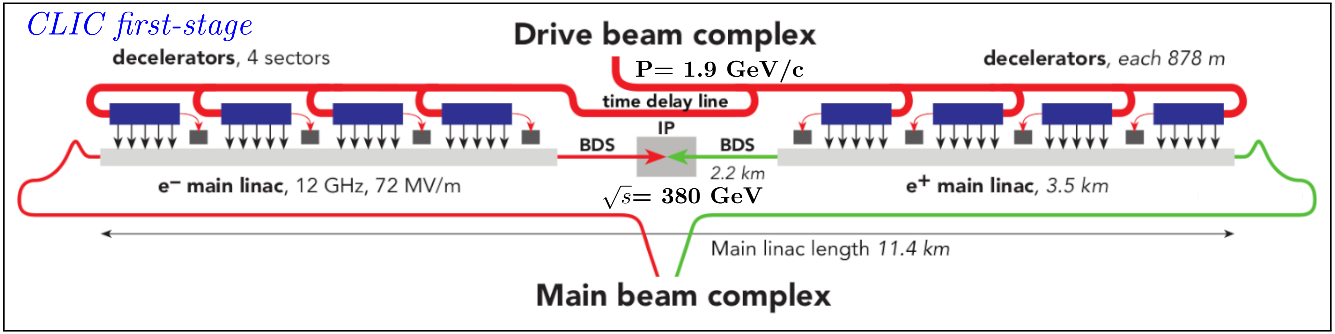


Longitudinal Slippage

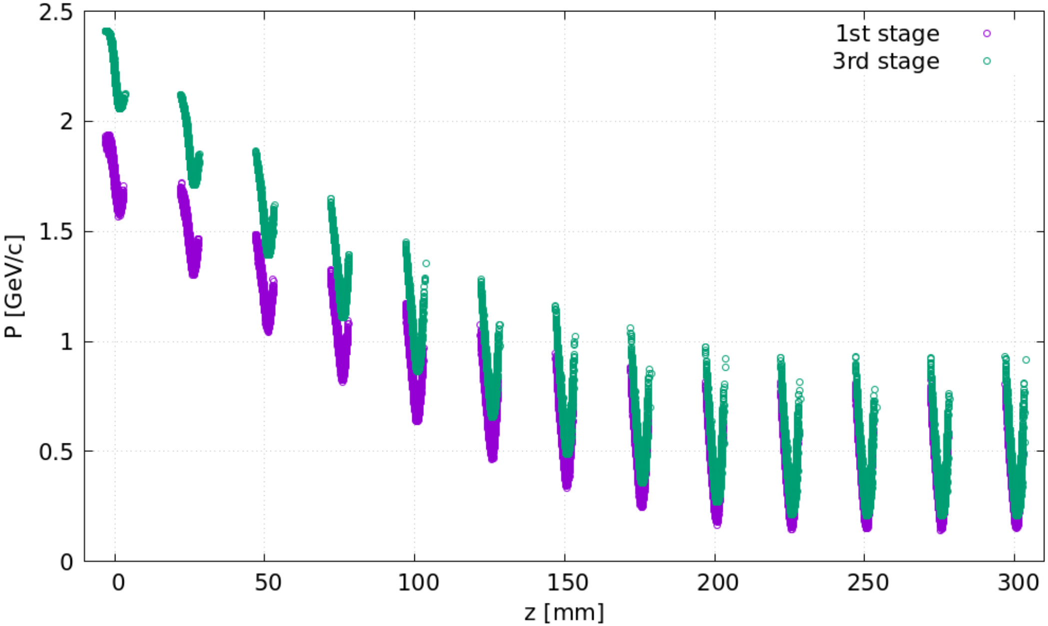


Updating the Decelerator Lattice



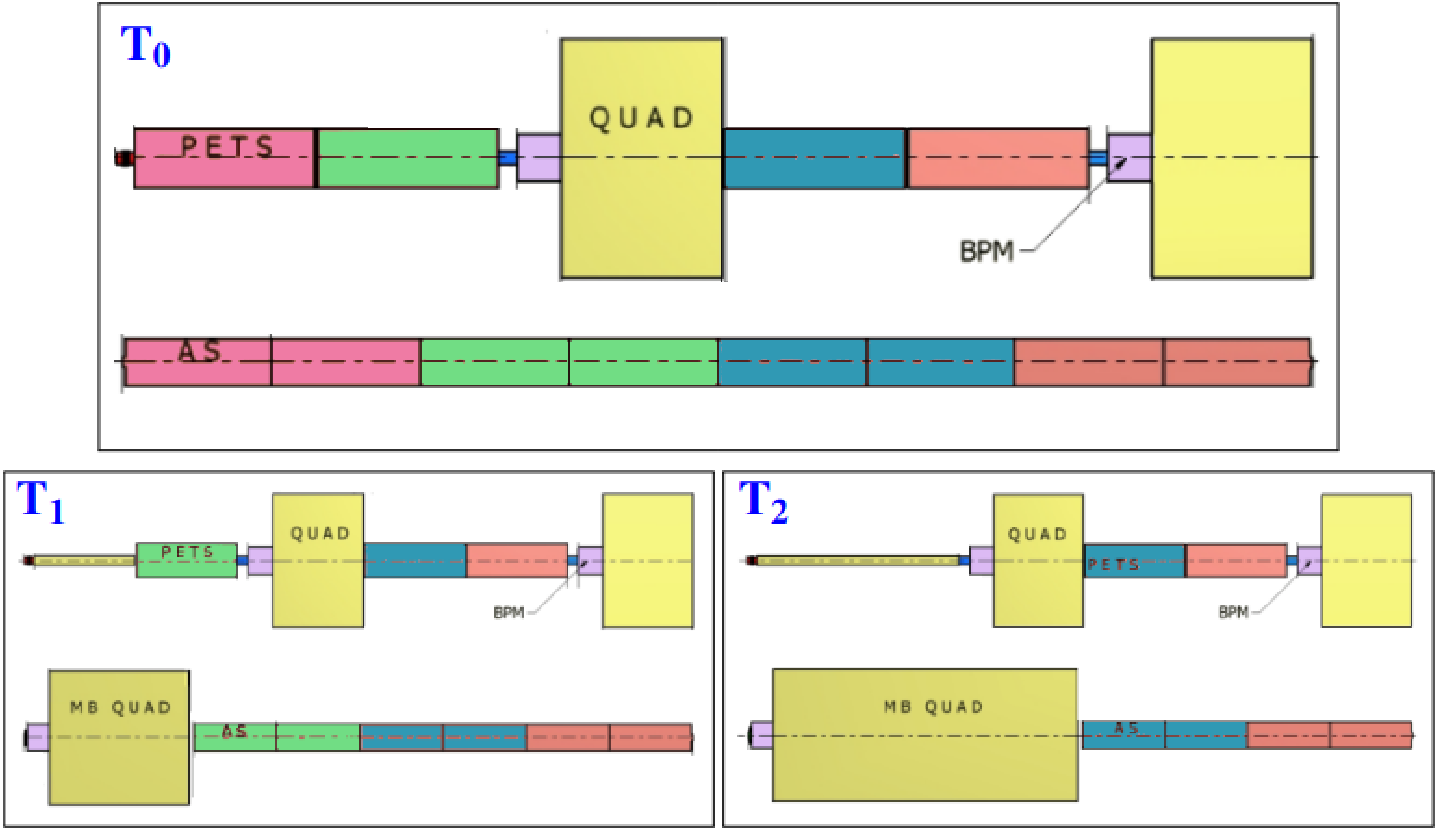


Updating the Decelerator Lattice



- L_{cell}: $2.01\,\text{m} \rightarrow 2.343\,\text{m}$
- L_{PETS}: $213\,\text{mm} \rightarrow 206\,\text{mm}$
- P_{initial}: $2.4\,\text{GeV} \rightarrow 1.9\,\text{GeV}$

