FCC-ee Injector Design Study

Salim Ogur

& on behalf of K. Oide, F. Zimmermann

KEK, Tsukuba, Ibaraki 30-Oct-2016

Outline

0. Review of Accelerators and Baseline Parameters

1. Linac Design

   < Positron Parameters >

2. Damping Ring Design

3. Conclusions

2

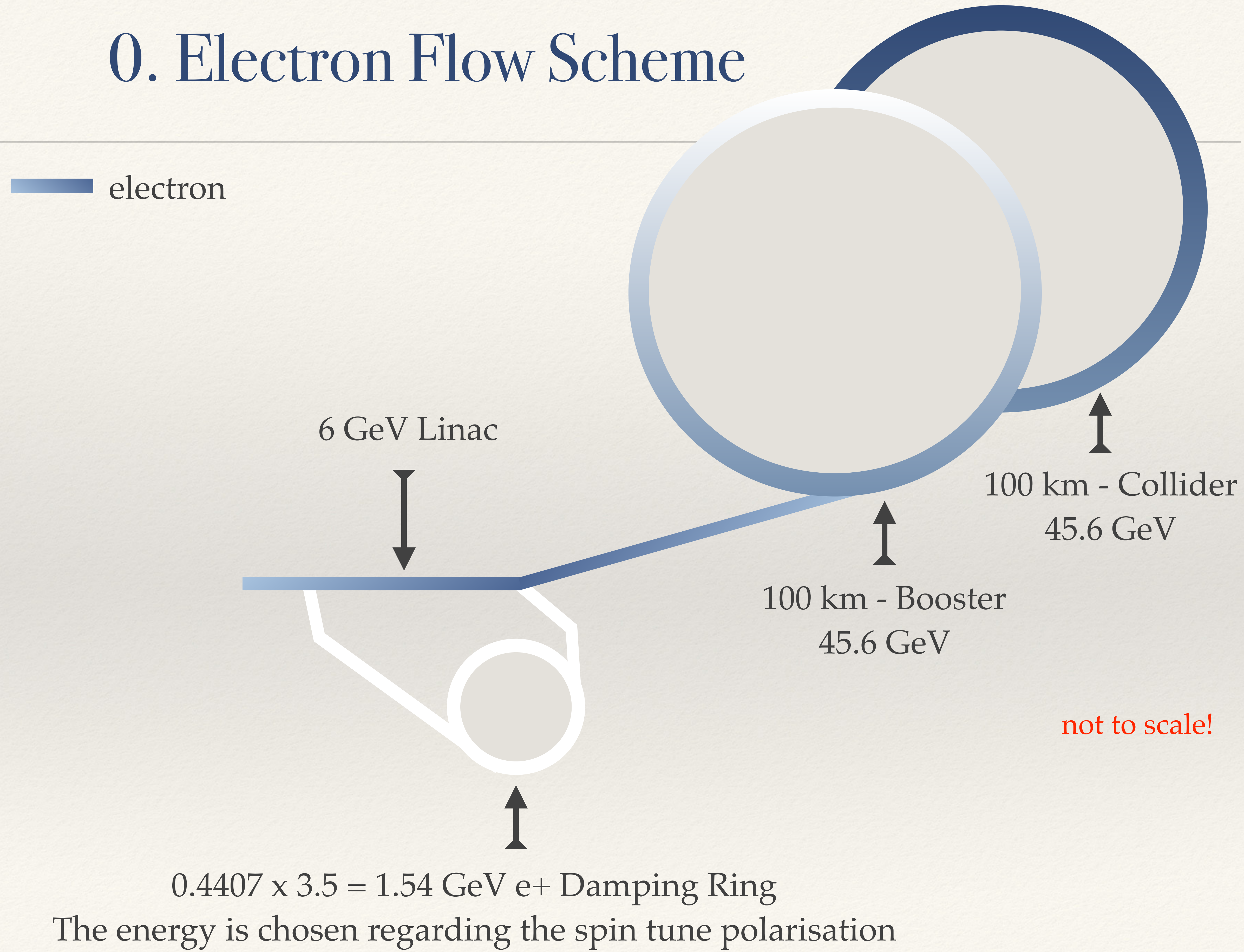
Motivation:

Operation Type	Final Energy [GeV]	Bunches /Beam	Bunch Population	Horizontal Emittance	Vertical Emittance
Z	**45.6**	**91500**	**3.3E+10**	**0.09 nm**	**1 pm**
W	80	5260	6E+10	0.26 nm	1 pm
H	120	780	8E+10	0.61 nm	1 pm
tt	175	81	1.7E+11	1.3 nm	1 pm

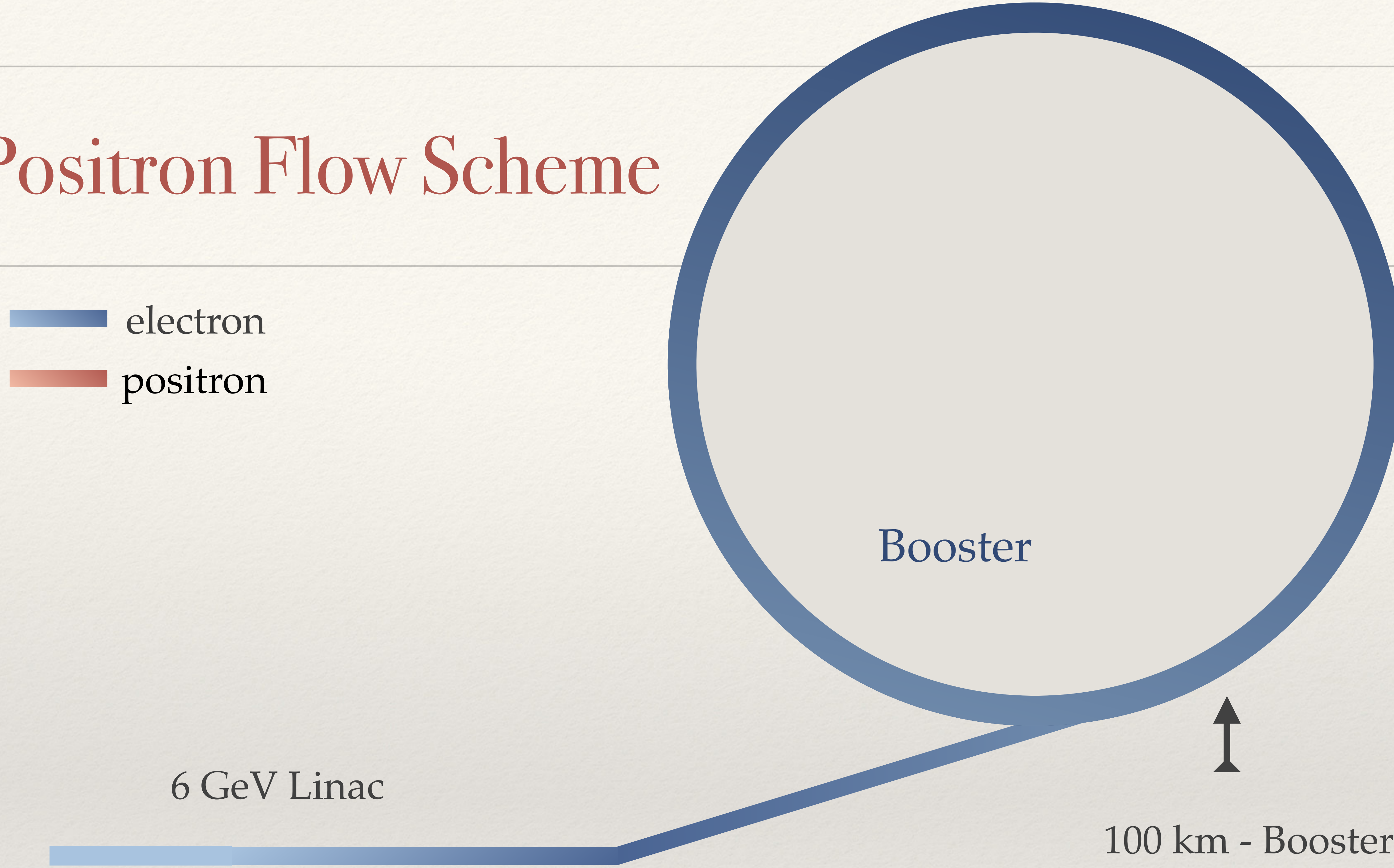
❖ FCC ee has 4 different operations, especially Z operation is challenging in terms of pre-injection since it requires the **highest total charge** and the **lowest emittance**.

❖ Therefore, **the fulfilling the requirements of Z-operation is to cover all other operations in terms of total charge and final geometric emittance in the collider.**

0. Electron Flow Scheme



0. Positron Flow Scheme



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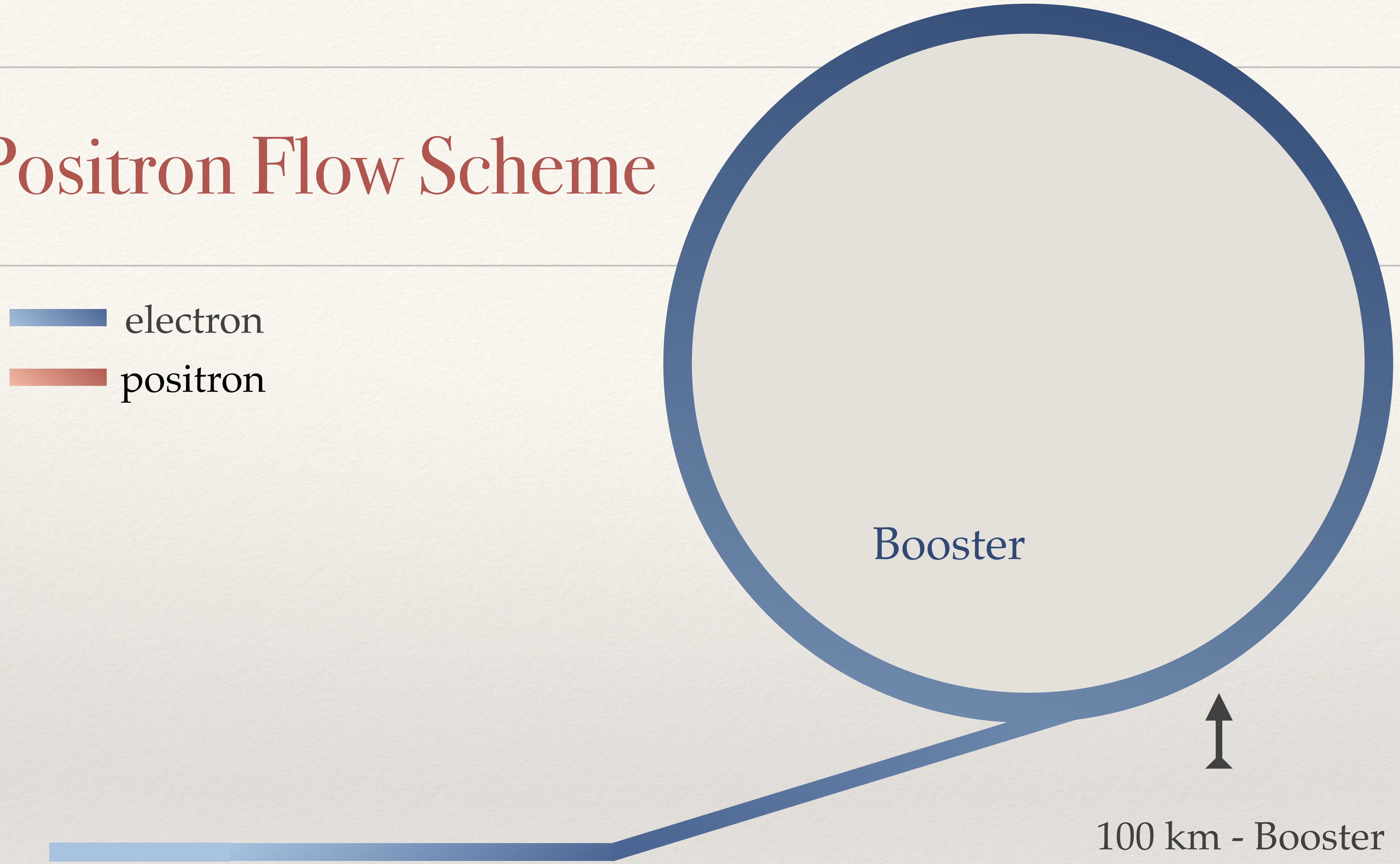

