AWAKE++ PEPIC Beam Line Exploratory Study

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A Plasma Electron Proton/Ion Collider, PEPIC

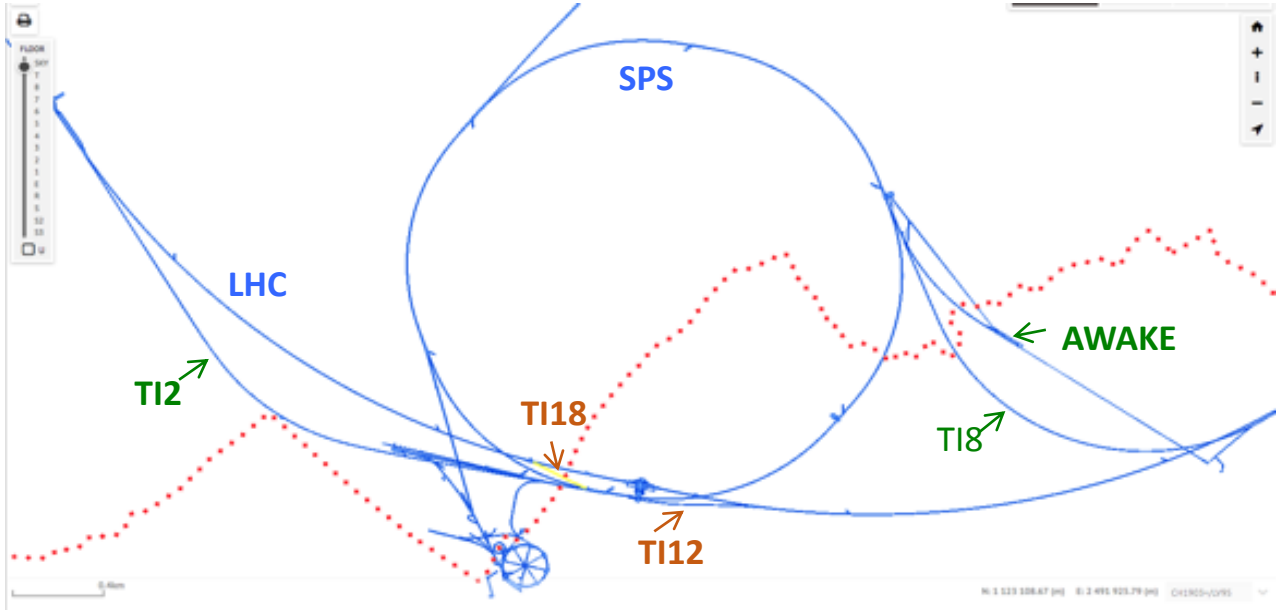
- LHeC like collider based on AWAKE plasma wakefield acceleration scheme
- 400 GeV p beam from the SPS
  → minimum bending radius of the beam line is the one of the SPS (1100 m, limited by the achievable field in normal conducting magnets)
- Electron beam with 100-150 GeV produced in 100 m (minimum length) to 200 m (maybe more realistic) long plasma cell(s)
  → LEP like beam, bending radius limited by synchrotron radiation losses. LEP radius (4300 m) as minimum bending radius is a safe assumption. Not a hard limit, synchrotron radiation losses could be compensated to a certain extend with a higher electron energy (and therefore longer plasma cell)
- Intensity of electron beam 1e9 e-

