PAUL SCHERRER INSTITUT

FUTURE CIRCULAR COLLIDER

FCC-ee electron Linacs design (WP1)

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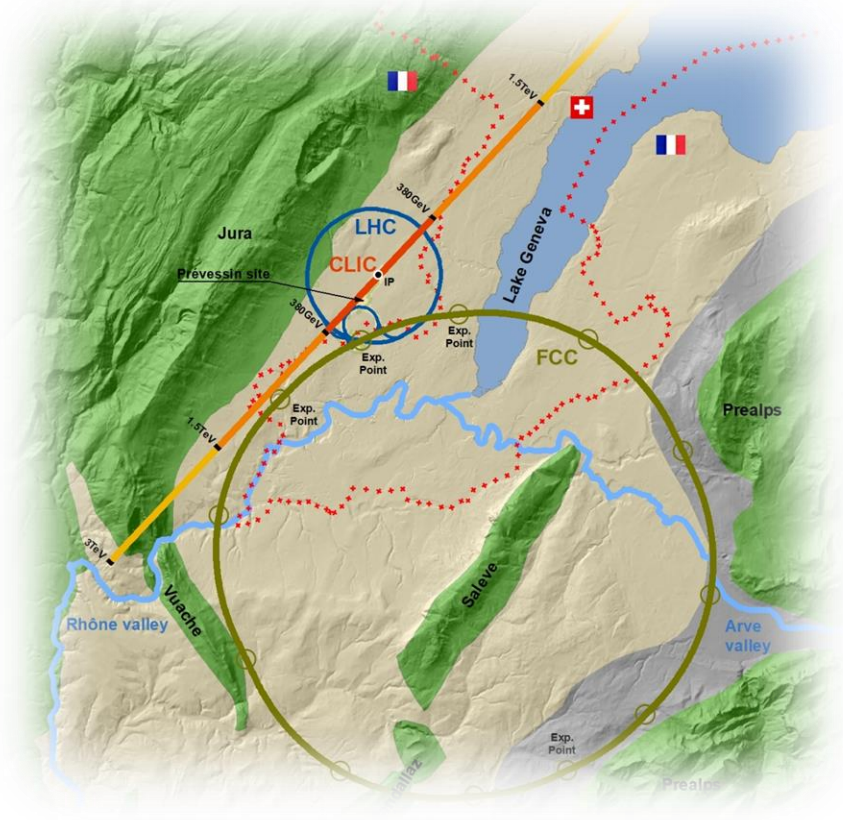
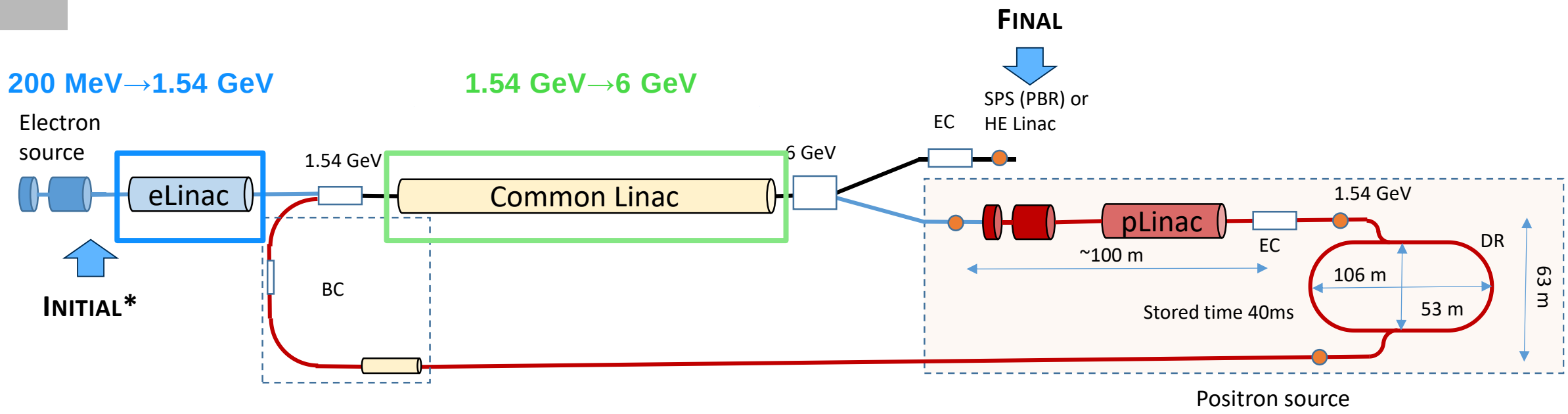
2022 FCC Week
30th May-3rd June 2022
Paris (France)

Outlook

- **Layout, inputs, and acceptance**
- **Single bunch dynamics:**
  - Emittance preservation: elements misalignment
  - Energy spread: RF curvature and longitudinal wakefield
- **Multi-bunch dynamics:**
  - Emittance preservation: jitter amplification
- **Baseline design**
- **Summary and next steps**



Layout, inputs, and acceptance



*Optimizations by T. Brezina and S. Doebert

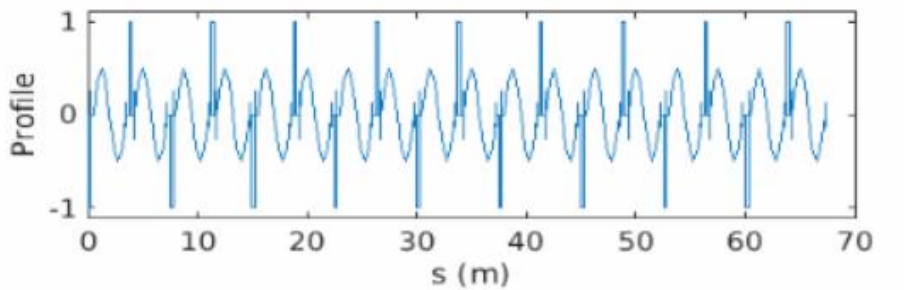
Layout, inputs, and acceptance

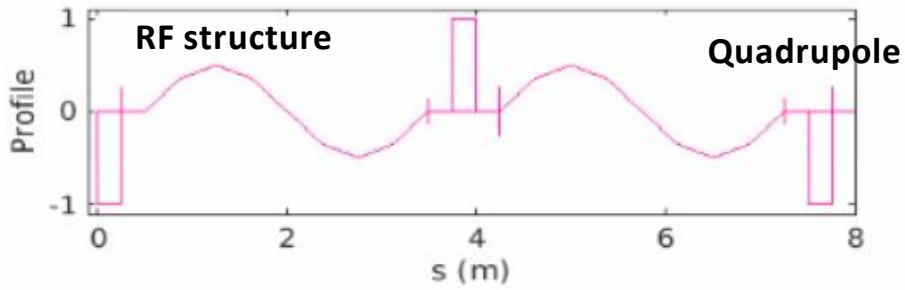
Parameter	Baseline	Alternative	Comments
Ring for injection	SPS/PBR	HE Linac	
Initial energy (MeV)	202		
Final energy (GeV)	6	20	
Charge (nC)	4 → 5.55	5.0	Determined by the positron production
Initial charge distribution	Gaussian/From tracking		
Number of bunches	2		
Bunch spacing (ns)	17.5-100		From BD Linac point of view used to define LRW
Initial transverse rms emittance (um)	3.3*, 6.1**		*at 4 nC-σ_z = 1.3 mm, **at 5 nC-σ_z = 0.65 mm
Final tolerated transverse rms emittance (um)	50		
Initial rms bunch length (mm)	1.3 → 0.65	~1 mm	Coming from energy chirp minimization
Final rms energy spread (%)	<0.1		How much “<“?

Linacs' modeling

Lattice modeling:

- FODO lattice with 90 degs phase advance/cell
- One quadrupole/RF structure. Option with half of the quadrupoles investigated.
- RF structures' wakefield: Bane model (a is the iris radius)





Simulation codes:

- MAD-X for the optics matching
- Elegant for the single bunch tracking simulations
- RF Track for the single and multi-bunch tracking simulations

QUADRUPOLES	e-Linac	Common Linac
Length (m)	0.25	
Gradient (T/m)	7.75…30	1…8
Number	18	60 (30)
Drift space (m)	0.25	

RF STRUCTURES	eLinac	Common Linac
Length (m)	3	3
Frequency (GHz)	2.0-2.8	2.8
Gradient (MV/m)	25	25
Number of cavities	18	60
Radius (a) over lambda	0.1…0.2	

Single bunch effects

Single-bunch effects are dominated by short-range **wakefield**, elements **misalignment**, **RF** curvature, and incoming **jitter**

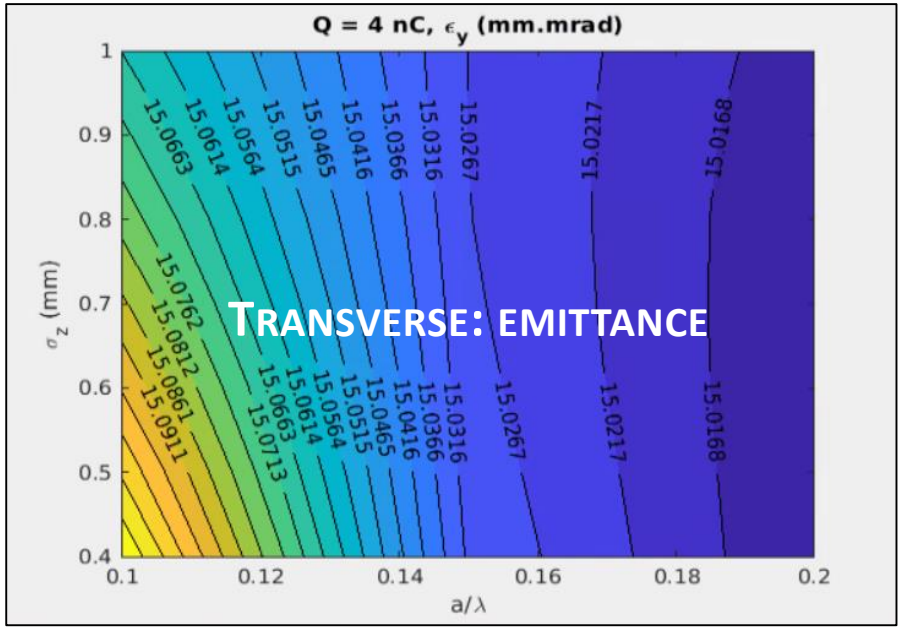
Emittance growth

- ***Sources***: off-axis orbit and/or random misalignments of several elements (RF structures and quadrupoles)
- ***Possible cures***: trajectory correction, optimization of the RF structures design, beam bunch length

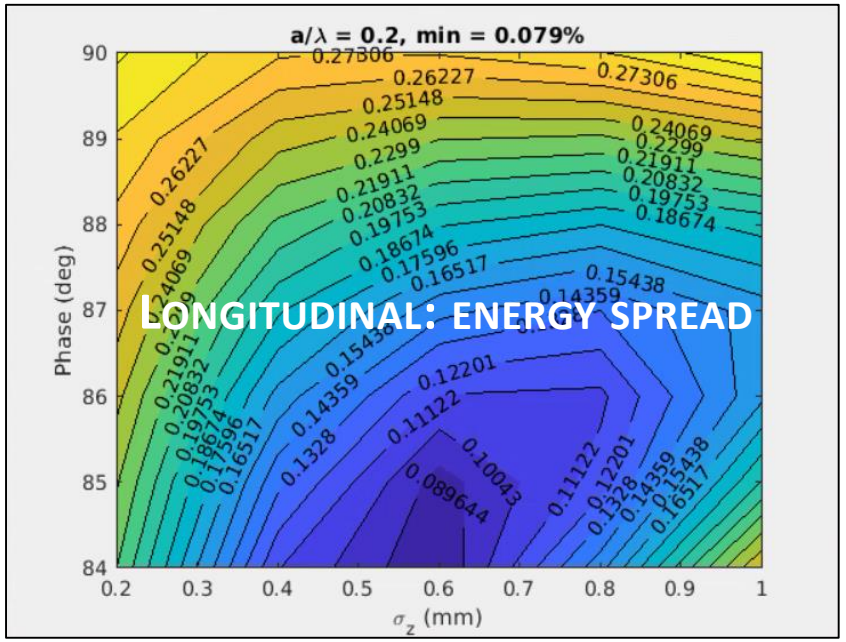
Projected energy spread

- ***Sources***: RF curvature and longitudinal wakefield vs bunch length
- ***Possible cures***: compensation of the RF curvature effect with the longitudinal wake potential

2D scans to determine the optimal working point

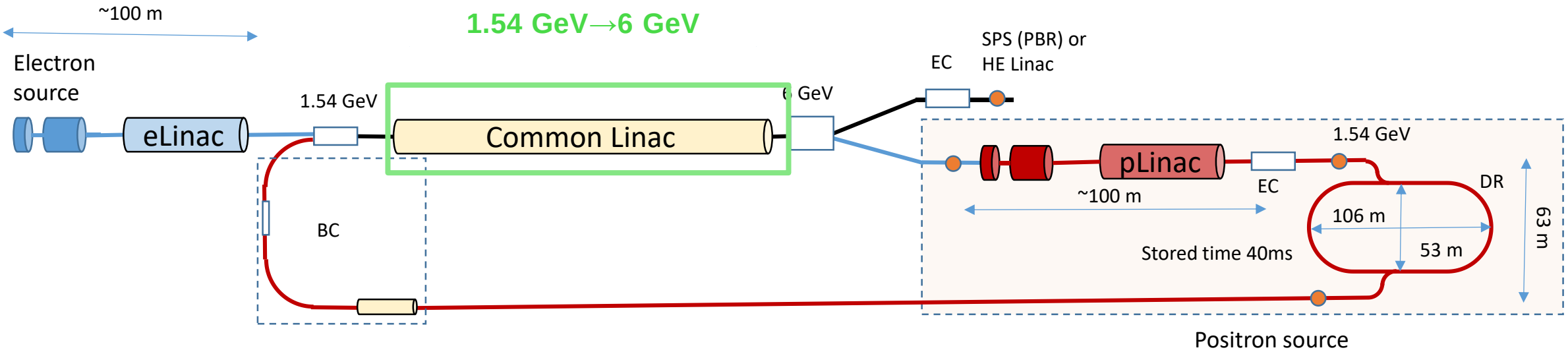


Scan of the rms bunch length (σ_z) and the aperture of the RF structures (a/λ)



Scan of the bunch length (σ_z) and the RF phase (90 deg corresponds to on-crest phase)

Transverse plane single bunch: common Linac

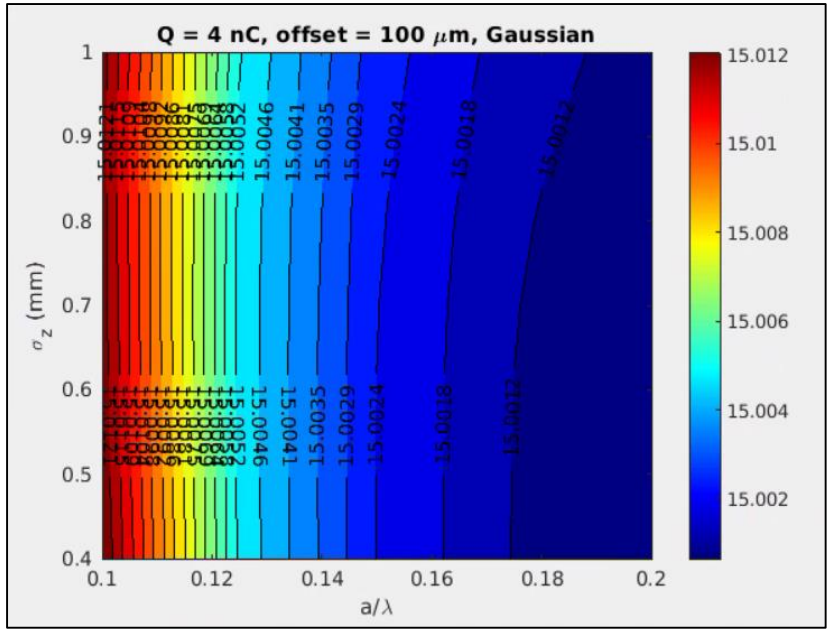


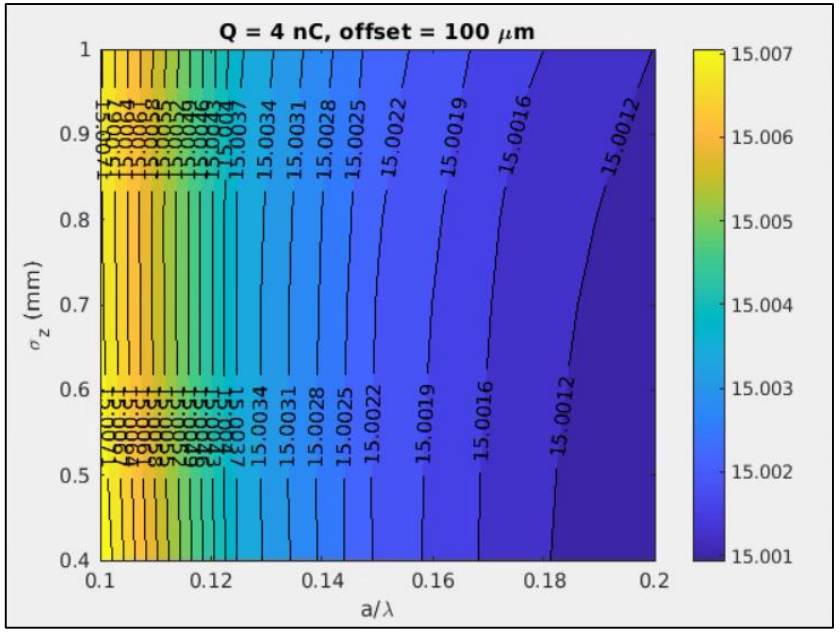
Sensitivity to RF structures misalignments

