A Design Study on Dogleg Type Bunch Compressor Line for TARLA Facility

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TARLA is the first and only accelerator-driven free-electron laser (FEL) facility in Turkey, capable of generating infrared (IR) laser radiation using a continuous and/or pulsed electron beam.

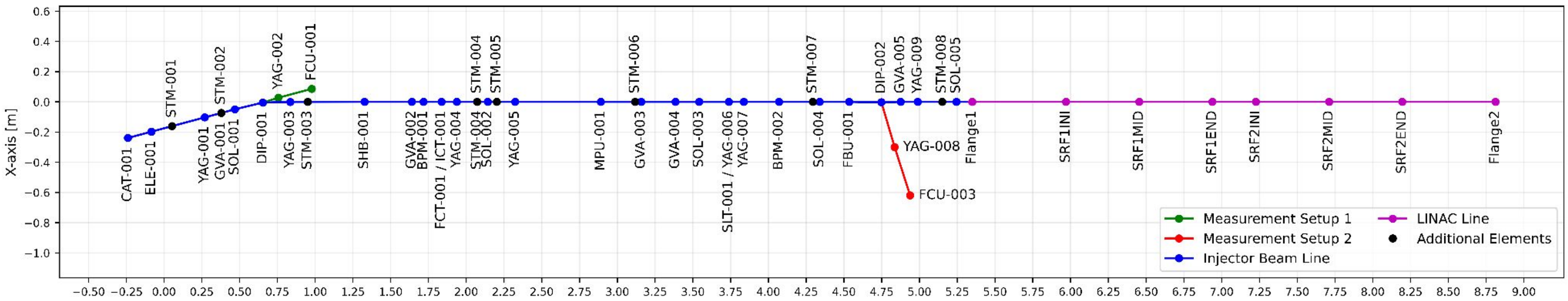
The targeted FEL wavelength range is from 3 to 300 μm, which is achieved using two optical resonators.

Each resonator consists of two concave mirrors (one fully reflective and one partially reflective) and an undulator positioned between them.

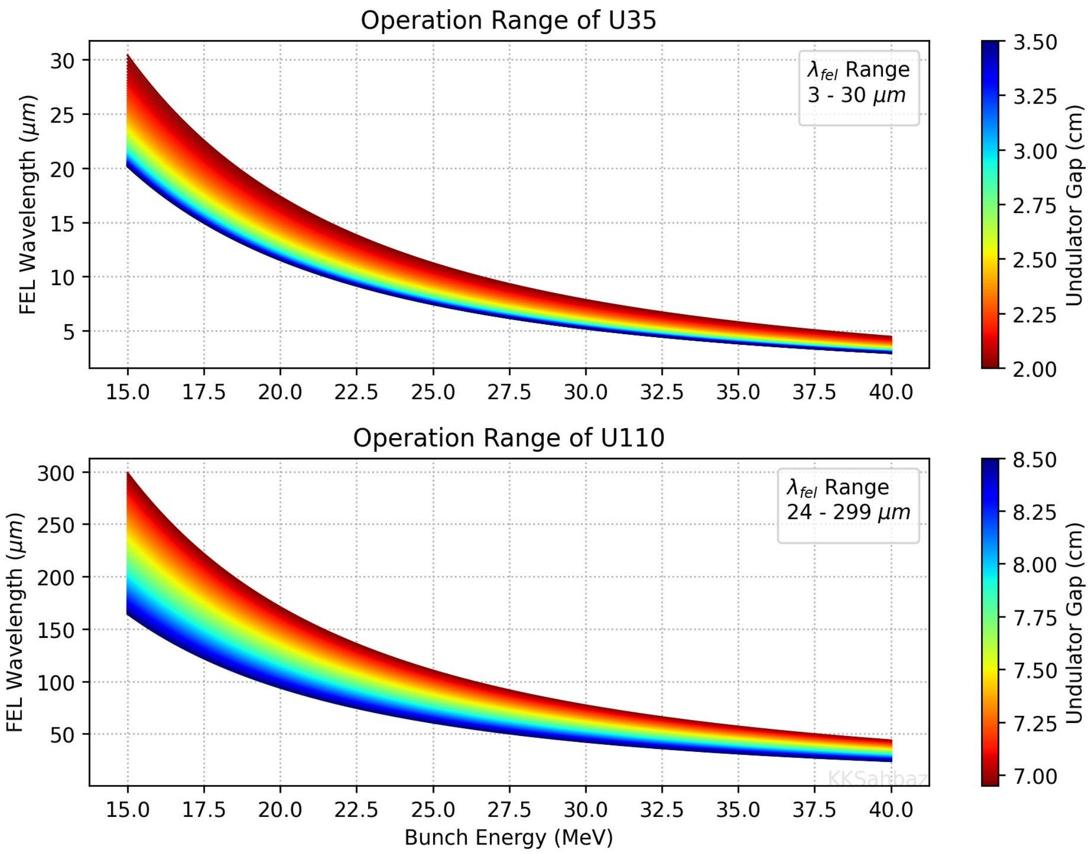
The undulators have different period lengths: 3.5 cm for U35 and 11 cm for U110.

By varying the incoming bunch energy between 15 - 40 MeV and adjusting the undulator gaps, the FEL wavelength (or frequency) can be tuned accordingly.

