FUTURE CIRCULAR COLLIDER

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Energy sawtooth due to SR and ECM

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R. Tomàs, D. Shatilov, J. Wenninger, and F. Zimmermann

2d FCC Polarization Workshop (EPOL) 2022

Joint EIC-FCC Working Meeting on e+/e- Polarization

20th September 2022

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

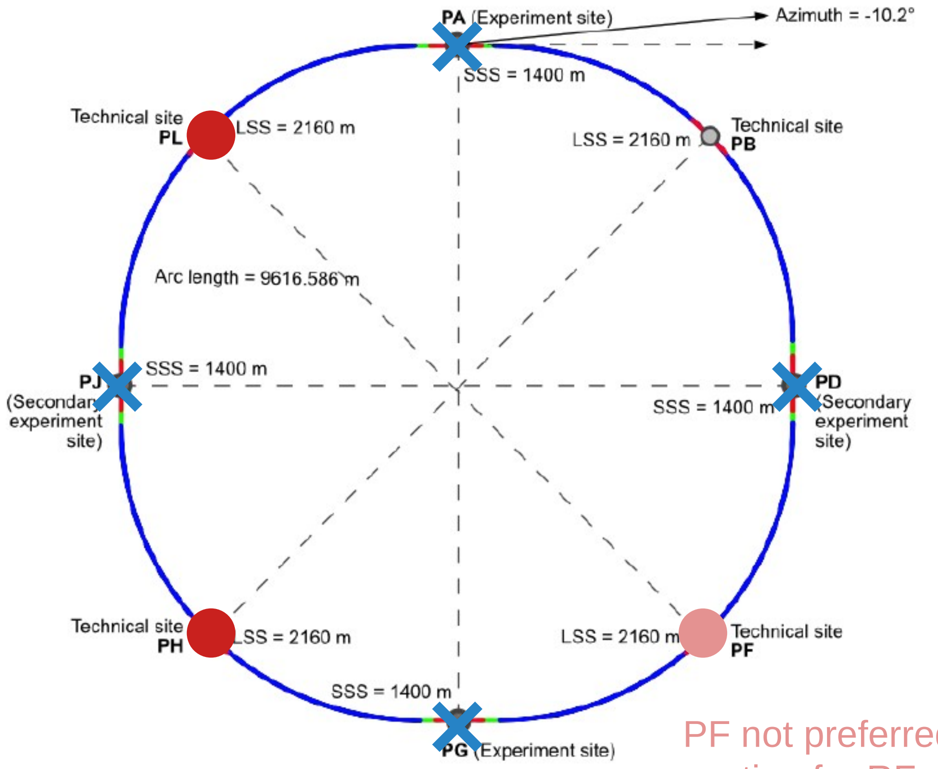
Overview FCC-ee

- Higgs and electro-weak factory
- 4 different beam energies
- New “lowest risk” 4 IPs scenario (✕)
  - Perfect symmetry
  - Perfect 4-fold superperiodicity
- 1 or 2 RF-sections (●)
- High precision physics experiments
- → **Up to few keV statistical precision achievable**

Energy calibration and polarization working group
With regular meetings since October 2021:
indico.cern.ch/category/8678

First set of results obtained in the FCC Design Study:

Polarization and Centre-of-mass Energy Calibration at FCC-ee, **arXiv:1909.12245**



PF not preferred section for RF

Considerations for Energies

- Beam energy and thus center-of-mass energy (ECM) depends on various parameters
- Placement, number and exact configuration of the RF-cavities

Physics requirements
- A: 1 RF-section, which is common (individual) for both beams
- B: 2 RF-sections, which are common (individual) for both beams
- C: 2 RF-sections, which are individual for each beam

Integration and cryogenics requirements
- High energy booster (HEB) and main rings in same tunnel
- PL and PH best suited to host RF-insertions
- PF not preferred option but not excluded
- Where will HEB and main ring cavities be installed?

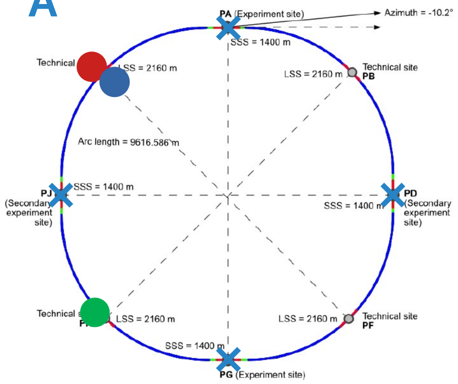
1 (Z-, WW-, and ZH-operation) or 2 (ttbar) RF-sections considered for the booster

Top-up-injection in PB

Energy difference must be wihtin momentum aperture of main rings

● … RF for positrons ● … RF for electrons ● … RF for booster

A



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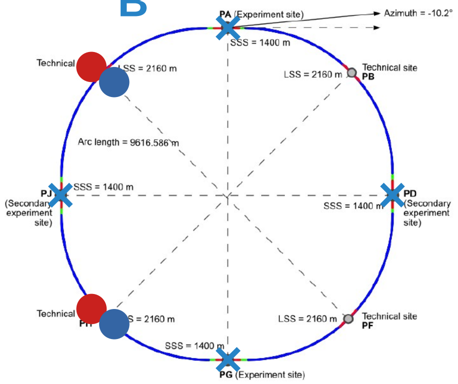
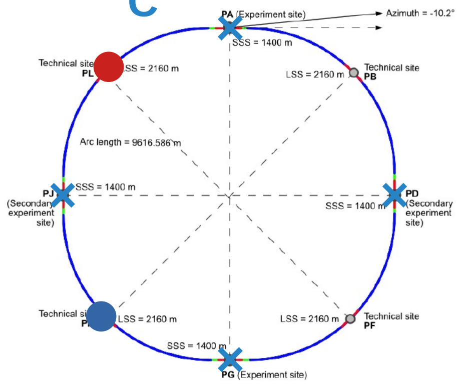


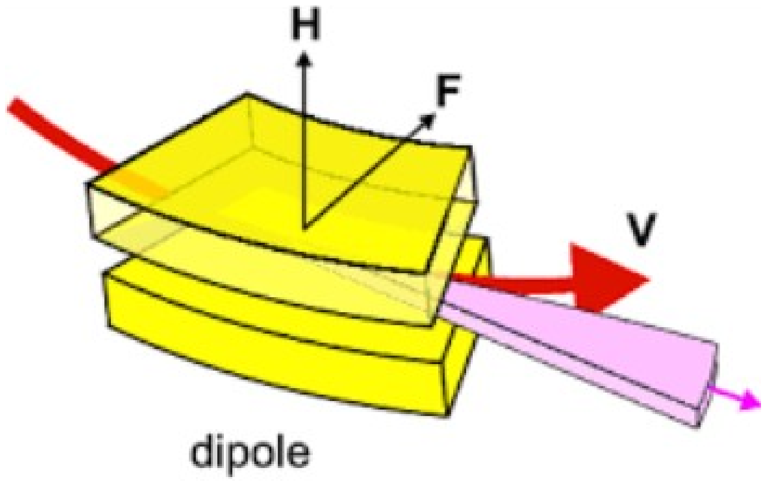
C



Considerations for Energies

- Beam energy and thus center-of-mass energy (ECM) depends on various parameters
- Placement, number and exact configuration of the RF-cavities
- Synchrotron radiation

