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

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CLIC mini week

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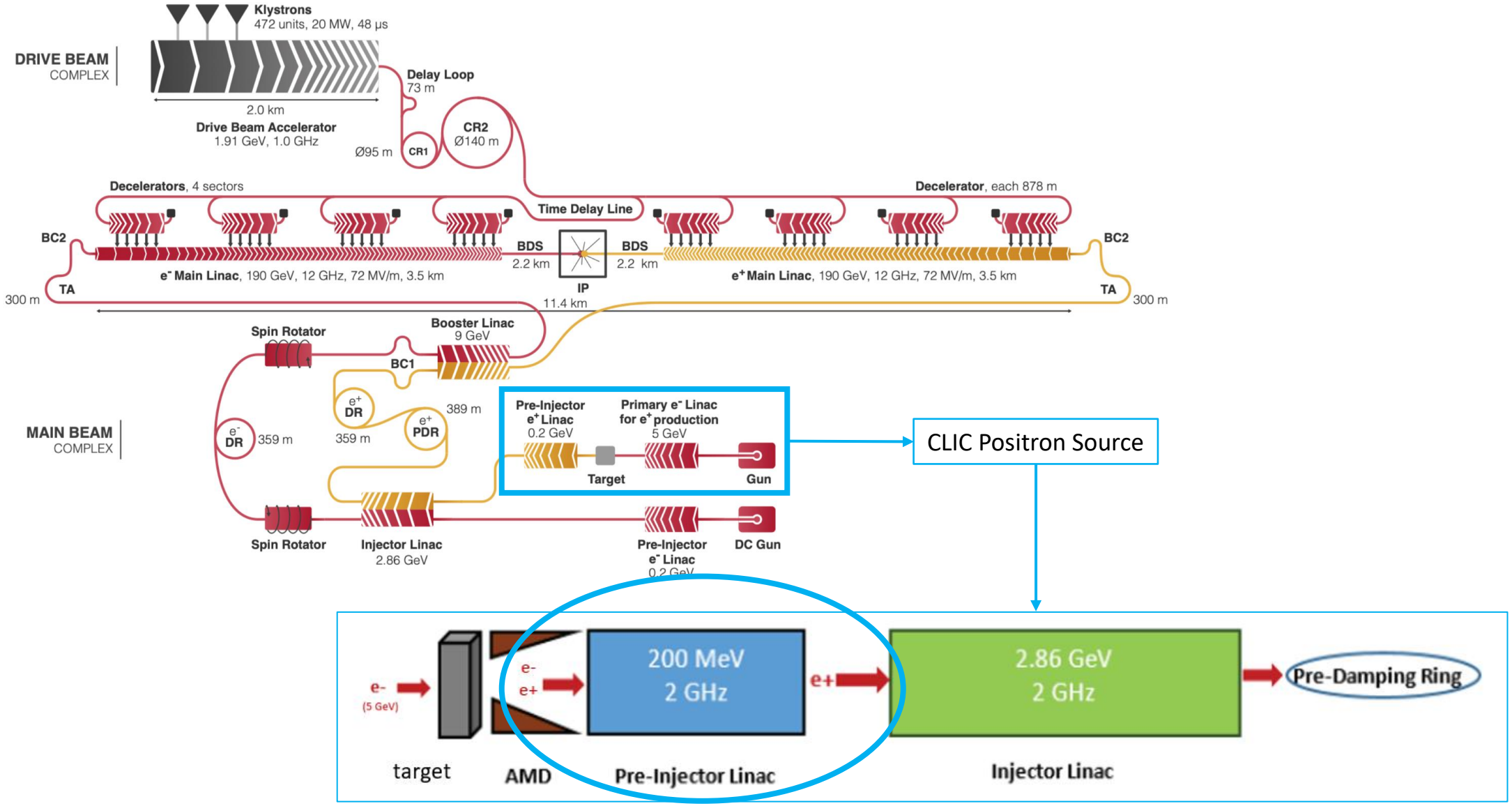
Table of content

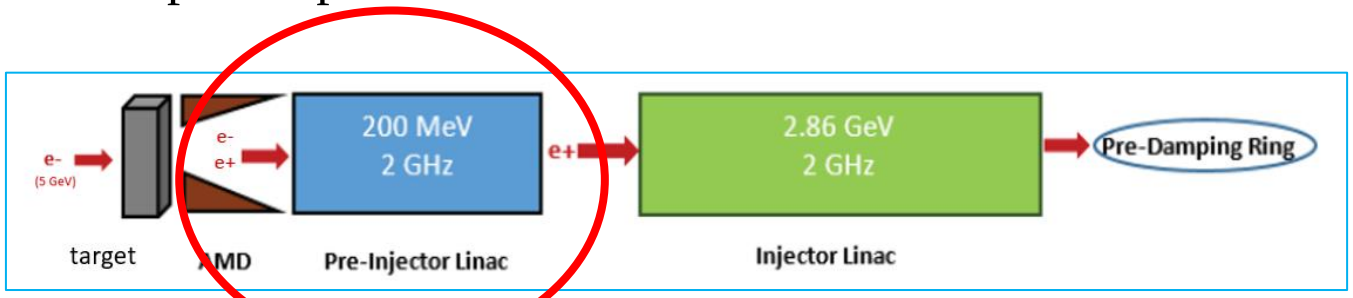
- Introduction
- Beam Loading effect
- RF-Track and Beam Loading
- Simulation and Results
- Summery

