WP1: FCCee injector linacs status report

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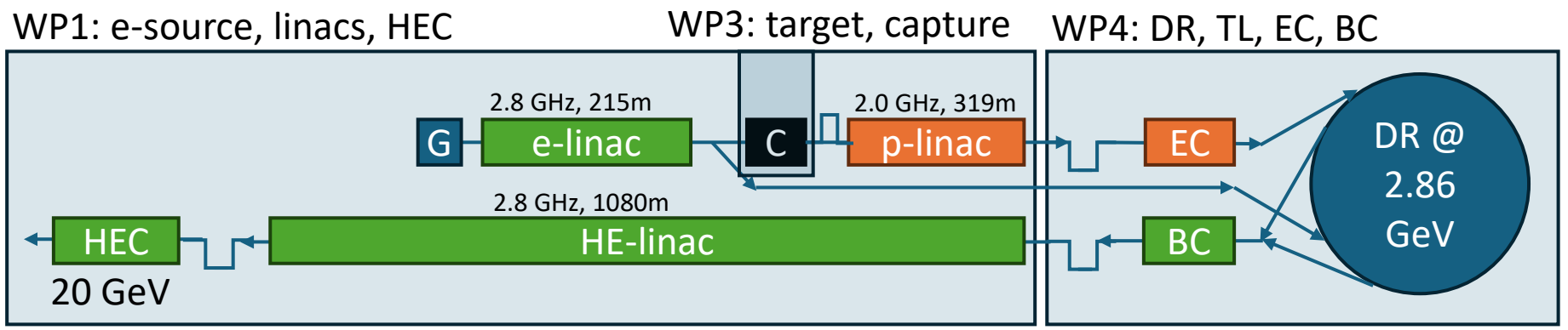
5/12/2024

New baseline layout (4 AS/module, 4 bunches@100 Hz)



Max. Klystron Power: 80 MW, Operating Klystron Power: 64 MW i.e. 20 % Margin

Linac	<a/λ>	Bunch Charge [nC]	Kly. power per structure [MW]	Loaded acc. gradients [MV/m]	Nb. modules	Linac lengths [m]	Oper. power consumptions [MW]	Max. power consumptions [MW]
e-linac *	0.15	5	14.2	19.5	14+1	215	2	2.5
p-linac**	0.2	15	15.4	13.3	22	319	8	9
HE-linac *	0.12	5	14.2	21.1	72	1080	9.5	11.5

* 3 μs RF pulse length, 6 μs HV pulse length
Assumes 25 m WR284 waveguide system length for one RF module
** 5 μs RF pulse length, 8 μs HV pulse length,
Assumes 25 m WR510 waveguide system length for one RF module
Assumes 6 structures (2 modules) for Capt. Linac, 20 structures (5 modules) for S1 Linac and 260 solenoids

Acc. Structure parameters

Structure parameters are calculated for the single bunch case.

	HE-linac	E-linac	P-linac
Frequency [GHz]	2.8	2.8	2
Avg. Aperture	0.12λ	0.15λ	0.2λ
Entr., exit aperture	14.85 mm, 10.85 mm	17.13 mm, 14.99 mm	30 mm, 30 mm
Iris thickness	2.84 mm → 4.04 mm	10.4 mm → 13.7 mm	14.3 mm → 20 mm
Vg (% c)	3.92 → 1.25	3.14→ 1.38	2.58 → 1.92
r/Q (kOhm/m)	3.63 → 4.38	3.28 → 3.67	1.49 → 1.52
Q	16571 → 16039	14599 → 13668	20977 → 19102
Structure Length [m]	3	3	3
Filling time	460 ns	486 ns	447 ns
SLED coupling	15	15	17
Eff. shunt impedance	102 .25 MΩ/m	87.17 MΩ/m	38.73 MΩ/m
Repetition rate [Hz]	100	100	100
Klystron power per structure	14.2MW	14.2 MW	15.4 MW
Average Structure Input Power	3.72 kW	3.76 kW	3.68 kW
G_{avg}	22 MV/m	20.3 MV/m	14.1 MV/m
E_{max} (instant.)	73 MV/m	77 MV/m	55 MV/m
$S_{c,max}$ (instant.)	501 mW/μm²	453 mW/μm²	298 mW/μm²

Acc. Structure parameters

Structure parameters are calculated for the four bunches case.

