FCC-ee injector linacs: design and RF frequency choices for the TDR

Alexej Grudiev on behalf of the FCC-ee injector linac design WG

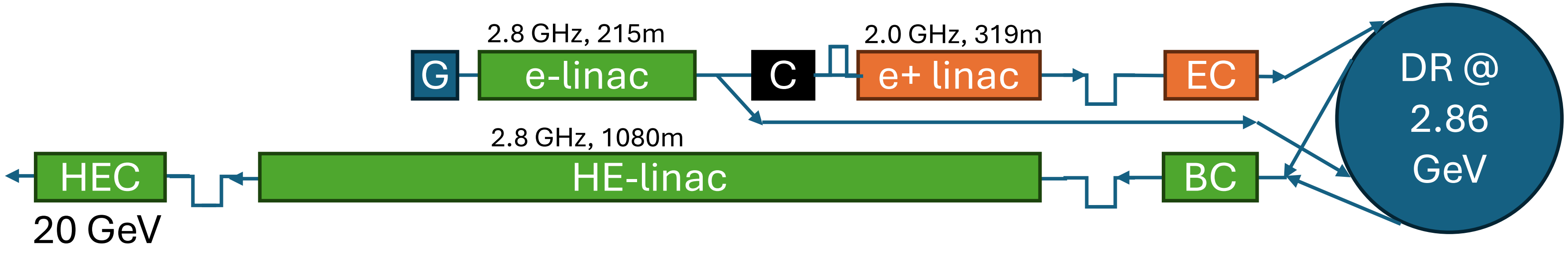
S. Bettoni, I. Chaikovska, P. Craievich, S. Doebert, A. Kurtulus, A. Latina, J.-Y. Raguin, Y. Zhao, and friends

Outline: from the past to the future

- **Overview of the Feasibility Study Report baseline for the FCC-ee injector complex linacs**
- **New design of the injector linacs for the TDR**
  - **New RF frequency European S-band versus FCC CR harmonic S-band**
  - **New damping ring design and final placement on CERN site**
- **Conclusion**

FSR baseline layout
4 AS/module, 4 bunches@100 Hz

FUTURE CIRCULAR COLLIDER



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
e+ linac**	0.2	15	15.4	13.3	21	304	8	8.5
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

