Challenges for the EM-Separator and its Alternatives

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SY-ABT
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Introduction

Need for beams separation in FCC-ee

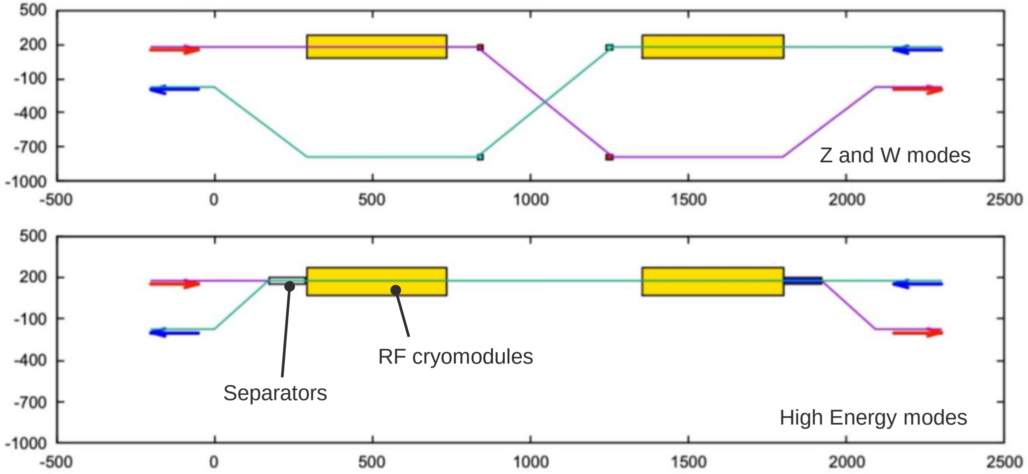
- e^+ and e^- beams share common RF sections and trajectories in H and $t\bar{t}$ modes.
- Given the same energy as well as the opposite charges and directions of the particle beams, separation cannot be achieved with magnetic elements alone.

Timing of the beams must ensure that no collision occurs

- This is done by having two trains of bunches per beam in H and $t\bar{t}$ modes (see slide 9).

RF Incoming beam must not be affected by the separators

- To avoid synchrotron radiation onto the RF cavities.



Schematics of the beam path configurations in the RF section at FCC Point PH [3]

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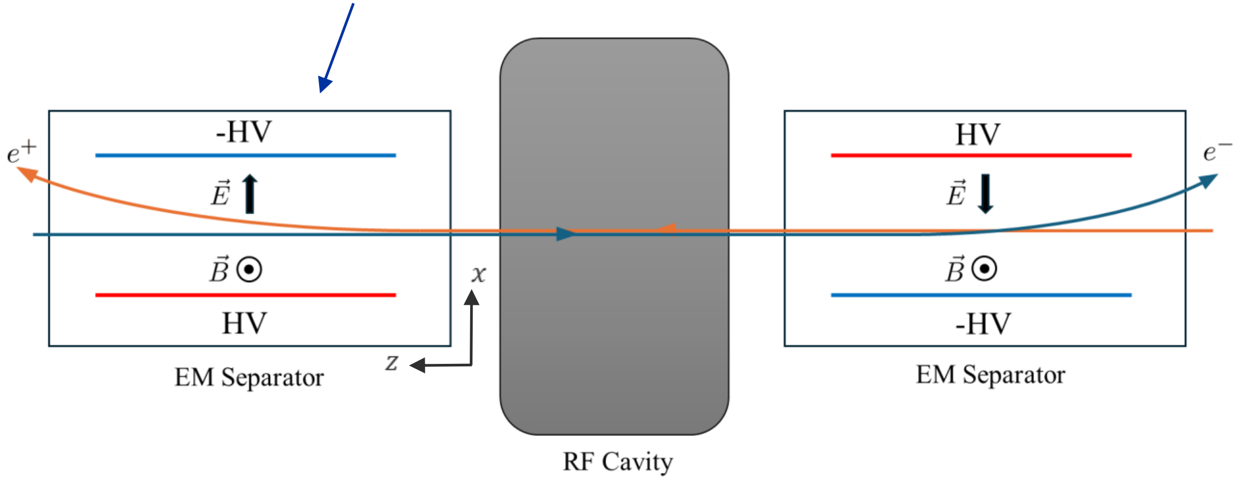
EMS | Principle

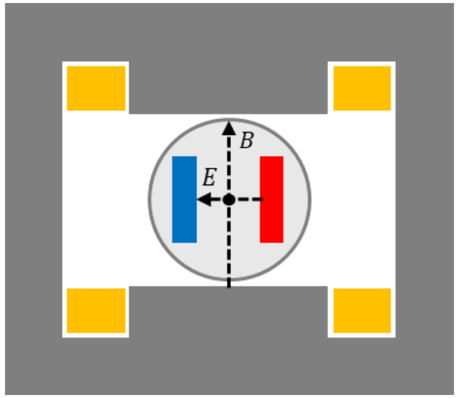
Combination of static electric and magnetic fields achieves the desired separation effect.