Imposed Gaussian distributed random offsets in both the transverse planes or a constant misalignments to all the RF structures along the Linac

Offset x = 100 um rms
Offset y = 100 um rms
Gaussian distribution

Offset x = 100 um
Offset y = 100 um
All the same offset*





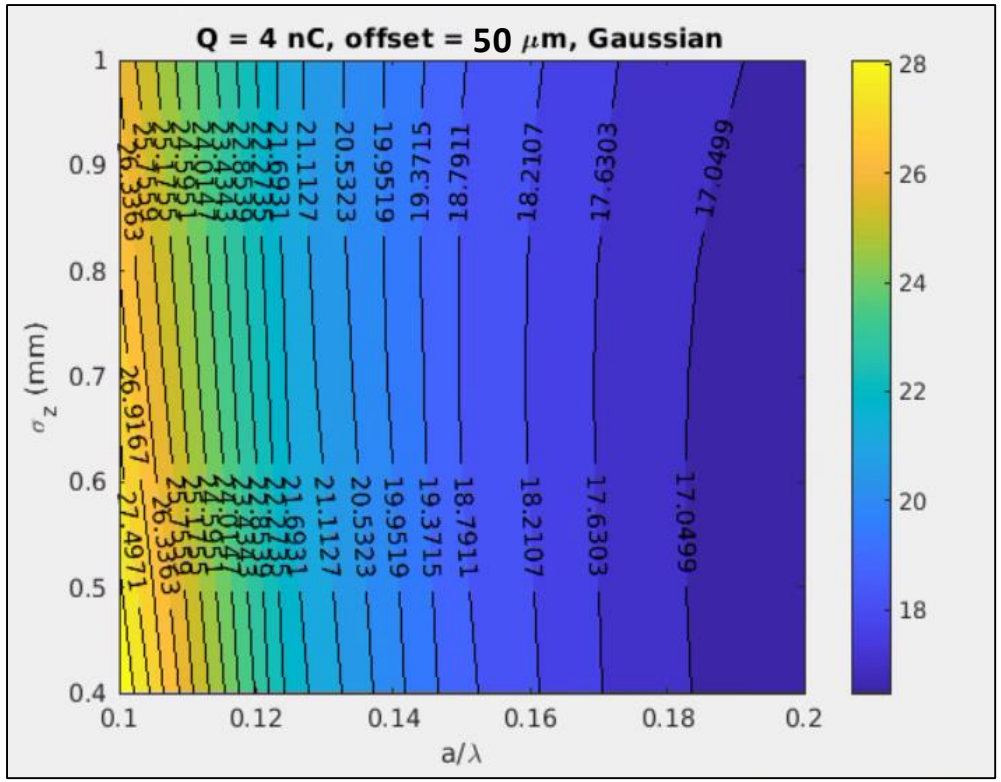
NEGLIGIBLE IMPACT ON THE EMITTANCE ► NO CONSTRAINTS ON THE RF DESIGN IN THE CONSIDERED PARAMETERS SPACE

*Same conclusion starting from smaller initial emittances: 5 mm.mrad and 10 mm.mrad

Sensitivity to quadrupoles misalignments

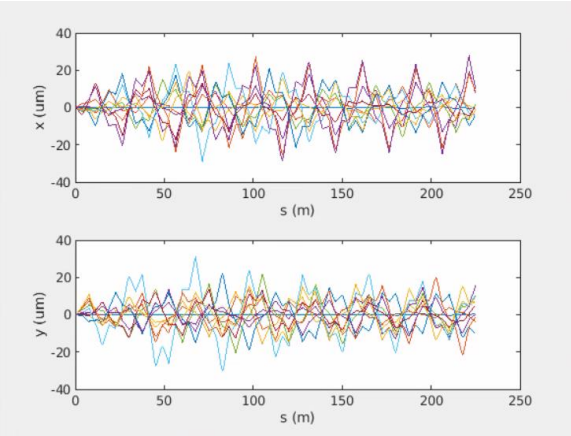
Imposed Gaussian distributed random offsets in both the transverse planes to all the quadrupoles along the Linac

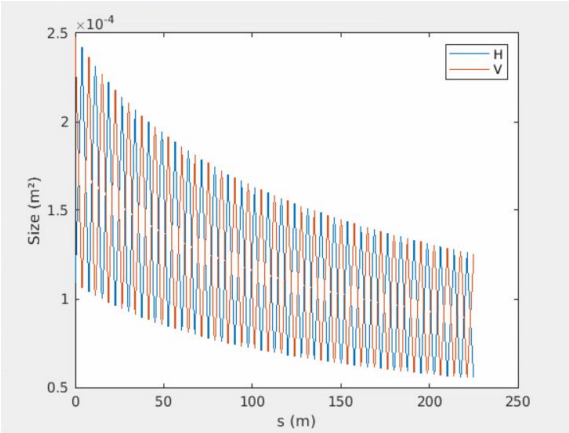
Offset x = 50 um rms
Offset y = 50 um rms
Gaussian distribution



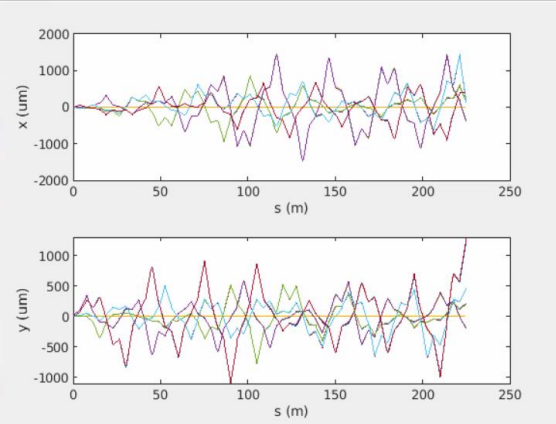
Still below tolerance, but impact on the emittance (almost a factor 2 in the worst case)

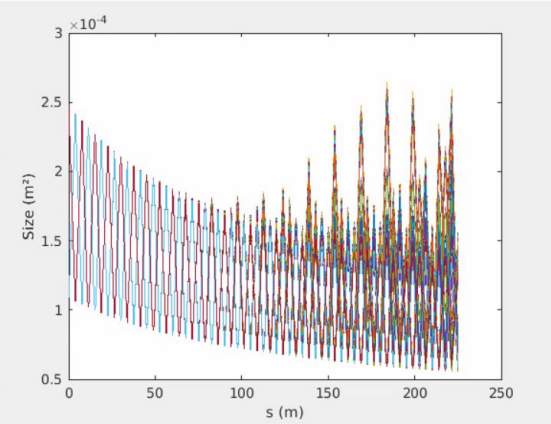
Only RF structures misalignments





Quadrupoles (quadrupoles and RF structures) misalignments

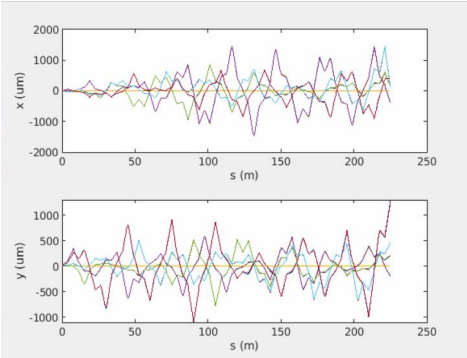




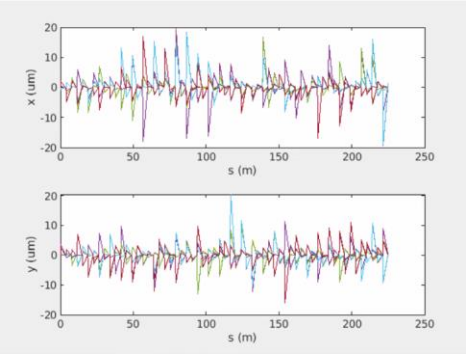
Orbit correction applied

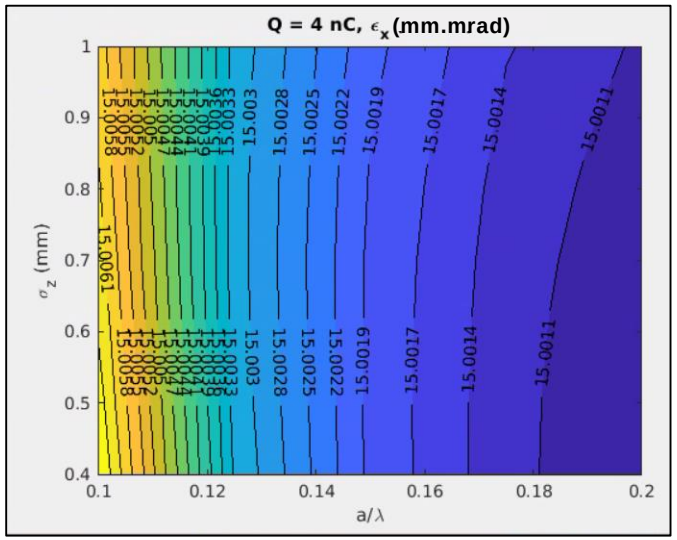
Quadrupoles
Offset x = 50 um rms
Offset y = 50 um rms
Gaussian distribution

w/o correction



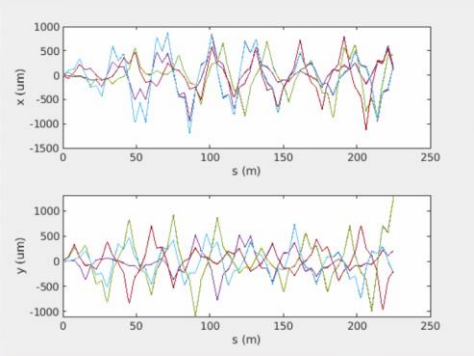
with correction



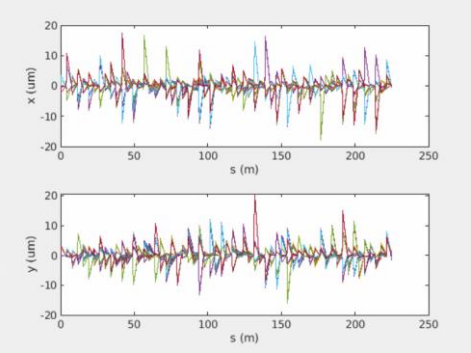


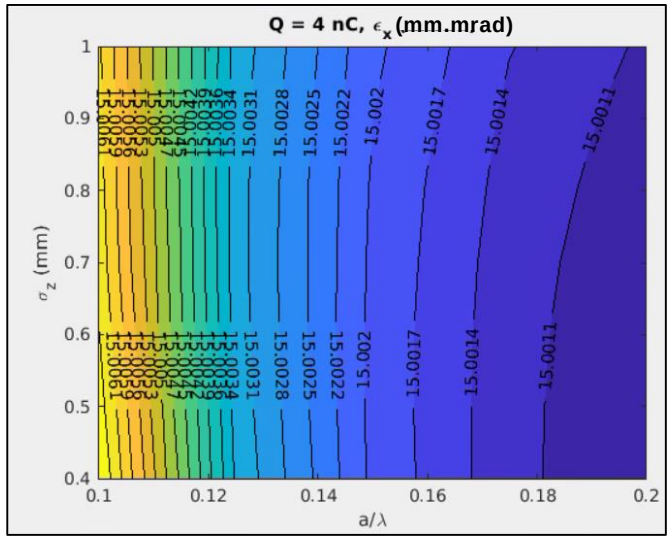
Quadrupoles
Offset x, y = 50 um rms
RF cavities
Offset x, y = 100 um rms
Gaussian distribution

w/o correction



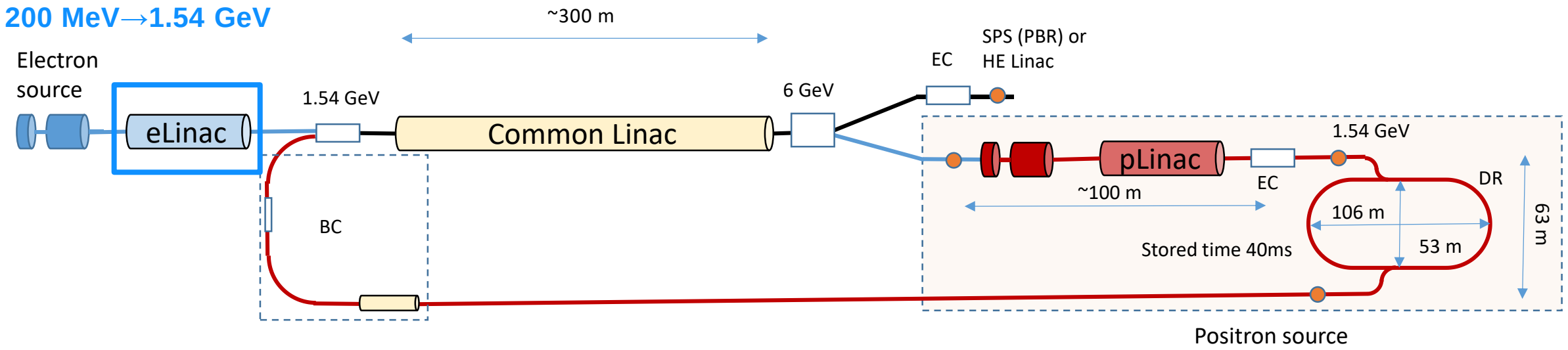
with correction





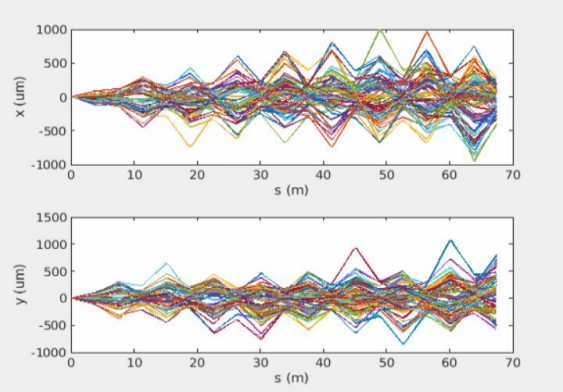
EMITTANCE INCREASE UNDER CONTROL FOR THE CONSIDERED CASES, BUT ORBIT STEERING IS ESSENTIAL FOR ELECTRONS (AND POSITRONS) SHARING THE SAME LINAC