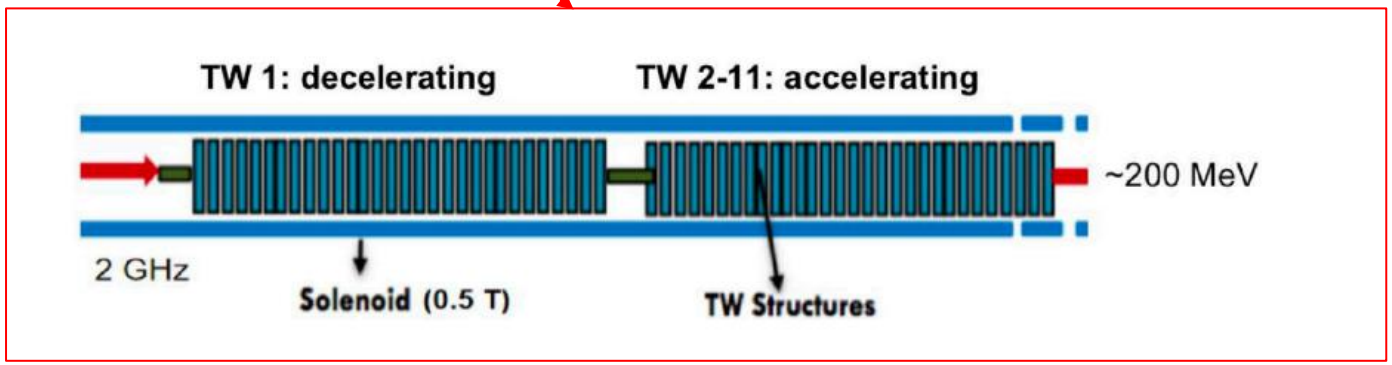
Introduction

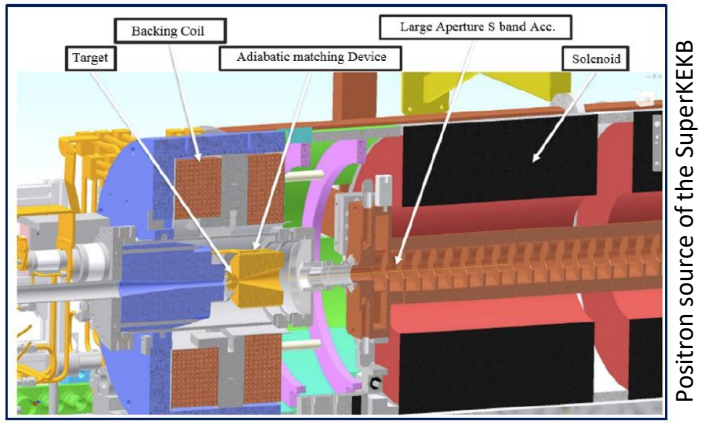


Introduction - CLIC Positron Source - Capture Linac

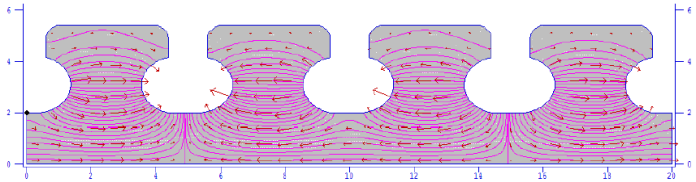
- 2 GHz room temperature, $2\pi/3$ phase advance per cell, traveling-wave accelerating structure
- Structure: 1.5 m long, 2 cm aperture (radius), 20 cm distance, with NC selonoid 0.5 T
- Number of structures: 11 => 1 for deceleration 10 for acceleration
- The captured positrons at the end of the CL reach 200 *M*eV energy.

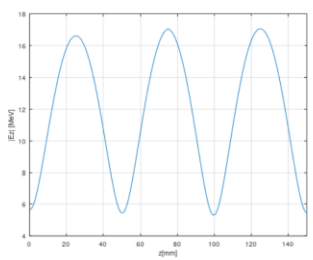


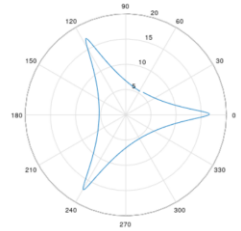




Positron source of the SuperKEKB







Optimisation of the CLIC positron source, Yongke Zhao, CLIC beam dynamics meeting,2021

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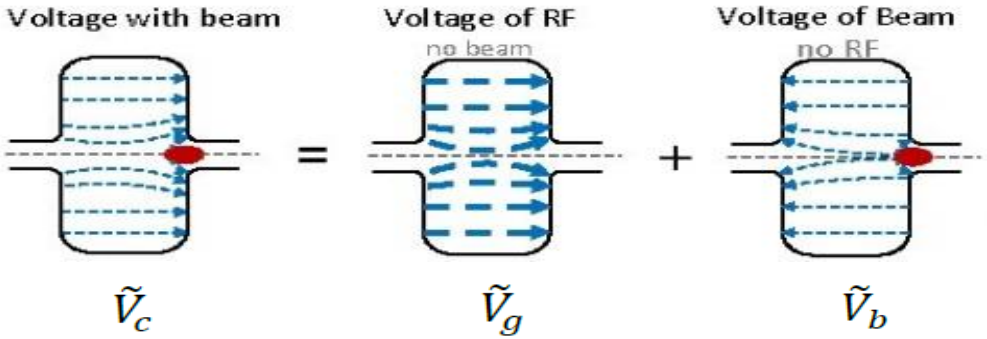
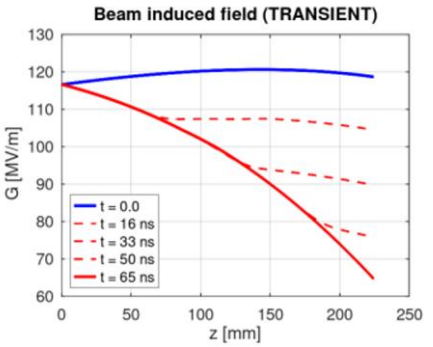
Cavity Beam Interactions and Beam Loading Effect

- A particle crossing a cavity would be affected by the excited fields in 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





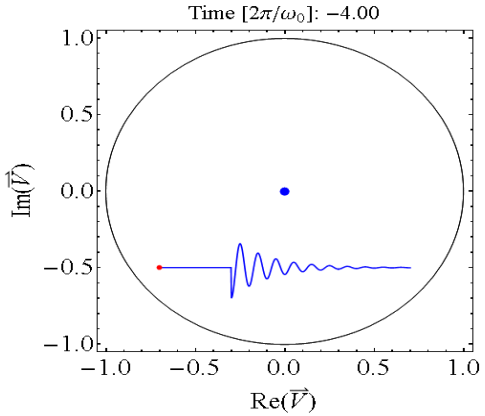
A. Grudiev, A.Lunin., Phys. Rev. Special topics 14, 052001 (2011)