Updating the Decelerator Lattice



Updating the Decelerator Lattice

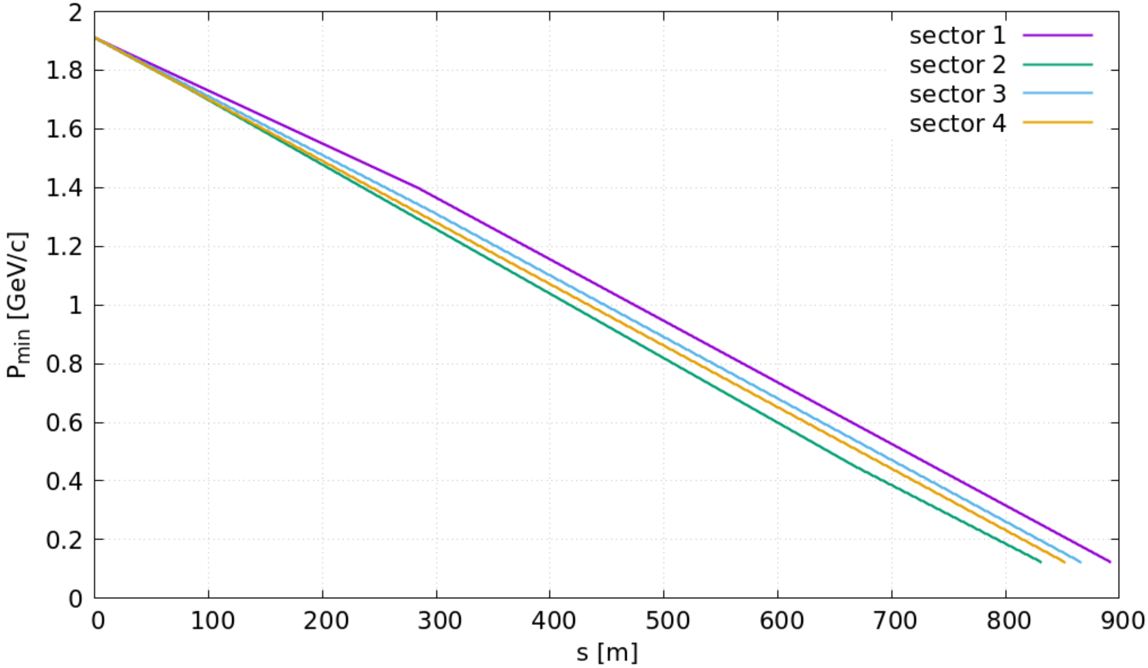
Table 4.2. *Periodic super-cells present in the first-stage decelerators.*

Super-Cell	Modules	Fill-Factor
$\mathbf{S_1}$	$\mathbf{T_1}$	75%
$\mathbf{S_2}$	$\mathbf{T_1 \cdot T_0}$	88%
$\mathbf{S_3}$	$\mathbf{T_1 \cdot T_0 \cdot T_0}$	92%
$\mathbf{S_4}$	$\mathbf{T_2 \cdot T_0 \cdot T_0}$	83%
$\mathbf{S_5}$	$\mathbf{T_2 \cdot T_0 \cdot T_0 \cdot T_0}$	88%

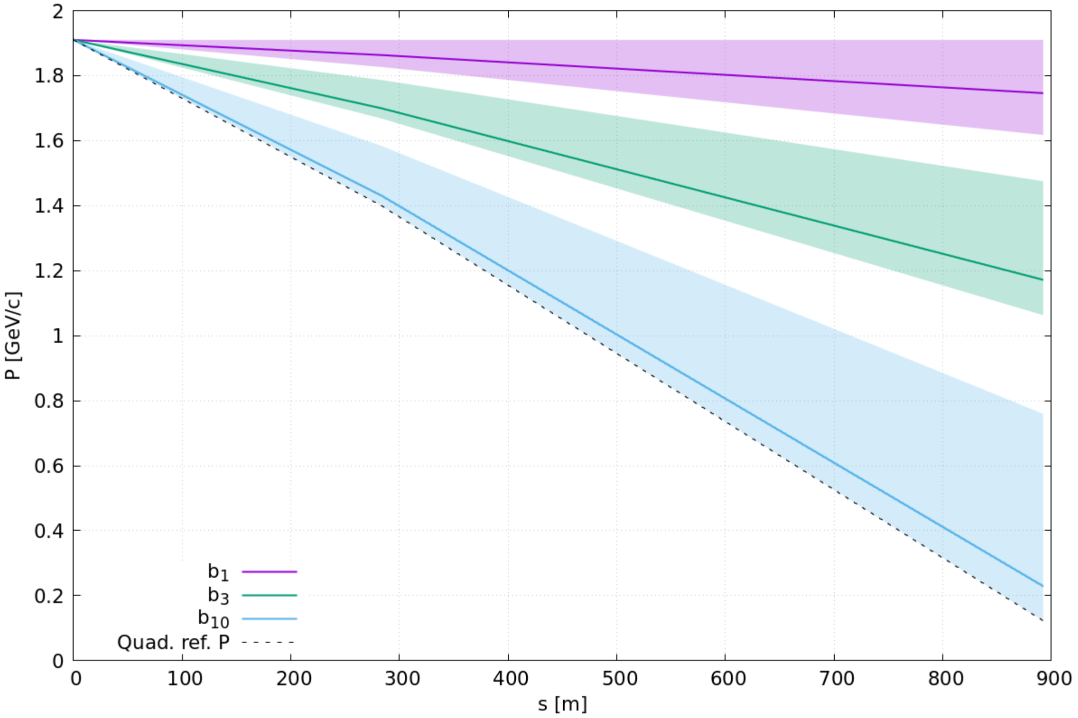
Table 4.3. *Super-cell construction of each Decelerator Sector.*