The Electro-Magnetic Separator (EMS) is operated at constant energy for each mode, i.e. in a pure DC application.

e^+ particles see a positive force due to $\vec{B}$ and a positive force due to $\vec{E}$
e^- particles see a positive force due to $\vec{B}$ and a negative force due to $\vec{E}$
if $\vec{B}$ and $\vec{E}$ are properly scaled and matched, the net force on e^- is zero



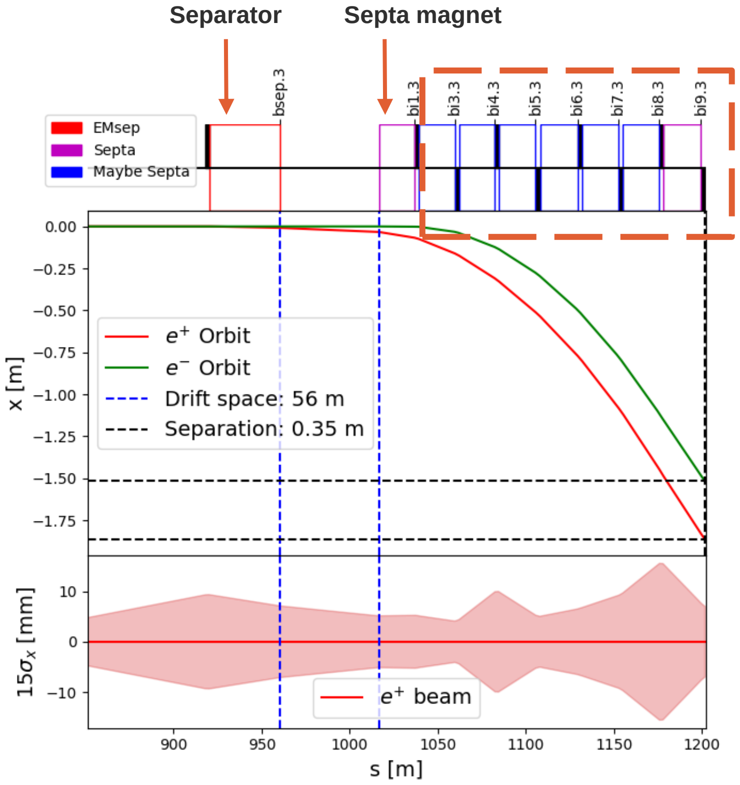
EMS principle using combination of static electric and magnetic fields



EMS cross section showing an outside vacuum dipole magnet and inside vacuum HV electrodes

EMS | Requirements and Specifications

Requirements were based on **lattice version GHC V25.1 [1]** with an RF section of 1790 m.
With **44 m allocated for the EMS** and assuming an average **field of 1 MV/m**, beam **deflection is 0.44 mrad**.
After a **drift space of 56 m**, the **beam separation is 33 mm** at the first septum.



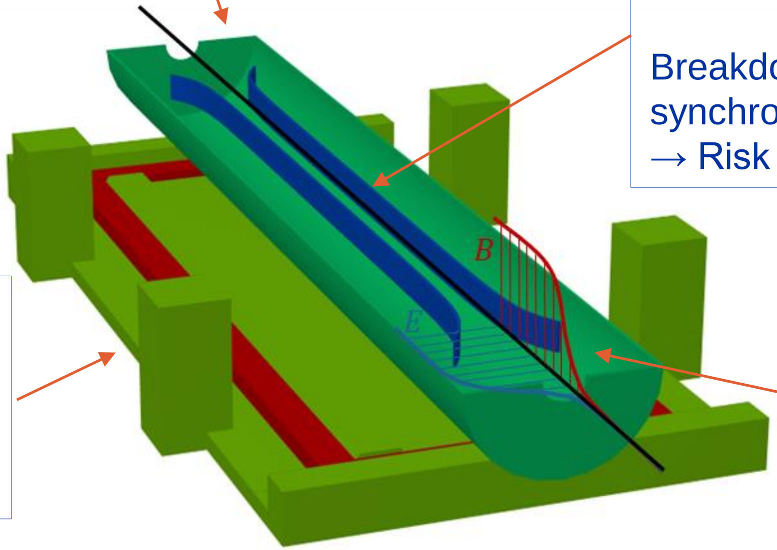
Beams separation layout

To be determined if these are septa or dipole magnets.
Requirements for each of the devices remain to be clarified.

Parameter	Value	Unit	Comment
Total length	44	m	
Segmentation	11	units	Segmentation assures the required mechanical manufacturing tolerances. Between devices : 0.1m for vacuum bellows, 0.4m for radiation masks
Device length	3.5	m	
Magnetic/Electric length	2.5	m	
Beam acceptance (Ø)	60	mm	
Beam deflection per element	40	µrad	
Electrode gap (H)	120	mm	Electrode gap larger than beam acceptance to reduce HV breakdown due to secondary electron emission
E_0	1.44	MV/m	
B_0	4.80	mT	Very low magnetic field to match 1MV/m (B=E/c)
$V_{nominal}$ electrodes	± 86.4	kV	
$I_{nominal}$ magnet	87	A	power requirement is low (<10V, <1kW per device)

EM-Separator Specifications

EMS | Technical Challenges



Vacuum vessel
Under vacuum system requires consideration for:

- Bakeout equipment
- Beam impedance preservation due to large cavity

HV electrodes
Subject to :

- Electron field emission due to high electric field
- Secondary electron emission due to radiation and particle strike
- Electrodes heating

Breakdown would lead to beam disturbances and synchrotron radiation production
→ Risk of breakdown must be mitigated

Electromagnetic dipole
Working at very low magnetic field:
Effect of hysteresis, remanence and external disturbances must be considered to minimize field error

E and B Fields
Must be matched everywhere to avoid synchrotron radiation production