external generator

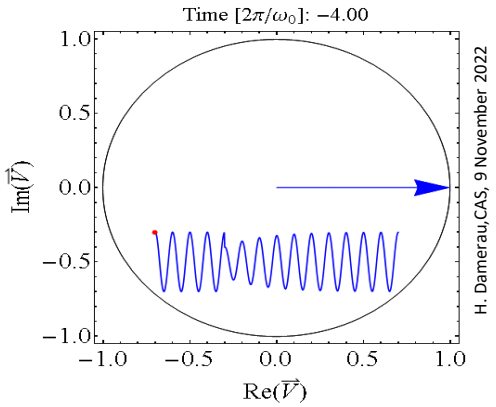
beam loading effect

Reduction of available accelerating gradient

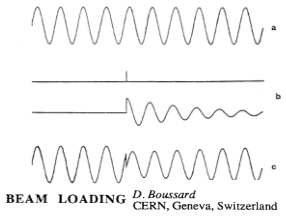
Cavity without external generator

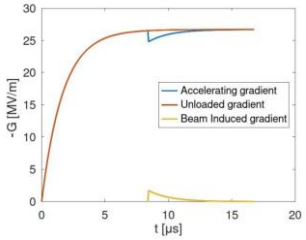


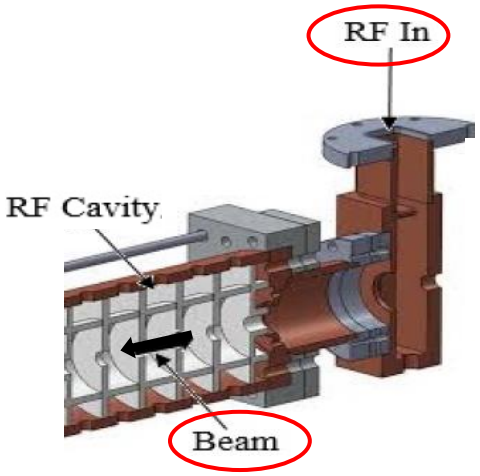
Cavity driven by external source

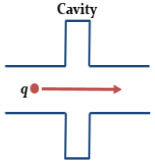


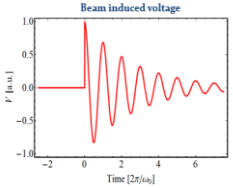
H. Damerau,CAS, 9 November 2022











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About 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:
  - TULIP, ELENA ring, the CLIC positron injector, and the AWAKE injector Linac.

Example (Octave interface)