	$\mathbf{S_1}$	$\mathbf{S_2}$	$\mathbf{S_3}$	$\mathbf{S_4}$	$\mathbf{S_5}$	**Length**
Sector 1	121	130	0	0	0	892 m
Sector 2	0	17	84	23	0	832 m
Sector 3	0	0	0	42	61	867 m
Sector 4	0	0	0	0	91	853 m

Decelerator Results

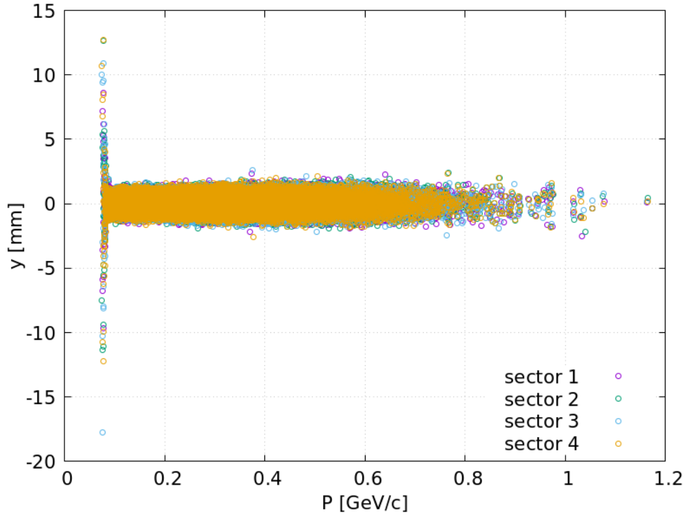


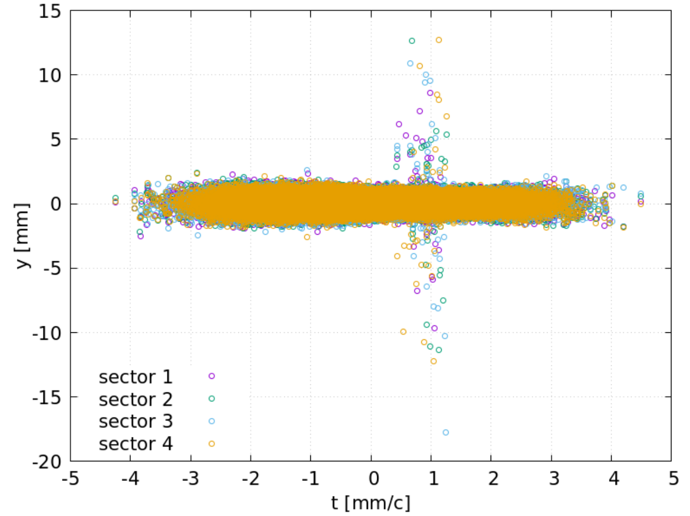
Decelerator Results - Reference Momentum



$$P_{\mathrm{ref}}(n) = P_0 \left[1 - \eta_{\mathrm{extr}} \frac{n}{N_{\mathrm{PETS}}} \right]$$