	HE-linac	E-linac	P-linac		
Eff. shunt impedance (Four bunches)	95.65 MΩ/m	81.69 MΩ/m	36 MΩ/m		
Klystron power per structure	14.2MW	14.2 MW	15.4 MW		
Unloaded G_{avg}	21.28 MV/m	19.66 MV/m	13.59 MV/m		
Bunch Charge	5 nC	5 nC	5 nC	10 nC	15 nC
Loaded G_{avg}	**21.06 MV/m**	**19.49 MV/m**	13.5 MV/m	13.42 MV/m	**13.31 MV/m**

Compansated

- **HE Linac:**

4 Bunches case:

P_klys = 14.2 MW

3m structure

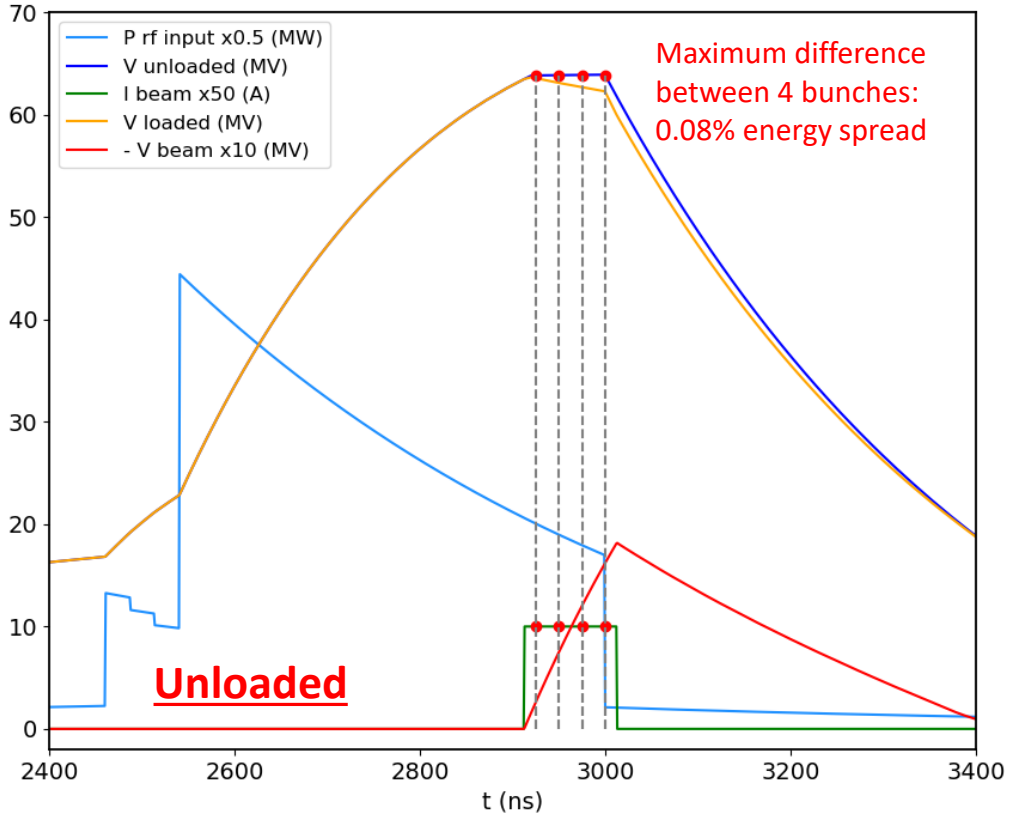
G = V/L

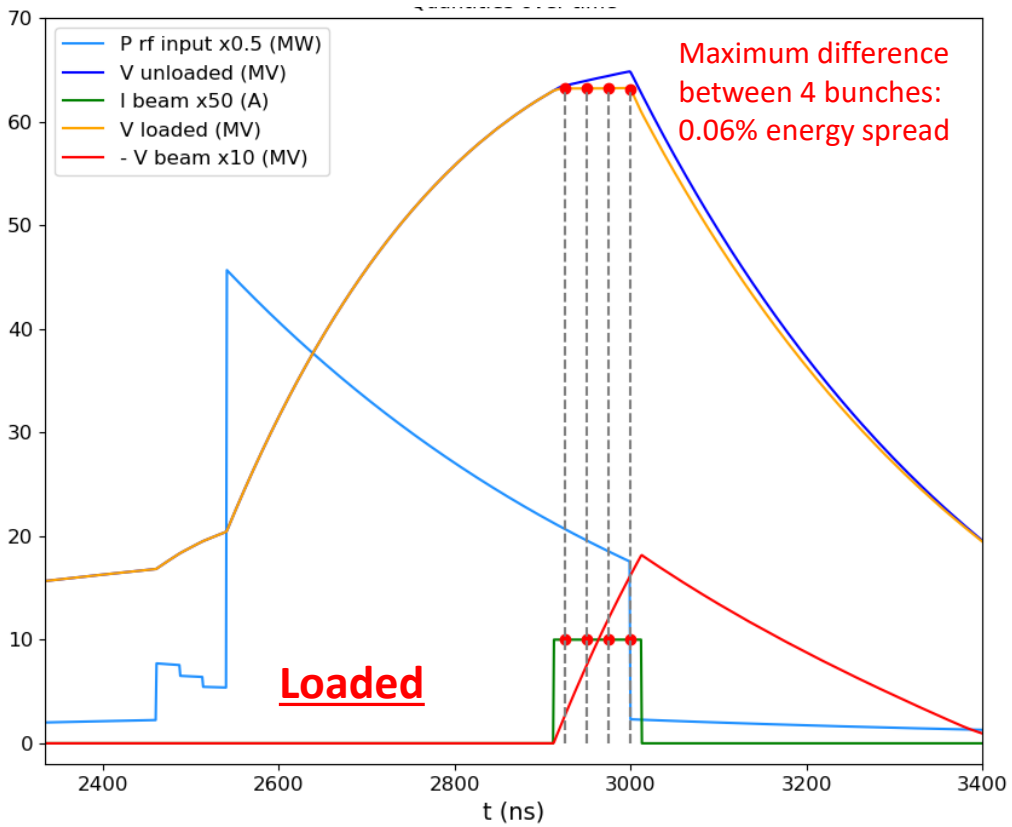
For bunch charge: 5 nC

25 ns of bunch spacing

Unloaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch	Rsh
Single Bunch	66 MV				102.25 MΩ/m
4 Bunches	63.81 MV	63.84 MV	63.86 MV	63.82 MV	95.65 MΩ/m

Loaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch
Single Bunch	65.75 MV			
4 Bunches	63.19 MV	63.19 MV	63.20 MV	63.16 MV