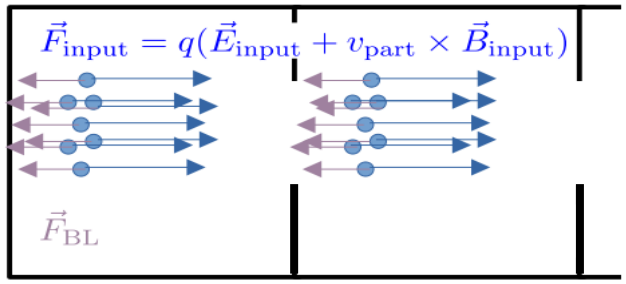
```
% load RF-Track
RF_Track;

% 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 can be understood with the Power-Diffusive model
- Self consistent module: additional decelerating kick attached to Drift spaces, TW and SW structure, field maps
- Compute force while tracking



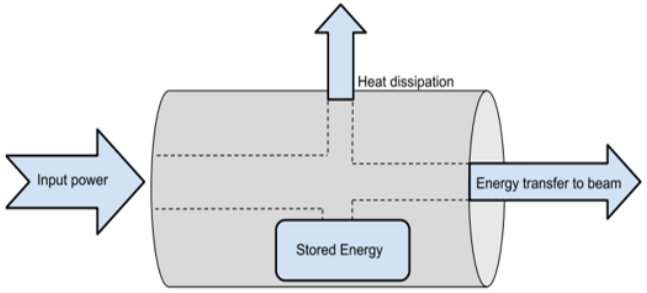
power-diffusive model

- From Poynting: Equation in terms of Gradient:

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

- Poynting Theorem

$$-\underbrace{\frac{\partial u(\vec{r},t)}{\partial t}}_{\text{Stored EM energy density variation}} = \underbrace{\vec{\nabla} \cdot \vec{S}(\vec{r},t)}_{\text{Power Flow \& Loss}} + \underbrace{\vec{E}(\vec{r},t) \cdot \vec{J}(\vec{r},t)}_{\text{Field-Beam Interaction}}$$



> Energy balance schematics for an accelerating structure

- Figures of merit:
  - Group velocity $v_g = \frac{P_{\text{flow}}}{w} [\text{m/s}]$
  - Quality factor $Q = \omega_{\text{RF}} \frac{w}{p_{\text{diss}}}$
  - Shunt impedance (p.u.l) $r_e = \frac{G_{\text{eff}}^2}{p_{\text{diss}}} [\Omega/\text{m}]$

More in : J.Olivares Herrador, A. Latina, et. al. Beam Loading Simulation for Relativistic and Ultrarelativistic Beams in the Tracking Code RF-Track. Linac 2022 *Edited*

