Linac Beam Dynamics

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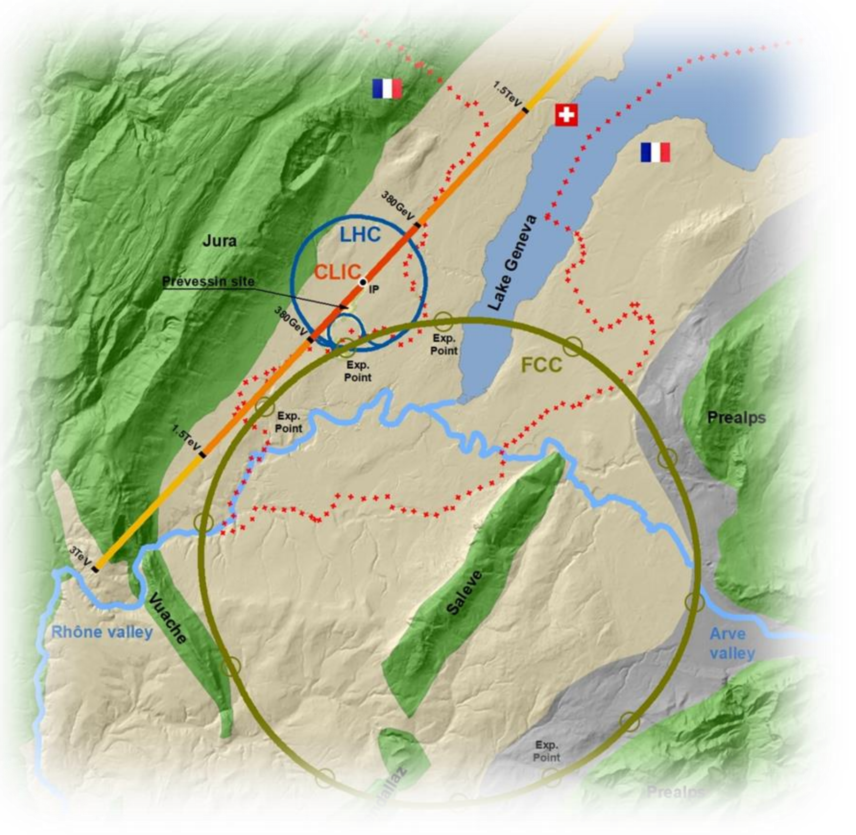
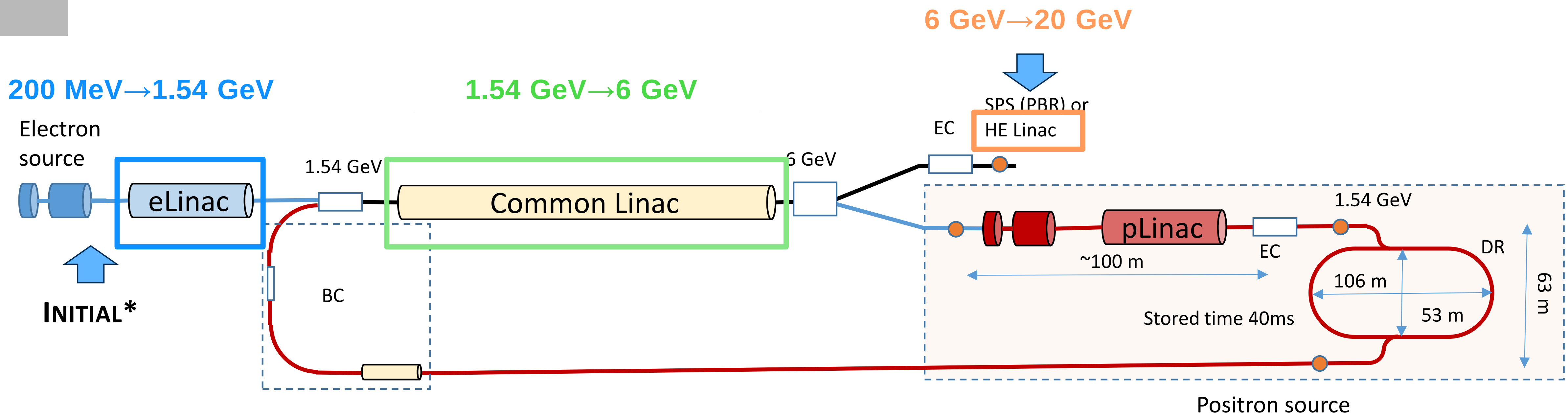
Outlook



- **Machine layout, inputs, and targets**
- **Design steps:**
  - Longitudinal: energy spread and bunch length optimizations
  - Transverse: emittance growth mitigation assuming different sources, RF geometries, and using several steering algorithms
- **Baseline design(s)**
- **Conclusions**

Layout, inputs, and acceptance



*Optimizations by T. Brezina before, Z. Vostrel now, and S. Doebert always

Layout, inputs, and acceptance

6 GeV→20 GeV

200 MeV→1.54 GeV

1.54 GeV→6 GeV

Parameter	Baseline	Alternative	Comments
Machine from 6 GeV beam energy	HE Linac	SPS (PBR)	Priority changed during the optimizations
Initial energy (MeV)	200		At the gun section exit
Linac final energy (GeV)	20	6	
Charge (nC)	5.0	5.5	4.4 nC at the collider injection (with some losses artificially included for safety margin)
Initial charge distribution	Gaussian/From tracking		
Number of bunches	2		
Bunch spacing (ns)	25		From BD Linac point of view used to define the maximum LRW
Initial transverse rms emittance (μm)	3.2		At bunch length σ_z = 1.0 mm even slightly better. At σ_z = 0.65 mm emittance ~ 5 μm Optimization by Z. Vostrel, S. Doebert
Final maximum transverse rms emittance (μm)	10		Budget 6.8 mm.mrad (static+dynamic)
Initial rms bunch length (mm)	1		From the linac(s) optimization w/o energy compressor-good for emittance
Final rms bunch length (mm)	1 → 4		Probably up to ~4 mm at the booster injection (under optimization by the booster+impedance group). We are **flexible**.
Final rms relative energy spread	0.1-0.15%		Under optimization by the booster group. We are **flexible**.

Longitudinal dynamics

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Several designs optimized

More reported at the 2022 FCC Week and 2022 ICFA workshop

Goal: bring the projected energy spread ~~below 0.1%*~~ **equal to 0.1-0.15%** at the end of the ~~common~~ **high energy** linac

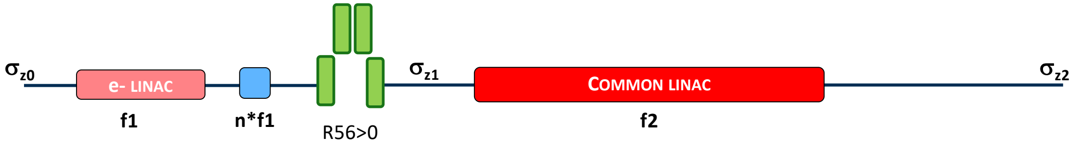
Considered scenarios:

1. Short bunch from the gun

- ✗ Fixed bunch length, and necessary bunch decompression at the end to match the final bunch length (large R_{56} if the energy chirp is small)
- ✓ Minimal hardware request
- ✓ No CSR emittance degradation

f = 2.8 GHz	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	73…74	<75…80	<80…85
Min δE/E	1e-3	5e-4	4e-4
Rms bunch length (mm)	0.8	0.4…0.65	<0.4…0.7

2. Bunch compressor at the exit of e- Linac



- ✗ More hardware necessary
- ✗ Possible emittance degradation due to CSR
- ✓ Very small values of energy spread achievable

f = 2.8 GHz	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. Shorter bunch from the gun and linearization

- ✓ Same advantages and disadvantages as 1., but a smaller value of energy spread (or equivalently longer bunch lengths) achievable
- ✓ Energy loss at the linarization

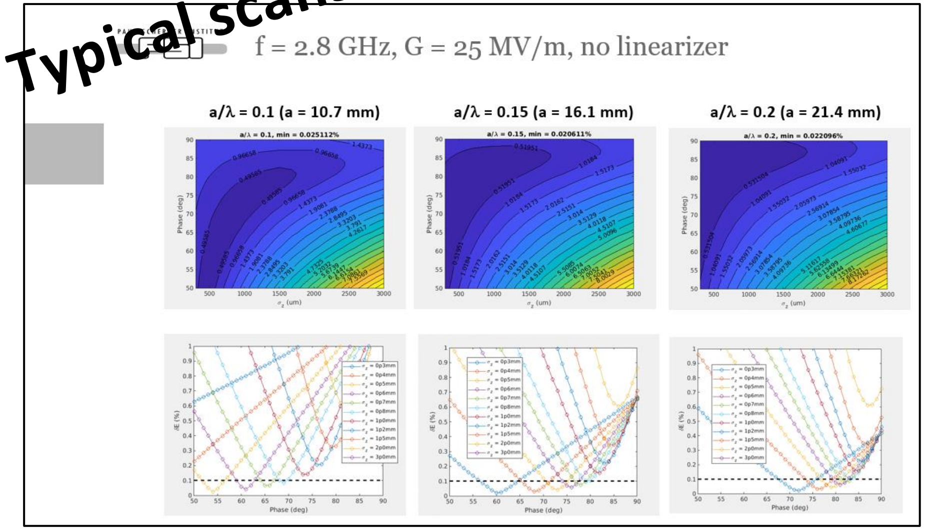
f = 2.8 GHz	a/λ = 0.10	a/λ = 0.15	a/λ = 0.20
Phase range (deg)	66…70	77…80	81…85
Min δE/E	2e-4	3e-4	3e-4
Rms bunch length (mm)	0.650		

Modular design: common linac

More reported at the 2022 FCC Week and 2022 ICFA workshop

We scan the RF frequency, gradient, and geometry (a/λ), where a is the RF iris radius to compute the relative energy spread at the end of the considered linac, and for each case the maximum bunch length and the corresponding phase giving the target energy spread are selected

Typical scans



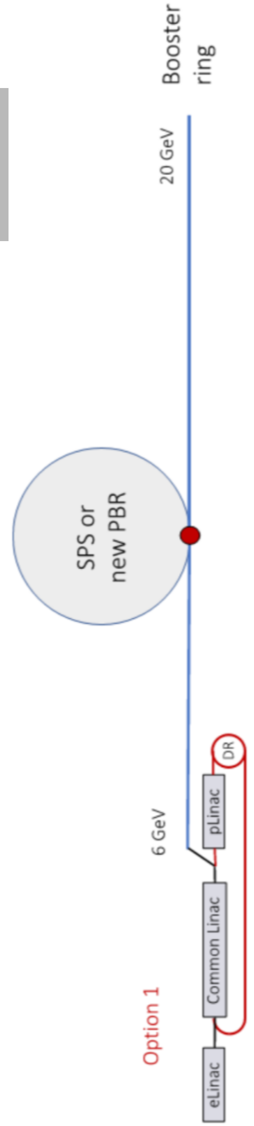
f (GHz)	G (MV/m)	a/λ	a (mm)	Maximum σ_z (mm)		Maximum phase (deg)	
				δ_E = 0.1 %	δ_E = 0.15 %	δ_E = 0.1 %	δ_E = 0.15 %
2.8**	25	0.1	10.7	0.8	1.2	69	89
2.8**	25	0.15	16.1	0.8	1	79	82
2.8**	25	0.2	21.4	0.7	0.8	82	82
2.8**	40	0.1	10.7	0.8	0.8	77	85
2.8**	40	0.15	16.1	0.7	1	82	79
2.8**	40	0.2	21.4	0.7	0.8	85	84
5.6**	25	0.1	5.4	No solution	No solution	No solution	No solution
5.6**	25	0.15	8.0	0.5	0.6	61	66
5.6**	25	0.2	10.7	0.5	0.6	74	66
5.6**	40	0.1	5.4	0.4	0.5	81	73
5.6**	40	0.15	8.0	0.5	0.5	71	72
5.6**	40	0.2	10.7	0.4	0.5	67	72
2.0*	25	0.1	15	1	1.2	78	81
2.0*	25	0.15	22.5	1	1.2	85	85
2.0*	25	0.2	30	1	1.2	84	86
2.0*	40	0.1	15	1	1.2	87	88
2.0*	40	0.15	22.5	1	1.2	86	84
2.0*	40	0.2	30	1	1.2	88	87

Possible to compose the linac(s) assuming different RF and bunch parameters

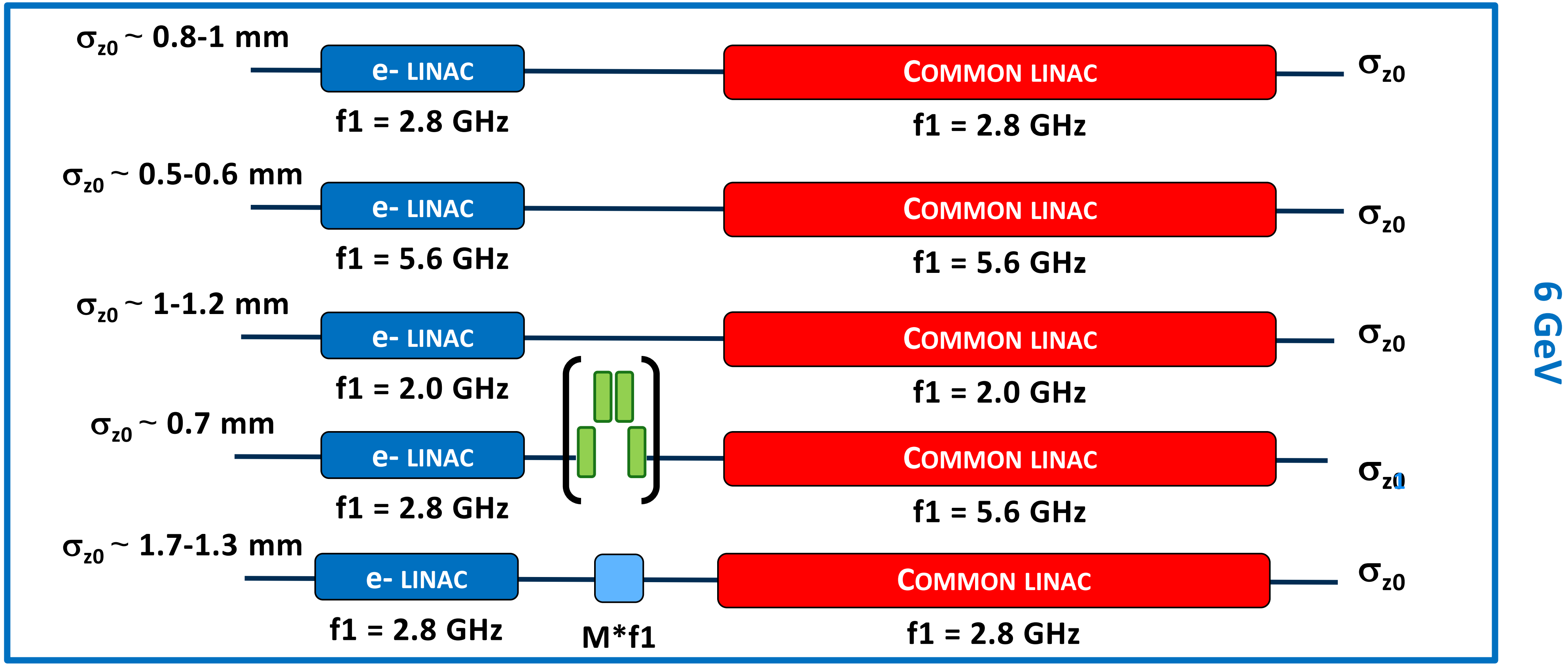
** Electron linac at 2.8 GHz
* Electron linac at 2 GHz

Most promising designs: common linac

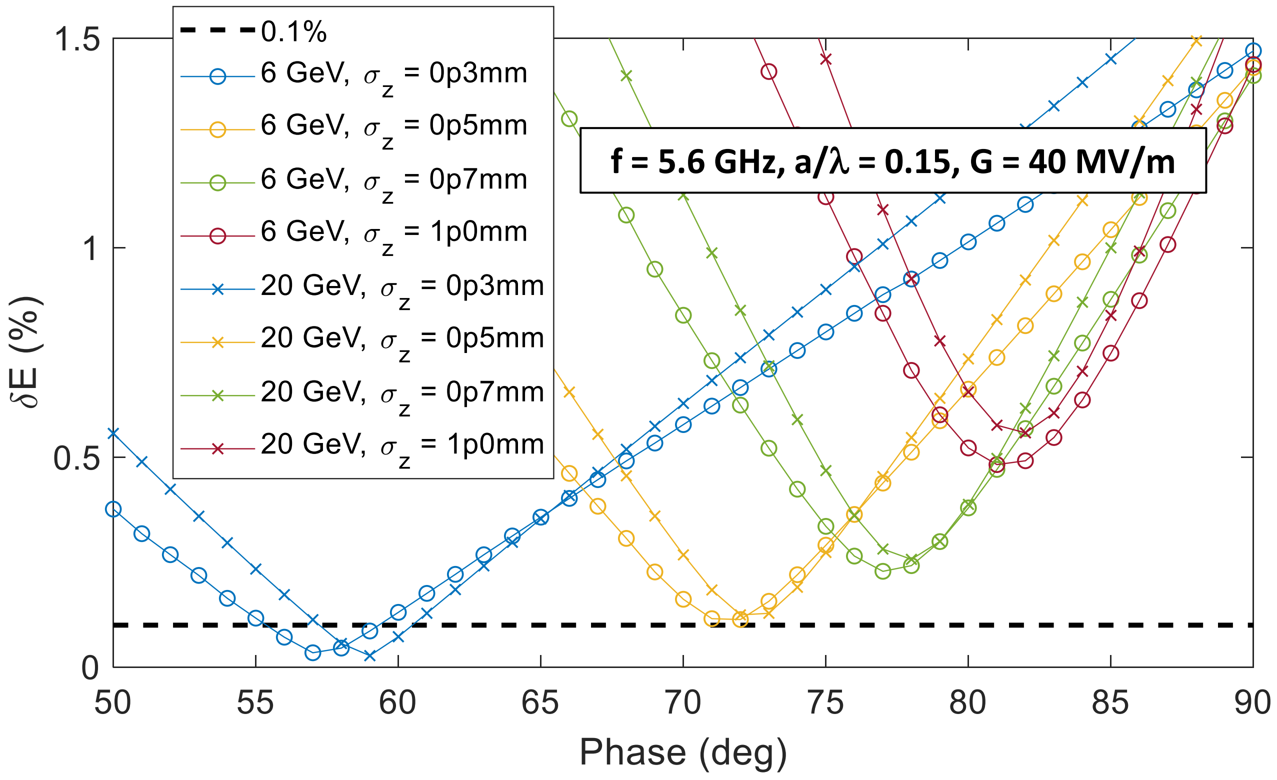
Target $\delta E/E$ = 0.1-0.15%, $\sigma_z \geq$ 1 up to few mm



f (GHz)	G (MV/m)	a/λ	a (mm)	Maximum σ_z (mm)		Maximum phase (deg)	
				δ_E = 0.1 %	δ_E = 0.15 %	δ_E = 0.1 %	δ_E = 0.15 %
2.8	25	0.15	16.1	0.8	1	79	82
5.6	25	0.2	10.7	0.5	0.6	74	66
5.6	40	0.2	10.7	0.4	0.5	67	72
2.0	25	0.1	15	1	1.2	78	81



Toward the High Energy (HE) linac (E = 6 GeV → 20 GeV)



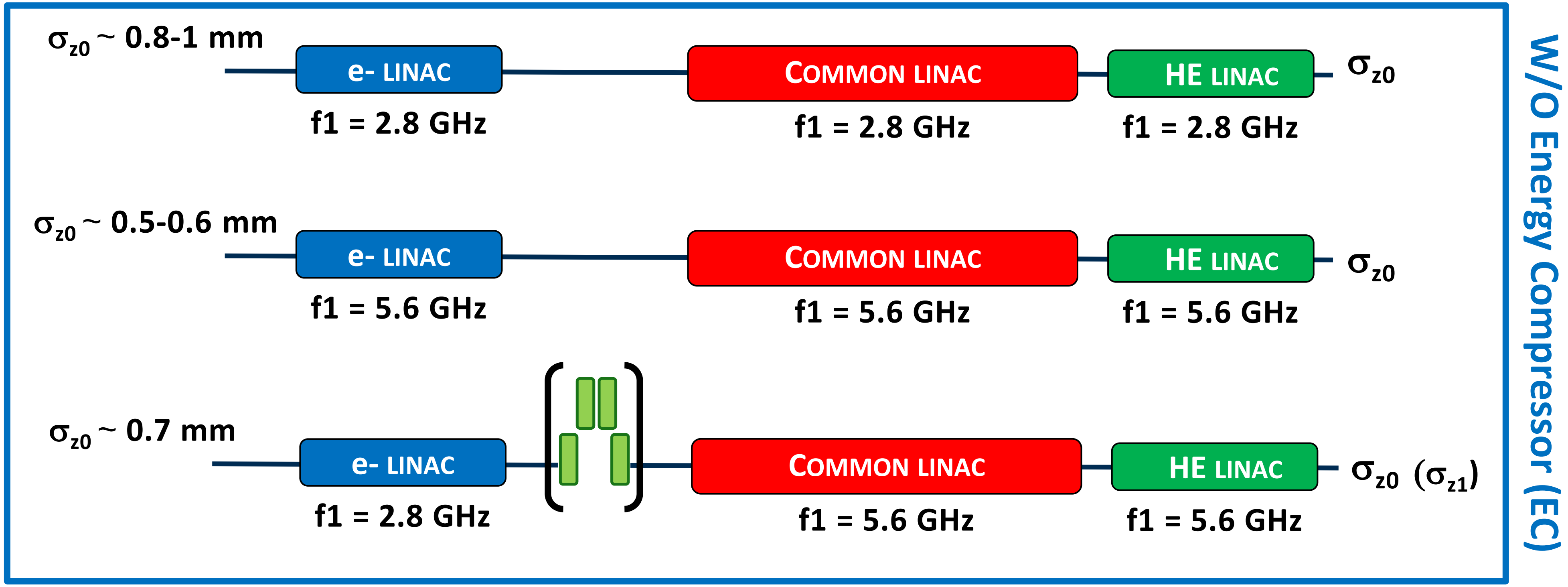
20 GeV vs 6 GeV linac:

- Minimum of the energy spread and corresponding working point (bunch length and operating phase) similar for the two cases → we can use the same table of the previous slide
- Strong impact on the linearizing cavity amplitude (in case we want to move to another scenario): alternative solutions must be considered

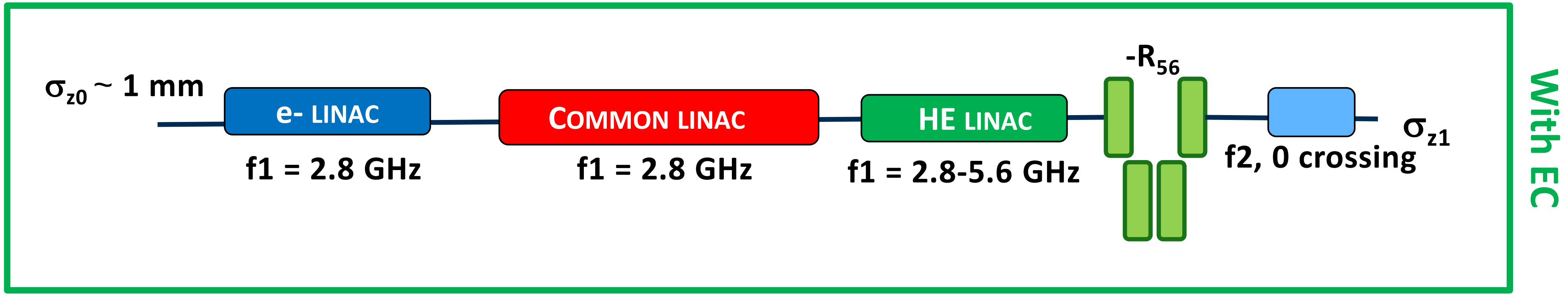
Most promising designs at 20 GeV

Target $\delta E/E$ = 0.1-0.15%, $\sigma_z \geq$ 1 up to few mm

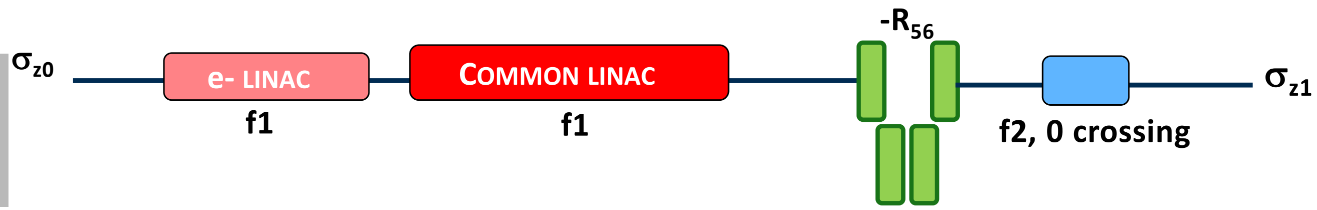
1. Reasonable optimal bunch length and energy spread obtained, good working point for emittance (relatively long pulse from the gun)
2. Bunch length at the limit to have a good emittance at the gun
3. Compressor (to keep reasonable energy spread) and decompressor (for the target bunch length) necessary also if target is ~1mm



4. Most flexible design:
- Possible and beneficial also for the injection to the SPS (6 GeV)
- High flexibility of the target bunch length (even several mm) and energy spread (separately tunable)
- Possible to use the R_{56} in the transfer line for the HE Linac

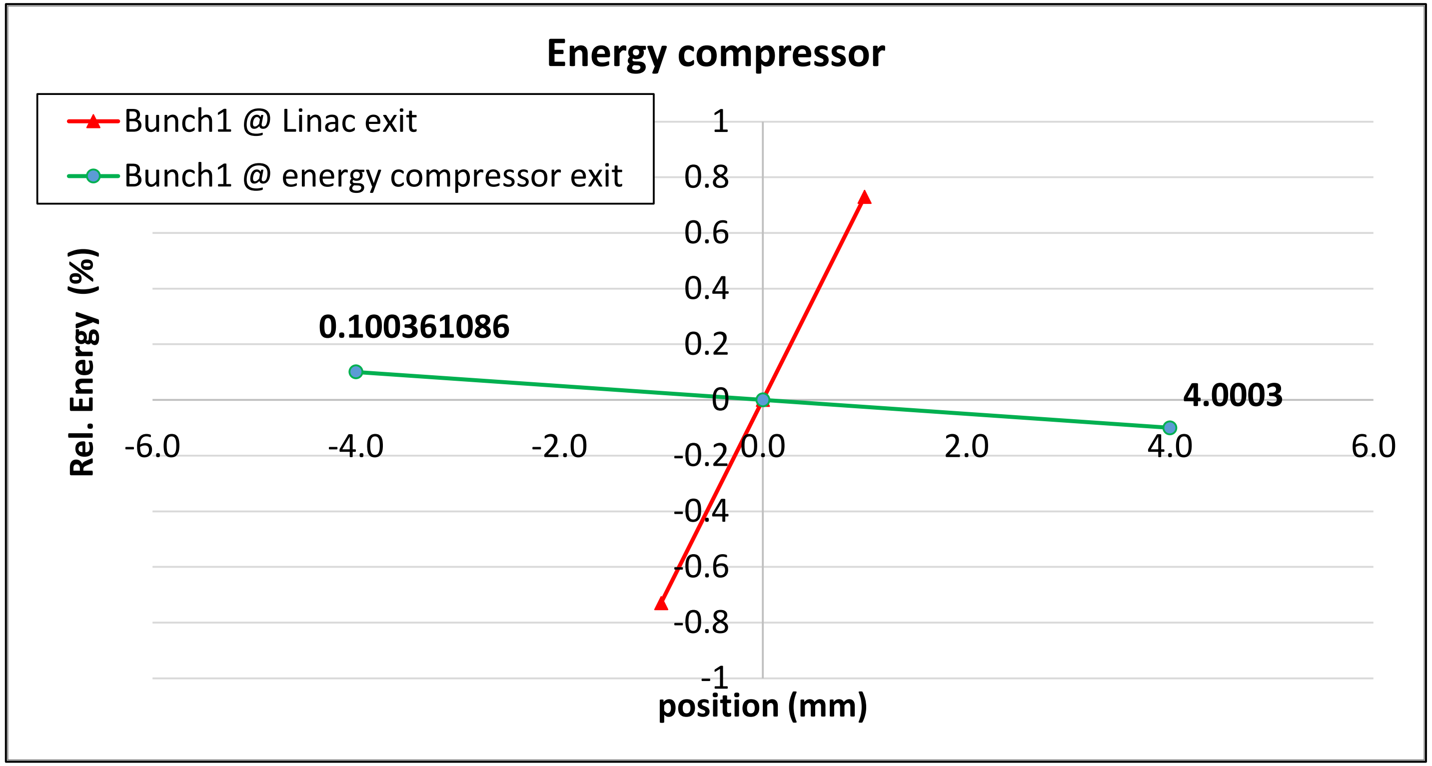


Energy compressor à la SuperKekB (a special thank to R. Zennaro)



Method:

- Chicane: energy difference → arrival time difference → phase difference
- Compensate the energy difference by applying the appropriate voltage downstream of the chicane (cavities at f2)

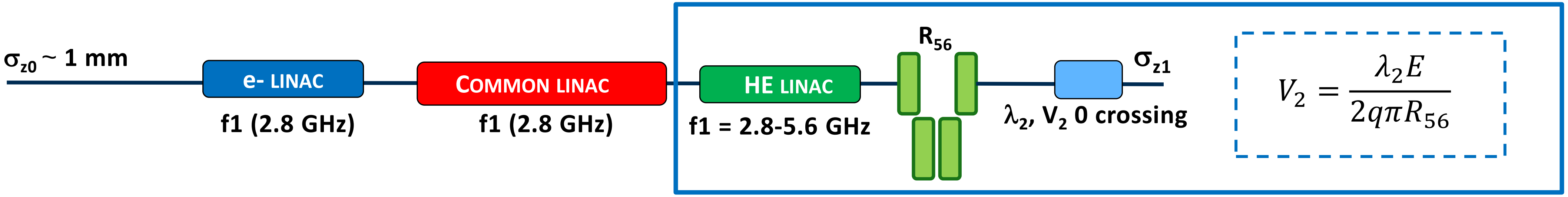


$$V_2 = \frac{\lambda_2 E}{2q\pi R_{56}}$$

Advantages:

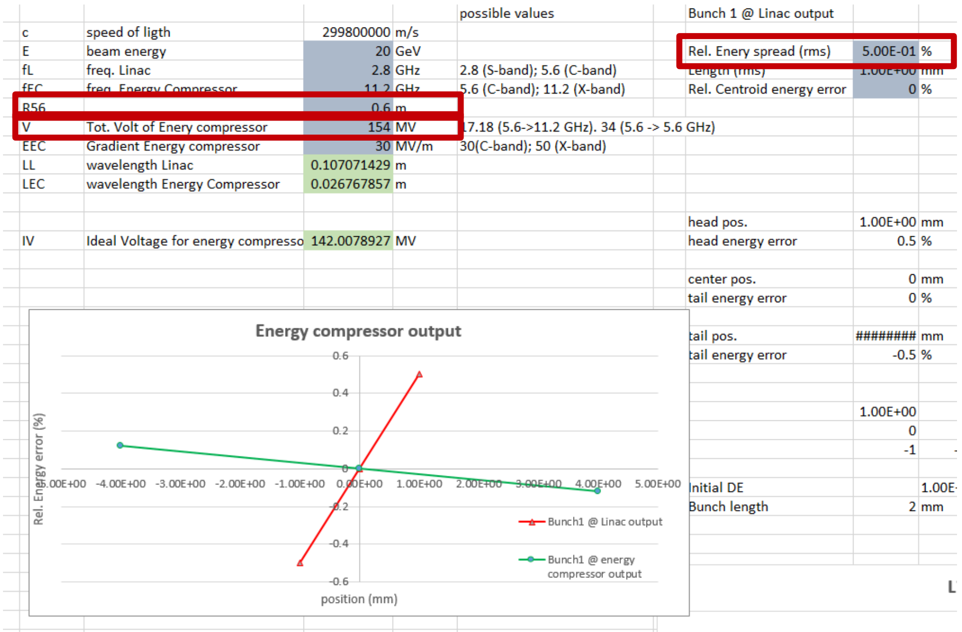
- Final energy spread and bunch length are not independent but separately adjustable
- Possible to use the R_{56} in the transfer line to the ring (transfer line group)

Optimization steps



Procedure:

1. **Chirp** determined by the upstream linacs (operating phase+beam loading at a given bunch length and charge)
2. Determine **R_{56}** to have the target bunch length
3. Given R_{56} compute the **voltage** to have the desired energy spread
4. Verify the results with **tracking** simulations. Necessary, because the energy-time distribution may be non-linear



Target values:

- Final energy spread ~0.1-0.15%. Determined the minimum achievable
- Final bunch length up to 4 mm. Less implies a smaller R_{56} and a larger RF voltage, more a larger R_{56} and a smaller RF voltage

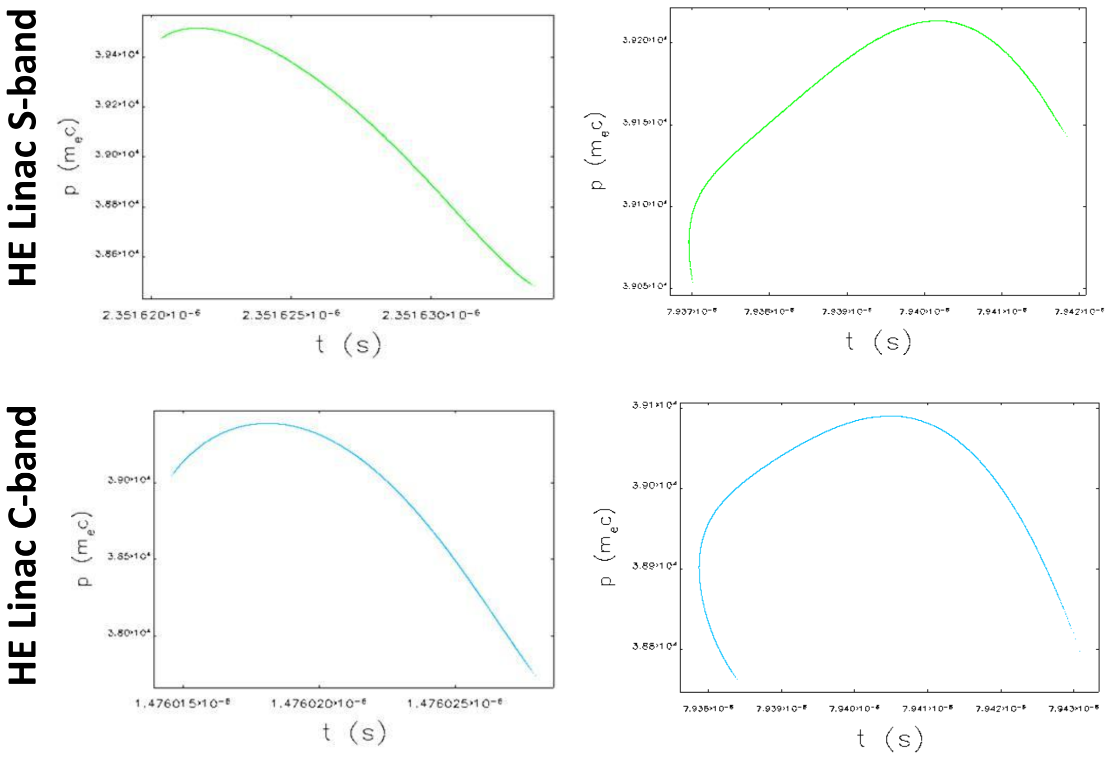
Comments:

- Different linac(s) RF structures' settings correspond to only different initial energy chirp: more R_{56} smaller voltage V_2
- For the time being simulated a four dipoles chicane. In reality the $R_{56} \neq 0$ element will be the line to the ring (transfer line WG)

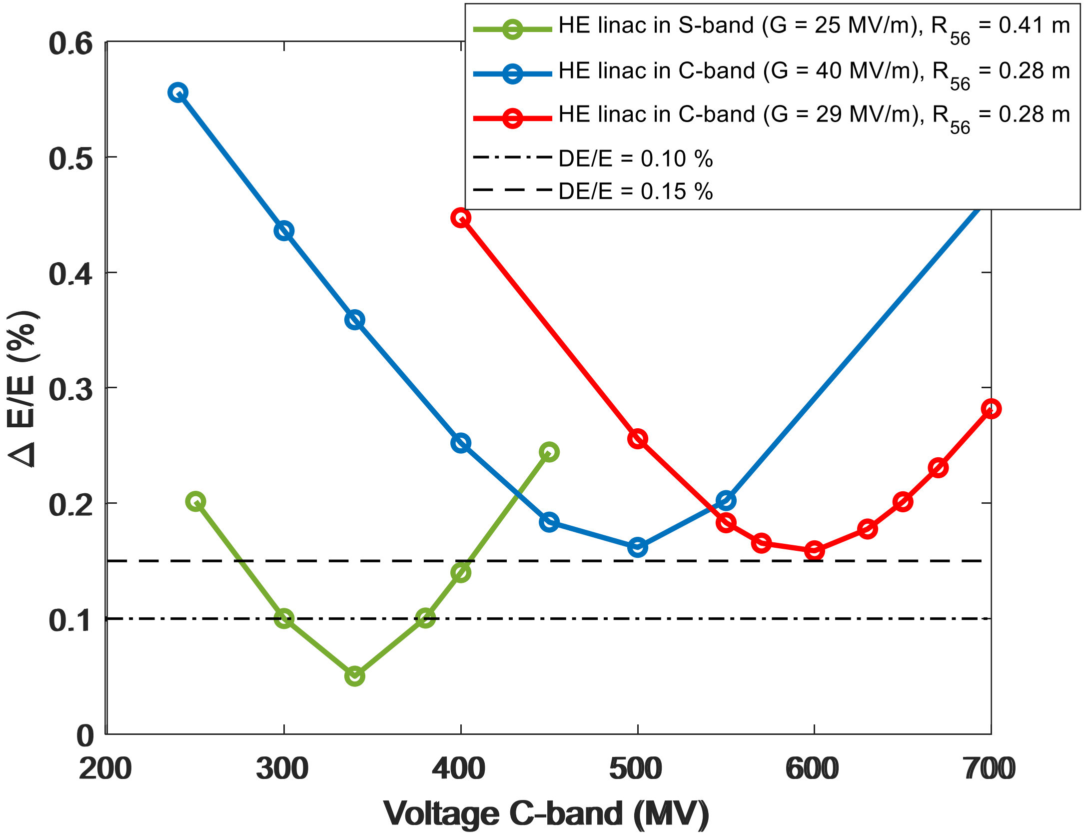
Setting Common (S-band) and HE Linac **on-crest**

$$V_2 = \frac{\lambda_2 E}{2 q \pi R_{56}}$$

At the HE Linac exit | **At the EC exit**



	HE linac S-band (G = 25 MV/m)	HE linac C-band a/λ = 0.20 (G = 40 MV/m)	HE linac C-band, a/λ = 0.19 (G = 29 MV/m)
Exit HE Linac δE/E (%)	0.74	1.1	1.3
R_{56} (m)	0.41	0.28	0.28



Assumed target bunch length = 4 mm (longer is even better for RF)

S-band HE Linac on-crest: δE/E = 0.05% achievable with 340 MV in C-band and 170 MV in X-band

C-band HE Linac on crest: minimum of δE/E limited to ~0.15% with 600 MV in C-band, 300 MV in X-band

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Energy compressor: baseline

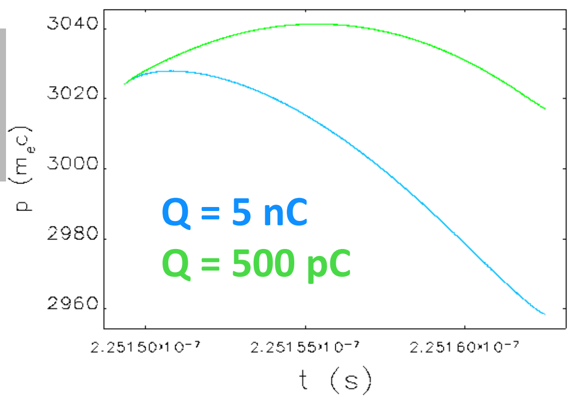
	HE Linac S-band (G = 25 MV/m, a/λ = 0.15)	HE Linac C-band (G = 29 MV/m, a/λ = 0.19)
Initial HE Linac δE/E (%)	0.74	1.2
R_{56} (m)	0.41	0.28
Voltage X δE/E = 0.15% (MV)	135	225
Voltage C δE/E = 0.15% (MV)	270	600
Voltage X minimum δE/E (MV)	170	300
Voltage C minimum δE/E (MV)	340	600
Length X-band cavities min (m)*	3.4	6
Length C-band cavities min (m)*	11.8	20.8
Minimum δE/E	5.1e-4	1.5e-3
Energy spread reduction	14	8
Initial bunch length (mm)	1	
Final bunch length (mm)	4	

- **On-crest** setting (off-crest in spare slides) better for *emittance growth* (and *RF efficiency)*, and it provides a reasonable value of the energy compressor R_{56} to reach the target bunch length
- This design provides **independent tuning** of bunch length (operating phase → chirp, R_{56} and which zero crossing→ σ_z) and energy spread (voltage V_2)

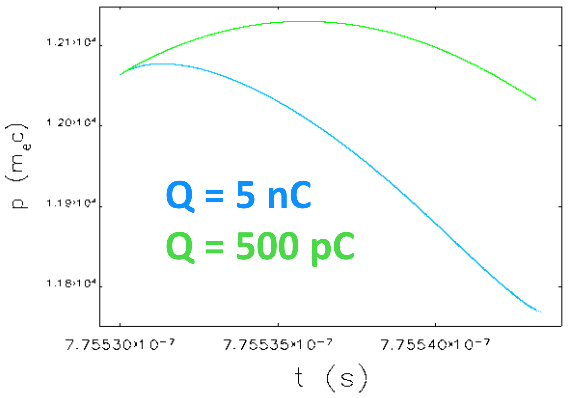
* Assuming one module/structure: C-band: 28.8 MV/m, X-band: 50 MV/m

Impact of the different bunch charges: start-to-end

e- Linac exit (1.54 GeV)

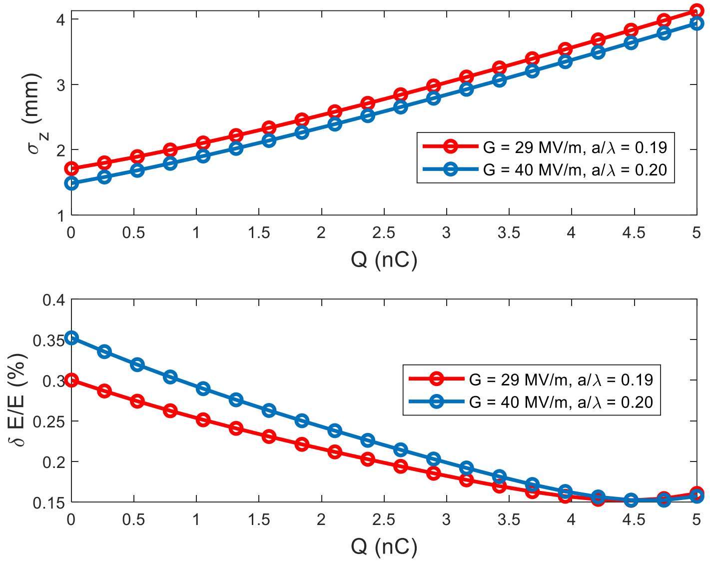


Common Linac exit (6 GeV)

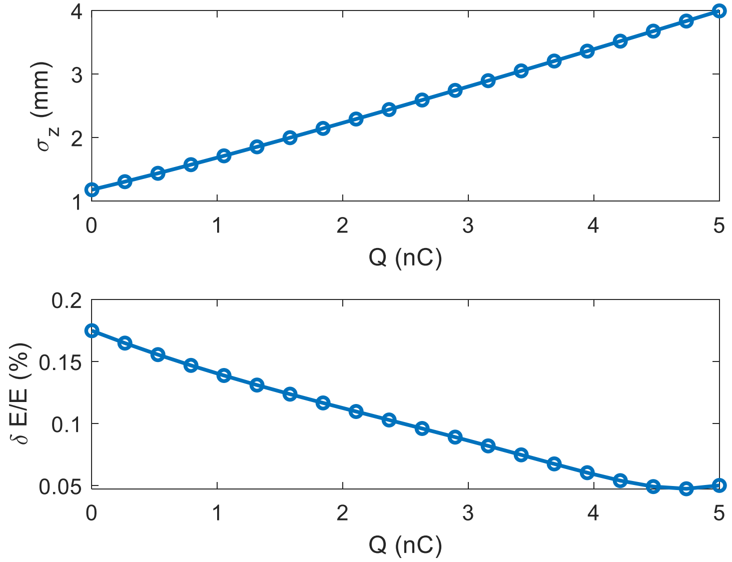


Energy spread at the exit of	Q = 5 nC	Q = 0.5 nC
Gun section (E = 200 MeV)	1.97e-3	1.97e-3
e- Linac (E = 1.54 GeV)	6.41e-3	1.74e-3
Common Linac (E = 6 GeV)	7.22e-3	1.76e-3

HE Linac C-band



HE Linac S-band



Procedure:

- Varied the beam charge from the exit of the gun section (200 MeV)
- Build a full model of the FCC Linacs up to 20 GeV
- Fiducialized the model (machine settings) on the nominal 5 nC charge
- Compared to the nominal the final bunch length and energy spread

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Transverse dynamics

Transverse dynamics

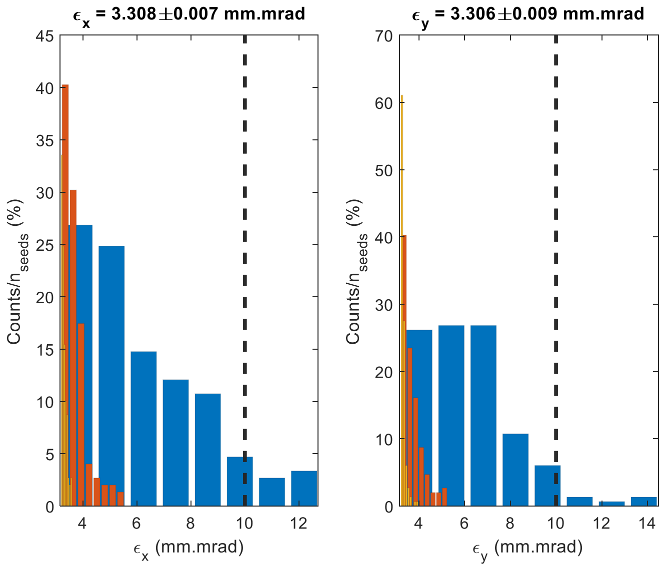
Single and multi bunch effects are dominated by long and short-range **wakefield**, elements **misalignment**, **RF** curvature, and incoming **jitter**

Beam quality degradation

- ***Sources***: off-axis orbit and/or random misalignments of several elements (RF structures and quadrupoles), and kick from one bunch to the following ones
- ***Possible cures***: trajectory correction, optimization of the RF structures design

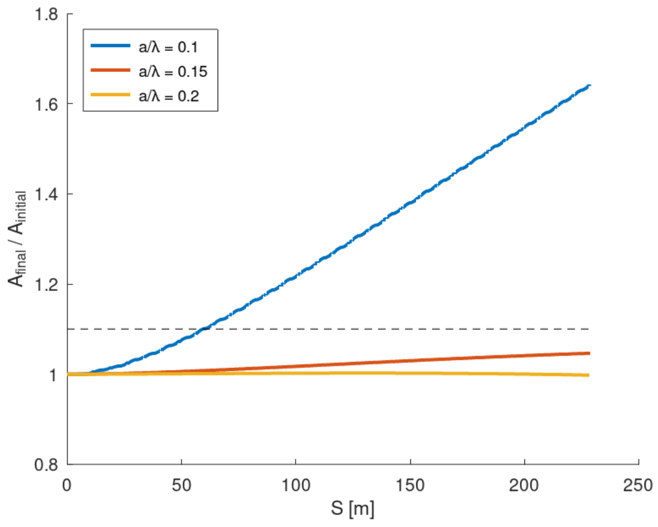
SINGLE BUNCH

Static misalignments



Distribution of the final emittance assuming certain misalignments of the elements

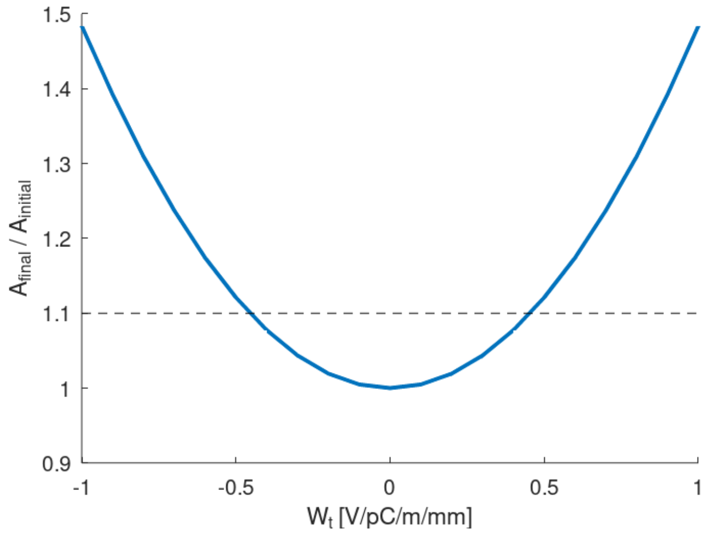
Jitters



Determination of the jitter amplification. **See 2022 FCC week talk and spares.**

MULTI-BUNCH

Long range effects

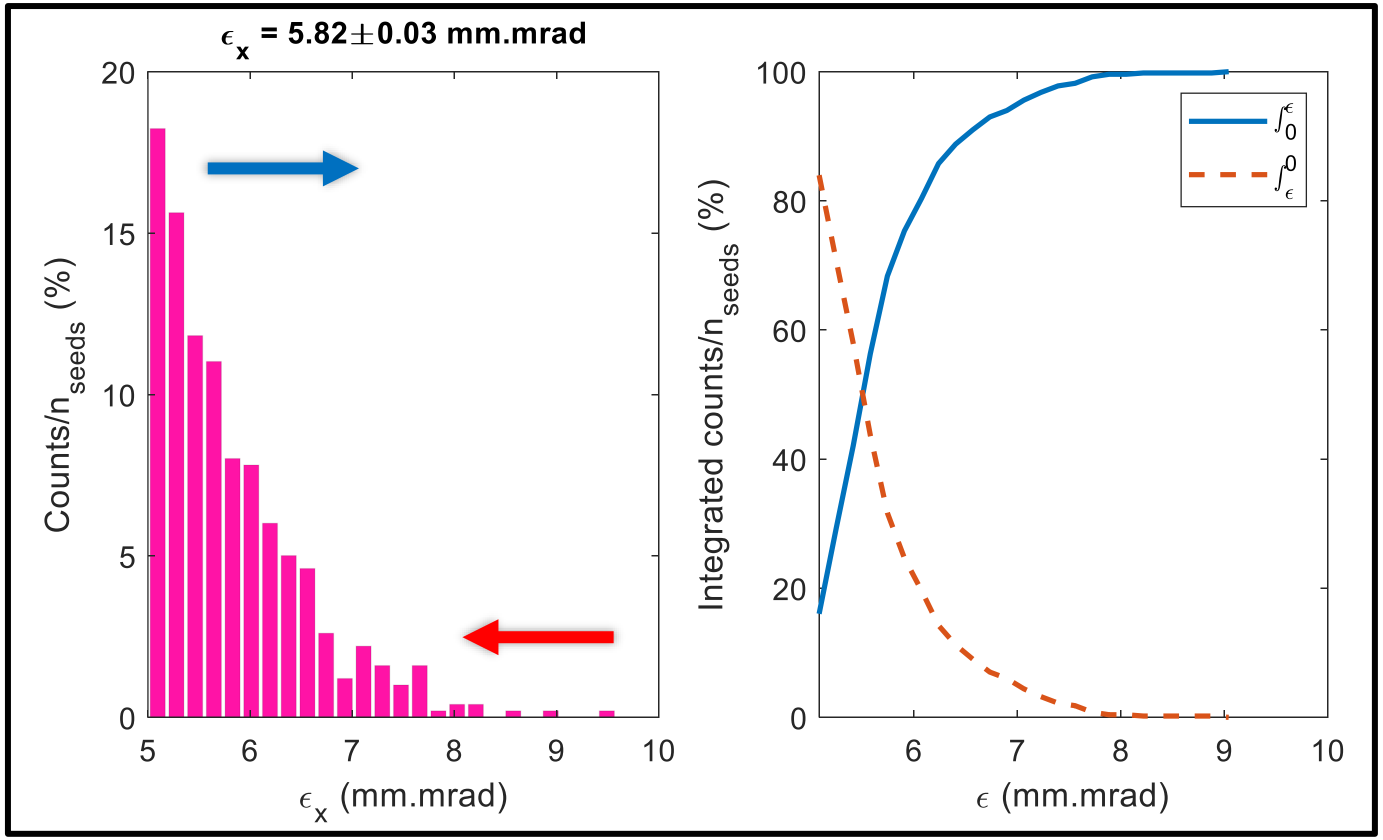


Determination of the acceptable strength of the kick. **See 2022 FCC week talk and spares.**

Way to quantify the "robustness" of the machine to misalignments

Analysis of the simulation results:

- Run N seeds (simulations) times a simulation
- Each seed gives final x and y emittance
- Shown the histogram of the emittance, its mean and std over the full set of simulations
- Sum of the normalized histogram from the smallest or the largest emittance computed



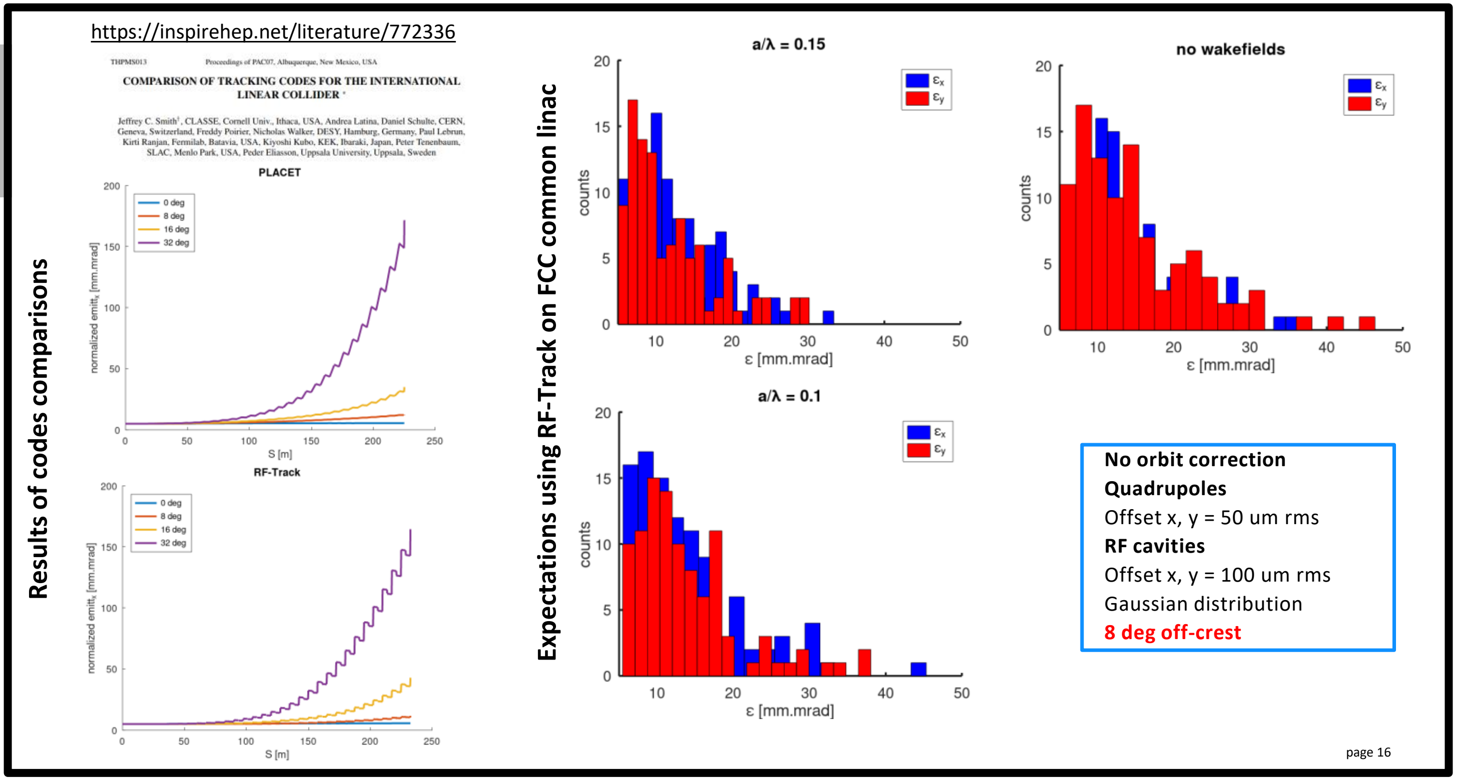
This quantifies the percentage of bad (above the threshold) or good (below the threshold) seeds relatively to the total number of trials

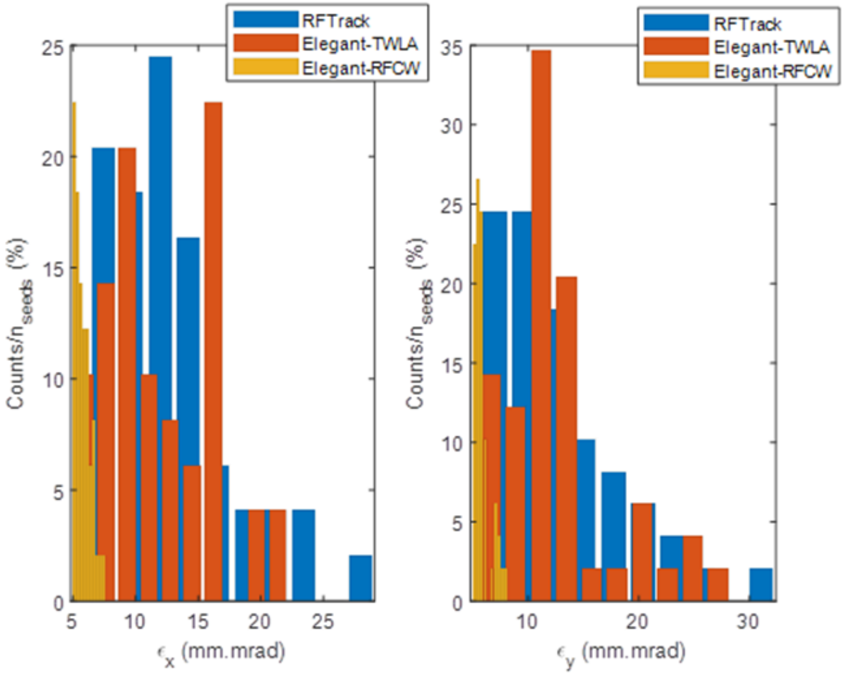
Parameters for the simulations:

- Typical values are between 200 and 1000 seeds
- The assumed initial emittance is **3.2 mm.mrad** at 5 nC with 1 mm rms laser pulse length (Z. Vostrel and S. Doebert)
- Very **pessimistic assumption** to compute the emittance growth (in CLIC for example 90% of the seeds). Here we consider ~99%

Simulation code: RF-Track vs Elegant

From the Orsay Mini-workshop presentation





Codes benchmarking

- Elegant foresaw a very small emittance increase
- Disagreement Elegant vs RF-Track
- Agreement RF-Track vs other codes, like Placet (verification by A. Latina)
- Problem pointed to M. Borland, new Elegant release in Feb 2023 to simulate the correct emittance growth in RF structure with also wakefield included

Important change in the design considerations!

