Beam Loading Studies in Positron Source of Capture Linac in Compact Linear Collider (CLIC)

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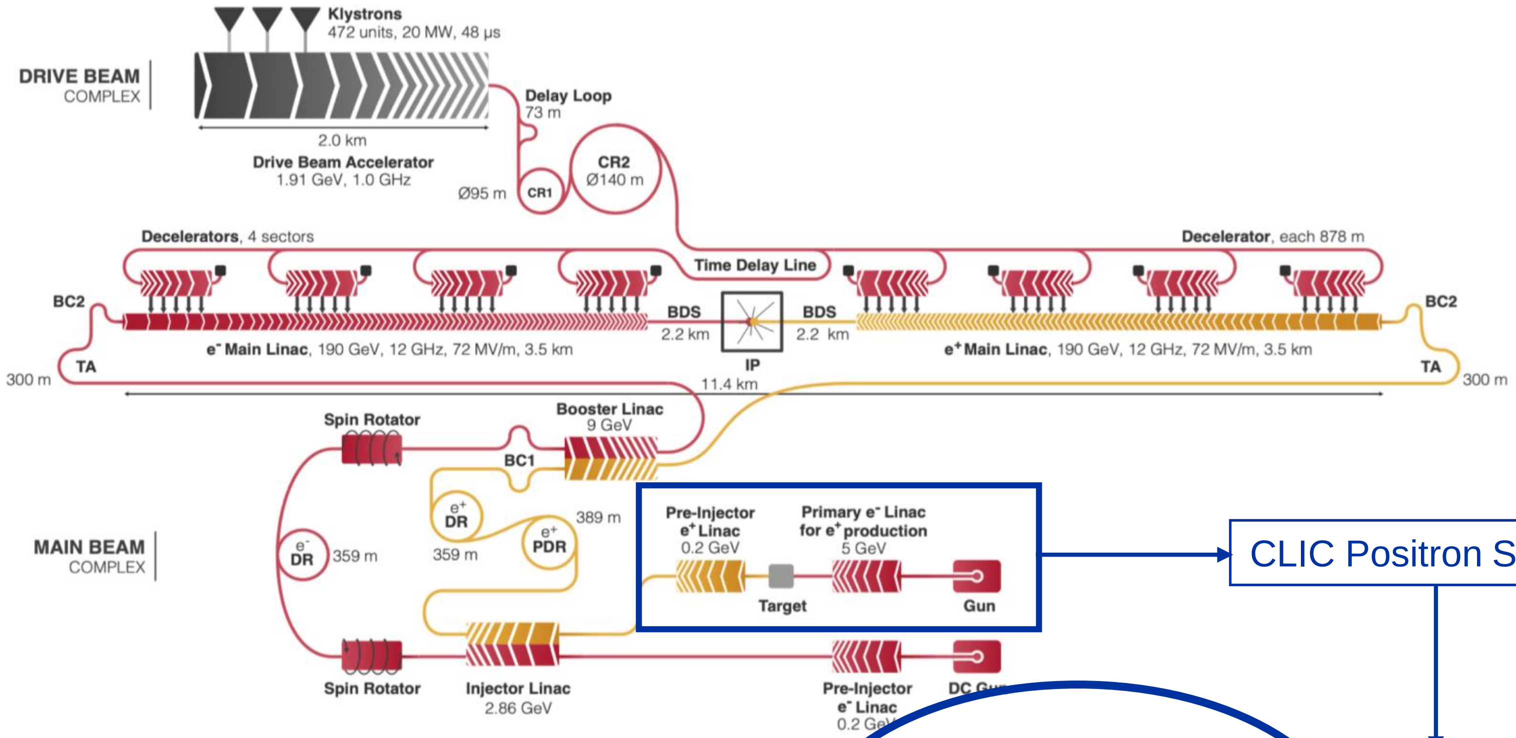
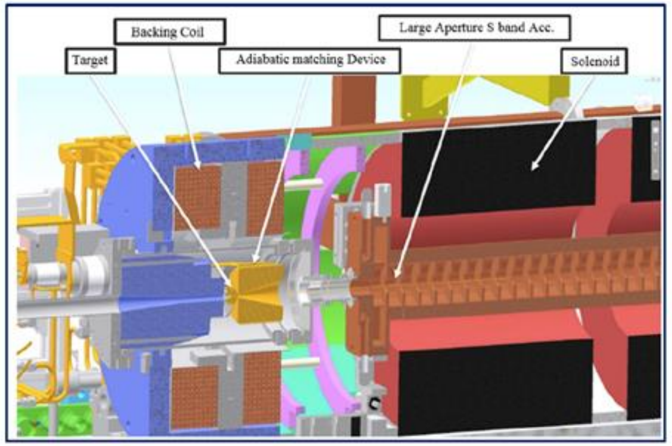
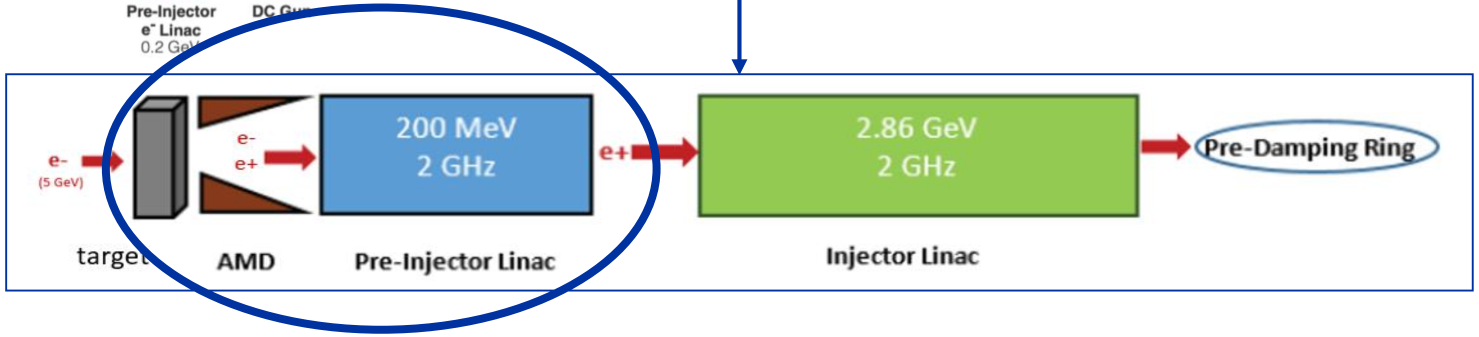
Introduction