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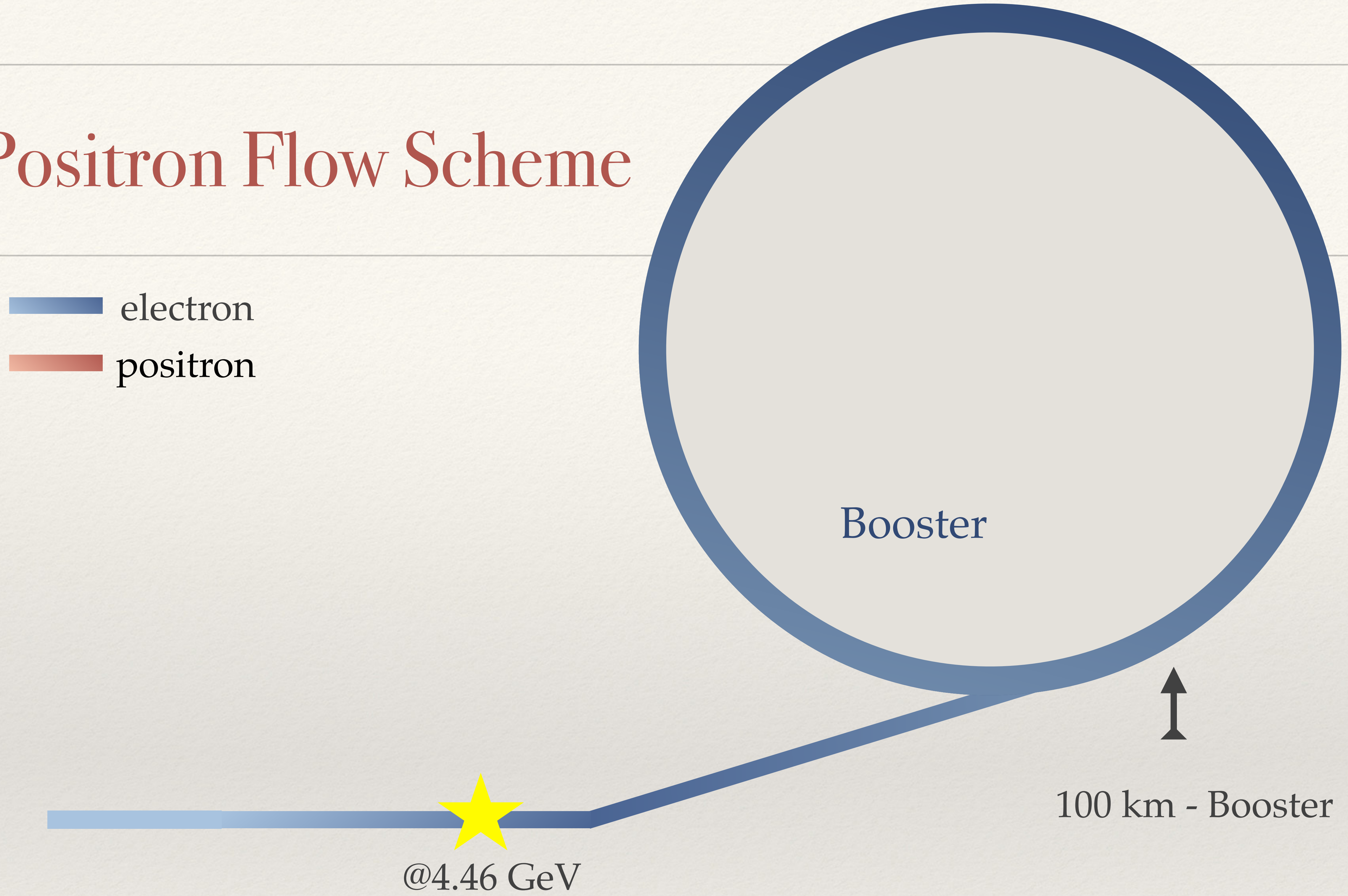

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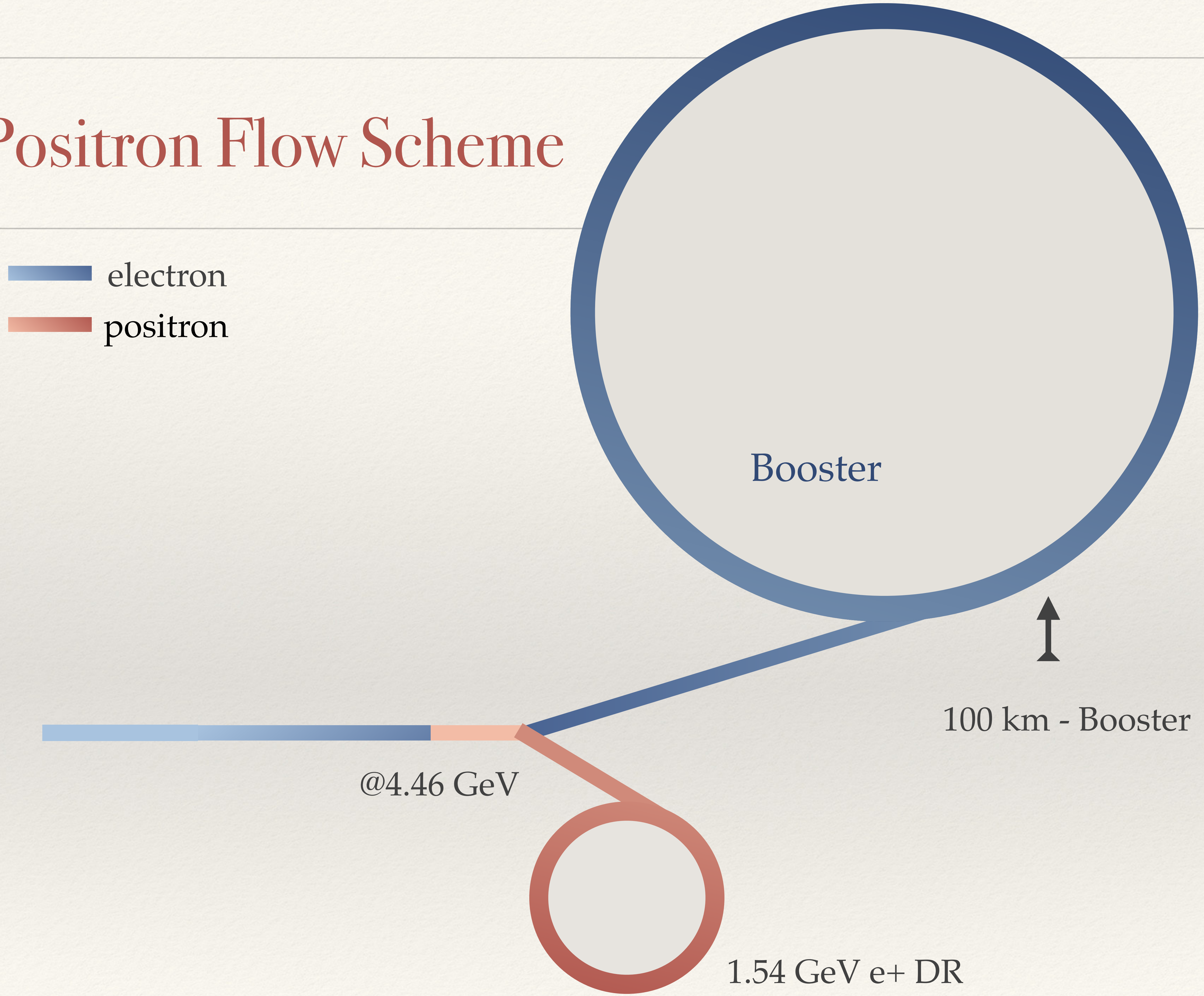

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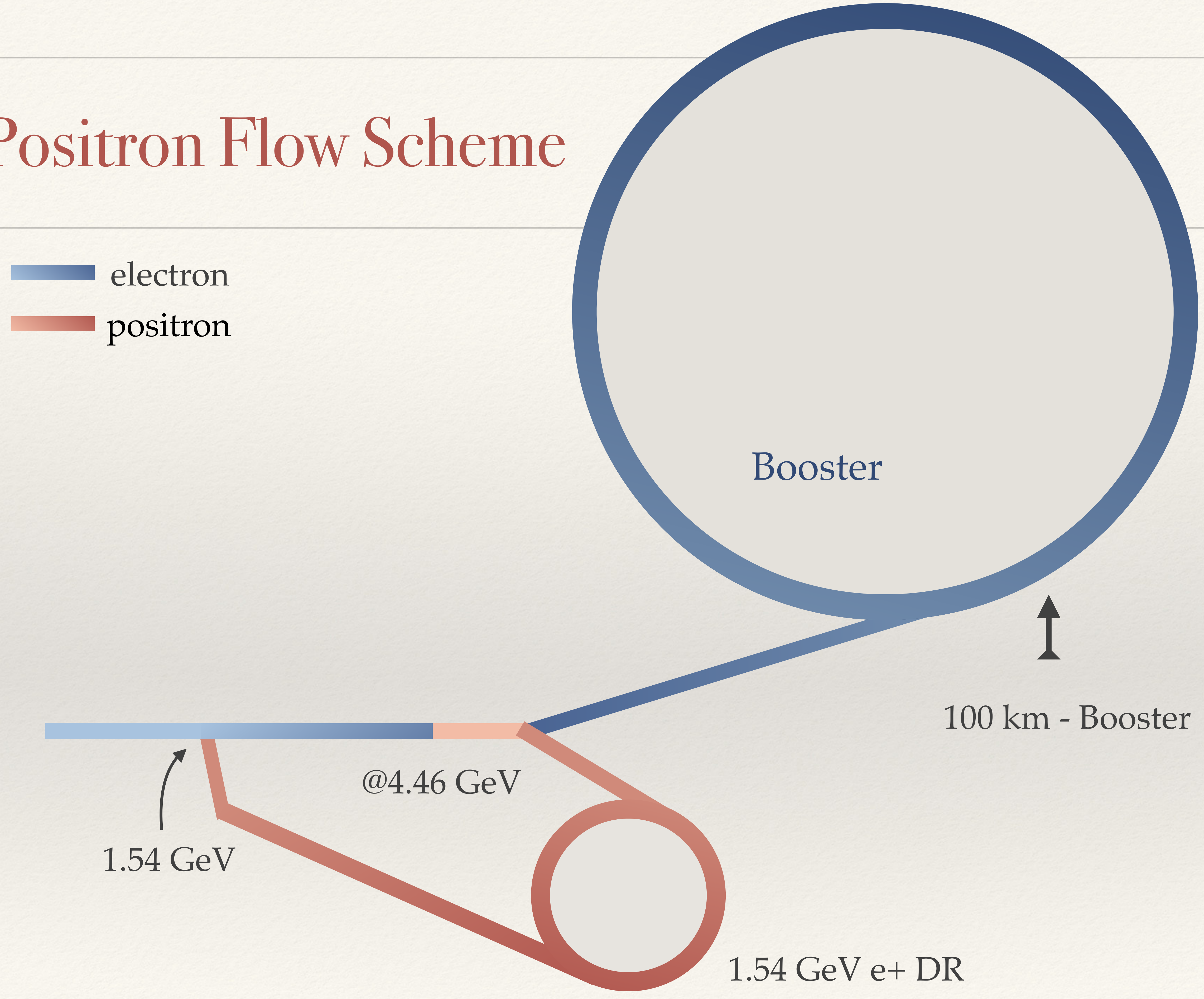