Scope of the study

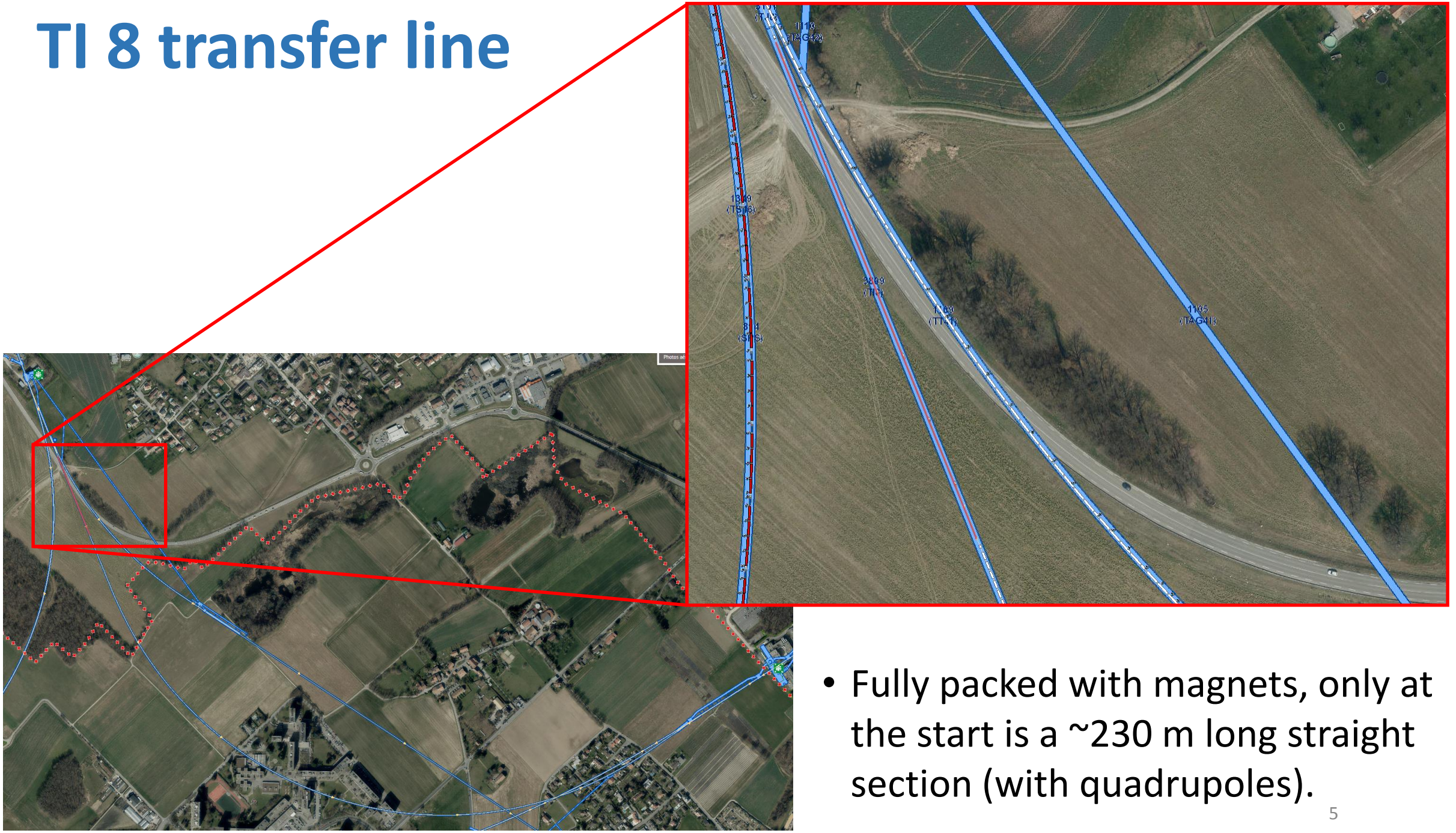
- Location of plasma cell
- Separation of proton and electron beam
- Beam transport of electron beam to the LHC
- Dumping of proton beam after plasma cell
- List of elements (types and quantities (0 order estimate))
- Civil engineering impact
- Summarize outcome on a document
- Limit of this study: Injection of electron beam into the LHC tunnel

Possible locations for PEPIC plasma acceleration stage

- Possible locations for pe- collider experiment would be either ALICE or LHCb.
- Since p beam is produced in the SPS a natural location for the plasma cell(s) would be in one of the transfer tunnels from the SPS to the LHC:
  - TI 2 SPS -> LHC beam 1
  - TI 8 SPS -> LHC beam 2
  - TI 12 old e- TL from SPS to LEP
  - TI 18 old e+ TL from SPS to LEP
- LHC needs to stay fully operational as pp collider
- PEPIC equipment needs to share space with existing equipment in LHC/TI2/TI8