CLIC Positron Source

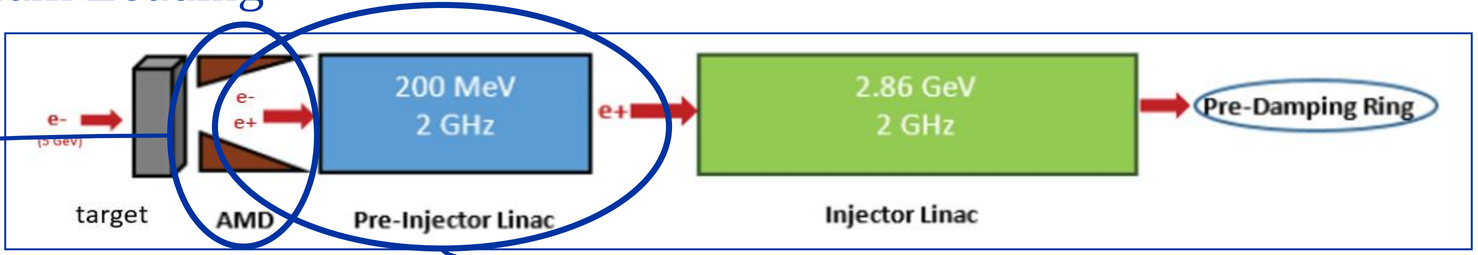


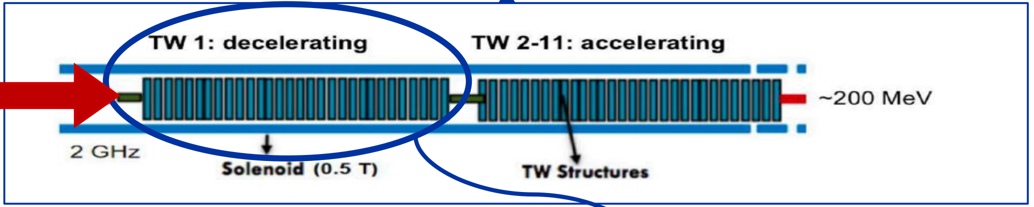
Positron source of the SuperKEKB

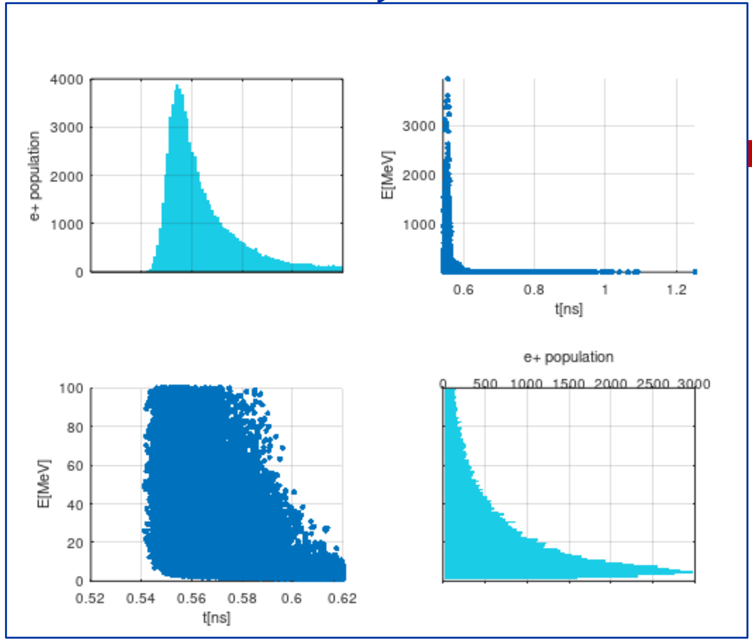


Challenges

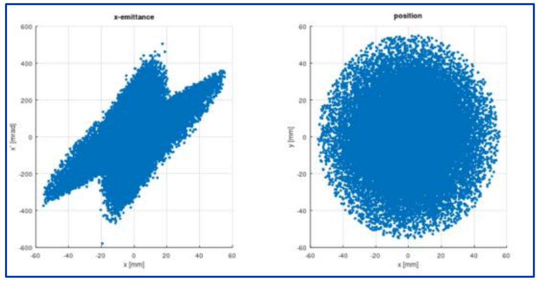
- Capture Linac includes both e- e+ with large energy-spread, large-bunch-length, large-emittance
- Structure suffers from both e- and e+ Beam Loading



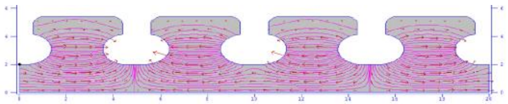




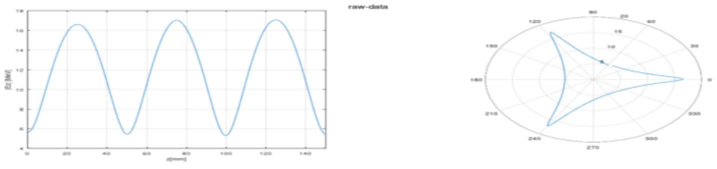
Longitudinal phase space



Transverse phase space



2 GHz room temperature $2\pi/3$ phase advance per cell traveling-wave accelerating structure



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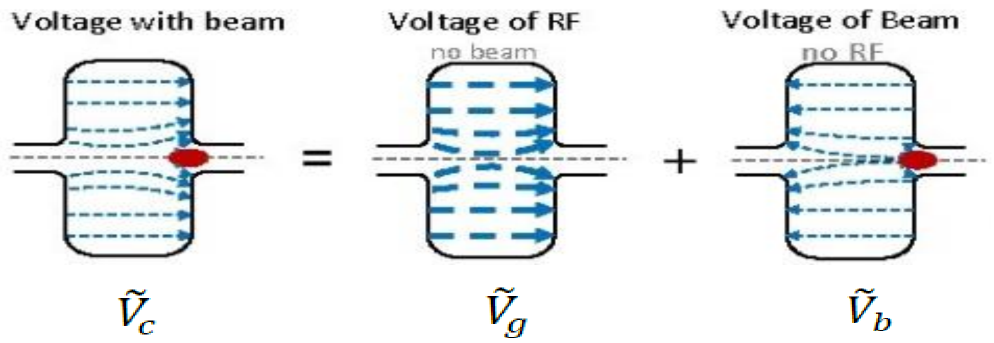
Cavity Beam Interactions and Beam Loading Effect

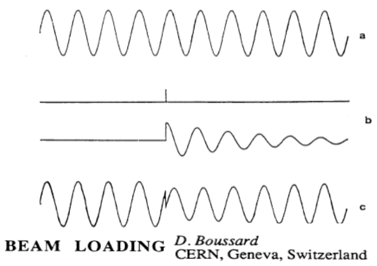
- A particle crossing a cavity would be affected by the excited fields inside the cavity.
- Care must be taken that there are two sources for exited fields.
- The induced excitation can reduce cavity voltage and hence the Gradient of the structure.
  - Lasts for a long time – Long range effect
  - Accumulated from bunch-to-bunch

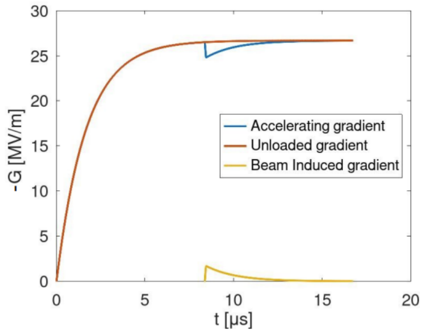
external generator

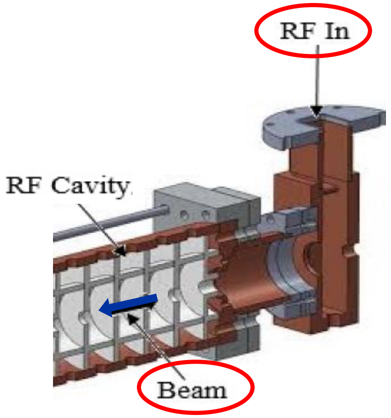
beam loading effect

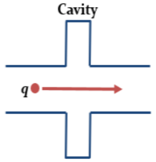
Reduction of available accelerating gradient

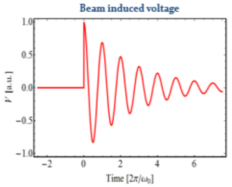












RF_Track

- a novel tracking code developed by Andrea Latina
- transport beams of particles
- solving fully relativistic equations of motion
- using parallel algorithms
- written in optimized and parallel C++
- user interfaces scripting languages
  - Octave
  - Python
- RF-Track has been tested successfully in several cases:
- ELENA ring, the CLIC positron injector, and the AWAKE injector Linac.

