Center-of-mass energy and boosts for various RF-configurations

Jacqueline Keintzel

Acknowledgements: Alain Blondel, Victor Caudan, Riccardo De Maria, Katsunobu Oide, Tobias Persson, Rogelio Tomas, Jorg Wenninger, Frank Zimmermann

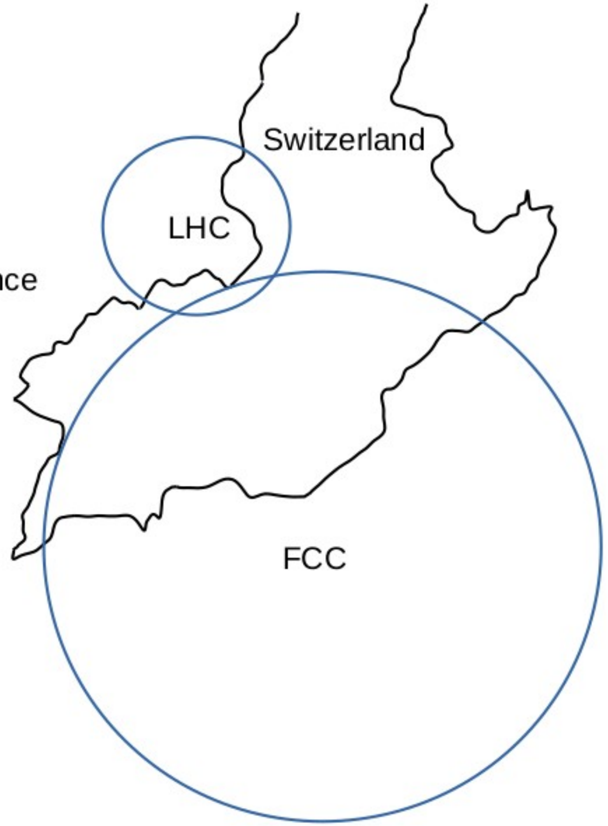
Future Circular Collider Week 2022
Energy Polarization, Calibration and Monochromatication Session
1st June 2022

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.

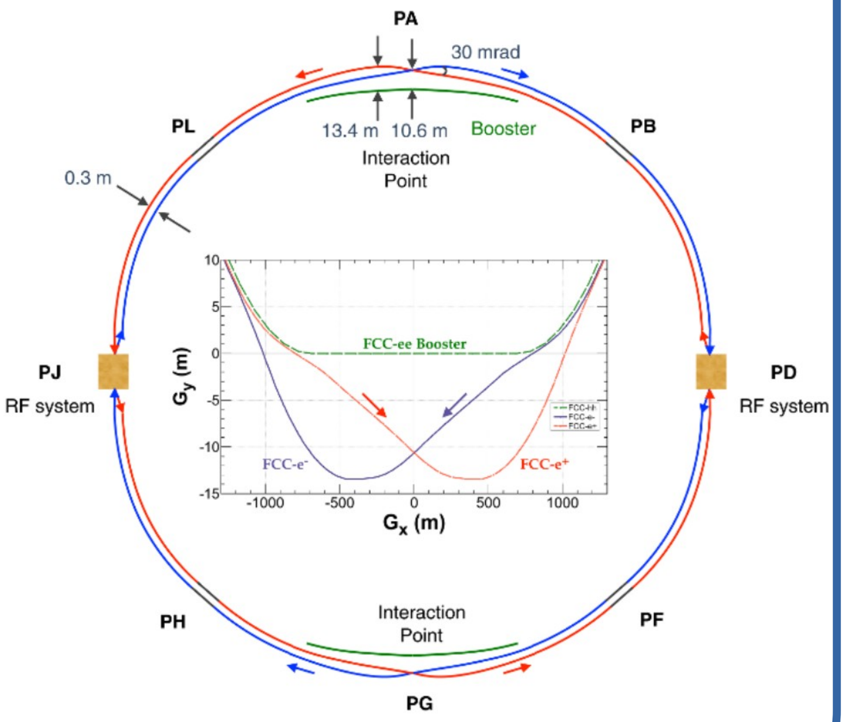
Future Circular Colliders

Inspired by LEP-LHC programm

Re-using CERN infrastructure

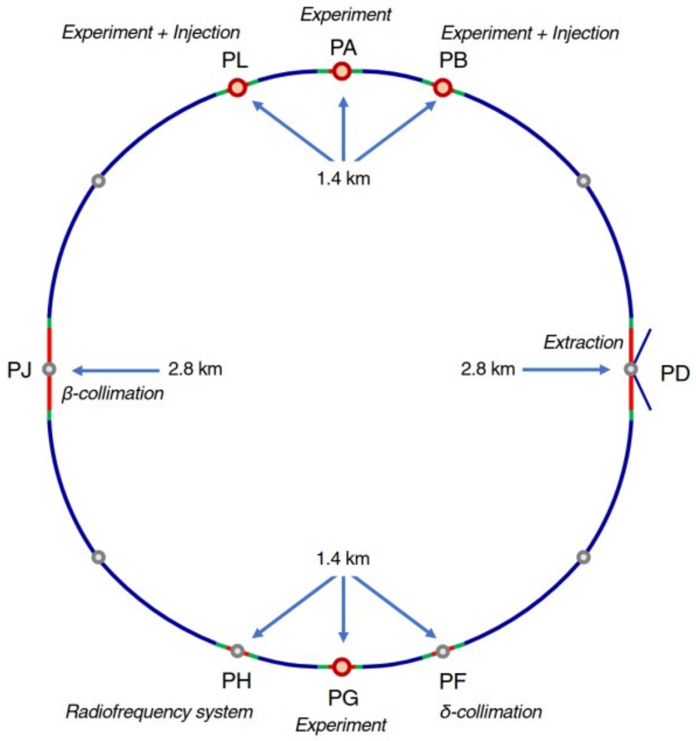


FCC-ee
Electron-positron collider



M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 261-623, 2019.