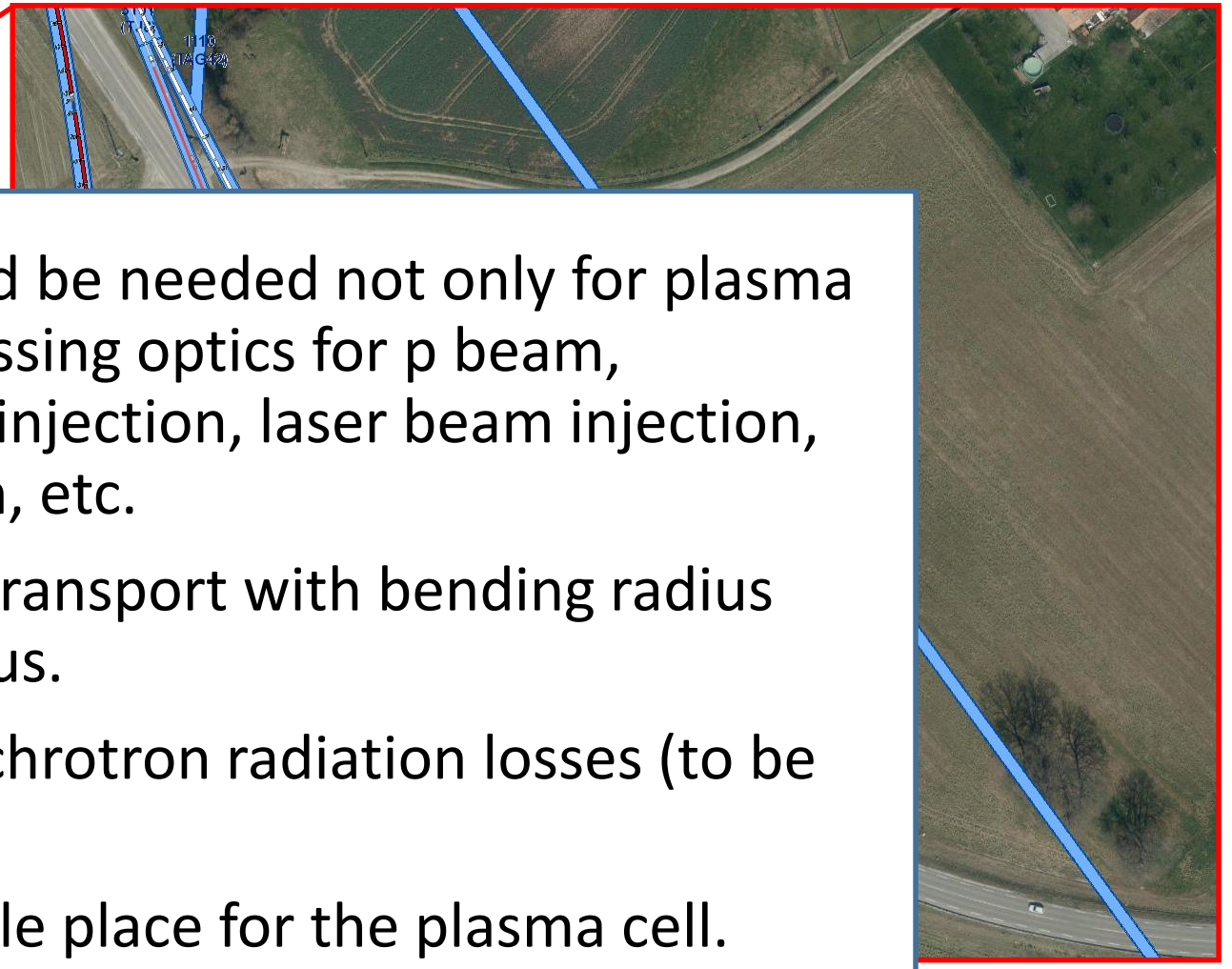


TI 8 transfer line

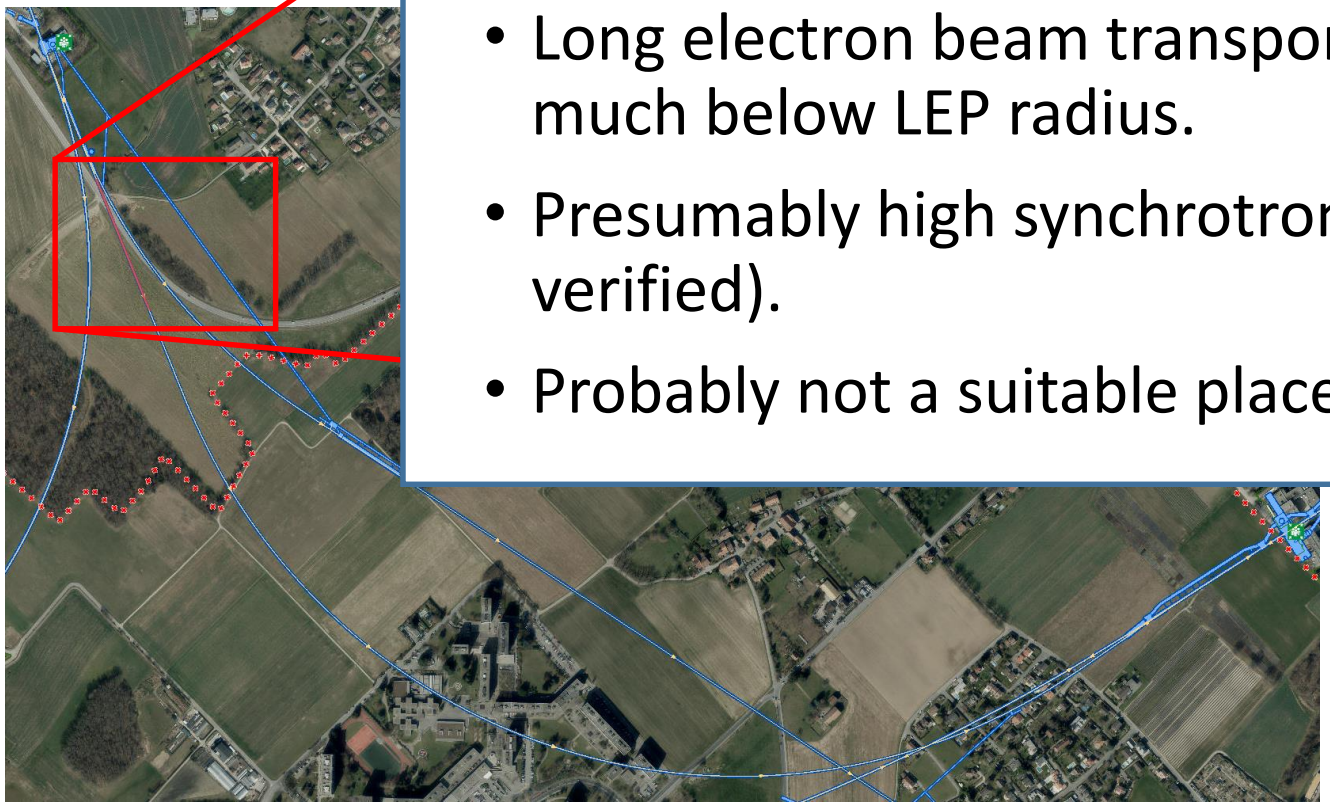


- Fully packed with magnets, only at the start is a ~230 m long straight section (with quadrupoles).

TI 8 transfer line



- Available space would be needed not only for plasma cell, but also for focussing optics for p beam, diagnostics, e- beam injection, laser beam injection, p/e- beam separation, etc.