Energy loss strongly energy (γ^4) dependent



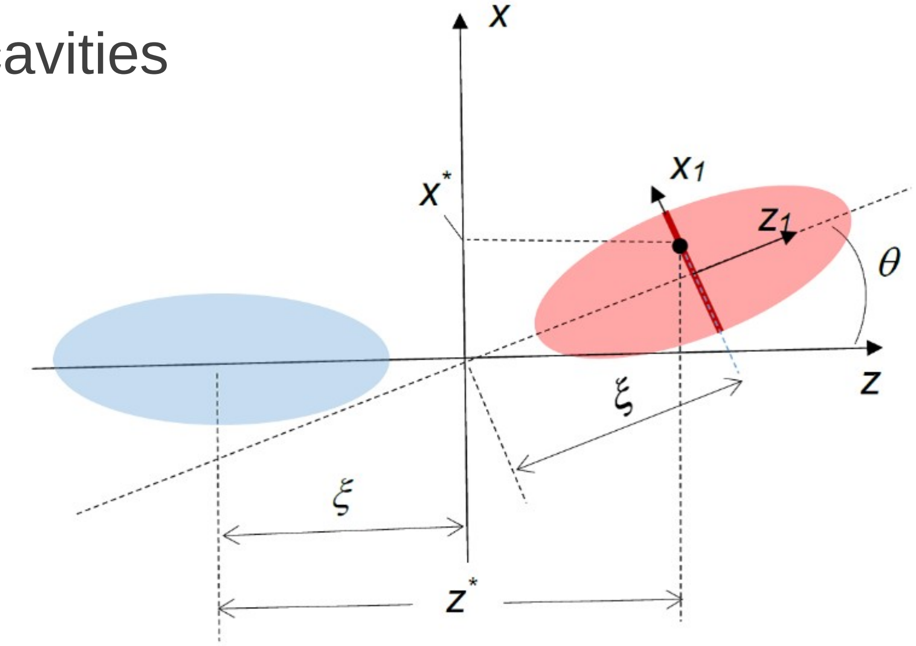
Average energy loss through a dipole

$$\Delta E\,[\mathrm{eV}] = \frac{2}{3}\frac{q_0}{4\pi\epsilon_0}\beta_{\mathrm{rel}}^3\gamma_{\mathrm{rel}}^4\int\frac{1}{\rho^2}\,\mathrm{d}s$$

L … Dipole length
ρ … Bending radius $\rho=L/\theta$
θ … Bending angle
q_0 … Unit charge
ε_0 … Vacuum permittivity
β_{rel} … ~ 1

Considerations for Energies

- Beam energy and thus center-of-mass energy (ECM) depends on various parameters
- Placement, number and exact configuration of the RF-cavities
- Synchrotron radiation
- Beamstrahlung



ρ_{min} … bending radius
N_p … bunch population
γ … relativistic gamma
σ_x … hor. Beam size
σ_z … bunch length
Xi … vert. Beam parameters
$\beta_{x,y}$ … β-function at IP
$\varepsilon_{x,y}$ … Transverse emittances

Bunch interacts with force field of opposing bunch, bending radius:

$$\frac{1}{\rho_{\min}} \propto \frac{N_p}{\gamma\sigma_x\sigma_z} \propto \frac{\xi_y}{\sqrt{\beta_x^*\beta_y^*}}\sqrt{\frac{\varepsilon_y}{\varepsilon_x}}$$

Synchrotron photons are emitted with critical energy:

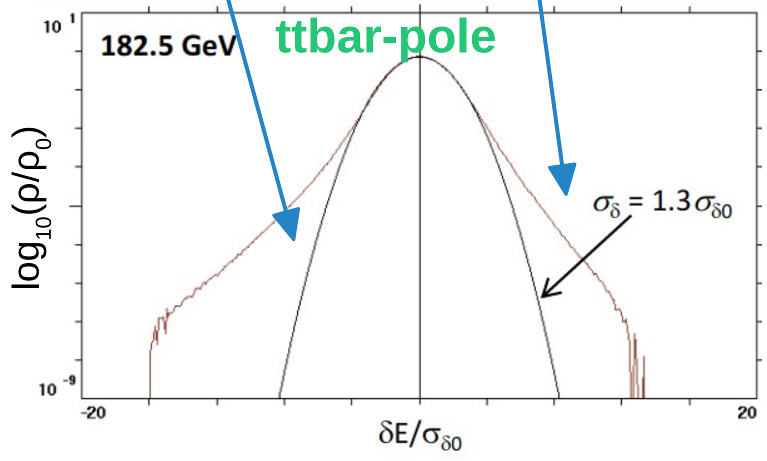
$$u_c \propto \frac{\gamma^3}{\rho} \propto \xi_y$$

A. Blondel, P. Janot, D. Shatilov

Beamstrahlung and Boosts

- Beamstrahlung (BS): crossing bunches interact with force field created by the other bunch
- Dominant effect: increased energy spread
- **Does not shift peak energy**

Beam energy spectrum with and without beamstrahlung

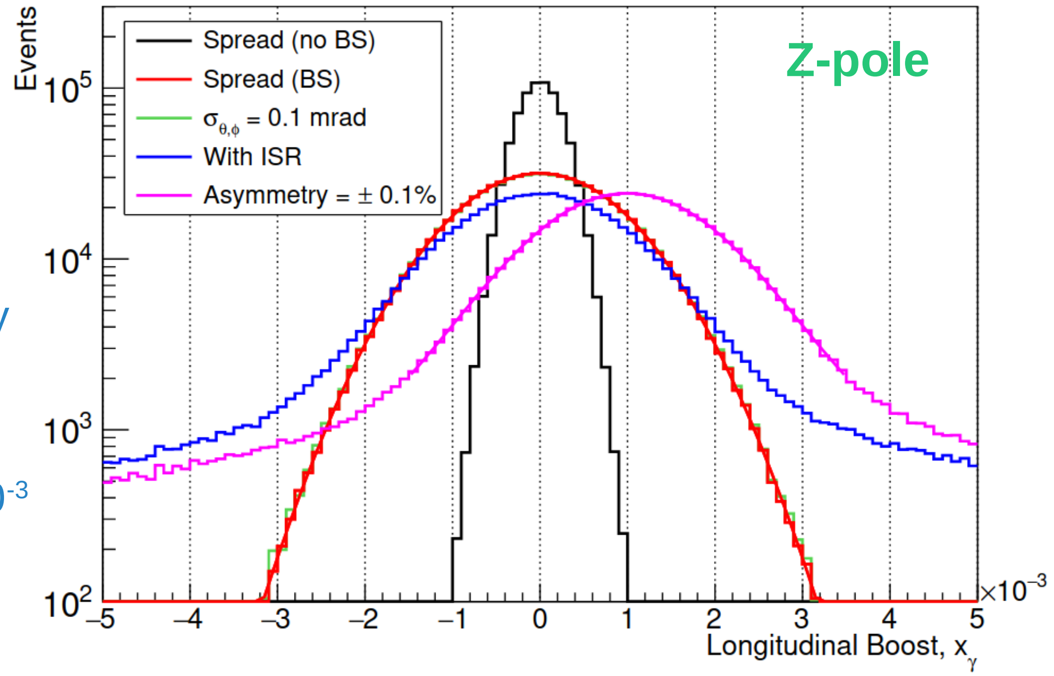


Black: no beamstrahlung
Red: + beamstrahlung
Green: + angular resolution
Blue: + photon emission
Pink: + asymmetry between electron and positron energy