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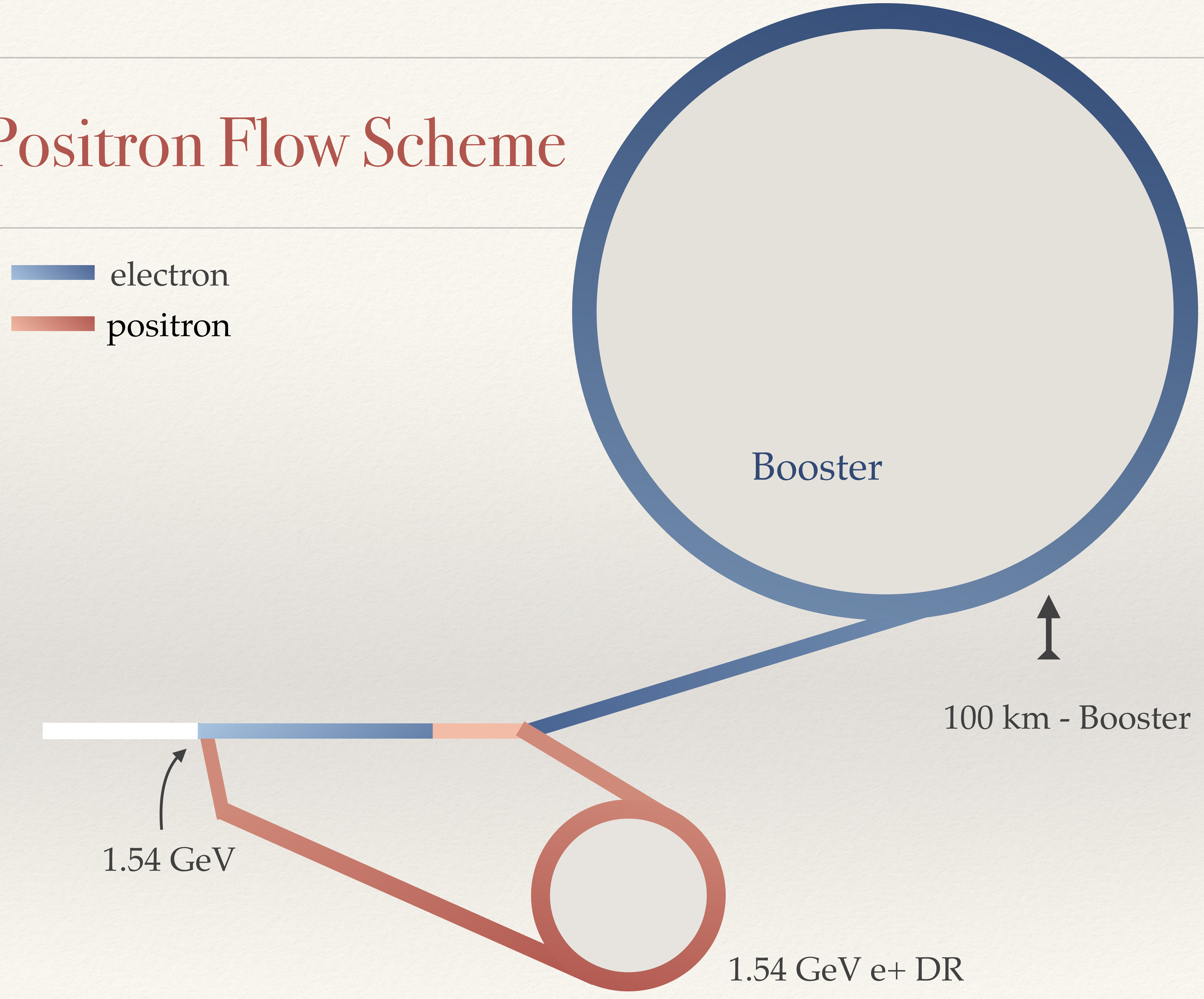

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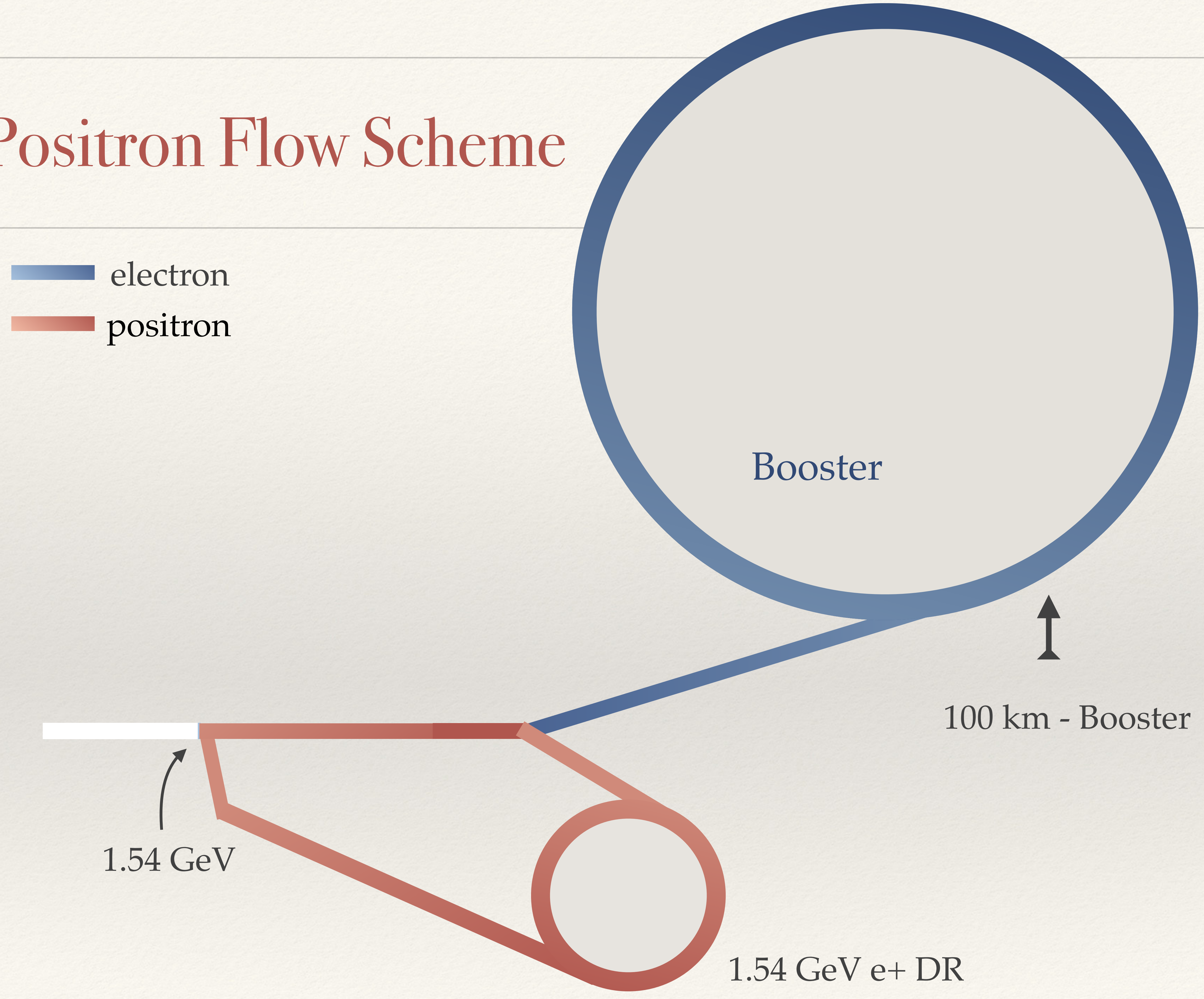

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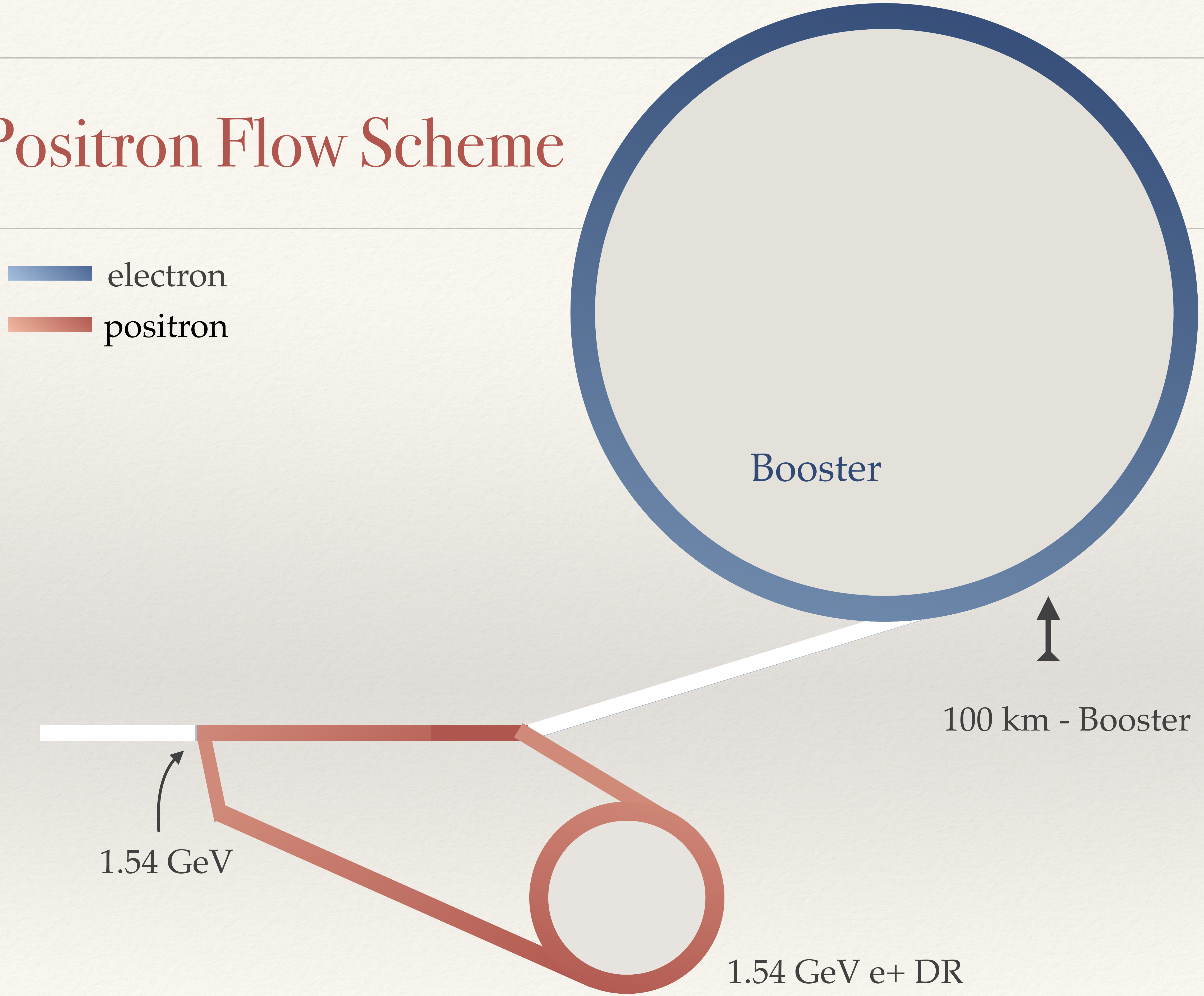