Machine errors and orbit steering in RF-Track

Elements misalignments

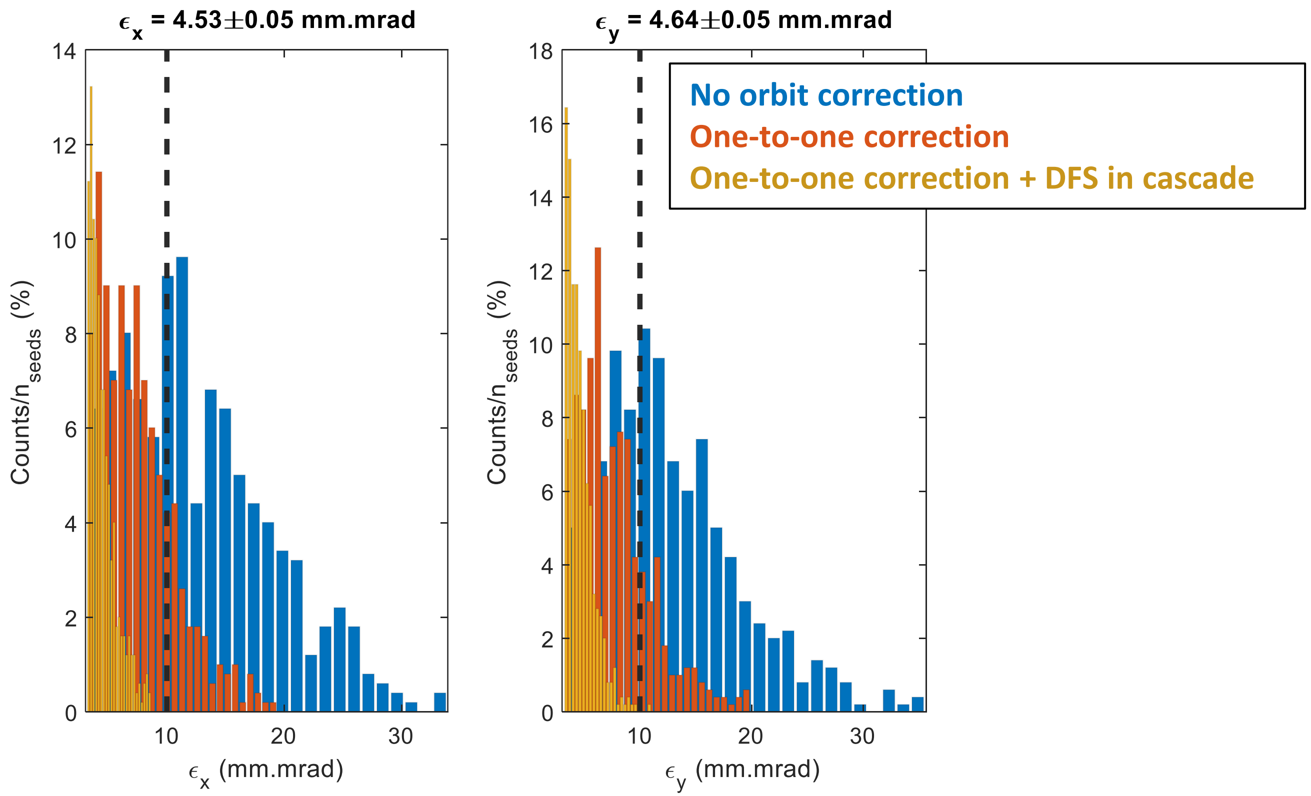
Quadrupoles	**RF cavities**	**BPM**
Offset x, y = 50 um rms	Offset x, y = 100 um rms	Offset x, y = 30 um rms
		Resolution x, y = 10 um
Gaussian distribution	Gaussian distribution	Gaussian distributions

Steering algorithms implemented in RF-Track

- **One-to-one orbit correction**
  1. Orbit x_i with errors computed
  2. Response matrix computed
  3. Correctors strengths calculated (SVD) to steer the beam

- **Dispersion Free Steering (DFS)**
  1. Orbit x_i with errors computed
  2. Response matrix computed
  3. Off-energy beam (different RF phase) orbit $x_{\Delta E,i}$ computed
  4. Response matrix computed
  5. Correctors strengths calculated, minimizing X^2 defined as:

$$\chi^2 = \sum_{\text{bpms}} x_i^2 + \omega^2 \sum_{\text{bpms}} (x_{\Delta E,i} - x_i)^2 + \beta^2 \sum_{\text{corrs}} \theta_j^2$$



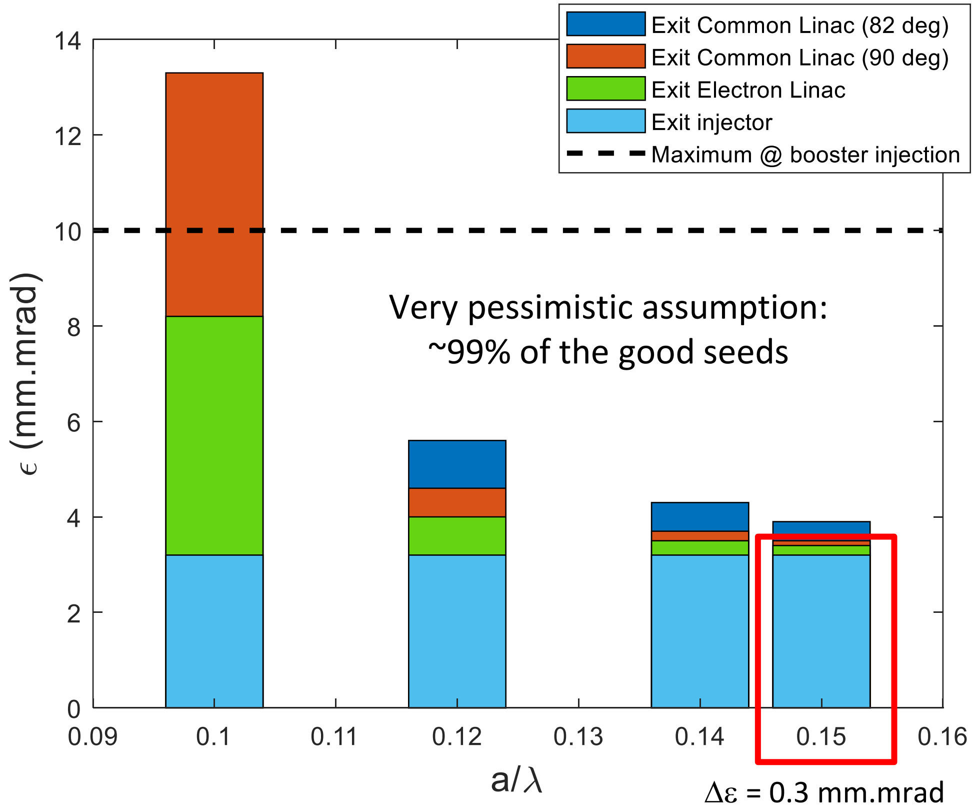
Electron + Common Linac (200 MeV → 1.54 GeV → 6 GeV)

a/λ	a (mm)	e- Linac	Common Linac (82 deg*)	Common Linac (90 deg)
0.10	10.7	5.0	/	5.1
0.12	12.9	0.8	1.6	0.6
0.13	13.9	/	/	/
0.14	15.0	0.3	0.8	0.2
0.15	**16.1**	**0.2**	0.5	**0.1**

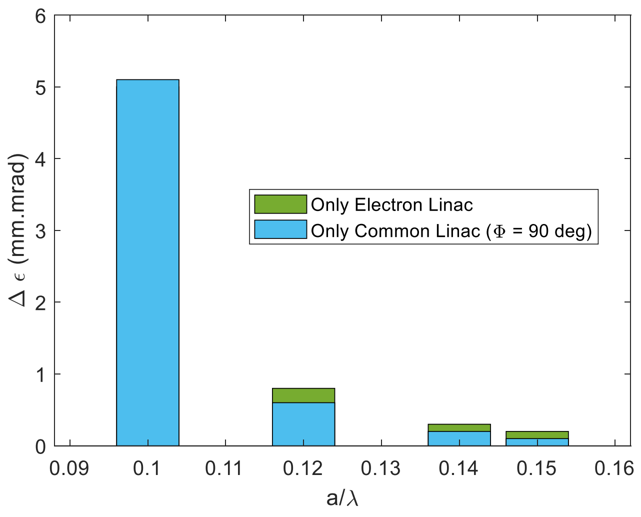
Selected
(<4 mm.mrad-injector requirement)

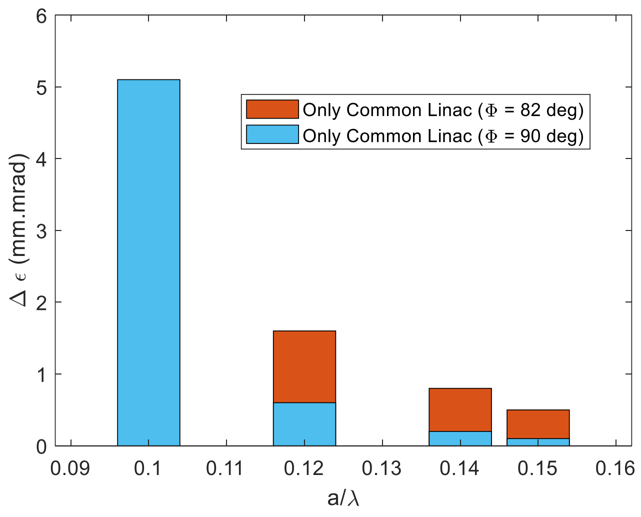
- Slightly more emittance growth in the e- Linac: shorter section, but with lower energy beam
- Improvement by a factor > 2.5 in emittance growth operating on-crest the Common Linac

Assumed initial emittance = 3.2 mm.mrad



Δε = 0.3 mm.mrad



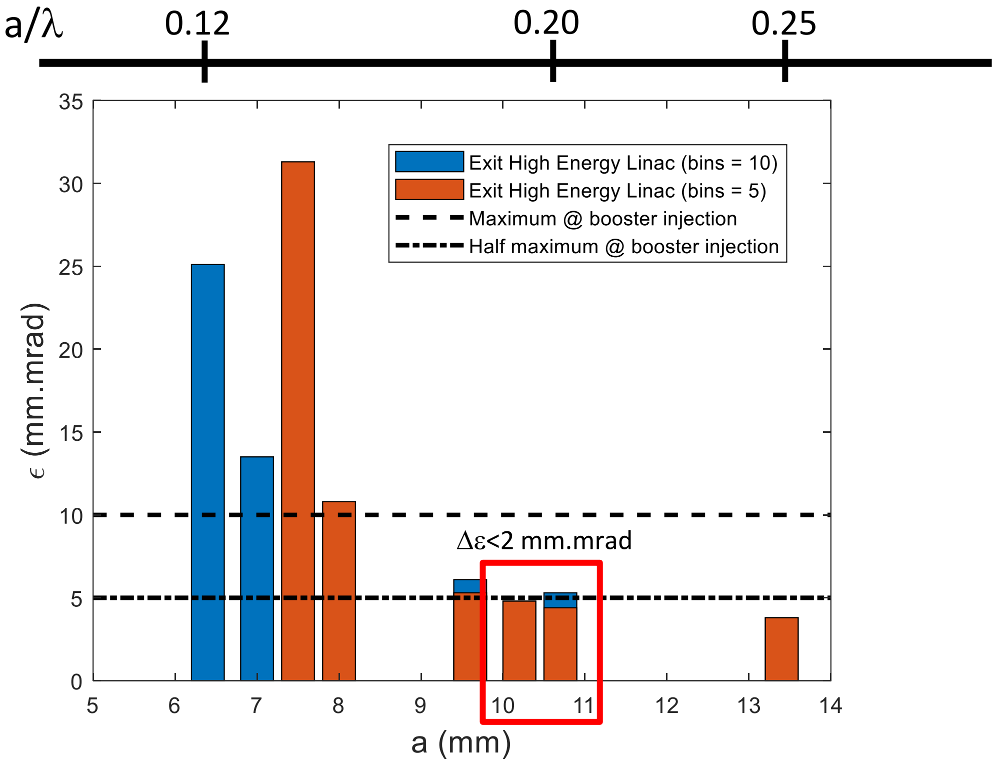


* The optimal phase for the energy spread optimization depends on a/λ, and the bunch length, and it will be revised (numbers known from modular design results), if necessary. This scan shows the sensitivity (2022 presentations).

High energy Linac, C-band and S-band, phase = 90 degrees

C-band (f = 5.6 GHz), gradient = **40 MV/m** (now 29 MV/m)

a/λ	a (mm)	Bins* = 1	Bins* = 5	Bins* = 10
0.12	6.4	/	/	21.6
0.13	7.0	/	/	10.0
0.14	7.5	/	27.8	7.7
0.15	8.0	/	7.3	5.4
0.18	9.6	/	1.8	2.6
0.19	***10.2***	***/***	***1.3***	***1.8***
0.20	**10.7**	**/**	**0.9**	**1.3**
0.25	13.4	0.8	0.3	0.3



S-band (f = 2.8 GHz), gradient = **25 MV/m** (now 29.5 MV/m)

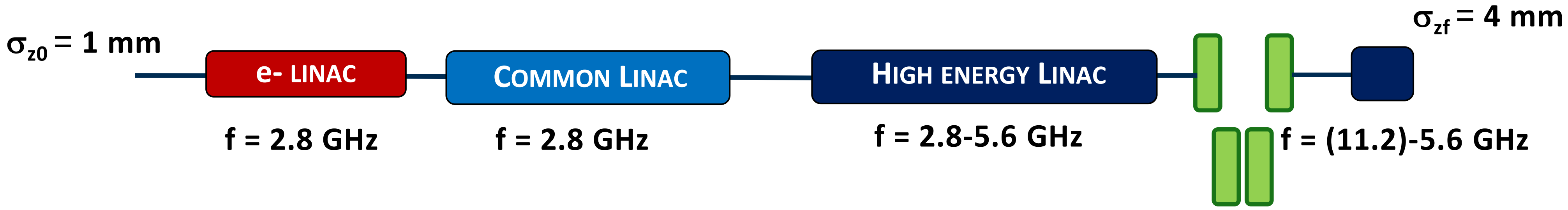
a/λ	a (mm)	Bins* = 1	Bins* = 5	Bins* = 10
0.15	**16.1**	**6.6**	**0.1**	**0.1**

These configurations provide a factor 2 margin on the emittance growth (more than safe considering the dynamic emittance growth sources) with a very pessimistic assumption of 99% of the good seeds

* Bins correspond to the number of sections the Linac is split in (more in the spare slides)

Baseline design

	e- Linac	Common Linac	HE Linac (C-band)	HE Linac (S-band)
a/λ	0.15	0.15	0.19/0.20	0.15
a (mm)	16.1	16.1	10.2/10.7	16.1 (still margin to shrink a)
f (GHz)	2.8	2.8	5.6	2.8
L (m)	3			

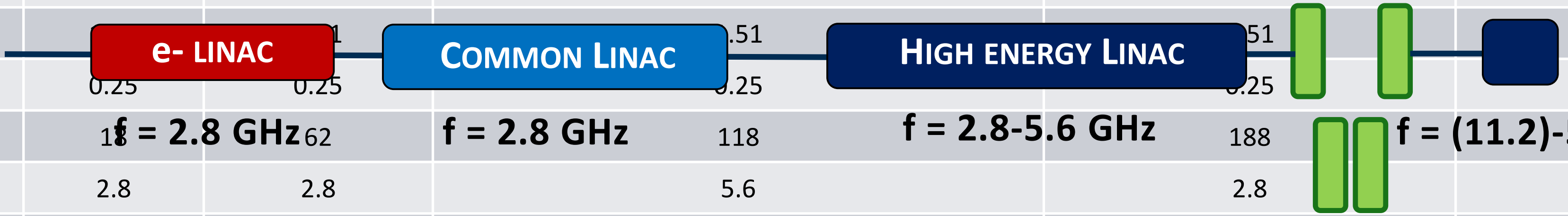


- These designs satisfy the requests on the emittance growth with about a factor 2 margin (giving margin for the dynamic effects)
- The presently considered gradient of the **S-band** is now larger than that simulated (better for emittance growth, worse for energy compressor-but margin there)
- The presently considered gradient of the **C-band** is now smaller than that simulated (worse for the emittance growth, better for the energy compressor)

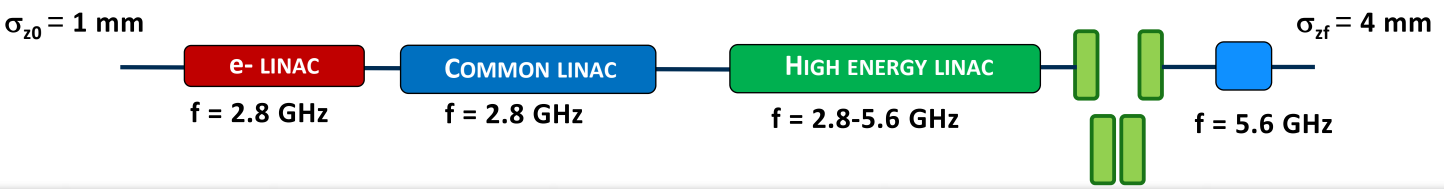
Now that a ***possible baseline design*** is defined, a study of the gradient vs aperture will determine the ***best design***

From 200 MeV to 20 GeV Linacs BD layouts

	e- Linac	Common Linac	HE Linac (C-band)	HE Linac (S-band)-margin	Energy compressor (HE Linac C-band)
δE/E initial	1.97e-03	6.46e-03	7.22e-03	7.22e-03	7.50e-03
δE/E final	6.46e-03	7.22e-03	7.50e-03 (a/λ = 0.25), 1.03e-2 (a/λ = 0.20)	7.40e-03	Minimum 5.10e-4
E initial	205.45 MeV	1.536 GeV	6.12 GeV	6.12 GeV	20.0215 GeV
E final	1.536 GeV	6.12 GeV	20.0215 GeV (a/λ = 0.25), 19.934 GeV (a/λ = 0.20)	20.015 GeV	20.0215 GeV
Initial bunch length (m)	9.82e-04	9.82e-04	9.82e-04	9.82e-04	9.82e-04
Final bunch length (m)	9.82e-04	9.82e-04	9.82e-04	4.00e-3	4.00e-03
N. BPM	18	62	118	188	Transfer line WG
N. Quadrupoles	18	62	118	188	Transfer line WG
K1 ($1/m^2$) = 1/(B*rho)*G	[illegible]	[illegible]1	[illegible].51	[illegible]51	Transfer line WG
Length quads (m)	0.25	0.25	[illegible].25	[illegible].25	Transfer line WG
N. structures	18	62	118	188	3
Frequency (GHz)	2.8	2.8	5.6	2.8	5.6 GHz
Gradient (MV/m)	25	25	40	25	40
a (mm) (a/l)	16.1 (0.15)	16.1 (0.15)	10.7 (0.2)	16.1 (0.15)	10.7 (0.2)
Length structures (m)	3	3	3	3	3
Phase (deg)	90	90	90	90	0
N. correctors	18	62	118	188	Transfer line WG
Max. strength correctors	<< 20 T.mm	<< 20 T.mm	< 20 T.mm	< 20 T.mm	Transfer line WG
Total length (m)	**67.5**	**232.5**	**442.5**	**705.0**	**Transfer line WG (for RF ≤ 20 m necessary)**



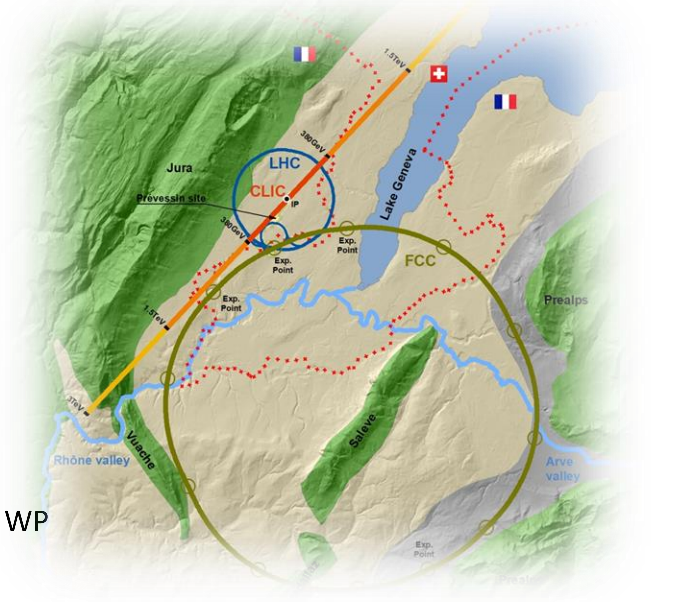
From 200 MeV to 20 GeV Linacs baseline layouts: machine



	e- Linac	Common Linac	HE Linac (C-band)	HE Linac (S-band)	Energy compressor (HE Linac C-band)
E initial	205.45 MeV	1.54 GeV	1.54 GeV	1.54 GeV	20 GeV
E final	1.54 GeV	6 GeV	20 GeV	20 GeV	20 GeV
Initial bunch length (m)	9.82e-04	9.82e-04	9.82e-04	9.82e-04	9.82e-04
Final bunch length (m)	9.82e-04	9.82e-04	9.82e-04	4.00e-3	4.00e-03
N. BPM, quad., correctors	18	70	176	164	Transfer line WG
Max G quadrupole (T/m)	5.1	20	100 (72)	100 (72)	Transfer line WG
Length quads (m)	0.25	0.25	0.25 (0.35)	0.25 (0.35)	Transfer line WG
N. Structures	18	70	176	168	3
Frequency (GHz)	2.8	2.8	5.6	2.8	5.6 GHz
Gradient (MV/m)	29.5	23.4	28.8	29.5	40
a (mm) (a/λ)	16.1 (0.15)	16.1 (0.15)	10.2/10.7 (0.19/0.20)	16.1 (0.15)	10.2/10.7 (0.19/0.20)
Length structures (m)	3	3	3	3	3
Operating phase (deg)	90	90	90	90	0
Max. strength correctors	<< 20 T.mm	<< 20 T.mm	< 20 T.mm	< 20 T.mm	Transfer line WG
Total length* (m)	**67.5**	**262.5**	**660**	**615**	**Transfer line WG (for RF ≤ 15 m necessary)**

Calculations done assuming the beam loading from the tracking simulations.
Number of structures/module computed by Jean-Yves Raguin and A. Grudiev. For more details see presentation by A. Grudiev at this week meeting.
*Including hot spares

Conclusions



Longitudinal dynamics:

- Design without energy compressor:
  - σ_z~1 mm or slightly more, $\delta E/E$~0.1-0.15% feasible
  - Decompressor necessary to match the target bunch length at the booster injection
- Design with energy compressor:
  - On-crest (preferred, but off-crest possible): better for (energy efficiency) and emittance growth
  - **S-band** High Energy Linac: several mm bunch length and energy spread ≤0.05% feasible
  - **C-band** High Energy Linac: several mm bunch length and energy spread ≤0.15% in the present design feasible
  - Impact of different charge for the 0-100% *charge scan* determined
  - *Flexible* design to eventually accommodate different specifications coming from the booster and the transfer line WP

Transverse dynamics:

- Emittance increase due to *static misalignments* of accelerator components is under control including a factor 2 margin for the selected geometry (several steering algorithms implemented in RF-Track)
- Comparison of the obtained results using several *tracking codes*: after this work now the codes agree

Ongoing: study of the impact on the beam of:

- Linacs' number of module/structure in WP1
- Optimization of the RF structure design in WP1

***Optimized* design(s) of the Linacs from 200 MeV to 20 GeV beam energy fulfilling the present booster requests**

Next steps will be to refine the *best* design, given the booster/SPS targets and transfer line tuning range

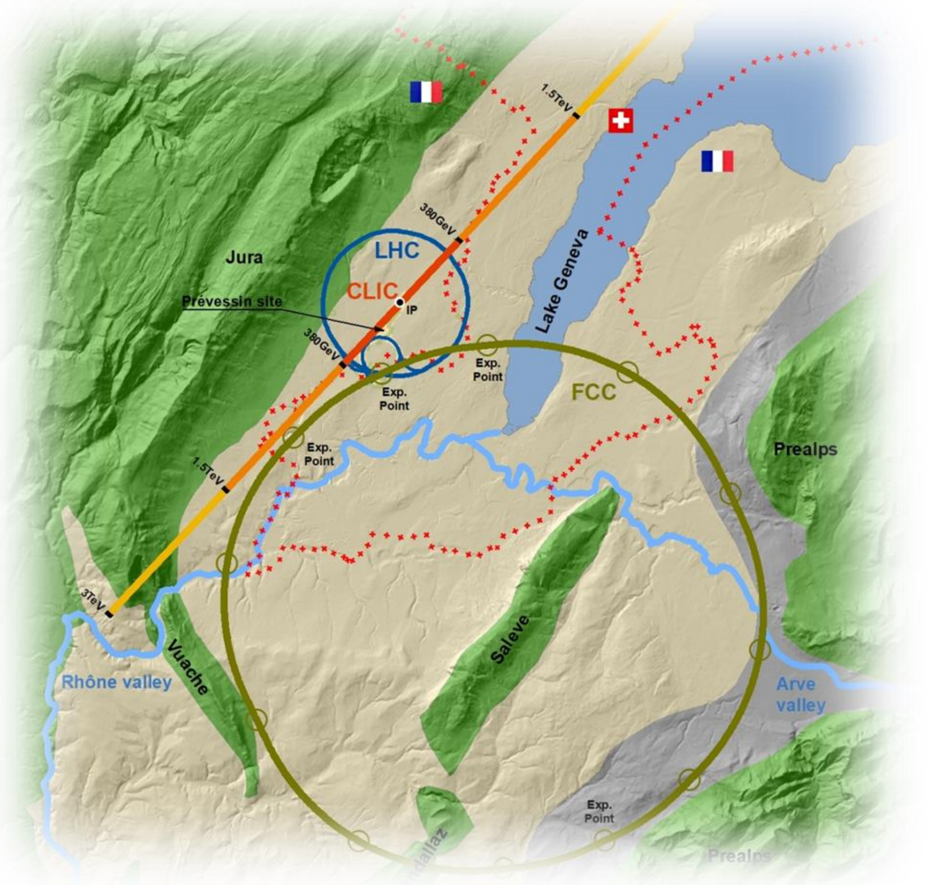
Acknowledgments…

…to the entire WP1, W. Bartmann,

M. Borland, A. Chance,

B. Dalena, Z. Geng, M. Migliorati, …

…CHART* and you for your attention



*This work was done under the auspices of CHART (Swiss Accelerator Research and Technology) Collaboration, https://chart.ch
CHART Scientific Report 2022: https://chart.ch/reports/

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.'

Conclusions

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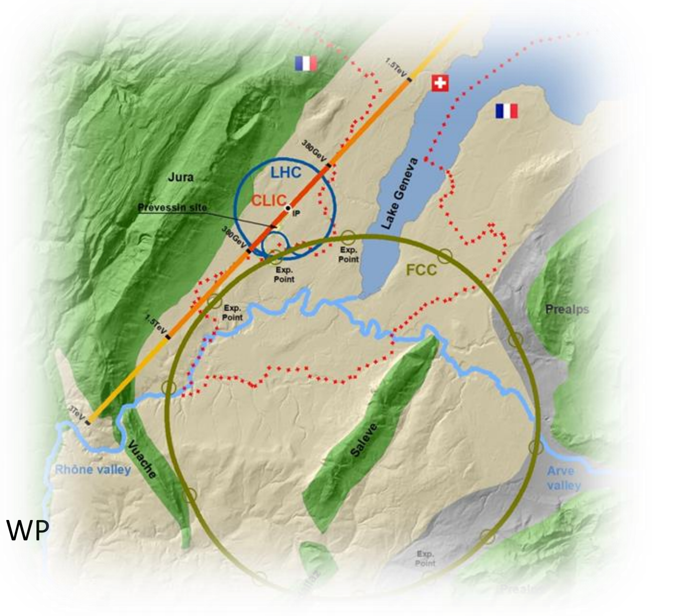

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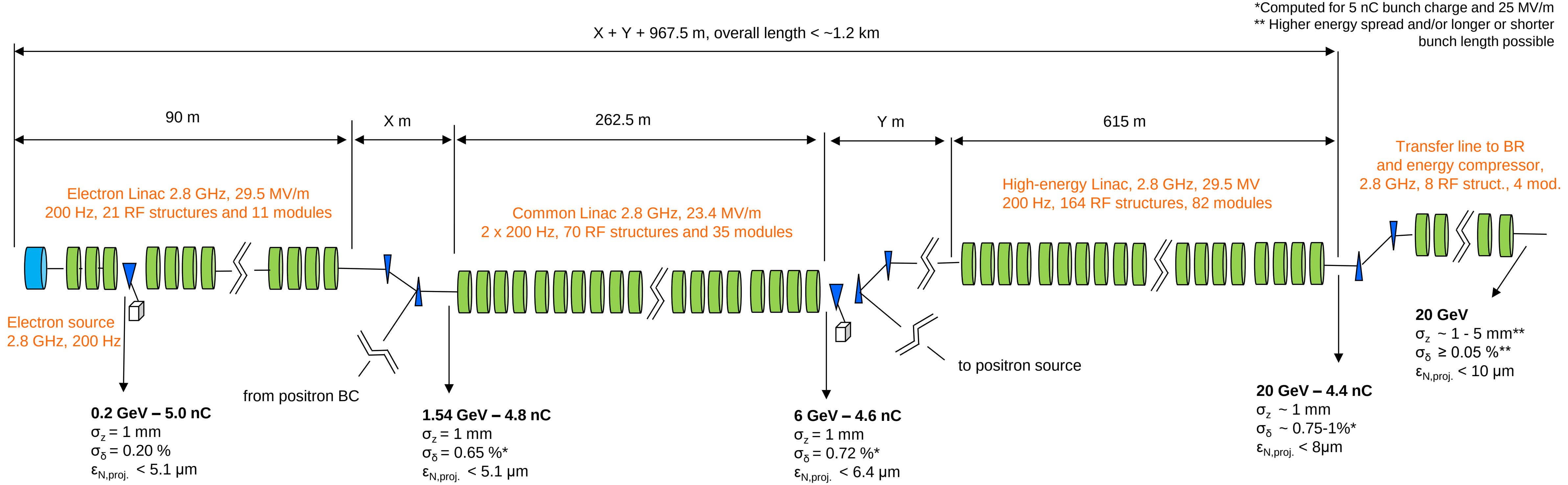
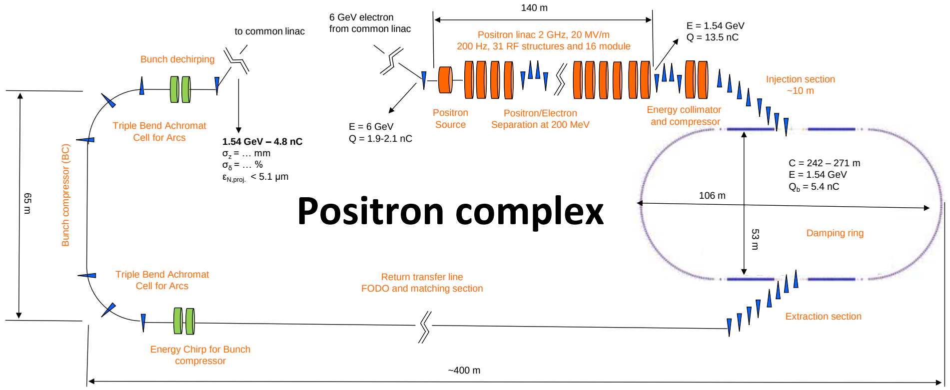
Present baseline layout





Layout scheme by P. Craievich, A. Grudiev. See P. Craievich presentation at this week meeting

SPARES

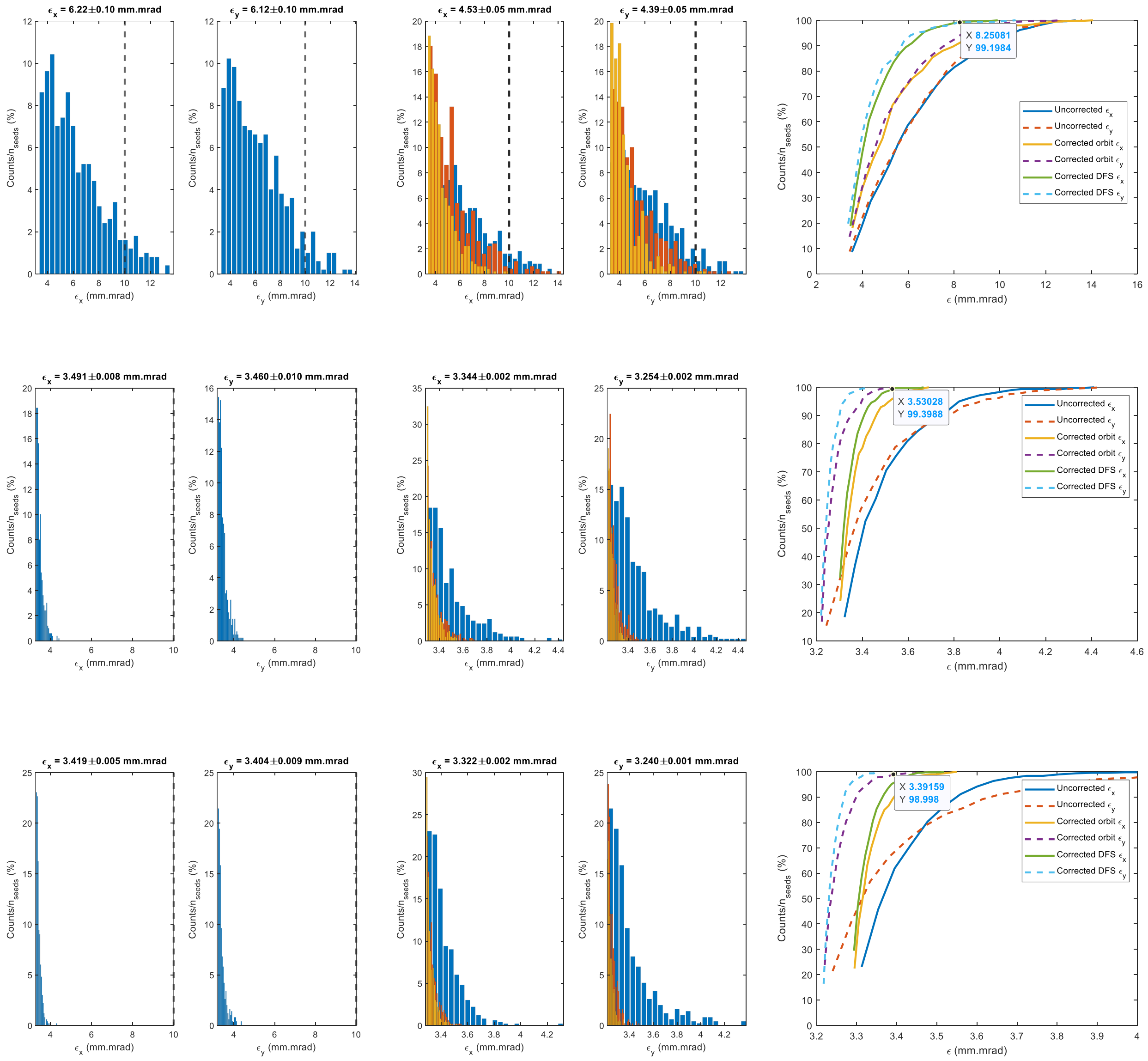
Transverse extra

Electron linac (0.2 GeV -> 1.54 GeV)

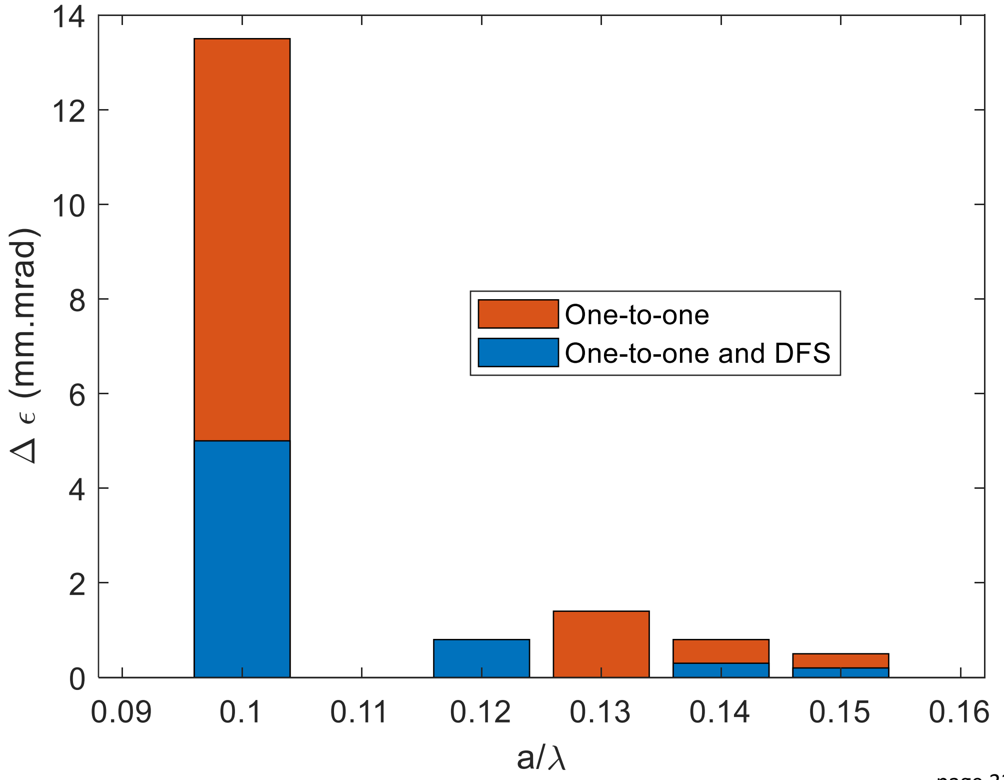
a/λ = 0.10

a/λ = 0.14

a/λ = 0.15

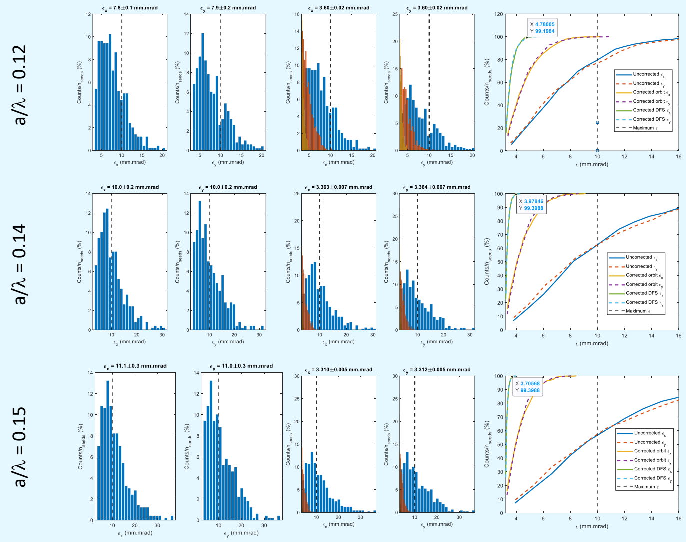


	One-to-one	One-to-one+DFS
a/λ = 0.10	13.5	5.0
a/λ = 0.12	/	0.8
a/λ = 0.13	1.4	/
a/λ = 0.14	0.8	0.3
a/λ = 0.15	0.5	0.2



Very pessimistic assumption: ~99% of the good seeds

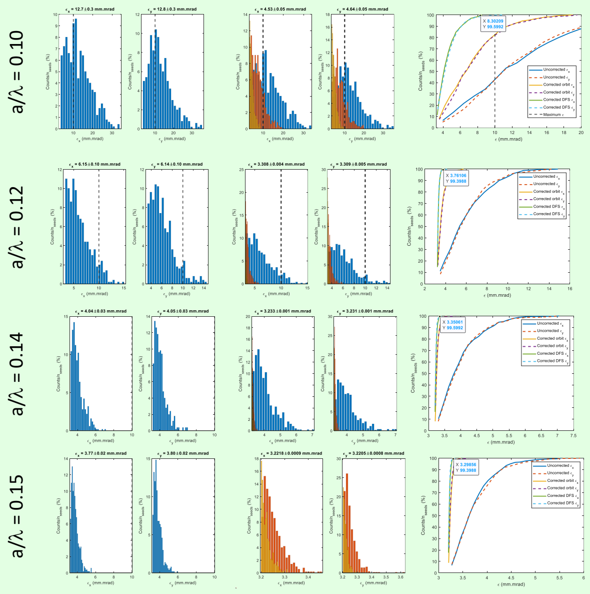
Common linac (1.54 GeV -> 6 GeV)

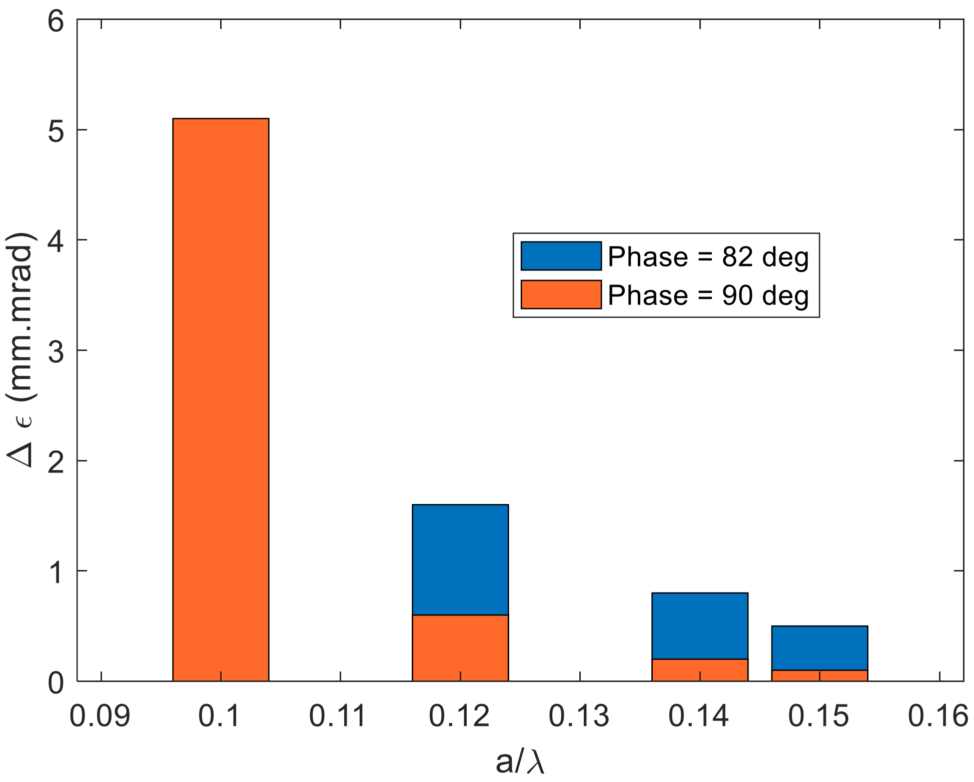


Phase = 82 deg
(without the energy compressor)

	Phase = 82 deg	Phase = 90 deg
a/λ = 0.10	/	5.1
a/λ = 0.12	1.6	0.6
a/λ = 0.13	/	/
a/λ = 0.14	0.8	0.2
a/λ = 0.15	0.5	0.1

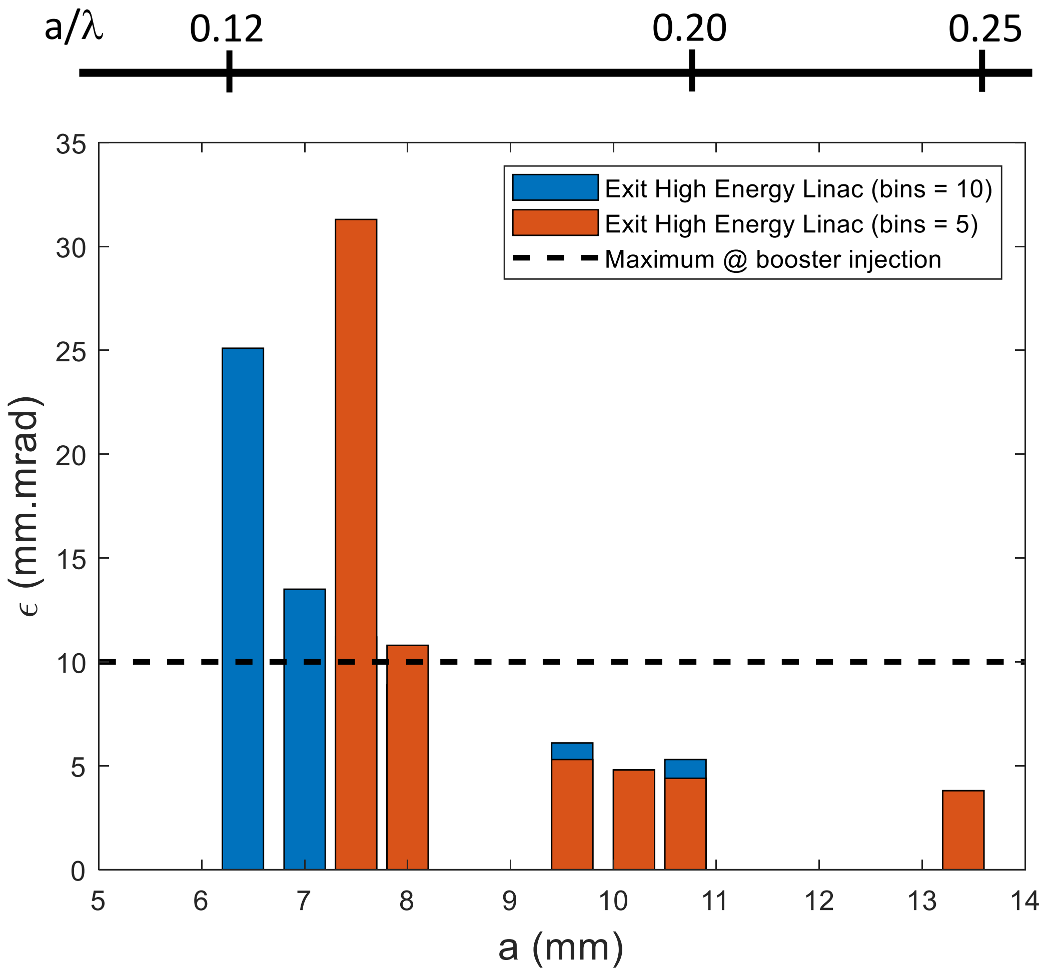
Phase = 90 deg
(implies the use of the energy compressor)





High energy linac, C-band, phase = 90 degrees

a/λ	a (mm)	Bins* = 1	Bins* = 5	Bins* = 10
0.12	6.4	/	/	21.6
0.13	7.0	/	/	10.0
0.14	7.5	/	27.8	7.7
0.15	8.0	/	7.3	5.4
0.18	9.6	/	1.8	2.6
0.19	10.2	/	1.3	1.8
0.20	10.7	/	0.9	1.3
0.25	13.4	0.8	0.3	0.3



- The biggest impact of the spitting of the sections is for the smallest apertures: bins = 5 and bins = 10 give similar results in the "region of interest"
- RF iris radius ~ 10 mm gives the final emittance at the exit of the linacs with a factor 2 margin (safe considering the other possible emittance growth sources)

* Bins corresponds to the number of sections the linac is split (more in the spare slides)

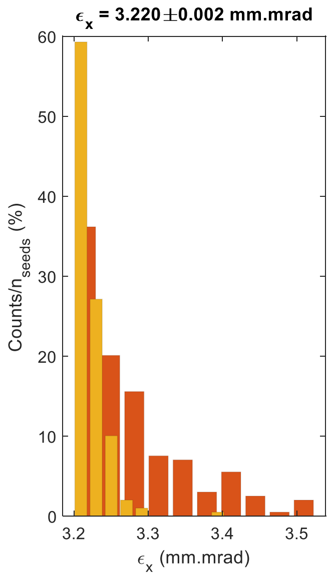
High energy linac, S-band, phase = 90 degrees

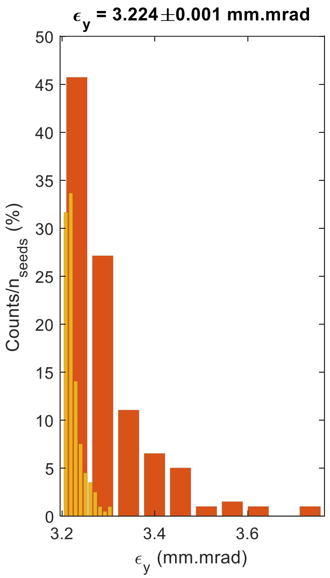
Considered the **S-band** option (f = 2.8 GHz), gradient = **25 MV/m**

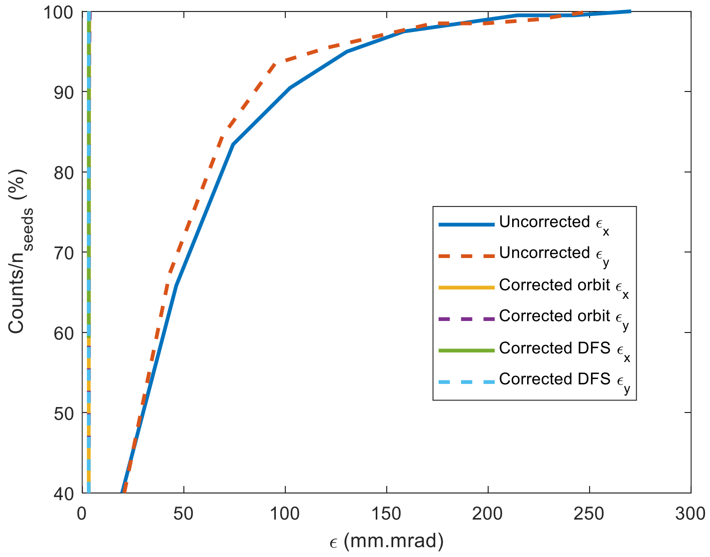
At the moment assumed the same geometry as the previous linacs. Possible to reduce the aperture.