FCC-hh
Proton-proton collider

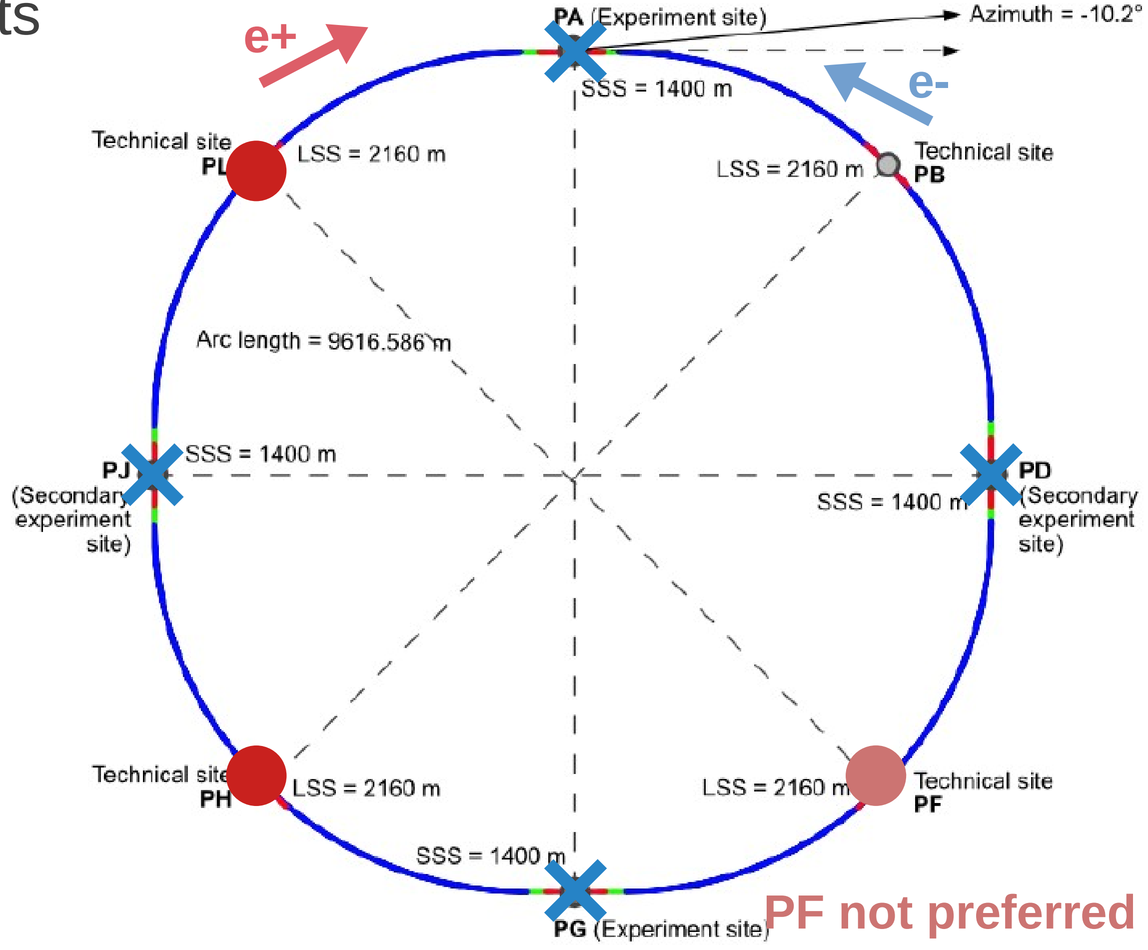


M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 755-1107, 2019.

Motivation

- Designed for high precision physics experiments
- FCC-ee demands precise knowledge of
  beam energies, center-of-mass energies and
  boosts at all Interaction Points (IPs)
- New "lowest risk" 4 IP (✕) scenario
- Beam energy depends on RF-location (●)
- One RF-point for Z-, WW-, and Higgs-lattice
- Two RF-points for ttbar-lattice

Talk: K. Hanke,
"The RF System of FCC-ee – General Considerations",
Thursday 2nd June 2022, 09:00



PF not preferred section

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

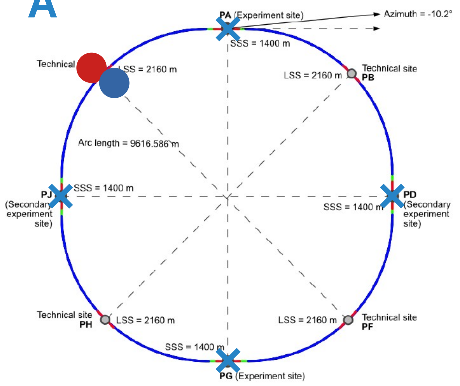
- A: 1 RF-section, which is common (individual) for both beams
- B: 2 RF-sections, which are common (individual) for both beams
- C: 2 RF-sections, which are individual for each beam

● … RF for positrons ● … RF for electrons

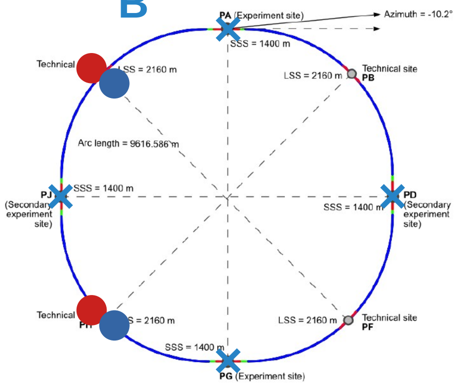
Integration and cryogenics requirements

Talk: F. Peauger, "Baseline and cavity options for FCC-ee", Tuesday 31st June 2022, 11:00

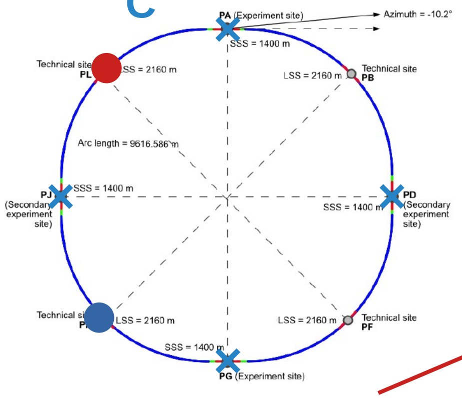
A



B



C



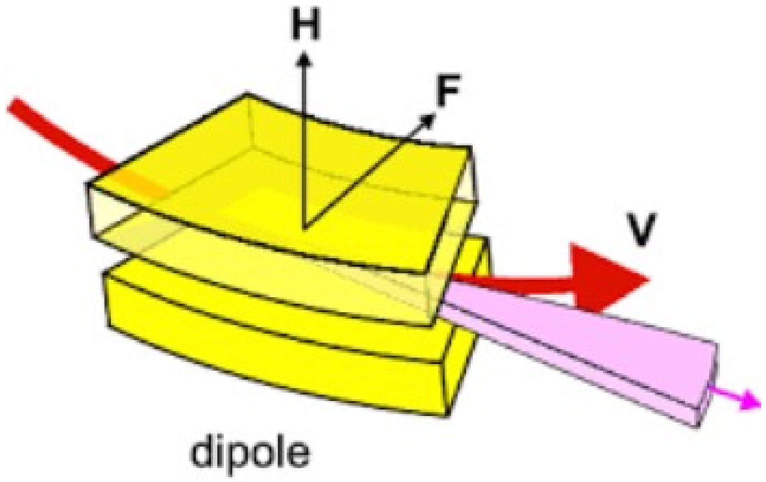
Talk: F. Valchkova, "Integration of FCC-ee RF Sections", Thusday 2nd June 2022, 09:30