Only asymmetric energies shift the center of the energy spectrum for dimuon events

Measuring 10^6 dimuon events yields precision of 10^{-3}
5 min measurements at FCC Z-mode gives boost precision of 50 keV and one 8 h shift will give 5 keV

Statistics of 1 million dimuon events at Z-pole
e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)



A. Blondel et al., arXiv:2019.12245, 2019.

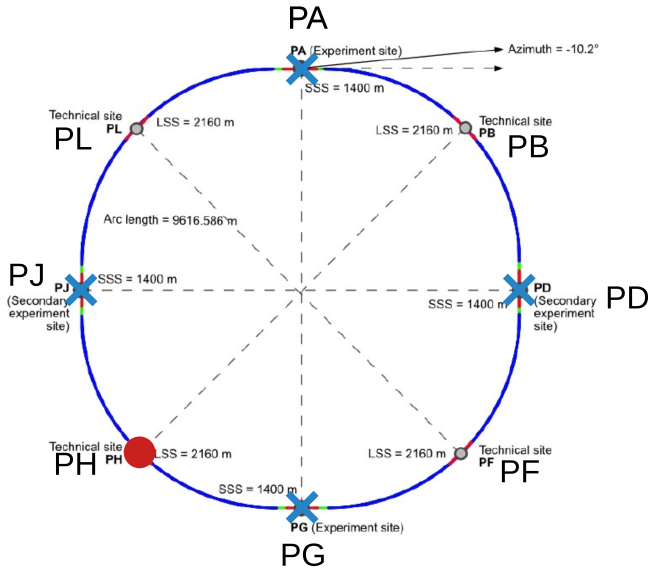
ECM and Boosts for Z-Mode

- **PH: 0.1 GV, 400 MHz** cavity
- ≲ 0.62 MeV beamstrahlung losses per beam and IP (simulations)
- 40 MeV radiation losses per revolution

One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts

IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439



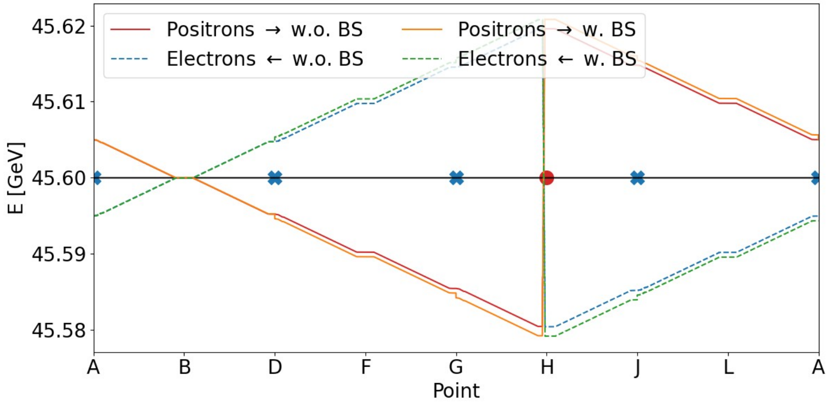
Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

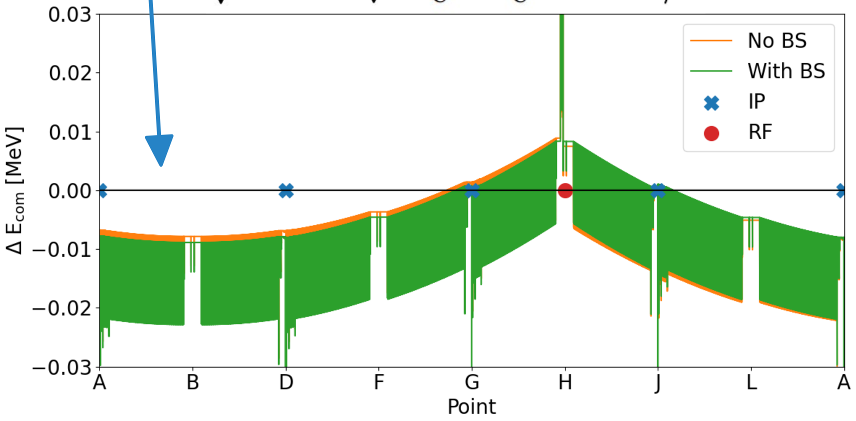
1 RF → almost constant ECM

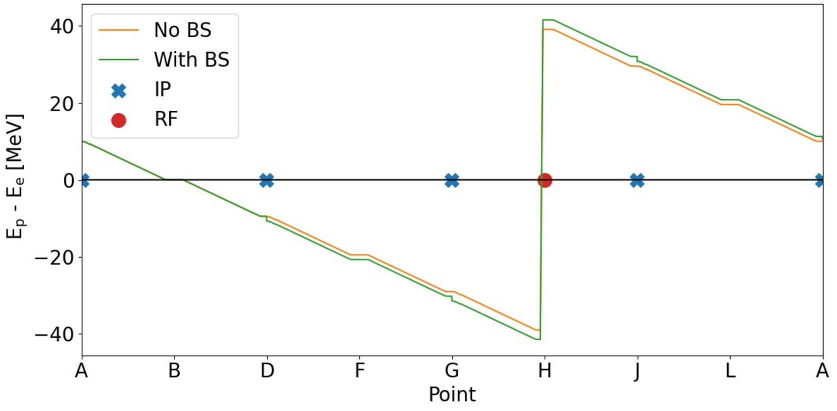
$$\Delta E \propto \gamma_{\text{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos \alpha/2$$