Example (Octave interface)

```
% load RF-Track
RF_Track;

% setup simulation
TL = setup_transferline;
B0 = setup_beam;

% track
B1 = TL.track(B0);

% inquire the phase space
T1 = B1.get_phase_space("%x %xp %y %yp");

% plot
plot(T1(:,1), T1(:,2), "*");
xlabel("x [mm]");
ylabel("x' [mrad]");
```

https://zenodo.org/record/4580369

https://abpcomputing.web.cern.ch/codes/codes_pages/RF-Track/

Beam Loading in RF_Track

- Gradient reduction due to beam-cavity interaction in TW structure can be understood with the Power-Diffusive model.
- Beam loading as a Self-consistent module implemented in RF_Track
  - Can be attached to Drift spaces, TW and SW structure, field maps

- From Poynting: Equation in terms of Gradient:

$$-\frac{\partial G_{\mathrm{eff}}}{\partial t} = v_g \frac{\partial G_{\mathrm{eff}}}{\partial z} + \left(-\frac{v_g Q}{r_{\mathrm{eff}}}\frac{\partial (r_{\mathrm{eff}}/Q)}{\partial z} + \frac{\omega}{Q} + \frac{\partial v_g}{\partial z}\right)\frac{G_{\mathrm{eff}}}{2} + \underbrace{\frac{\omega r_{\mathrm{eff}} \tilde{I}}{2Q}}_{\text{Beam Loading term!}}$$

DOI: 10.1103/PhysRevSTAB.14.052001

Parameter	Value
Structure frequency	2 GHz
Q- factor	18346
Input power	59.54 MW
Average group velocity	0.0145 c
Filling time	333 ns
Number of bunch per train	312
Bunch spacing	0.5 ns
Population per bunch	7.5e9
Train length	156 ns

```
%import RF_Track
RF_Track;

%Define Bunch
B = Bunch6d(mass, population, charge, [ X XP Y YP T P ];)

%Define RF_Structure
load('field.dat.gz');
TW = RF_Field(  field.Ex, ... % Efield [V/m]
                field.Ey, ...
                field.Ez, ...
                field.Bx, ... % Bfield [T]
                field.By, ...
                field.Bz, ...
                field.xa(1), ... % x0,y0 [m]
                field.ya(1), ...
                field.hx, ... % mesh size [m]
                field.hy, ...
                field.hz, ...
                field.za(end), ... % length [m]
                field.frequency, ... % [Hz]
                field.direction, ... % +1, -1, 0
                field.P_map, ... % [W]
                field.P_actual);

%BL_effect
BL = BeamLoading(TW, Pactual, VG, QQ, phaseadvance, Bcharge , Bpopulation, fB, BNumber);%Transient

%append BL to TW
TW.add_collective_effect(BL);

%Define Lattice
LS = Lattice();
LS.append(TW);

%Tracking
B0 = LS.track(B);
AA = B0.get_phase_space();
```

DOI: 10.3389/fphy.2024.1348042

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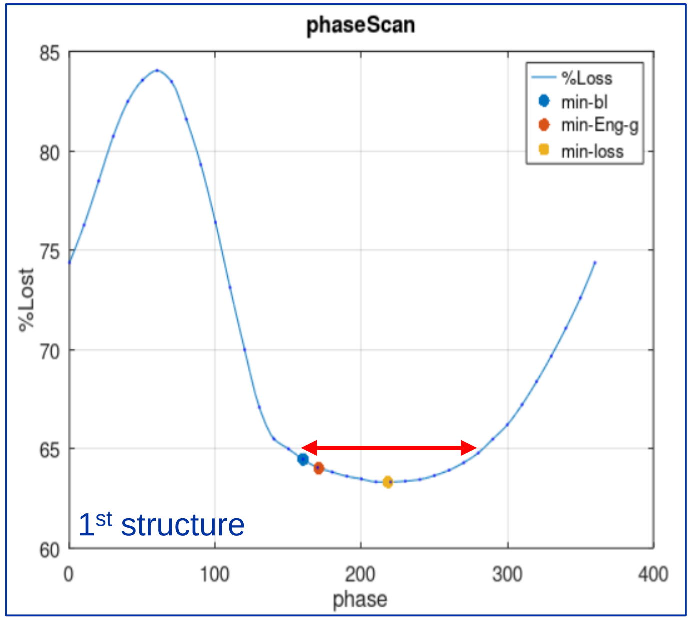
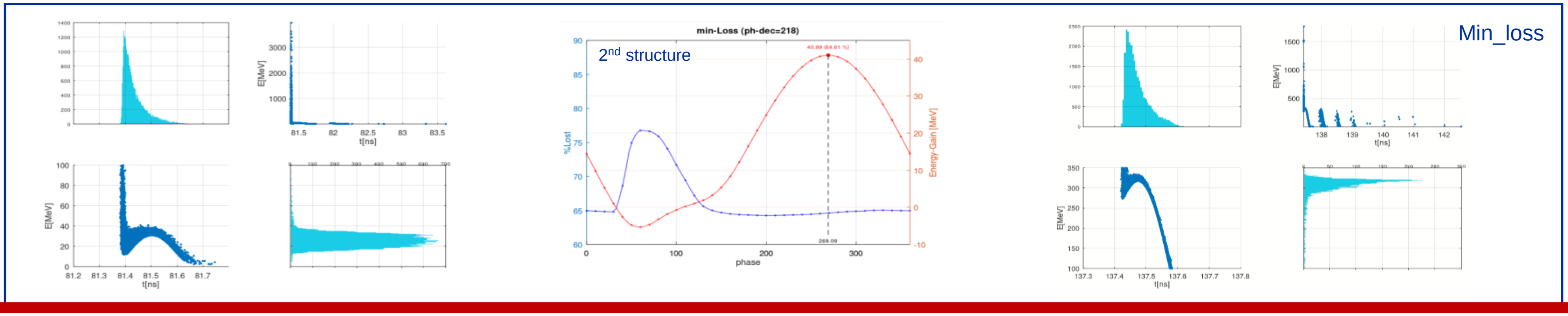
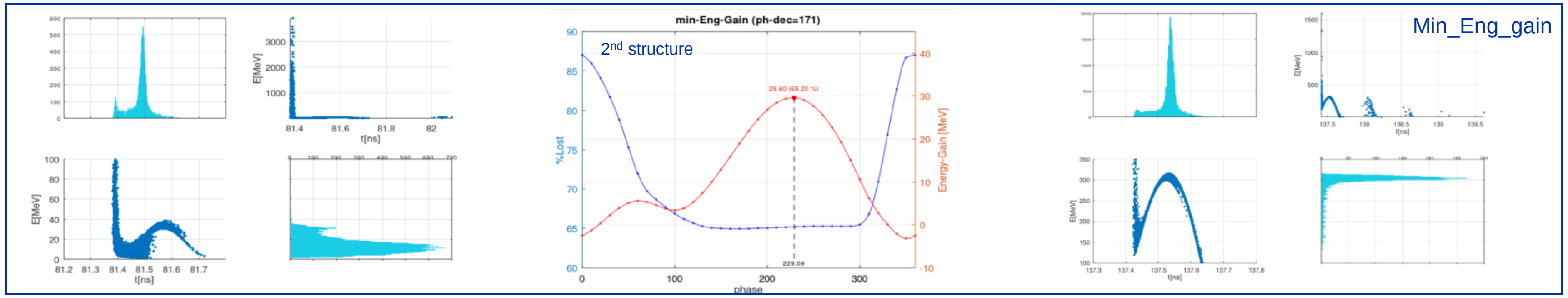
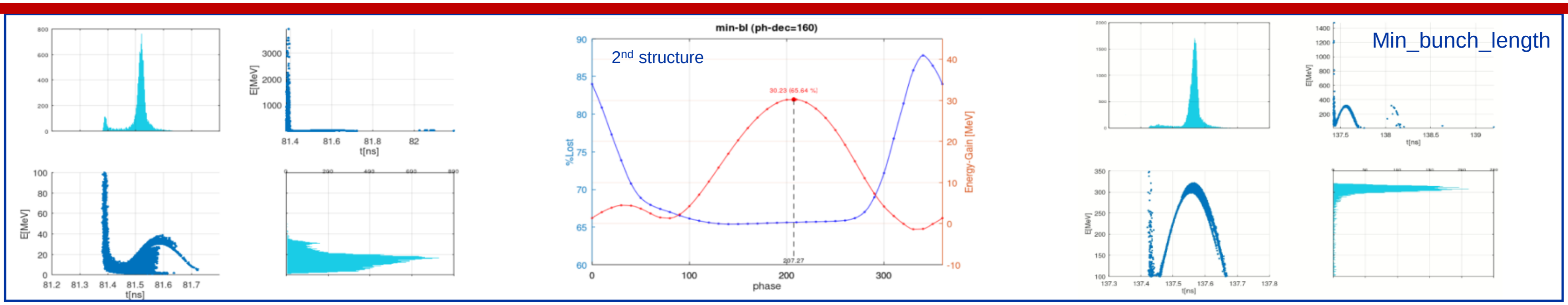
Phase Scan