Talk: A. Blondel, "FCC-ee EPOL", Wednesday 1st June 2022, 09:00

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



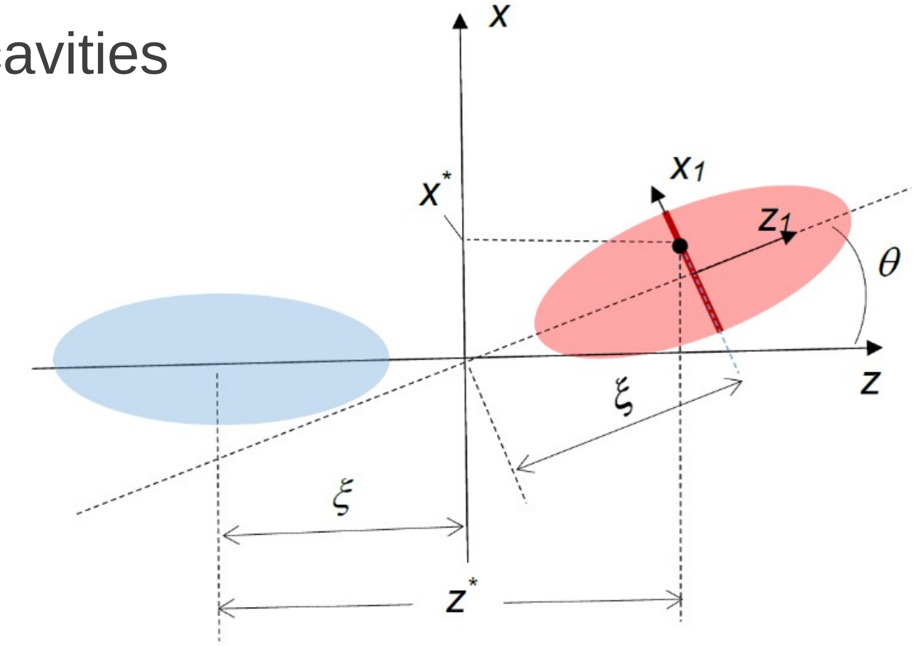
Average energy loss through a dipole

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

L … Dipole length
ρ … Bending radius ρ=L/θ
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:

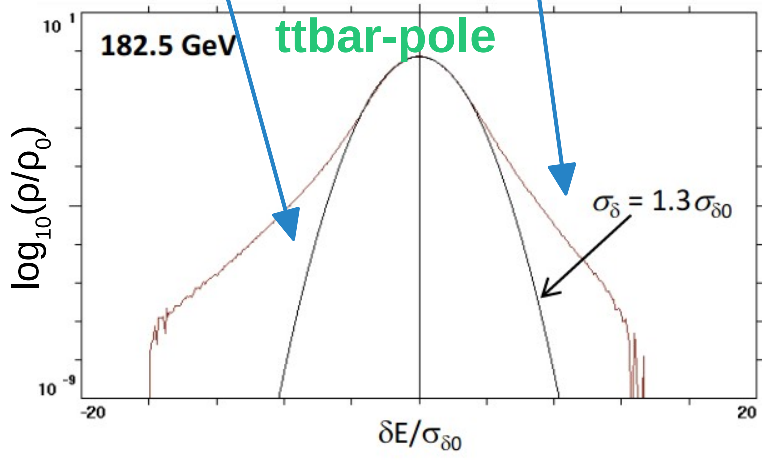
$$u_c \propto \frac{\gamma^3}{\rho} \propto \xi_y$$

Talk: A. Chiarma,
“Machine induced backgrounds in the FCC-ee MDI region and Beamstrahlung radiation ”,
Thursday 2nd June 2022, 14:35

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

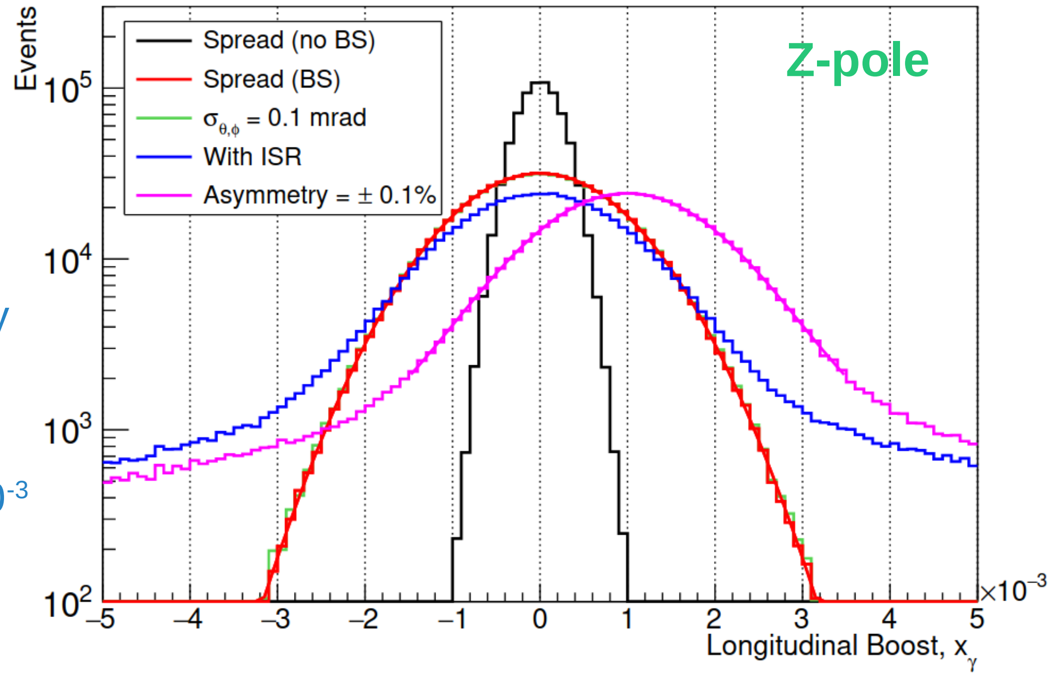


Black: no beamstrahlung
Red: + beamstrahlung
Green: + angular resolution
Blue: + photon emission
Pink: + asymmetry between electron and positron energy

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.

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
- Circumference changes, e.g. earth tides
- Dispersion at the interaction point
- Chromatic optics functions
- Optics errors
- …

Talk: T. Charles,
“Optics correction studies”,
Tuesday 31st May 2022, 09:50

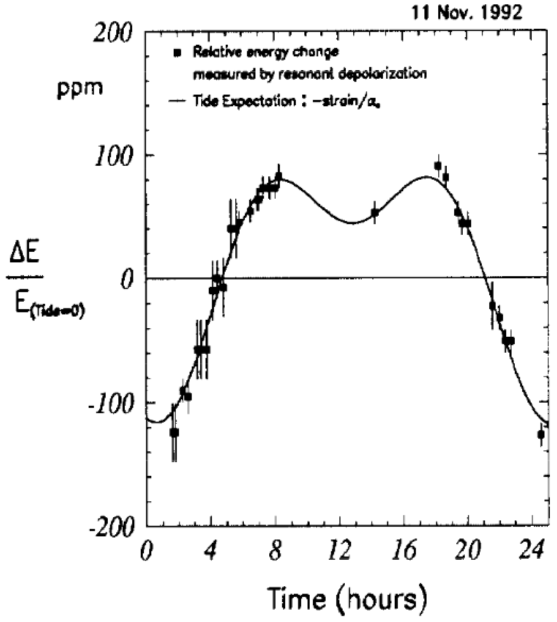
Talk: R. Tomas,
“Correction and tuning”,
Wednesday 1st June 2022, 14:00

Change of ECM due to dispersion at the IP

$$\Delta\sqrt{s} = -2u_0 \frac{\sigma_E^2 (D_{u1} - D_{u2})}{E_0(\sigma_{B1}^2 + \sigma_{B2}^2)}$$