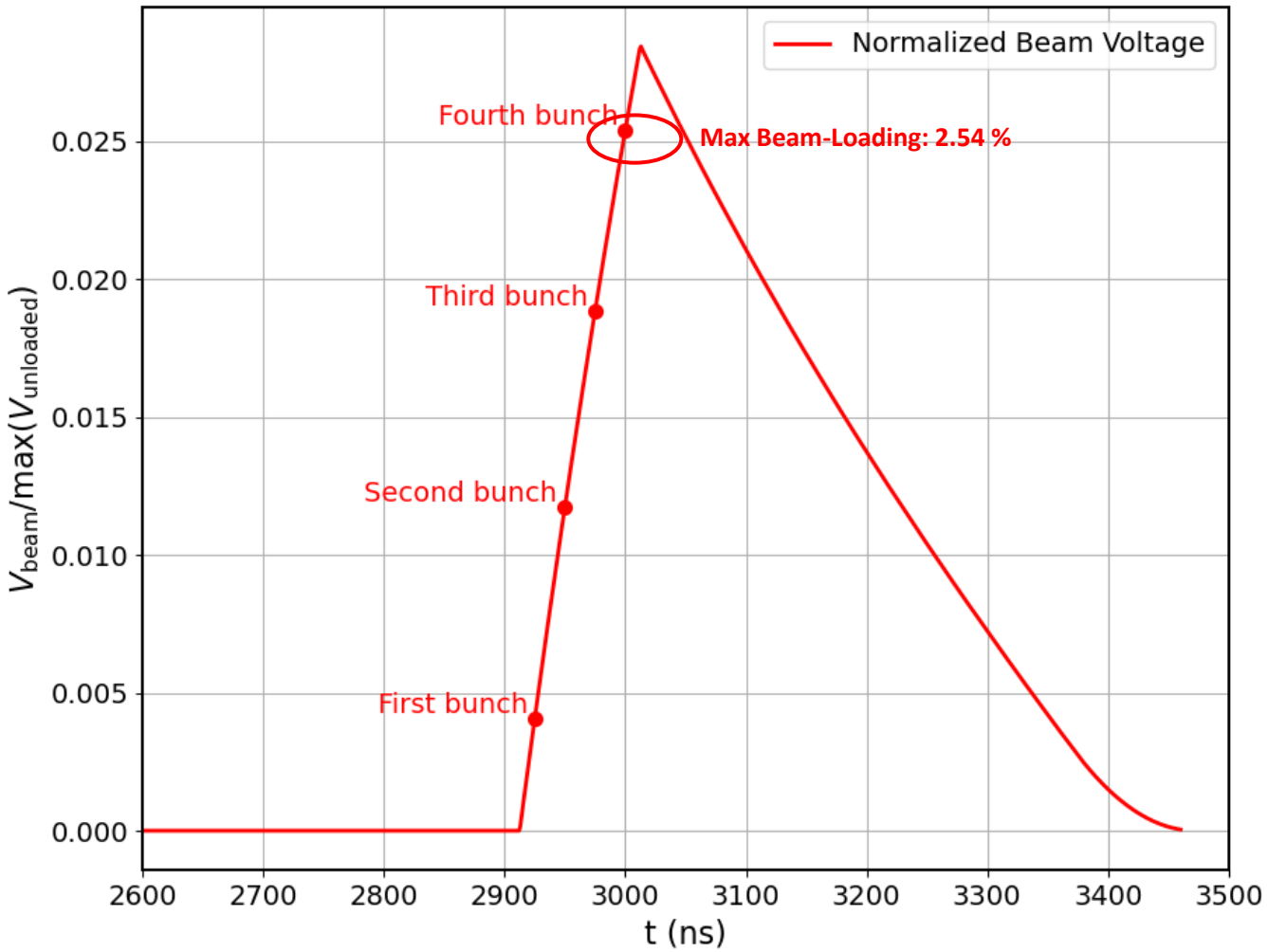


- **HE Linac:**

4 Bunches case:

For bunch charge: 5 nC
25 ns of bunch spacing

Beam loading effect