Decelerator Results - Reference Momentum

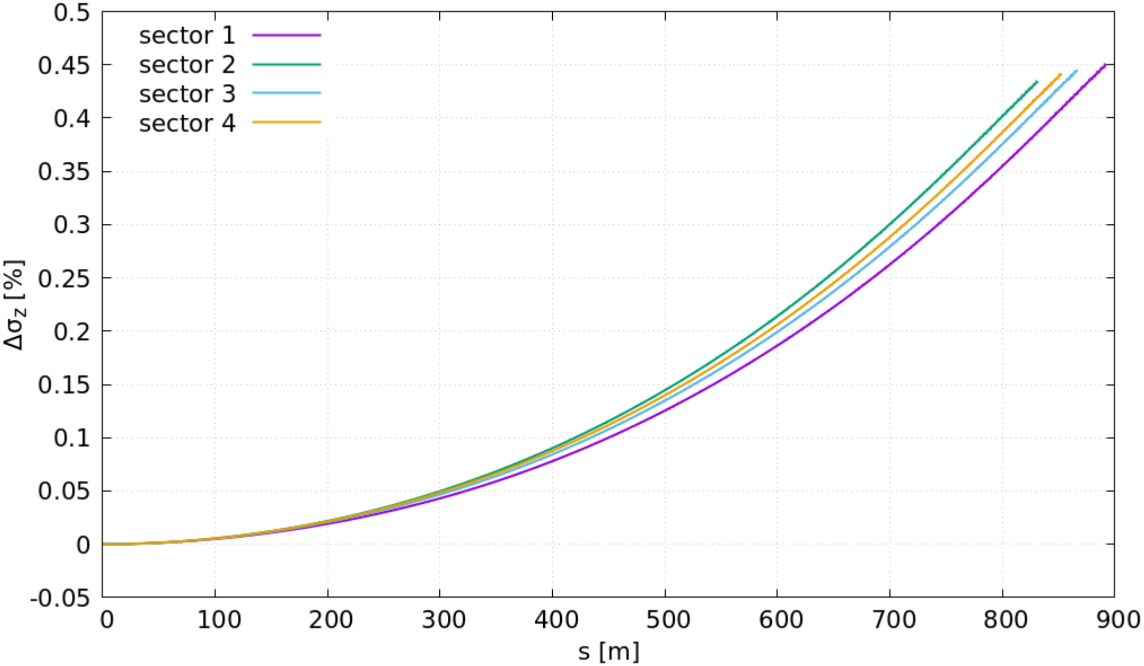




Solution:

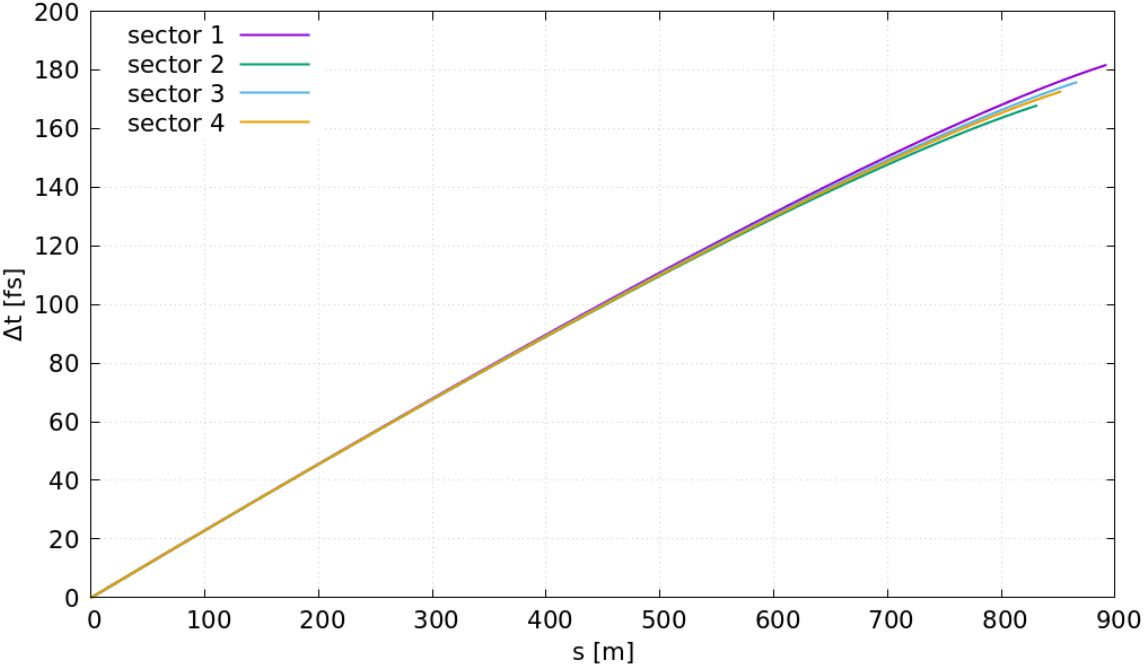
$$P_{\text{ref}}(n) = (P_0 - \delta_0)\left[1 - \eta_{\text{extr}}\frac{n}{N_{\text{PETS}}}\right]$$