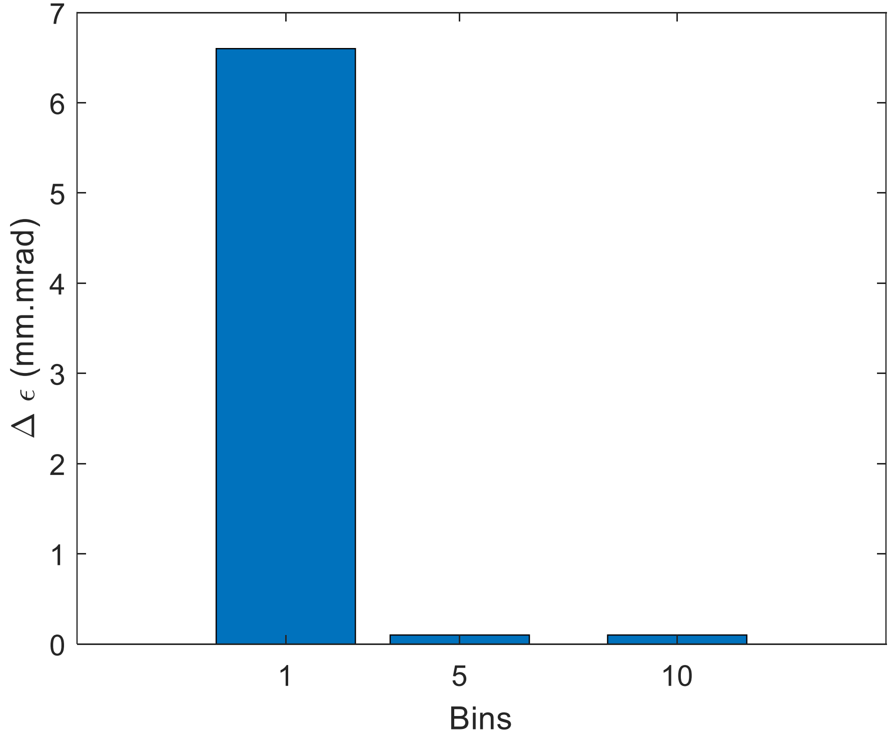
a/λ	a (mm)	Bins = 1	Bins = 5	Bins = 10
0.15	16.1	6.6	0.1	0.1

MAKE ONE SLIDE WITH THE PREVIOUS ONE







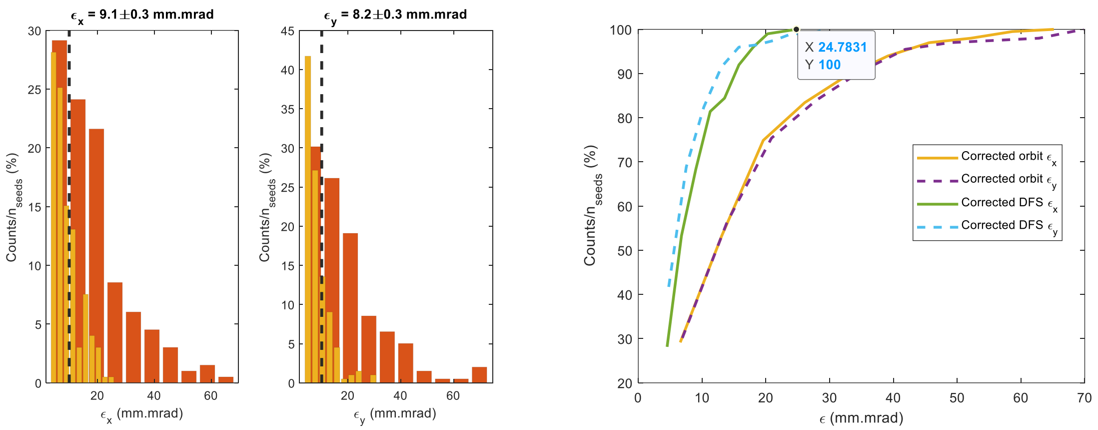


Also this configuration feasible with a certain margin (smaller gradient than C-band-longer linac-larger effect of the wakefield)

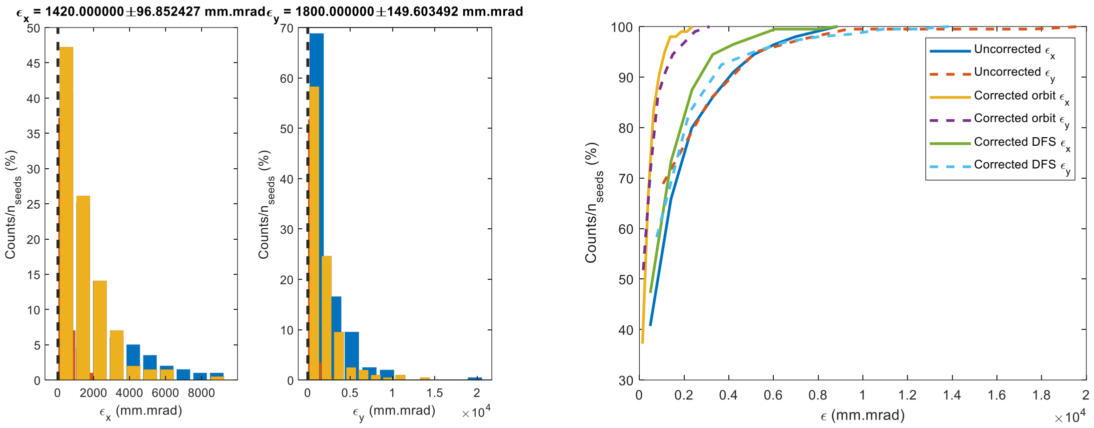
High energy linac, phase = 90 degrees, C-band (5.6 GHz)

Considered the **C-band** option (f = 5.6 GHz), gradient = **40 MV/m**

Expected behavior



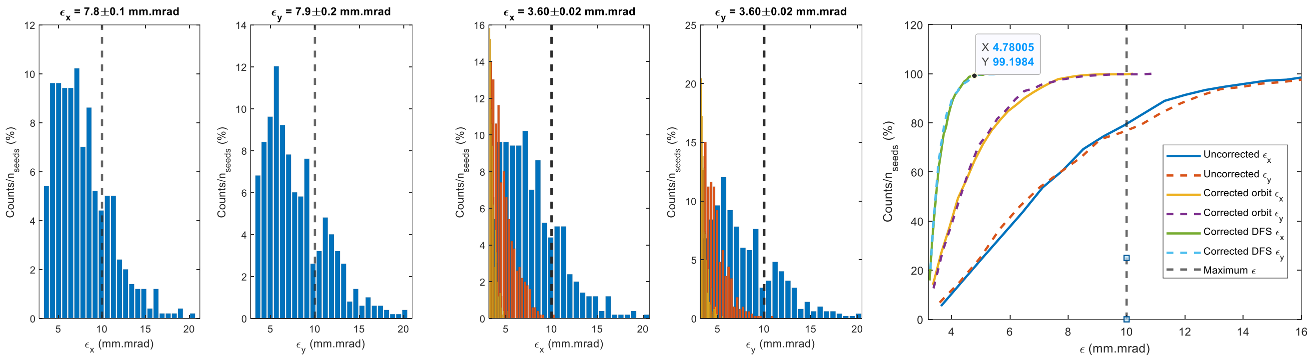
Observed behavior



- For the smaller apertures the DFS applied to the full linac degrades the final emittance
- We applied the corrections in sections (bins): this corresponds to have several spatially-sequential corrections
- Simulations repeated for bins = 5 and 10
- Scheme worked at FACET (A. Latina, et al.), and even improved having a certain overlap among the several sections (not in these simulations yet)

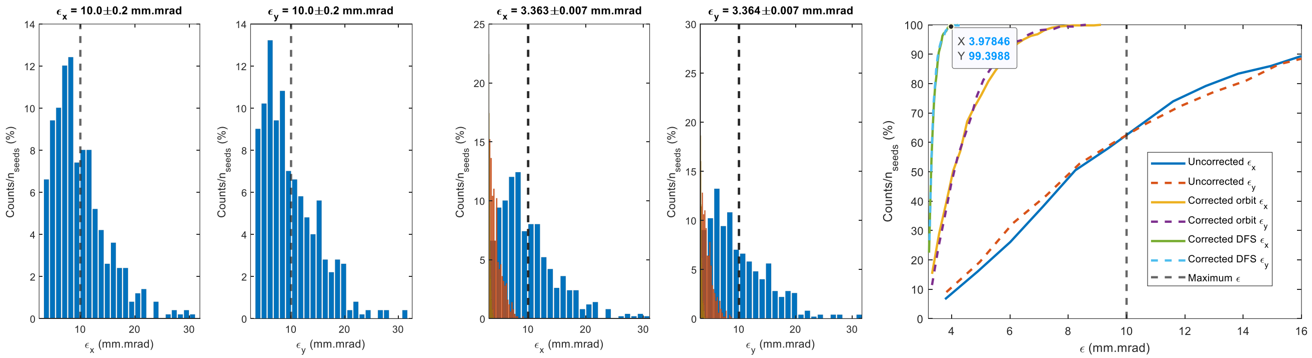
Common linac (1.54 GeV -> 6 GeV), phase = 82 degrees

$a/\lambda = 0.12$



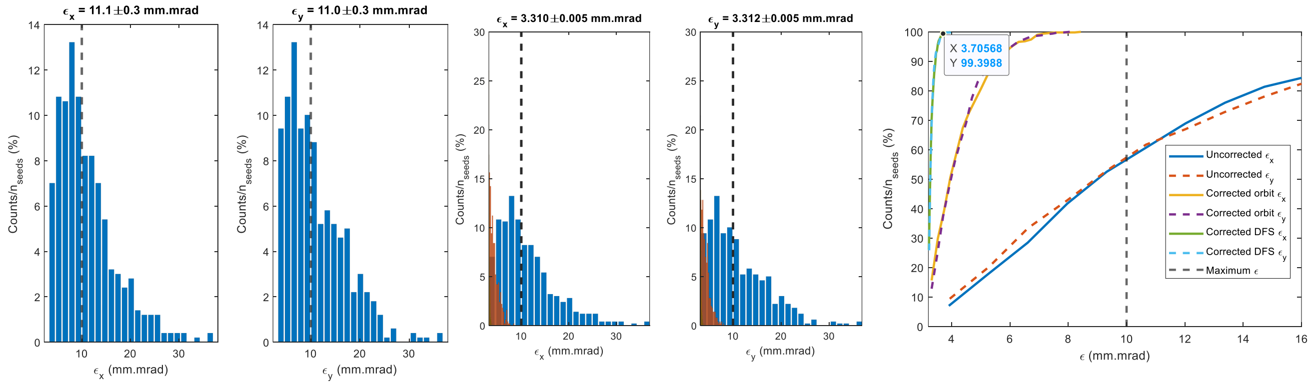
$\Delta\varepsilon$ = 1.6 mm.mrad

$a/\lambda = 0.14$



$\Delta\varepsilon$ = 0.8 mm.mrad

$a/\lambda = 0.15$



$\Delta\varepsilon$ = 0.5 mm.mrad

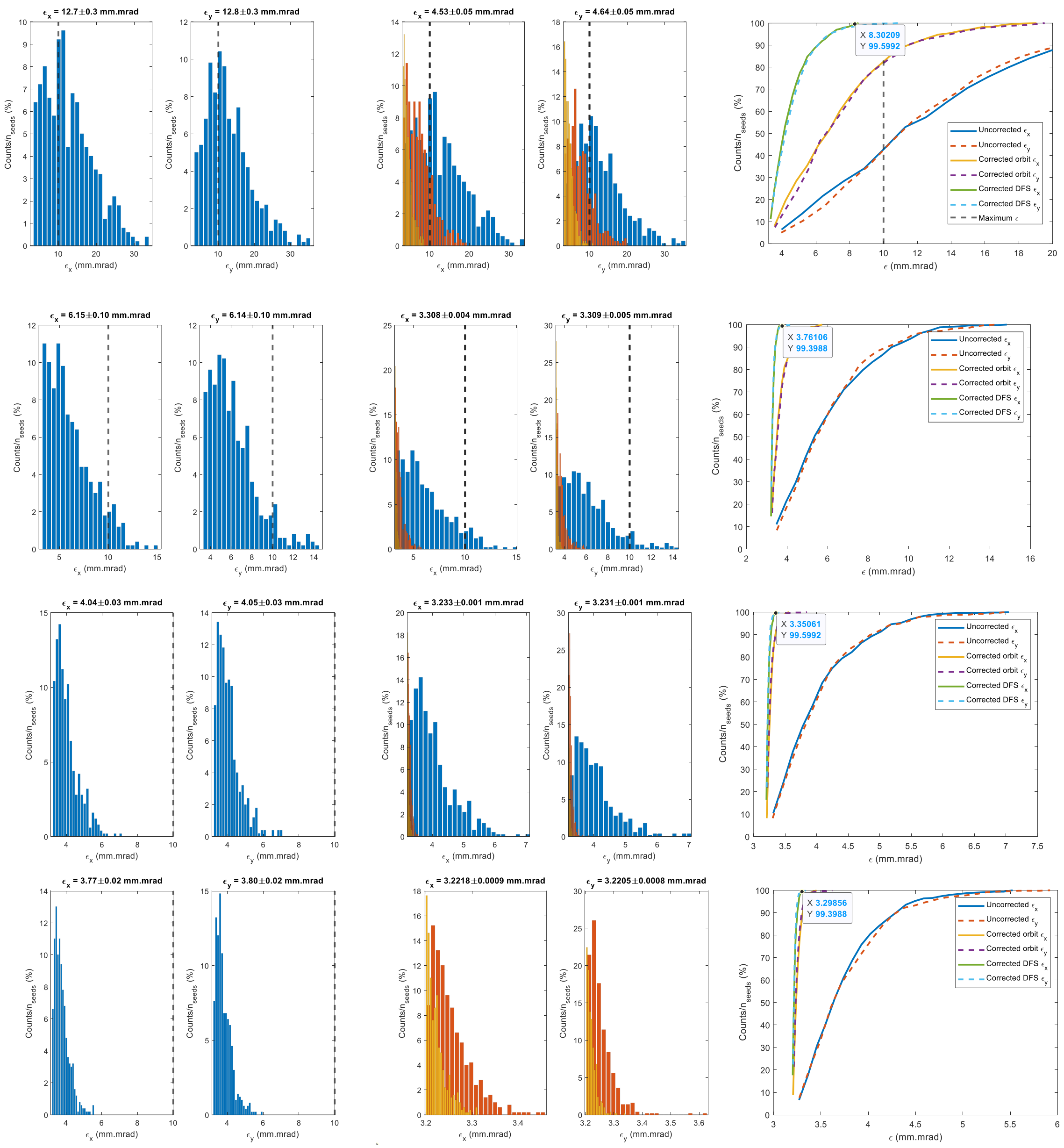
Common linac (1.54 GeV -> 6 GeV), phase = 90 degrees vs 82 degrees

a/λ = 0.10

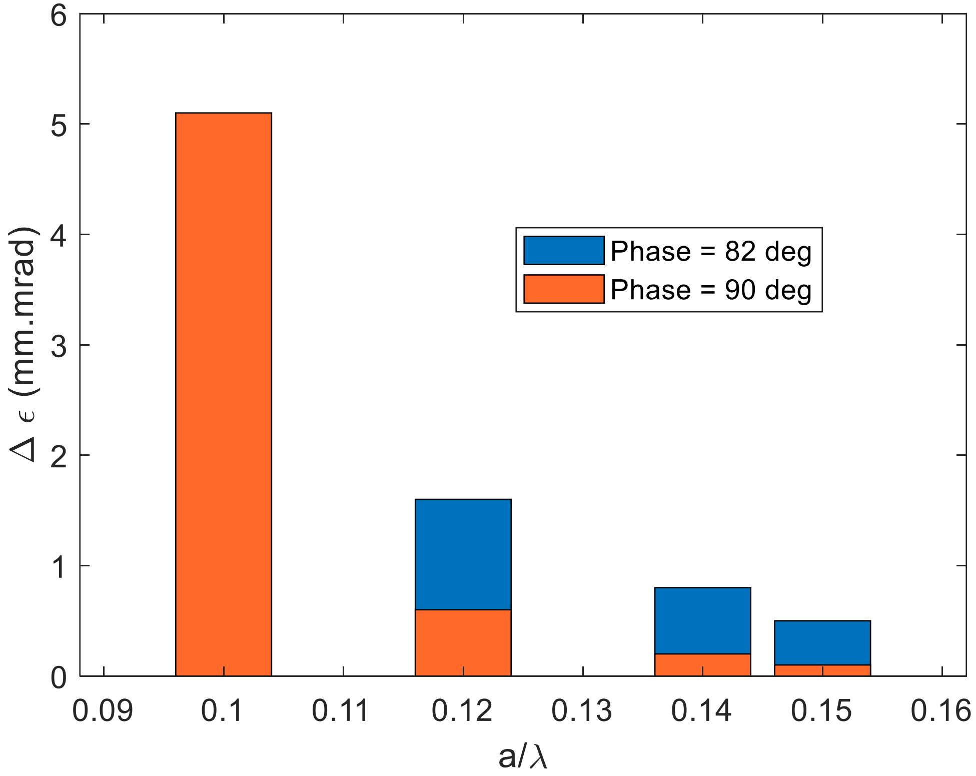
a/λ = 0.12

a/λ = 0.14

a/λ = 0.15



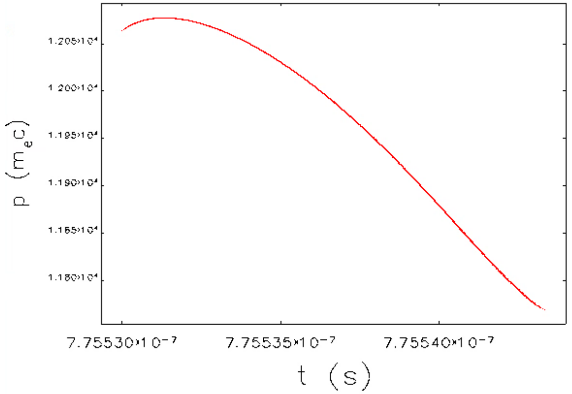
	Phase = 82 deg	Phase = 90 deg
a/λ = 0.10	/	5.1
a/λ = 0.12	1.6	0.6
a/λ = 0.13	/	/
a/λ = 0.14	0.8	0.2
a/λ = 0.15	0.5	0.1



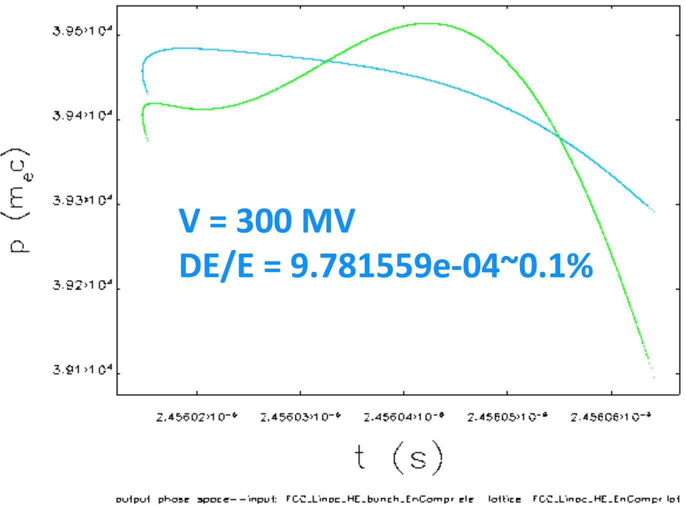
Energy compressor extra

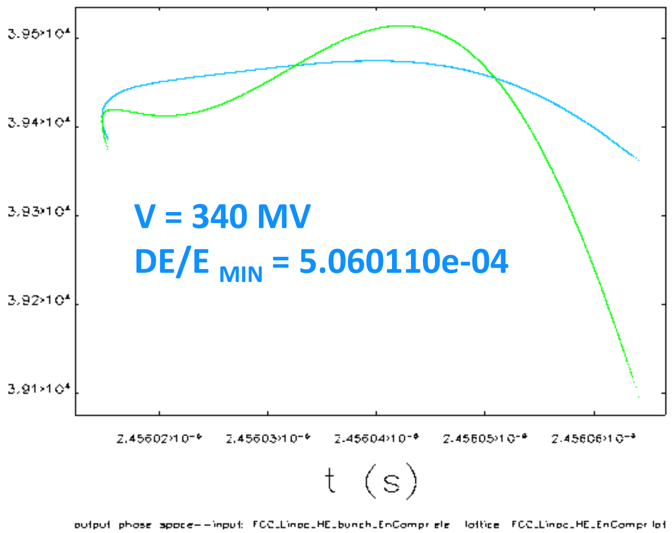
Setting Common (S-band) and HE (C-band*) Linac **on-crest**

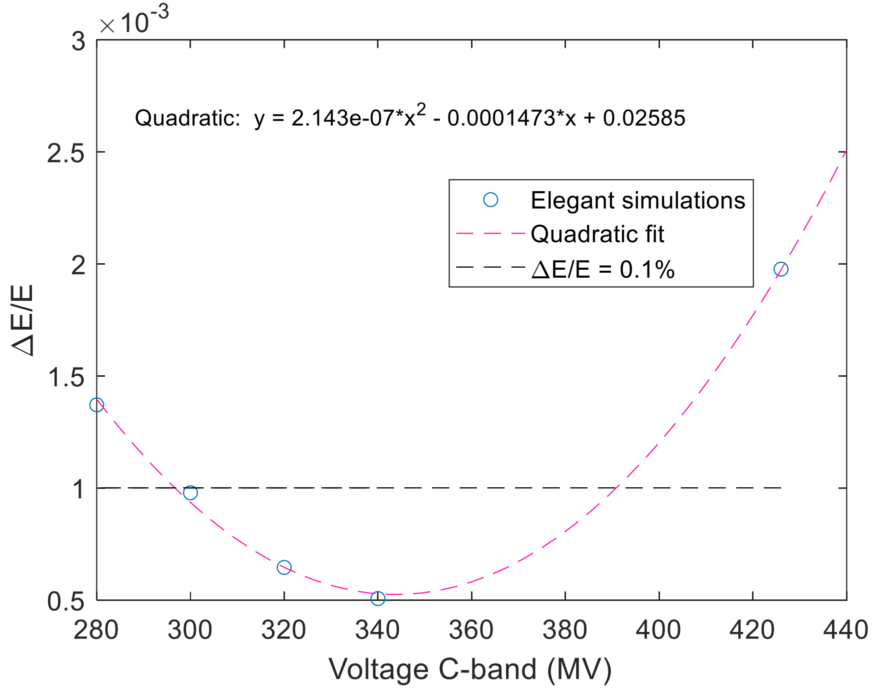
At the HE Linac exit



- Much more "monotonic" than the previous case: analytical model already good enough to determine the working point
- R56 = **0.4 m**, final bunch length = 4 mm
- Case of the **X-band** and the **C-band** analyzed





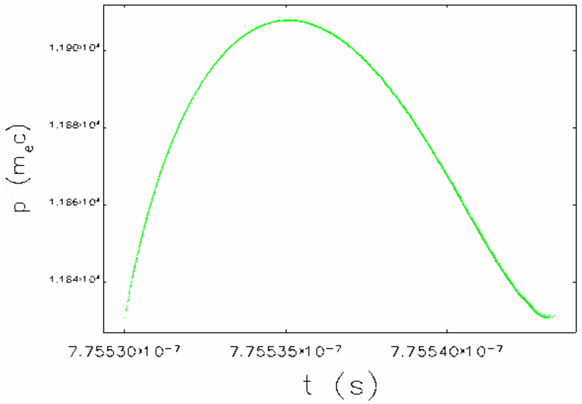


Target bunch length and DE/E achievable with a factor 2 margin with a reasonable voltage in C-band (relatively small R_{56})

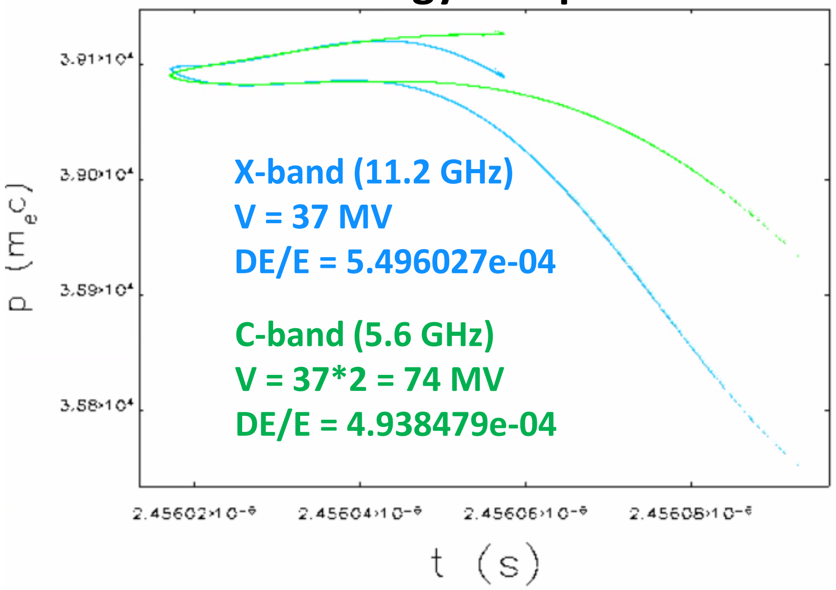
* Very similar findings in case of the S-band high energy linac: V = 340 MV → DE/E = 5.015721e-4, V = 300 MV → DE/E = 1.000953e-3 in C-band

Design Common and HE (S-band) Linacs **off-crest** (82 deg-minimize DE/E)

At the HE Linac exit



At the Energy Compressor exit



Elegant start-to-end simulations:

- Energy spread at the entrance of HE linac is far from being "monotonic"
- R_{56} to have a factor 4 (from 1 mm) decompression is **2.5 m**

Results:

- Voltage of about 40 MV in X-band (~80 MV in C-band) to minimize the final energy spread: minimum $\delta E/E$= 5.5e-4 (5.0e-4 in C-band)
- Due to the small value of the computed voltage, tested also the C-band option. In this case a smaller energy spread reached: minimum of $\delta E/E$= 4.9e-4

Target bunch length and DE achievable with a factor 2 margin on $\delta E/E$ with a reasonable voltage in C-band (large R_{56}, but it seems to be feasible in the transfer line to the booster)

Beam loading

PAUL SCHERRER INSTITUT

Dependence on the bunch charge (single bunch)

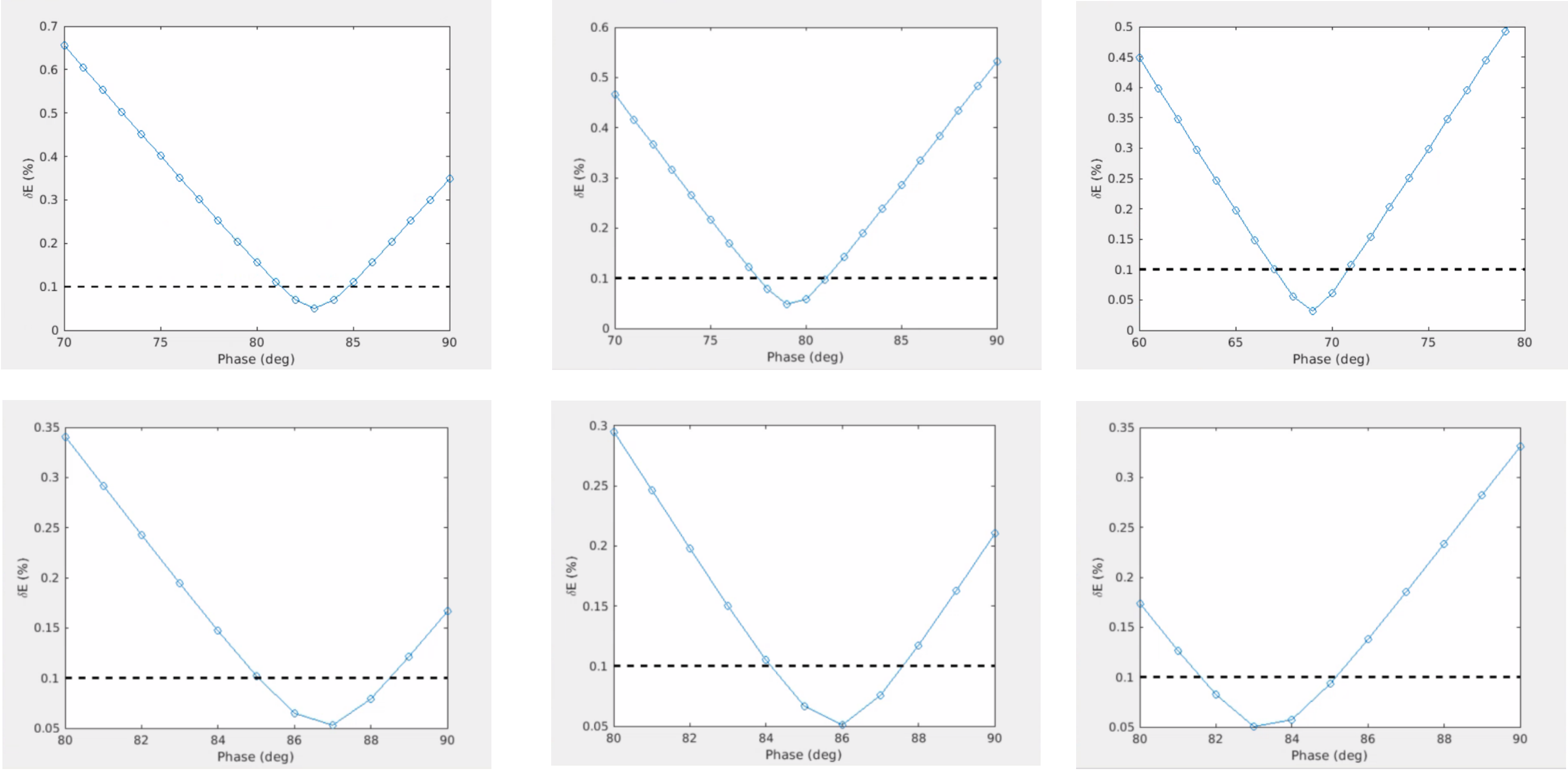
- The machine will run at 4 nC down to 1 nC bunch charge
- Checked the solution for 1 nC compared to 4 nC case

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?

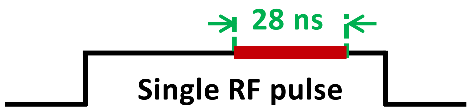
Considering the present design

Acting on the laser

- Change the arrival time of the laser on the cathode
- This changes the phase seen by the bunch when entering in the RF structures
- How much is the velocity of this process? Use two lasers?

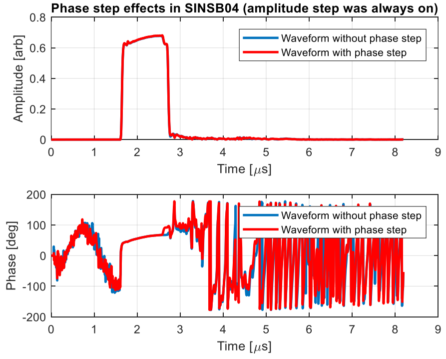
Acting on the RF

- Manipulate the RF in such a way that the bunch(es) see different phases
- Implemented at SwissFEL for the two bunch operation (distance 28 ns)
- Which is the limit of this method?

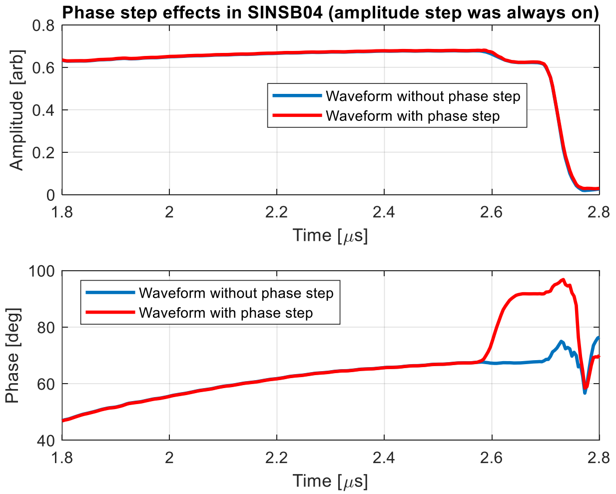


Phase and amplitude steps introduced along the **single RF pulse** to independently control bunch 1 and bunch 2

Developed by Z. Geng for SwissFEL (PSI)



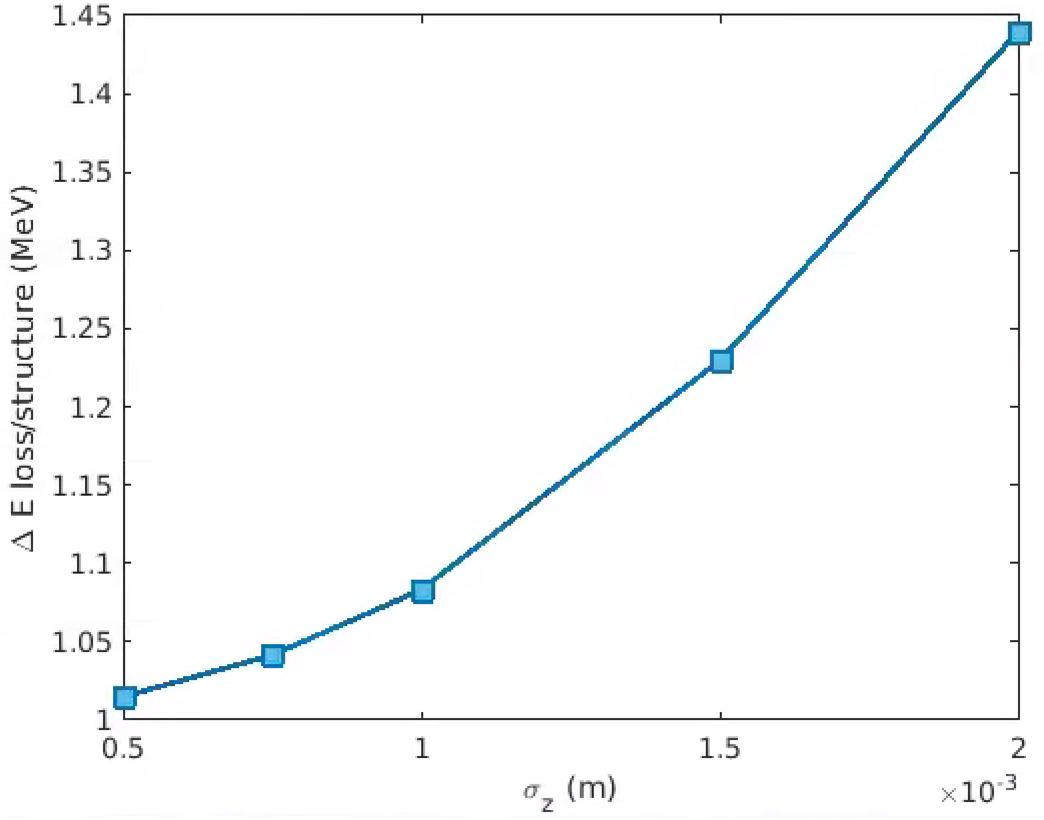
Change in phase



	Amplitude (%)	Phase (deg)
Gun (S-band)	-1.8 ~ 0.9	±1.3
S-band structures	-1.7 ~ 0.0	±0.8
X-band structures	-21.6 ~ 0	±11.5
C-band structures	-4.8 ~ -2.9	±0.9

Beam loading

Electron and Common linac and HE linac
S-band



HE C-band linac

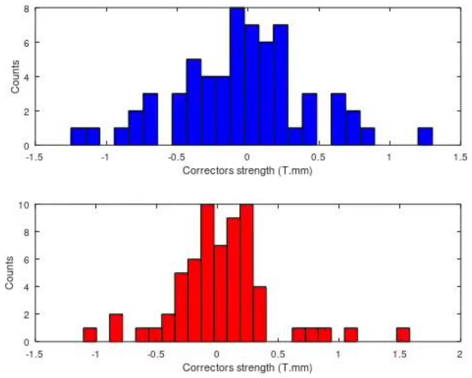
- Nstructures = 118, L = 3 m, G = 40 MV/m, f = 5.6 GHz
- Expected DE = 118*40 MV/m*3 m = 14.160 GeV
- Simulated DE = (-1.197420e+04+3.900980e+04)*0.511*1e-3 = 13.8152 GeV
- 14.160-13.8152 = 344.8 MeV
- **DE beam loading/structure = 2.922 MeV/structure**

Magnet feasibility

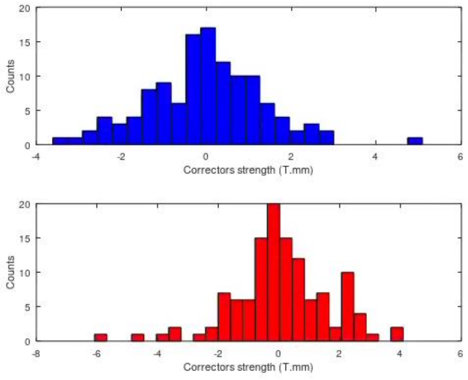
Are our **magnets** “realistic”?

Correctors

Random case at common linac



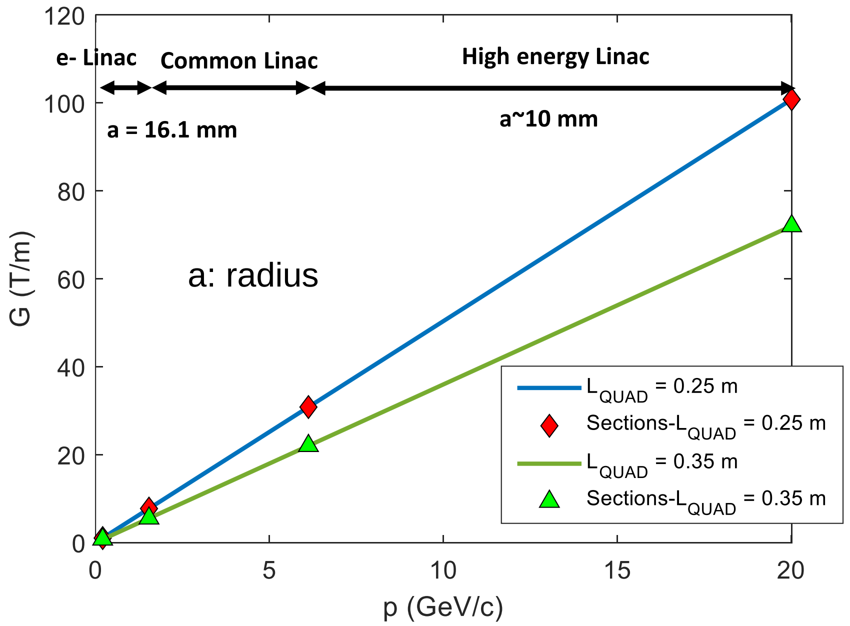
Random case at HE linac C-band, $a/\lambda = 0.25$



Booster~20 T.mm
Available field integral 38 T.mm

Quadrupoles

	a (mm)
e- Linac	16.1
Common Linac	16.1
HE Linac (C-band)	10.2
HE Linac (S-band)	≤16.1



SLS2.0 quadrupoles (C. Calzolaio)

	QPH
Magnetic length [mm]	140
Iron pole length [mm]	130
Nominal Gradient [T/m]	98
Radial aperture [mm]	10.5
Pole Tip Field [T]	1.03
N. of magnets in the ring	55
Max. Current [A]	70
Resistance [mΩ]	191
Power max. [W]	938
Conductor [mm²]	5 mm x 5 mm, Φ_{water}: 3 mm
Windings	75
Cooling Circuit	One per pole
Cooling Water ΔP[bar]	4
Cooling Water ΔT [°C]	6.7

Already existing quadrupoles which closely satisfy our requests.
Still margin increasing by about 30% the quadrupole length to further increase the margin

Several designs longitudinal

Several designs optimized

More reported at the 2022 FCC Week and 2022 ICFA workshop

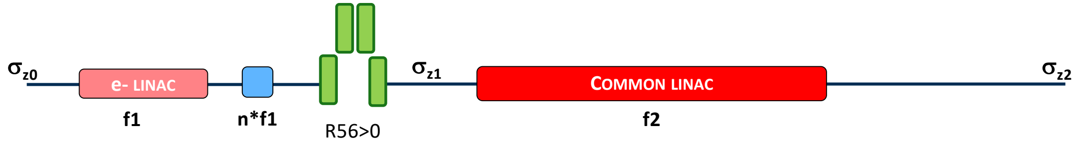
Goal: bring the projected energy spread ~~below 0.1%*~~ **equal to 0.1-0.15%** at the end of the ~~common~~ **high energy** linac

Considered scenarios:

1. **Short bunch from the gun**

- ✓ Possible large emittance at the exit of the gun section
- ✓ Possible large longitudinal space charge effect
- ✓ Minimal hardware request
- ✓ No bunch length variation due to arrival time and RF jitter
- ✓ No CSR

2. **Bunch compressor at the exit of e- Linac**



- ✓ More hardware necessary: linearizing cavities and bunch compressor
- ✓ Possible emittance degradation due to CSR
- ✓ Solution depends on the arrival time and RF jitter
- ✓ Very small values of energy spread achievable

3. **Shorter bunch from the gun and linearization**

- ✓ Same advantages and disadvantages as 1., but a smaller value of energy spread (or equivalently longer bunch lengths) achievable

Optimization strategy

Shorter bunch

- Less RF curvature -> smaller energy spread
- More beam loading

- Worse usage of the RF energy if we minimize the energy spread (off-crest operation)
- More emittance growth (see later)

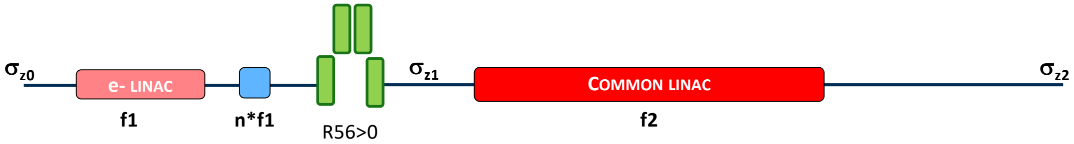
Possible scenarios

More reported at the 2022 FCC Week and 2022 ICFA workshop

1. SHORTER FROM THE GUN

f = 2.8 GHz	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	4e-4
Rms bunch length (mm)	0.8	0.4…0.65	<0.4…0.7

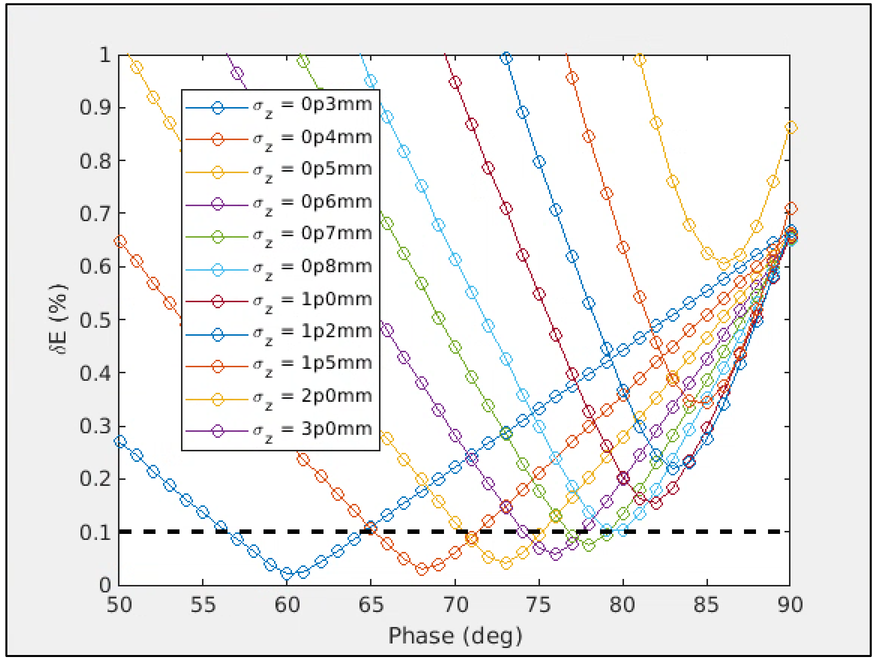
2. BUNCH COMPRESSION



f = 2.8 GHz	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

f = 2.8 GHz	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	3e-4
Rms bunch length (mm)	0.650		



- These values represent the **minimum** achievable energy spread and the corresponding bunch length
- More on scenario 2 and 3 presented at the 2022 FCC week

Multi-bunch and orbit jitter

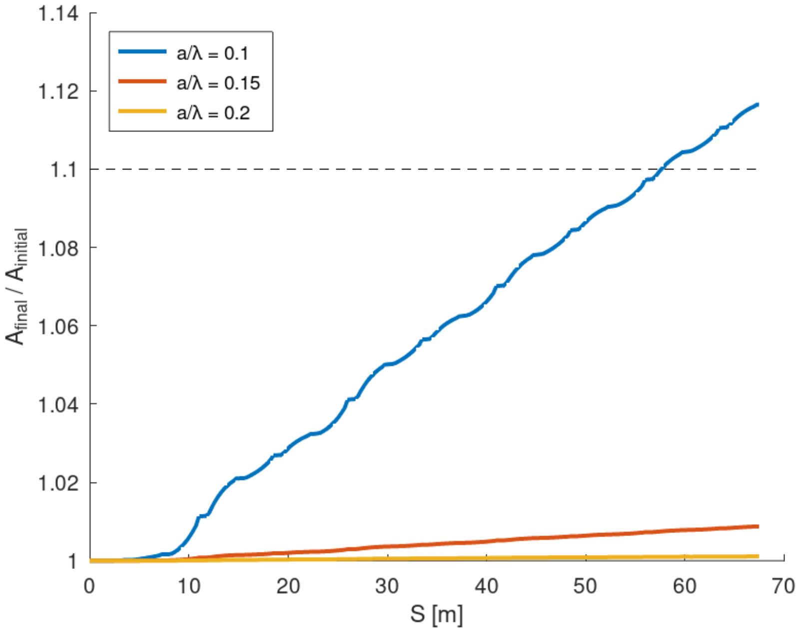
Incoming jitters

- **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**:

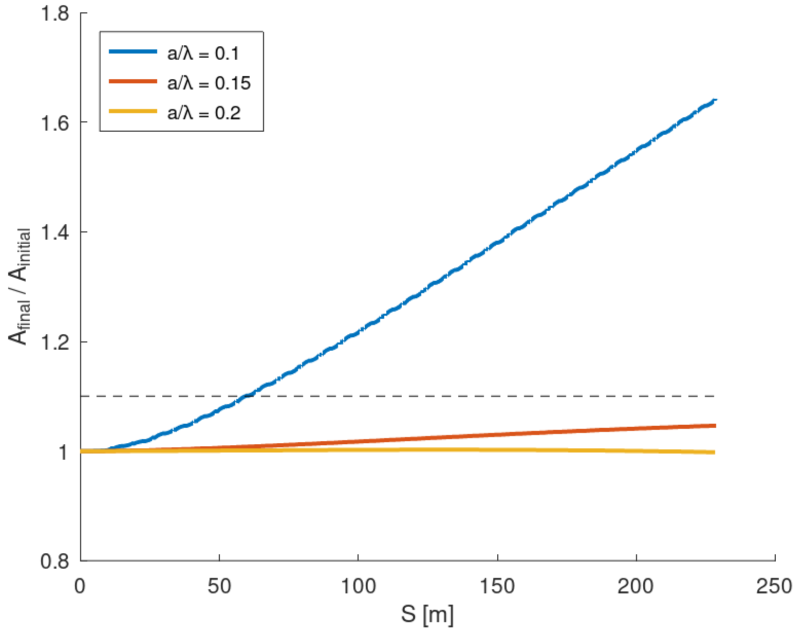
<u>Jitter* amplification</u>

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

E- LINAC



COMMON LINAC



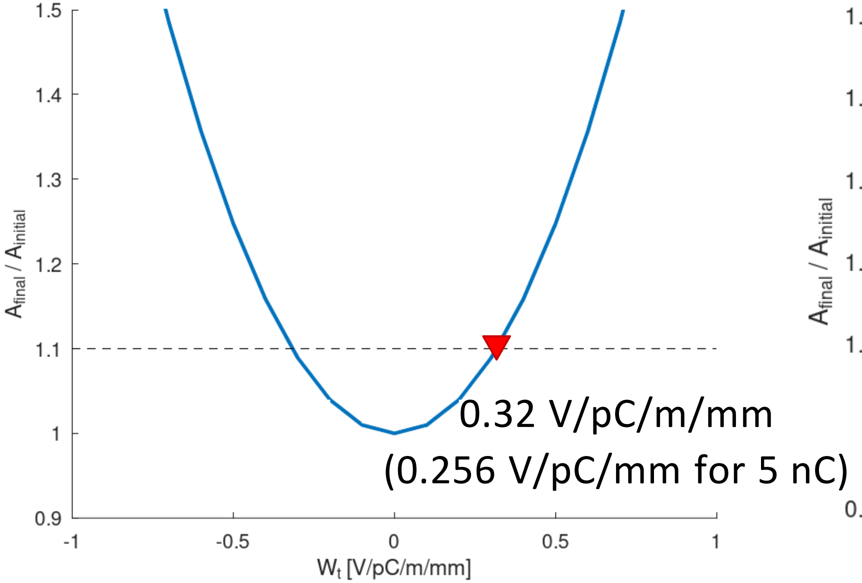
NO LARGE IMPACT IN E-LINAC, AND SIGNIFICANT DEGRADATION ALONG THE COMMON LINAC FOR MORE EXTREME GEOMETRIES

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

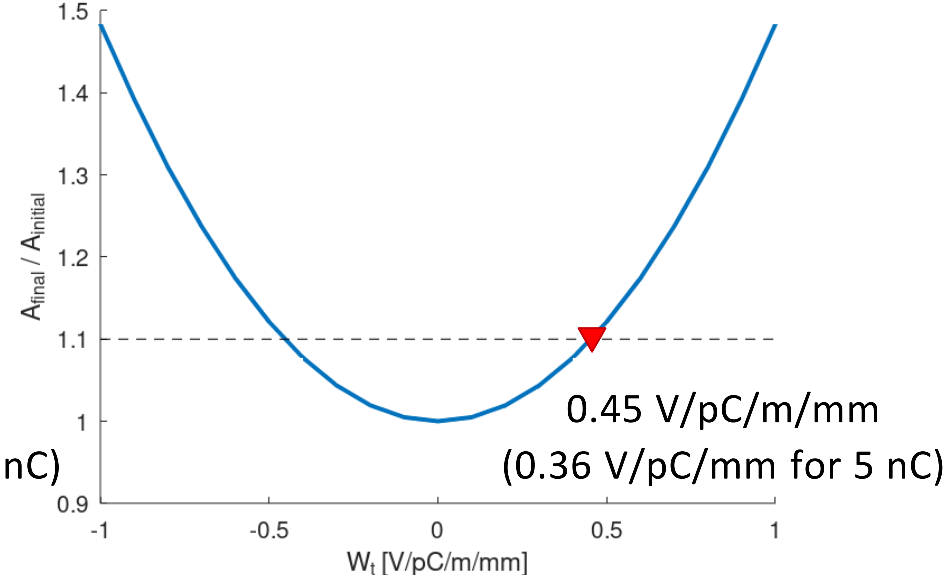
Jitter amplification

- **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



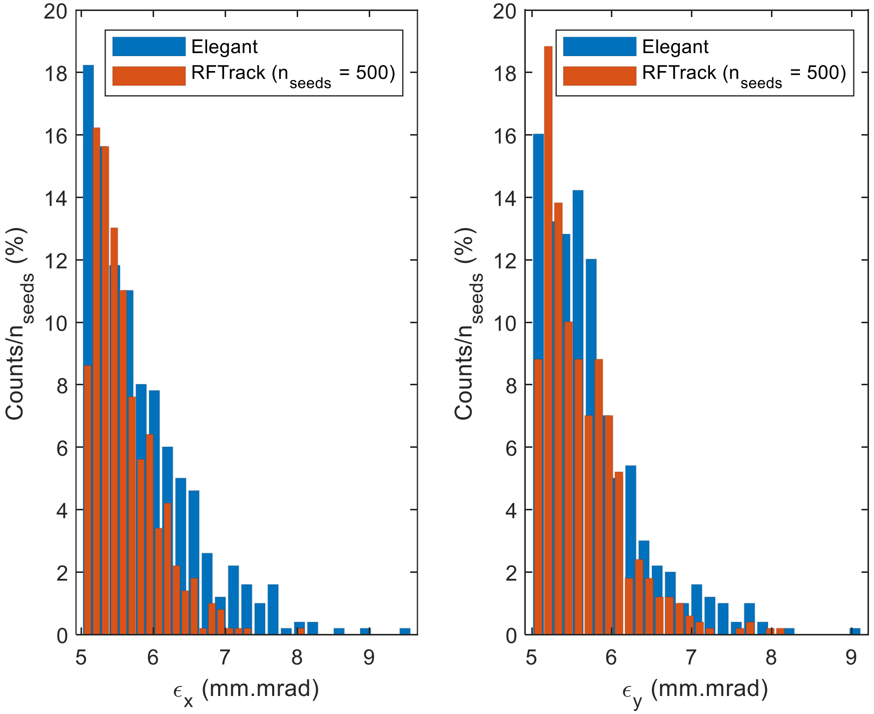
RF structures optimized to produce a maximum kick~0.2 V/pC/mm at 17.5 ns time separation (H. W. Pommerenke)

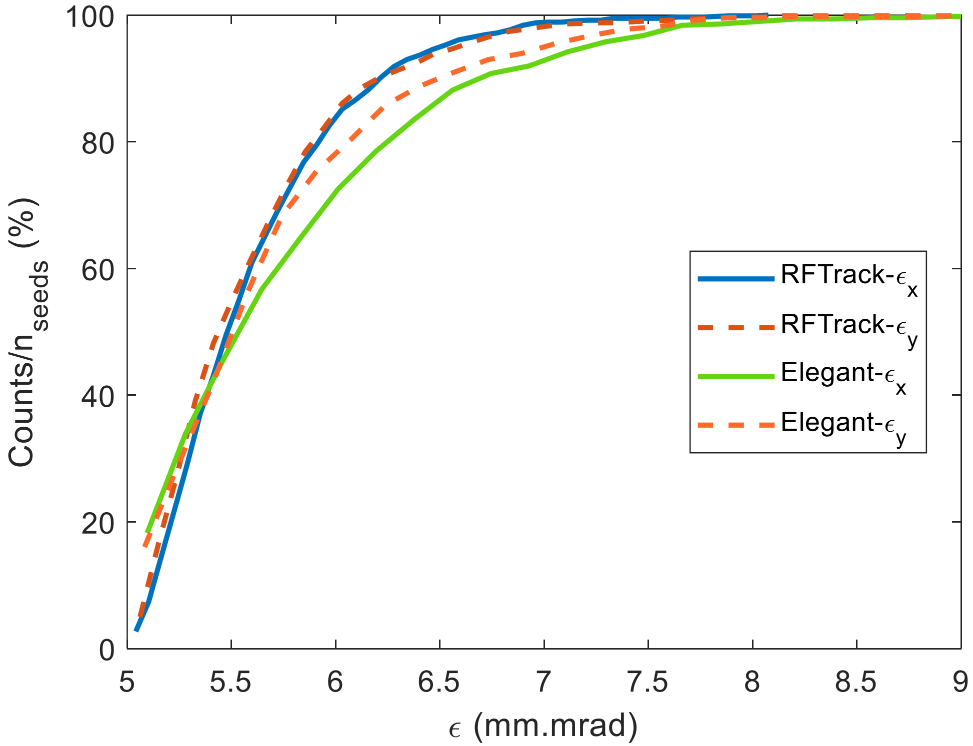
Elegant vs RF-Track

Modeling studies ongoing

RFTrack (code developed by A. Latina): 0 deg, 1000 seeds → ϵ_x = 5.60±0.02 mm.mrad ϵ_y = 5.63±0.02 mm.mrad

Elegant: 82 deg, 500 seeds → ϵ_x = 5.82±0.03 mm.mrad ϵ_y = 5.73±0.03 mm.mrad





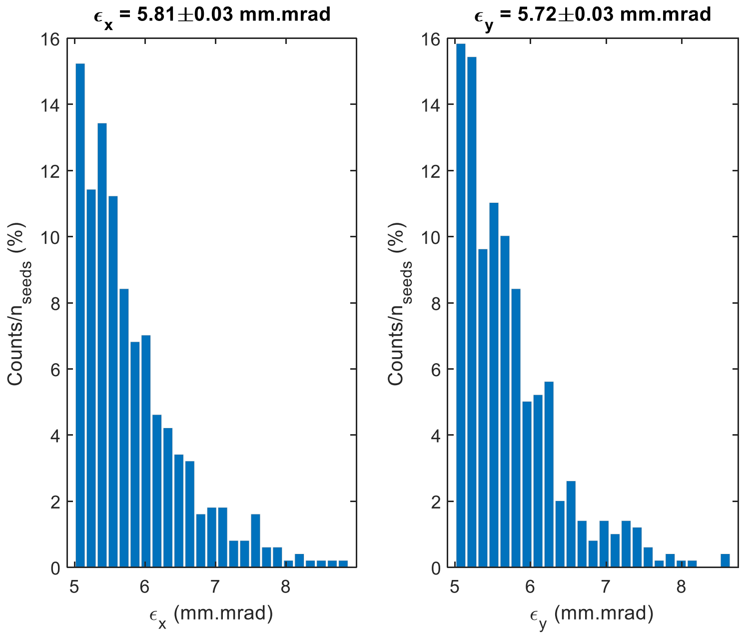
- If the RF structures are operated on-crest Elegant and RFTrack give similar results, whereas if the RF structures are operated off-crest the two codes disagree
- Discrepancy is much smaller for smaller RF apertures
- For RF apertures corresponding to a/λ = 0.15 at 2.8 GHz 0% of the seeds reaches 50 mm.mrad in Elegant and RFTrack (this used for the multi-bunch, and the outcome is the maximum a/λ = 0.1)

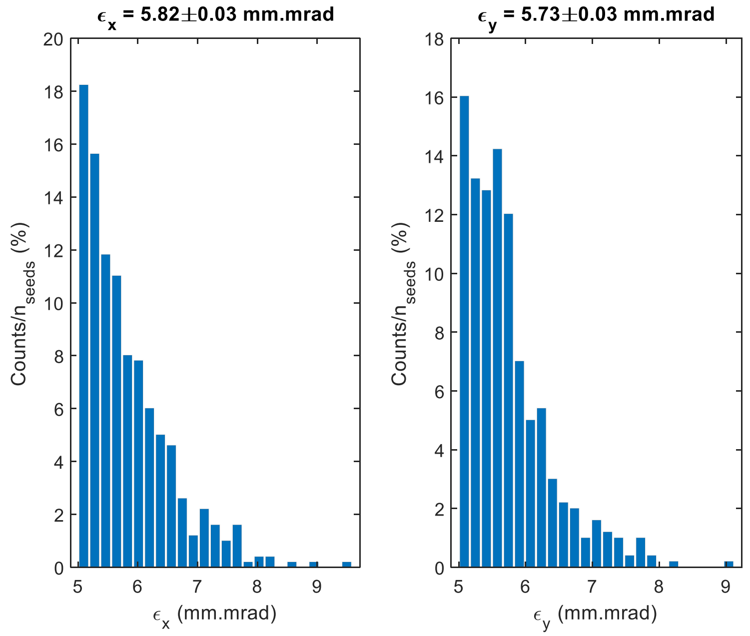
More on codes comparison (Placet vs others) inPAC'07 and analytical vs Elegant: FEL '05

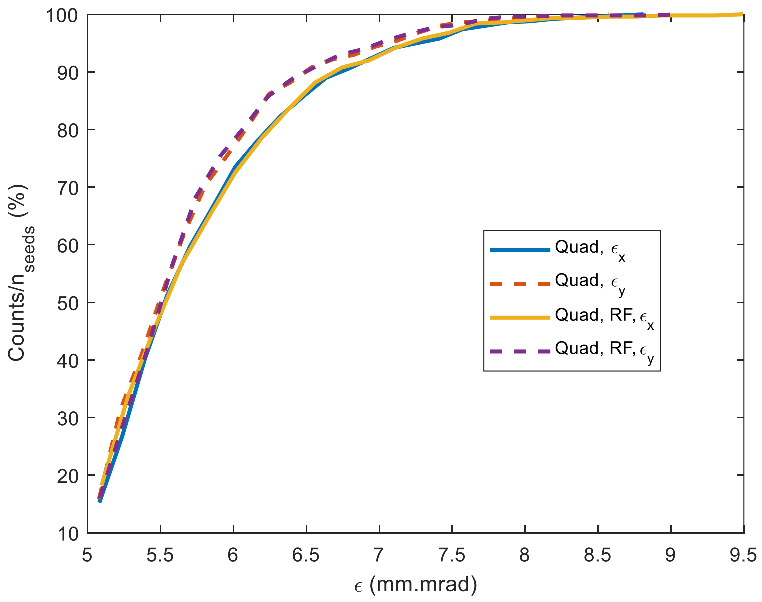
$a/\lambda = 0.15$ (a = 16.1 mm, f = 2.8 GHz)

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

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





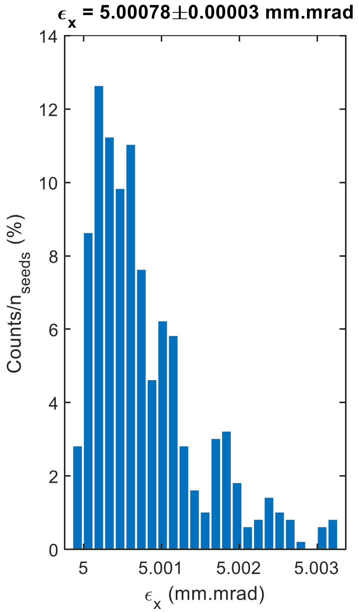


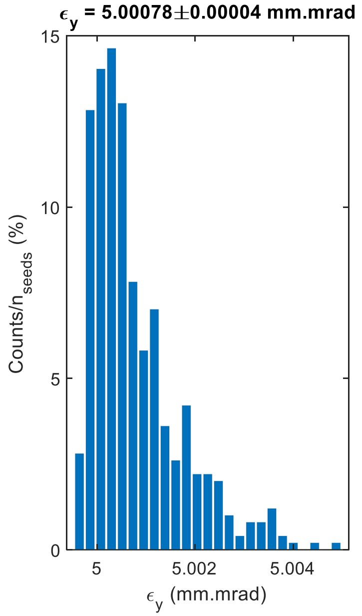
- Quadrupoles misalignments dominate the possible emittance increase (negligible emittance increase misaligning only the RF structures by 100 um Gaussian rms noise)
- Emittance increase by about a factor 2 for less than 10% of the seeds

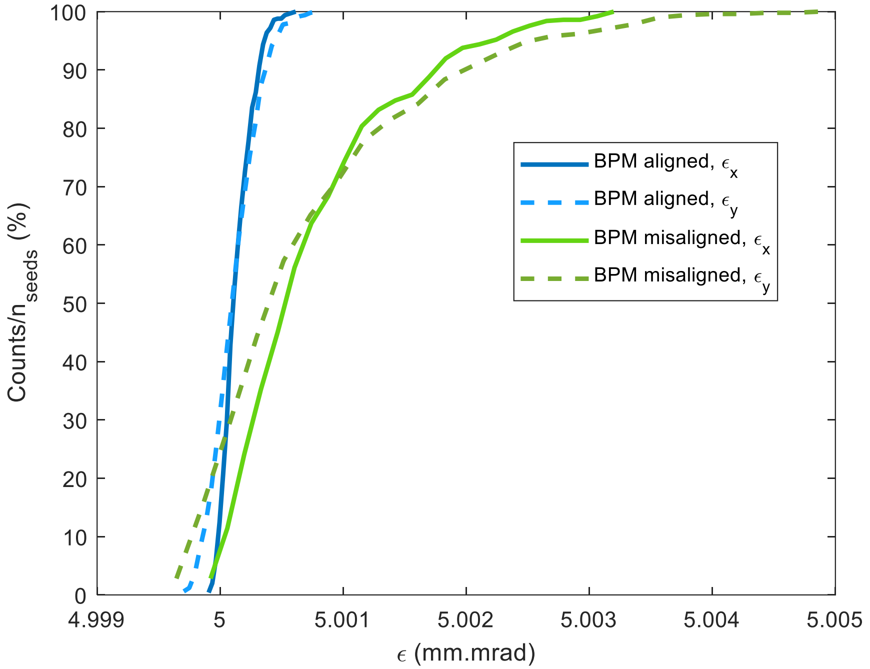
a/λ = 0.15 (a = 16.1 mm, f = 2.8 GHz), with orbit correction

Aligned BPM

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



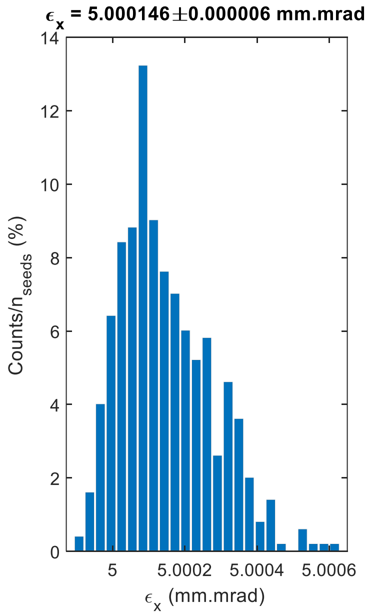


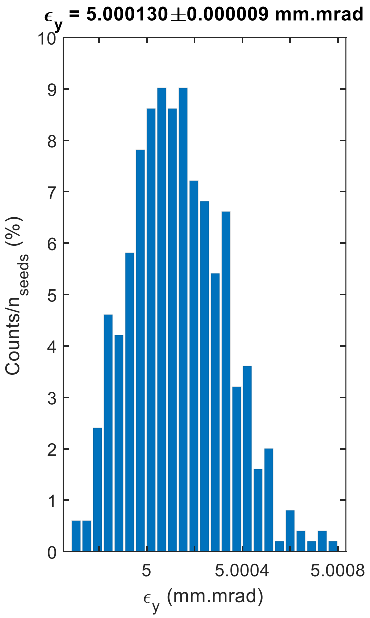


ORBITA NO
ORBITA SI

Misaligned BPM

Quadrupoles
Offset x, y = 50 um rms
RF cavities
Offset x, y = 100 um rms
BPM
Offset x, y = 30 um rms
Gaussian distribution





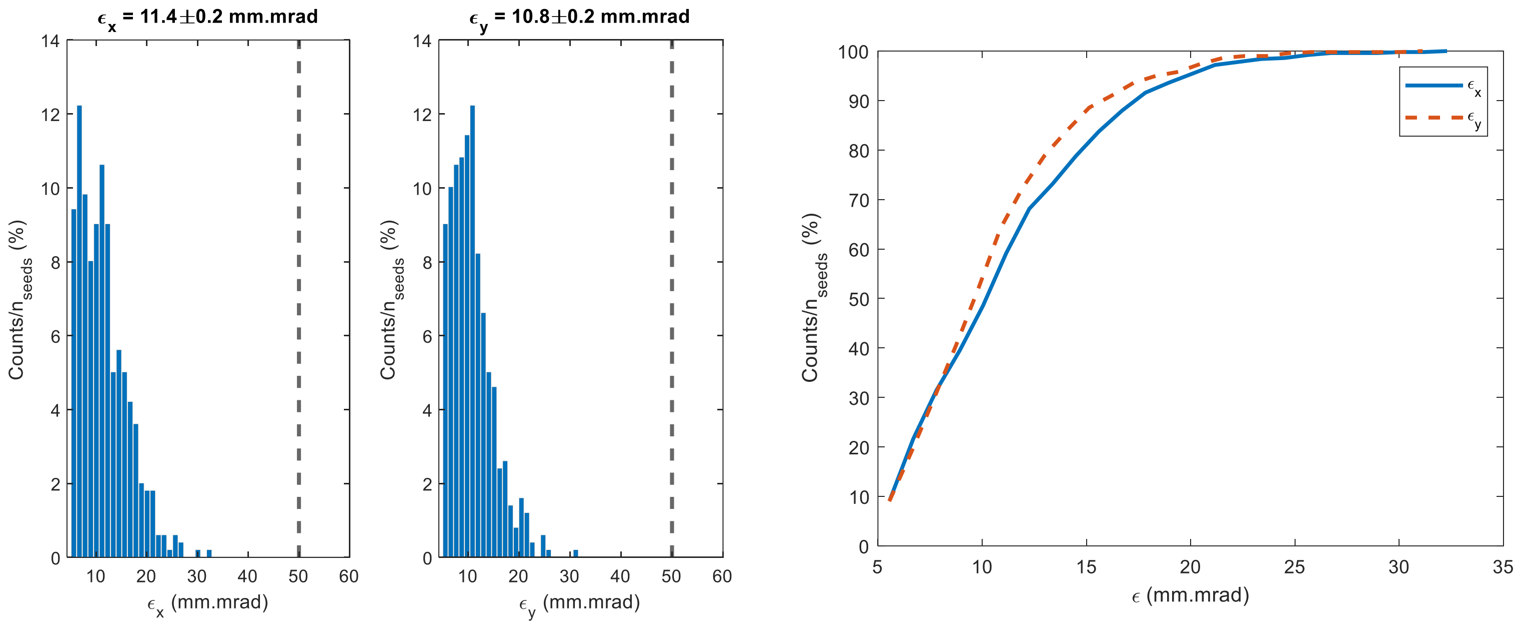
- Orbit correction cures the observed emittance increase
- BPM alignment does not seem to be an issue (at least up to 30 um)

Smaller RF structure aperture: $a/\lambda = 0.1$ ($a = 10.7$ mm, $f = 2.8$ GHz)

SKIP

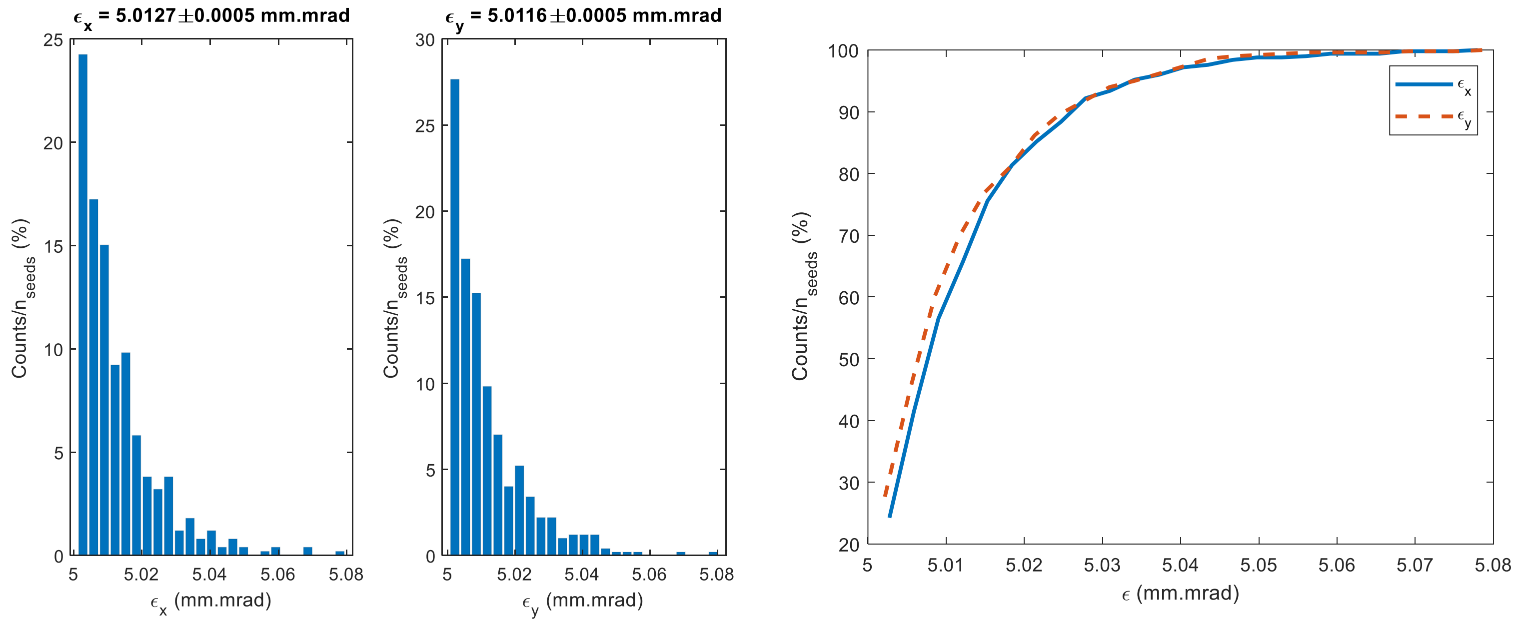
No orbit correction

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



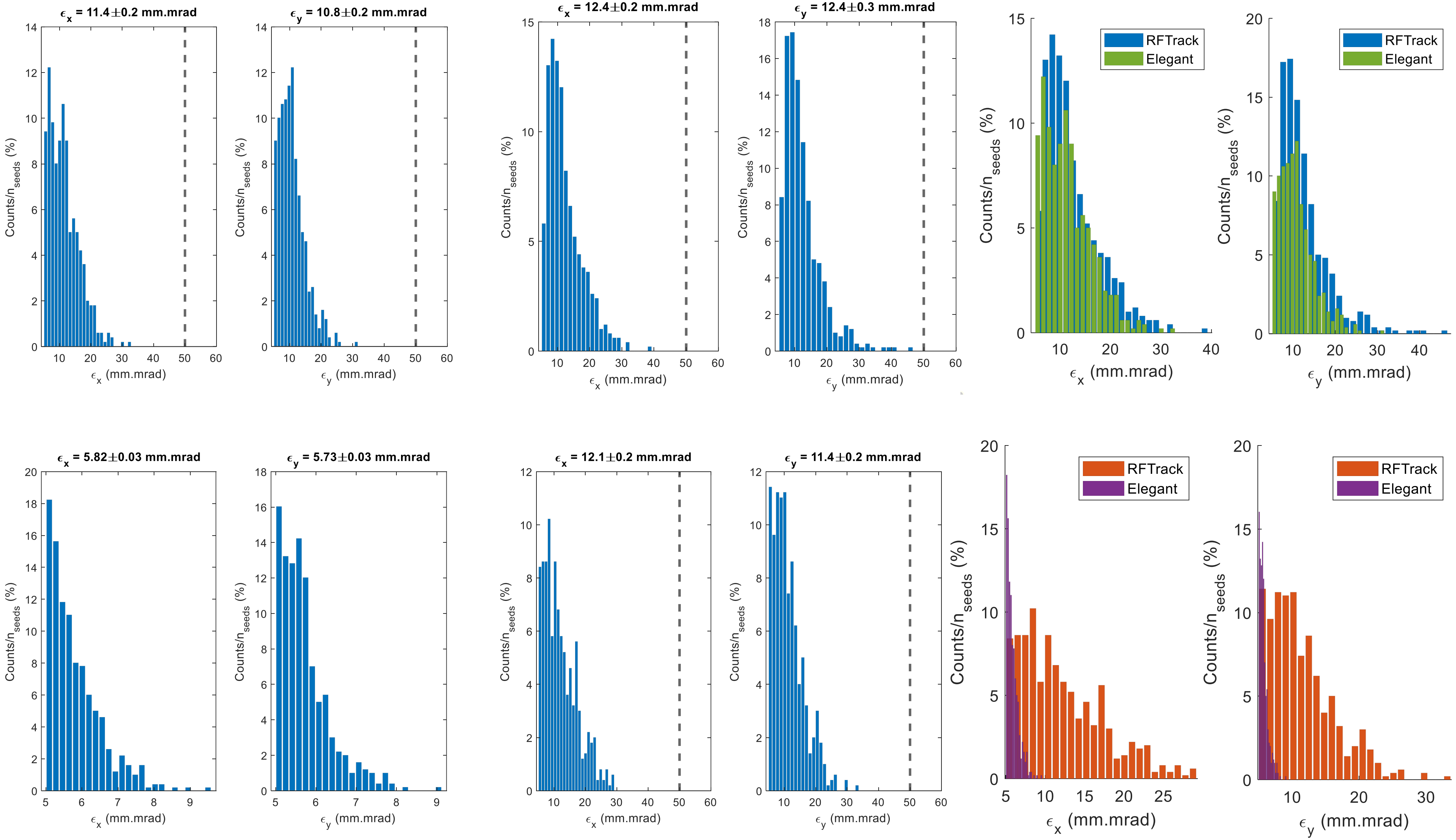
Orbit correction

Quadrupoles
Offset x, y = 50 um rms
RF cavities
Offset x, y = 100 um rms
BPM
Offset x, y = 30 um rms
Gaussian distribution



Elegant vs RFTrack comparison (off-crest by 8 degrees)

Elegant **RFTrack**



a/λ = 0.1

a/λ = 0.15

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

Impact of the bunch length

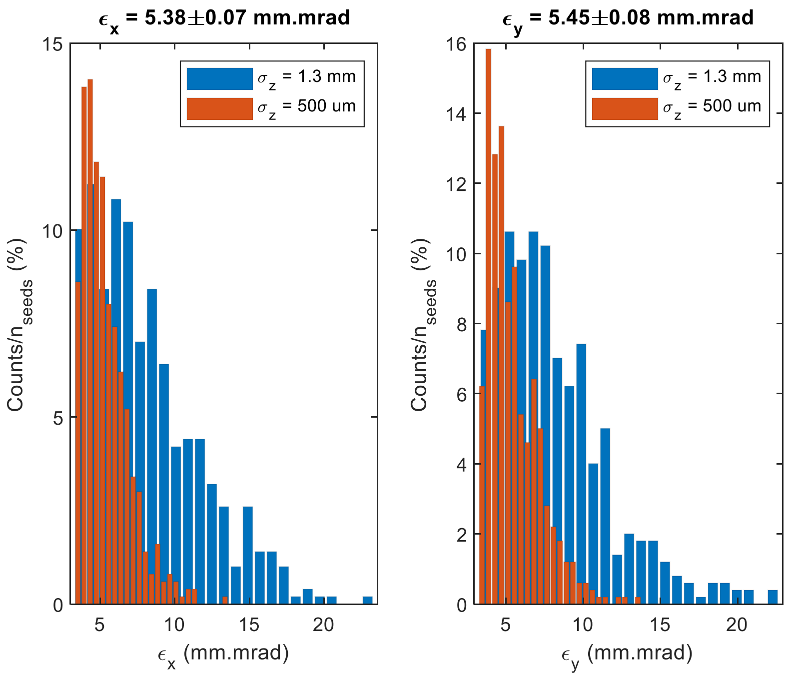
Bunch length

How much are we affected by the bunch length on the emittance increase?
Can we go to longer bunch length to have an even better emittance to start with (Znedev-Steffen's distribution)?
If we go to smaller bunch length how much does the emittance increase change?

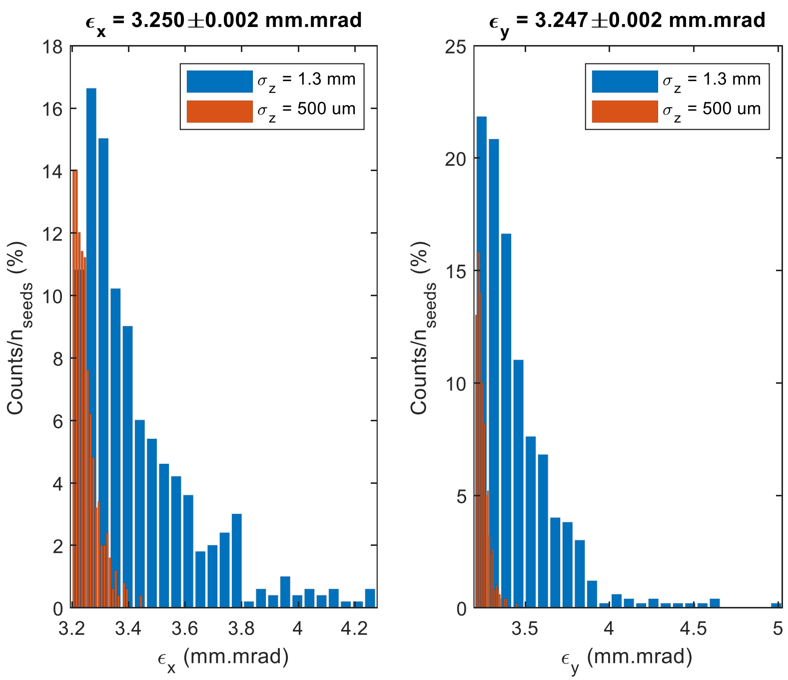
As example taken common linac, on-crest, a/l = 0.12 to be fast

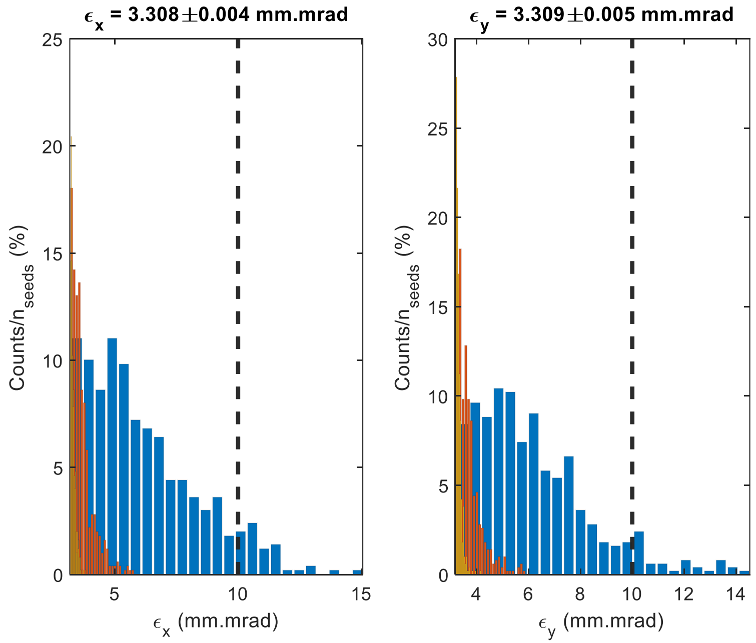
/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok/0_deg/ShortPulse/*um/a_lambda_0p12

Start



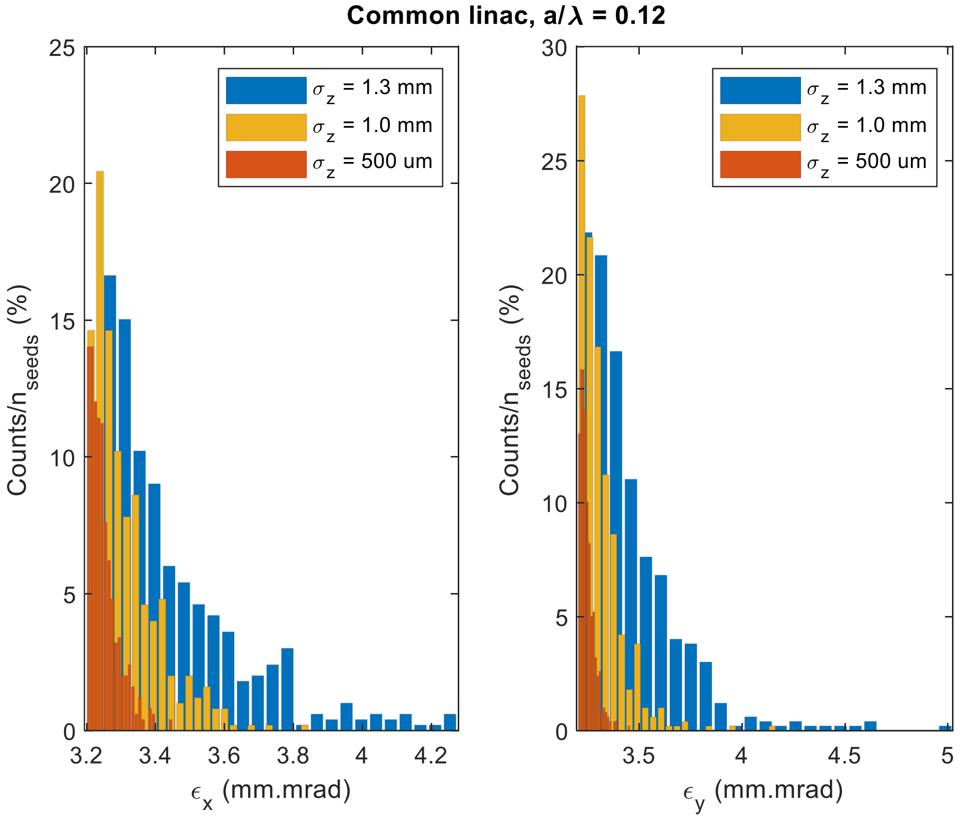
Corrected

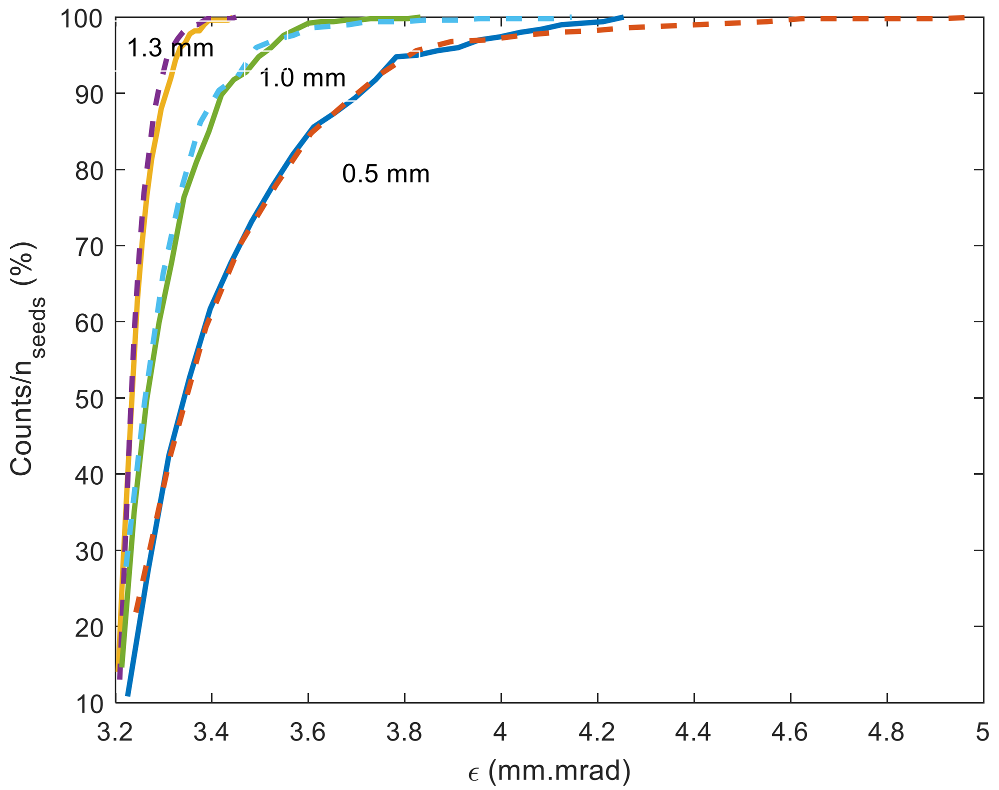




Bunch length = 1 mm
Start
Corrected

Bunch length, after the last meeting added to the uploaded slides





Effect expected even more pronounced for the HE linac

Disagreement RFTrack vs Elegant: observation

From the Orsay's Mini-workshop presentation

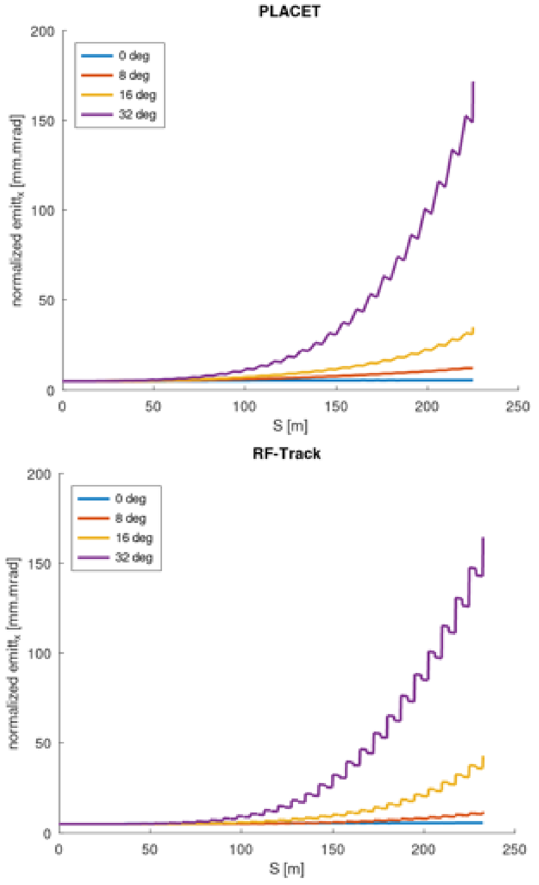
Results of codes comparisons

https://inspirehep.net/literature/772336

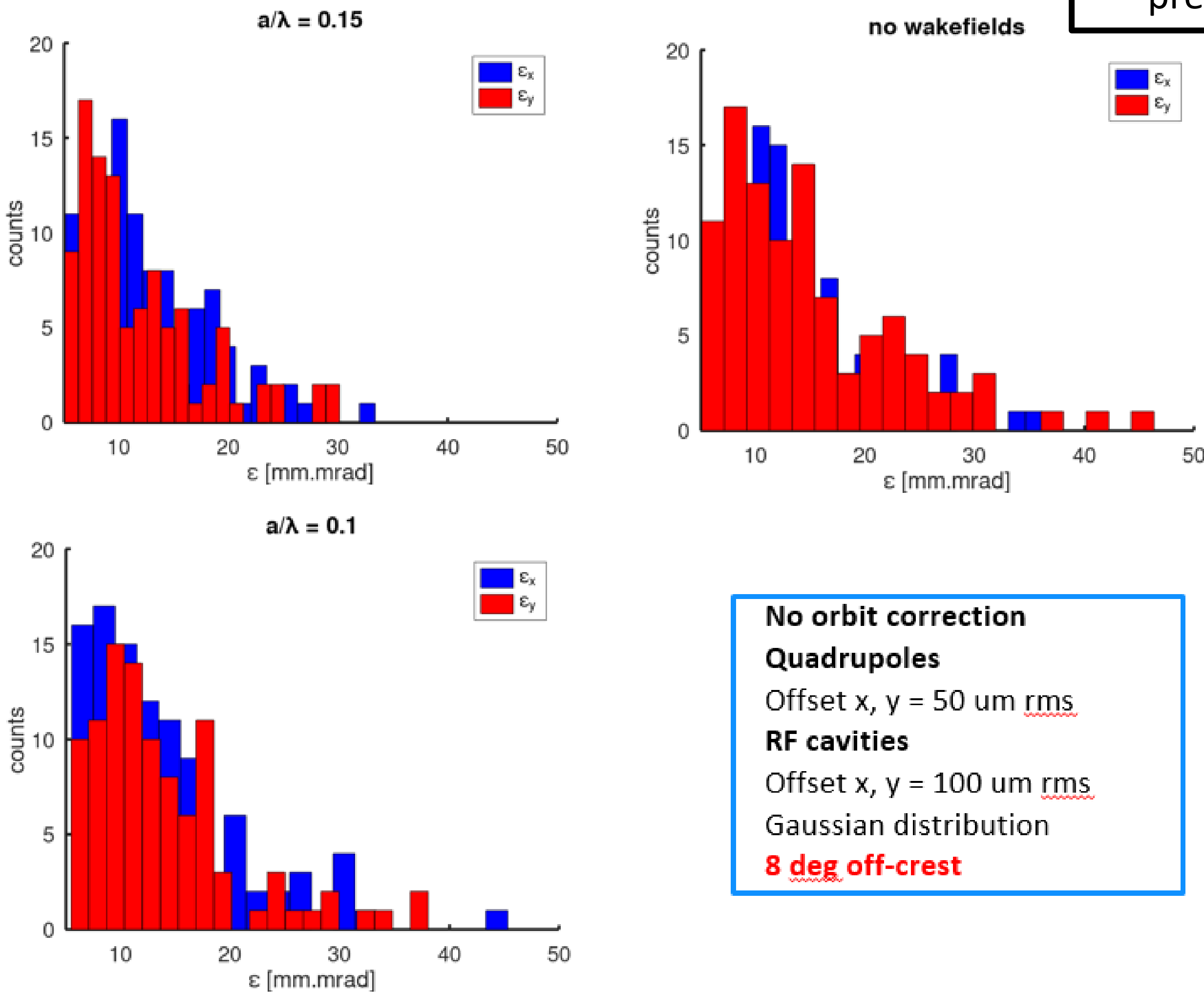
THPMS013 Proceedings of PAC07, Albuquerque, New Mexico, USA

COMPARISON OF TRACKING CODES FOR THE INTERNATIONAL LINEAR COLLIDER *

Jeffrey C. Smith[†], CLASSE, Cornell Univ., Ithaca, USA, Andrea Latina, Daniel Schulte, CERN, Geneva, Switzerland, Freddy Poirier, Nicholas Walker, DESY, Hamburg, Germany, Paul Lebrun, Kirti Ranjan, Fermilab, Batavia, USA, Kiyoshi Kubo, KEK, Ibaraki, Japan, Peter Tenenbaum, SLAC, Menlo Park, USA, Peder Eliasson, Uppsala University, Uppsala, Sweden



Expectations using RFTrack on FCC common linac



No orbit correction

Quadrupoles

Offset x, y = 50 um rms

RF cavities

Offset x, y = 100 um rms

Gaussian distribution

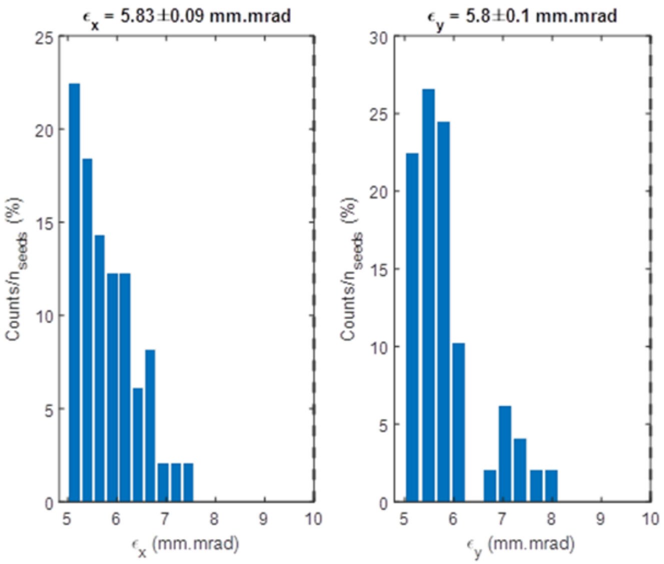
8 deg off-crest

page 16

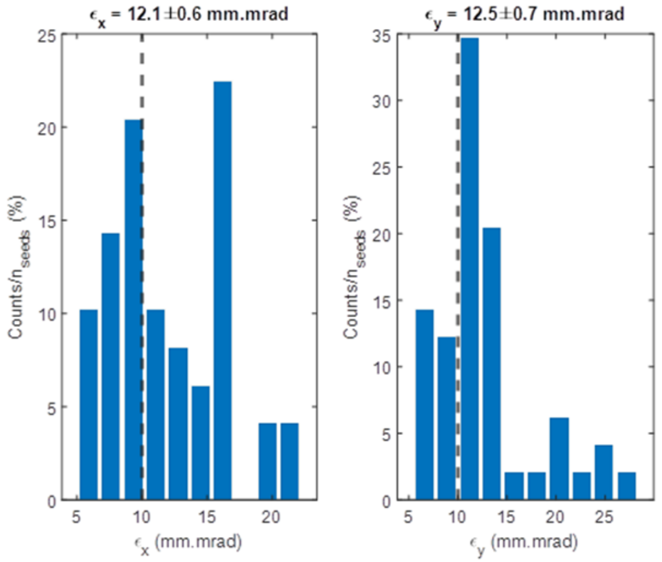
PAUL SCHERRER INSTITUT

Disagreement RFTrack vs Elegant

Elegant-RFCW (the element that I used in the past simulations):



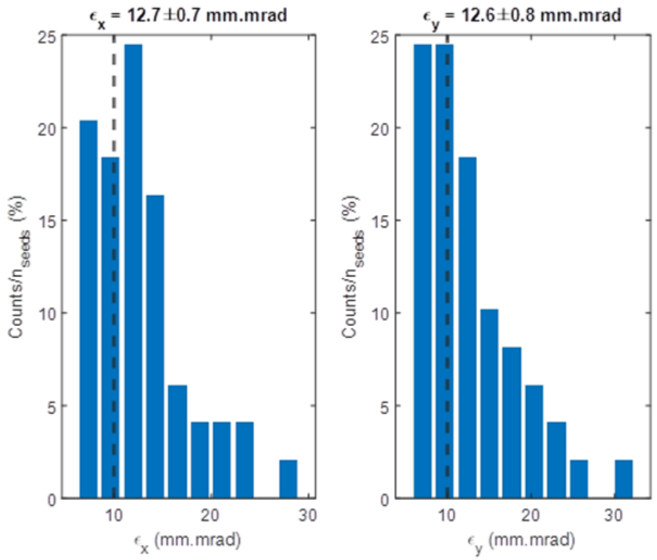
Elegant-TWLA (new element that Borland suggested to try):

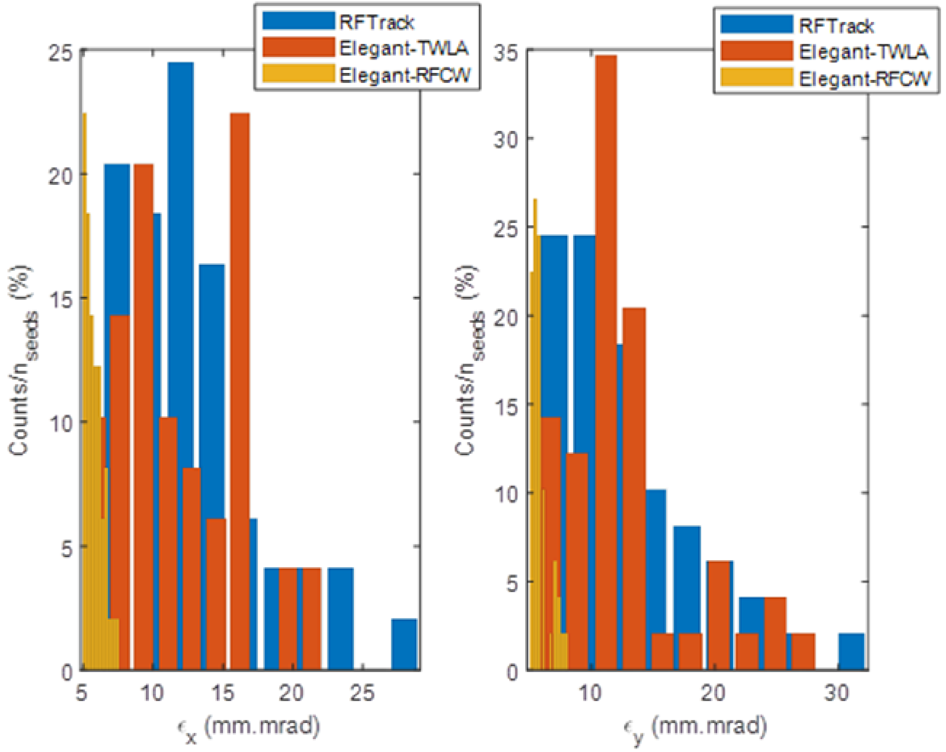


RFTrack (and Placet) produced the correct the result

Now Elegant agrees with it (them)

RFTrack:





RFTrack: Andrea implemented the orbit correction

Elegant: Borland will add this effect to the RFCW, and release a new version of Elegant

Machine errors and orbit steering in RF-Track

DFS simultaneously corrects the orbit, x_i , and minimizes the difference between the nominal and a dispersive trajectory, $x_{\Delta E,i}$. This corresponds to minimizing:

$$\chi^2 = \sum_{\text{bpms}} x_i^2 + \omega^2 \sum_{\text{bpms}} (x_{\Delta E,i} - x_i)^2 + \beta^2 \sum_{\text{corrs}} \theta_j^2$$

which is equivalent to solving the system of equations:

$$\begin{pmatrix} \mathbf{x} \\ \omega(\mathbf{x}_{\Delta E} - \mathbf{x}) \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathbf{R} \\ \omega\mathbf{D} \\ \beta\mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix} \quad \text{with} \quad R_{ij} = \frac{\partial y_i}{\partial \theta_j} \quad \text{and} \quad D_{ij} = R_{\Delta E,\,ij} - R_{ij}$$

It is a least-square problem that can be solved using a SVD.