Beam Loading in RF_Track -Example (Octave)

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

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

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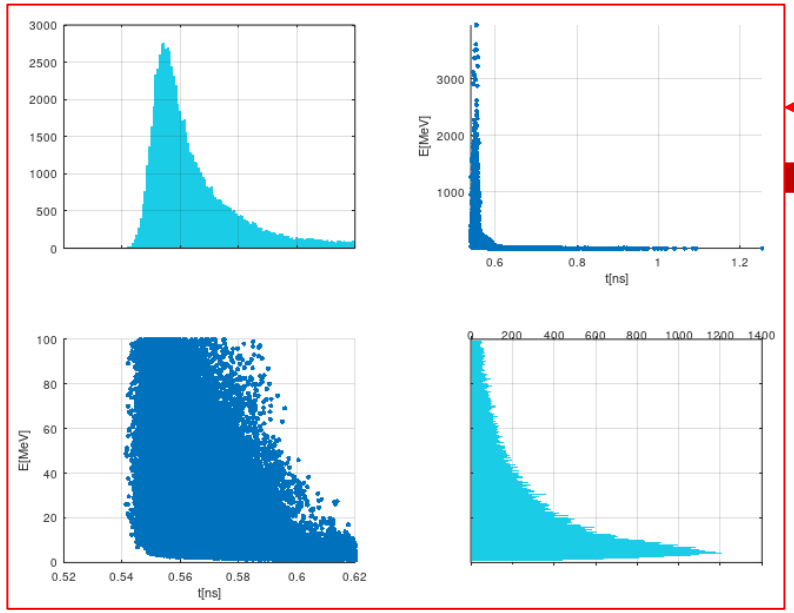
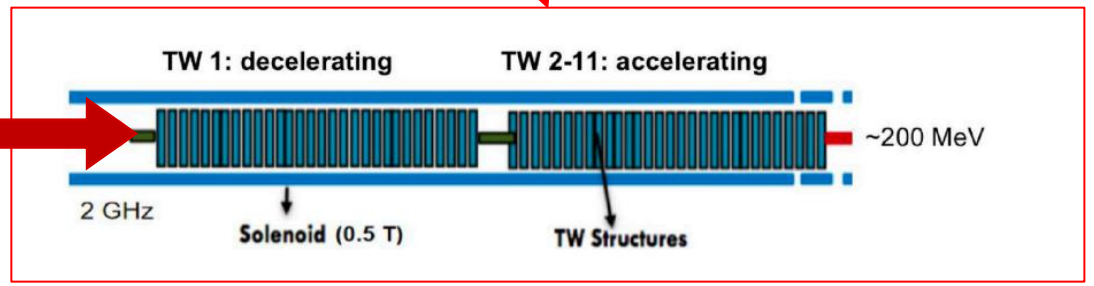
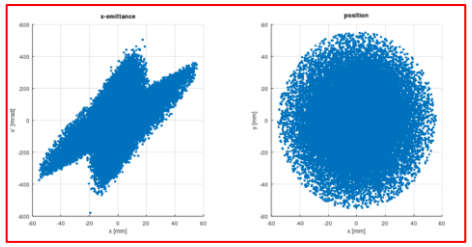
Challenges

- Capture Linac includes both e- e+ with large energy-spread, large-bunch-length, large-emittance
- Structure suffers from both e- and e+ Beam Loading
- Goal: Preserve as many e+ as possible and prepare them for entry into the pre-damping ring for emittance reduction

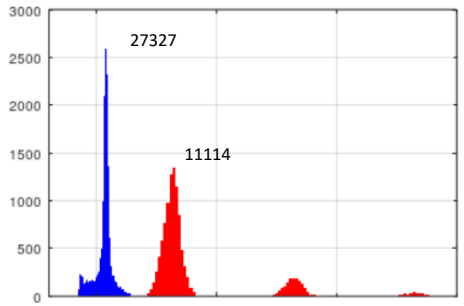


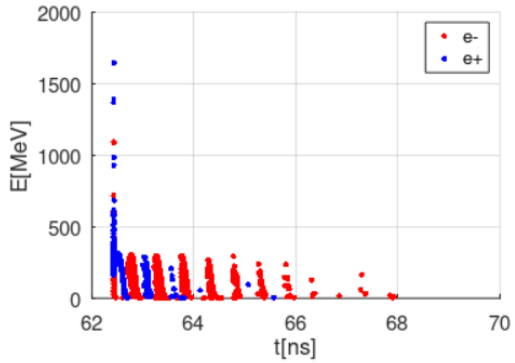


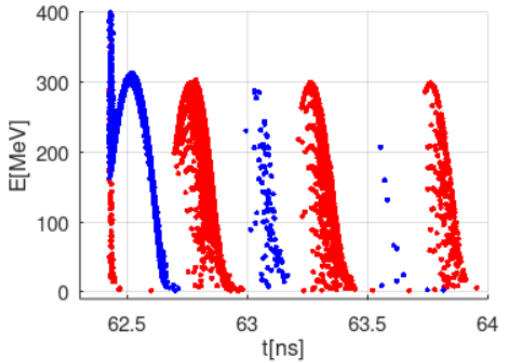


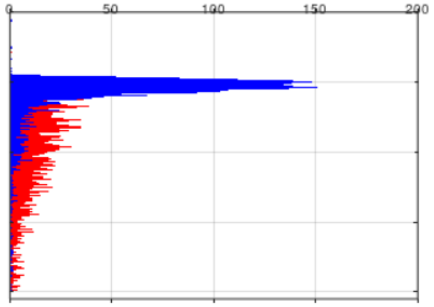
e- e+ outputs

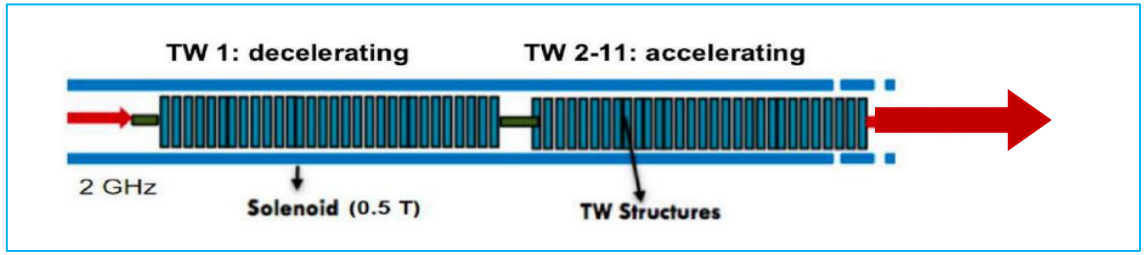
- Most of the positrons are lost at the beginning of the pipe => Cooling needs to be addressed.
- Electrons have a phase shift of π degree apart with respect to positrons, moving to the accelerating phase and gaining energy.

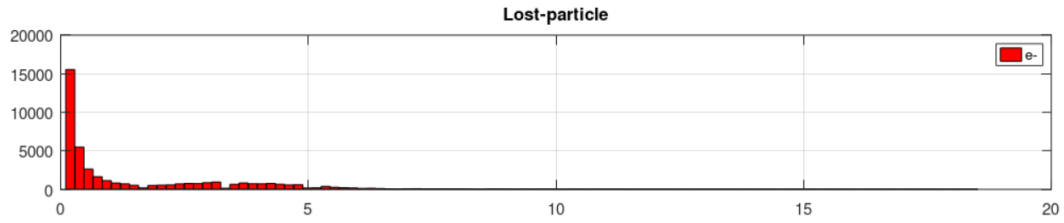


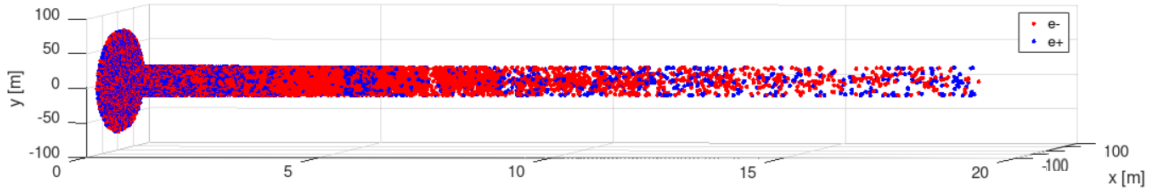


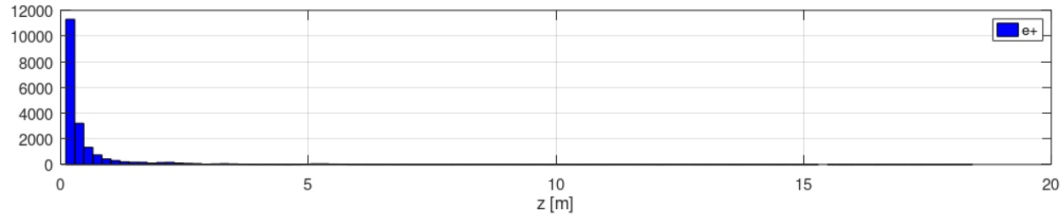




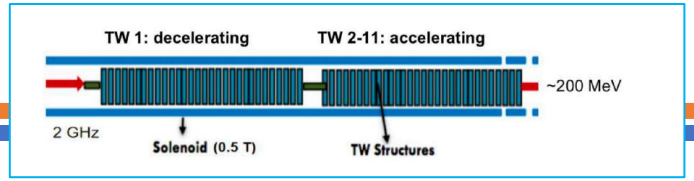








Phase Scan