Boost: + for e+; - for e-







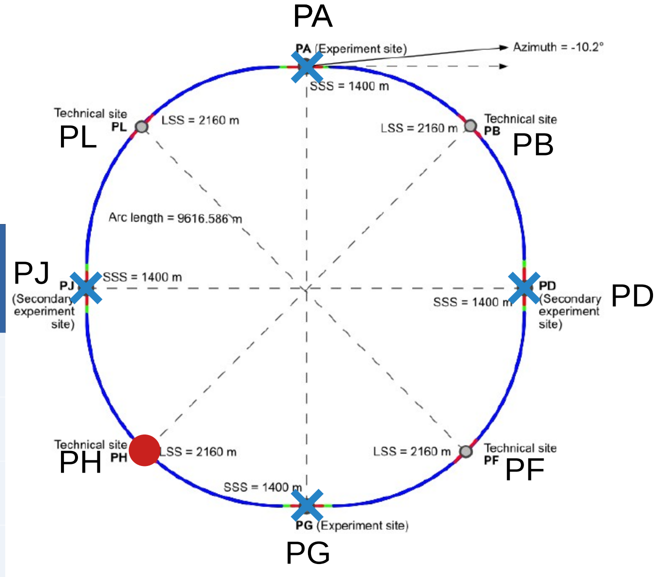
ECM and Boosts for WW-Mode

- **PH: 0.75 GV 400 MHz** cavity
- ≲ 1.4 MeV beamstrahlung losses per beam and IP (simulations)
- 370 MeV radiation losses per revolution

1.1 muon pairs per second for 2 IPs
~100 keV after 10 days

Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

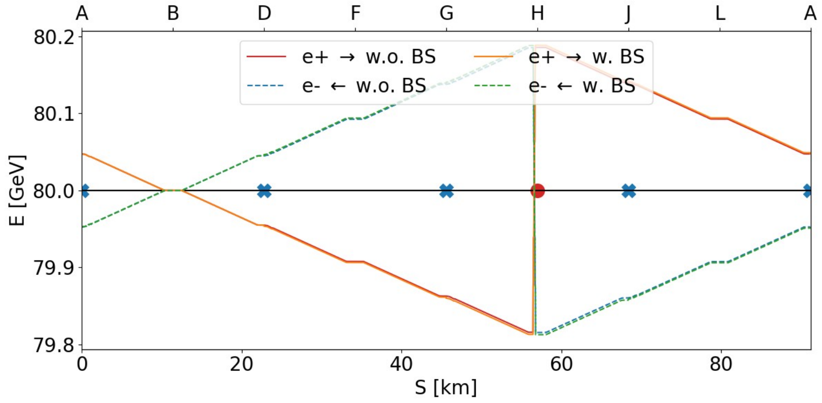
IP	ΔECM [keV]	Boost [MeV]
PA	- 379.203	96.402
PD	- 384.749	- 91.447
PG	40.753	- 279.299
PJ	57.530	284.254