U_0 … nominal ECM
$D_{u1,2}$ … dispersion at the IP
E_0… nominal energy
$\sigma_{B1,2}$ … beam size at the IP

Energy change due to earth tides in LEP
→ needs to be compensated by RF



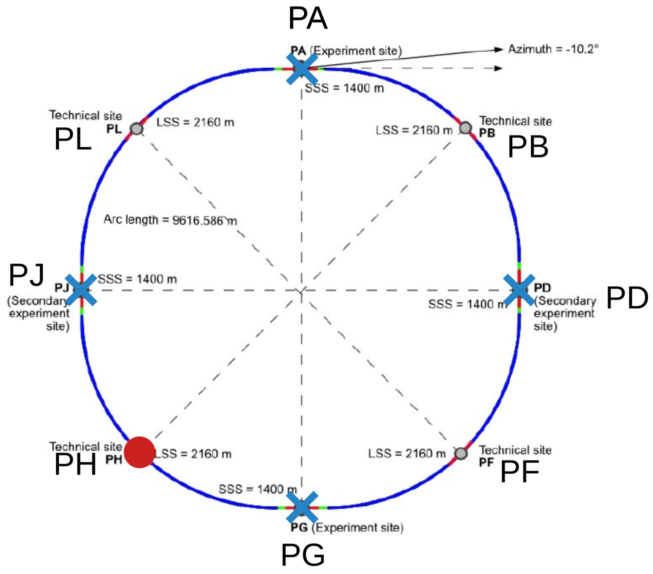
Many more things to consider to determine collision energy

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

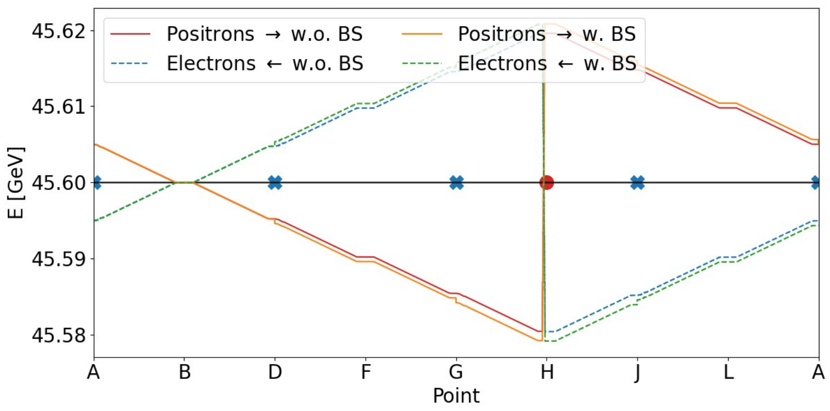
Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