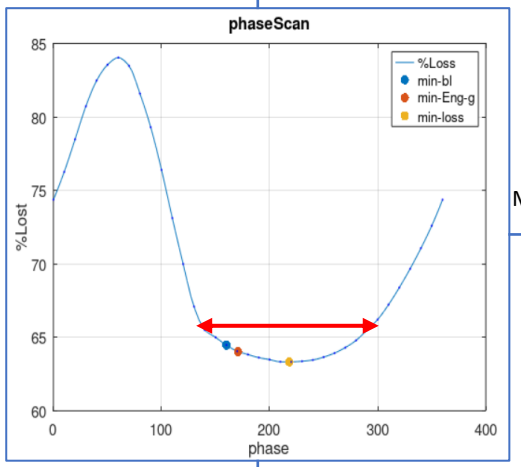


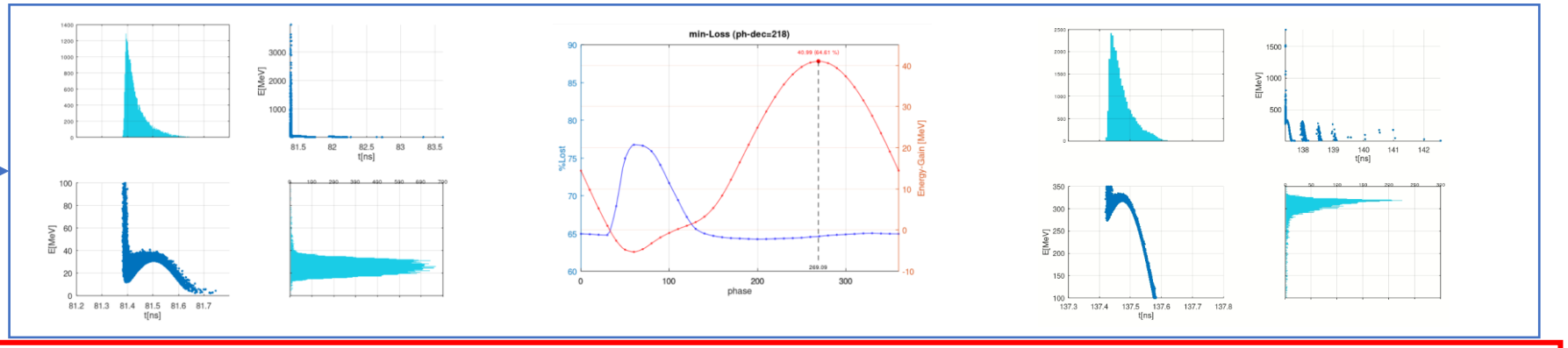
- The structure can be optimized through different criteria.

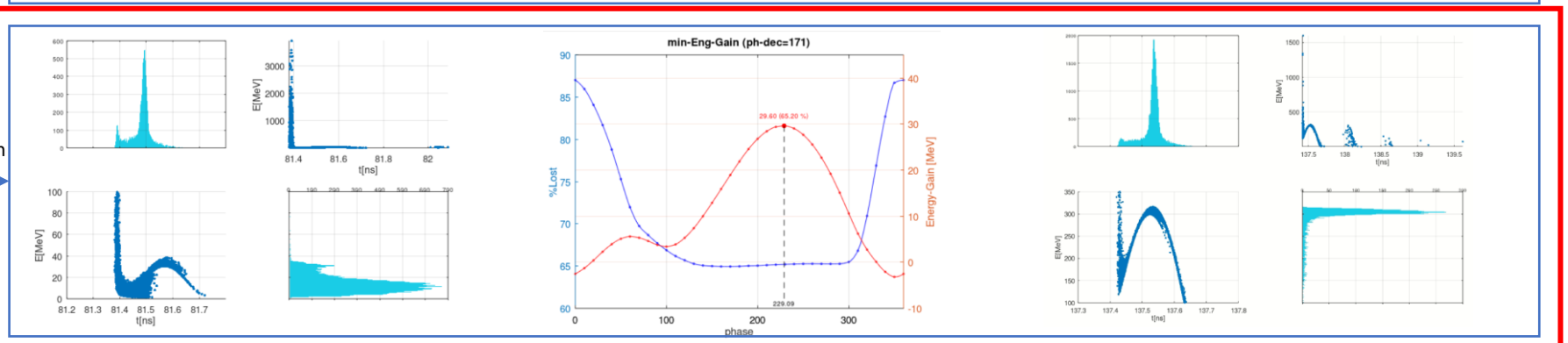
Min_loss

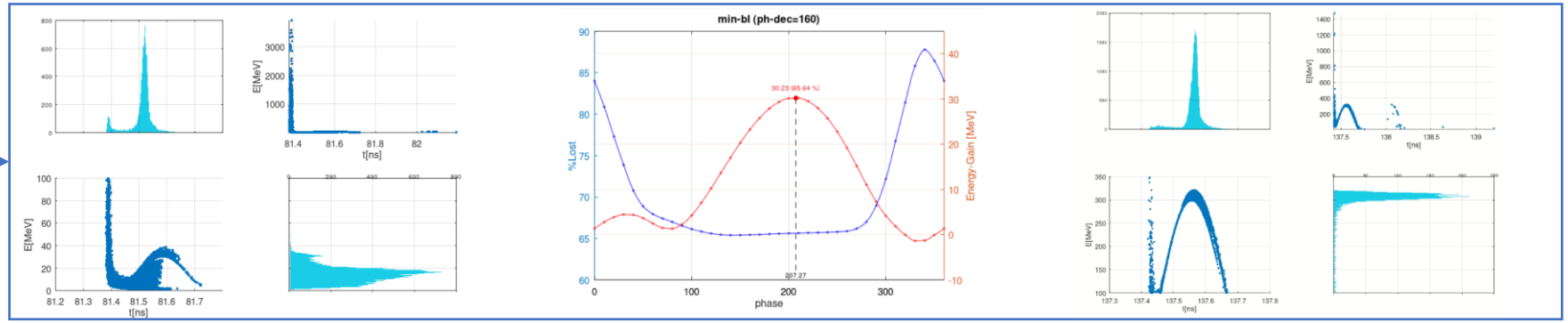
Min_Eng_gain

Min_bunch_length

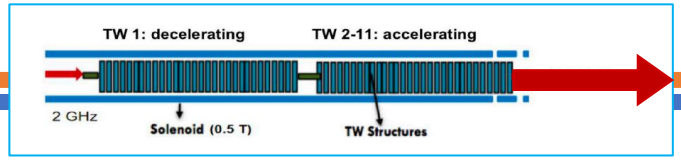




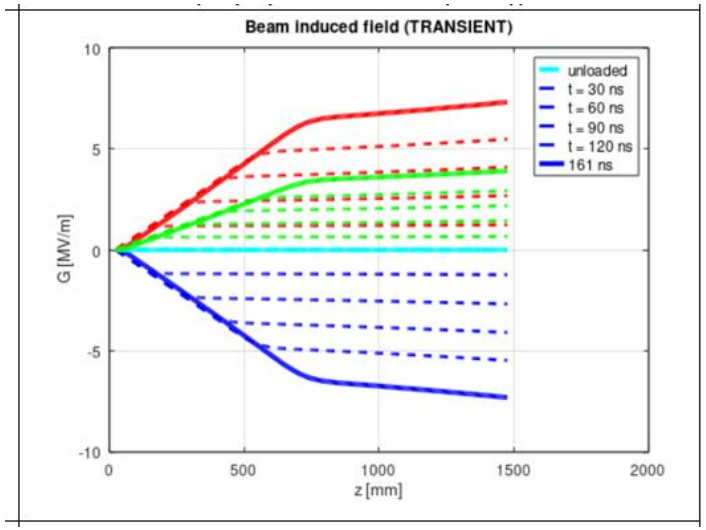


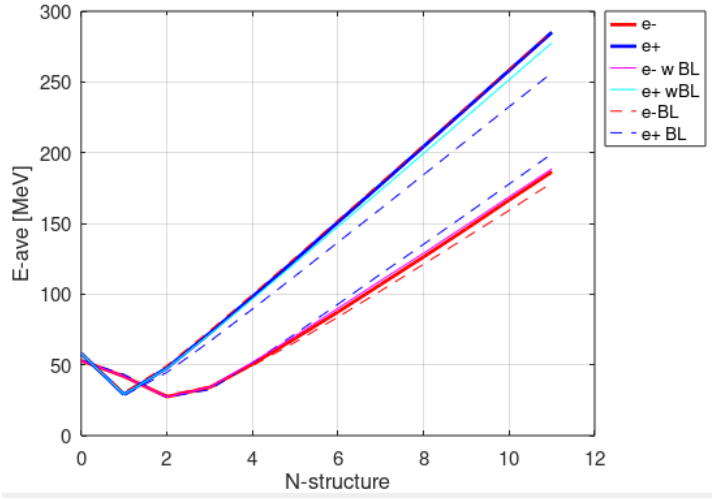


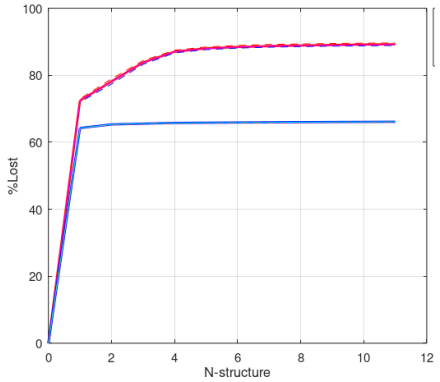
Beam Loading results

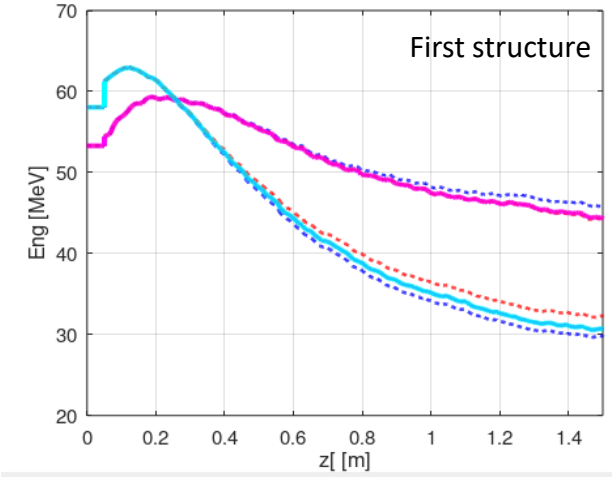


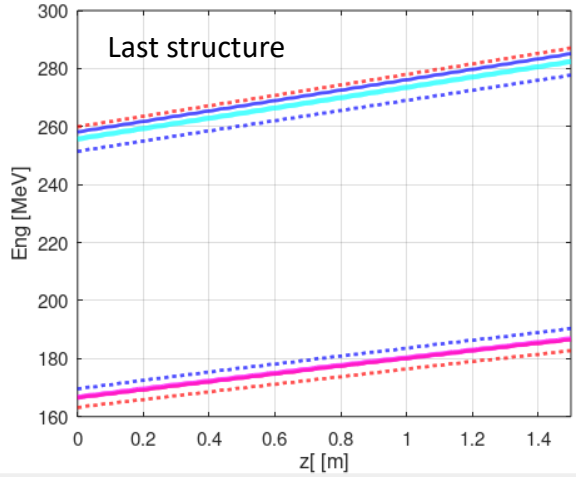
❖ Gradient reduction for middle bunch n=150











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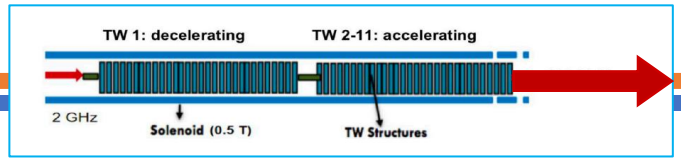
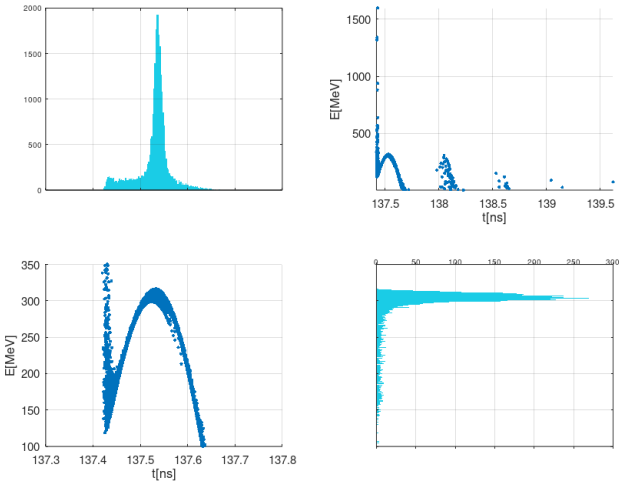


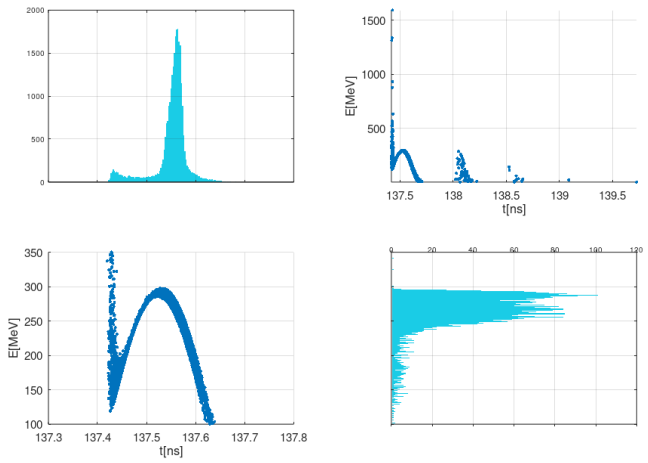
- Positron phase space with e+ BL with both e+ e- BL w/o BL

w/o BL



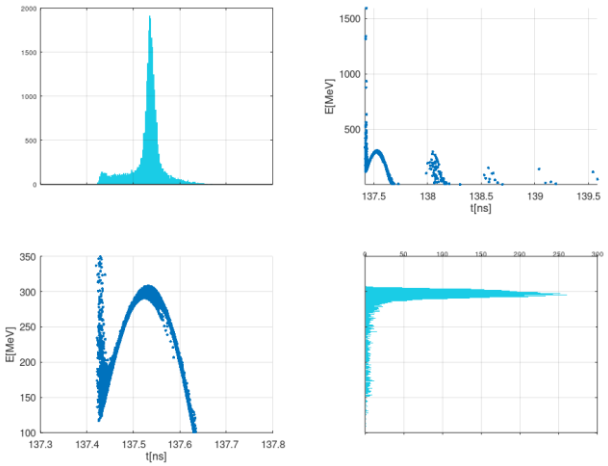
unit	input	output
%Lost	66.11 %	
Eng_Gain/Loss [MeV]	226.81	
N_particle [#]	81254	27538
ave-Eng [MeV]	58	285.09
EngSpread [MeV]	123.41	47.12
bunch_length [ns]	0.0322	0.0528
bunch_length [degree]	23.18	37.99
beamSize-x [mm]	12.67	7.22
beamSize-y [mm]	12.70	7.19
emittance-x [mm.mrad]	9274.20	9336.52
emittance-y [mm.mrad]	9227.00	9245.70

w/ e+ BL



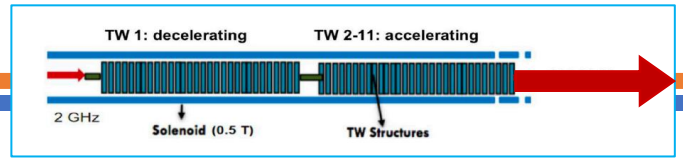