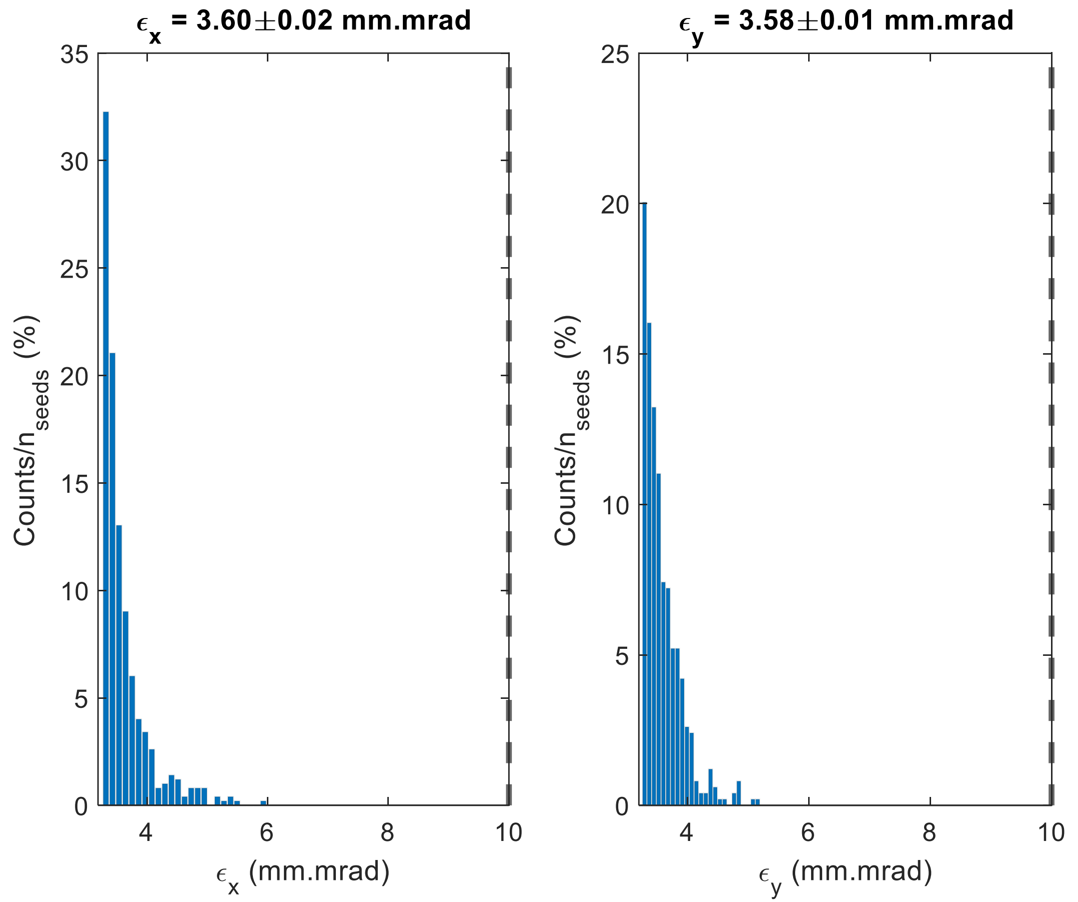
The free parameter ω accounts for the relative weight of the orbit w.r.t. the dispersive term; β is a regularization parameter to modify the condition number of the system matrix.

$$\omega^2 = \frac{\sigma^2_{\text{bpm resolution}} + \sigma^2_{\text{bpm position}}}{2\sigma^2_{\text{bpm resolution}}}$$

Electron linac no orbit correction

a/l = 0.15, on-crest

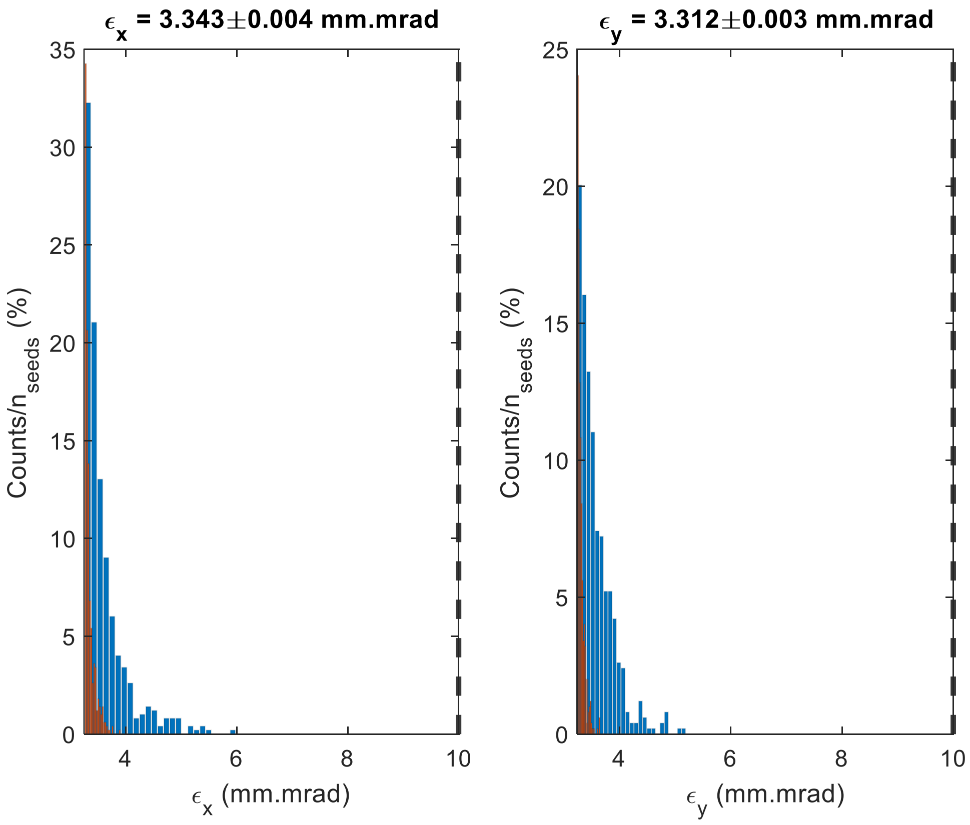
RF (100 um), quad (50 um), misaligned Gaussian distribution, 500 seeds

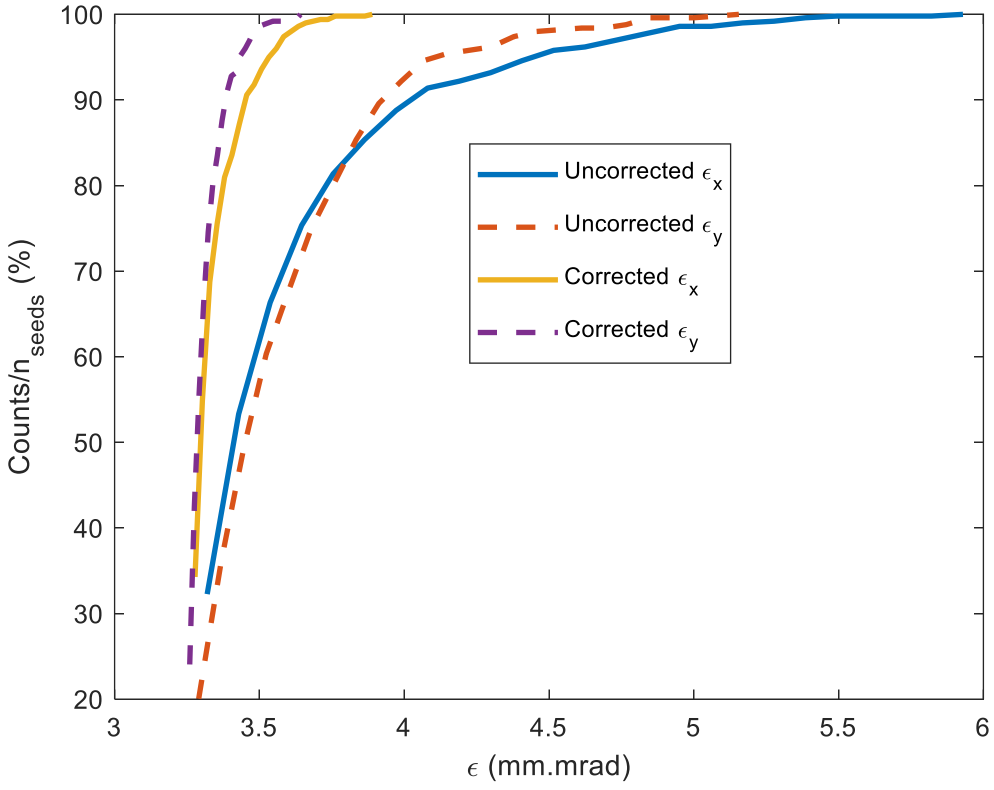


It does not seem to be critical for the static misalignments

Electron linac **with orbit correction**

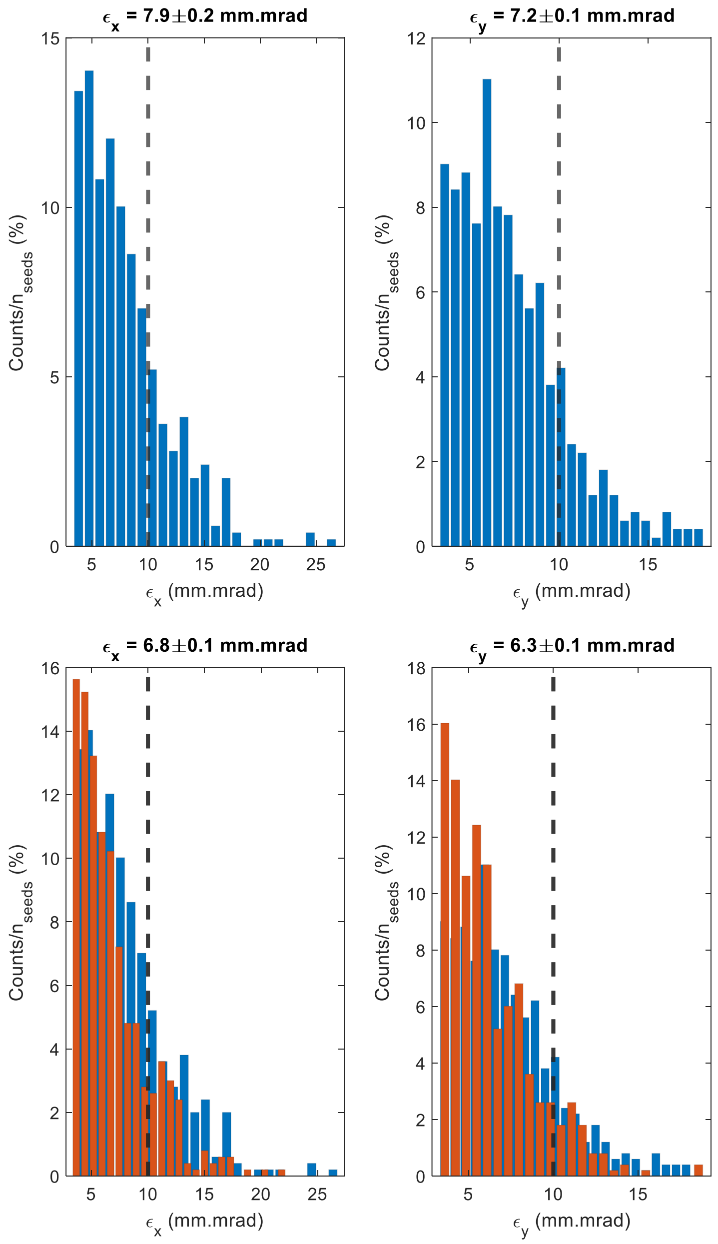
a/l = 0.15, on-crest
RF (100 um), quad (50 um), BPM (30 um) misaligned Gaussian distribution, 500 seeds



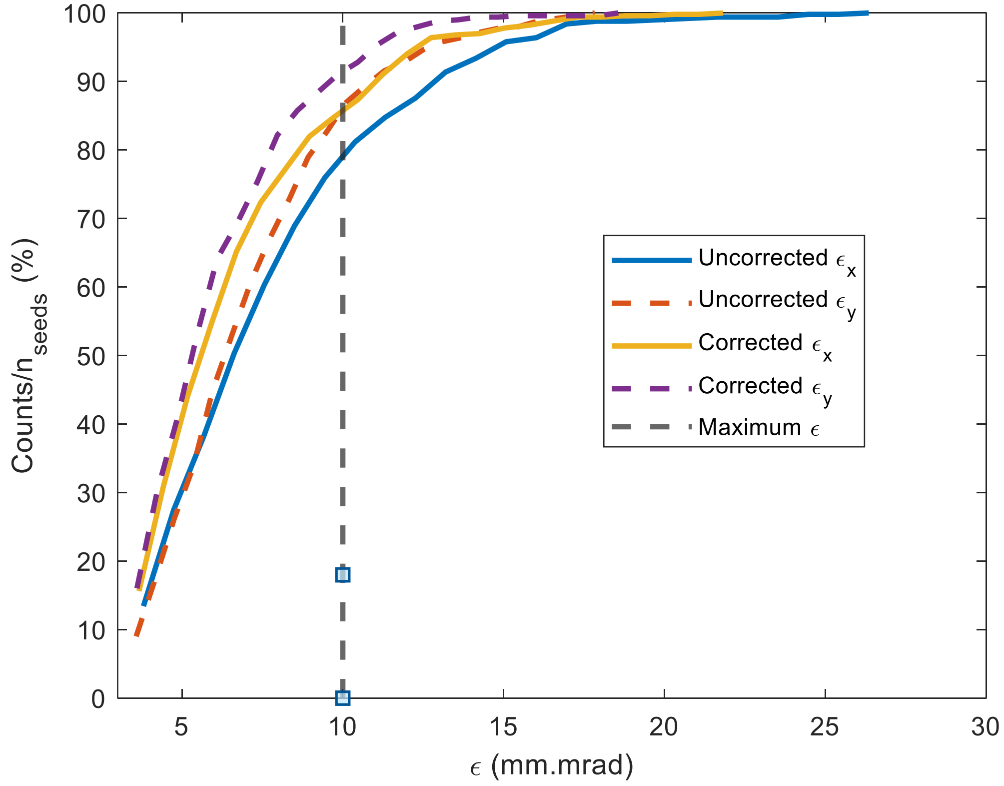


It does not seem to be critical for the static misalignments

Electron linac without/with orbit correction, **a/l = 0.1**



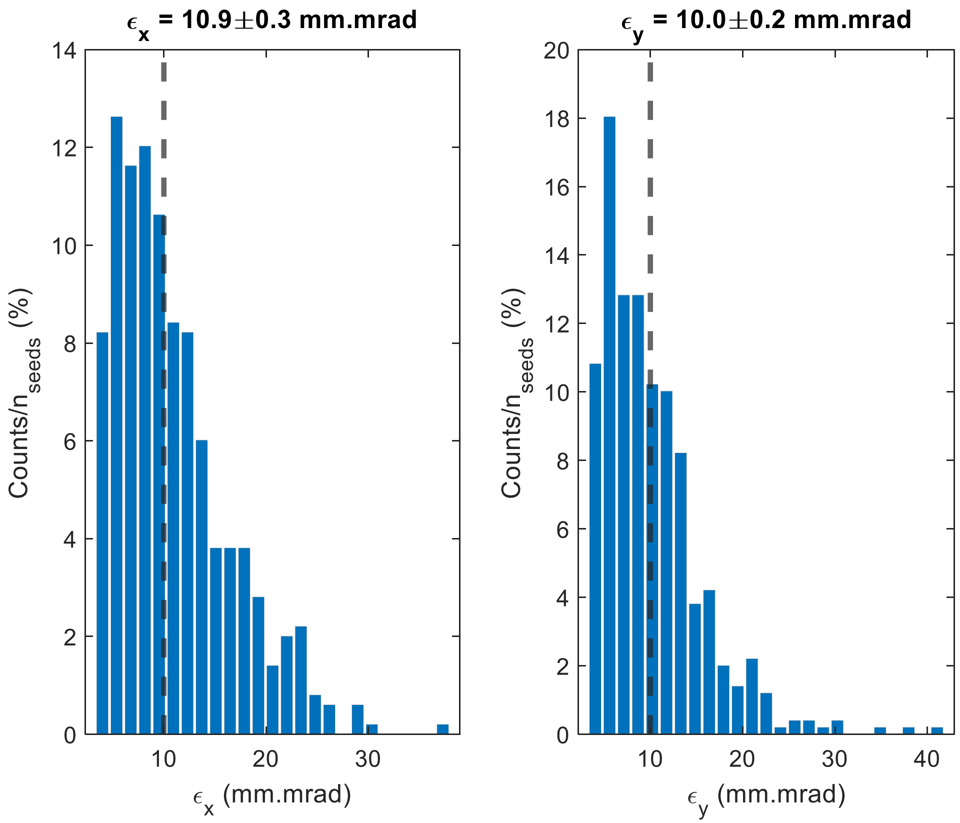
/data/user/bettoni_s/RFTrack_sim/Single_Transv/OrbitCorr/Linac1_ok/a_lambda_0p10



Problematic for static misalignments at least with one-to-one correction

Common linac no orbit correction

a/l = 0.15, 82 degrees
RF (100 um), quad (50 um), misaligned Gaussian distribution, 500 seeds

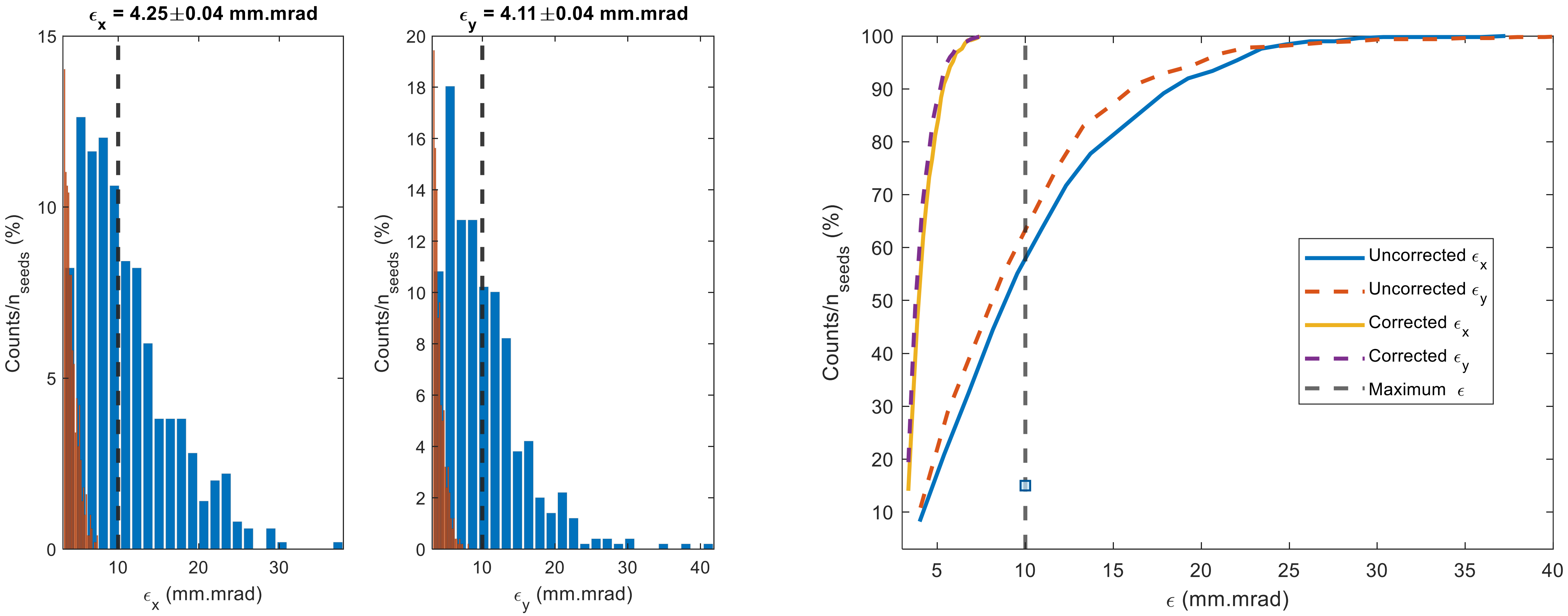


Critical

Common linac **with orbit correction**

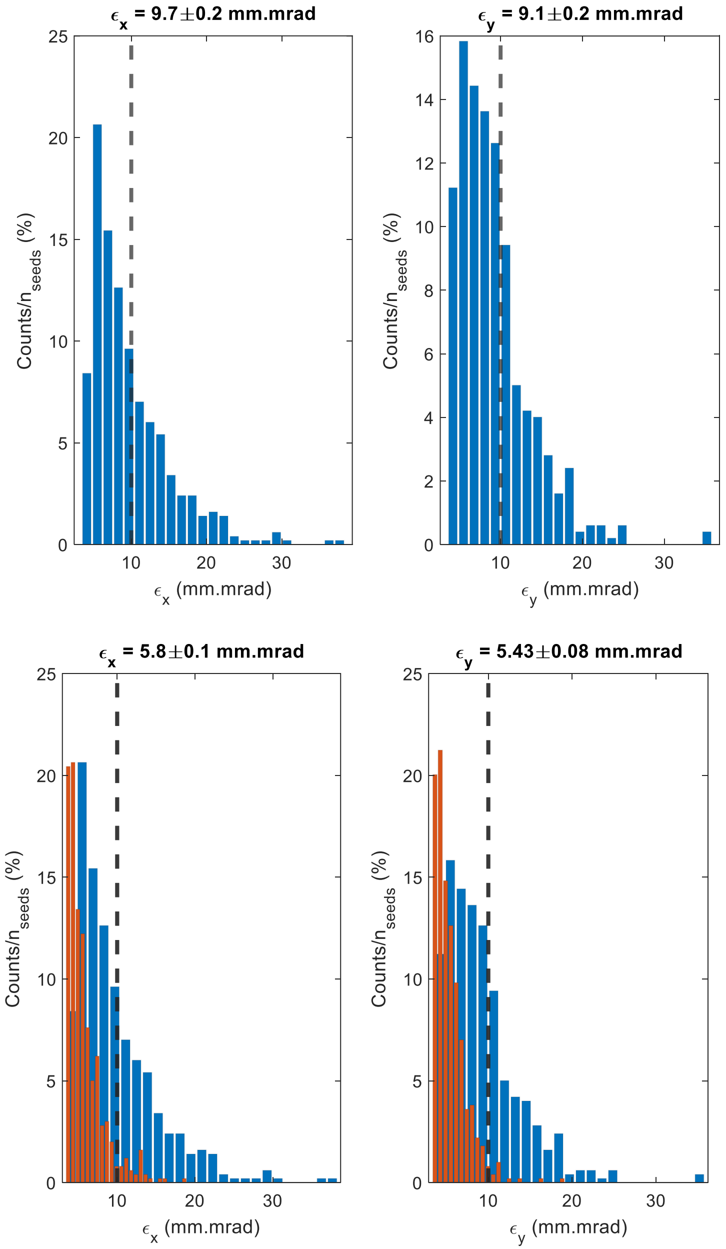
a/l = 0.15, 82 degrees

RF (100 um), quad (50 um), BPM (30 um) misaligned Gaussian distribution, 500 seeds

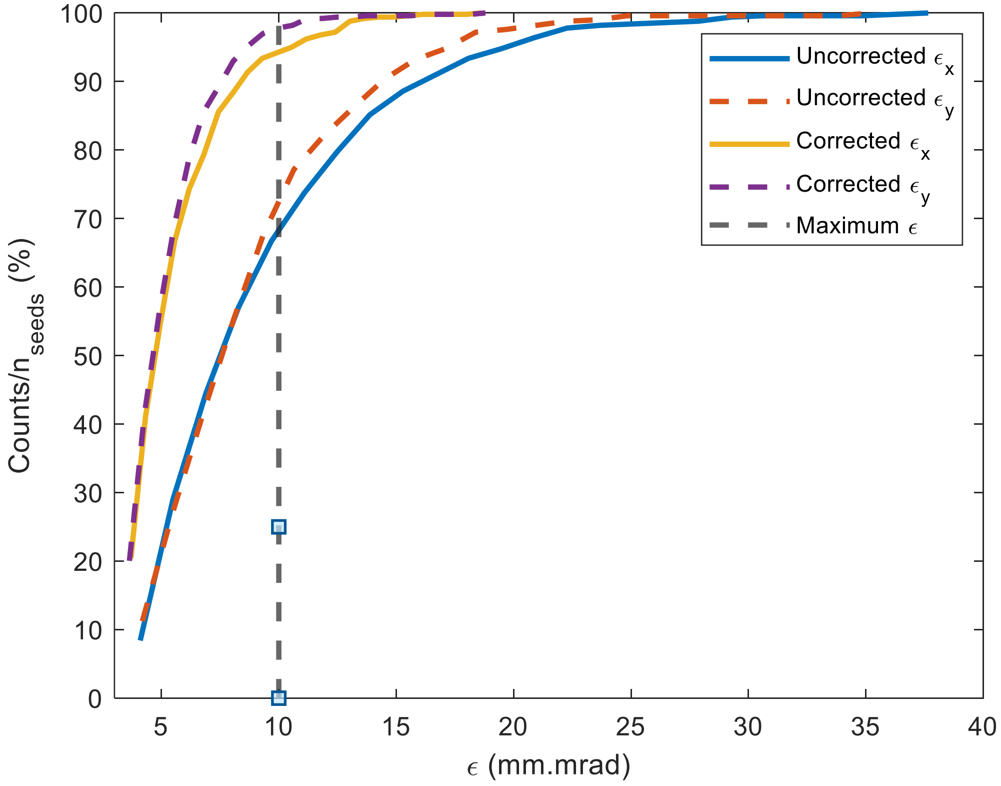


Situation recovered

Common linac without/with orbit correction, **a/l = 0.1**



/data/user/bettoni_s/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/a_lamba_0p10



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Orbit jitter amplification

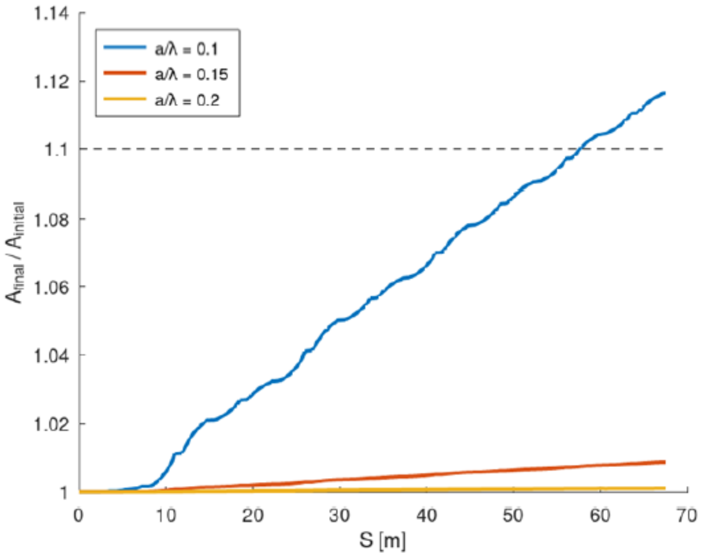


Figure 17: Action amplification as a function of the electron linac location for several geometries labelled by a/λ. The rf frequency is 2.8 GHz. The dashed line indicates the 10 % increase with respect to the initial values.

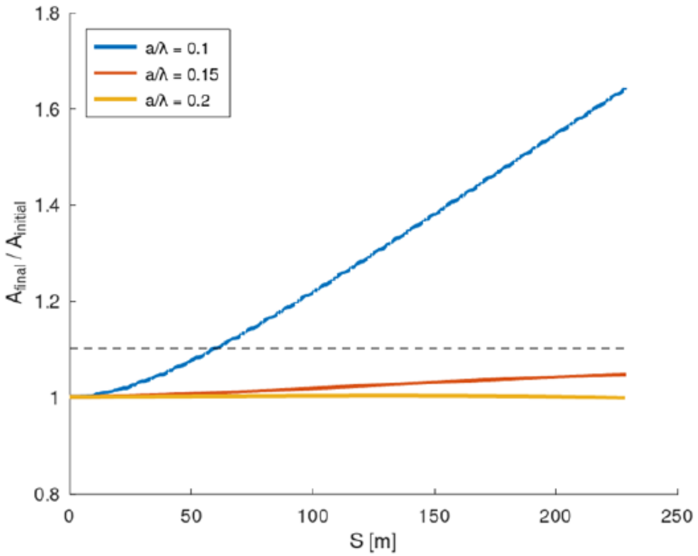


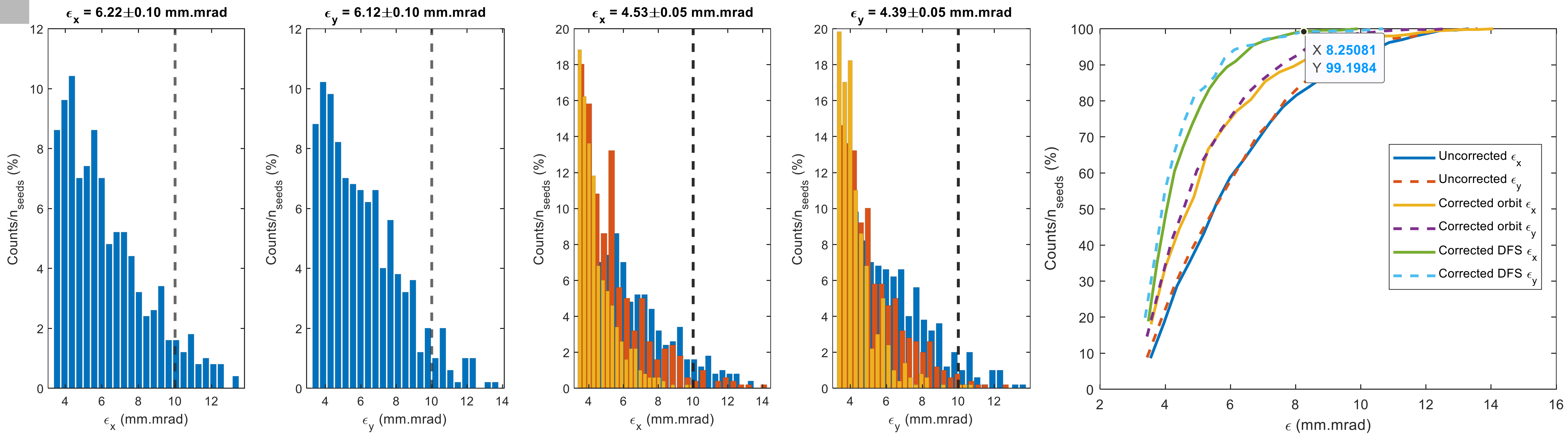
Figure 18: Action amplification as a function of the common linac location for several geometries labelled by a/λ. The dashed line indicates the 10 % increase from the initial values.

At the moment this is determining the smallest aperture of the rf structures looking at the transverse dynamics. Also for the longitudinal…see next slide

Electron linac (0.2 GeV -> 1.54 GeV)

Electron linac, a/l = 0.10

GOOD DFS

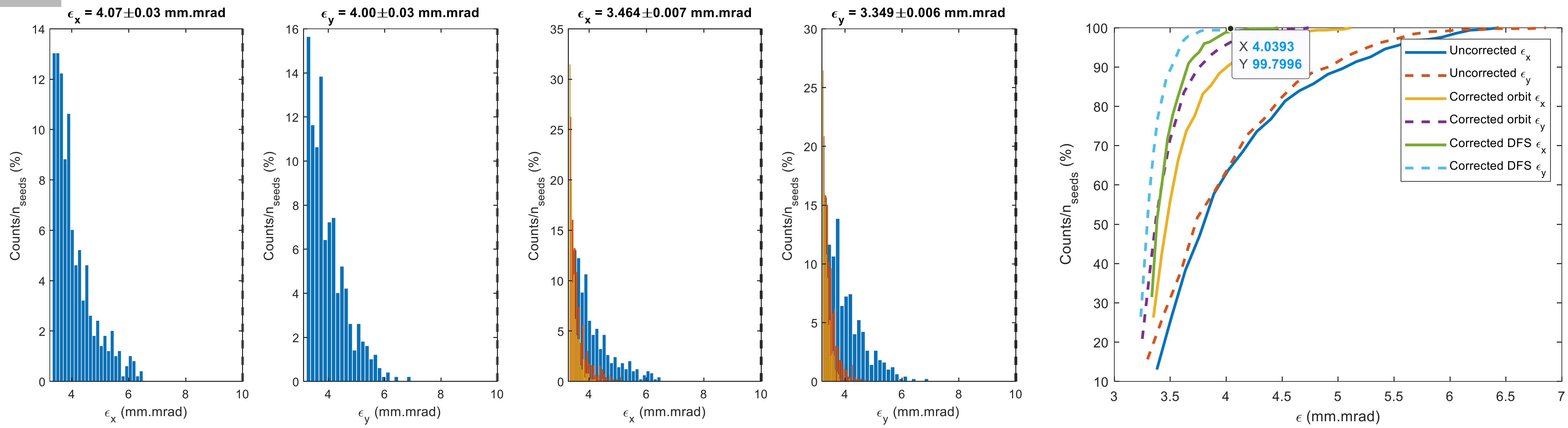


100% seeds: Δε = 5 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac1_ok/DFS/Ok/a_lambda*

Electron linac, **a/l = 0.12**

GOOD DFS

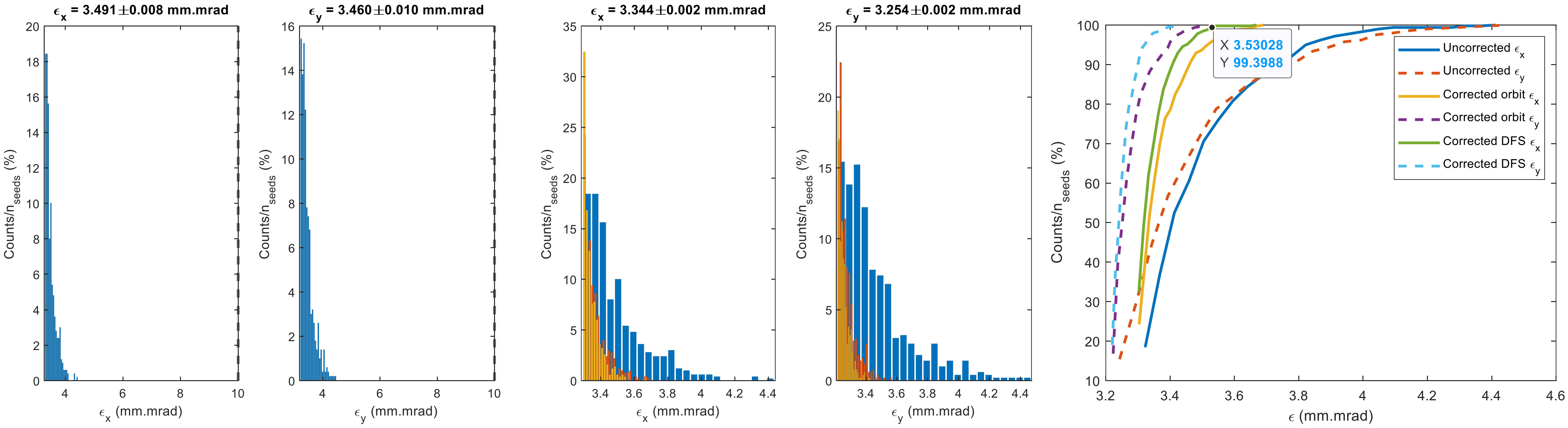


100% seeds: $\Delta\varepsilon$ = 0.8 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac1_ok/DFS/Ok/a_lambda*

Electron linac, a/l = 0.14

GOOD DFS

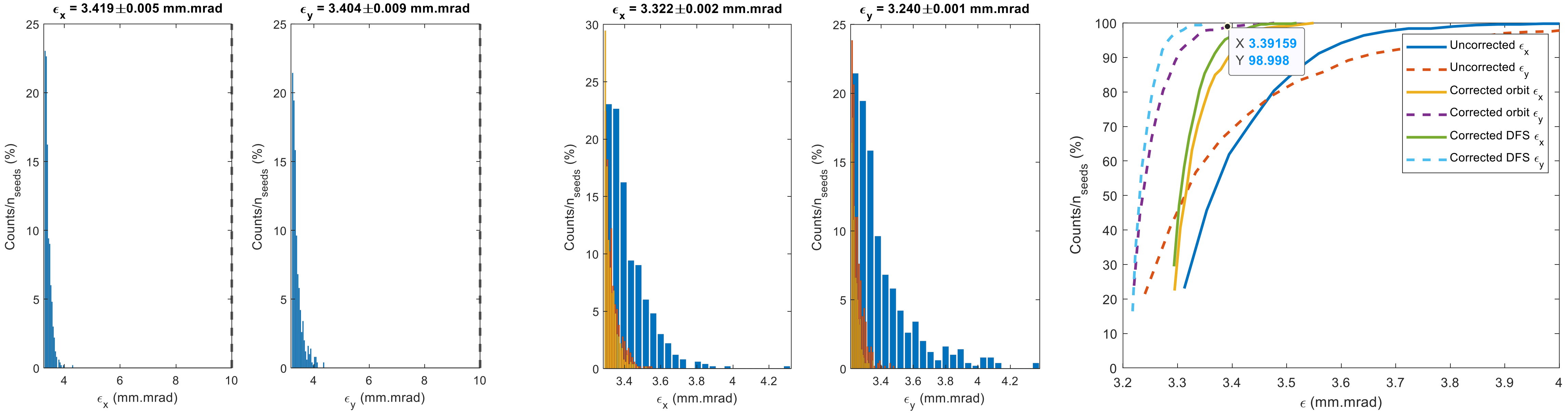


100% seeds: $\Delta\varepsilon$ = 0.3 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac1_ok/DFS/Ok/a_lambda*

Electron linac, a/l = 0.15

GOOD DFS



100% seeds: $\Delta\varepsilon$ = 0.2 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac1_ok/DFS/Ok/a_lambda*

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Electron linac: summary

GOOD DFS

Electron linac, S-band (2.8 GHz), on-crest, emittance increase (mm.mrad):

	~One-to-one	DFS
a/l = 0.10	13.5	5.0
a/l = 0.12	/	0.8
a/l = 0.13	1.4	/
a/l = 0.14	0.8	0.3
a/l = 0.15	0.5	0.2

sigmaX_quad = 0.050; % mm rms
sigmaY_quad = 0.050; % mm rms

sigmaX_rf = 0.100; % mm rms
sigmaY_rf = 0.100; % mm rms

sigmaX_bpm = 0.030; % mm rms
sigmaY_bpm = 0.030; % mm rms

sigmaBPMS = 0.010; % mm, bpm resolution

Initial emittance = 3.2 mm.mrad
500 seeds
RF-Track

Assuming a very pessimistic way to estimate the emittance increase (~99% seeds) the emittance at the end of the electron linac is <4 mm.mrad for a/l>=0.12

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac1_ok/DFS/Ok/a_lambda*

Common linac (1.54 eV -> 6 GeV)

GOOD DFS

Common linac, a/l = 0.10

Stopped by the cluster at seed n. 456 over 500

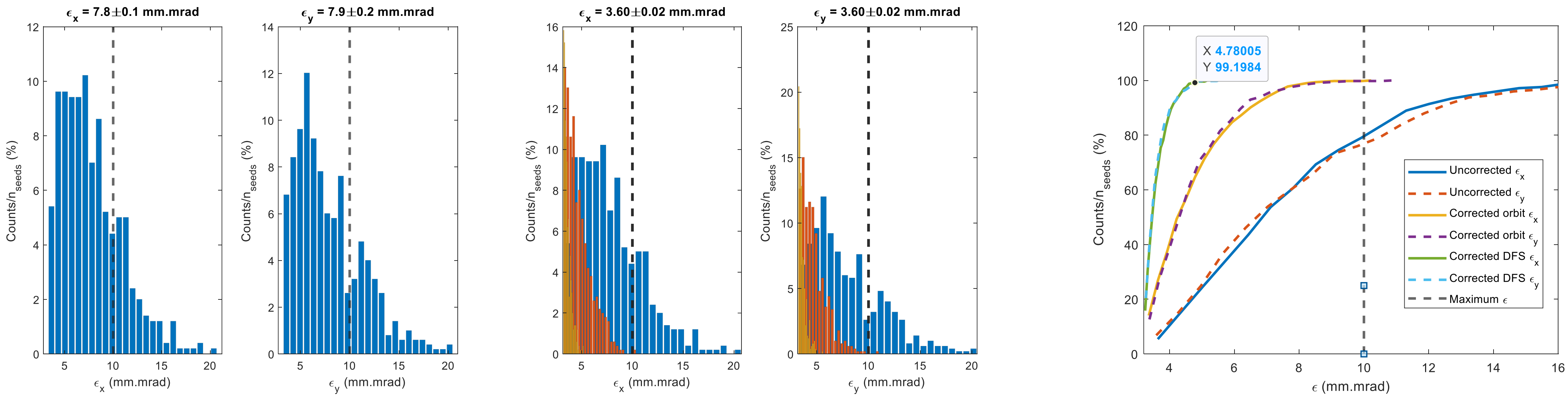
```
Machine seed n. 450
Elapsed time is 200.995 seconds.
Uncorrected bunch: 10.4182, 35.0441
---------------------
Corrected bunch: 4.1634, 6.855
Machine seed n. 451
Elapsed time is 200.639 seconds.
Uncorrected bunch: 6.9875, 19.7454
---------------------
Corrected bunch: 3.8031, 5.2225
Machine seed n. 452
Elapsed time is 201.343 seconds.
Uncorrected bunch: 15.3222, 10.2668
---------------------
Corrected bunch: 3.9718, 4.1807
```

100% seeds: $\Delta\varepsilon$ > 10 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok

Common linac, a/l = 0.12

GOOD DFS

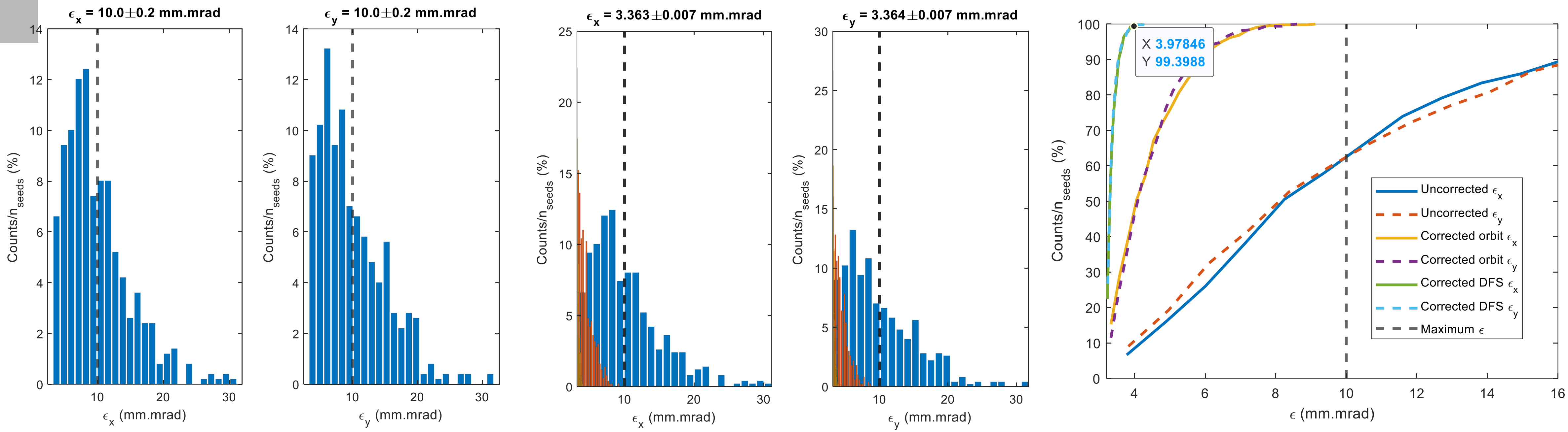


100% seeds: $\Delta\varepsilon$ = 1.6 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok

Common linac, a/l = 0.14

GOOD DFS

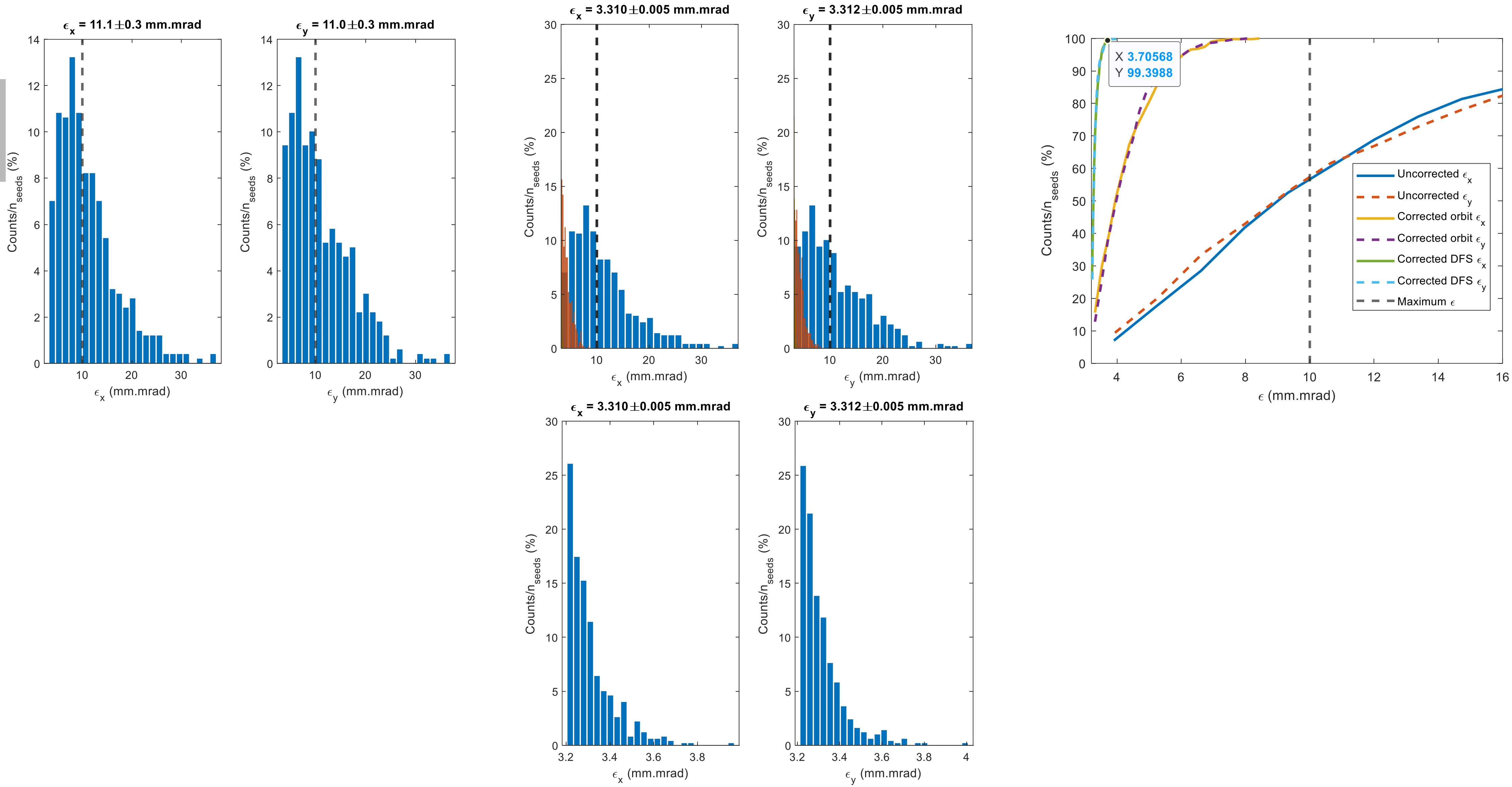


100% seeds: $\Delta\varepsilon$ = 0.8 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok

Common linac, a/l = 0.15

GOOD DFS



100% seeds: $\Delta\varepsilon$ = 0.5 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok

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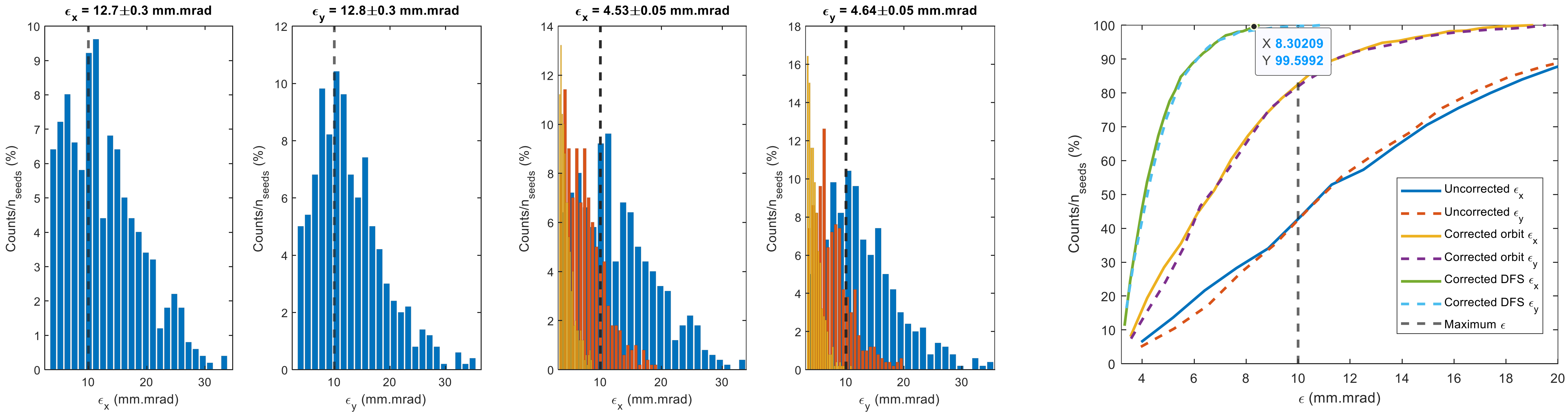
Common linac, a/l = 0.10, **at 0 deg**

GOOD DFS

I check what happens when I stay at 0 deg in common linac. See optimization for the HE linac option