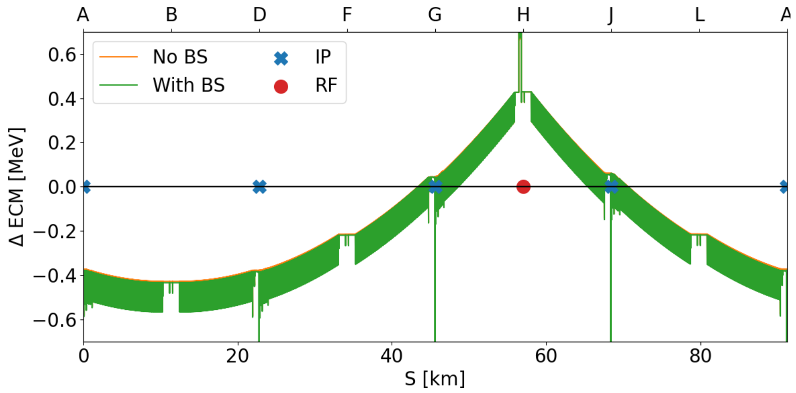


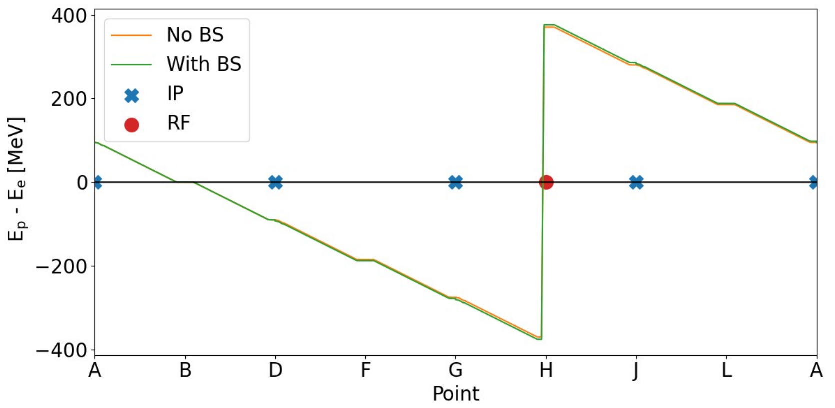
Boost: + for e+; - for e-

$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos\alpha/2$$

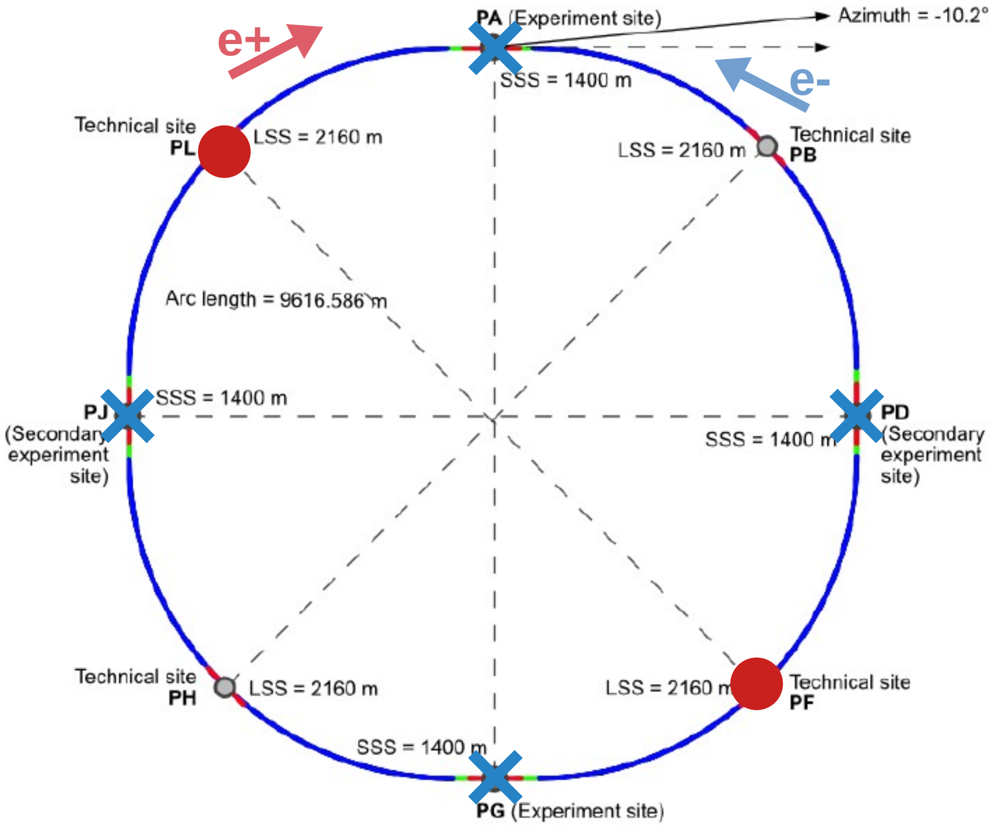




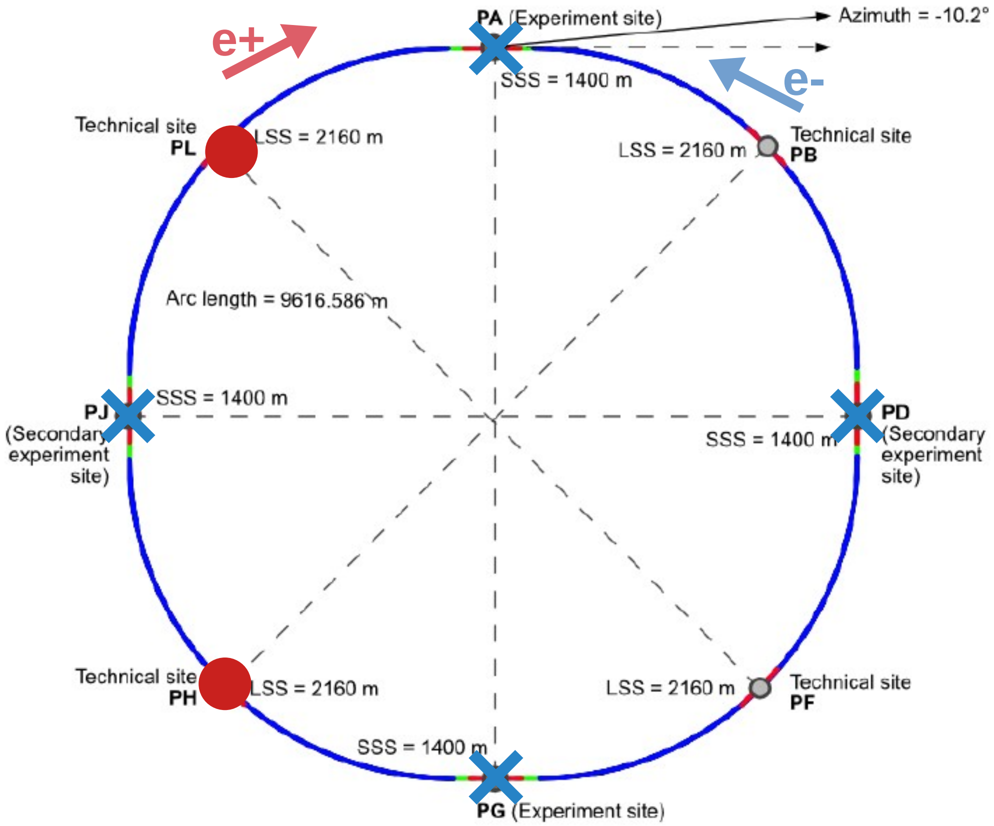


RF-Placements for ttbar-Mode

- Two placement options for the RF-cavities (●), for now no errors considered



Symmetrical option



Asymmetrical option

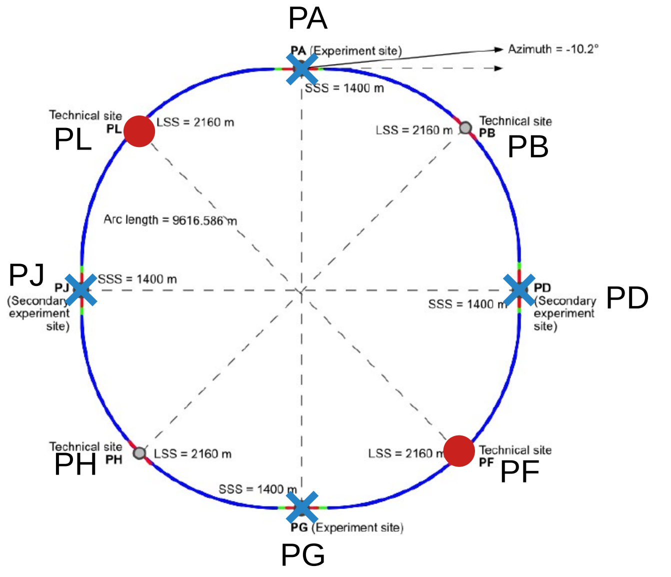
ECM and Boosts for ttbar-Mode

- **PF: 5 GV, 400 MHz** cavity and **PL: 6.7 GV, 800 MHz** cavity
- ≲ 14 MeV beamstrahlung losses per beam and IP
- 10 GeV radiation losses per revolution

Different ECM and boosts at the IPs result from, radiation losses and BS

BS small impact on boosts

Main rings

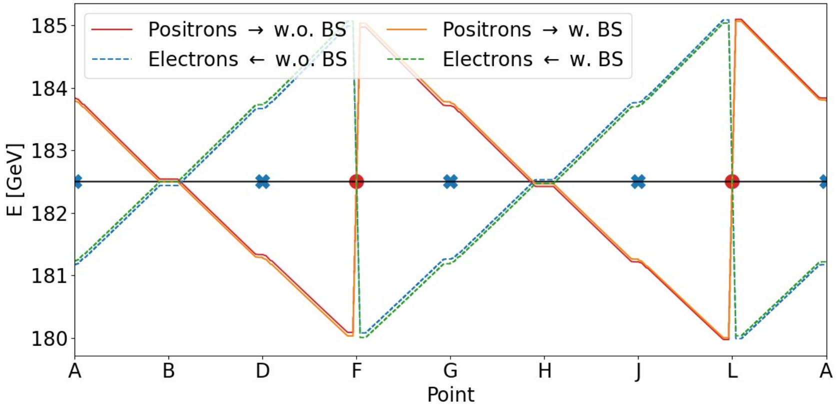


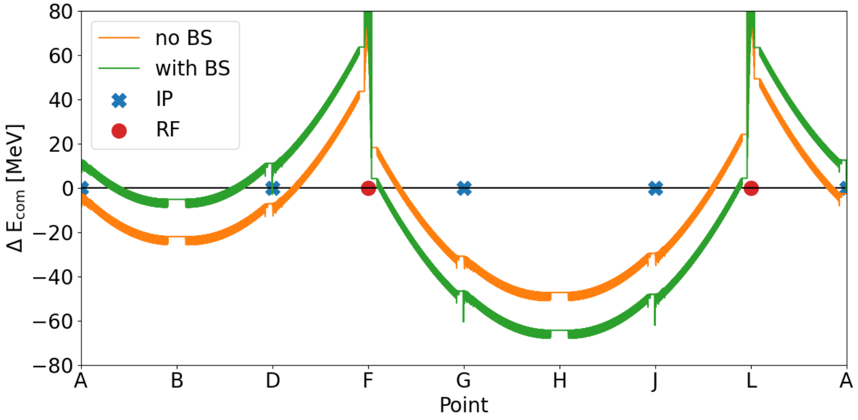
IP	ΔECM [MeV]	Boost [GeV]
PA	12.663	2.574
PD	11.043	- 2.455
PG	- 46.531	2.573
PJ	- 48.155	- 2.454