Golden pulse applied

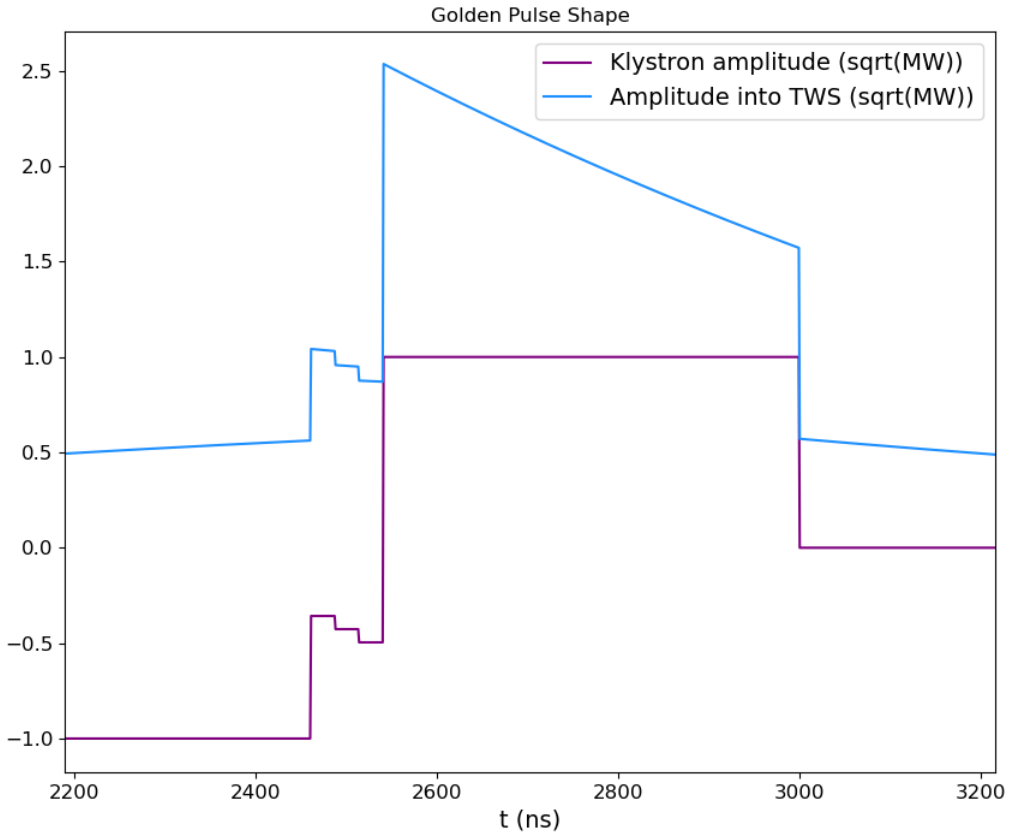
- **HE Linac:**

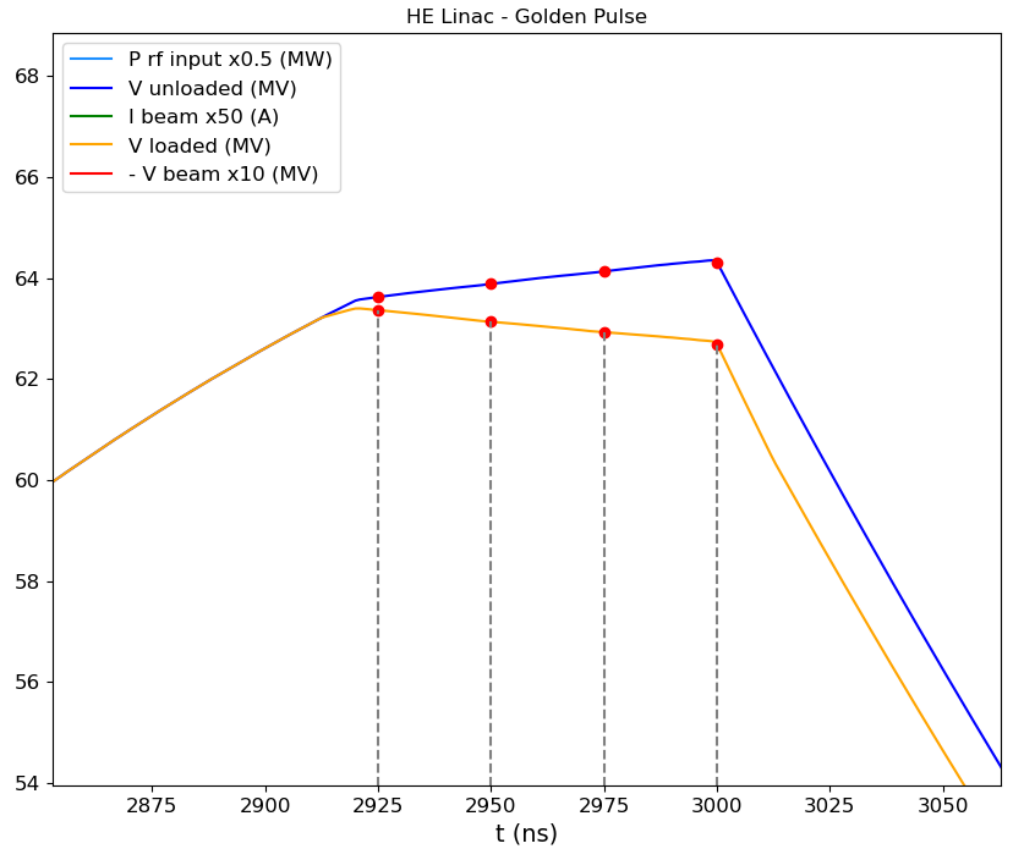
4 Bunches case:

Unloaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch	
Single Bunch	66 MV				
4 Bunches	63.63 MV	63.89 MV	64.13 MV	64.30 MV	+1.1% energy spread

Loaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch	
Single Bunch	65.75 MV				
4 Bunches	63.37 MV	63.14 MV	62.93 MV	62.68 MV	-1.1 % energy spread

For bunch charge: 5 nC
25 ns of bunch spacing





e- and HE linac: static effects

Sensitivity to static misalignments

- Assumed rms Gaussian distributed misalignments: 50 um for quadrupoles, 100 um per RF structures, and 30 um per BPM
- Applied one-to-one correction and DFS (including 10 um resolution) in cascade
- More than the 98% of the good seeds considered in the calculation of the emittance growth

- **e- linac:**
  - Emittance good enough for the positron production (e-linac)
  - Emittance expected to be good enough for the injection to DR (tbc by the DR group)
- **HE linac:**
  - Emittance growth fulfilling the booster requirements

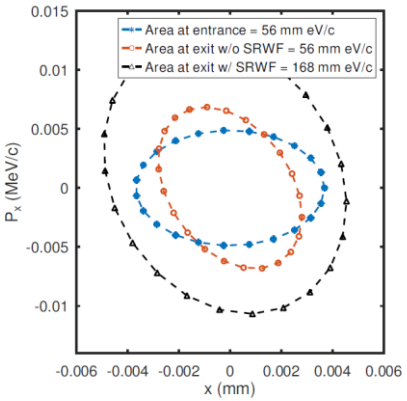
Emittance growth under control

ε_x (mm.mrad)		ε_y (mm.mrad)	
Maximum	**Design**	**Maximum**	**Design**
20	<12	2	1.6

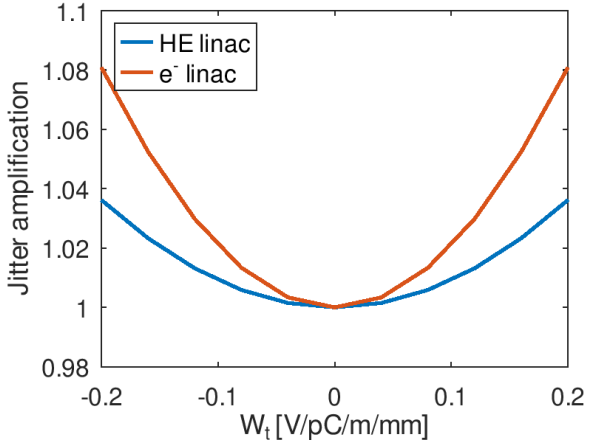
e- and HE linac: dynamics effects

e- linac		HE linac	
Multi-bunch	**Single bunch**	**Multi-bunch**	**Single bunch**
1.03	1.18	1.02	1.01