Operational TARLA Accelerator Line Map[2, 3]



The live section of the TARLA accelerator beamline prior to the BC section is shown above. This beamline was commissioned in May 2024 and successfully accelerated the beam to an energy level of 18.3 MeV.



On the left, the graphs show the radiation wavelengths that can be generated by scanning the input energy and gap length for the U35 and U110 undulators.

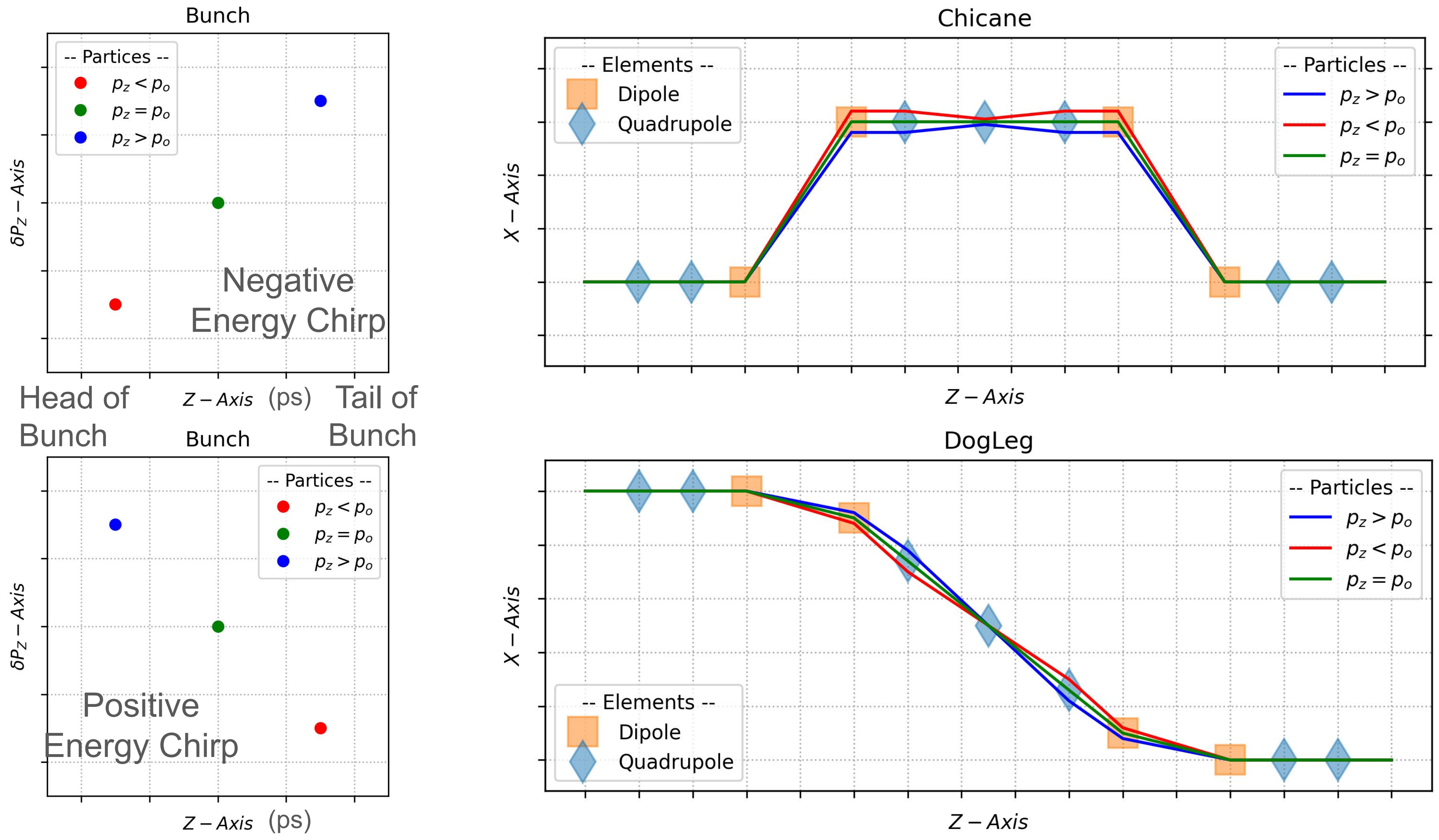
To ensure a continuous wavelength range between 3 - 300 µm, the undulator gap lengths have been set between 2 - 3.5 cm for U35 and 7-8.5 cm for U110.

To tune the bunch energy, the operating phases of the cavities in LINAC-1 and LINAC-2 can be adjusted.

Introduction[1, 4, 5, 6]

To generate laser radiation at TARLA facility, an optical resonator centered around the undulator is employed. The resonator amplifies radiation at a specific wavelength while suppressing other components. In order to satisfy the resonance condition, the electron bunch must meet certain statistical requirements. Among these, the bunch length is a critical parameter for maximizing laser brightness.

To modify the length of a bunch traveling at nearly the speed of light, a beamline known as a magnetic bunch compressor (BC) must be designed. This line separates particles based on their momenta and directs them through slightly different path lengths, causing them to travel longer or shorter distances.