- Long electron beam transport with bending radius much below LEP radius.
- Presumably high synchrotron radiation losses (to be verified).
- Probably not a suitable place for the plasma cell.



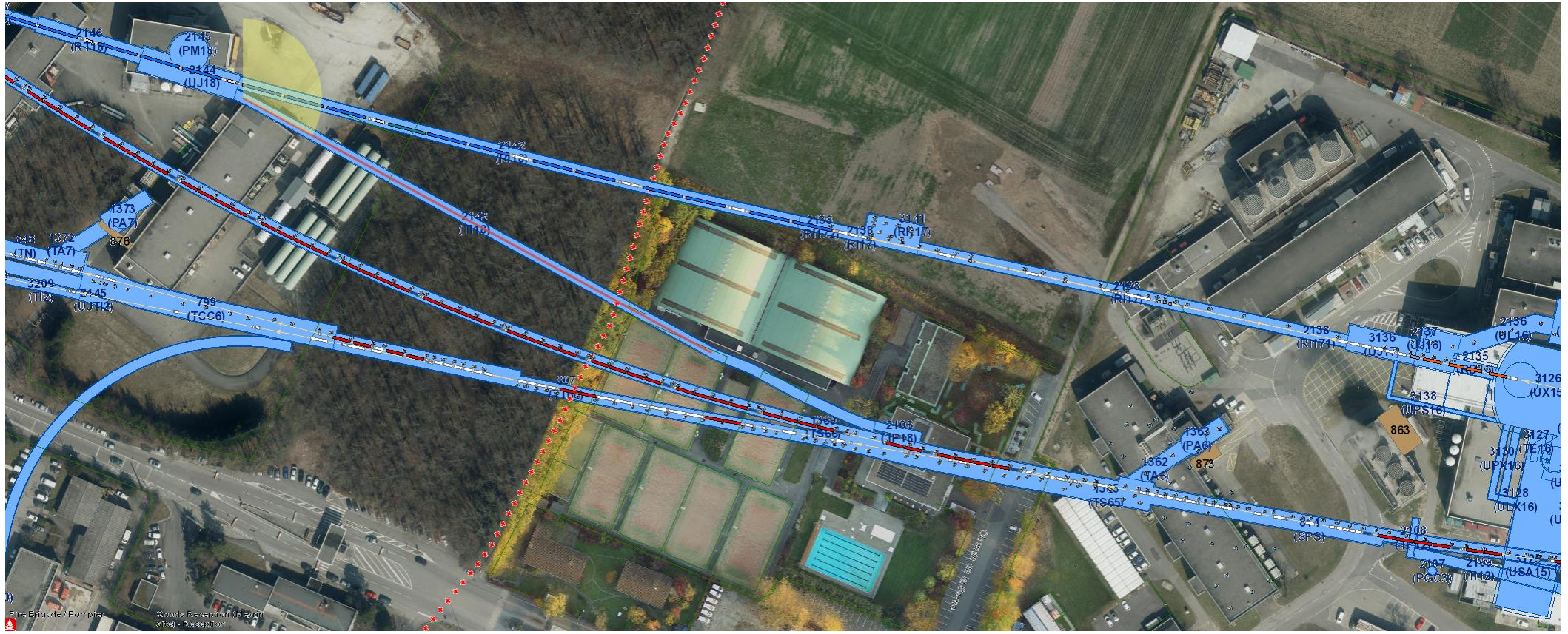
- Fully packed with magnets, only at the start is a ~230 m long straight section (with quadrupoles).