HE Linac: CR filling mode

4 Bunches case:

P_klys = 14.2 MW

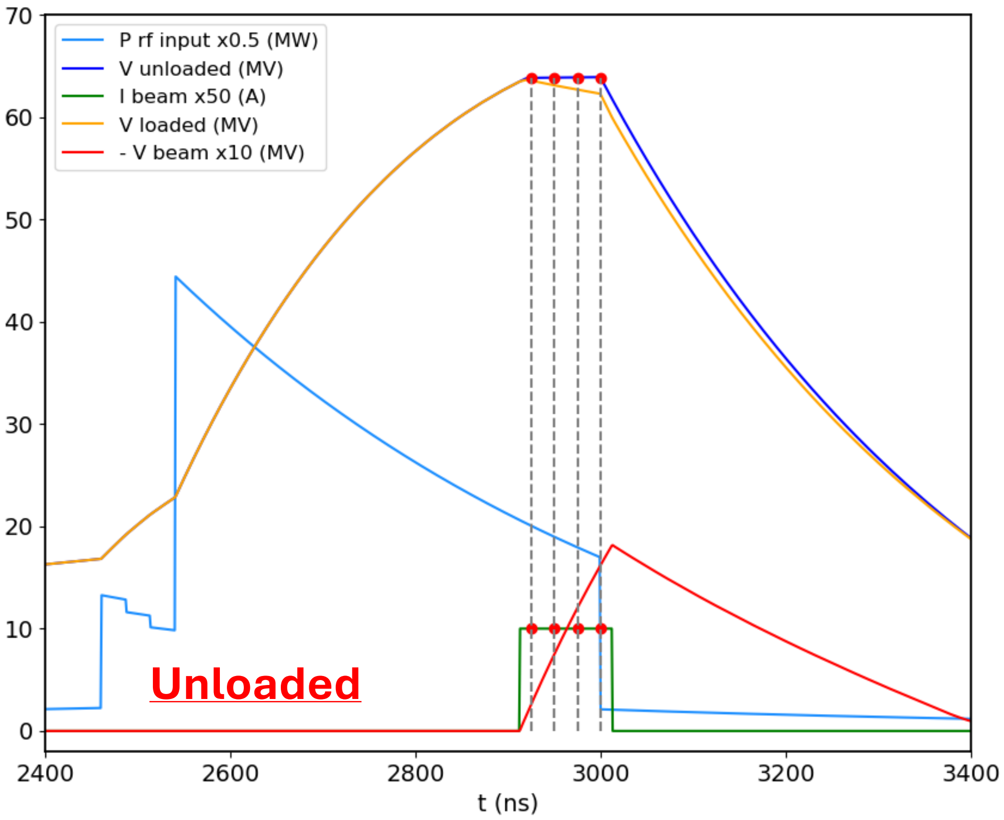
3m structure

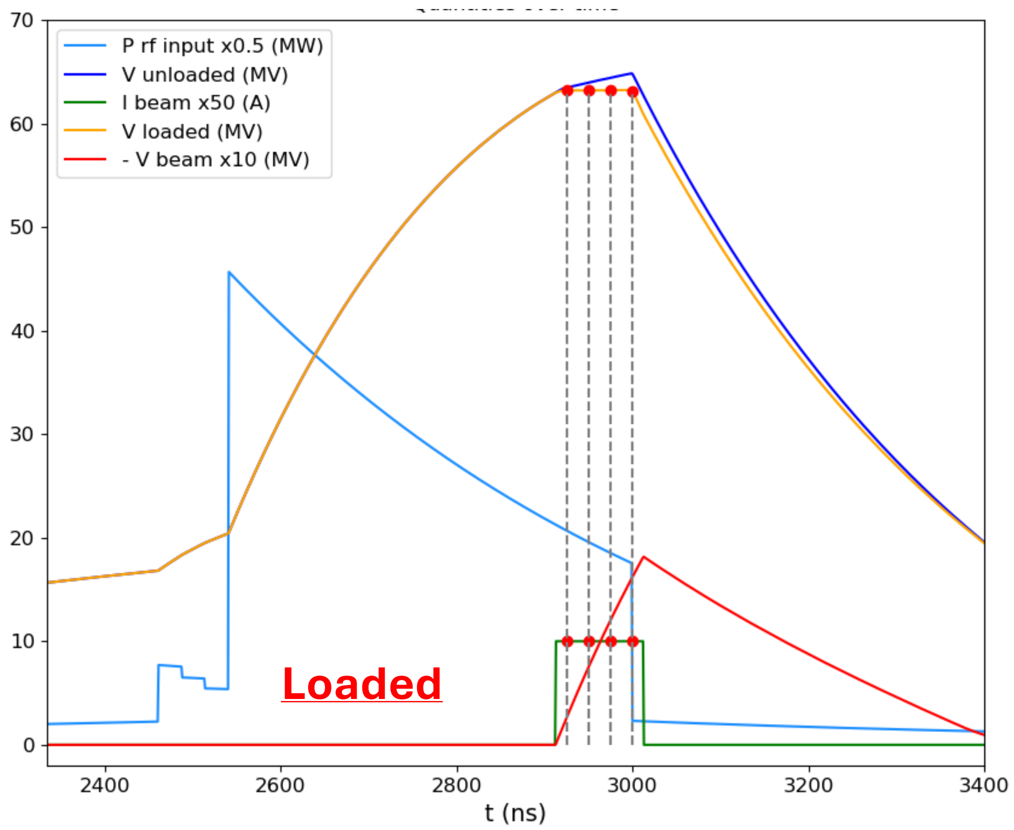
G = V/L

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
	1st Bunch	**2nd Bunch**	**3rd Bunch**	**4th Bunch**	
Loaded Voltages	63.19 MV	63.19 MV	63.20 MV	63.16 MV	





HE Linac: top-up operation using "golden" pulse

4 Bunches case:

P_klys = 14.2 MW
3m structure
G = V/L

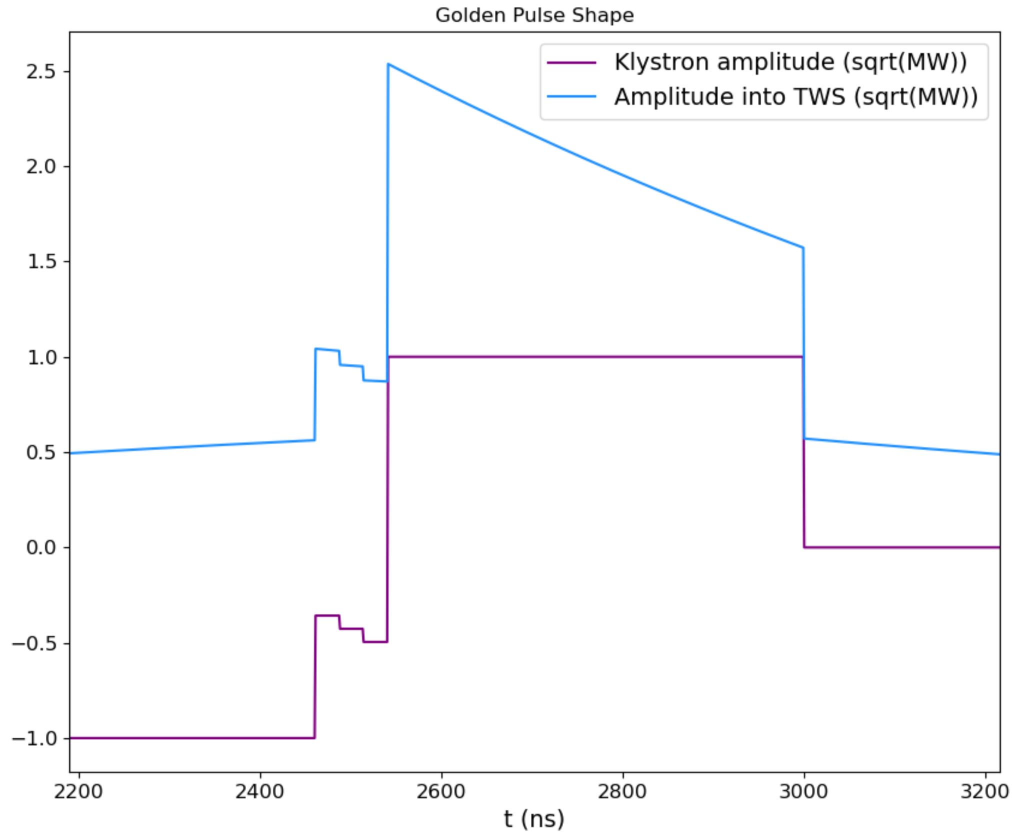
For bunch charge: 5 nC
25 ns of bunch spacing