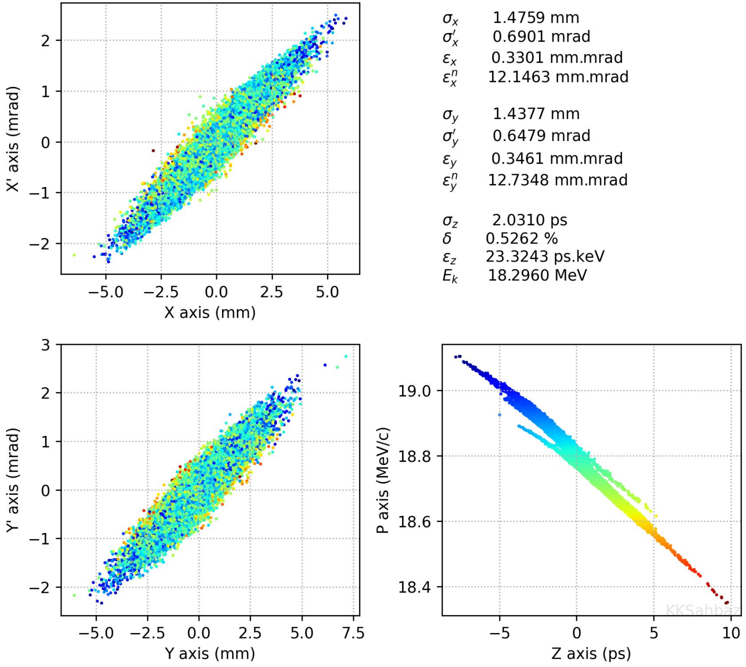
Bunch
-- Partices --
$p_z < p_o$
$p_z = p_o$
$p_z > p_o$
$\delta P_Z - Axis$
Negative Energy Chirp
Head of Bunch
$Z - Axis$ (ps)
Tail of Bunch
Chicane
-- Elements --
Dipole
Quadrupole
-- Particles --
$p_z > p_o$
$p_z < p_o$
$p_z = p_o$
$X - Axis$
$Z - Axis$
Bunch
-- Partices --
$p_z < p_o$
$p_z = p_o$
$p_z > p_o$
$\delta P_Z - Axis$
Positive Energy Chirp
$Z - Axis$ (ps)
DogLeg
-- Particles --
$p_z > p_o$
$p_z < p_o$
$p_z = p_o$
-- Elements --
Dipole
Quadrupole
$X - Axis$
$Z - Axis$

Objective

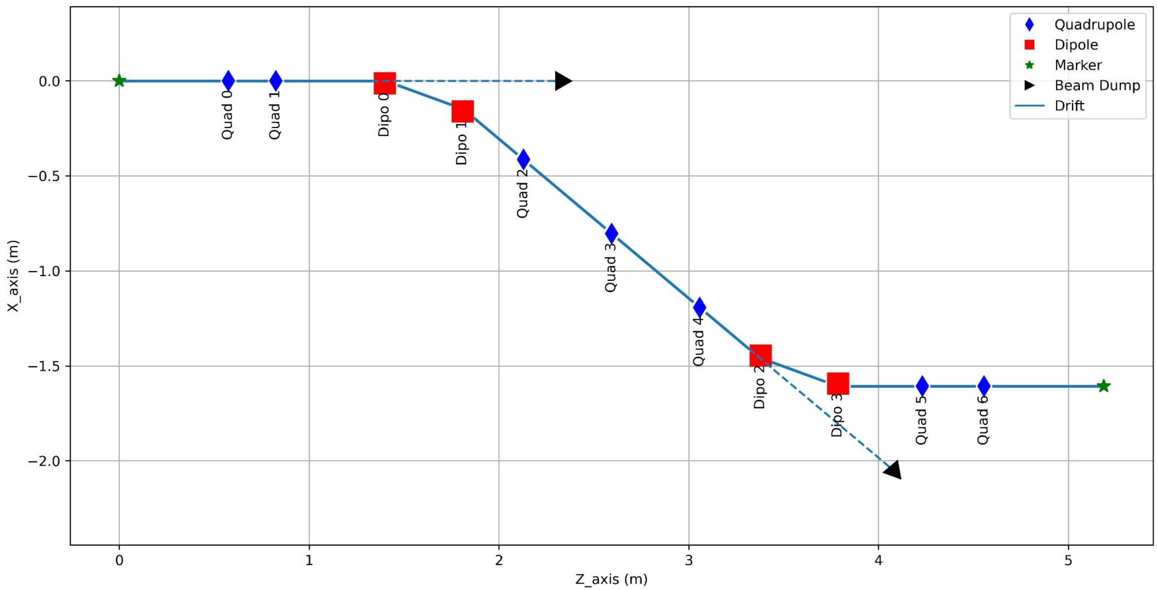
According to the FEL specifications outlined in the Introduction, the bunch length must be shorter than 150 μm to produce 3 μm laser radiation, which corresponds to approximately 0.5 ps in the time domain. To achieve this, the bunch, originally 2 ps in length, as illustrated in the diagram on the right, must be maximum level of 0.5 ps.

The longitudinal phase space shown in the bottom right illustrates the momentum distribution of the particles with respect to their positions along the time axis.