TI 12 transfer line tunnel

- Tunnel currently not used for beams.
- Contains a 275 m long straight section.
- However, tunnel direction is opposite to the SPS beam direction.
- Therefore, it cannot be used for PEPIC.

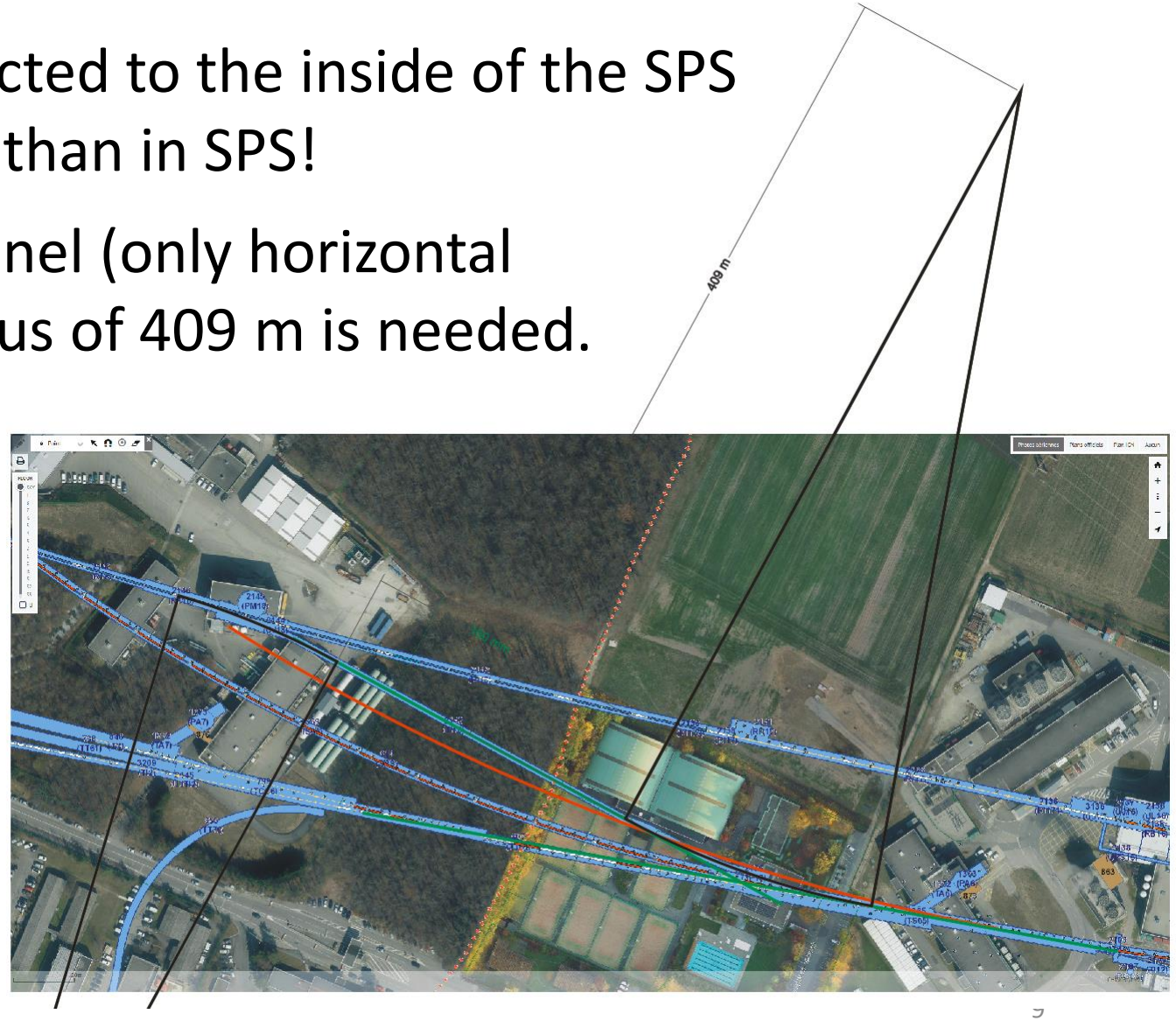
TI 18 transfer line tunnel

- Tunnel currently not used for beams.
- Contains a 190 m long straight section.
- Tunnel direction is in the SPS beam direction.