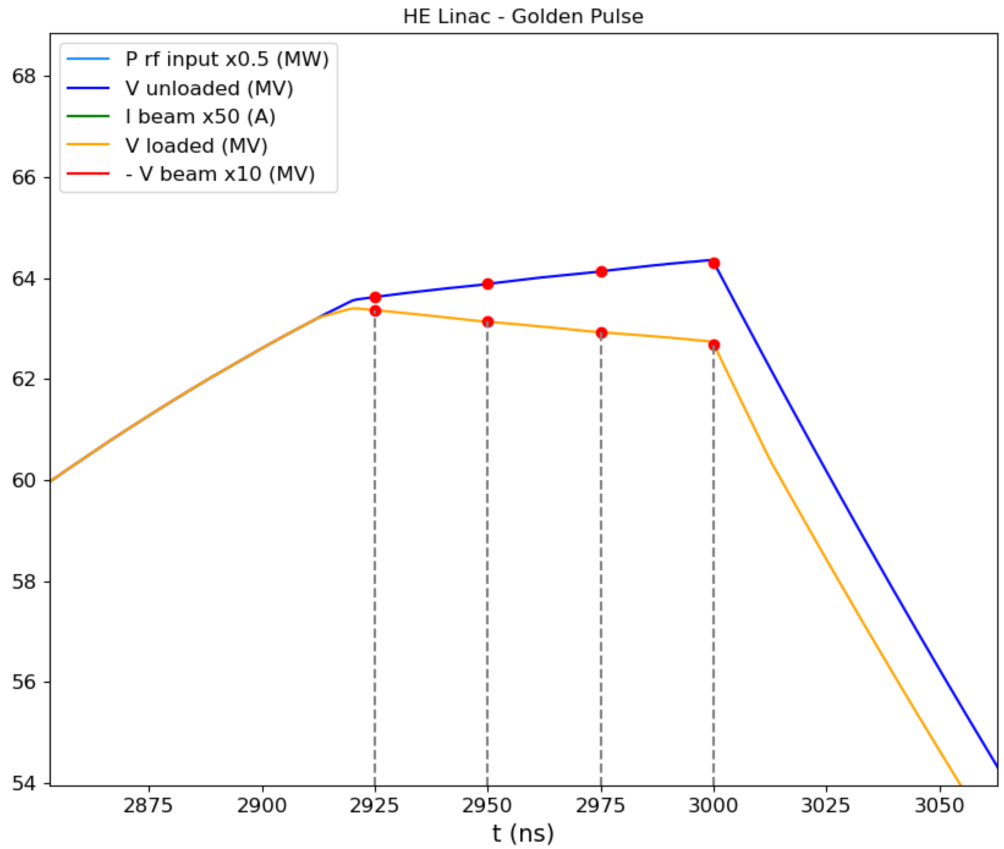
	1^{st} Bunch	2^{nd} Bunch	3^{rd} Bunch	4^{th} Bunch
Unloaded Voltages	63.63 MV	63.89 MV	64.13 MV	64.30 MV

+1.1% energy spread

	1^{st} Bunch	2^{nd} Bunch	3^{rd} Bunch	4^{th} Bunch
Loaded Voltages	63.37 MV	63.14 MV	62.93 MV	62.68 MV

-1.1 % energy spread





See poster:
A. Kurtulus, et. al
"RF Design and Optimization of the High-Energy Linac for the FCC-ee Injector Complex"

e- and HE linac beam dynamics: static effects

Sensitivity to <u>static</u> 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
- **HE linac:**
  - Emittance growth fulfilling the booster requirements

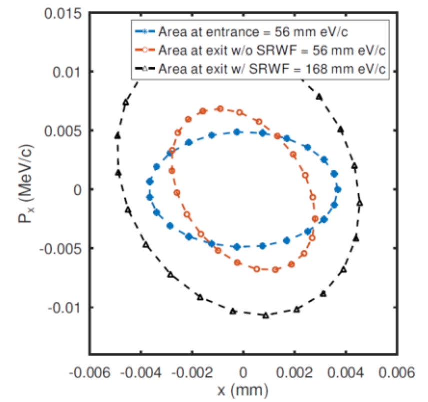
Emittance growth under control

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

e- and HE linac: dynamic effects

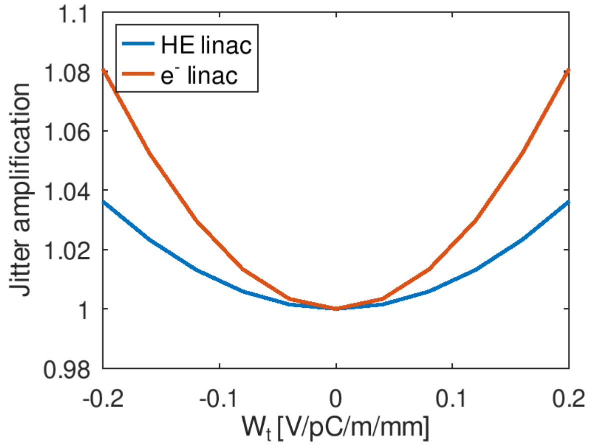
e- linac		HE linac	
Multi-bunch	Single bunch	Multi-bunch	Single bunch
1.03	1.18	1.02	1.01