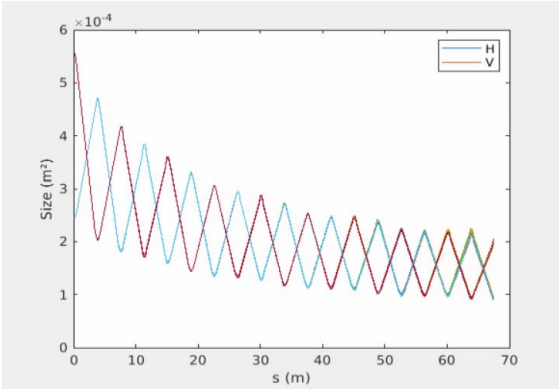
Transverse plane single bunch: e- Linac

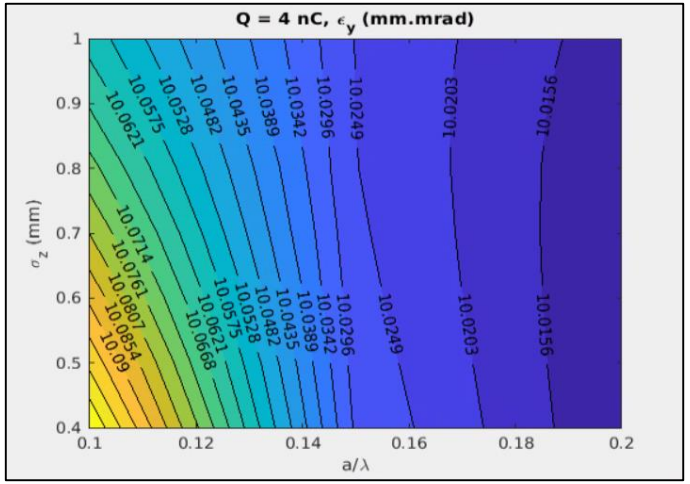


Sensitivity to misalignments and orbit correction

w/o correction*







Quadrupoles

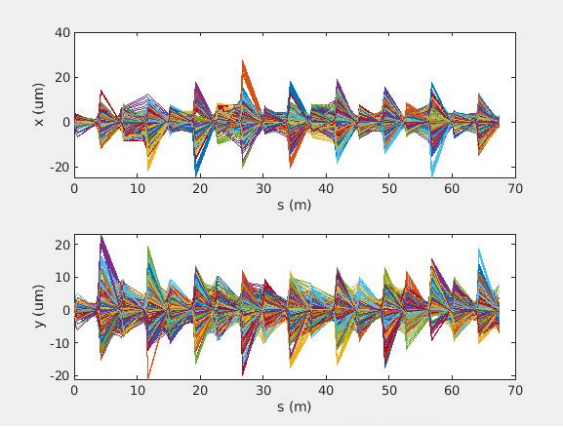
Offset x, y = 50 um rms

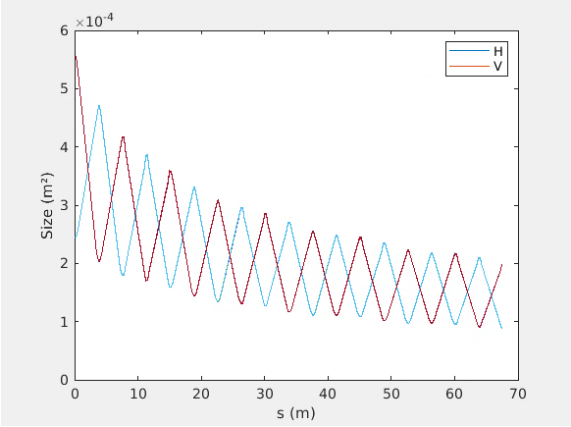
RF cavities

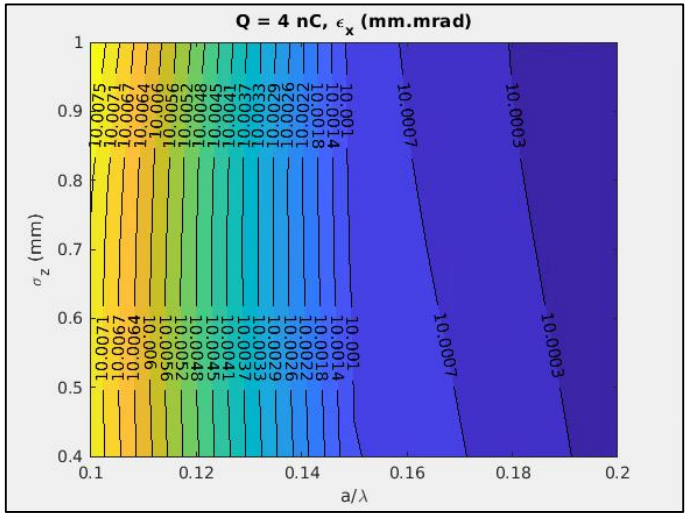
Offset x, y = 100 um rms

Gaussian distribution

with correction*







NEGLIGIBLE IMPACT ON THE EMITTANCE FOR RF AND QUADS MISALIGNMENTS ► NO CONSTRAINTS ON THE RF DESIGN IN THE CONSIDERED PARAMETERS SPACE

*Same conclusion starting from smaller initial emittance: 3 mm.mrad and 5 mm.mrad

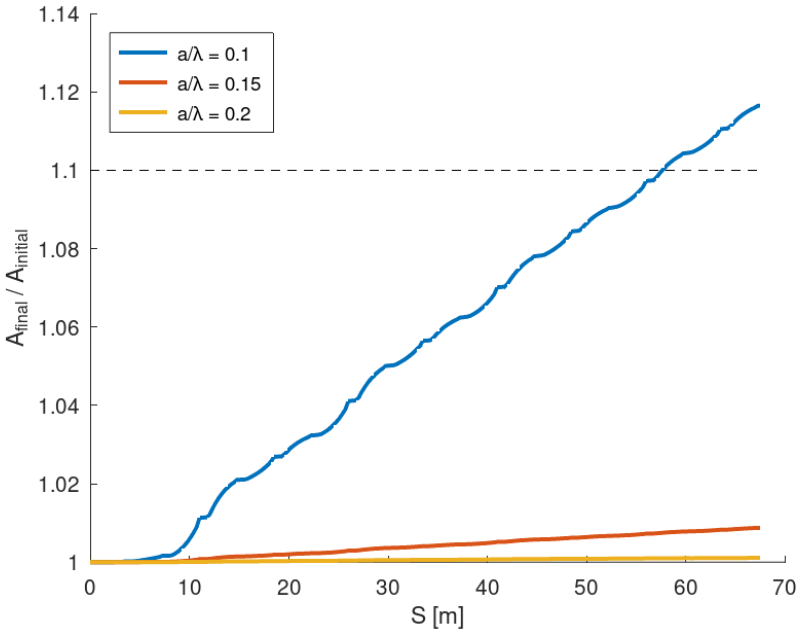
Incoming jitters

- **Possible incoming jitter sources**:
  - **Arrival time**: negligible
  - **Mean energy**: to be verified, but not expected to be critical
  - **Charge**: covered in a precedent presentation*, and to be investigated with the new lattice
  - **Orbit**:

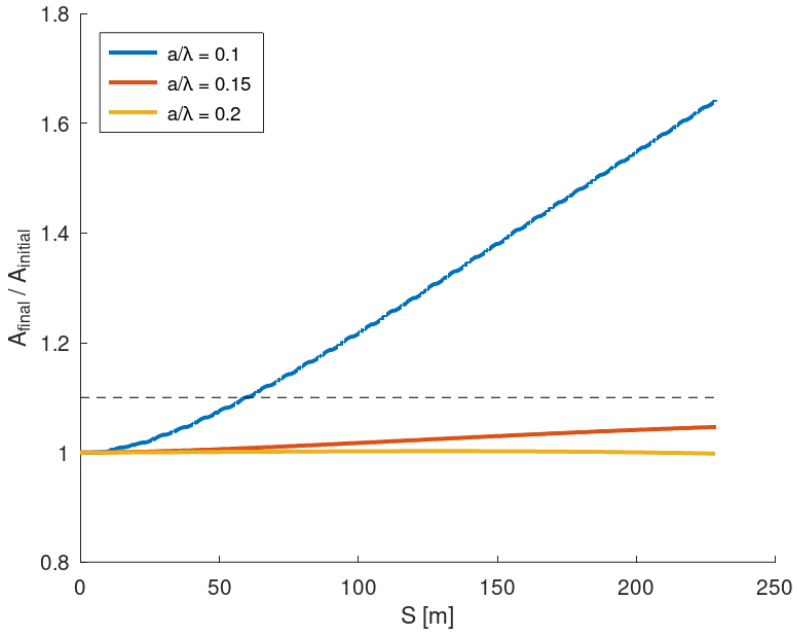
Action* increase

Increase of the area of the beam transverse phase space assuming 10% of the size as incoming jitter

E- LINAC



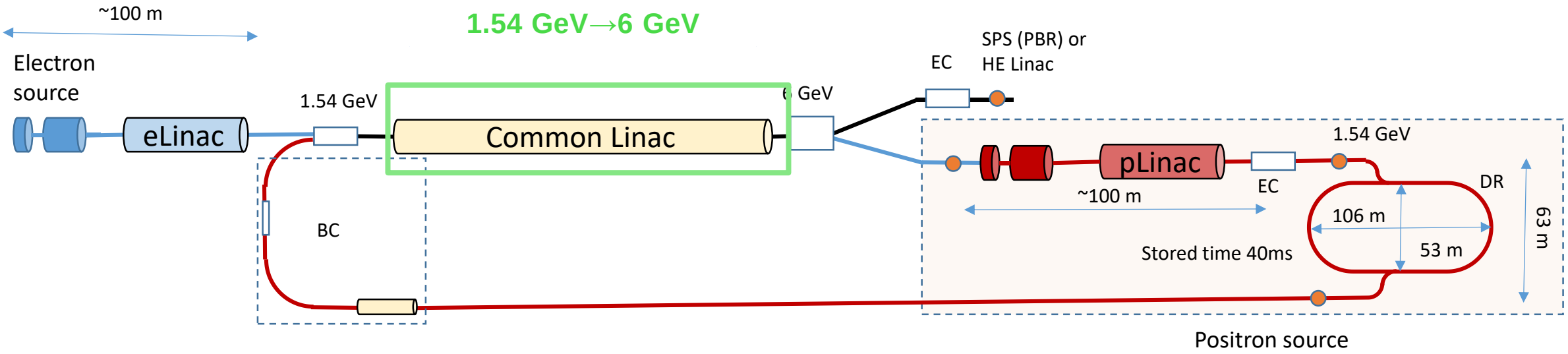
COMMON LINAC



NO LARGE IMPACT IN E-LINAC, AND SIGNIFICANT DEGRADATION ALONG THE COMMON LINAC FOR MORE EXTREME GEOMETRIES

* A. Latina in FCC Injector review meeting: https://indico.cern.ch/event/1025852/contributions/4307595/attachments/2228176/3776428

Longitudinal plane single bunch: common Linac



Energy spread optimization

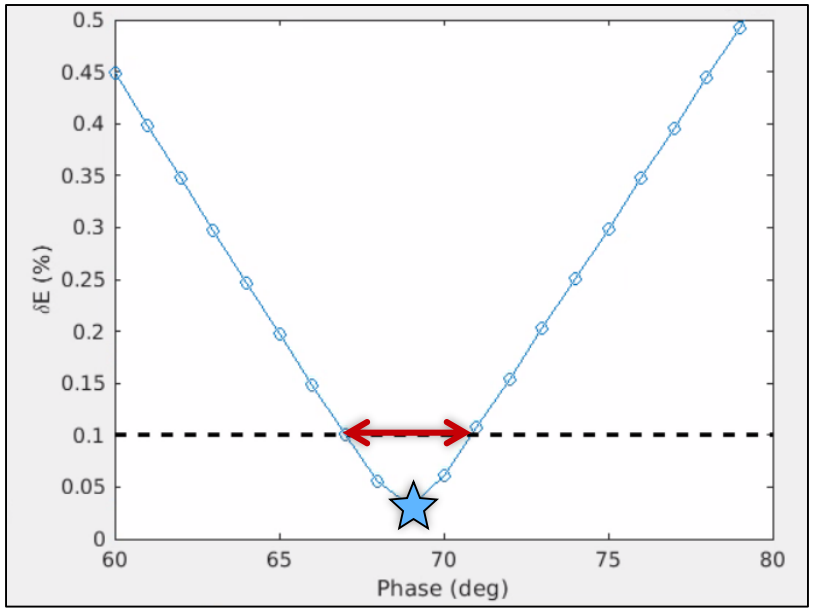
Goal: bring the projected energy spread **below 0.1%** at the SPS injection. How much below?

Considered scenarios:

1. **Shorter bunch from the gun (before this work it was 1.3 mm)**
   - ✓ Possible emittance degradation
   - ✓ Possible longitudinal space charge effect
   - ✓ No CSR

2. **Bunch compressor at e- Linac**
   - ✓ Loss energy due to the off-crest operation along the e-Linac
   - ✓ Extra hardware necessary: linearizing cavities and bunch compressor
   - ✓ Possible emittance degradation due to CSR
   - ✓ Solution depends on the arrival time jitter and RF stability
   - ✓ Very small values of energy spread possible

3. **Shorter bunch from the gun and linearization**
   - ✓ Some extra hardware necessary: linearizing cavities
   - ✓ Small values of energy spread possible
   - ✓ No CSR effects

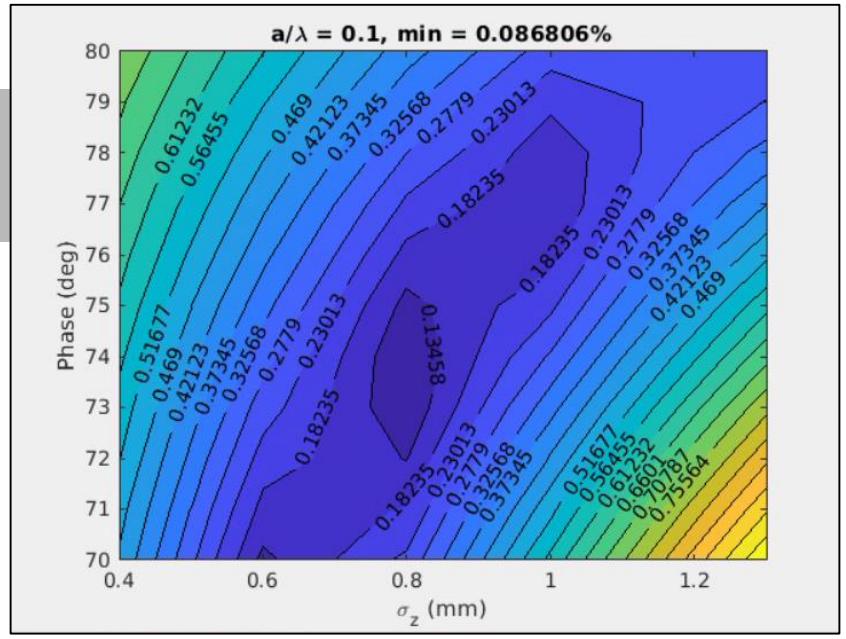


Considered parameters:

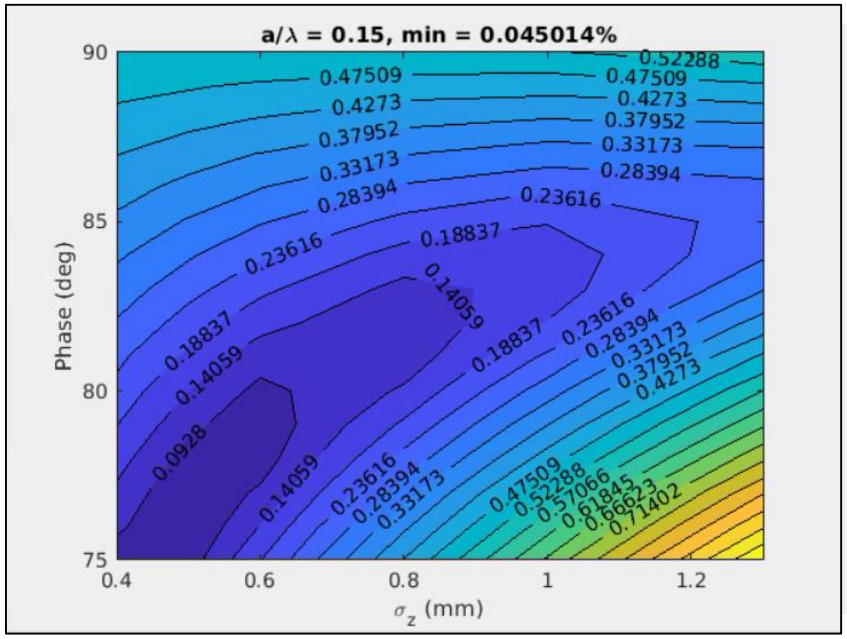
- **Phase extent:** phase range where the final energy spread fulfils is inside the acceptance → stability
- **Minimum** final energy spread
- **Bunch length range** → machine layout and beam specifications