→ Fields matching error to be minimised by design

basic representation of the EMS toplogy

EMS | Prototyping Needs

Local matching of Electric and Magnetic fields

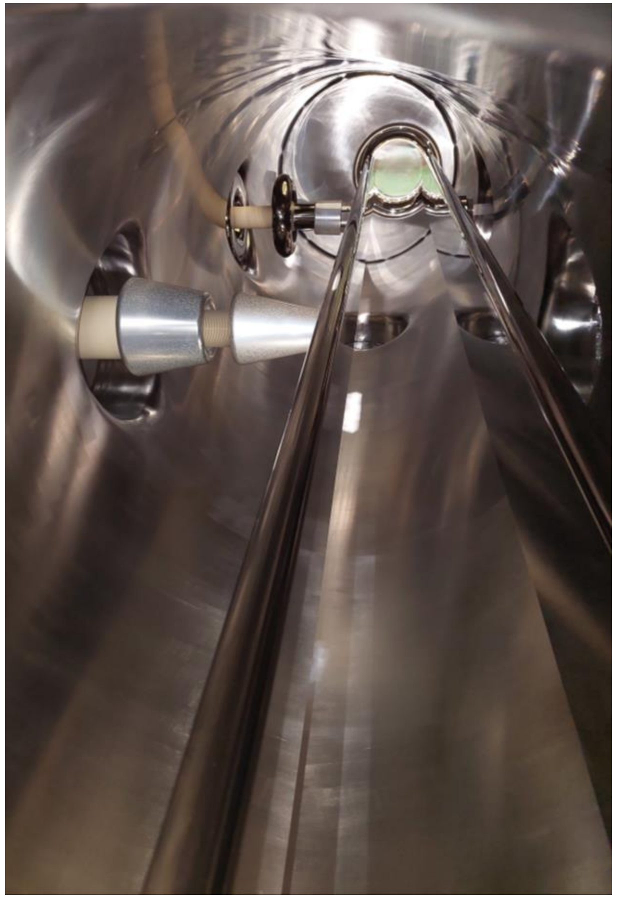
- Adressed by CERN by optimisation of the system topology and design
- Remaing error after optimisation and impact on synchrotron radiation is under study with numerical model
- First electromagnet prototype can be implemented on the LEP Electrostatic Separator
- Accuracy and repeatability of the low-field (<5mT) electromagnet will be tested

High-Voltage breakdown rate in vacuum and radiation environment

- Studies are ongoing in collaboration with University of Tartu (Estonia) to better understand and quantify the breakdown rate depending on X-Ray impact on electrodes, PhD student will join the section in 2025
- Breakdown rate can be mitigated by design (avoiding field enhancement, radiation shielding, electrodes cooling, good vacuum), by material (surface roughness, work function) and by HV conditioning
- LEP Electrostatic Separator is available for HV testing

Beam impedance preservation of EMS

- Study has to be launched



LEP electrostatic separator as a basis for EMS prototype

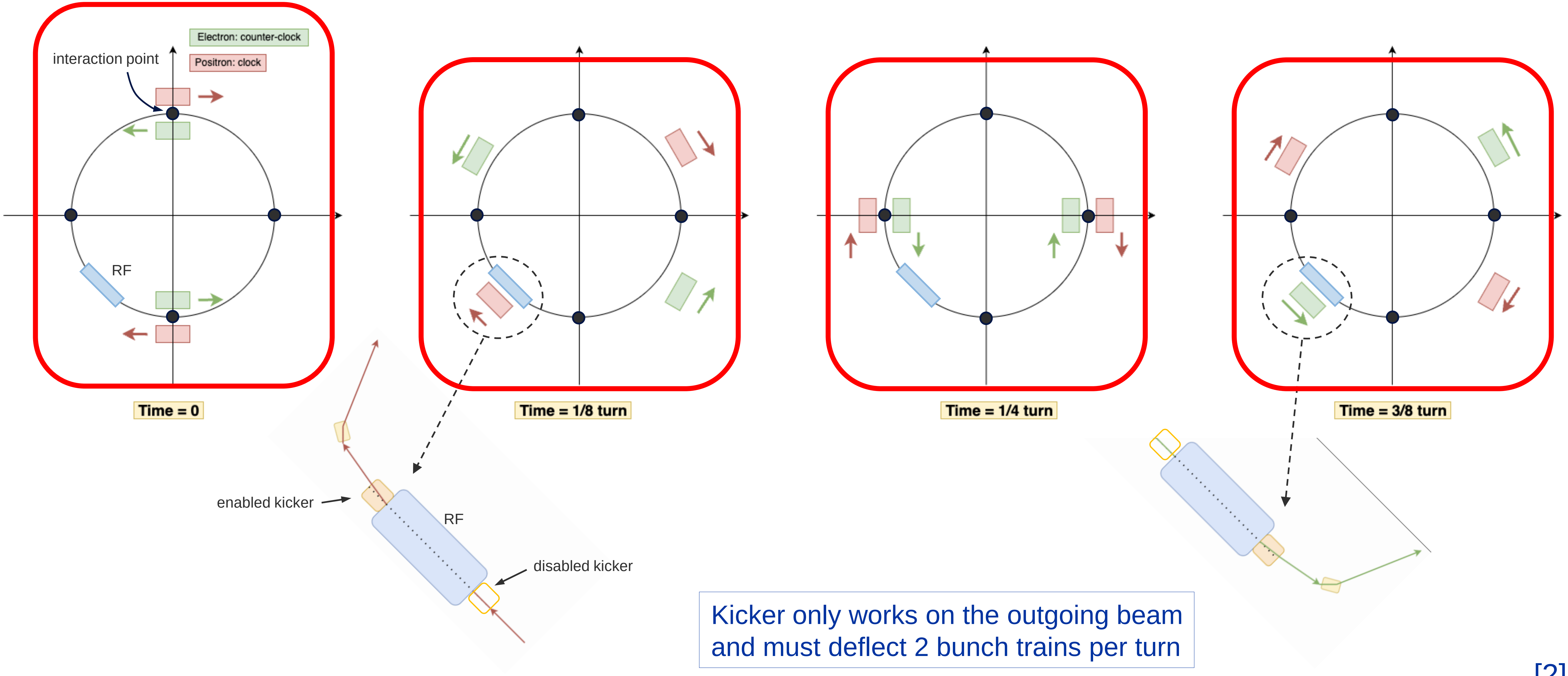
Prototyping necessary to confirm its feasibility!