- The structure can be optimized through different criteria.



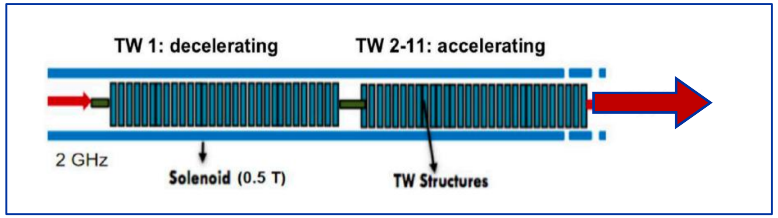


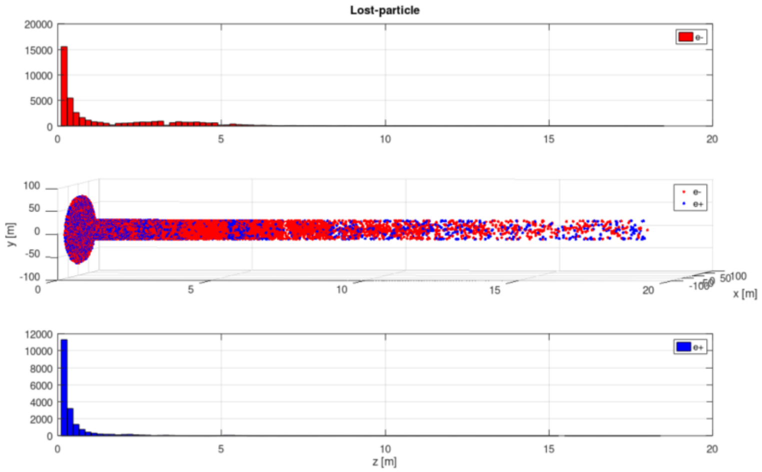


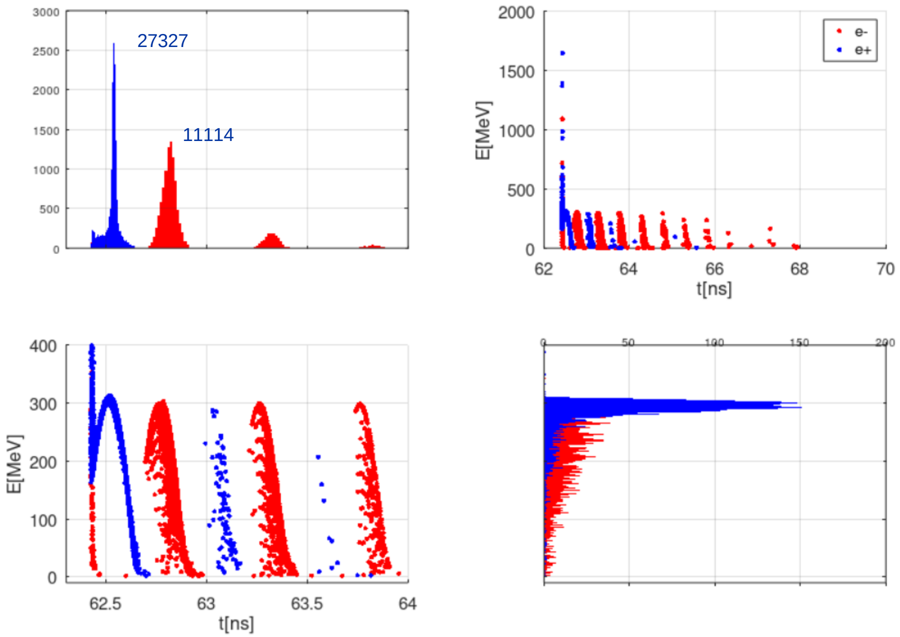


e- e+ outputs

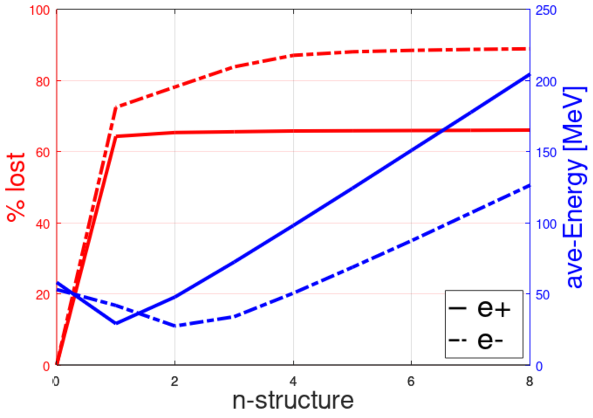
- Most of the positrons are lost at the beginning of the pipe => Cooling needs to be addressed.
- Electrons have a phase shift of π degree apart with respect to positrons, moving to the accelerating phase and gaining energy.