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

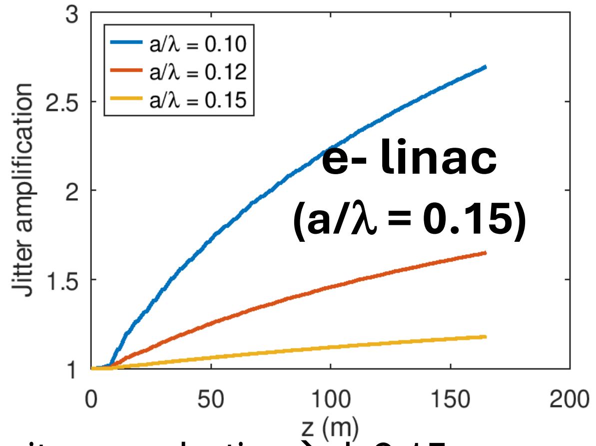


Multi-bunch

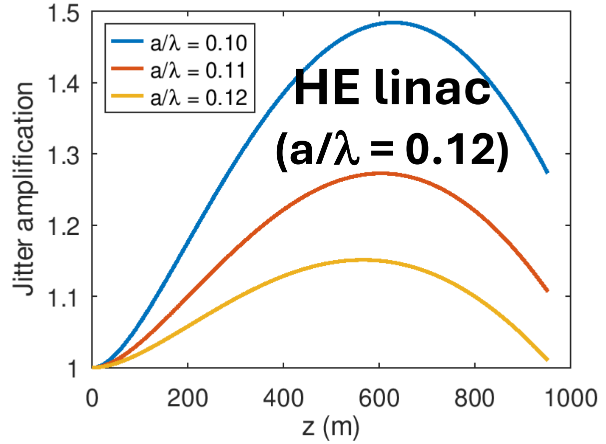
Single bunch



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



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

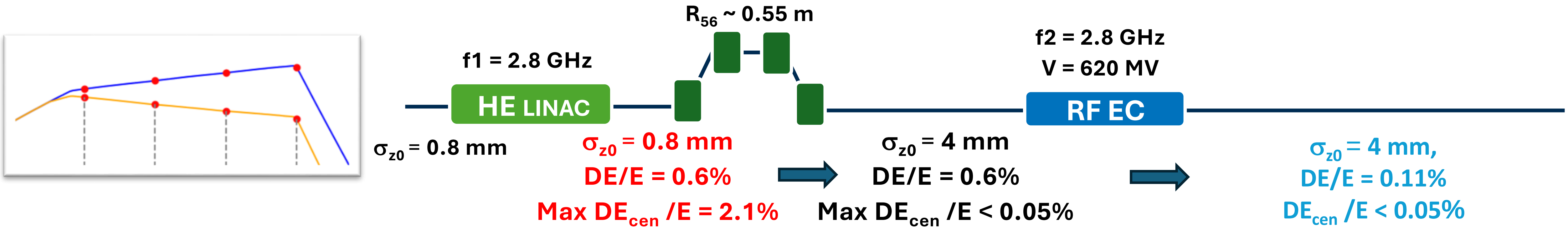


Booster→ok

No showstoppers identified

See talk: S. Bettoni, et. al "FCC-ee injector: linacs design for single- and multi-bunch effects"

Single and Multi-bunch energy spread reduction: “golden” pulse and high energy compressor (HEC)



- Total length <100 m including matching sections upstream and along HEC
- For the **top-up operation** with variable (0-100%) charges in each of the 4 bunches, LLRF used to generate a **<u>unique</u> golden pulse**
- HEC is used to match both the single- and multi- bunch target parameters, see below

Q = 5 nC: DE/E ~ 0.11%. Factor 3 smaller DE/E possible (single-bunch)

	Bunch 1	Bunch 2	Bunch 3	Bunch 4
Single bunch DE/E (%)	0.11	0.11	0.10	0.09
Rms bunch length (mm)	4.06	4.07	4.09	4.10
DE/E centroid from B1 (%)	0	-0.01	-0.03	-0.05
Dt from bunch 1 (ps)	0	5.7	11.0	17.3

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

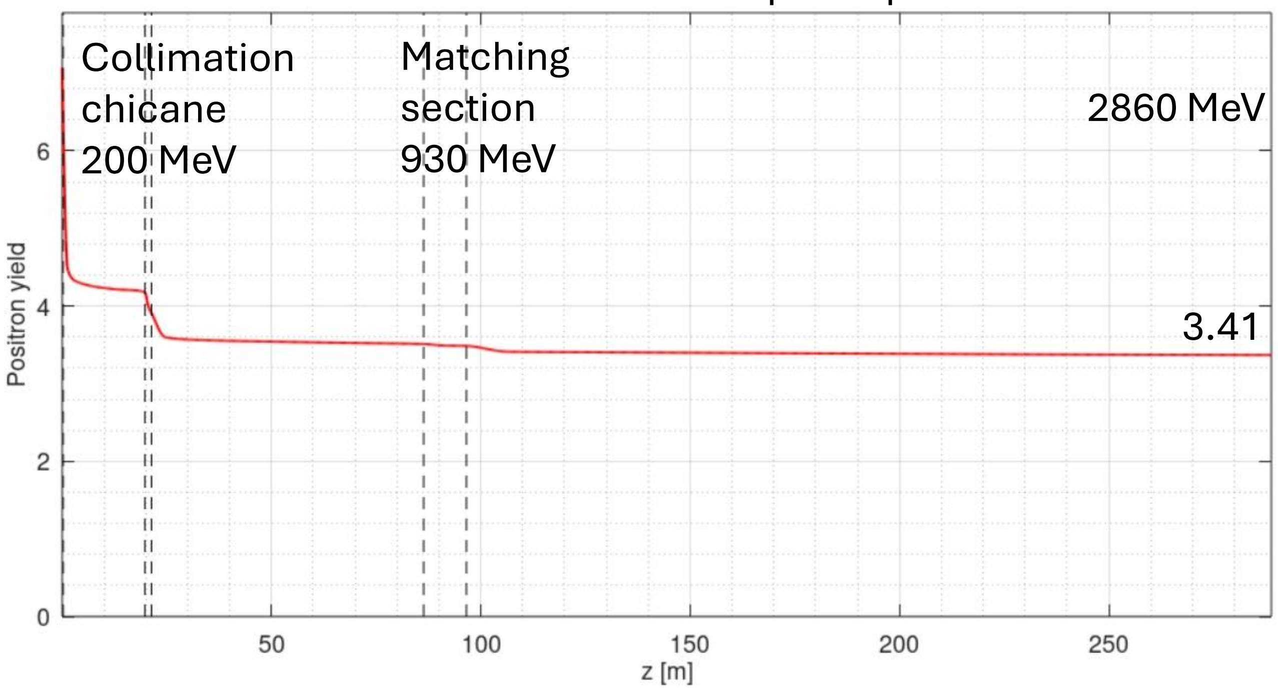
	Bunch 1	Bunch 2	Bunch 3	Bunch 4
Single bunch DE/E (%)	0.13	0.13	0.12	0.12
Rms bunch length (mm)	1.04	1.04	1.03	1.03
DE/E centroid from B1@5nC (%)	0.14	0.21	0.29	0.36
Dt from B1@5nC (ps)	-29	-35	-41	-45

See talk: S. Bettoni, et. al
“FCC-ee injector: linacs design for single- and multi-bunch effects”