Contents

Kicker | Introduction

- **Kicker system has been very recently proposed as an alternative option to EMS**
- **The interest has been triggered by the CEPC project where they have similar approaches [8]**
- **Feasibility analysis is at a very early stage**

Kicker | Principle



Kicker only works on the outgoing beam and must deflect 2 bunch trains per turn

[2]

Kicker | Requirements

Kicker requirements depend on:

- **filling scheme** (baseline and alternative options have been investigated)
- **how beams are deflected** (train by train, batch by batch or bunch by bunch)

Deflection method	Train by Train	Train by Train		Batch by Batch	Bunch by Bunch
Filling scheme	Baseline (feasibility report)	Short batch spacing 25 ns	Long batch spacing H : 850, ttbar : 4600 ns	25 to 4600 ns batch spacing	25 ns bunch spacing
Maximum repetition rate	6618 Hz	6618 Hz		215kHz - 20 MHz	40 MHz
Flat-top time	58 µs	3.75 µs	64.78 µs	25 ns	0.1ns
Rise time	25 µs	79.6 µs	18.6 µs	12.5 ns - 2300 ns	12.5 ns
Fall time	9 µs	63.6 µs	2.6 µs	12.5 ns - 2300 ns	12.5 ns
Flat-top stability (Higgs)	Approx. < 0.04% (0.1 σx)	Approx. < 0.04% (0.1 σx)		Approx. < 0.04% (0.1 σx)	
Flat-top stability (ttbar)	Approx. < 0.06% (0.1 σx)	Approx. < 0.06% (0.1 σx)		Approx. < 0.06% (0.1 σx)	

Alternatives filling schemes explored by ABT

RF technology more suitable ?

Most feasible case for a kicker,
because of short flat-top and long rise/fall time compared to other cases

[2]

Kicker | Technical Challenges

Kicker acts on the beam at every turn

- Not a typical mode of operation for conventional beam transfer equipment

<u>Extremely strict requirements</u> on flattop stability and repeatability (typical kicker: ±1% but <0.04% is required)

- **Would need significant R&D to ensure and verify if achievable** (metrology)
- Longer required flattop length makes achieving the stability requirements much more difficult

A fast-acting system is always a concern for machine protection

- Risks include mis-kicks, erratic kicks, missing kicks, and synchronization errors

Needs short cable between kickers and generators → Alcove location is to be optimized.

Batch by Batch and Bunch by Bunch are not feasible with beam-transfer kicker systems

- Given the high integrated field requirements in combination with tens of megahertz repetition rates

Feasibility needs to be assessed in detail and much R&D would be needed!

System Reliability

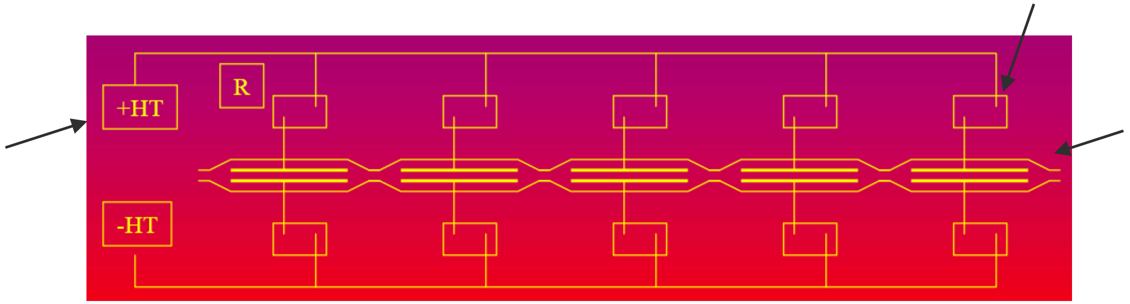
What happens if the separation system fails?

- The beam could hit the septum blade.
- The beam could ends up circulating in the wrong beam pipe.

Reliability will be critical

EMS:

Risk of failure mainly come from HV breakdown:
- HV breakdown rate must be minimized by design.
- Consequence of failure can be mitigated by decoupling segmented EMS devices so that it does not affect the entire system.



HV-DC supply scheme showing generator, decoupling resistors and EMS devices [9]

Kicker:

A pulsed system requires more advanced control and involve more potential sources of failure such as:
Mis-kick, erratic kick, missing kick, synchronization
- Risk analysis will have to be conducted in details at an early stage.

Comparison of EMS and Kicker

	EMS	**Kicker**
Maturity	• Novel equipment type • Needs R&D and prototyping • LEP experience is an advantage	• Novel application for beam-transfer kickers • needs R&D and prototyping if first feasibility analysis is approved
Complexity	• Simple DC operation • Complexity in the design, geometric tolerances and HV phenomena • Limited power dissipation (20kW)	• Pulsed system operation with strict timing • Very high field stability requirements • More complex system (kicker, gen., ctrl.) • Higher power dissipation (100kW, t.b.c)
Integration	• Easy integration in the current baseline	• Can require special alcoves due to short cables requirement
Feasibility	• Technical concept is under devlopment • Prototyping is the next step	• Initial feasibility analysis to be continued • Strongly dependant on filling scheme

EMS probably constitutes a simpler system,
but both options still present uncertainties that need to be clarified.