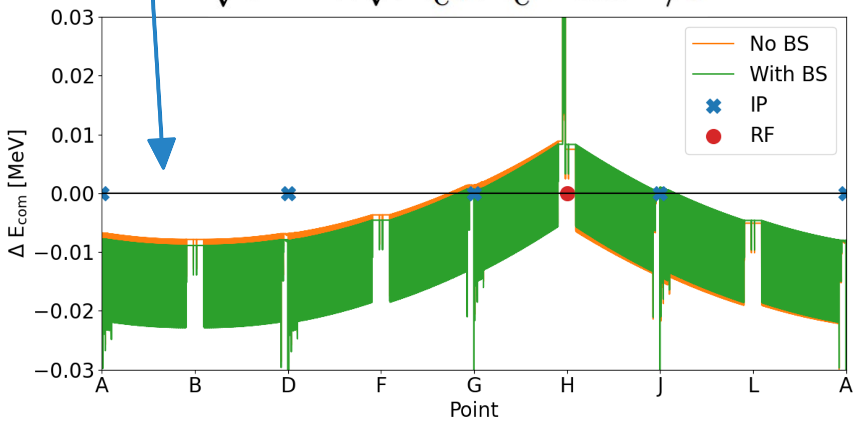
1 RF → almost constant ECM

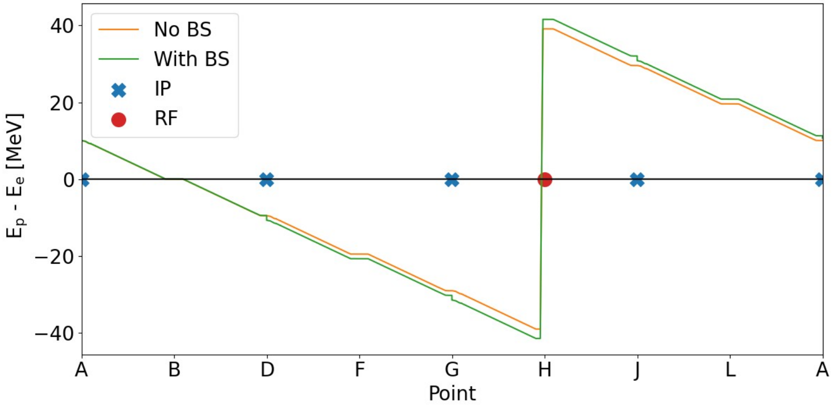
Boost: + for e+; - for e-

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

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





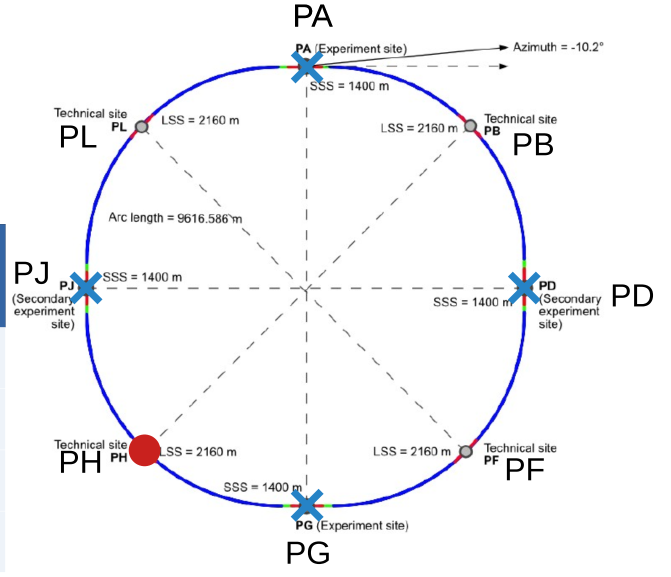


ECM and Boosts for WW-Mode

- **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

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

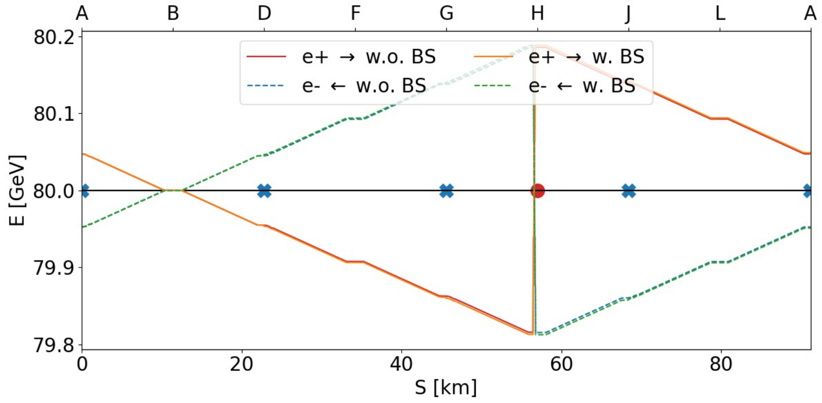


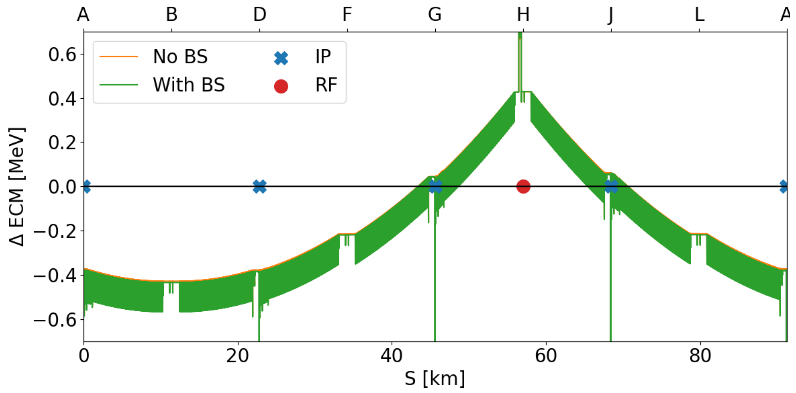
Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

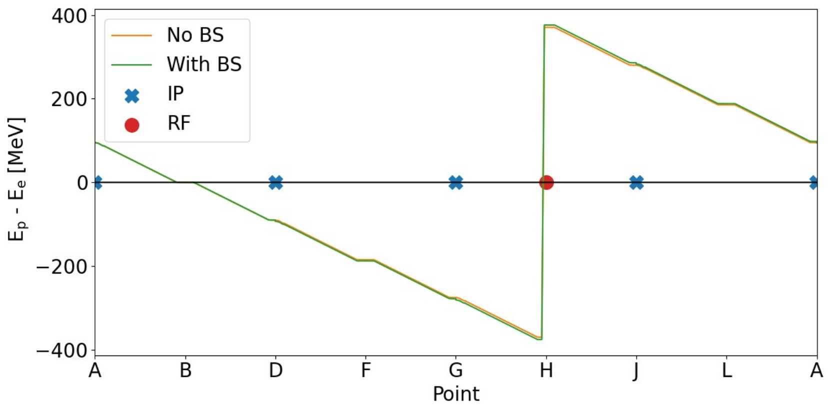
$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