Since time axis is inversely proportional to momentum distribution, the energy chirp of the bunch is positive.



Composite phase space diagram of the outlet of LINAC-1



Considering the positive energy chirp, the BC line should be of the dogleg type. To compress the bunch, the system must include four dipole magnets, seven quadrupole magnets to preserve beam symmetry and prevent particle loss, and diagnostic elements to monitor beam parameters at various locations along the line.

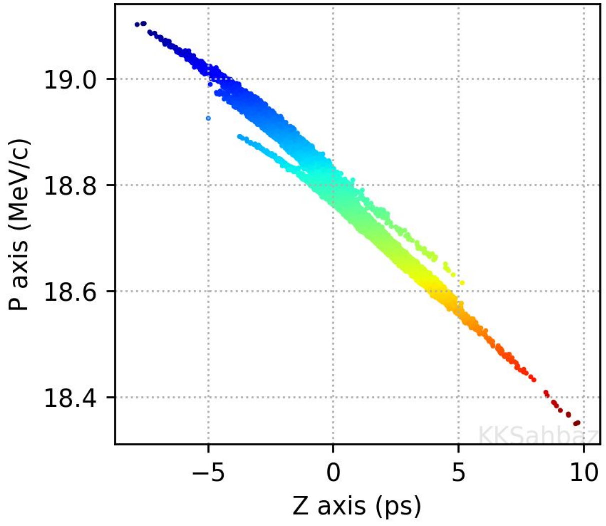
FEL Requirements and Beam Parameters

According to the longitudinal phase space diagram shown on the left, the bunch has a length of 2 ps (0.6 mm) and an energy spread of 0.5%. Considering that the particles with the highest momentum are located at the head of the bunch, the energy chirp is approximately 8.3 m^{-1}.

$$\frac{\sigma_{z,out}}{\sigma_{z,in}} = |1 + h \cdot R_{56}|$$

To achieve maximum theoretical compression, the BC line must have an R_{56} value of -0.12 m, which is determined by the distance between the successive dipole magnets.

Although the bunch length may fall below 0.5 ps under maximum compression, this does not degrade the FEL brilliance and is thus not a limiting factor.



σ_z 2.0310 ps
δ 0.5262 %
ε_z 23.3243 ps.keV
E_k 18.2960 MeV

Simulation Tools and Methodology [7, 8, 9]

To carry out the design and theoretical verification of the BC section, three different beam dynamics simulation tools were used, each offering specific advantages in distinct domains:

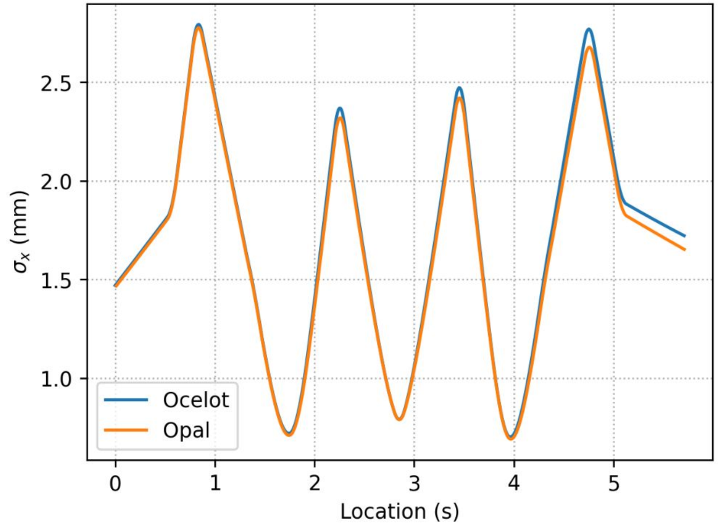
- MAD-X was used for positioning the elements within the BC line and monitoring the Twiss parameters quickly.
- OCELOT was employed for performing multi-particle simulations and analyzing chromaticity of bunch and coulomb interactions among particles (dipole approximation is identical to MAD-X).
- OPAL was utilized to simulate realistic magnetic field maps and compare with OCELOT Results (dipole mags. has a different approximation).