Decelerator Results - Bunch lengthening



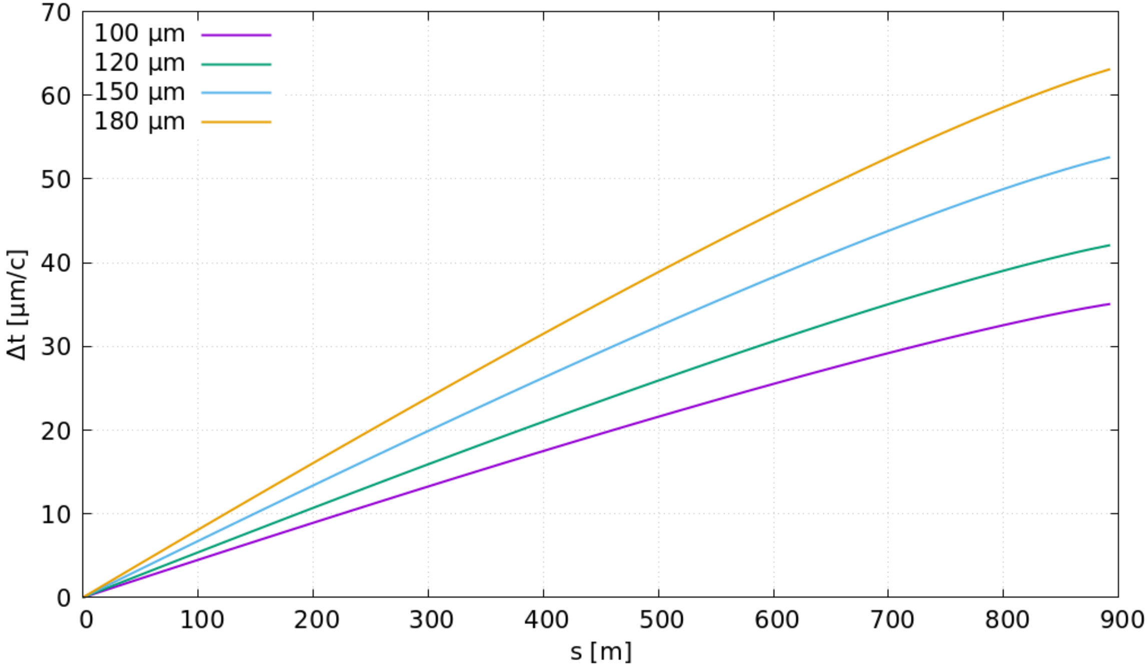
- Bunch length tolerance: 1%
- Power extraction decrease of 0.03%

Decelerator Results - Bunch Delay



- Drive-Beam to Main-Beam synchronization tolerance: 70 fs
- RF needs to be able to correct it

Decelerator Results - Emittance Dependency



- A similar effect can be observed regarding bunch-length

Conclusion

- The CLIC project is technologically mature
- `PLACET3` is the ideal tracking tool for re-circulation topologies like the Drive-Beam (and LHeC, and Muon injectors)
- Non-linear optics of the Delay Loop optimized for transverse and longitudinal chromatic effects
- ISR impacts the Delay Loop longitudinal profile
- CSR impacts the Delay Loop emittance and δ
- There is a definitive need for bunch-lengthening
- Design of the Delay Loop Bypass
- Design of the 1st-stage Decelerator Sectors
- Bunch-length increase due to longitudinal slippage within tolerance
- Bunch phase delay due to longitudinal slippage not within tolerance, RF correction necessary
- Longitudinal slippage correlation with transverse emittance

Outlook

- Combiner Rings 1 and 2 optimized and evaluated for radiation impact in a similar fashion to the Delay Loop - **Ongoing**
- Re-establishment of start-to-end recombination
- **Graduate!**