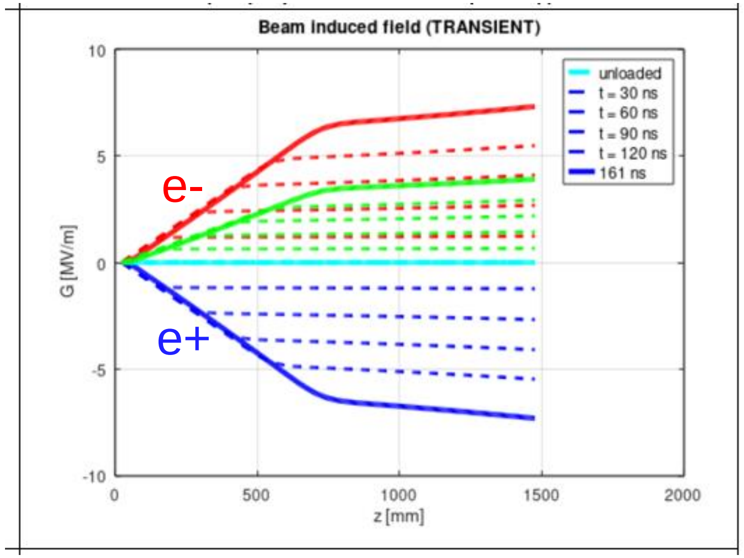


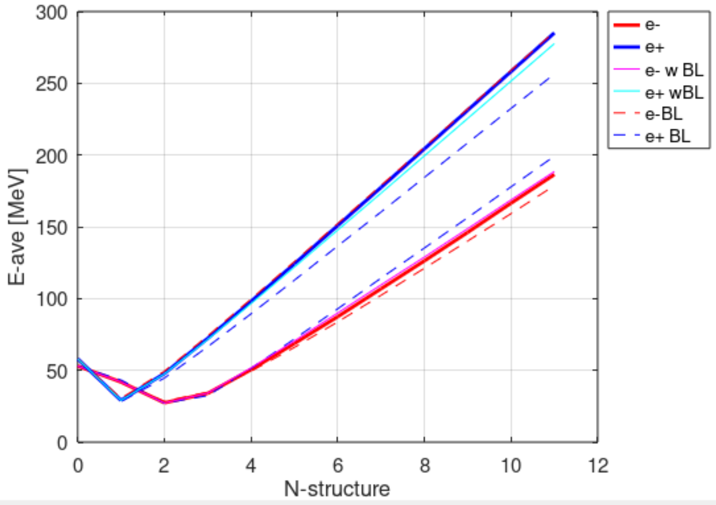
Longitudinal phase space

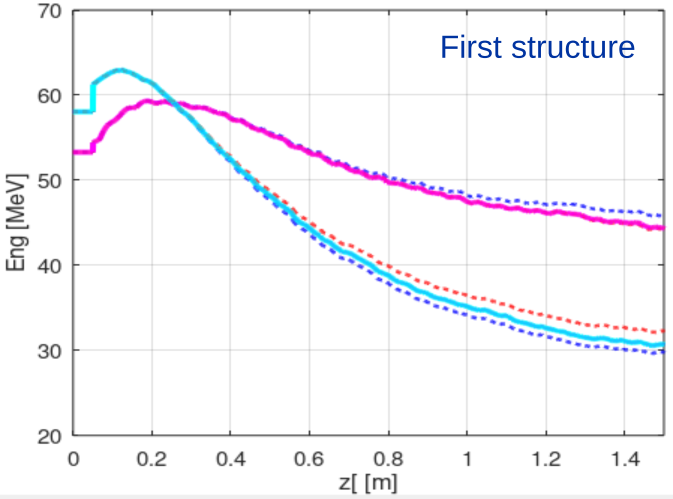


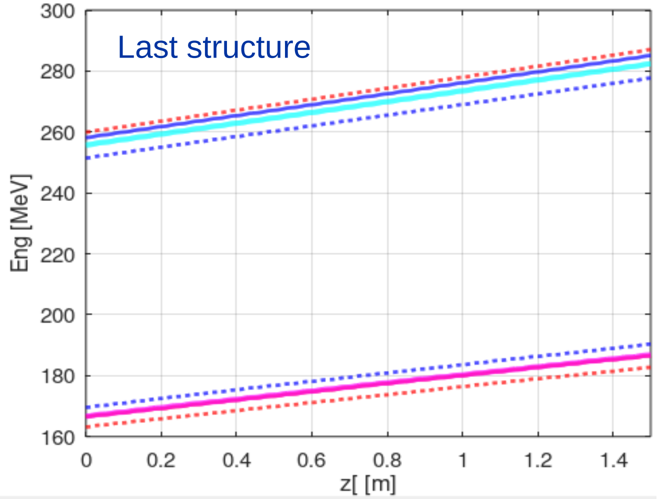
Beam Loading results

- Gradient reduction for middle bunch n=150



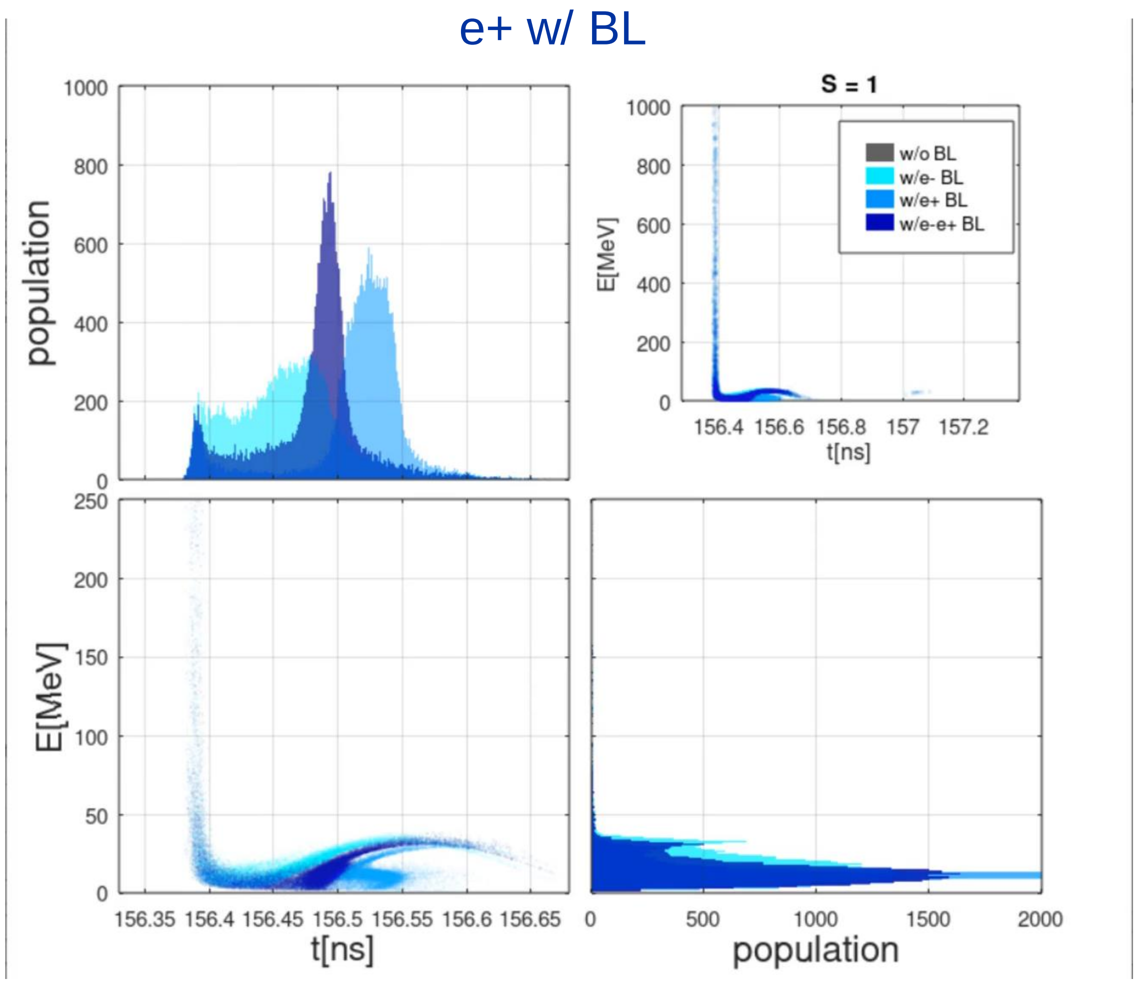






Beam Loading results

- Beam Loading effect on longitudinal phase space for n=300 (Most Affected by Beam Loading)



Beam Loading results: Transient effect

- $\tau_f > \tau_{train} \Rightarrow$ transient Beam Loading affects particles.
- Bunch-to-bunch variation