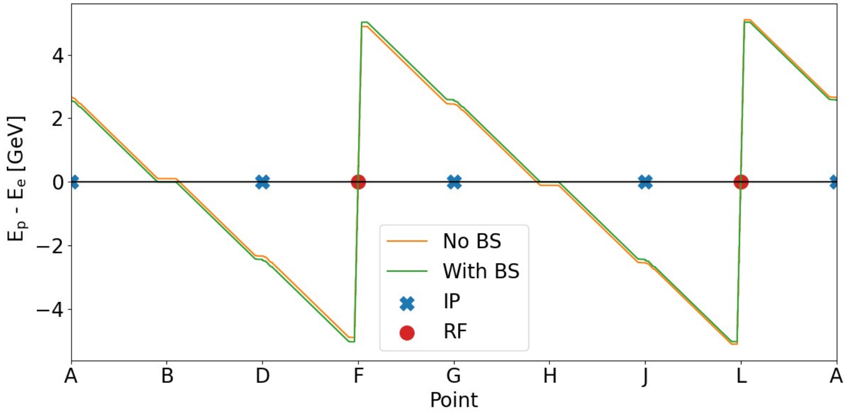
Boost: + for e+; - for e-

$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{\mathrm{e}+}E_{\mathrm{e}-}}\cos \alpha/2$$







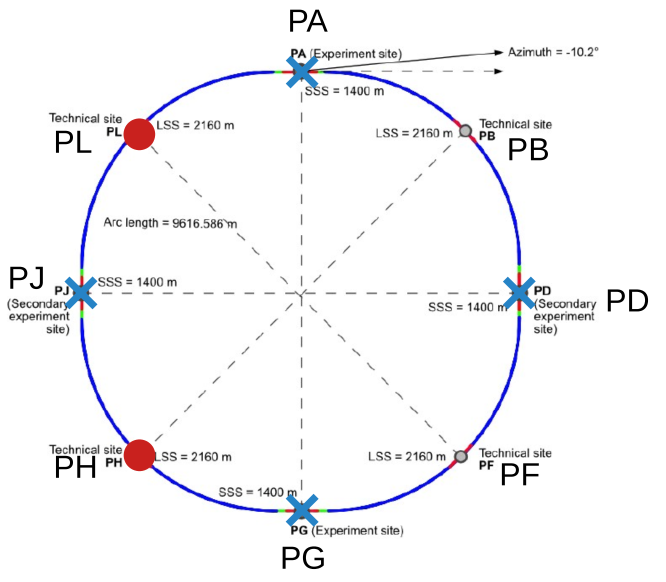
ECM and Boosts for ttbar-Mode

- **PH: 5 GV, 400 MHz** cavity and **PL: 6.7 GV, 800 MHz** cavity
- ≨ 14 MeV beamstrahlung losses per beam and IP
- 10 GeV radiation losses per revolution

Different ECM and boosts at the IPs result from asymmetric RF placement, radiation losses and BS

BS small impact on boosts

Main rings

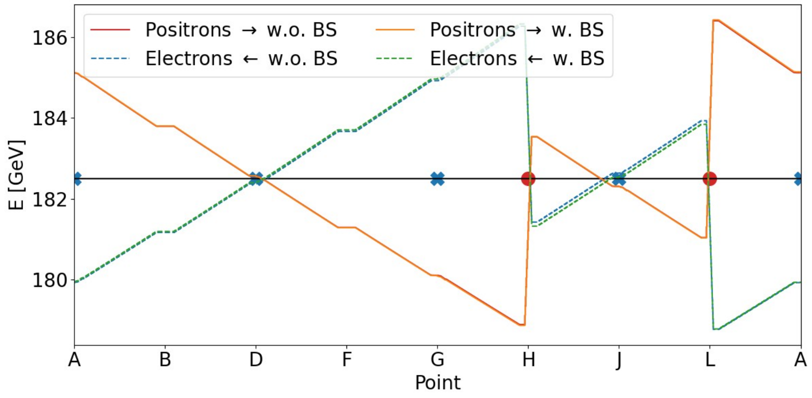


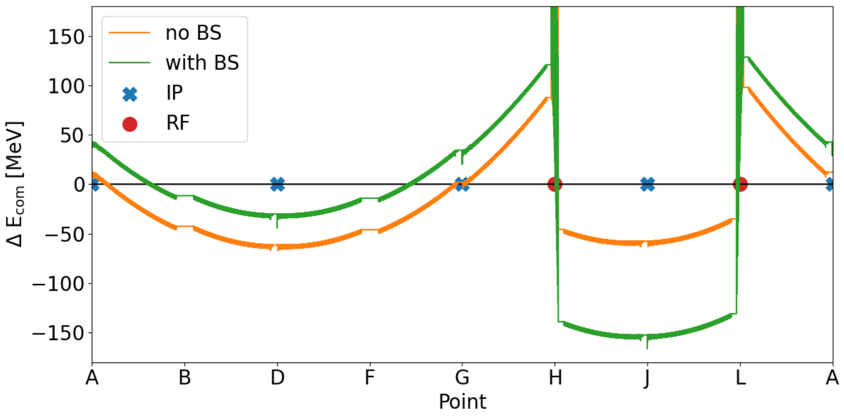
IP	ΔECM [MeV]	Boost [GeV]
PA	42.813	5.187
PD	- 30.176	0.157
PG	34.236	- 4.873
PJ	-152.467	- 0.233