$$\mathrm{JA} = \sqrt{\frac{A_{\mathrm{final}}}{A_{\mathrm{initial}}}}.$$

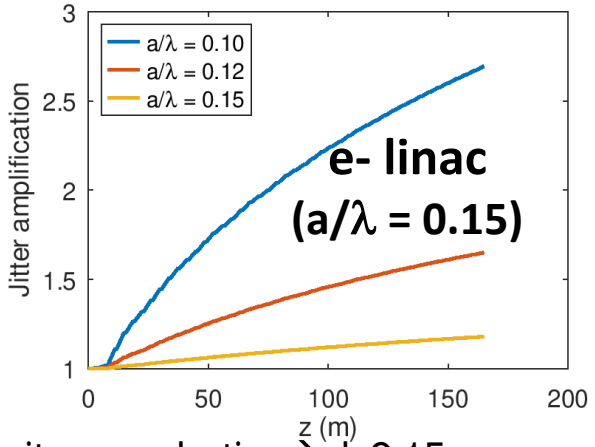


Multi-bunch

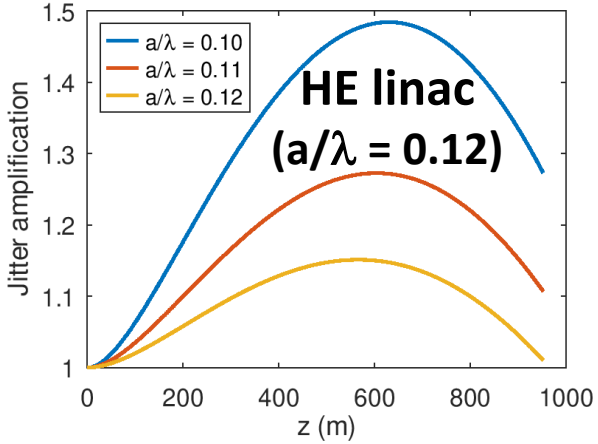


From the previous design RF optimized for a maximum kick=0.11 V/pC/m/mm

Single bunch



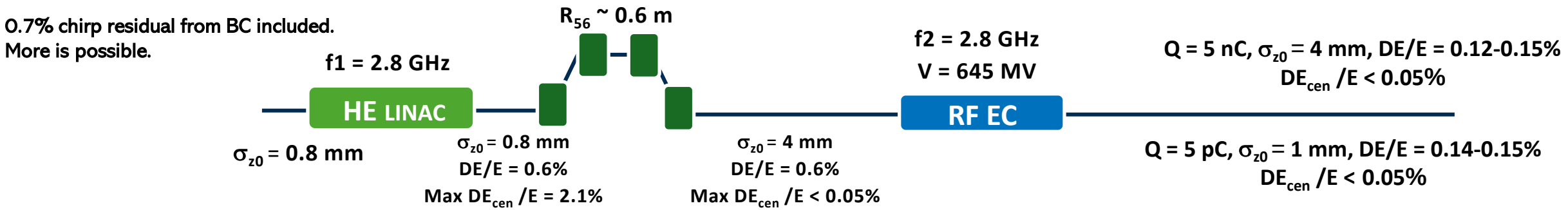
Positron production→ok 0.15
Damping ring→ waiting for an answer



Booster→ok

No showstoppers identified

Longitudinal phase space manipulation: “golden” pulse and energy compressor (EC)



- Total length <100 m including matching sections upstream and along EC
- On-crest operating phase to optimize the transverse beam quality and maximize the acceleration efficiency
- For the **top-up operation** with variable (0-100%) charges in each of the 4 bunches, LLRF used to generate a **unique golden pulse**
- EC is used to match both the single- and multi- bunch target parameters, see below

Q = 5 nC: DE/E~0.1-0.15%. Factor 3 smaller DE/E possible (single-bunch)

	Bunch 1	Bunch 2	Bunch 3	Bunch 4
Single bunch DE/E (%)	0.15	0.15	0.14	0.12
Rms bunch length (mm)	4.04	4.05	4.07	4.09
DE/E centroid from bunch 1 (%)	0	-0.003	-0.007	-0.019
Dt from bunch 1 (ps)	0	5.7	10.9	17.2

Q = 5 pC → machine settings unchanged vs the high Q

	Bunch 1	Bunch 2	Bunch 3	Bunch 4
Single bunch DE/E (%)	0.14	0.15	0.14	0.14
Rms bunch length (mm)	1.03	1.02	1.02	1.02
DE/E centroid from bunch 1 (%)	<0.011	0.011	0.030	0.049
Dt from bunch 1 (ps)	0	-0.6	-1.2	-1.6
Dt from bunch 1 absolute (ps)	-28.9	-29.5	-30.1	-30.5