These parameters seem to be acceptable by the booster

e+ linac: design, transmission and yield

Primary
e-bunch:
4.5 nC

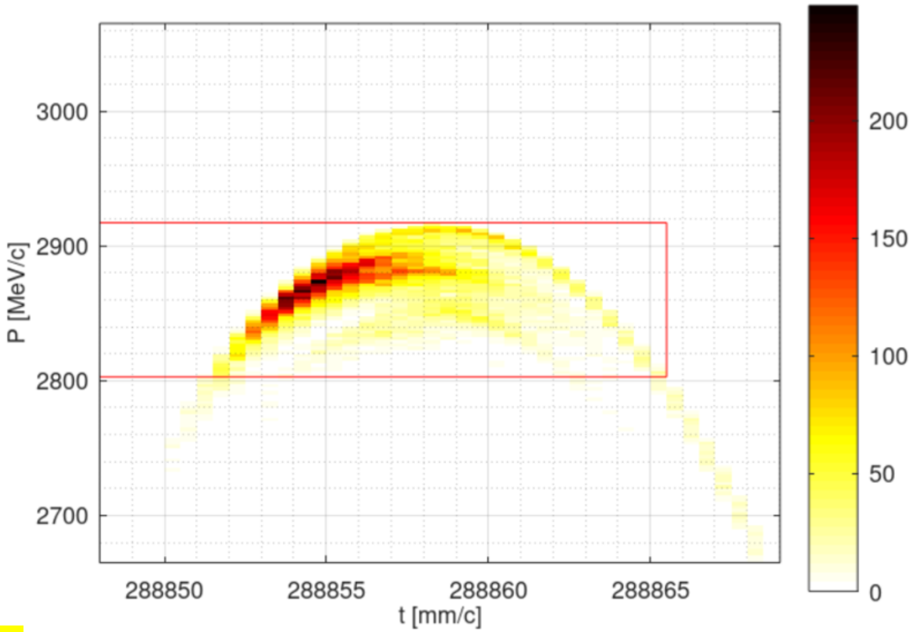


3.01
13.5 nC
σ_z = 3 mm
σ_E = 0.95 %
$\varepsilon_{Nx,y}$ = 13 mm*rad

See talk: I. Chaikovska, "Positron production for FCC-ee"

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



From FSR to TDR

- The baseline schematic layout remains basically the same for the TDR.
- However, the design of the linacs and associated sub-system must be adapted to accommodate the following changes:
    - RF frequency from 2.8 GHz to 3 GHz in e- and HE linacs. (Straightforward)
    - In e+ linacs, we will attempt to move from 2 GHz to 3 GHz given the acceptance of the new DR at 2.86 GeV. (Difficult)
    - Site-related space constraints must be addressed given the final placement as well as DR and TL layout
- Finally, engineering design will be done for the TDR

FCCee linacs: the exact RF frequency (Case of the Z-mode, 4 bunches, 100 Hz)

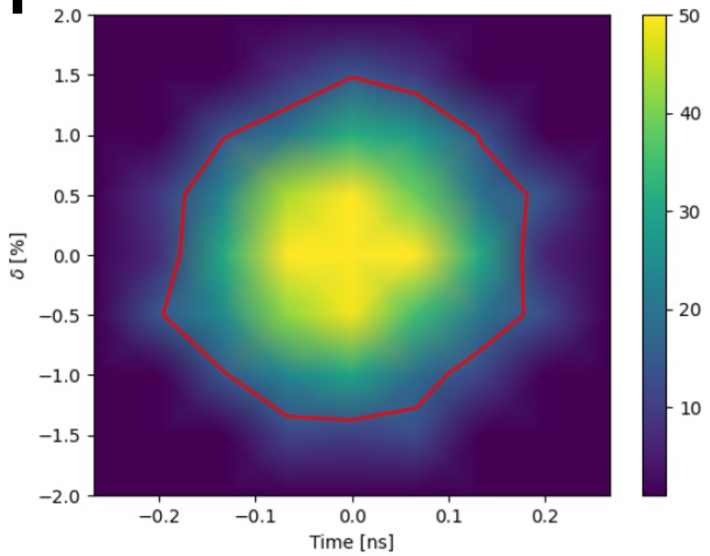
- Nominal bunch spacing: 25 ns
- Minimum time step to modify the bunch spacing: 5 ns => 200MHz. So that every second bucket in CR can be used potentially.
- RF frequency in CR: f_CR = 400.788 MHz (FCC FSR, Table 1.2)
- RF frequency in linacs (S-band): f_LI = f_CR*15/2 = 3005.91 MHz
- Standard EU S-band: f_EU = 2998.5 MHz
- Difference: f_LI – f_EU = 7.41 MHz

Booster Ring dynamic aperture at injection (preliminary)

4 bunch train

BR bucket length:
2*400.788MHz => 374.0mm,

f_LI (3005.91MHz)
wavelength: **99.73** mm
EU S-band (2998.5MHz)
wavelength: **99.98** mm



Courtesy of A. Chance

Normalized emittance at injection 10 μm x 10 μm

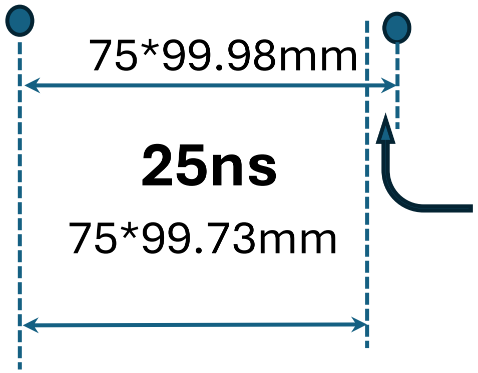
1000 turns, initial grid in number of σ, angles (in the X-Y plane), time and delta.