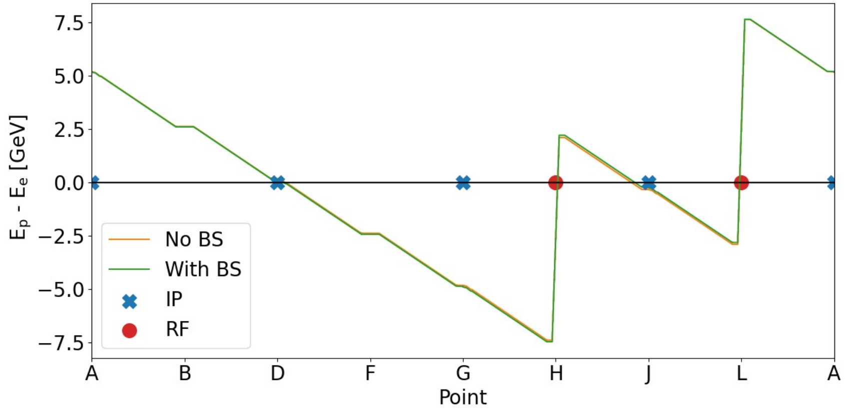
Boost: + for e+; - for e-

$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos \alpha/2$$





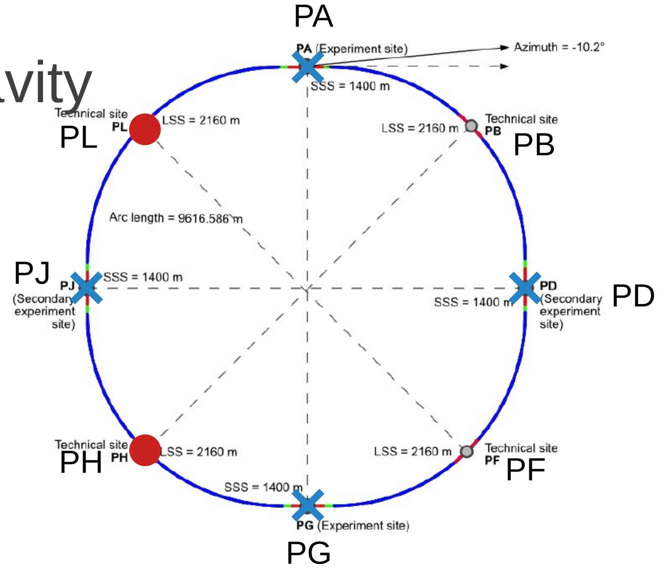


ECM and Boosts for ttbar-Mode

- **PL: 2.48 GV 400 MHz + 4.6 GV 800 MHz**, **PH: 4.6 GV, 800 MHz** cavity
- Beamstrahlung not yet included
- 10 GeV radiation losses per revolution

Although studies not yet completed, splitting the 800 MHz RF system seems tentatively beneficial for more equal ECM and boosts

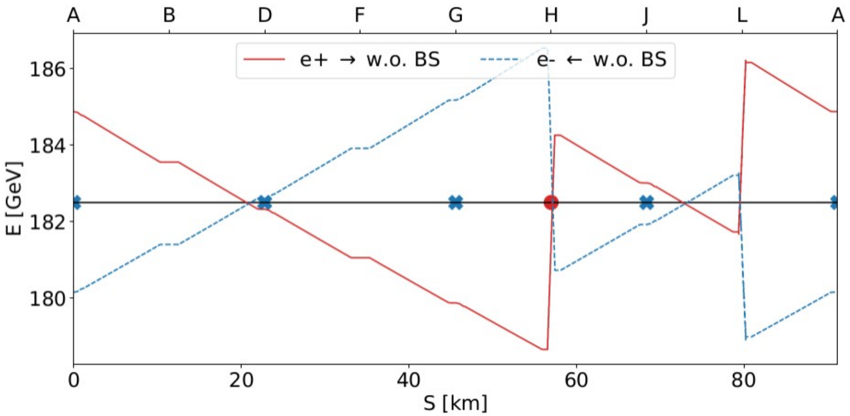
IP	ΔECM [MeV]	Boost [GeV]
PA	-0.060	4.711
PD	- 60.621	-0.289
PG	15.793	- 5.290
PJ	-61.877	-1.084

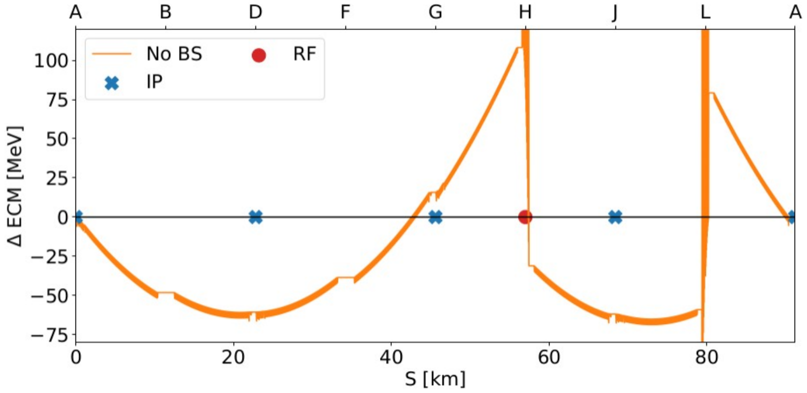


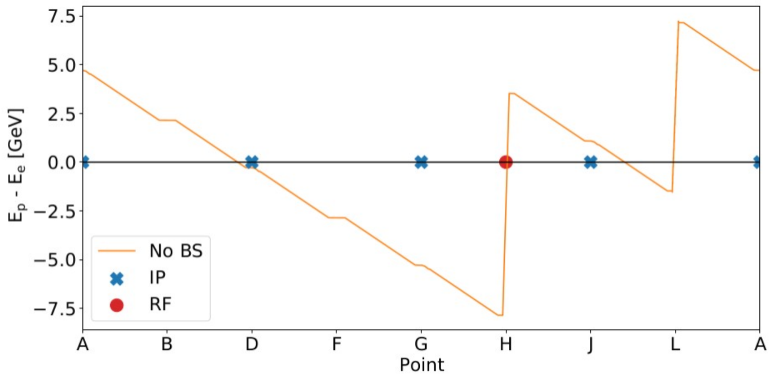
$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{\mathrm{e+}}E_{\mathrm{e-}}}\cos\alpha/2$$

Boost: + for e+; - for e-







RF-Placements for ttbar-Mode

- Different placement options for the RF-cavities of main rings and booster studied

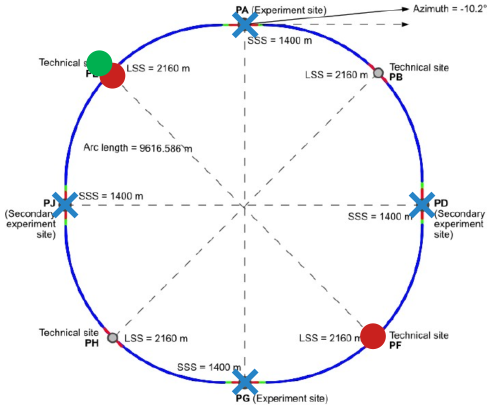
2 RF sections required for split cryo

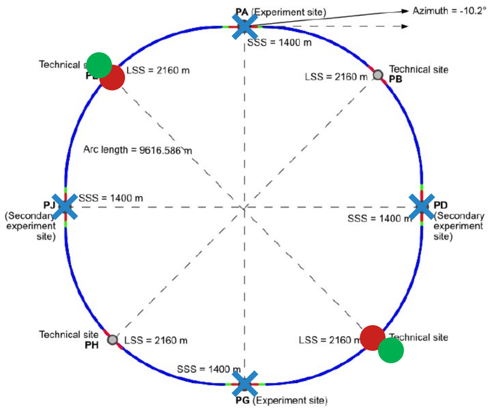
2 RF for the main rings
1 RF for the booster