unit	input	output
%Lost	66.58 %	
Eng_Gain/Loss [MeV]	198.35	
N_particle [#]	81254	27158
ave-Eng [MeV]	58	256.49
EngSpread [MeV]	123.41	41.79
bunch_length [ns]	0.0322	0.0522
bunch_length [degree]	23.18	37.60
beamSize-x [mm]	12.67	7.27
beamSize-y [mm]	12.70	7.15
emittance-x [mm.mrad]	9422.29	9326.06
emittance-y [mm.mrad]	9247.44	9250.02

w/ e+ e- BL



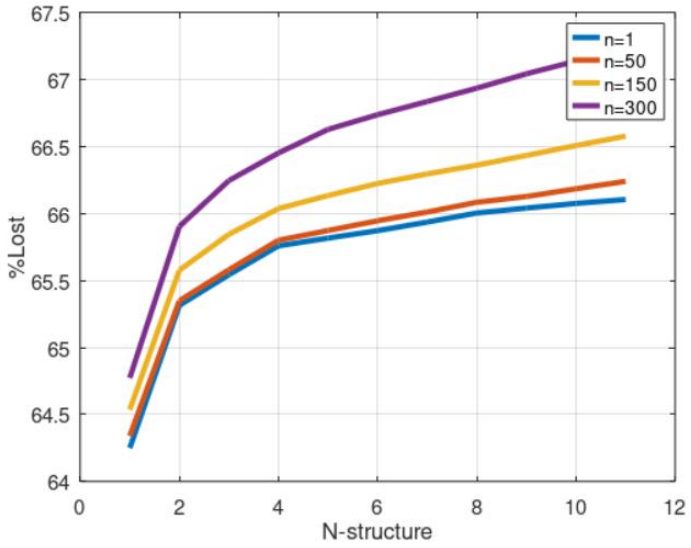
unit	input	output
%Lost	66.12 %	
Eng_Gain/Loss [MeV]	219.33	
N_particle [#]	81254	27529
ave-Eng [MeV]	58	277.62
EngSpread [MeV]	123.41	45.88
bunch_length [ns]	0.0322	0.0560
bunch_length [degree]	23.18	40.33
beamSize-x [mm]	12.67	7.25
beamSize-y [mm]	12.70	7.22
emittance-x [mm.mrad]	9315.61	9377.41
emittance-y [mm.mrad]	9259.78	9271.00

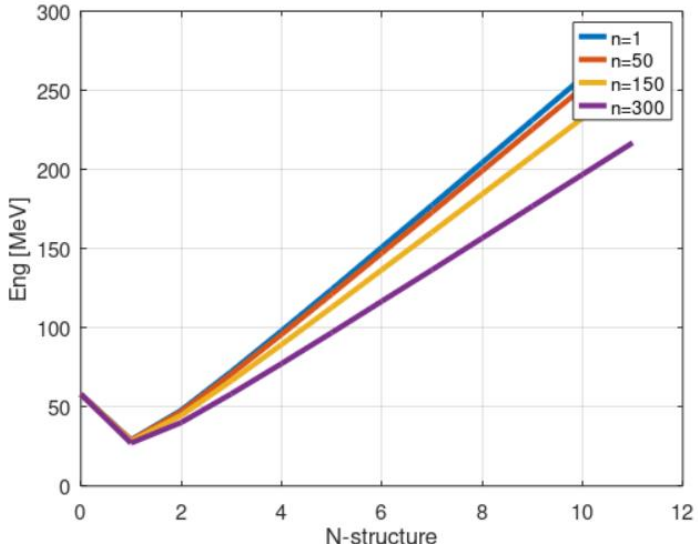
Beam Loading results



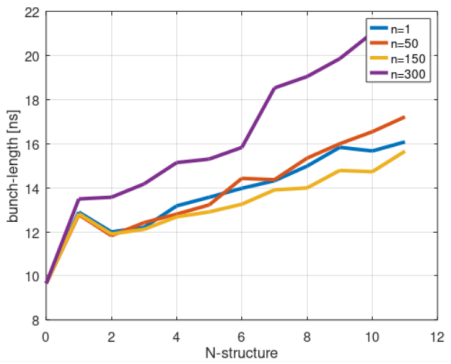
- $\tau_f > \tau_{train} \Rightarrow$ transient Beam Loading affects particles.
- bunch-to-bunch variation

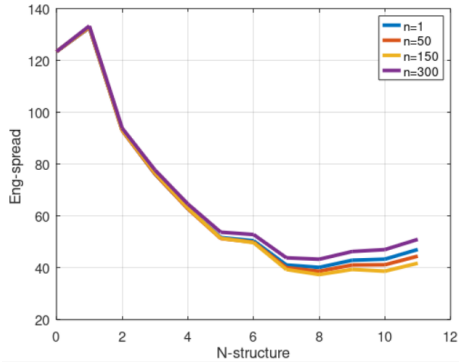
e+ with e+ Beam Loading

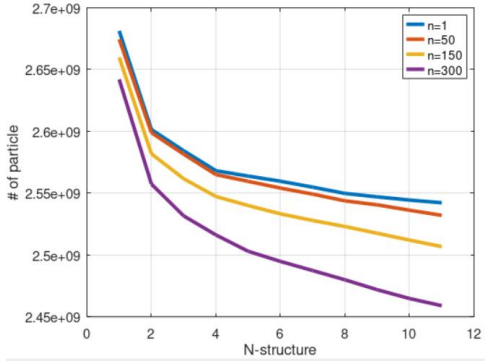


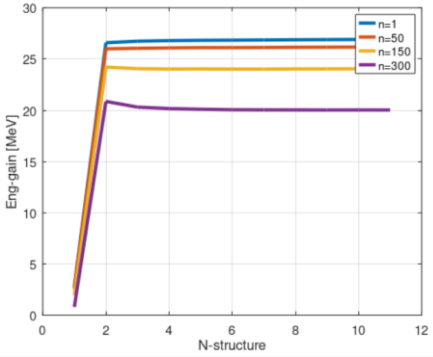


Need more consideration





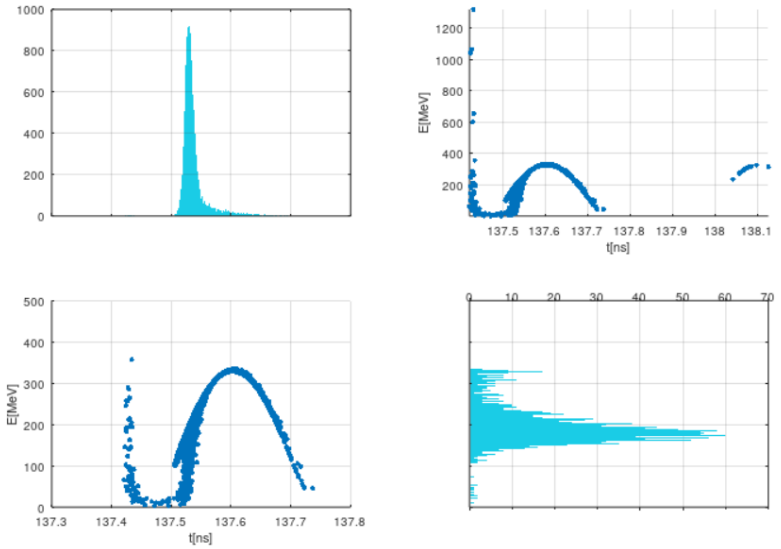




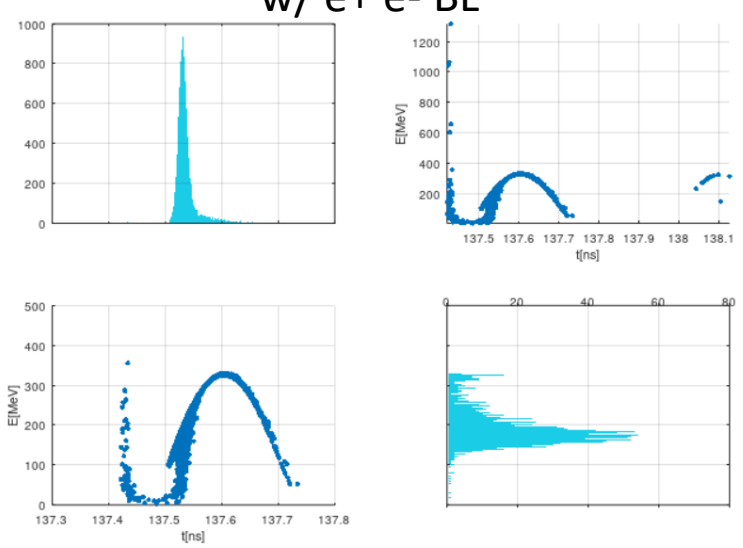
Beam Loading effect in optimized phase