1. Shorter bunch from the gun

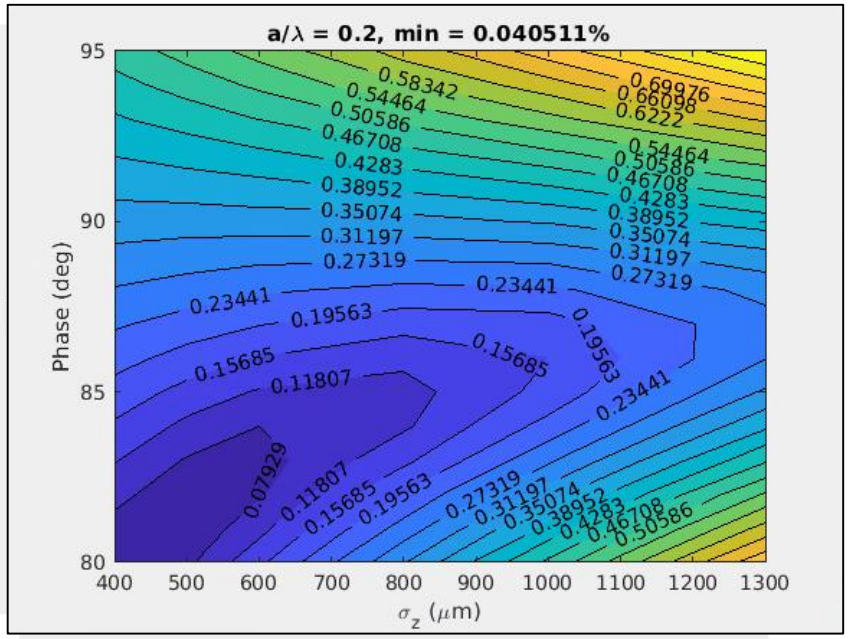
a/λ = 0.10

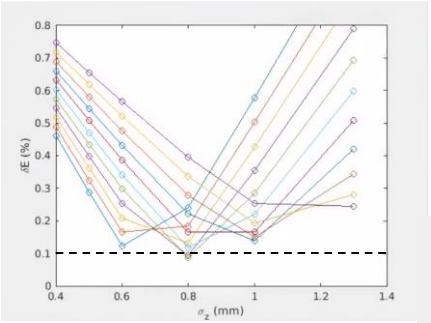


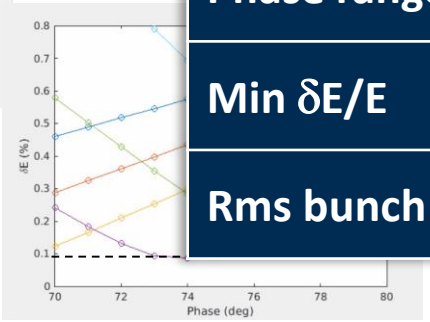
a/λ = 0.15

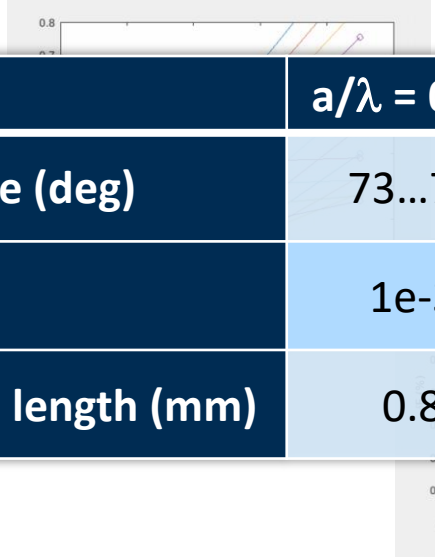


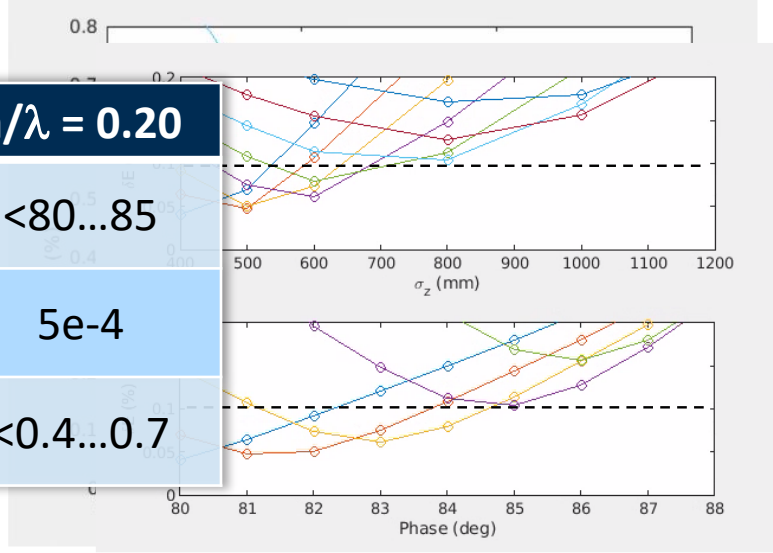
a/λ = 0.20











	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	73…74	<75…81	<80…85
Min δE/E	1e-3	5e-4	5e-4
Rms bunch length (mm)	0.8	0.4…0.65	<0.4…0.7

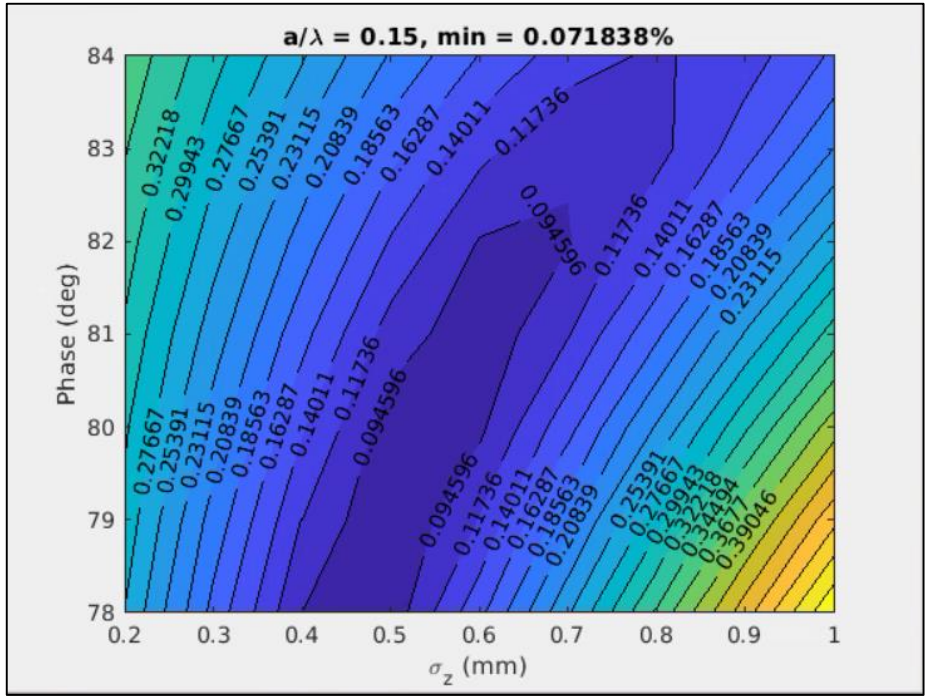
2. Compression at e-Linac: starting parameters

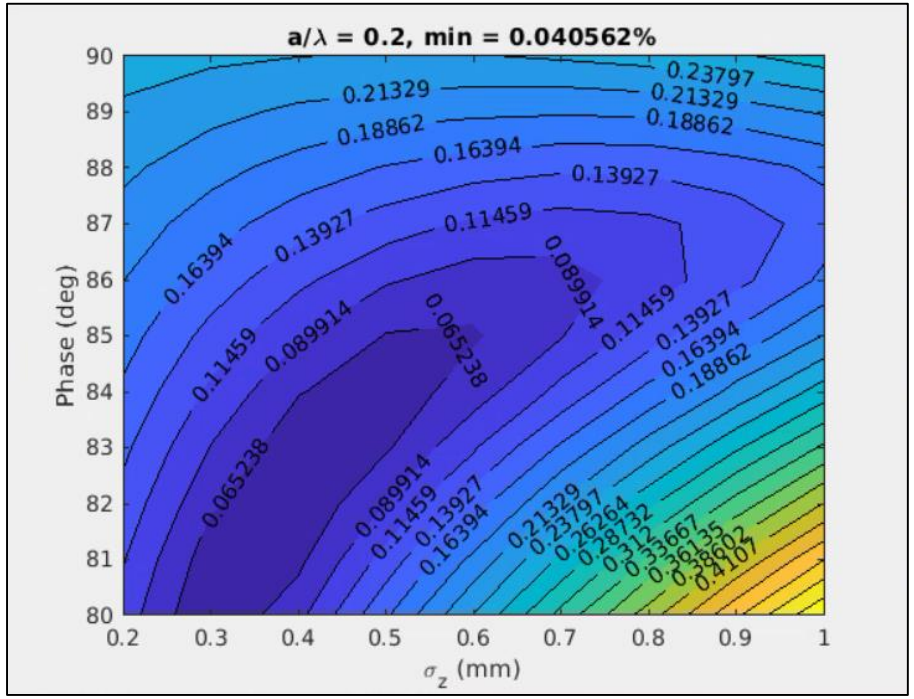
$$CF = \frac{1}{1 - A \cdot R_{56}}$$

CF: compression factor
A: energy chirp
R_{56}: time-energy transport matrix element

$$A = \frac{1 - \frac{1}{CF}}{R_{56}}$$

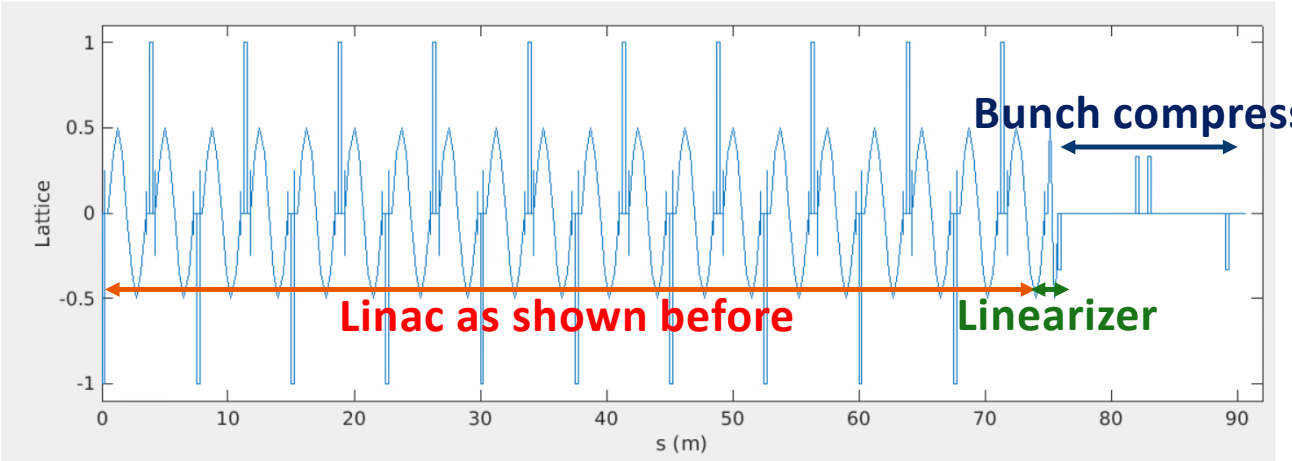
- **Simulations setup**:
  - Constant bunch length along e-Linac
  - Varied the bunch length at the end of e-Linac
  - Final energy chirp and slice energy spread scaled with the compression factor and R56 and with the compression factor, respectively





Optimal bunch length in the range of 0.3…0.7 mm depending on the RF geometry and RF operation phase

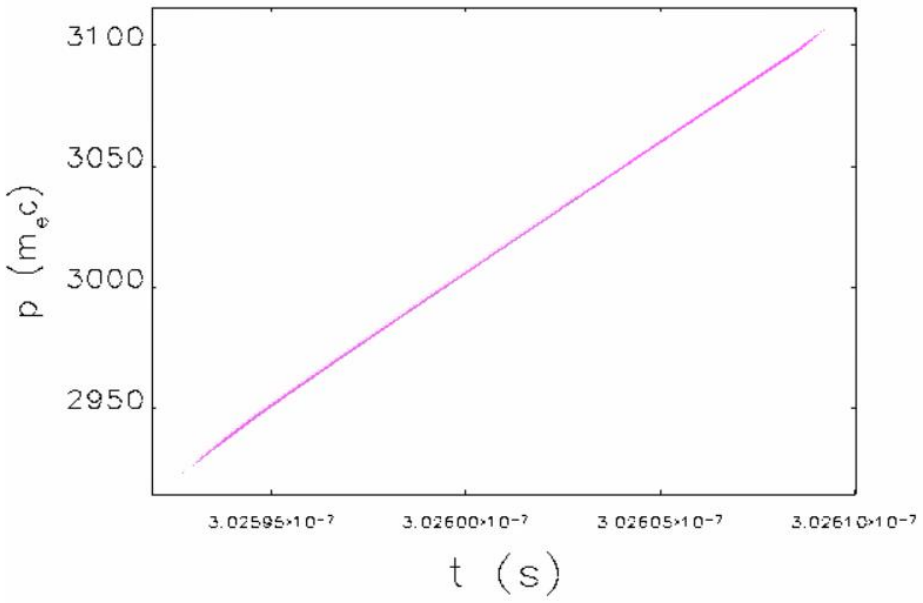
2. Compression at e-Linac: modeling



Dipole length (m)	0.250185
Dipole angle (deg)	3.82
Linearizer f (GHz)	4*2.8 = 11.2
Phase linearizer (deg)	270

Frequency (GHz)	2.8		
Linac 1 phase (deg)	75	72	73
Initial bunch length (mm)	1.3		
Final bunch length (um)	457	238	312
Bend angle (deg)	3.82		
R56 (mm)	63.4		
Linearizer (11.2 GHz) voltage (MV)	100		
Linac length (m)	90		
Initial energy (MeV)	202		
Final energy (GeV)	1.54		

At the end of e- Linac (457 um case)



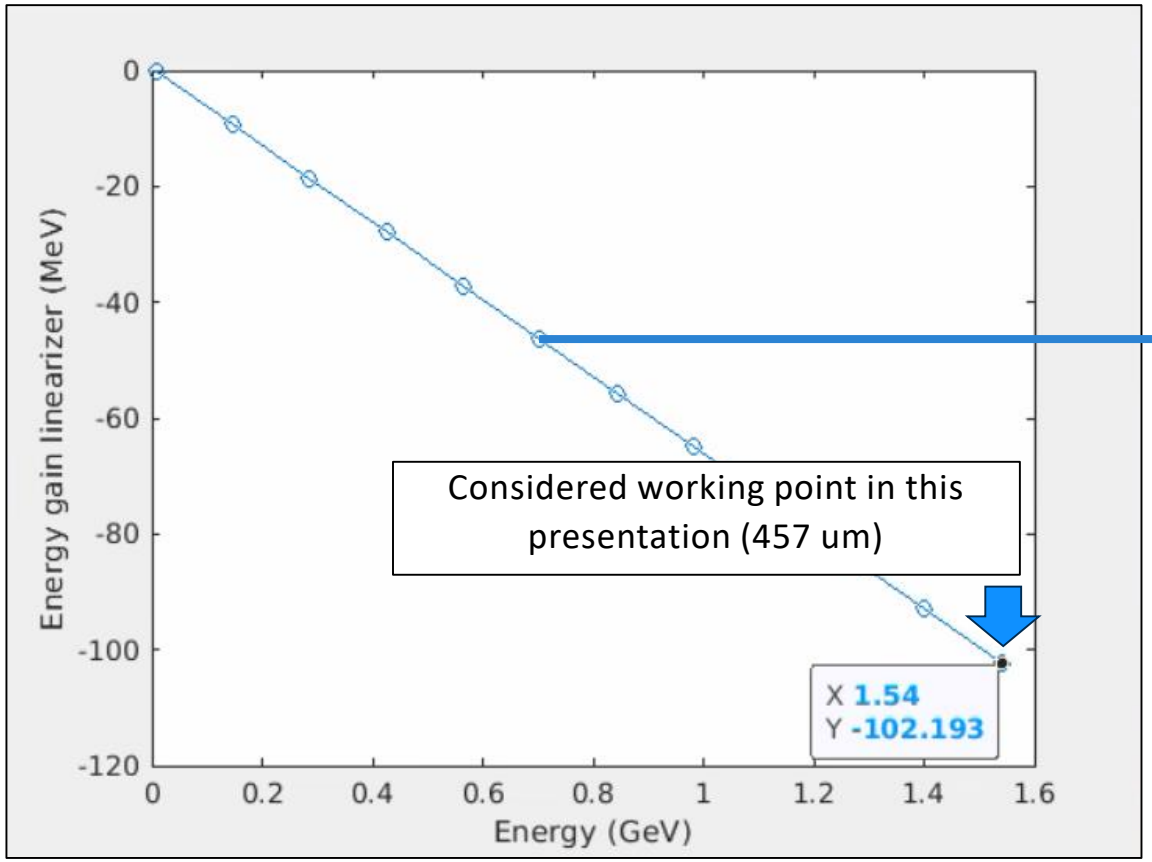
2. Compression at e-Linac: possible improvement