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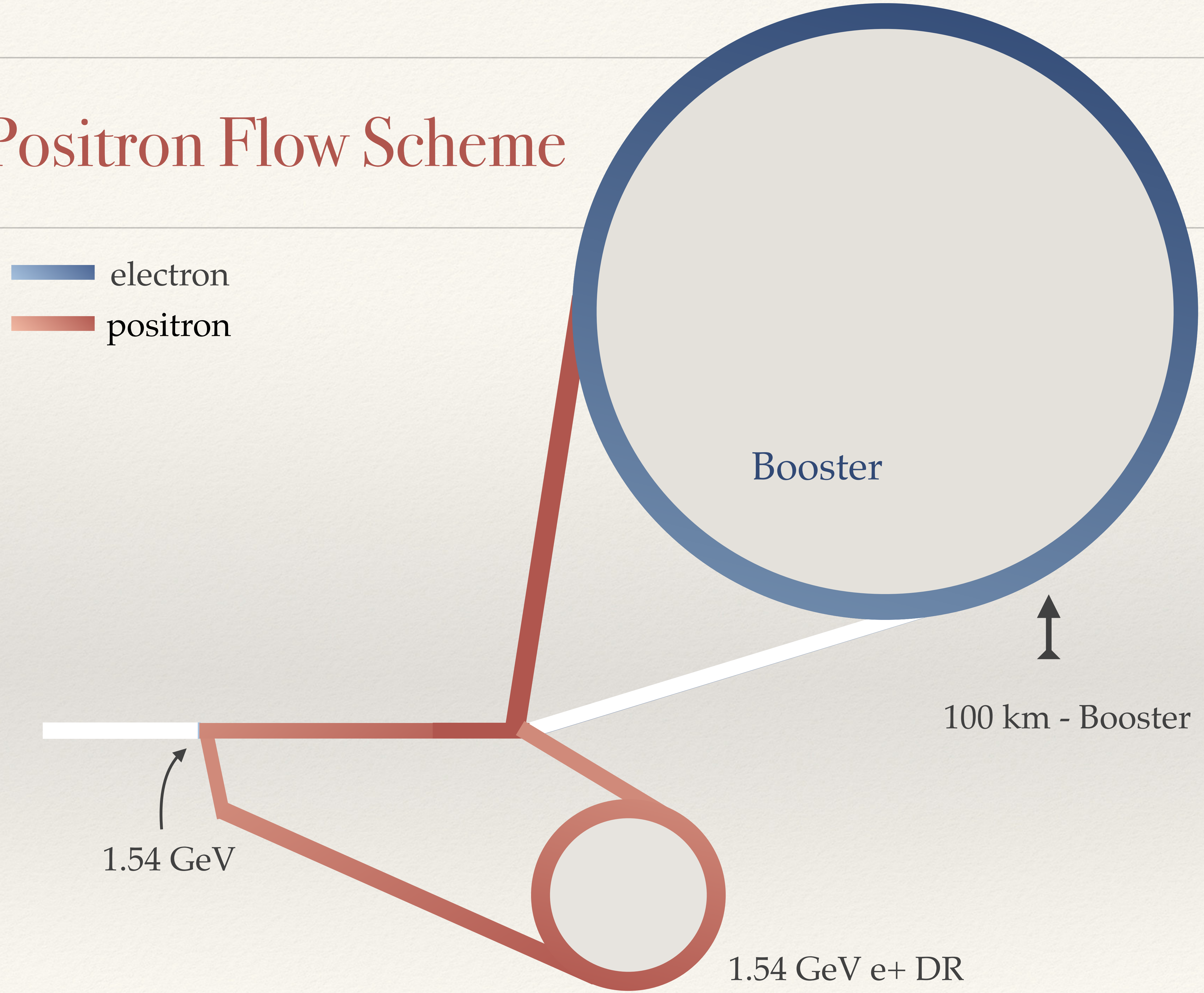

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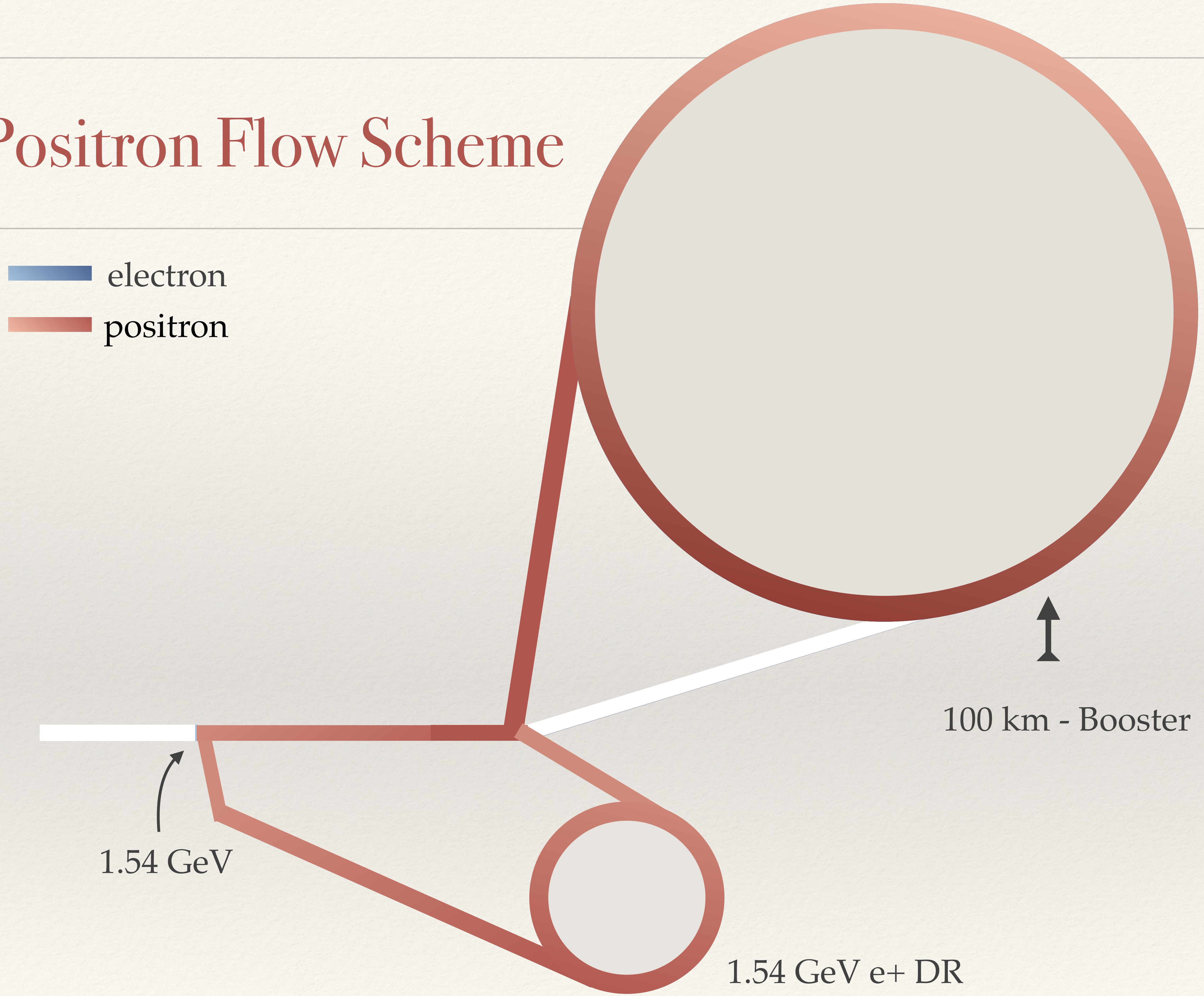

0. Booster- the first Fill-up of the Collider

- The Booster fill time is suggested as 4 seconds and 6 more seconds for the acceleration of the available bunches. The electrons are injected with f=100 Hz from the linac with 2 bunches per RF Pulse (we are working on SLED acceleration scheme to check the possibility of accelerating 4 bunches per RF pulse or more). Therefore,

4 [seconds]*100 [Hz]* 2 [Bunches/RF Pulse] = 800 Bunches

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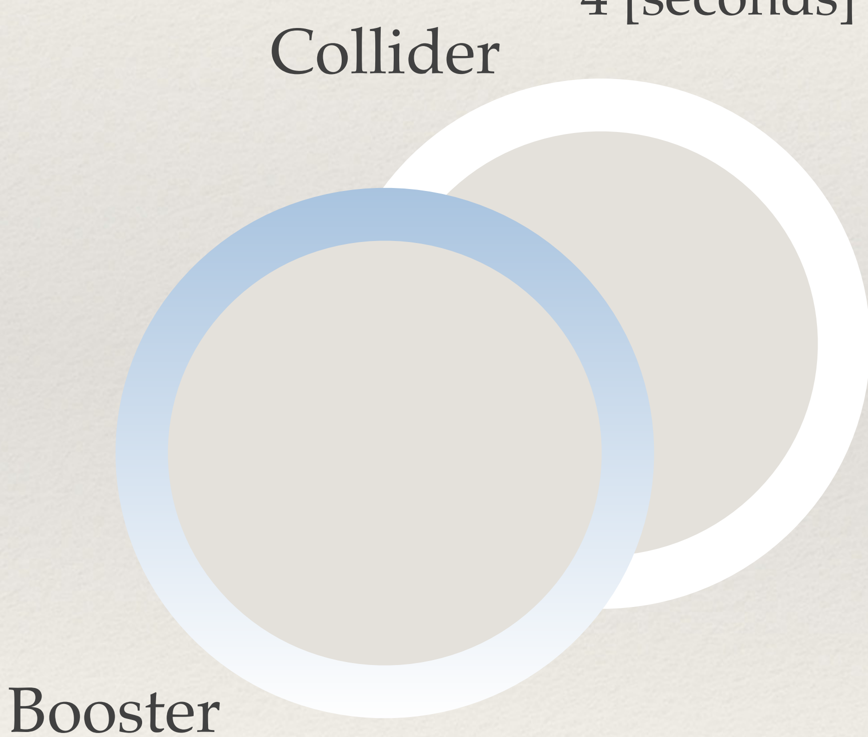

t=10 seconds,
the booster has 800 bunches
the collider has 0 bunch

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t=10 seconds,
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the collider has 0 bunch

t=20 seconds,
the booster has 800 bunches
the collider has 800 bunches

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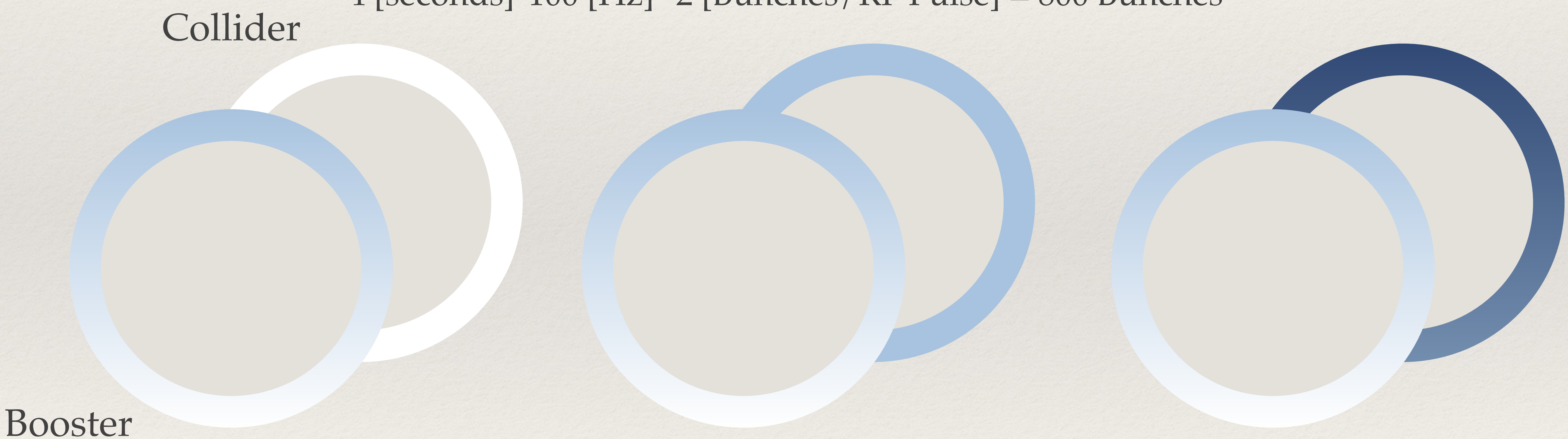


t=10 seconds,
the booster has 800 bunches
the collider has 0 bunch

t=20 seconds,
the booster has 800 bunches
the collider has 800 bunches

t=1150 seconds (~19 mins),
the booster has 800 bunches
the collider has 92000 bunches

0. Overview of Emittance Evolution

★Aim: Linac is optimised to accelerate 4E10 particles. The expected beam population at the end of linac is 3.3E10 at 6 GeV. Therefore, the Linac should at least have 83% of transmission. Meanwhile the exiting beam emittance should match the requirements:

e- Accelerators	Energy	Rel. Gamma Ratio	EmitX	EmitY
Collider Aims	45.6	-	0.09 nm	1 pm
Collider Accepts	45.6	-	27.3 nm	2 nm
Booster Exit	45.6	-	0.09 nm	0.13 nm
Booster Entrance	6	7.6	0.7 nm	1.0 nm
Linac Exit	6	-	**0.7 nm**	**1.0 nm**
Linac Entrance	0.012	500	**0.35 μm**	**0.5 μm**

❖ Assuming normalised emittance kept constant at 8/12 μm (h/v) throughout the re-entrance of the linac, thru transfer to the booster, inside the booster and injection to the collider.