The red region corresponds to a region with a DA of 15σ

Single bunch length: 5 σ = 20 mm (~67 ps)

Temporal acceptance 45 mm (0.15 ns)

→ this leaves margin to accepted temporal jitter and offset of 25 mm (83 ps), compatible with beam parameters at the exit of the EC



If EU S-band is used in linacs, the 2nd bunch will be shifted from the center of the bucket in the BR by : 75*(99.98-99.73) = **18.5mm**, the 3rd by 2*18.5mm = 37mm, 4th by **55.5mm**

OR all 4 bunches are shifted like this: 1. **-27.75**, 2. -9.25, 3. 9.25, 4. **27.75 > 25mm**

This is not acceptable by the booster even without any longitudinal jitter and/or the bunch phase shift due to multi-bunch energy spread reduction in HEC

What if high energy compressor chicane is also used to correct the bunch spacing

- R56 ~ 550 mm => dE ~ 27.75mm * 20 GeV / 550 mm ~ 1000 MeV
- V_RF(@3GHz) = 1000MeV/sin(2π 27.75mm/100mm) = 1015 MV > 620MV
- sin(2π 27.75mm/100mm) ~1 we are far from linear regime
- This is not good for correction linear bunch phase shift due to different RF frequencies
- AND the single bunch energy chirp is different between 4 bunches, => different final single bunch energy spread
- **The HEC cannot be used both for single bunch energy compression and bunch spacing correction, at least using 3 GHz**
- Significantly lower RF frequency for the HEC is needed to make both

Timing and synchronization of linacs and rings

- In case, linacs run at Standard EU S-band: f_EU = 2998.5 MHz which is different from the Ring harmonic of 15*f_CR/2 = 3005.91 MHz
- The synchronization system will have to take care of the frequency difference: 7.41 MHz.
- This will set some constraints on the timing and synchronization between linacs and rings.

- **Bottom line: there are number of challenges if the S-band used in the linacs is not the harmonic of the CR RF frequency**

What are the challenges of using different from Eu S-band RF frequency of 3005.9 MHz?

Examples of different S-band RF frequencies used in Europe

	S-Band frequencies			
Lab		MHz		
PSI	SWISS FEL	2998.80		Riccardo
DESY	FLASH=XFEL	2997.20		Rolf Jonas
DESY	SINBAD	2997.92		Rolf Jonas
DESY	LINAC 2	2997.98	±2MHz	Rolf Jonas
Daresbury	CLARA	2998.50		Graeme
Trieste	FERMI	2998.01		Nuaman
CERN	CLIC	2998.55		Steffen
	Canon E37327A	2998.80	±1MHz	Riccardo

- Typical klystron operating frequency specs are nominal f_RF **±1MHz**
- Some operational experience shows that **±2MHz is OK**

- Nevertheless **+7 MHz** will require different specs for FCCee klystrons: **3005.9±1MHz**

- This is **no problem** for mid and long term when **new klystrons** must be purchased (developed)

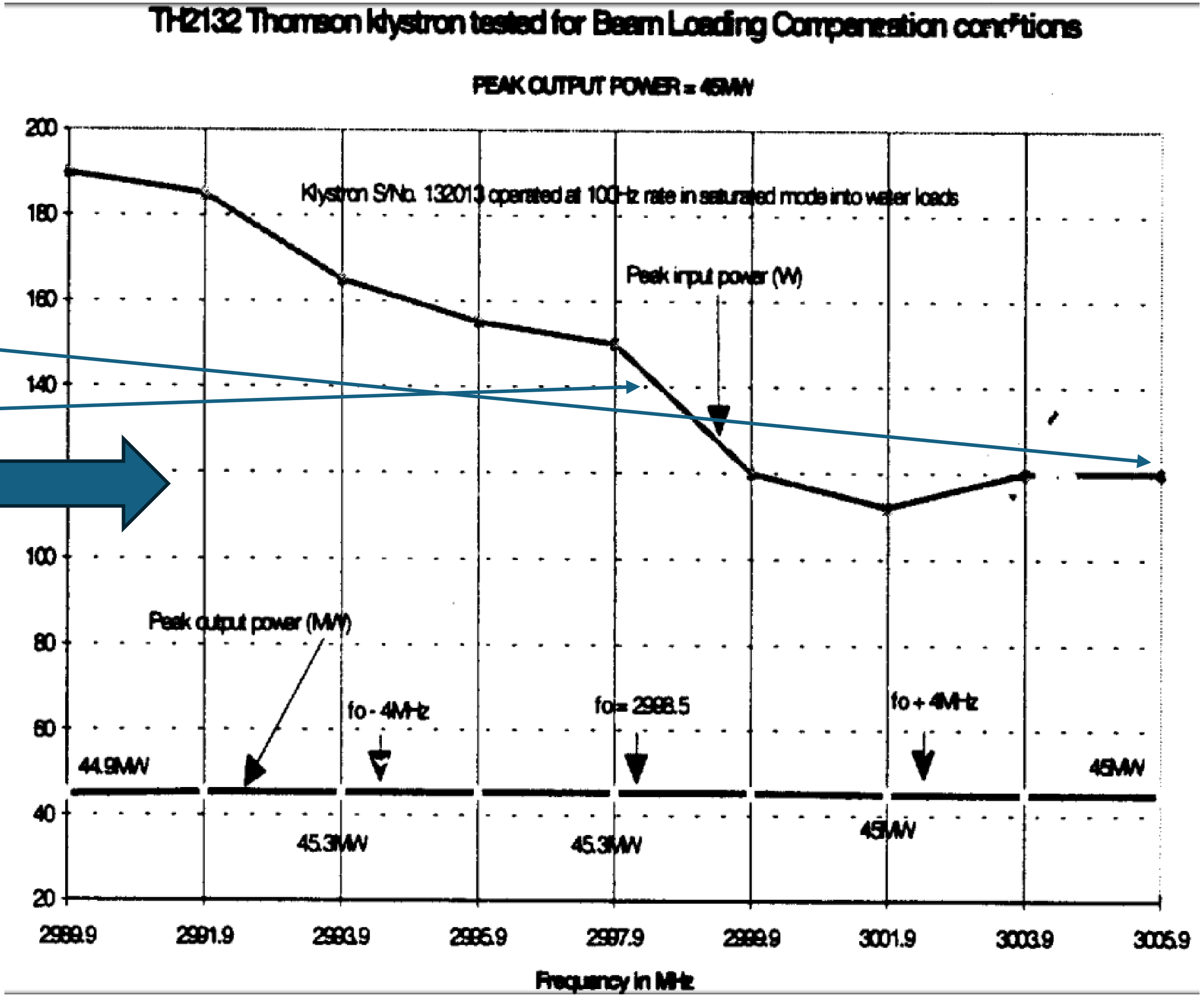
- **What about** short term and potential use of **existing klystrons?**