Outlook

EMS:

- **Development will continue as the baseline solution**
  Design concept is under active development and will keep going
- **Main challenges have been identified and must be adressed**
  (e.g. field quality, HV breakdown rate, system integration, beam impedance)
- **EMS requires prototyping**
  LEP electrostatic separator will be used as a basis

Kicker:

- **Studies will be launched to determine the feasibility of kicker system**
  This will include the cost, the impact on the required space in the FCC tunnel and the required space in alcoves
- **It would be of interest to investigate other technologies than beam-transfer kicker**
  e.g. feasibility and impact of kicking at higher frequencies (bunch by bunch or batch by batch), see [7] and [8]
- **Filling scheme (bunch train length) has a major impact on kicker requirements and feasibility**

Back-up slides

Kicker | Repetition frequency

- **Kick the beam train by train**
  - Each kicker works 2 times in one turn, frequency: $2 \times f_{rev} = 6618$ Hz

- **Kick the beam batch by batch**
  - Each batch has 2 bunch, batch length: 50 ns
  - Batch separation varying from 25 ns to 4600 ns
  - Frequency: 217 kHz to 20 MHz

- **Kick the beam bunch by bunch**
  - The smallest bunch separation is 25 ns
  - frequency: $2 \times f_{rev} = 40$ MHz

Train by train: Baseline

- **Each beam only has two bunch trains**

- **Higgs mode:**
  - **Number of trains: 2**
  - Bunch train length: 57.4 us
  - Batch spacing: 750 ns
    - **Bunches per batch: 2**
    - **Bunches spacing: 25 ns**

- **ttbar mode:**
  - **Number of trains: 2**
  - Bunch train length: 57.4 us
  - Batch spacing: 3800 ns

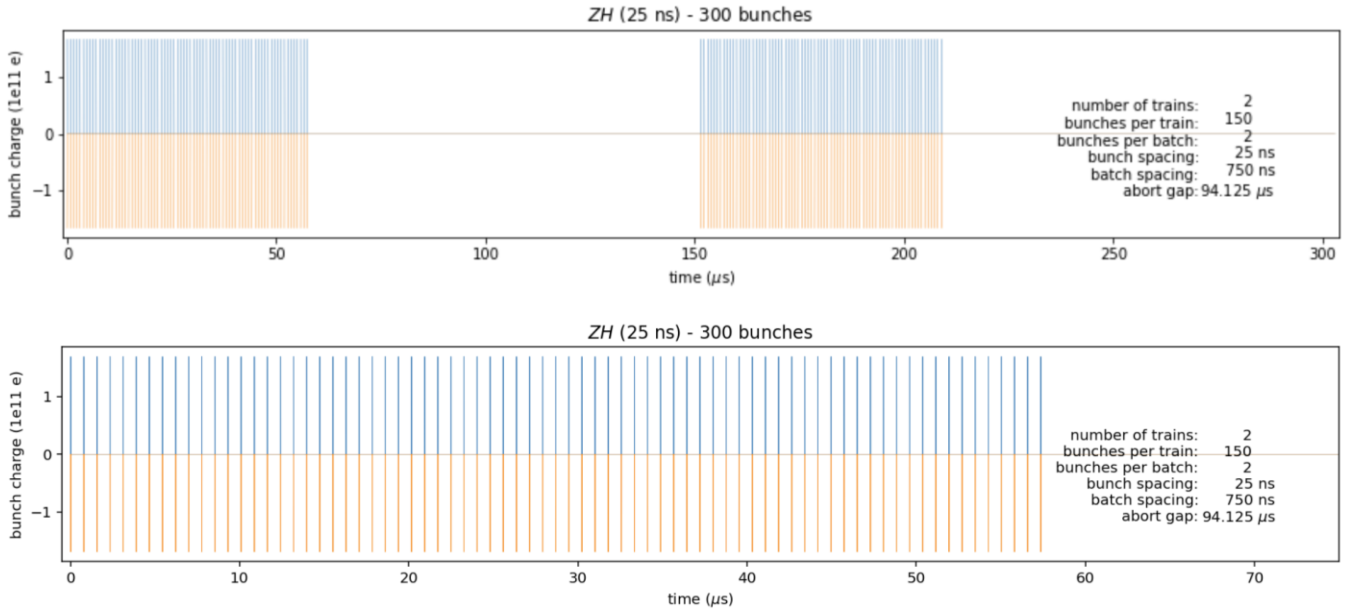


Fig. 2.15: Filling pattern for ZH mode (top) and a close-up view of the first train (bottom), with the e^+ beam shown in blue and the e^- beam in orange.