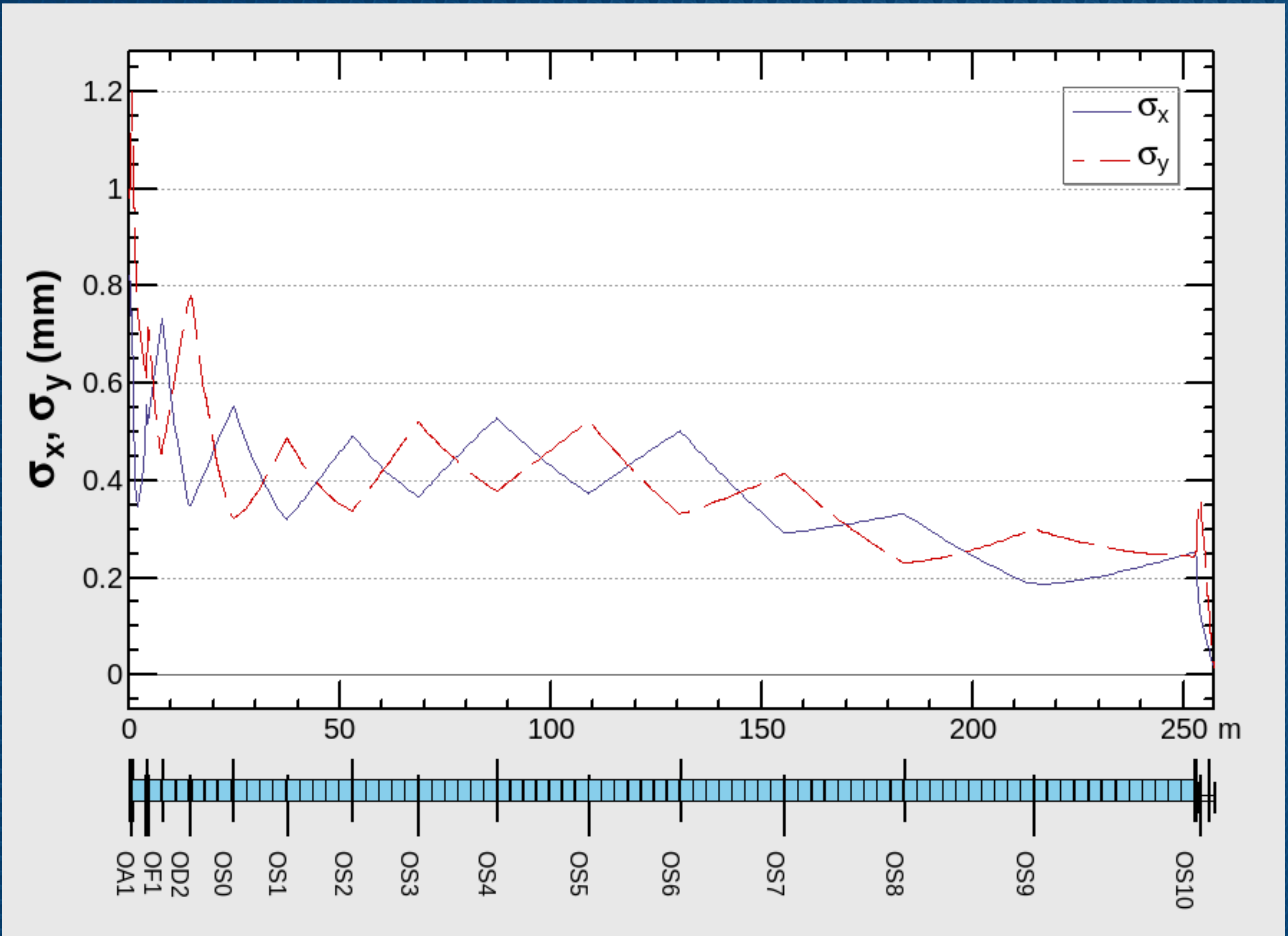
1. Linac - Basics

- The Linac is deploying cavities of ~2.97 m length with 10 mm aperture size at frequency 2855.98 MHz (S-band).

- The Wakefields have been turned on through the linac simulations.

- Normal conducting linac with 100 Hz repetition, it is optimised to accelerate 4E10 particles per bunch which is intentionally above full-charge(3.3E10) concerning the probable transmission loss.

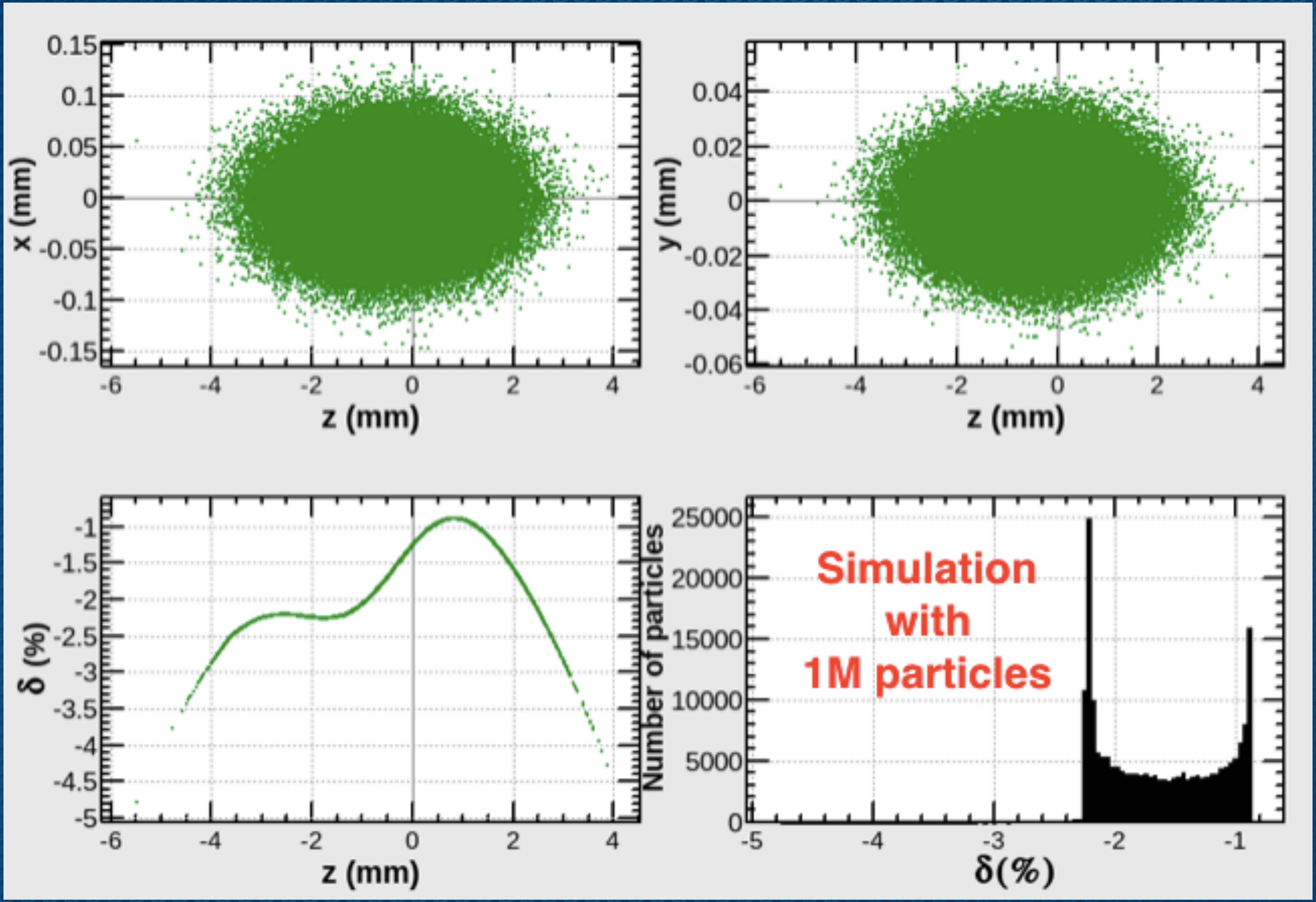
1. Linac - Optics



Parameter	Value
Initial Energy [MeV]	12
Final Energy [GeV]	6
Length [m]	257.3
Initial Emittance (h/v) [μm]	0.35/0.5
Final Emittance (h/v) [nm]	0.7/1.0
# of cavities	80
Gradient [MV/m]	25
Grad. thru acc. [MV/m]	23

- Gaussian Random Beam with 1 mm bunch length and 1% energy spread

1. Linac - Beam Profile



1. Linac - Misalignments

Table 2: Misalignment Study

Element	Simulated Error
Injectional Error (h/v)	0.1 mm
Injectional Momentum Error (h/v)	0.1 mrad
Quadrupole Misalignment (h/v)	0.1 mm
Cavity Misalignment (h/v)	0.1 mm

- Realistic errors have been introduced to study transmission and orbit correction. Each error refers to 1 sigma in Monte Carlo simulation (Gaussian distribution).

- About 3 m long 2.856 GHz cavities with 10 mm aperture size are used.

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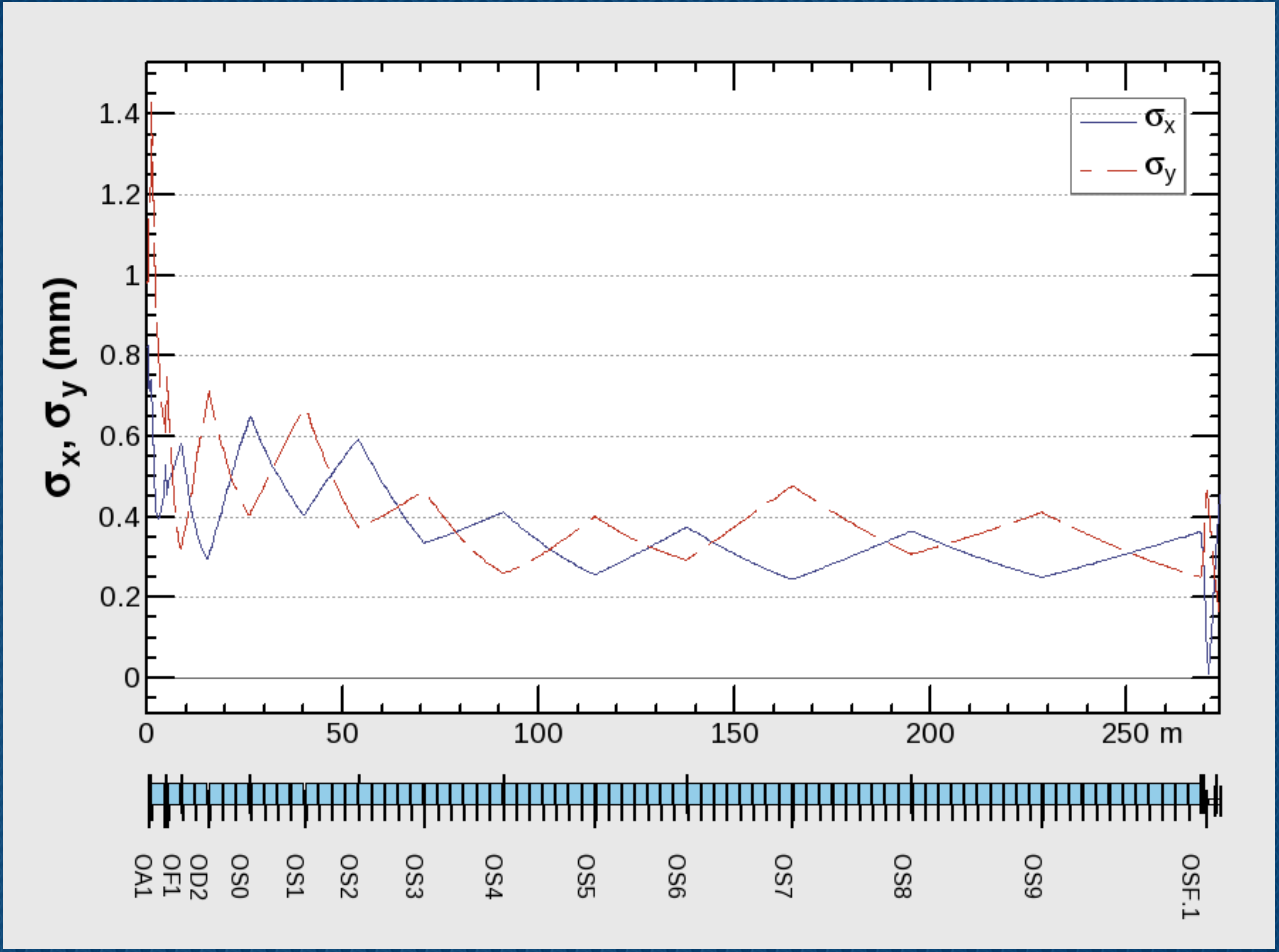
Transmission drop to 33% !!