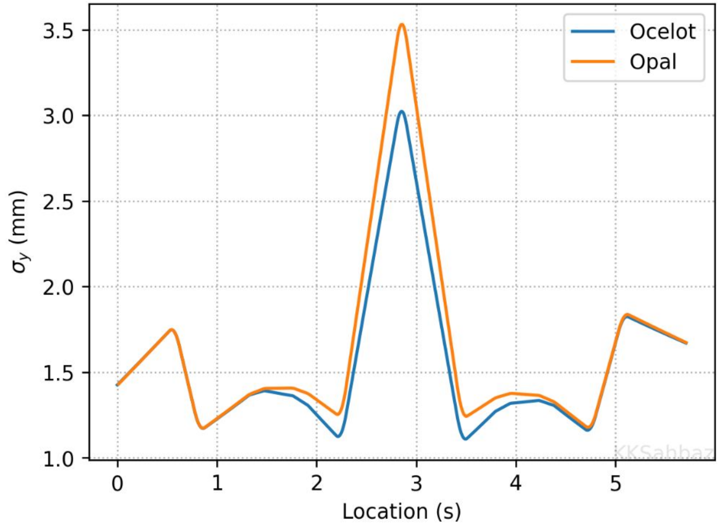
Optimization scheme

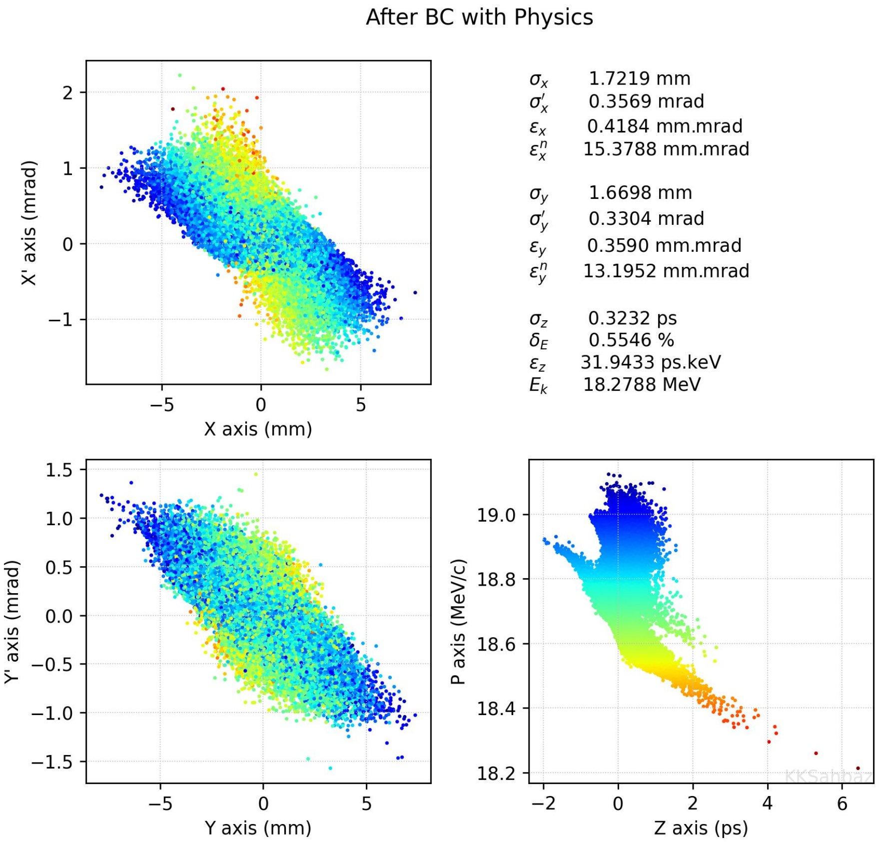
MAD-X
Adjusting Quad Strengths in order to nullify correlation between orthogonal axes

OCELOT
Adjusting magnet positions to decrease non-linear effects on the bunch by minimizing the σ_z

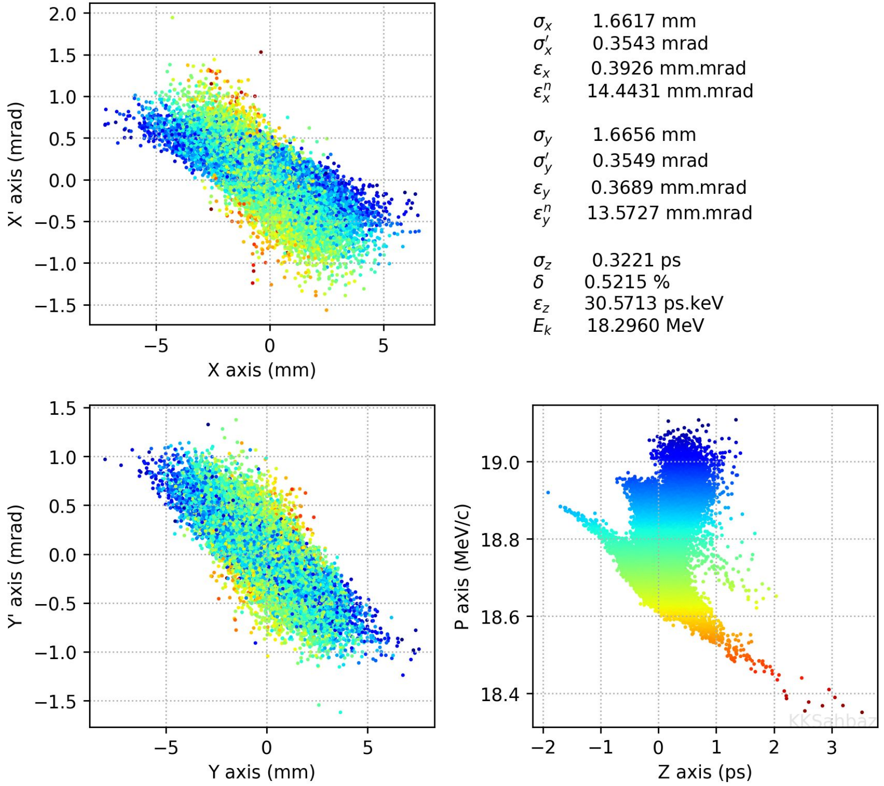
OPAL
Re-adjusting Quad Strengths due to differences of dipole magnet dynamics in OPAL