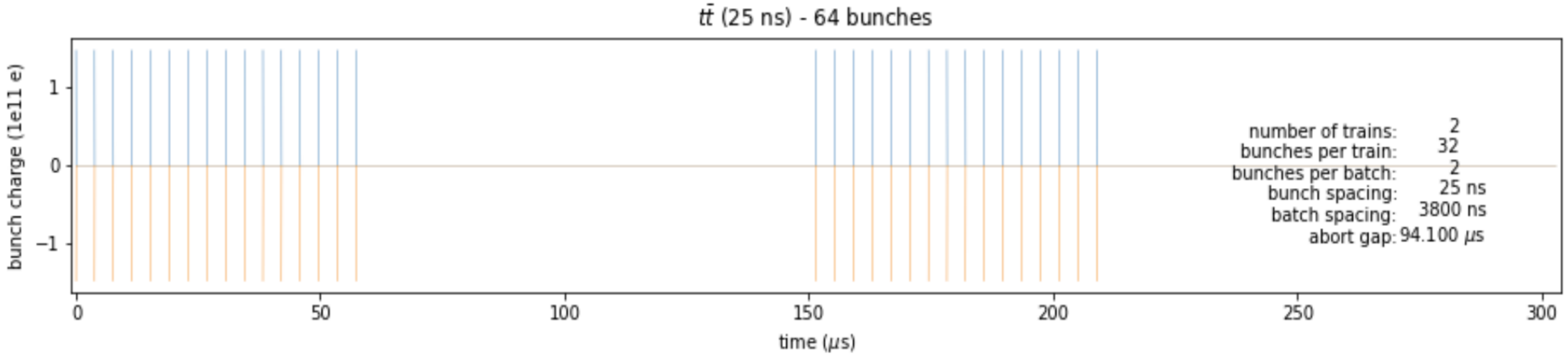
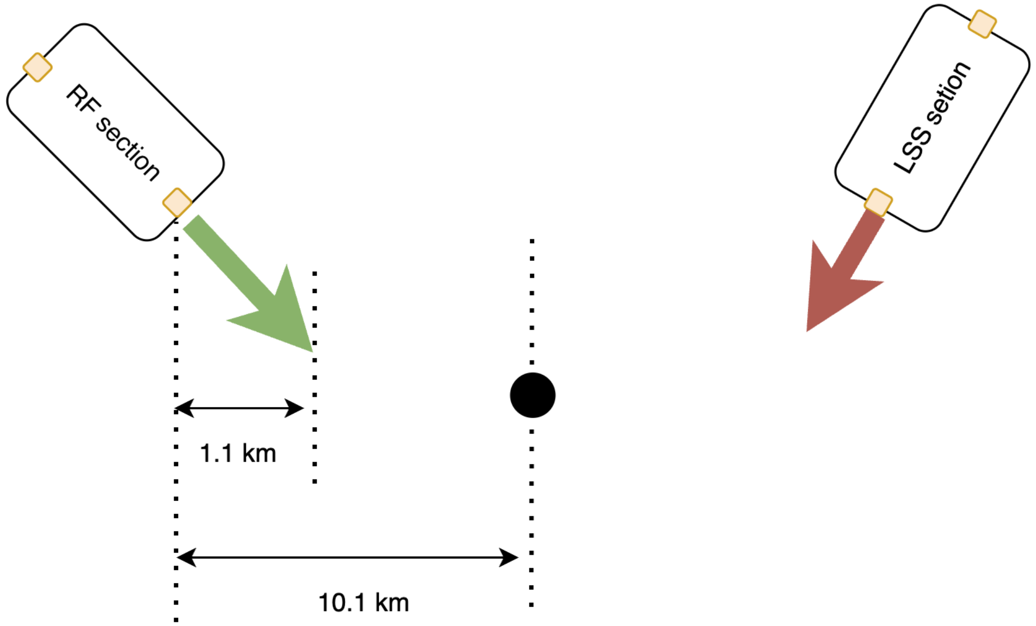


Fig. 2.16: Filling pattern for the $t\bar{t}$ mode.

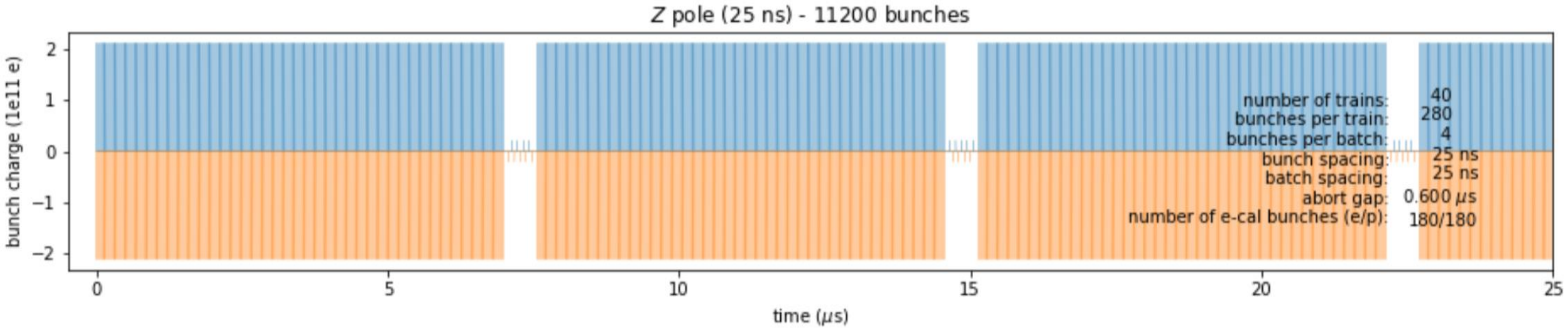
Train by train：Short bunch spacing 25 ns

- **Each beam only has two bunch trains**

- **Higgs mode:**
  - **Number of trains: 2**
  - Bunch number: 300
  - Bunch train length: 1.1 km
  - Bunches/Batch spacing: 25 ns
    - **Bunches per batch: 2**