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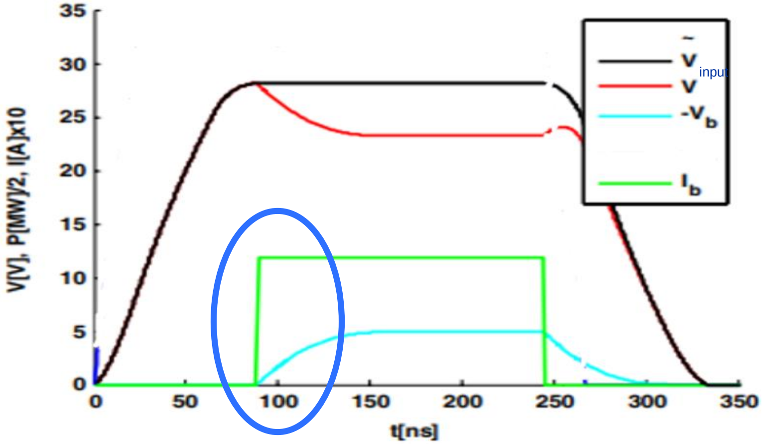
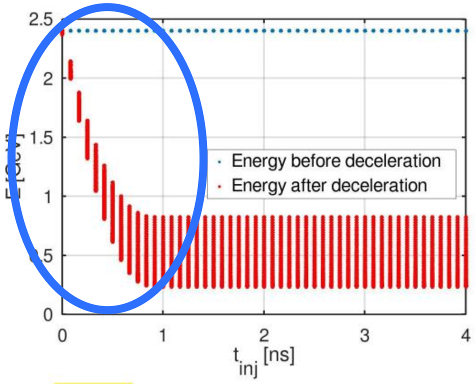
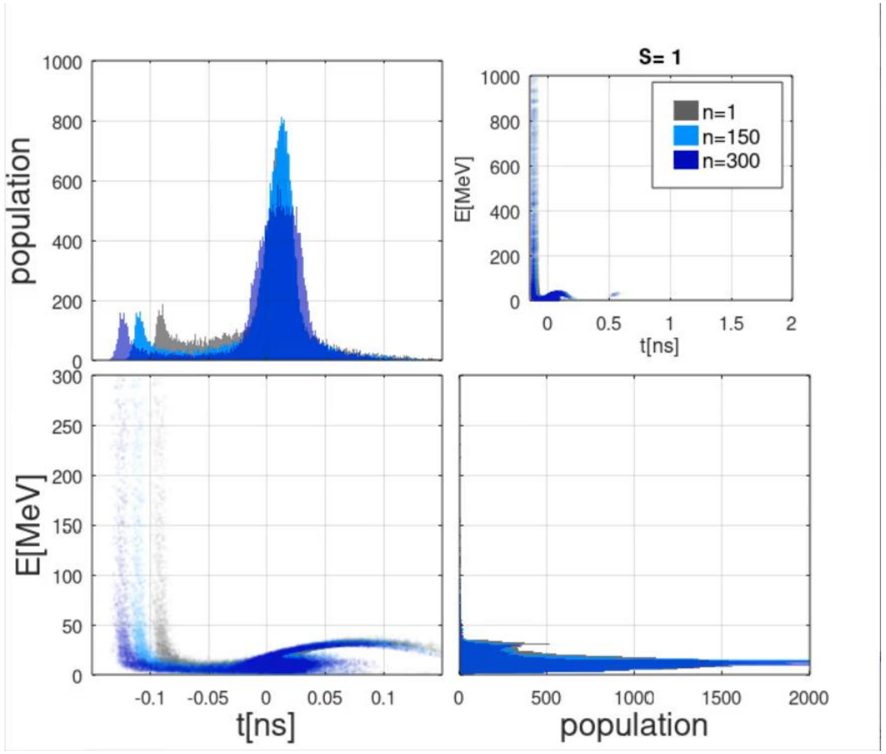