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

Boost: + for e+; - for e-

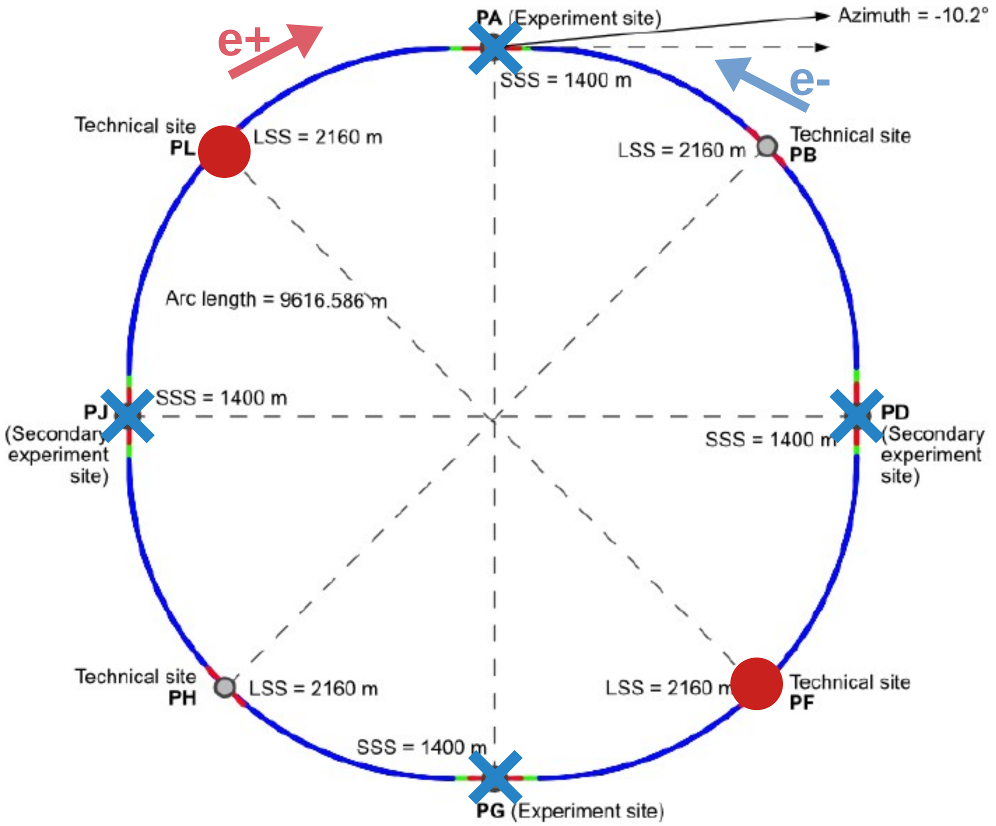




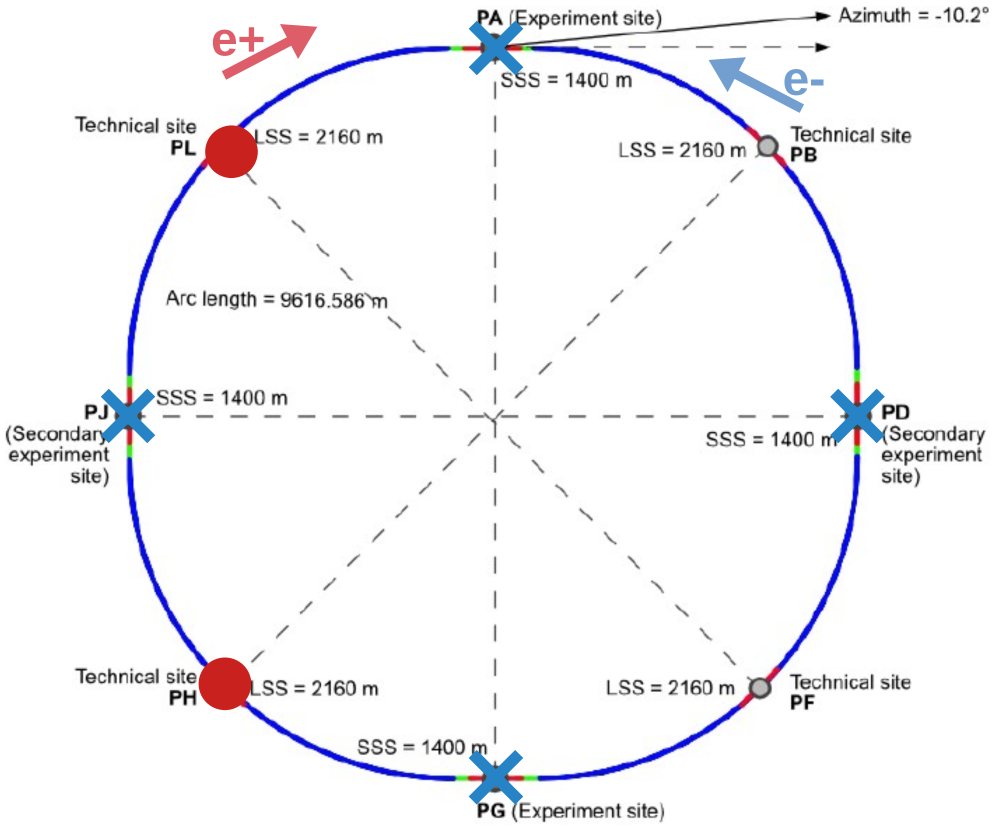


RF-Placements for ttbar-Mode

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



Symmetrical option



Asymmetrical option

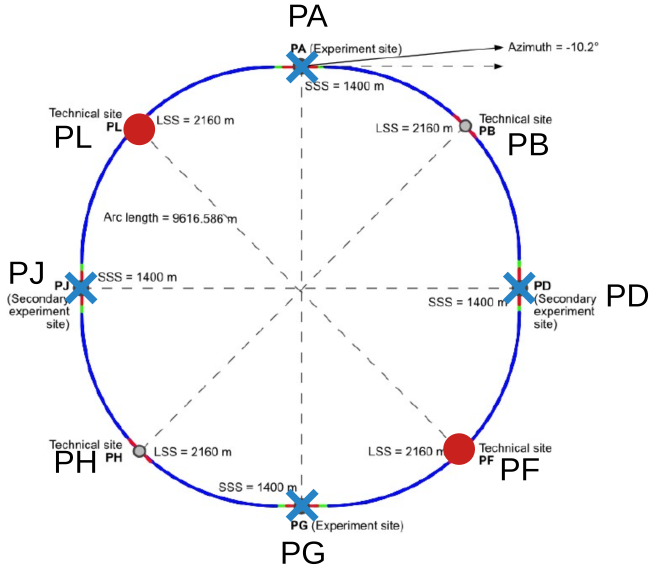
ECM and Boosts for ttbar-Mode

- **PF: 5 GV, 400 MHz** cavity and **PL: 6.7 GV, 800 MHz** cavity
- $\lessapprox$ 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

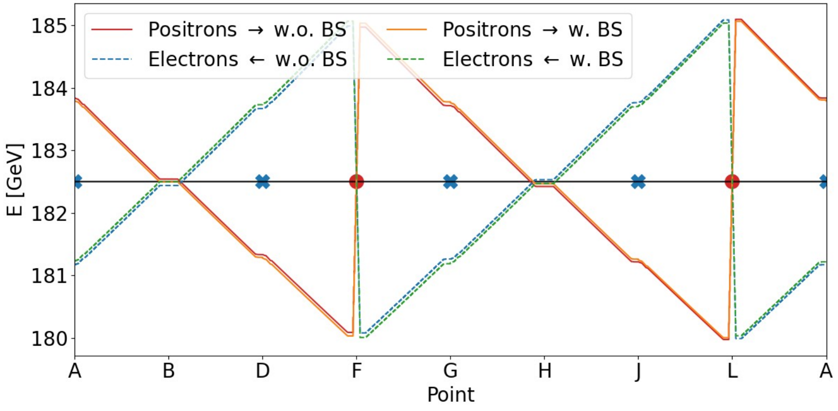
IP	ΔECM [MeV]	Boost [GeV]
PA	12.663	2.574
PD	11.043	- 2.455
PG	- 46.531	2.573
PJ	- 48.155	- 2.454