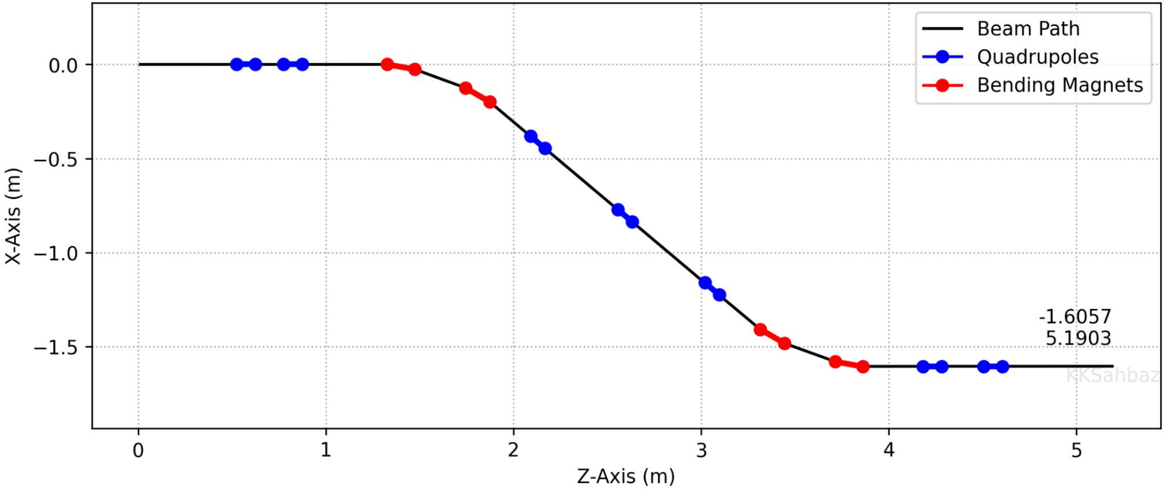


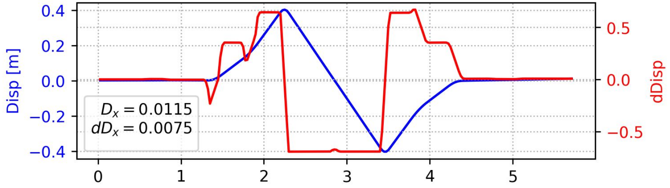


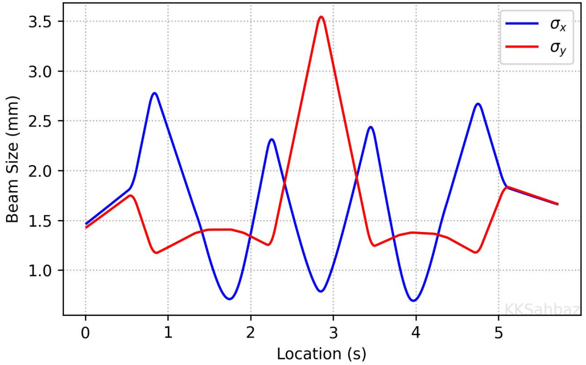
Phase space diagrams at the end of BC line simulated by OCELOT