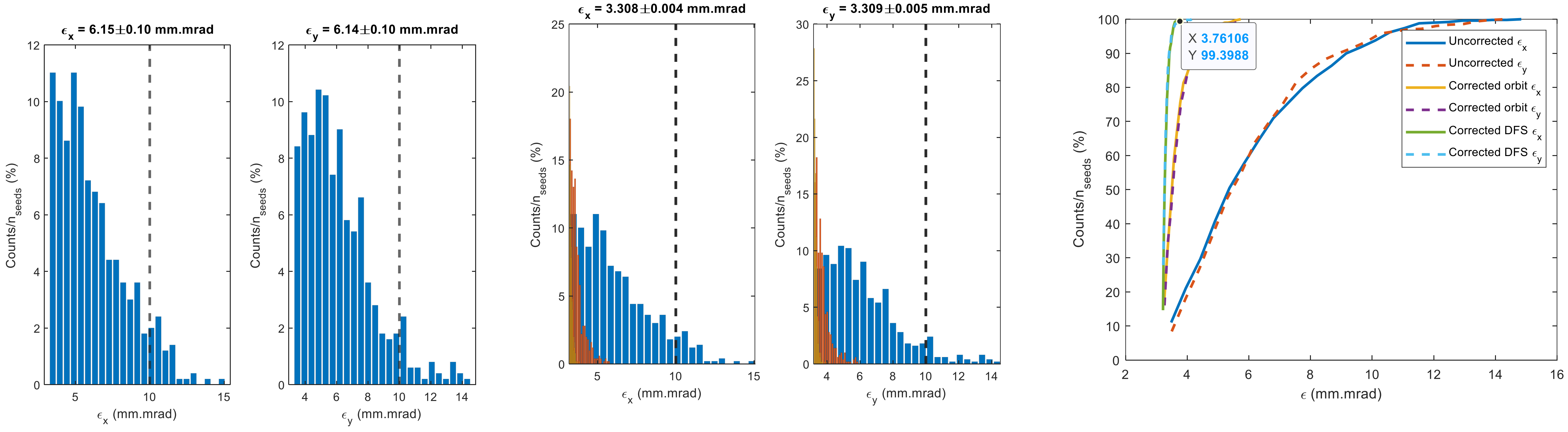


100% seeds: $\Delta\varepsilon$ = 5.1 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok/0_deg/a_lambda_0p*

Common linac, **a/l = 0.12**, at 0 deg

GOOD DFS



100% seeds: $\Delta\varepsilon$ = 0.6 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok/0_deg/a_lambda_0p*

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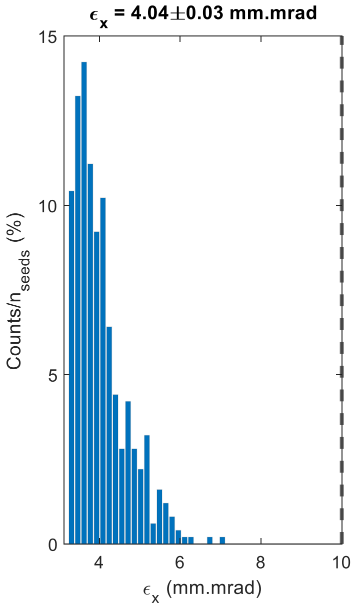
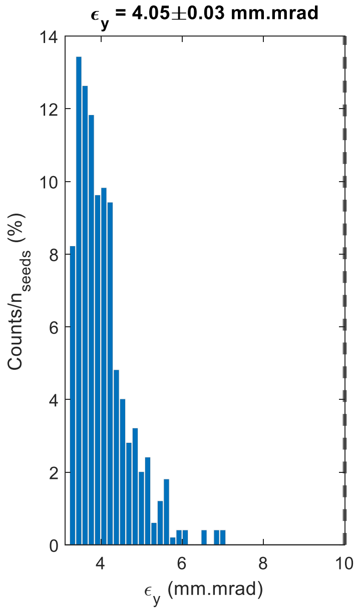
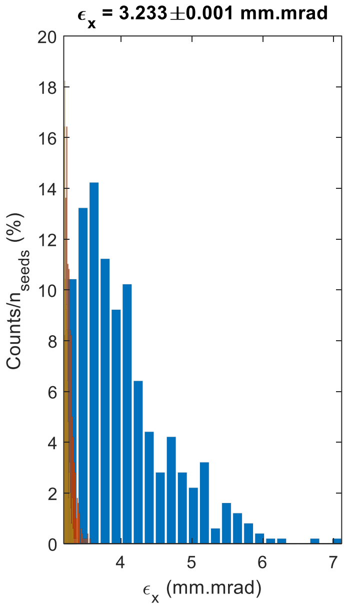
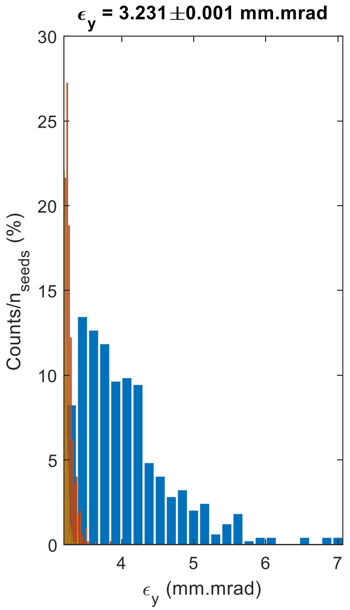
Common linac, **a/l = 0.14**, at 0 deg

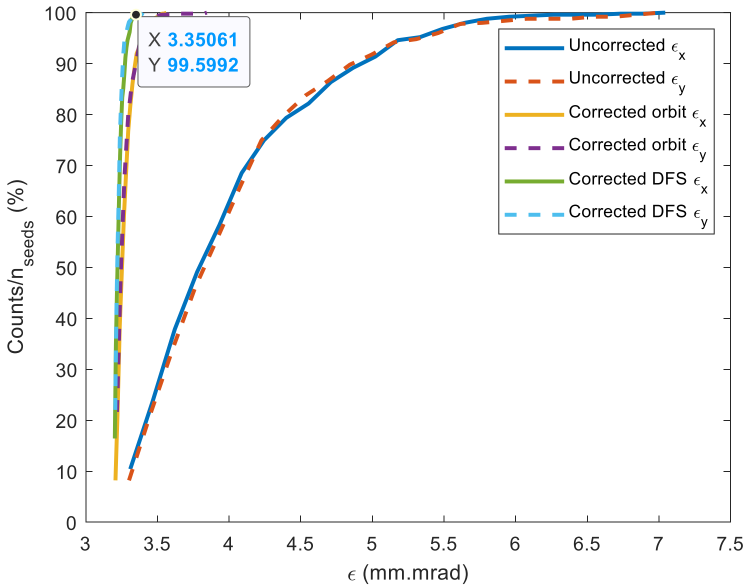
GOOD DFS









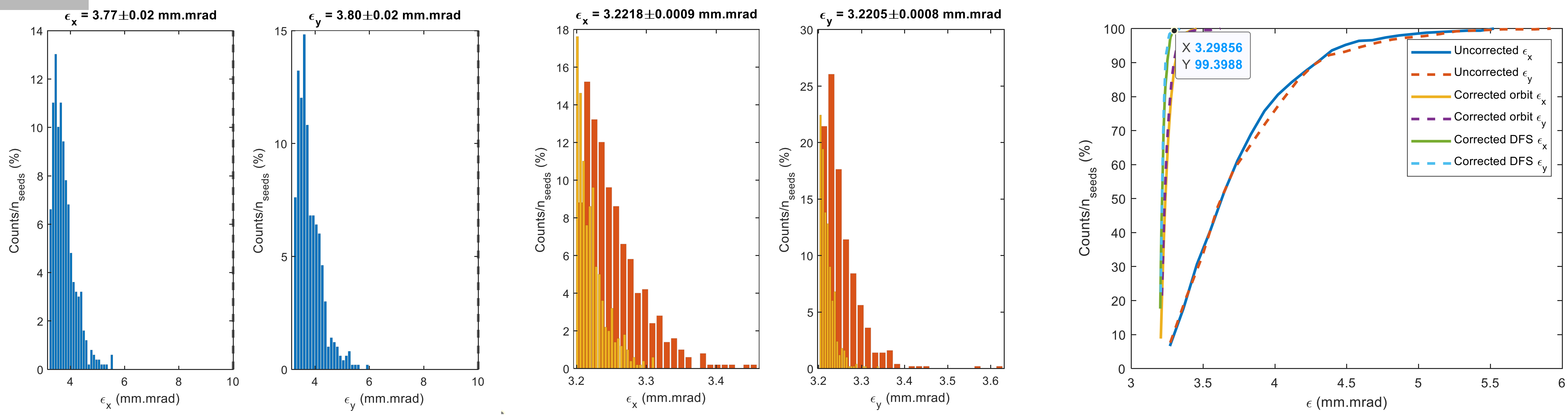


100% seeds: $\Delta\varepsilon$ = 0.2 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok/0_deg/a_lambda_0p*

GOOD DFS

Common linac, **a/l = 0.15**, at 0 deg



100% seeds: $\Delta\varepsilon$ = 0.1 mm.mrad

/psi/home/bettoni_s/data/RFTrack_sim/Single_Transv/OrbitCorr/Linac2_ok/DFS/Ok/0_deg/a_lambda_0p*

Common linac: summary

GOOD DFS

Common linac only, S-band (2.8 GHz), emittance increase (mm.mrad)

	82 deg* (~one-to-one)	82 deg* (DFS)	0 deg (DFS)
a/l = 0.10	13.0		5.1
a/l = 0.12	/	1.6	0.6
a/l = 0.14	6.1	0.8	0.2
a/l = 0.15	3.7	0.5	0.1

sigmaX_quad = 0.050; % mm rms
sigmaY_quad = 0.050; % mm rms

sigmaX_rf = 0.100; % mm rms
sigmaY_rf = 0.100; % mm rms

sigmaX_bpm = 0.030; % mm rms
sigmaY_bpm = 0.030; % mm rms

sigmaBPMS = 0.010; % mm, bpm resolution

Initial emittance = 3.2 mm.mrad
500 seeds
RF-Track

* The optimal phase will be different for different a/l, and the bunch length, and it will be revised. This scan shows the sensitivity (report n. 5)

f (GHz)	G (MV/m)	a/λ	a (mm)	Maximum σ_z (mm)		Maximum phase (deg)	
				δ_E = 0.1 %	δ_E = 0.15 %	δ_E = 0.1 %	δ_E = 0.15 %
2.8	25	0.1	10.7	0.8	1.2	69	89
2.8	25	0.15	16.1	0.8	1	79	81
2.8	25	0.2	21.4	0.7	0.8	82	81
2.8	40	0.1	10.7	0.8	0.8	77	85
2.8	40	0.15	16.1	0.7	1	82	79
2.8	40	0.2	21.4	0.7	0.8	85	84
5.6	25	0.1	5.4	NaN	NaN	NaN	NaN
5.6	25	0.15	8.0	0.5	0.8	61	87
5.6	25	0.2	10.7	0.5	0.6	74	66
5.6	40	0.1	5.4	0.4	0.5	81	73
5.6	40	0.15	8.0	0.5	0.5	71	72
5.6	40	0.2	10.7	0.4	0.5	67	72

Exit of the common linac: summary

Emittance at the exit of the common linac for several geometries

	Electron linac	Common linac (82 deg)	Common linac (90 deg)	Final (cl 82 deg)	Final (cl 90 deg)
a/l = 0.10	0.10		5.1		
a/l = 0.12	0.8	1.6	0.6	5.6	4.6
a/l = 0.14	0.3	0.8	0.2	4.3	3.7
a/l = 0.15	**0.2**	**0.5**	**0.1**	**3.9**	**3.5**

Starting emittance is 3.2 mm.mrad, bunch length = 1 mm (optimal values may be different in case we move away form the 0.15 case and bunch length)
a/l = 0.10 was problematic for the jitter

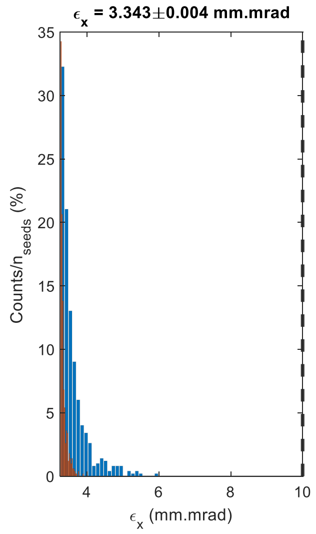
Final emittance<6 mm.mrad (pessimistic estimation), bunch length = 1 mm, final energy spread = 0.15%

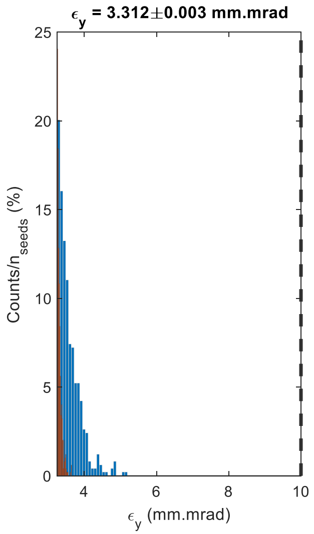
Agreed a/l = 0.15 during the meeting. To be kept also for the HE linac

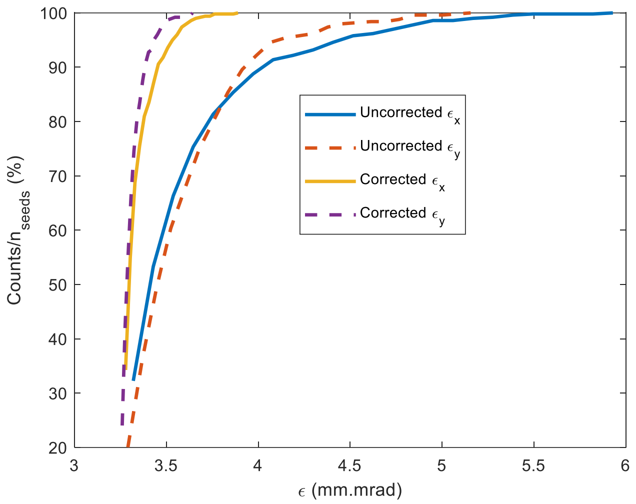
Summary electron linac

On-crest, bunch length = 1 mm

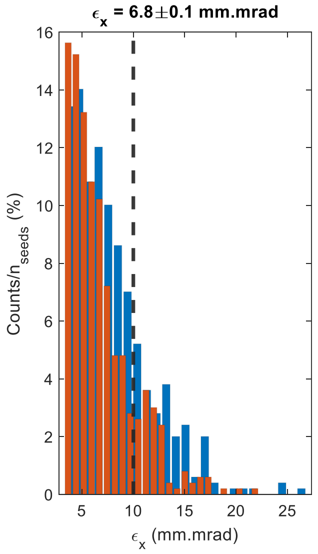
0.15

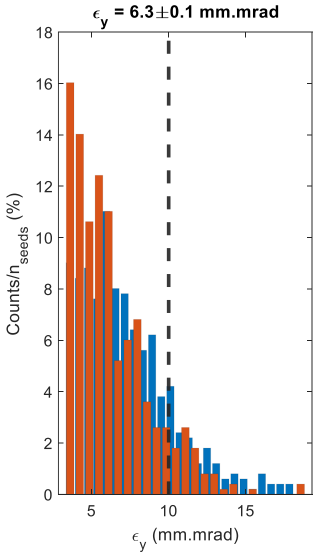


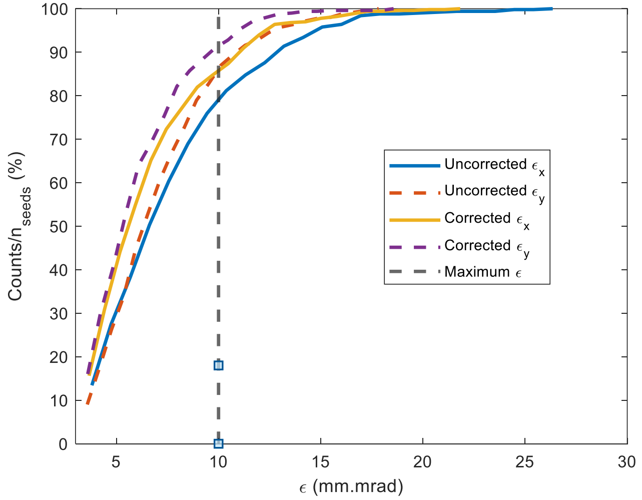




0.10







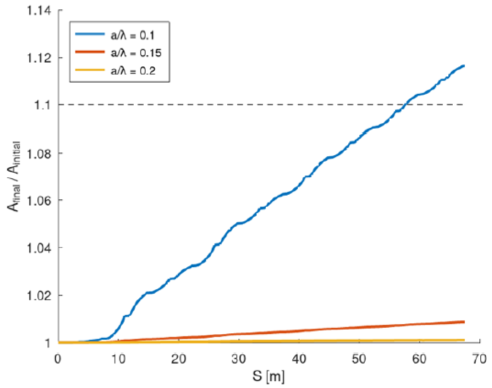


Figure 17: Action amplification as a function of the electron linac location for several geometries labelled by a/λ. The rf frequency is 2.8 GHz. The dashed line indicates the 10 % increase with respect to the initial values.

0.15 (a = 16.1 mm): ok also without the orbit correction
0.10 (a = 10.7 mm): at the limit also with the orbit correction

Between 0.10 and 0.15: probably 0.13-0.14 ok

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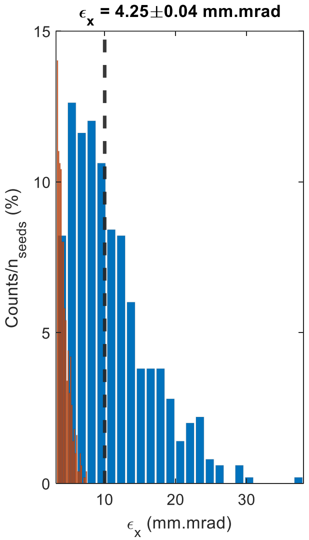
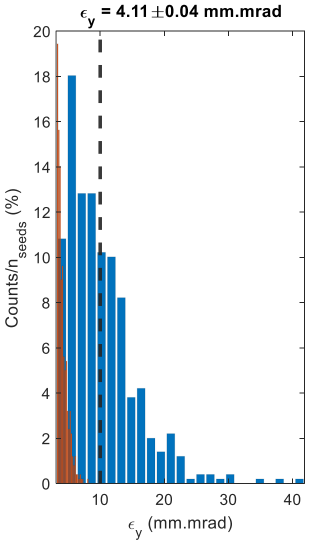
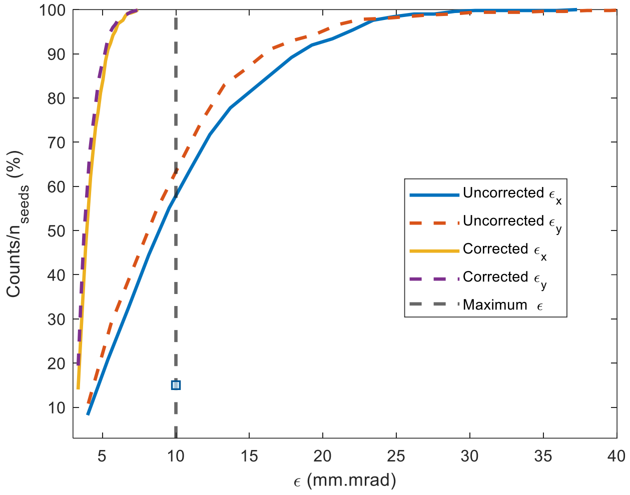
Summary **common linac**

-8 deg, bunch length = 1 mm

0.15







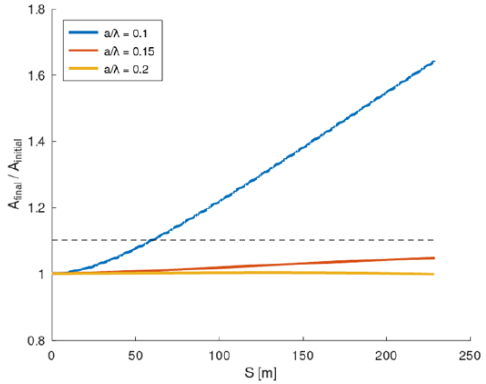
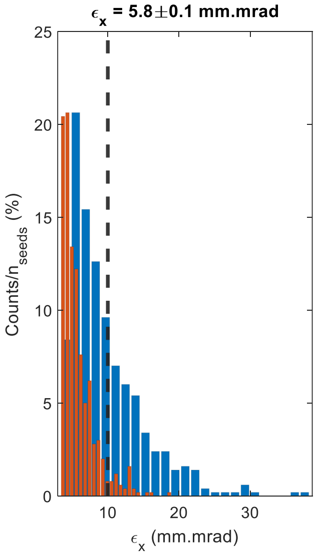
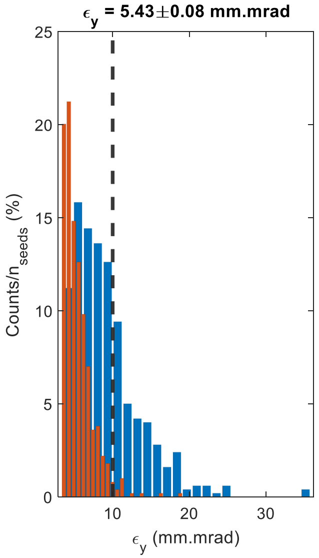
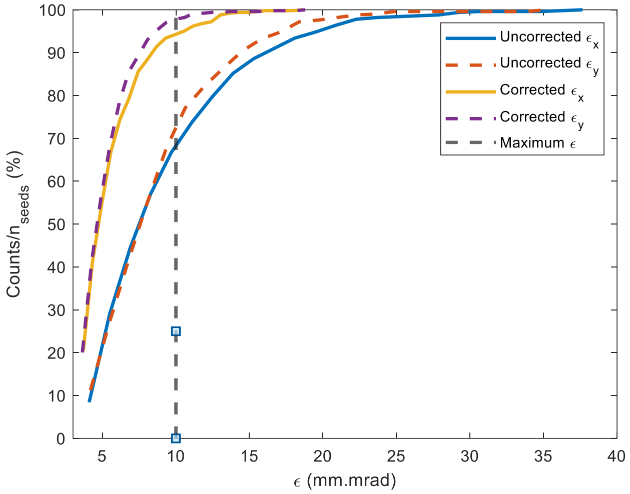


Figure 18: Action amplification as a function of the common linac location for several geometries labelled by a/λ. The dashed line indicates the 10 % increase from the initial values.

0.10







Better situation than for the e-linac

0.15 (a = 16.1 mm): ok also without the orbit correction
0.10 (a = 10.7 mm): at the limit but close to good situation with orbit correction (few % seeds not good)

Between 0.10 and 0.15: probably 0.11-0.12 ok

- Considering the small difference, better to have the same cavity for both?
- I will run a scan at the intermediate points

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C-band (f = 5.6 GHz), Nbins = 5

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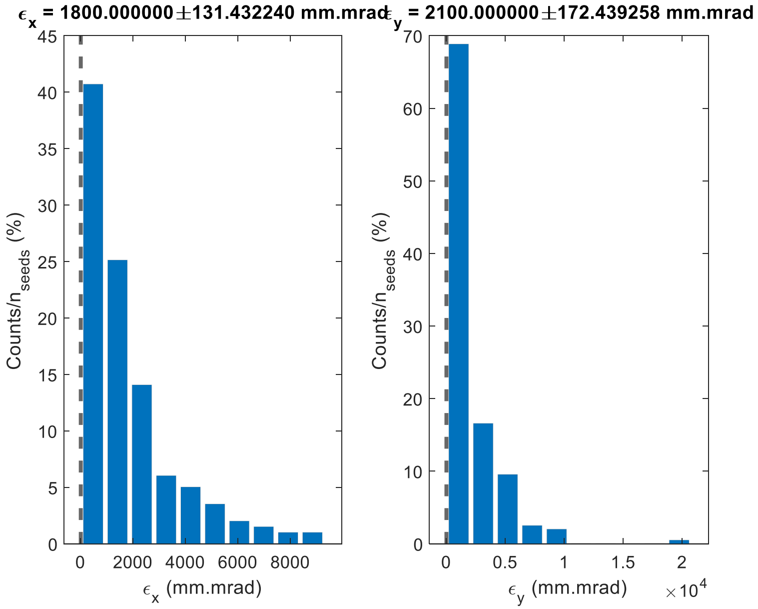
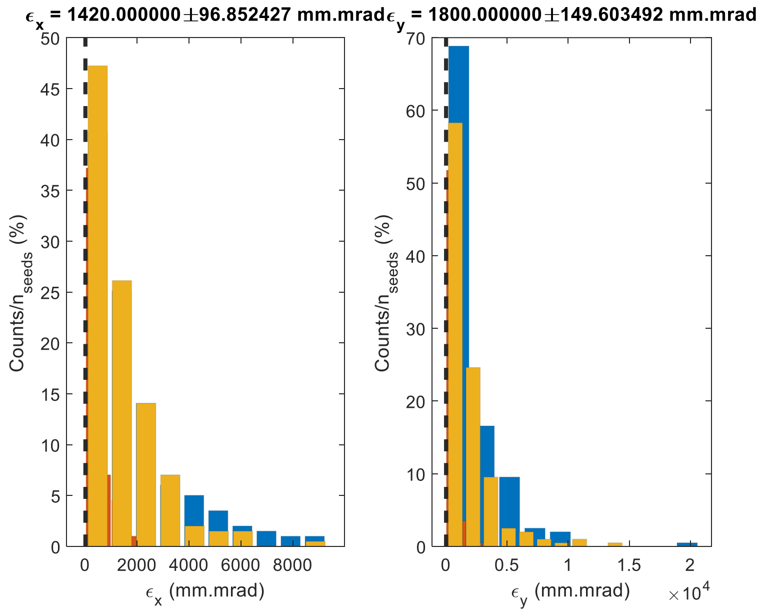
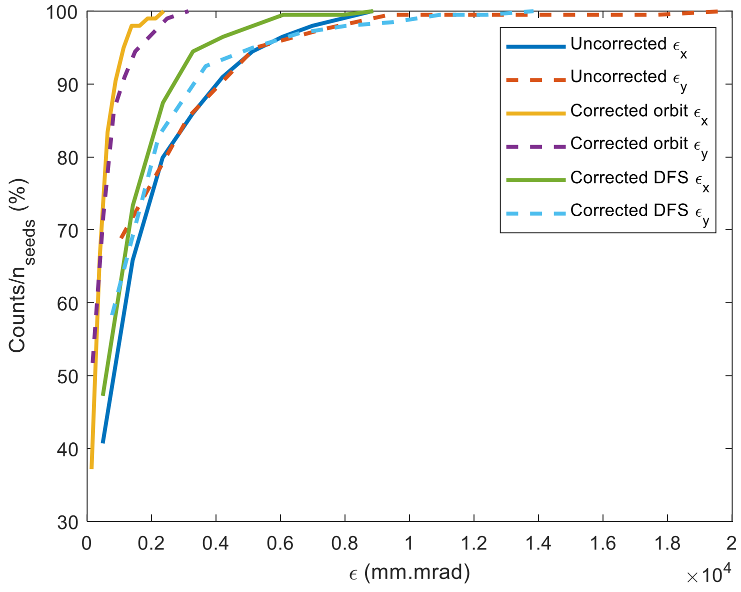
a/l = 0.12, a = 6.4 mm

- Not good DFS

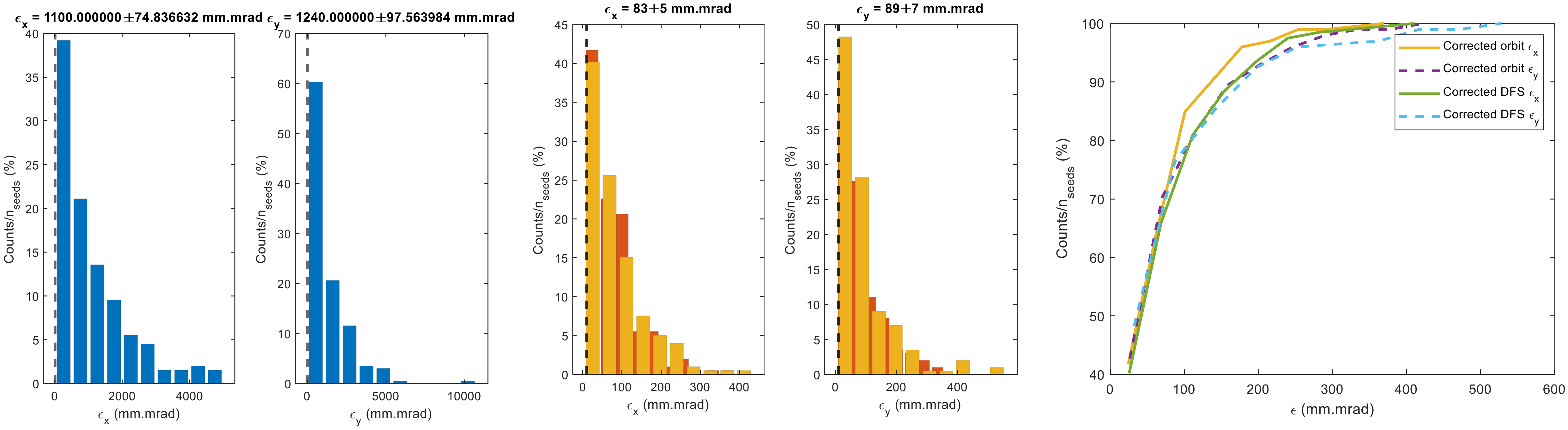






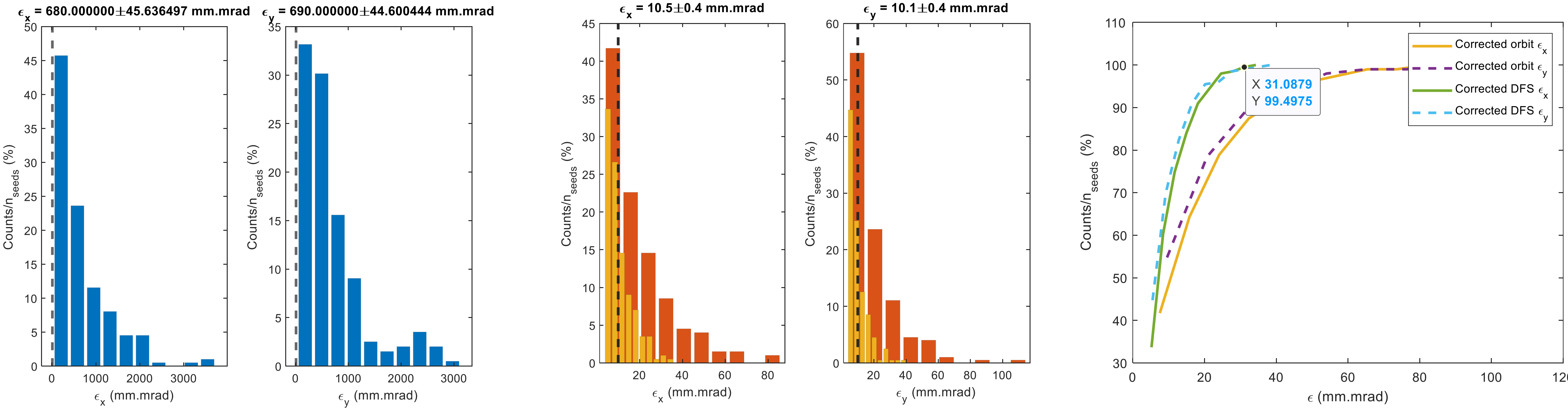
a/l = 0.13, a = 7 mm

- Not good DFS



a/l = 0.14, a = 7.5 mm

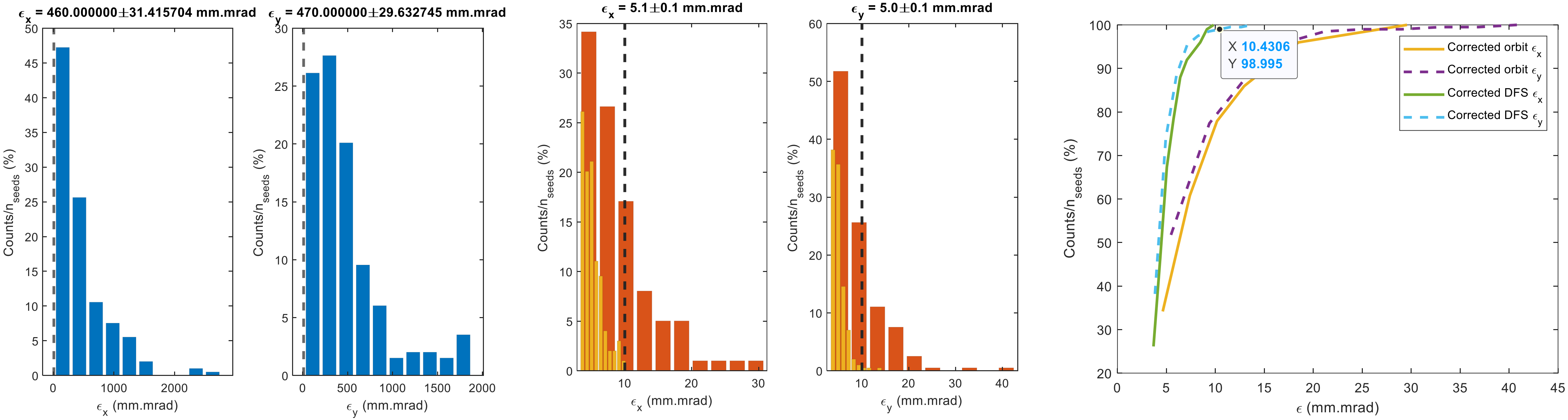
- Ok DFS



Δε = 31-3.2 = 27.8 mm.mrad

a/l = 0.15, a = 8 mm

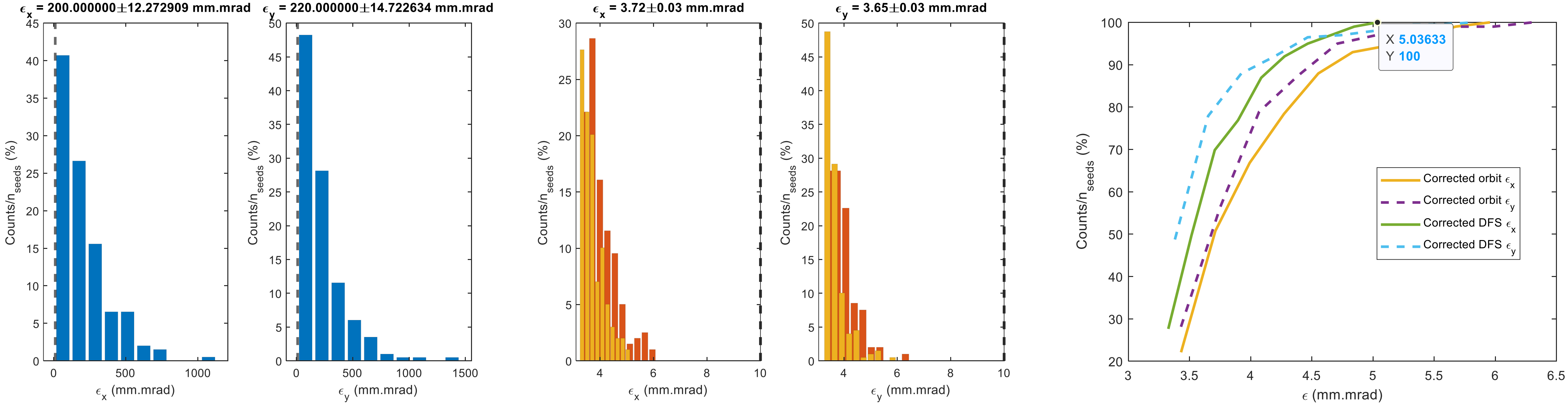
- Ok DFS



$\Delta\varepsilon$ = 10.5-3.2 = 7.3 mm.mrad

a/l = 0.18, a = 9.6 mm

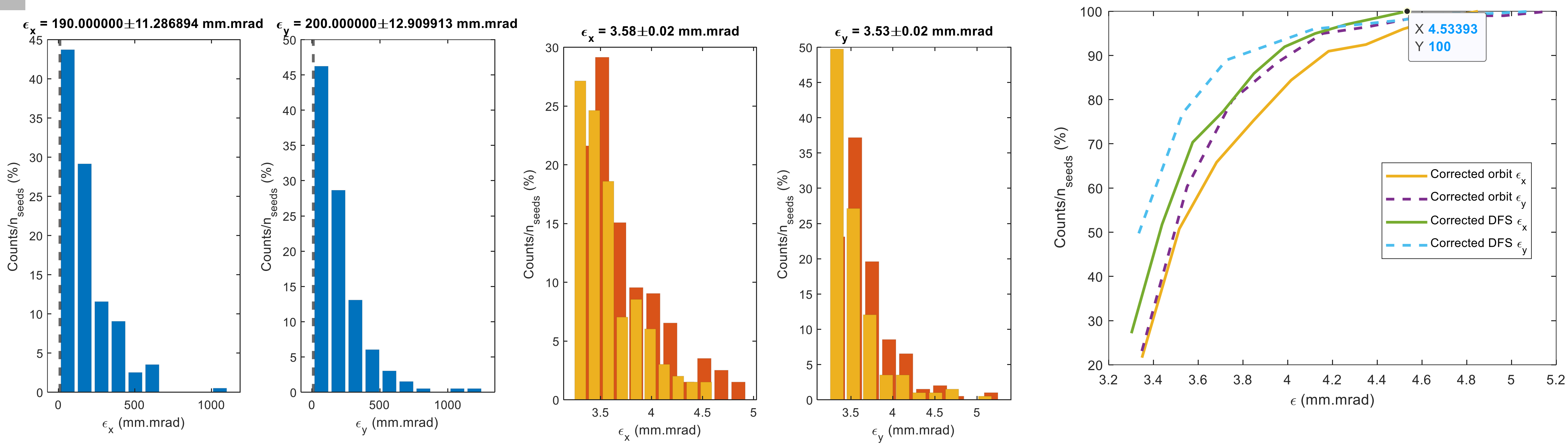
- Mainly orbit correction already ok
- ADDED



$\Delta\varepsilon$ = 5-3.2 = 1.8 mm.mrad

a/l = 0.19, a = 10.2 mm

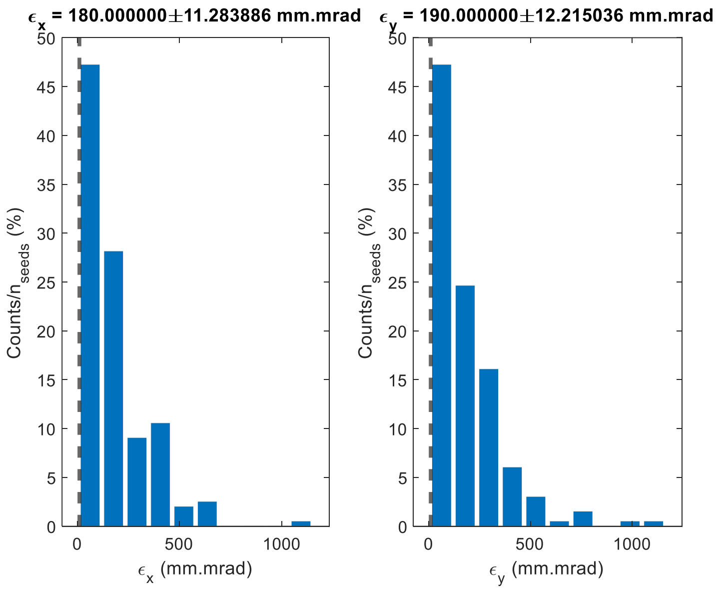
- Mainly orbit correction already ok
- ADDED

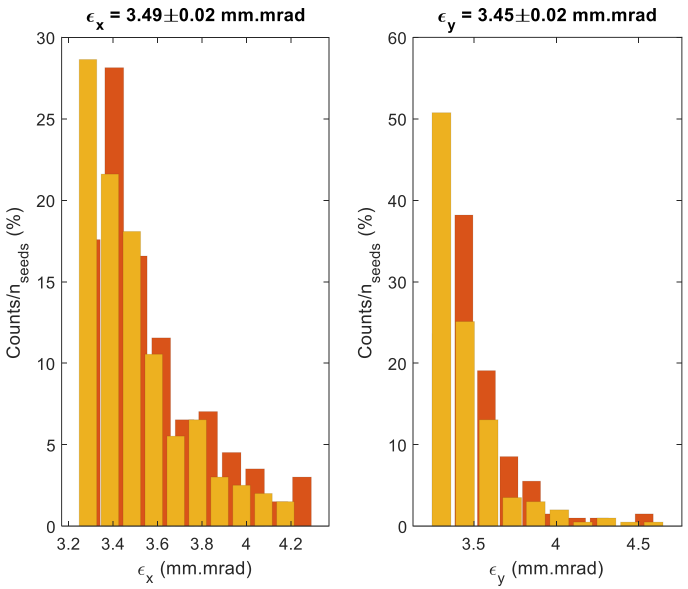


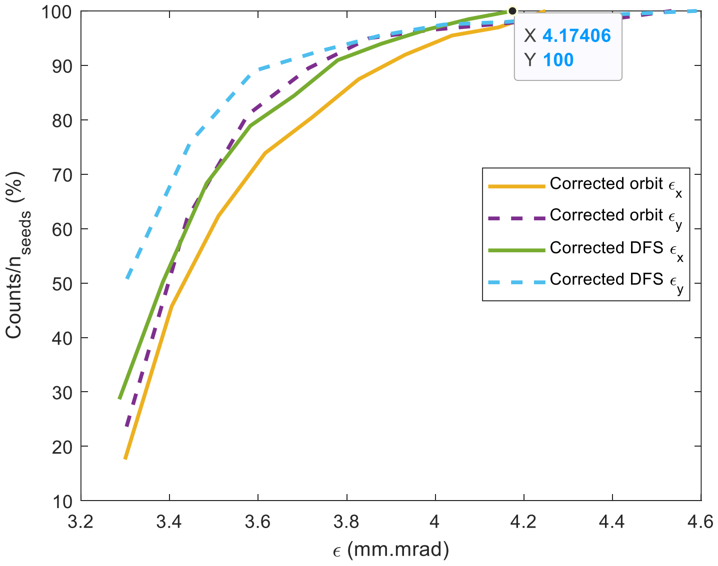
$\Delta\varepsilon$ = 4.5-3.2 = 1.3 mm.mrad

a/l = 0.20, a = 10.7 mm

- Mainly orbit correction already ok



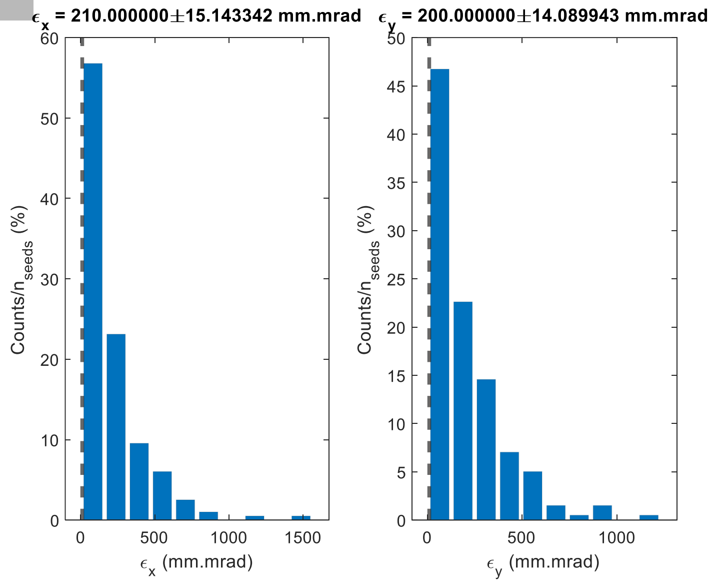


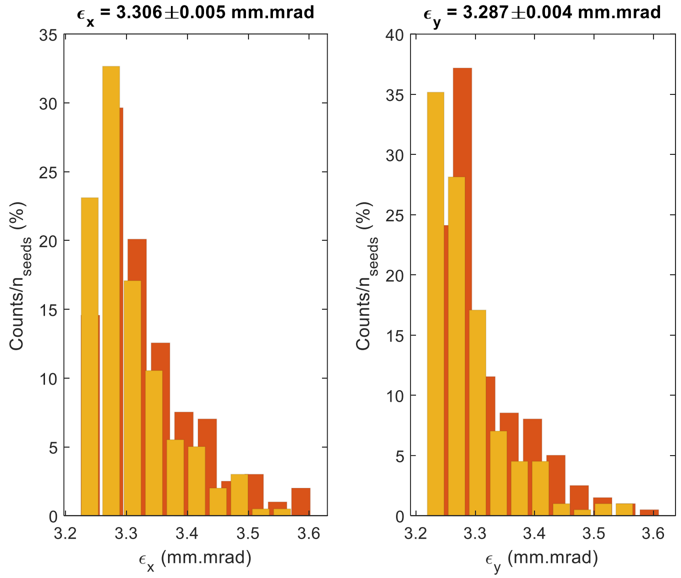


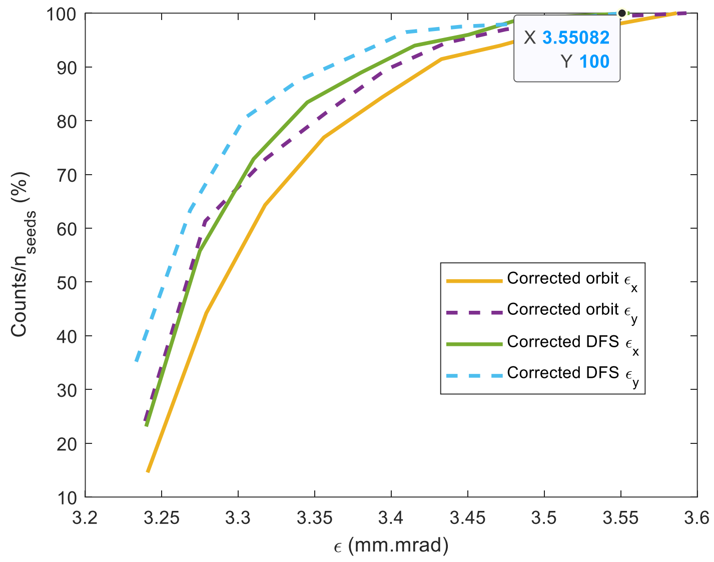
$\Delta\varepsilon$ = 4.1-3.2 = 0.9 mm.mrad

a/l = 0.25, a = 13.4 mm

- Mainly orbit correction already ok







Δε = 3.5-3.2 = 0.3 mm.mrad

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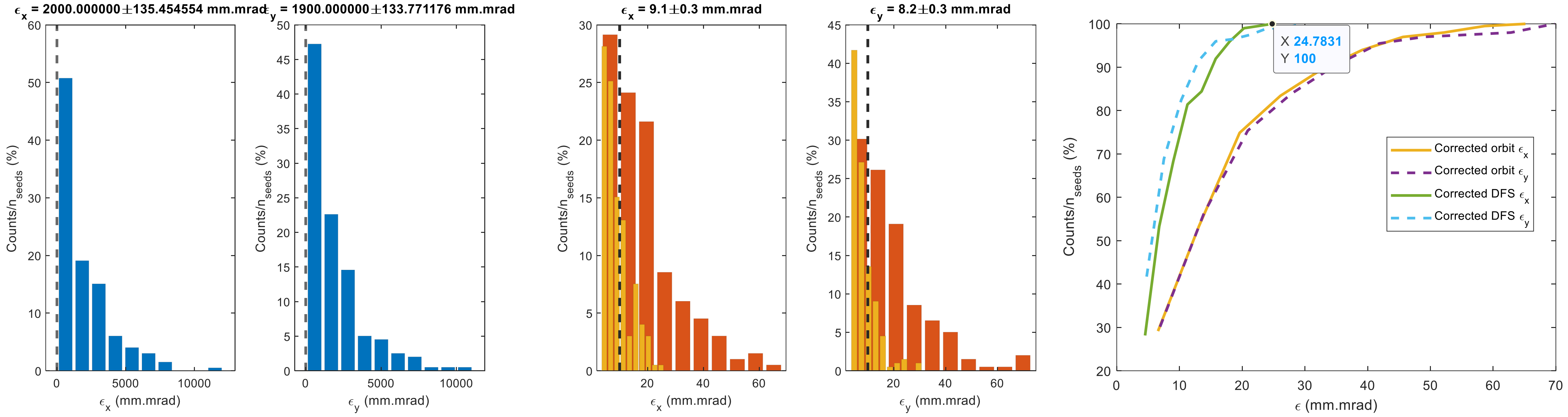
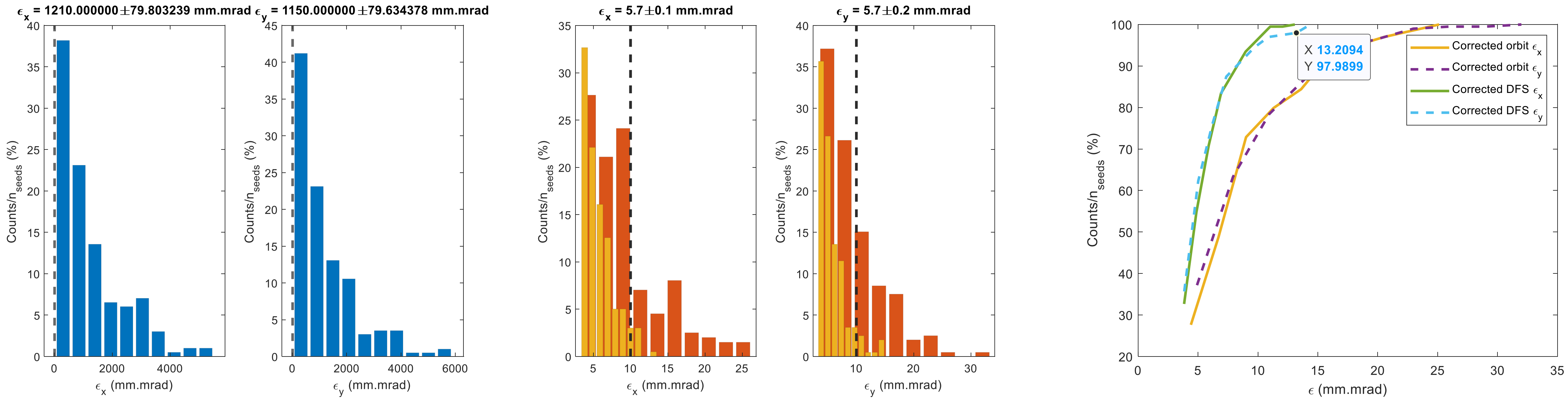
C-band (f = 5.6 GHz), **Nbins = 10**

a/l = 0.12, a = 6.4 mm



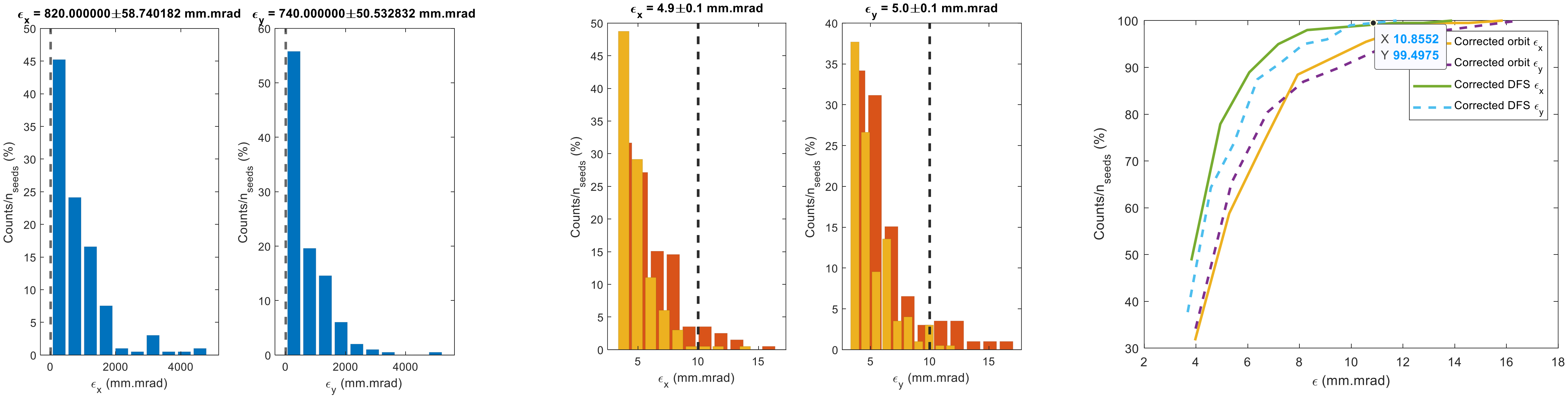
$\Delta\varepsilon$ = 24.8-3.2 = 21.6 mm.mrad

a/l = 0.13, a = 7 mm



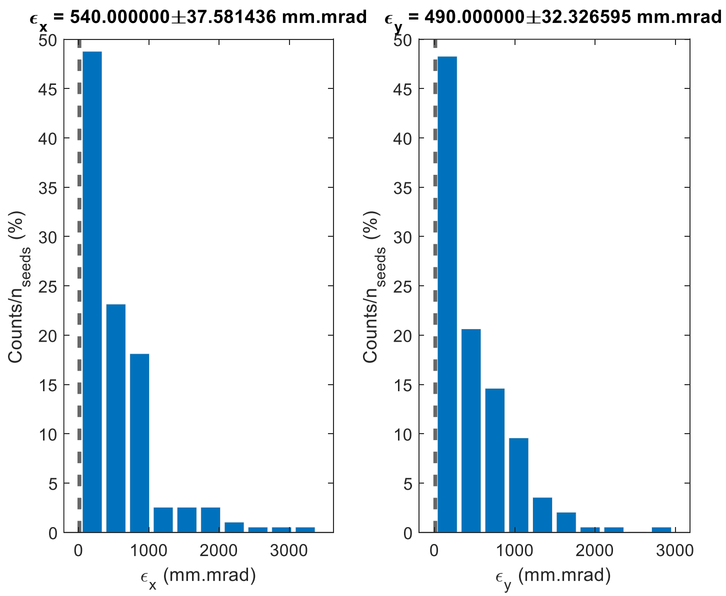
$\Delta\varepsilon$ = 13.2-3.2 = 10 mm.mrad