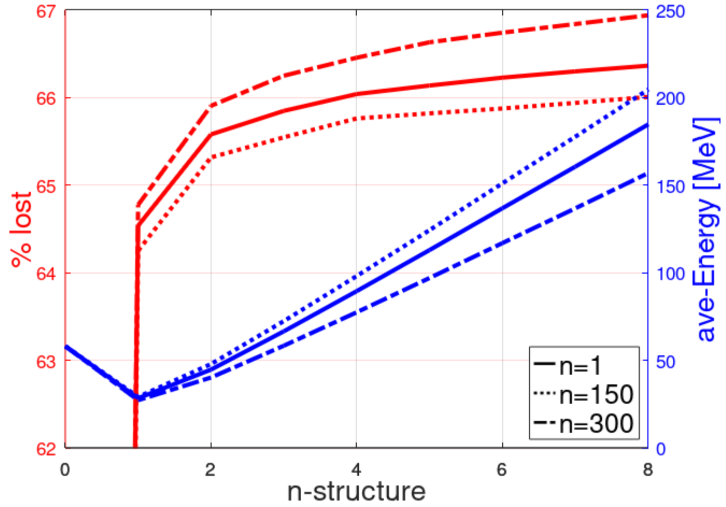


DOI: 10.1103/PhysRevSTAB.14.052001

e+ w/ e+ BL

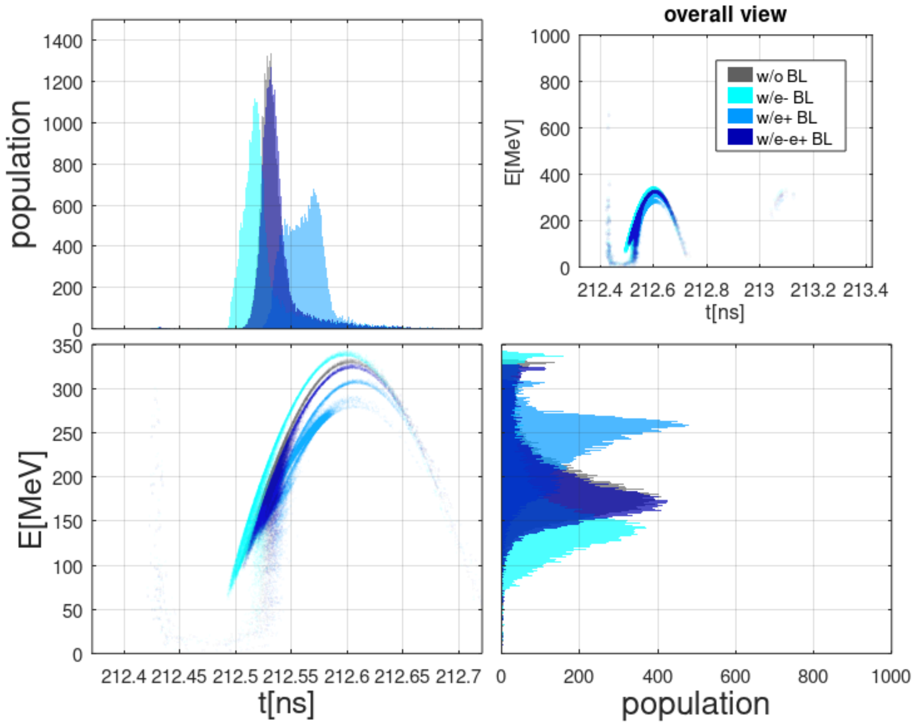


longitudinal phase space for first, middle and last bunch

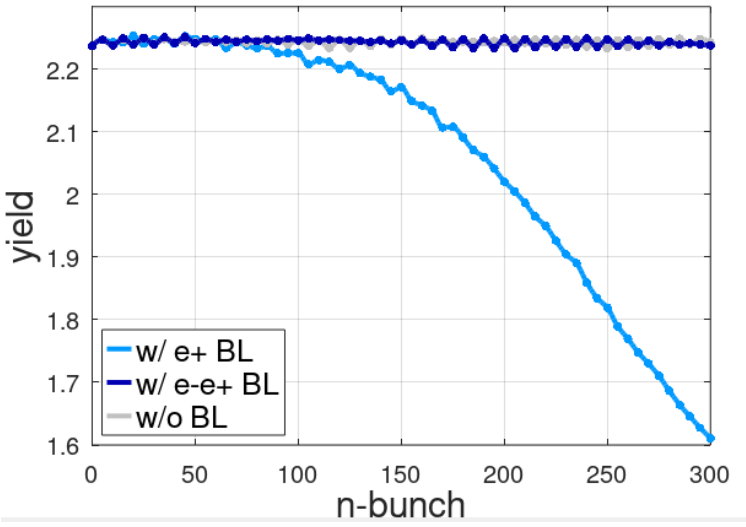


Yield spread

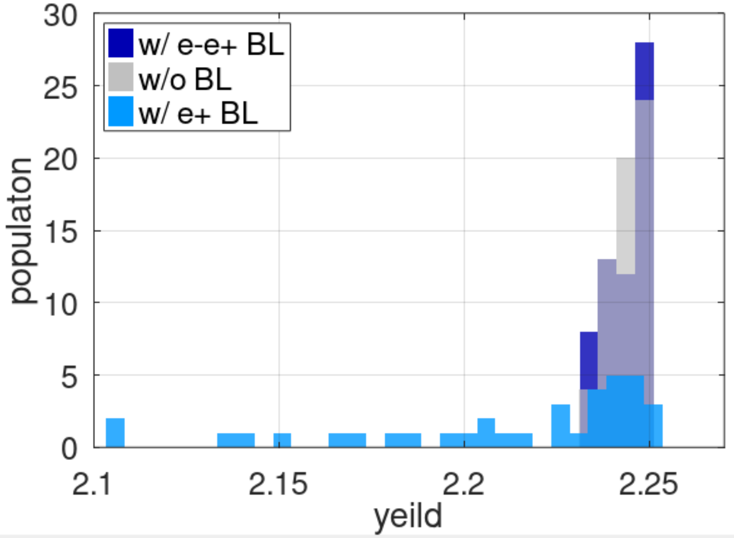
- A former optimization demonstrated a yield of 2.2 using 11 structures [DOI:10.18429/JACoW-IPAC2021-WEPAB014].
- Impact of positron beam loading on optimized yield



longitudinal phase space for n=300



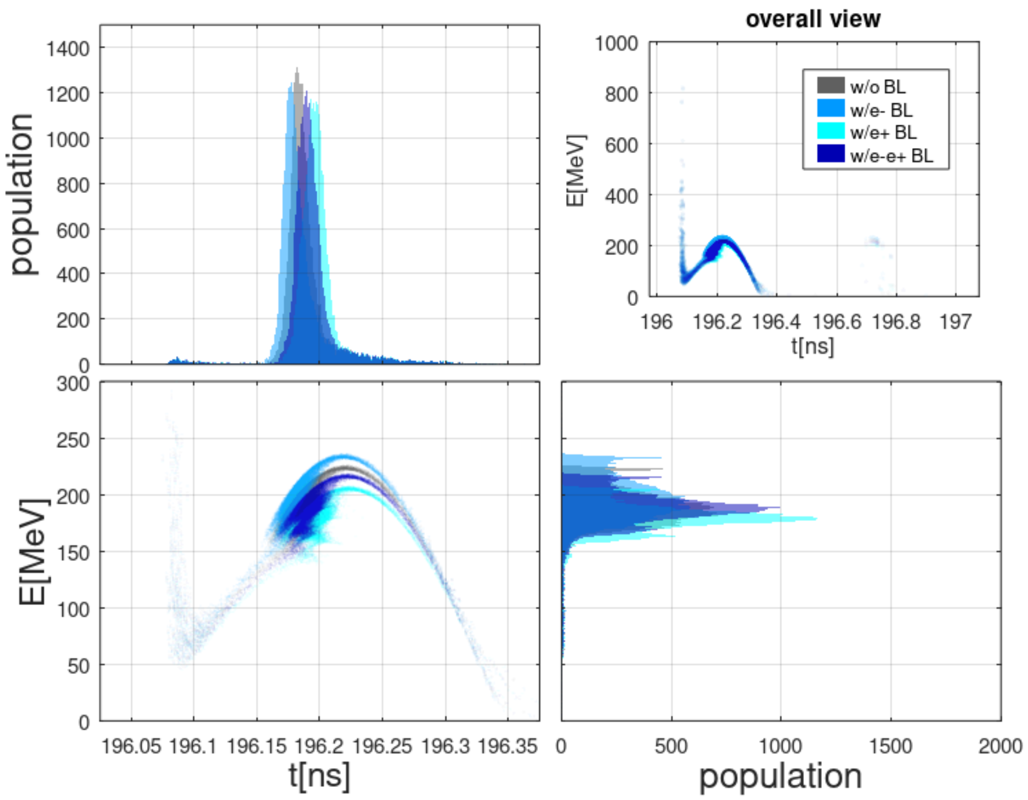
Yield per bunch along the bunch train



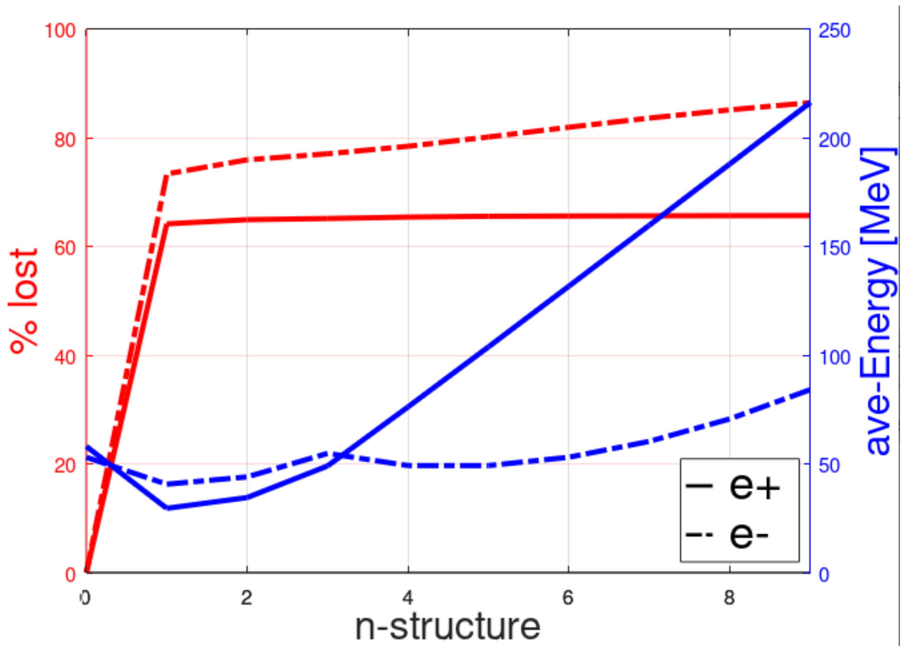
Yield histogram for a bunch train

Further optimization

- Longitudinal phase space is less influenced by beam loading.
- Achieve a 200 MeV goal with fewer structures.
- The greater difference in energy between electrons and positrons results in easier separation in next stages.



longitudinal phase space for n=300



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Discussion and outlook

✓ Achievements:

- Tracking of electron and positrons in capture Linac of positron source of the CLIC has been performed using RF_Track.
- Beam Loading with respect to presence of both electron and positron has been studied with the aid of Beam Loading simulation module in RF_Track.
- Beam loading significantly affects bunches with large energy and velocity spreads.
- Transient beam loading requires careful attention, especially when the bunch train is shorter than the filling time of the accelerator structure, as individual bunches are significantly affected by beam loading.
- The presence of electrons could effectively compensate for beam loading effects.
- Studies are still ongoing ….