These parameters seem to be acceptable by the booster

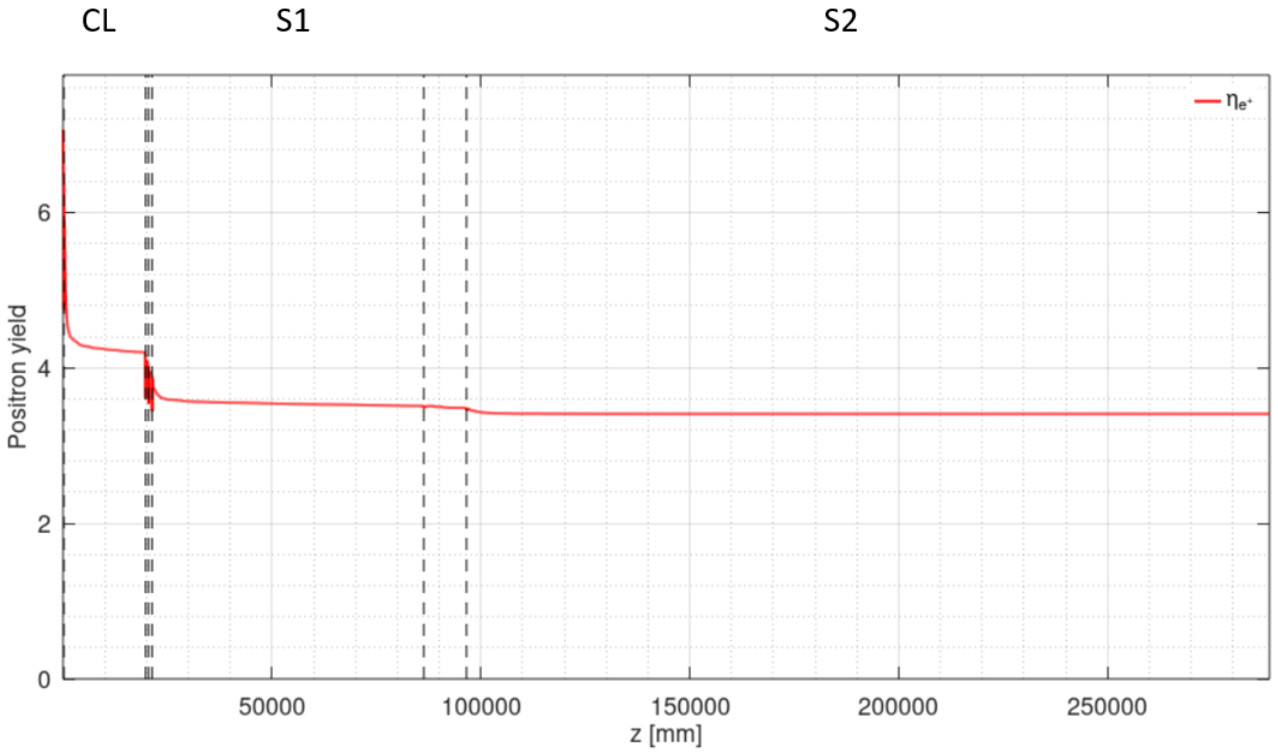
p-linac design

- Section 1 (S1)
  - Structure a=30mm, L = 3m and solenoids
  - N = 20, G = 13.3 MV/m, ϕ = -10° (optimized for max. yield)
  - Average energy (around bunch core) at exit: 931.7 MeV
- Section 2 (S2)
  - Structure a = 30mm, L = 3m
  - Periodic FODO cells. 2 structures per FODO cell. FODO phase advance: 76.345° (optimized for min. beta)
  - Quadrupole length: 0.4 m. Quadrupole-Structure distance: 0.15 m. Quadrupole spacing: 3.3 m
  - N = 52, G = 12.756 MV/m, ϕ = 5° (optimized for max. yield)
  - Average energy (around bunch core) at exit: 2.866 GeV

Parameter	Value
Collective effects considered	Space charge; Short-range wakefield
Primary electron bunch charge assumed for collective effects [nC]	5.0
Bunch length (around bunch core) at PL exit [mm]	3.0
Energy spread (around bunch core) at PL exit [%]	0.95
Total positron yield (all positrons) at PL exit	3.41
Expected DR accepted yield with ±2% energy acceptance at PL exit	3.01
Normalized X, Y emittances (accepted positrons) at PL exit [mm*rad]	13.1, 13.0
Geometric X, Y emittances at (accepted positrons) PL exit [mm*mrad]	2.34, 2.32