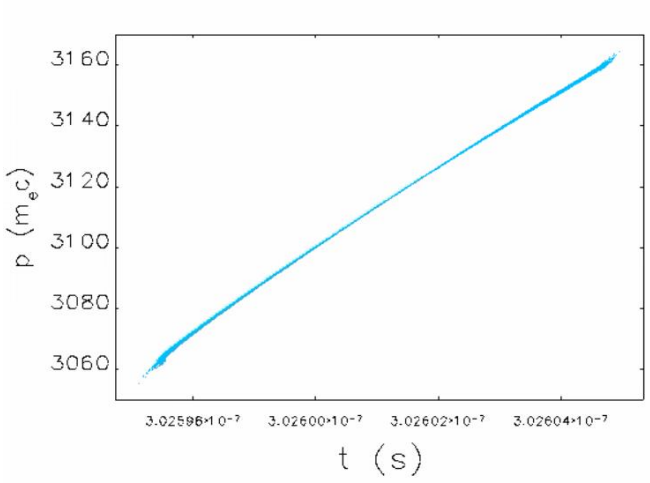
Goal: reduce the amplitude of the linearizing cavity

$$eV_x = \frac{E_0\left\{1+\frac{1}{2\pi^2}\frac{\lambda_s^2 T_{566}}{|R_{56}|^3}\left(1-\sigma_z/\sigma_{z_0}\right)^2\right\} - E_i}{\left(\lambda_s/\lambda_x\right)^2 - 1}.$$ *

R56 = 63.4e-3 %m, T566 = -3/2*R56

lambda_RF = c/f_RF, lambda_linearizer = lambda_RF/**4** %m





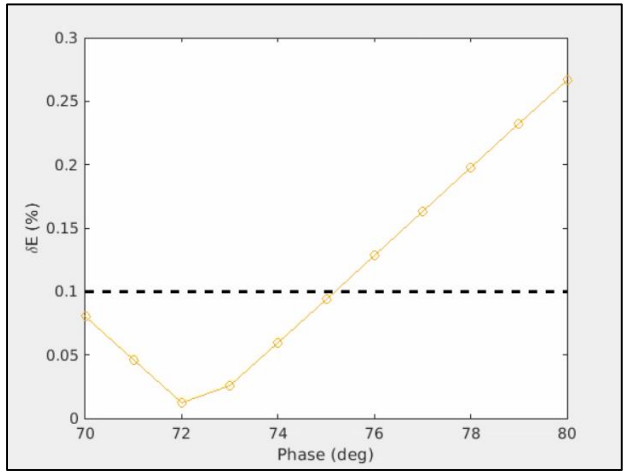
Parameters "available" for the optimization:

- Compressor chicane energy: less for smaller linearizing cavity voltage, more for emittance preservation
- Compression factor: smaller for emittance preservation, larger to have a negligible RF curvature downstream of the compressor

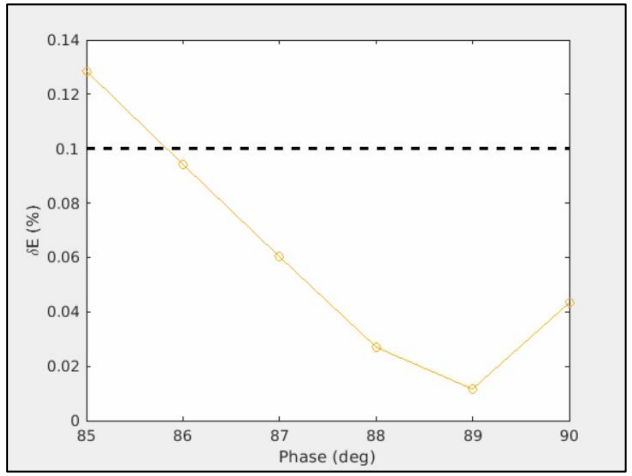
*https://www.slac.stanford.edu/pubs/slactns/tn04/slac-tn-05-004.pdf

2. Compression at e-Linac: results

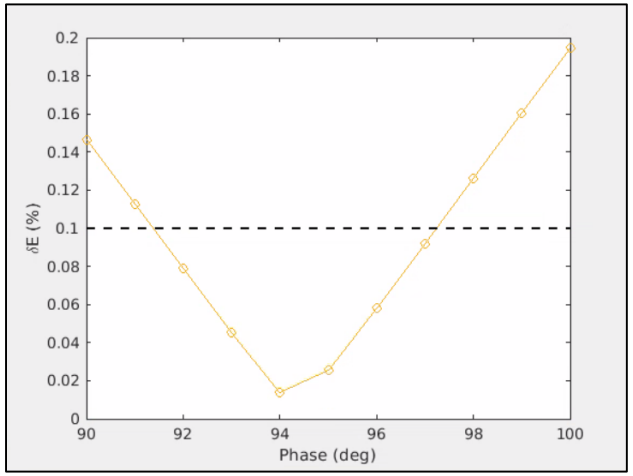
a/λ = 0.10



a/λ = 0.15



a/λ = 0.20



	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	<70…75	86…>90	<80…85
Min δE/E	1e-4	1e-4	1e-4
Rms bunch length (mm)	0.457		

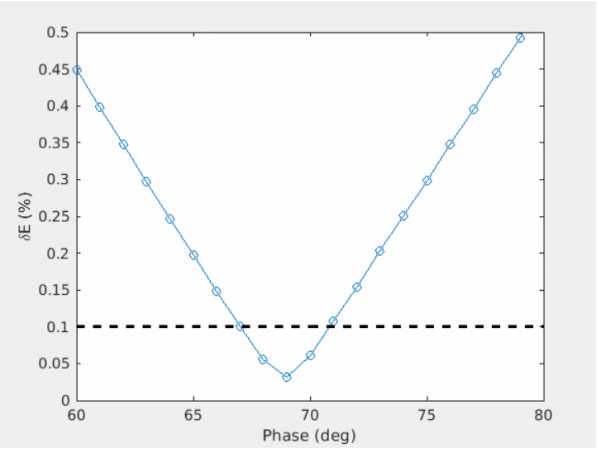
FOR ALL THE GEOMETRIES THE FINAL ENERGY SPREAD << 0.1%

THE SOLUTION AT a/λ = 0.15 CORRESPONDS TO THE E- LINAC ON-CREST OPERATION REGION (THE MOST ENERGY EFFICIENT)

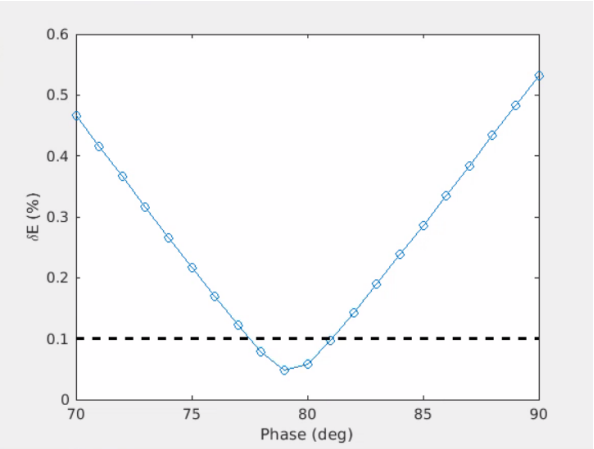
3. Shorter bunch from the gun and linearization

- Intermediate solution:
  - Moderately shorter rms pulse length: possible emittance degradation at the low energy section
  - Linearizing cavity
  - No bunch compression: no other possible emittance degradation

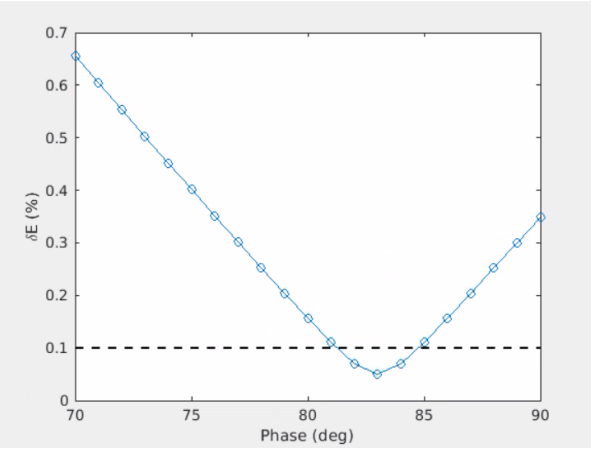
a/λ = 0.10



a/λ = 0.15



a/λ = 0.20



	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	66…70	77…81	81…85
Min δE/E	2e-4	3e-4	4e-4
Rms bunch length (mm)	0.650		

SMALLER VALUES OF ENERGY SPREAD REACHABLE COMPARED TO THE CONFIGURATION 1

Discussion

Several solutions satisfy the present requirements

1. Shorter from the gun*

	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	73…74	<75…81	<80…85
Min δE/E	1e-3	5e-4	5e-4
Rms bunch length (mm)	0.8	0.4…0.65	<0.4…0.7

2. Bunch compression

	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	<70…75	86…>90	<80…85
Min δE/E	1e-4	1e-4	1e-4
Rms bunch length (mm)		0.457	

3. Linearization

	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	66…70	77…81	81…85
Min δE/E	2e-4	3e-4	4e-4
Rms bunch length (mm)		0.650	

How to choose the best one?

- **The ring energy acceptance**: is much less than 0.1% beneficial?
- **Easiness of operation, cost, and possible emittance degradation mechanisms**
- **Tolerance**: “good phase region” extension, more or less critical the arrival time jitter (compression), …
- **RF efficiency**: smaller aperture still beneficial also if the optimum working point is off-crest? Up to which extent?

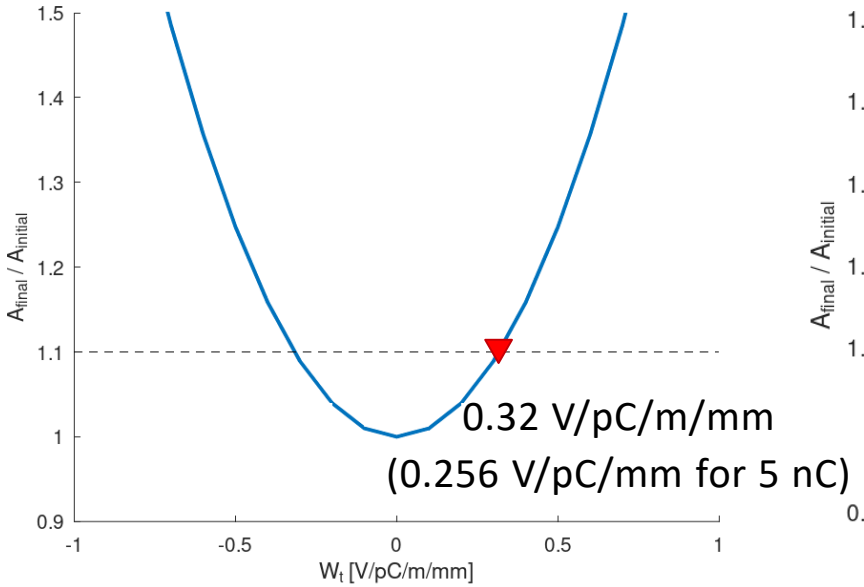
*First optimization by S. Doebert gives emittance 6.1 mm.mrad (even increasing the charge from 4 nC to 5 nC)

Multi-bunch

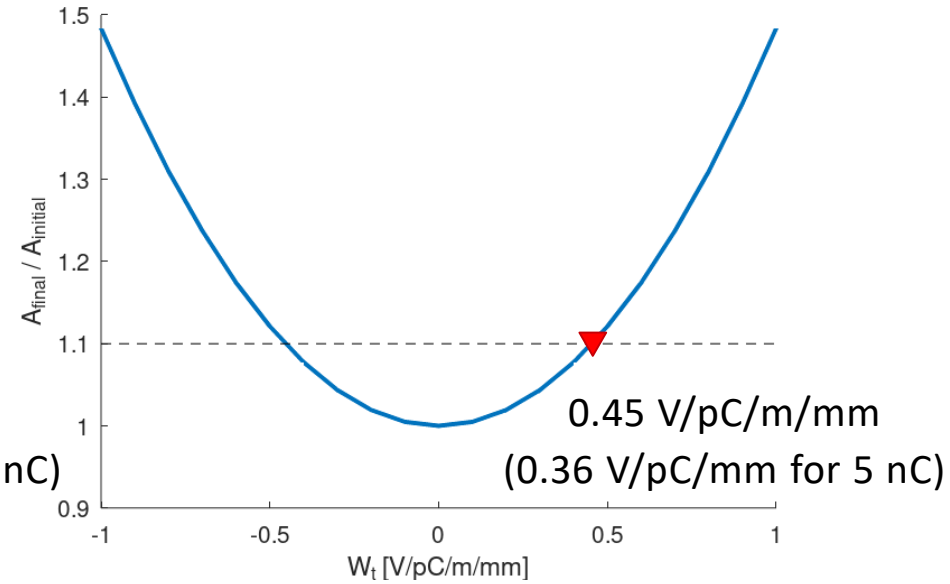
Jitter amplification

- **Simulations' strategy: provide specifications for the RF design**
  - Imposed a kick to the second bunch to simulate the long range wakefield generated by the first bunch to the following one: **independent on** the bunch **time** separation
  - Determined the **tolerable kick** to maintain the action increase below a threshold (10% increase)
  - RF design aims to produce transverse wakefield below this value. This contributes to determine the **minimum bunch separation**

e-Linac

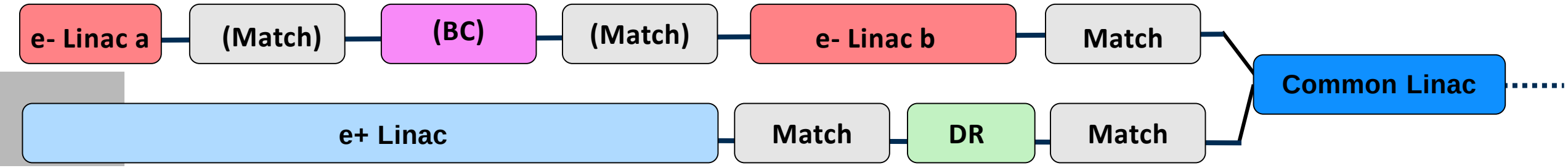


Common Linac



RF structures optimized to produce a maximum kick~0.2 V/pC/mm at 17.5 ns time separation (H. W. Pommerenke)

“Minimalistic” schematic layout: a closer look



Schematic layout must include:

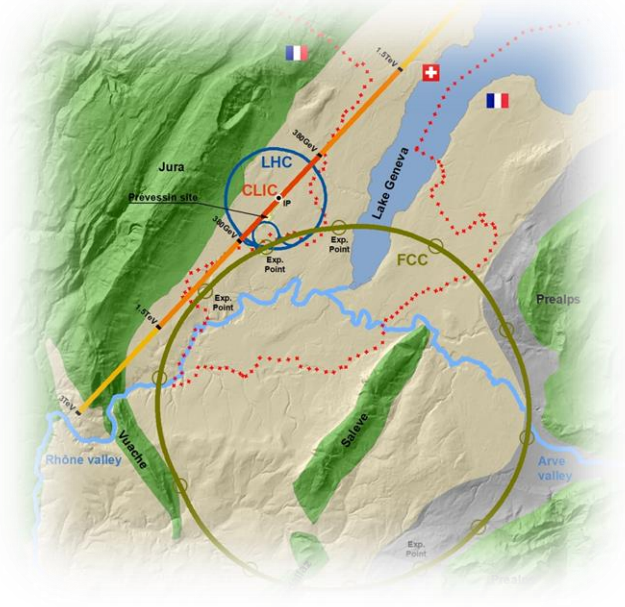
-
-
-

	e- Linac	Common Linac	Comments
RF structures			
Length (m)	3		It can be changed to maximize RF efficiency
Gradient (MV/m)	25		It can be slightly changed
Frequency (GHz)	2.8*	2.8	*2.0 GHz already investigated
Iris radius (mm)	21.4 (a/λ = 0.2)	16.1 (a/λ = 0.15)	*16.1 mm shifts the optimal phase by 2 degrees (advantageous)
Operating phase (deg)	90	78*	*83 assuming 21.4 mm aperture
Max kick 2nd bunch (V/pC/m/mm)	0.32 (0.256 at 5 nC)	0.45 (0.36 at 5 nC)	0.2 feasible at 17.5…100 ns
Number of structures	18*	60	+eventually linearizing cavities
Quadrupoles			
Gradient (T/m)	7.75…30	1…8	
Length (m)	0.25		
Number of quadrupoles	18	60	

Conclusions

Longitudinal and transverse beam dynamics studies:

- *Single bunch* studies (misalignment of RF structures and quadrupoles as well): orbit correction allows maintaining the emittance
- Jitter amplification due to *multi-bunch* effect: maximum tolerated kick due to long range wakefield used as input for the RF design
- Several scenarios to keep the *energy spread* at the SPS injection below and much below the specifications studied



Baseline design which fulfill the requests proposed

Next steps and possible improvements:

- Toward an even most *efficient design*: fine tuning of the aperture of the RF structures vs off-crest operation vs bunch length
- Possibly the design will undergo to a *revision* once the beam charge will be fixed (depending on the positron production process optimization)
- Design of the independent matching and orbit control for the electrons and positrons *"merging" sections*
- May a much *smaller* (up to a factor 10) *energy spread* at the ring injection be beneficial?