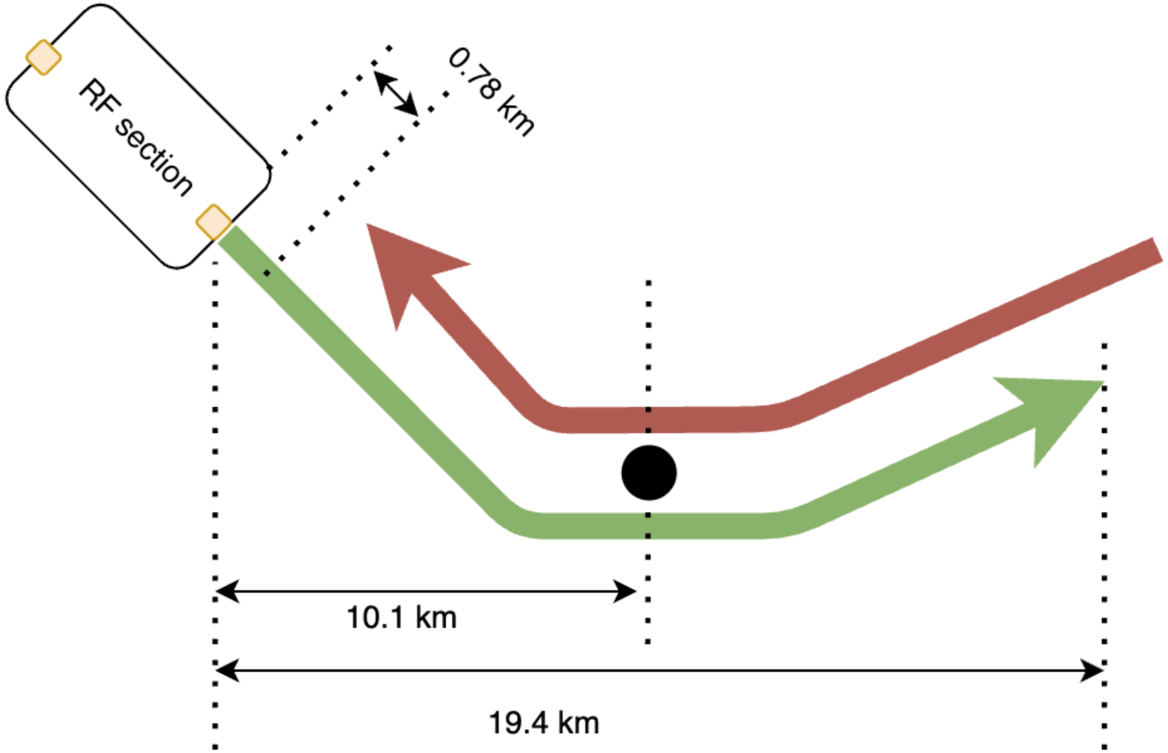
Similar filling structure with Z mode, but much less bunch number



Train by train: Long batch spacing

- **Higgs mode:**
  - **Number of trains: 2**
  - Bunch number: 300
  - Bunch train length: 19.42 km
  - Batch spacing: 850 ns
    - **Bunches per batch: 2**
    - Bunch spacing: 25 ns

- **ttbar mode**
  - **Number of trains: 2**
  - Bunch number: 60
  - Batch spacing: 4600 ns
  - Bunch train length: 19.42 km



Beam collision occurs when bunch train length larger than **20.2 km**

Kicker | Technology Options

Stripline kicker

- Similar challenges than EMS related to under vacuum HV system + additional challenges

◀ **Not followed-up further**

Impedance matched transmission line type kicker

◀ **Not followed-up further**

- Complex under vacuum magnet.
- High duty cycle (2.5% for 25 ns bunch spacing, 38% for Baseline) leads to very high-power loss per termination
  E.g., 20 single turn kicker magnets with 1 m magnetic length and 30 mm aperture, Z = 10 Ω:
  370 kW (2,5% duty cycle) to 7,4 MW (38% duty cycle) total losses in terminations.
- However, termination beneficial for flattop quality.

Lumped inductance kicker magnet

- Multiturn option, short circuit termination
- Needs large rise and fall time budget (~20 µs)
- Significant power flow between kicker and generator (>>kW range), need for cooling
- Challenges regarding flattop, repeatability and machine protection remain

◀ **Most promising option**

Feasibility needs to be assessed in detail, much R&D would be needed!

Other types of kicker technologies to be explored ?

- For example: ‘resonant kicker’, see [7] and [8]
- To be verified whether faster system (e.g. by batch or by bunch) could offer any advantages

Kicker | Multiturn Lumped Inductance System

Currently **favored option** for possible further studies

Needs **large rise and fall time** budget (~20 µs)

- To accommodate settling times for flat top and flat bottom ringing
- To allow for higher inductance kicker magnets at moderate driving voltages
- To cope with effects of eventual long cables

Significant power flow between kicker and generator (>>kW range)

- Due to high repetition rate combined with the energy stored in the magnetic field to be ramped up and down
- leads to cooling requirements to be assessed

Challenges regarding flattop, repeatability and machine protection remain

- Complex power modulator would be required, probably with droop compensation, flattop regulation, energy recovery, …

Feasibility needs to be assessed in detail and much R&D would be needed!