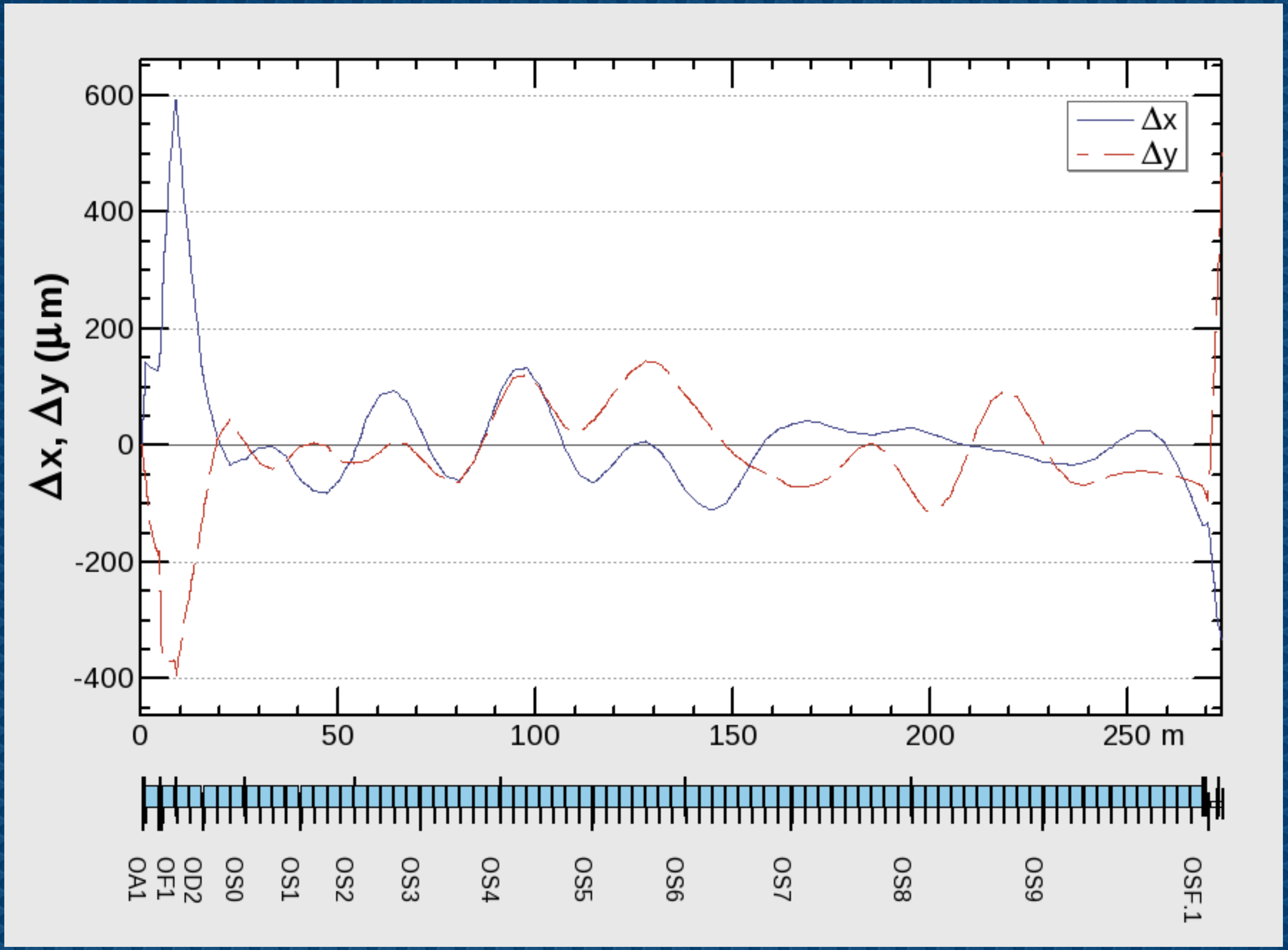
- ❖ Realistic errors have been introduced to study transmission and orbit correction. Each error refers to 1 sigma in Monte Carlo simulation (Gaussian distribution).
- ❖ About 3 m long 2.856 GHz cavities with 10 mm aperture size are used.

1. Linac- Orbit Correction(First Step)



❖ Beam envelope oscillations have not been changed dramatically after deploying a steerer magnet for each cavity.

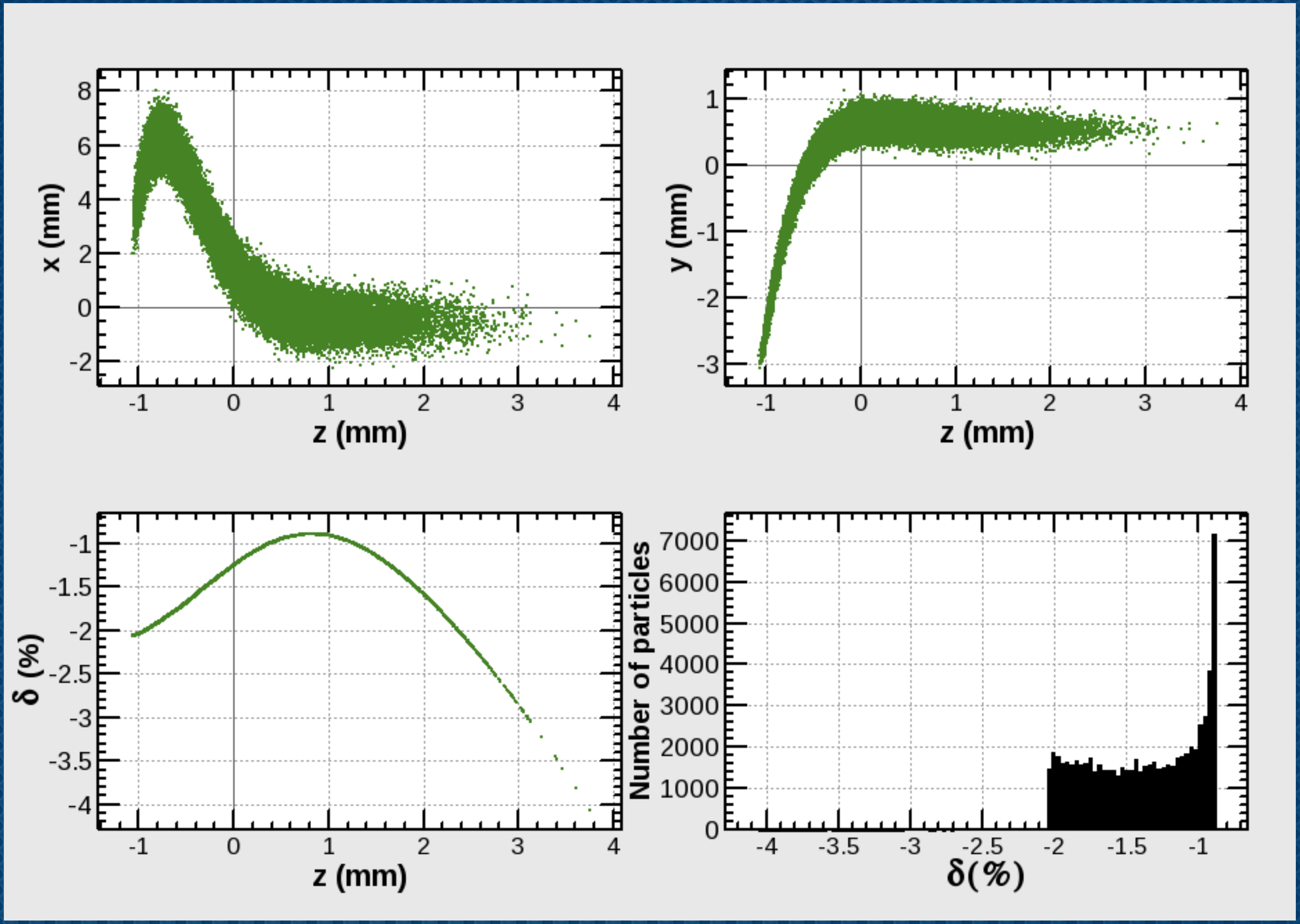
2. Linac- Orbit Correction(First Step)



- The gradients of the steerers are dynamically set to re-center the misaligned incoming beam to the cavity center by the code written by K.Oide.

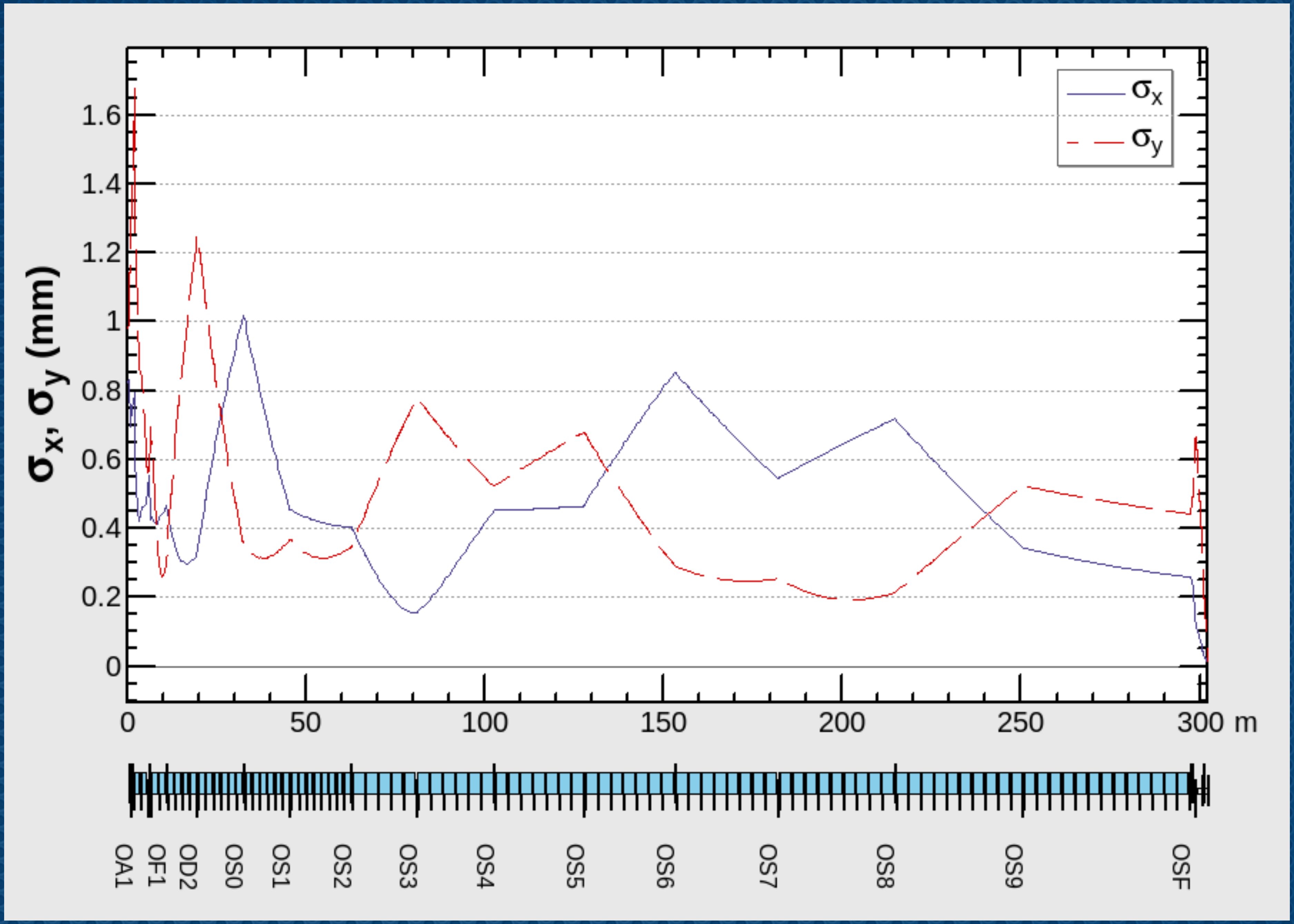
- Physically, this script corresponds to a readout of BPM, and then to determine the gradient of the steerers depending on that.