✓ future plans and studies:

- Further optimization for finding appropriate phase and gradient in the presence of Beam Loading to maximize the yield.
- Further optimization to investigate and compensate bunch to bunch variation due to Beam Loading effect.
- Further studies to investigate the behavior of electrons within the structure and their impact on the beam loading effect.

Thanks for your attention

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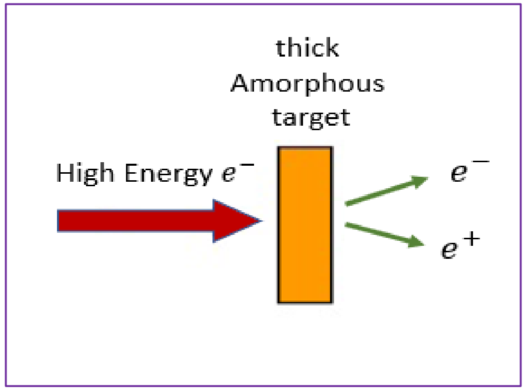
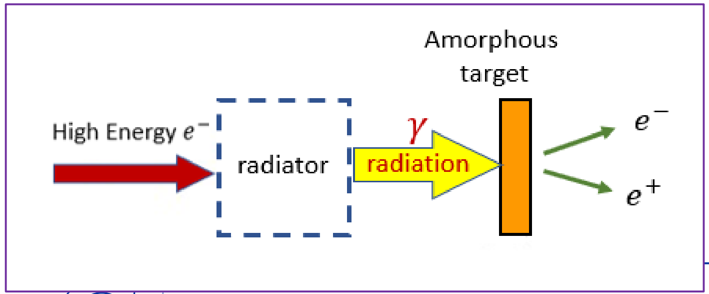
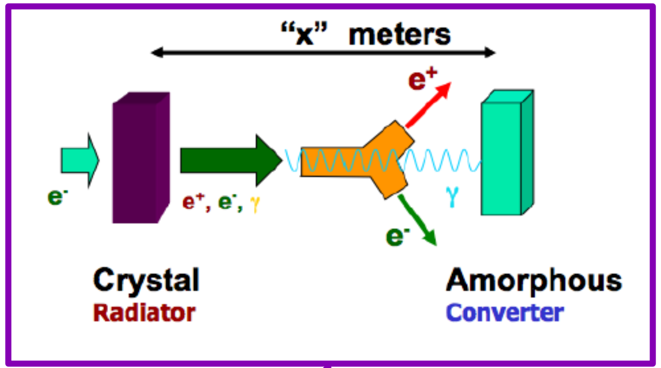
backup

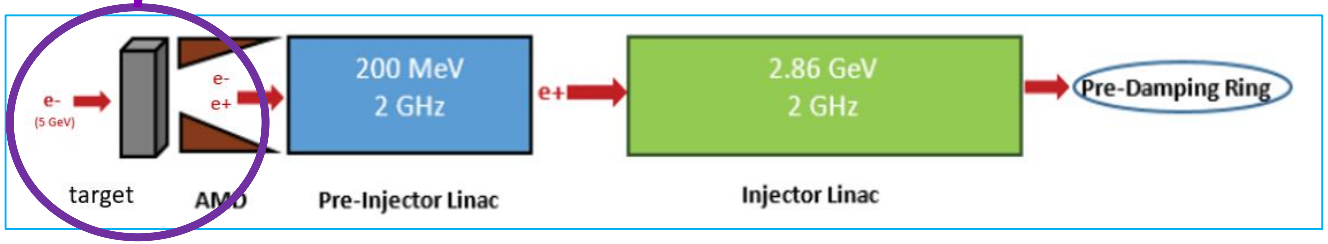
CLIC Positron Source

- Different type
  - conventional
  - advance
    - Hybrid
    - Undulator based
    - Laser Compton base

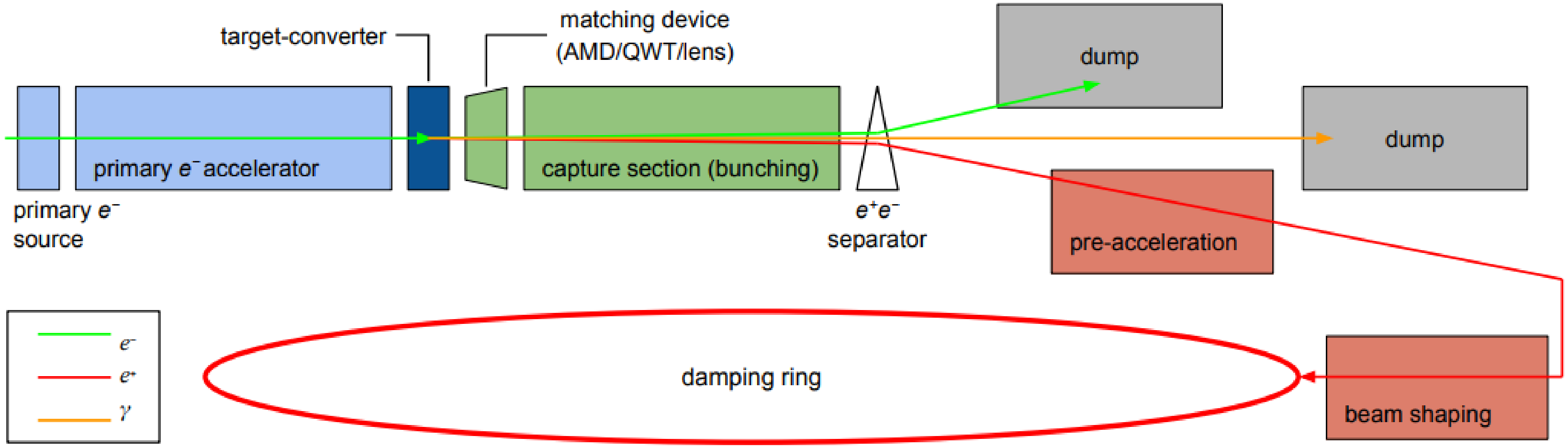








Positron Source complex



Different sub-systems of the positron source basic scheme.

arXiv:2202.04939v2 [physics.acc-ph] 29 Mar 2022

inputs

e+	unit	input
N_particle	[#]	81254
ave-Eng	[MeV]	58
EngSpread	[MeV]	123.409
ave-time	[mm/c]	171
bunch_length	[ns]	0.0322
bunch_length	[degree]	23.18
beamSize-x	[mm]	12.67
beamSize-y	[mm]	12.70
emittance-x	[mm.mrad]	99084.22
emittance-y	[mm.mrad]	99581.53

e-	unit	input
N_particle	[#]	92906
ave-Eng	[MeV]	53
EngSpread	[MeV]	116.342
ave-time	[mm/c]	174
bunch_length	[ns]	0.0549
bunch_length	[degree]	39.50
beamSize-x	[mm]	12.59
beamSize-y	[mm]	12.56
emittance-x	[mm.mrad]	96178.16
emittance-y	[mm.mrad]	96676.89

- Electrons have a phase shift of π degree apart with respect to positrons, moving to the accelerating phase and gaining energy