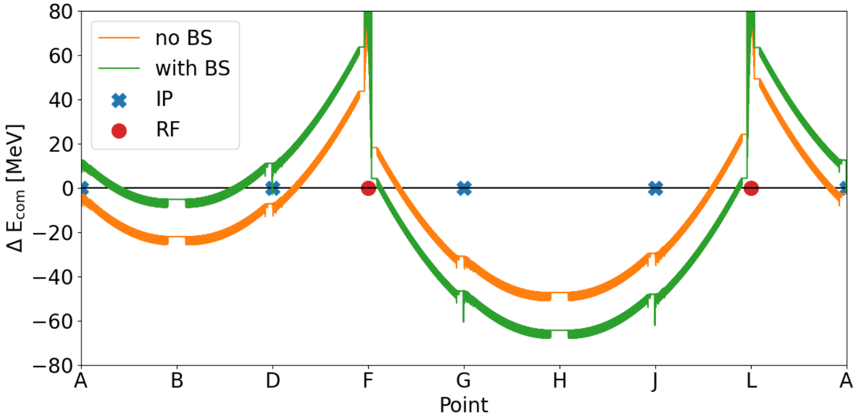


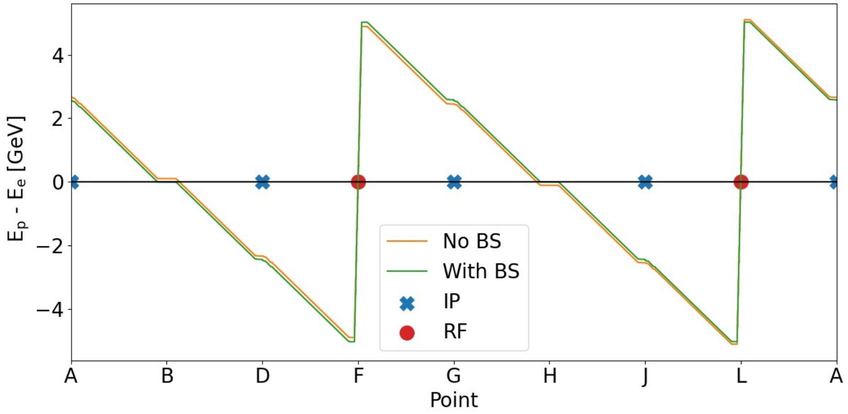
Boost: + for e+; - for e-

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

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







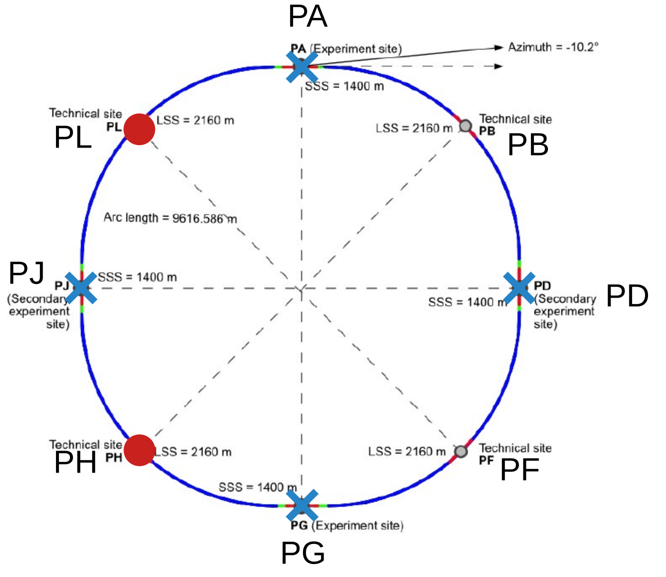
ECM and Boosts for ttbar-Mode

- **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

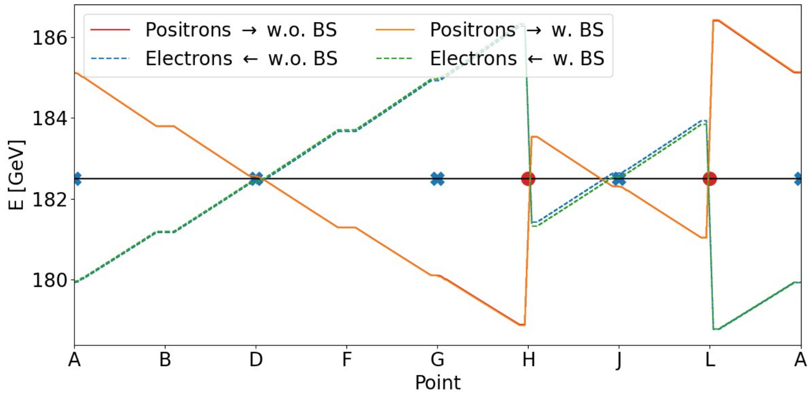
IP	ΔECM [MeV]	Boost [GeV]
PA	42.813	5.187
PD	- 30.176	0.157
PG	34.236	- 4.873
PJ	-152.467	- 0.233

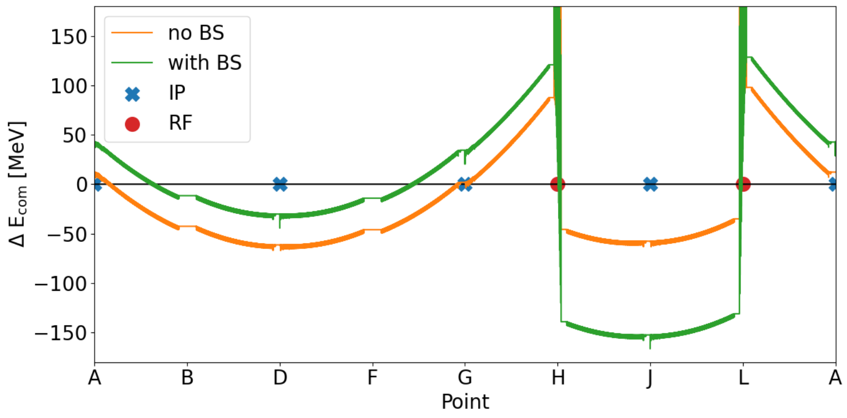


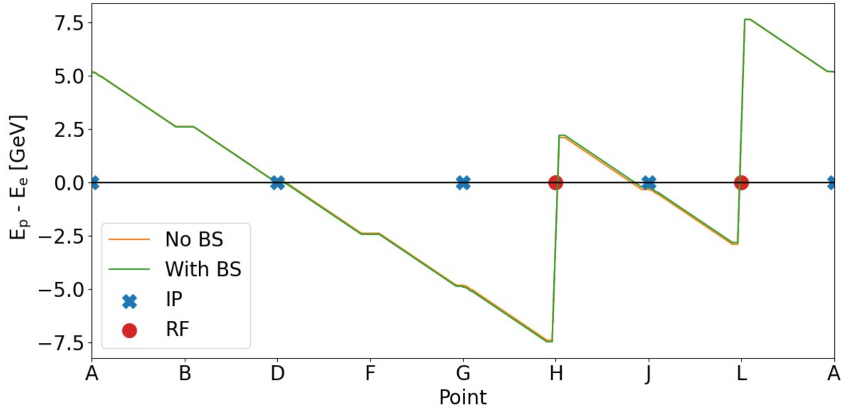
Boost: + for e+; - for e-

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

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





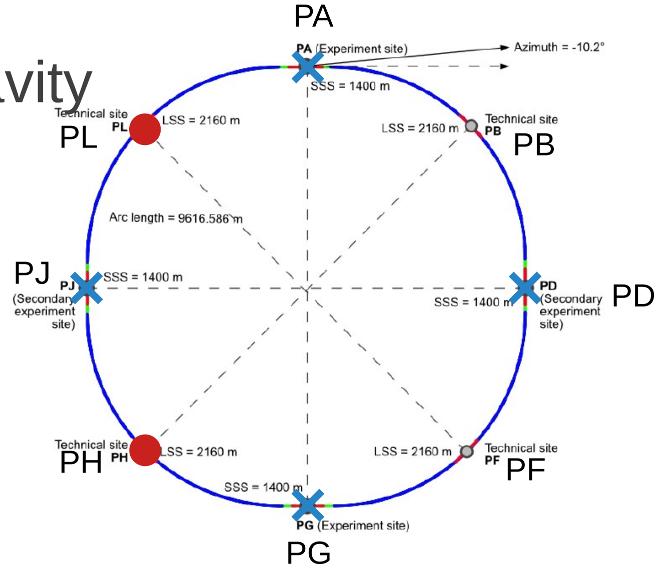


ECM and Boosts for ttbar-Mode

- **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

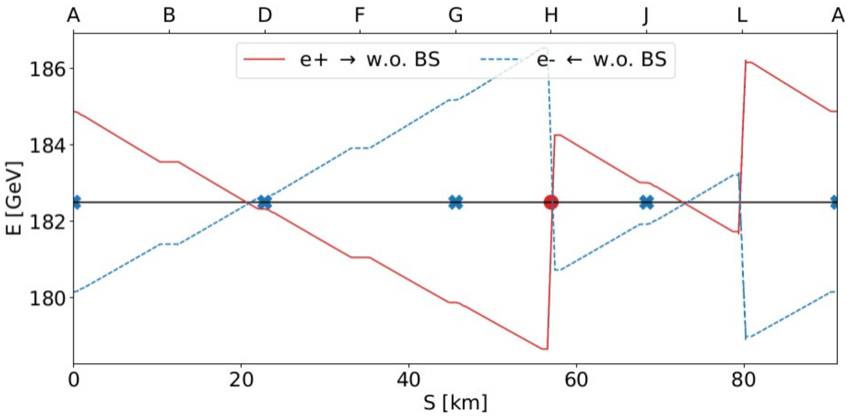
IP	ΔECM [MeV]	Boost [GeV]
PA	-0.060	4.711
PD	- 60.621	-0.289
PG	15.793	- 5.290
PJ	-61.877	-1.084