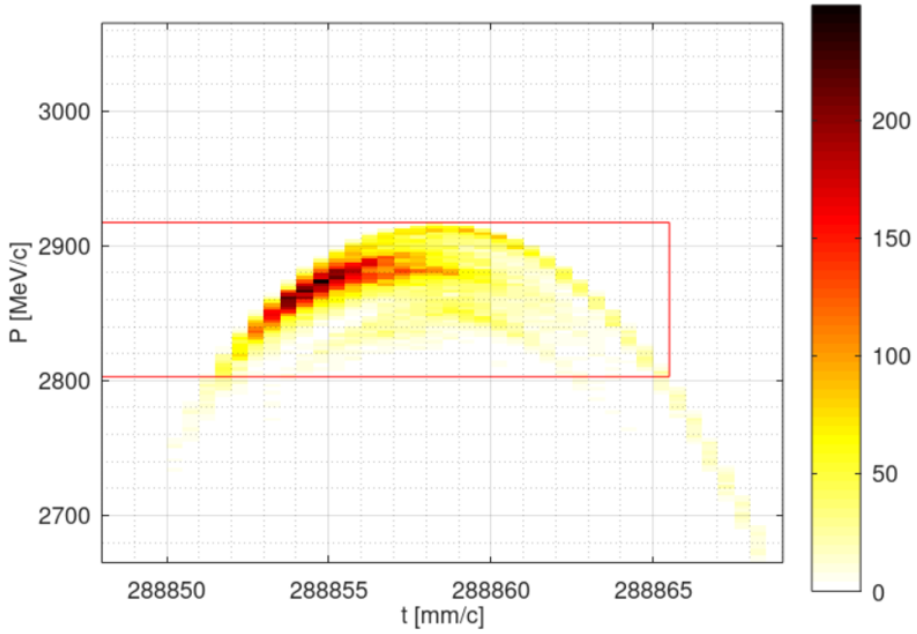
in p-linac transmission and yield

Yield evolution along z



Longitudinal phase space

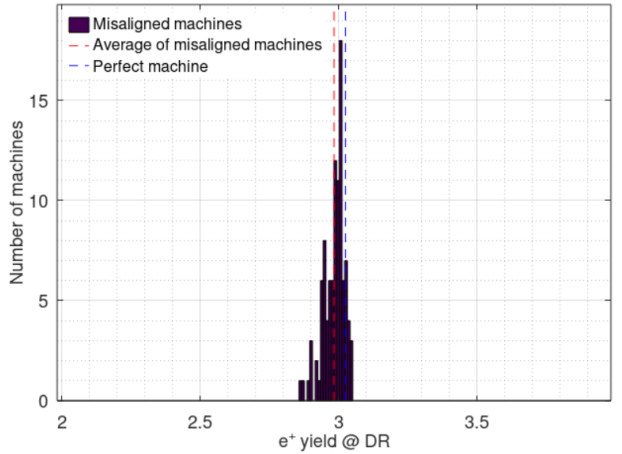
- At PL exit
  - Total yield: **3.41**
  - Yield with cuts (2.86 GeV ± 2% in energy, ±10 mm/c time): 3.01

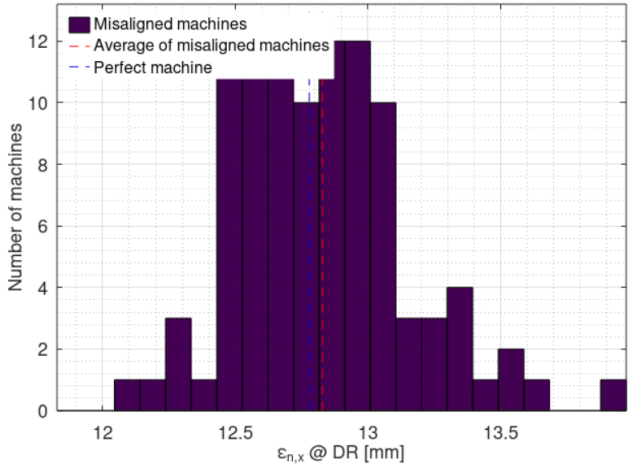


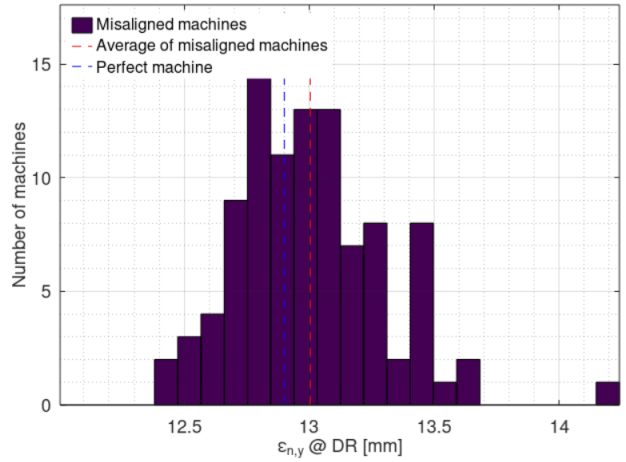
p-linac imperfections

- Imperfections considered
  - **Position** error (x, y): σ = **100 um** for all elements
  - **Angular** error (roll, pitch, yaw): σ = **100 urad** for all elements, except that σ = **200 urad** for all NC solenoids and dipoles
  - Magnatic **strength** error: σ = **0.1%** for all magnets
  - RF **gradient** error: σ = **1%** for all RF structures
  - RF **phase** error: σ = **0.1°** for all RF structures
  - Beam **position jitter** (x, y): σ = **100 um** for e^+ beam from target
  - Beam **angular jitter** (x', y'): σ = **100 urad** for e^+ beam from target

- 100 random machines with imperfections
- Compared with perfect machine:
  - Average DR accepted e+ yield reduction: 1.3% (3.01 → 2.97)
  - Average normalized X / Y emittance increase: 0.4% / 0.8% (13.1 / 13.0 mm → 13.2 / 13.1 mm)
- Impact of considered imperfections is negligible







Conclusion and outlook

- Solid design of the linacs. Ready for documenting in FS report.
- Few minor points on the top-up operation with “golden” pulse to be checked:
  - Bunch-to-bunch energy spread in e- and p-linac and DR acceptance
  - Bunch-to-bunch energy spread in e-linac and impact on positron production
- Next steps for 2025 pre-TDR phase,
  - Move to 3GHz
  - Fit in the CERN site constrains
- …