- Beam loading effect on an optimized structure with a focus on achieving maximum yield in the DR entrance.

w/o BL



w/ e+ e- BL



e+ w/o BL	unit	input	output
%Lost		65.41 %	
Eng_Gain/Loss	[MeV]	138.88	
N_particle	[#]	81254	28107
ave-Eng	[MeV]	58	196.93
EngSpread	[MeV]	123.41	49.86
bunch_length	[ns]	0.0322	0.0262
bunch_length	[degree]	23.18	18.88
beamSize-x	[mm]	12.67	7.19
beamSize-y	[mm]	12.70	7.06
emittance-x	[mm.mrad]	9358.18	9321.17
emittance-y	[mm.mrad]	9210.44	9180.48

e+e- BL	unit	input	output
%Lost		65.41 %	
Eng_Gain/Loss	[MeV]	135.40	
N_particle	[#]	81254	28109
ave-Eng	[MeV]	58	193.44
EngSpread	[MeV]	123.41	49.22
bunch_length	[ns]	0.0322	0.0263
bunch_length	[degree]	23.18	18.92
beamSize-x	[mm]	12.67	7.20
beamSize-y	[mm]	12.70	7.09
emittance-x	[mm.mrad]	9361.31	9351.61
emittance-y	[mm.mrad]	9214.70	9210.40

Summery

- 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.
- The effect of BL in an optimized structure (based on maximum yield in DR entrance) has been studied.
- studies are still ongoing….
- OUTLOOK:
  - Further optimization for finding appropriate phase and gradient in the presence of Beam Loading
  - Further optimization to investigate and compensate bunch to bunch variation

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Thanks for your attention