A swiss “thank you”…

Questions?

Comments?

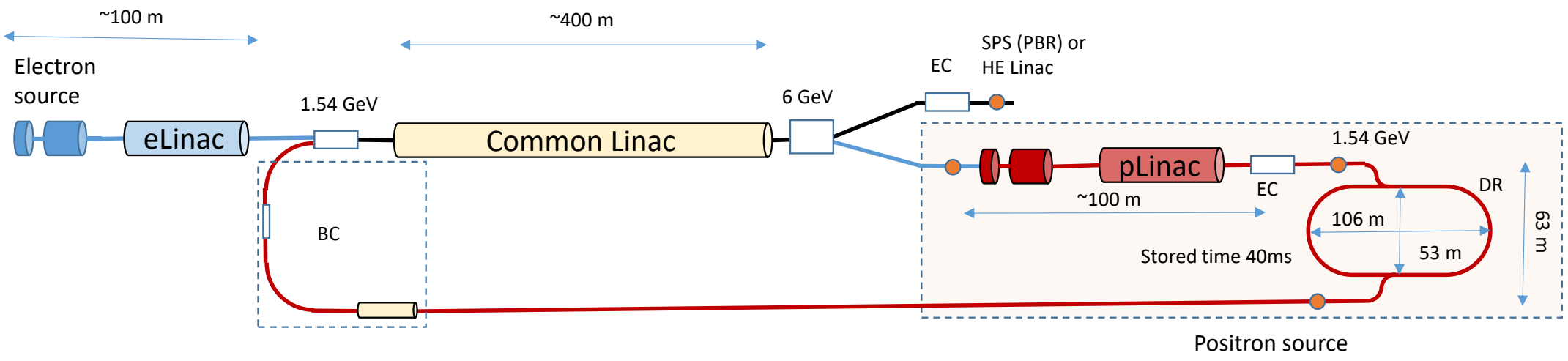
…to CHART* and to you for your attention

***This work was done under the auspices of CHART (Swiss Accelerator Research and Technology Collaboration, https://chart.ch**

FCCIS: 'This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.'

Spares

Baseline and alternative designs



Electron source

Bunch length 1.3 mm rms
E = 202 MeV
Emittance = 3.3 mm.mrad

Bunch length 0.650 mm rms
E = 202 MeV
Emittance = 6.1 mm.mrad

Electron Linac

a = 21.4 mm (a/lambda = 0.2)
Phase = 90 deg
L = 3 m
G = 25 MV/m

a = 16.1 mm (a/lambda = 0.15)
Phase = 90 deg
L = 3 m
G = 25 MV/m

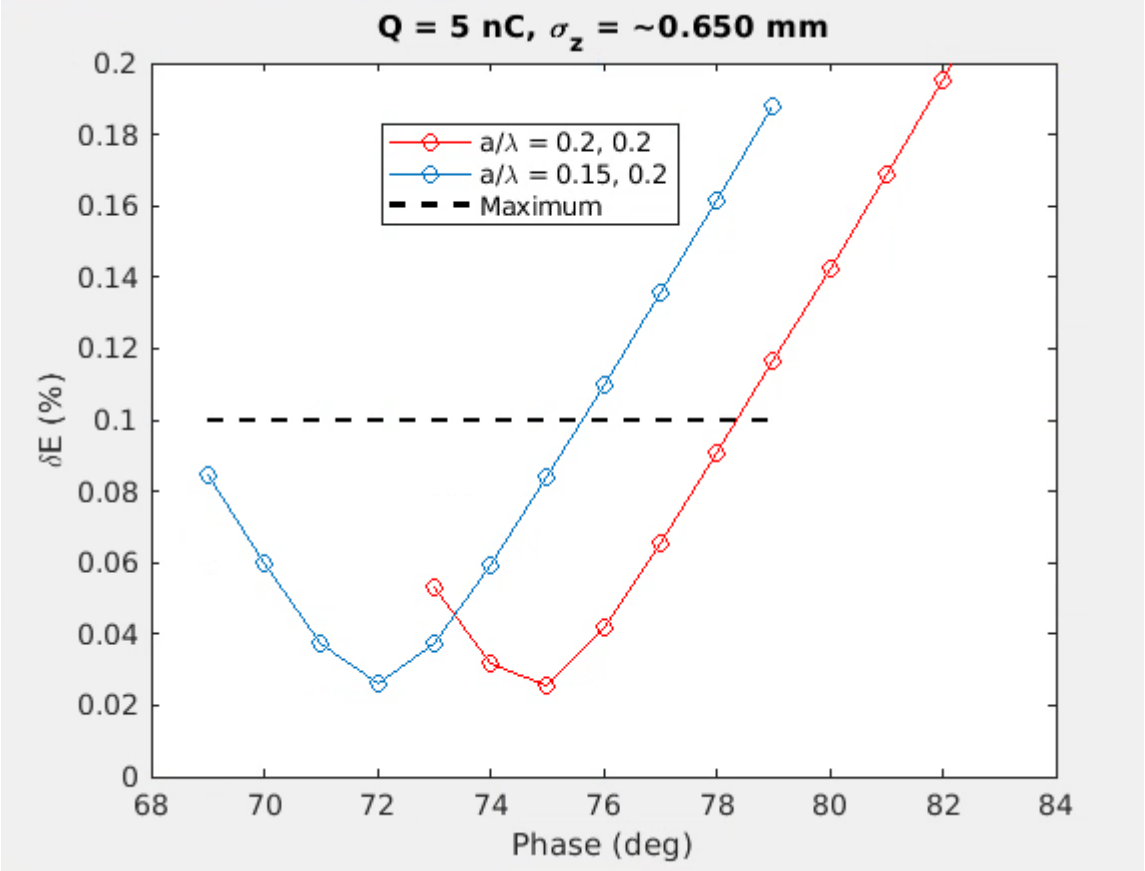
Common Linac

a = 16.1 mm (a/lambda = 0.15)
Phase = 78 deg
L = 3 m
G = 25 MV/m

Q = 4 → 5 nC: 3 degs more off-crest
e- Linac from 0.15 to 0.2: 3 degs more off-crest

Q = 5 nC-start2end

- Newly optimized shorter distribution

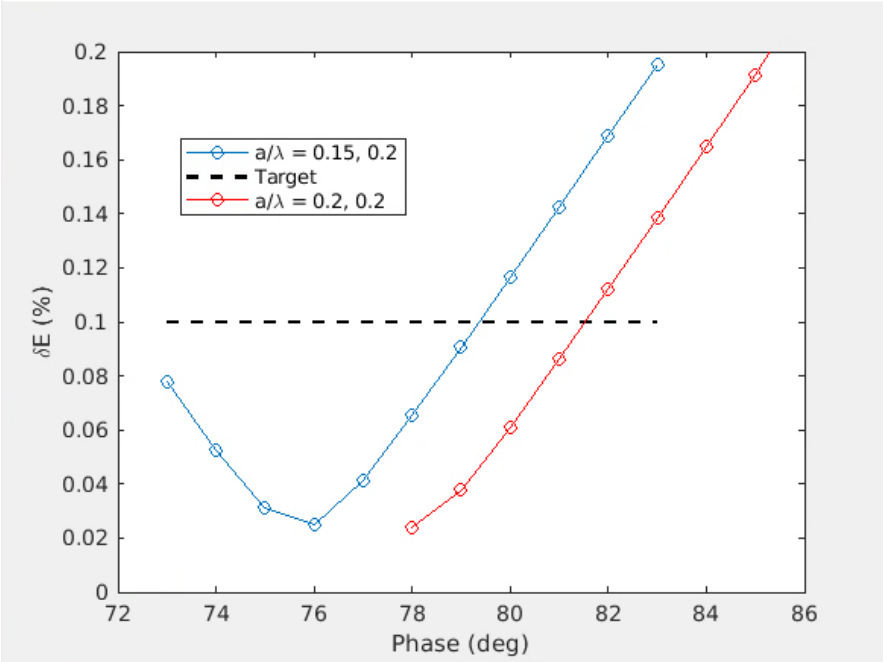


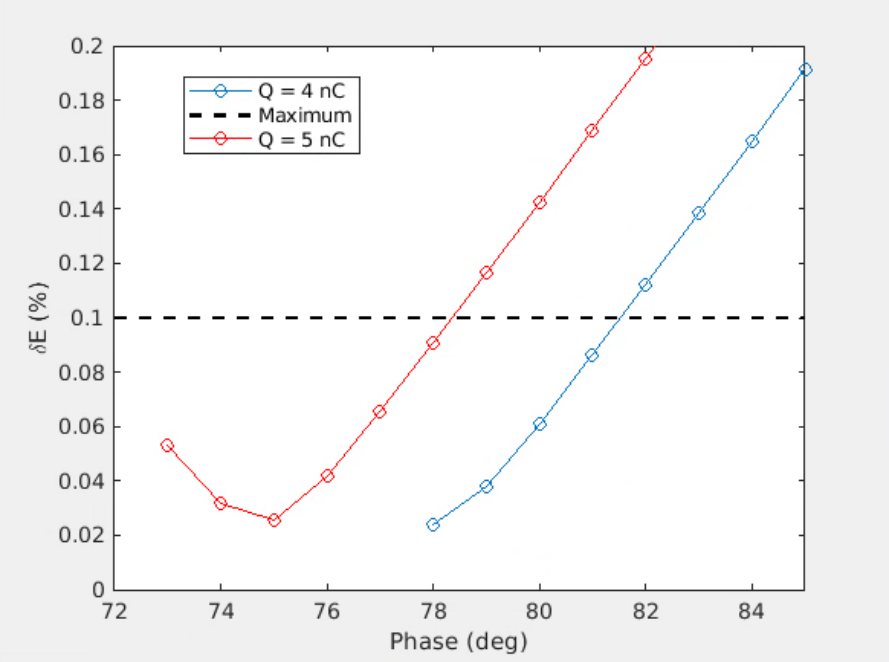
The distribution is a bit shorter than expected, but fine tuning

To keep in mind

- Start-to-end fits with expectations, also if the newly optimized initial distribution seems to be a bit shorter than 650 um
- From 0.15 to 0.2 a/lambda in e-Linac moves the optimal phase by 2 degrees
- From 4 to 5 nC moves the optimal phase by 3 degrees
- All this at this bunch length

- It can be partially recovered by elongating the bunch length, but the maximum bunch length to stay below 0.1% final energy spread is 800 um, as expected from previous simulations (otherwise RF curvature starts to make impossible to stay below 0.1% final energy spread)

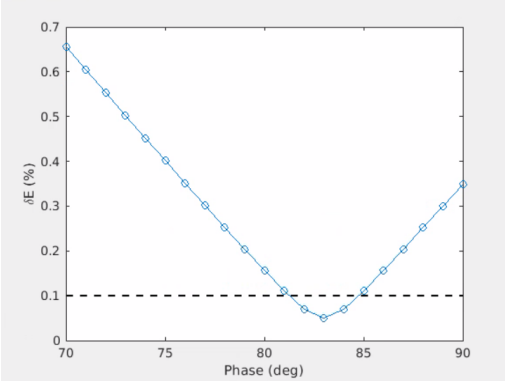
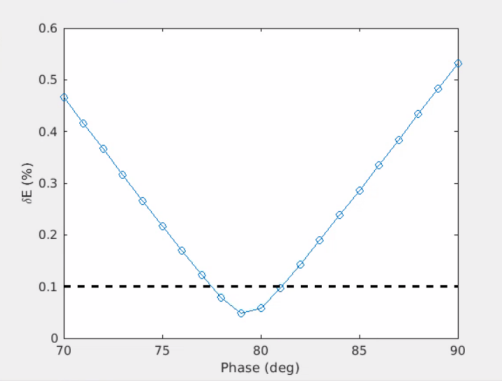
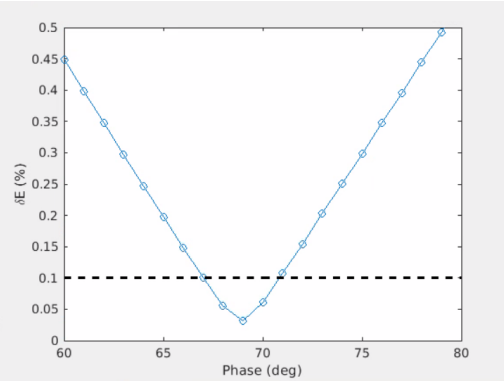
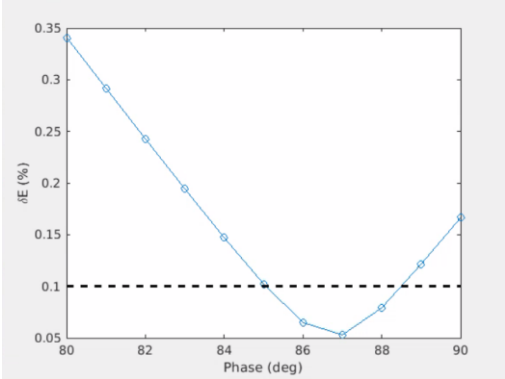
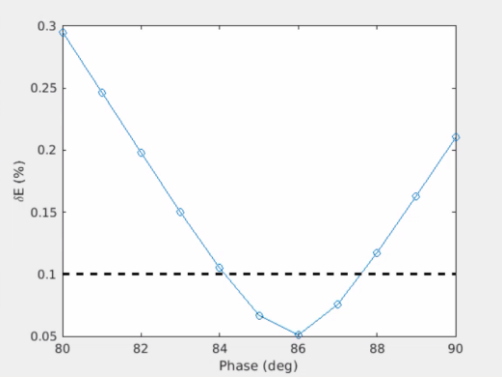
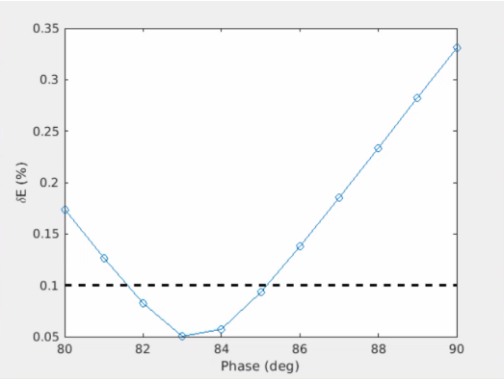




Dependence on the bunch charge (single bunch)

- The machine will run at 4 nC down to 1 nC bunch charge
- Checked the solution for 1 nC compared to 4 nC case

Shorter (650 um) from the gun and linearization

	a/λ = 0.20	**a/λ = 0.15**	**a/λ = 0.10**
Q = 4 nC			
Q = 1 nC			

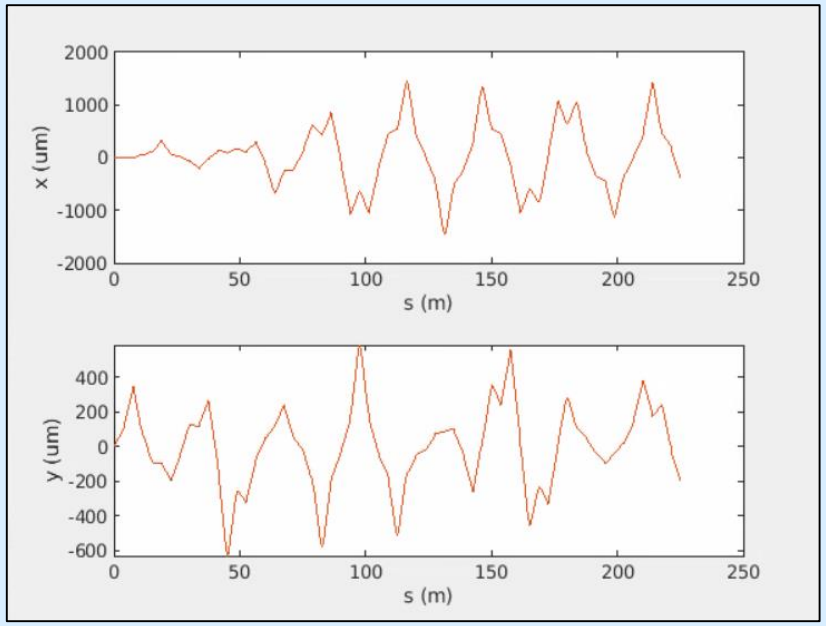
Do we want to choose the RF design based on BD, or optimize BD given the best RF design?