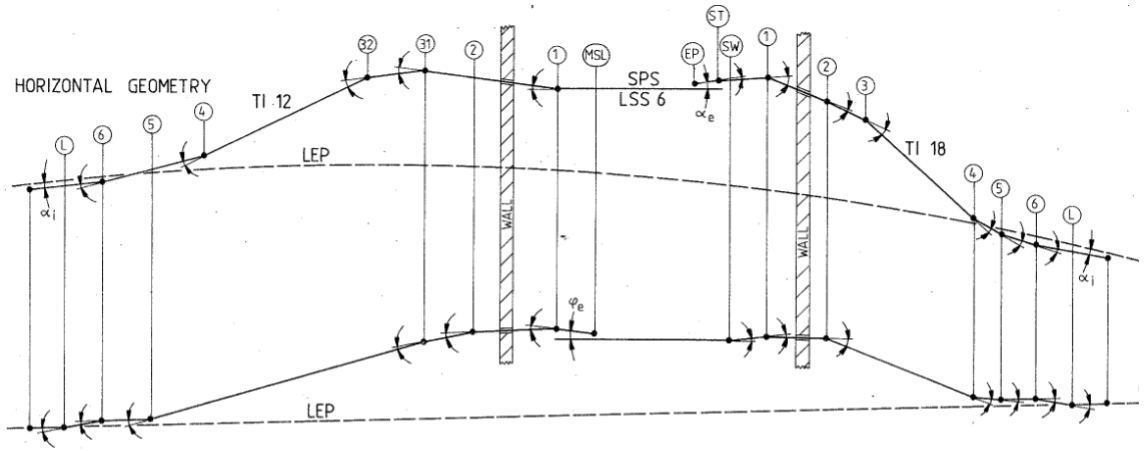
TI 18 transfer line tunnel

- However, beam needs to be extracted to the inside of the SPS → smaller bending angle needed than in SPS!
- To squeeze beam into existing tunnel (only horizontal plane considered!) a bending radius of 409 m is needed.
- With 70% filling factor as in SPS 4.7 T magnets would be required.
- A beam path with SPS radius would not fit into the tunnel.



TI 18 transfer line tunnel

- In addition a substantial height difference of ~40 m needs to be overcome in a short distance, which yields to a large tunnel slope of ~15%.
- Additional 18 6.62 m long MBB type bending magnets would be needed to deflect the beam onto this slope and another 18 to deflect the beam back to horizontal plane.



MSL = Septum magnet e⁻ extraction
EP = Extraction point TT 60
ST = Steering dipole [MDLH]
SW = Switch TT 60 – TI 18 [IMCV]
L = Steel septum magnet [IMSA]

Bend	TI 12		TI 18	
	Hor. defl. [rad]	Vert. defl. [rad]	Hor. defl. [rad]	Vert. defl. [rad]
α_e	—	—	0,0092	—
φ_e	—	0,05567	—	—
ST	—	—	−0,000744	0
SW	—	—	0	0,036429
1	−0,061577	−0,063149	−0,200713	−0,036429
2	0	−0,087818	−0,070125	−0,154441
3 31	0,107567	−0,004399	−0,05718	0
3 32	0,107681	0		
4	−0,022248	0	0,062651	0,157593
5	0	0,087818	0,055669	0,00967
6	−0,095	−0,036395	0,095	−0,036425
L	0	0,036396	0	0,036425
α_i	−0,001023	—	0,001023	—

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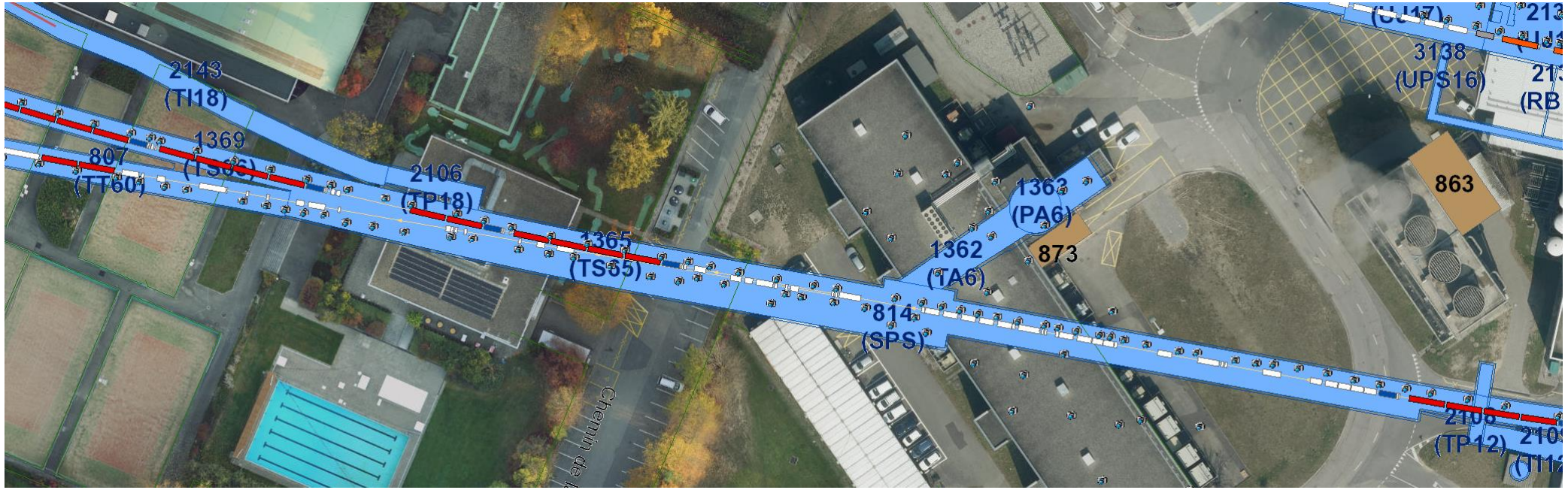
TI 18 transfer line tunnel