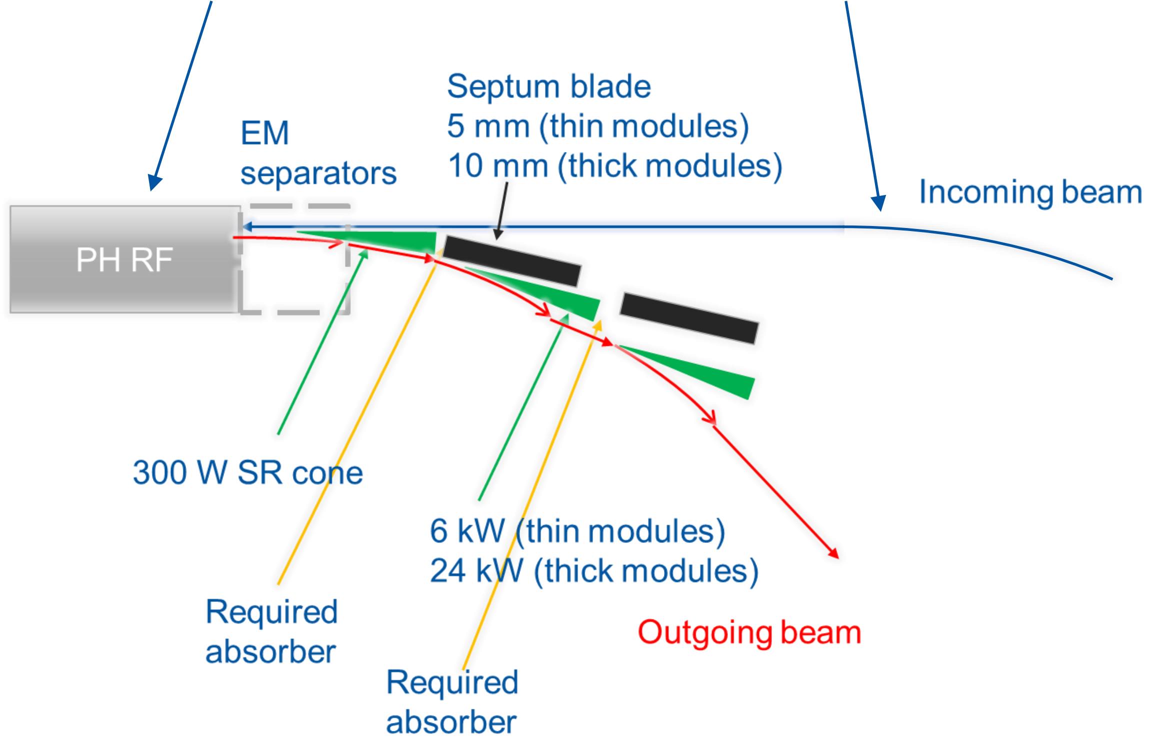
SR shielding considerations

Total synchrotron radiation power of ~200 kW from the outgoing beam and critical photon 2-4 times higher than arc

- Mature concept will need to handle the SR of the outgoing beam
- Possible iteration between field/design and constraints

To be continued towards the pre-TDR

EM-Separators very sensitive to SR:
Absorber between separator devices and in front of EMS to be considered



Synchrotron radiation from the outgoing beam (Illustration not showing the number of module nor correct scales) [5]

EMS | Principle

Combination of static electric and magnetic fields achieves the desired separation effect.

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e^+ particles see a positive force due to $\vec{B}$ and a positive force due to $\vec{E}$
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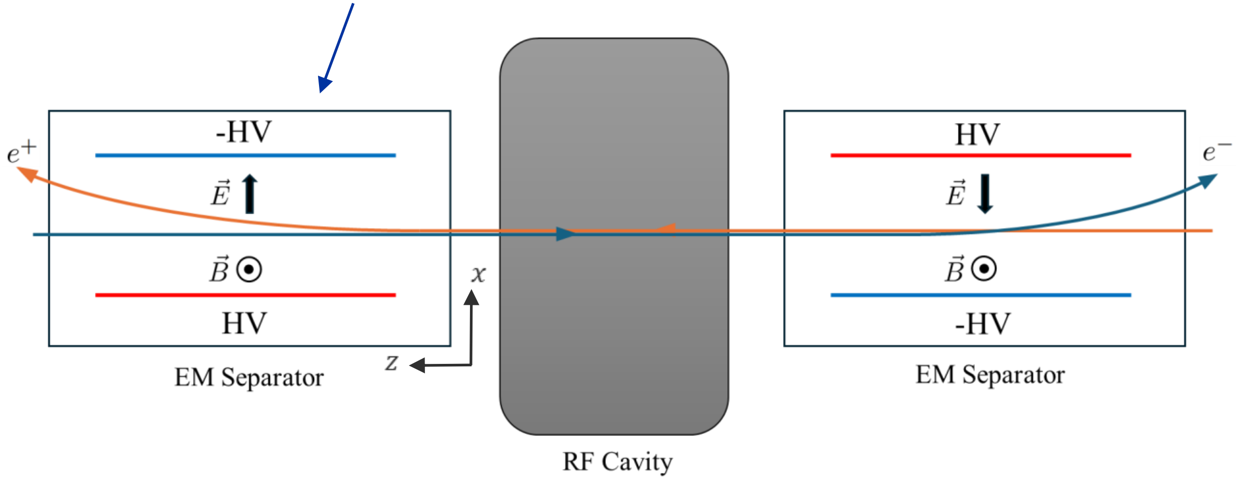
if $\vec{B}$ and $\vec{E}$ are properly scaled and matched, the net force on e^- is zero



EMS principle using combination of static electric and magnetic fields

To have net electromagnetic force of zero :

$$\underbrace{q \cdot E_x}_{F_{el\,x}} + \underbrace{(-q \cdot v_z \cdot B_y)}_{F_{mag\,x}} = 0$$

By considering an electric field of ~ 1 MV/m, this results in a **very low magnetic field**:

$$|B_y| = \frac{E_x}{c} = \mathbf{3.34\ mT}$$

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