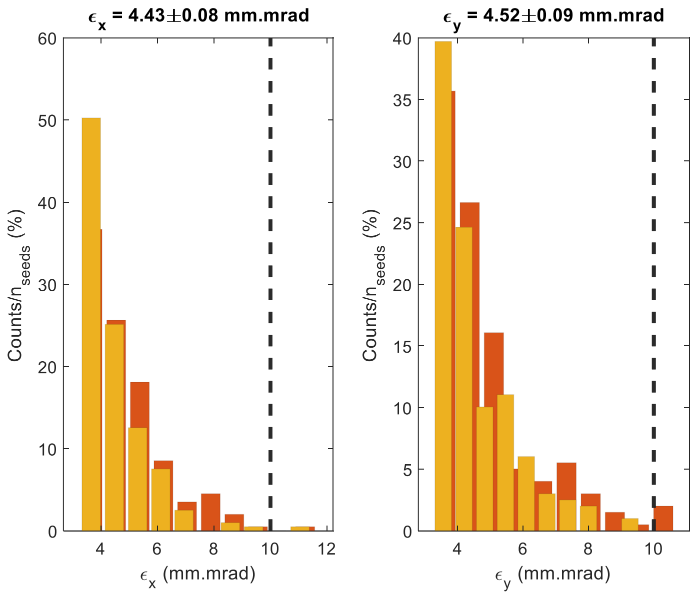
a/l = 0.14, a = 7.5 mm

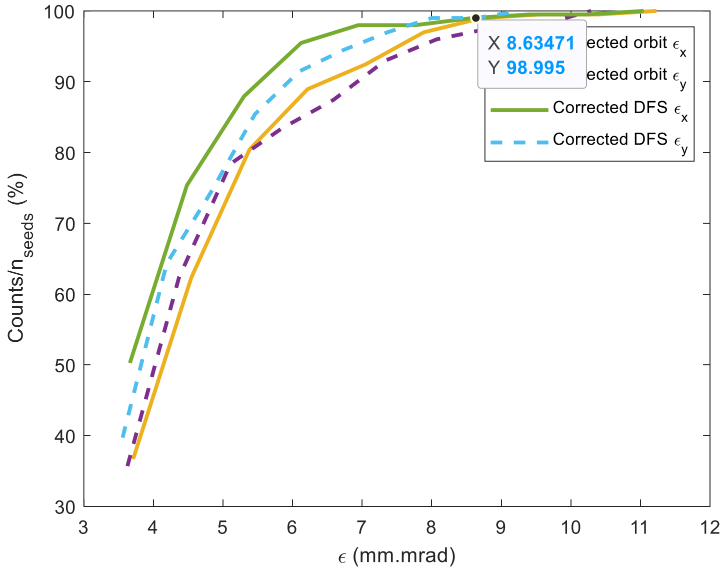


$\Delta\varepsilon$ = 10.9-3.2 = 7.7 mm.mrad

a/l = 0.15, a = 8 mm

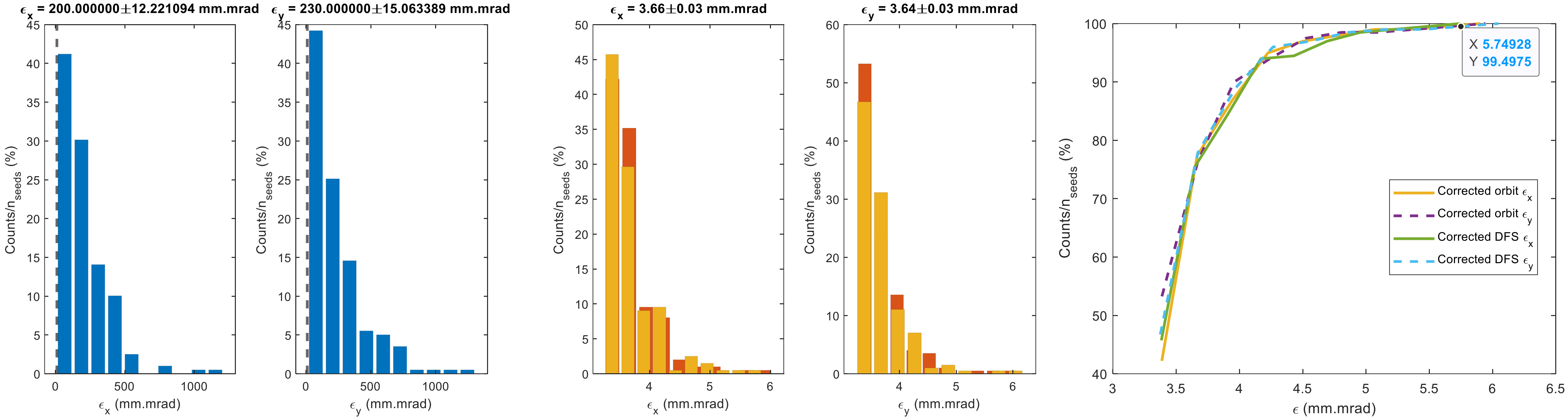






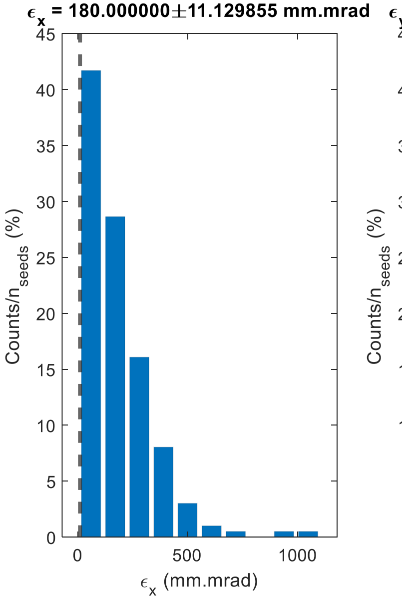
$\Delta\varepsilon$ = 8.6-3.2 = 5.4 mm.mrad

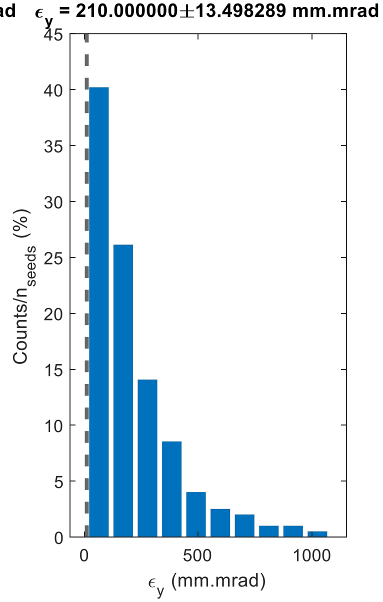
a/l = 0.18, a = 9.6 mm

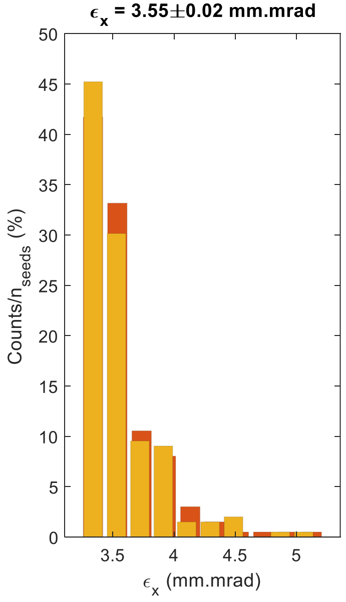


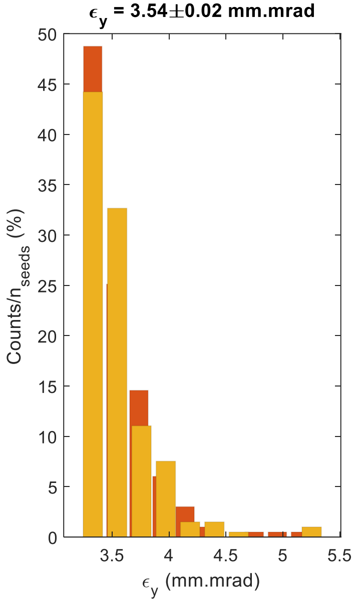
$\Delta\varepsilon$ = 5.8-3.2 = 2.6 mm.mrad

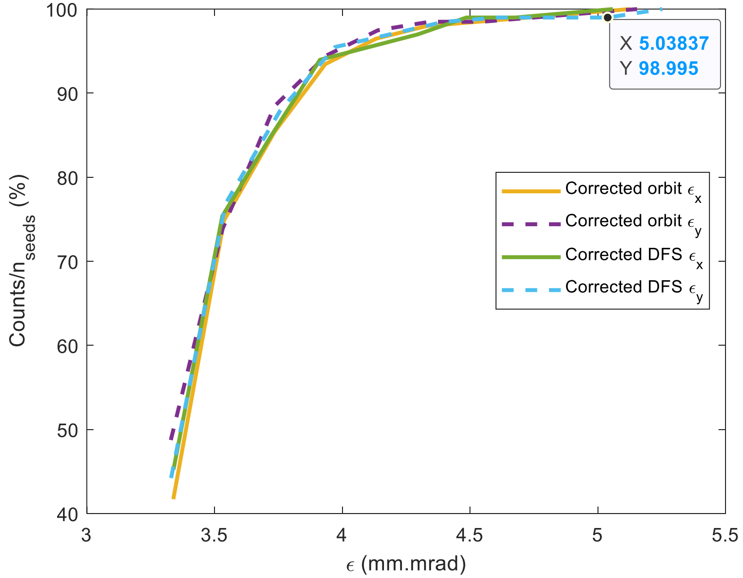
a/l = 0.19, a = 10.2 mm





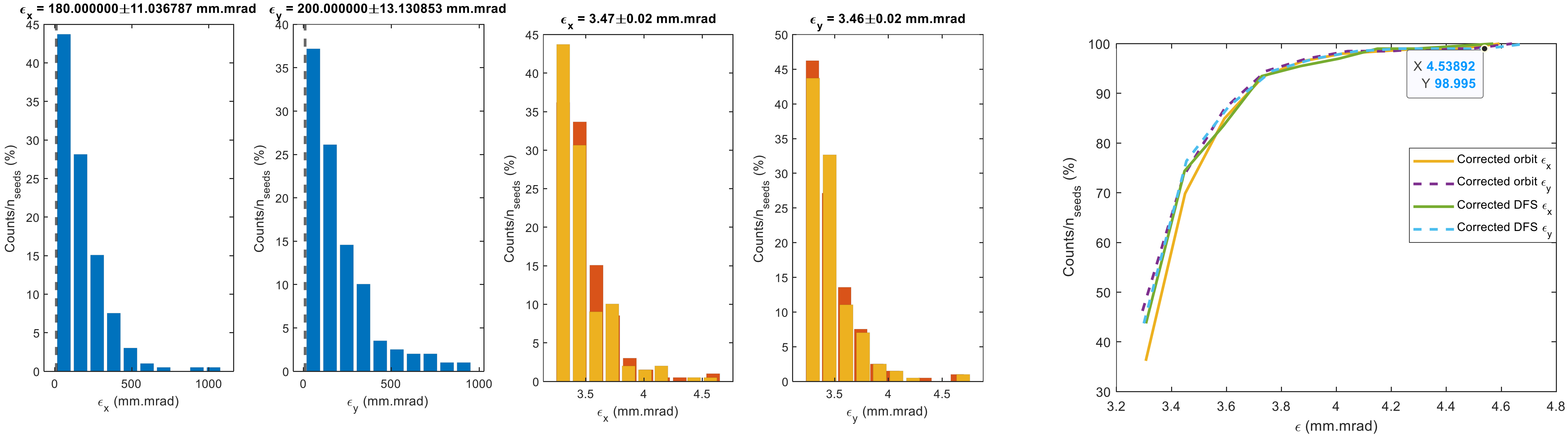






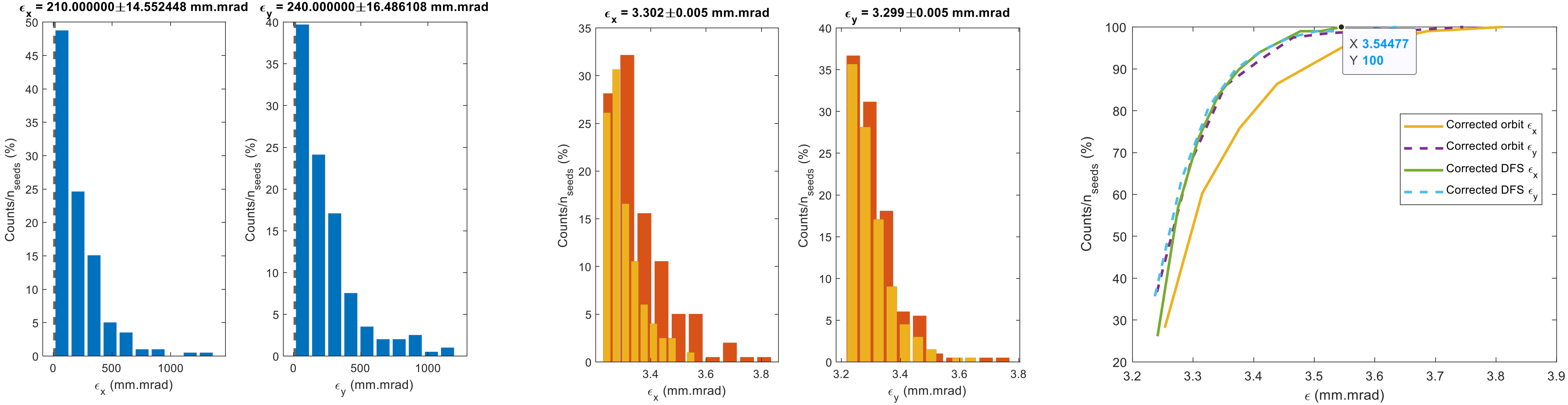
$\Delta\varepsilon$ = 5-3.2 = 1.8 mm.mrad

a/l = 0.20, a = 10.7 mm



Δε = 4.5-3.2 = 1.3 mm.mrad

a/l = 0.25, a = 13.4 mm



Δε = 3.5-3.2 = 0.3 mm.mrad

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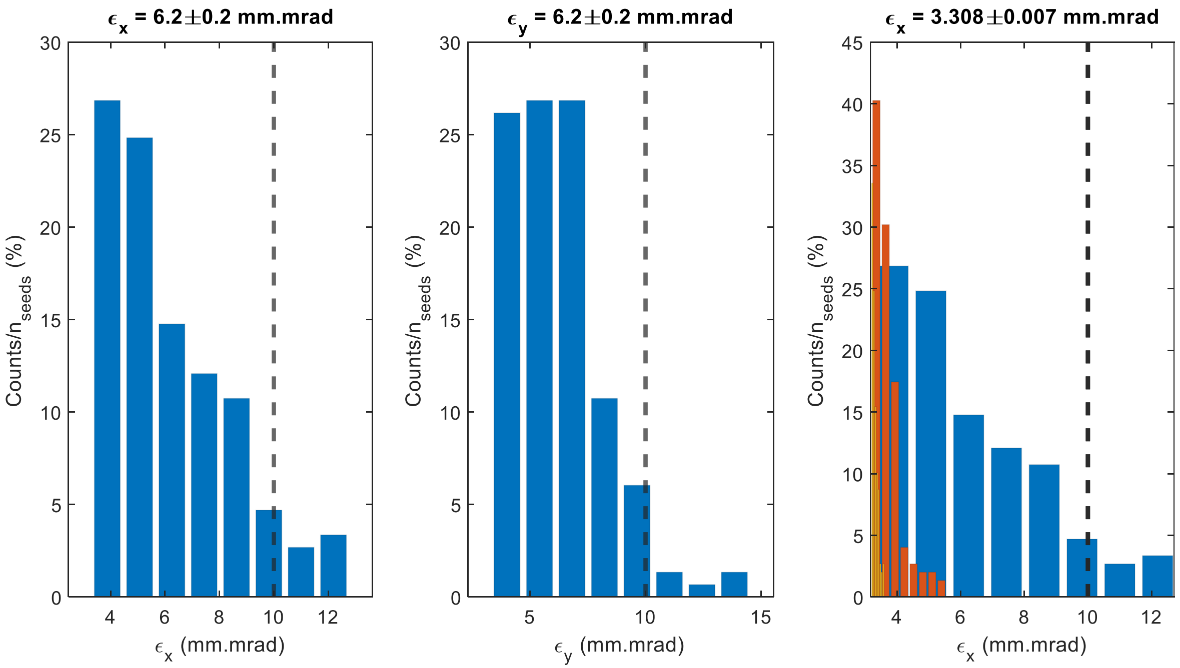
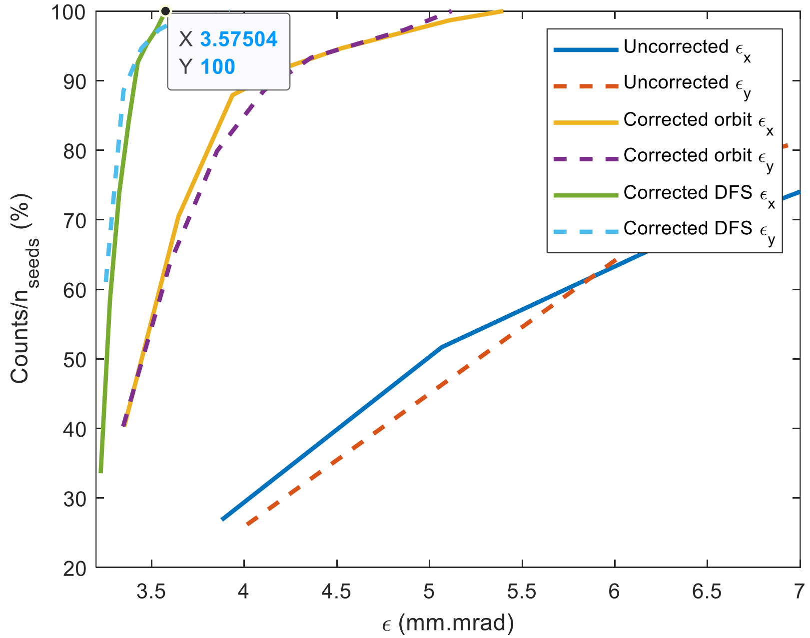
Check of the emittance growth in sections
(I take as example the common linac, a/l = 0.12, f = 2.8 GHz,
150 seeds)

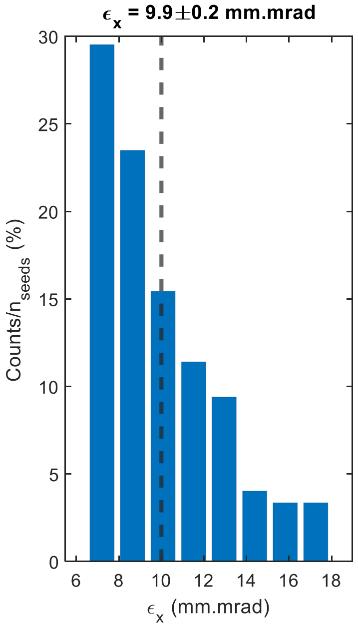
Starting emittance = 3.2 mm.mrad

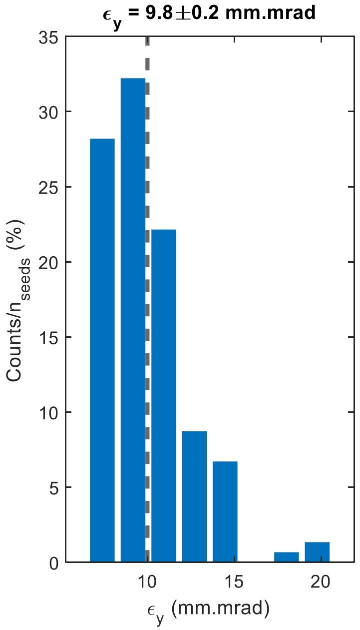


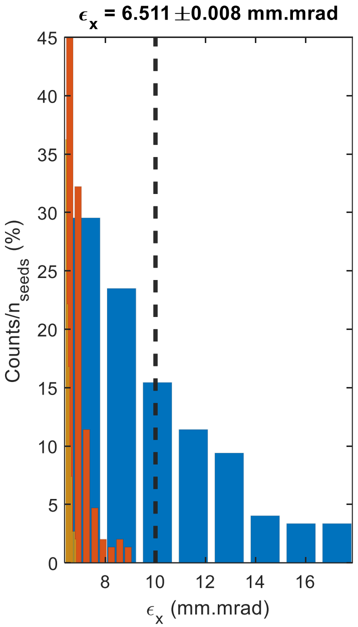


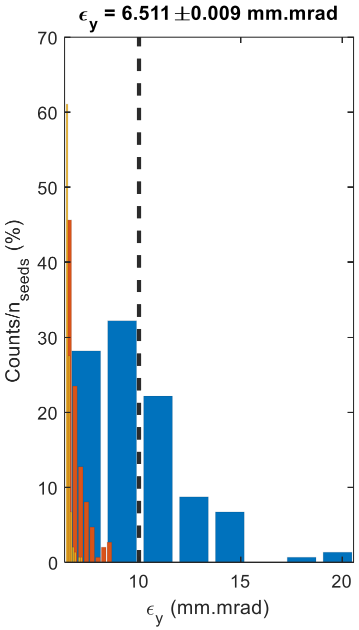
$\Delta\varepsilon = 3.6 - 3.2 = 0.4$ mm.mrad

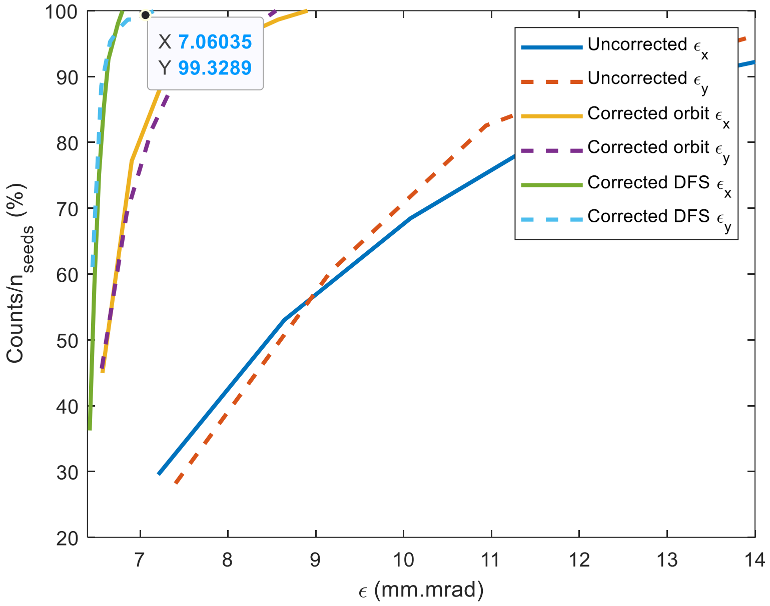
Starting emittance = 3.2*2 = 6.4 mm.mrad





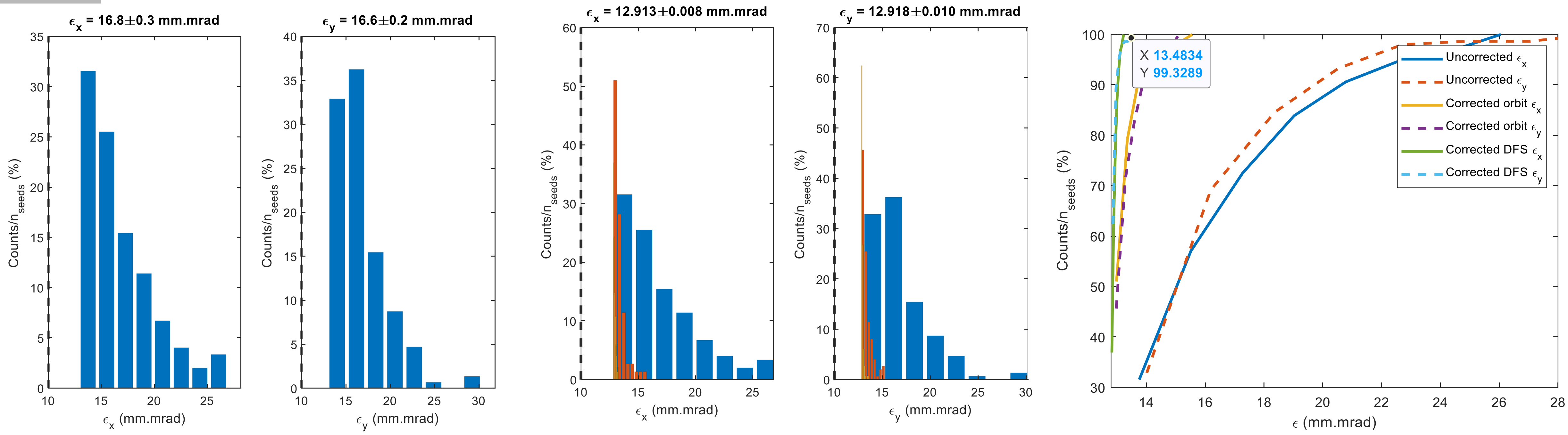






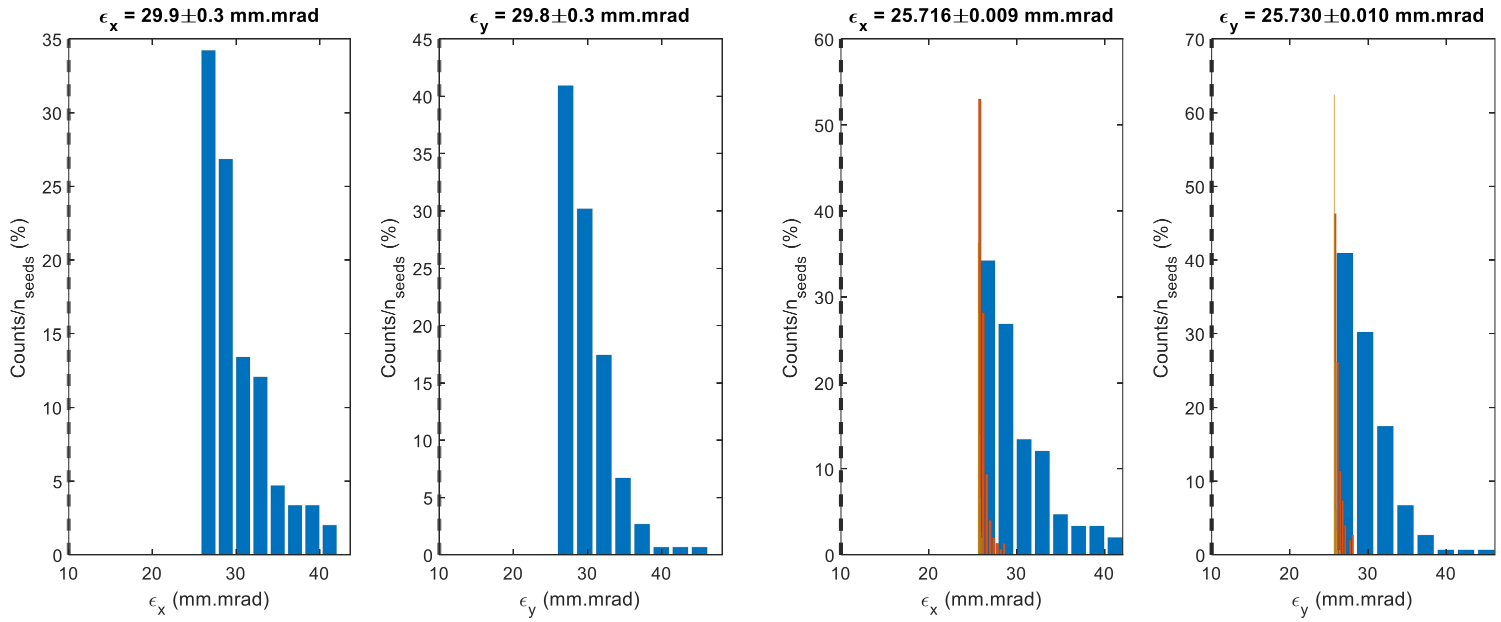
Δε = 7-6.4 = 0.6 mm.mrad

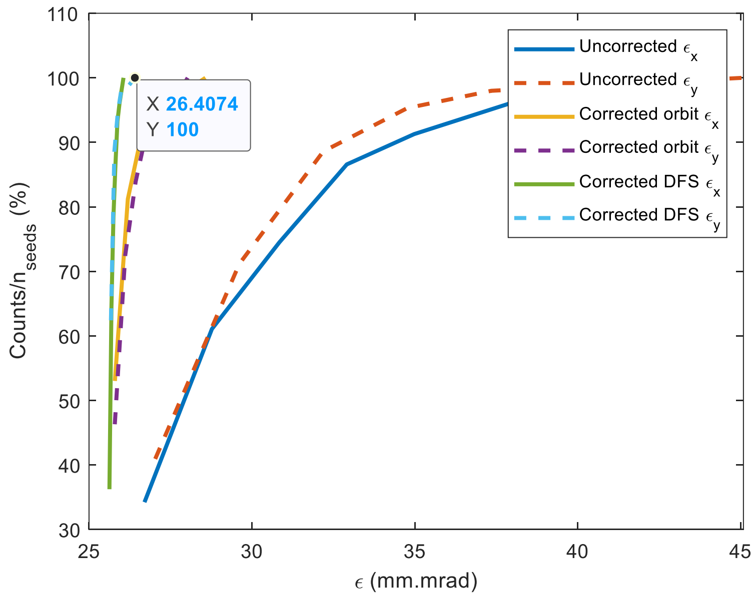
Starting emittance = 3.2*4 = 12.8 mm.mrad



$\Delta\varepsilon$ = 13.5-12.8 = 0.7 mm.mrad

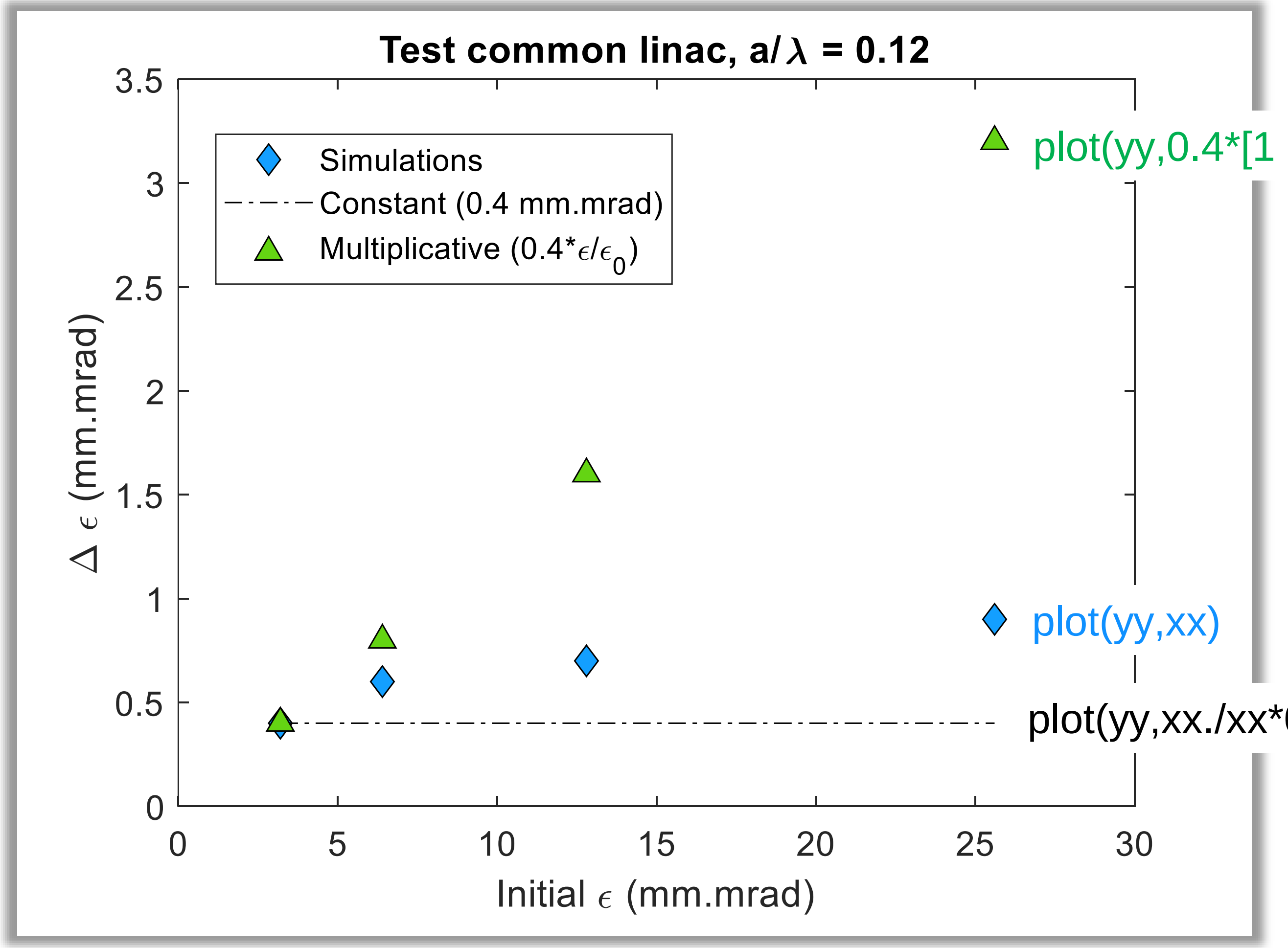
Starting emittance = 3.2*8 = 25.6 mm.mrad





$\Delta\varepsilon$ = 26.4-25.6 = 0.9 mm.mrad

Emittance growth vs section



Starting emittances = [3.2 3.2*2 3.2*4 3.2*8];

Emittance increases = [0.4 0.6 0.7 0.9];

Good at first use the emittance growth/section: confirmed the results discussed at the latest meeting

C:\Users\bettoni_s\switchdrive\Backup Documents\FCC\10_Progress_Linacs

Digression about the quadrupole strength 1/2 (triggered by J-Y)

At the moment what is assume is:

$$B\rho\ [\mathrm{T \cdot m}] = 3.3356\, pc\ [\mathrm{GeV}]\,.$$

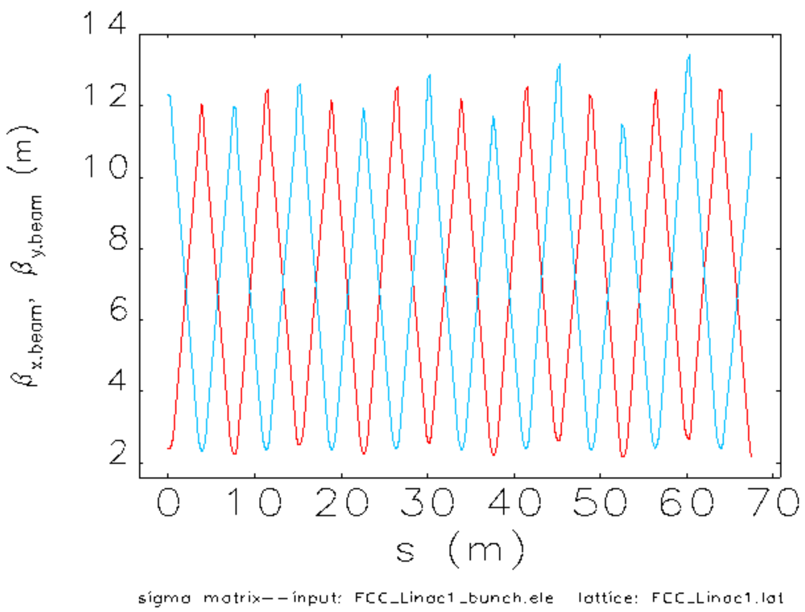
K1 = 1/(B*rho)*G

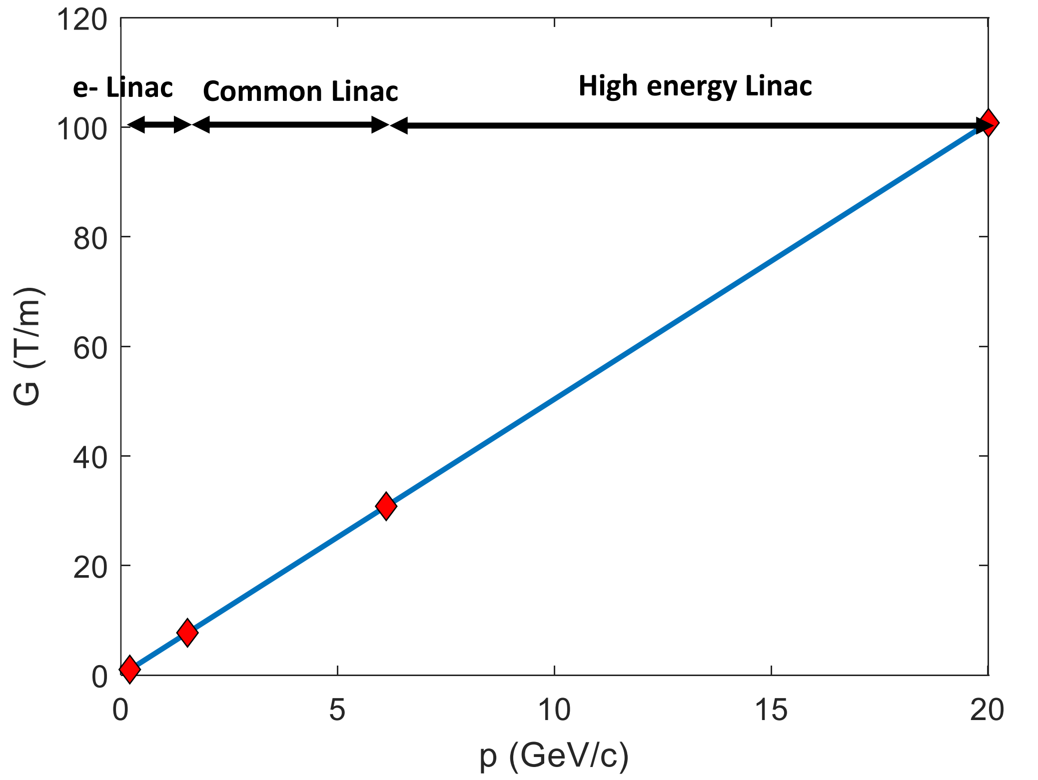
E = [0.205 1.536 6.12 20.0125];

B_rho = 3.3356*E = [0.6838   5.1235   20.4139   66.7537];

k1 = 1.51;

G = B_rho*k1 = [1.0325   7.7365   30.8249 100.7981];





This was looking reasonable for the first linacs. We may think for the high energy linac

Digression about the quadrupole strength 2/2

Achievable values to be determined (magnet group or scaling law)

PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 052401 (2016)

High gradient quadrupoles for low emittance storage rings

G. Le Bec,* J. Chavanne, C. Benabderrahmane, L. Farvacque, L. Goirand, S. Liuzzo, P. Raimondi, and F. Villar
ESRF–The European Synchrotron, 38000 Grenoble, France
(Received 29 February 2016; published 9 May 2016)

https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.19.052401

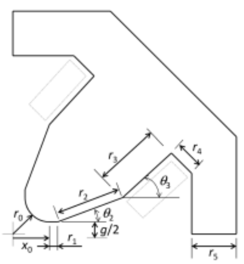
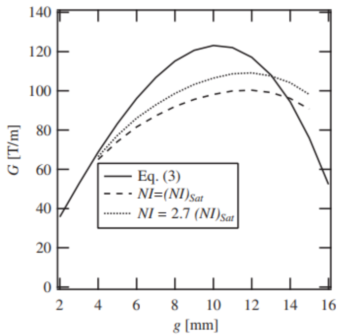


FIG. 3. Definition of the main geometrical magnet parameters.



g: diameter

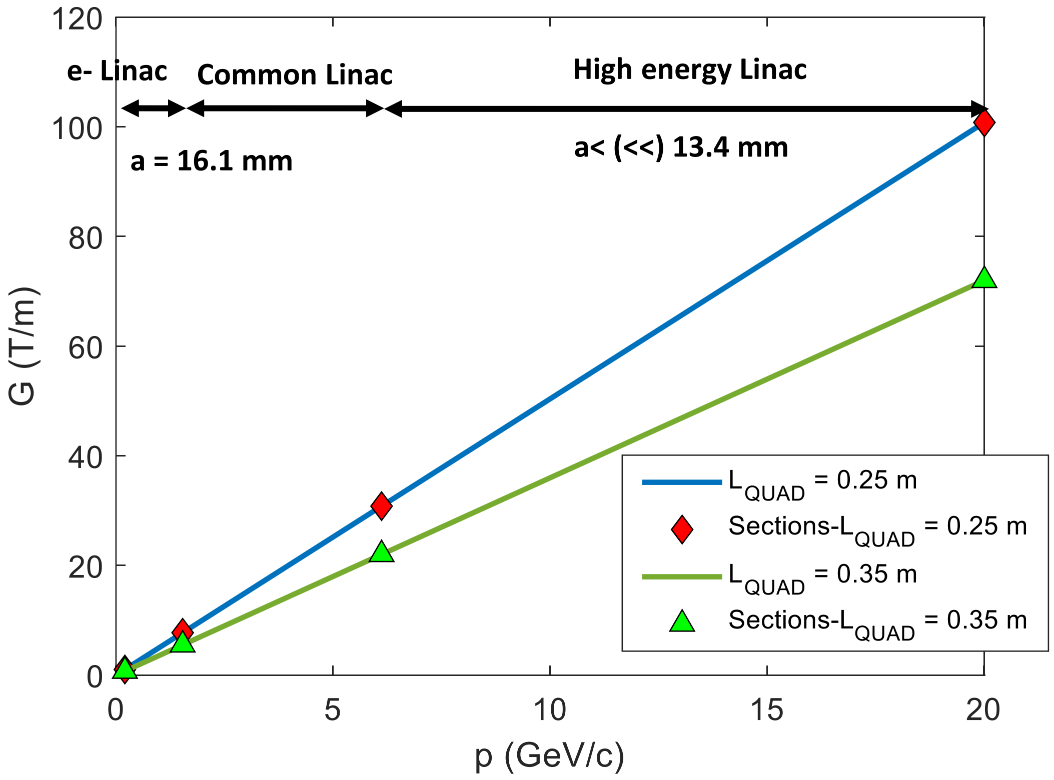
a = g/2 -> a = 16 mm -> g = diameter = 32 mm

http://www-library.desy.de/ahluwali/HERA-98-05/chapter5.pdf

Name	Type	L_m (m)	G_{max} (T/m)	R_p (mm)	B_p (T)	# Req.	Comments
QI	Q	1.88	27.	37	0.980	6	Split coil for synchrotron radiation
QJ	Q	1.88	18.	50	0.900	4	Split coil for synchrotron radiation
QM	Q+D	3.40	25.	37	0.925	8	Half-quadr., mirror plate with cut-out
QN	Q	1.95	30.	35	1.050	12	High current density septum coil
Q8	Q	3.85	26	35	0.950	4	Septum coil magnet
Q9	Q	3.85	26	35	0.950	4	Small return yoke
QR	Q	3.00	24.	35	0.840	–	Reuse existing QR magnets

SLS 2.0: Max k1 = 10 m-2 at 2.7 GeV -> G = 90 MV/m, radius chamber ~9 mm

a: radius



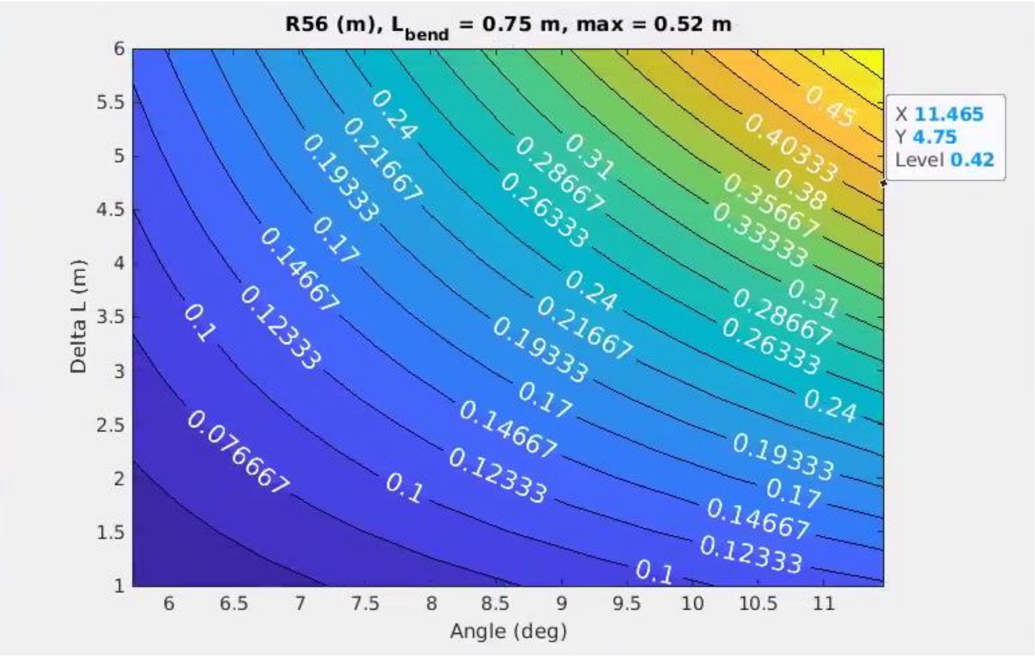
We have to consider to:

- Change the optics
- Increase the length of the quadrupoles (from 25 cm to 50 cm would give a maximum gradient of 50 T/m)

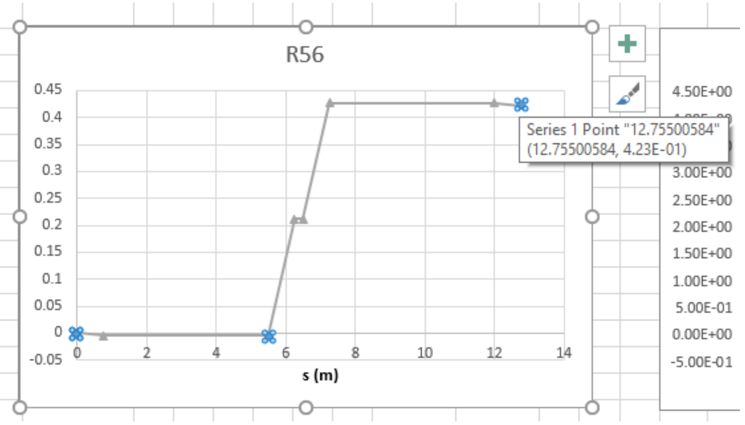
A possible reasonable layout

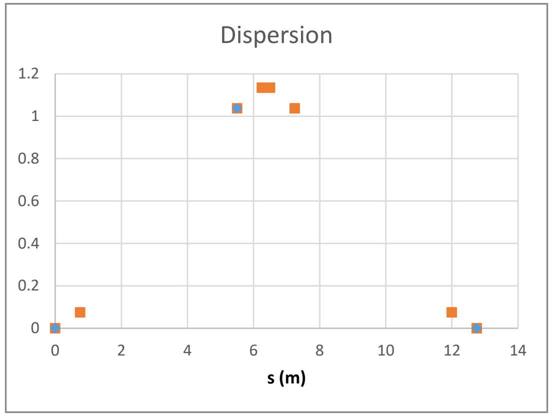
Angle~12 deg, total length chicane ~ 13 m
Lbend ~0.75-1 m (depends on the technical possibilities)

R56 vs chicane parameters



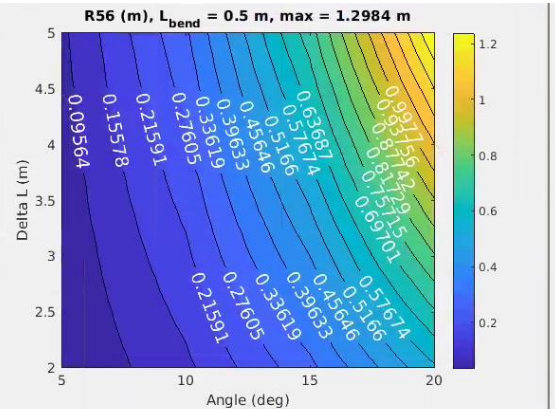
MAD-X model

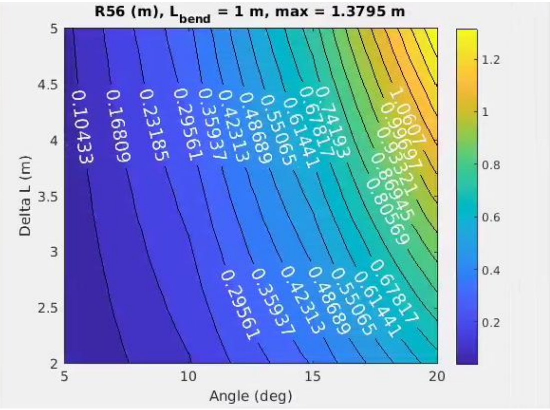


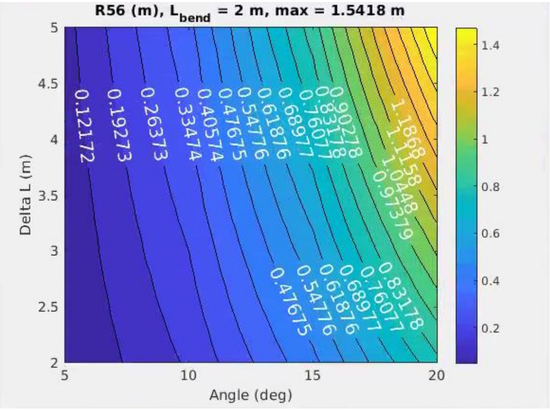


This + the xls file (from Riccardo) allows a fast optimization of the parameters

- Beam size moderately small (Dmax = 1 m)
- Bend length can be adjusted for technical requests (not very impacting)