- LSS6 in the SPS is already densely occupied by the extraction elements for the west extraction towards TI 2 and HiRadMat.
- It is not obvious where the required extraction elements for PEPIC could be installed



TI 18 transfer line tunnel

Conclusion:

- The usage of the TI 18 tunnel for installation of a plasma acceleration stage for PEPIC is excluded

TI 2 transfer line

- In contrast to TI 8 the TI 2 transfer line has a 540 m long straight section, close to its end.
- This sections contains only quadrupoles, correctors and beam instrumentation elements in a regular FODO lattice with 30 m half cell length.

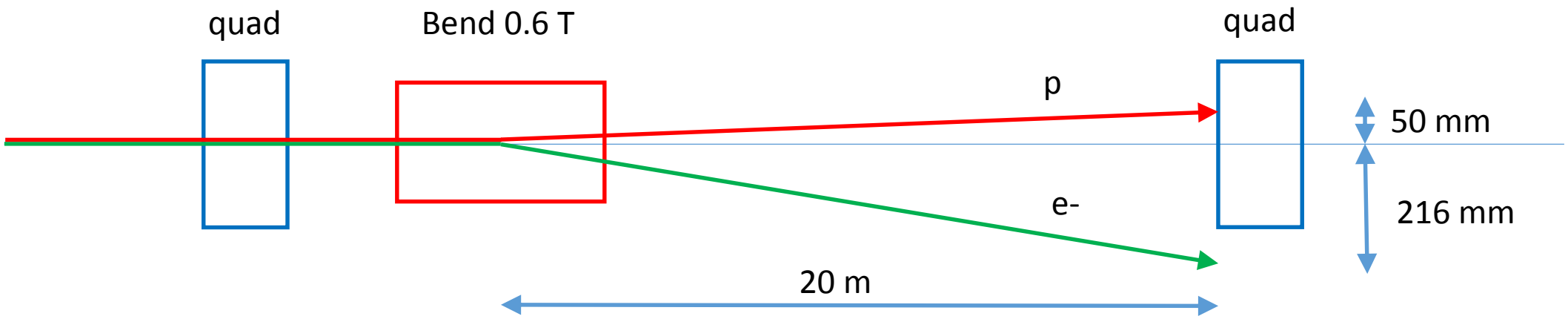
TI 2 transfer line

- There are 18 empty half cells available.
- 25 m in each half cell could be used for installing plasma cells and other AWAKE equipment (focussing quadrupoles, electron/laser injection, diagnostics).
- Downstream of the plasma cells the electron beam needs to be separated from the proton beam and transported in a own beam line, e.g. on top or on the side of the existing line.
- The proton beam needs to be safely dumped, either in a new dedicated beam dump or downstream TED.
- The aperture of TI 2 is rather small (diameter 29 mm)

TI 2 transfer line

Beam separation:

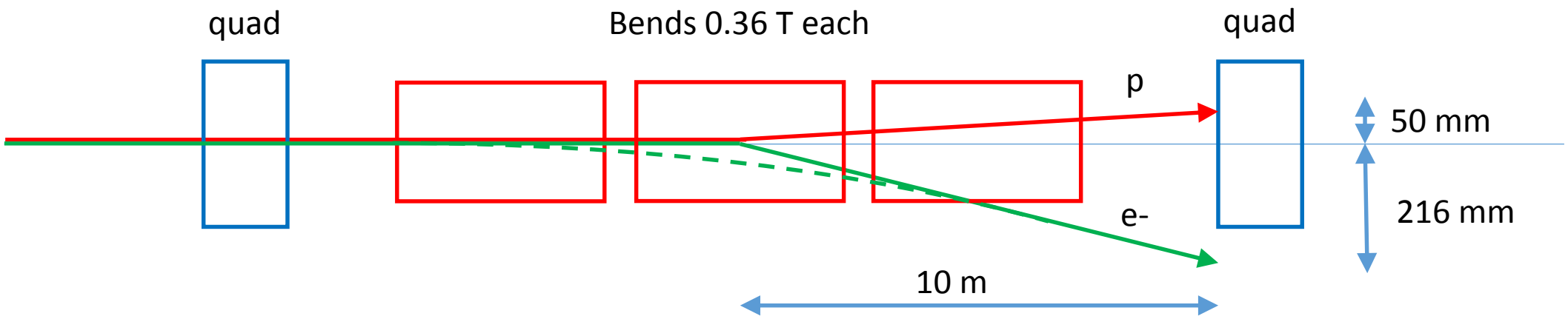
- By single bending magnet (6 m)