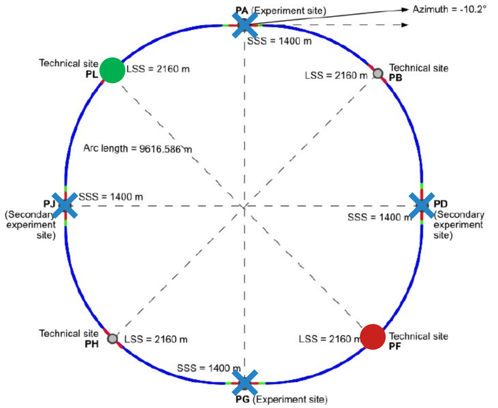
2 RF for the main rings
1 RF for the booster

1 RF for the main rings
1 RF for the booster

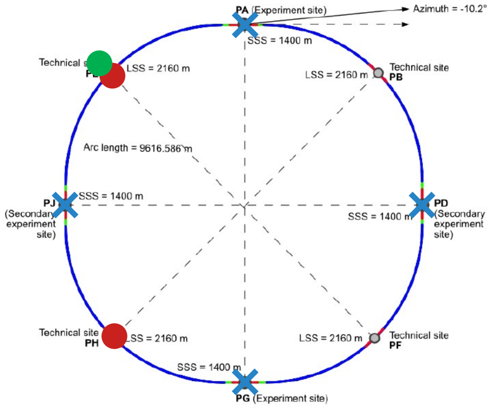
Symmetrically placed
In the lattice:
PL and PF

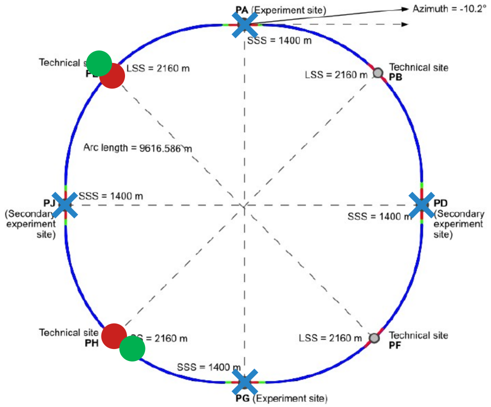


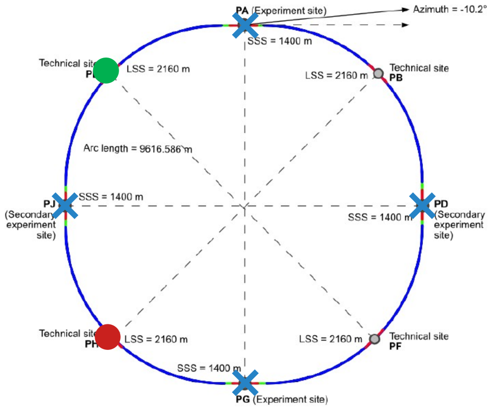




Asymmetrically placed
In the lattice:
PL and PH



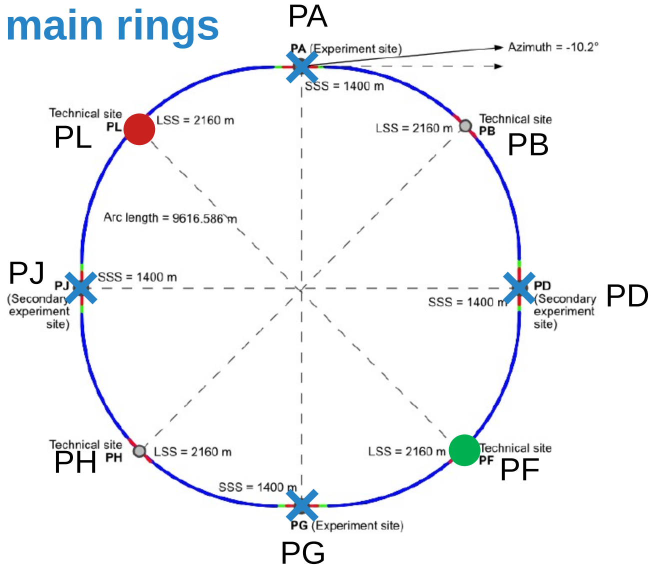




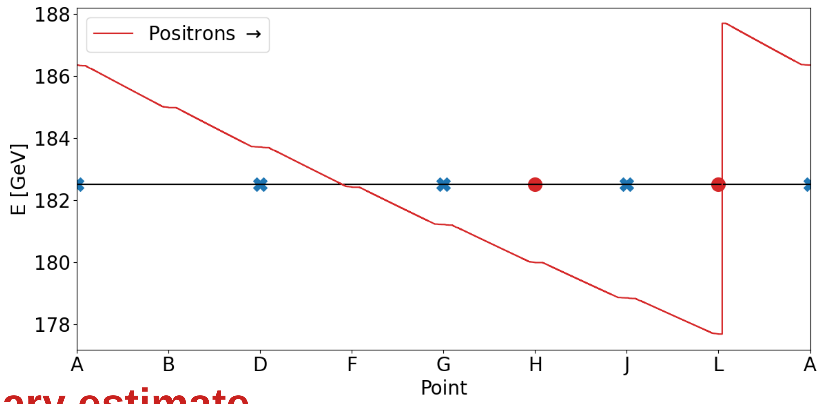
Momentum Difference ttbar-Mode

- Top-up injection in PB
- Energy difference at injection point to be considered

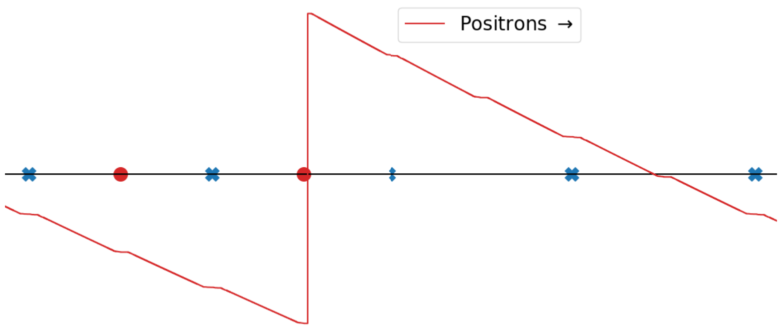
Booster into main rings



Main ring positrons
PB: ~184.973 GeV
(+1.36 %)



Preliminary estimate



Booster positrons
PB: ~179.978 GeV
(-1.38 %)

Largest energy difference if one RF-section for booster and main ring and separated as much as possible in the lattice

Injected beam about 5 GeV (-2.75 %) lower energy than stored beam at PB

To be considered for top-up injection strategy

Summary

- Determination of ECM at each IP not trivial since beam energies not constant
  - First presented studies include synchrotron radiation losses and beamstrahlung
  - Future studies will include optics errors, chromatic optics functions, dispersion, etc.

- One RF-point for both beams lead to almost constant ECM
  - Physics requirements for Z- and WW-lattice fulfilled
- Two RF-points lead to larger ECM offsets and boosts
  - Studied layouts fulfill physics requirements at top energy

- Impact of different energy between injected and stored beam at to be studied

FUTURE CIRCULAR COLLIDER

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Thank you!

Energy calibration and polarization
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