Phase space diagrams at the end of BC line simulated by OPAL

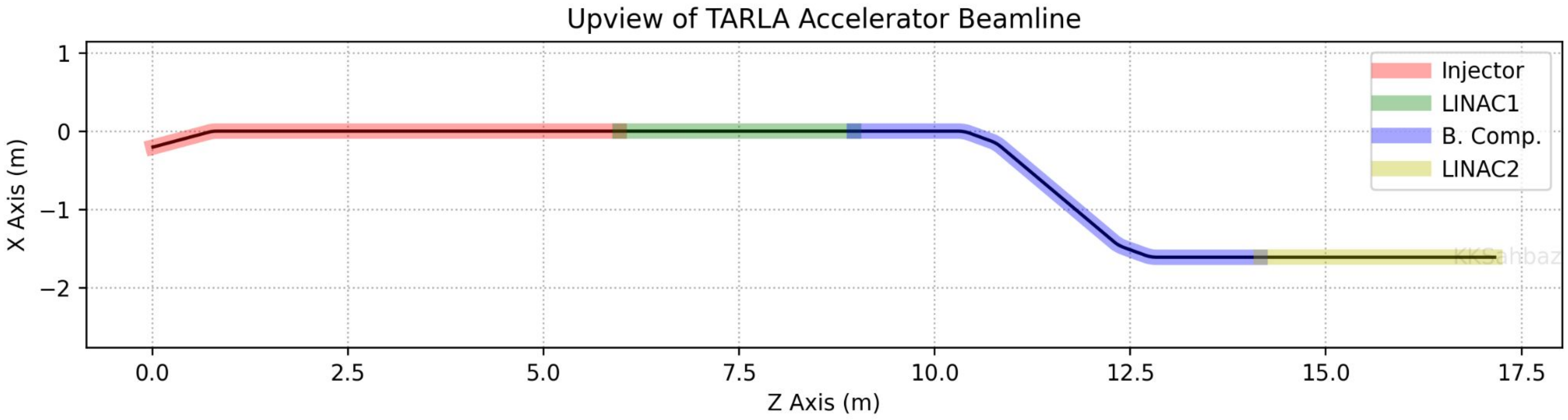




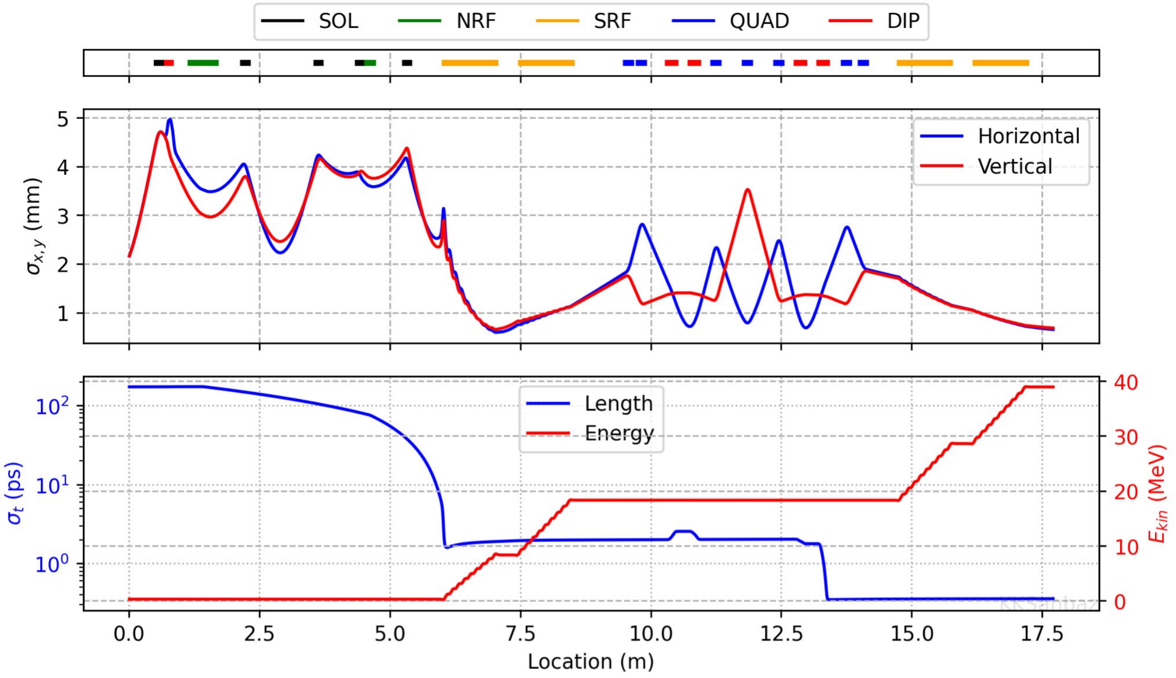


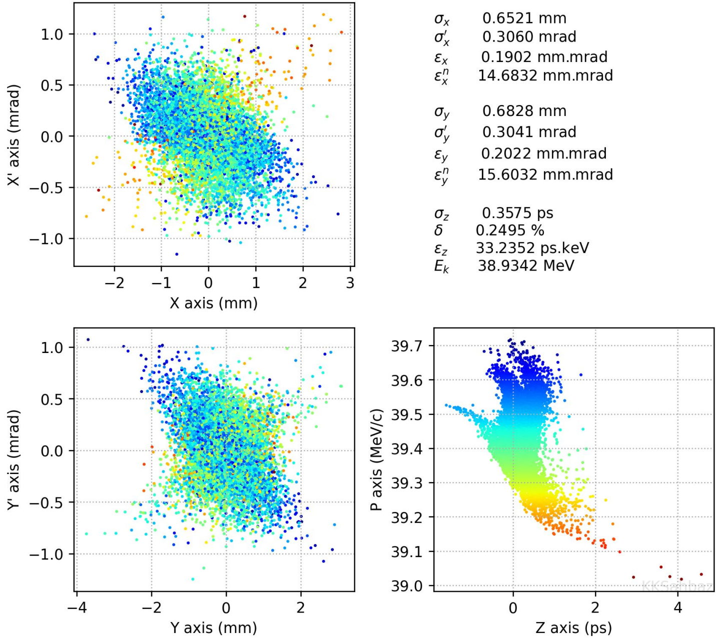
The coordinates of the quadrupole and dipole magnets along the BC line are shown on the left, while the dispersion and beam sizes calculated through OPAL simulations are presented on the right.

Integration with Injector and LINAC Sections



The injector, LINAC1, BC, and LINAC2 lines were integrated into a unified simulation input card, producing a regionally segmented beamline as illustrated above.