Use of EU S-band klystron at 3005.9 MHz

CTF2 TDR, CLIC note 304, 1996

S-Band frequencies	
	MHz
CLIC	2998.55
CTF2 RF gun	3000.50
CTF2 HCS1	3006.36
CTF2 HCS2	2990.74
Thomson TH2132	2998.5

- Based on the measurement done for the CTF2
- 2998.5 klystron can be operated at nominal output RF power (45MW) at 3006 MHz.
- Due to lower gain higher power might be required for the driver amplifier
- **This should not be a problem**
- **More measurements are needed**



RF power for Linacs: existing S-band klystrons

THALES


S band klystrons:

- Strong heritage on 45 MW 20kW family (2856MHz and 2998 MHz)
- Demonstrated life time > 40000 hours
- Production > 25 klystrons / year
- TH2100L : 60MW 1.5µs 100 Hz operating at 350 kV 408A installed at PSI.

New Products in S band

- Increase of peak power up to 80MW 4µs 120Hz is achievable with conventional klystron technology.
- Development can be launched only for significant quantities.

Thales Klystrons for linacs - High Gradient Day - 31 January 2013

THALES

CANON former TOSHIBA

E3712

Typical Operations

Frequency	2.856 GHz
Peak Power	80, 100 MW
Pulse Length	4, 1 µs
Repetition Rate	50 pps
Beam Voltage	400, 422 kV
Efficiency	42, 46%

Accelerator Facilities
KEK-ATF, SP-8, Osaka Univ., SAGA-LS, Tokyo Univ. of Science, AIST, PLS(KOREA), NSRL(China), etc.

Total number of installed unit : 82 units

- FCC-ee injector linacs 3 GHz klystron parameters: **80 MW, 3 us, 100 Hz**
- **Several suppliers** have klystrons with **very close parameters**, but
- A **new dedicated** tube will be developed for the **FCC injector linacs**

2998.5 MHz version exists.
E37333 build for CLARA (UK)
Nominal parameters:
70 MW, 100 Hz, 3 us

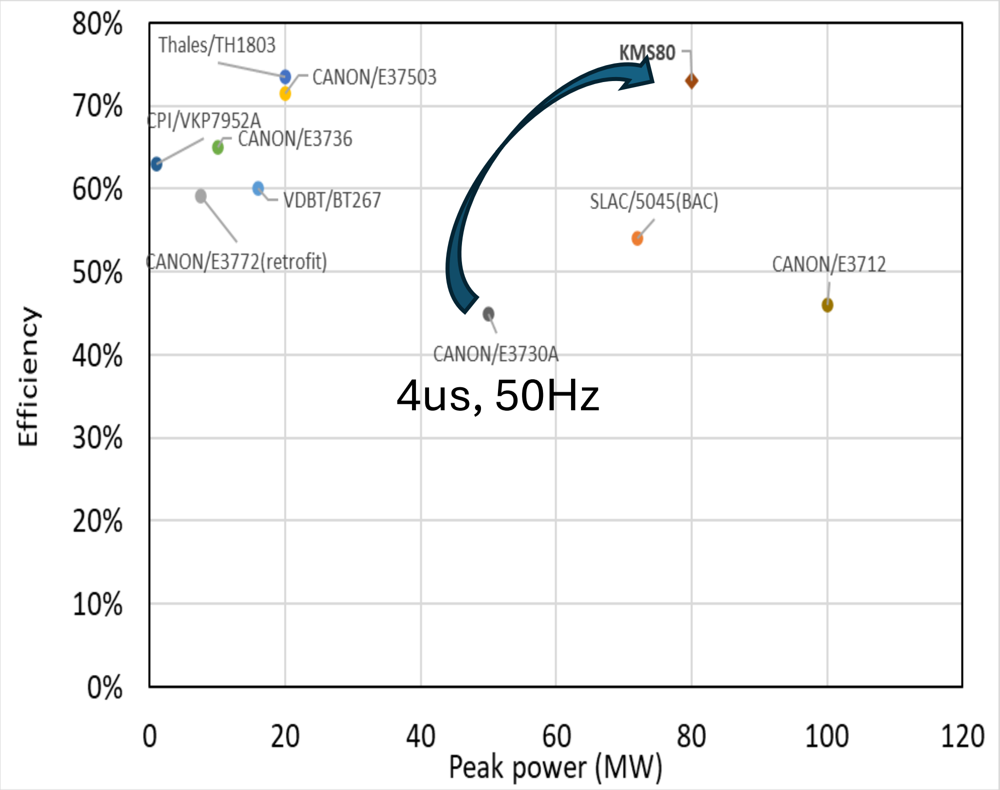
New design of high efficiency S-band Multi Beam Klystron (MBK) for KEK injector linac: KMS80

- The overall parameters of KMS80

Parameters(unit)	value
Frequency(MHz)	2856
Gun voltage(kV)	300
Total gun current(A)	366.4
Beam No.	8
Output power(MW)	80
Expected efficiency	73%

(Courtesy of Takuya Natsui)

- For dual records in both efficiency and output power in the field of S-band MBKs



Shengchang Wang, at [2nd Workshop on efficient RF sources (23-25 September 2024): Overview · Indico]

High efficiency RF power for FCC-ee linacs

- R&D at KEK/CANON on the high efficiency MBK with 80 MW, 4 us, 50 Hz, 73% is very encouraging (1st prototype to be tested 2026)
- It paves the way to **high efficiency** RF power source for FCC-ee injector linacs: 80 MW, 3 us, 100 Hz, **>70%**
- Increasing klystron efficiency from 42% to 70 % is not only big reduction of the **power consumption** in the linacs from 19.5 MW to 13.7 MW
- BUT it is also a significant reduction of the **investment cost**:
  - modulator cost which dominates with 29% the linac hardware cost
  - infrastructure cost: CV, EL