- Bending angle 0.011 rad, energy loss of e- beam 16%
- Relative large deflection of the proton beam. -> Beam hits the magnet.
- Energy of the synchrotron radiation pulse hitting the downstream TI 2 elements: 2.5 J (= 25 TW peak power in 100 fs pulse)
  Is this a problem?

TI 2 transfer line

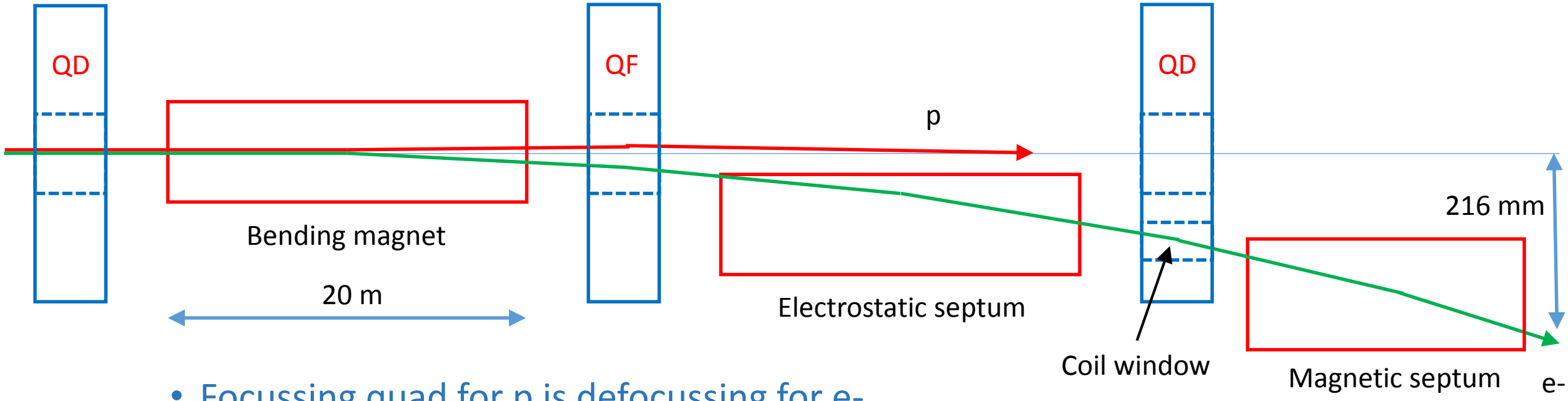
- More magnets (20 m):



- Bending angle 0.022 rad, energy loss of e- beam 9.5%
- Same problem with the deflection of the proton beam.
- Energy of the synchrotron radiation pulse hitting the downstream TI 2 elements: 1.5 J (= 15 TW peak power in 100 fs pulse)
- Situation not significantly improved concerning single bend scheme.

TI 2 transfer line

- Separation scheme over multiple half cells:



- Focussing quad for p is defocussing for e-
- Reduced energy loss for e- beam and reduced synchrotron radiation power.
- Reduced deflection of p beam. It might be able to transport p beam to TED.
- To be studied more in detail

Open questions and assumptions

- Damaging effects of synchrotron radiation.
- Does the energy loss due to synchrotron radiation increase (or decrease) energy spread?
- List of elements.

Assumptions:

- Lattice of e- beam line the same as p beam line.
- Electron beam transport up to the LHC tunnel.
- Only unpolarised electrons will be used.

Conclusion

- The TI 2 transfer line tunnel seems to be the only solution for housing the plasma acceleration stage of PEPIC without building a new transfer line tunnel.
- With this setup only dedicated PEPIC runs are possible, since the plasma cell needs to be moved out of the beam path or at least emptied for regular LHC operation.
- Although this solution makes a maximum use of existing tunnels, further new, non-negligible underground buildings are required: Laser lab, tunnel for electron gun, technical gallery for equipment, tunnel for proton beam dump, etc.

Outlook

- Having several plasma cells instead of one large plasma cell is not so favoured.
- For using only one long plasma cell, the corresponding space must be created in TI 2:
  - Changing the lattice and optics in TI 2.
  - Building a bypass beam line in TI 2 for AWAKE++. Could be in enlarged TI 2 tunnel or separate tunnel.
- To be studied…