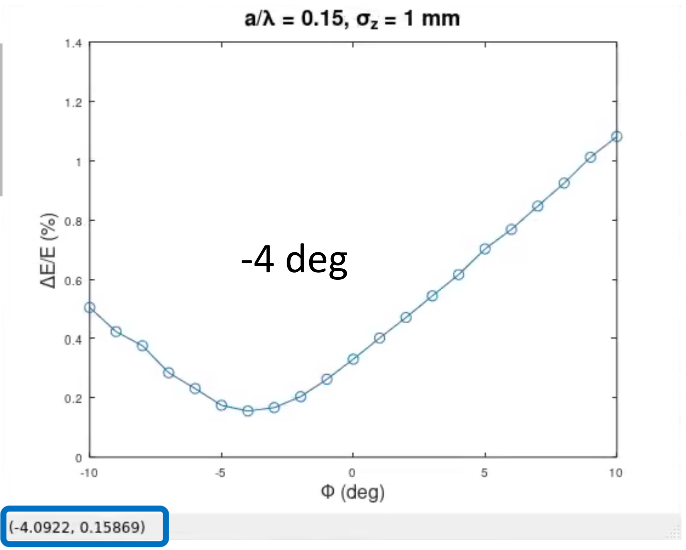


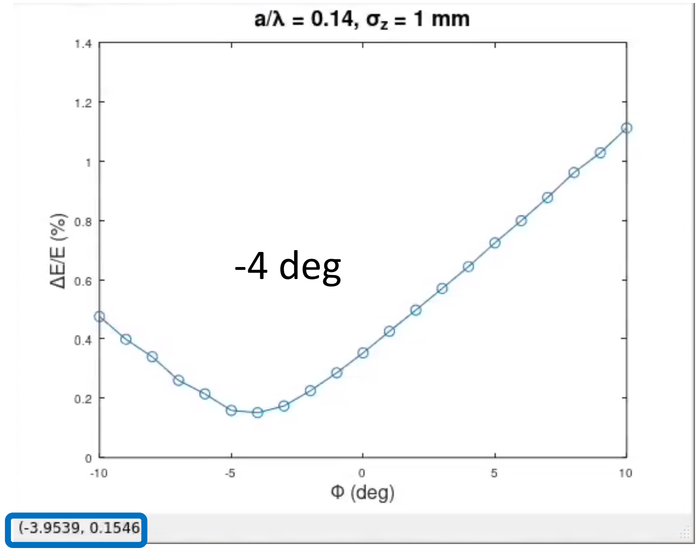
Model check longitudinal

Verification longitudinal RF-Track vs Elegant

RF-Track 0 deg -> on crest operation

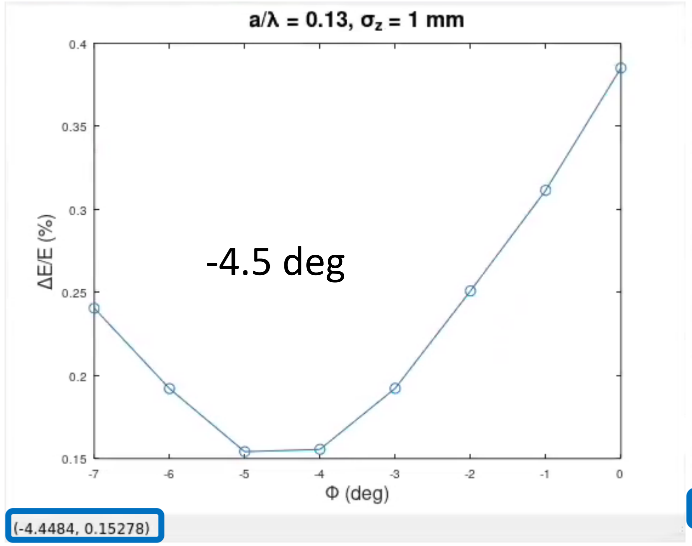
In Elegant: 82 deg (90 is on-crest operation)

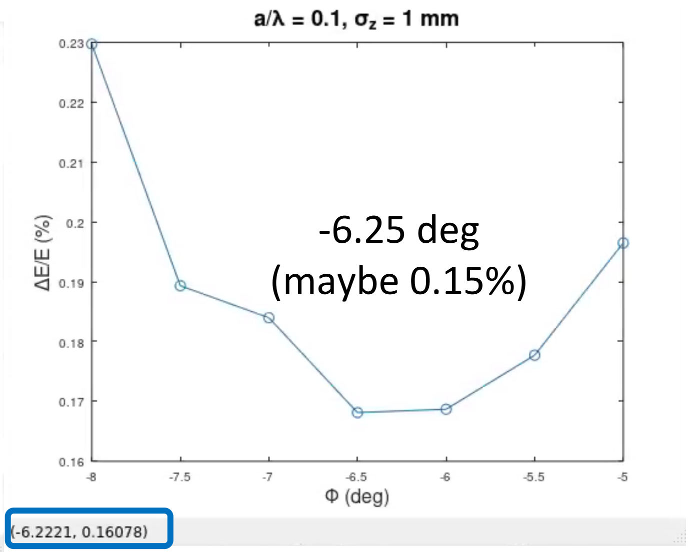


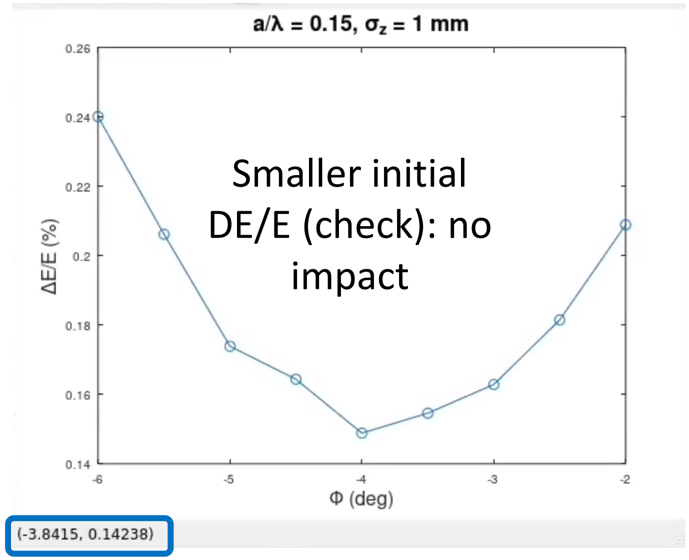


Differences:

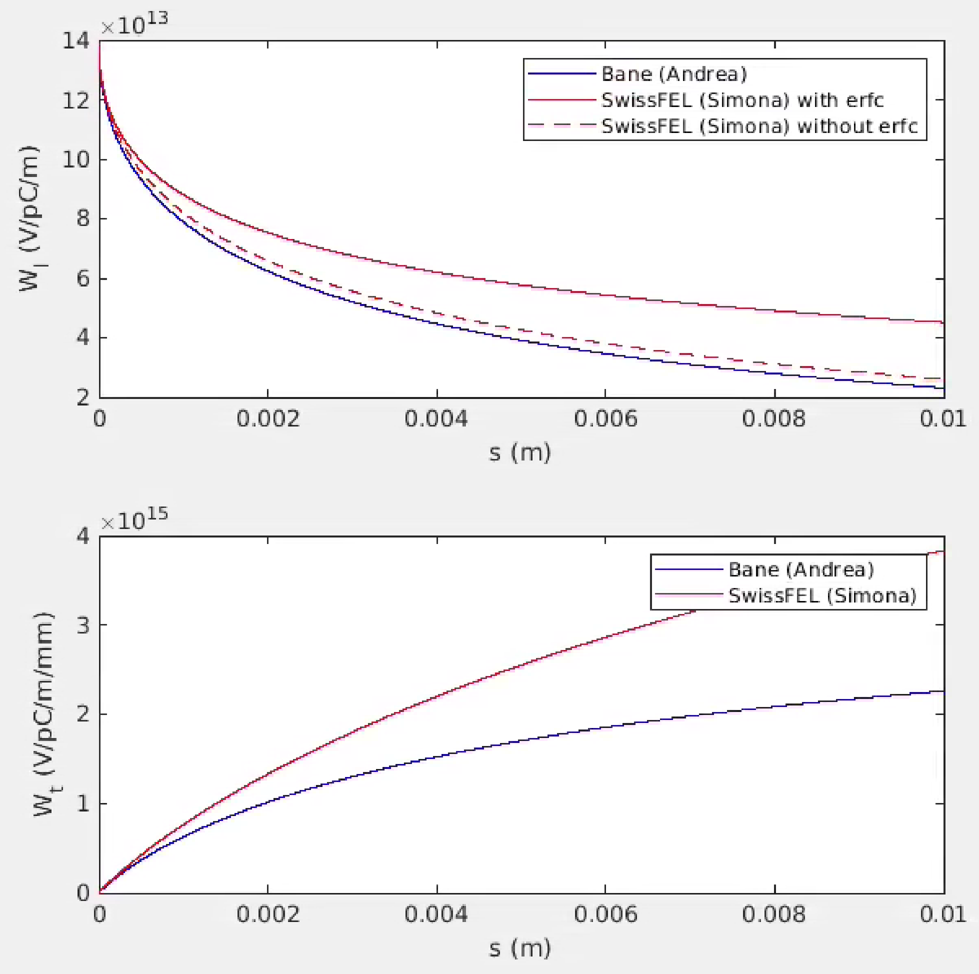
- RF-Track for the moment started with an initial DE/E, not the real distribution. Script available.
- Different wakefield model. Clarified by Alexej, but the run were not all re-run yet
- Code used







Wakefield check, and optimal phase retuning



Already discussed, but I did not re-run all the simulations

% V/pC/m

Z0 * c / pi / m^2 = (1 / 27.81625138611302) V/pC/m

s0 = -0.41 * pow(a,1.8) * pow(g,1.6) / pow(l,2.4); % m

Wl = exp(-sqrt(s/s0)) / (a2 * 27.81625138611302); % V/pC/m

% V/pC/m/mm, 4 * Z0 * c / pi / m^3 = (1 / 6954.062846528255) V/pC/m/mm

s1 = -0.169 * pow(a,1.79) * pow(g,0.38) / pow(l,1.17); % m

s1_a4 = s1 / (a^4); % 1/m^3

sqrt_s_s1 = sqrt(s/s1);

Wt = s1_a4 * (1-(1+sqrt_s_s1)*exp(-sqrt_s_s1)) / 6954.062846528255; % V/pC/m/mm

I use these formulas, and I re-run the simulations to check which is the optimal phase for the common linac

SKIP IF TIME NOT ENOUGH

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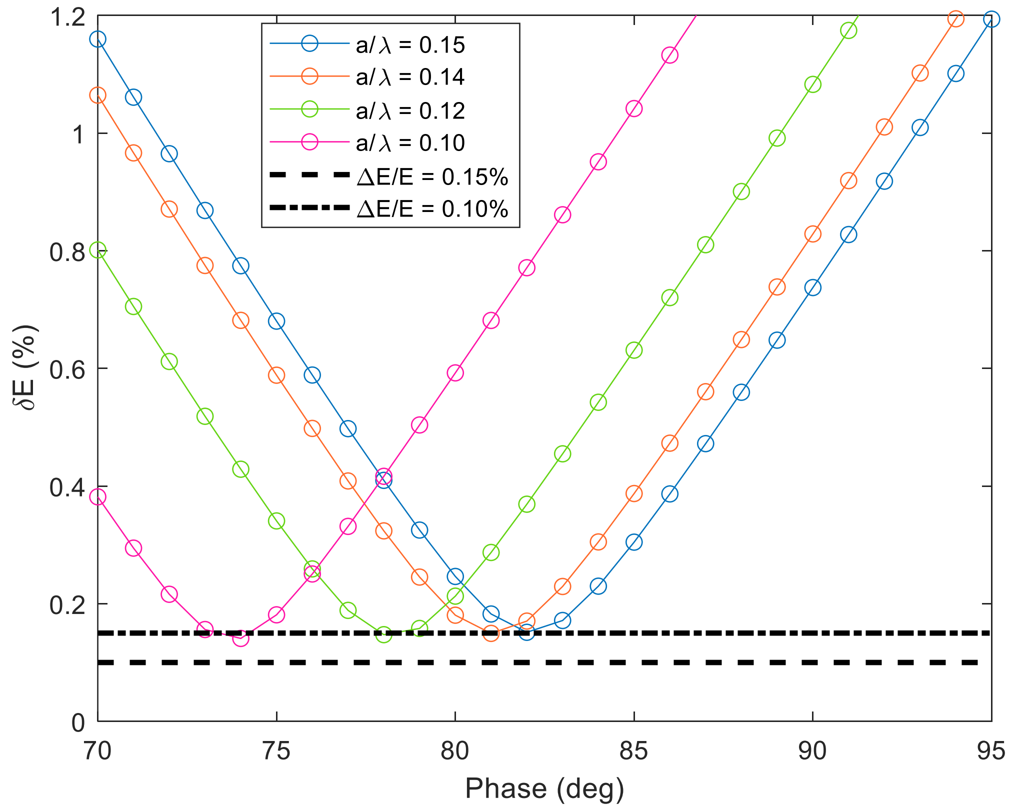
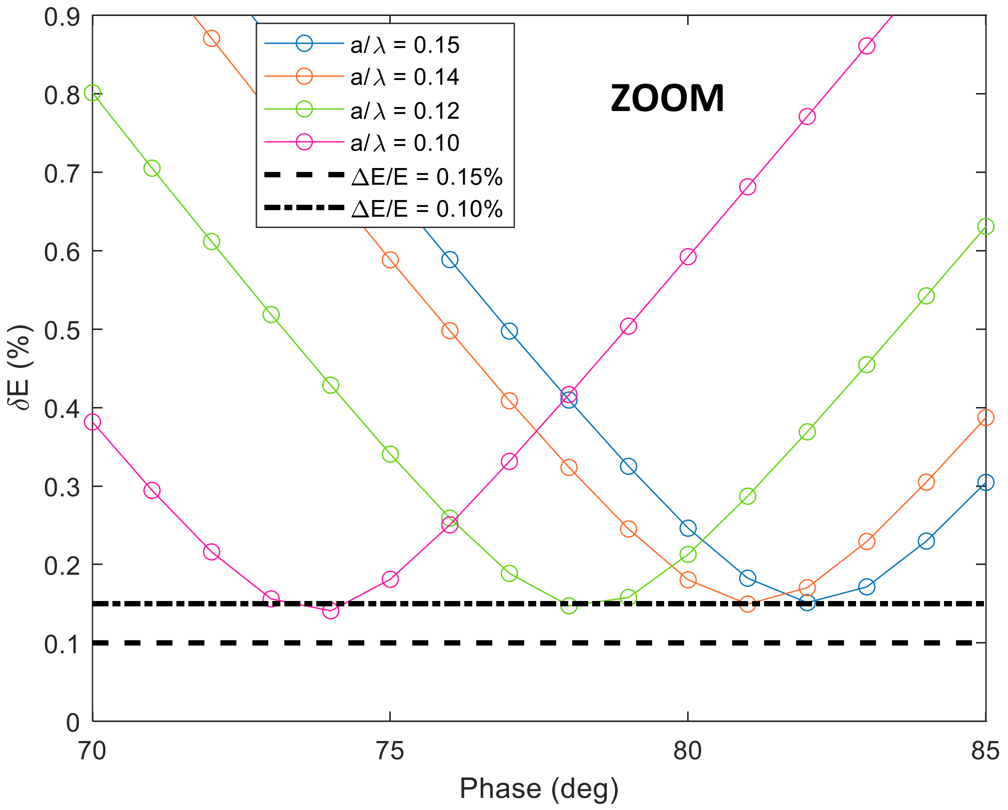
Common linac, **Bane wake**, a/l = 0.15

For all the cases I will run a scan phase = [70:1:110]. A phase of 90 deg corresponds to on-crest

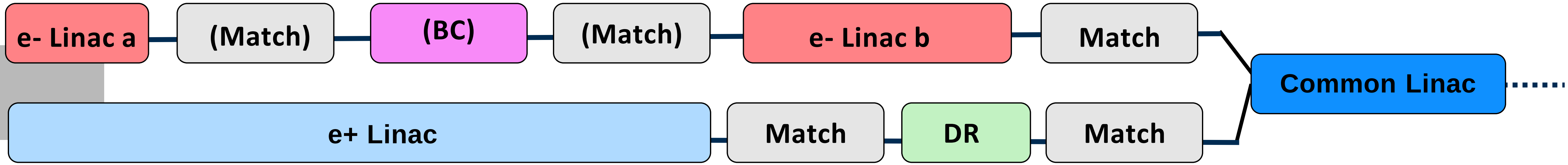
/psi/home/bettoni_s/data/Elegant_sim/FCC/Full_model/Linac_2/PureBane/Run/a_l_0p*





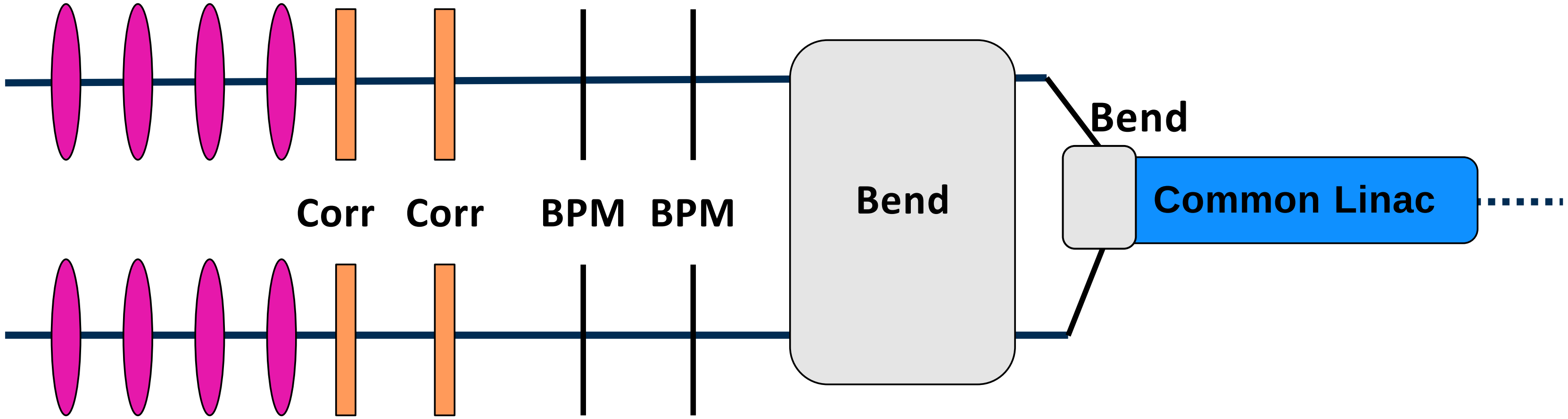
Very similar to the previous result, but few degs different from RF-Track. It may be the initial distribution

“Minimalistic” schematic layout: a closer look



Schematic layout must include:

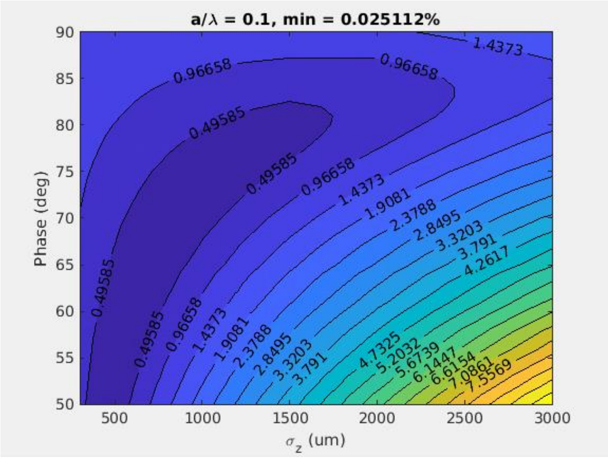
- Matching sections to and after the compression chicanes (if present)
- Independent matching sections to the common Linac (swap of βx and βy for electrons and positrons)
- Independent launch orbit for electrons and positrons at the entrance of the common Linac

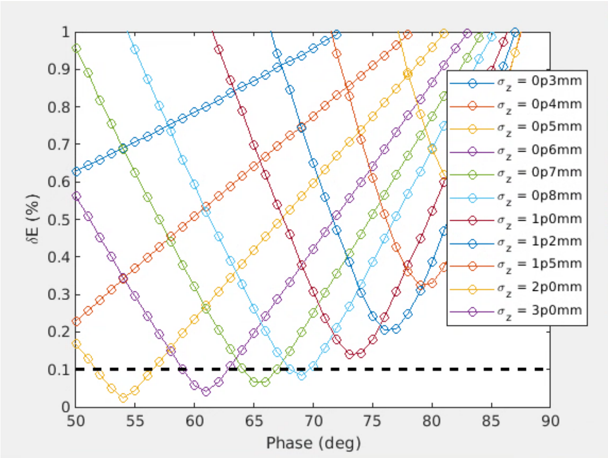


f = 2.8 GHz, G = 25 MV/m, no linearizer

/psi/home/bettoni_s/Matlab_works/Scan_FCC

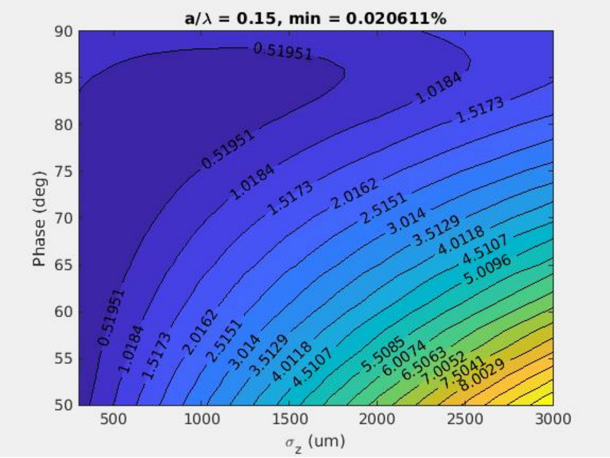
a/λ = 0.1 (a = 10.7 mm)

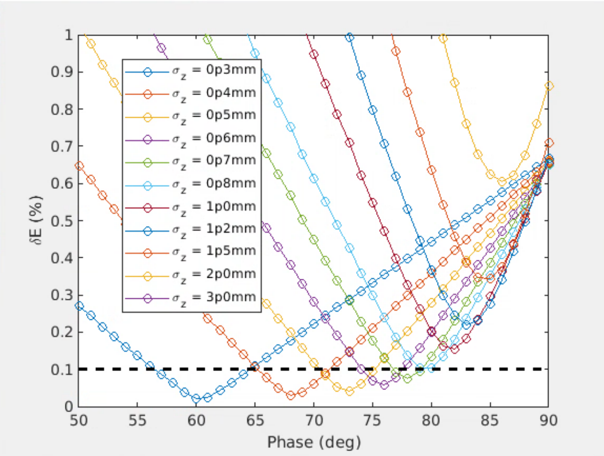




f_2p8GHz_G_25MVm_al_0p1.fig

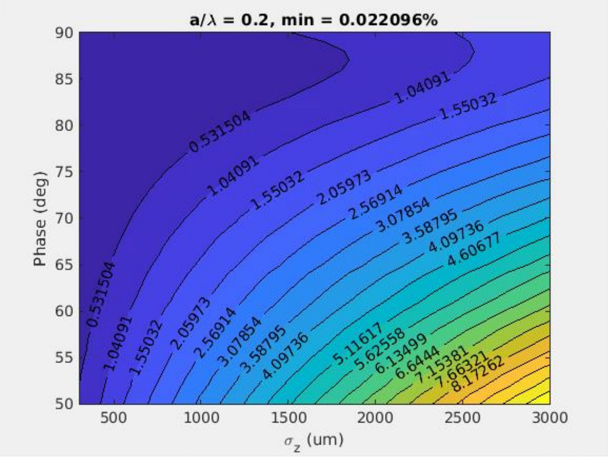
a/λ = 0.15 (a = 16.1 mm)

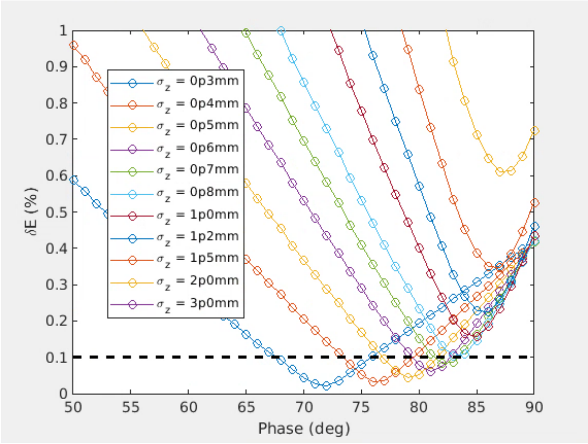




f_2p8GHz_G_25MVm_al_0p15.fig

a/λ = 0.2 (a = 21.4 mm)

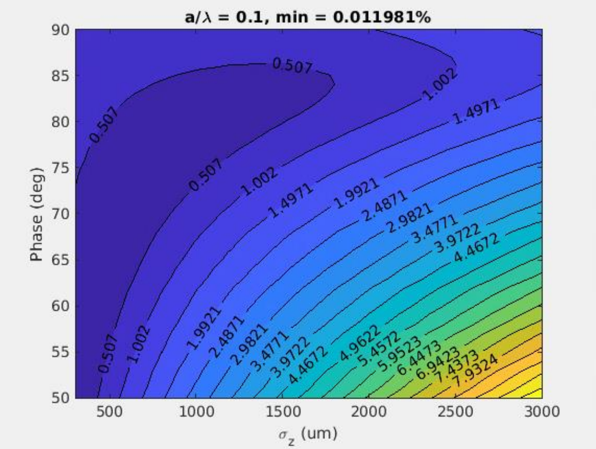


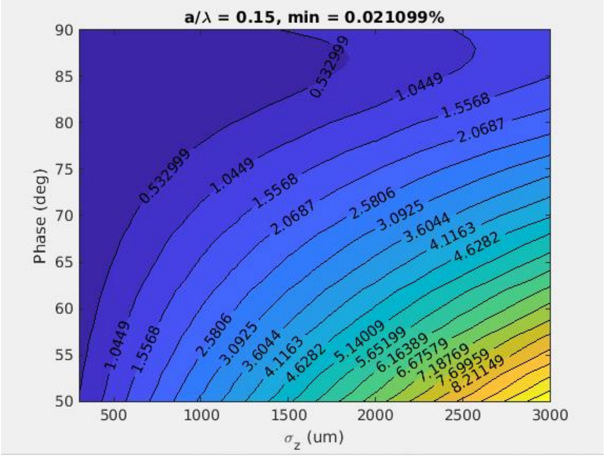


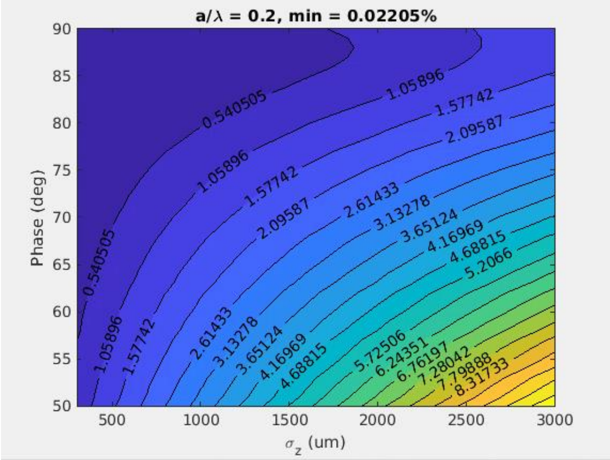
f_2p8GHz_G_25MVm_al_0p2.fig

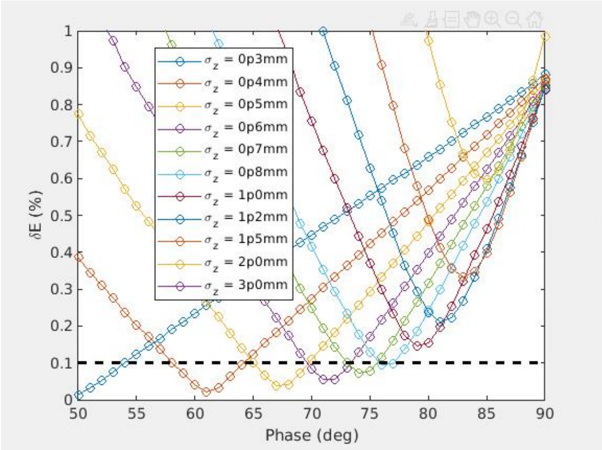
f = 2.8 GHz, G = 40 MV/m, no linearizer

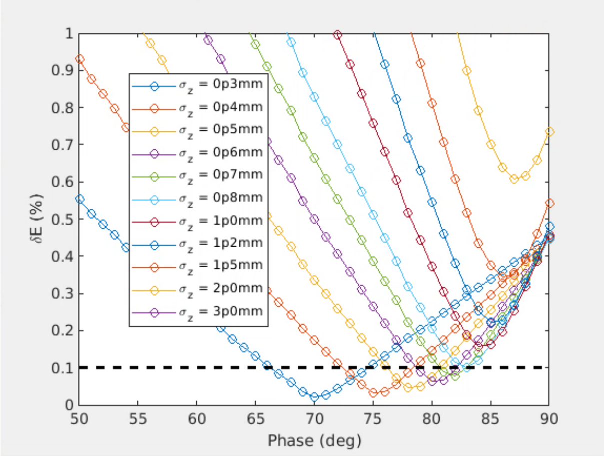
a/λ = 0.1 (a = 10.7 mm)	a/λ = 0.15 (a = 16.1 mm)	a/λ = 0.2 (a = 21.4 mm)

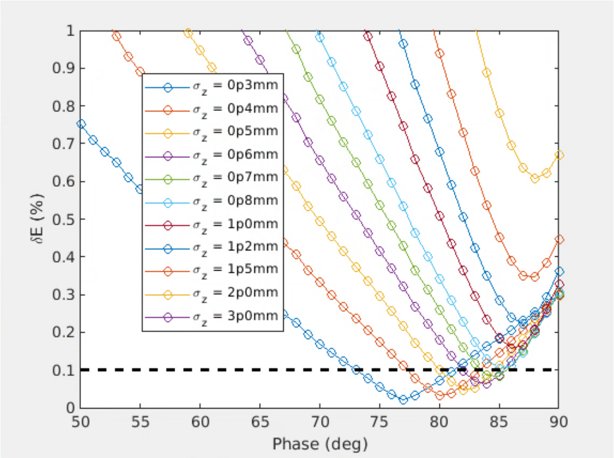










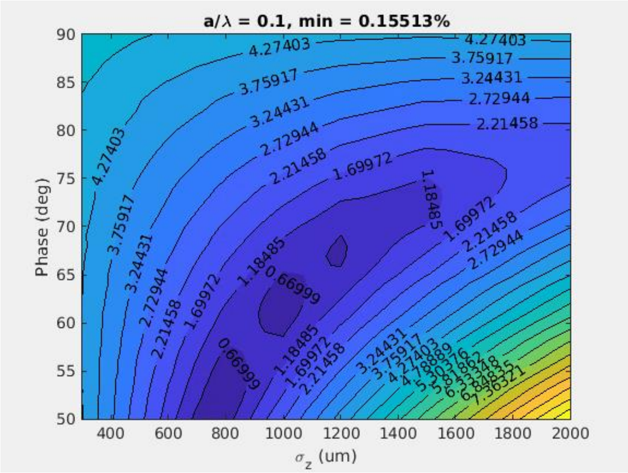


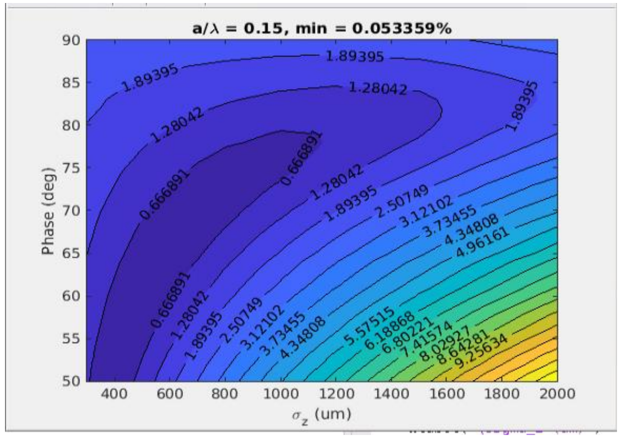
f_2p8GHz_G_40MVm_al_0p1.fig   f_2p8GHz_G_40MVm_al_0p15.fig   f_2p8GHz_G_40MVm_al_0p2.fig

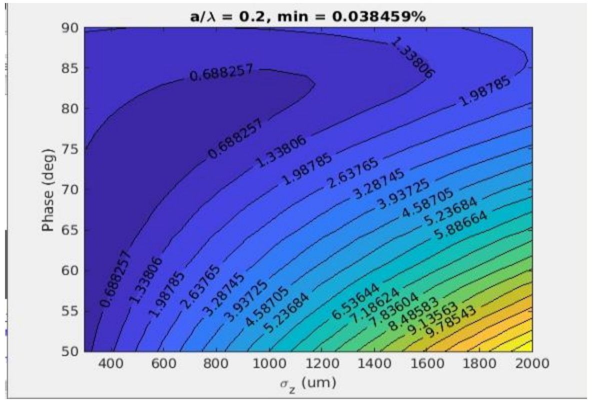
f = 5.6 GHz, G = 25 MV/m, no linearizer

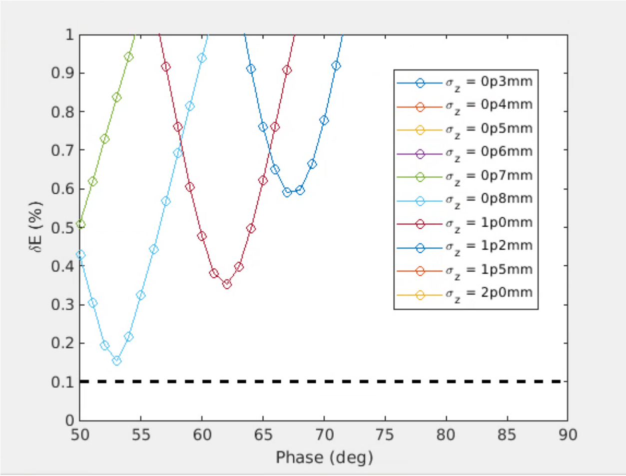
/psi/home/bettoni_s/Matlab_works/Scan_FCC

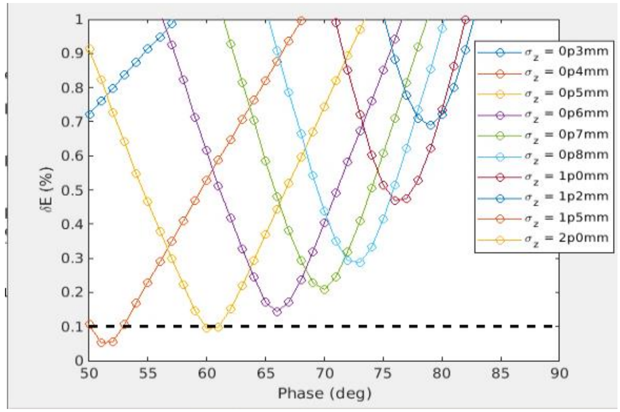
a/λ = 0.1 (a = 5.4 mm) | **a/λ = 0.15 (a = 8 mm)** | **a/λ = 0.2 (a = 10.7 mm)**

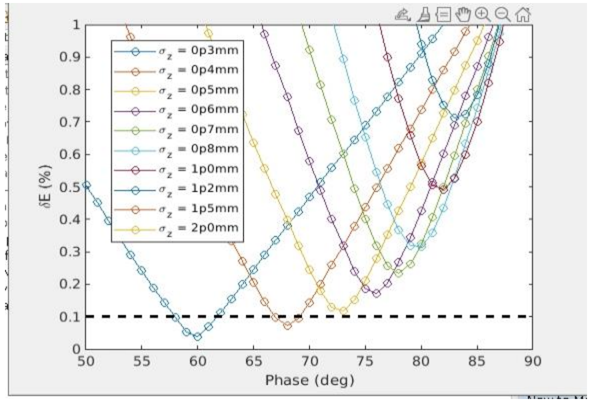








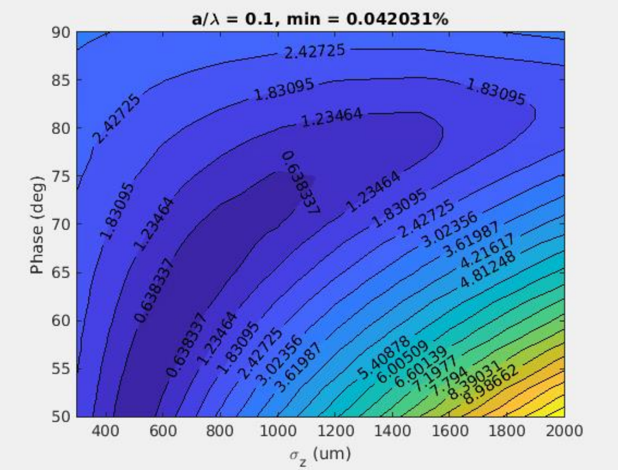


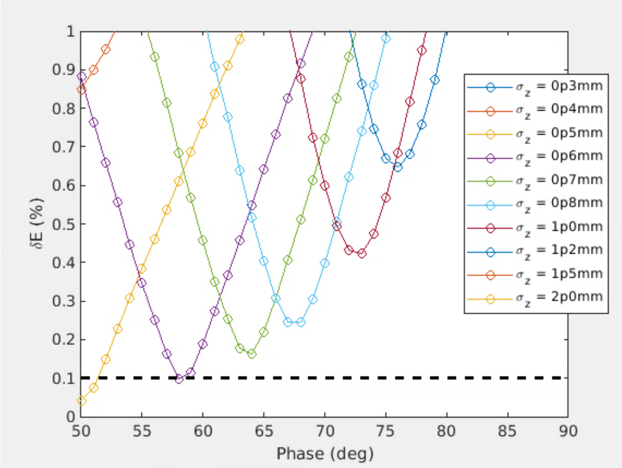


f_5p6GHz_G_25MVm_al_0p1.fig | f_5p6GHz_G_25MVm_al_0p15.fig | f_5p6GHz_G_25MVm_al_0p2.fig

f = 5.6 GHz, G = 40 MV/m, no linearizer

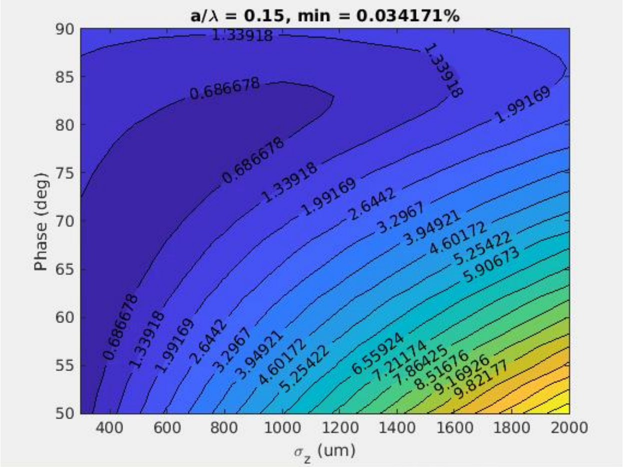
a/λ = 0.1 (a = 5.4 mm)

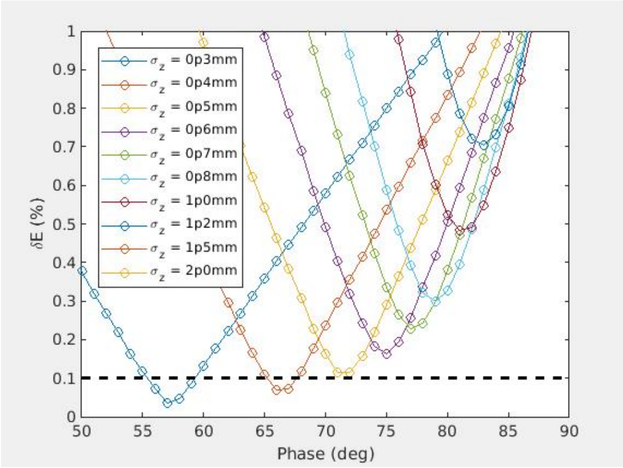




f_5p6GHz_G_40MVm_al_0p1.fig

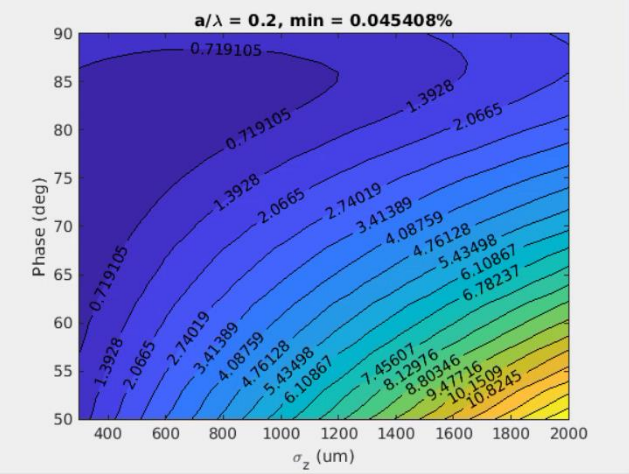
a/λ = 0.15 (a = 8 mm)

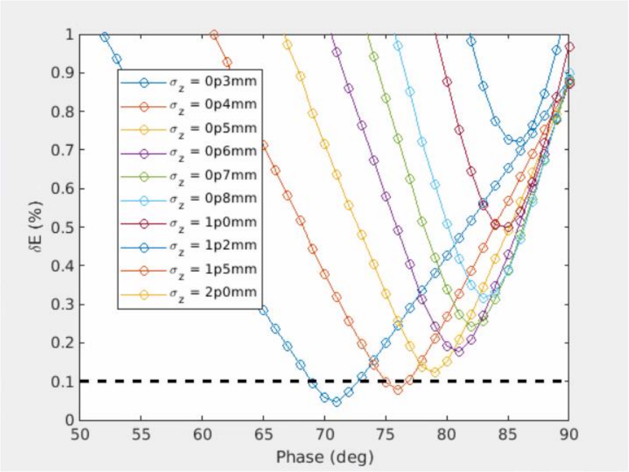




f_5p6GHz_G_40MVm_al_0p15.fig

a/λ = 0.2 (a = 10.7 mm)





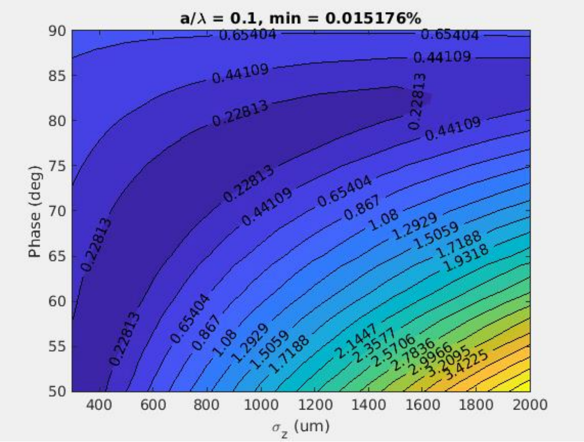
f_5p6GHz_G_40MVm_al_0p2.fig

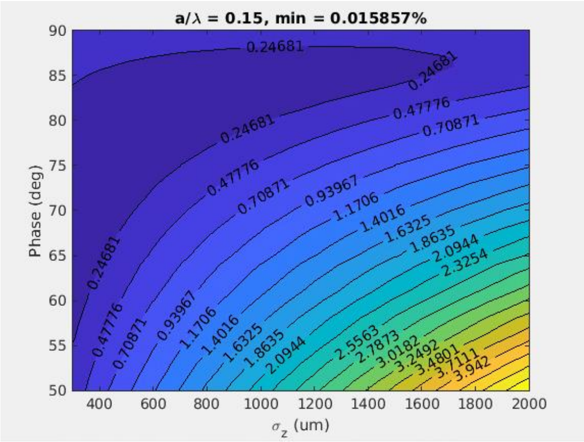
PAUL SCHERRER INSTITUT

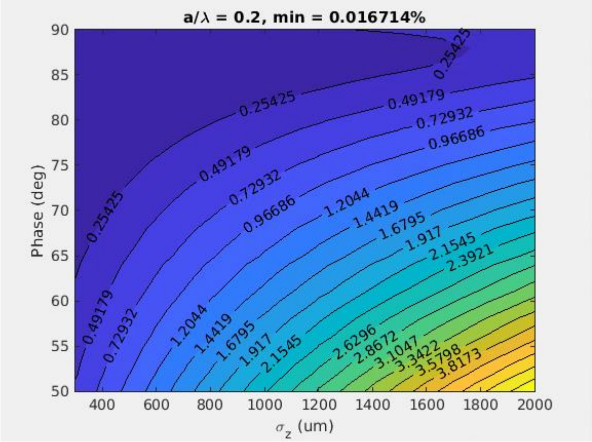
f = 2.0 GHz, G = 25 MV/m, no linearizer

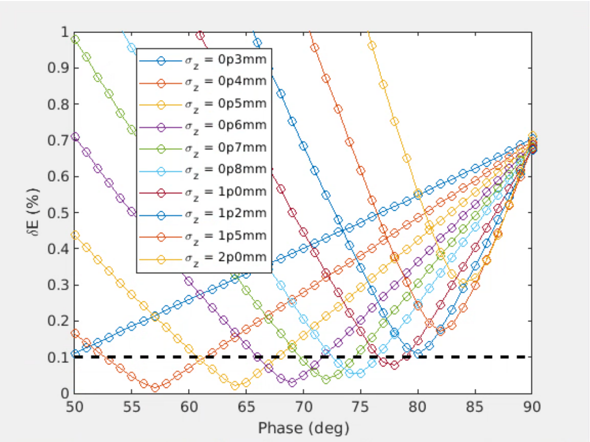
Electron linac run at 2 GHz. To be consistent with the previous a/λ = 0.2 (~3 deg difference expected)

a/λ = 0.1 (a = 15 mm)	a/λ = 0.15 (a = 22.5 mm)	a/λ = 0.2 (a = 30 mm)

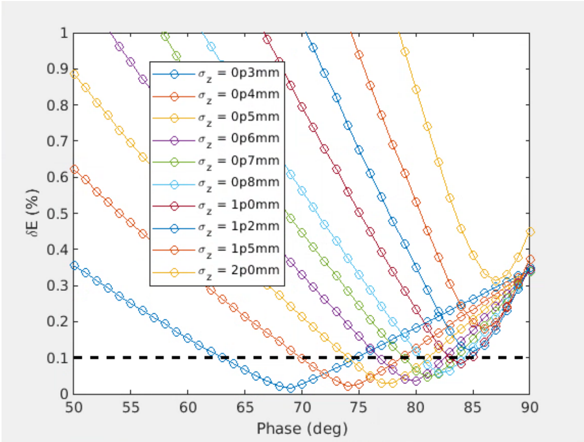




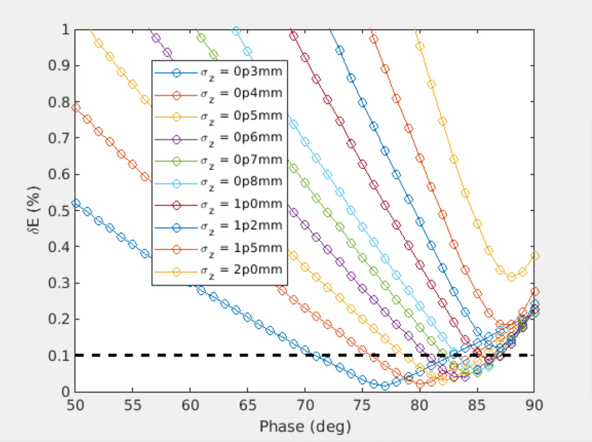




f_2p0GHz_G_25MVm_al_0p1.fig



f_2p0GHz_G_25MVm_al_0p15.fig



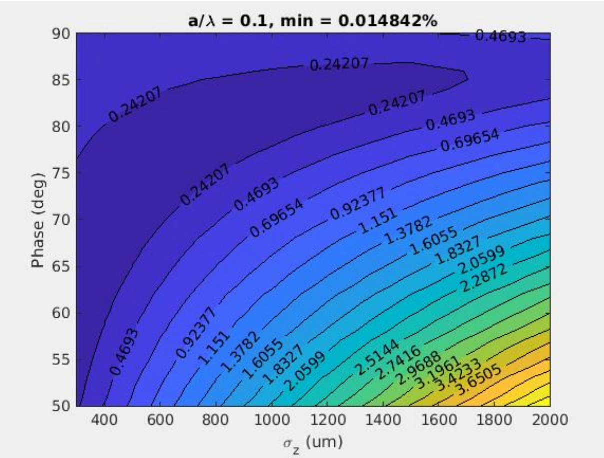
f_2p0GHz_G_25MVm_al_0p2.fig

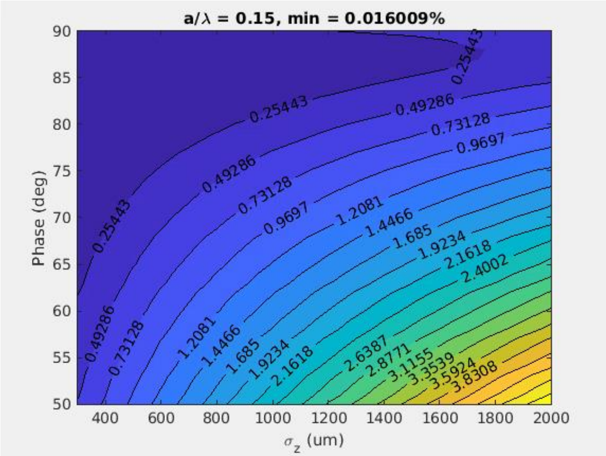
PAUL SCHERRER INSTITUT

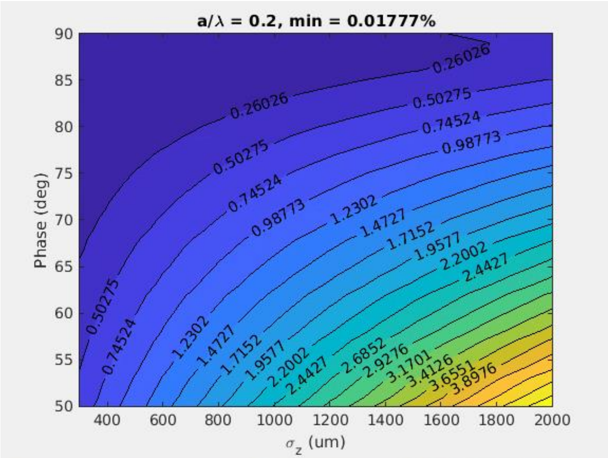
f = 2.0 GHz, G = 40 MV/m, no linearizer

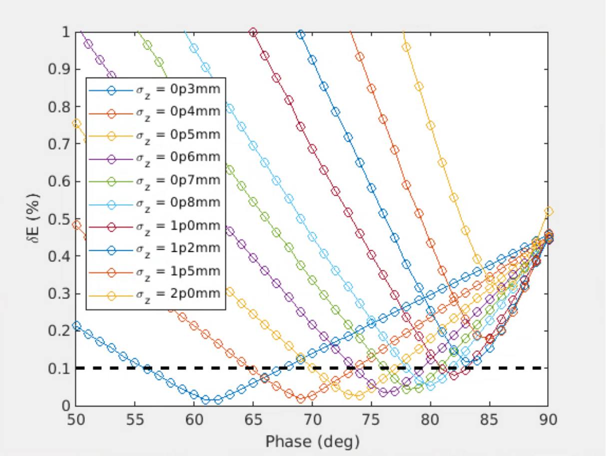
Electron linac run at 2 GHz. To be consistent with the previous a/λ = 0.2 (~3 deg difference expected)

a/λ = 0.1 (a = 15 mm)	a/λ = 0.15 (a = 22.5 mm)	a/λ = 0.2 (a = 30 mm)

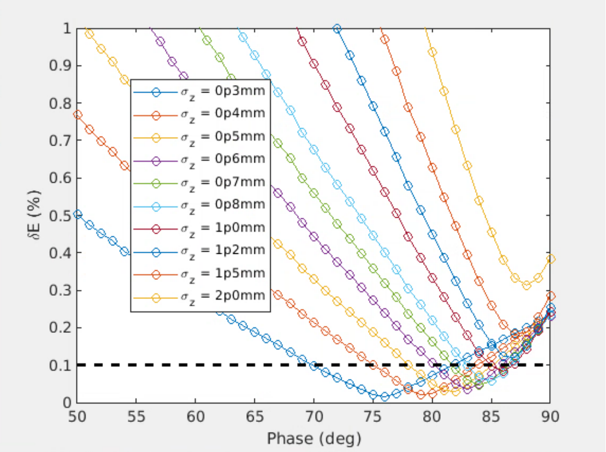




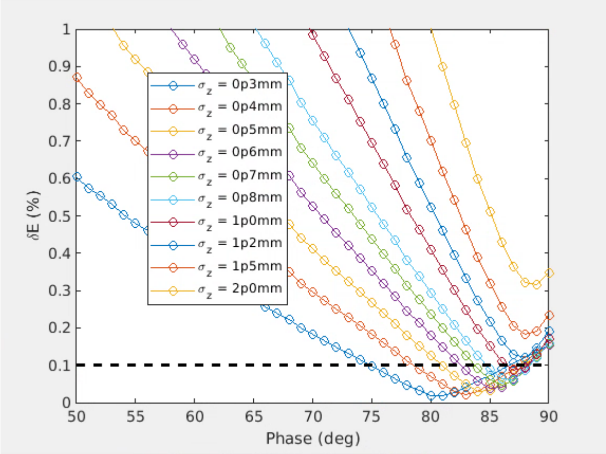




f_2p0GHz_G_40MVm_al_0p1.fig



f_2p0GHz_G_40MVm_al_0p15.fig



f_2p0GHz_G_40MVm_al_0p2.fig