Conclusions

- Robust design of the FCC-ee injector linacs has been done for the Feasibility Study Report
- It must be adjusted and reoptimized for the TDR to address several changes including new RF frequency, new DR acceptance, site constraints
- It seems that the choice between European S-band 2998.5 and the CR harmonic 3006.9 MHz favor the latter one due to simpler overall compatibility of the linacs and rings with minimum impact on the RF power systems
- The design for the TDR is a chance to push the sustainability of the FCC even further by developing a high efficiency (>70%) multi-beam klystron as RF power source for the injector linacs

Thank you for your attention

PSI	B. Auchmann, I. M. Besana, S. Bettoni, P. Craievich, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, R. Ischebeck, P. Juranic, J. Kosse, F. Marcellini, U. Michlmayr, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Reiche, R. Rotundo, S. Sanfilippo, M. Schär, N. Strohmaier, N. Vallis, M. Zykova, R. Zennaro, H.H. Braun, M. Seidel all the technical groups involved in the P3 experiment
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Spare slides

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/μm^2	453 mW/μm^2	298 mW/μm^2

Acc. Structure parameters

Structure parameters are calculated for the four bunches case.

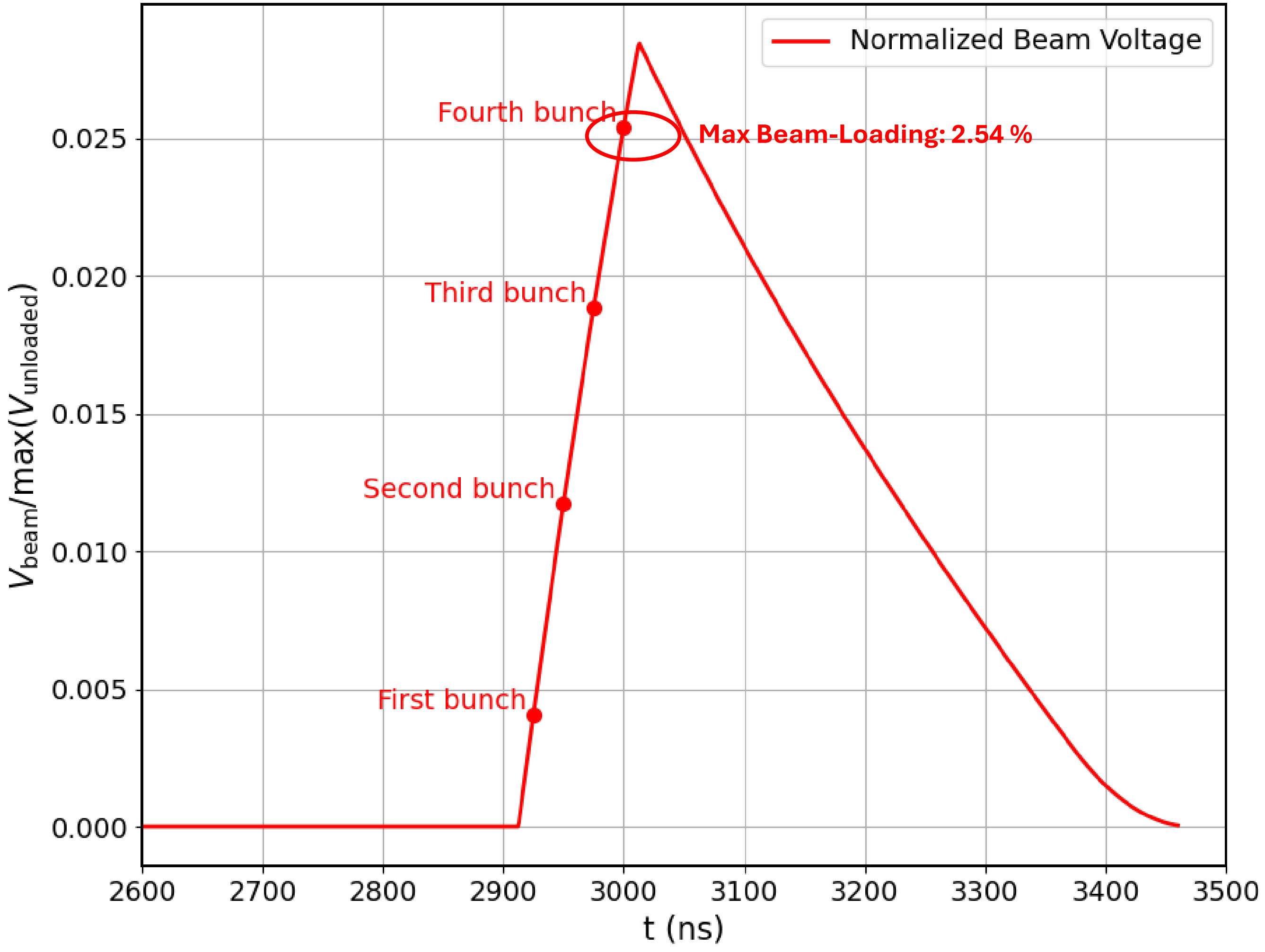
	HE-linac	E-linac	P-linac		
Eff. shunt impedance (Four bunches)	95.65 MΩ/m	81.69 MΩ/m	36 MΩ/m		
Klystron power per structure	14.2MW	14.2 MW	15.4 MW		
Unloaded G_{avg}	21.28 MV/m	19.66 MV/m	13.59 MV/m		
Bunch Charge	5 nC	5 nC	5 nC	10 nC	15 nC
Loaded G_{avg}	21.06 MV/m	19.49 MV/m	13.5 MV/m	13.42 MV/m	13.31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

- **HE Linac:**

4 Bunches case:

Beam loading effect

For bunch charge: 5 nC
25 ns of bunch spacing



e+ 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

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
  - Magnetic **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