1. Linac- Orbit Correction(First Step)



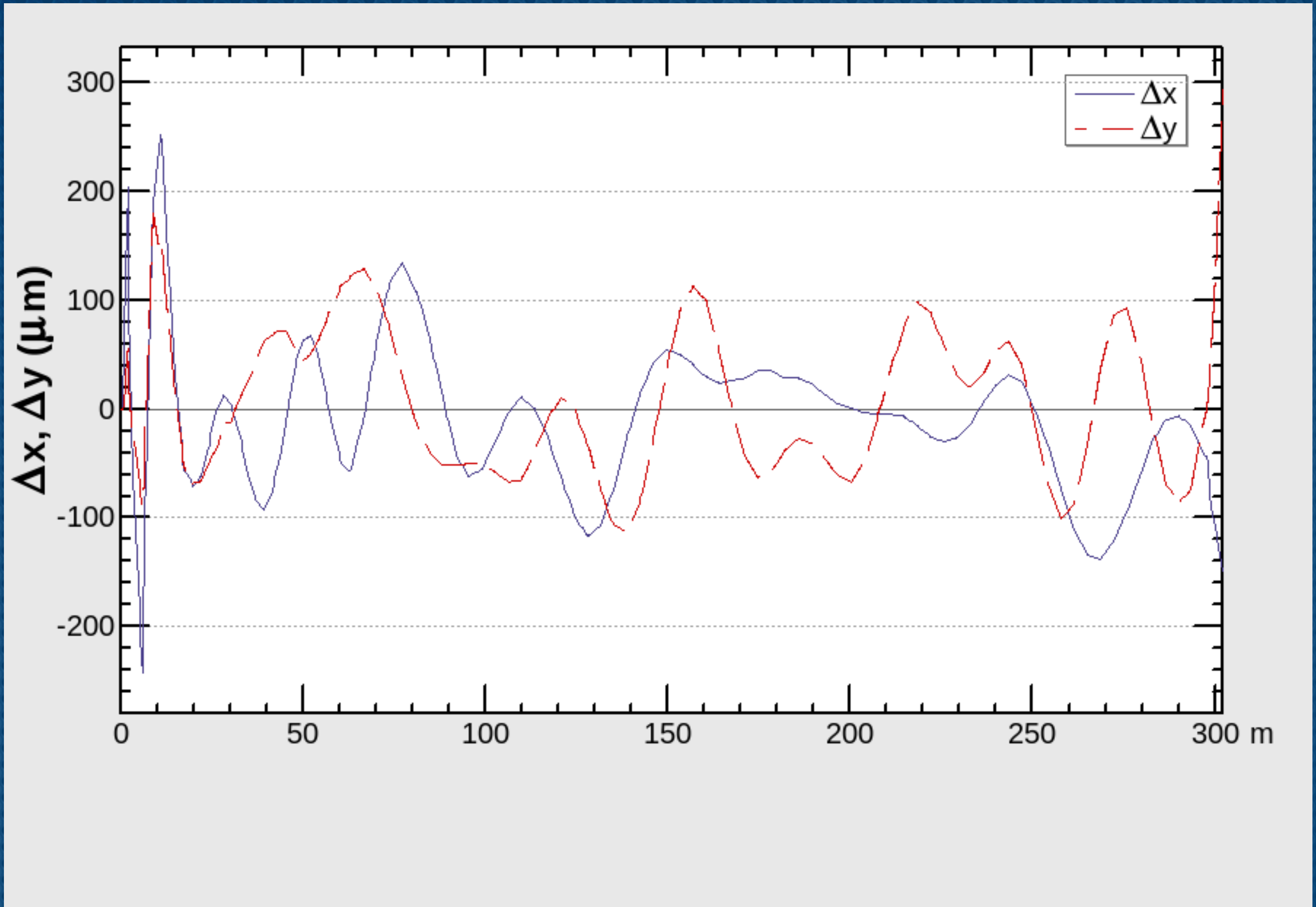
- The transmission is 69%.

1. Linac- Orbit Correction(Second Step)



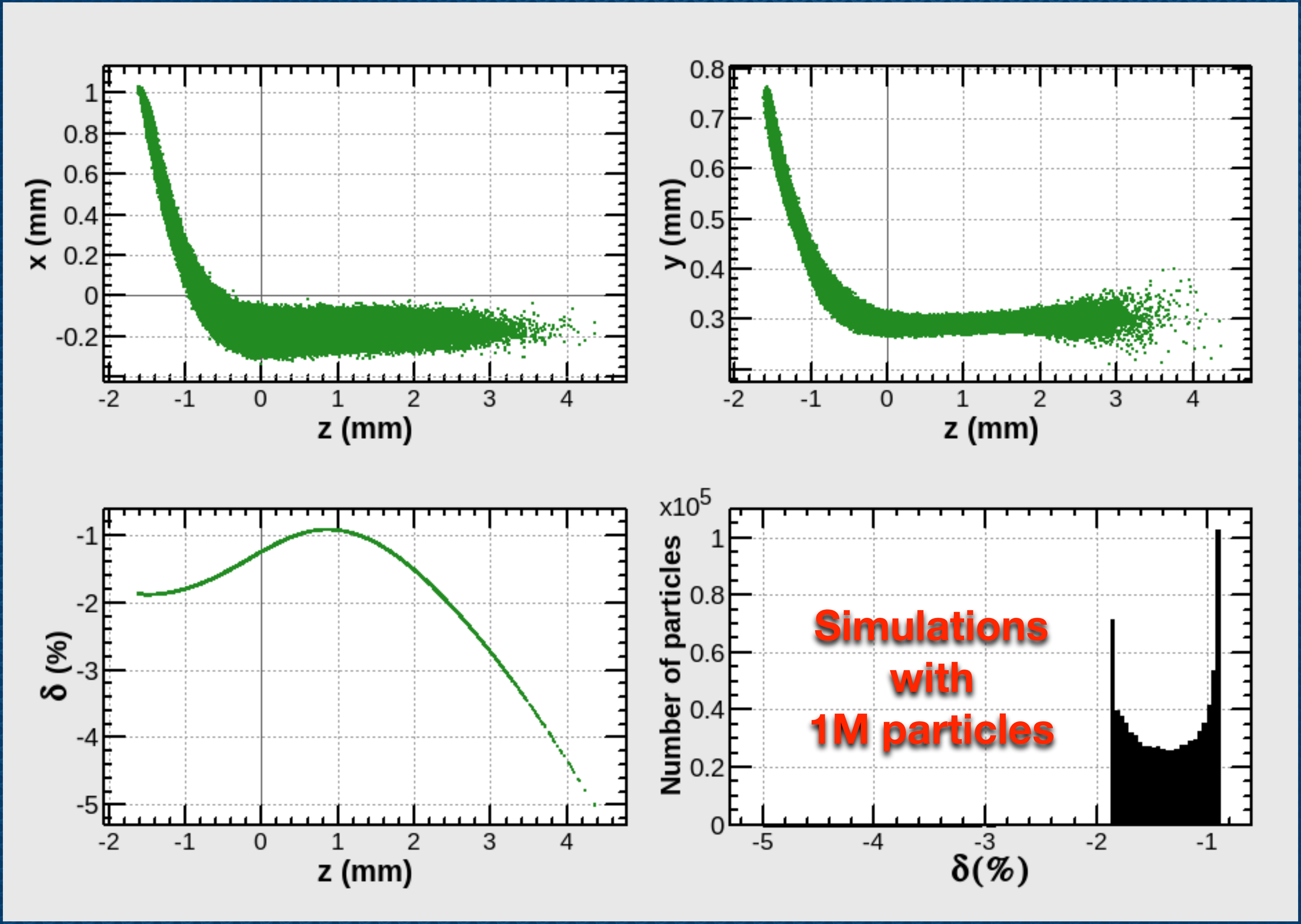
- Half length cavities with 20 mm aperture have been deployed to reduce the impact of the wakefields in the low energy part.

1. Linac- Orbit Correction(Second Step)



- Thanks to shorter cavities and larger aperture, the impact of the wakes decreased. Besides, we can steer the beam in a shorter distances.

1. Orbit Correction- Beam Profile



1 . Linac - Results

@ the end of Linac	Results
Transmission Required	83%
Transmission Provided	88%
Emittance (h/v) Required	0.7/1.0 nm
Emittance (h/v) Provided	60/51 nm

- Wakefields cause the beam to shape like “banana”, and this inevitably makes the emittance much bigger.
- Deploying half-length cavities (14.3 wavelengths=1.5 m) reduce the effect of the wakefields in low energy part. Aperture size doubled; meanwhile the gradient is kept below 27 MV/m.
- As on-going study, the emittance grow, and getting rid off “banana” shape is under consideration.

<Overview of Damping Necessities>

e+ Accelerators	Energy [GeV]	Rel. Gamma Ratio	EmitX	EmitY
Damping Ring	1.54	-	**0.76 μm ***	**0.71 μm ***
Damping Ring exit	1.54	-	2.66 nm	3.9 nm
Booster exit	45.6	29.6	0.09 nm	0.13 nm

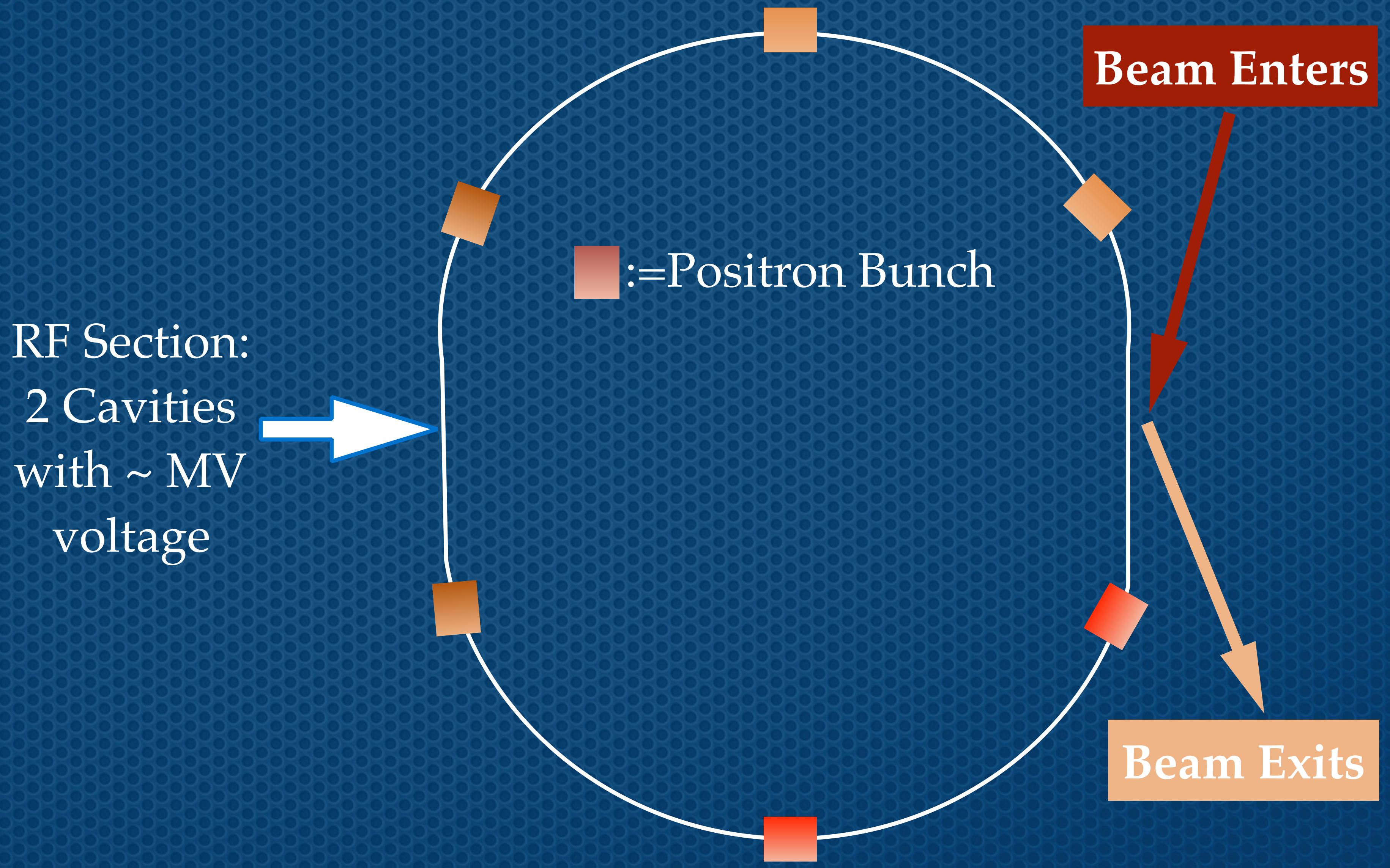
➡ Assuming no normalised emittance shrink or blow throughout the re-entrance of the linac, thru transfer to the booster, inside the booster and injection to the collider.