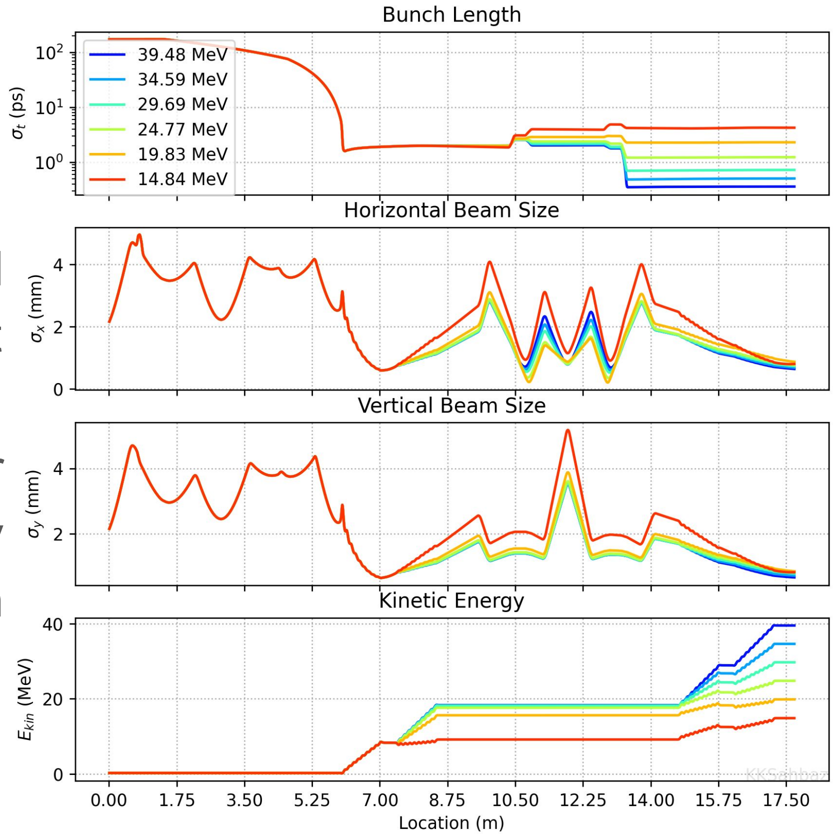


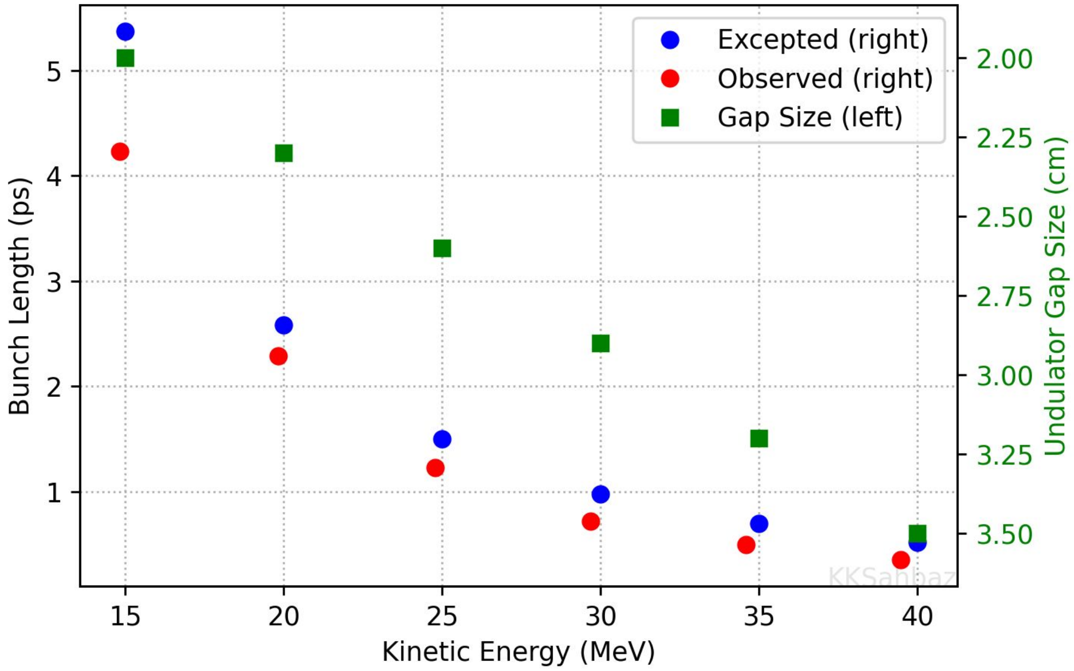


The left panel shows the evolution of the bunch parameters—transverse and longitudinal sizes, as well as energy—along the beamline based on the simulation results. The right panel presents the phase space diagrams of the bunch at the exit of LINAC2, representing the final output of the fully integrated beamline.

Bunch Generation for Various FEL Wavelengths

Achieving the required bunch lengths and energies is crucial for FEL generation at various wavelengths. The combined graph on the right shows simulation results for producing bunches in the 15-40 MeV energy range, presenting the evolution of bunch length and energy along the beamline.





The graph shows the expected and simulated bunch lengths along with the corresponding undulator gap settings. Based on these adjustments, the FEL wavelength is expected to be in the range of 3-30 µm (operation range of U35).

Conclusion

The design of the BC section has been completed. The entire beamline, including the injector and linac sections, was integrated and simulated to assess the performance at the minimum FEL wavelength (max. compression).

Subsequently, the bunch length and energy values required to produce longer FEL wavelengths were obtained by adjusting the cavity phases, and the results were compared with the target values. Although the simulated bunch length for 30 μm FEL generation was found to be shorter than the target value, this is not a reason for decreasing the FEL brilliance so, it is cool.

References

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