Orbit correction

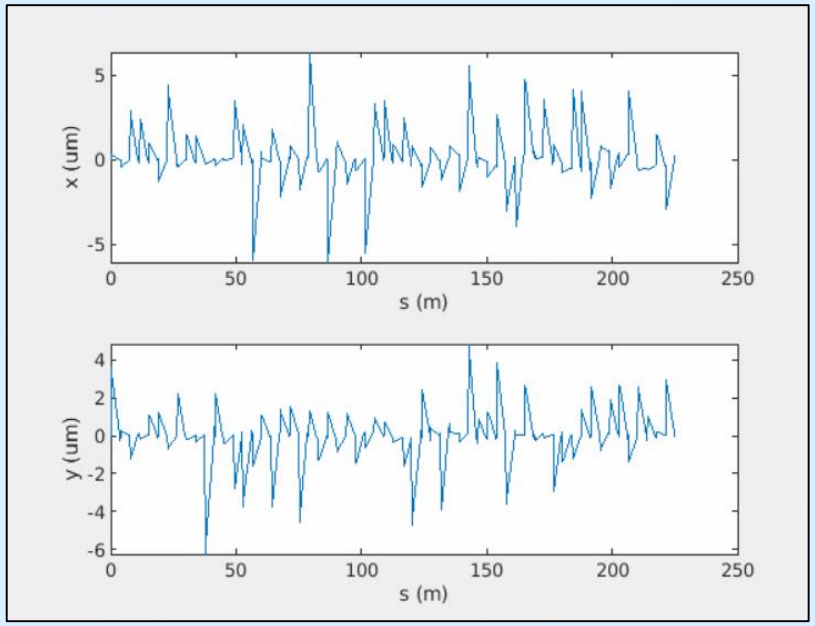
- **Built-in algorithms for our case (Elegant)**:
  - *One-to-one*: pairing one corrector with the next downstream BPM
  - *One-to-best*: attempts to find a BPM with a large response to each corrector
  - *Global*: uses the global response matrix

- **Simulated scenarios**:
  1. *One-to-one* with 2 corrector and 2 BPM each 3 quadrupoles
  2. *One-to-one* with 1 corrector and 1 BPM each 3 quadrupoles (max kick<100 urad). Considered in the following.

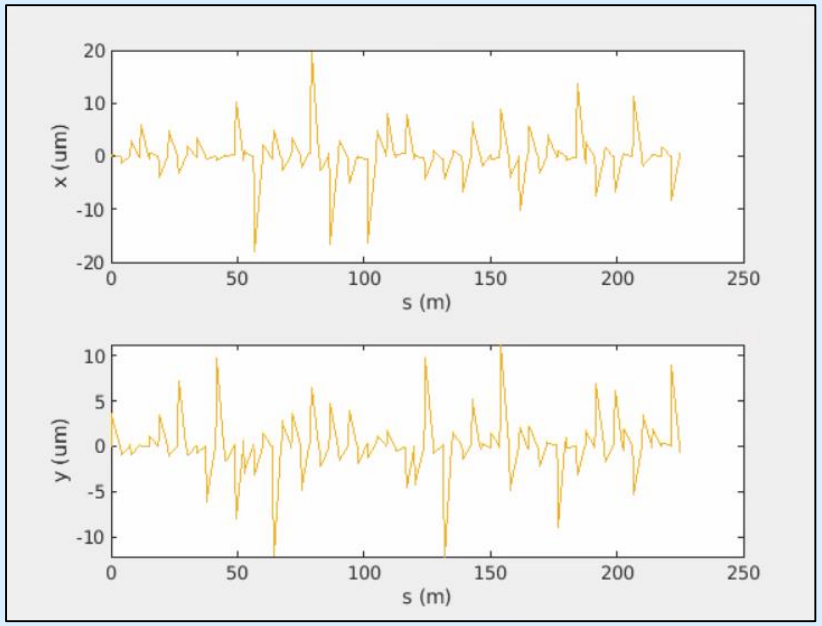
No orbit correction



Case 1

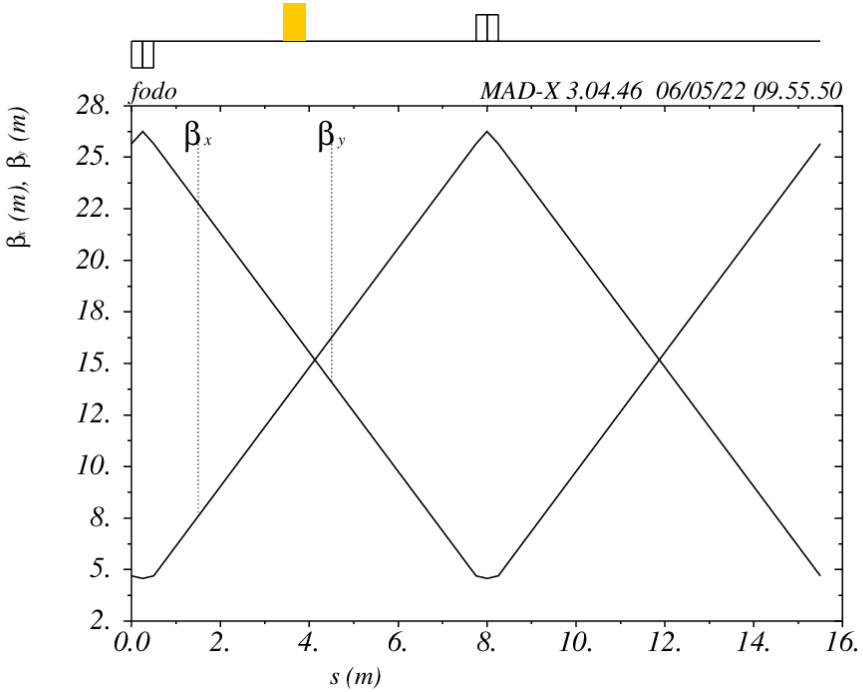


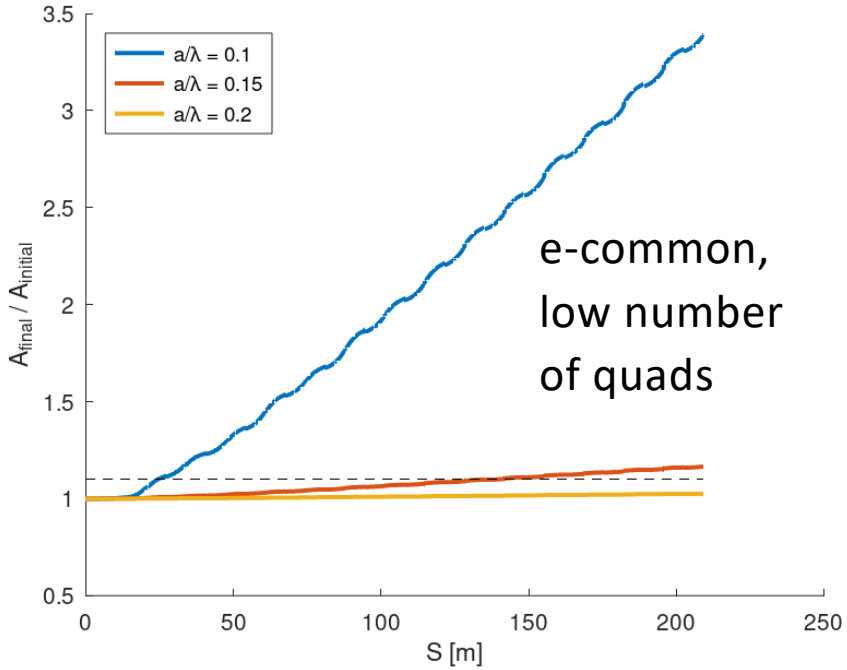
Case 2

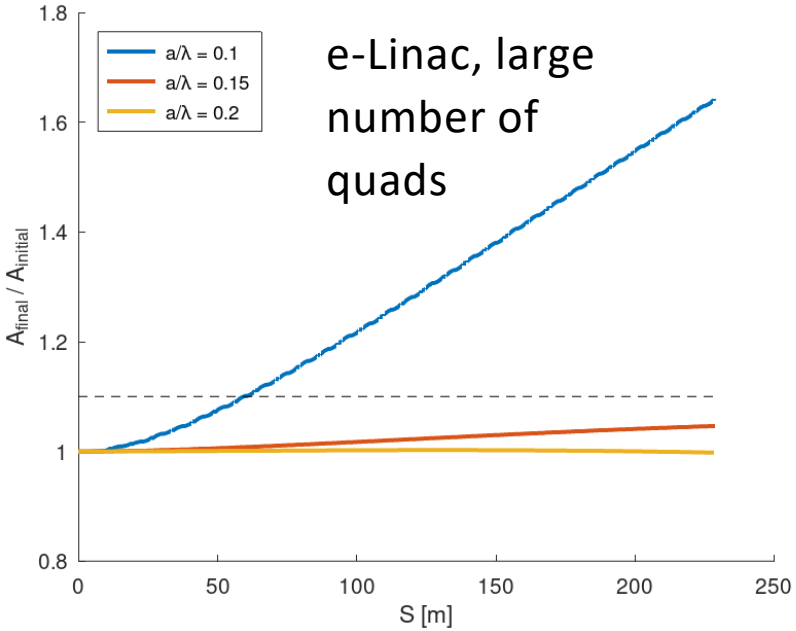


Different lattice

Case with one quadrupole each two structures

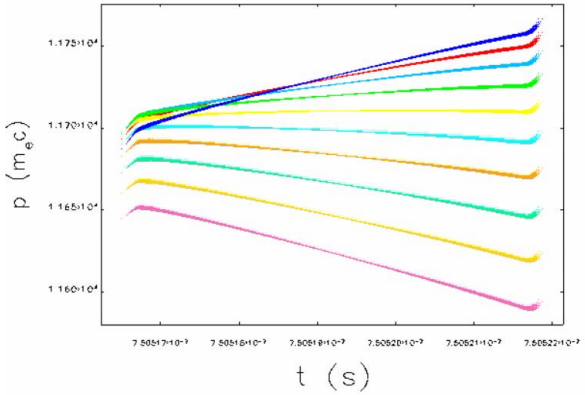




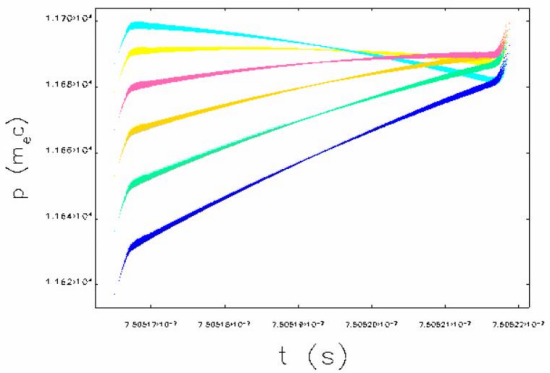


Best working point?

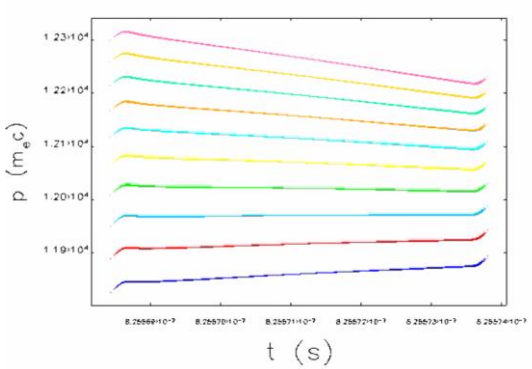
a/λ = 0.20

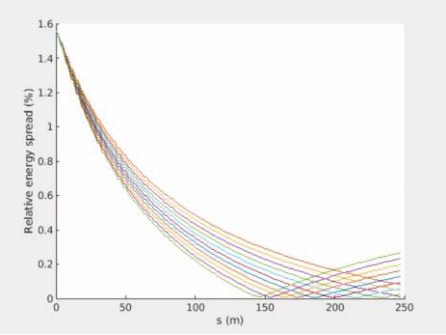


a/λ = 0.15

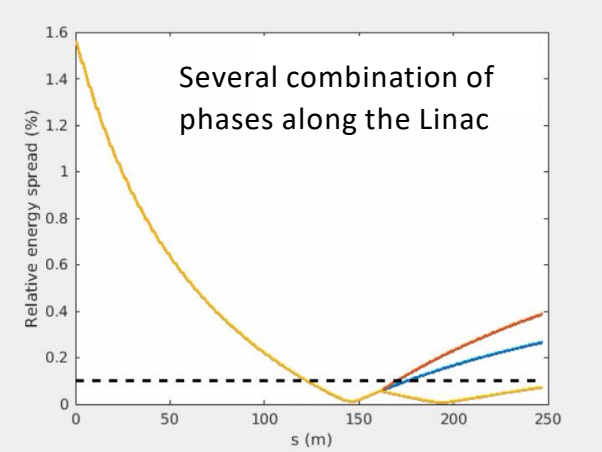


a/λ = 0.10





We may run some structures off-crest, and some others on crest. More off-crest gives a more linear dechirp, but also more energy jitter due to arrival time jitter and RF timing jitter.

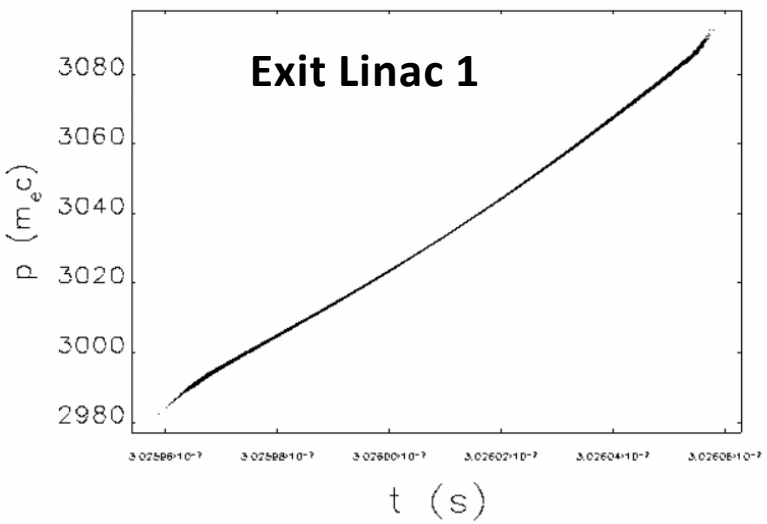


Many more solutions are possible.
I would pick up one with the beginning as much as possible on crest, and after off-crest: better for transverse and we use the more linear part of the RF, but jitter?