*** KEK positron data is adapted to the FCC-ee selection of energy and bunch charge !**

2. Damping Ring - Overview

❖ Circumference of the DR 216 meter ↔ 720 ns for the speed of light.

— 3 trains x 2 bunches ⇒ 120 ns spacing;



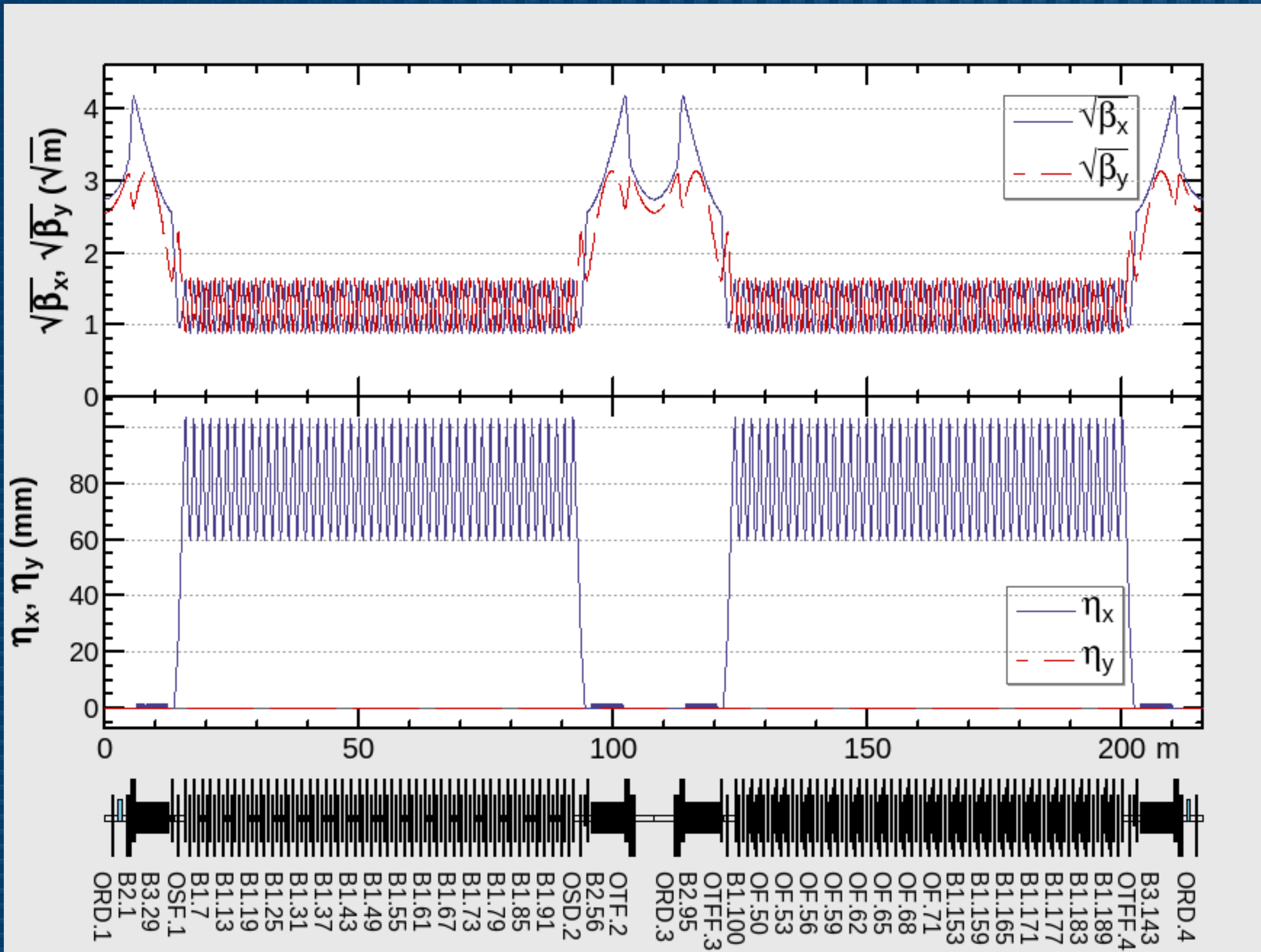
< Positron Acceleration- Time Schedule>

RF time [ms]	Linac	Damping Ring	Booster
0-20	accelerates 2 bunches of e-	damps 2 bunches of e+	empty
20-40	accelerates 2 bunches of e-	damps 4 bunches of e+	empty
40-50	accelerates 2 bunches of e-	damps 6 bunches of e+	empty
50-60	accelerates 2 bunches of e+	damps 4 bunches of e+	accumulates 2 e+ bunches
60-70	accelerates 2 bunches of e-	damps 6 bunches of e+	accumulates 2 e+ bunches
70-80	accelerates 2 bunches of e+	damps 4 bunches of e+	accumulates 4 e+ bunches
80-90	accelerates 2 bunches of e-	damps 6 bunches of e+	accumulates 4 e+ bunches
90-100	accelerates 2 bunches of e+	damps 4 bunches of e+	accumulates 6 e+ bunches
100-110	accelerates 2 bunches of e-	damps 6 bunches of e+	accumulates 6 e+ bunches
(T= 20 ms periodic) 1200+50 ms			accumulates 60 x 2 e+ bunches
at the end of 4 s			400 e+ bunches

❖ 100 Hz i.e.10 ms Linac repetition with 2 bunches per RF pulse where bunch population is 4E10 e- or e+.

➡ **This scheme enables positron bunches 50 millisecond inside the damping ring !**

2 . Damping Ring - Optics



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Parameter	Value
tau_x [millisecond]	11.0
tau_y [millisecond]	11.4
emit_x [nm]	1.3
emit_y	-
Circumference [m]	216
# of bends	192
Dipole Field [T]	0.67
Wiggler Field [T]	1.65
Cell_tune_x [rad]	0.193
Cell_tune_y [rad]	0.183

2 . Damping Ring - DA

```
! ***** DYNAMIC APERTURE *****
!
 DynamicApertureSurvey[{{0,300},{0,300},Range[-120,120,10]},
  1000, Output->6];
Turns =1000 Maximum number of particles =350
Range     Xmin:   0.000 Xmax: 300.000
         (Ymin:   0.000 Ymax: 300.000)
          Zmin:-120.000 Zmax: 120.000
Display:   100 turns/character
     NZ     0----|----1----|----2----|----3----|----4----|----5
 -120.00   1 A7A349321711 3       .         .         .         .
 -110.00   7 AAAAAAA251.1     1 42.         .         .         .
 -100.00   9 **AAAAAAA65952       .  11     .         .         .
  -90.00  13 ******AAAAAAA3A7211 1          .         .         .
  -80.00  14 *******AAAAAAA99A4A2111        .         .         .
  -70.00  16 *********AAAAAAA754546832  1   .         .         .
  -60.00  21 **************AAAAAAA23714211211         .         .
  -50.00  22 ***************AAAAAAA8AAA6A4131     1   .         .
  -40.00  26 *******************AAAAAAA54914442791 1  .         .
  -30.00  30 ***********************AAAAAAA439A222  122         .
  -20.00  34 ***************************AAAAAAA259A111          .
  -10.00  33 **************************AAAAAAA6AA65111A         .
    0.00  39 ********************************AAAAAAA2411  1     .
   10.00  33 **************************AAAAAAA9854A12.211 1     .
   20.00  35 ****************************AAAAAAA123115 1        .
   30.00  30 ***********************AAAAAAA96A2233 3 .13   12A  .
   40.00  27 ********************AAAAAAA3AA33311 4   .         .
   50.00  23 ****************AAAAAAA3AAA143.          .     1   .
   60.00  21 **************AAAAAAA6A41 A38 . 1        .         .
   70.00  17 **********AAAAAAA6A111A  5111 A          .         .
   80.00  14 *******AAAAAAA5AAA3 .A 1       .         .         .
   90.00  11 ****AAAAAAA98A483  1A          .         .         .
  100.00  10 ***AAAAAAA45223321   .         .         .         .
  110.00   6 AAAAAA22  .          .         .         .         .
  120.00   0 7AAA44A   .    2     .         .         .         .
     NZ     0----|----1----|----2----|----3----|----4----|----5
    Score:   492
```

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- ❖ 234 sigmas in transverse
- ❖ 110 sigmas in longitudinal

Ring is tuned:

- ★ nxcell = 0.193
- ★ nycell = 0.183
- ★ NX = 20.087
- ★ NY = 19.163
- ★ Cavity Voltage: 2 MV

2 . Damping Ring - Results

❖ The performance of the Damping Ring in the transverse directions:

e+ Accelerators	Energy [GeV]	Emittance_X	Emittance_Y
Damping Ring entrance	1.54	0.76 μm	0.71 μm
Damping Ring exit (target)	1.54	2.66 nm	3.9 nm
Damping Ring exit (t=50 ms)	1.54	1.36 nm	0.1 nm

❖ Hence, we reach the target at t_x=35 ms, t_y=29 ms; meanwhile the allocated time is 50 ms.

2 . Damping Ring - Results

❖ The performance of the Damping Ring in the transverse directions:

Natural Emittance	DA Needed	DA Created	Acceptance Needed [3 sigma]	Acceptance Provided
1.3 nm	73 sigmas	234 sigmas	6.84 μm	**69.5 μm**

PS: 1-sigma emittance is 0.76 μm

2 . Damping Ring - Results

- The performance of the Damping Ring in the longitudinal direction:

  — Natural emittance : 3.56 μm for 2 MV cavity voltage

$$3.56\ \mu m * (110)^2 = 43.1\ mm$$

which is surpassing the acceptance which is at least 9 times of the adapted KEKB initial positron emittance in z-axis:

$$1\ mm * (3)^2 = 9\ mm$$

2 . Damping Ring - Results

- The performance of the Damping Ring in the longitudinal direction:

  — Bucket Height : 0.0838
  — Energy Spread : 6.71E-4

  —> Dynamic Aperture : 110 σ < 125 σ

2 . Damping Ring - Results

❖ The performance of the Damping Ring in the longitudinal phase space:

— Natural emittance : 3.56 μm for 2 MV cavity voltage
— Bunch Length : 5.30 mm

$$\Rightarrow \beta_z = \frac{\sigma_z^2}{\epsilon_z} = \frac{(5.30\ mm)^2}{3.56\ \mu m} = 7.9\ m$$ which is bigger than the

beam size provided by the KEKB positron data:

$$\beta_z = \frac{\sigma_z^2}{\varepsilon_z} = \frac{(0.041\ m)^2}{0.001\ m} = 1.7\ m$$

energy compressor !!

Conclusions-Linac

❖ 6 GeV S- Band Linac has become 299 meters with 28 half-length and 64 full-length (i.e. 3 m) cavities. There are 22 quadrupoles, and 92 steerer magnets.

❖ The acceleration gradient is around 25 MV/m and 2 bunches per RF pulse are sent. These are quite feasible with the recent technology.

❖ The linac transmission is 88%, which can be increased even more. Yet, the emittance blow has to be cured.

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Conclusions-DR

- ❖ Damping Ring consists of standard FODO lattice (with sextupoles), and normal conducting wigglers. DR also has additional 16 quadrupoles in straight sections to control the ring tune. All magnets (except wigglers with 1.65 T) are below 0.8 T.

- ❖ Damping Ring totally covers the FCC-ee positron damping requirements.

- ❖ Collider for Z-operation will be filled from the scratch with 91500 bunches of e- in 19 mins, and same number of e+ in 27 mins. Such that in 46 mins, the collisions can start.

- ❖ Accelerating more than 2 bunches per RF pulse is under consideration to reduce the time for the first fill of the collider.

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