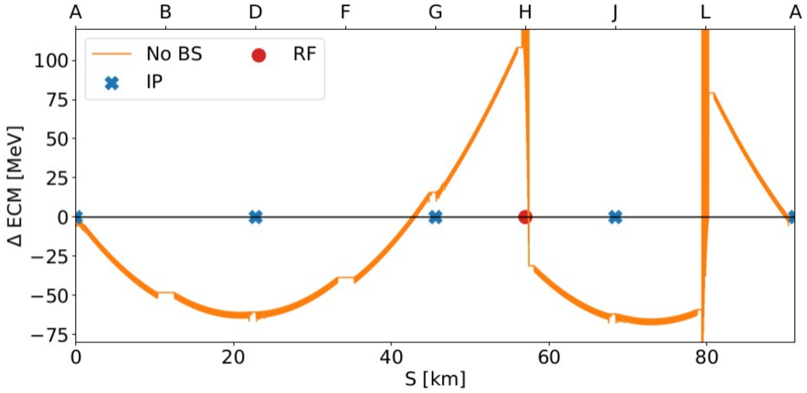


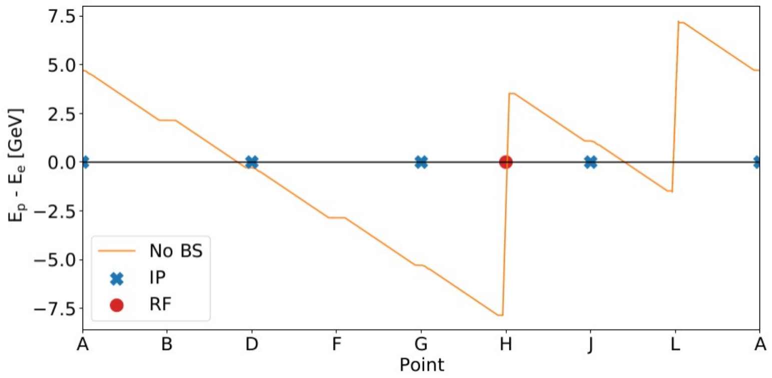
$$\Delta E \propto \gamma_{\mathrm{rel}}^{4}$$

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

Boost: + for e+; - for e-



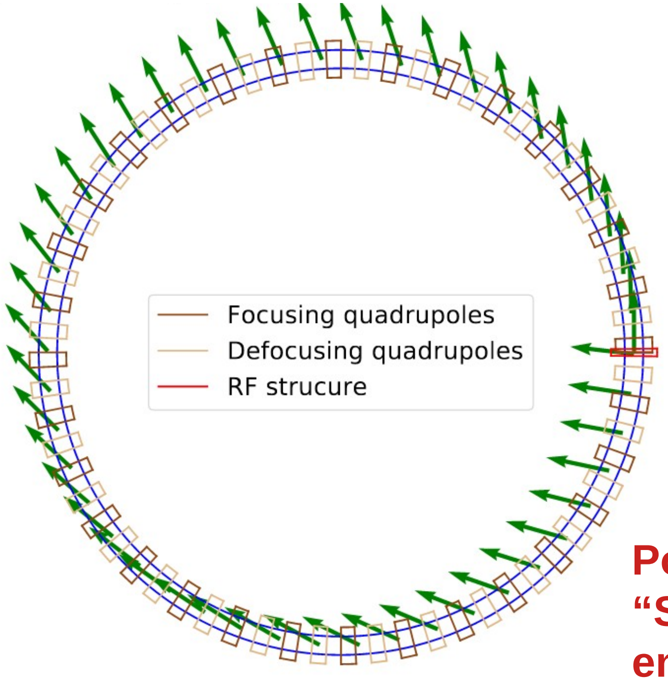




Energy from Spin Tune

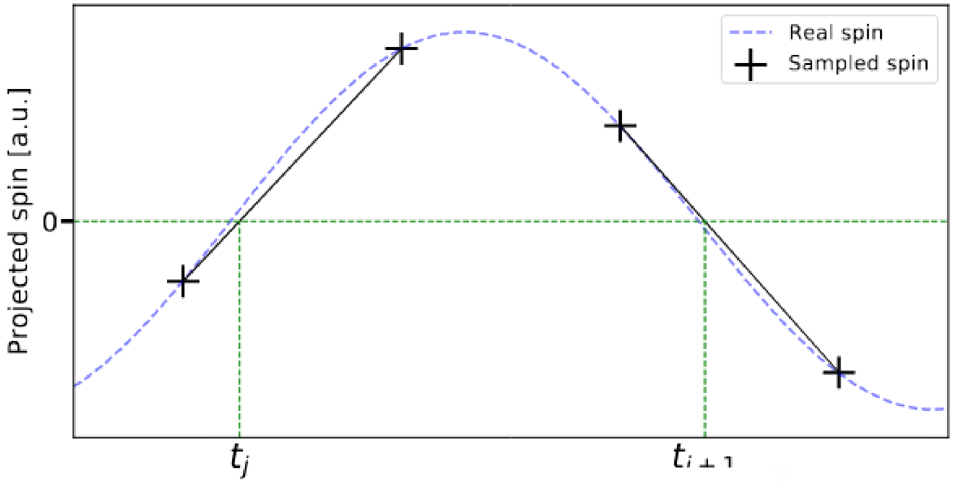
- Using resonant depolarization and polarimeter to determine average beam energy
- Understand spin dynamics in a synchrotron essential

Spin movement through FODO lattice with 100 m circumference



$$E = mc^2 \left(\frac{\nu}{a} - 1 \right)$$

E … energy
m … mass
c … speed of light
ν … spin tune
a … anomalous magnetic dipole moment



$$\nu_j \approx \frac{1}{2(t_{j+1} - t_j)} \frac{1}{f_{\text{rev}}}$$

Poster: V. Caudan,
“Spin precession as a method for beam energy measurement”,
Thursday 2nd June 2022, from 16:00

Talk: I. Koop,
“Study of the depolarization process, possible biases”,
Thursday 2nd June 2022, from 09:20

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

- Depolarization of polarized beams used to determine average beam energy

Thank you!

Centre-of-mass energy and boosts for various RF configurations

Jacqueline Keintzel

Acknowledgements: Alain Blondel, Victor Caudan, Riccardo De Maria, Katsunobu Oide, Tobias Persson, Rogelio Tomas, Jorg Wenninger, Frank Zimmermann

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ECM and Boosts for ttbar-Mode

- **PH: 2.48 GV, 400 MHz** cavity and **PL: 9.19 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

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

IP	ΔECM [MeV]	Boost [GeV]
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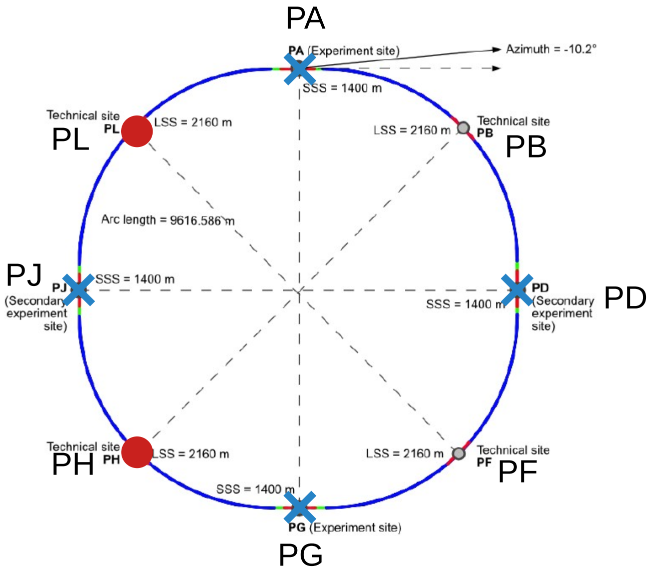
PG	34.236	- 4.873
PJ	-152.467	- 0.233

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



Boost: + for e+; - for e-