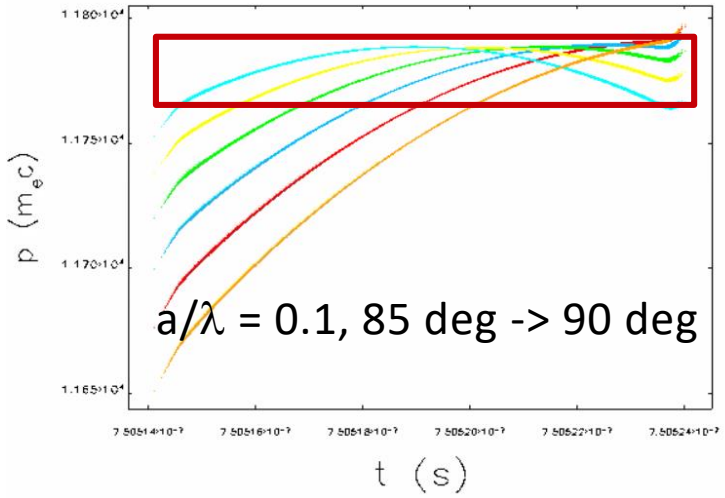
Another possible distribution: longer bunch length

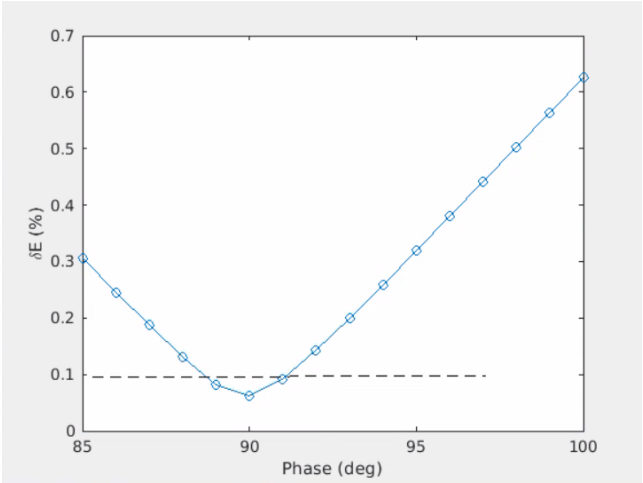
I check with the longer bunch of 800 um at the end of Linac 1

Linac 1 phase (deg)	80
Initial bunch length (mm)	1.3
Final bunch length (mm)	0.8
R56 (mm)	63.4



Possible second parameters set





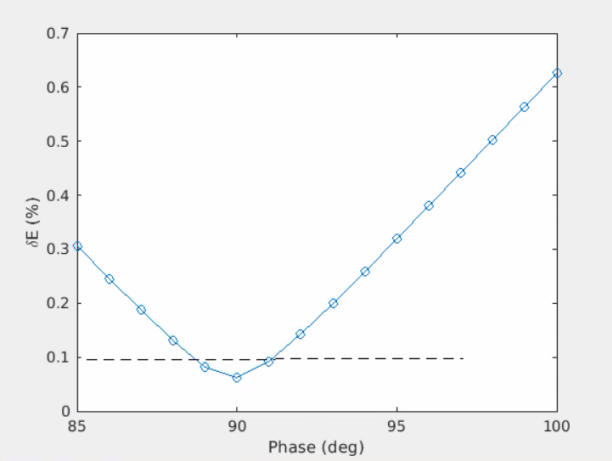
Still some curvature from Linac 2 visible, but we fulfill the specification

If necessary, we may relax the compression

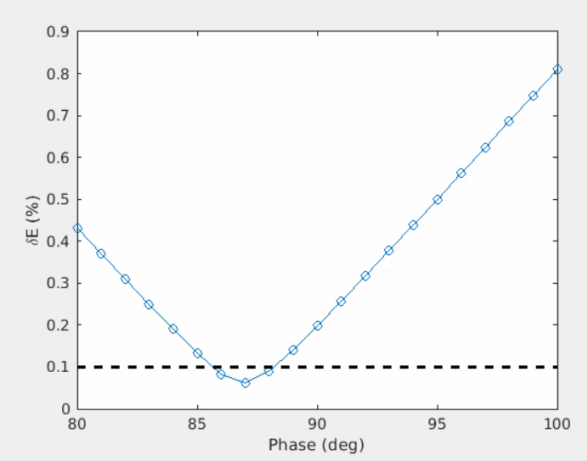
Bunch length = 800 um from e- Linac

- Initial bunch length compressed and linearized 0.8 mm
- /psi/home/bettoni_s/data/Elegant_sim/FCC/Linac_2/Run_8_distr

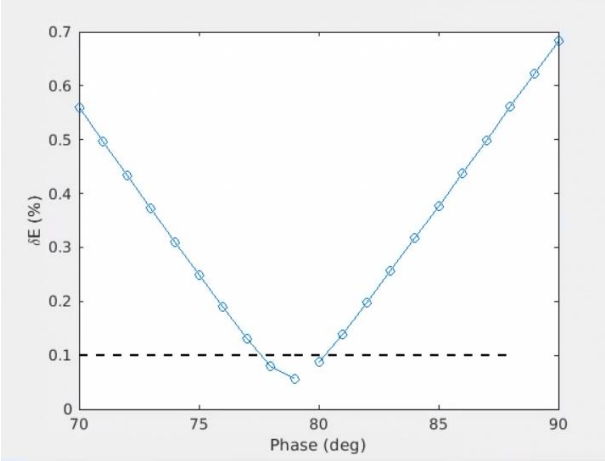
a/λ = 0.20



a/λ = 0.15



a/λ = 0.10

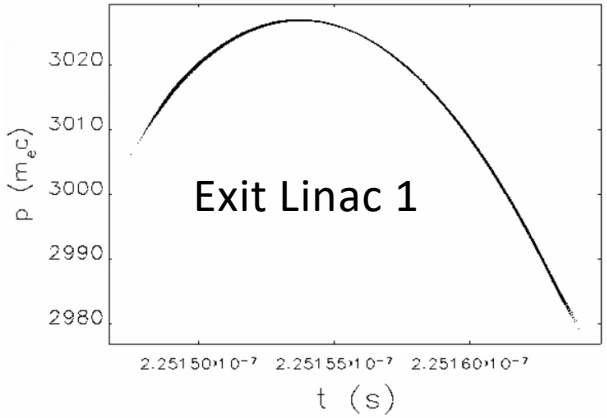


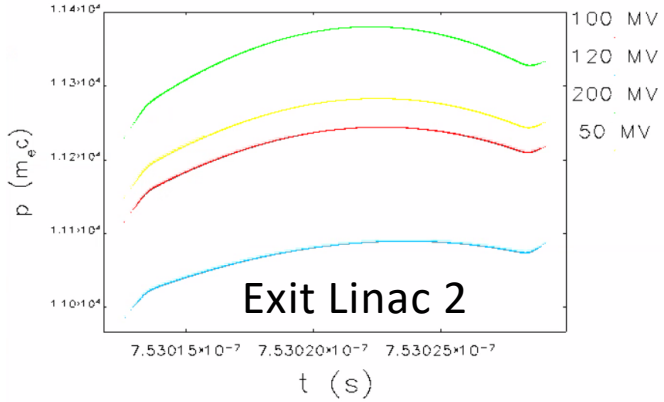
All the geometries satisfy the conditions. Maybe a finer tuning of the linearizer amplitude may give more margin.

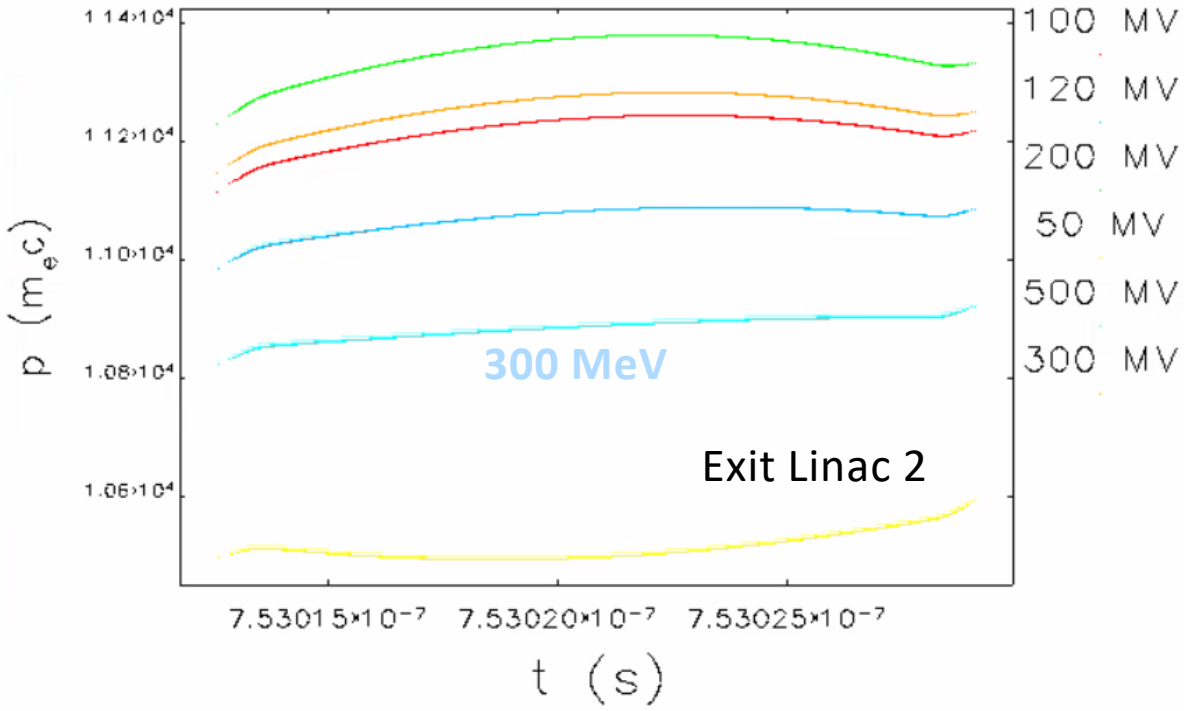
Linearization, no compression

- Linac 1 on crest, Linac 2 on crest, no BC, linearizer at the end of Linac 2
- /psi/home/bettoni_s/data/Elegant_sim/FCC/Linac_1/Run_4 and /psi/home/bettoni_s/data/Elegant_sim/FCC/Linac_2/Run_9_distr

- Cumulated RF curvature
- When you go off-crest you have more linear curvature, and this helps to reduce the SINXB amplitude. From the energy gain efficiency this is not the best case: less energy gain in Linac 1, more energy reduction by the linearizer (anti-crest)







Compression optimization

Presented at a past FCC week

Bunch Compression and CSR Mitigation

Tessa Charles

Frank Zimmermann, Katsunobu Oide and Mark Boland

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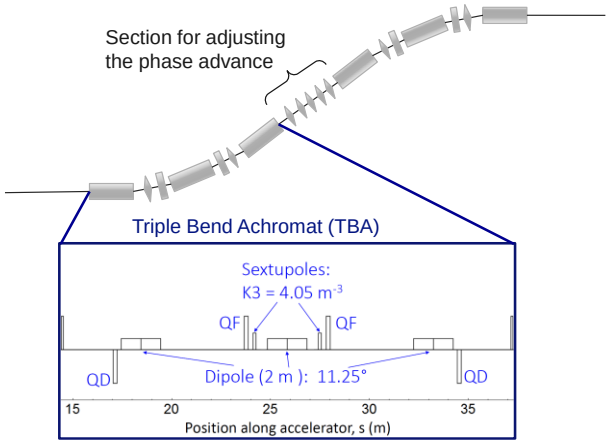
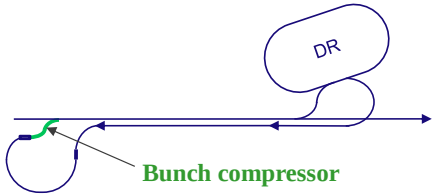
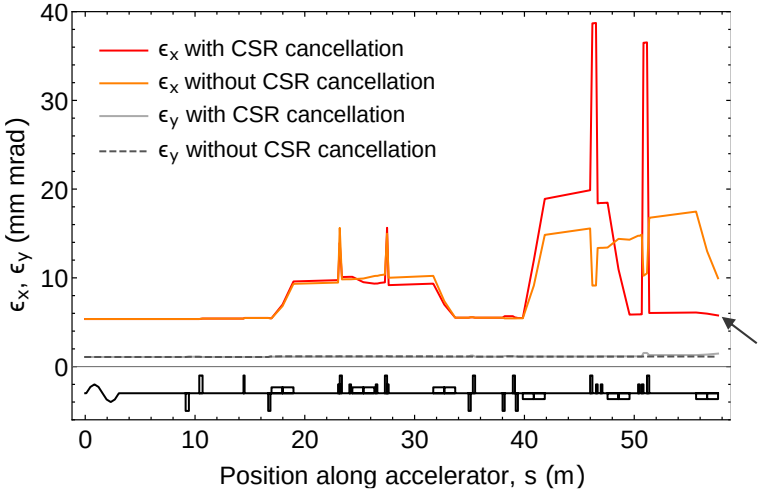
FCC week 2018, Amsterdam 1





Properties of dogleg:

R56 = 0.409 m
T566 = 0.161 m
U5666 = 0.163 m



Final $\varepsilon_{x,N}$ = 5.72 mm mrad

CSR is included in drifts, and ISR included.

Initial CSR-induced emittance growth	Emittance growth after CSR cancellation technique applied
85.8 %	6.9 %

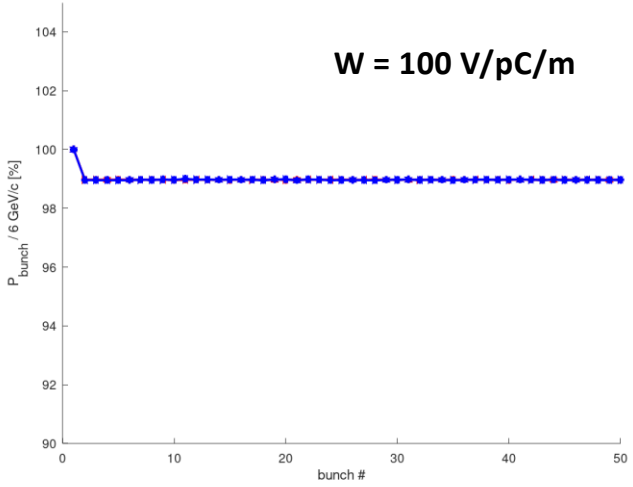
After passing through all of the dipoles, the off-momentum particles (in each slice) return to the initial trajectory. Therefore, minimizing the emittance growth.

She had to optimize a large compression factor, R56 very large, so CSR more extreme than in our case of moderate compression

Other effects to be considered

- **Beam loading**
  - Energy loss induced by the first bunch due to long range longitudinal wakefield

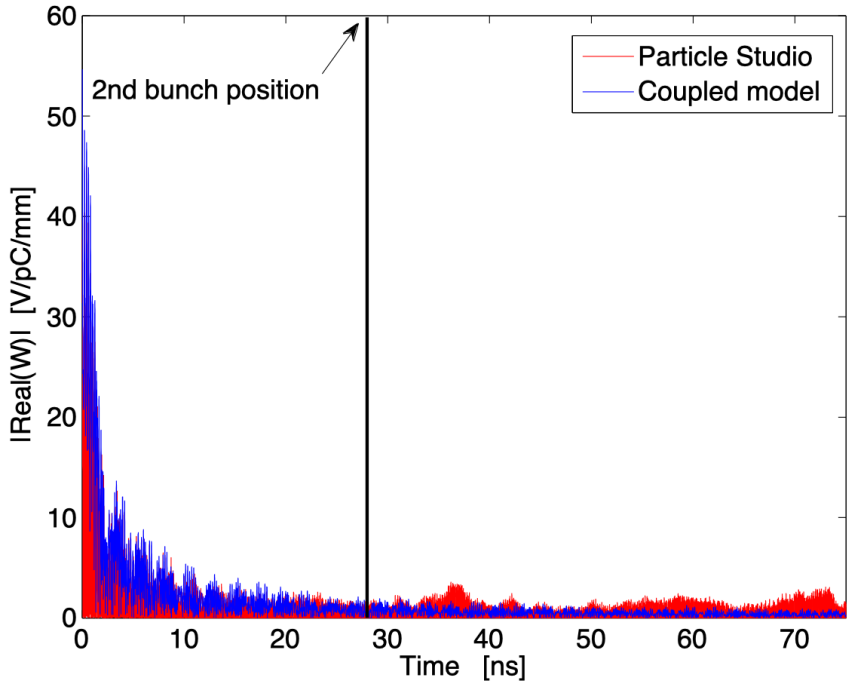
To be compensated with different energy gain for the two bunches



- **Charge jitter**
  - Energy loss induced by the first bunch due to long range longitudinal

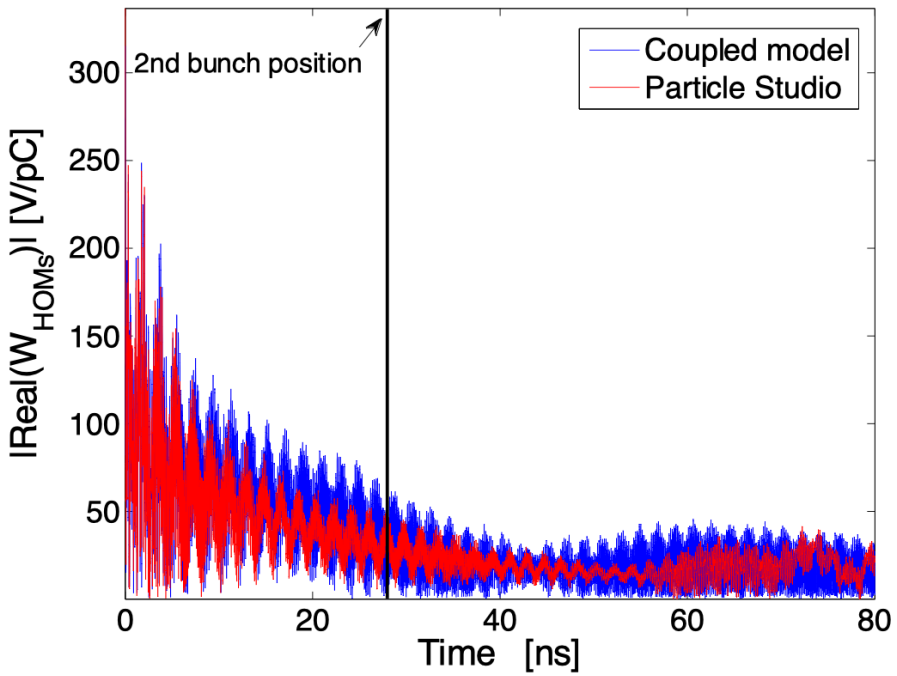
Multi-bunch effects

Example: SwissFEL C-band cavities (f = 5.712 GHz)



Long-range transverse wakefield

(Causes transverse jitter amplification)



Long-range longitudinal wakefield

(Causes multi-bunch beam loading)